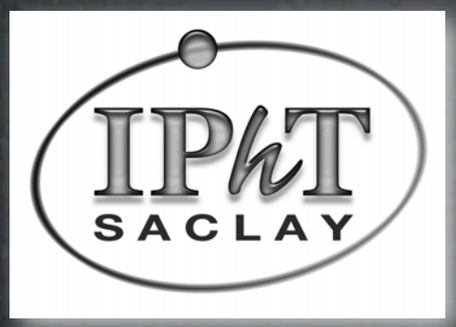
7 February 2014
IAP Paris

DM Indirect and Direct Detection phenomenology:
some anomalies and a status assessment

Marco Cirelli
(CNRS IPhT Saclay)



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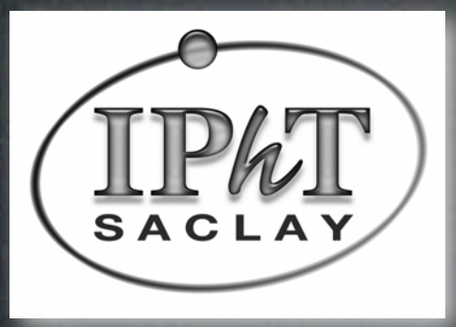

Introduction

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DM exists

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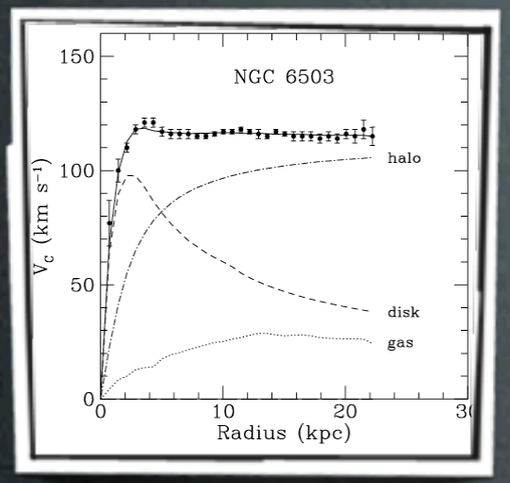
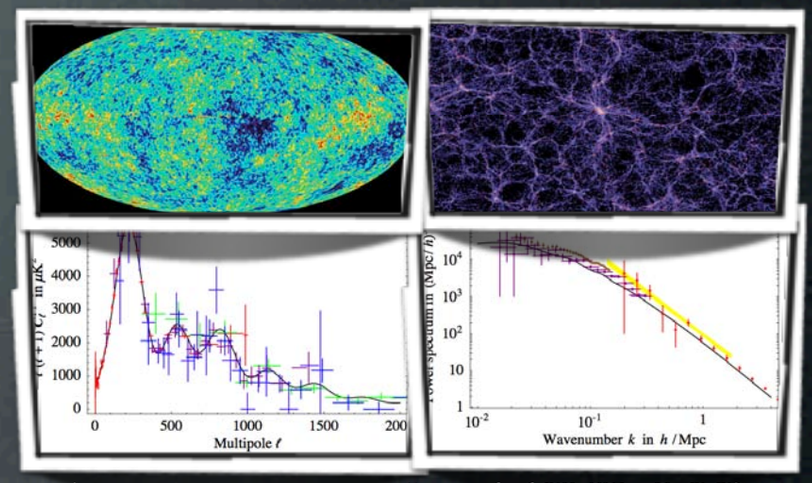


galactic rotation curves

weak lensing (e.g. in clusters)



'precision cosmology' (CMB, LSS)

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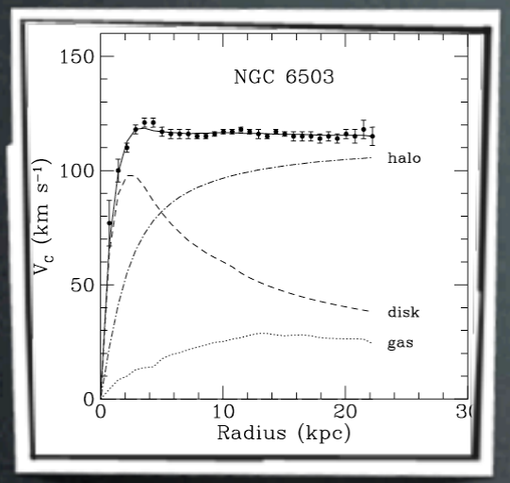

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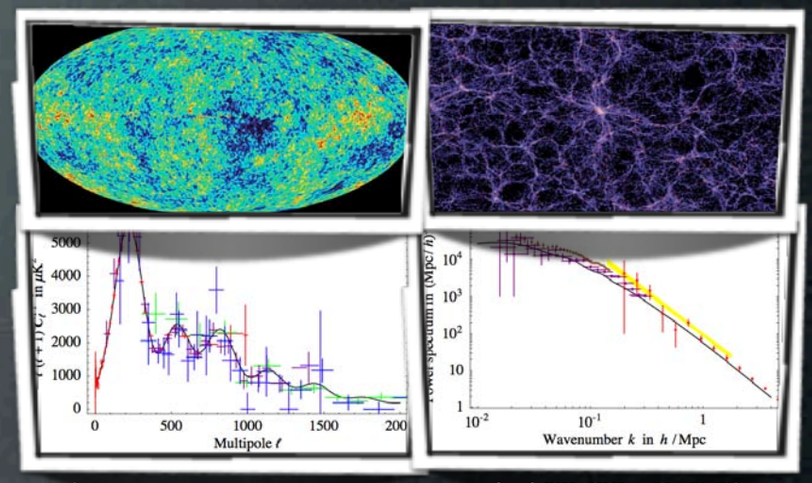

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DM is a neutral, very long lived, feebly interacting particle.

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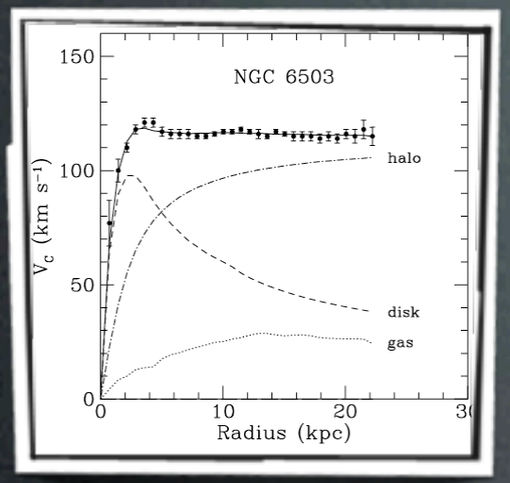

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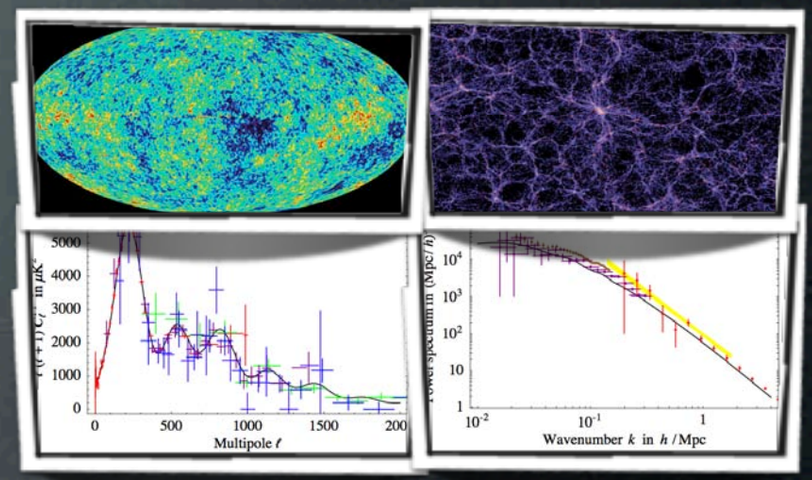
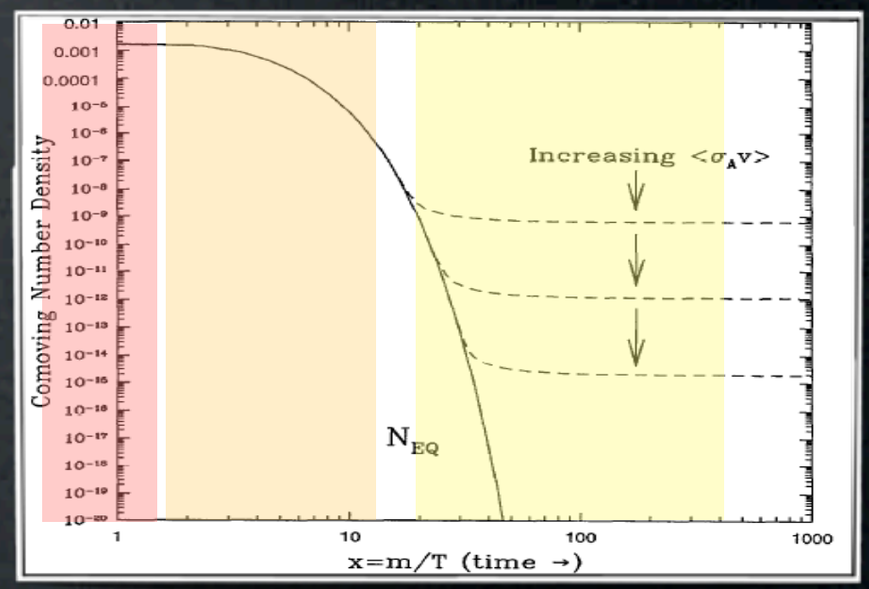


'precision cosmology' (CMB, LSS)

DM is a neutral, very long lived, feebly interacting particle.

Some of us believe in the WIMP miracle.

- *weak*-scale mass (10 GeV - 1 TeV)
- *weak* interactions $\sigma v = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$
- give automatically correct abundance



DM detection

direct detection

Xenon, CDMS (Dama/Libra?)

production at colliders

LHC

indirect

- γ from annihil in galactic center or halo and from synchrotron emission

  Fermi, HESS, radio telescopes
- e^+ from annihil in galactic halo or center

  PAMELA, Fermi, AMS-02
- $\bar{p}$ from annihil in galactic halo or center
- $\bar{d}$ from annihil in galactic halo or center

  GAPS
- $\nu, \bar{\nu}$ from annihil in massive bodies

  Icecube, Km3Net

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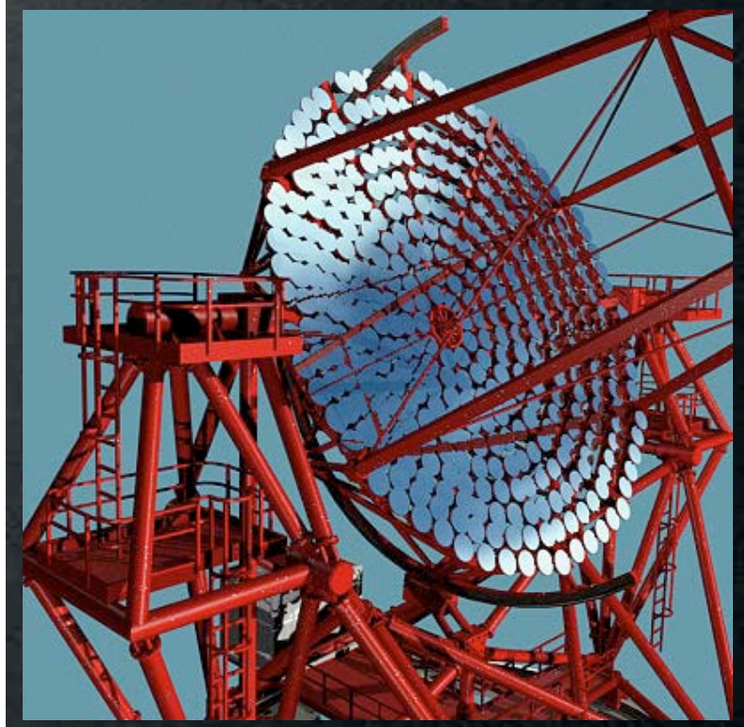
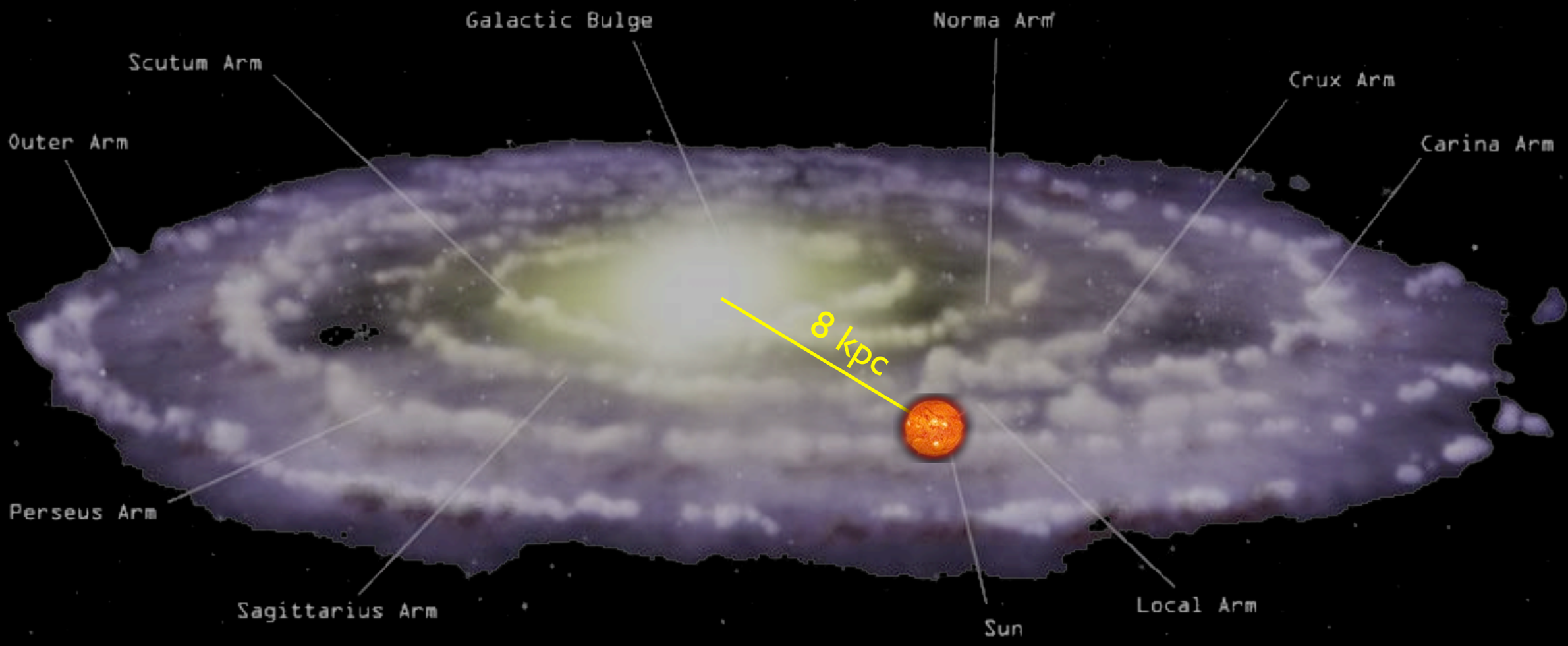
Charged CRs



1. the PAMELA/Fermi/HESS ‘excesses’

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



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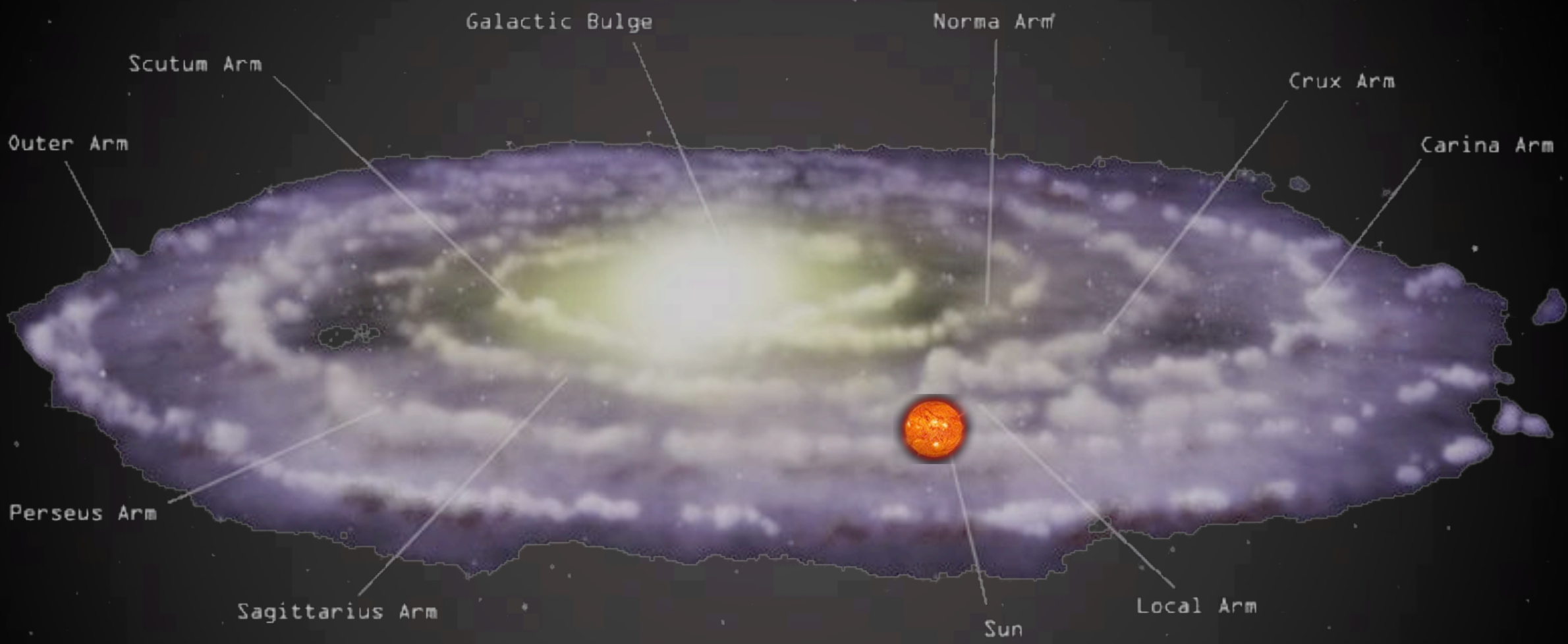

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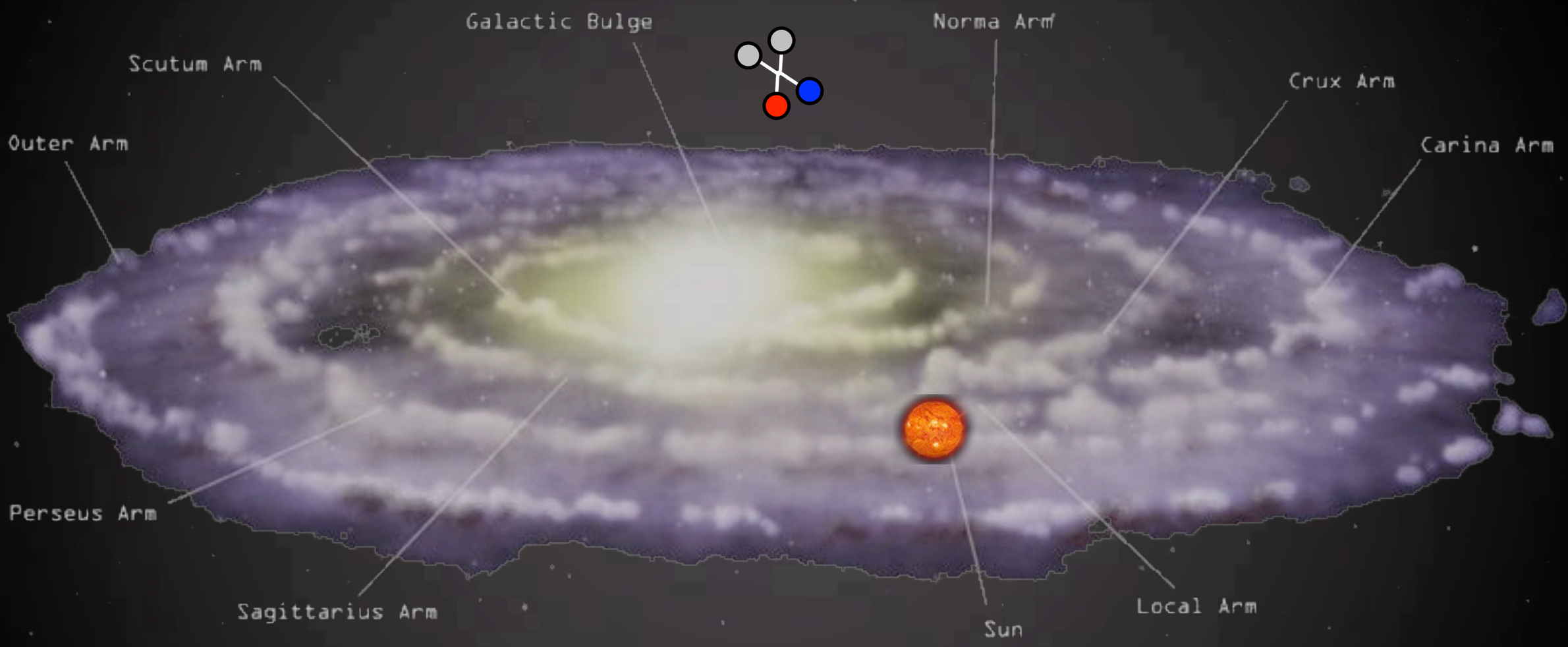

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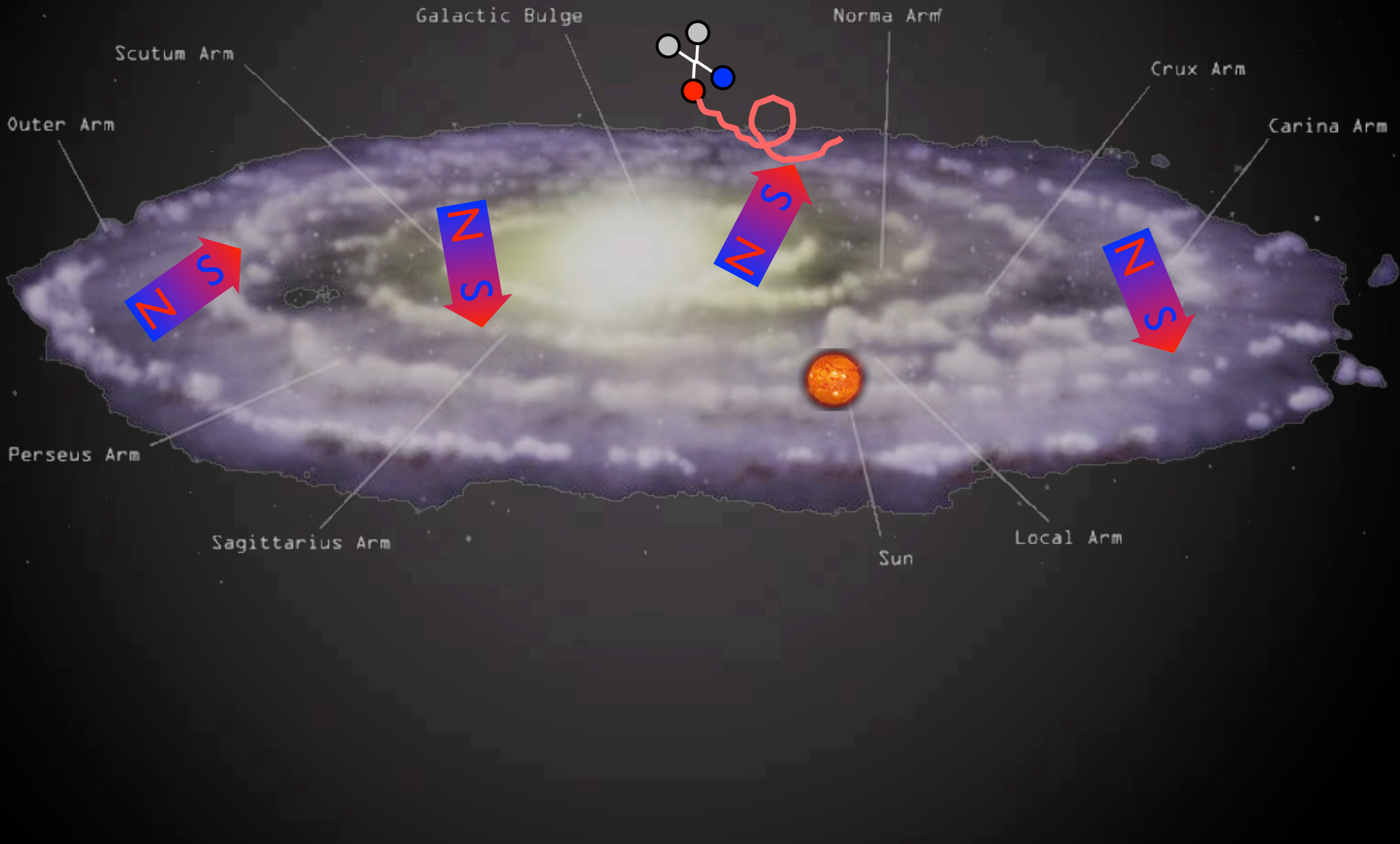

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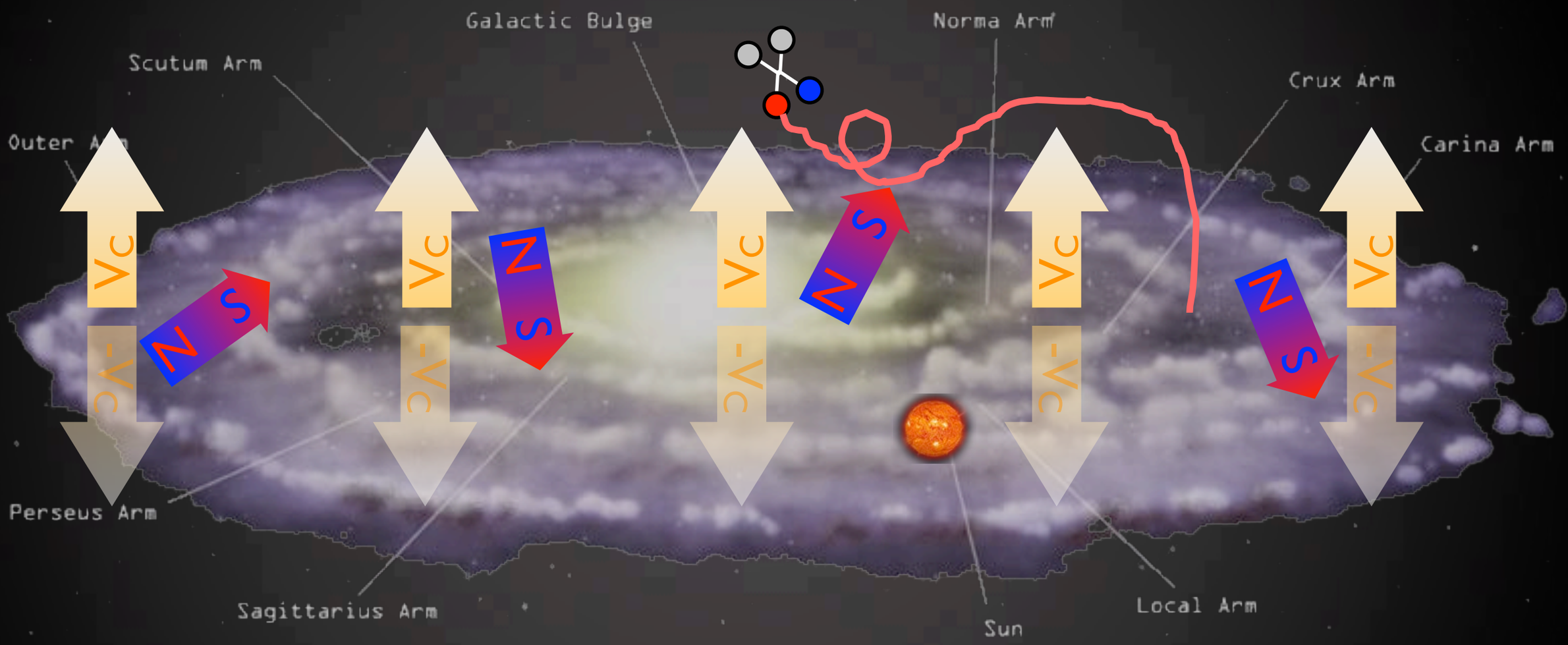

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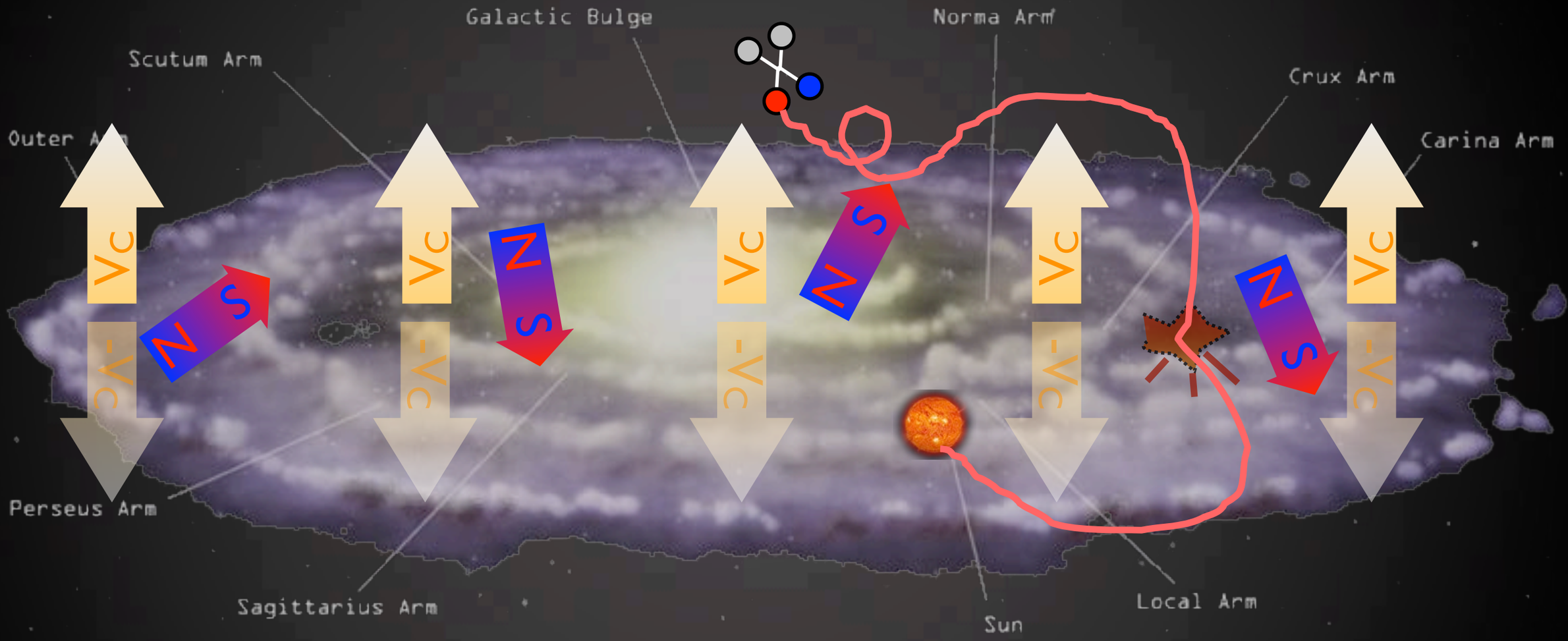

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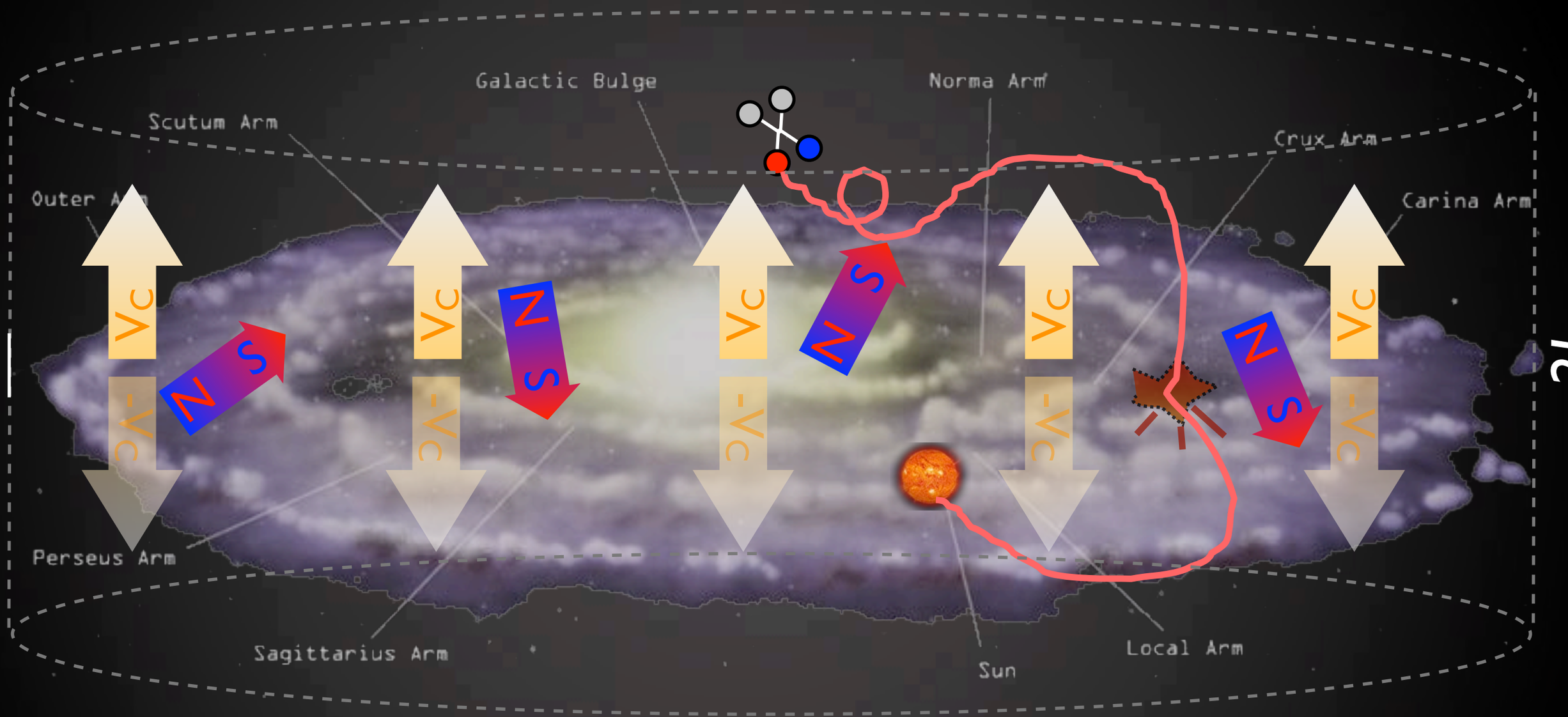


Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maurin, Brun... '90s, '00s

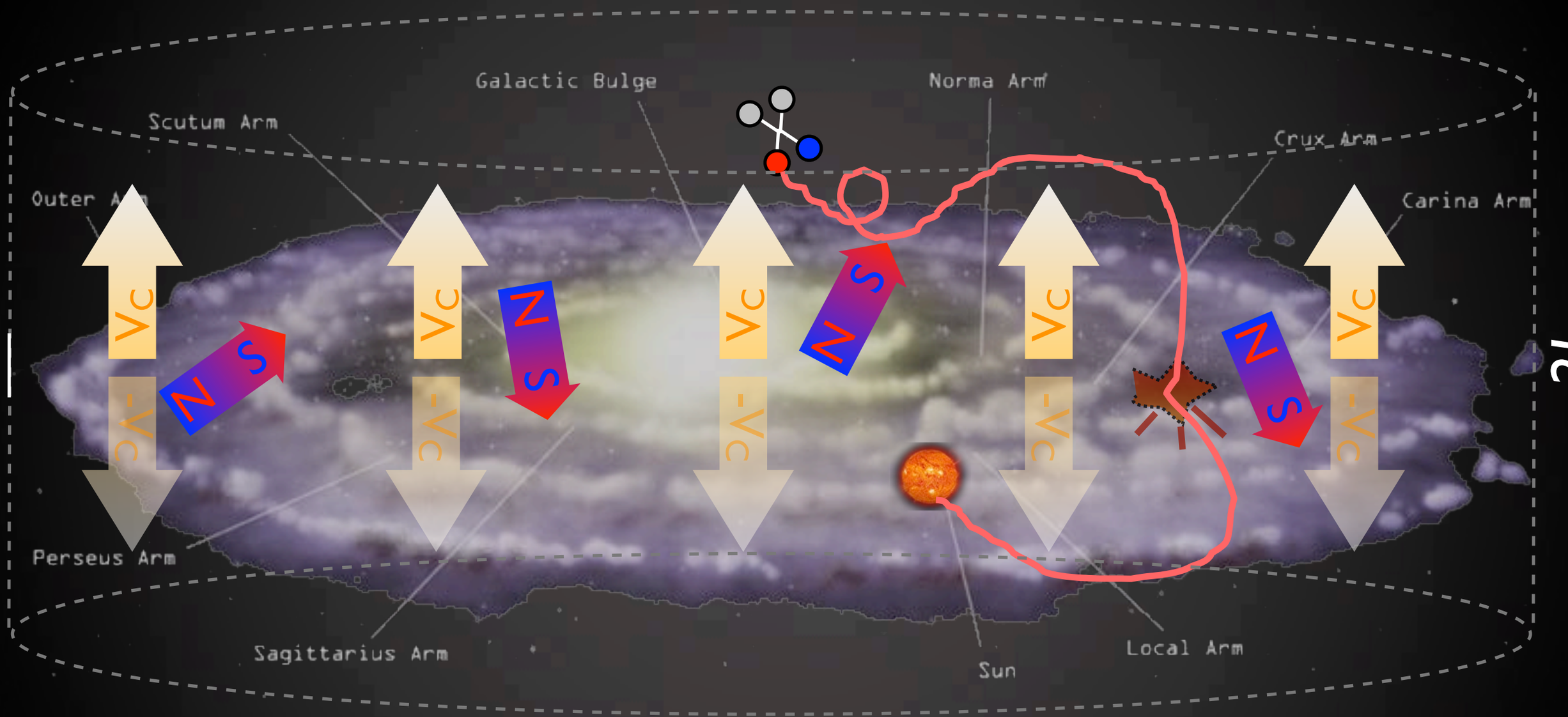
spectrum

$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E) f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\rm inj} - 2h\delta(z)\Gamma_{\rm spall} f$$

diffusion | energy loss | convective wind | source | spallations [uncert]

Indirect Detection: basics

$\bar{p}$ and e^+ from DM annihilations in halo



What sets the overall expected flux?

$$\text{flux} \propto n^2 \, \sigma_{\text{annihilation}}$$

Indirect Detection: basics

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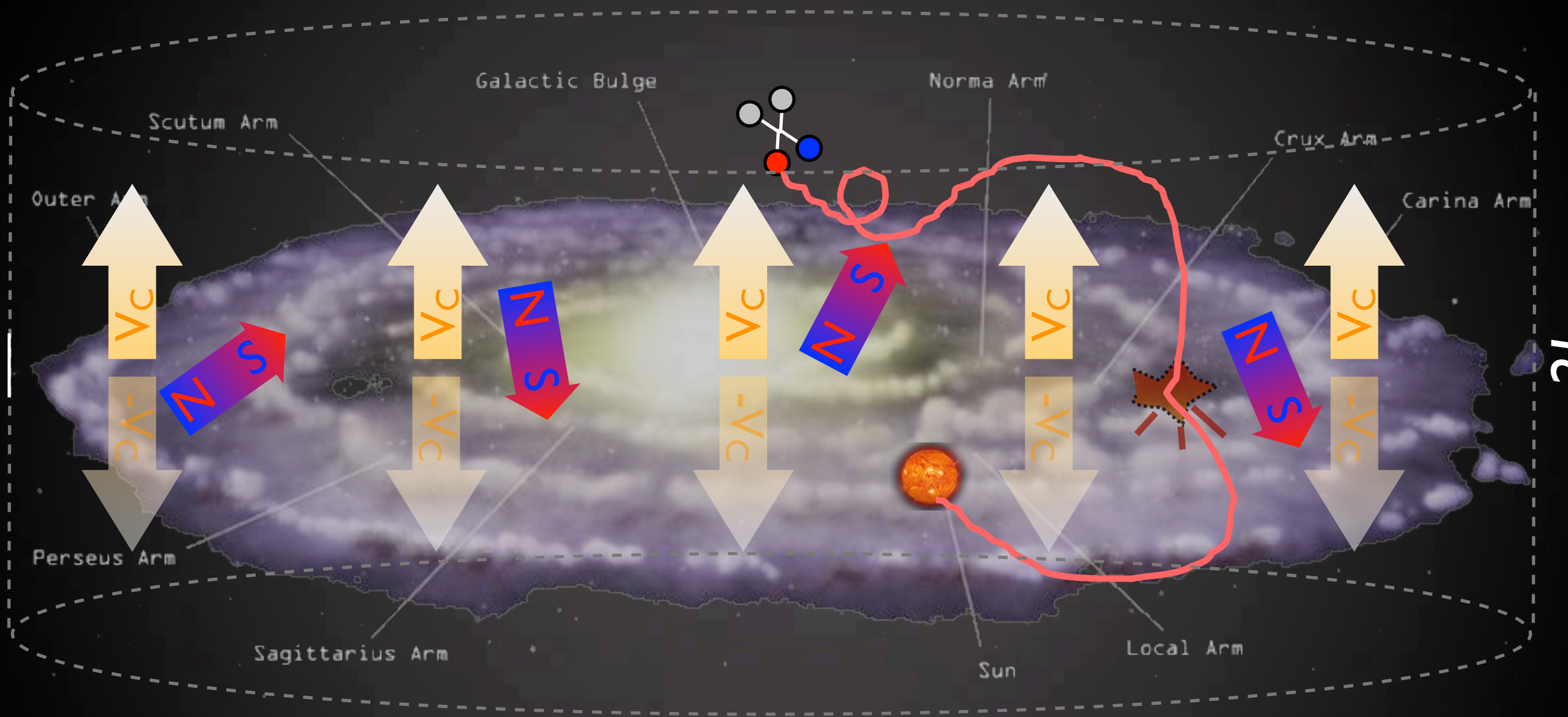

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$$\text{flux} \propto \underbrace{n^2}_{\text{astro\& cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

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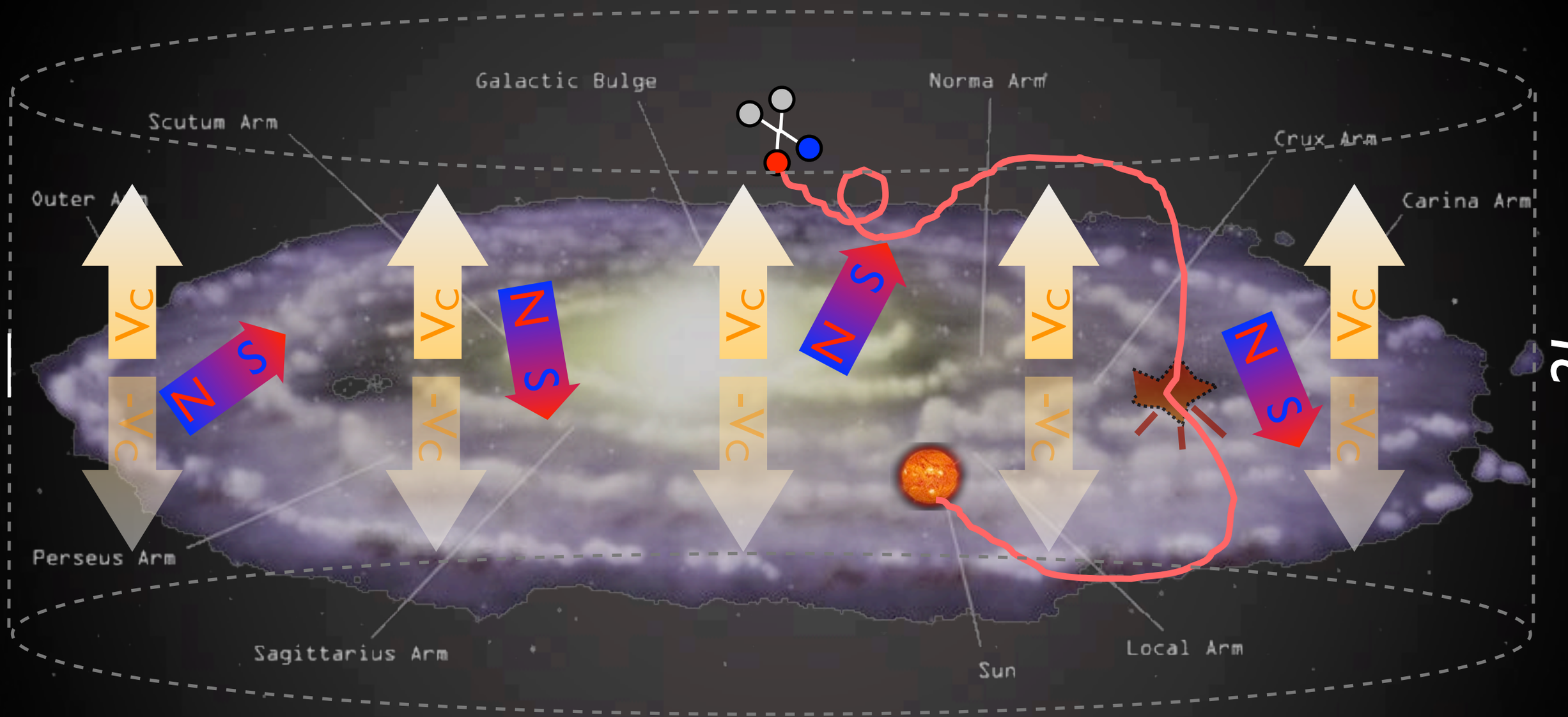


What sets the overall expected flux?

$$\text{flux} \propto \underbrace{n^2}_{\text{astro\&cosmo}} \underbrace{\sigma_{\text{annihilation}}}_{\text{particle}}$$

reference cross section:

$$\sigma v = 3 \cdot 10^{-26} \text{cm}^3/\text{sec}$$

DM halo profiles

From N-body numerical simulations:

$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto}: \quad \rho_{\rm Ein}(r) = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha}-1\right]\right\}$$

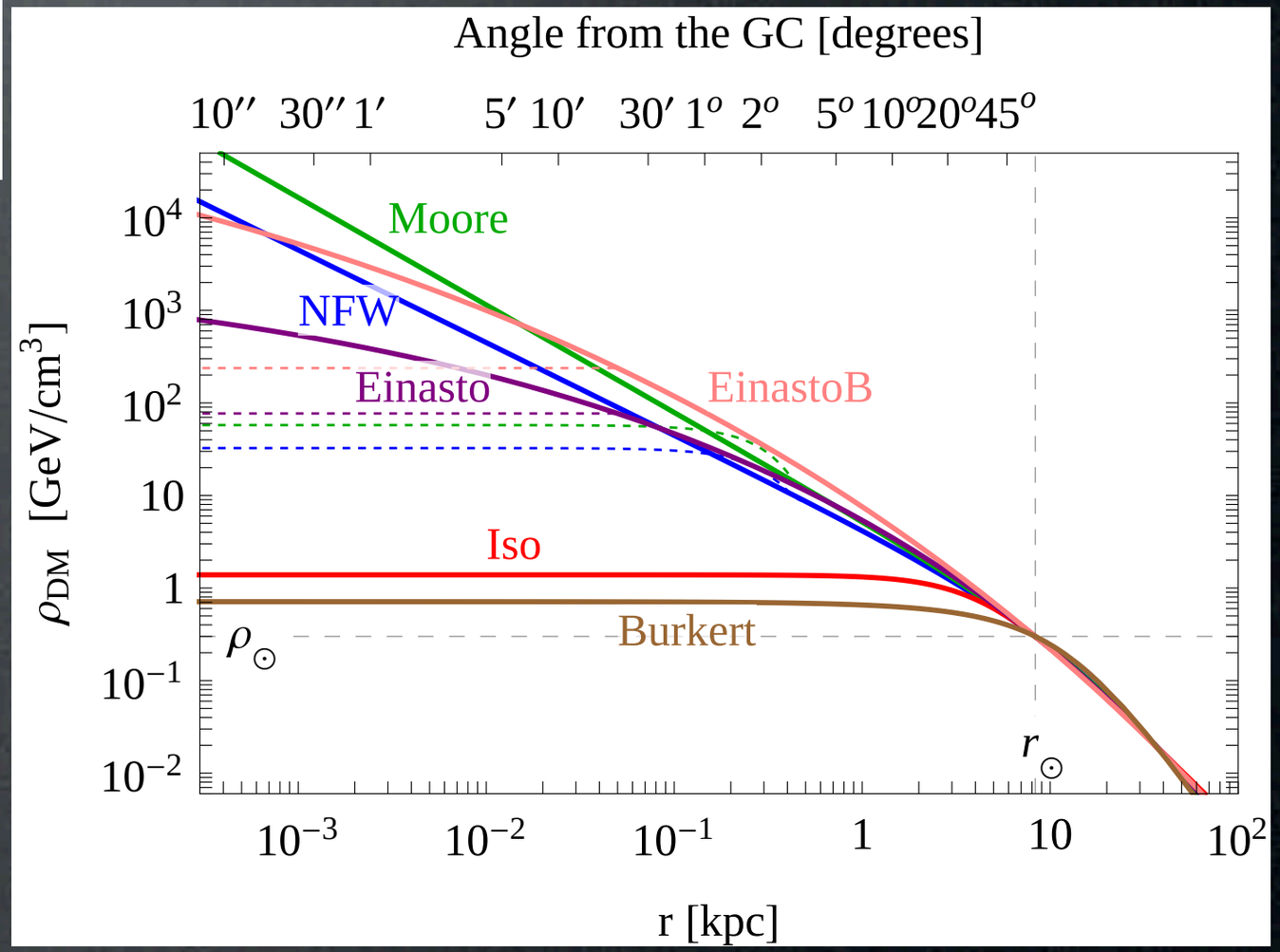
$$\text{Isothermal}: \quad \rho_{\rm Iso}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\text{Burkert}: \quad \rho_{\rm Bur}(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$

$$\text{Moore}: \quad \rho_{\rm Moo}(r) = \rho_s \left(\frac{r_s}{r}\right)^{1.16}\left(1+\frac{r}{r_s}\right)^{-1.84}$$

At small r: $\rho(r) \propto 1/r^{\gamma}$

DM halo	α	r_s [kpc]	ρ_s [GeV/cm^3]
NFW	–	24.42	0.184
Einasto	0.17	28.44	0.033
EinastoB	0.11	35.24	0.021
Isothermal	–	4.38	1.387
Burkert	–	12.67	0.712
Moore	–	30.28	0.105



6 profiles:

cuspy: NFW, Moore

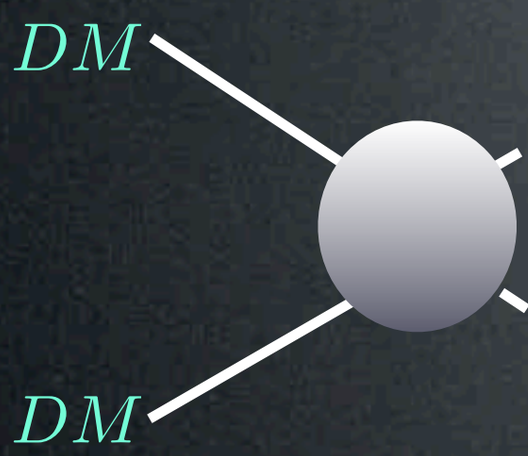
mild: Einasto

smooth: isothermal, Burkert

EinastoB = steepened Einasto

(effect of baryons?)

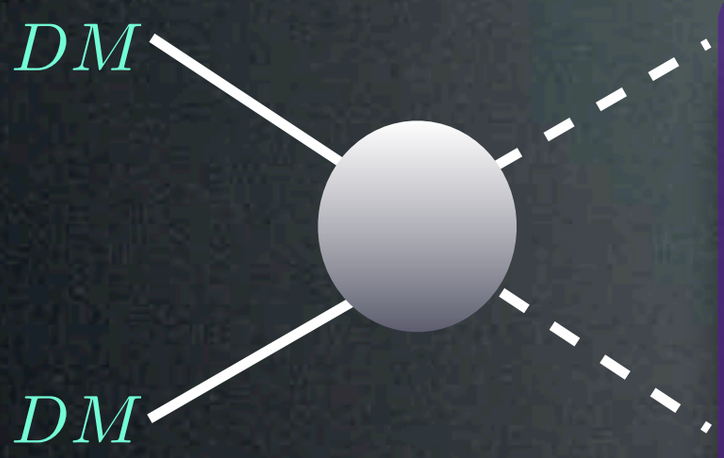
Indirect Detection: basics



$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$$

Indirect Detection: basics



$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

primary channels

$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

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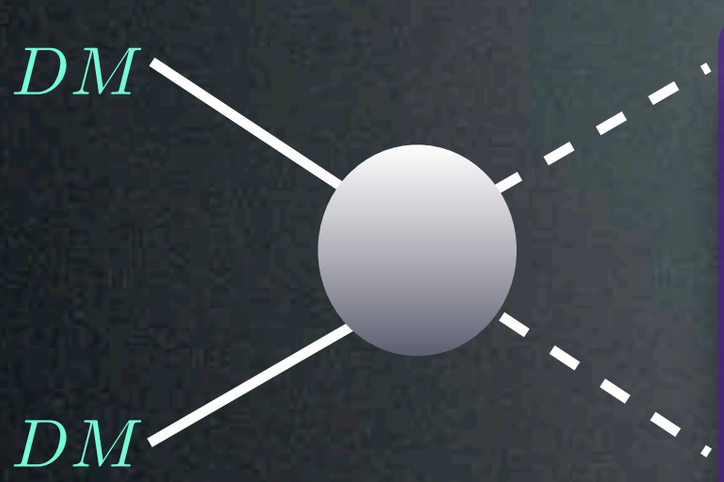

$W^-, Z, b, \tau^-, t, h \ldots$

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decay

$\rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

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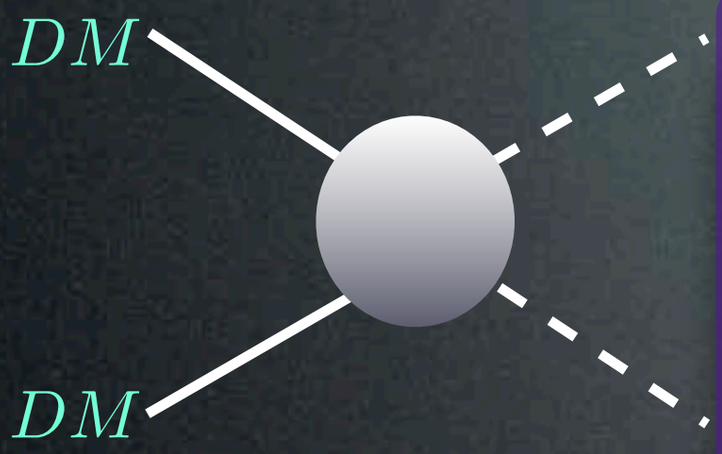

$W^-, Z, b, \tau^-, t, h \ldots$

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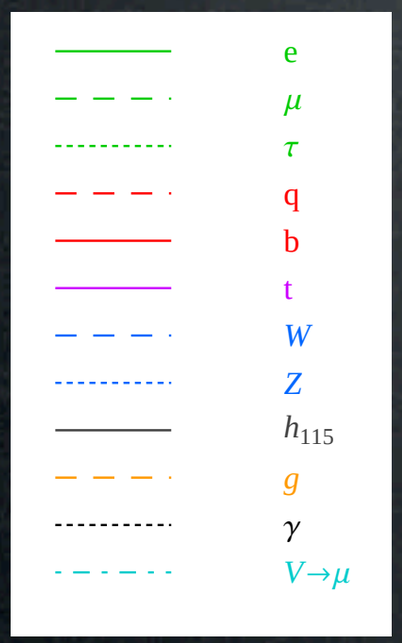
$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots$

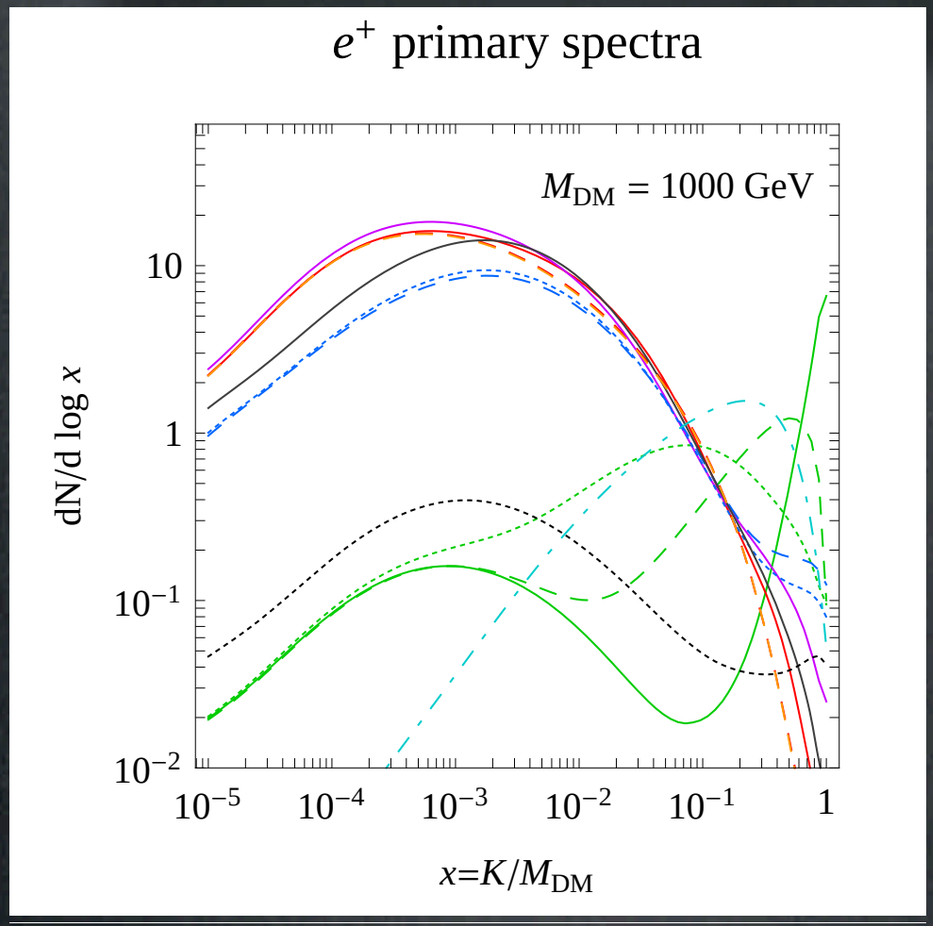
decay

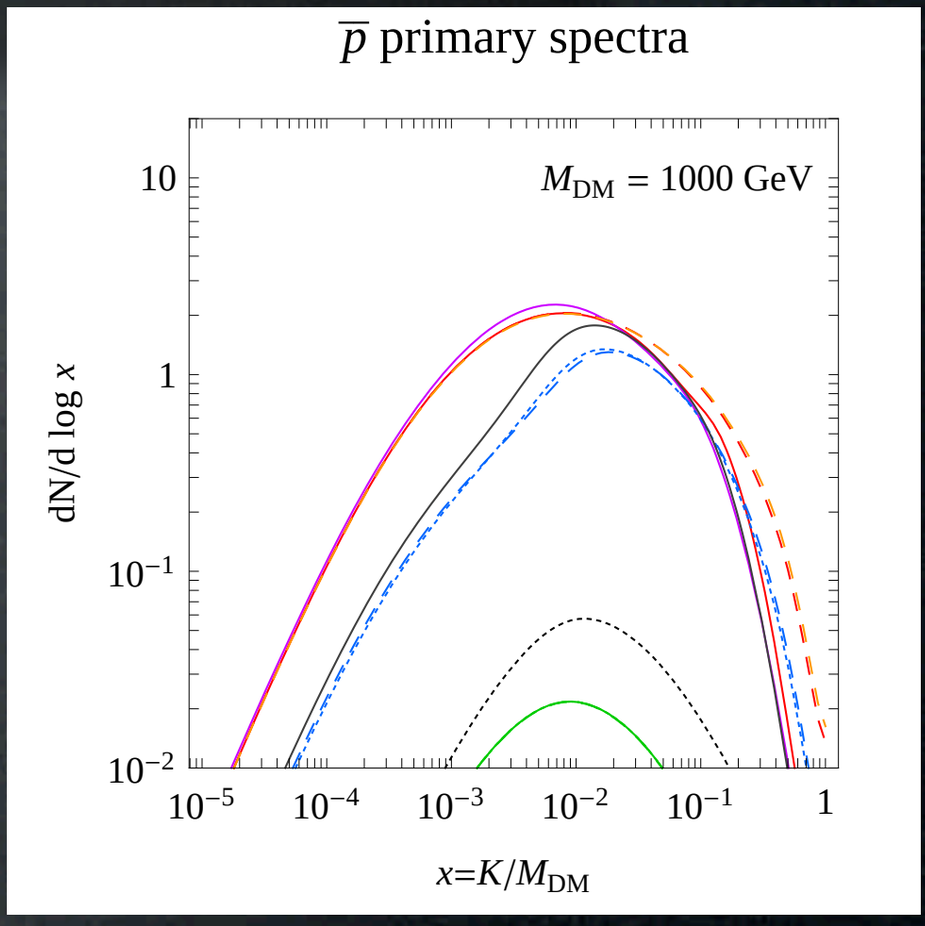
$e^\mp, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

final products

$e^\pm, \overset{(-)}{p}, \overset{(-)}{D} \ldots$







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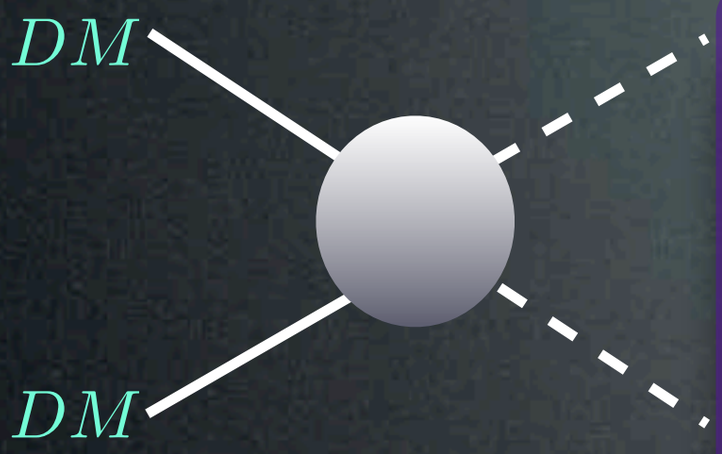

$W^-, Z, b, \tau^-, t, h \ldots$

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$\rightsquigarrow e^{\mp}, \overset{(-)}{p}, \overset{(-)}{D} \ldots$

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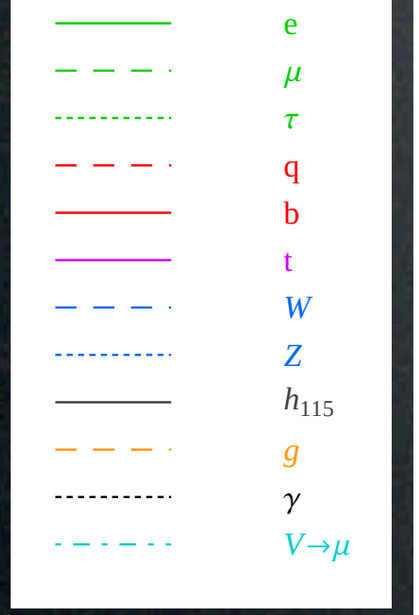
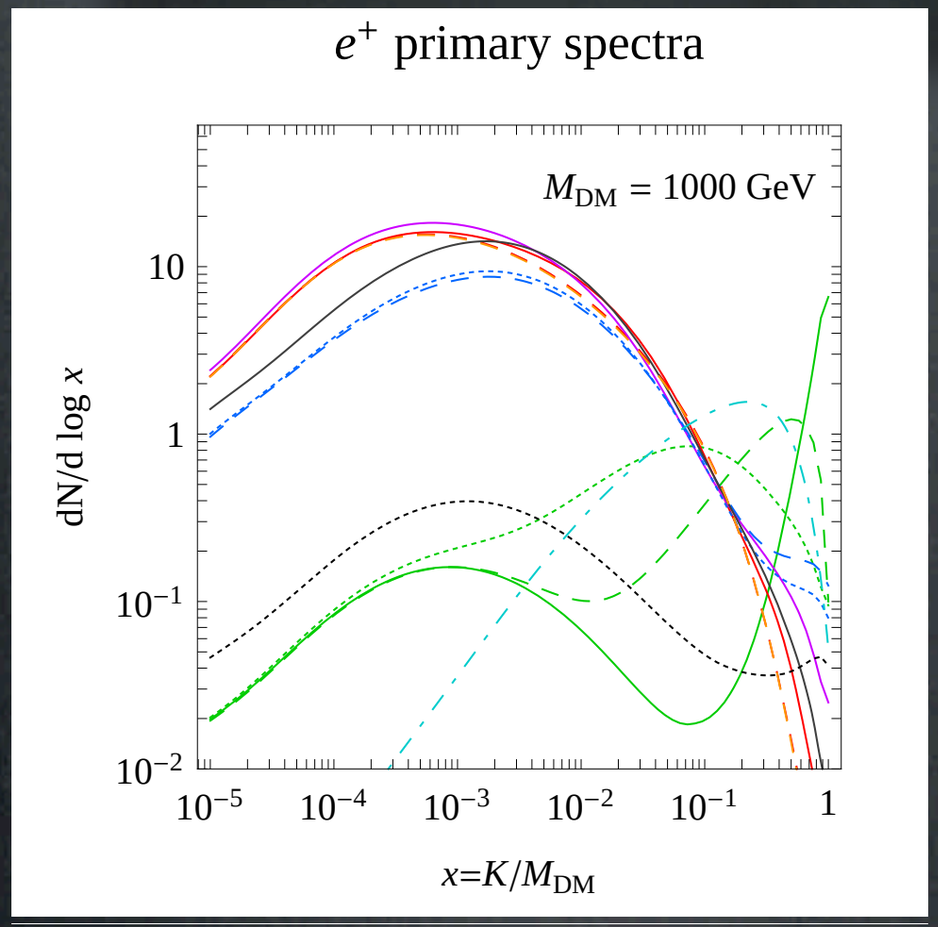
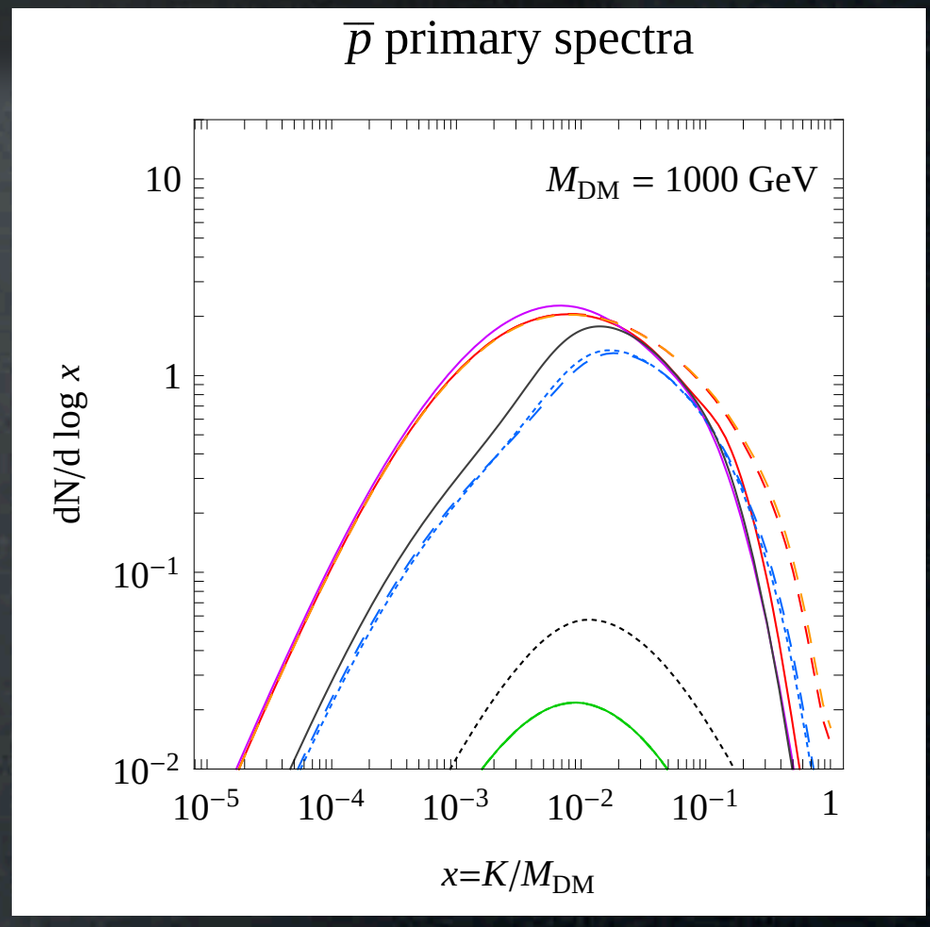




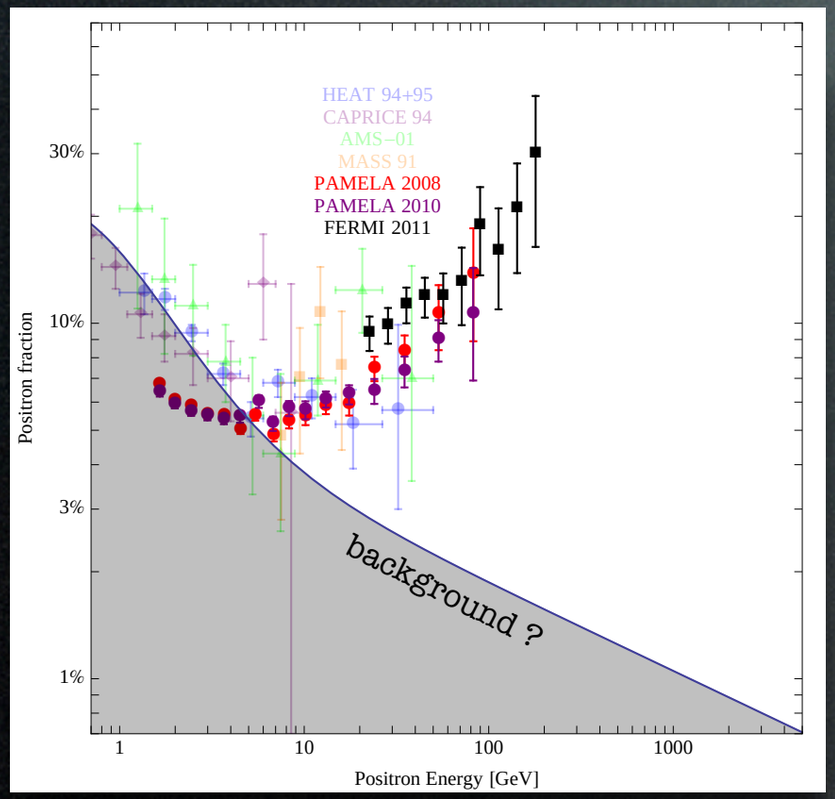


So what are the particle physics parameters?

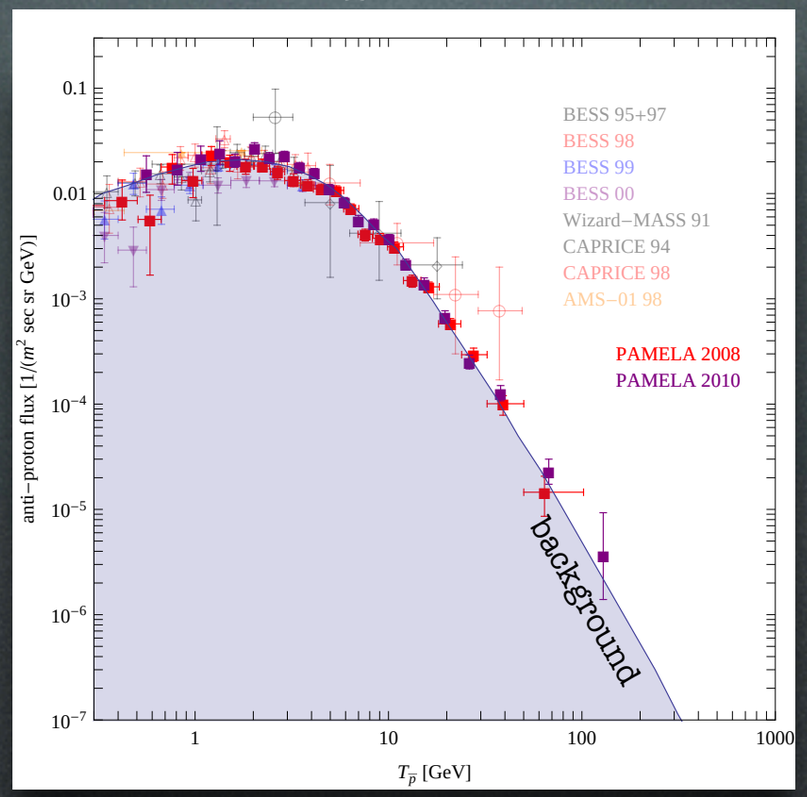
1. Dark Matter mass
2. primary channel(s)

Positrons & Electrons

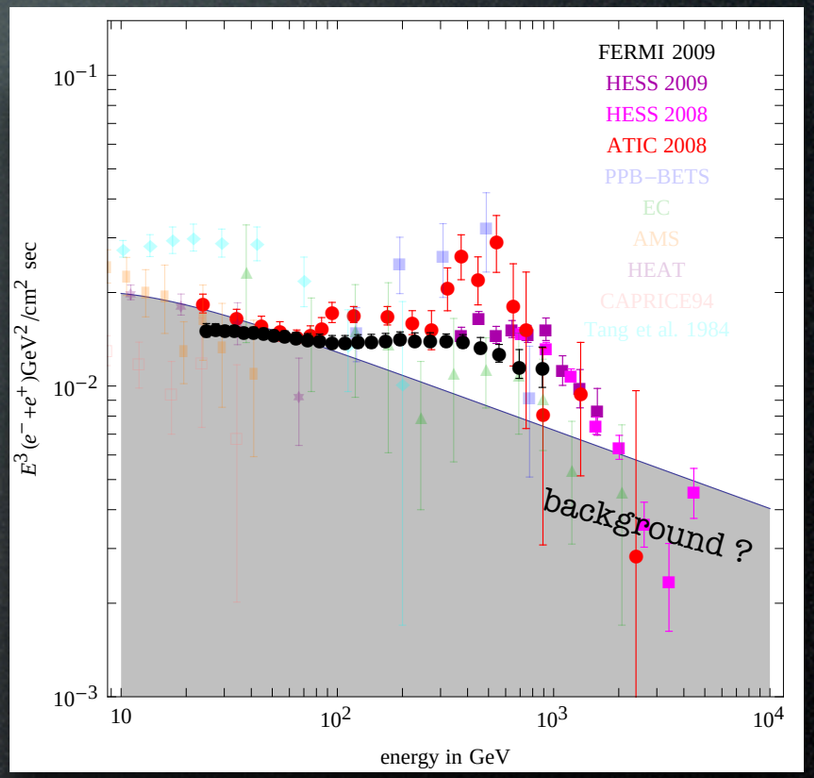
positron fraction



antiprotons



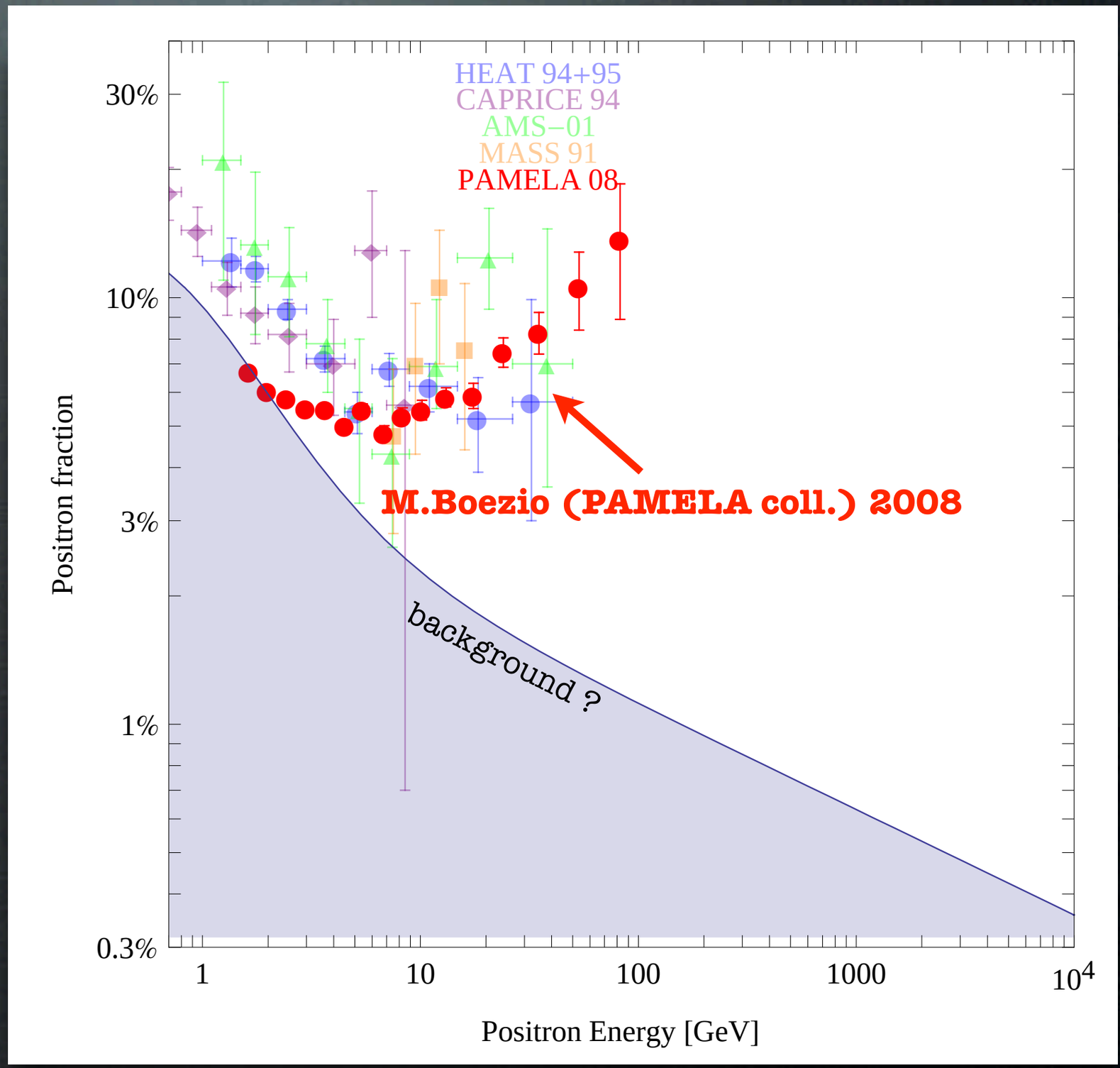
electrons + positrons



Positrons & Electrons

Positrons from PAMELA:

- steep e^+ excess above 10 GeV!
- very large flux!



positron fraction: $\frac{e^+}{e^+ + e^-}$

(9430 e^+ initially collected)

(errors statistical only in this plot, that's why larger at high energy)

Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

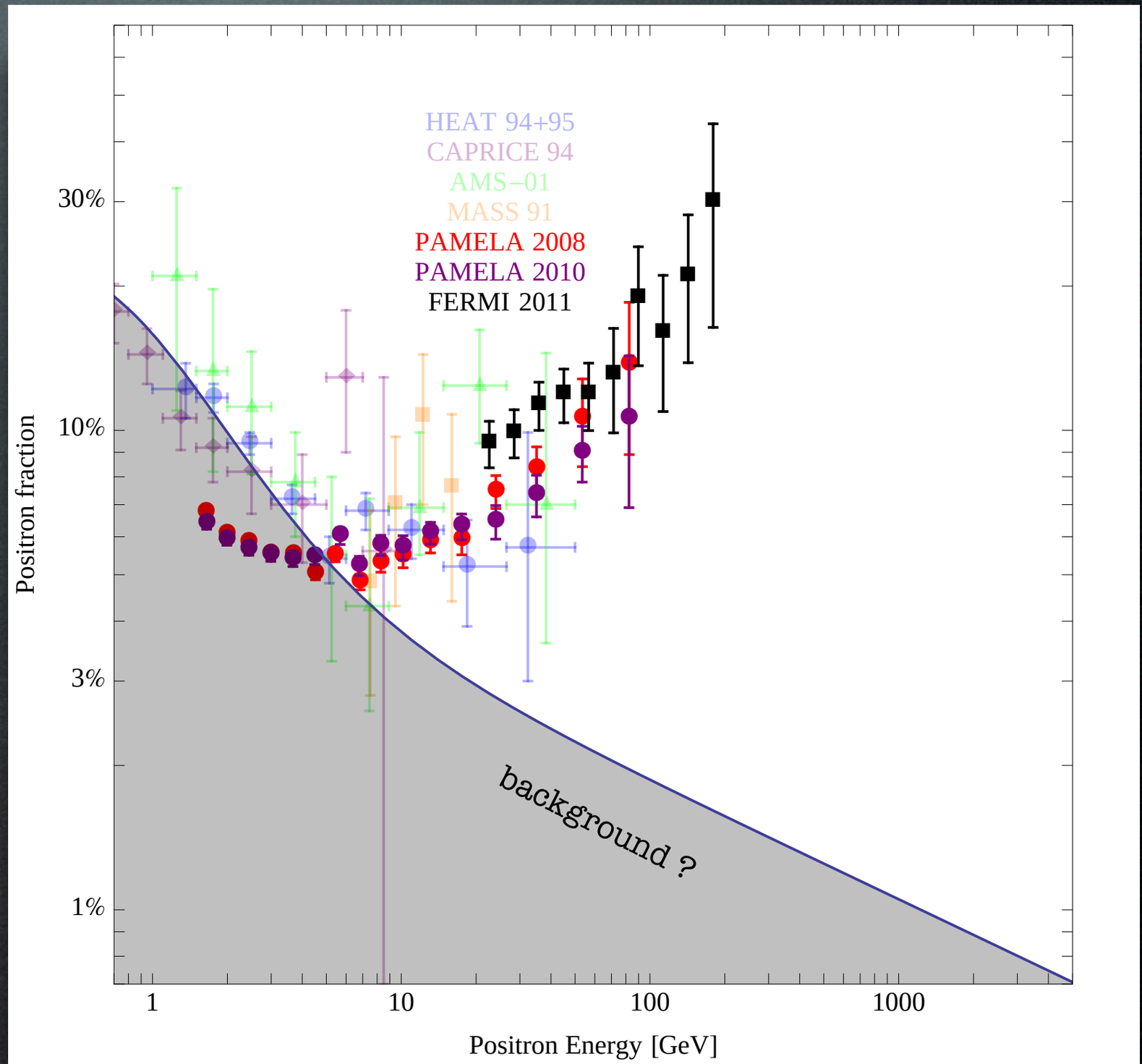
[backgnd]

Positrons & Electrons

Positrons from PAMELA and FERMI:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\dfrac{e^+}{e^+ + e^-}$



Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

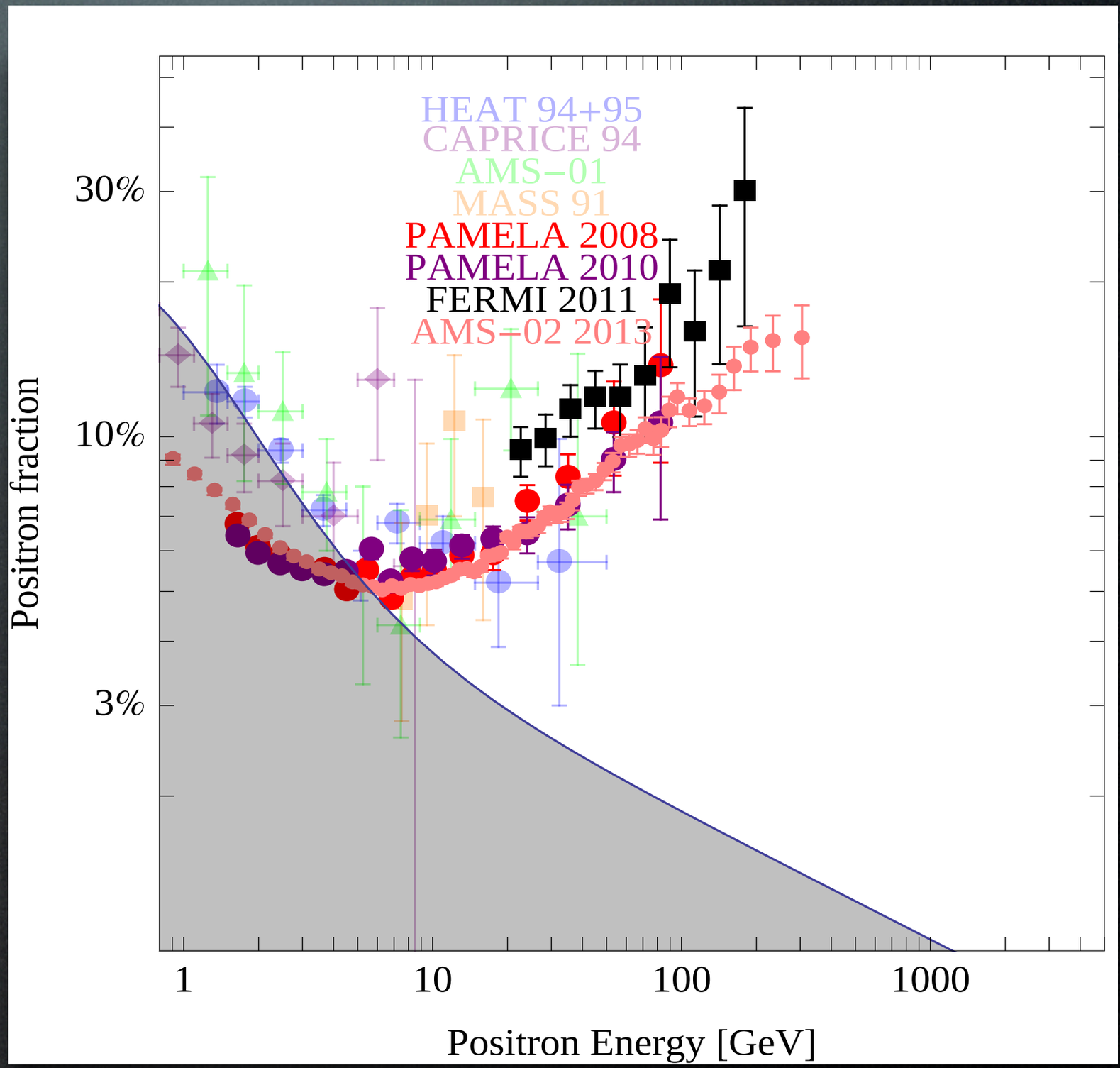
Fermi coll., 1109.0521

Positrons & Electrons

Positrons from PAMELA and FERMI and AMS-02:

- steep e^+ excess above 10 GeV!
- very large flux!

positron fraction: $\frac{e^+}{e^+ + e^-}$



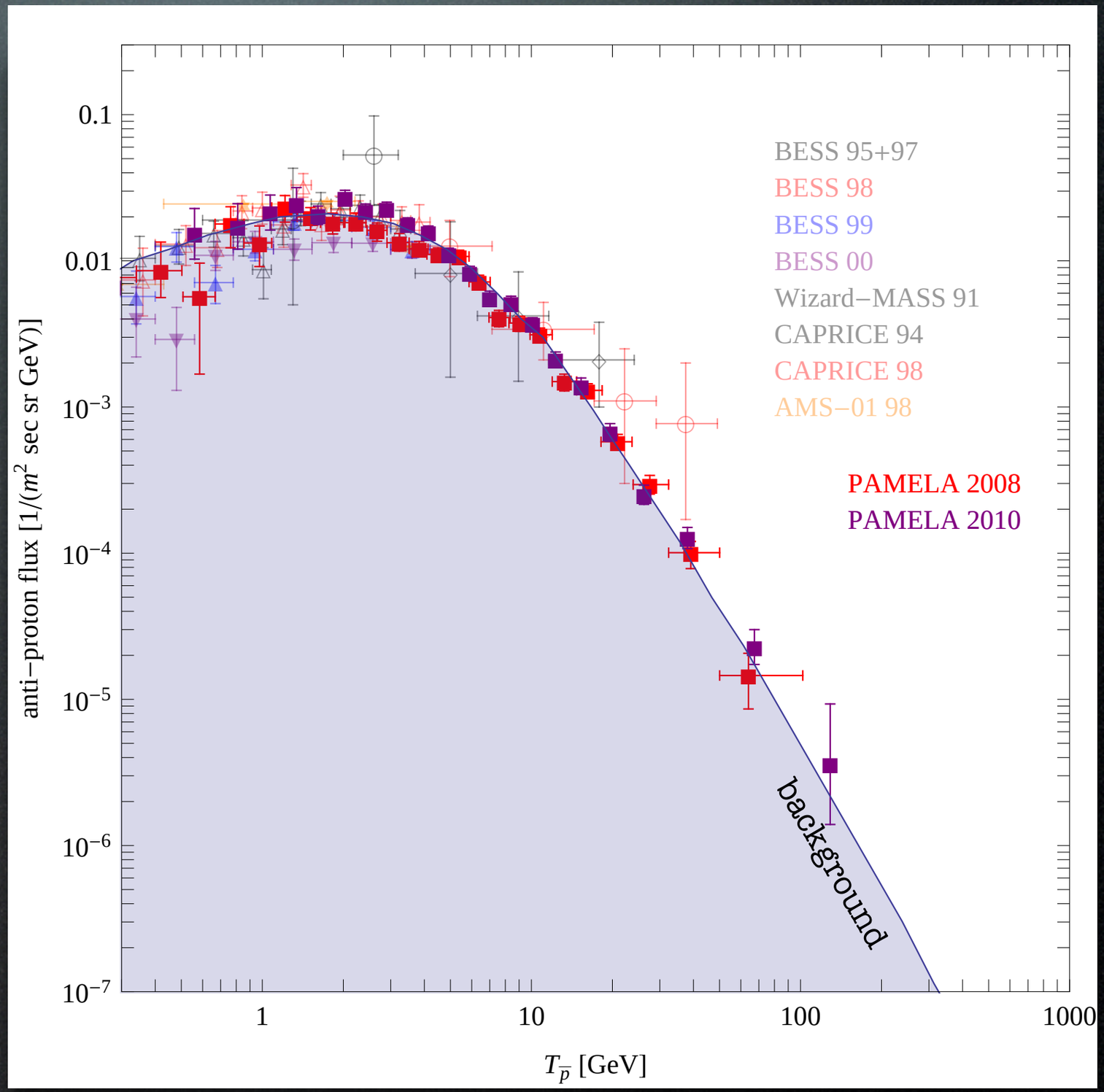
Adriani et al., Nature 458 (2009) 607; ApP 34 (2010) 1

Fermi coll., 1109.0521 **AMS-02 coll., PRL 110, 141102 (2013)**

Antiprotons

Antiprotons from PAMELA:

- consistent with the background



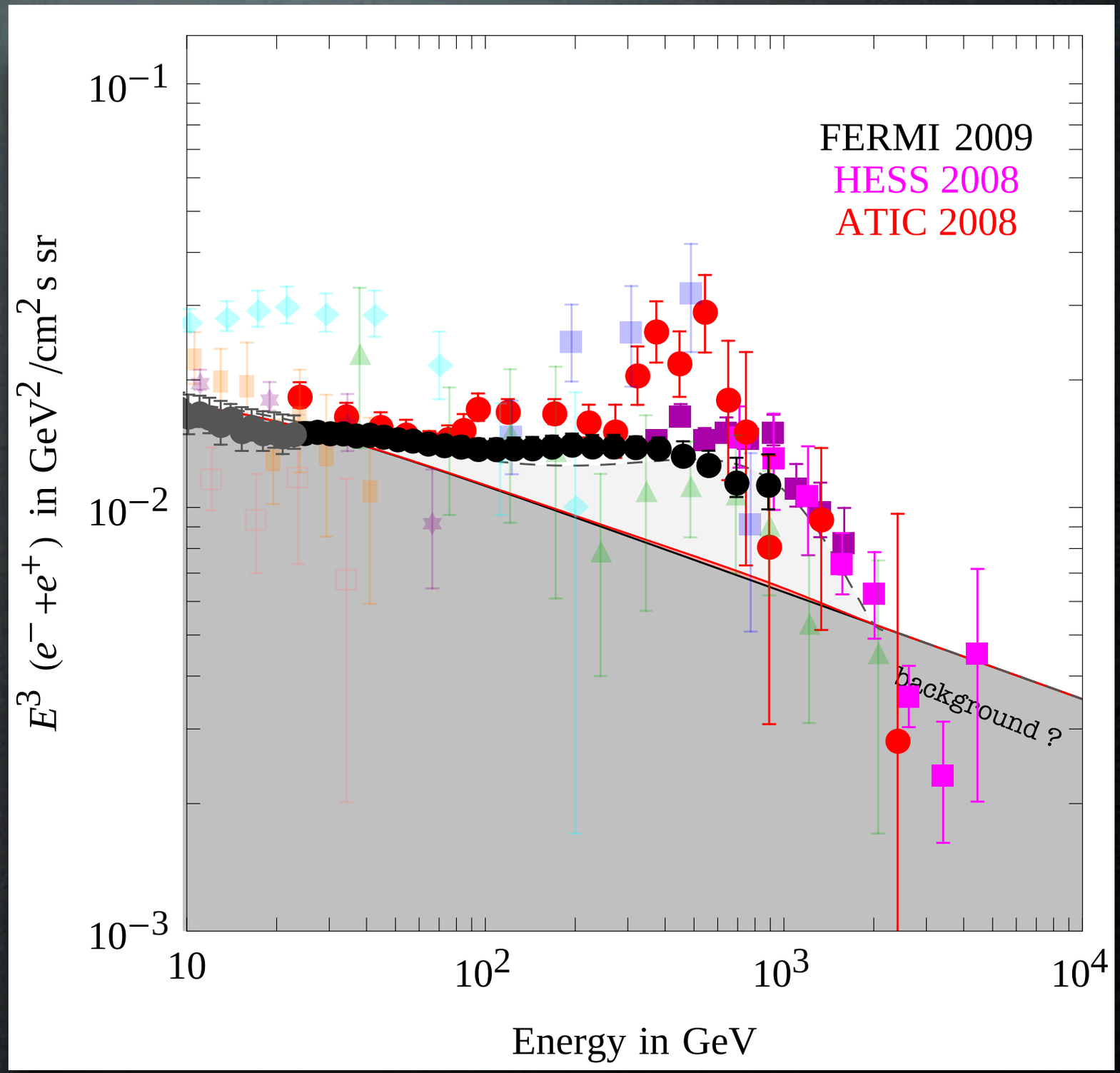
(about 1000 $\bar{p}$ collected initially)

Adriani et al., PRL 105 (2010) 121101, 1007.0821

Indirect Detection: hints

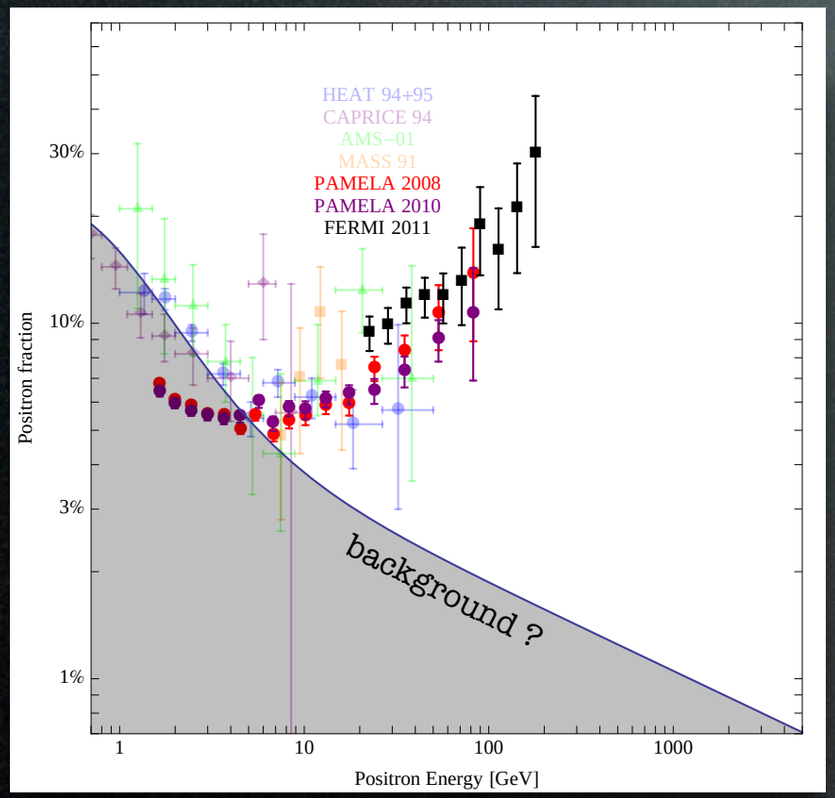
Electrons + positrons adding FERMI and HESS:

- no $e^+ + e^-$ excess
- spectrum $\sim E^{-3.04}$
- a (smooth) cutoff?

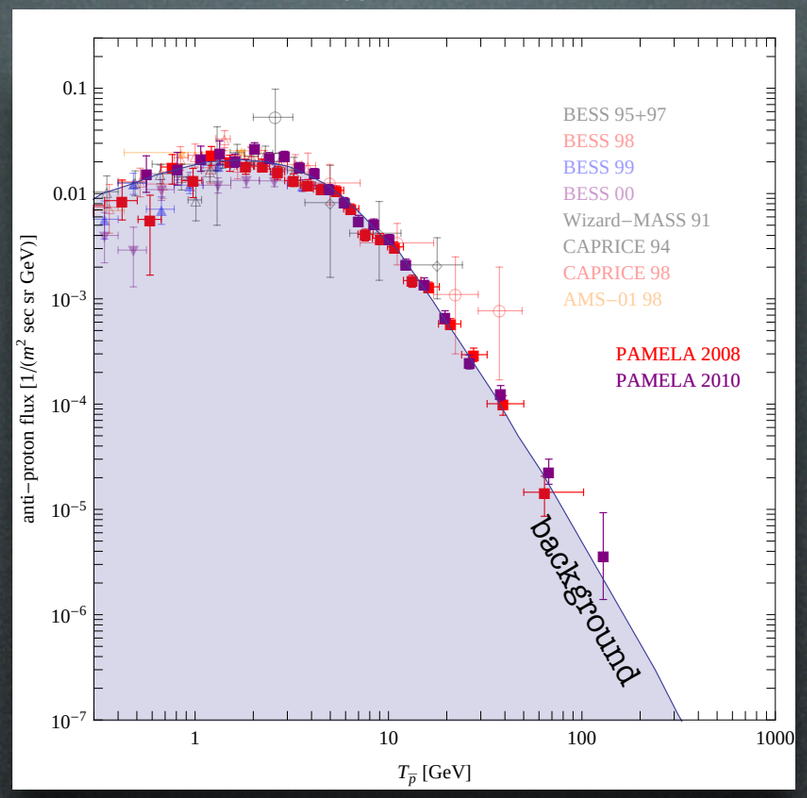


Positrons & Electrons

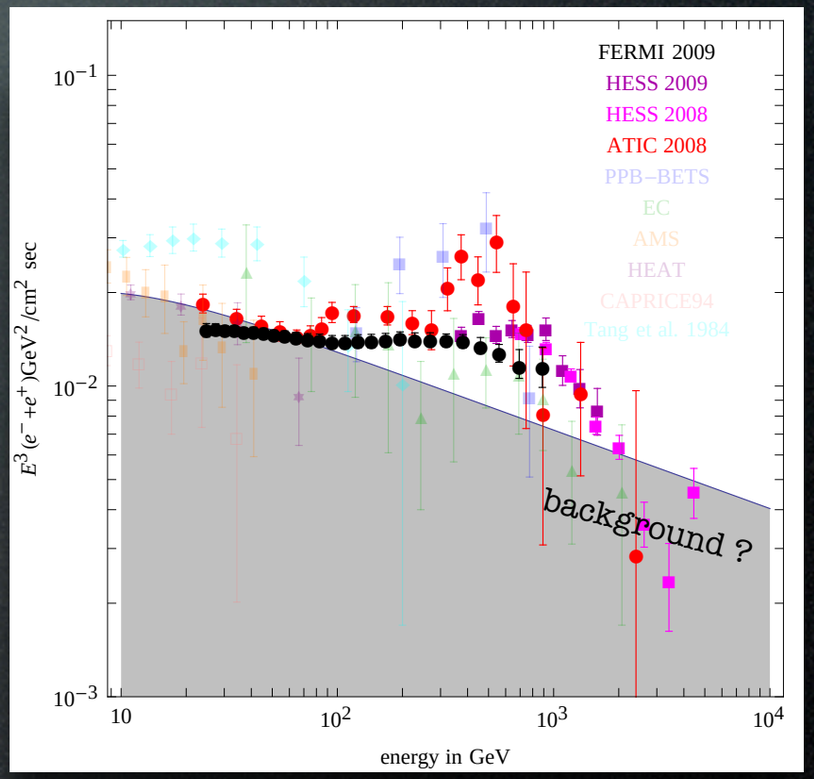
positron fraction



antiprotons



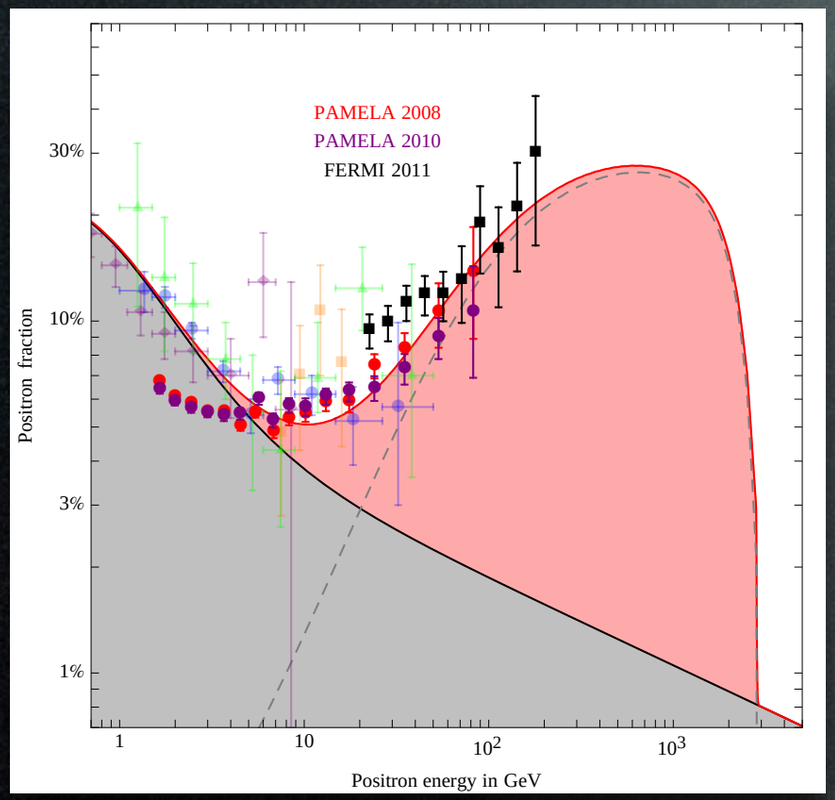
electrons + positrons



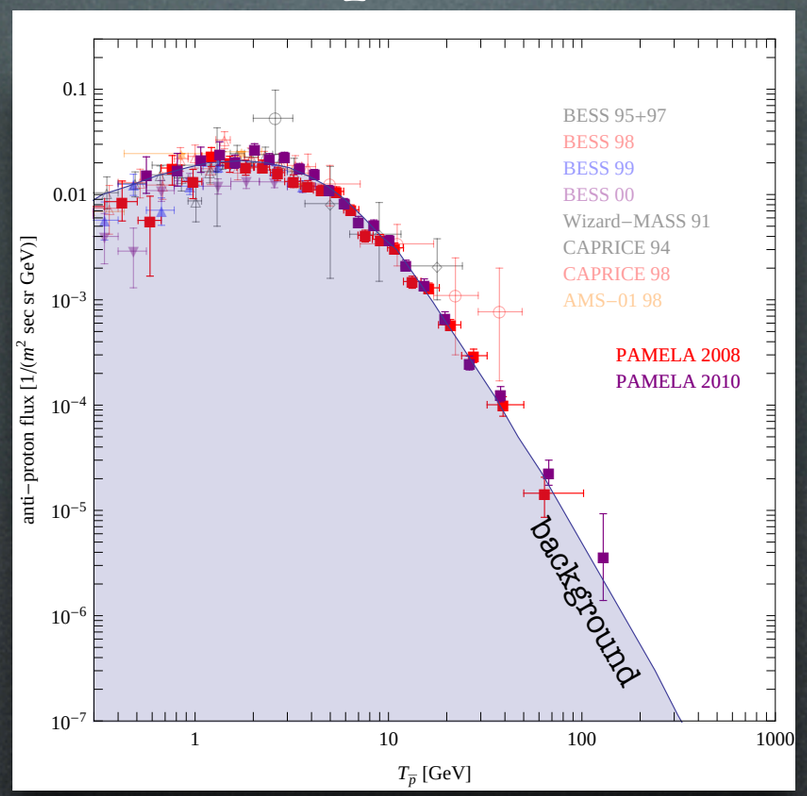
Are these signals of Dark Matter?

Positrons & Electrons

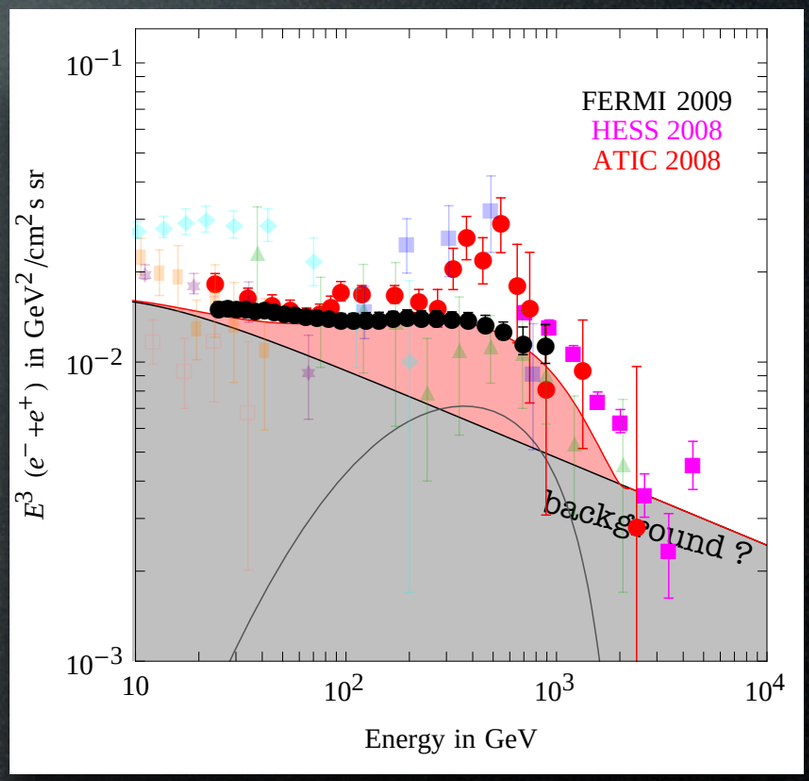
positron fraction



antiprotons



electrons + positrons

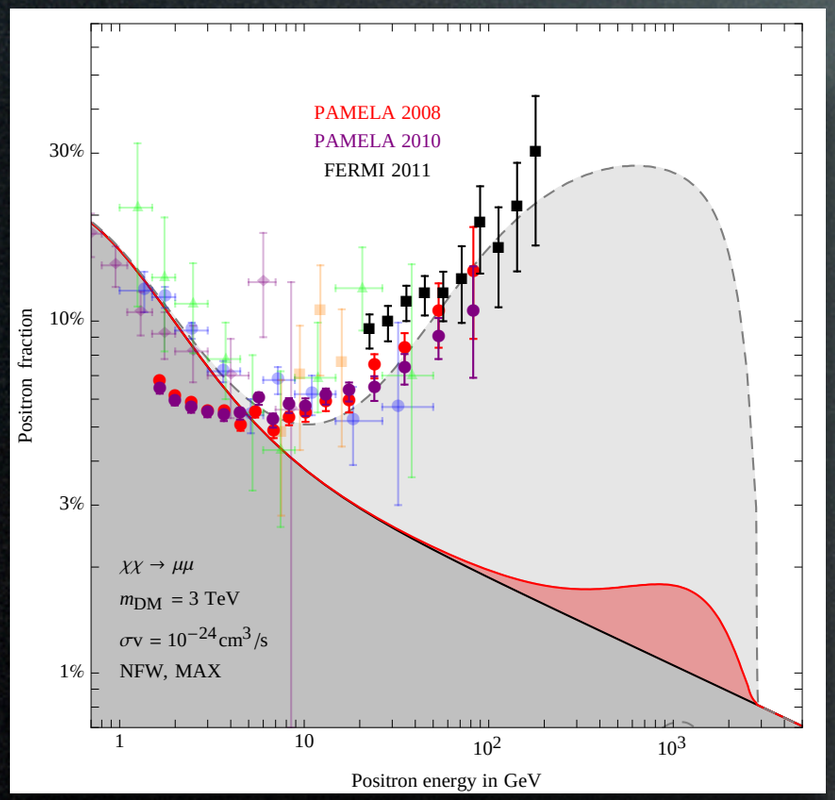


Are these signals of Dark Matter?

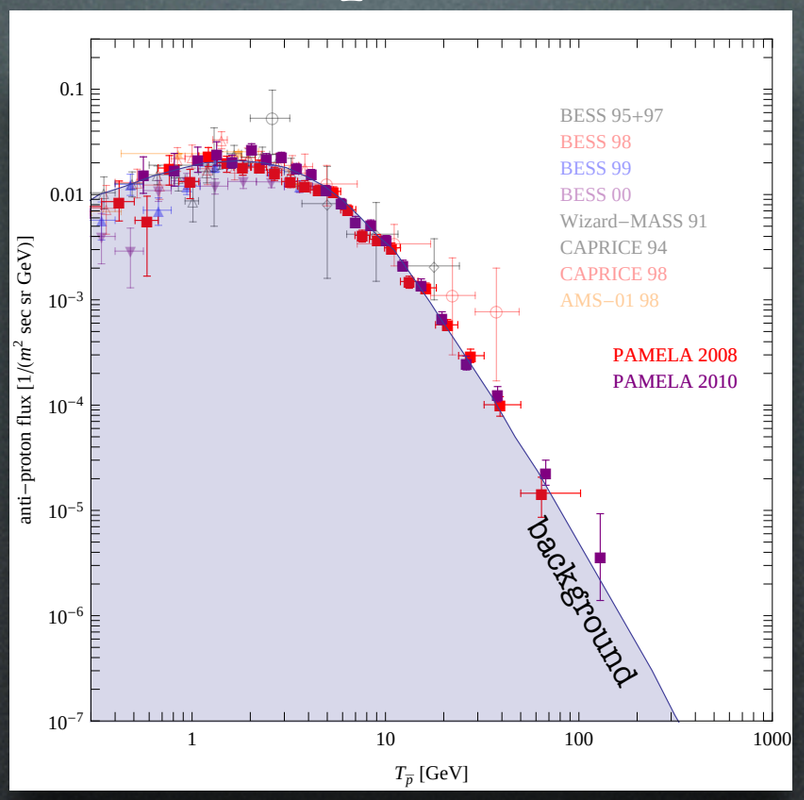
YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

Positrons & Electrons

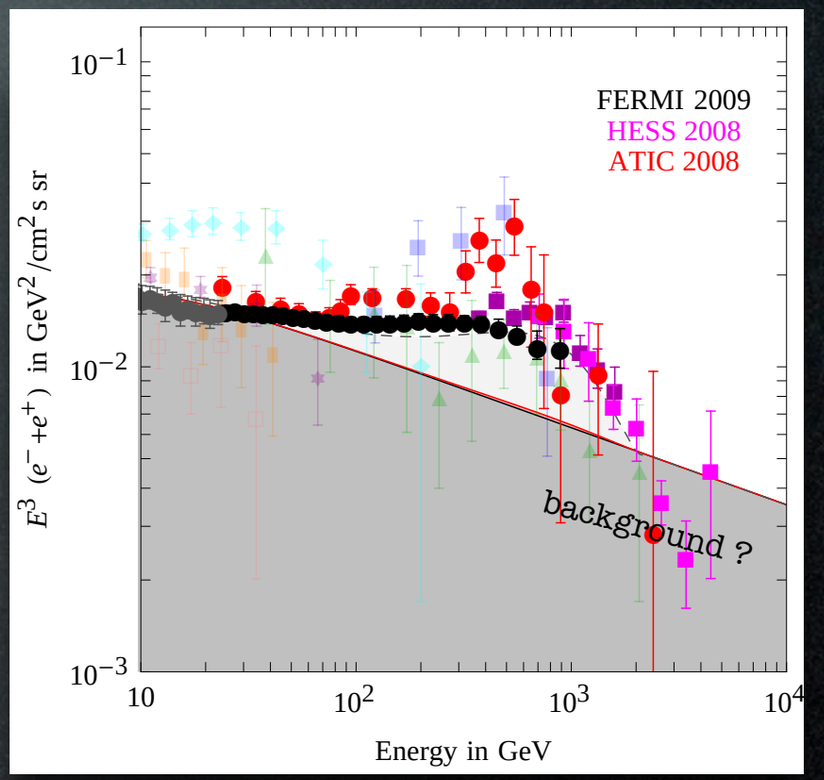
positron fraction



antiprotons



electrons + positrons



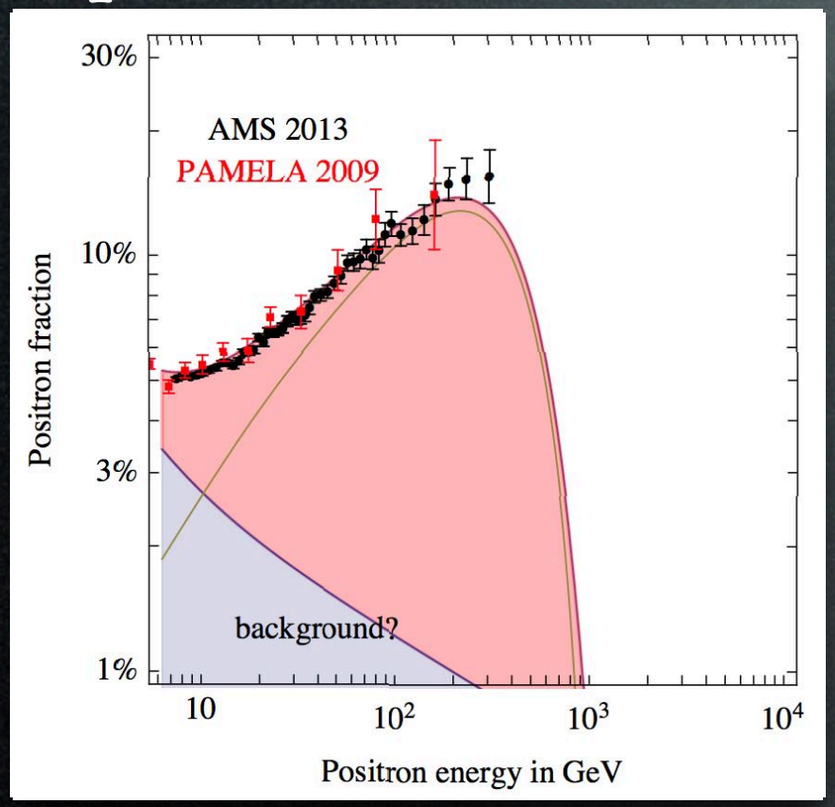
Are these signals of Dark Matter?

YES: few TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$

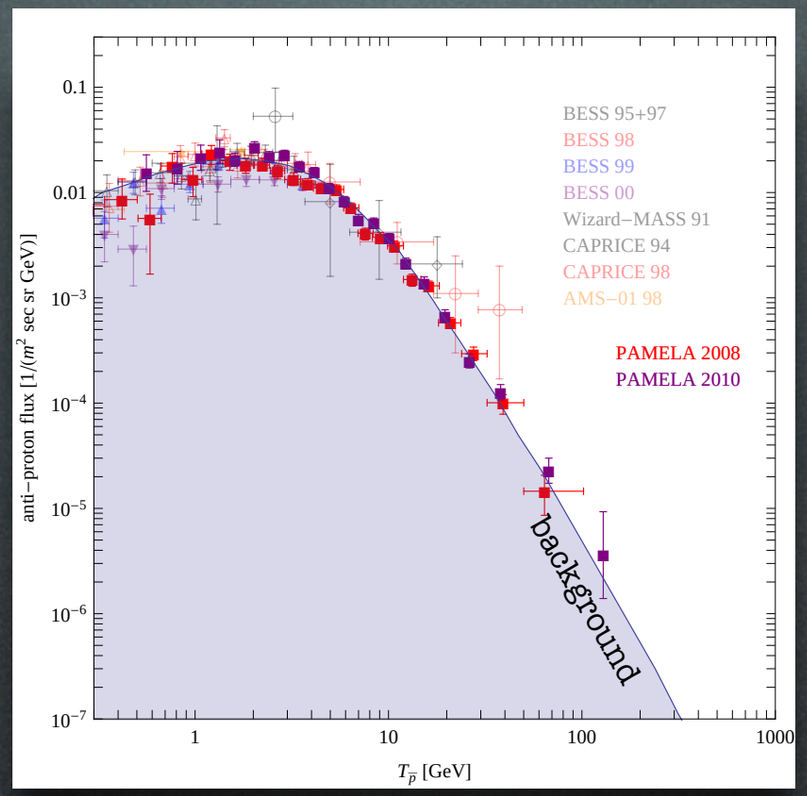
NO: a formidable 'background' for future searches

PS: post AMS 2013

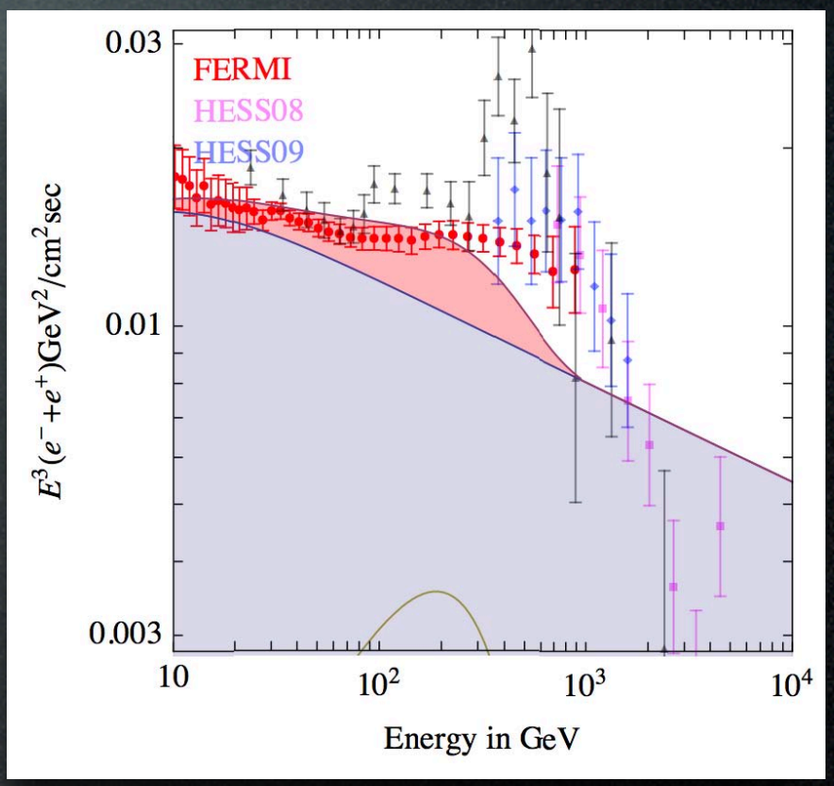
positron fraction



antiprotons



electrons + positrons

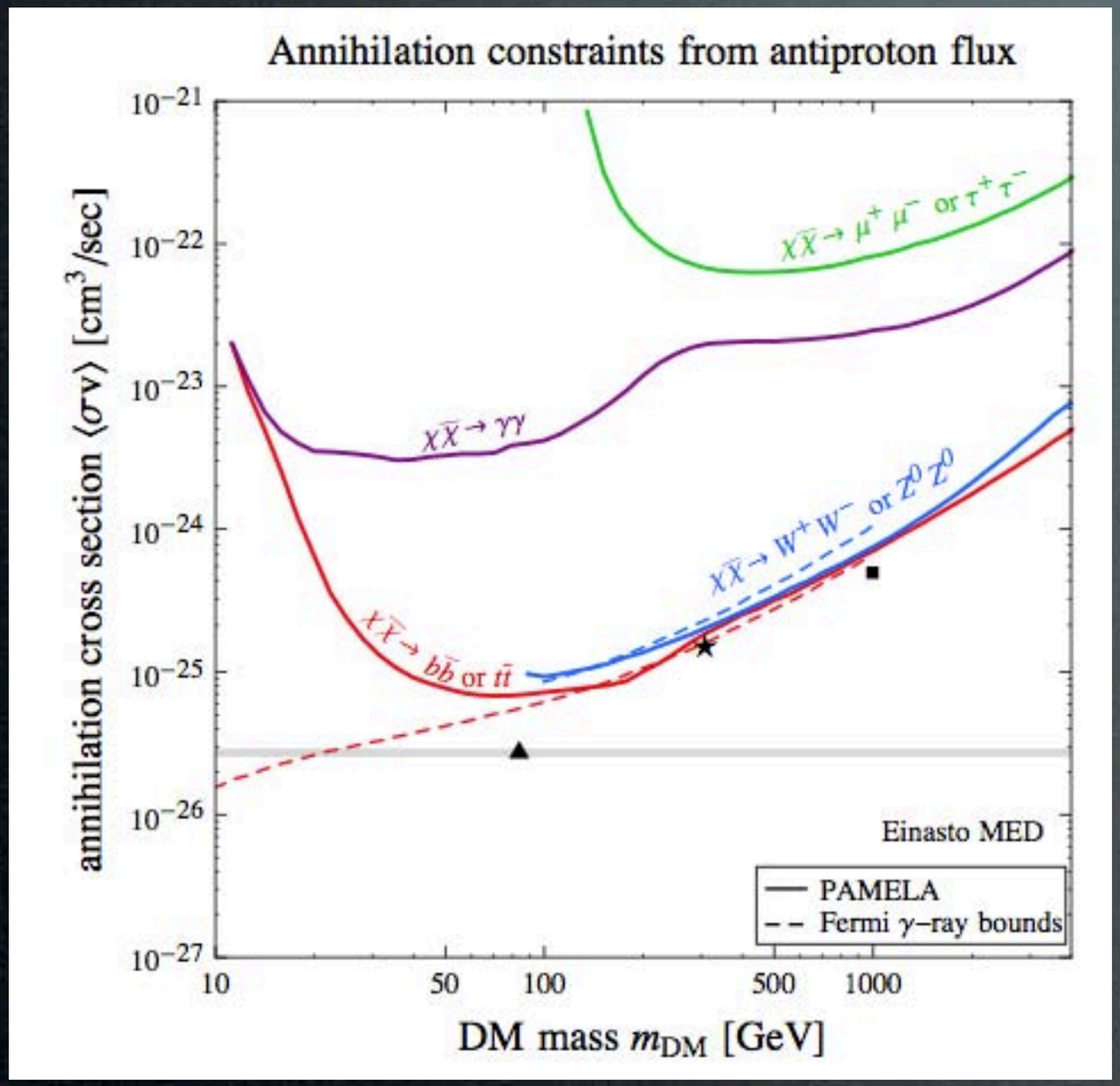


Are these signals of Dark Matter?

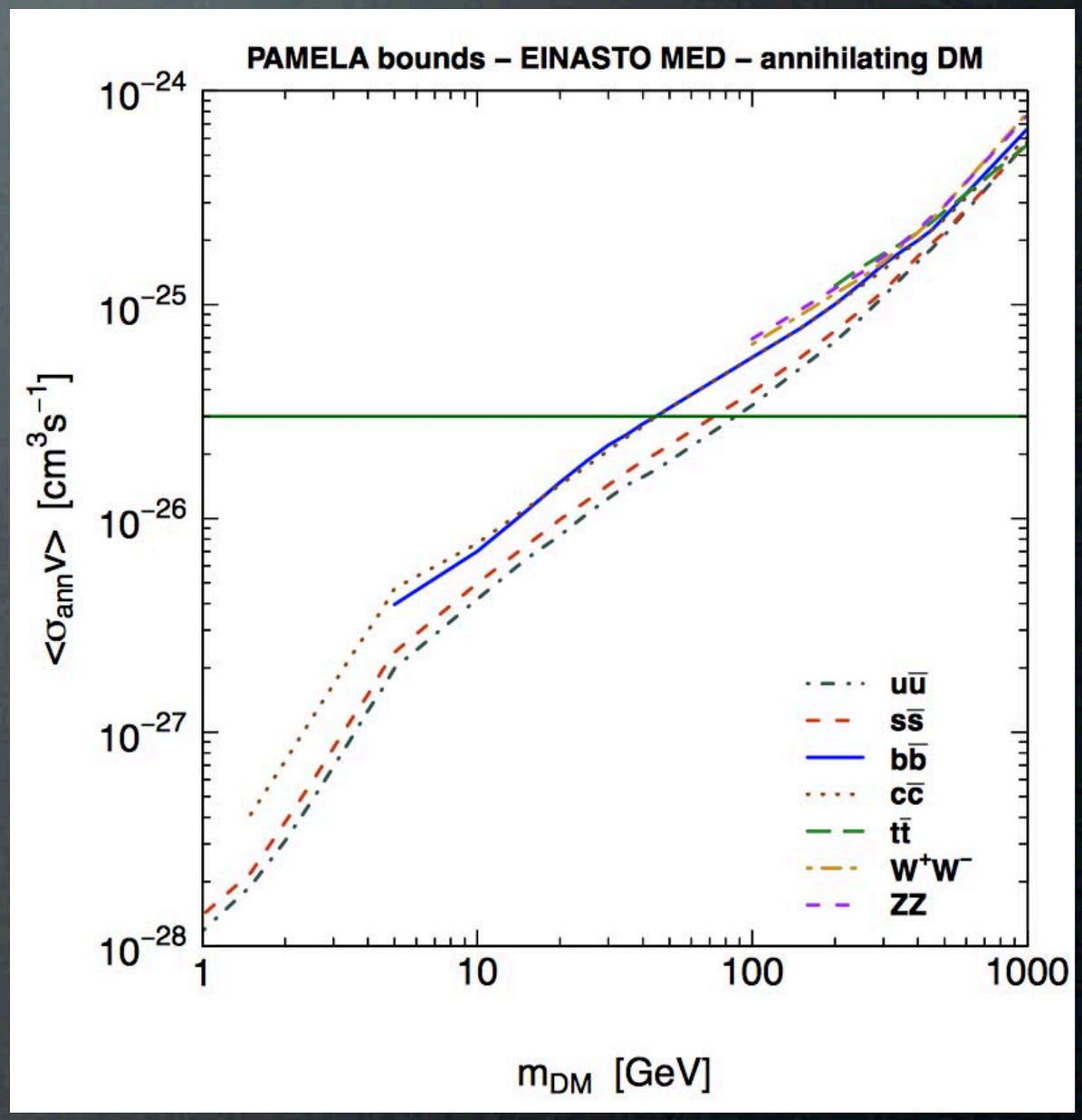
YES: one TeV, leptophilic DM
with huge $\langle \sigma v \rangle \approx 10^{-23}\,\mathrm{cm}^3/\mathrm{sec}$
'tension' between positron frac and $e^+ + e^-$

Antiproton constraints

Constraints are powerful...



Cirelli, Giesen 1301.7079



Fornengo, Maccione, Vittino 1312.3579

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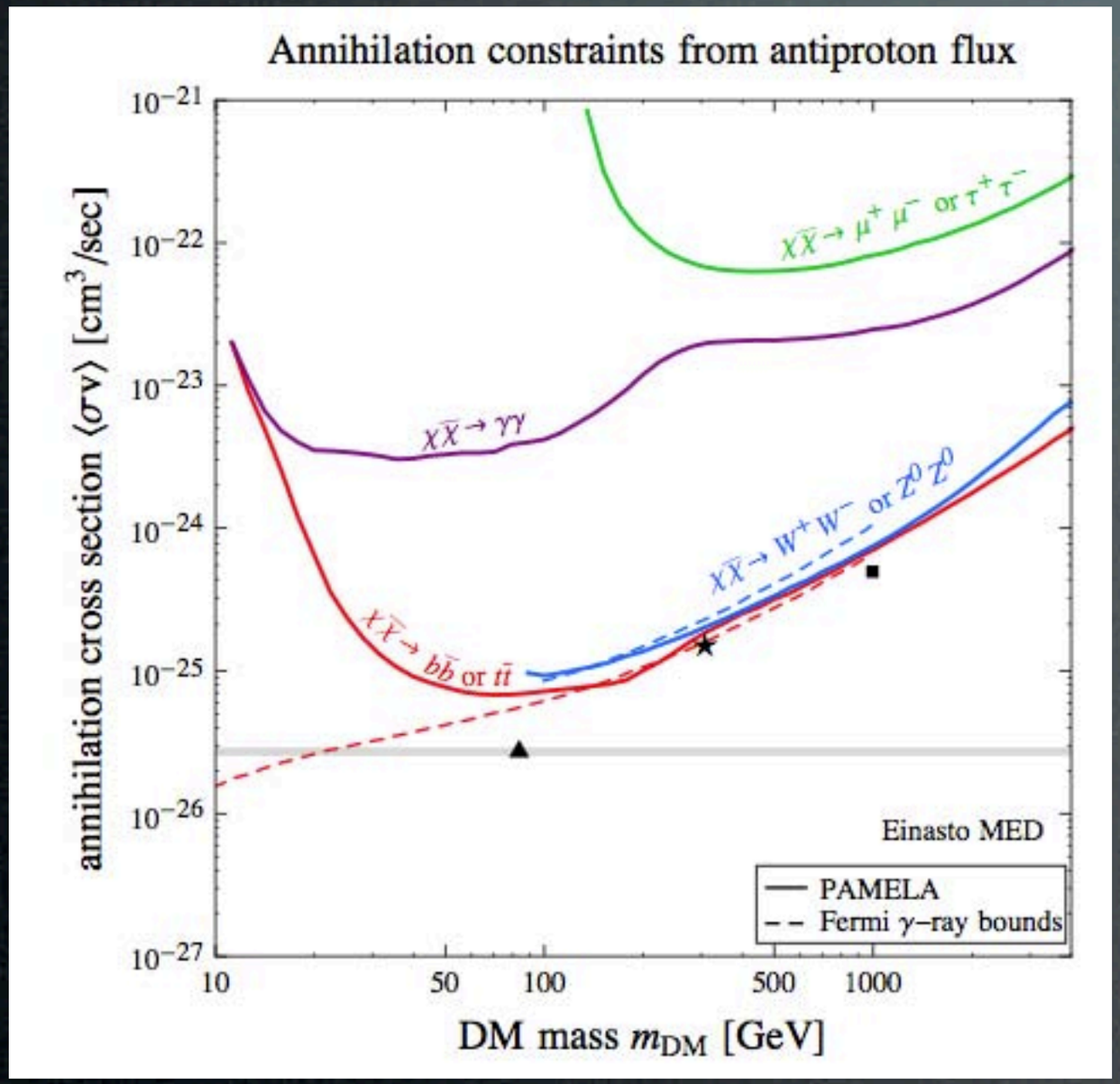
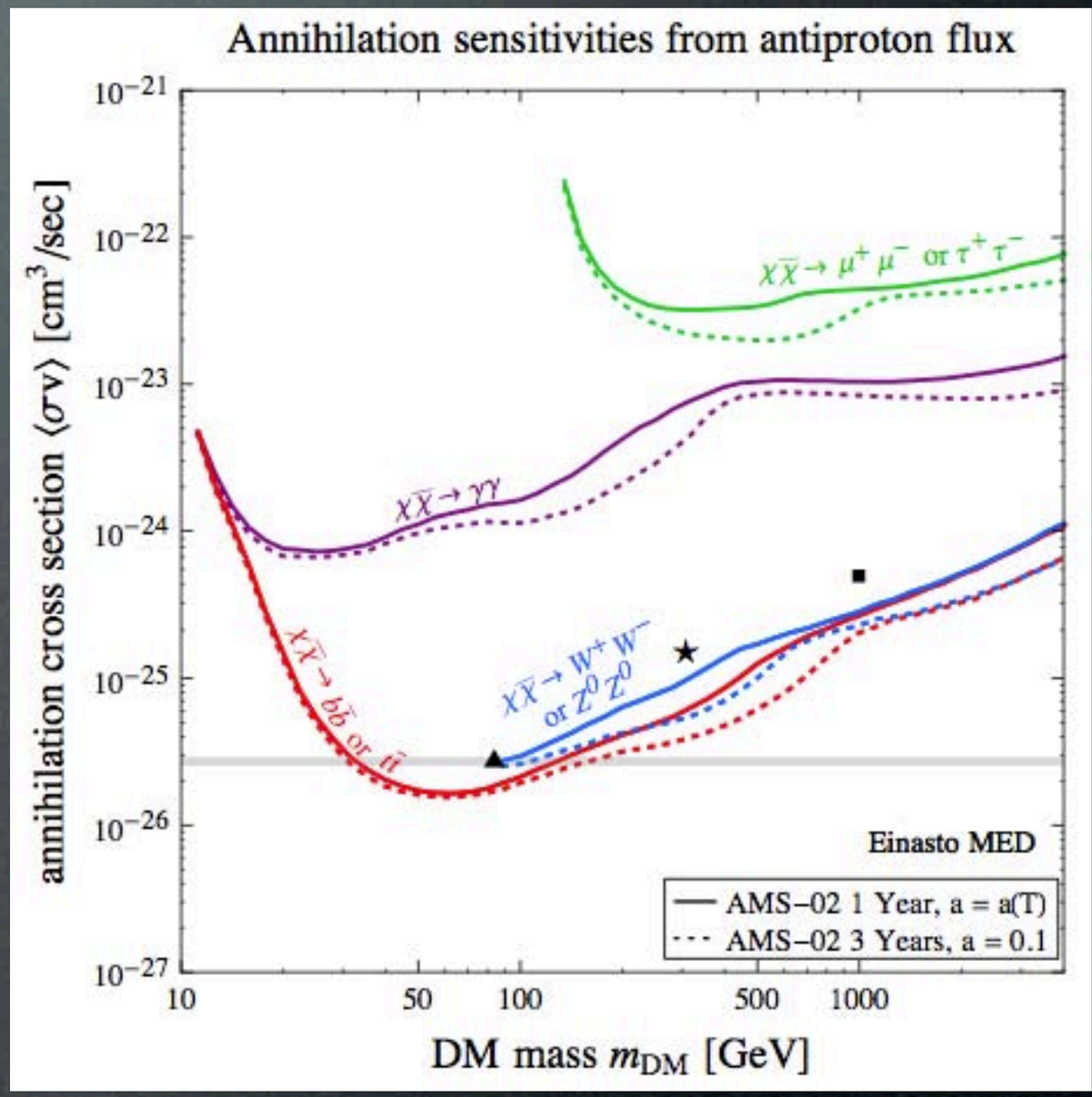


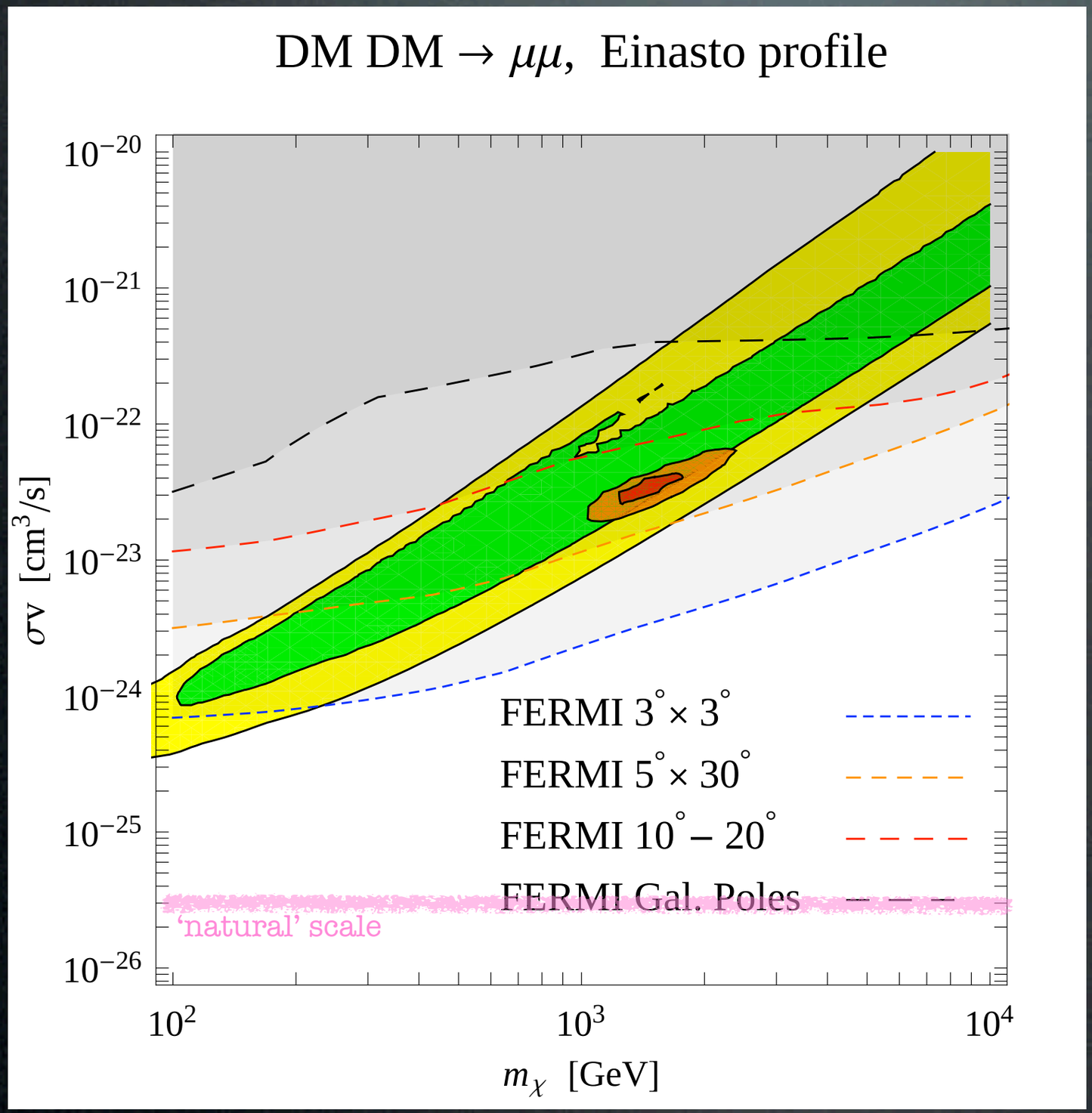
AMS-02 will improve



Cirelli, Giesen 1301.7079

Gamma constraints

γ from Inverse Compton on $e^{\pm}$ in halo

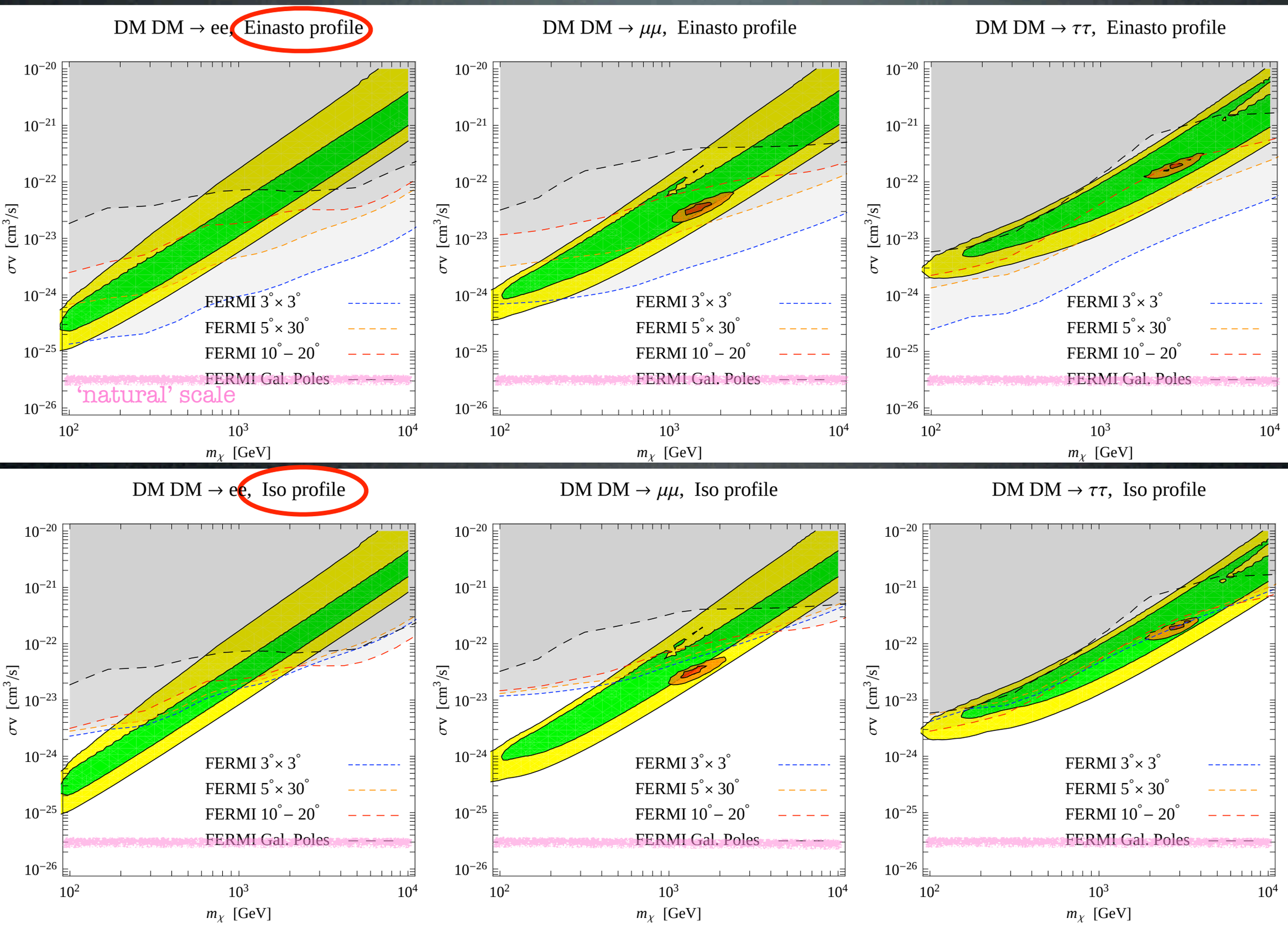


Cirelli, Panci, Serpico 0912.0663

The PAMELA and FERMI regions are in conflict with these gamma constraints

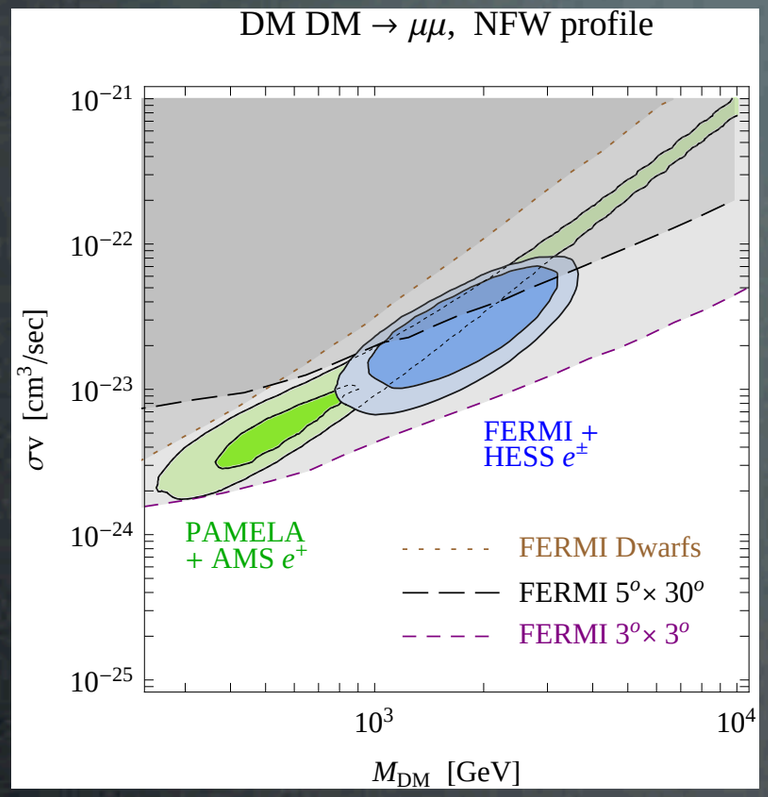
Gamma constraints

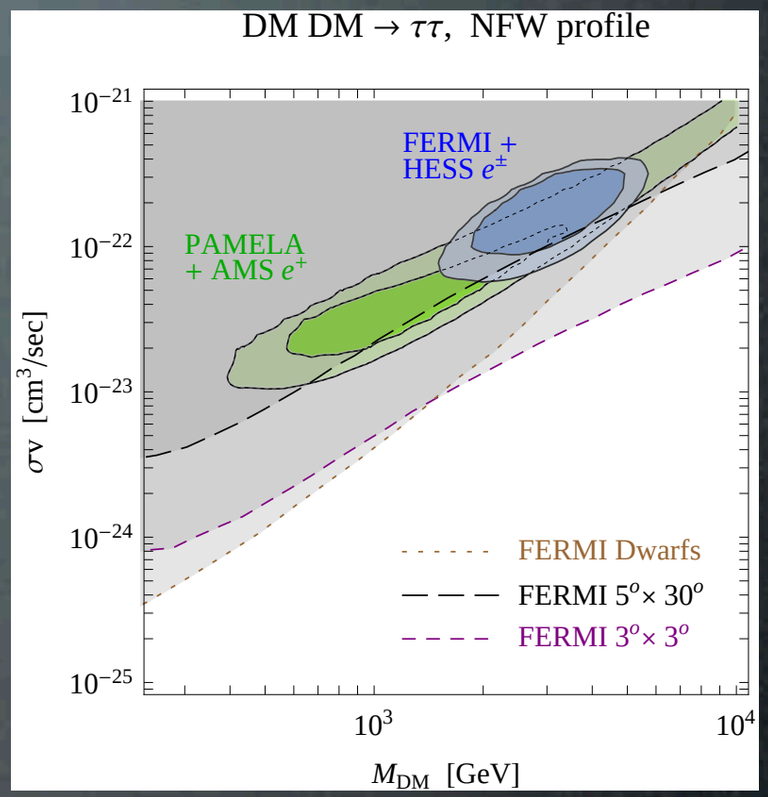
γ from Inverse Compton on $e^{\pm}$ in halo

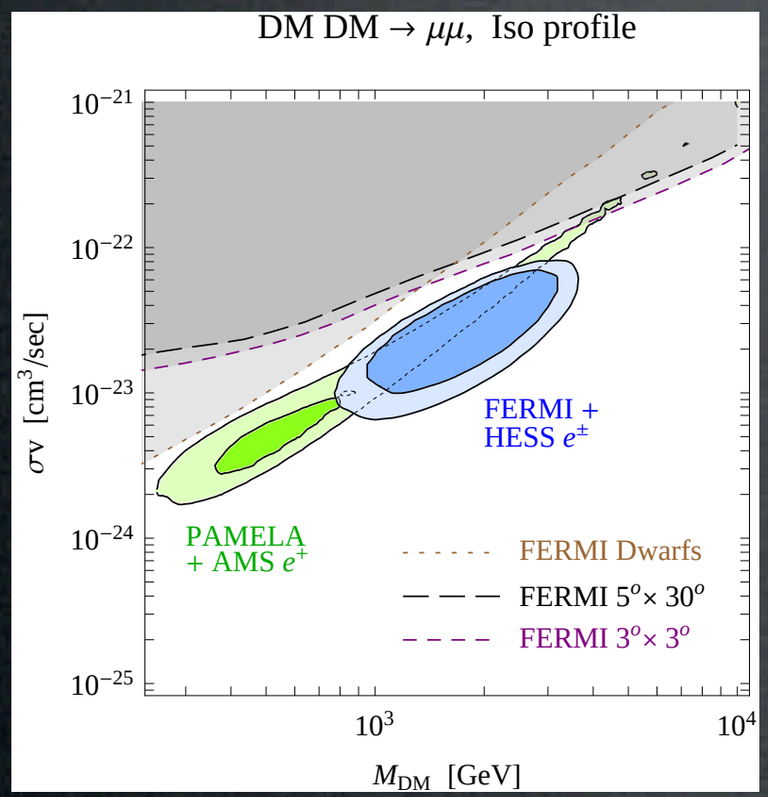


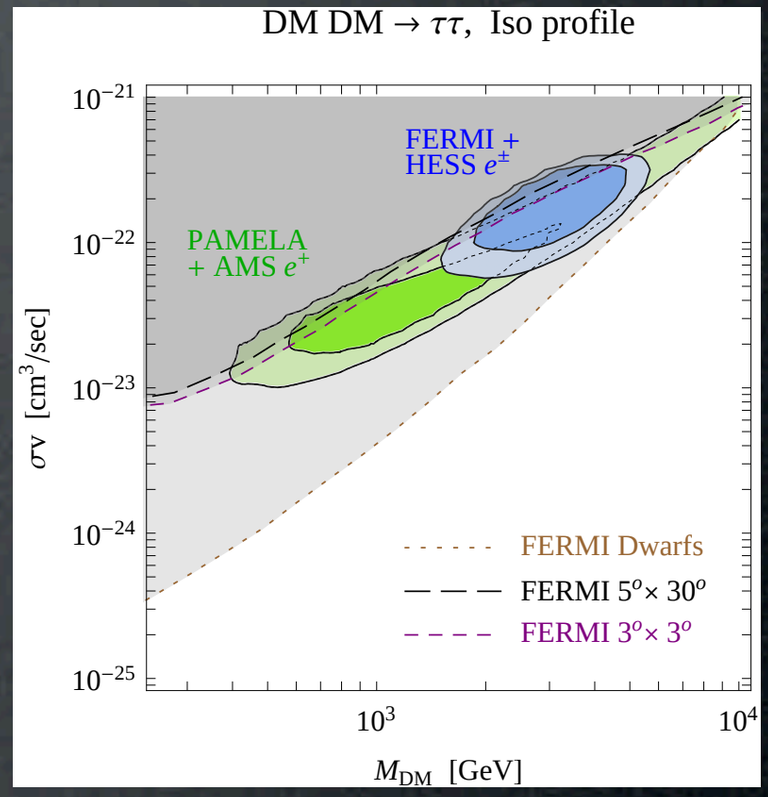
Cirelli, Panci, Serpico 0912.0663

PS: post AMS 2013







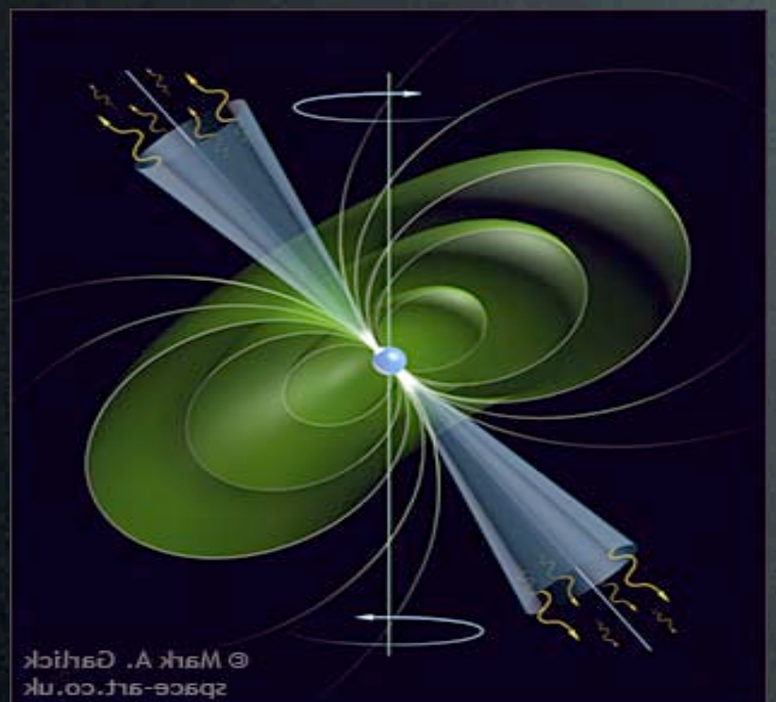


Addendum (2013) to Cirelli, Kadastik, Raidal, Strumia 0809.2409 (2008)

Astrophysical explanation?

Astrophysical explanation?

Or perhaps it's just a young, nearby pulsar...



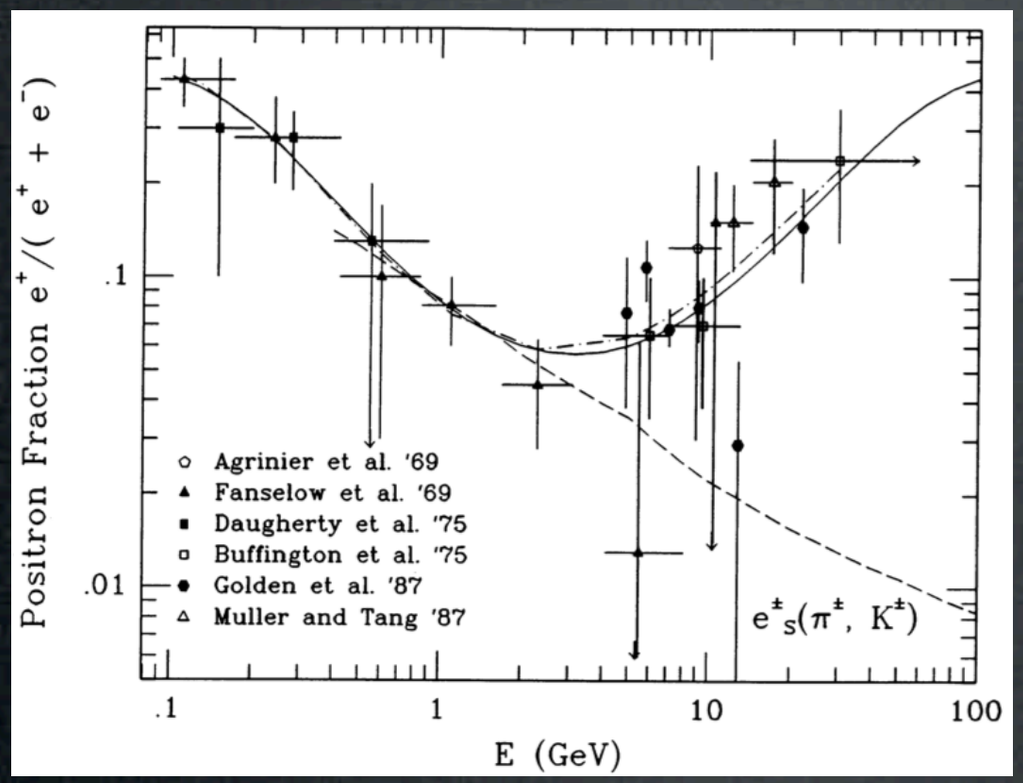
'Mechanism': the spinning $\vec{B}$ of the pulsar strips e^- that emit γ that make production of $e^\pm$ pairs that are trapped in the cloud, further accelerated and later released at $\tau \sim 0 \rightarrow 10^5$ yr (typical total energy output: 10^{46} erg).

Must be young (T < 10^5 yr) and nearby (< 1 kpc);
if not: too much diffusion, low energy, too low flux.

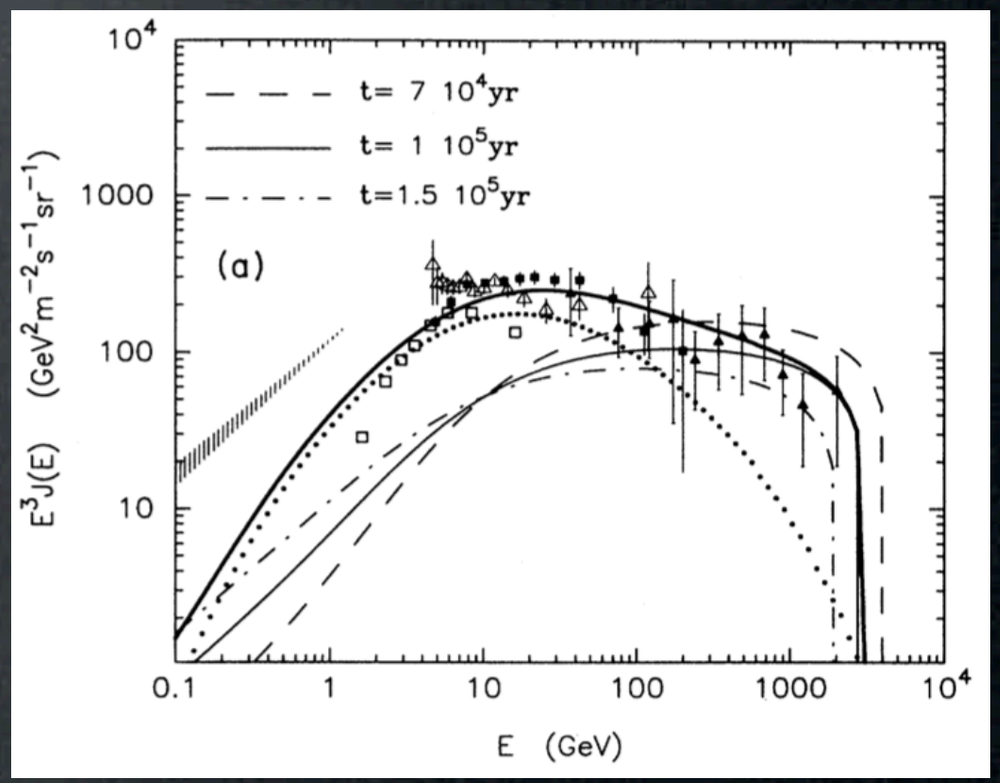
Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

$(1.4 < p < 2.4,$ Profumo 2008)

Not a new idea:



A.Boulares, APJ 342 (**1989**)



Atoyan, Aharonian, Volk (**1995**)

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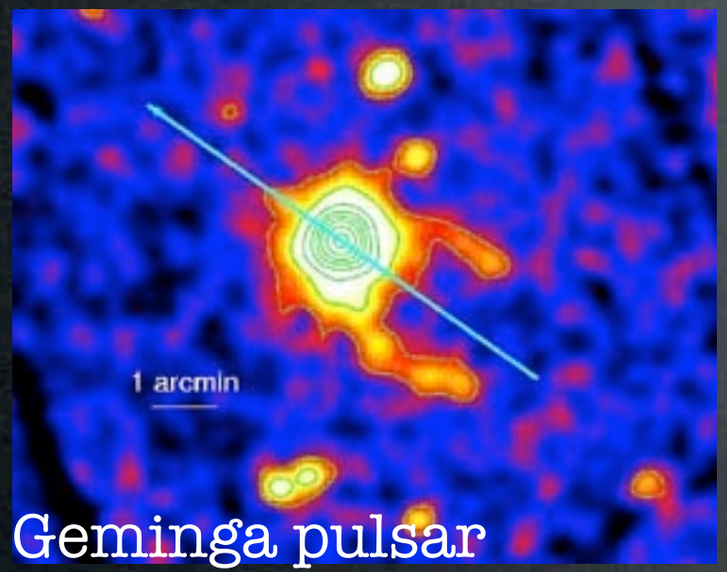

Geminga pulsar

(funny that it means:
"it is not there" in milanese)

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if not: too much diffusion, low energy, too low flux.

Predicted flux: $\Phi_{e^\pm} \approx E^{-p} \exp(E/E_c)$ with $p \approx 2$ and $E_c \sim$ many TeV

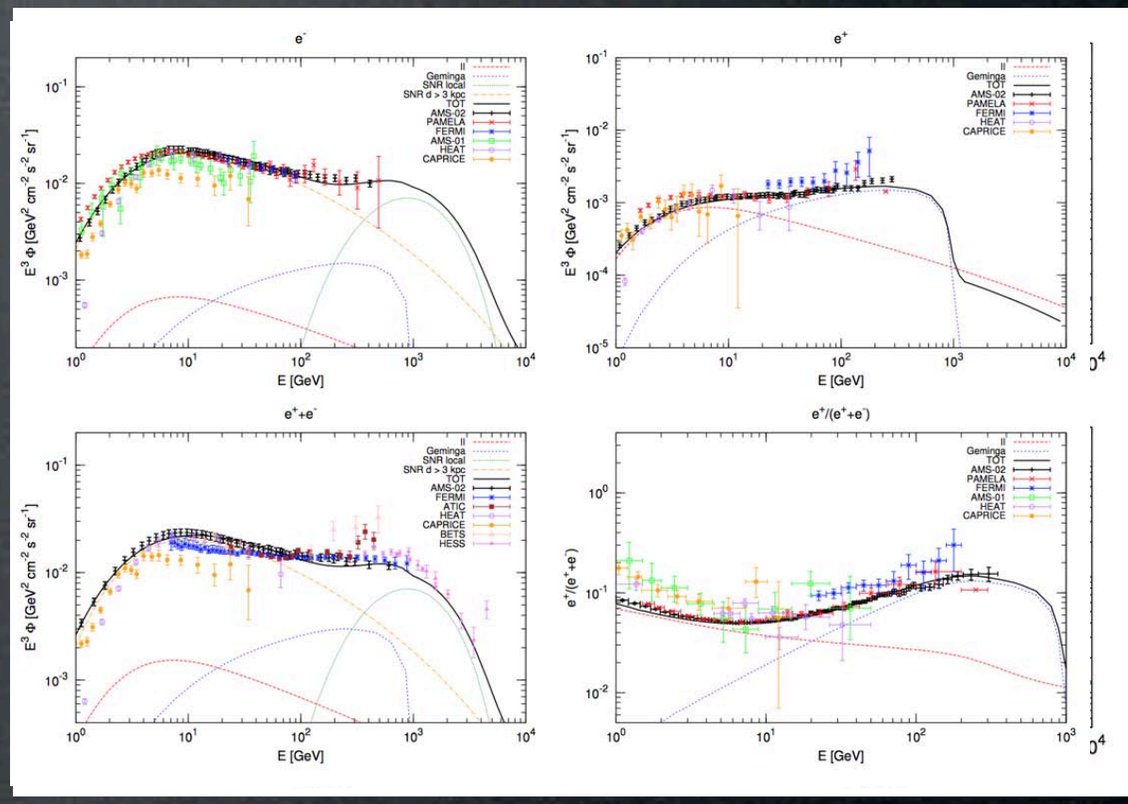
Try the fit with known nearby pulsars:

Büshing, de Jager et al. 0804.0220

TABLE 1
LIST OF NEARBY SNRS

SNR	Distance (kpc)	Age (yr)	E_{max} [a] (TeV)
SN 185	0.95	1.8×10^3	1.7×10^2
S147	0.80	4.6×10^3	63
HB 21	0.80	1.9×10^4	14
G65.3+5.7	0.80	2.0×10^4	13
Cygnus Loop	0.44	2.0×10^4	13
Vela	0.30	1.1×10^4	25
Monogem	0.30	8.6×10^4	2.8
Loop1	0.17	2.0×10^5	1.2
Geminga	0.4	3.4×10^5	0.67

pulsar	E_{cut}	α	E_{tot}	$\log(A_e)$	γ_1	γ_2	R^e_{br}	c_{e+}	ϕ_e
Geminga	1.0	1.98	14.2	-8.93	1.74	2.75	3.61	1.53	720
Monogem	0.62	2.04	3.30	-8.93	1.75	2.75	3.62	1.61	735



Yin et al. 1304.4128
Di Mauro et al., 1402.0321

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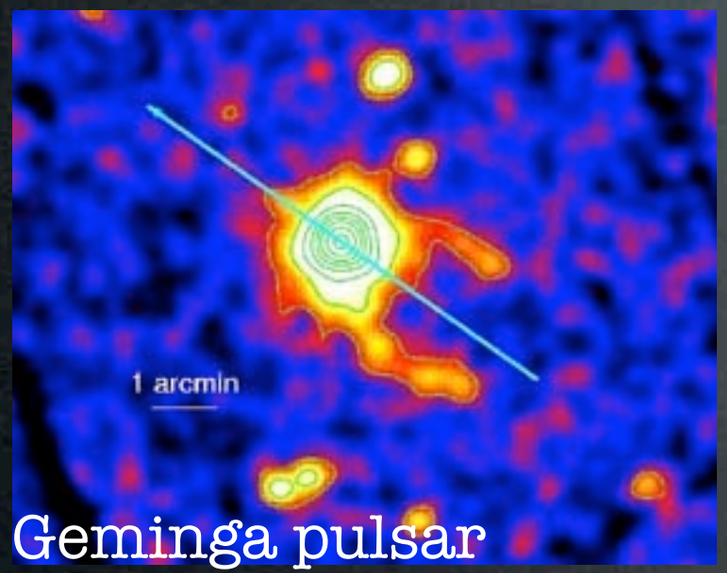

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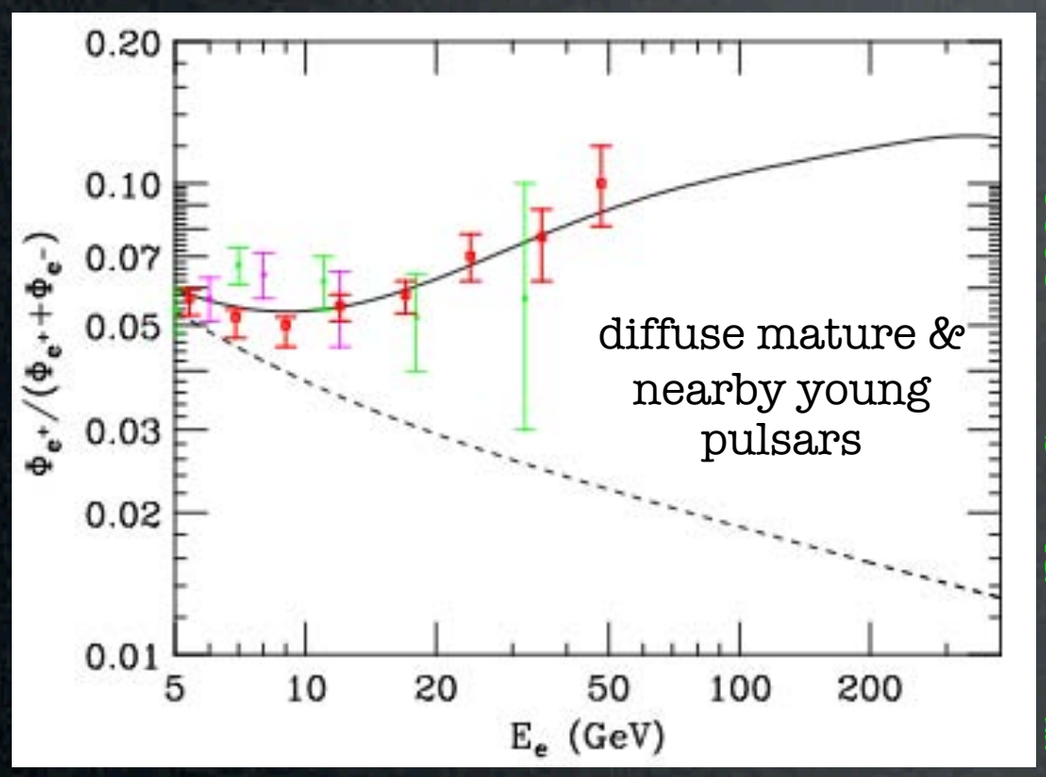
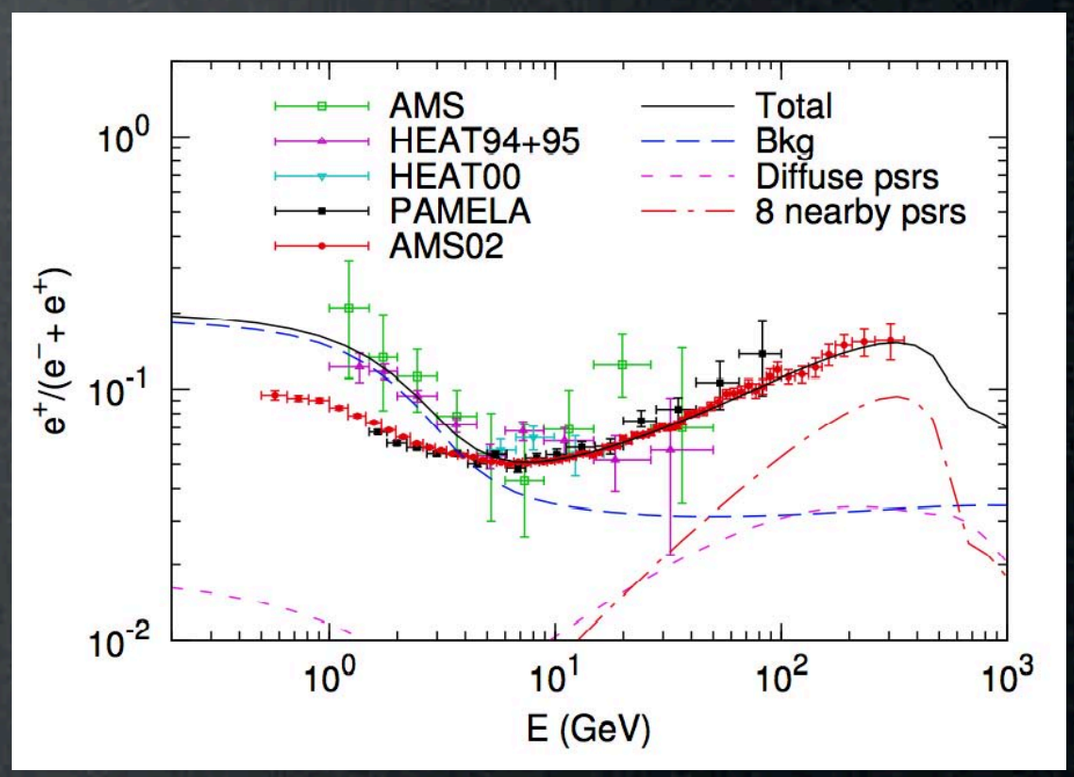
Try the fit with known nearby pulsars + diffuse mature pulsars:



Hooper, Blasi, Serpico 2008



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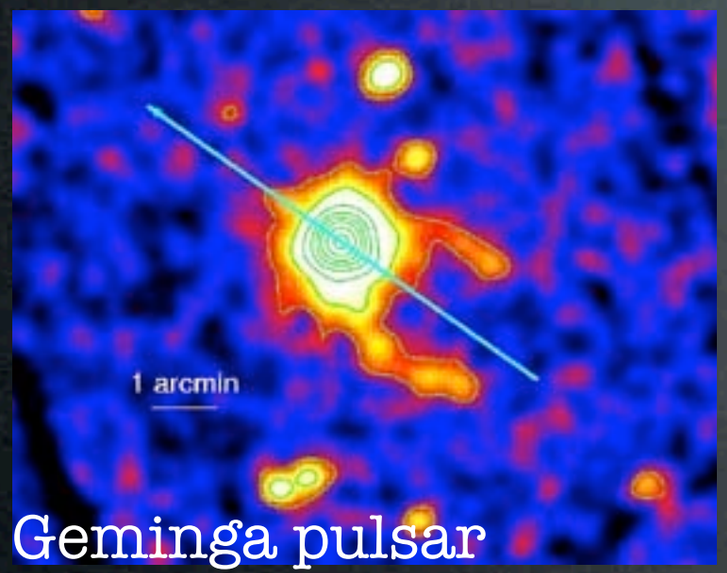

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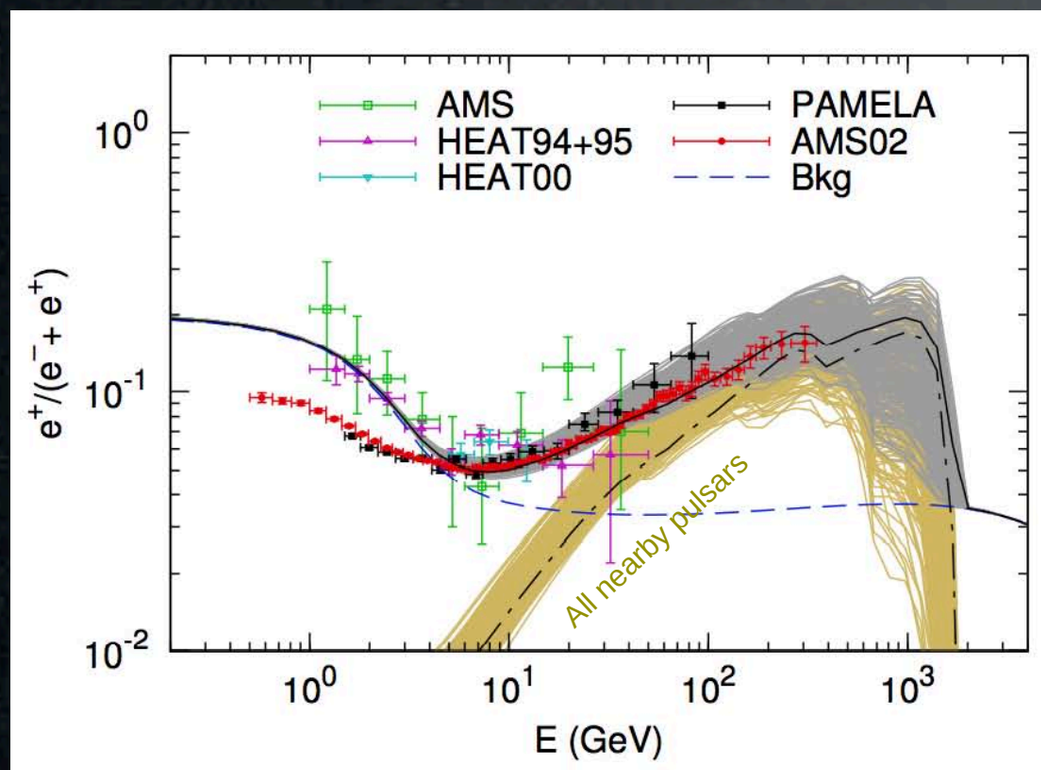
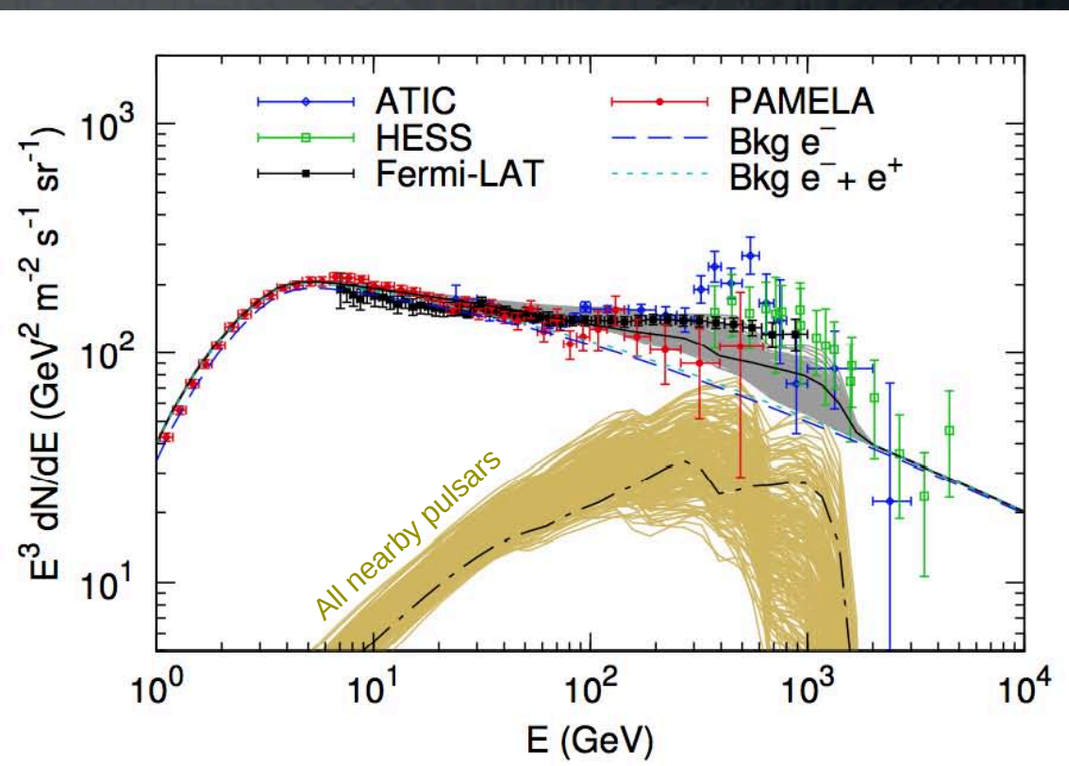
PAMELA + FERMI + HESS can be well fitted by pulsars:





D.Grasso et al. (sub-FERMI collab.) 0905.0636

Yin et al. 1304.4128

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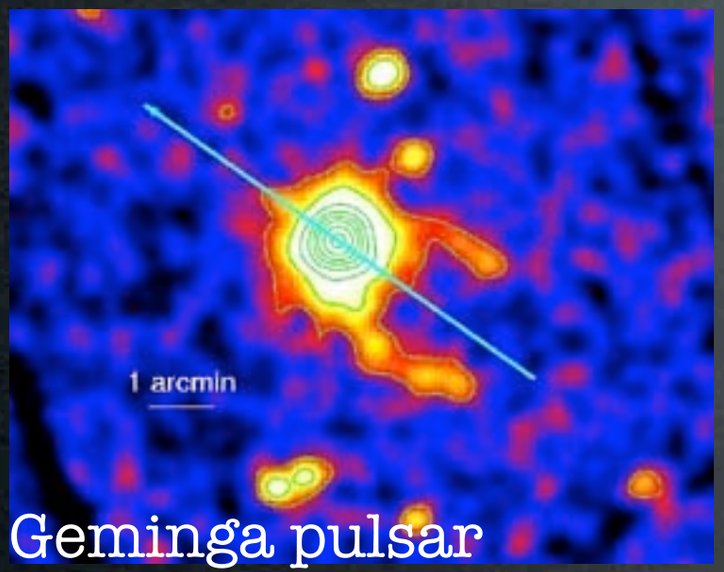

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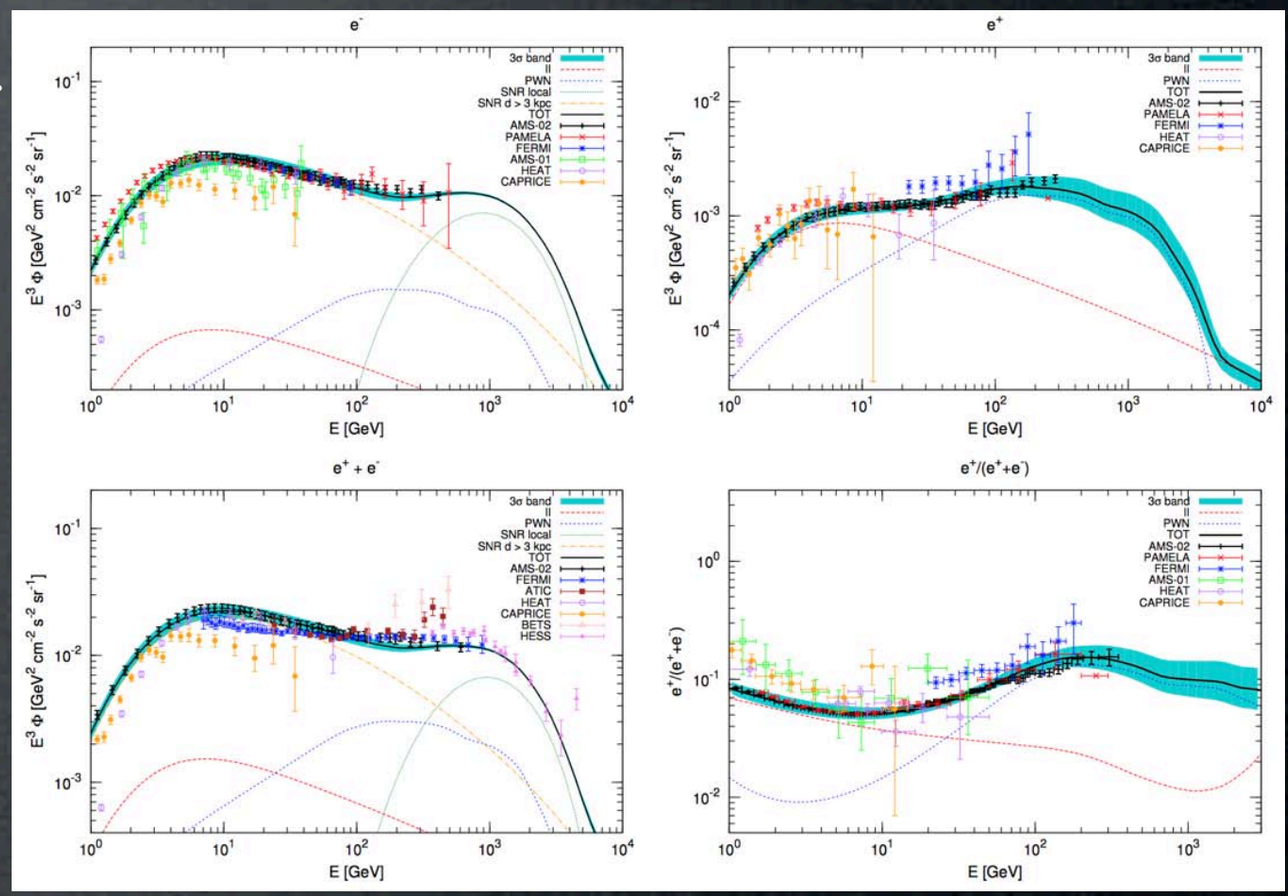
Even better, a combination of several astro sources...

local SNR
+ far SNR
+ PWN
+ secondaries



Di Mauro et al., 1402.0321

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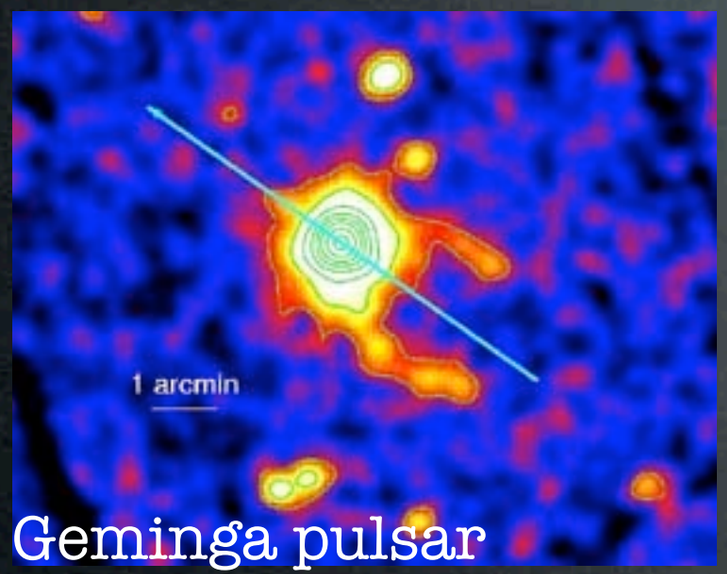

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Even better, a combination of several astro sources...

Open issue.

(look for anisotropies,
(both for single source and collection in disk)
antiprotons, gammas...
(Fermi is discovering a pulsar a week)
or shape of the spectrum...)

e.g. Yuksel, Kistler, Stanev 0810.2784
Hall, Hooper 0811.3362

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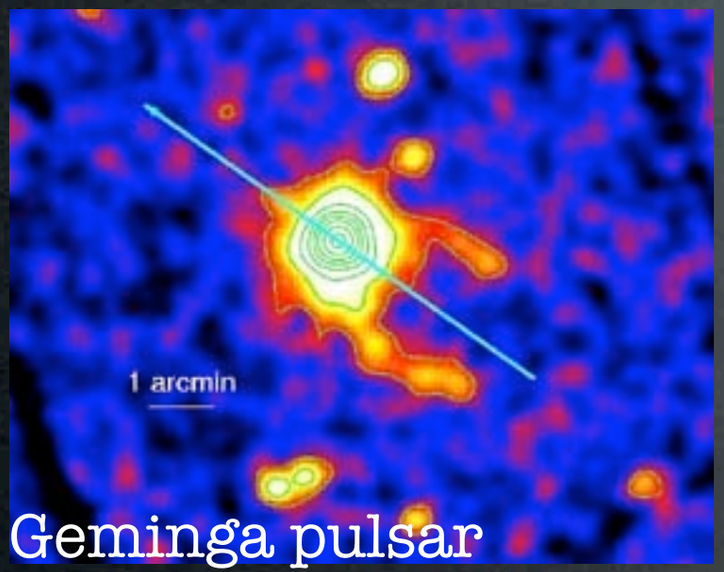

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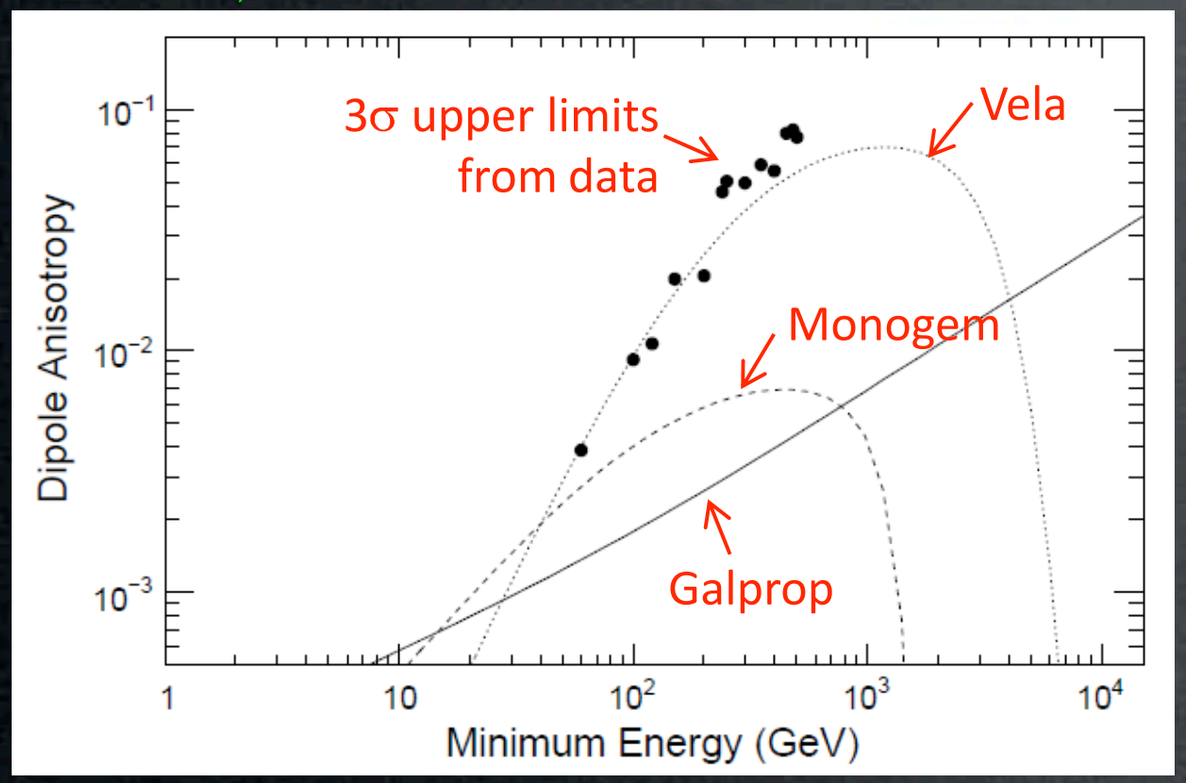
Fermi coll., 1008.5119



Rule out one single bright source.

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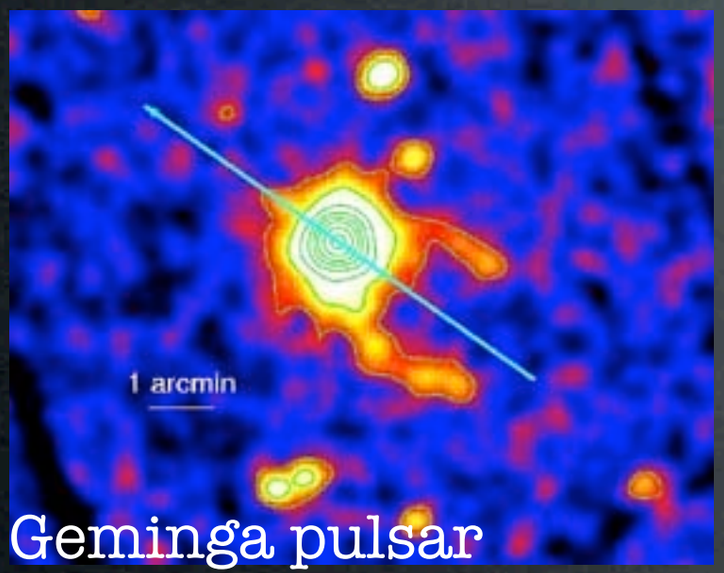

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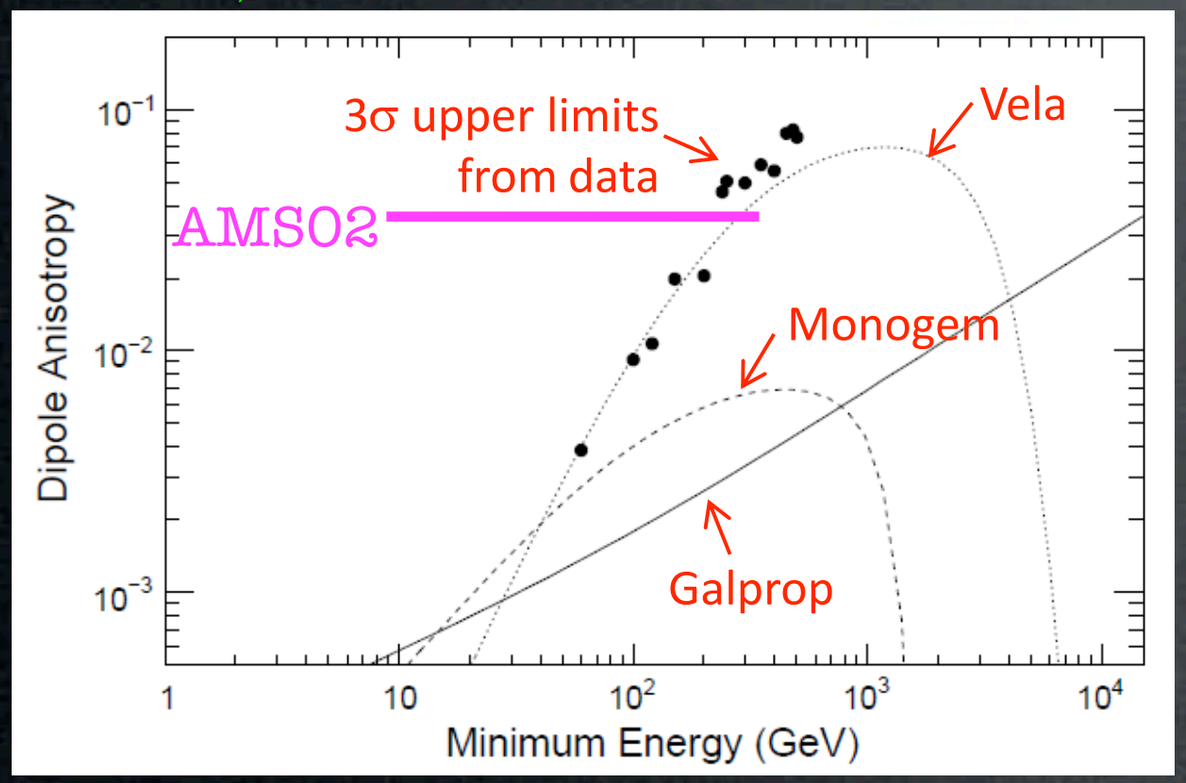

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Theorist's reaction

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1. the 'PAMELA frenzy'

Challenges for the 'conventional' DM candidates

Needs:	**SuSy DM**	**KK DM**
- TeV or multi-TeV masses	difficult	ok
- no hadronic channels	difficult	difficult
- very large flux	no	ok

for any Majorana DM,
s-wave annihilation cross section

$$\sigma_{\rm ann}(\mathrm{DM}\,\mathrm{D\bar{M}} \to f\bar{f}) \propto \left(\frac{m_f}{M_{\rm DM}}\right)^2$$

Enhancement

How to reconcile $\sigma = 3 \cdot 10^{-26} \mathrm{cm}^3/\mathrm{sec}$ with $\sigma \simeq 10^{-23} \mathrm{cm}^3/\mathrm{sec}$?

- DM is produced non-thermally: the annihilation cross section today is unrelated to the production process

	at freeze-out	***today***
- astrophysical boost	no clumps	clumps
- resonance effect	off-resonance	on-resonance
- Sommerfeld effect	$v/c \simeq 0.1$	$v/c \simeq 10^{-3}$
+ (Wimponium)		

Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

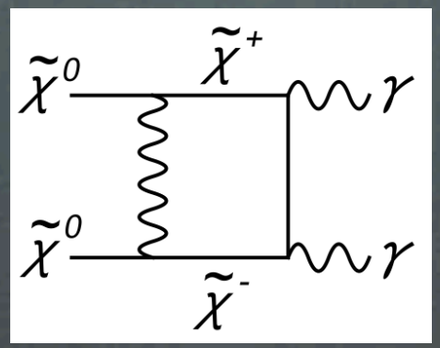
Sommerfeld Enhancement

NP QM effect that can enhance the annihilation cross section by orders of magnitude in the regime of small velocity and relatively long range force.

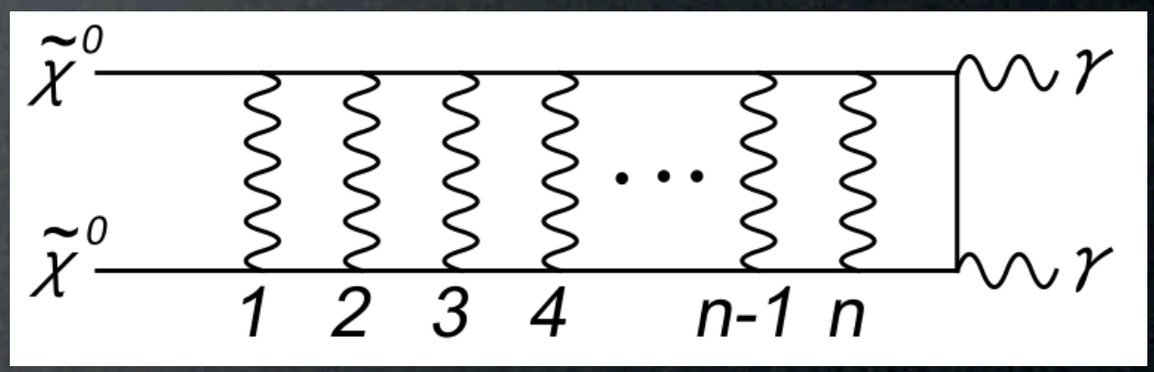
In terms of Feynman diagrams:

Hisano et al. hep-ph/0412403

First order cross section:



Adding a rung to the ladder: $\times \left(\frac{\alpha M}{m_W}\right)$



For $\alpha M/m_V \gtrsim 1$ the perturbative expansion breaks down,
need to resum all orders
i.e.: keep the full interaction potential.

Model building

- Minimal extensions of the SM:
  heavy WIMPS (Minimal DM, Inert Doublet)

Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:

New models with a rich Dark sector

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- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

Decaying DM

DM need not be absolutely stable,
just $\tau_{\rm DM} \gtrsim \tau_{\rm universe} \simeq 4.3\ 10^{17}{\rm sec}$.

The current CR anomalies can be due to decay with:

$$\tau_{\rm decay} \approx 10^{26}{\rm sec}$$

Motivations from theory?

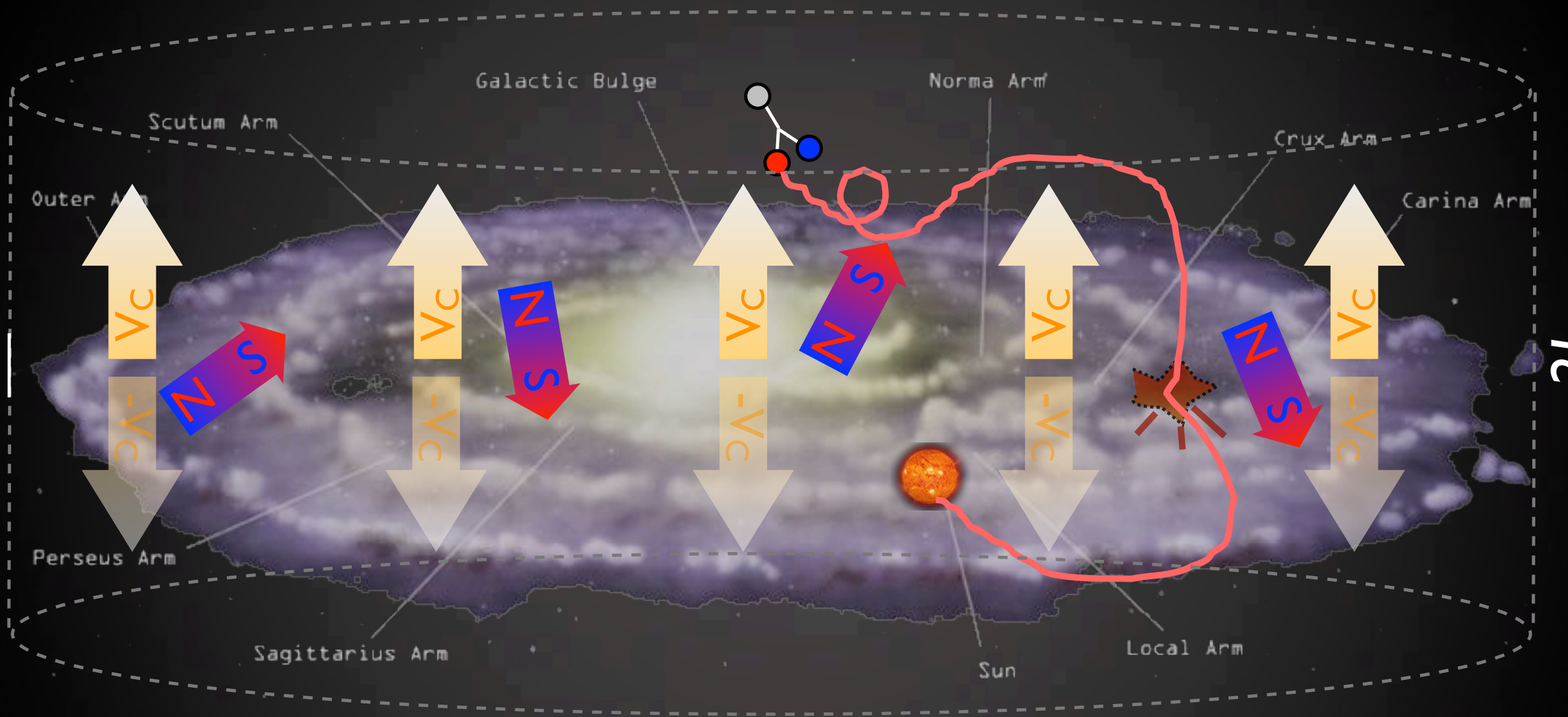
- dim 6 suppressed operator in GUT Arvanitaki, Dimopoulos et al., 2008+09

$$\tau_{\rm DM} \simeq 3 \cdot 10^{27}{\rm sec} \left(\frac{1\ {\rm TeV}}{M_{\rm DM}}\right)^5 \left(\frac{M_{\rm GUT}}{2 \cdot 10^{16}\,{\rm GeV}}\right)^4$$

- or in TechniColor Nardi, Sannino, Strumia 2008
- gravitino in SuSy with broken R-parity...

Indirect Detection

$\bar{p}$ and e^+ from DM decay in halo



What sets the overall expected flux?

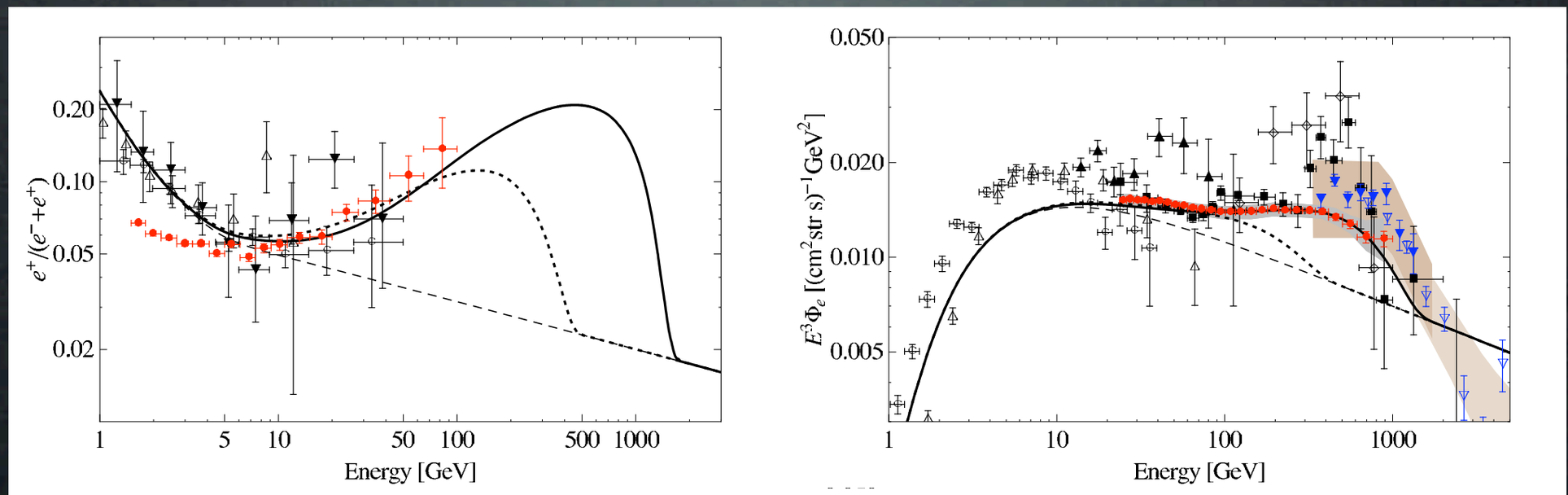
$$\text{flux} \propto n\ \Gamma_{\text{decay}}$$

$$\Gamma_{\text{decay}}^{-1} = \tau_{\text{decay}} \approx 10^{26}\text{sec}$$

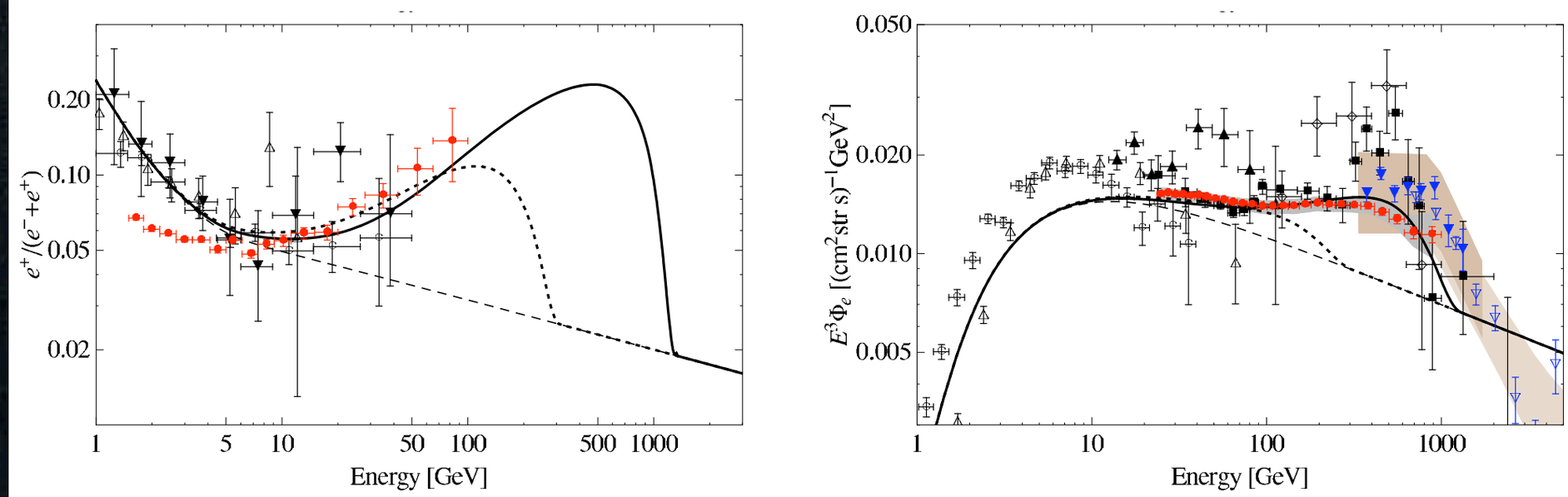
Decaying DM

Which DM spectra can fit the data?

E.g. a fermionic $\mathrm{DM} \to \mu^+\mu^-\nu$ with $M_{\mathrm{DM}} = 3.5\,\mathrm{TeV}$:



E.g. a scalar $\mathrm{DM} \to \mu^+\mu^-$ with $M_{\mathrm{DM}} = 2.5\,\mathrm{TeV}$:

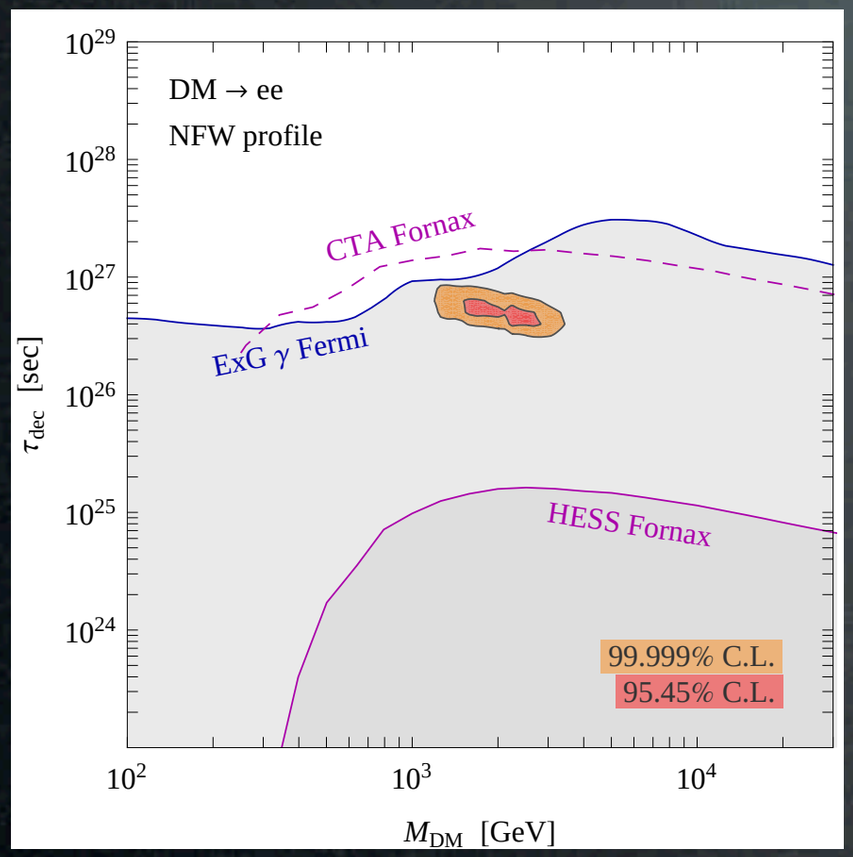


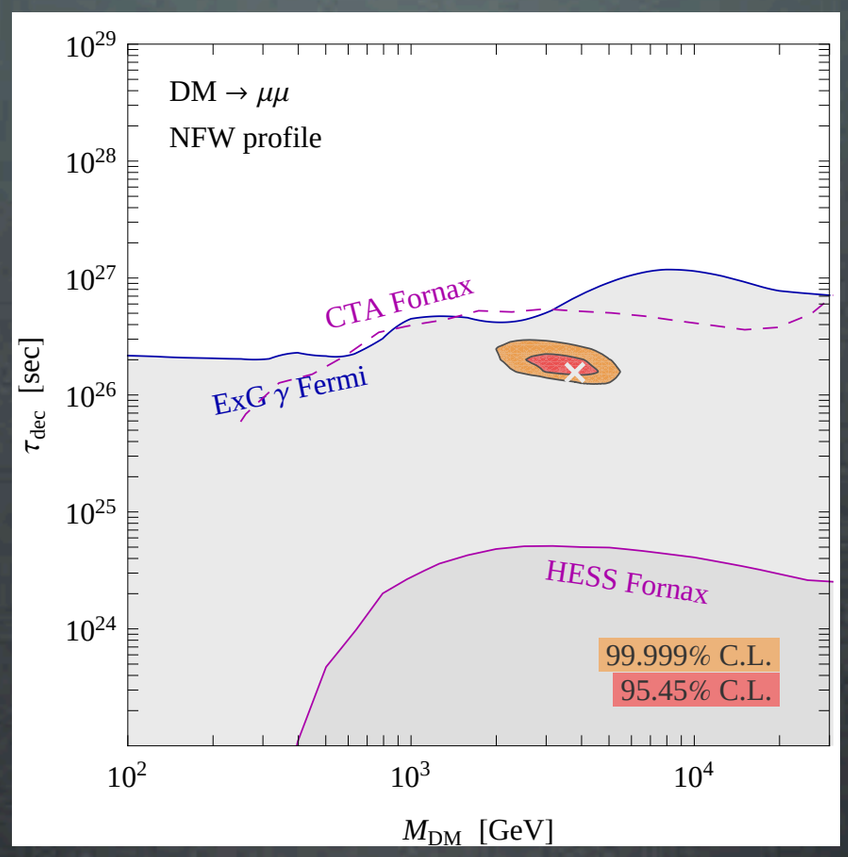
Ibarra, Tran, Weniger 2009

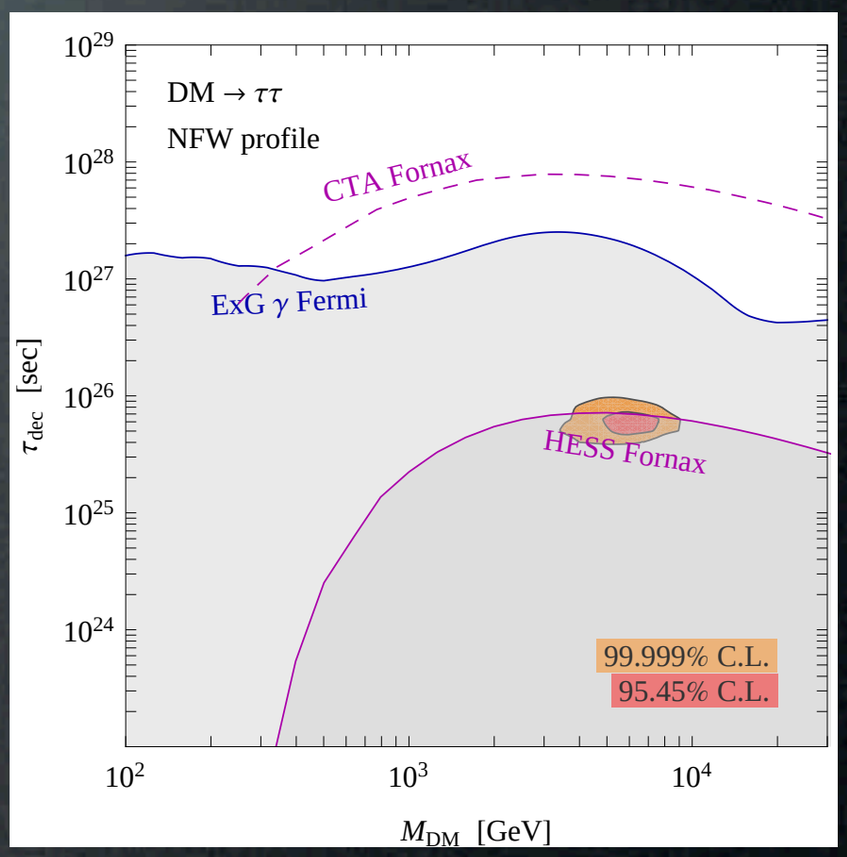
Decaying DM

But, again: gamma ray constraints

(although: no radio, neutrino constraints)







Cirelli, Moulin, Panci, Serpico, Viana 1205.5283

The PAMELA and FERMI regions are in conflict with these gamma constraints.

Model building

- Minimal extensions of the SM:
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Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

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- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153

A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075

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- Minimal extensions of the SM:
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Cirelli, Strumia et al. 2005-2009 Tytgat et al. 0901.2556

- More drastic extensions:
  New models with a rich Dark sector
  - TeV mass DM
  - new forces (that Sommerfeld enhance)
  - leptophilic because: - kinematics (light mediator)
    - DM carries lepton #

- Decaying DM

Ibarra et al., 2007-2009 Nardi, Sannino, Strumia 0811.4153
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The "Theory of DM"

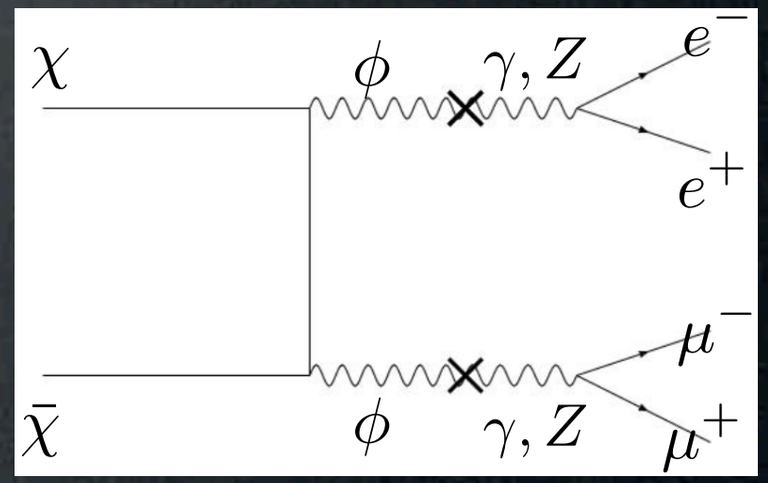
Arkani-Hamed, Weiner, Finkbeiner et al. 0810.0713
0811.3641

Basic ingredients:

χ Dark Matter particle, decoupled from SM, mass $M \sim 700+$ GeV

ϕ new gauge boson ("Dark photon"),
couples only to DM, with typical gauge strength, $m_\phi \sim$ few GeV
- mediates Sommerfeld enhancement of $\chi\bar{\chi}$ annihilation:
$\alpha M/m_V \gtrsim 1$ fulfilled

- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit



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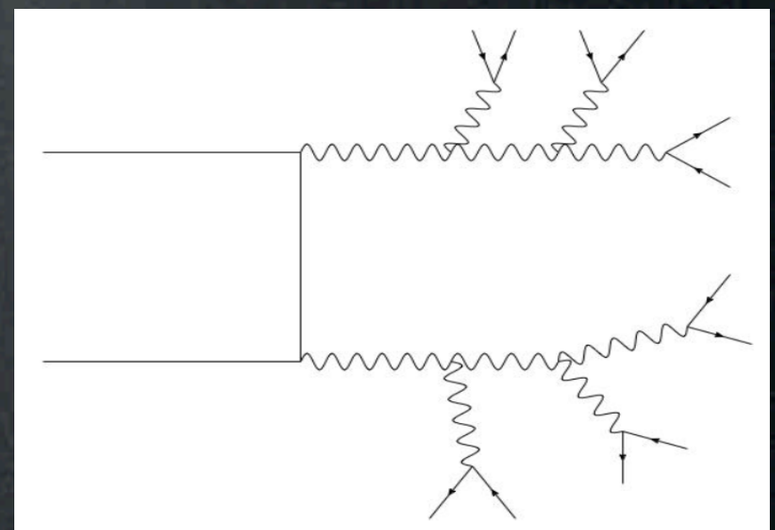


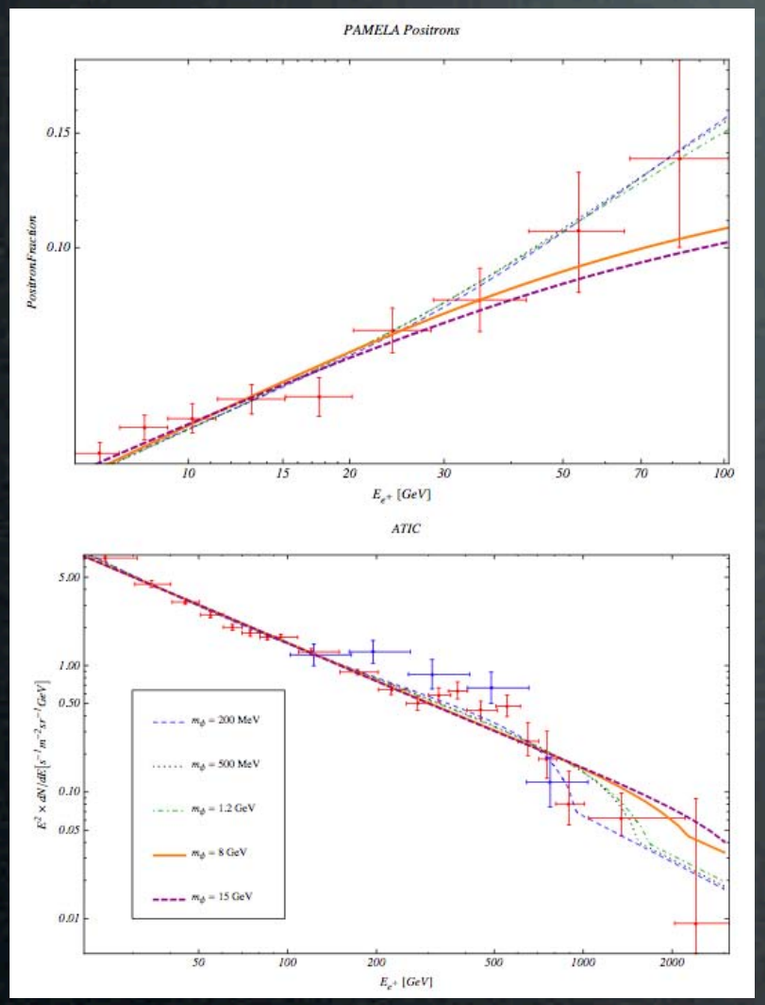
- decays only into e^+e^- or $\mu^+\mu^-$
for kinematical limit

Extras:

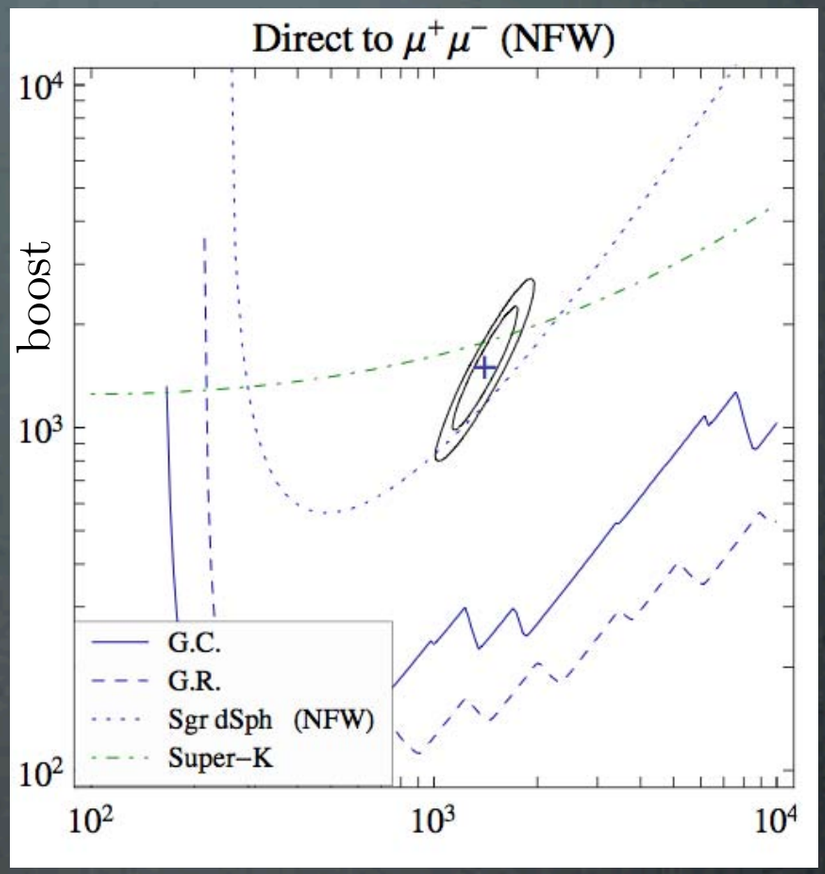
χ is a multiplet of states and ϕ is non-abelian gauge boson:
splitting $\delta M \sim 200$ KeV (via loops of non-abelian bosons)
- inelastic scattering explains DAMA
- eXcited state decay $\chi\chi \to \chi\chi^*$ explains INTEGRAL
$\hookrightarrow e^+e^-$

The "Theory of DM"

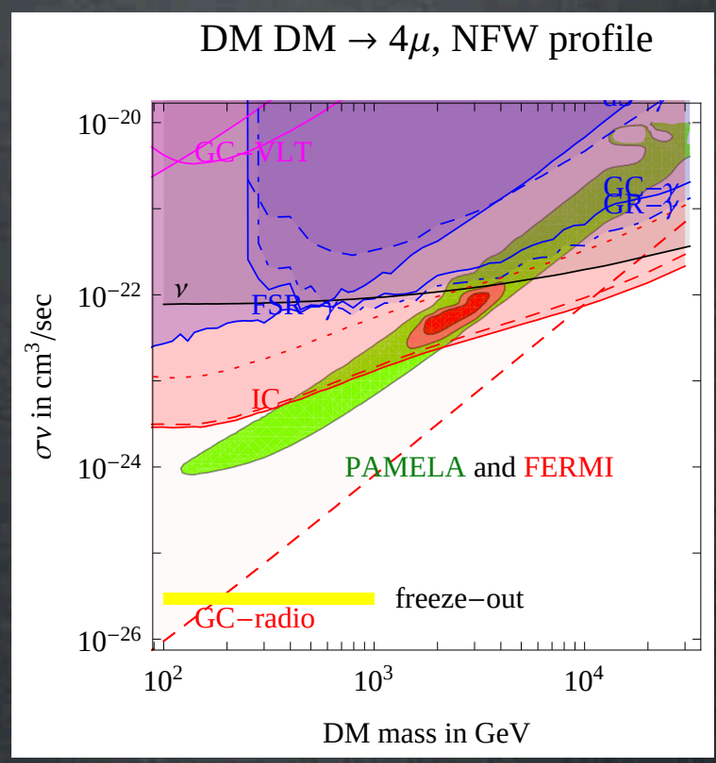
Phenomenology:

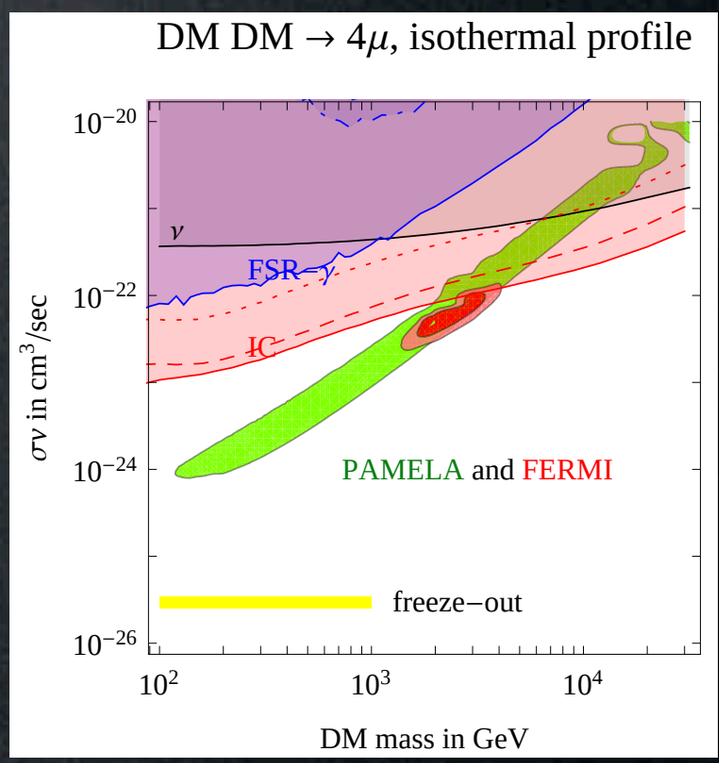


Meade, Papucci, Volanski 0901.2925



Mardon, Nomura, Stolarski, Thaler 0901.2926





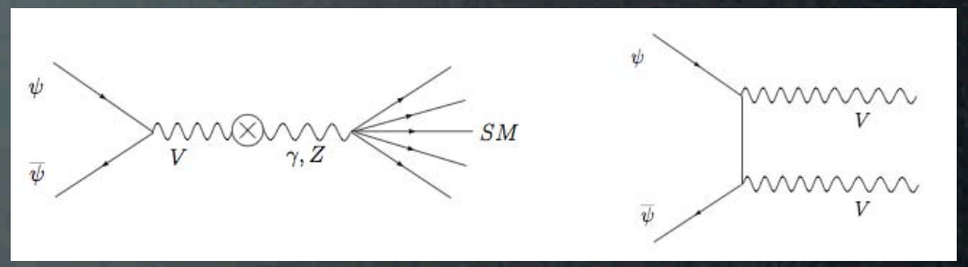
Strumia, Papucci 0912.0742

Variations

(selected)

★ pioneering: Secluded DM, U(1) Stückelberg extension of SM

Pospelov, Ritz et al 0711.4866 P.Nath et al 0810.5762



★ Axion Portal: ϕ is pseudoscalar axion-like

Nomura, Thaler 0810.5397

★ singlet-extended UED: χ is KK RNnu, ϕ is an extra bulk singlet

Bai, Han 0811.0387

★ split UED: χ annihilates only to leptons because quarks are on another brane

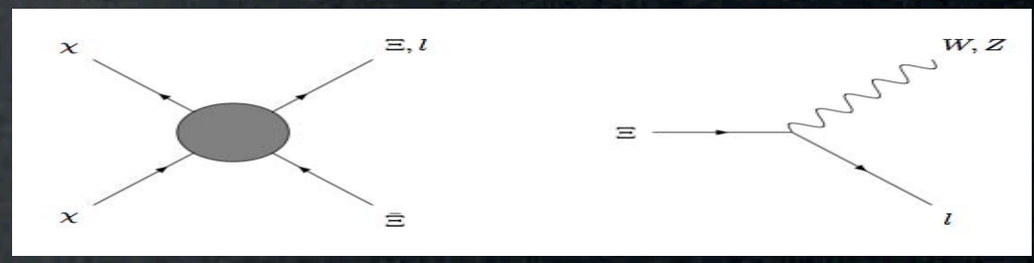
Park, Shu 0901.0720

★ DM carrying lepton number: χ charged under $U(1)_{L_\mu - L_\tau}$, ϕ gauge boson $(m_\phi \sim \text{tens GeV})$

Cirelli, Kadastik, Raidal, Strumia 0809.2409 Fox, Poppitz 0811.0399

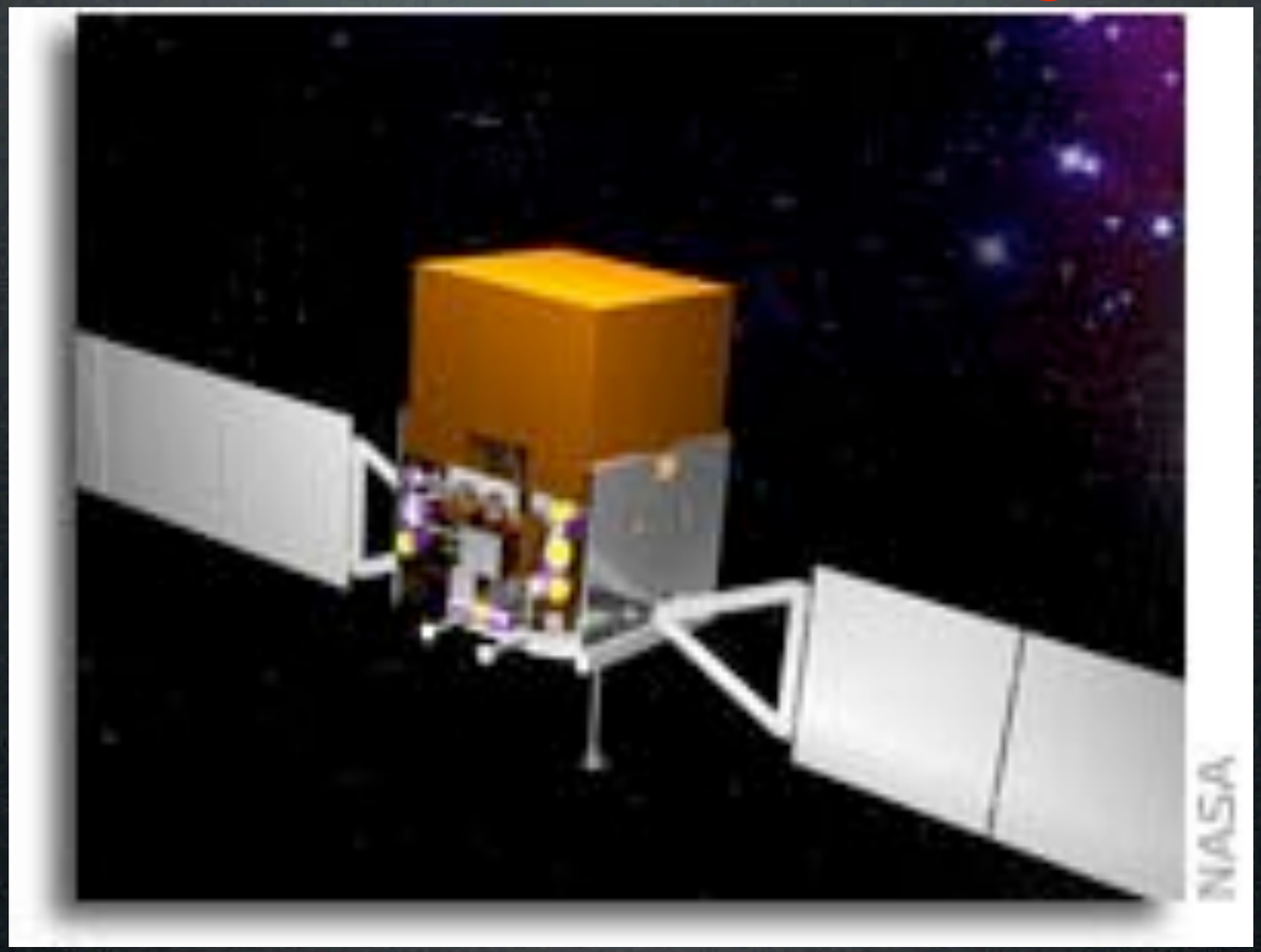
★ New Heavy Lepton: χ annihilates into Ξ that carries lepton number and decays weakly $(\sim \text{TeV})$ $(\sim 100\text{s GeV})$

Phalen, Pierce, Weiner 0901.3165



★ ……

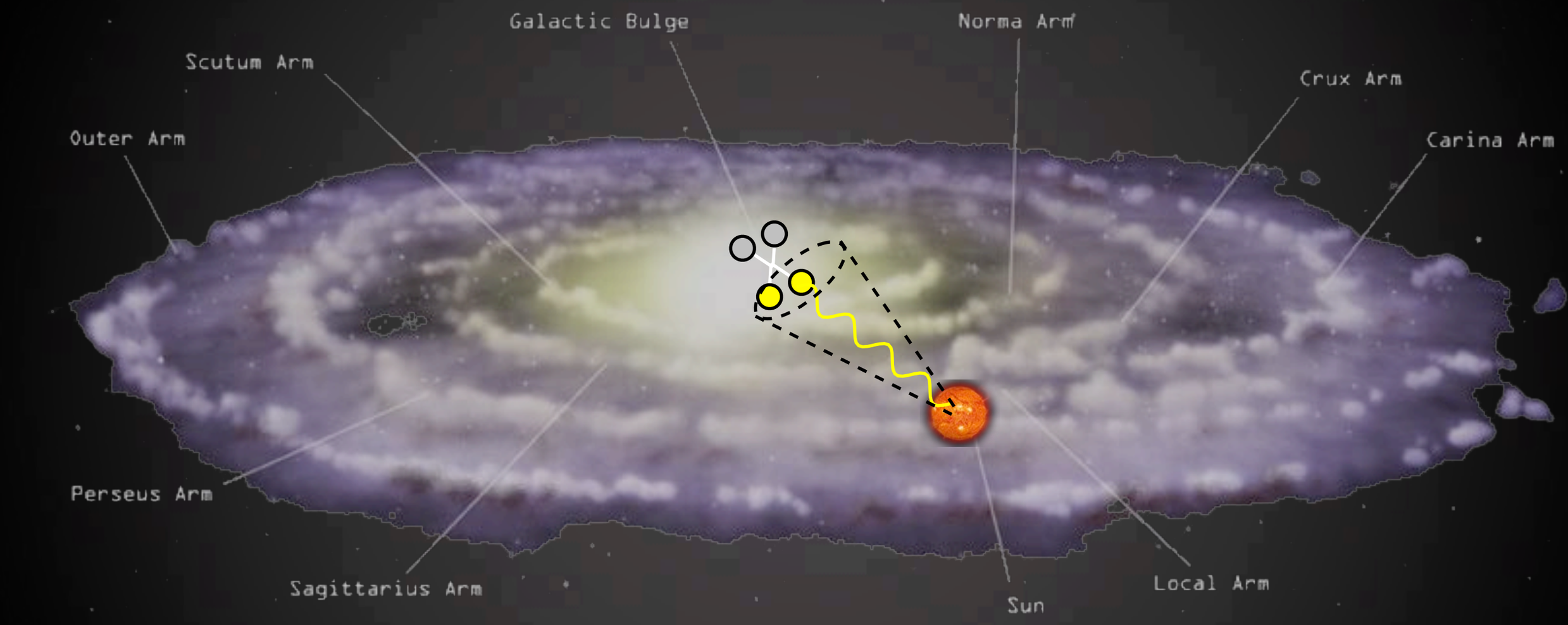
Gamma rays

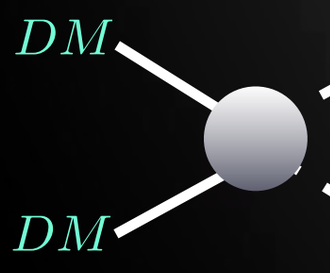


2. the ‘130 GeV line’

Basic picture: targets

γ from DM annihilations in galactic center



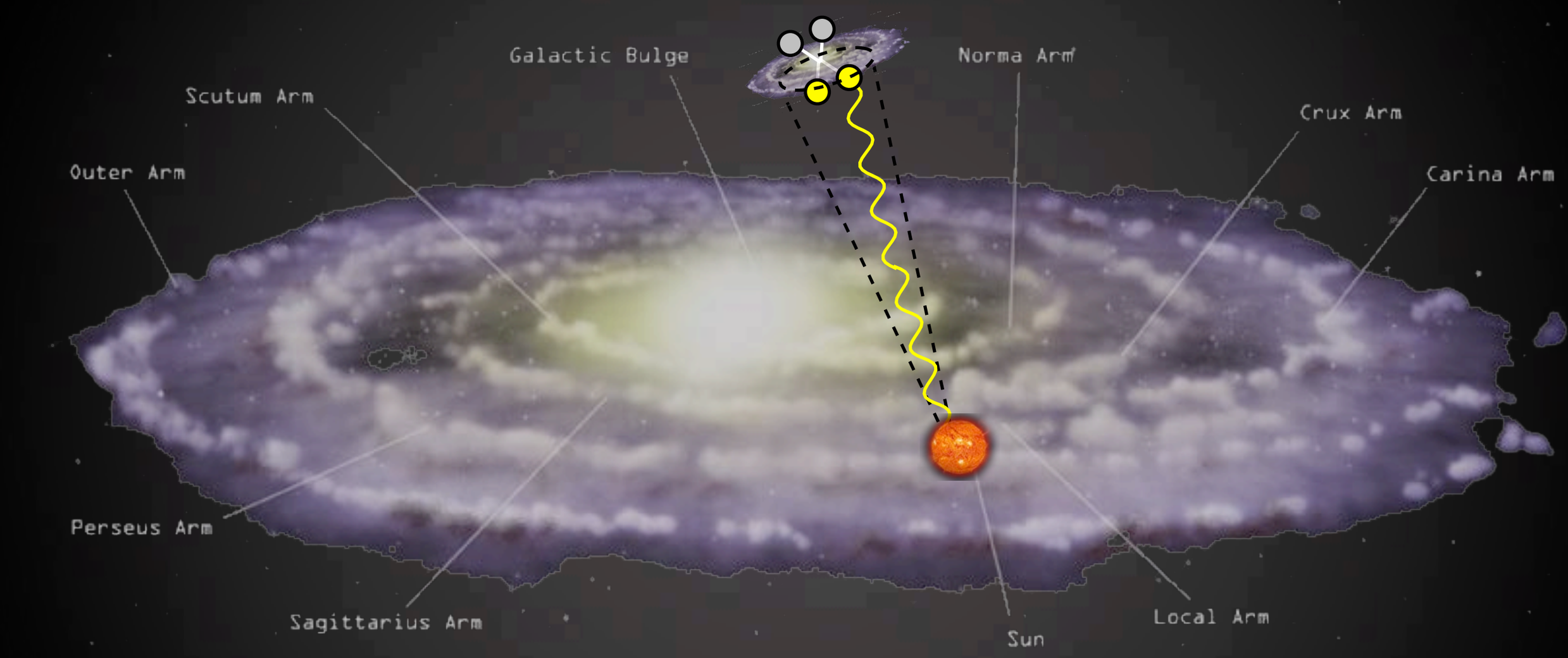


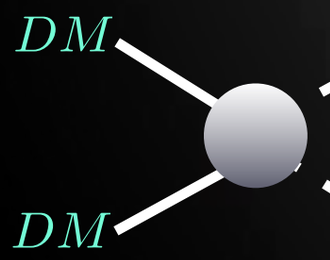
$$W^-, Z, b, \tau^-, t, h \ldots \rightsquigarrow e^{\mp},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

$$W^+, Z, \bar{b}, \tau^+, \bar{t}, h \ldots \rightsquigarrow e^{\pm},\ \overset{(-)}{p},\ \overset{(-)}{D}\ \ldots \text{ and } \gamma$$

Basic picture: targets

γ from DM annihilations in dwarf galaxies





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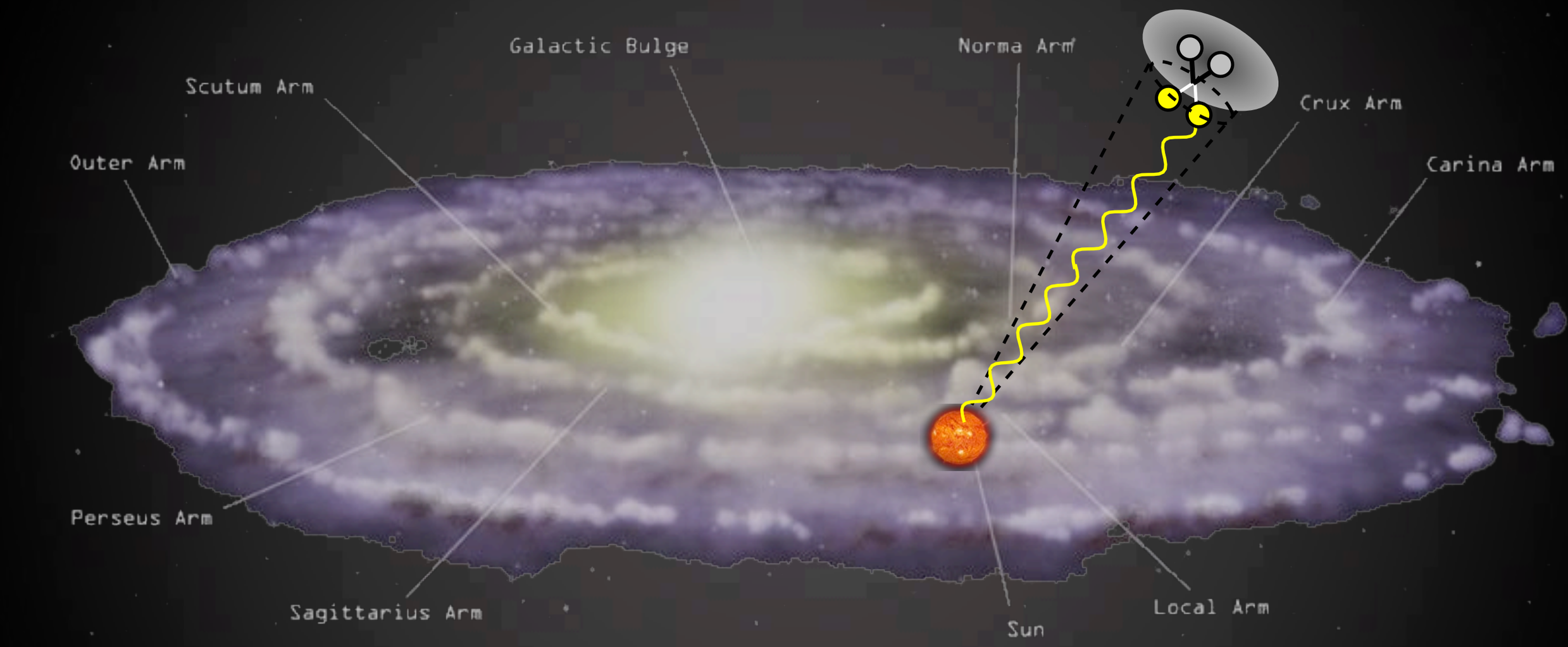
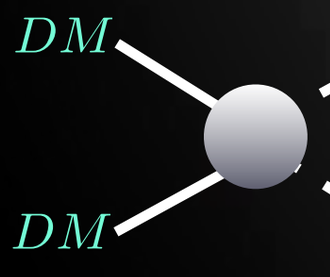
Basic picture: targets

γ from DM annihilations in subhaloes





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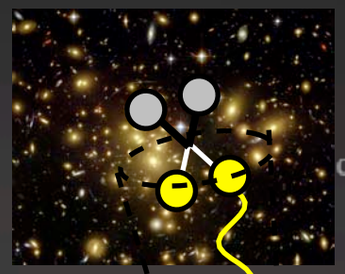
Basic picture: targets

γ from DM annihilations in galaxy clusters



Galactic Bulge

orma Arm

Scutum Arm

Crux Arm

Outer Arm

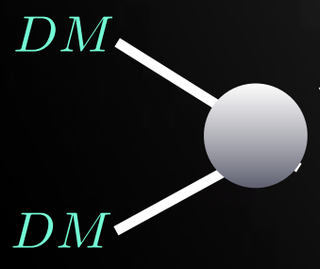
Carina Arm

Perseus Arm

Sagittarius Arm

Sun

Local Arm



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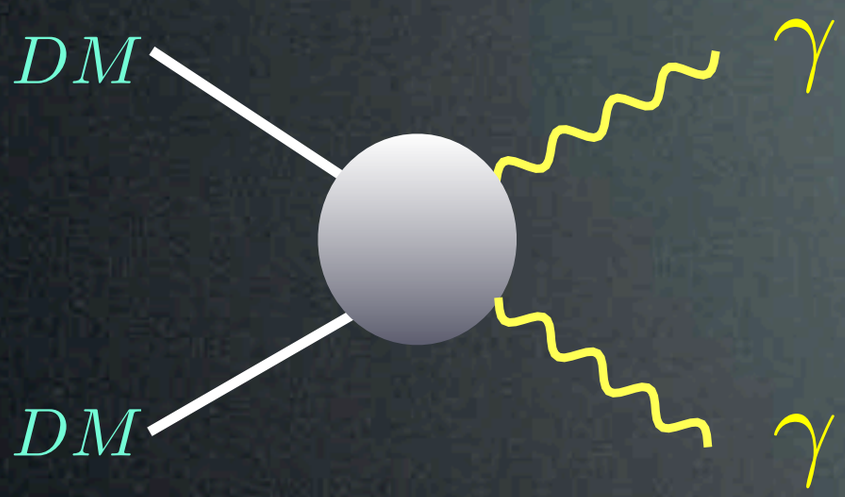
Prompt emission: line(s)



primary
channels

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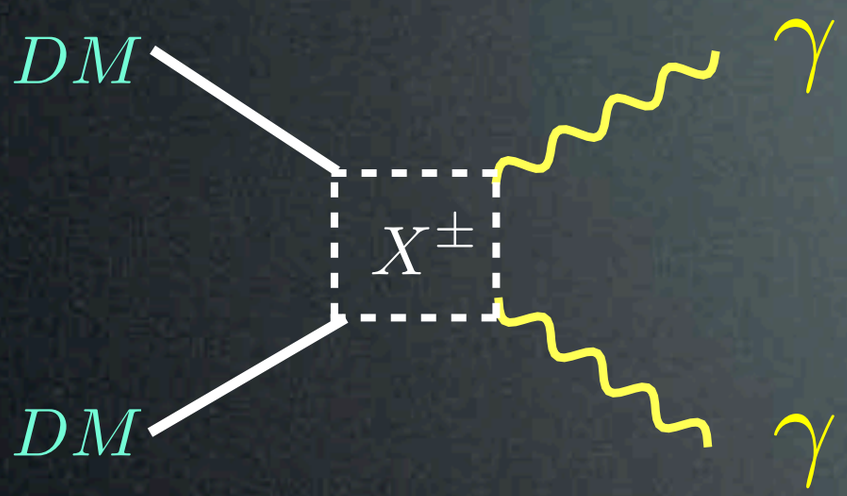
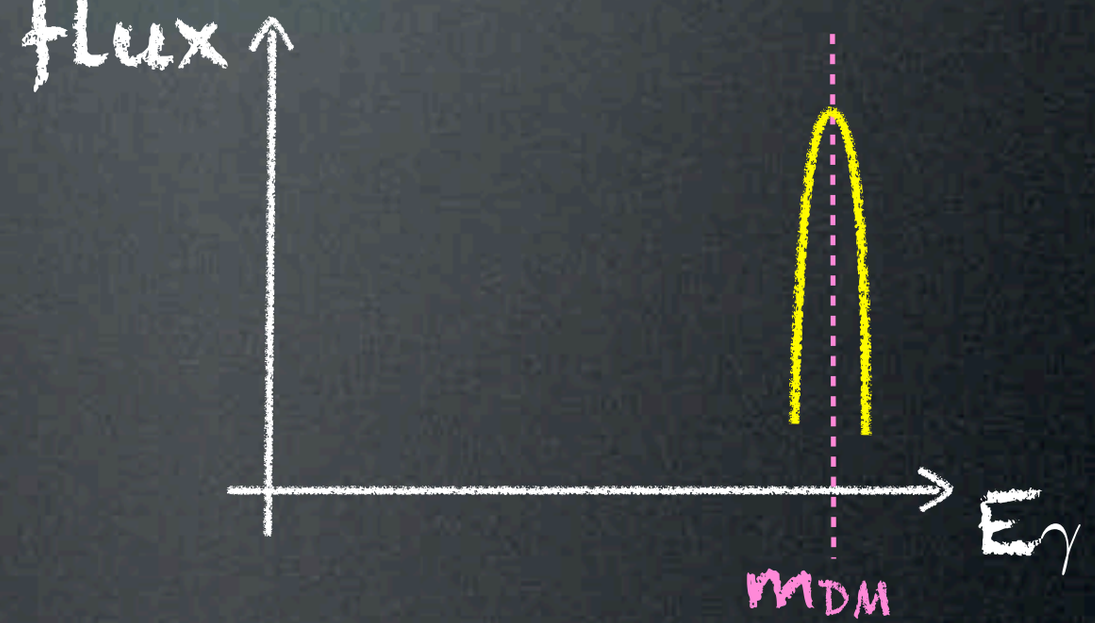
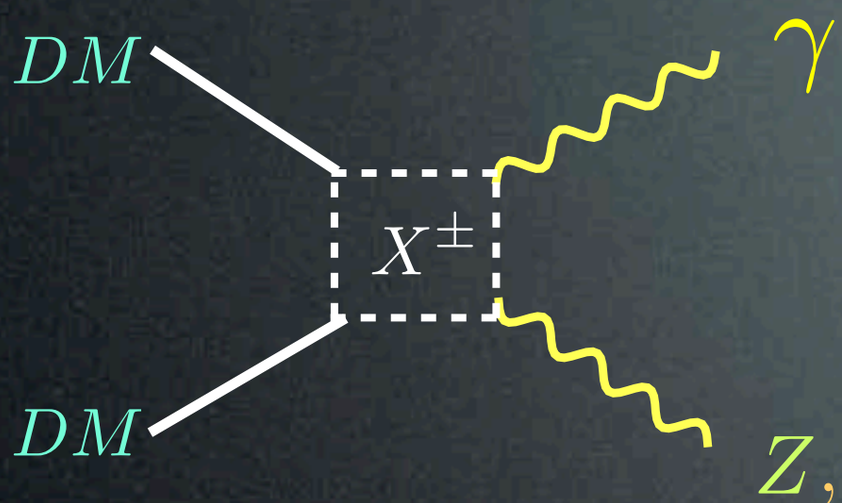


primary channels

$$E_\gamma = m_{\rm DM}$$



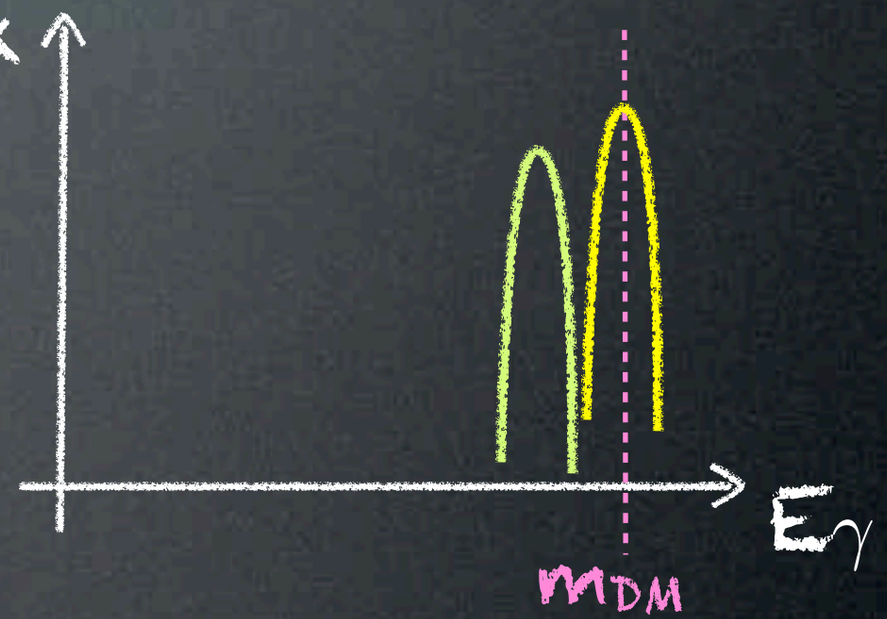
Prompt emission: line(s)



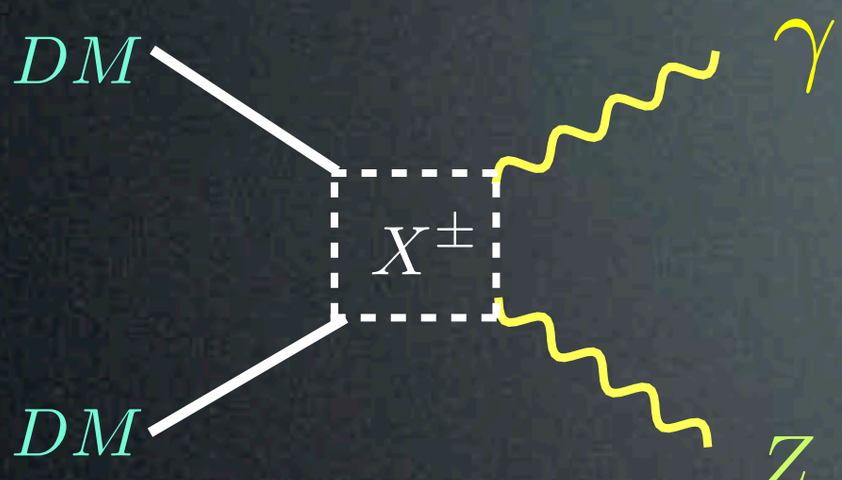
primary channels

$$E_\gamma = m_{\rm DM}$$

$$E_\gamma = m_{\rm DM}\left(1 - \frac{m_Z^2}{4\,m_{\rm DM}^2}\right)$$



Prompt emission: line(s)



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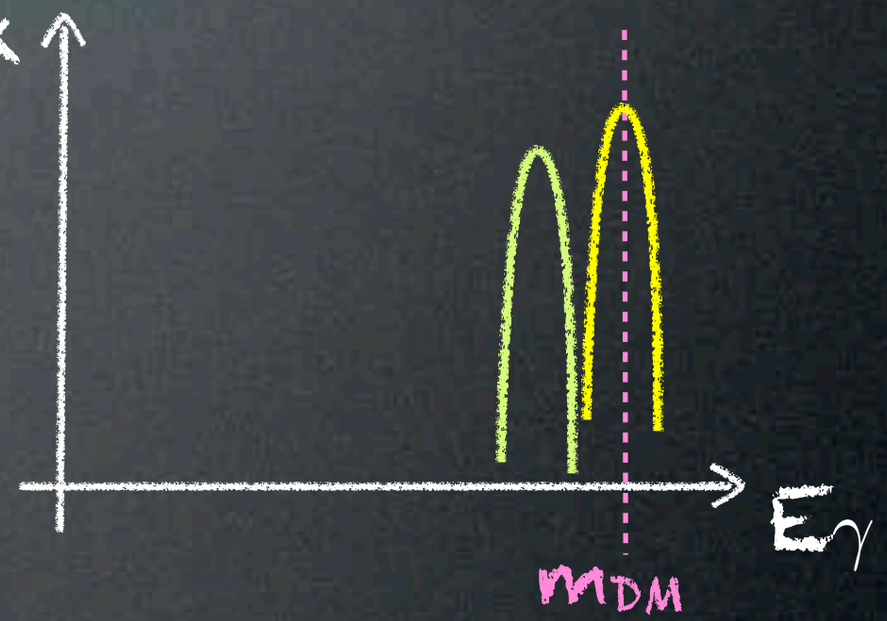
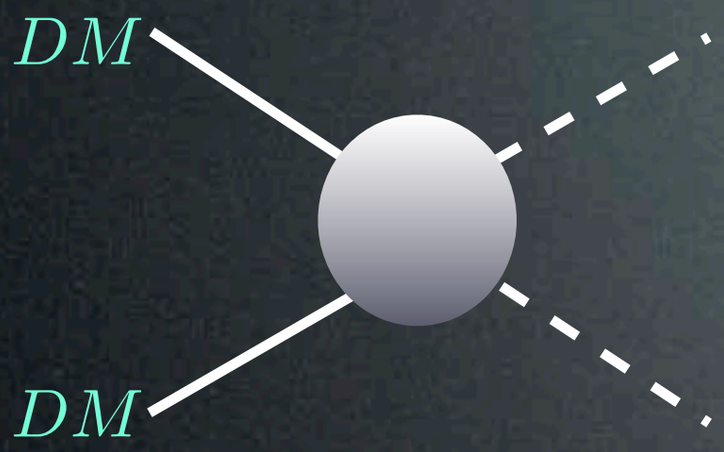


So what are the particle physics parameters?

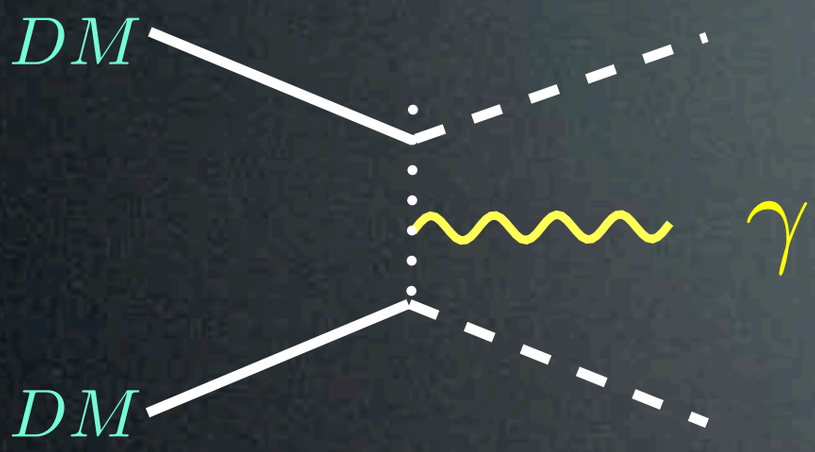
1. Dark Matter mass

2. annihilation cross section $\sigma_{\rm ann}$

Prompt emission: sharp features



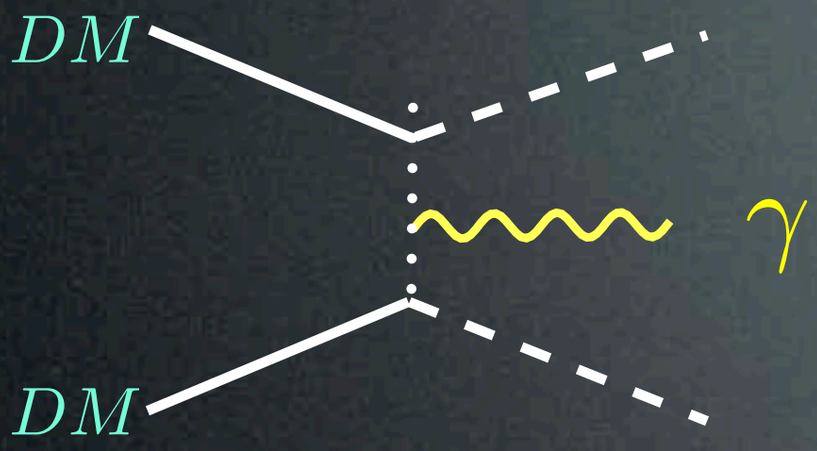
Prompt emission: sharp features



Internal Bremsstrahlung

Bergström 1989

Prompt emission: sharp features



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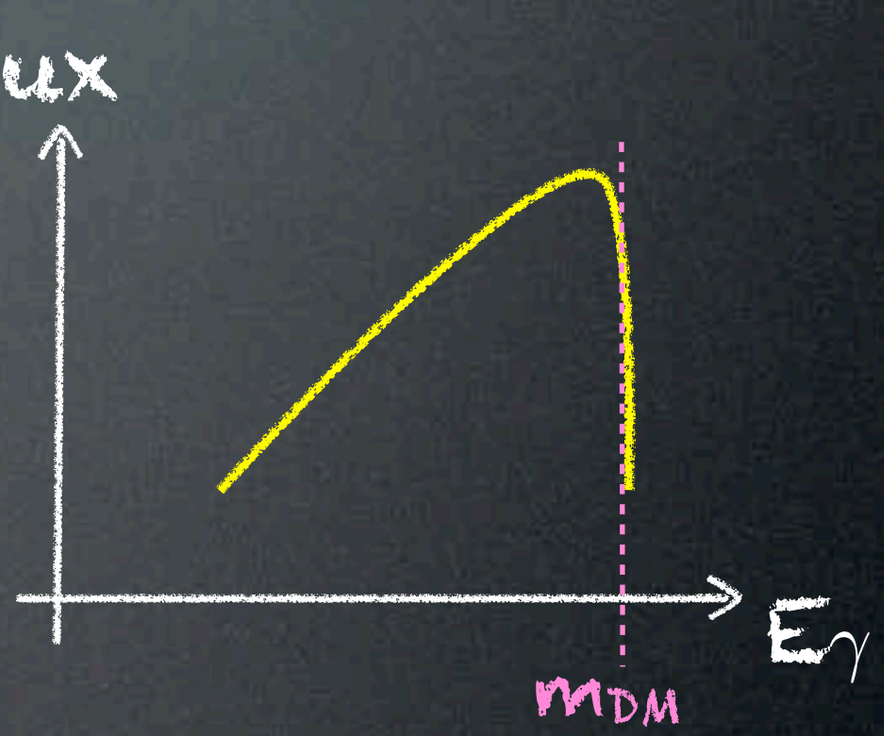
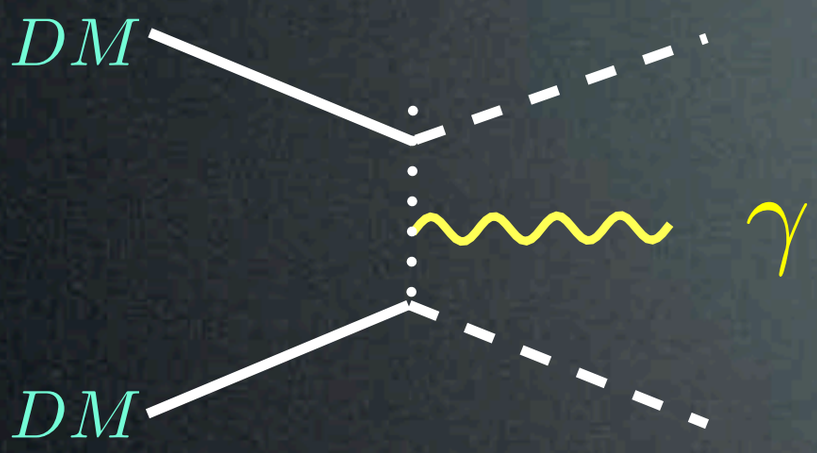


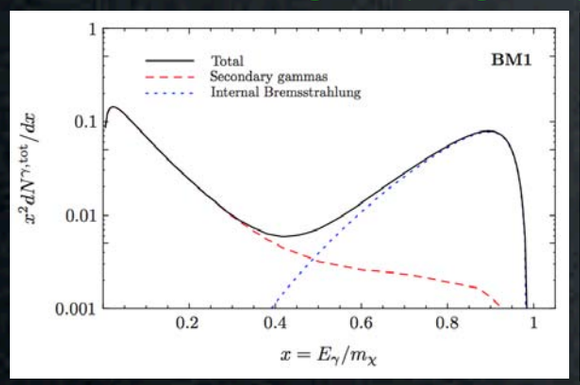
Prompt emission: sharp features

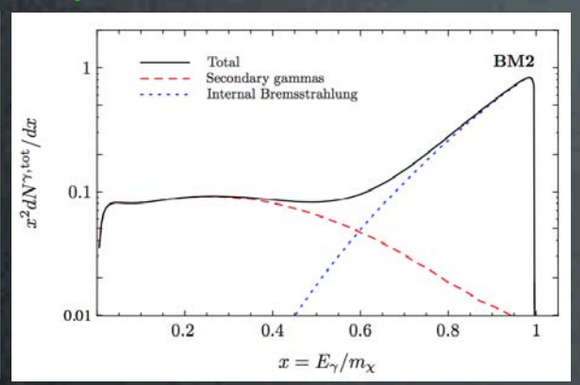


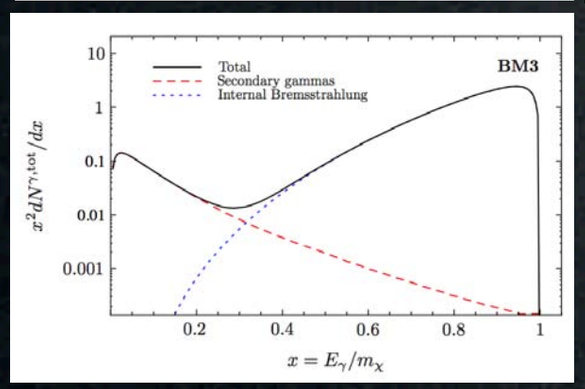
Internal Bremsstrahlung

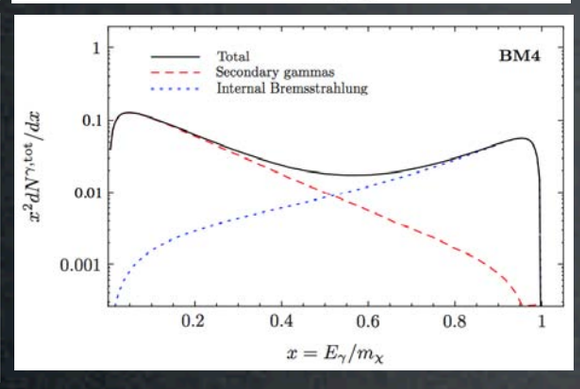
Bergström 1989

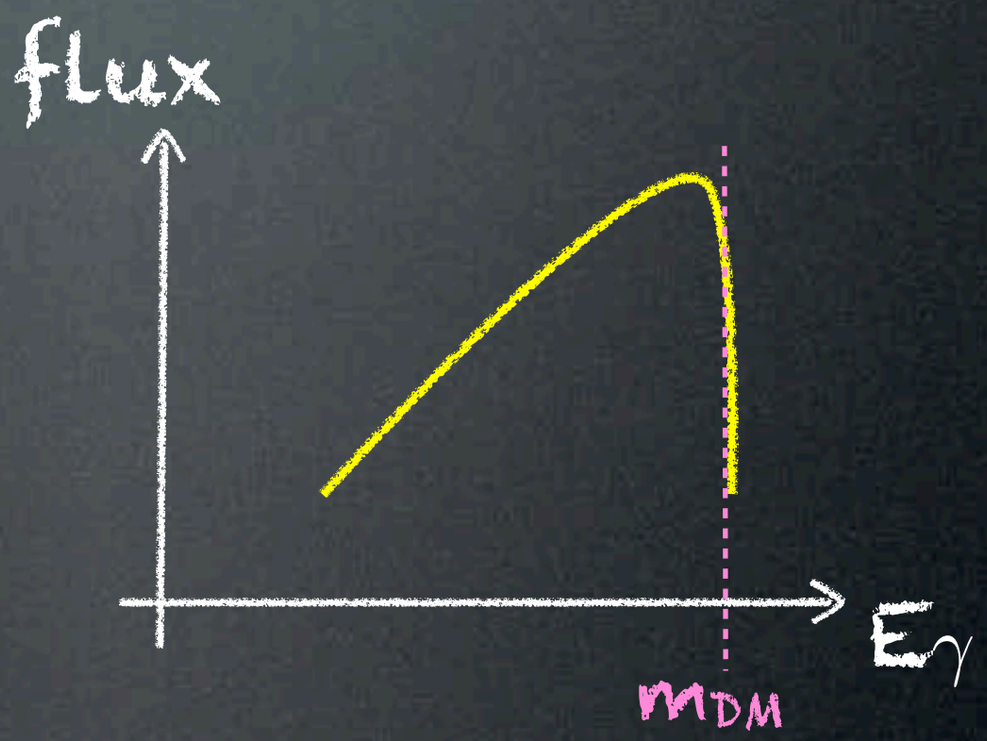
Bringmann, Bergstrom, Edsjo 0710.3169









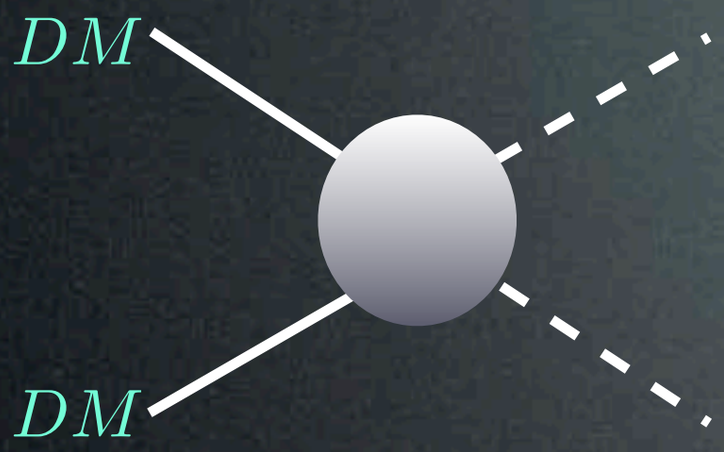


So what are the particle physics parameters?

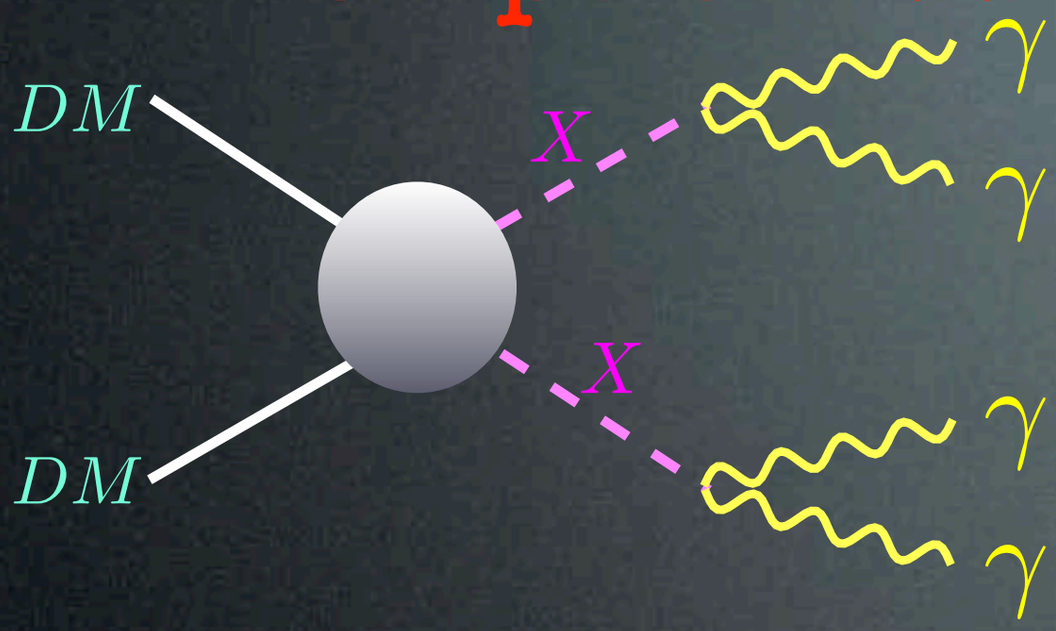
1. Dark Matter mass.

The rest depends on the model

Prompt emission: sharp features



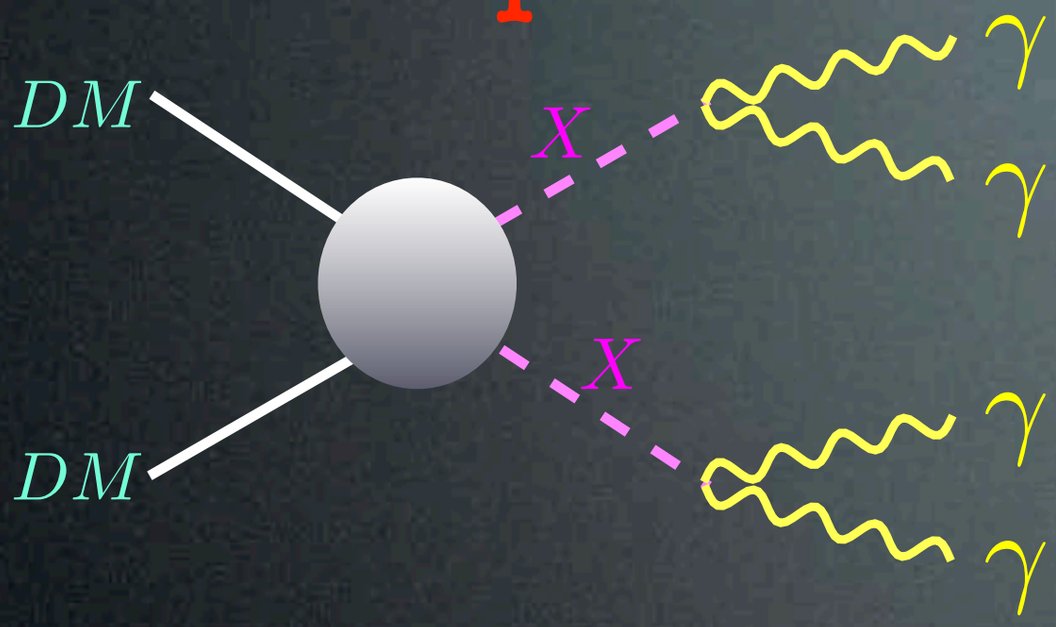
Prompt emission: sharp features



Metastable intermediate states

Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Prompt emission: sharp features

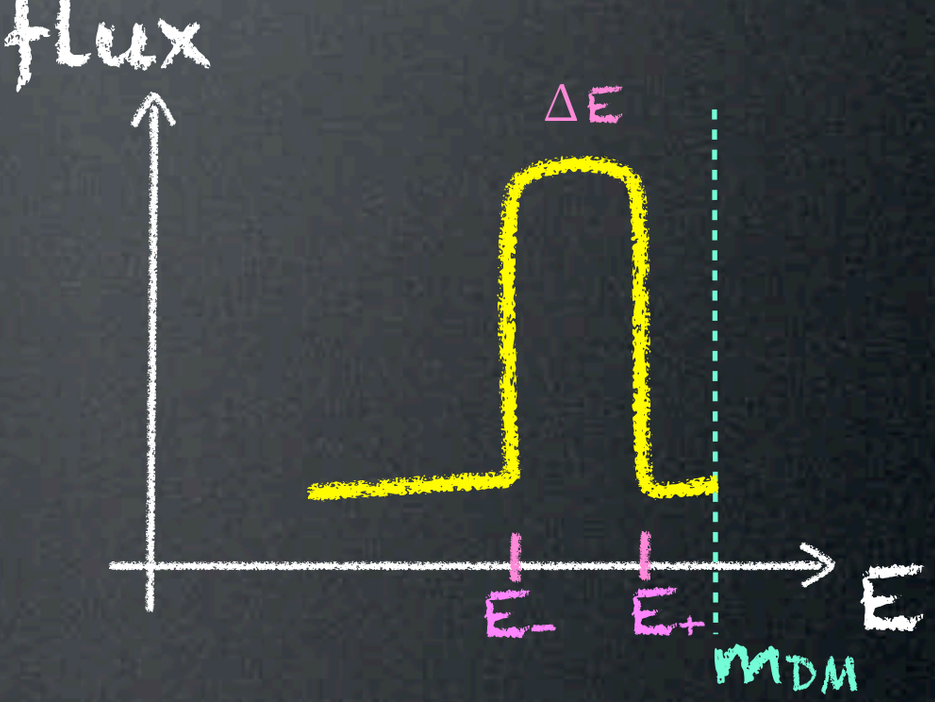


Ibarra, Lopez Gehler, Pato 1205.0007
Fan, Reece 1209.1097

Metastable intermediate states

$$E_\pm = \frac{m_{\rm DM}}{2}\left(1 \pm \sqrt{1 - \frac{m_X^2}{m_{\rm DM}^2}}\right)$$

$$\Delta E = \sqrt{m_{\rm DM}^2 - m_X^2}$$



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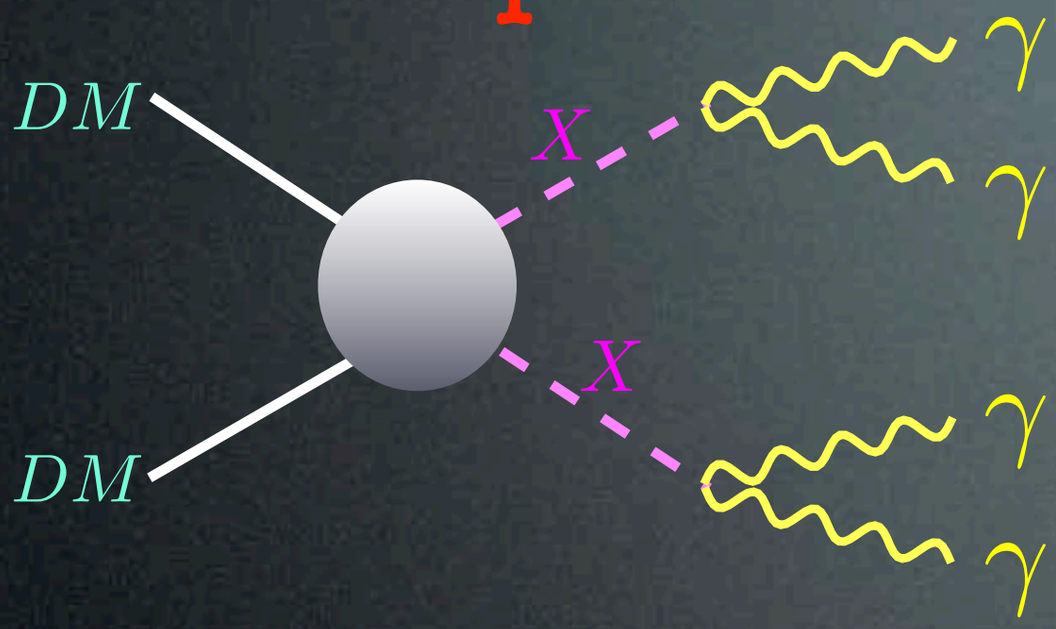

Ibarra, Lopez Gehler, Pato 1205.0007
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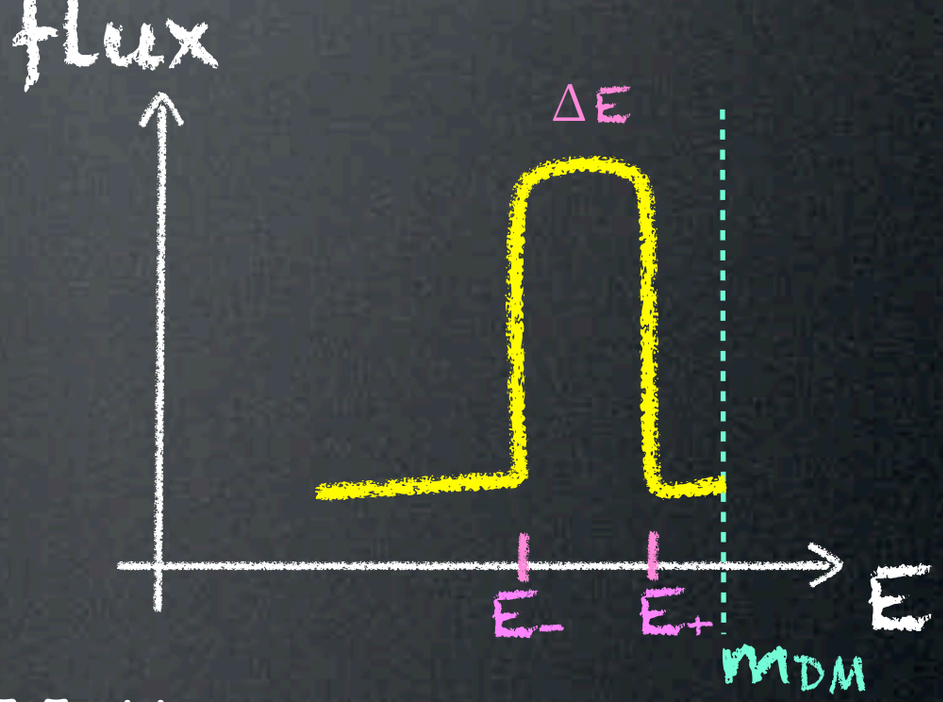
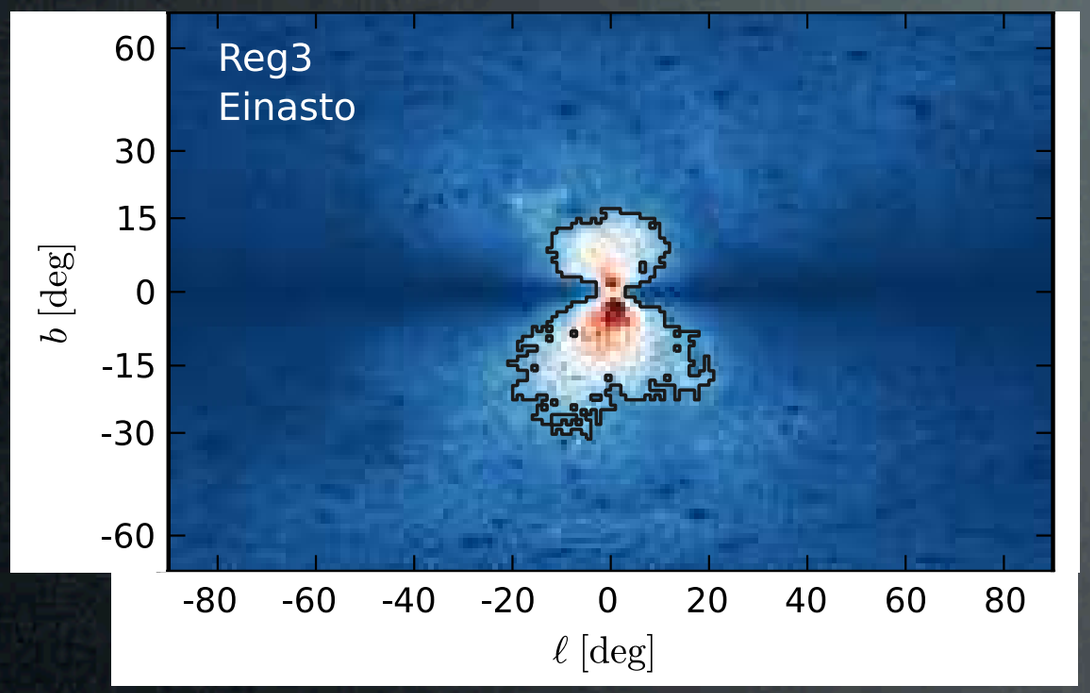


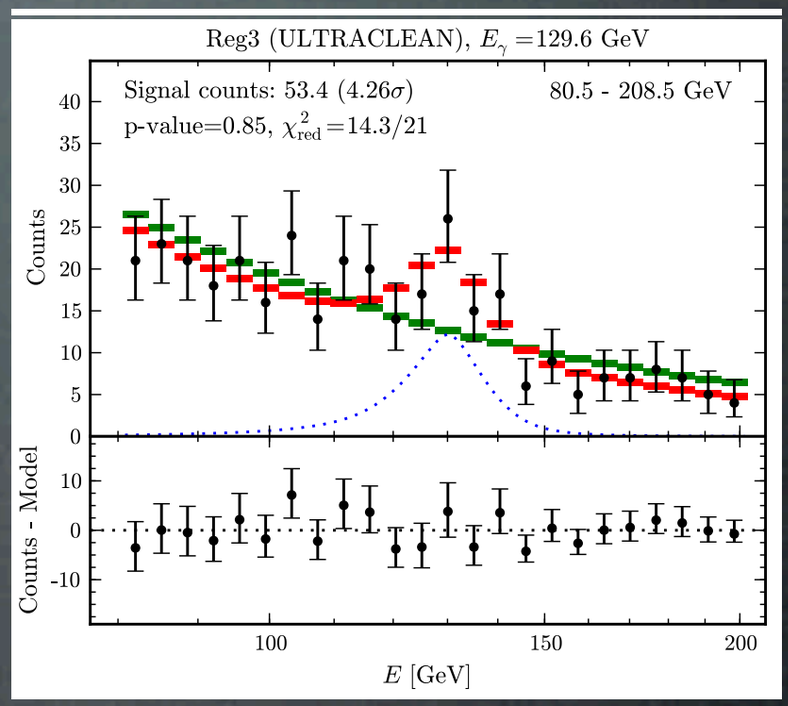
So what are the particle physics parameters?

1. Dark Matter mass
2. The mediator mass

Fermi 130 GeV line

What if a signal of DM is *already* hidden in Fermi diffuse γ data?





Ch. Weniger, 1204.2797

4.6σ (3.3σ with LEE)

$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \simeq 1.3 \cdot 10^{-27} \mathrm{cm}^3/\mathrm{s}$ (large!)

Fermi 130 GeV line

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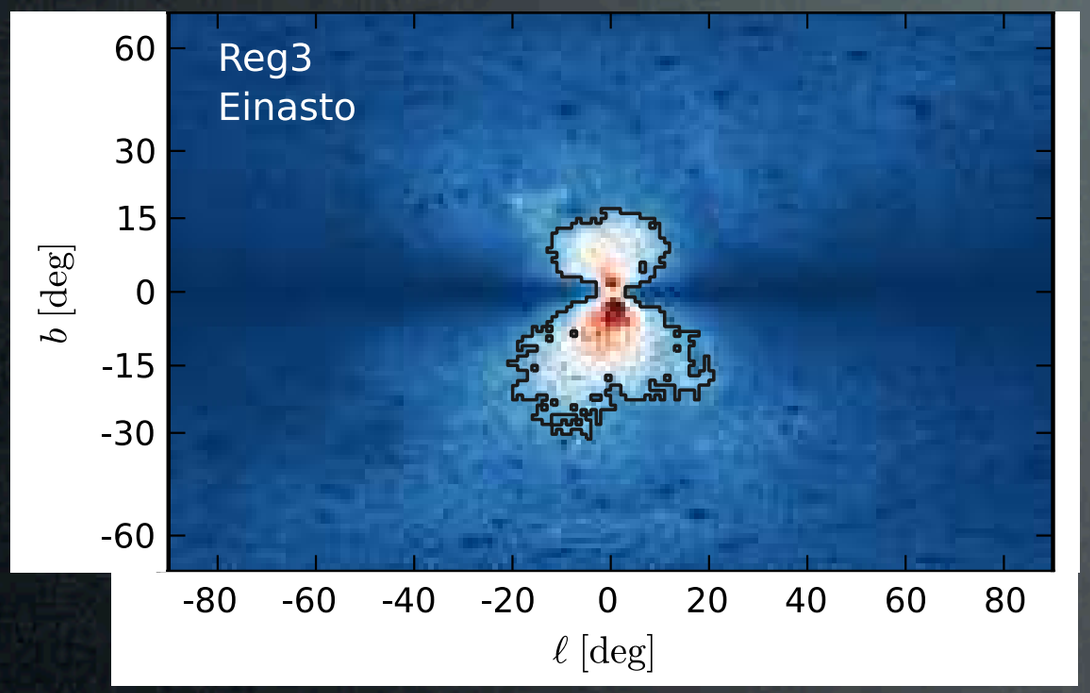

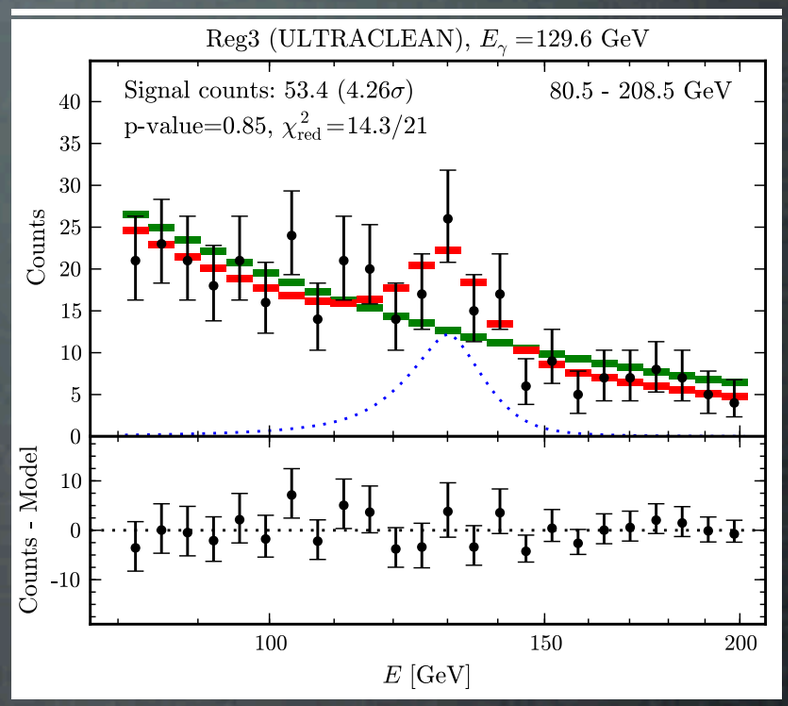

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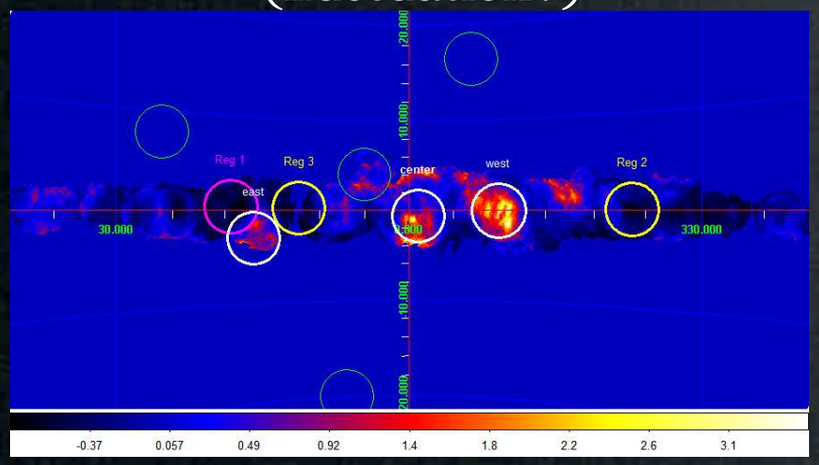
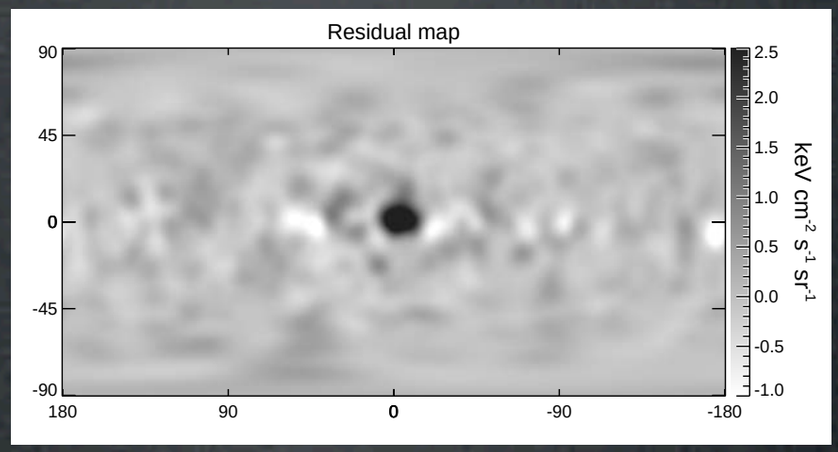
Similar excesses found elsewhere (fluctuation?)



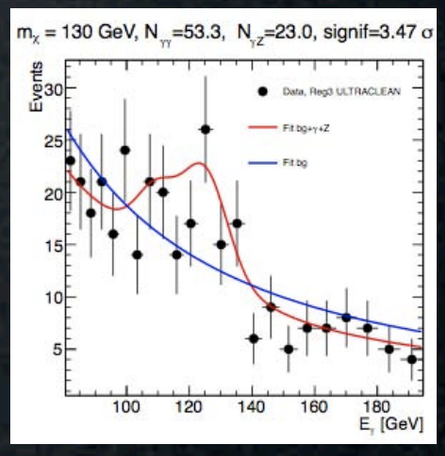
Boyarsky, Malyshev, Ruchayskyi, 1205.4700

The excess is only in the GC (actually, a bit off-set)



Su, Finkbeiner, 1206.1616

And there might be 2 lines: 111 GeV, 129 GeV



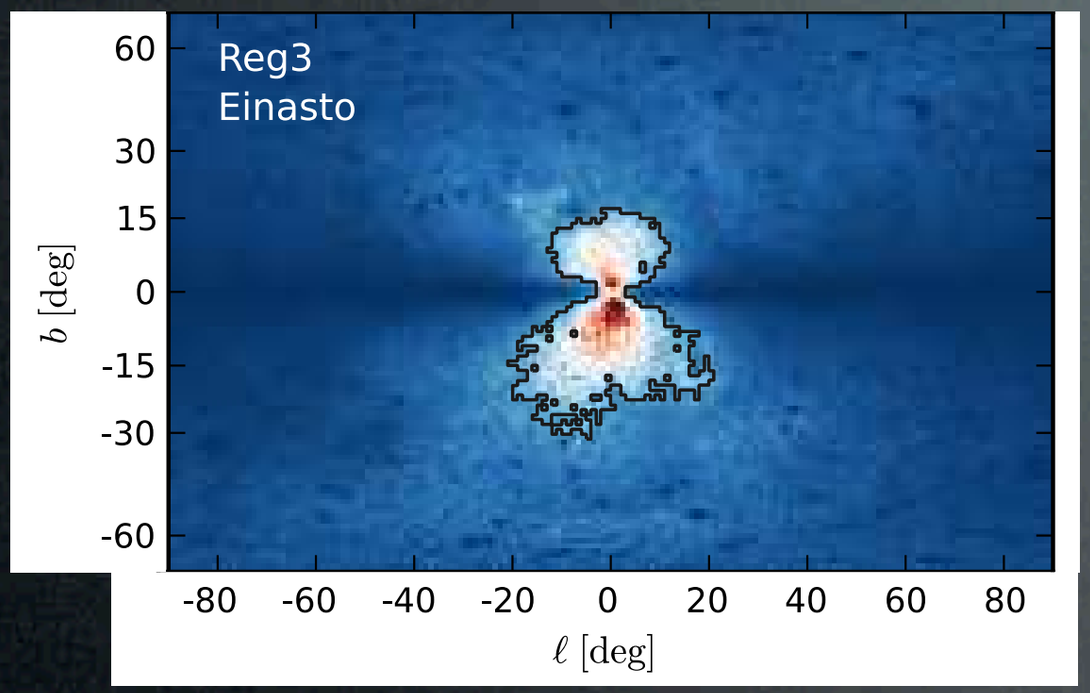
Rajaraman, Tait, Whiteson 1205.4723

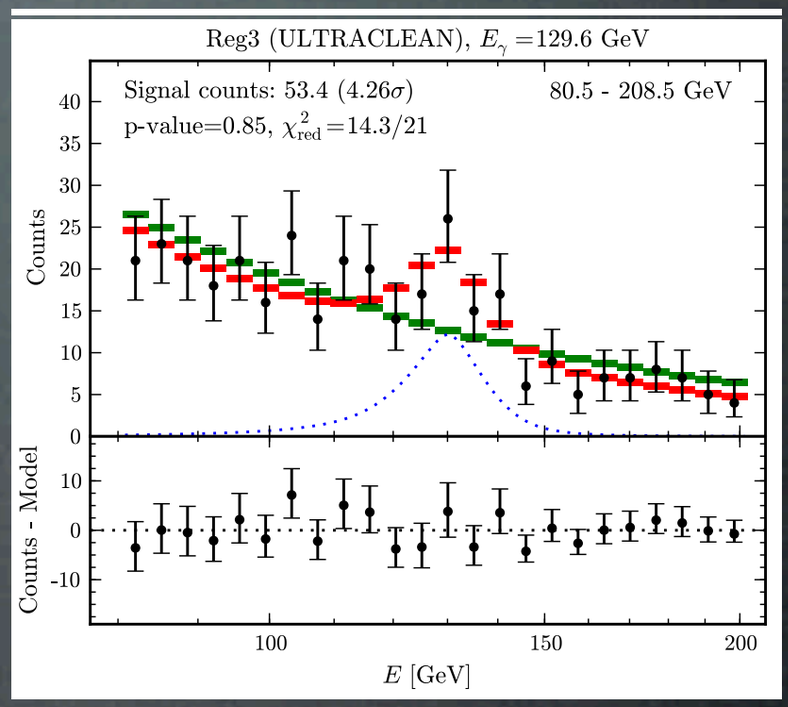
Su, Finkbeiner 1206.1616

Su Finkbeiner 1207.7060

Fermi 130 GeV line

What if a signal of DM is *already* hidden in Fermi diffuse γ data?





Ch. Weniger, 1204.2797

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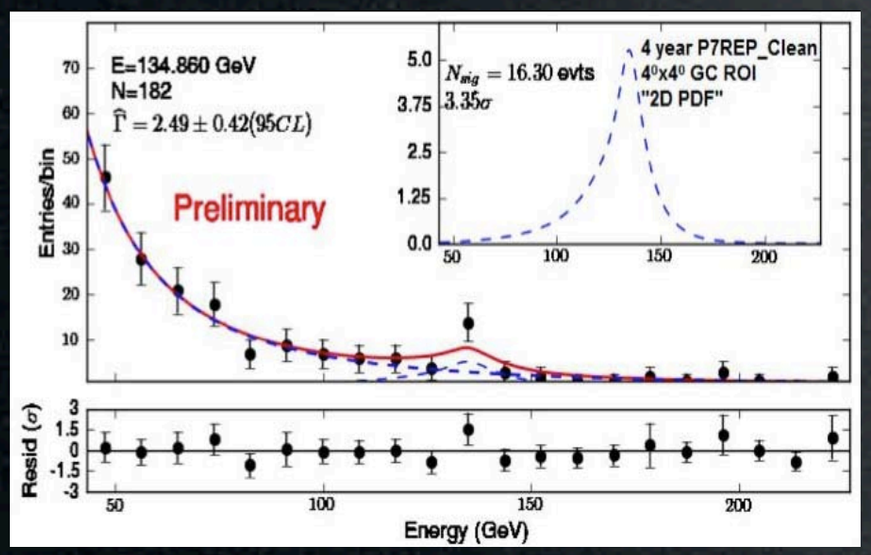
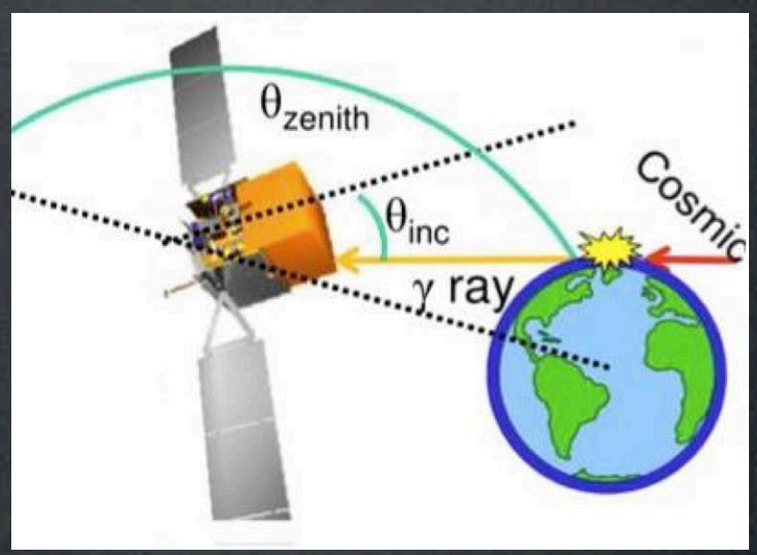
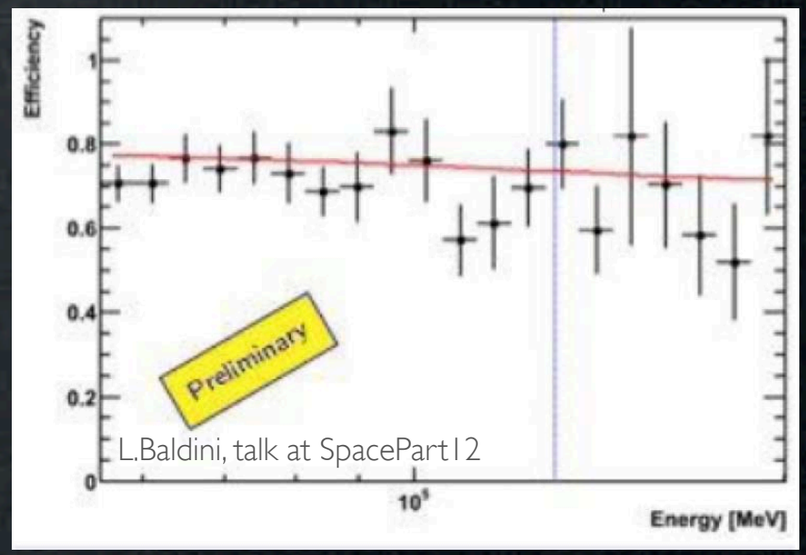
The Fermi coll's cold shower. An instrumental effect?







Theorist's reaction

2. the '130 GeV line' frenzy

It's 'easy' to make a line: any 2-body final state with at least one γ. But:

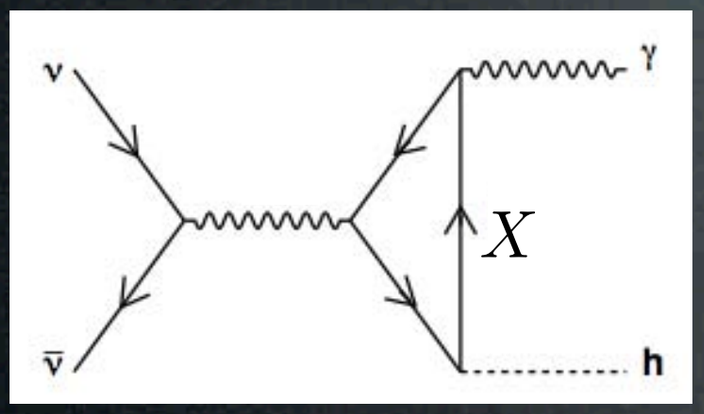
Challenges

DM is <u>neutral</u>: need '**something**' to couple to γ

Challenges

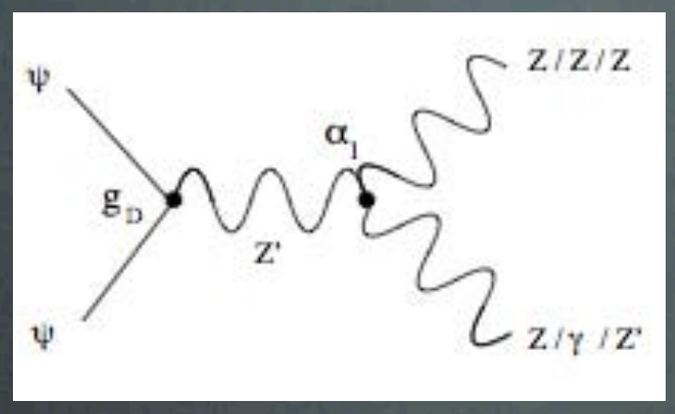
DM is neutral: need '*something*' to couple to γ

a loop



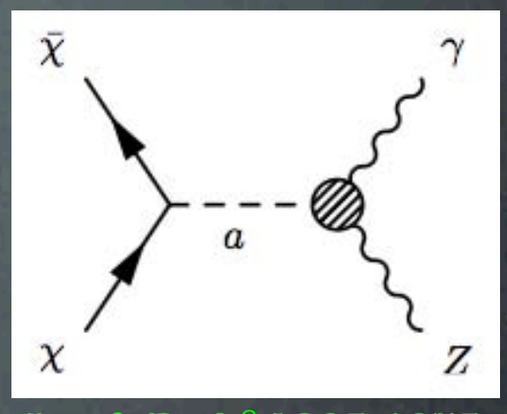
'Higgs in space!' 0912.0004
Kyae, Park 1205.4151
Cline 1205.2688

Chern-Simons



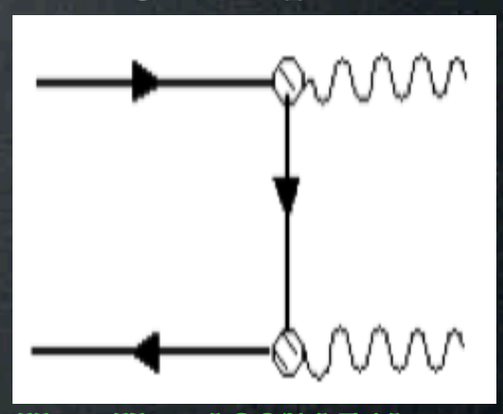
Dudas et al., 1205.1520

axions



Lee & Park[2] 1205.4675

magn dipole



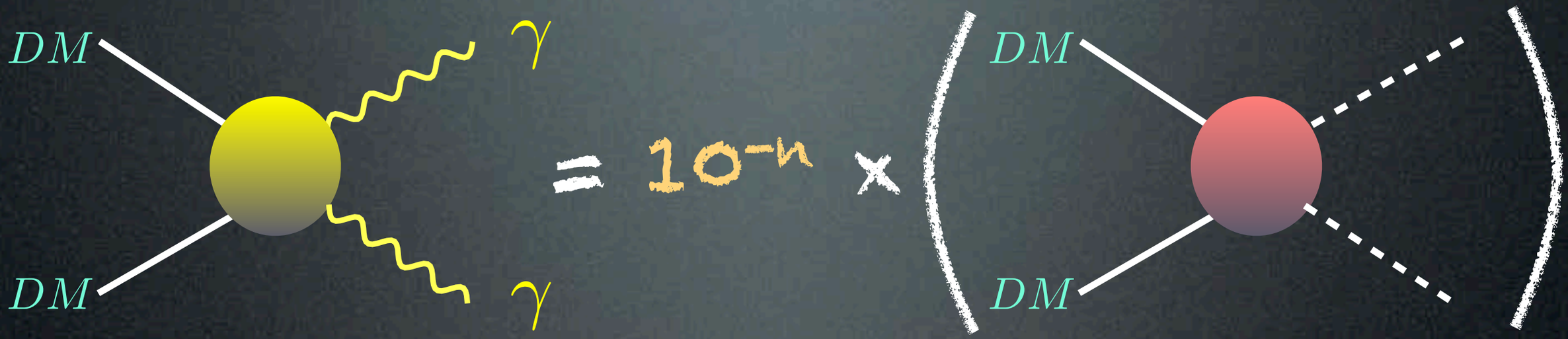
Heo, Kim 1207.1341

...

$X \in$ SM
MSSM
dark sector...

Challenges

DM is <u>neutral</u>: need '**something**' to couple to γ



The '**something**' implies usually a suppression,

Challenges

DM is <u>neutral</u>: need '**something**' to couple to γ

The '**something**' implies usually a suppression,
but one needs a large $\gamma\gamma$ cross section (o(10^{-27} cm^3/s))

Challenges

DM is neutral: need '*something*' to couple to γ

The '*something*' implies usually a suppression,
but one needs a large $\gamma\gamma$ cross section ($o(10^{-27}\,cm^3/s)$)

so the corresponding unsuppressed processes
are **too** large:

- may overshoot other observations
- too large annihilation in the EU

Buchmuller, Garny 1206.7056
Cohen et al. 1207.0800
Cholis, Tavakoli, Ullio 1207.1468
Huang et al. 1208.0267

Challenges

DM is neutral: need '*something*' to couple to γ

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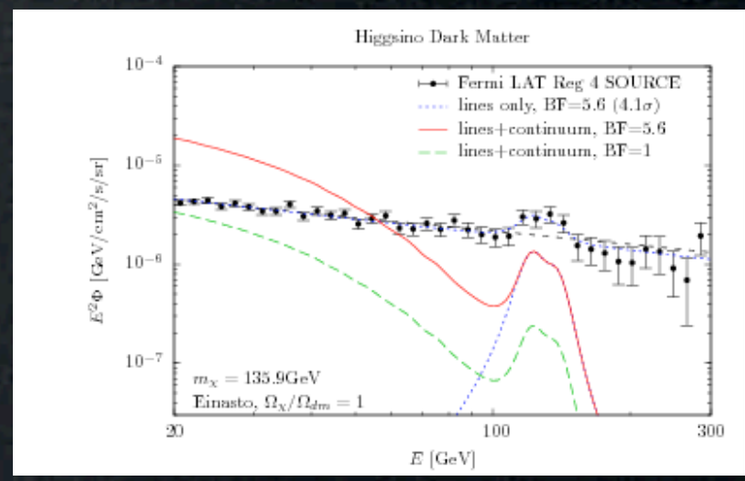
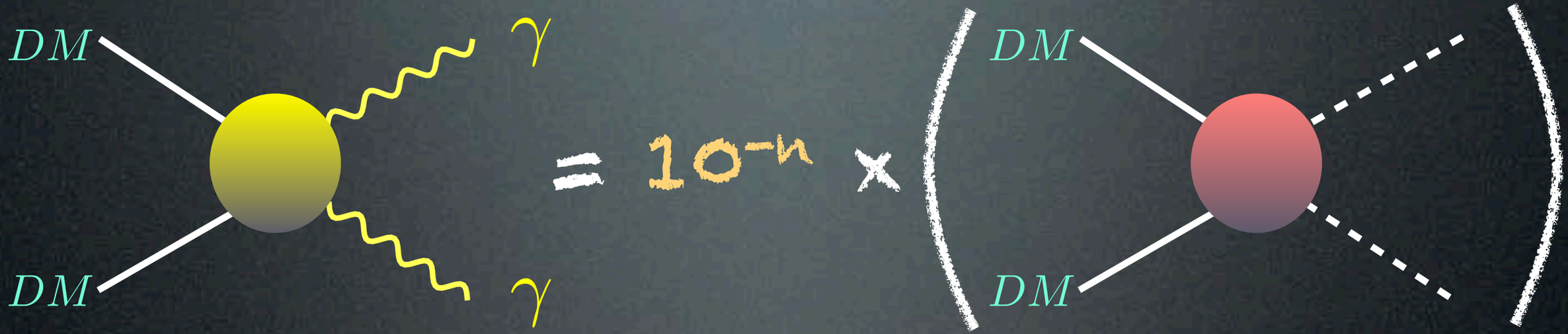


Challenges

DM is neutral: need '*something*' to couple to γ



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so the corresponding unsuppressed processes are **too** large:

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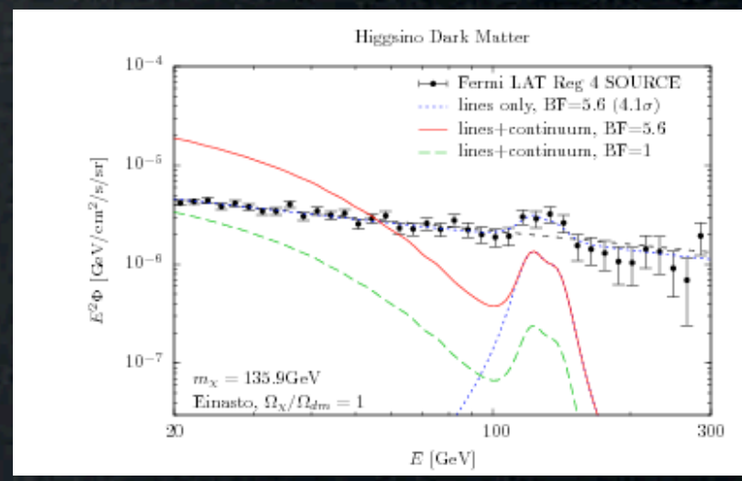
But solutions exist



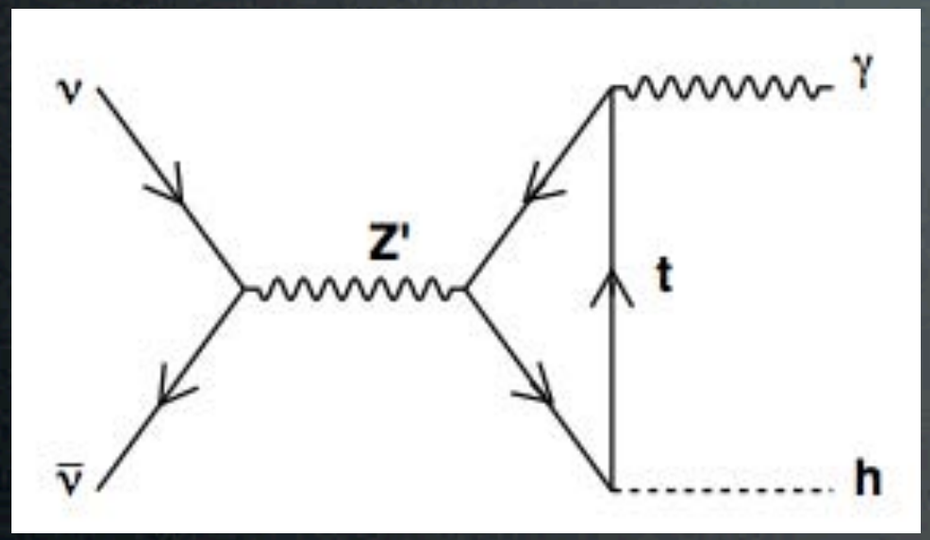
Model building

not exhaustive!

Ex. 1: 'resonance, loop and forbidden channel'

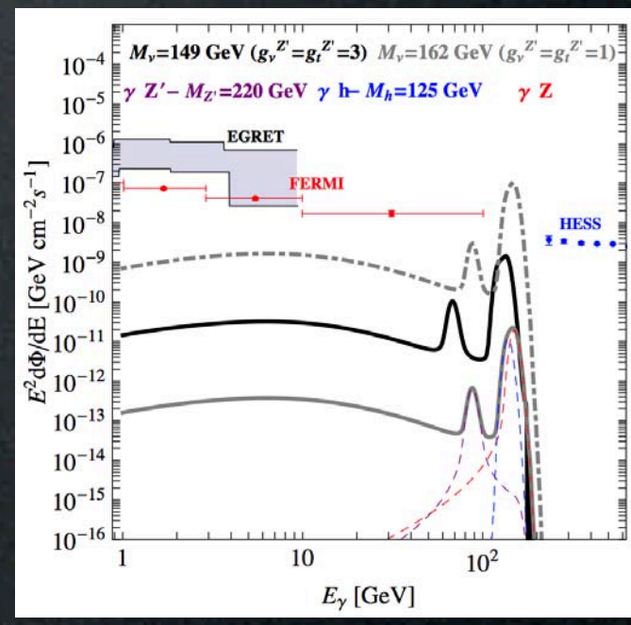
(a) DM charged under U'(1)
(b) Z' is t_R-philic
(c) $m_{DM} \lesssim m_{top}$

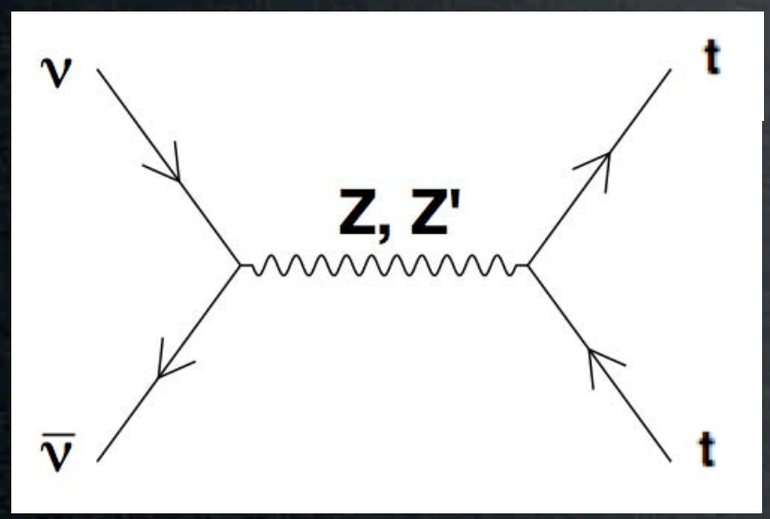
Jackson, Servant, Shaughnessy, Tait, Taoso, 'Higgs in space', 0912.0004



➡ line(s)

with large rate
if on resonance (a)
(masses & couplings)





today:
kinematically forbidden (c)
little in other channels (b) (only via Z-Z' mixing)
➡ small continuum

Early Universe:
➡ relic abundance

However:
- anomalies, need to UV complete (b)

Model building

not exhaustive!

Ex. 2: 'resonance, tri-boson vertices, Chern-Simons'

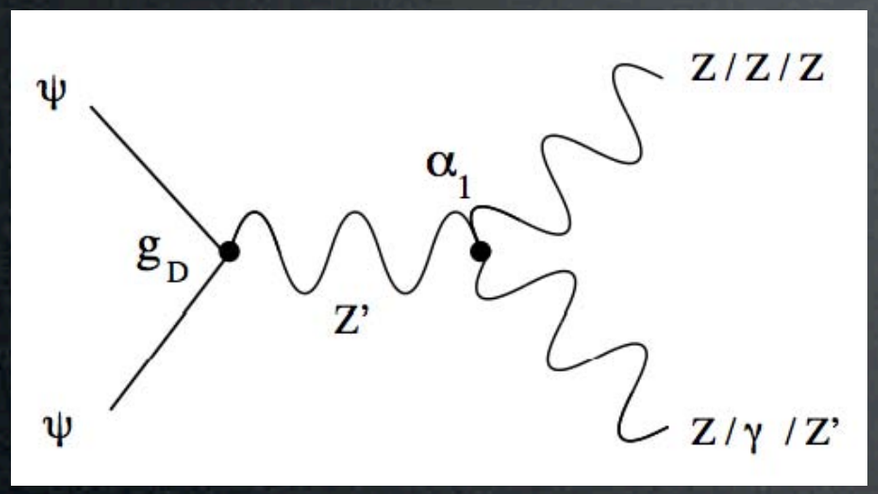
(a) DM charged under U'(1)

(b) anomaly cancellation → tri-boson CS terms

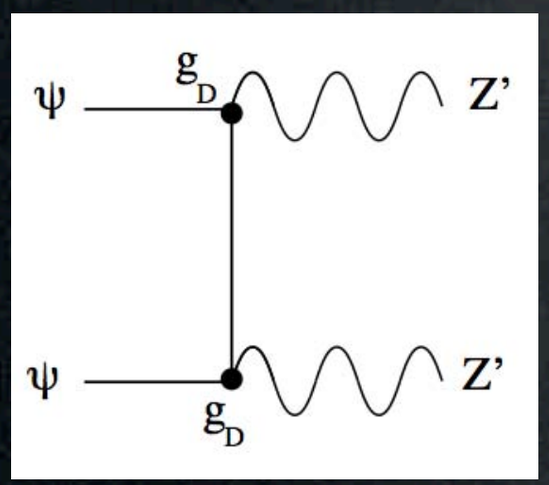
$$\mathcal{L}_{\rm CS} = \alpha\, \varepsilon^{\mu\nu\rho\sigma}\, Z'_\mu Z_\nu F^Y_{\rho\sigma}$$

Dudas, Mambrini, Pokorski, Romagnoni 2009-2012, 1205.1520

(c) $m_{Z'} < m_{DM}$



→ line (b)



→ relic abundance

a different diagram wrt to line, open thanks to (c), works for large gauge coupling and small (loop?) CS coeff

→ Continuum? Under control

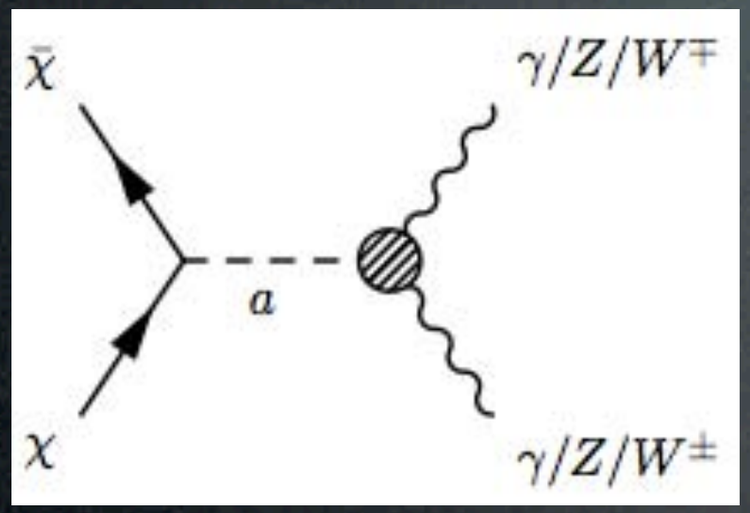
Model building

not exhaustive!

Ex. 3: 'pseudo-scalar mediation, p- and s-waves'

(a) DM charged under $U(1)_{PQ}$
(b) anomalies → tri-boson terms

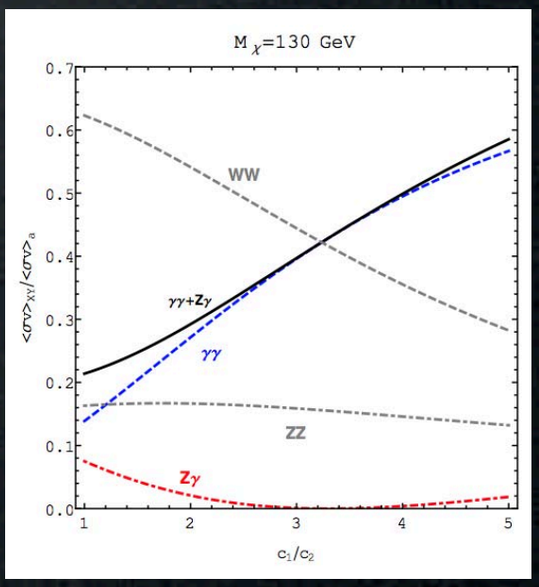
Lee, Park², 1205.4675

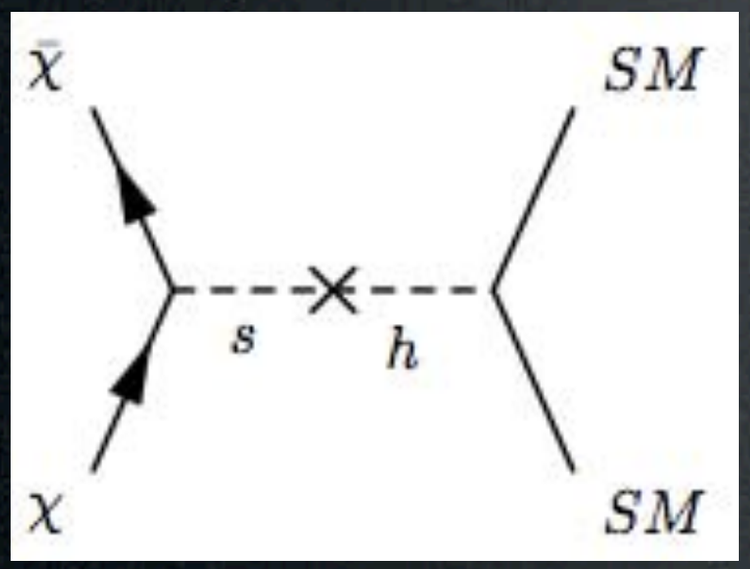


➡ line (b)

with large rate
if on resonance (a)

➡ Continuum? Assume couplings to W and Z are suppressed





Exchange of s/h is p-wave, i.e. v dependent.

Suppressed today, large in EU.

➡ relic abundance

Model building

not exhaustive!

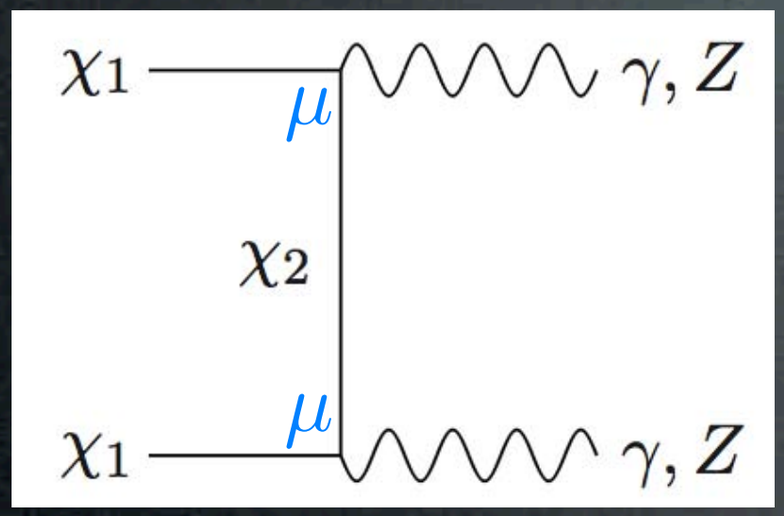
Ex. 4: 'magnetic moments and coannihilations'

Tulin, Yu, Zurek 1208.0009
Cline, Moore, Frey 1208.2685

(a) DM has a magnetic moment

$$\mu\, \bar{\chi}_1 \sigma_{\mu\nu} \chi_2\, F^{\mu\nu}$$

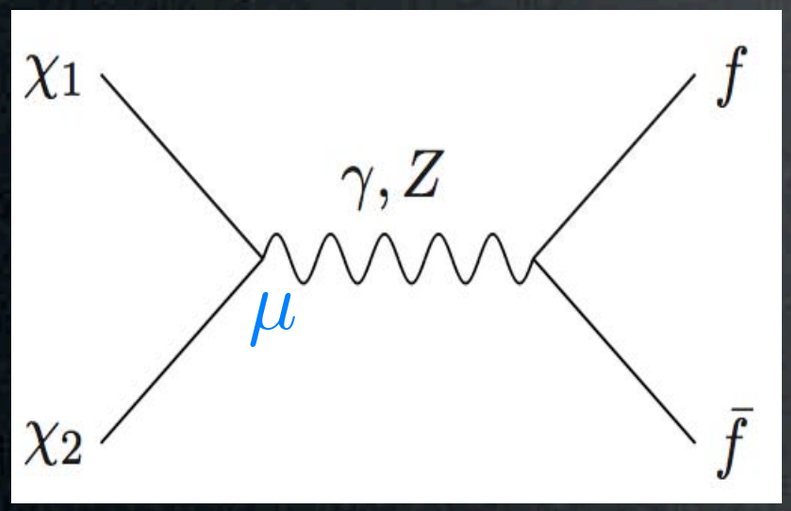
(b) DM sits in a multiplet with ~10 GeV splitting



➡ line (a)

with large rate
if μ is large

➡ Continuum? Under control (it's same order as $\gamma\gamma$)



➡ relic abundance

is set by coannihilations,
they would be too effective for large μ,
but the splitting (b) suppresses.

➡ Continuum? Ultra suppressed by the splitting (b)

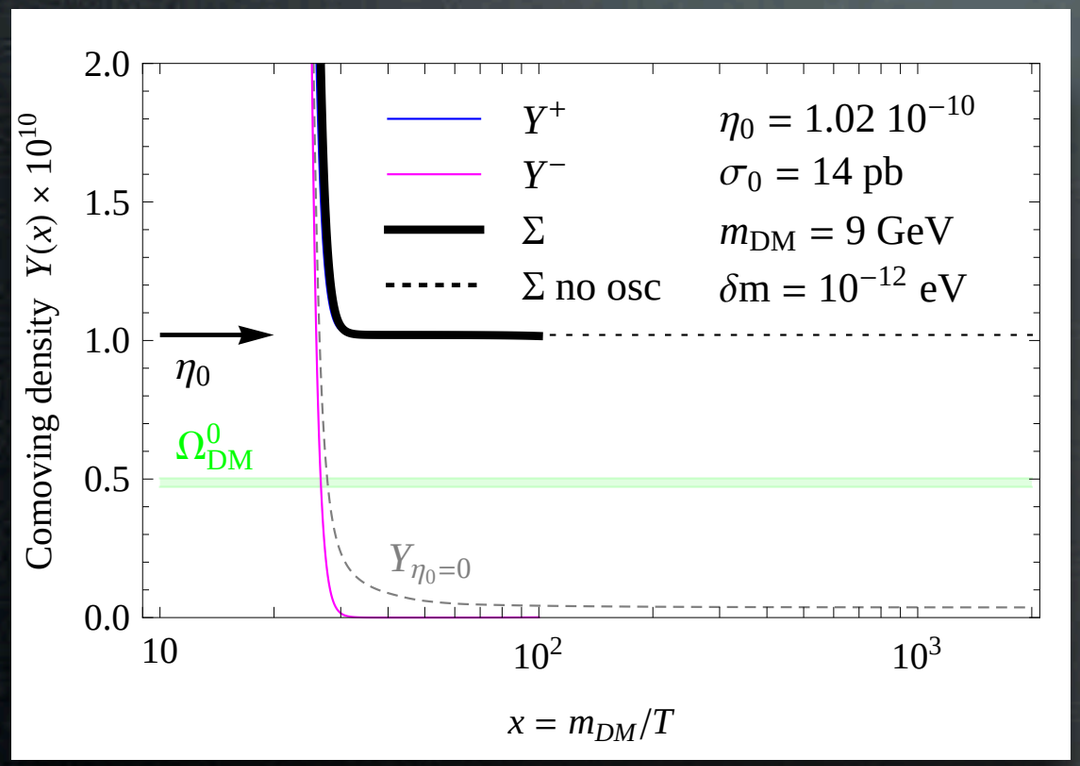
Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

(a) DM-$\overline{\text{DM}}$ initial asymmetry
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

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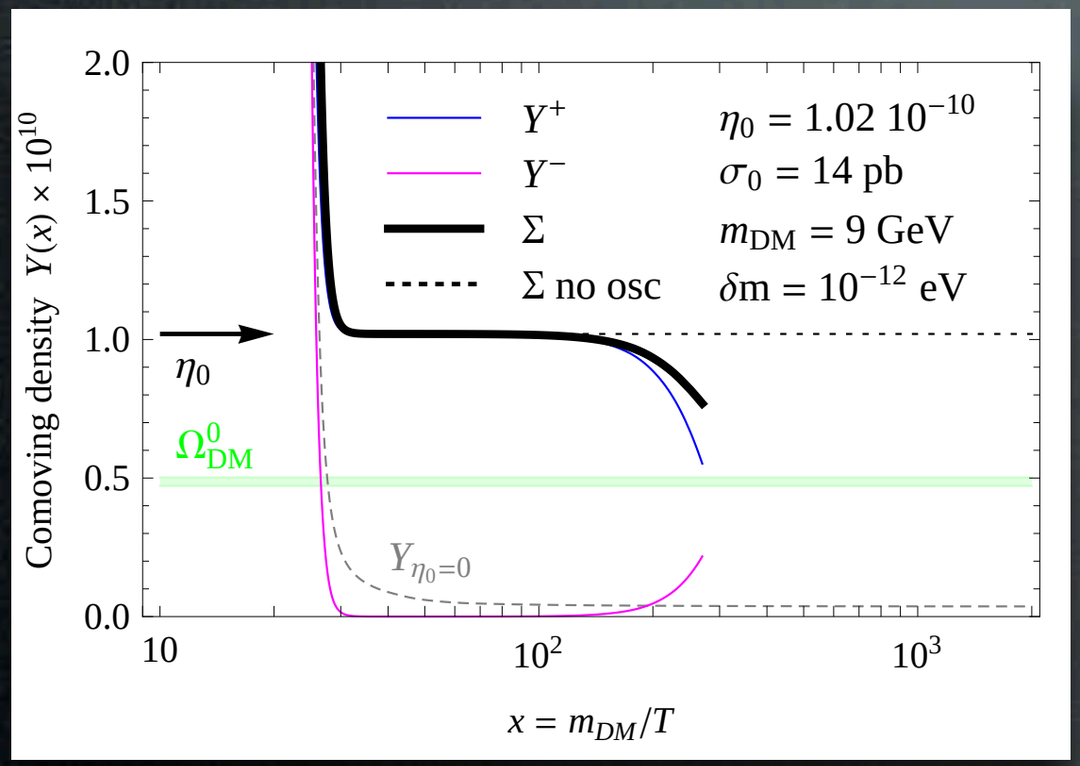

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
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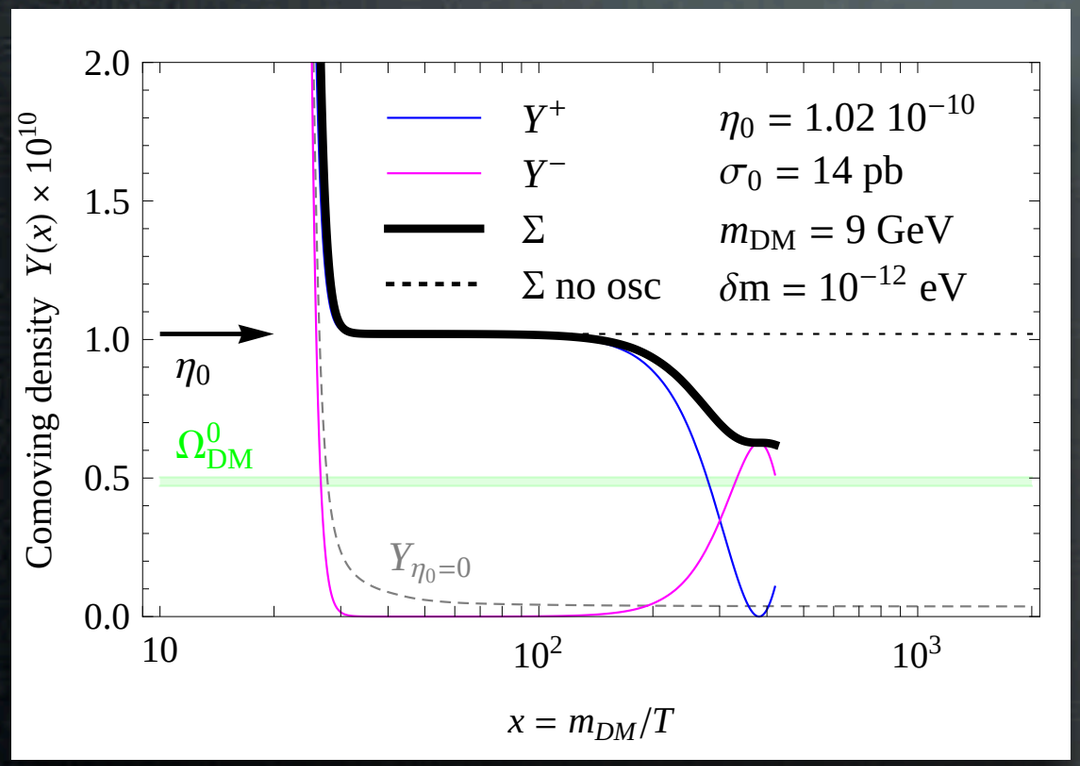

relic abundance (a)

is produced via the asymmetry
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Annihilations resume (b)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
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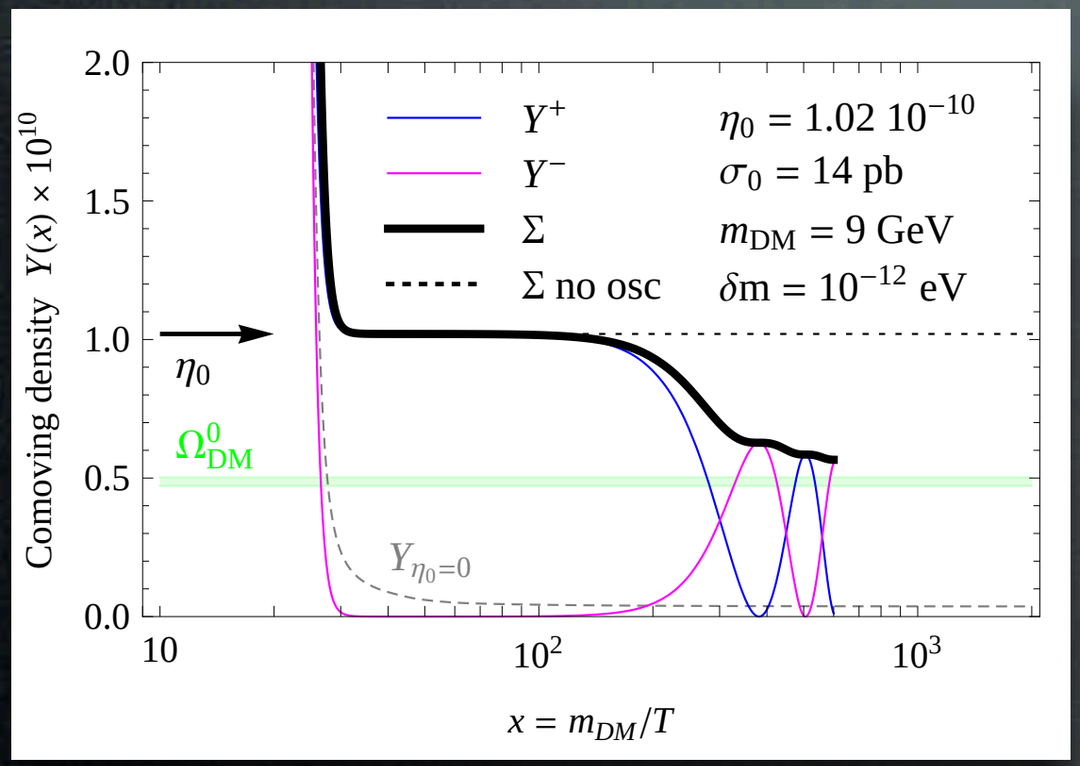

relic abundance (a)

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Annihilations resume (b)

Model building

not exhaustive!

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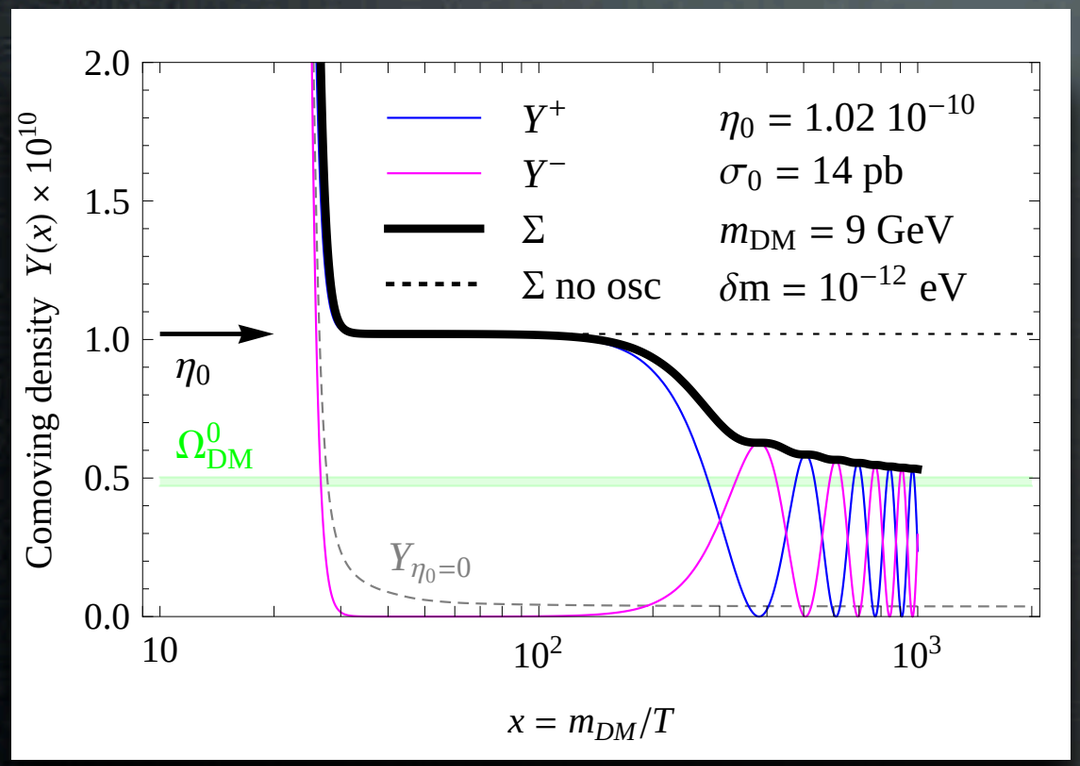

relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b)

(and the cross section needs to be large)

Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

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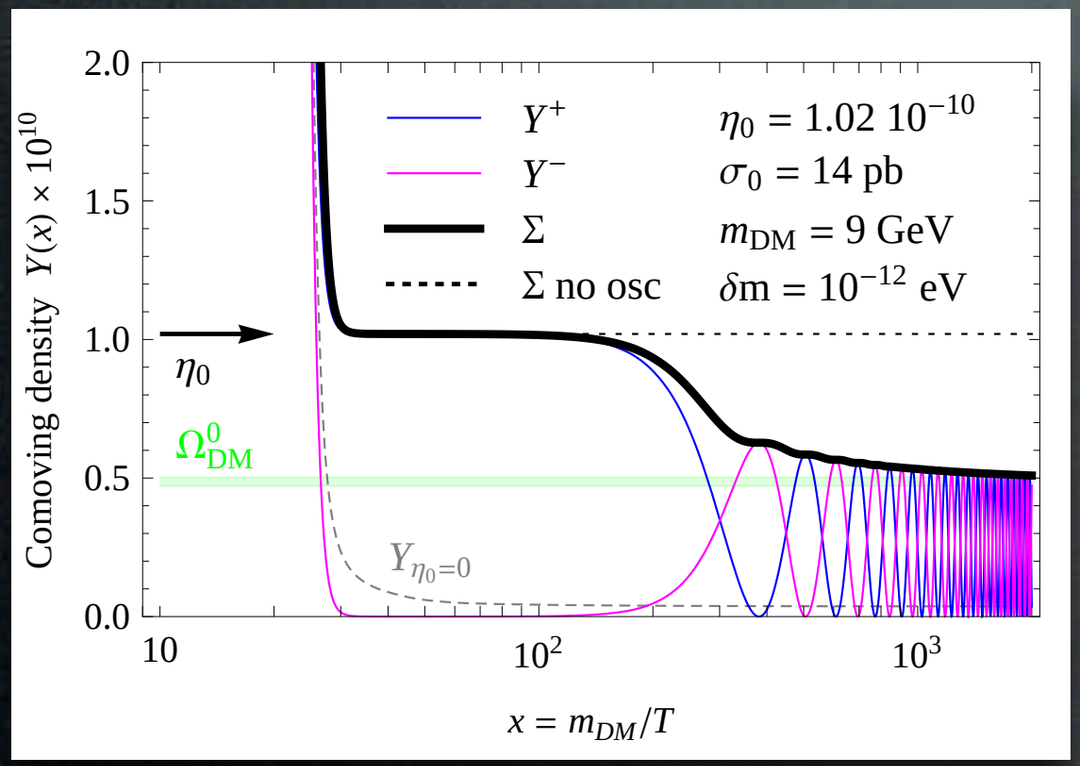
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



→ relic abundance (a)

is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) → line
(and the cross section needs to be large)

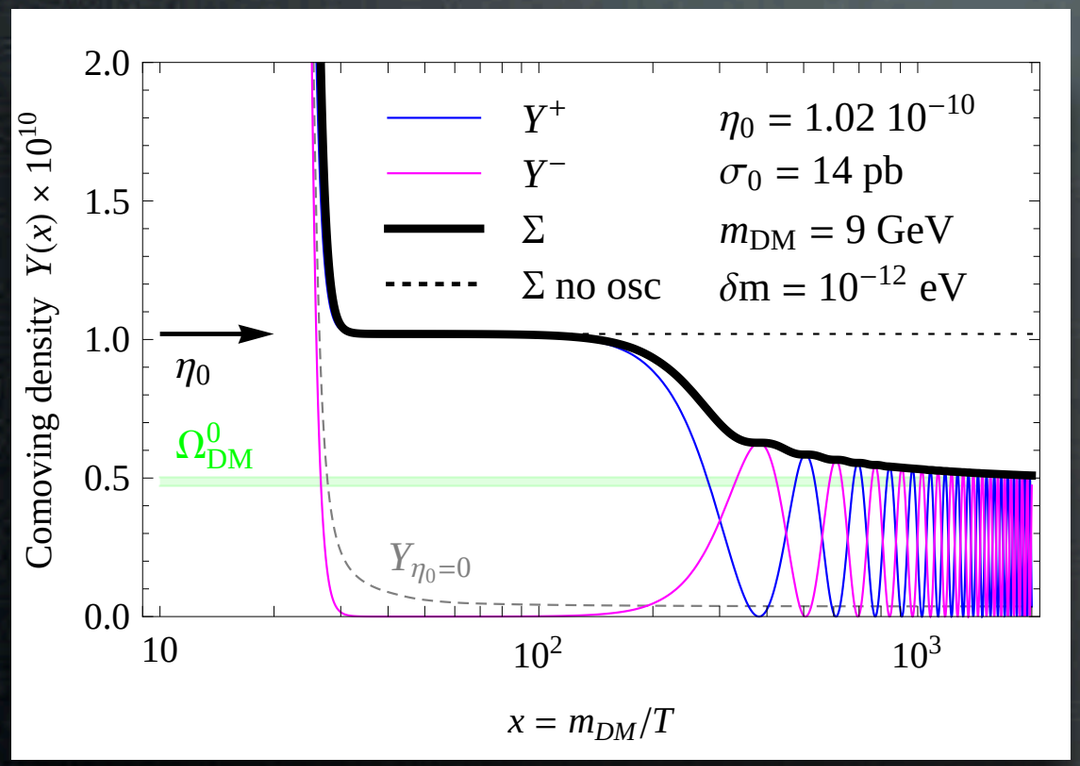
Model building

not exhaustive!

Nussinov 1985
Kaplan, Luty, Zurek 2009
Cirelli, Panci, Servant, Zaharijas 2011
Tulin, Yu, Zurek 1208.0009

Ex. 5: 'asymmetric DM'

(a) DM-$\overline{\text{DM}}$ initial asymmetry
(b) DM-$\overline{\text{DM}}$ mixing → late time oscillations, re-balance



➡ relic abundance (a)

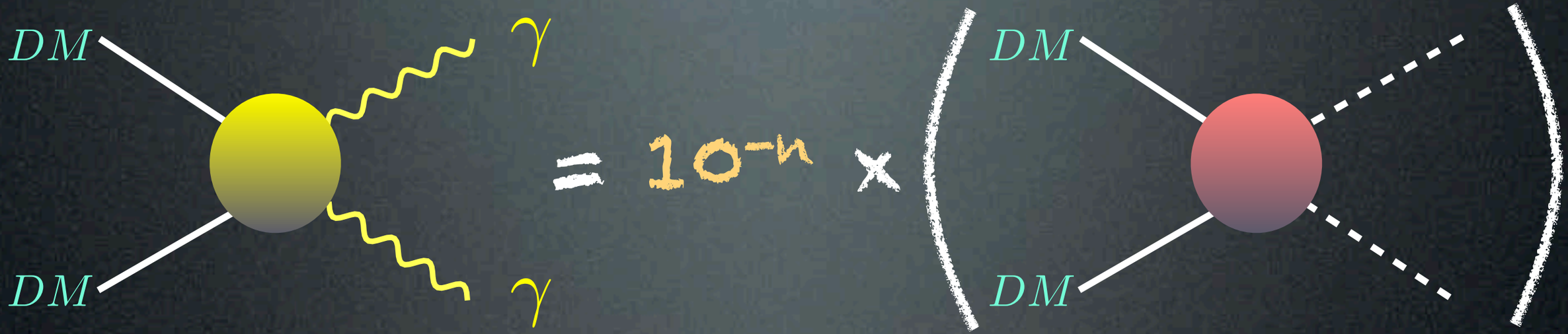
is produced via the asymmetry
is decoupled from the annihilation

Annihilations resume (b) ➡ line
(and the cross section needs to be large)

➡ Continuum? Needs to be suppressed in some way today.

Challenges

DM is neutral: need '*something*' to couple to γ

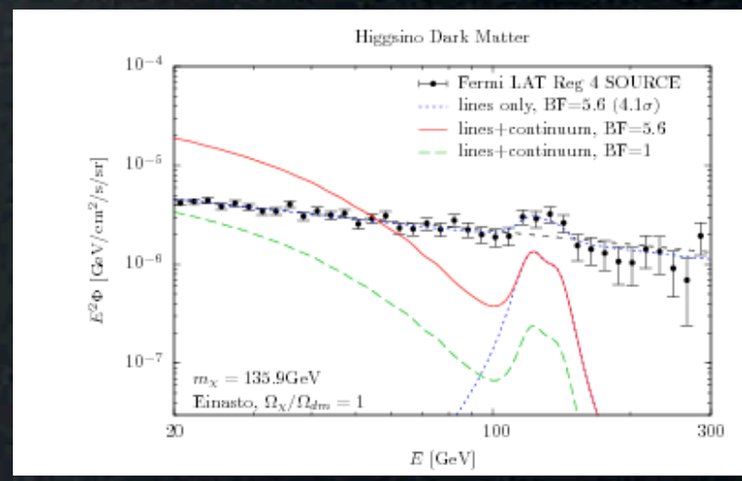


The '*something*' implies usually a suppression, but one needs a large $\gamma\gamma$ cross section ($o(10^{-27}\,cm^3/s)$)

so the corresponding unsuppressed processes are **too** large:

- may overshoot other observations
- too large annihilation in the EU

But solutions exist



Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

Model building

- may overshoot other observations
- too large annihilation in the EU

But solutions exist

In summary:

- kinematically forbidden channel
- different diagrams
- s-wave vs p-wave
- coannihilations and splitting
- DM production is decoupled from annihilations
- ...

Direct Detection

3. the ‘DAMA/CoGeNT/CRESST anomaly’

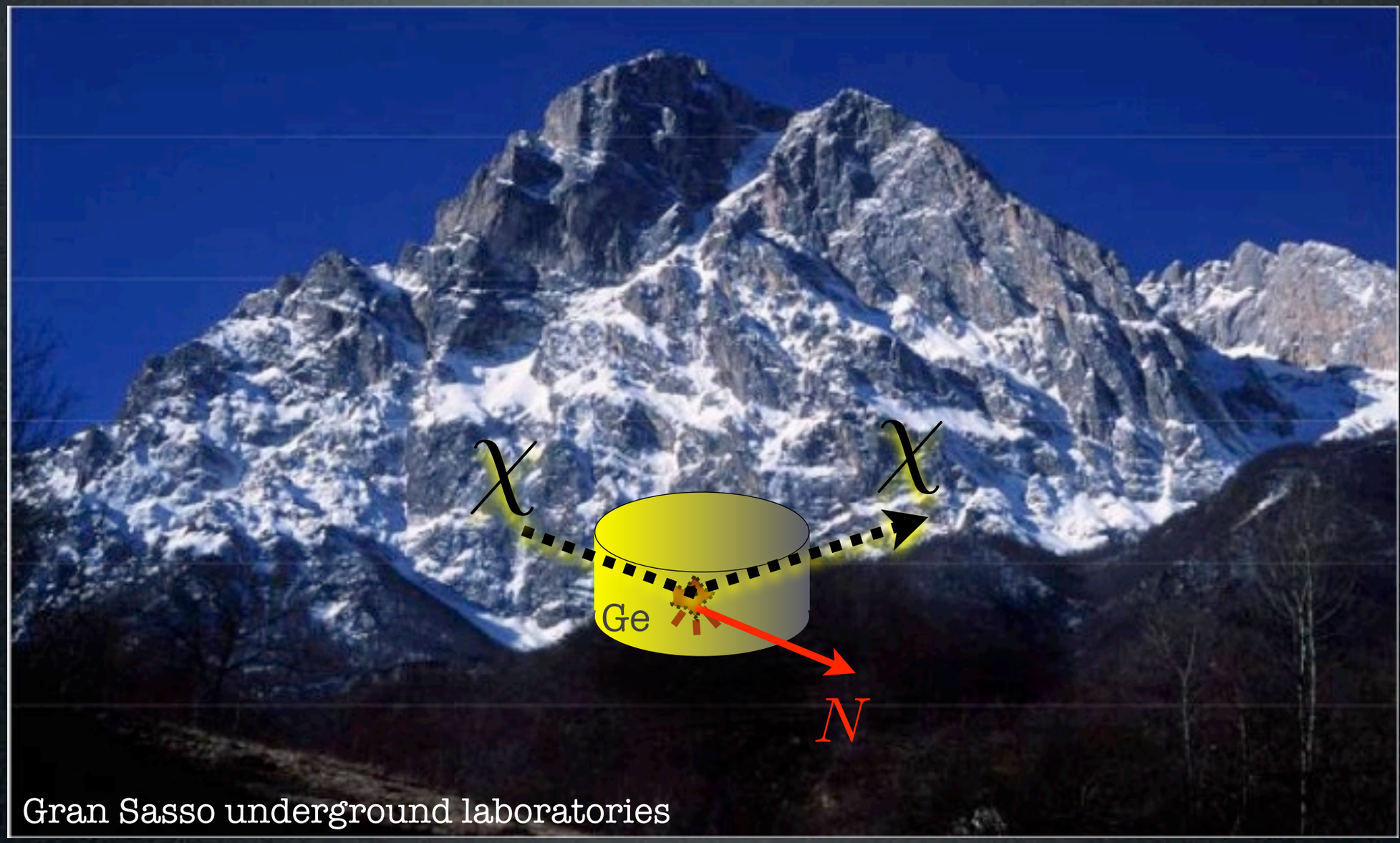
Direct Detection: **basics**

Gran Sasso underground laboratories

Direct Detection: basics

Gran Sasso underground laboratories

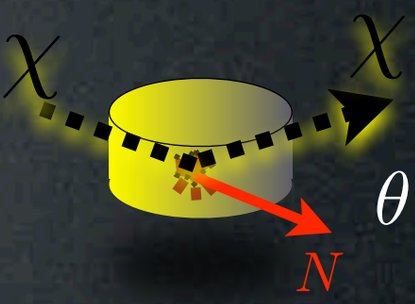
Direct Detection: basics



Gran Sasso underground laboratories

Direct Detection: basics

recoil energy $\quad E_R = \dfrac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$



$$\mu_\chi = \frac{m_\chi\, m_N}{m_\chi + m_N} \to \begin{cases} m_\chi \text{ for small } m_\chi \\ m_N \text{ for large } m_\chi \end{cases}$$

recoil energy spectrum

$$\frac{dR}{dE_R} = \frac{1}{2}\frac{\rho_\odot}{m_\chi}\frac{\sigma}{\mu^2}\int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{1}{v} f(\vec{v})\ \mathrm{d}\vec{v}$$

with $\quad f(\vec{v}) \propto e^{-v^2/V_c^2}$ + motion of Earth in (static?)halo

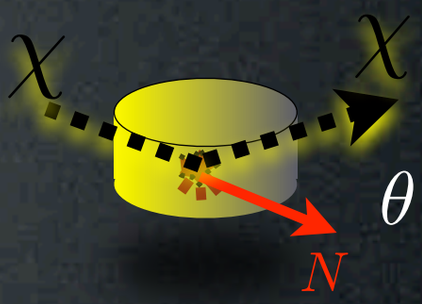
$$\sigma \approx \sigma_n^{\rm SI}\, A^4 \quad \times \text{nuclear form factors}$$

number of events

$$N = \mathcal{E}\,\mathcal{T} \int_{E_{\rm thres}}^{E_{\rm max}} \frac{dR}{dE_R}\, dE_R$$

Direct Detection: basics

recoil energy $$E_R = \frac{\mu_\chi^2 v^2}{m_N}(1-\cos\theta)$$



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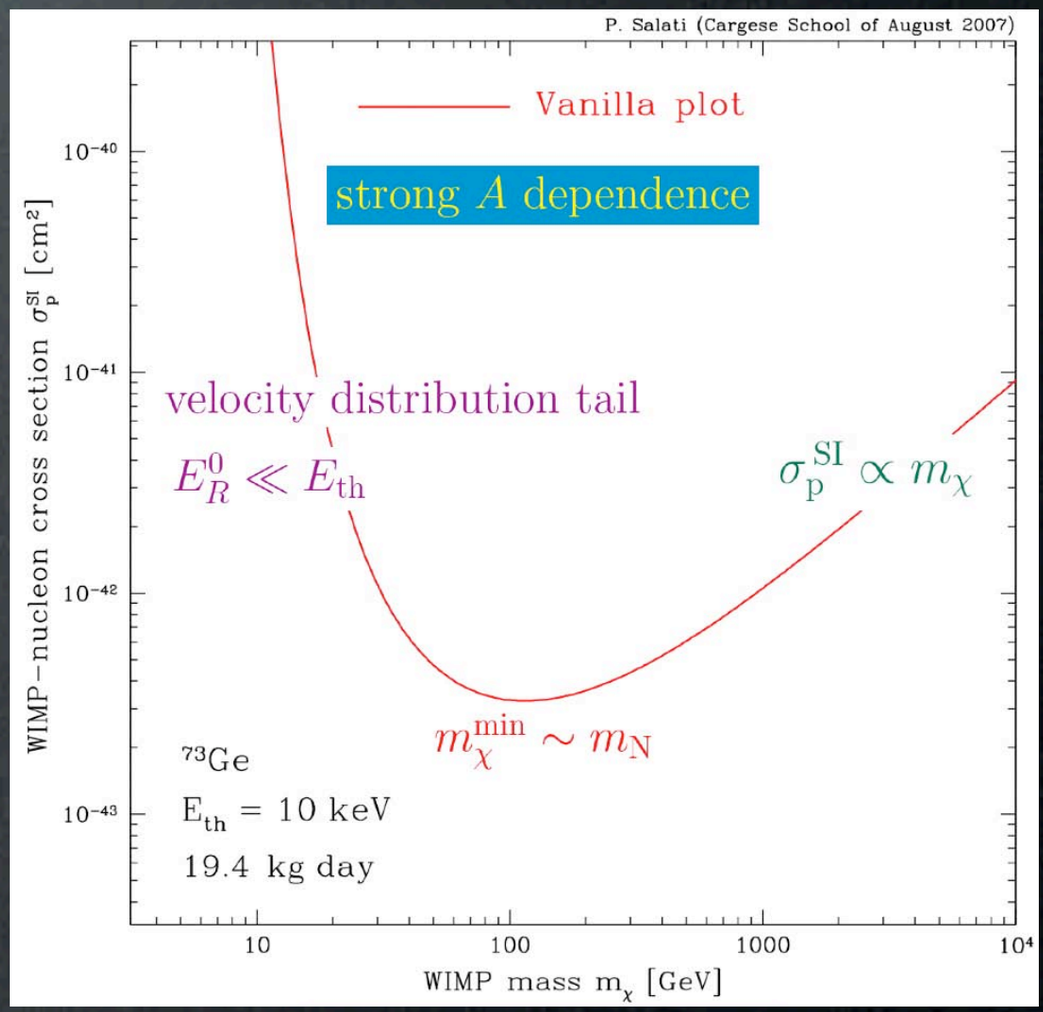

P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

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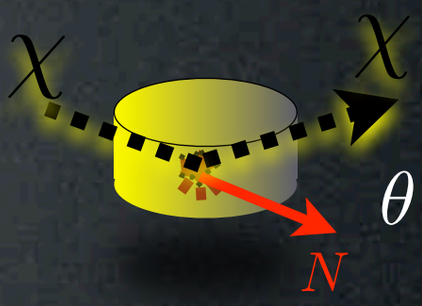

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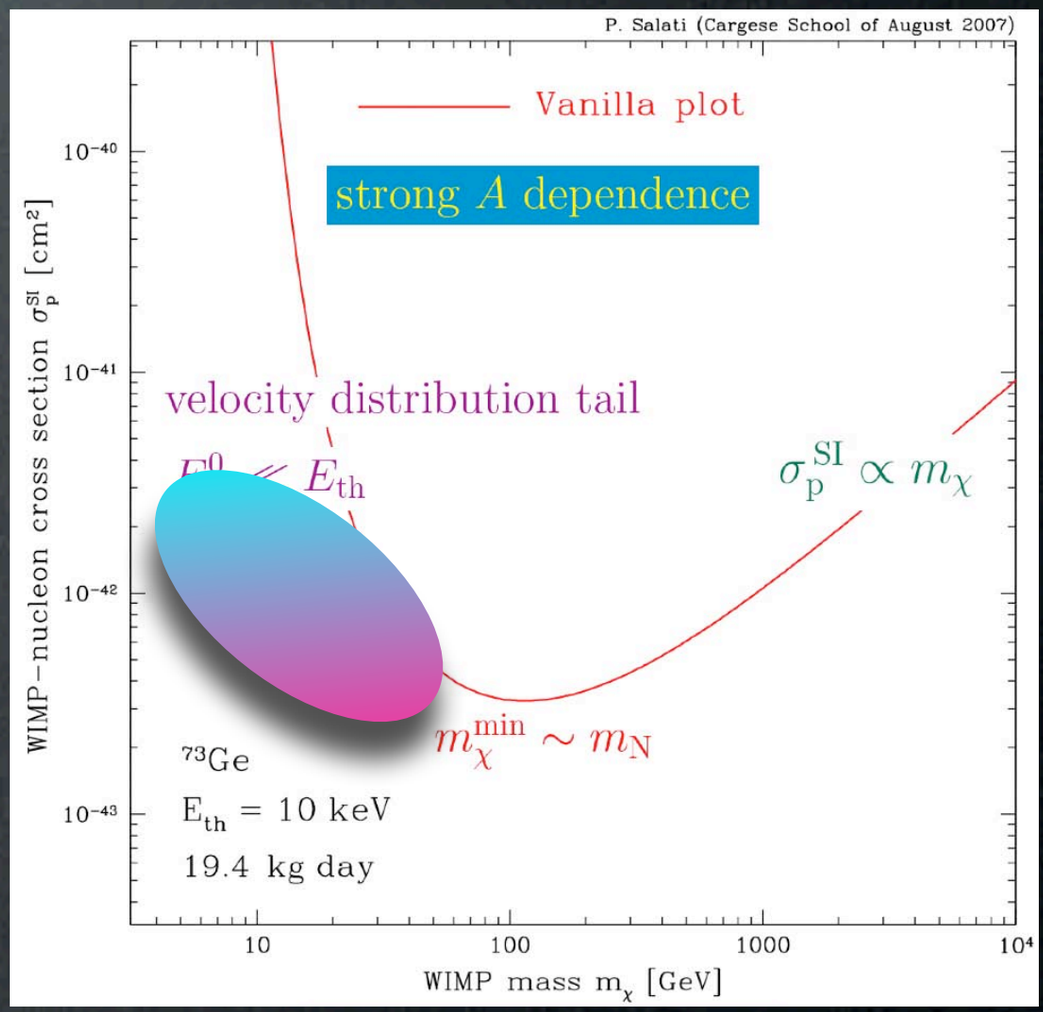
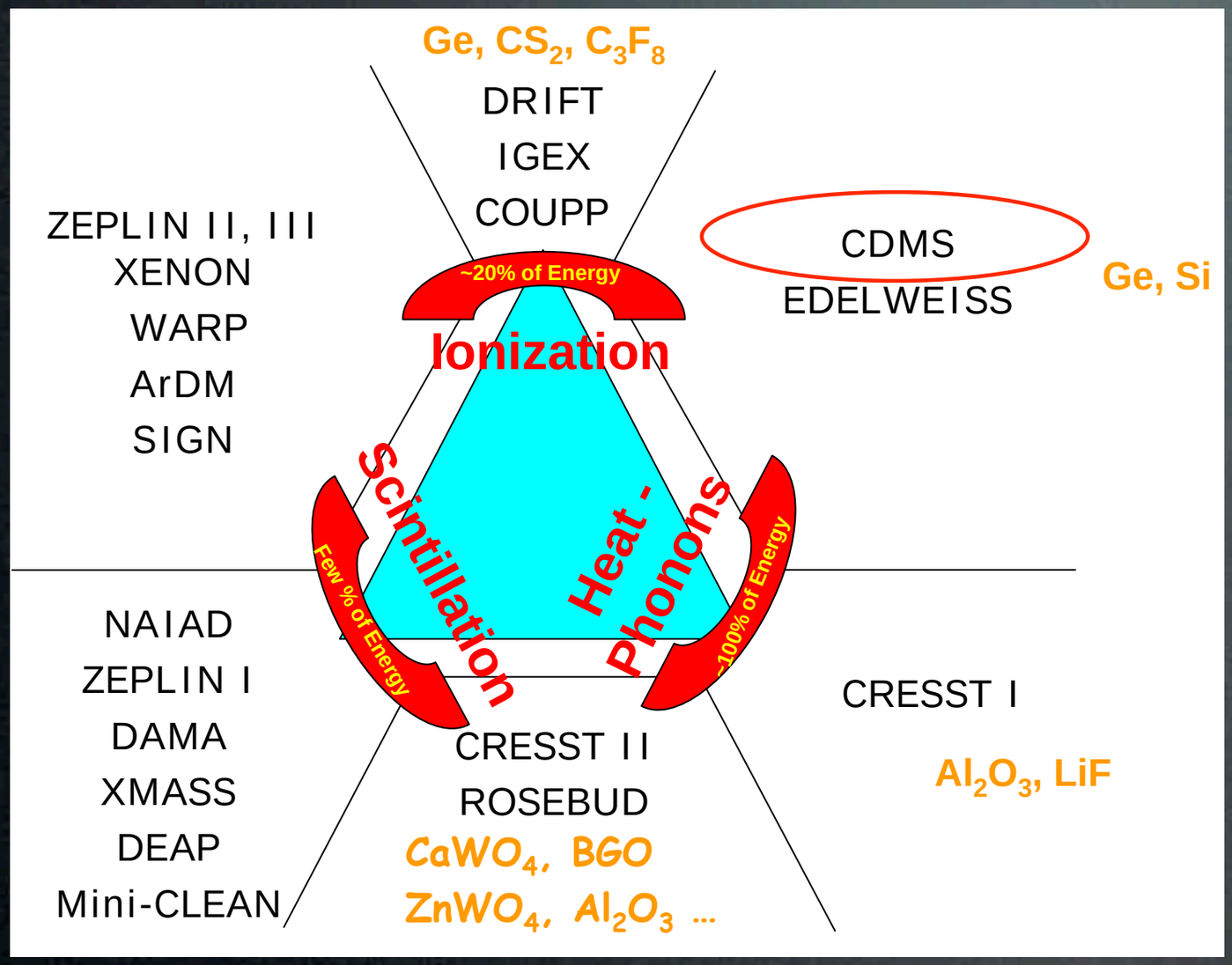


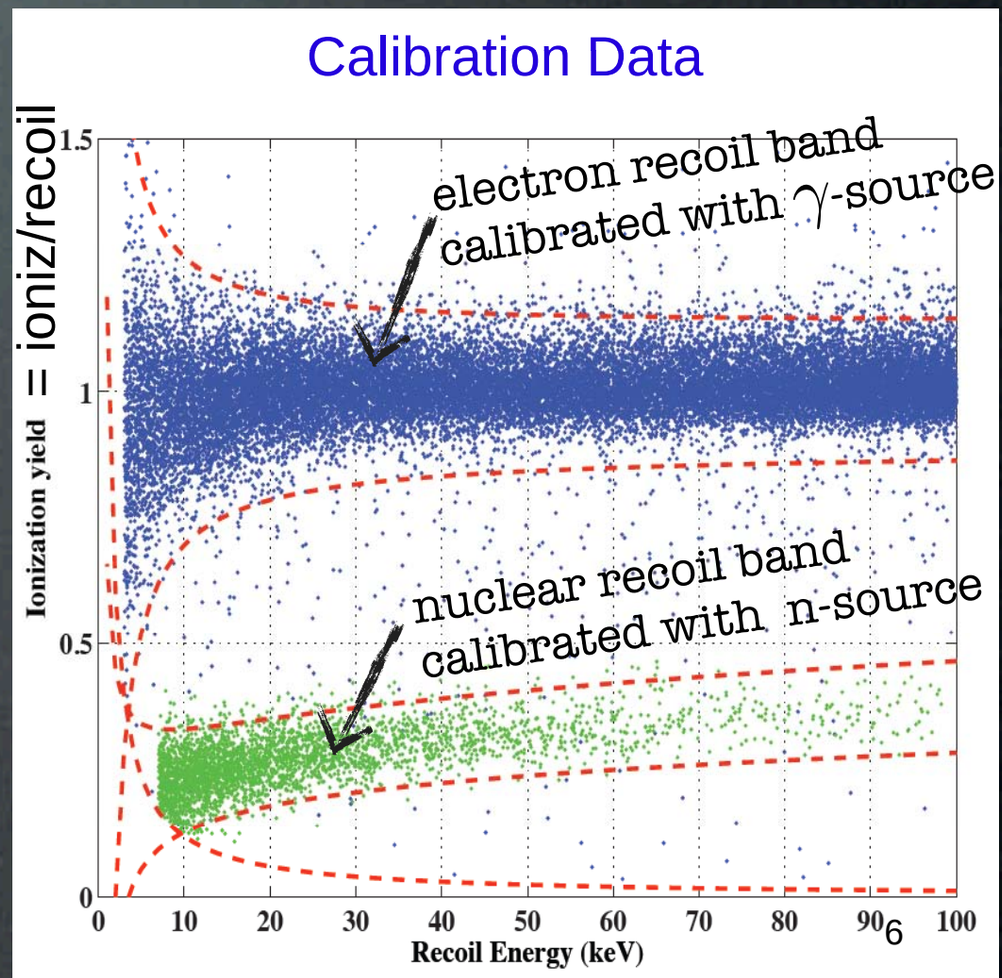
P.Salati, proceedings of Cargèse 2007

Direct Detection: basics

Background rejection



[credit: B.Sadoulet]



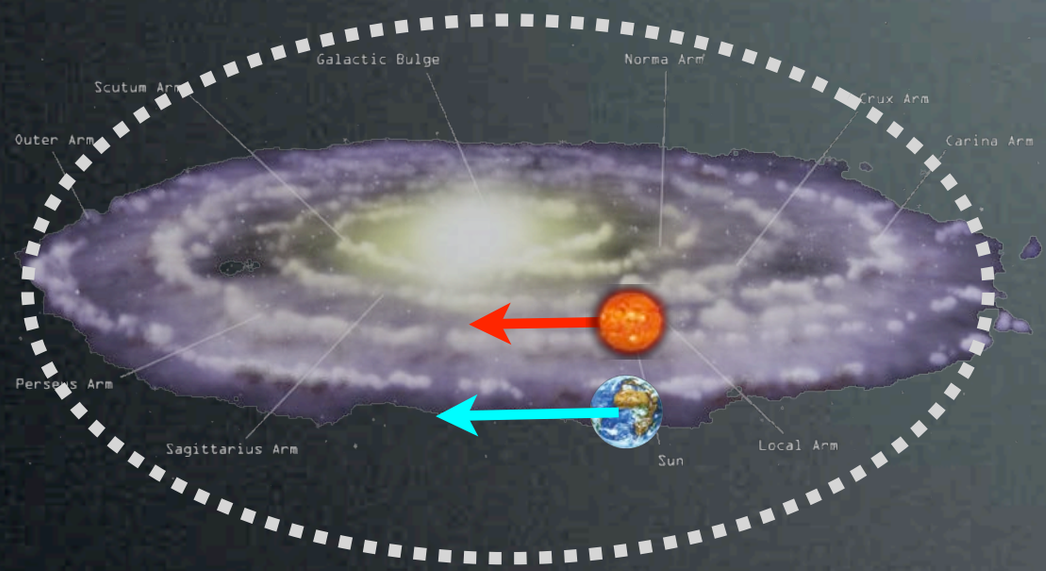
CDMS coll.

measure two quantities to discriminate Sign & Bkgd, on event-by-event basis

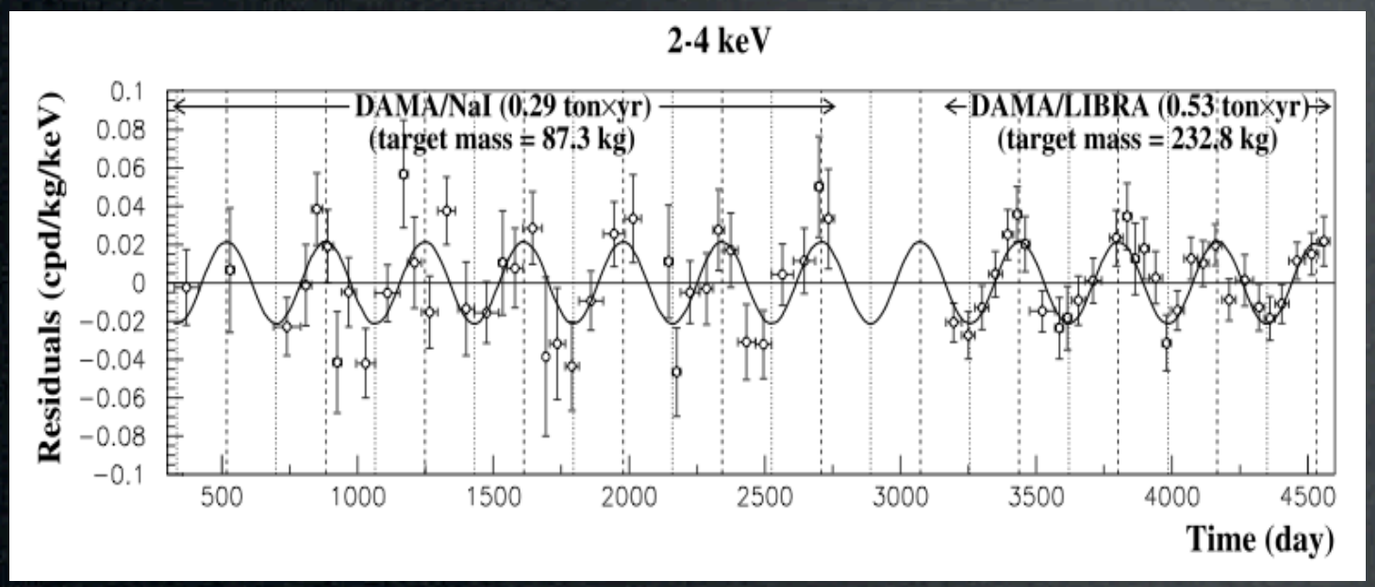
Direct Detection: hints

DAMA/Libra

NaI(Tl)



Annual modulation seen (9.3 σ):

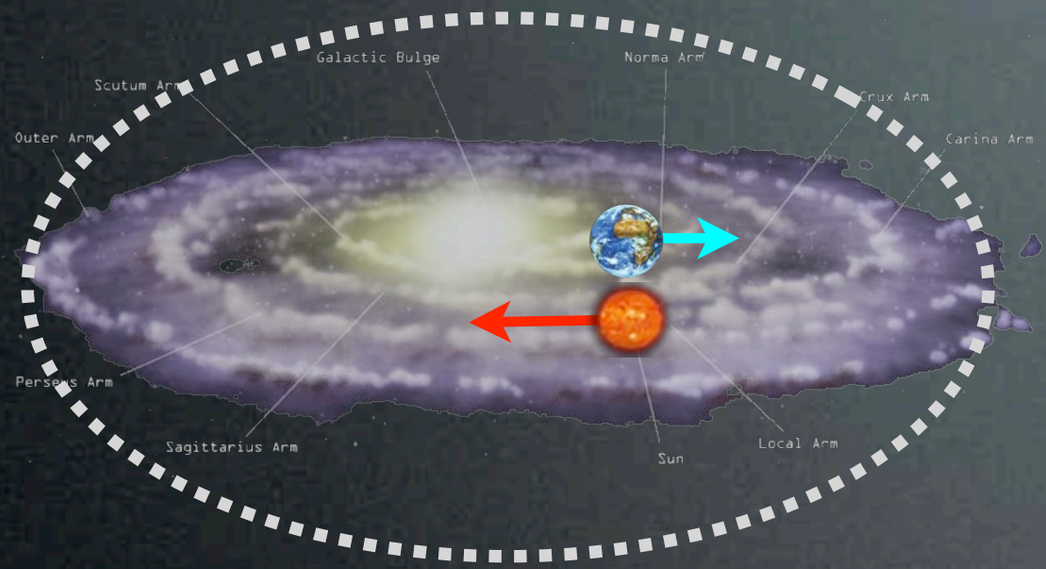


DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

Direct Detection: hints

DAMA/Libra

NaI(Tl)



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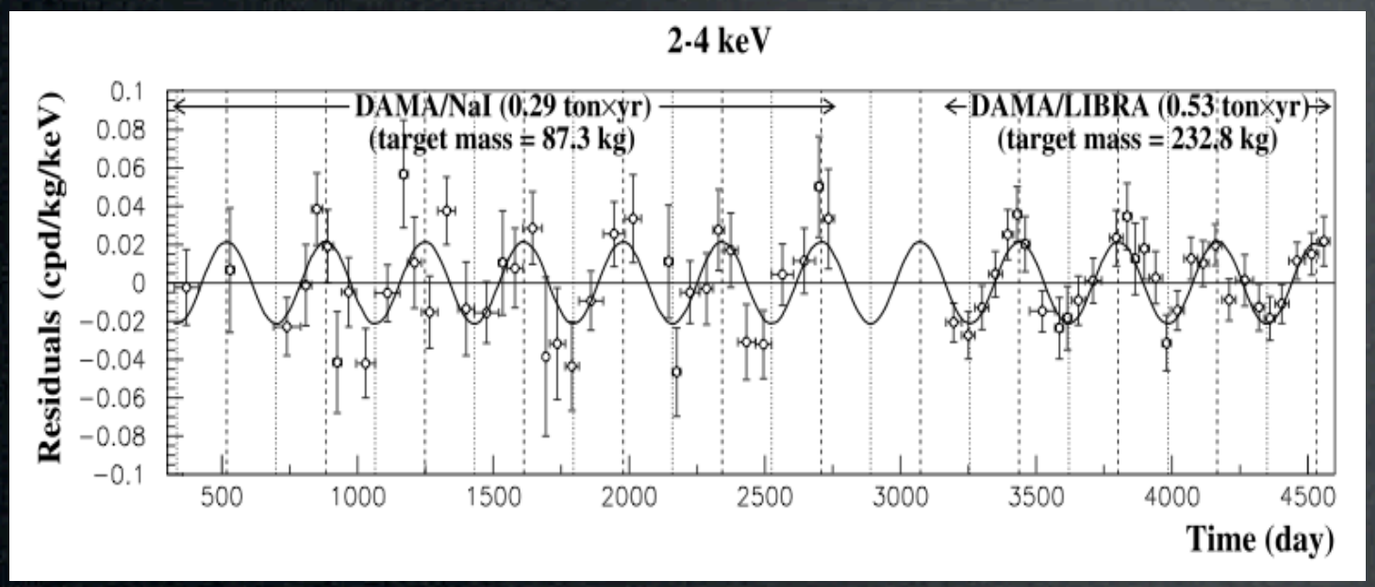
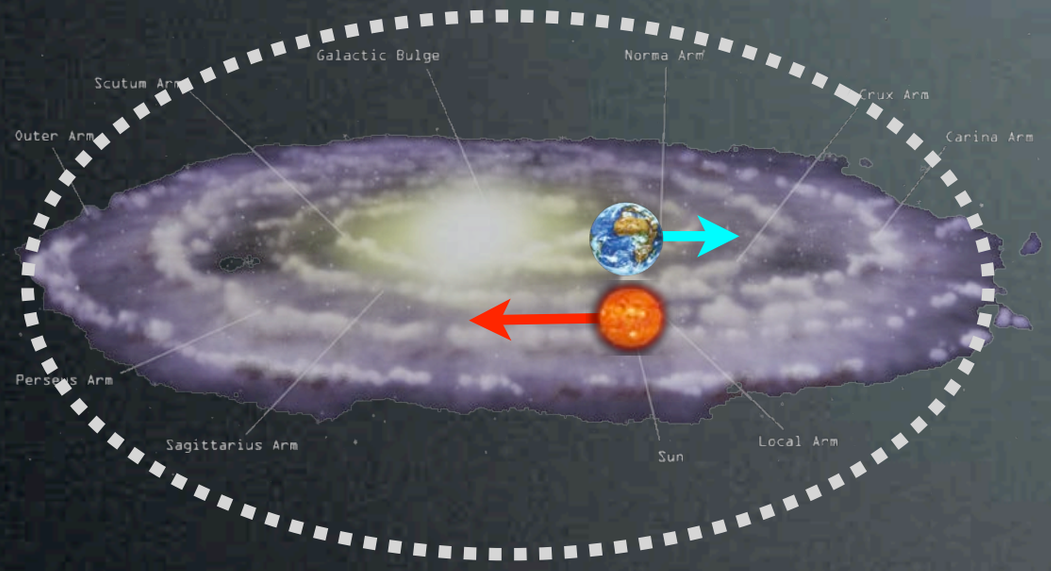


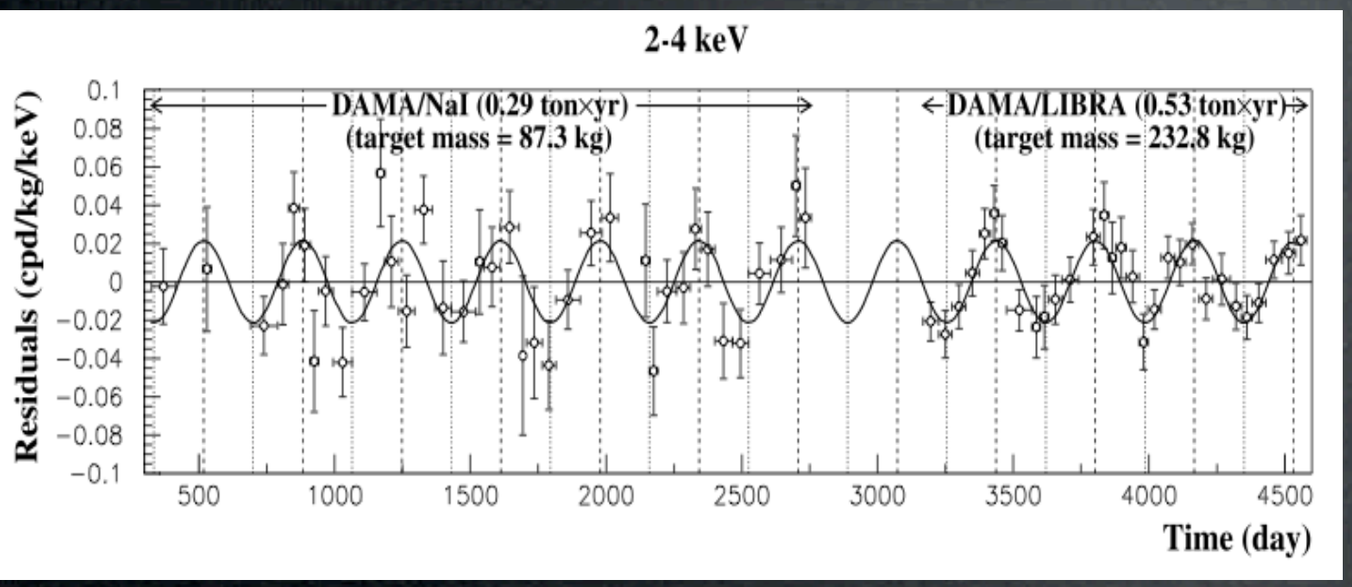
DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

Direct Detection: hints

DAMA/Libra



Annual modulation seen (9.3 σ):



DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

An instrumental effect?

Summary of the results obtained in the additional investigations of possible systematics or side reactions
(DAMA/LIBRA - NIMA592(2008)297, EPJC56(2008)333)

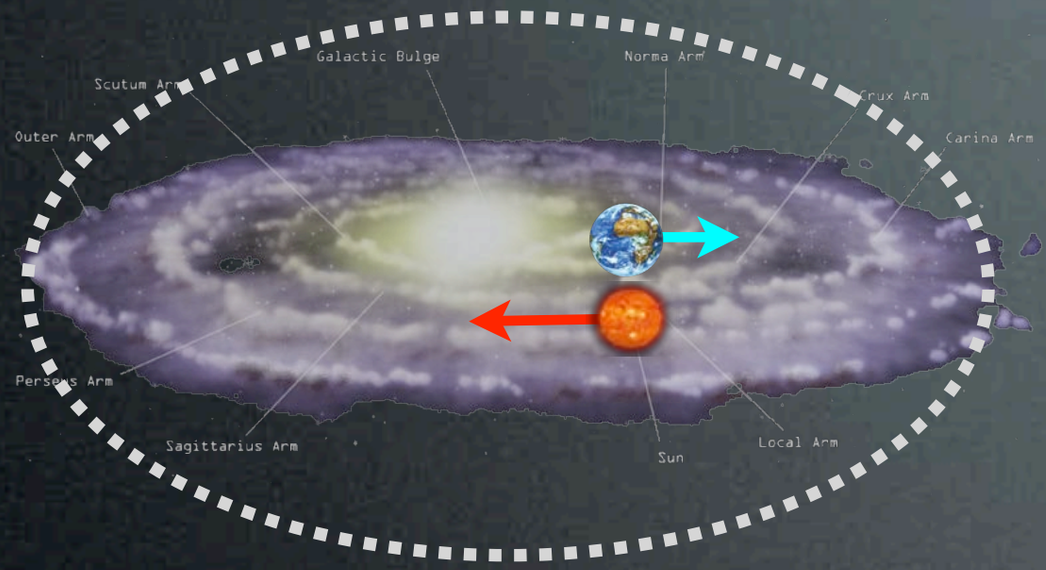
Source	*Main comment*	*Cautious upper limit (90%C.L.)*
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + instrinsic calibrations	**<1-2 ×10^{-4} cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured by MACRO	**<3×10^{-5} cpd/kg/keV**

+ even if larger they cannot satisfy all the requirements of annual modulation signature → **Thus, they can not mimic the observed annual modulation effect**

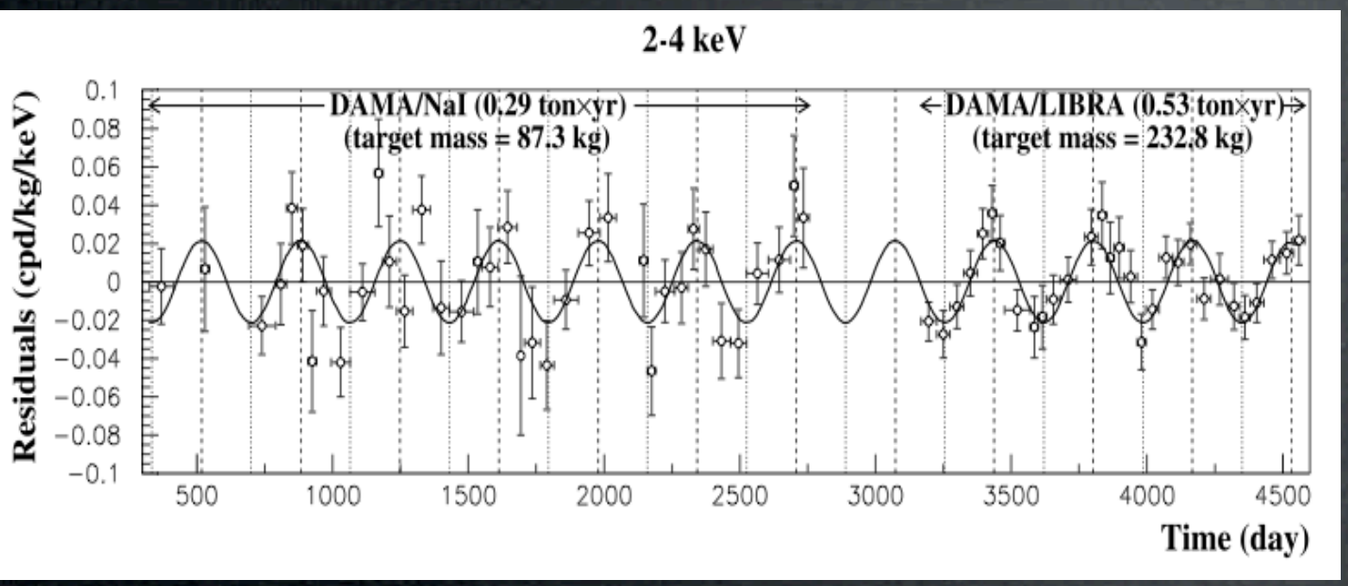
'NO!' e.g. P.Belli, KITP workshop 12.2009

Direct Detection: hints

DAMA/Libra



Annual modulation seen (9.3 σ):

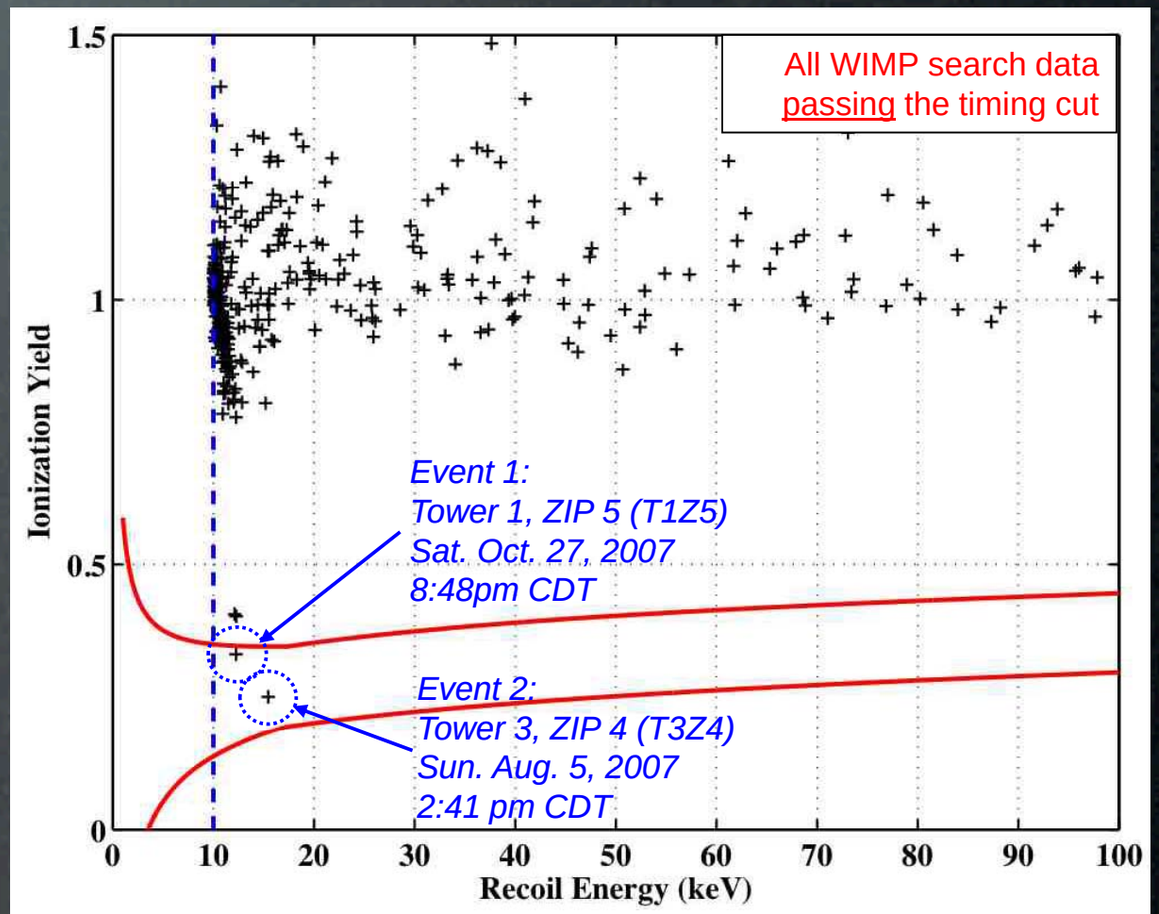


DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

CDMS

Ge+Si

2 events seen,
with 0.6 exp'd background

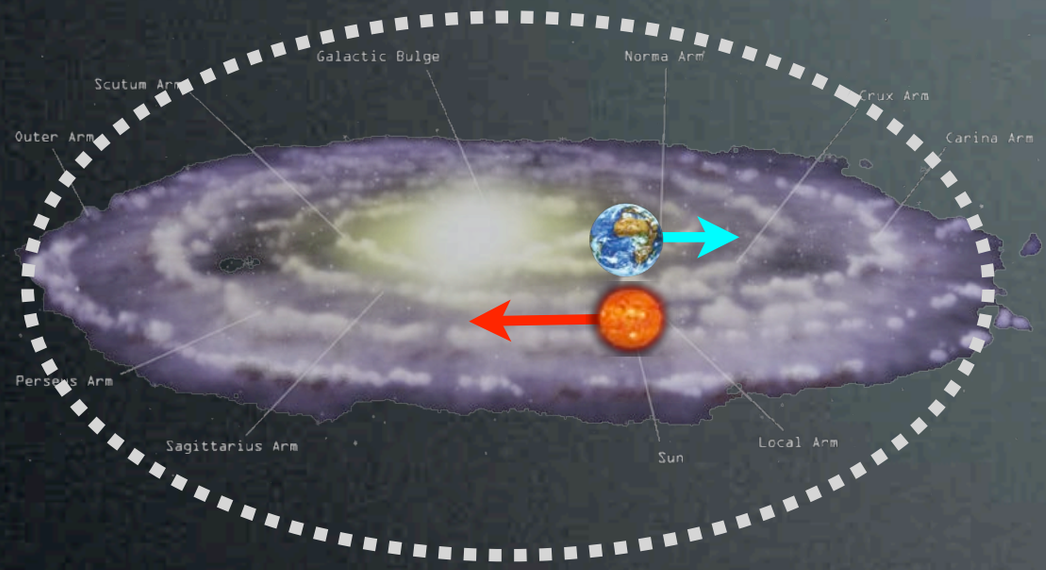


CDMS coll., Science 327 (2010), 0912.3592

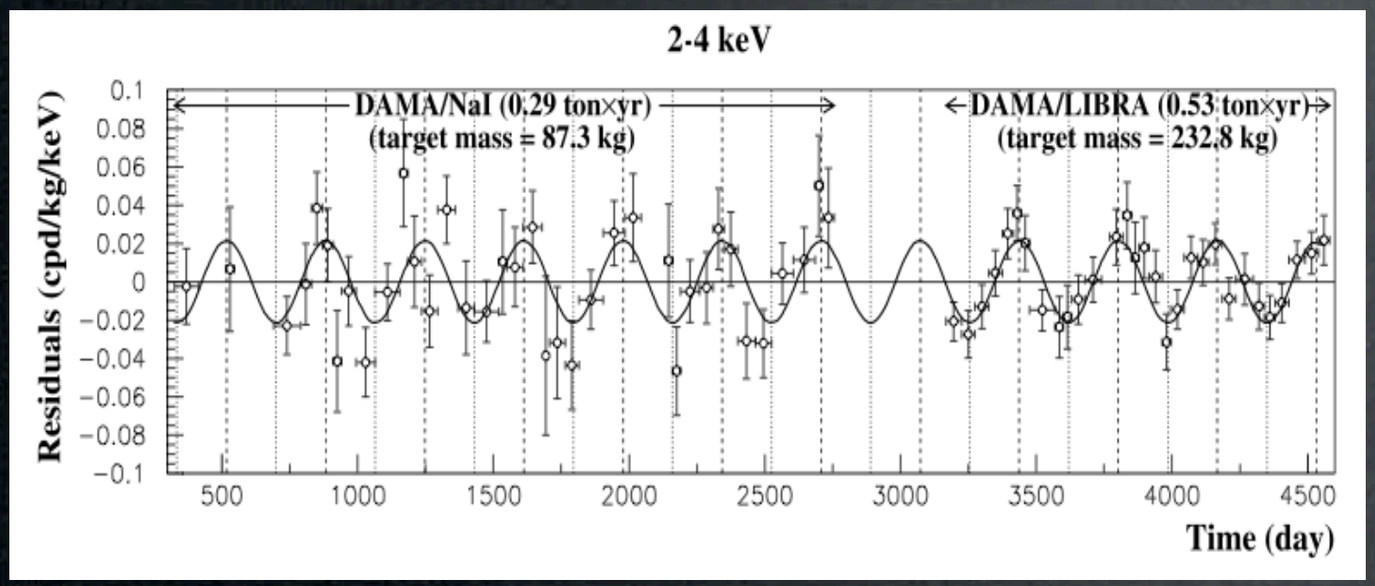
cited 650 times

Direct Detection: hints

DAMA/Libra



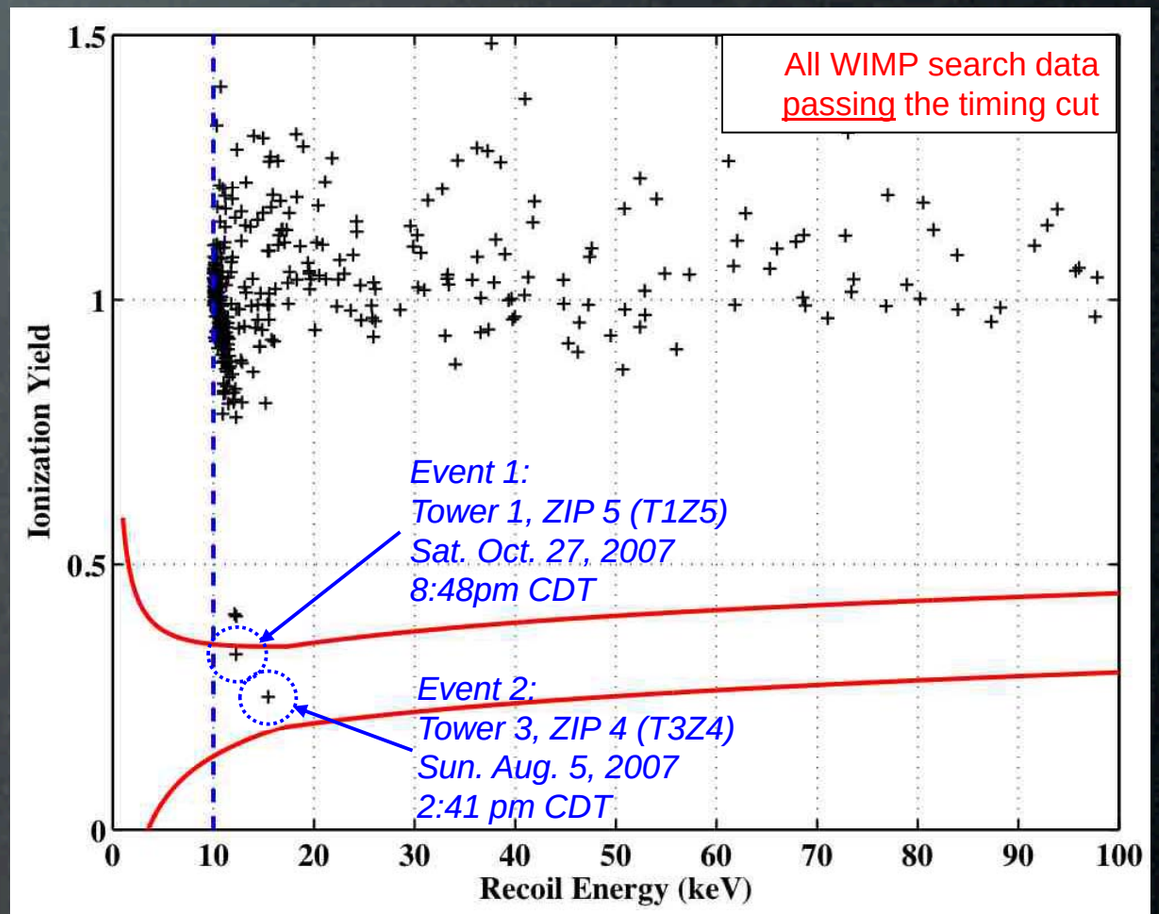
Annual modulation seen (9.3 σ):



DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

CDMS Ge+Si

2 events seen,
with 0.6 exp'd background



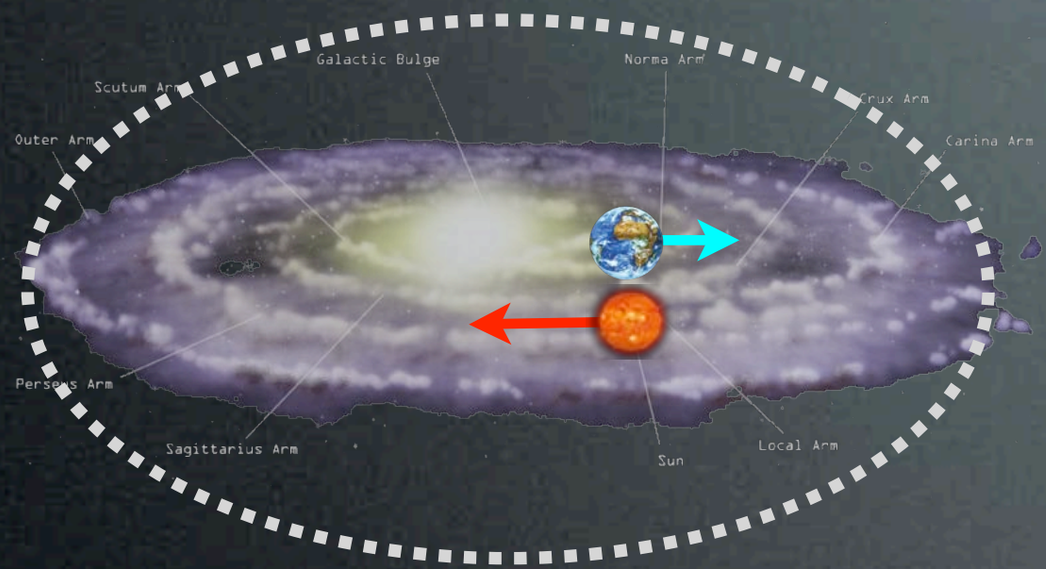
CDMS coll., Science 327 (2010), 0912.3592

cited 650 times

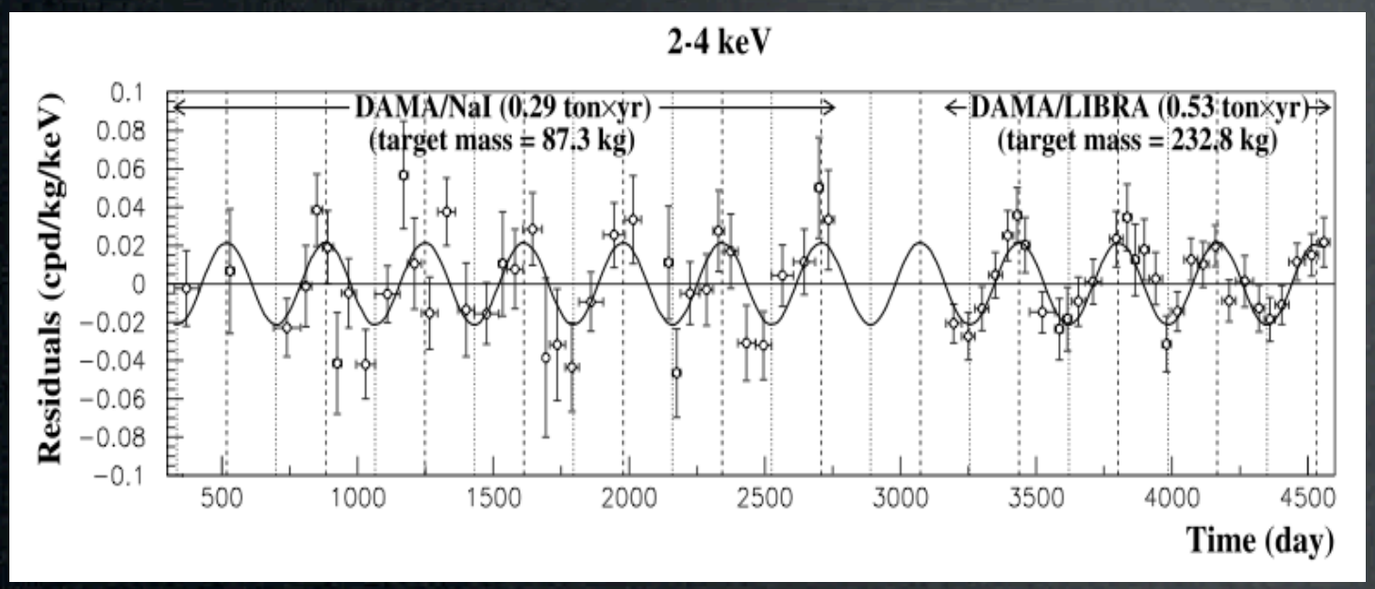
+ CDMS-Si (2013): 3 events with 0.41 exp'd background (almost 3σ)

Direct Detection: hints

DAMA/Libra



Annual modulation seen (9.3 σ):

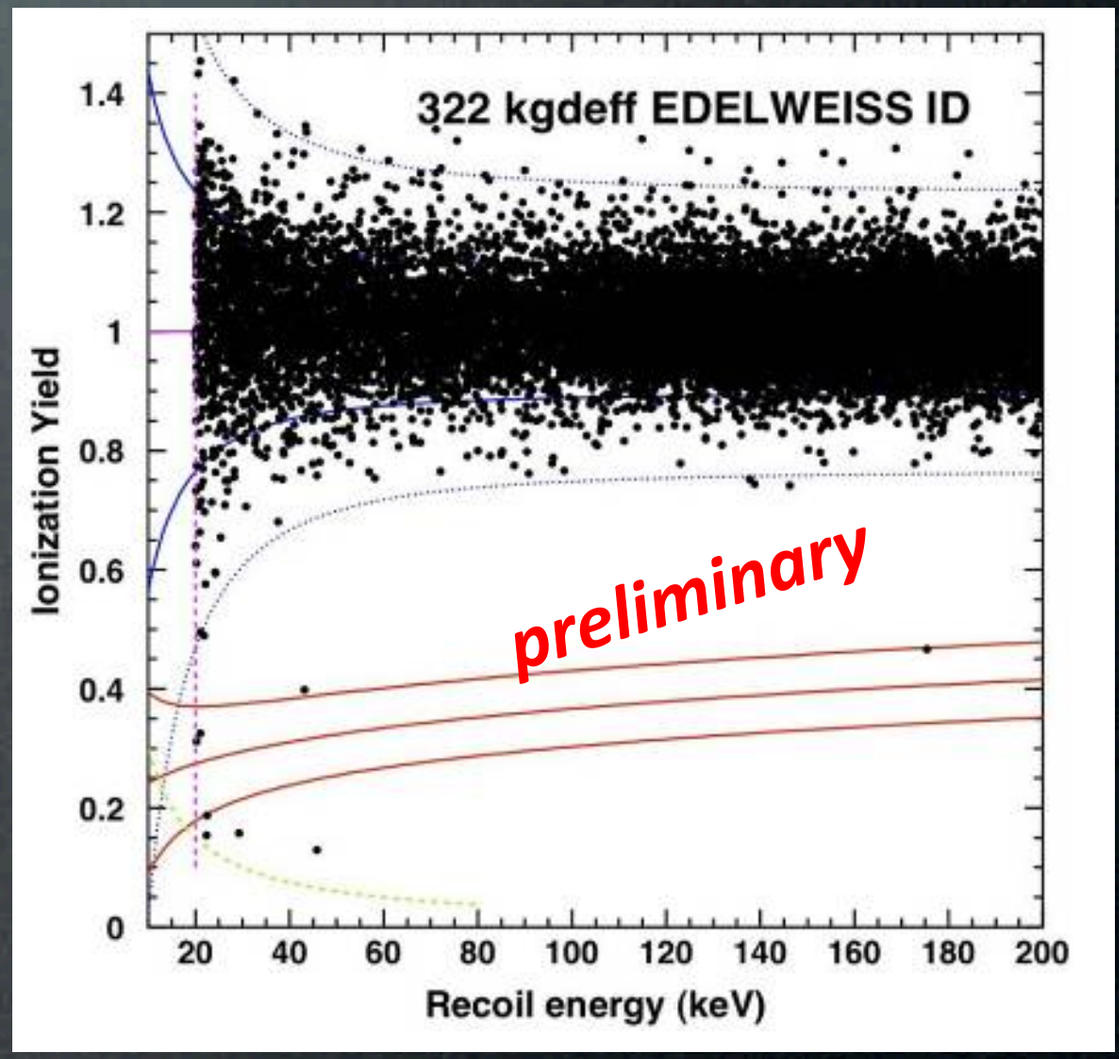


DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

Edelweiss Ge

3 events seen

'background starts to appear'

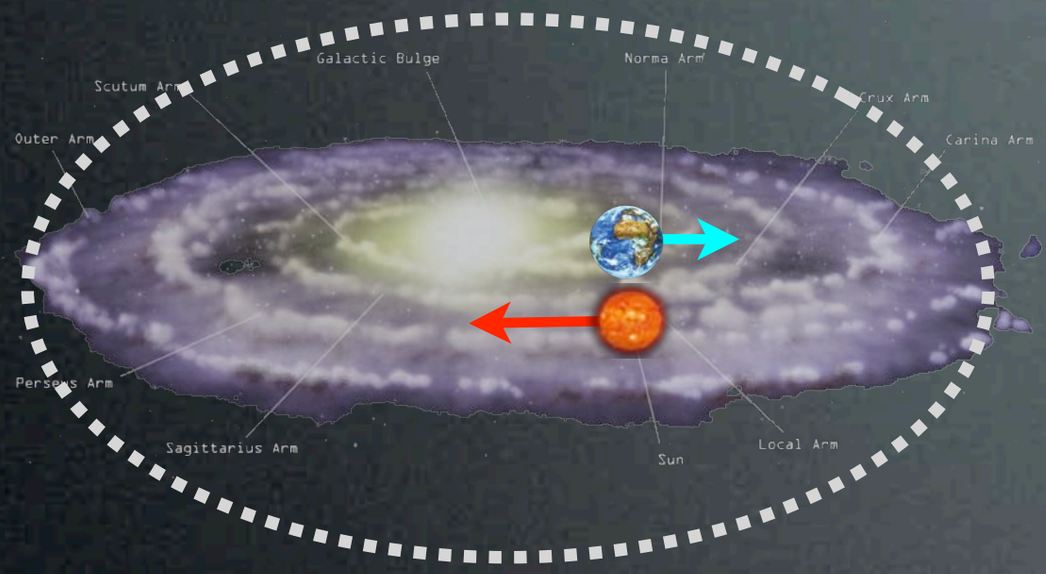


Edelweiss coll, TeVPA 2010
and 1011.2319

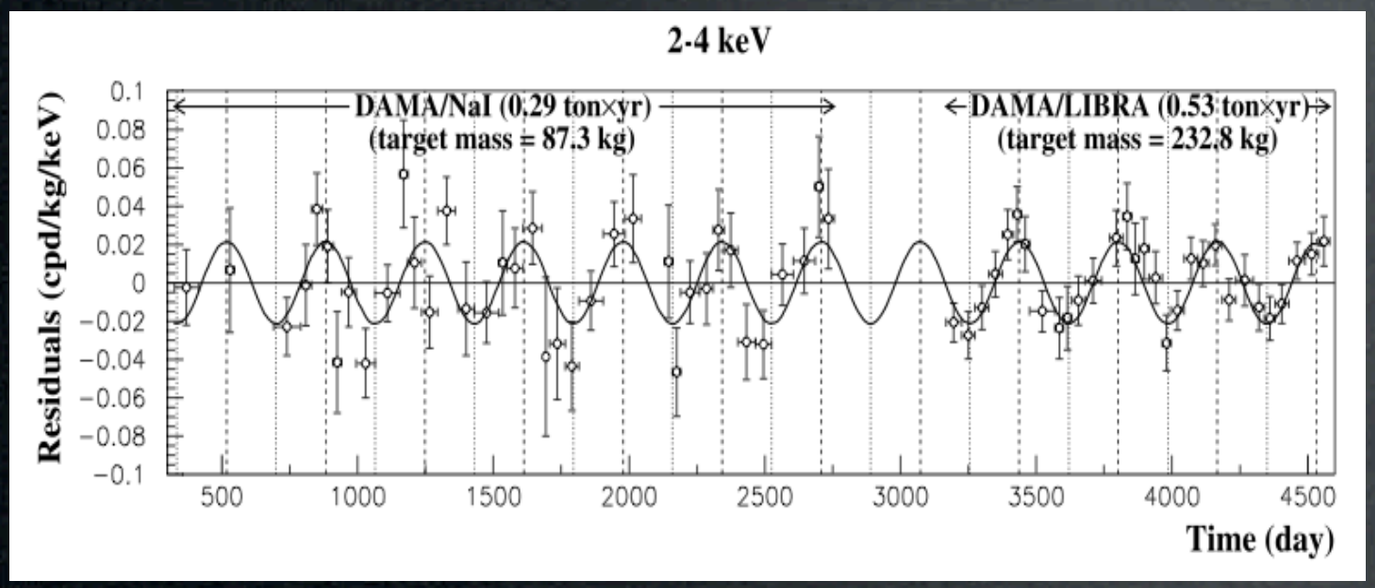
cited 600/10 = 60 times

Direct Detection: hints

DAMA/Libra



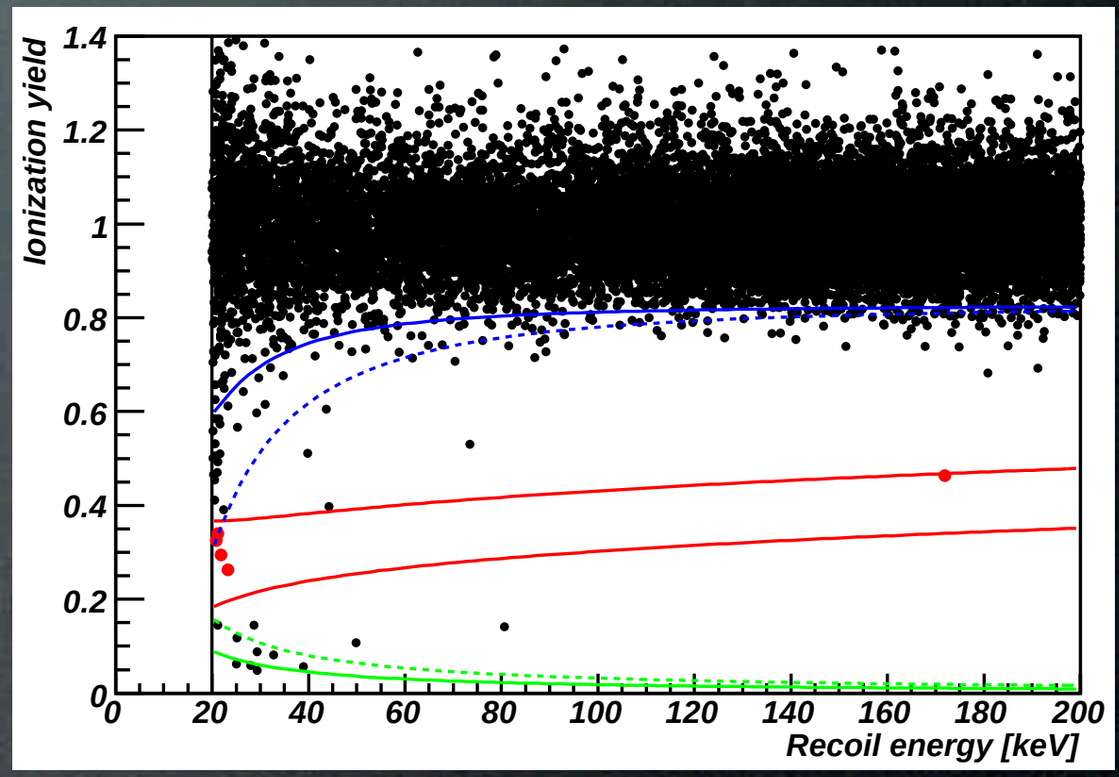
Annual modulation seen (9.3 σ):



DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

Edelweiss Ge

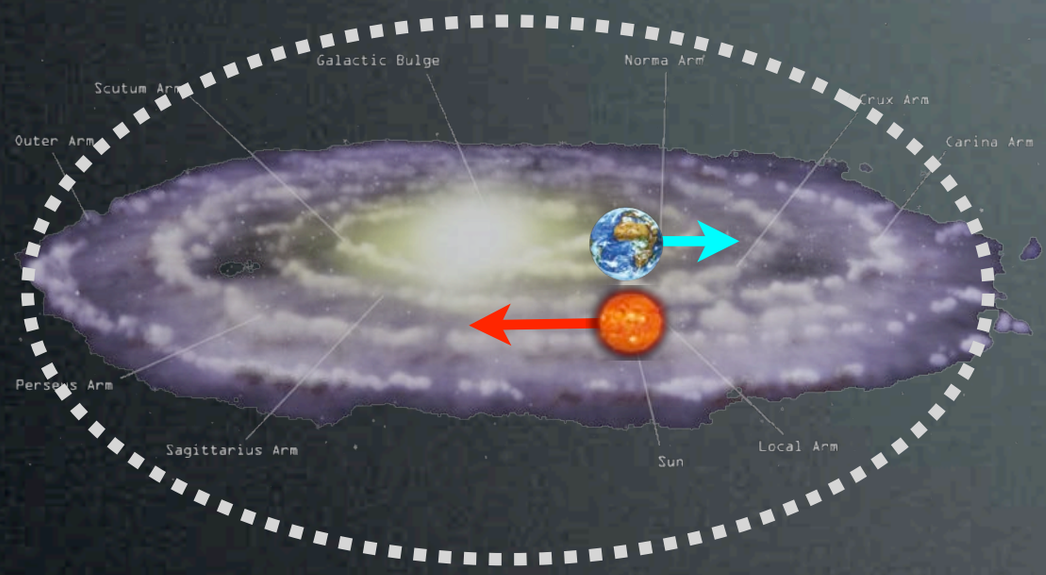
5 events seen,
with 3 exp'd background



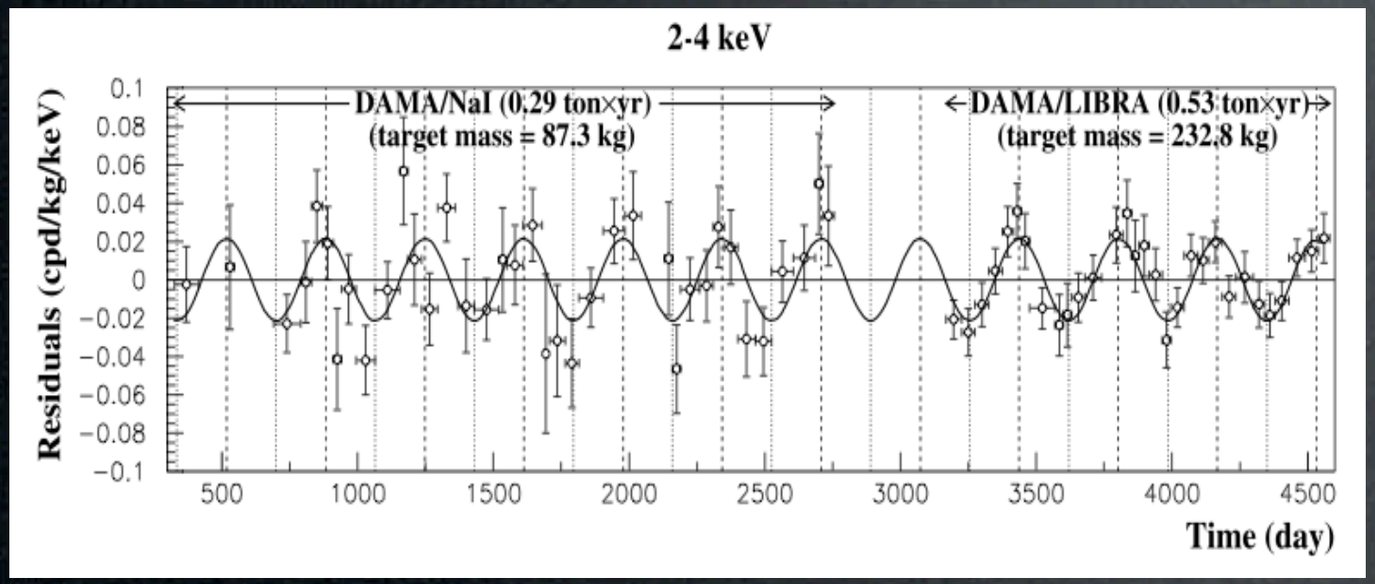
Edelweiss coll, 1103.4070

Direct Detection: hints

DAMA/Libra



Annual modulation seen (9.3 σ):

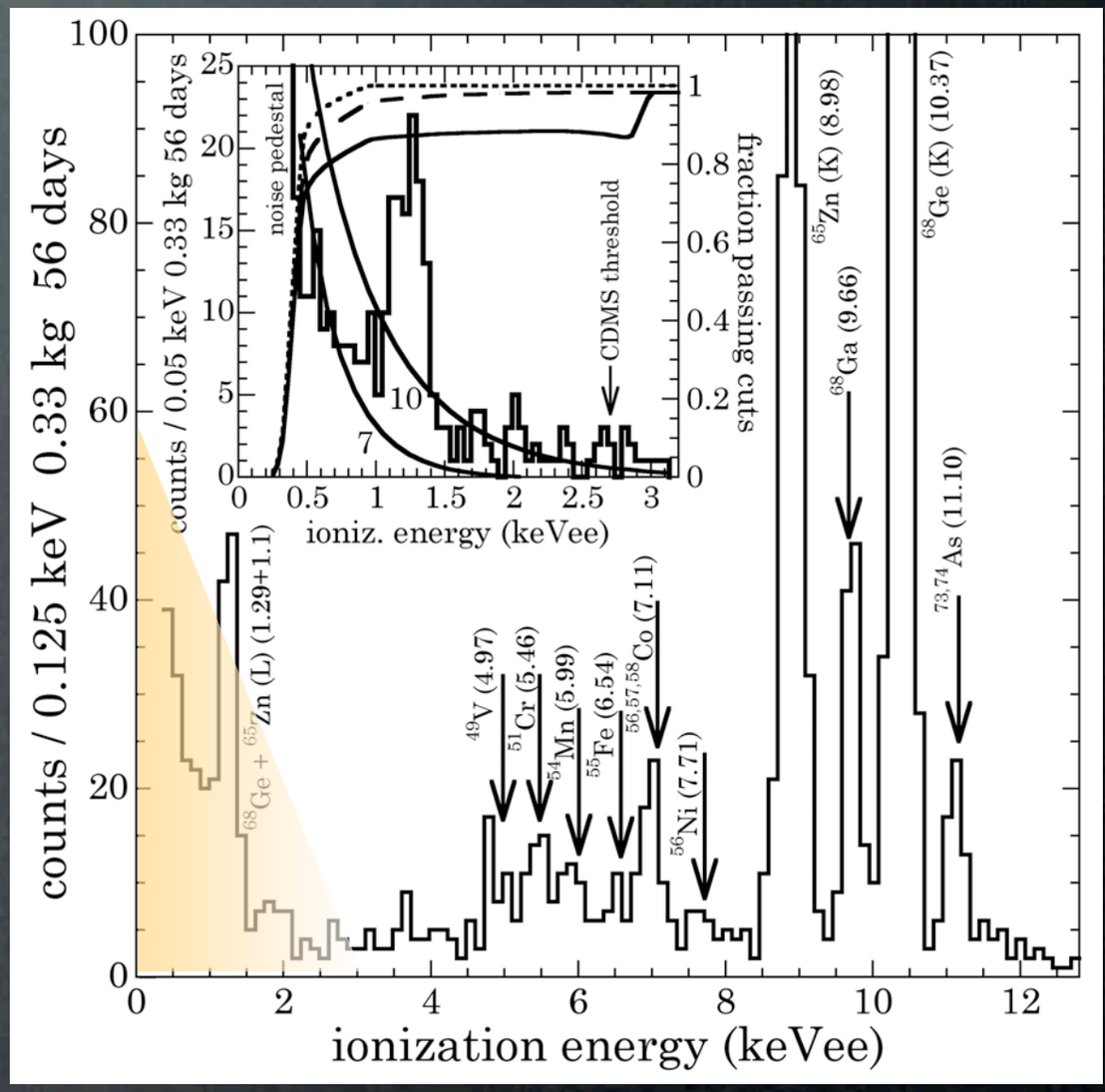


DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

CoGeNT

Ge

'irreducible excess of bulk events below 3 KeVee'

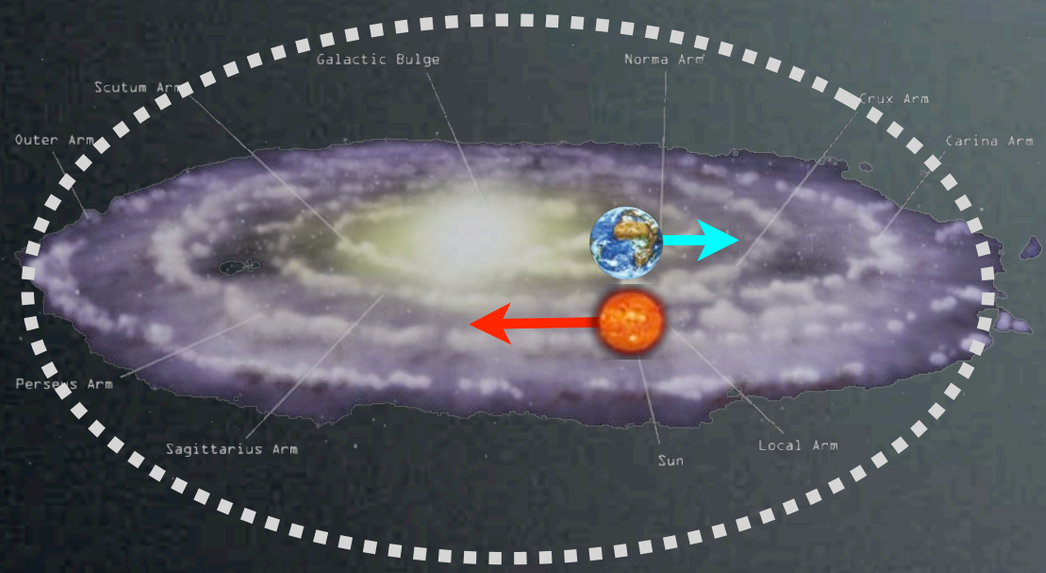


CoGeNT Coll., 1002.4703

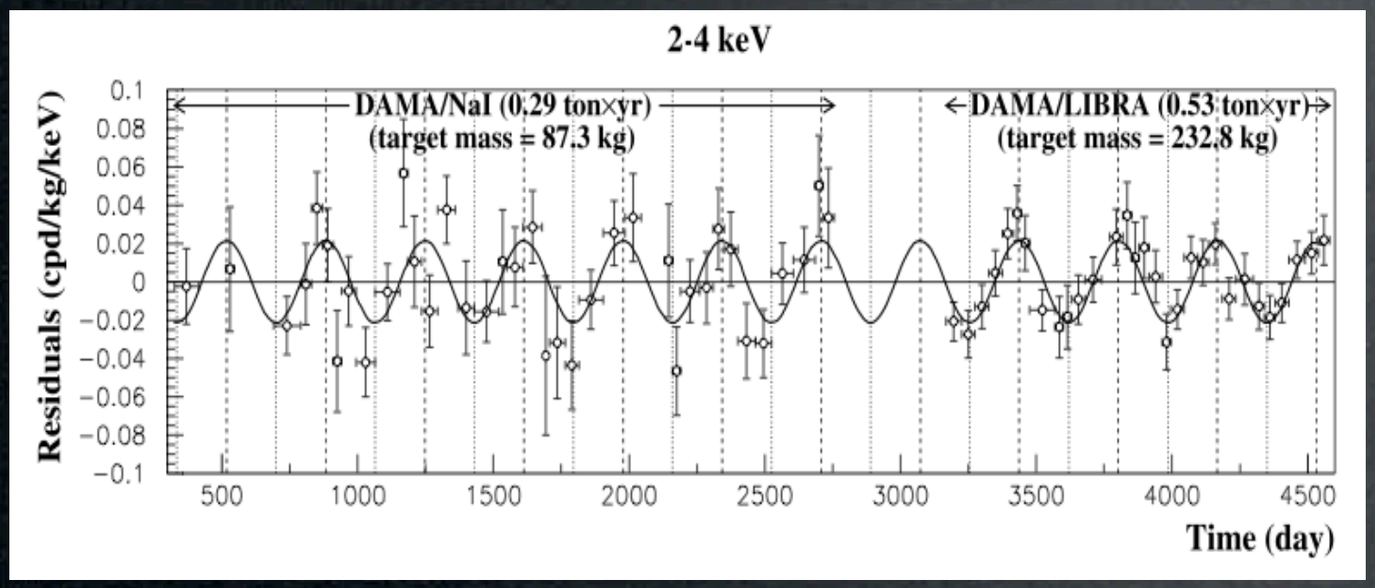
We lack a satisfactorily explanation [...]. It is tempting to consider a cosmological origin [...]. Prudence and past experience prompt us to continue work to exhaust less exotic possibilities.

Direct Detection: hints

DAMA/Libra



Annual modulation seen (9.3 σ):

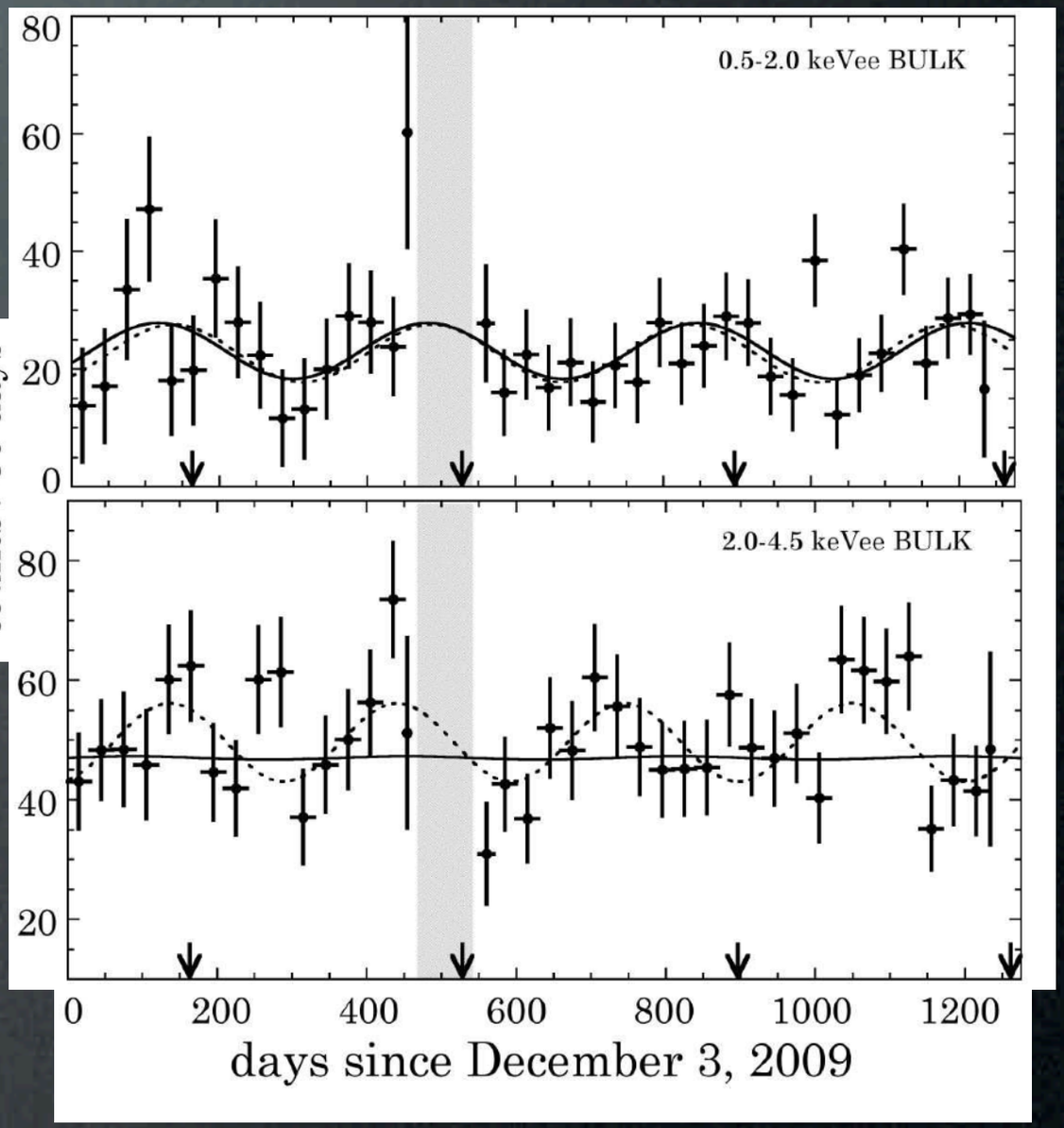


DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

CoGeNT

Ge

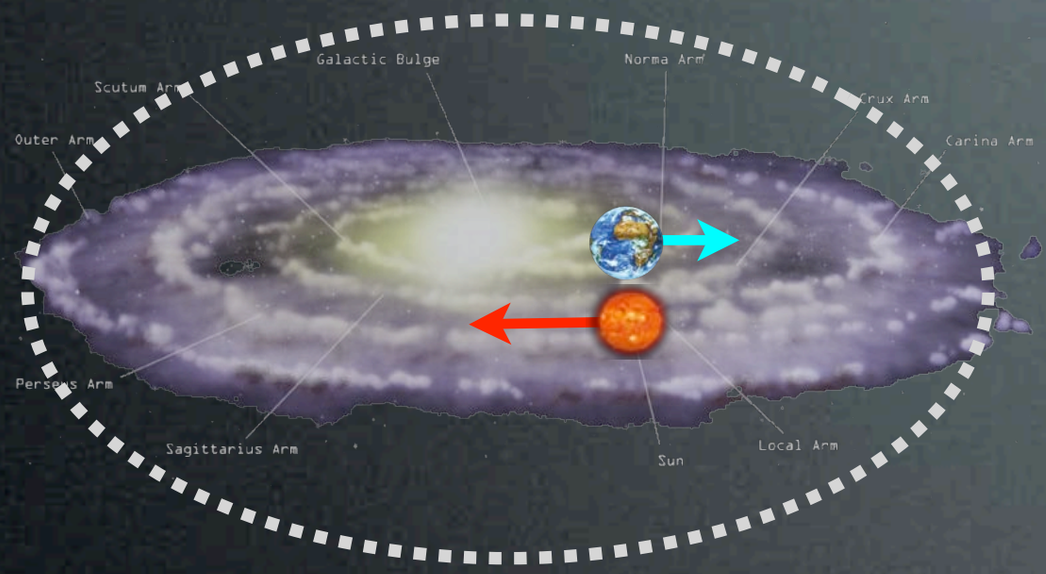
'annual modulation
at 2.2 σ significance'



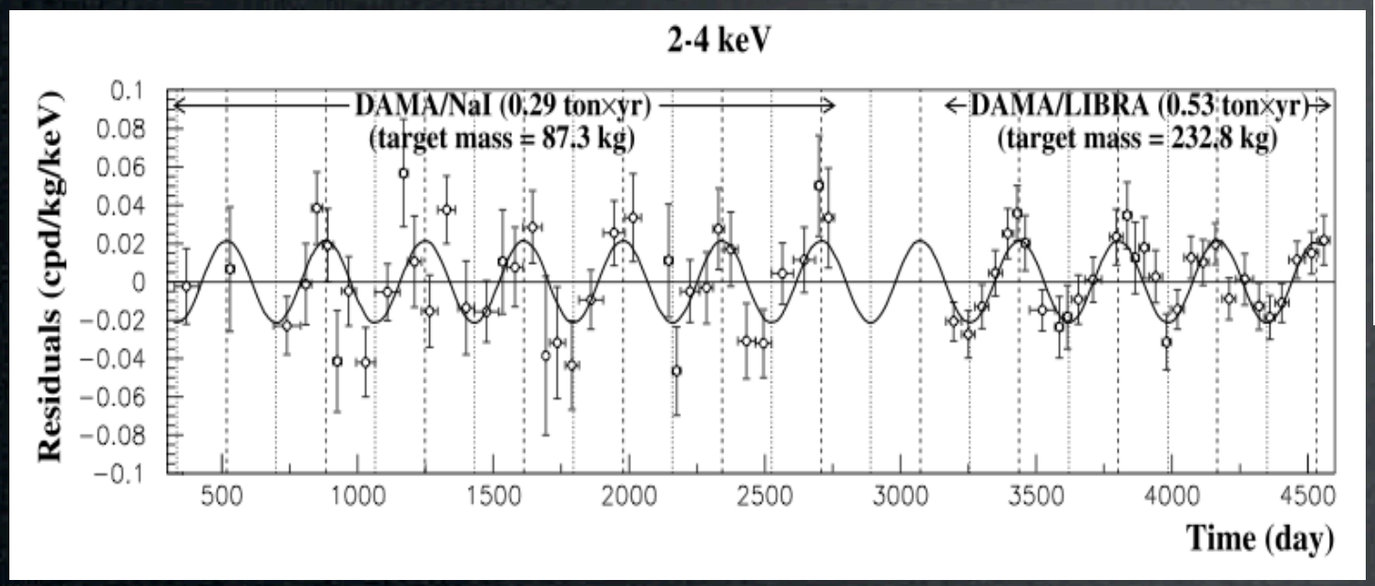
CoGeNT coll., 1401.3295

Direct Detection: hints

DAMA/Libra



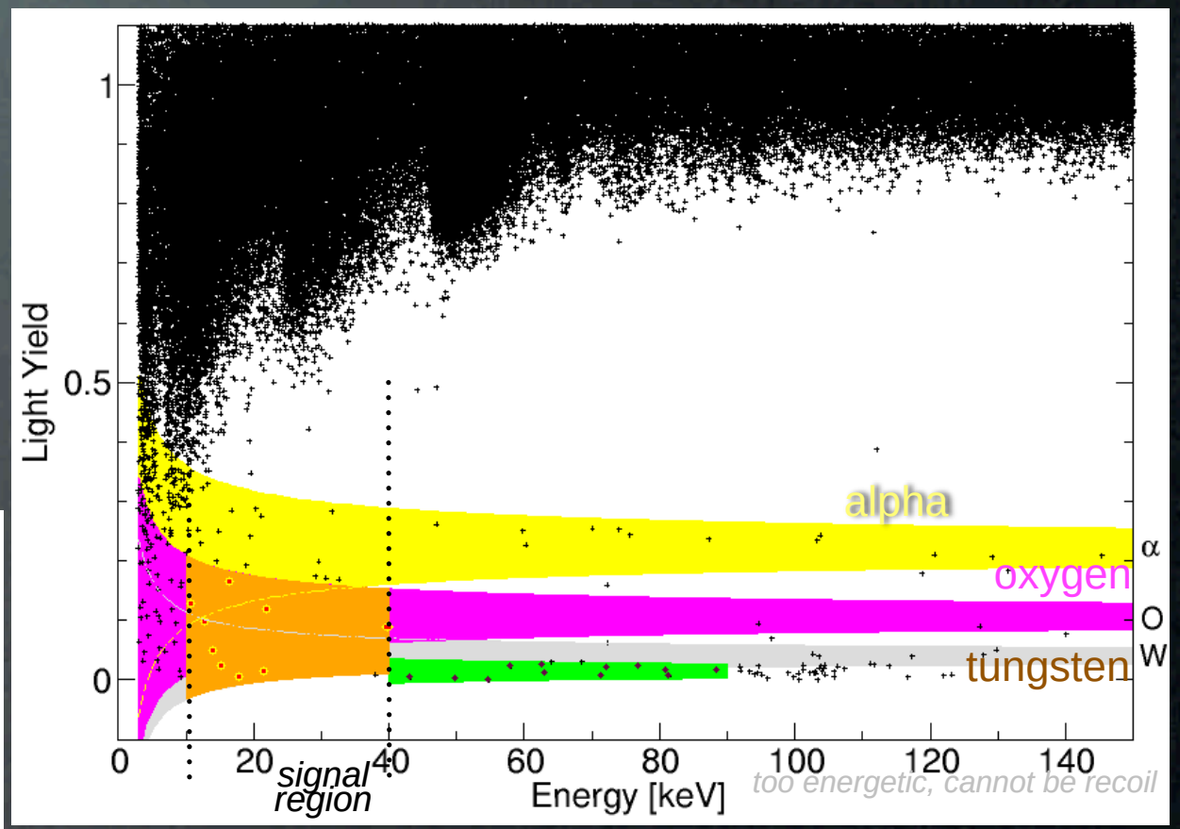
Annual modulation seen (9.3 σ):



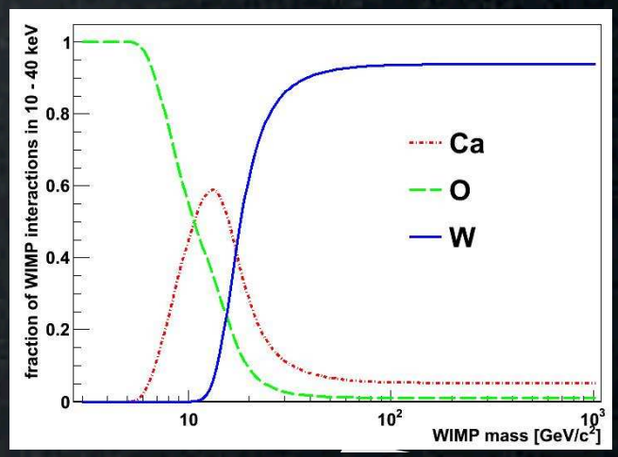
DAMA Coll., 0804.2741, 2008
+ DAMA/Libra 1308.5189

CRESST-II $CaWO_4$

67 events seen on Oxygen, twice the exp'd background



CRESST-II Coll., 1109.0702



Theorist's reaction

3. the 'light DM' fit-olympics

Direct Detection: hints

Plotolympics 2011: fits performed by different groups

Belli+Fornengo+al., 1106.4667

Farina+Pappadopulo+Strumia+ Volansky, 1107.0715

Arina+Hamann+Wong, 1105.5121

(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.2721

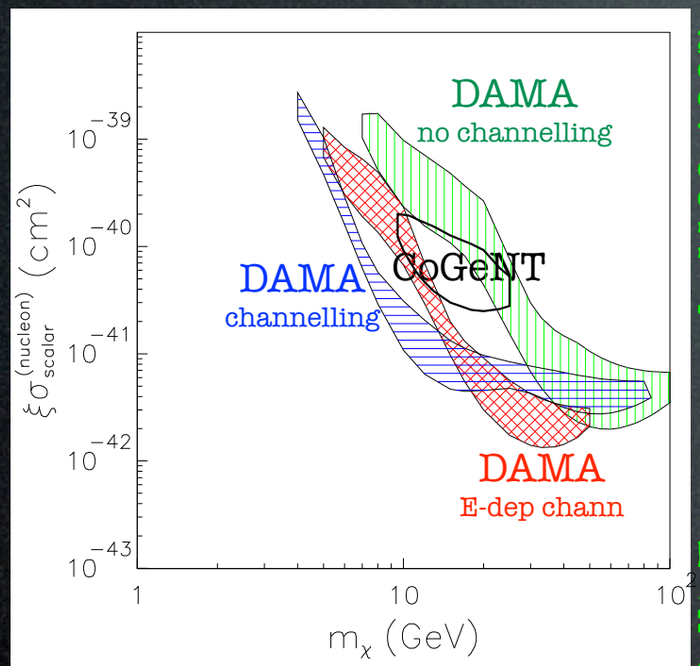
Hooper+Kelso, 1106.1066

Space available
Call 911-drk-mttr now!

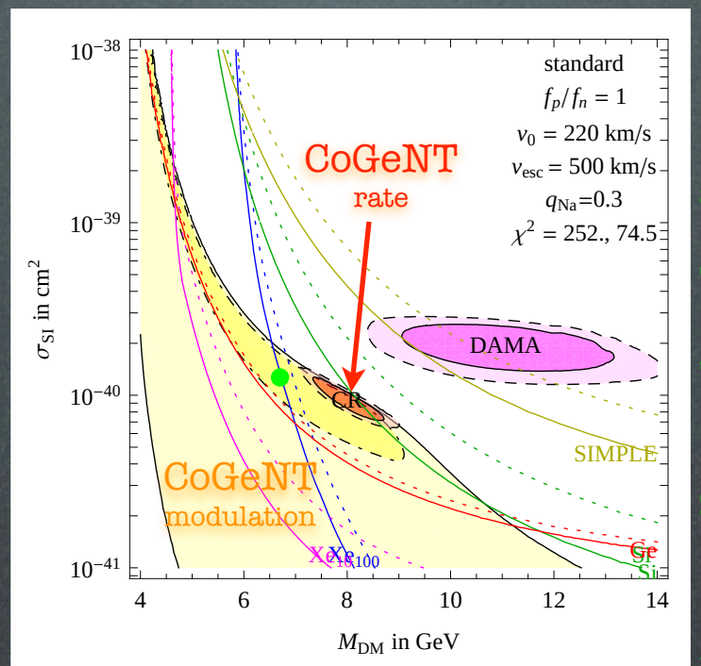
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

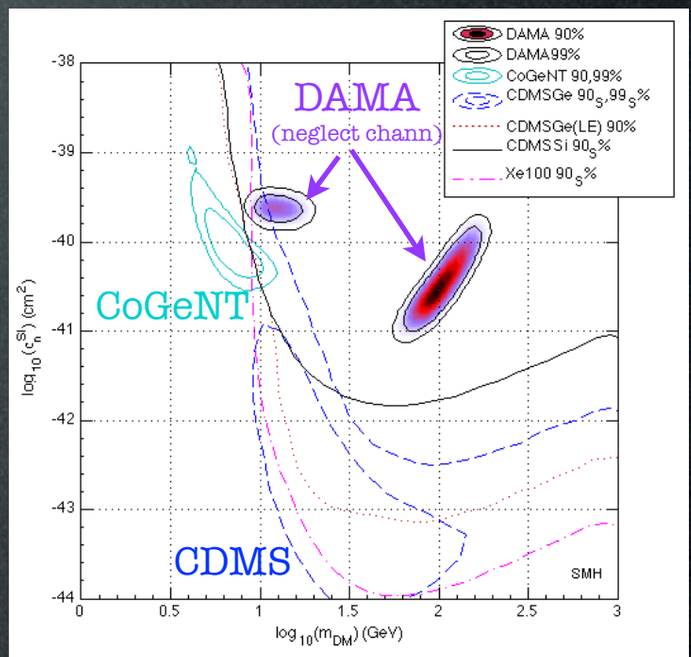
Discipline: Standard Fit: SI, standard halo



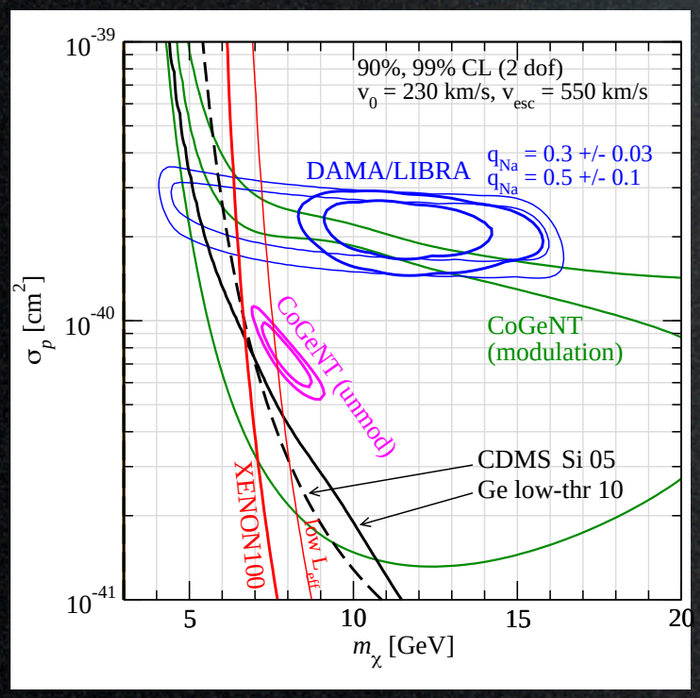
Belli+Fornengo+al., 1106.4667



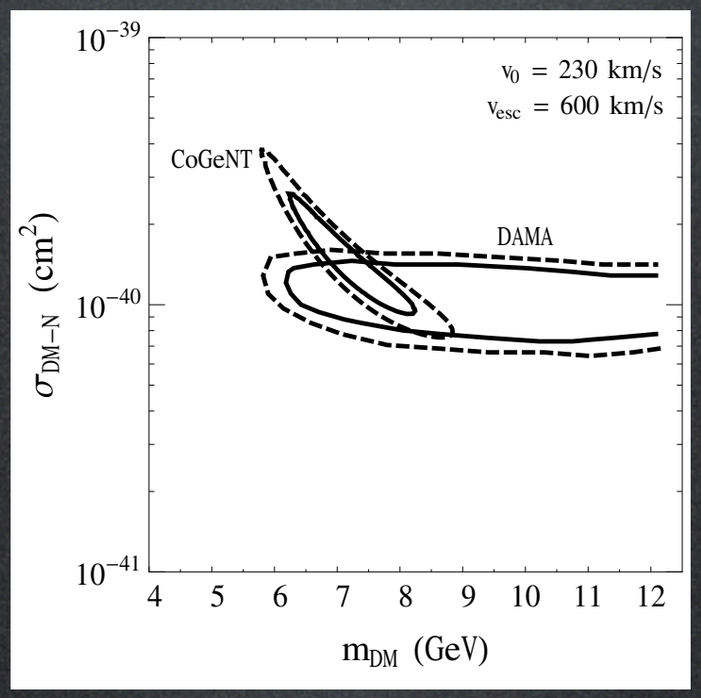
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

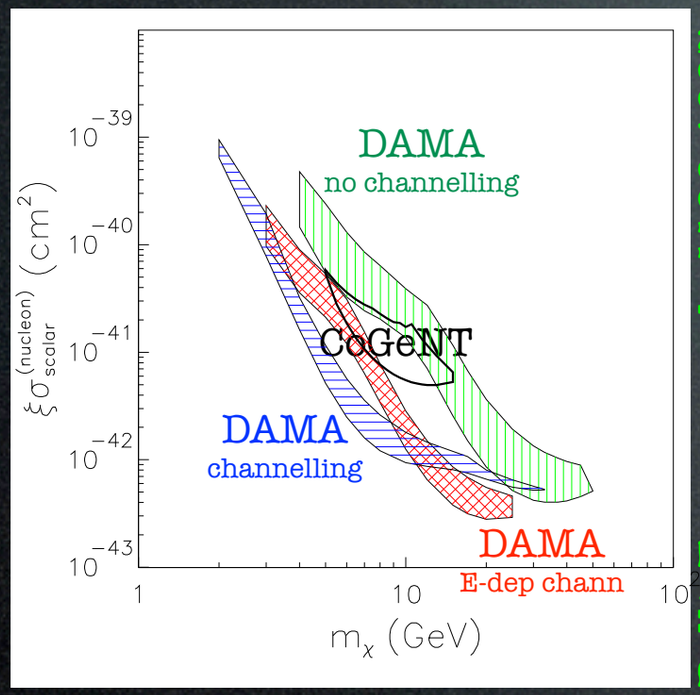
Comments:

- the ballparks agree, but the individual regions differ
  [do not ask me why]
- DAMA and CoGeNT overlap or not???

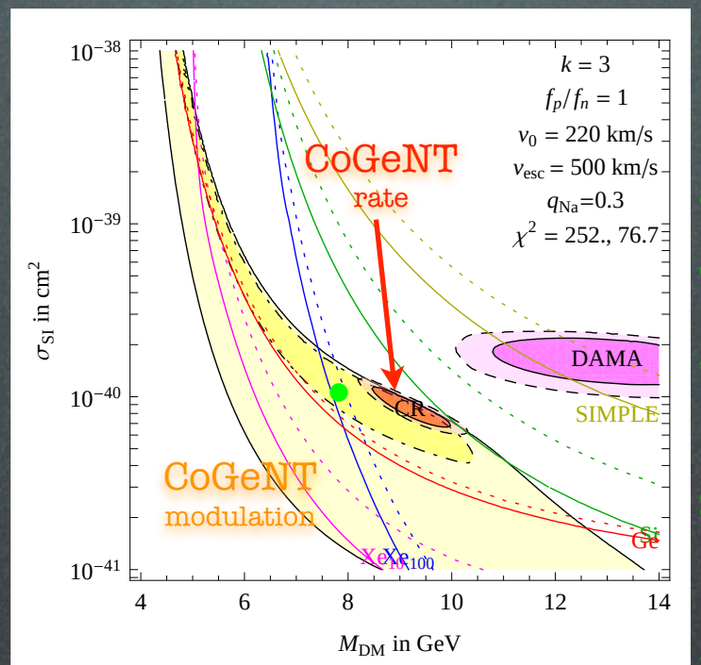
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

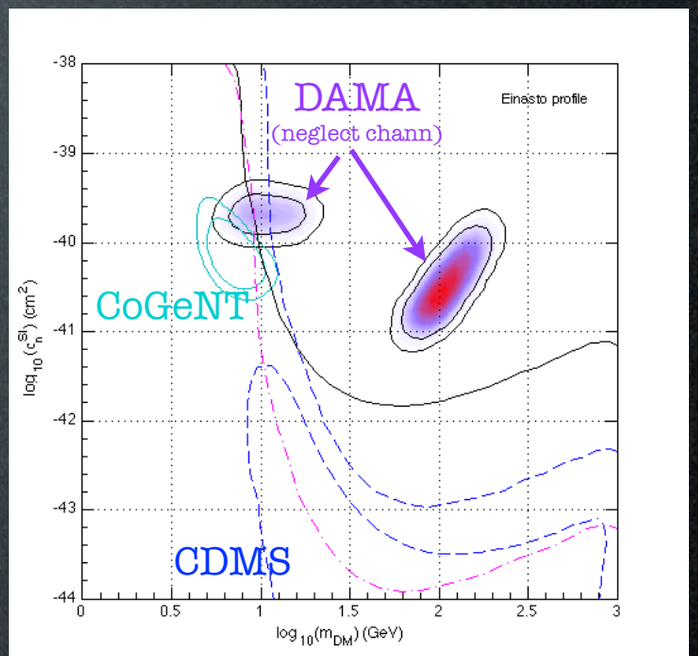
Discipline: Astro Fit: modifying velocity distrib, local density, profile...



Belli+Formengo+al., 1106.4667



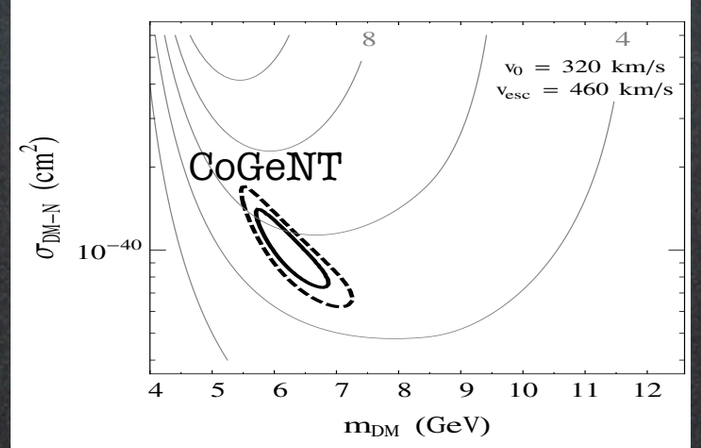
Farina+Pappadopulo+Strumia+ Volansky, 1107.0715



Arina+Hamann+Wong, 1105.5121

Boycott

(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.



Hooper+Kelso, 1106.1066

Comments:

- not big quantitative change

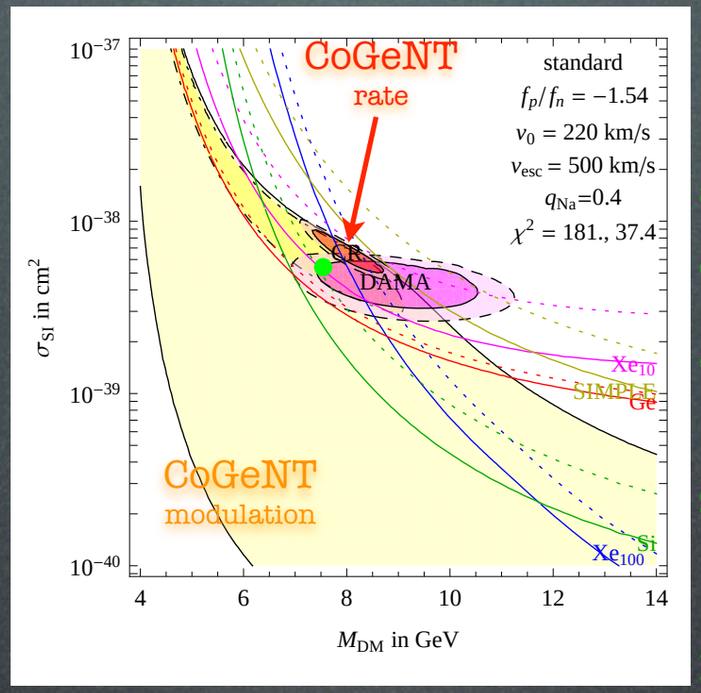
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

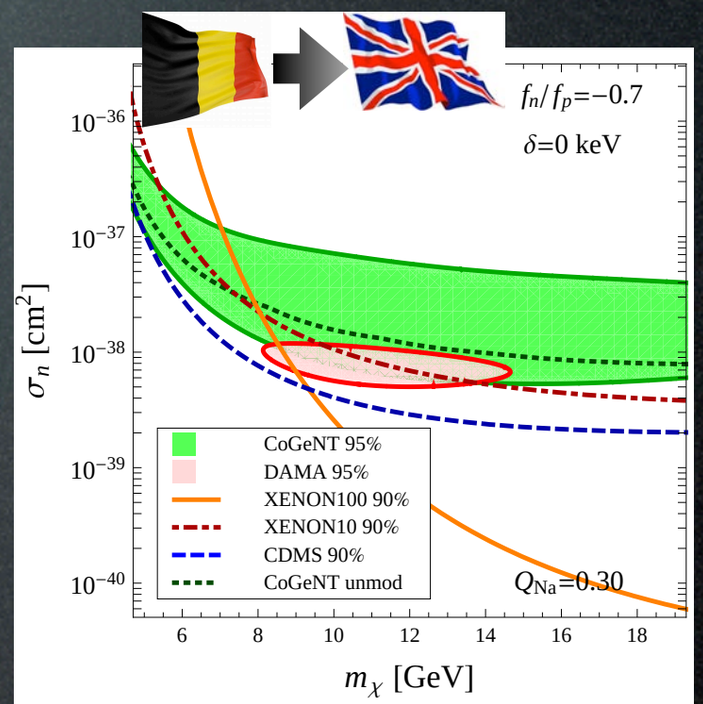
Discipline: Isospin Fit: assuming different coupling to **p** and **n**...

Boycott

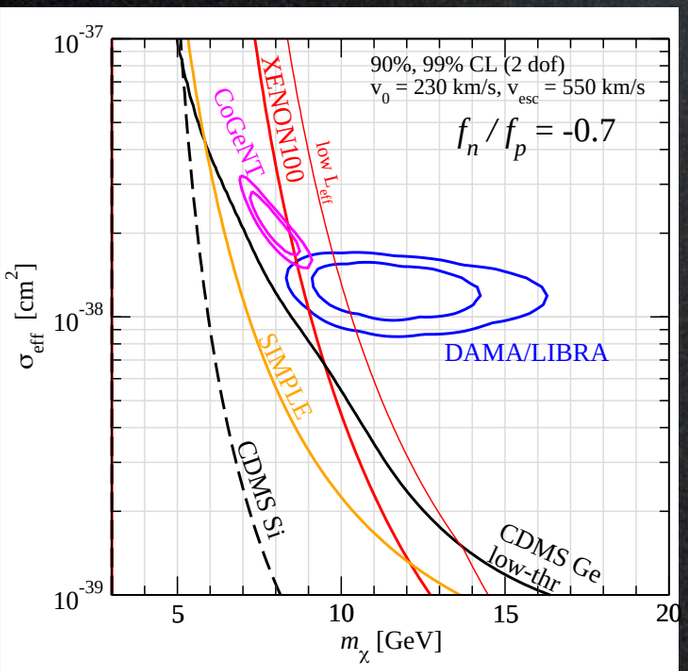
Belli+Bernabei+Cerulli+Formengo+al., 1106.4667



Farina+Pappadopulo+Strumia+Tenkanen+Tucker-Smith+Urbano+Xue, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

Not qualified

Hooper+Kelso, 1106.1066

Comments:

- those who dared to try find some improvement

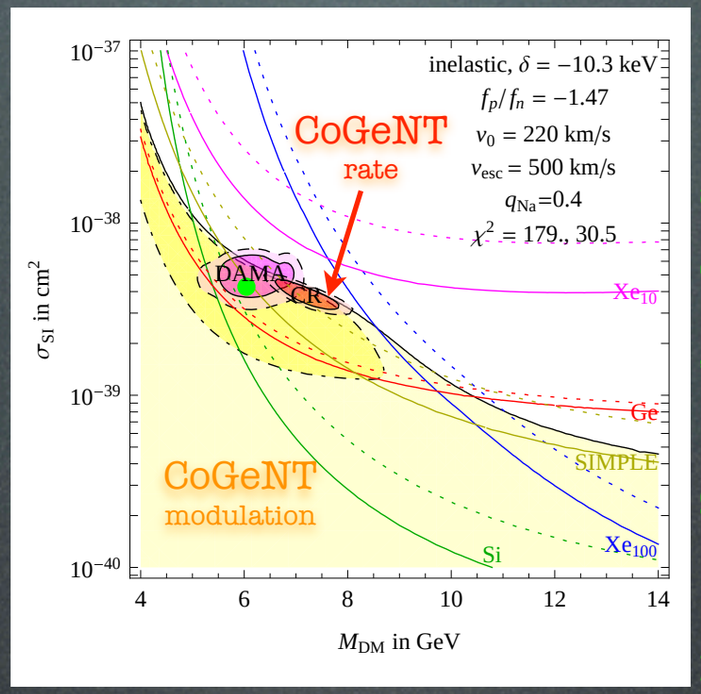
Direct Detection: hints

Plotolympics 2011: fits performed by different groups

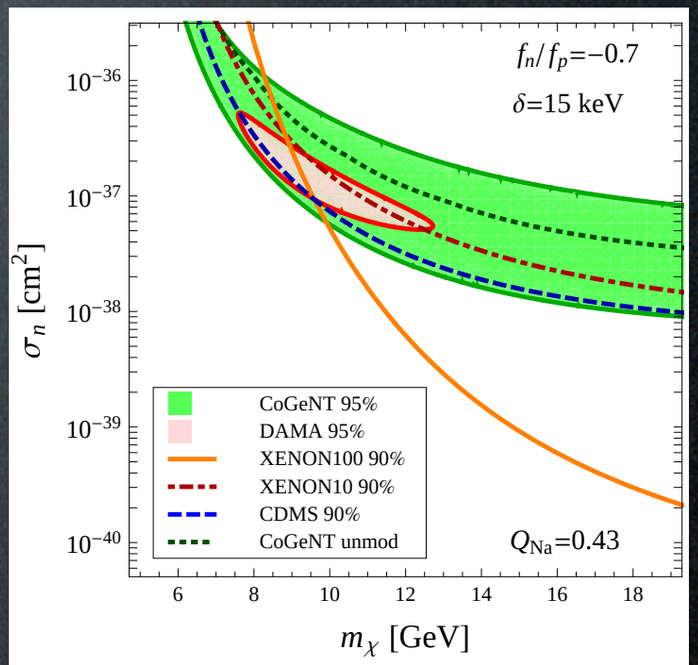
Discipline: Isospin & Inelastic Fit: different coupling + inelastic scatt

Boycott

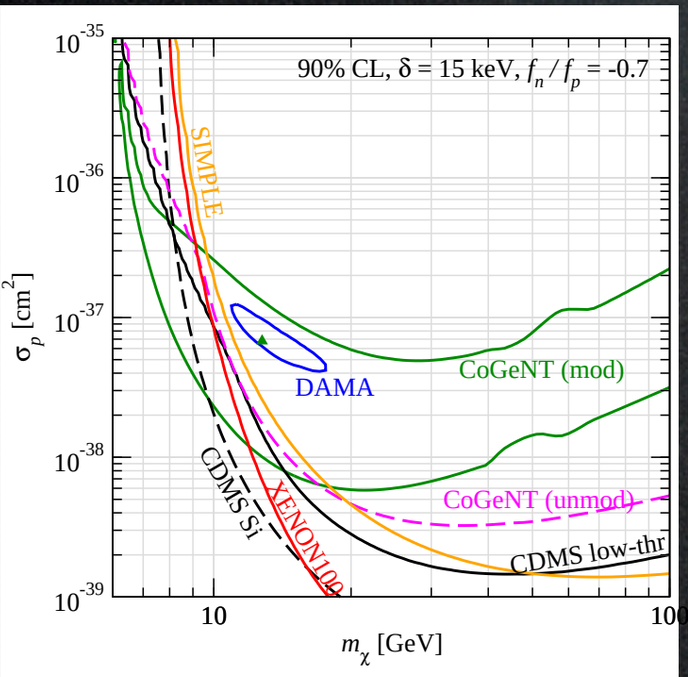
Belli+Fornengo+al., 1106.4667



Farina+Pappadopulo+Strumia+Volansky, 1107.0715



Frandsen+Kahlhoefer+al., 1105.3734



(Kopp+)Schwetz+Zupan, 1106.6241 & 1110.

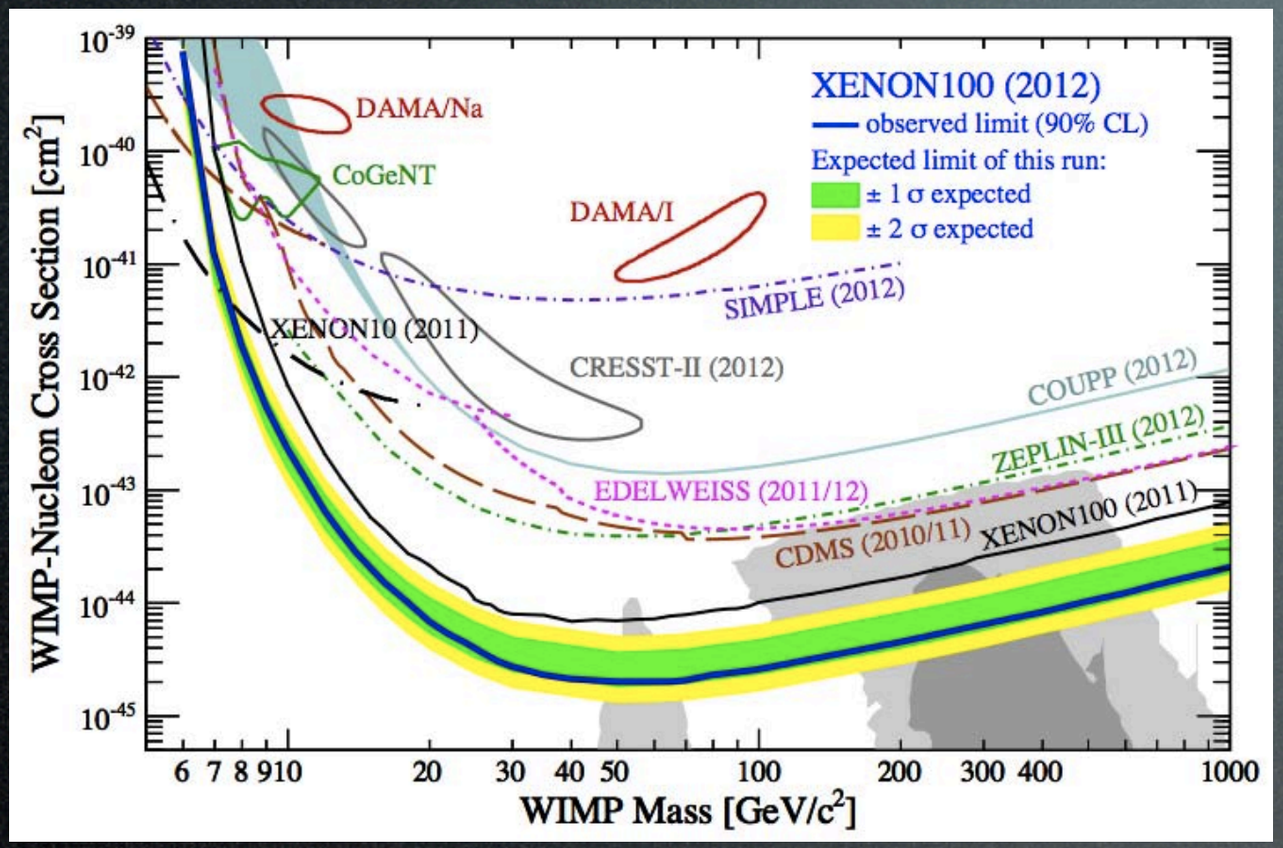
Not qualified

Hooper+Kelso, 1106.1066

Comments:

- those who dared to try find some **more** improvement

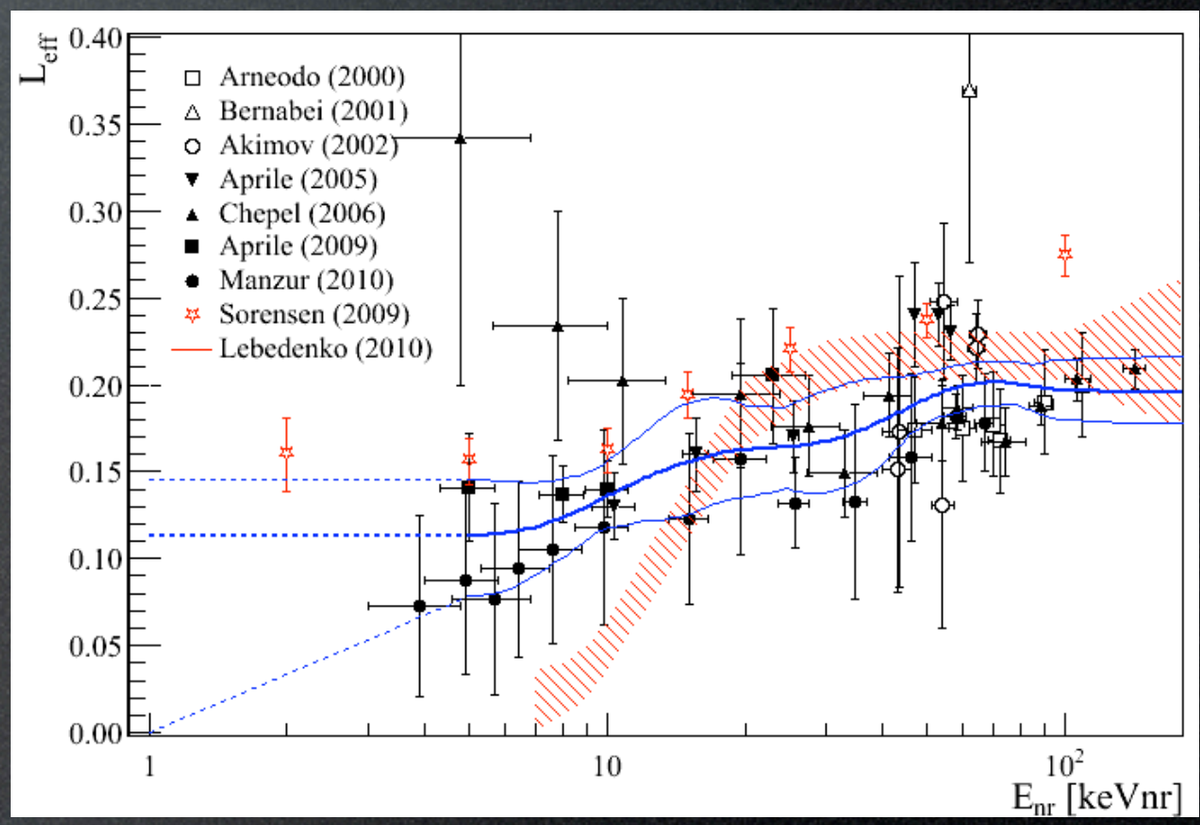
Direct Detection: constraints



Xenon 100 XENON 100 Coll., 1207.5988

225 live days
2 events seen
(1.0 exp'd bkgd)

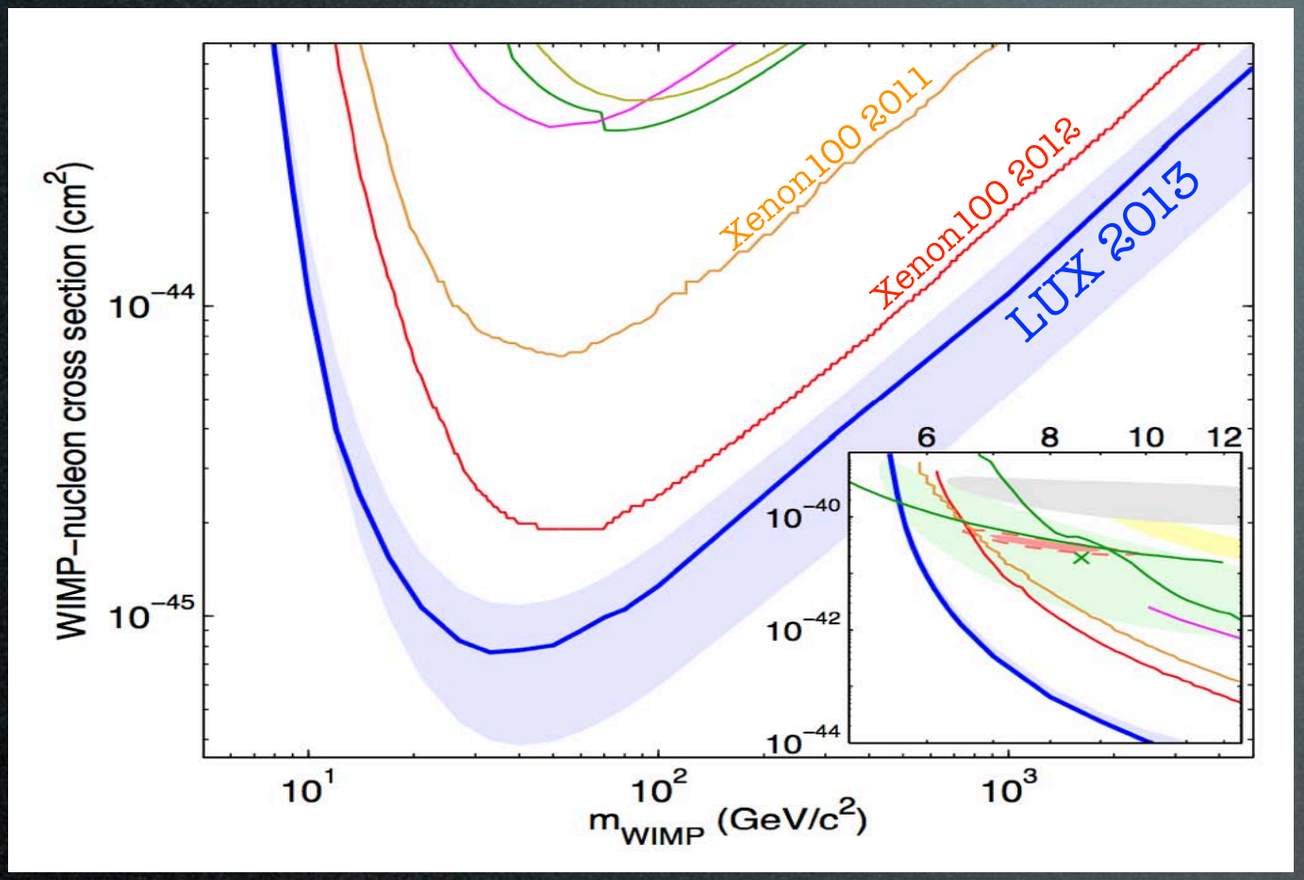
scintillation efficiency in LXe



XENON 100 Coll., 1005.2615

ferocious criticism in
Collar & McKinsey, 1005.0838v1, v2, v3

Direct Detection: constraints

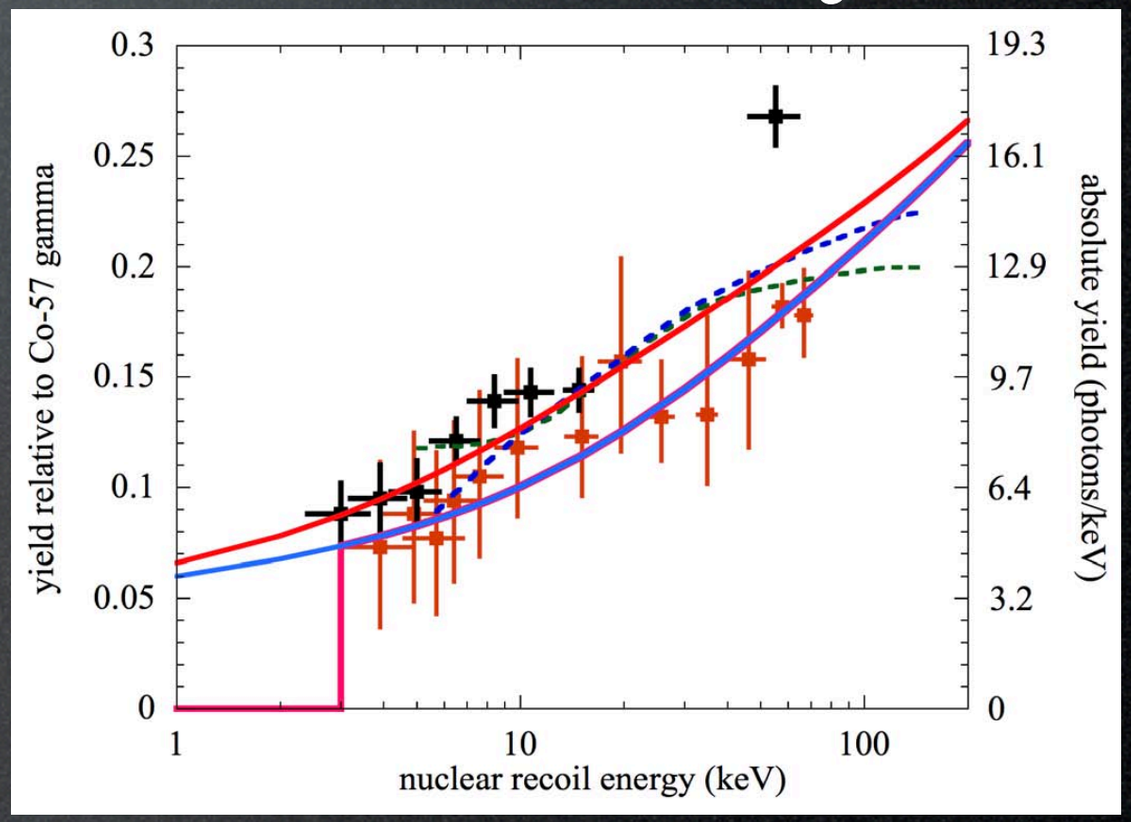


LUX

LUX Coll., 1310.8214

85 live days

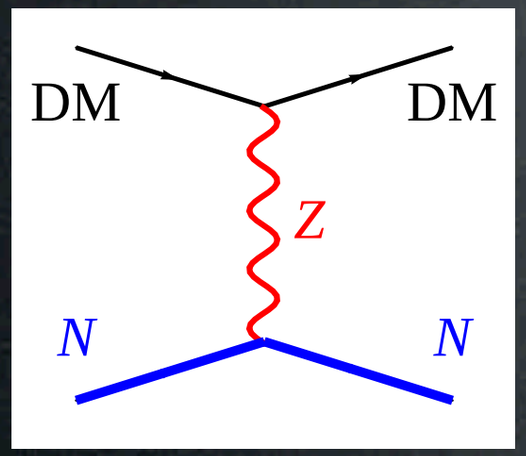
scintillation efficiency in LXe



R.Gaitskell, LUX Coll., talk at SURF on 30/10/2013

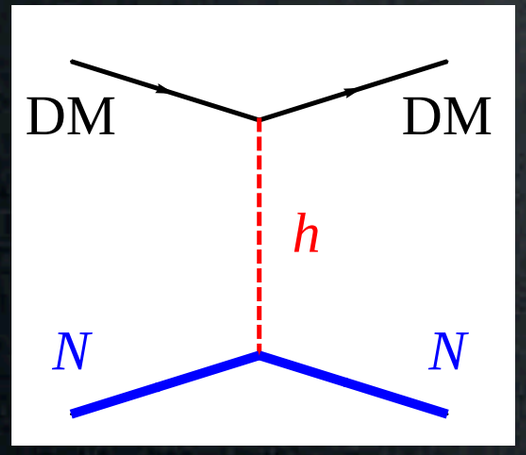
Direct Detection: '**theory**'

SM weak scale SI interactions



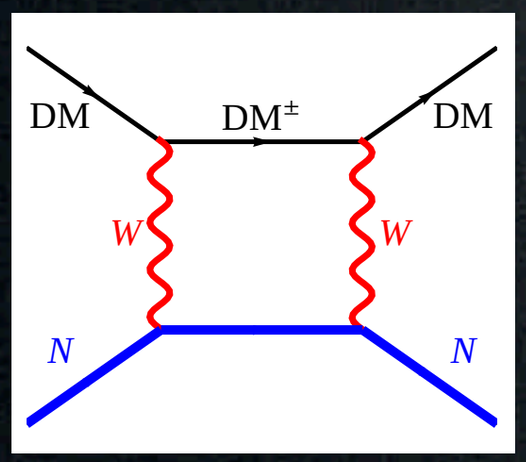
tree level, vector

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^2}{M_Z^4}$$



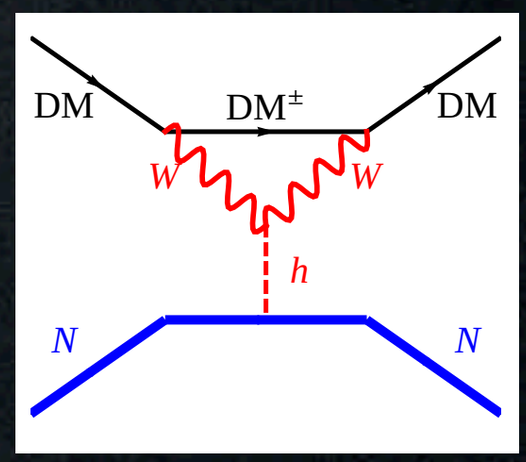
tree level, scalar

$$\sigma_{\rm SI} \sim \frac{\alpha^2 \ m_N^4}{M_h^6}$$



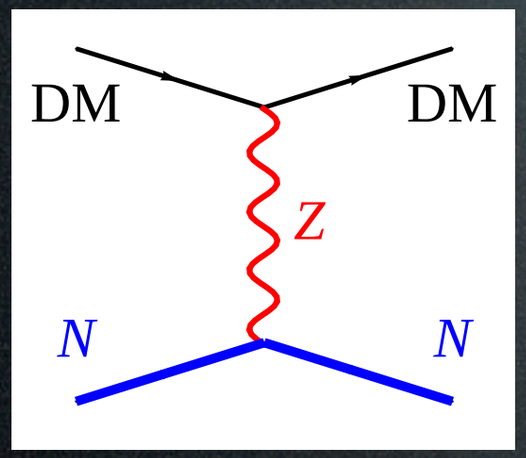
one loop

$$\sigma_{\rm SI} \sim \frac{\alpha^4 \ m_N^4}{M_W^6}$$

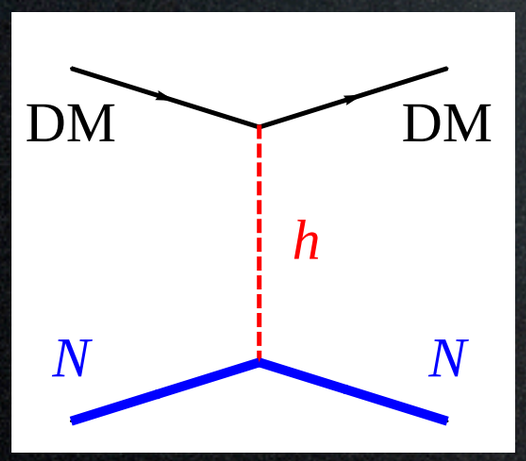


Direct Detection: 'theory'

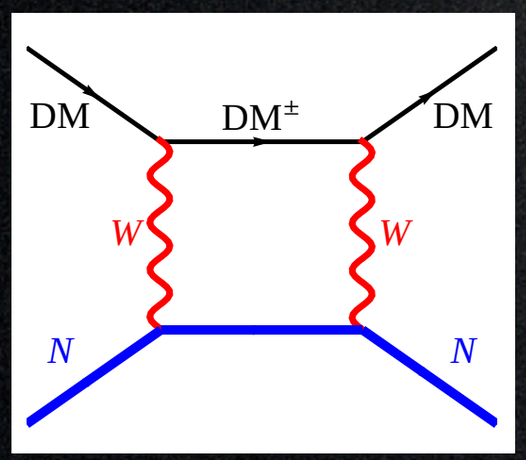
SM weak scale SI interactions



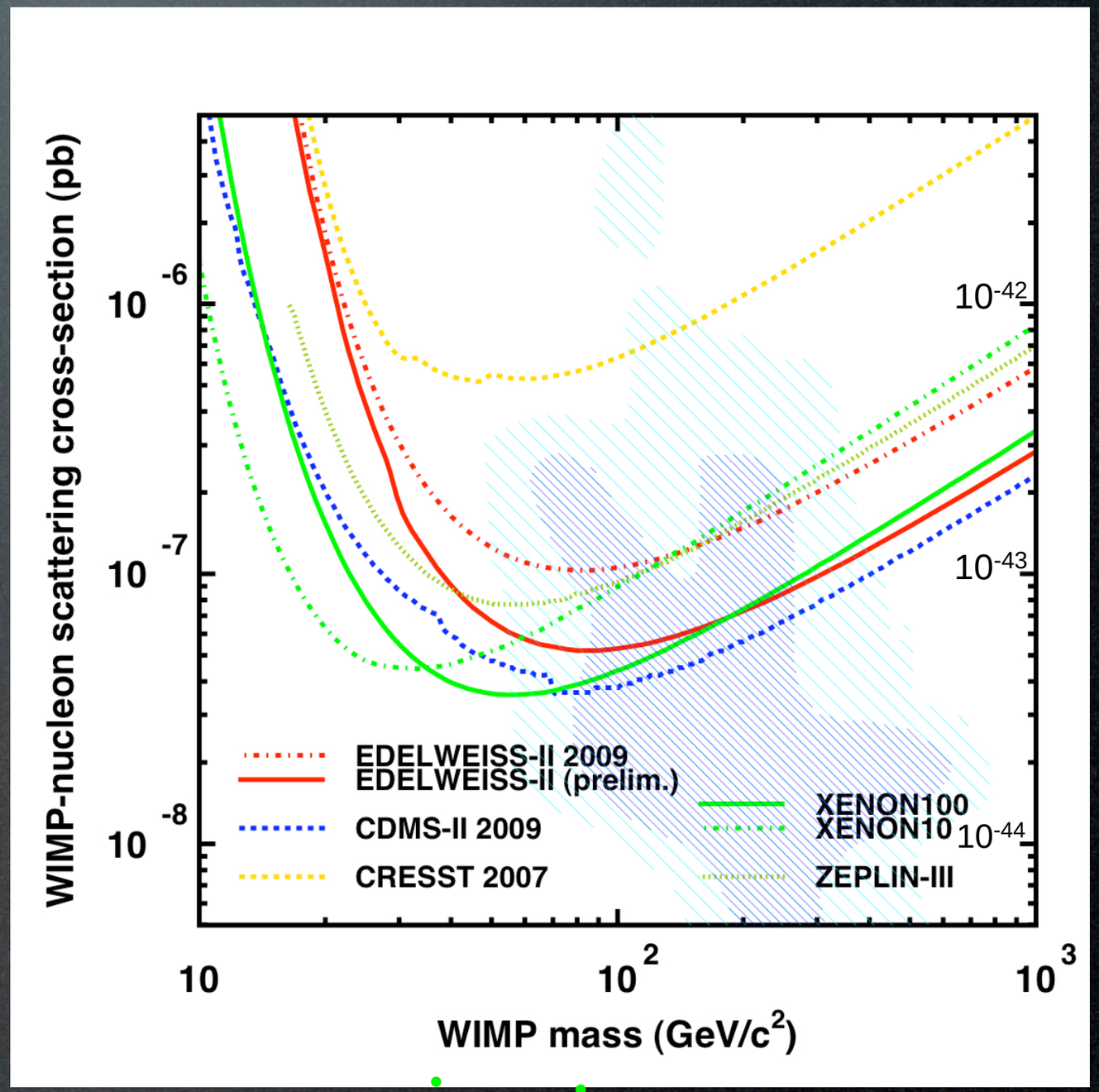
tree level, vector



tree level, scalar

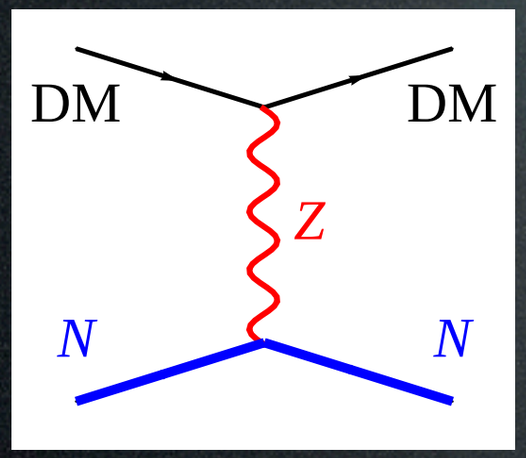


one loop

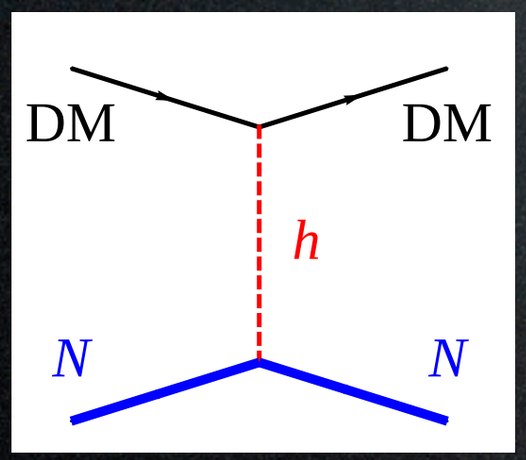


Direct Detection: 'theory'

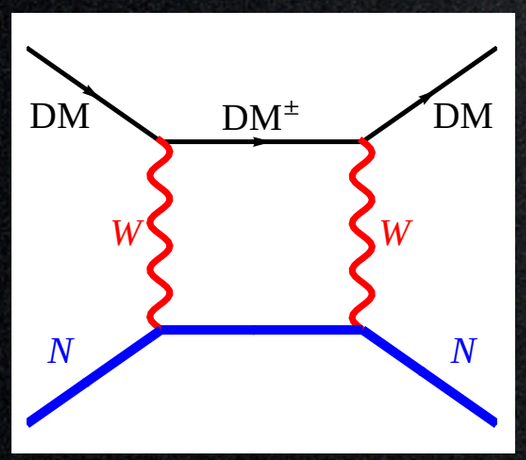
SM weak scale SI interactions



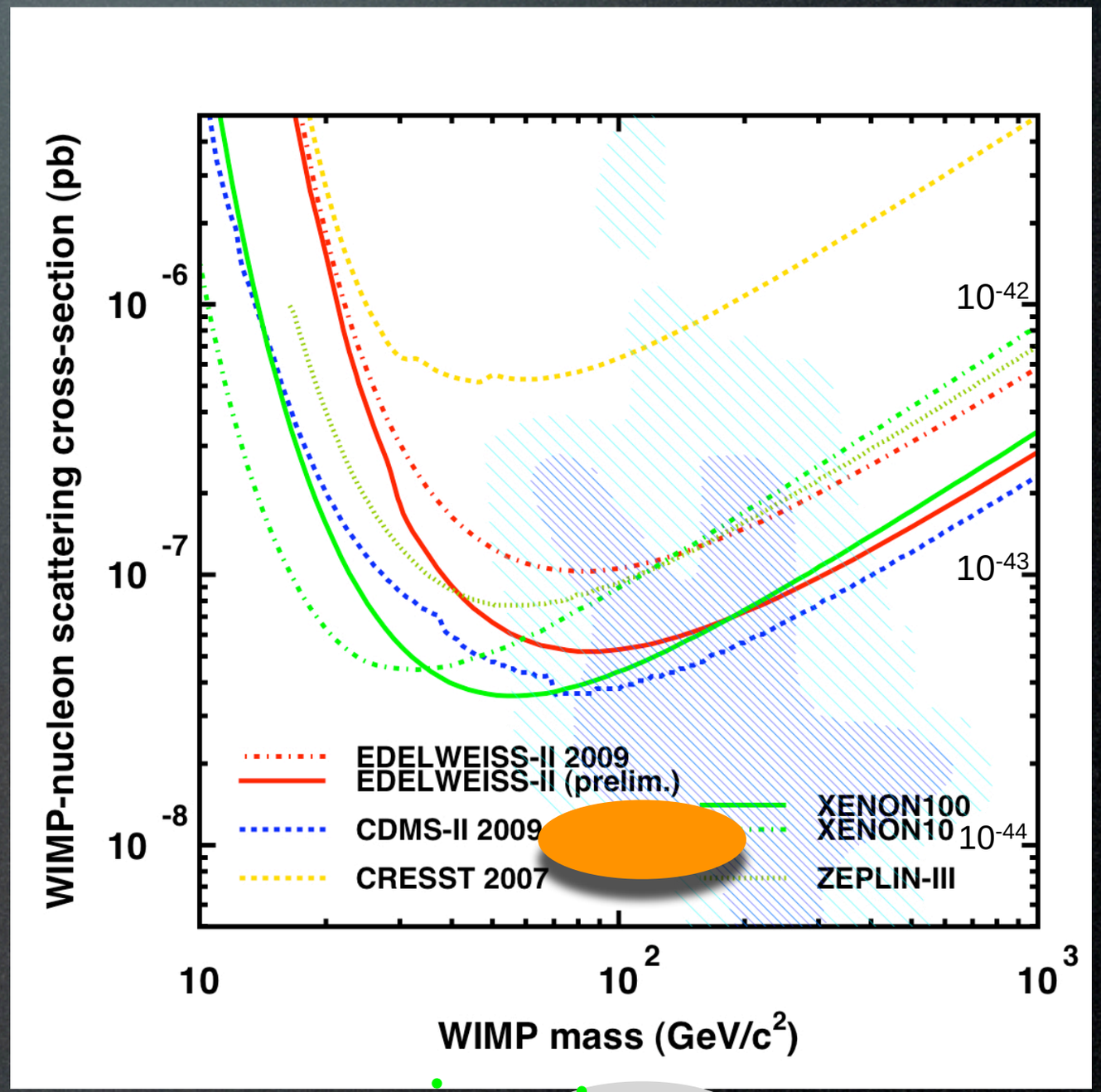
tree level, vector



tree level, scalar

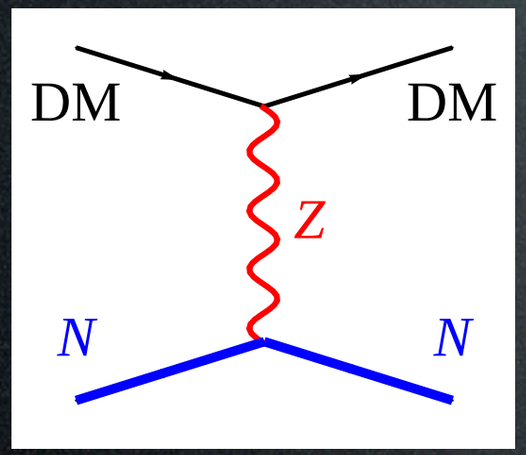


one loop



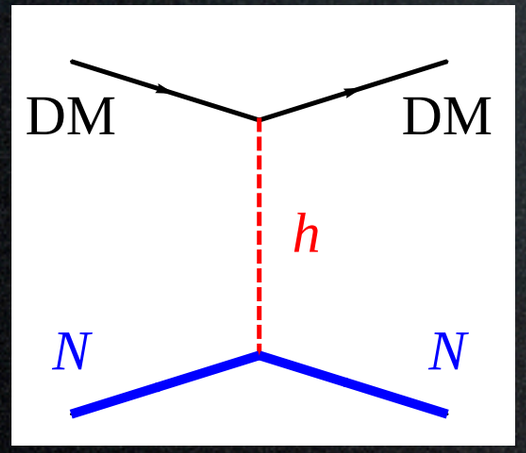
Direct Detection: 'theory'

SM weak scale SI interactions

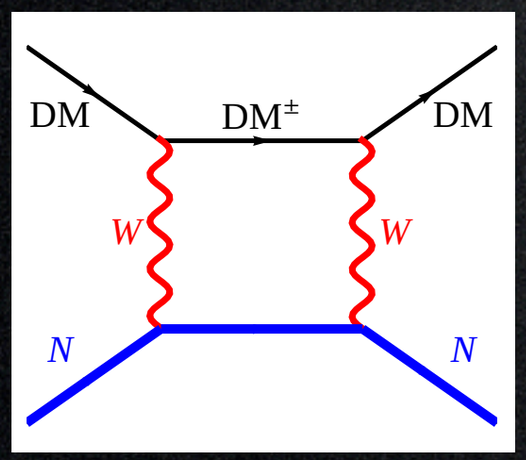


tree level, vector

Still viable under which conditions?



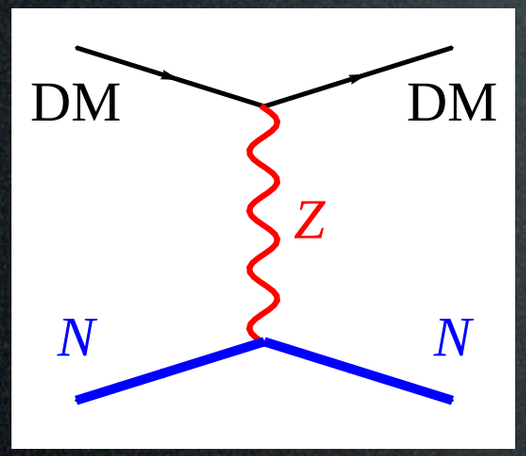
tree level, scalar



one loop

Direct Detection: 'theory'

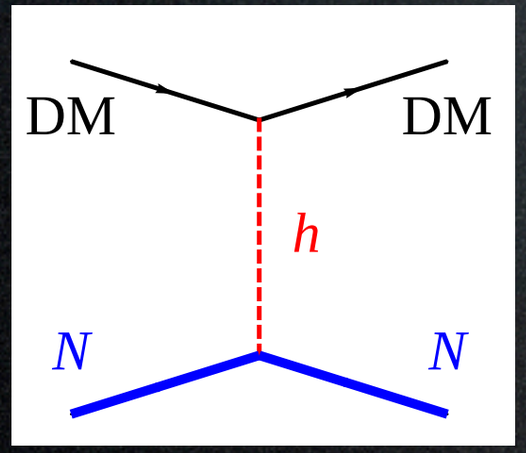
SM weak scale SI interactions



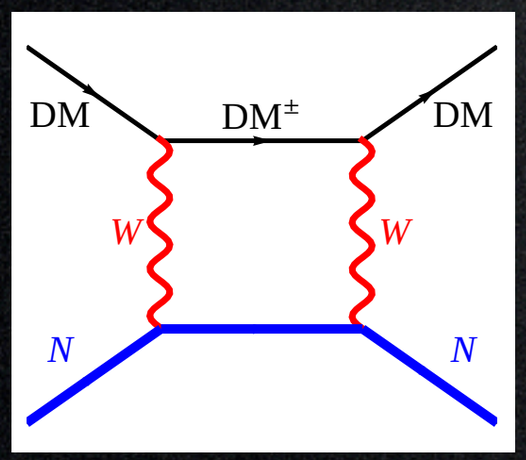
~~tree level, vector~~

Still viable under which conditions?

- real particle
  (Majorana fermion, real scalar)



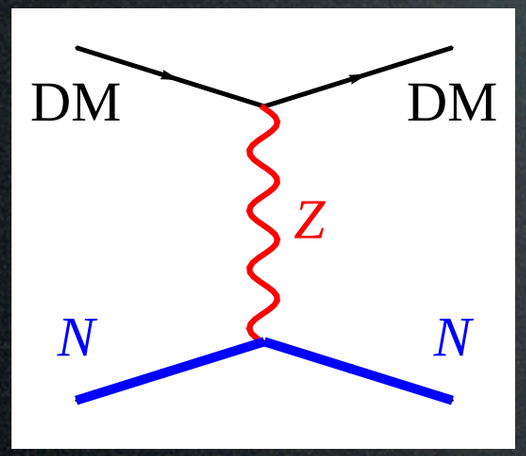
tree level, scalar



one loop

Direct Detection: 'theory'

SM weak scale SI interactions



tree level, vector

Still viable under which conditions?

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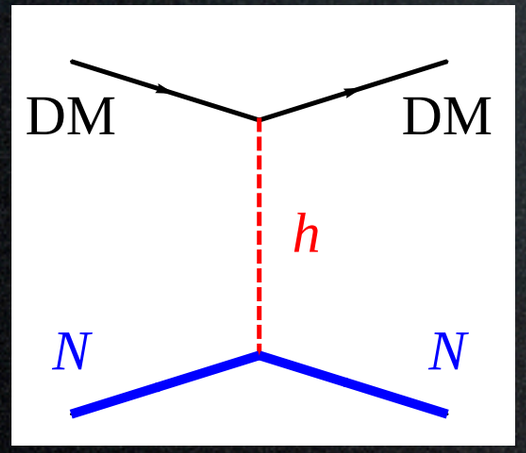
  (Majorana fermion, real scalar)



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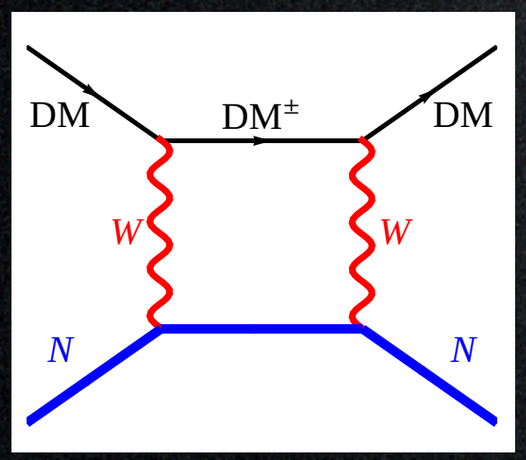

one loop

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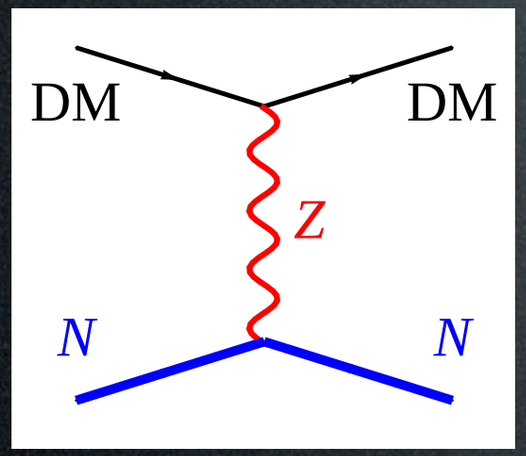

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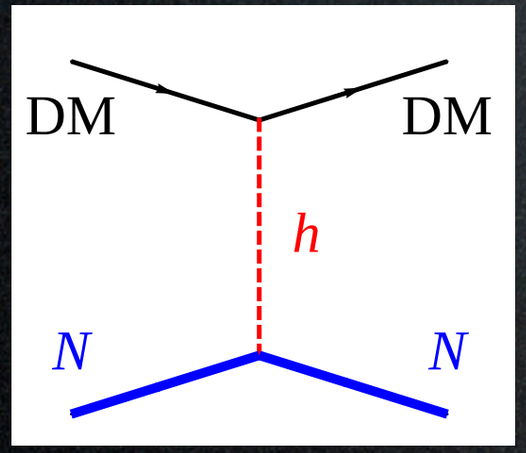

tree level, scalar

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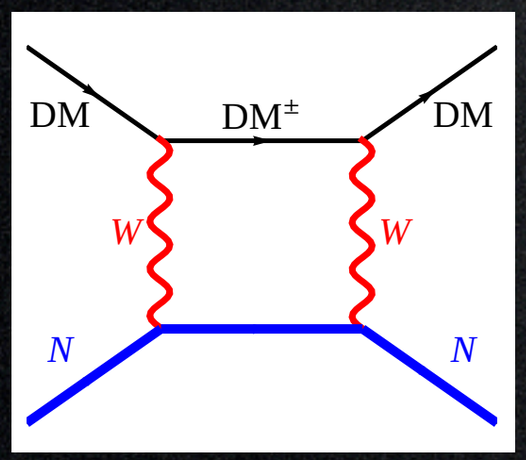
- inelastic scattering



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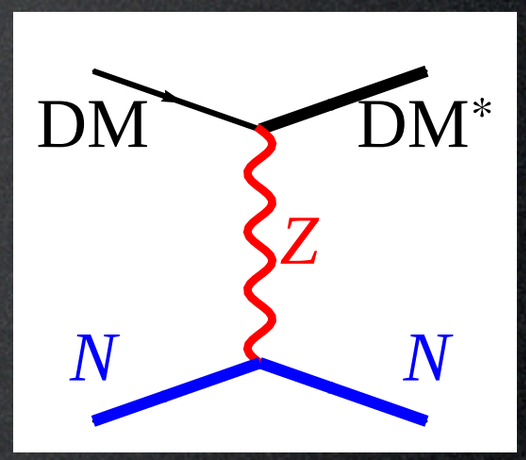

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