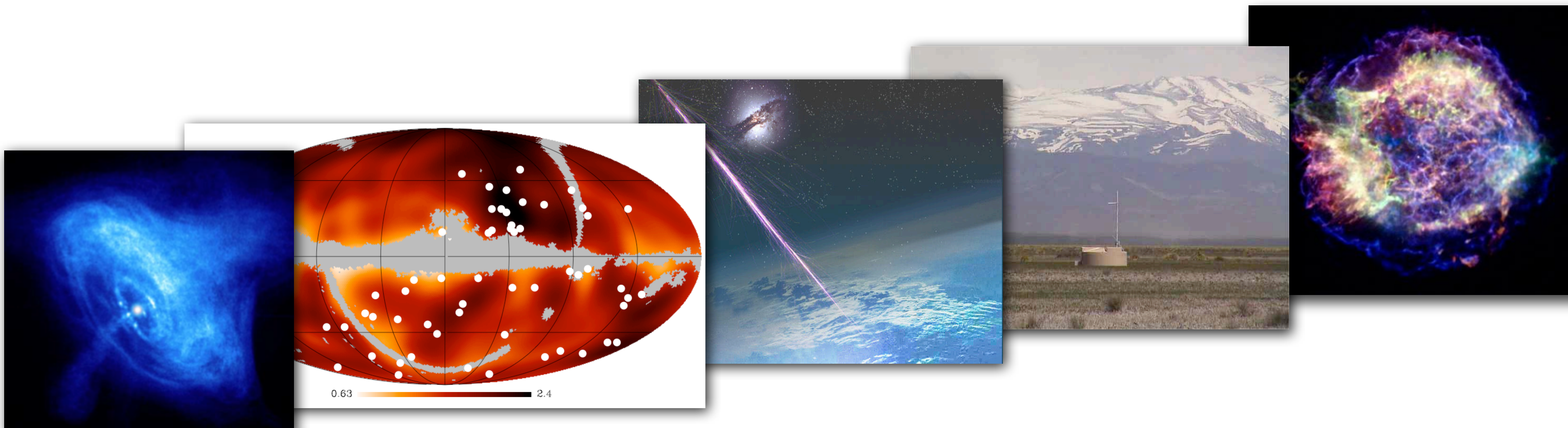
Ultrahigh energy cosmic rays, pulsars, and supernovae

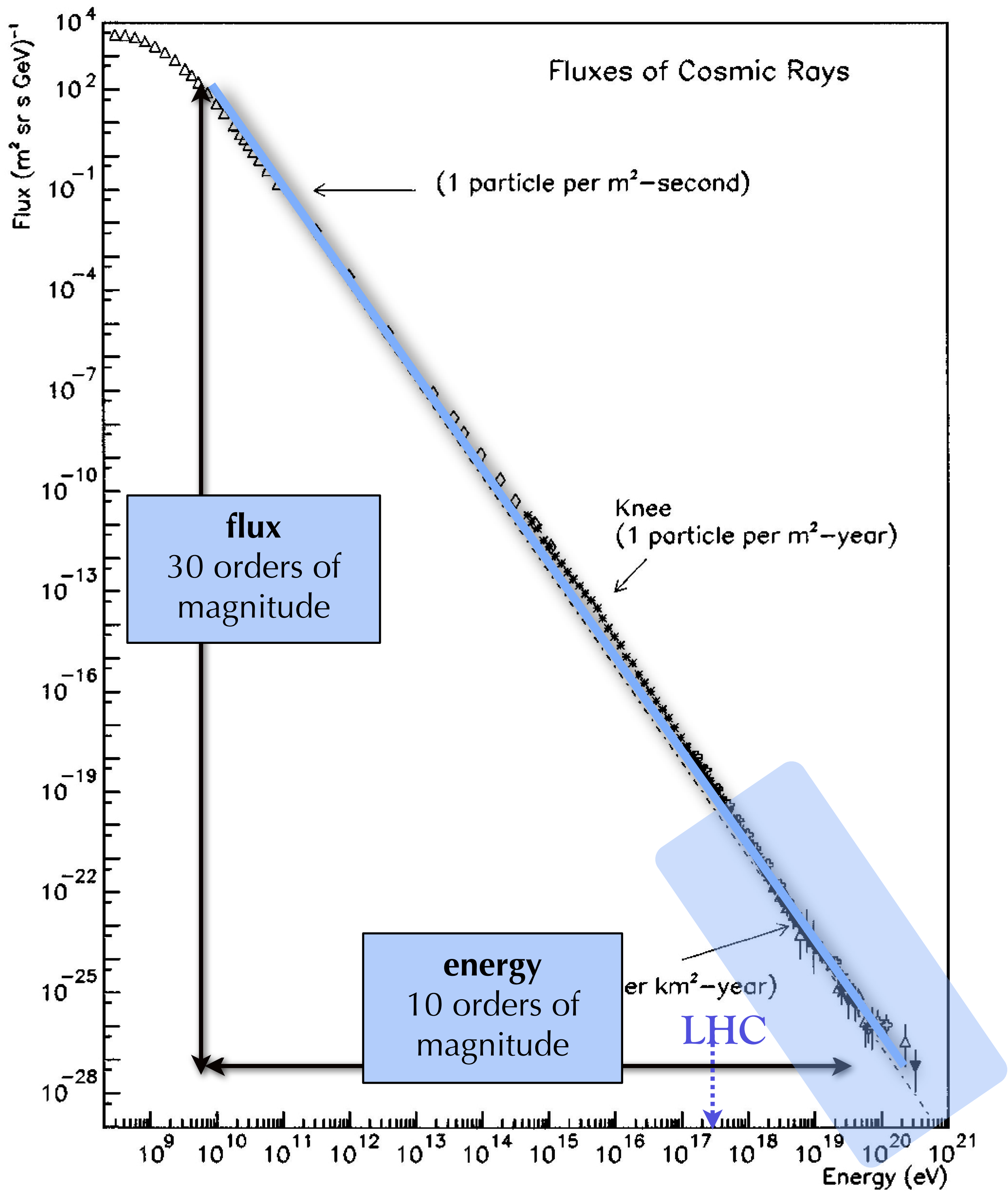


Kumiko Kotera

Institut d'Astrophysique de Paris

IAP Colloquium - 11/05/12

The puzzle of ultrahigh energy cosmic rays



Why do we care about cosmic-rays?

Energies that cannot be reproduced on Earth!
Universe thru different eyes

The puzzle:

What source(s)?
What physical mechanism(s)?

Why is it so difficult?

Astrophysical issues:

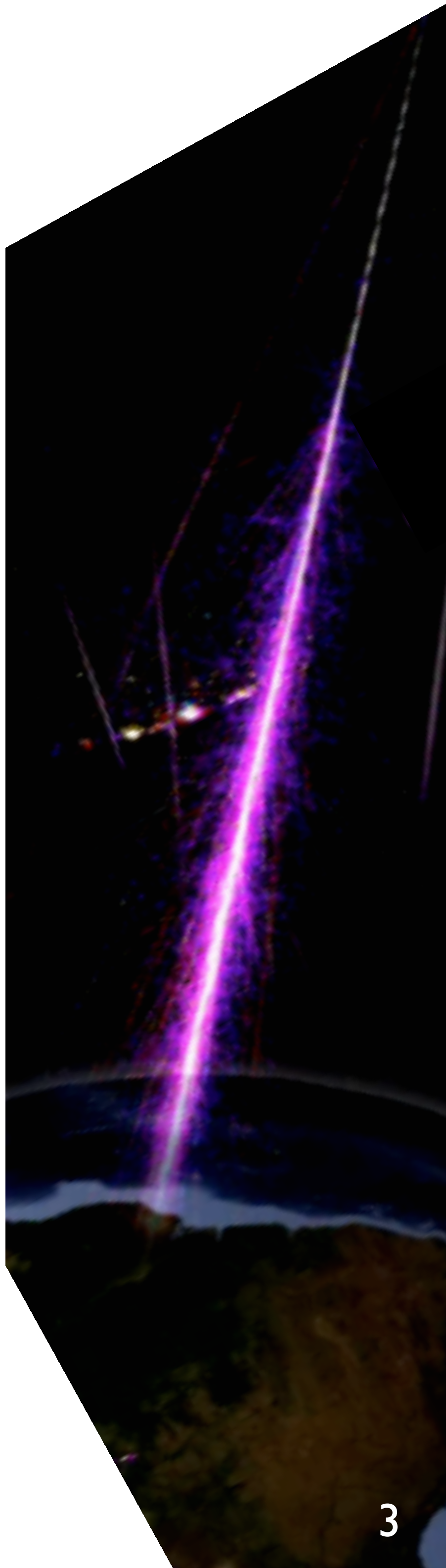
- UHECRs are charged particles *and* the Universe is magnetized
- Physics of powerful astrophysical objects is not known in detail

Particle Physics issues:

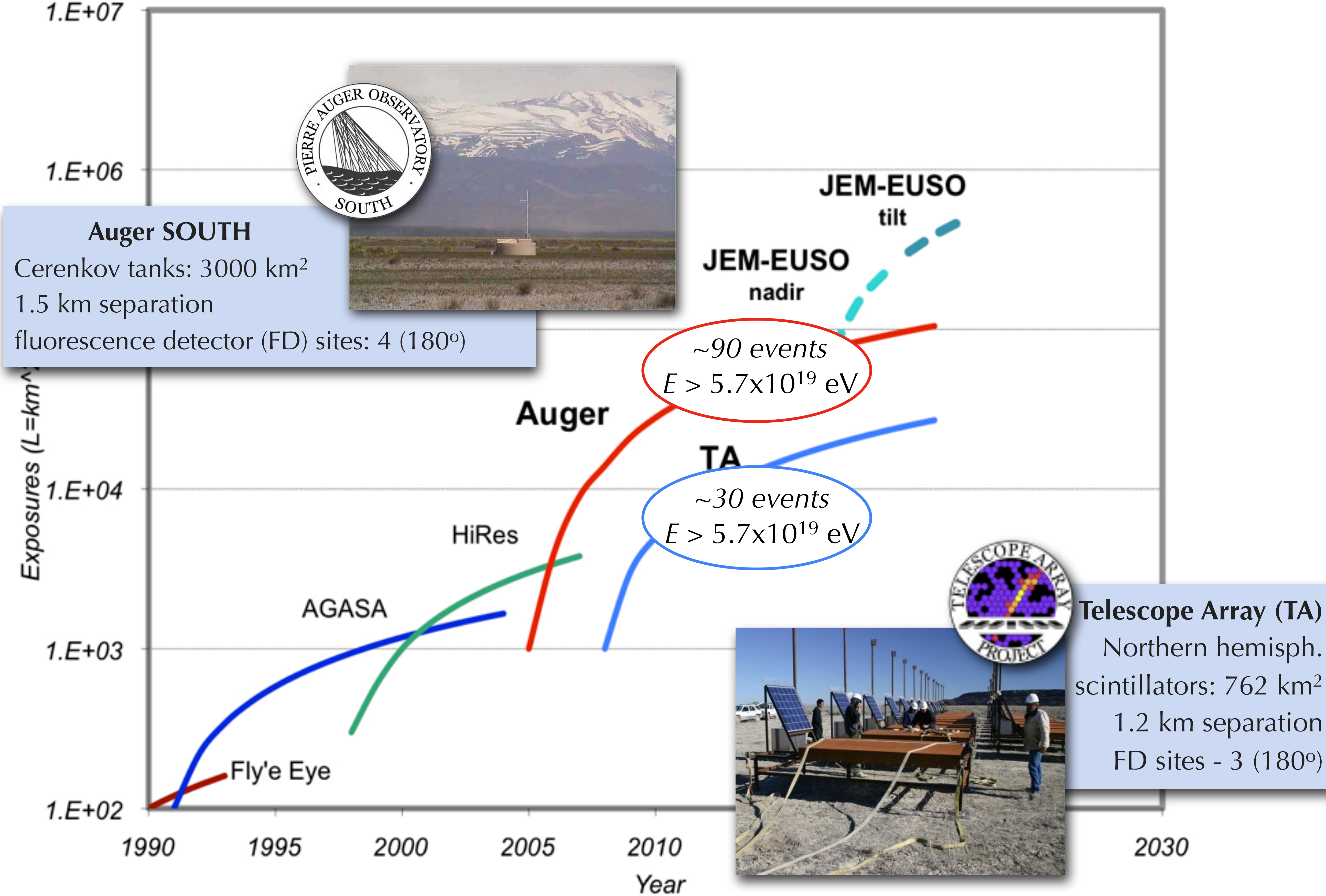
ultrahigh energies that cannot be reproduced on Earth ($E \sim 2 \times 10^{20}$ eV)
shower development (hadronic interactions) still unknown

What observational information do we have?

- energetics
- arrival directions in sky
- chemical composition
- multi-messengers (neutrinos, gamma-rays)

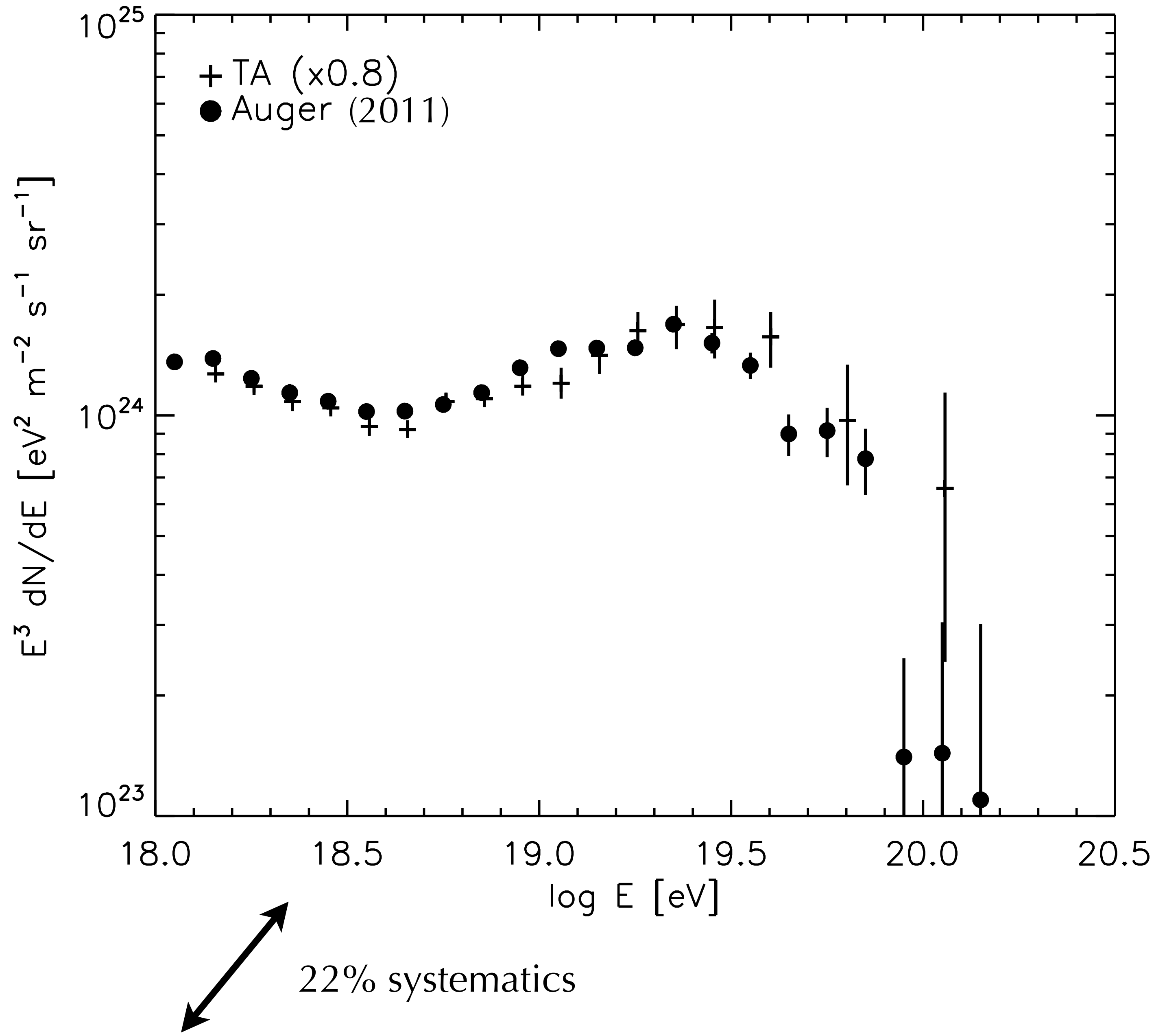


Since 1990 in ultrahigh energy cosmic rays



K.K. & Olinto 11

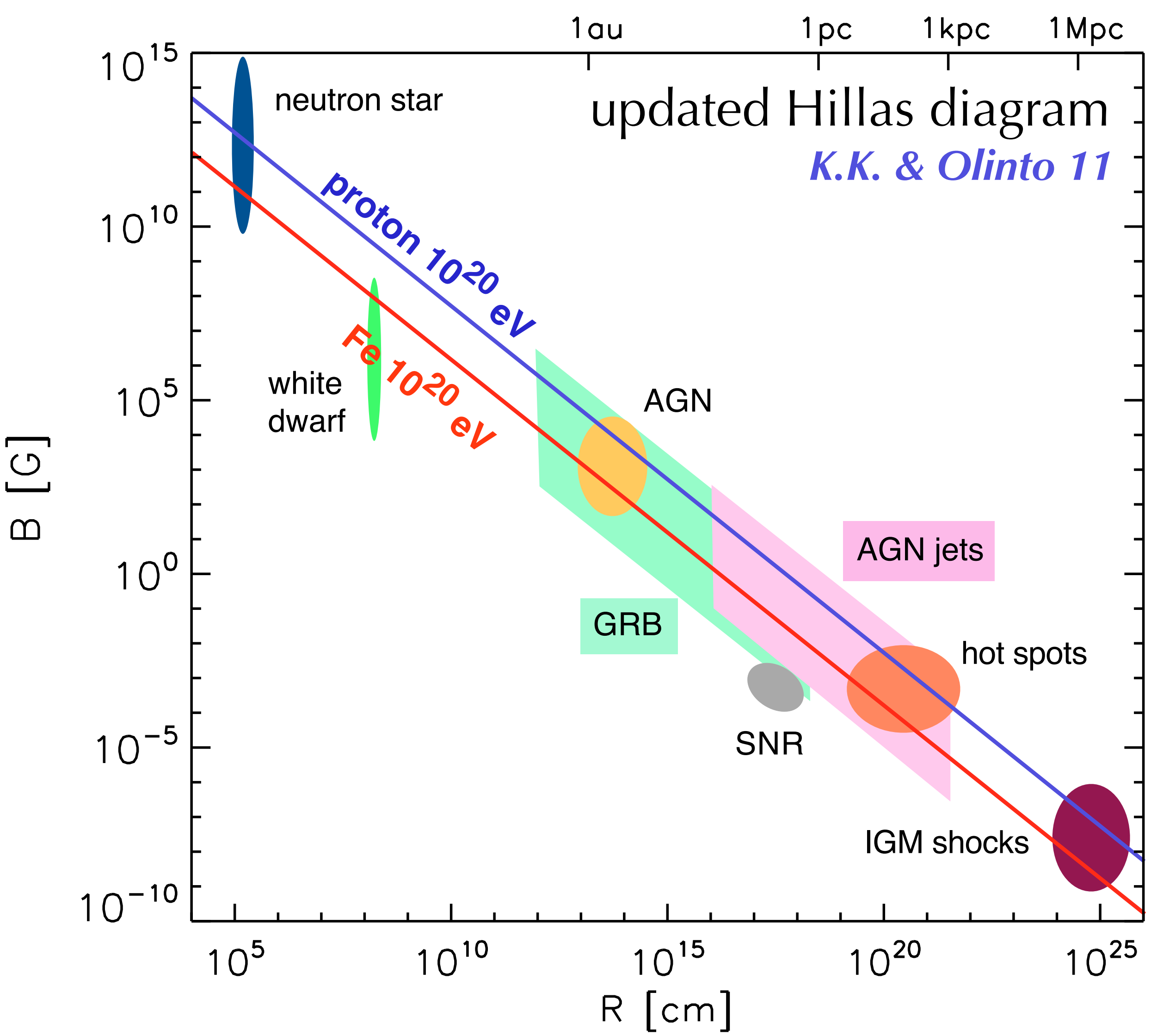
Crucial information from the energy spectrum



UHECR energy budget [@E=10^{19} eV]:
$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}
Katz et al. 09

acceleration to E>10^{20} eV
necessary magnetic luminosity
($L_B \equiv \varepsilon_B L_{outflow}$):
$L_B > 10^{45.5}$ erg/s Γ^2 β^{-1}
Lemoine & Waxman 09

EUHECR > 10^{20} eV: first selection of local sources



confinement of particle in source:
particle Larmor radius < size of source

$$r_{\rm L} \leq L$$

$$r_{\rm L} = 1.08\ {\rm Mpc}\, Z^{-1} \left(\frac{E}{10^{18}\ {\rm eV}}\right) \left(\frac{B}{1\ {\rm nG}}\right)^{-1}$$

! caution when applied to relativistic outflows

black holes/jets/hot spots
acceleration limited
by radiation losses
e.g. Norman et al. 1995, Rachen & Biermann 1995, Henri et al. 1999, ...moine & Waxman 2009

steady sources

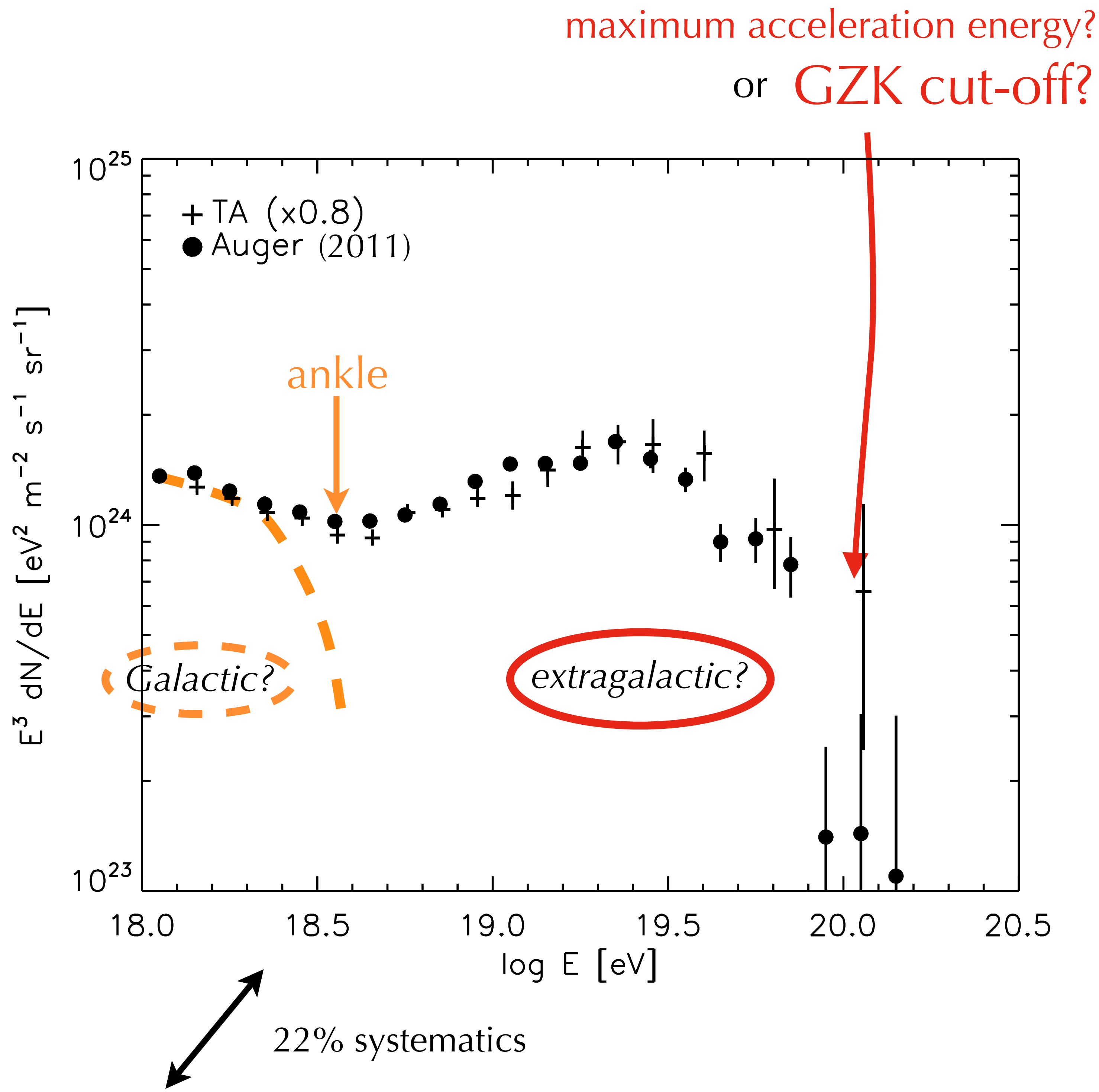
...etion shocks
... ~ 1-10 Mpc, $B_{\rm downstr}$ ~ 1 μG
--> E ~ 10^{20} eV ?
but maybe $B_{\rm upstream}$ << 1 μG
e.g. Kang et al. 1997, Miniati et al., 2000, Murase et al. 2008

accelation ok,
but tight energy budget
because rare source
e.g. Waxman 1995, ...tri 1995, Murase 2008

transient sources

very promising for those found in superluminous supernova!
Fang, K.K., Olinto 2012

Crucial information from the energy spectrum



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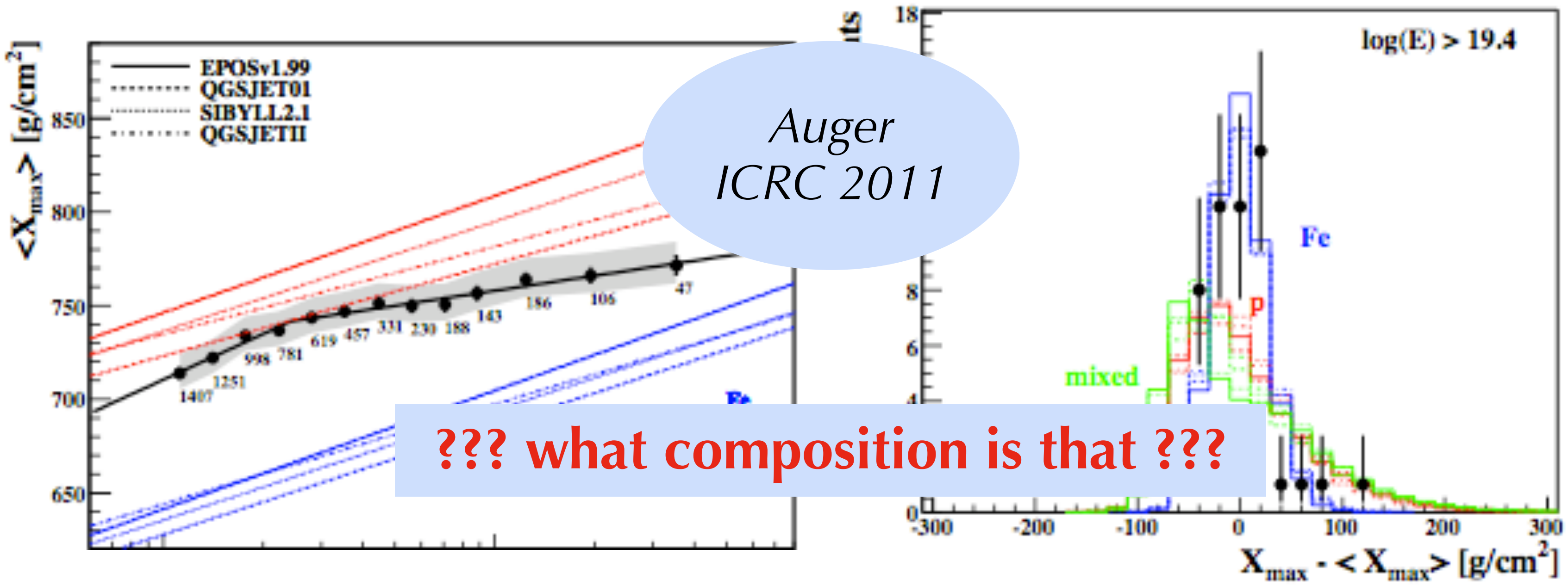
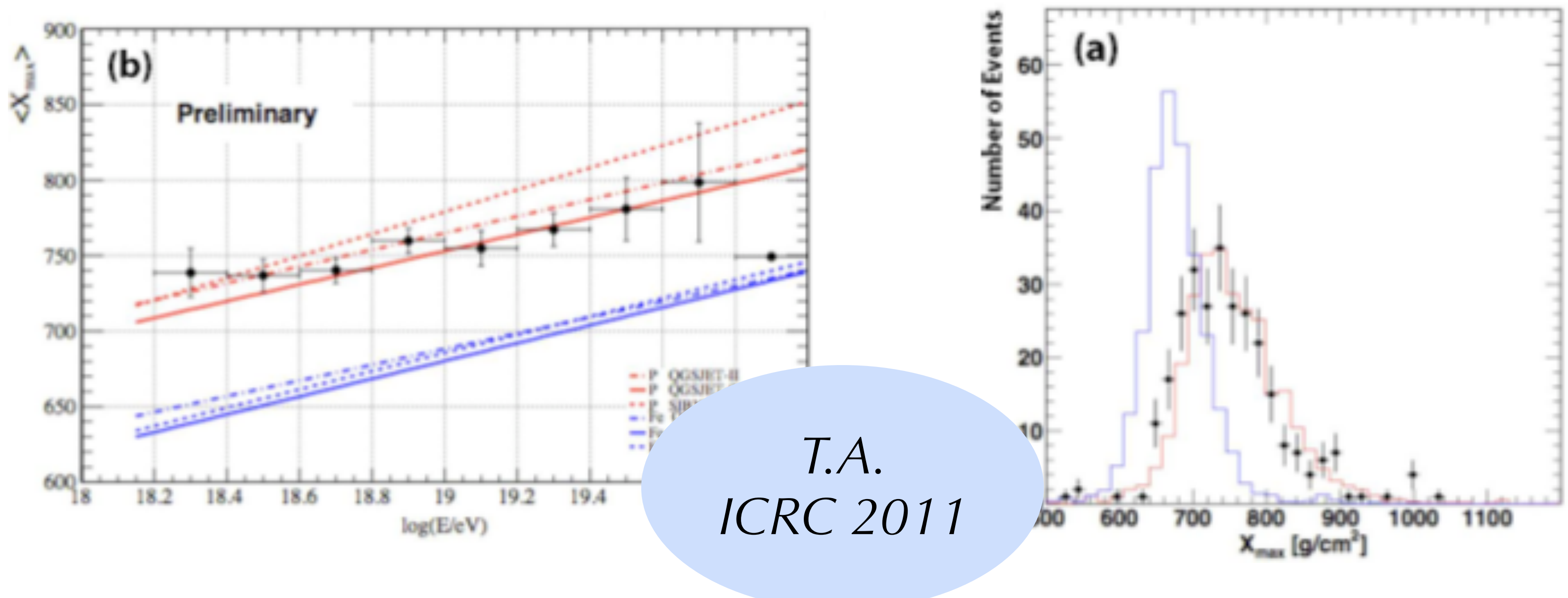
Lemoine & Waxman 09

for particles with E > E_{GZK} (~6x10^{19}eV)
sources within ~ few 100 Mpc

ankle @ E~$10^{18.5}$ eV:
Galactic/extragalactic transition?

Puzzling composition measurements

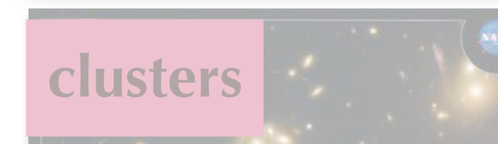




talk by R. Engel,
+ Session T7

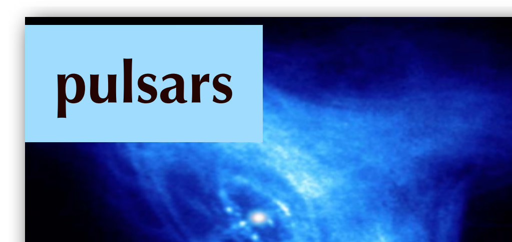
at the sources:
heavy nuclei if **metal-rich** or **nucleosynthesis**
escape difficult due to **photo-disintegration** in source?

heavy nuclei?



e.g., Lemoine 02, Pruet et al. 02, Wang et al. 08, Murase et al. 08

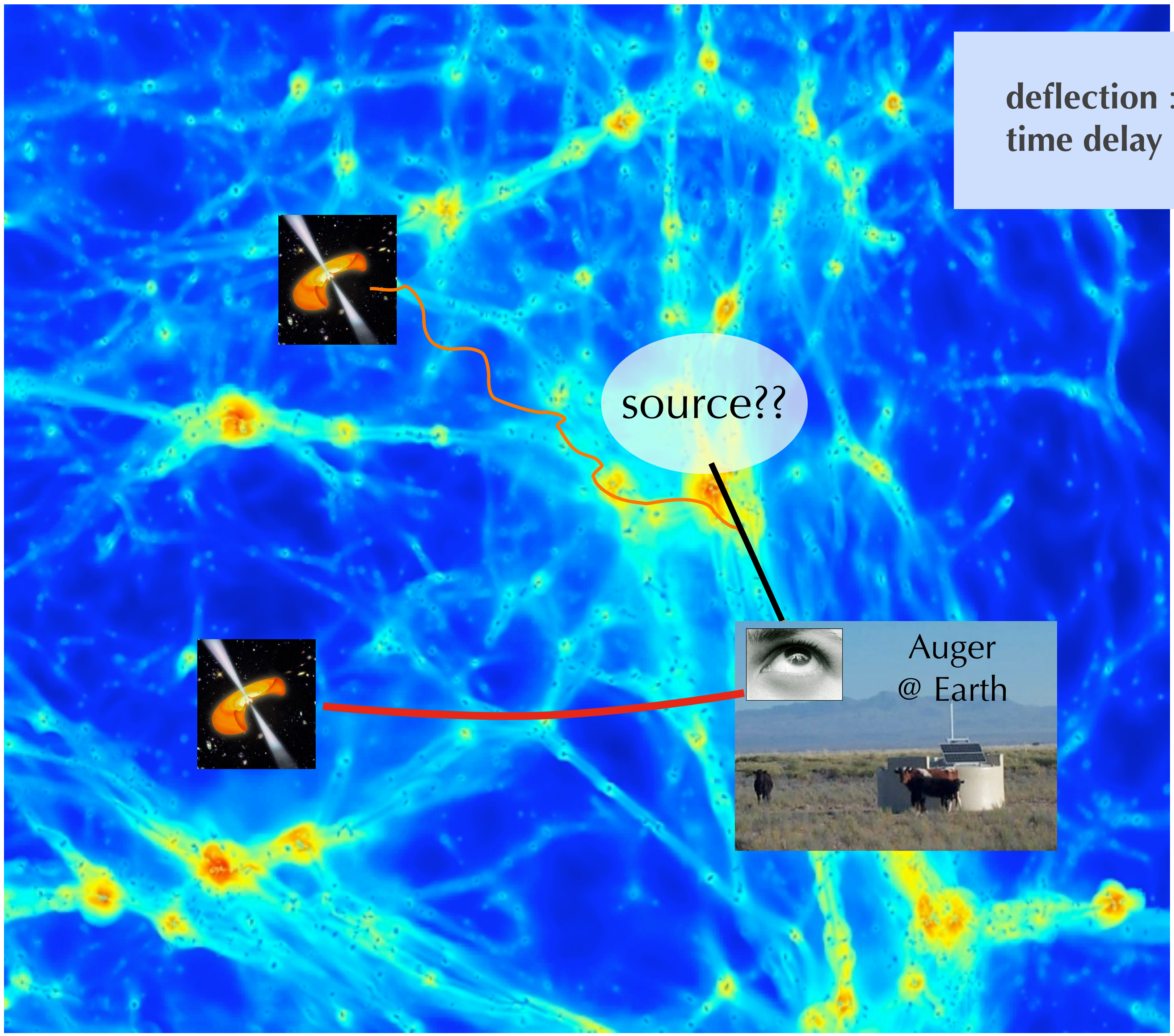
hope for GRBs: *Horiuchi et al. 2012*



e.g., Ruderman & Sutherland 75, Arons & Scharlemann 79, Blasi et al. 00, Fang et al. 2012

metal-rich surface, iron could escape

Arrival directions in the sky & magnetic fields



deflection : spatial decorrelation
time delay : temporal decorrelation if transient source

Extragalactic magnetic fields?

poorly known (no observation)
upper limits: B $l_{coh}^{1/2}$ < 1-10 nG $Mpc^{1/2}$
simulations --> complex and contradictory

Beck 08, Vallée 04, Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Donnert et al. 09...

Propagation of UHECR in extragalactic magnetic fields?

complicated because B not known
standard B lead to low proton deflections

e.g., Dolag et al. 05, Sigl et al. 05, Ryu et al. 98, Takami & Sato 08, KK & Lemoine 08a, KK & Lemoine 08b

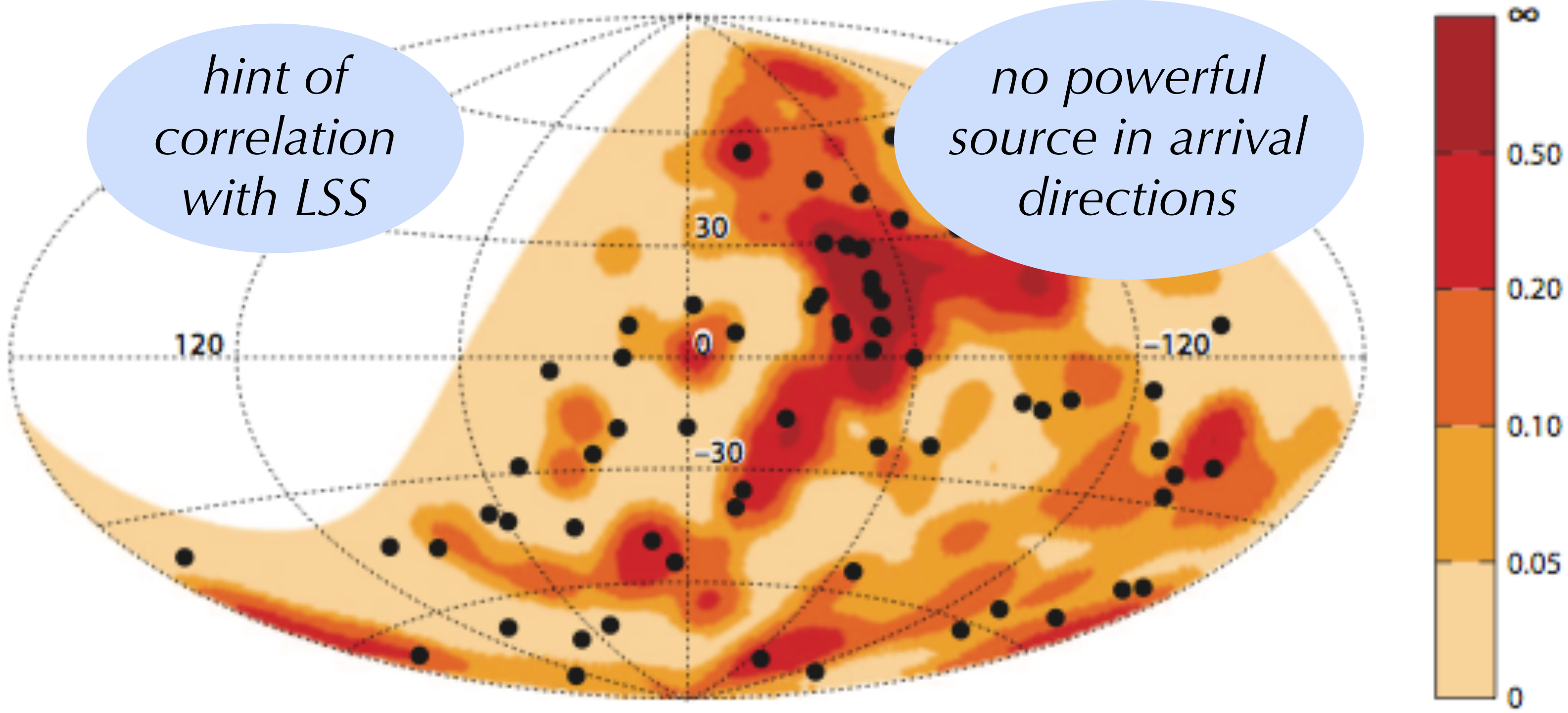
+ Galactic magnetic fields...

Arrival directions in the sky seen by Auger

density map of 2MRS

hint of correlation with LSS

no powerful source in arrival directions



steady sources? **OR** **transient source?**

- particularly strong extragalactic magnetic field
- UHECR = heavy nuclei

source already extinguished when UHECR arrives
correlation with LSS with no visible counterpart

no correlation with
secondary neutrinos, photons, grav. waves

>165 events (>4 years with Auger South)
to reach a 5σ significance

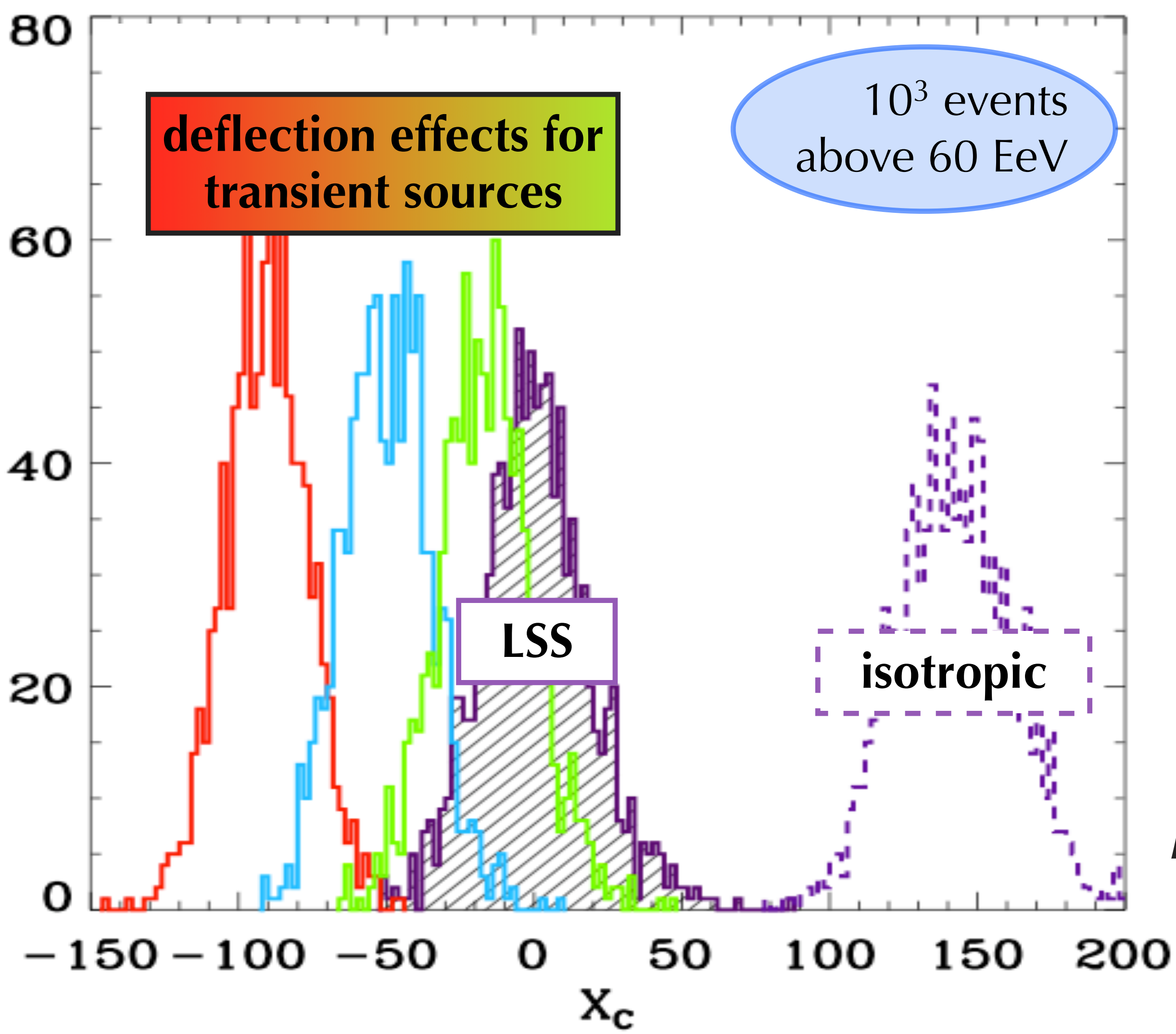
Will better statistics help?

Separate source populations with anisotropy

YES

time delay effects (deflections in magnetic fields)
-> distribution of UHECRs for **transient sources** different from LSS

separation possible for

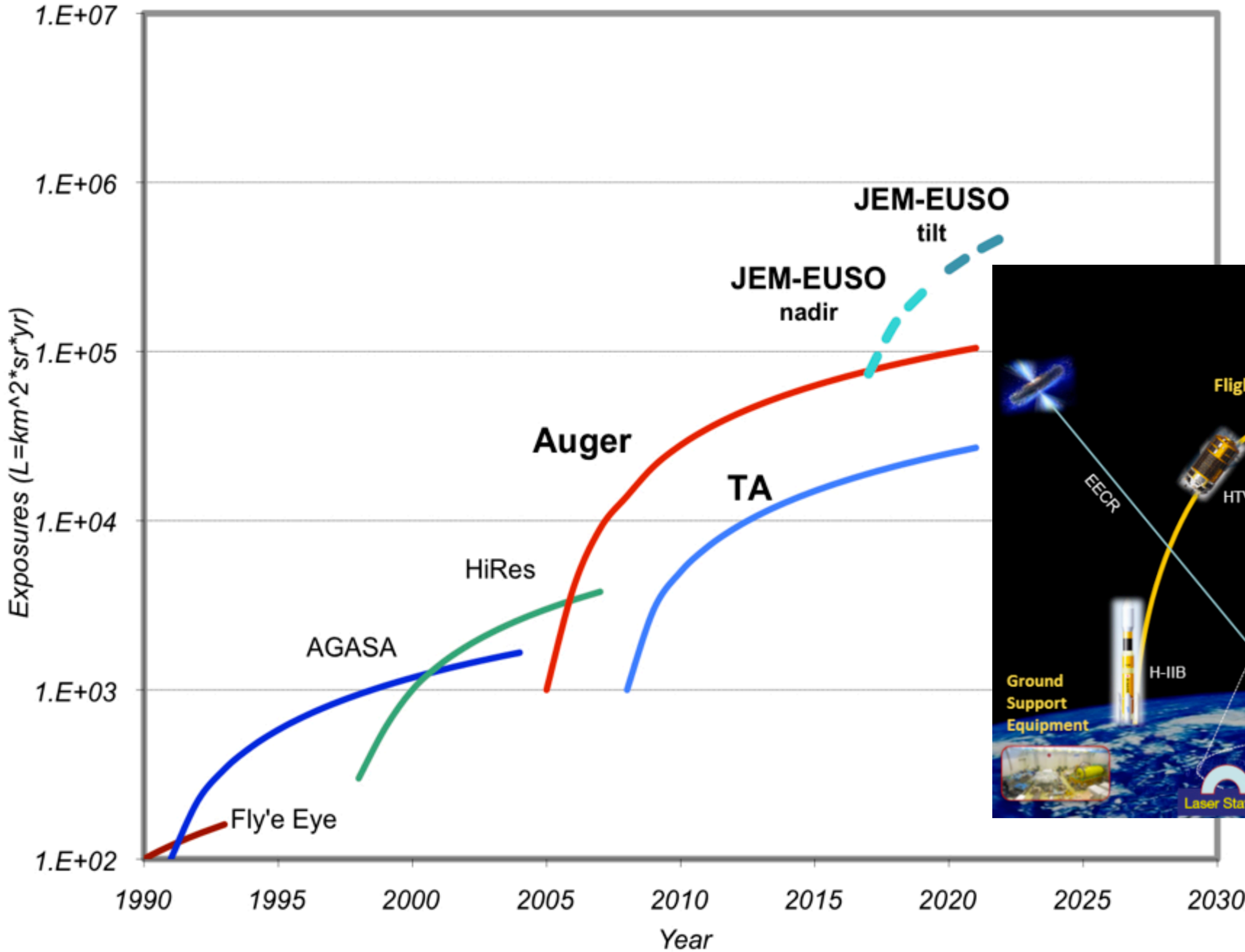


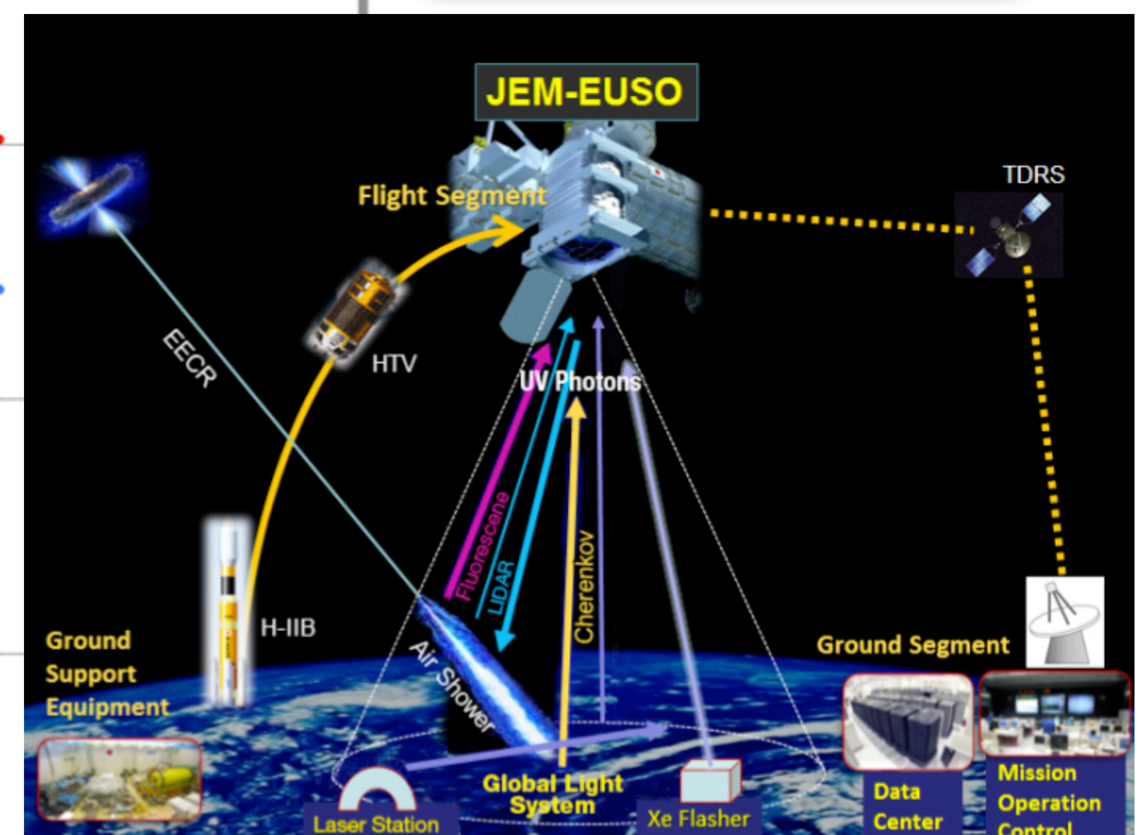
Kalli, Lemoine, K.K., 2011

measurement of correlation btw observed and predicted event distributions

$$X_C = \sum_{i=1}^{N_{tot}} \frac{(N_i^T - \langle N_{i,\mathrm{LSS}}\rangle)(\langle N_{i,\mathrm{iso}}\rangle - \langle N_{i,\mathrm{LSS}}\rangle)}{\langle N_{i,\mathrm{LSS}}\rangle}$$

A clear necessity: increasing the statistics...





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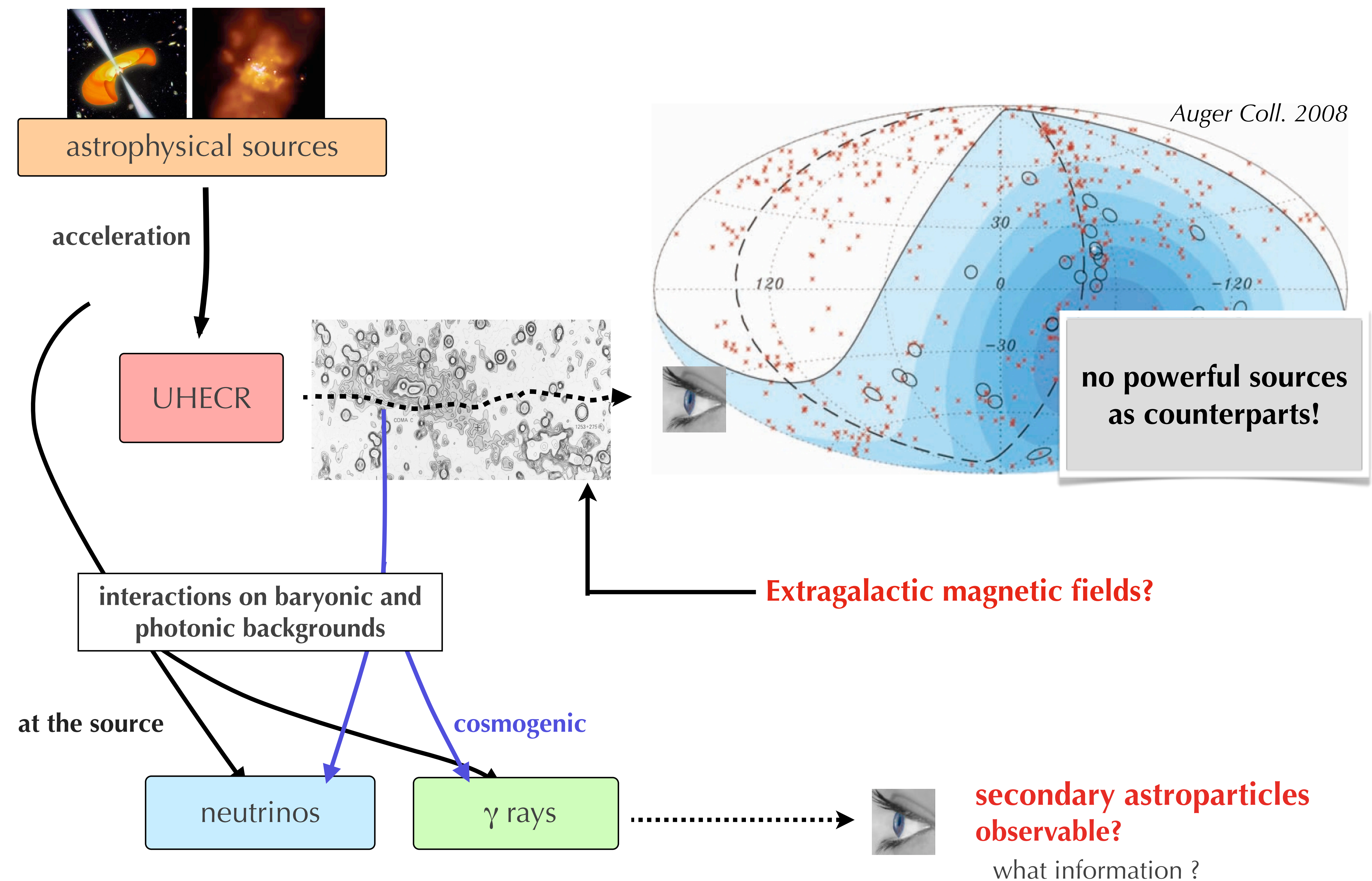
$E_{th} > 10^{20}$ eV

duty cycle 20%

Auger S x (~30)

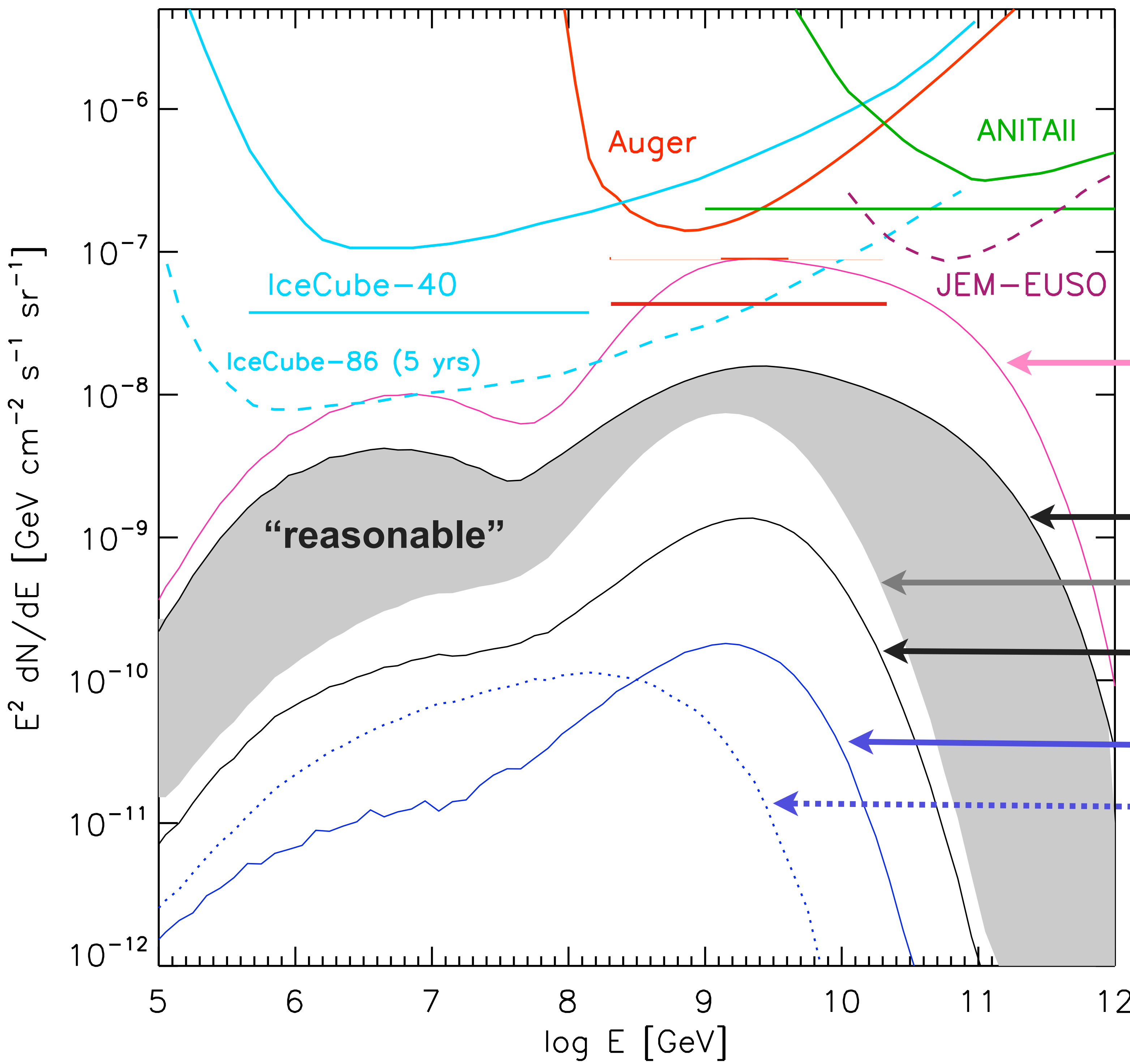
Adams et al. 2012, arXiv:1203.3451

... and look at other messengers



What cosmogenic neutrinos could tell us

K.K., Allard & Olinto, 2010
see also Decerprit & Allard 2011



cosmogenic neutrino fluxes
and instrument sensivities

FRII galaxies and other sources with strong emissivity evolution

excluded by Auger and soon by IceCube

proton dominated dip model

proton dominated ankle model

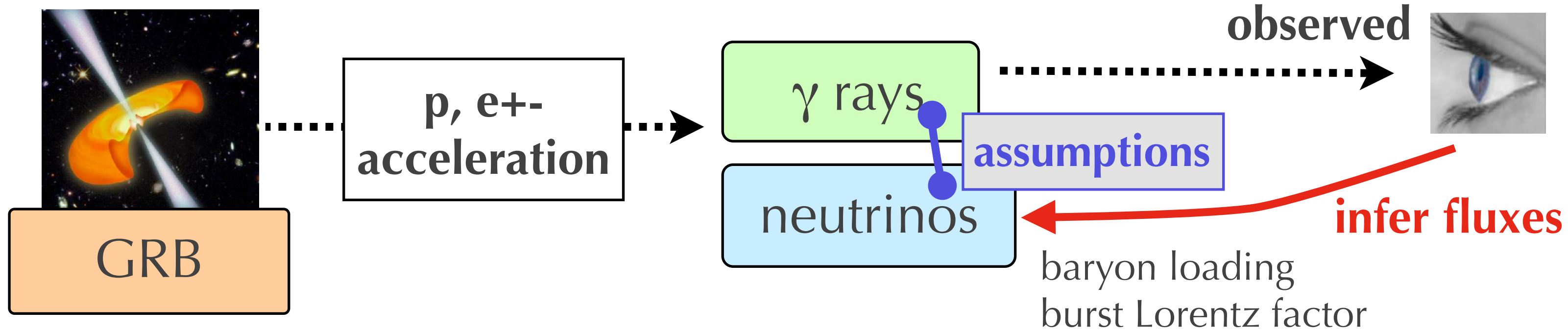
proton dom., no source evolution

pure iron, no source evolution

iron rich, no source evolution

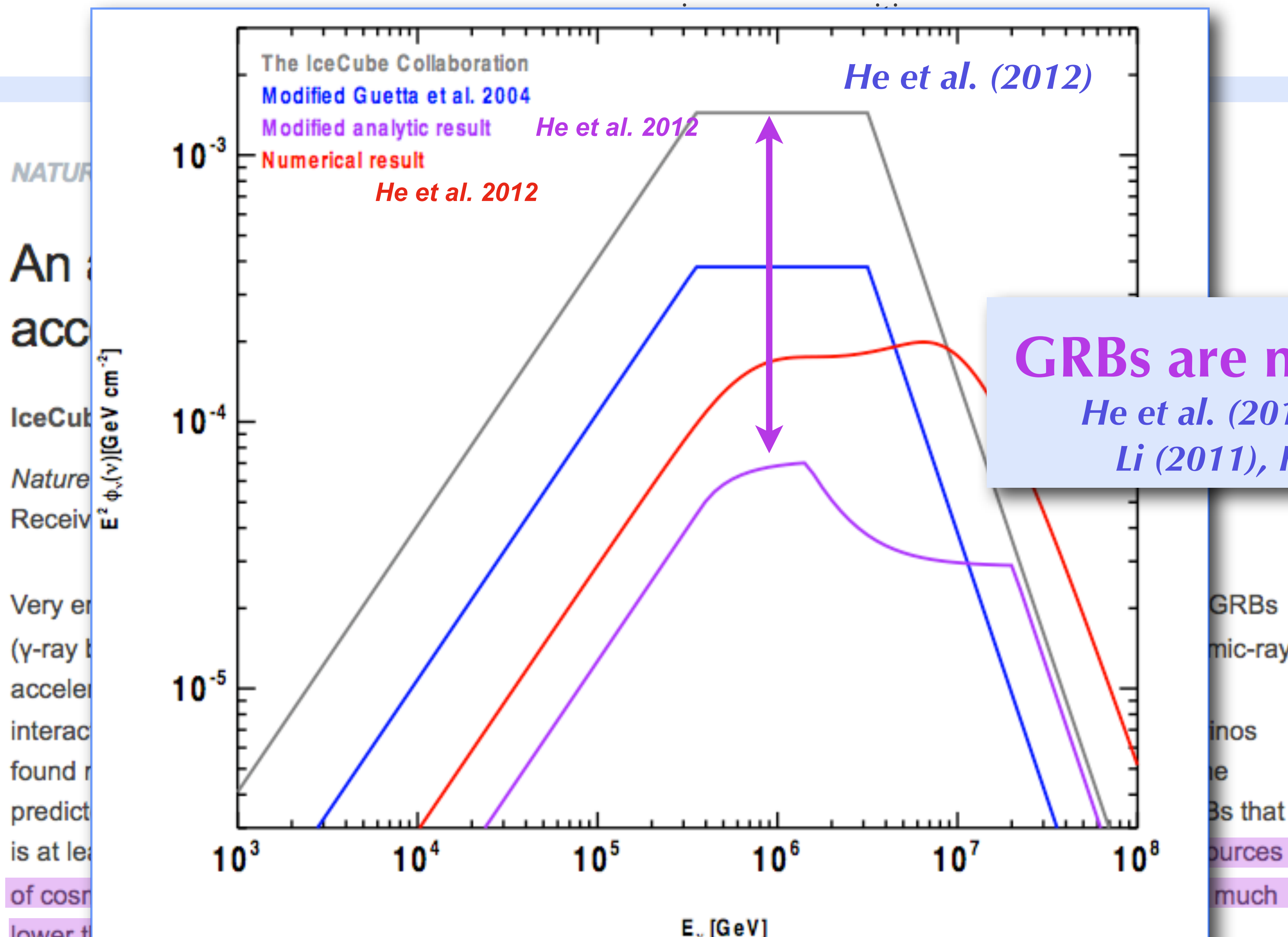
1) top-down models excluded
2) FRII galaxies excluded
3) reasonable models within reach?
4) there is a bottom

Neutrino fluxes expected at the source



baryon loading
burst Lorentz factor
Emin, Emax of cosmic rays
acceleration region (internal/external/reverse shock?)

e.g., Waxman & Bahcall limit (1997)

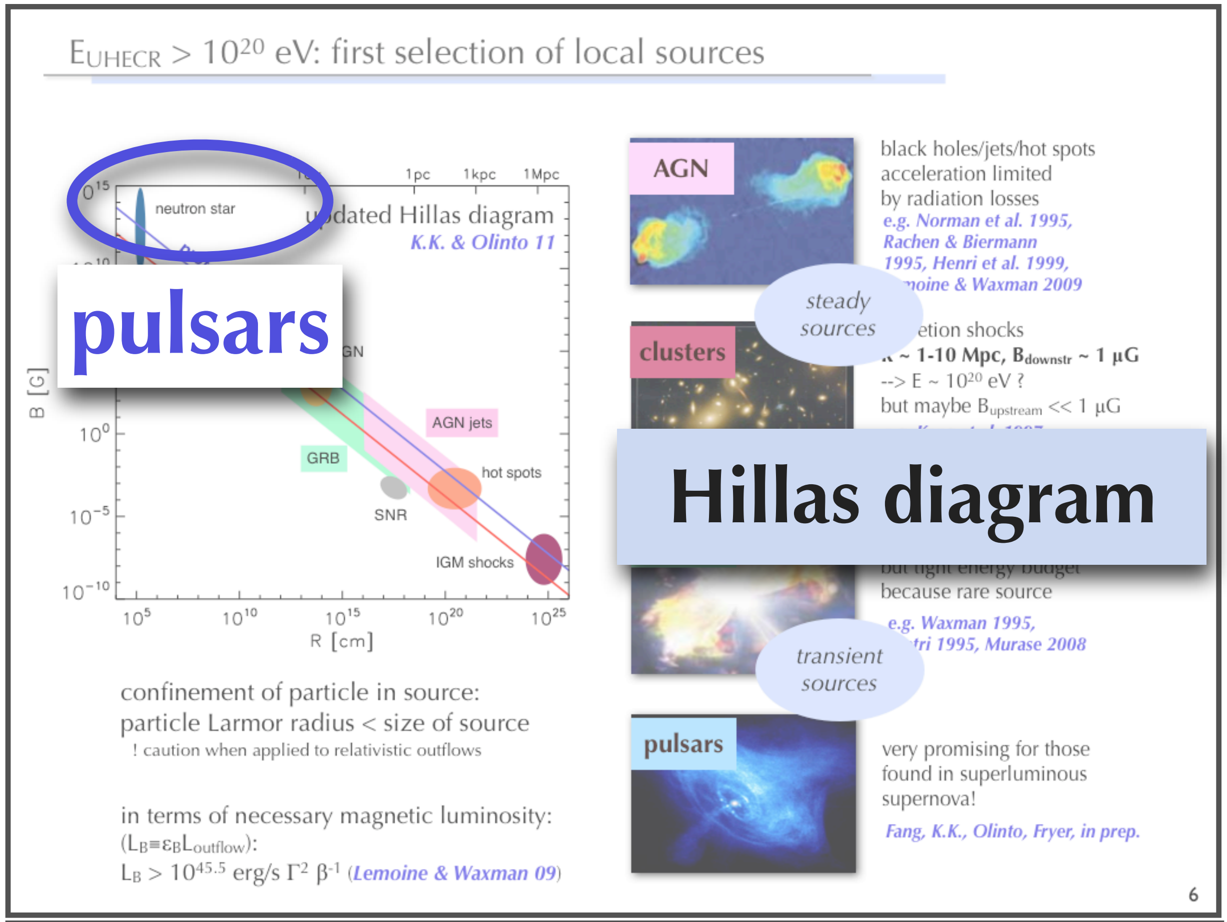


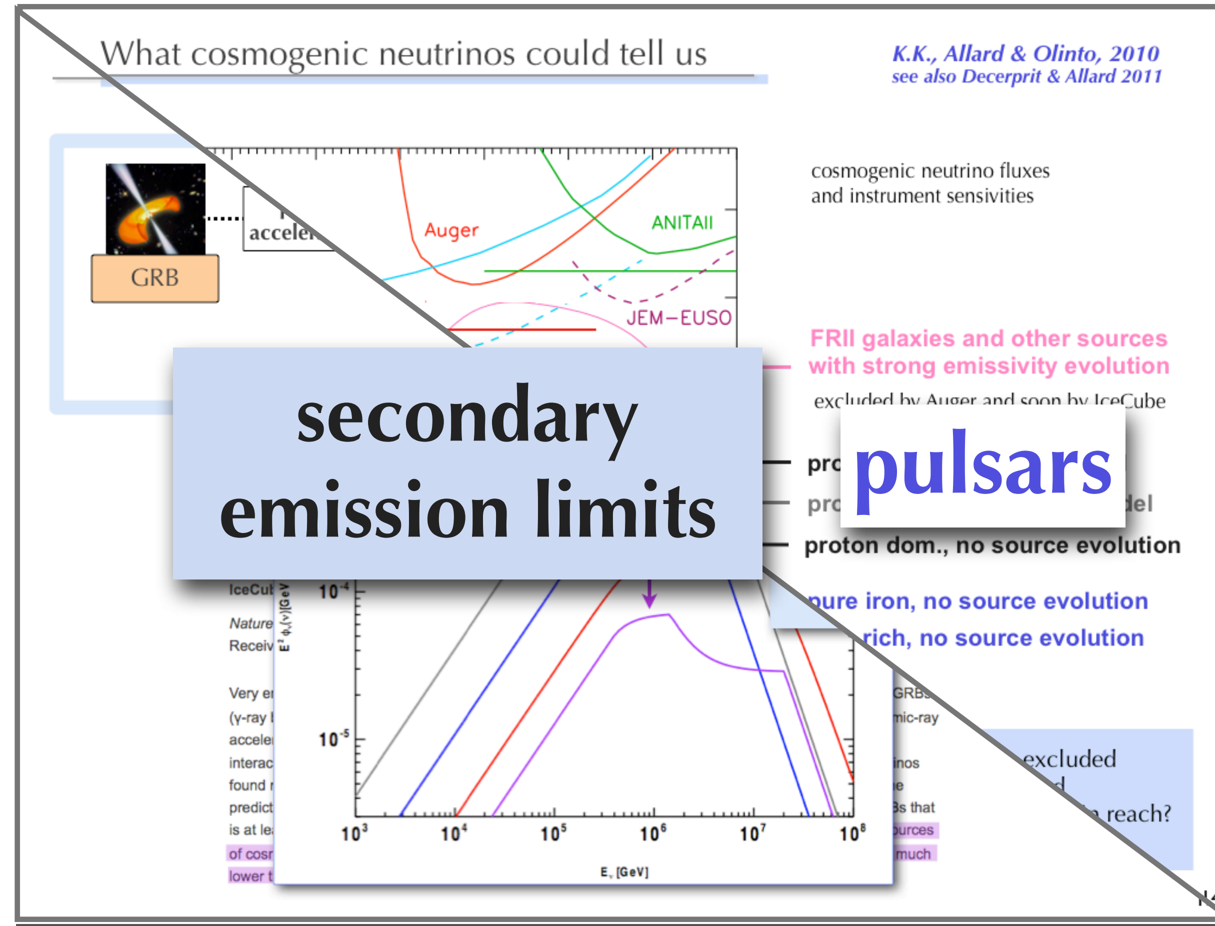
GRBs are not ruled out yet...

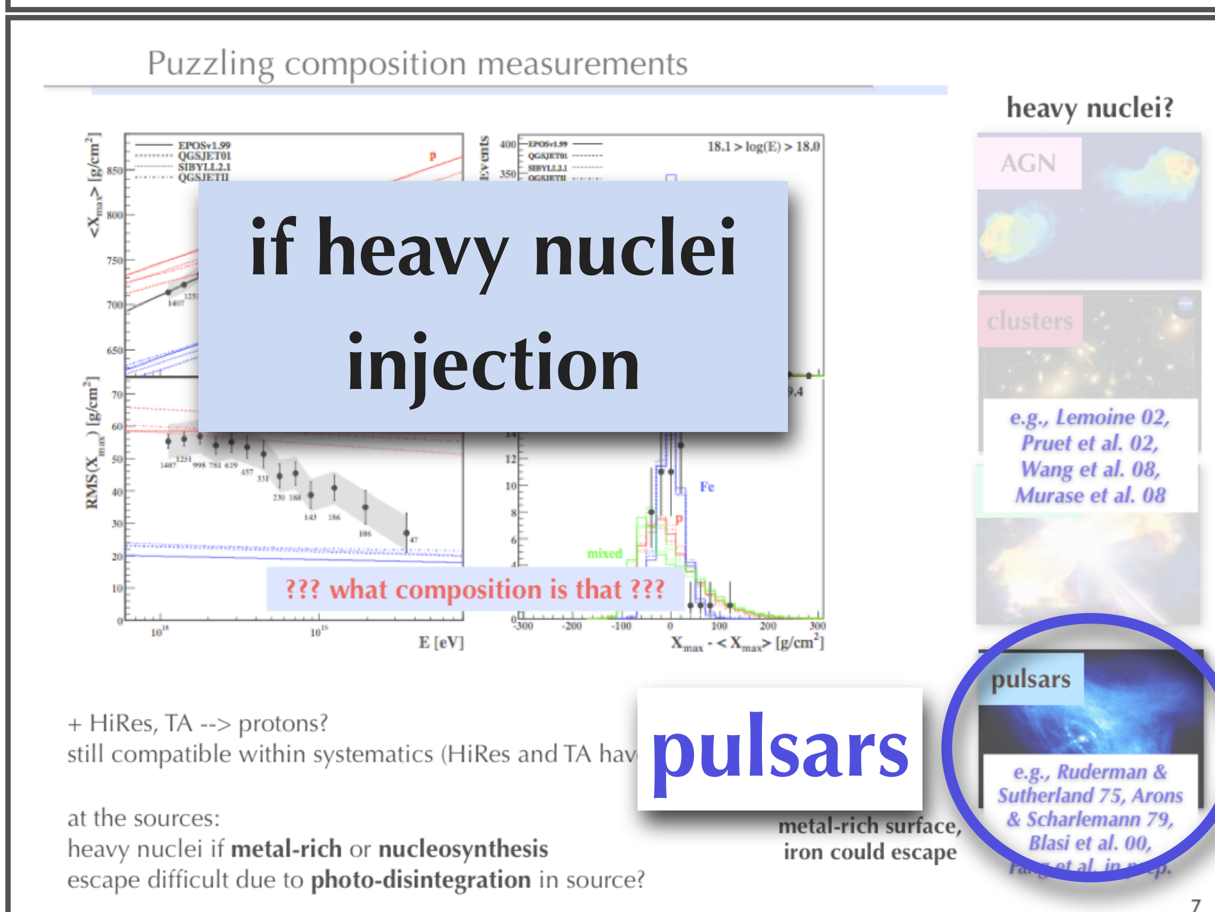
He et al. (2012) arXiv:1204.0857

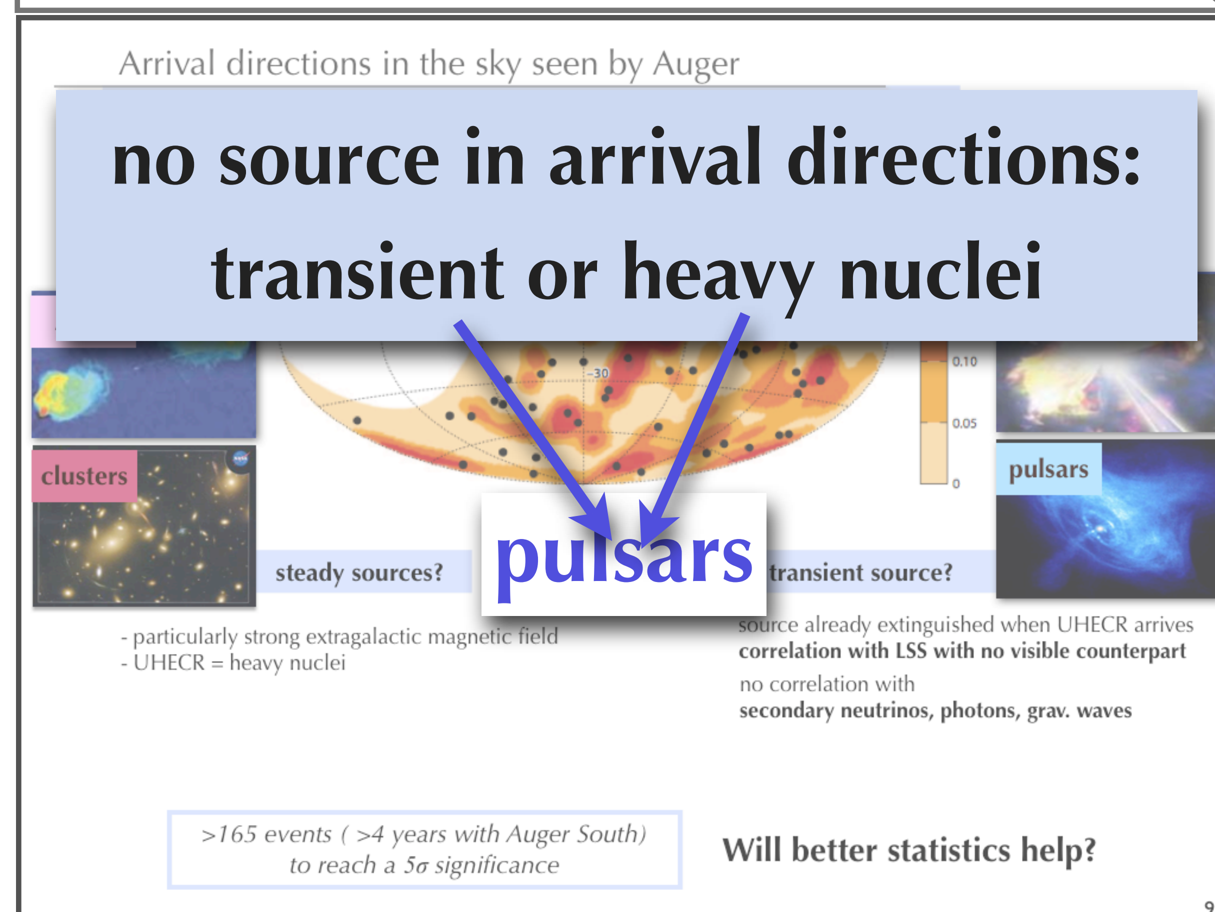
Li (2011), Hümmer (2011)

Meanwhile, case/case study of sources…









Acceleration of UHECR in newly-born ms pulsars

Blasi et al. 00,
Arons 03,
Fang, KK, Olinto 2012

unipolar induction in the pulsar wind

strong magnetic field $\mathbf{B}$
fast rotation velocity $\mathbf{\Omega}$

$$\mathbf{E} = -\mathbf{\Omega} \times \mathbf{B}$$

particles accelerated to energy:

$$E(\Omega) \sim 8.6 \times 10^{20}\, Z_{26}\eta_1\Omega_4^2\mu_{31}\ \mathrm{eV}$$

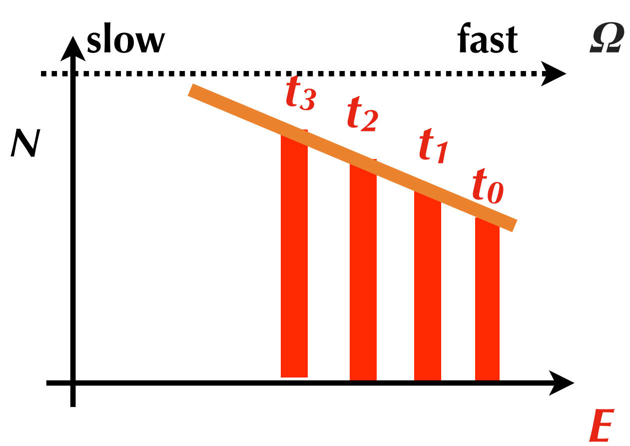
10%: fraction of voltage experienced by particles

magnetic moment 10^{31} cgs ($B \sim 10^{13}$ G)

rotation velocity $10^4\ \mathrm{s}^{-1}$

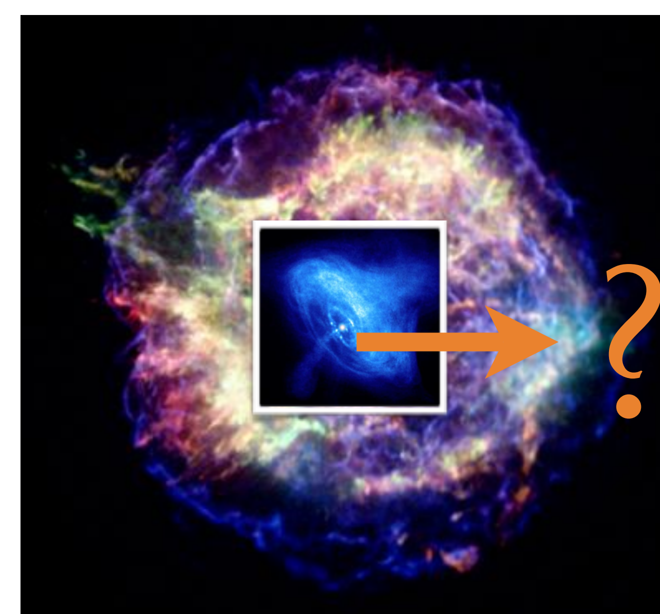
pulsar spins down

energy spectrum for one pulsar:



$$\frac{\mathrm{d}N_\mathrm{i}}{\mathrm{d}E} = \frac{9}{2}\frac{c^2 I}{ZeB_* R_*^3 E}\left(1 + \frac{E}{E_\mathrm{g}}\right)^{-1}$$

hard injection spectrum:
-1 slope



supernova envelope: do accelerated particles survive?

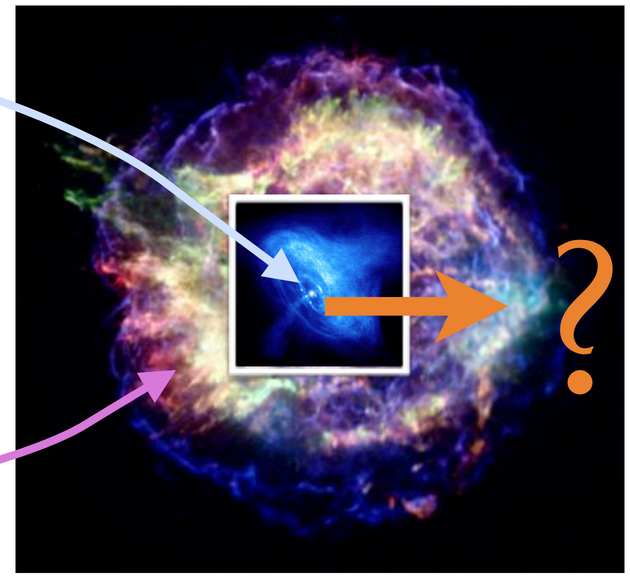
SN envelope = dense baryonic background
UHECR experience hadronic interactions

Parameter space for successful acceleration+escape

Fang, KK, Olinto 2012

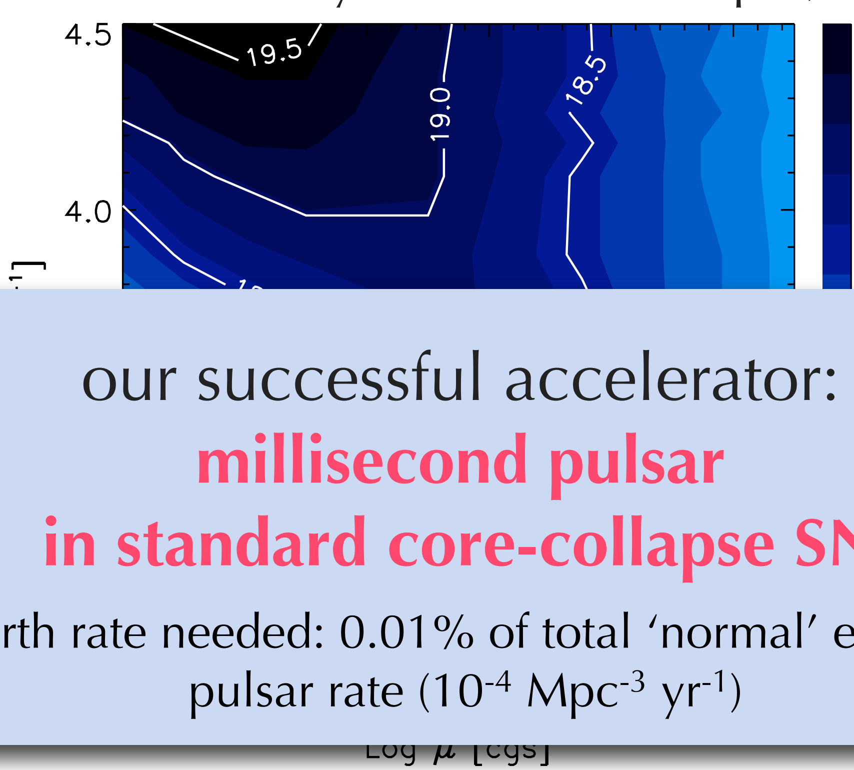
pulsar
magnetic moment μ,
rotation velocity Ω,
particle acceleration rate η

supernova
ejecta energy E_{ej},
ejected mass M_{ej},

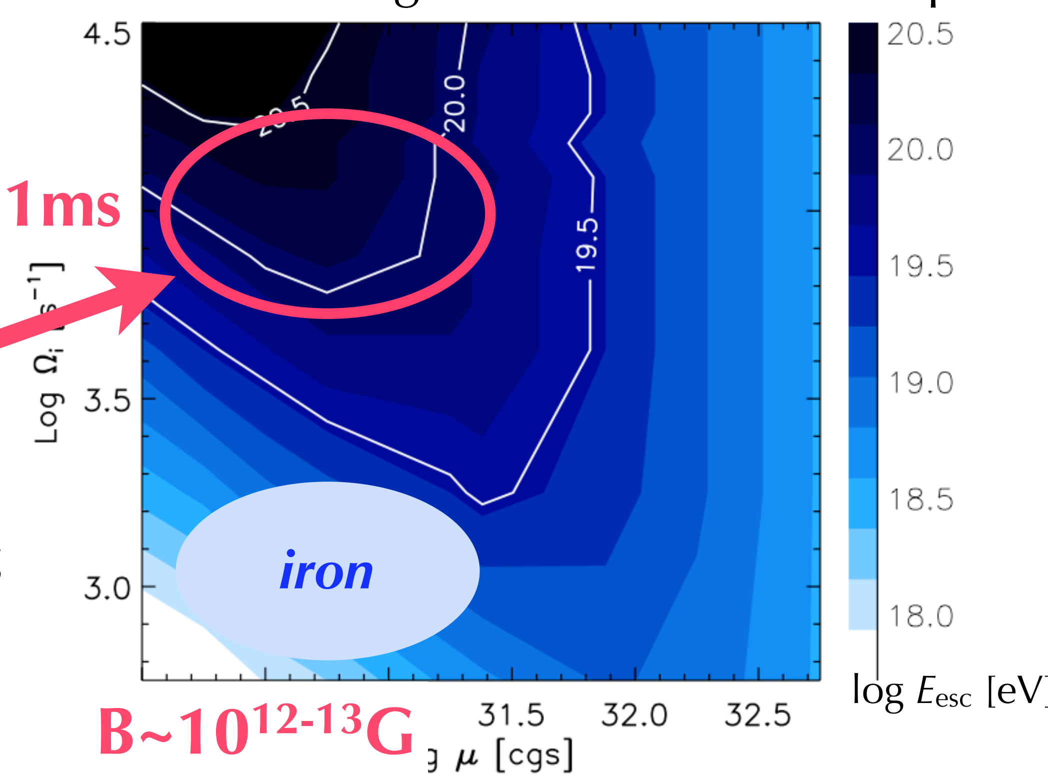


- Analytical estimates
- Monte-Carlo propagation, hadronic interactions with EPOS + CONEX

tight for protons
(would work for very dilute SN envelopes)



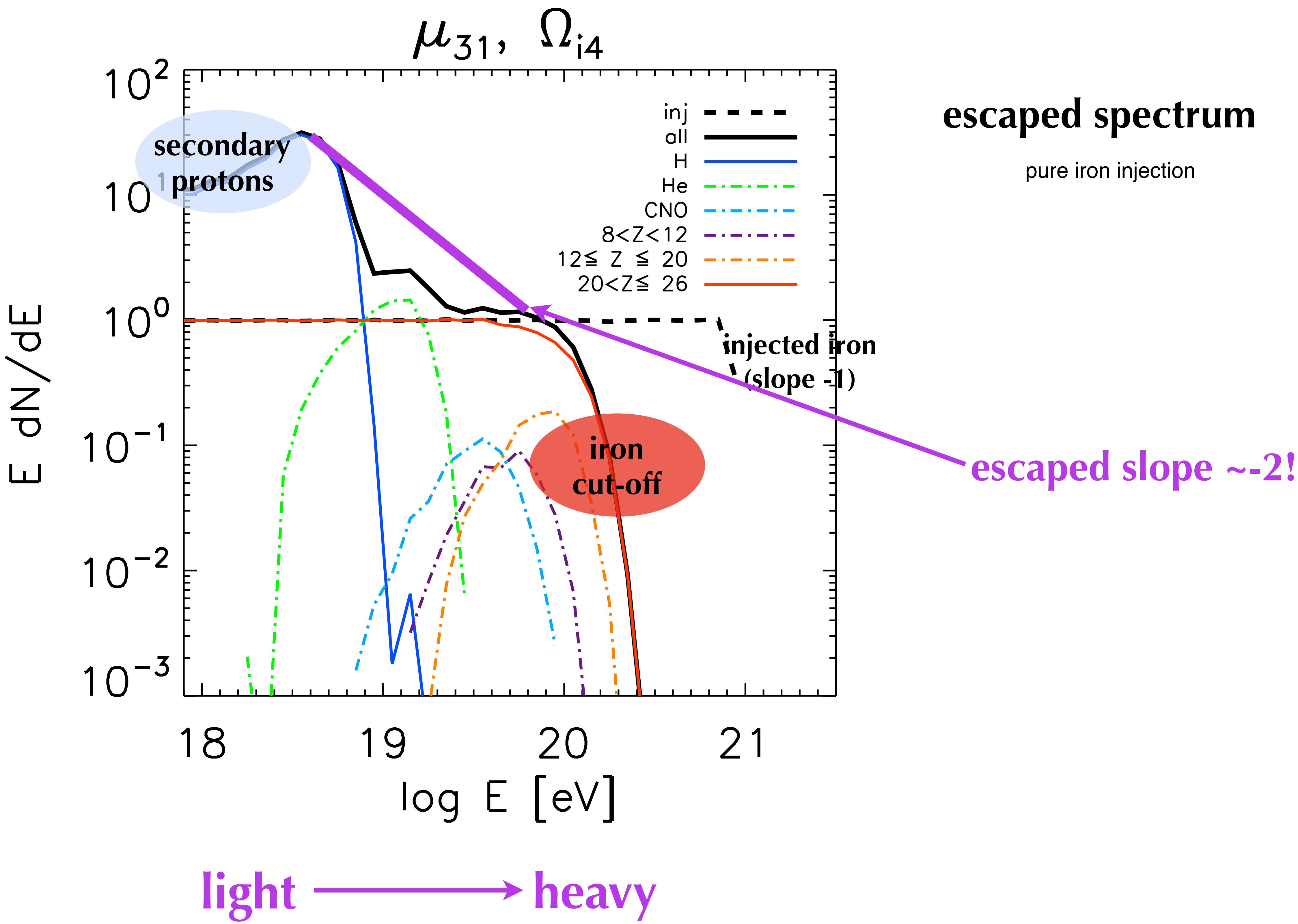
OK for iron:
accelerated to Z x higher E when SN envelope dilute



our successful accelerator:
millisecond pulsar
in standard core-collapse SN
birth rate needed: 0.01% of total 'normal' extrag. pulsar rate (10^{-4} Mpc^{-3} yr^{-1})

Collateral good news: spectrum, composition!

Fang, KK, Olinto 2012

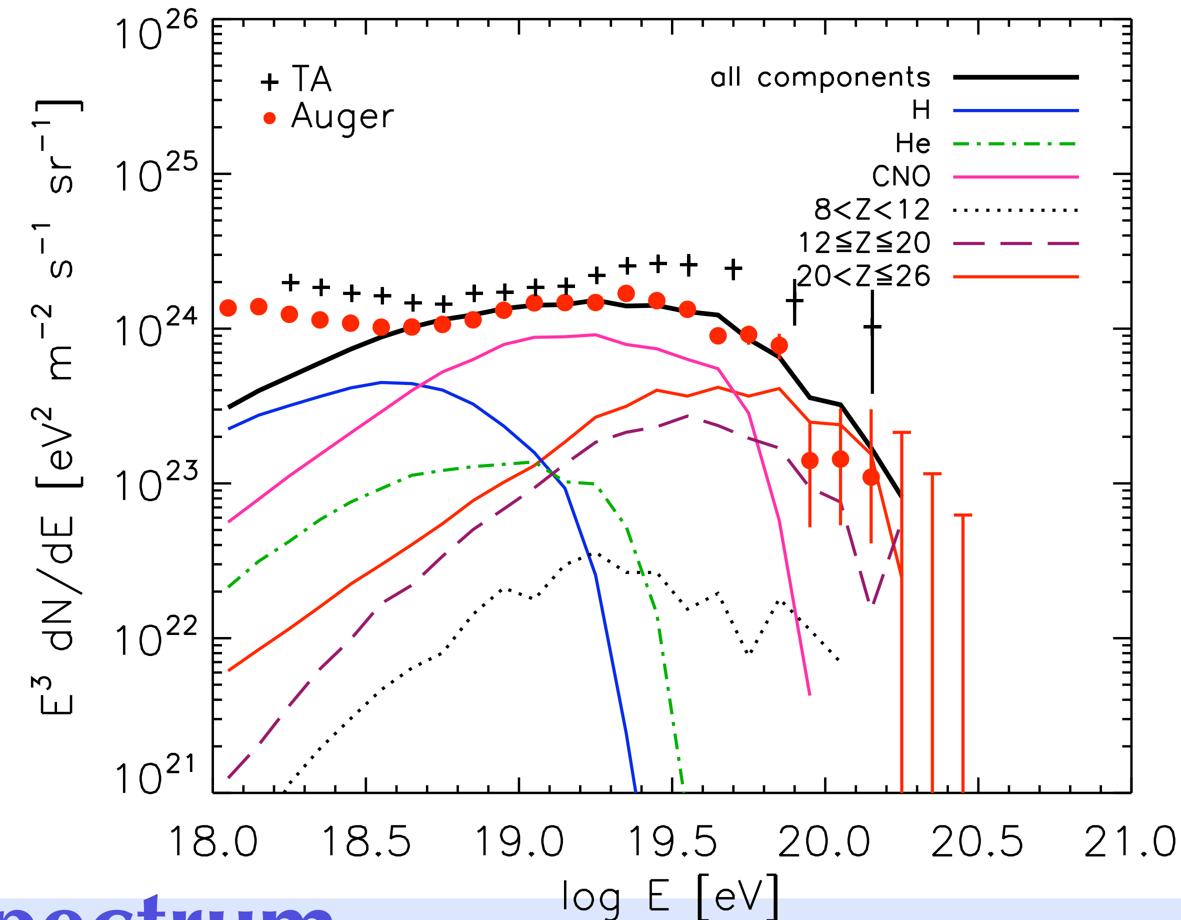


escaped spectrum

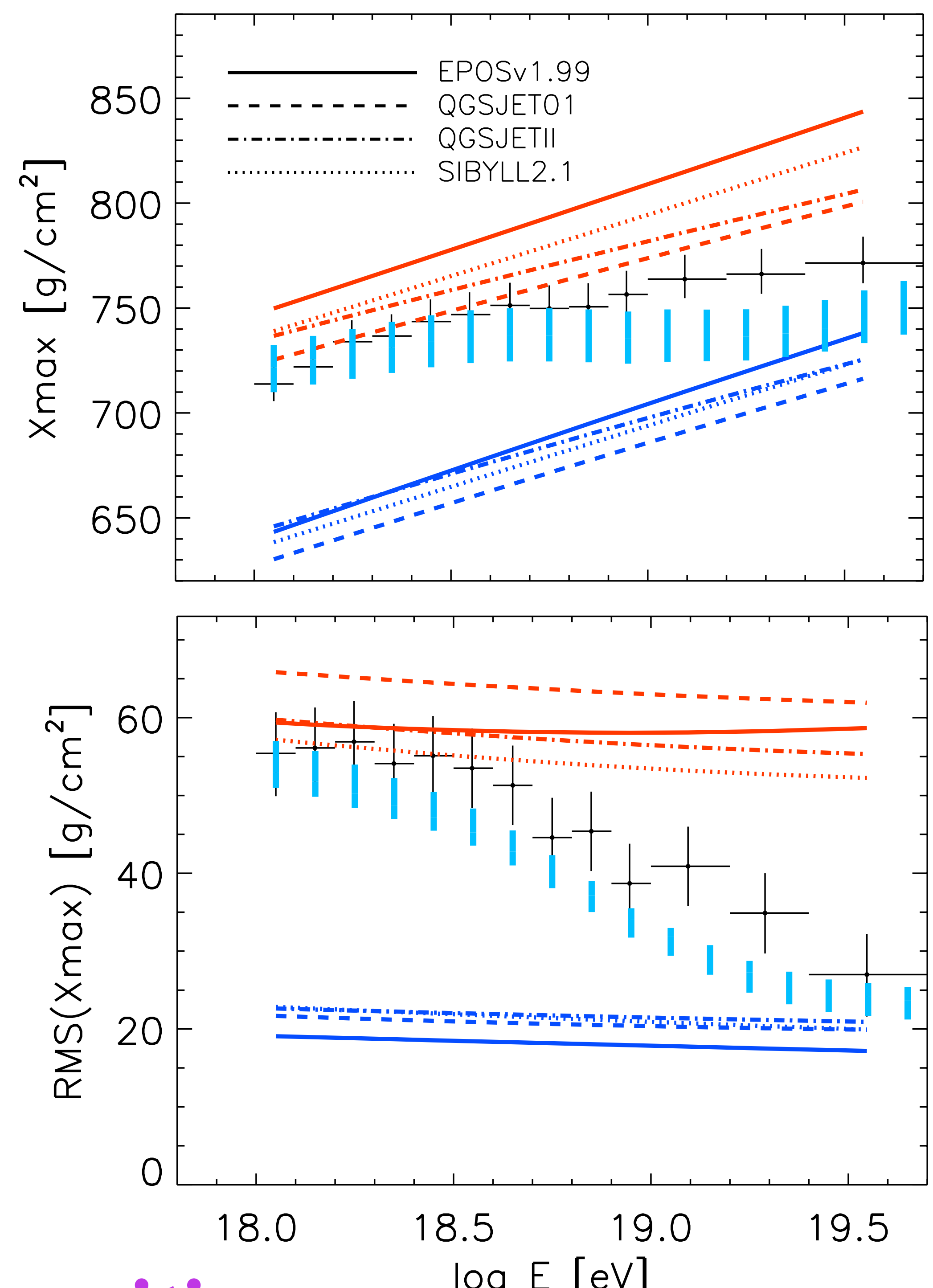
pure iron injection

A scenario that fits UHECR Auger data (rare)

Fang, KK, Olinto 2012
Fang, KK, Olinto, in prep.



spectrum



composition

propagated 75%p, 20%CNO, 5%Fe @injection

Smoking gun of the millisecond pulsar scenario

Fang, KK, Olinto 2012

energy spectrum at E>10^{20} eV

E_{cut} --> no recovery expected unlike in GZK cut-off

arrival directions

- no coincidence from source out of Local Group expected, as pulsars cannot be observed
- ms pulsar in core-collapse SN in our Local Group:

protons: a burst lasting $\delta t_{\rm Gal} \sim 0.1\, Z^2 \left(\frac{r}{2\,{\rm kpc}}\right)^2 \left(\frac{B_{\rm turb}}{4\,\mu{\rm G}}\right)^2 \left(\frac{\lambda_{\rm turb}}{50\,{\rm pc}}\right) \left(\frac{E}{E_{\rm GZK}}\right)^{-2}$ yr.

delayed of that time after onset of explosion.

iron: will appear as an increase of number of events for ~70 years

if sudden decrease of number of events happens, could be associated with birth of pulsar 70 yrs ago

but some anisotropy would then be apparent

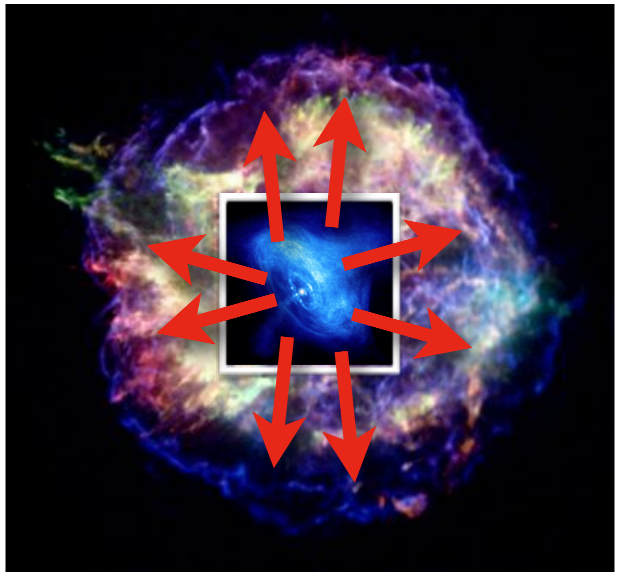
secondaries

- neutrinos produced during escape possibly observable by IceCube
  (***Murase et al. 2009*** --> *high density chosen though*)
- diffuse gravitational wave signatures in some highly optimistic cases (***K.K. 2011***)

A signature in the SN light curve?

KK, Phinney, Olinto in prep.

pulsar millisecond with $B \sim 10^{13}$G



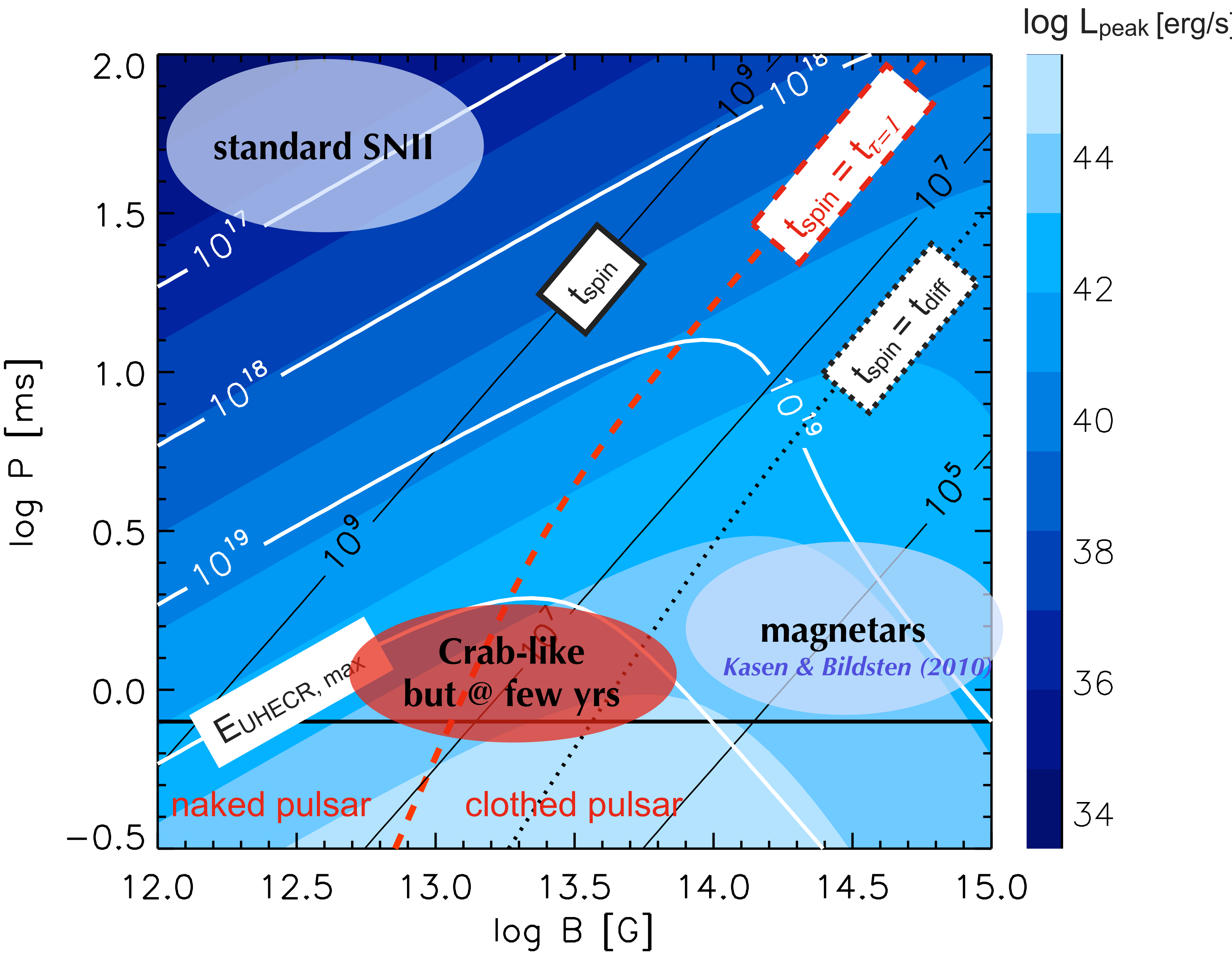
injection of LARGE pulsar rotational energy into SN ejecta $E \sim 10^{52}$ erg

↓

change radiation emission from SN

$M_{ej} = 5\ M_{sun}$
$E_{SN} = 10^{51}$ erg

10% pulsar rotational energy into radiation



Peculiar supernova lightcurves

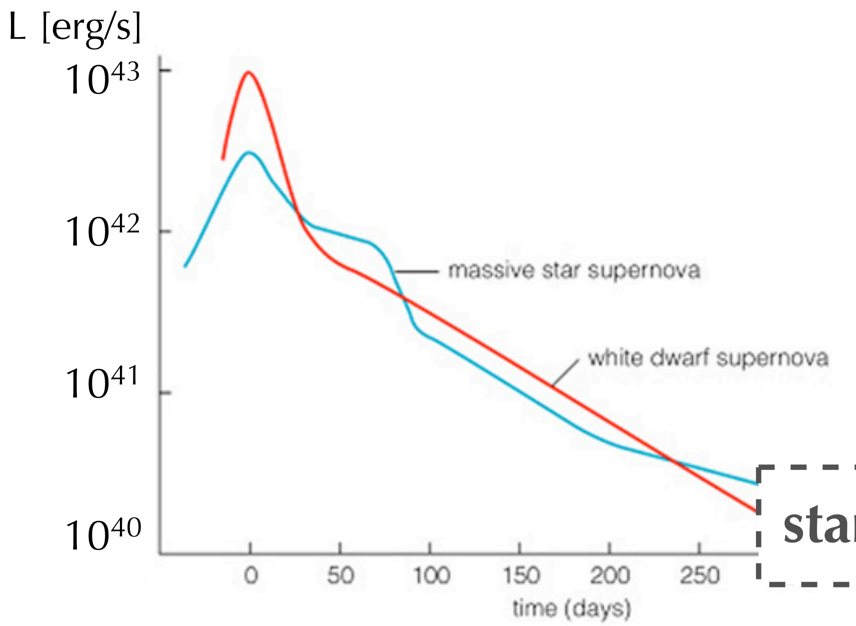
KK, Phinney, Olinto in prep.

analytical 1 zone model

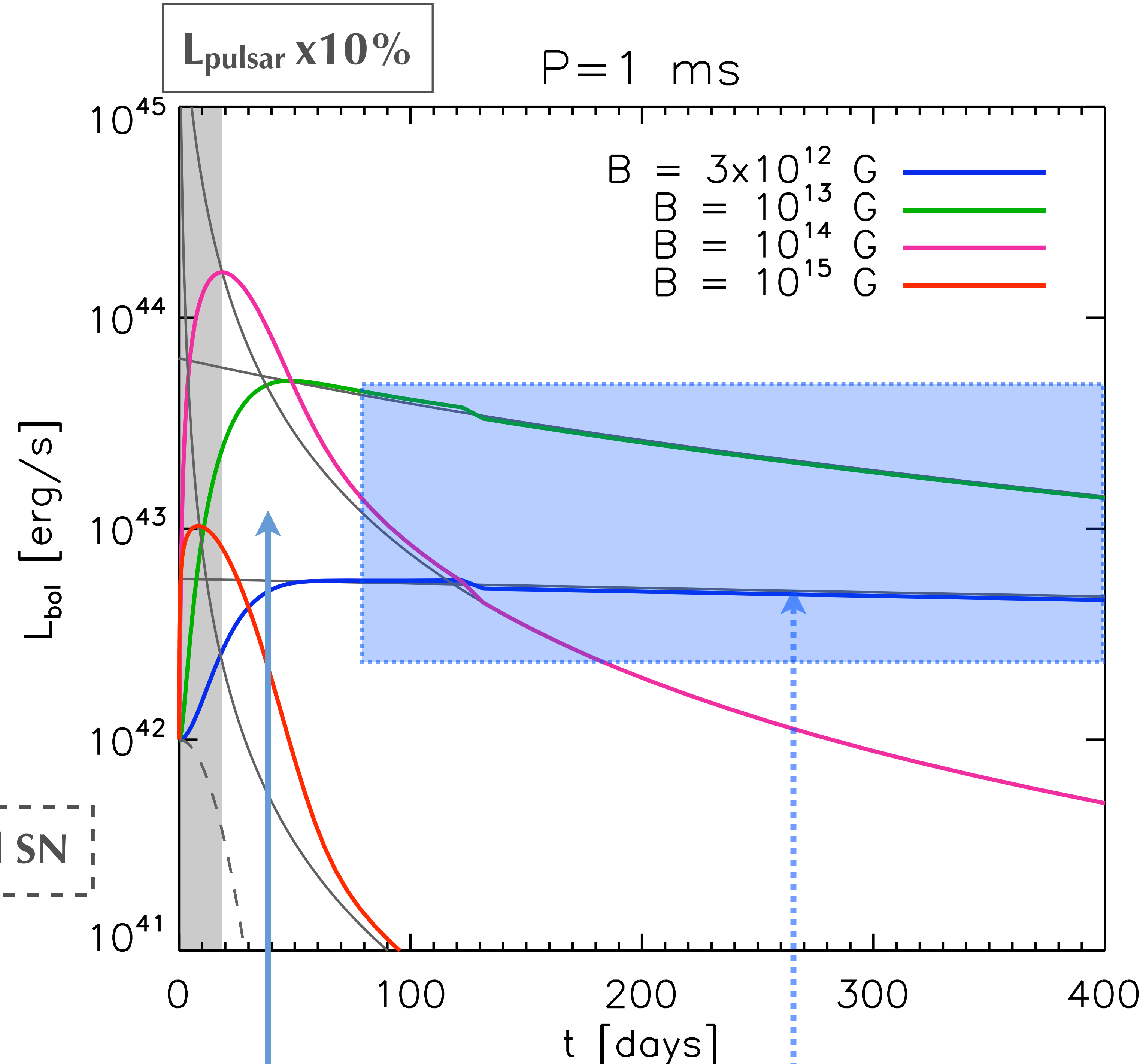
$M_{ej} = 5\ M_{sun}$

$E_{SN} = 10^{51}$ erg

10% pulsar rotational energy into radiation



standard SN



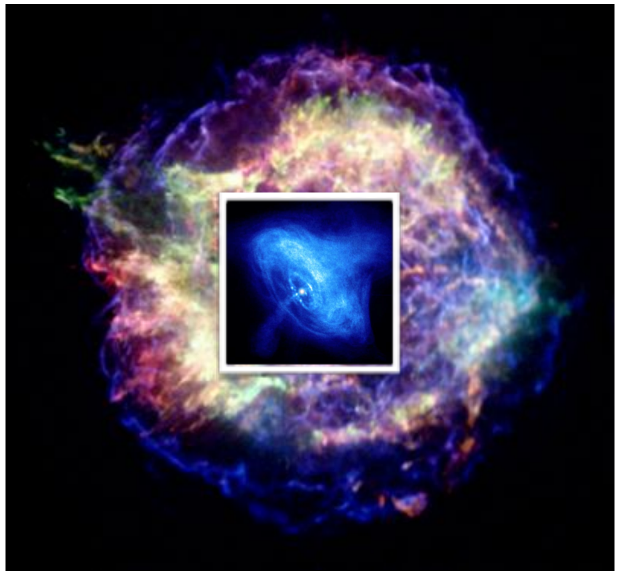
newly formed SN remnant powered by millisecond pulsar:

- possibly ultraluminous
- interesting lightcurve @ few years

high plateau (in bol.)

Peculiar supernova lightcurves

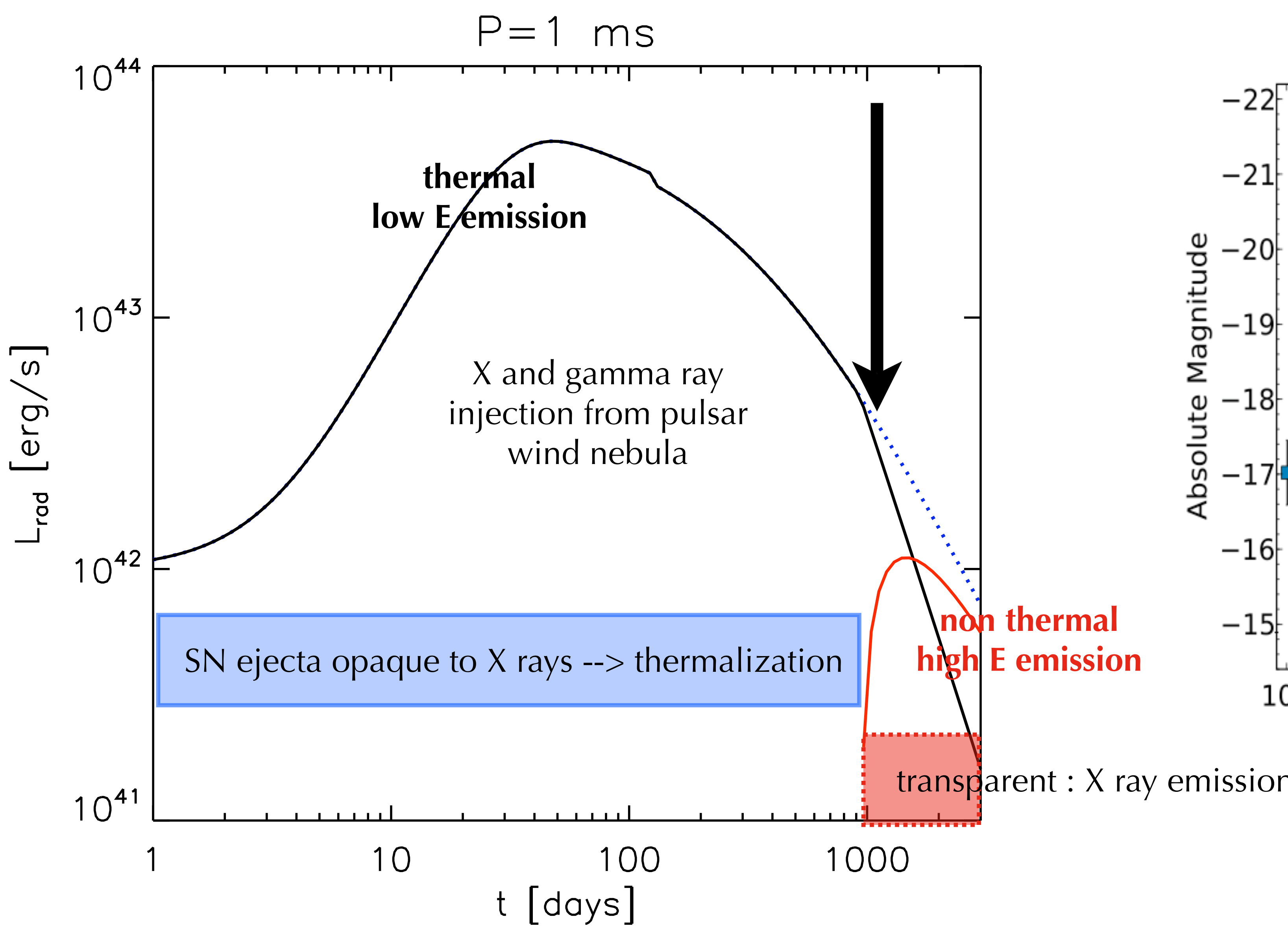
KK, Phinney, Olinto in prep.

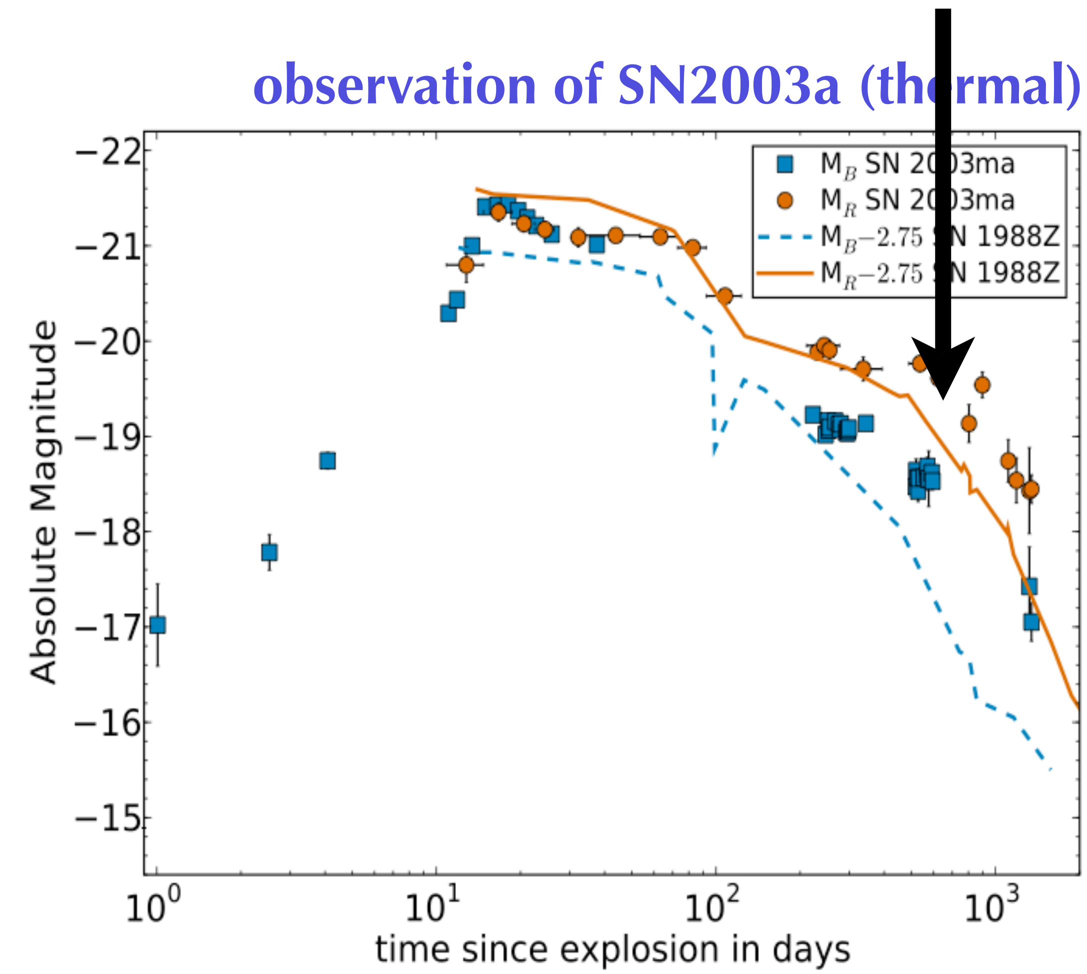


$M_{ej} = 5\ M_{sun}$
$E_{SN} = 10^{51}$ erg

10% pulsar rotational energy into radiation

Follow up of SN lightcurves over **a few years** will be crucial





Rest et al. (2011)

What will be needed to find the sources of UHECRs

UHECR data:

more statistics for anisotropy signatures (transient/steady sources)
more statistics for shape of energy spectrum at highest E
more statistics for chemical composition at highest E

JEM-EUSO

Particle Physics:

shower development, parameters for hadronic interactions

Astrophysics:

better understanding of most powerful sources: escape issues
measurements of intergalactic magnetic fields

multi-wavelength studies from radio to gamma-rays

measurement of gamma-ray halos? (e.g. Neronov & Semikoz 09)

Other messengers:

cosmogenic neutrinos (produced during propagation)
gamma-rays (GeV to UHE)
gravitational waves *KK 2011*

KK, Allard & Olinto 2010
KK, Allard & Lemoine 2011

could be observed for reasonable source scenarios if composition is dominated by protons

Surprisingly promising candidate: millisecond pulsars

signatures if birth in our Local Group
look for signatures in SN light curves @ few years after explosion

Fang, KK, Olinto 2012
Fang, KK, Olinto in prep.
KK, Phinney, Olinto in prep.