IAU sympo 324: New Frontiers in Black Hole Astrophysics

# Multi-Messenger Approaches to Galactic PeVatrons

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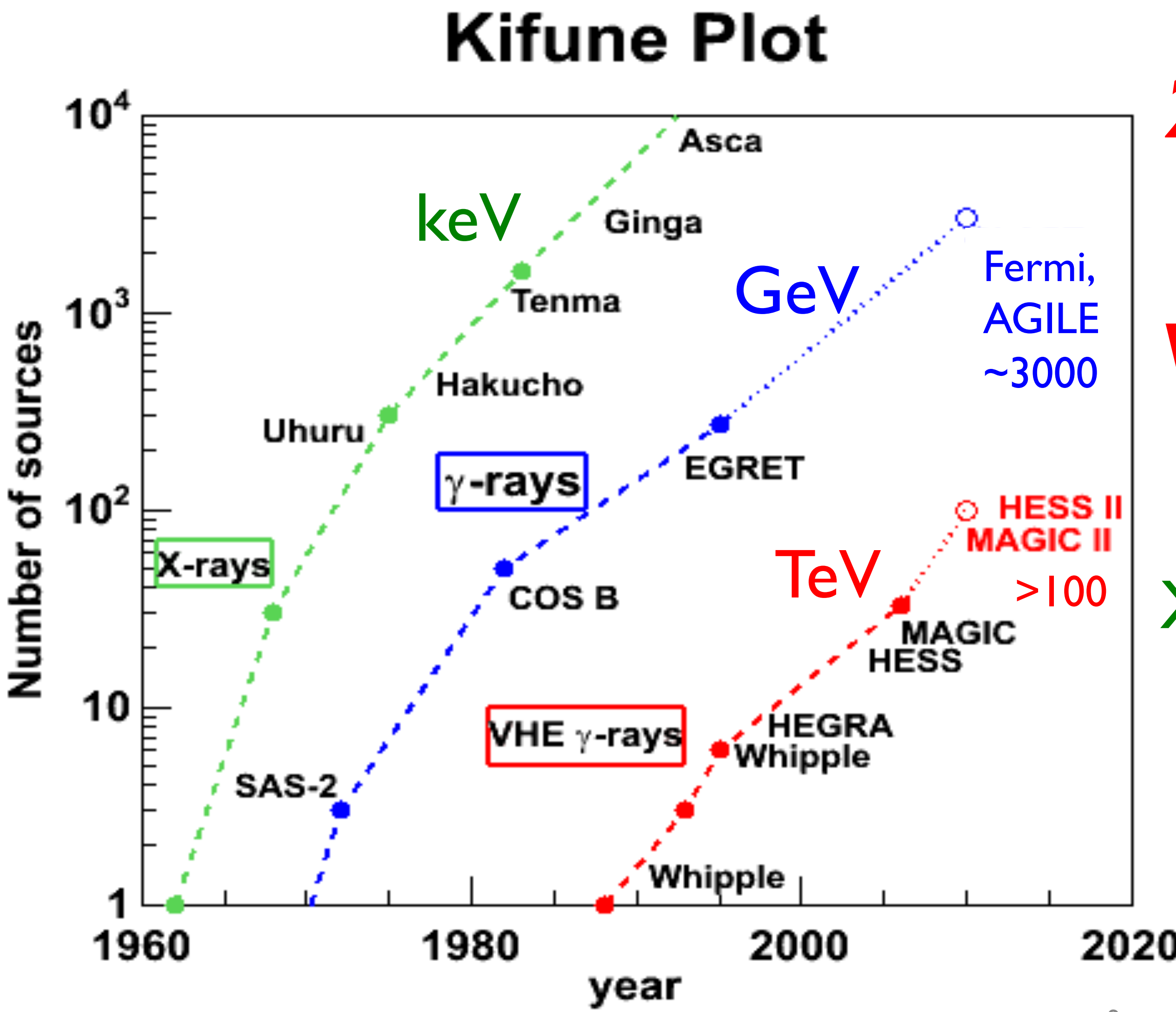
# Multi-Wavelength Era

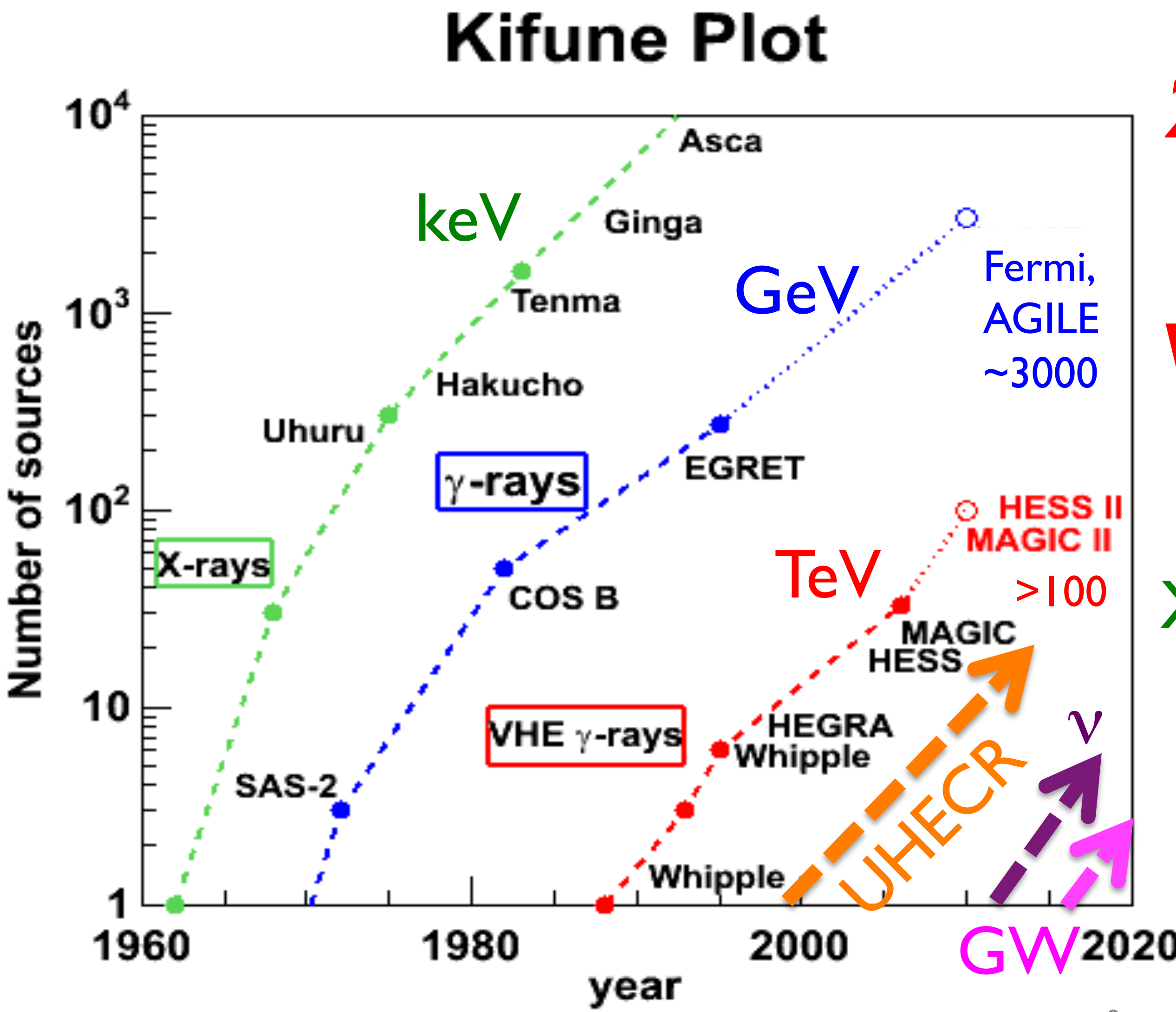



***20th century: Multi-wavelength***

μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

\# of sources are increasing exponentially

# Multi-Messenger Era




**20th century: *Multi-wavelength***

μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

\# of sources are increasing exponentially

# Multi-Messenger Era

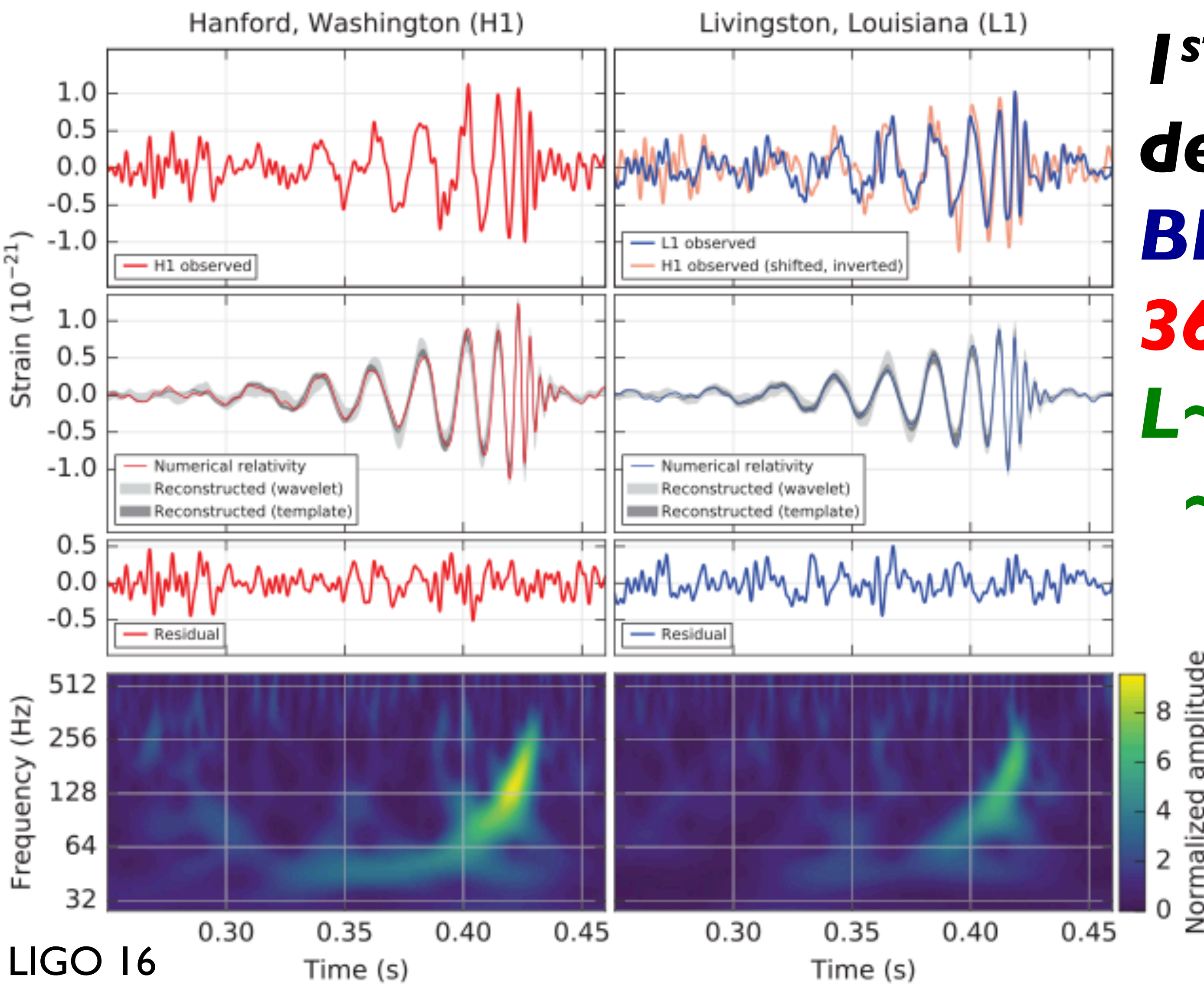

**21th Century: Multi-Messenger Era**

# Contents

- **Gravitational wave**
  - BH-BH!!!
  - Galactic PeVatrons? TeV unIDs? — KI, Matsumoto, Teraki, Kashiyama & Murase in prep.
- **Heavy cosmic ray**
  - r-process cosmic rays — Kyutoku+ 13, Kyutoku & KI 16; Takami+ 14
  - He & C hardening — Ohira & KI 11, Ohira+ 16
- **Ultra-long GRB** — Suwa & KI 11; Matsumoto+ 15, 16; Murase & KI 13
  - Collapsar? HE ν?
  - WD TDE — KI, Hotokezaka & Piran 16

# We Did It!

# GW150914




LIGO 16

***$1^{st}$ direct detection***

***BH-BH***

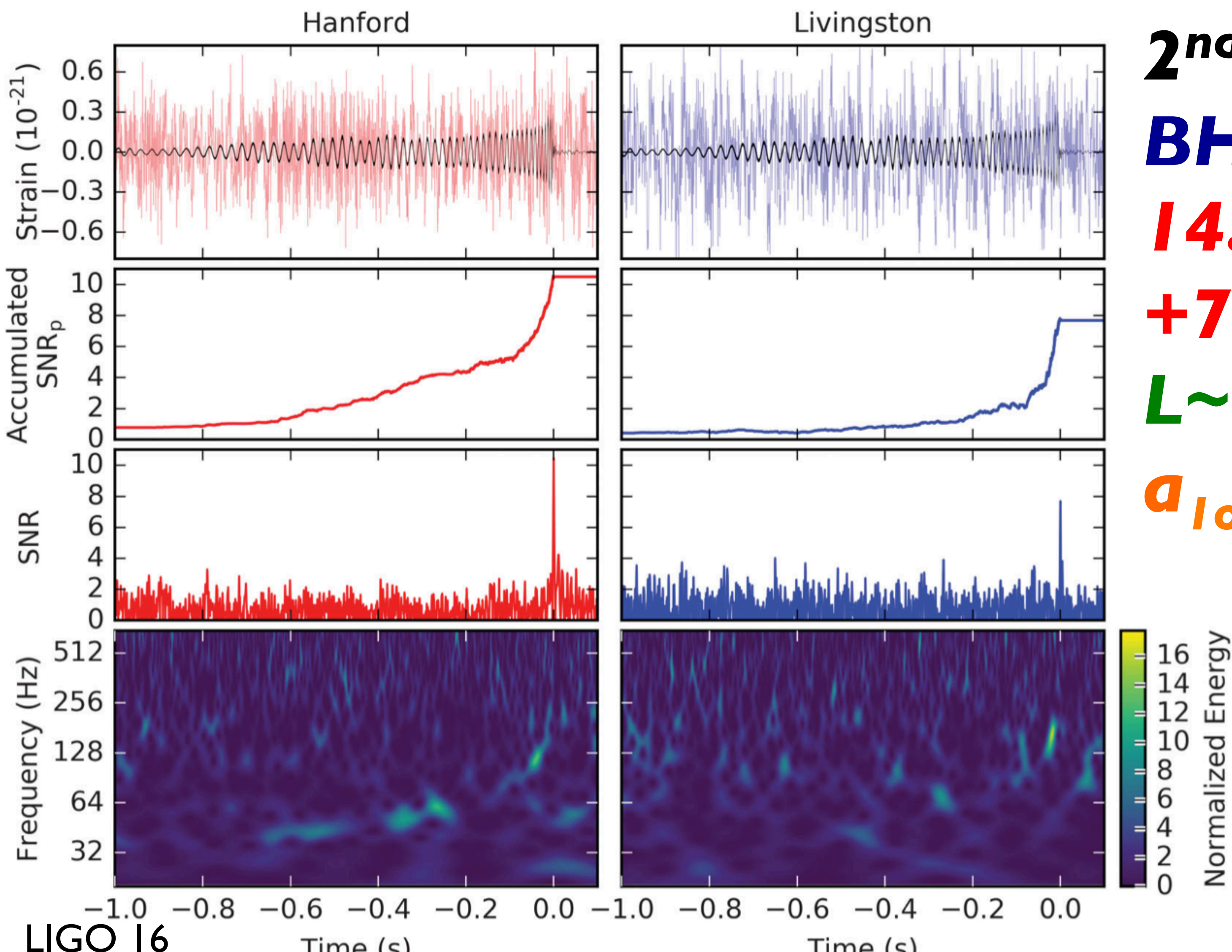
***$36M_\odot+29M_\odot$***

***$L\sim200M_\odot c^2/s$***

***$\sim10^{-3}\ c^5/G$***

30-350Hz bandpass
First at L1
6.9+0.5-0.4ms
later at H1

# GW151226




LIGO 16

***2nd event***

***BH-BH***

***$14.2M_\odot$ $+7.5M_\odot$***

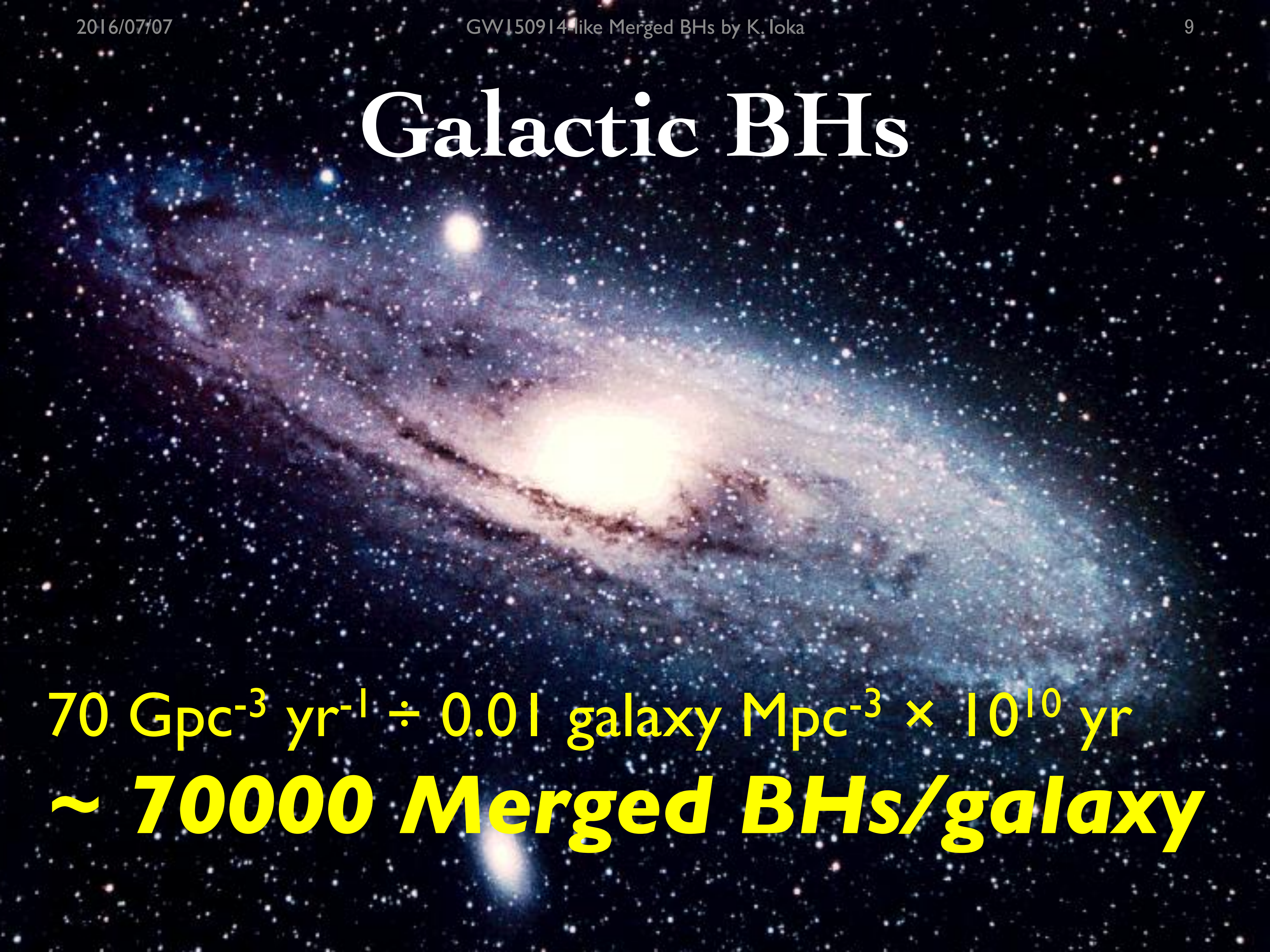
***$L\sim170M_\odot c^2/s$***

***$a_{1or2} > 0.2$***

LVT151012

$R_{GW}$~9-240 events $Gpc^{-3}$ $yr^{-1}$

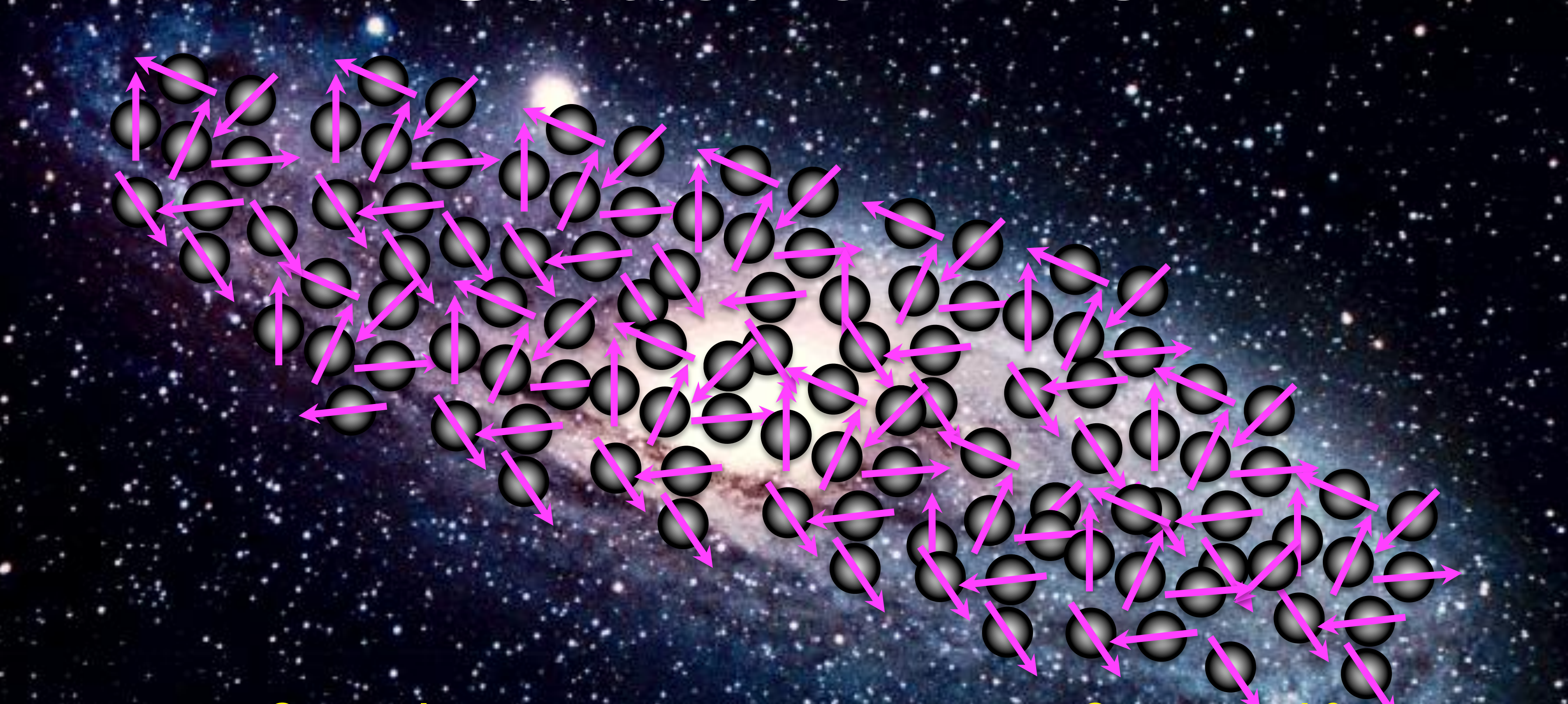
# Galactic BHs



70 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} \div 0.01$ galaxy $\mathrm{Mpc}^{-3} \times 10^{10}$ yr

***~ 70000 Merged BHs/galaxy***

# Galactic BHs



70 $\mathrm{Gpc^{-3}\ yr^{-1}} \div 0.01$ galaxy $\mathrm{Mpc^{-3}} \times 10^{10}$ yr

***~ 70000 Merged BHs/galaxy***

# Old Problem

- Eddington 20's
- Hoyle & Lyttleton 39
- Bondi & Hoyle 44
- Bondi 52
- Zel'dovich 64
- Salperter 64
- Lynden-Bell 69
- Shvartsman 71
- Michel 72
- Shapiro 73
- Shakura & Sunyaev 73
- Meszaros 75
- Ipser & Price 77, 82, 83
- Grindlay+ 78
- Carr 79
- McDowell 85
- Campana & Pardi 93
- Heckler & Kolb 96
- Fujita+ 98
- Popov & Prokhorov 98
- Armitage & Natarajan 99
- Agol & Kamionkowski 02
- Chisholm+ 03
- Barkov+ 12
- Motch & Pakull 12
- Fender+ 13

**GWs put a lower limit on #(spinning BHs)**

# Spin Energy

$$E_{\rm spin} = \left(1 - \sqrt{\frac{1+\sqrt{1-a_*^2}}{2}}\right) Mc^2$$

$$\cong 7\% \times Mc^2 \sim 1\times 10^{54}\,{\rm erg}\left(\frac{M}{10 M_\odot}\right)$$

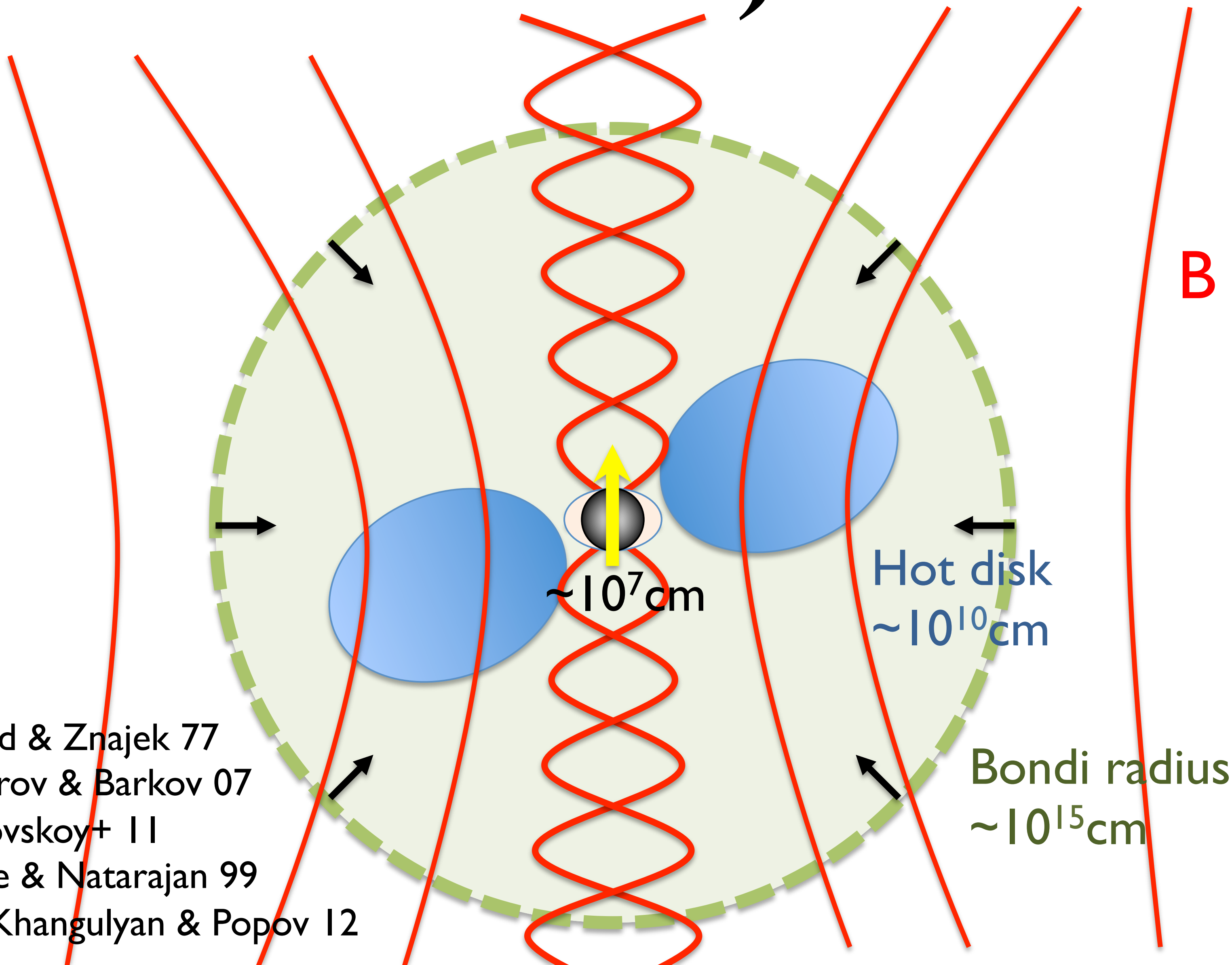
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7\times 10^4\ {\rm BHs} \times 1 \times 10^{54}\,{\rm erg}$$

$$\sim 9 \times 10^{58}\,{\rm erg}$$

$$\sim \frac{10^{10}\,{\rm yr}}{100\,{\rm yr}}\ {\rm supernovae}$$

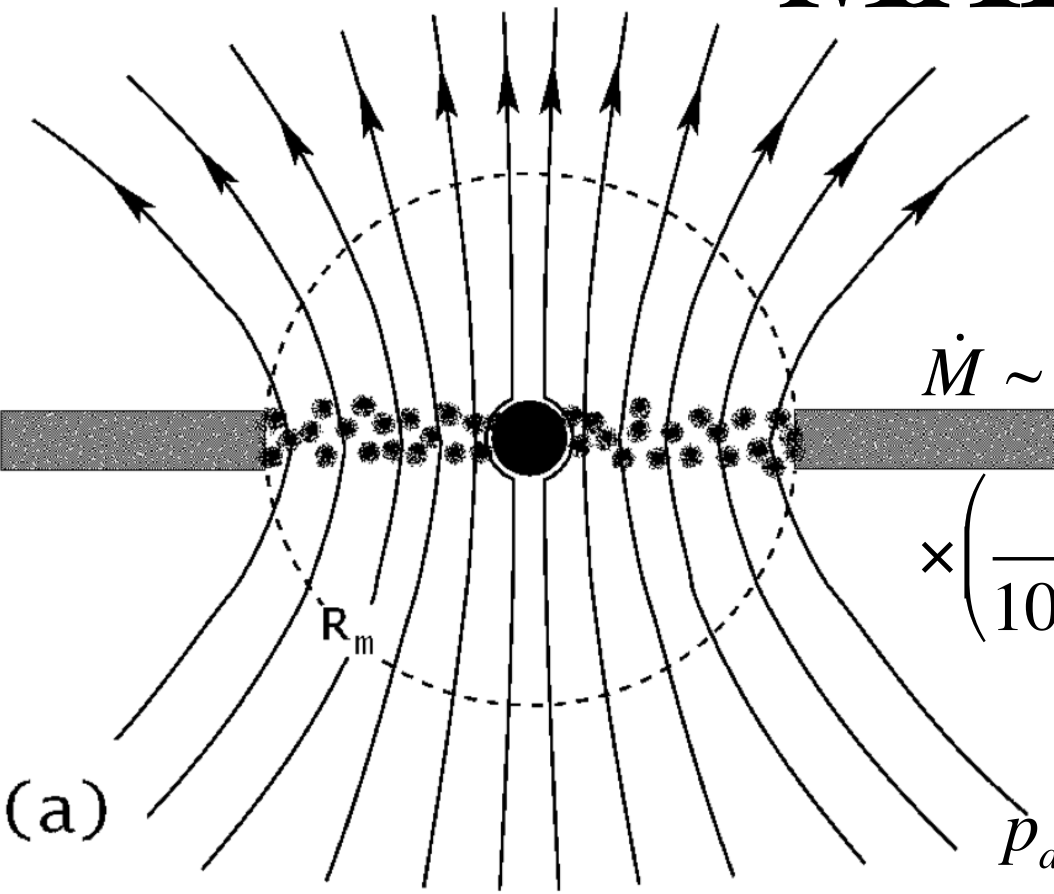
**Comparable to supernovae ever happened!**

# Blandford-Znajek Effect




Blandford & Znajek 77
Komissarov & Barkov 07
Tchekhovskoy+ 11
Armitage & Natarajan 99
Barkov, Khangulyan & Popov 12

# MAD




Magnetically Arrested Disk

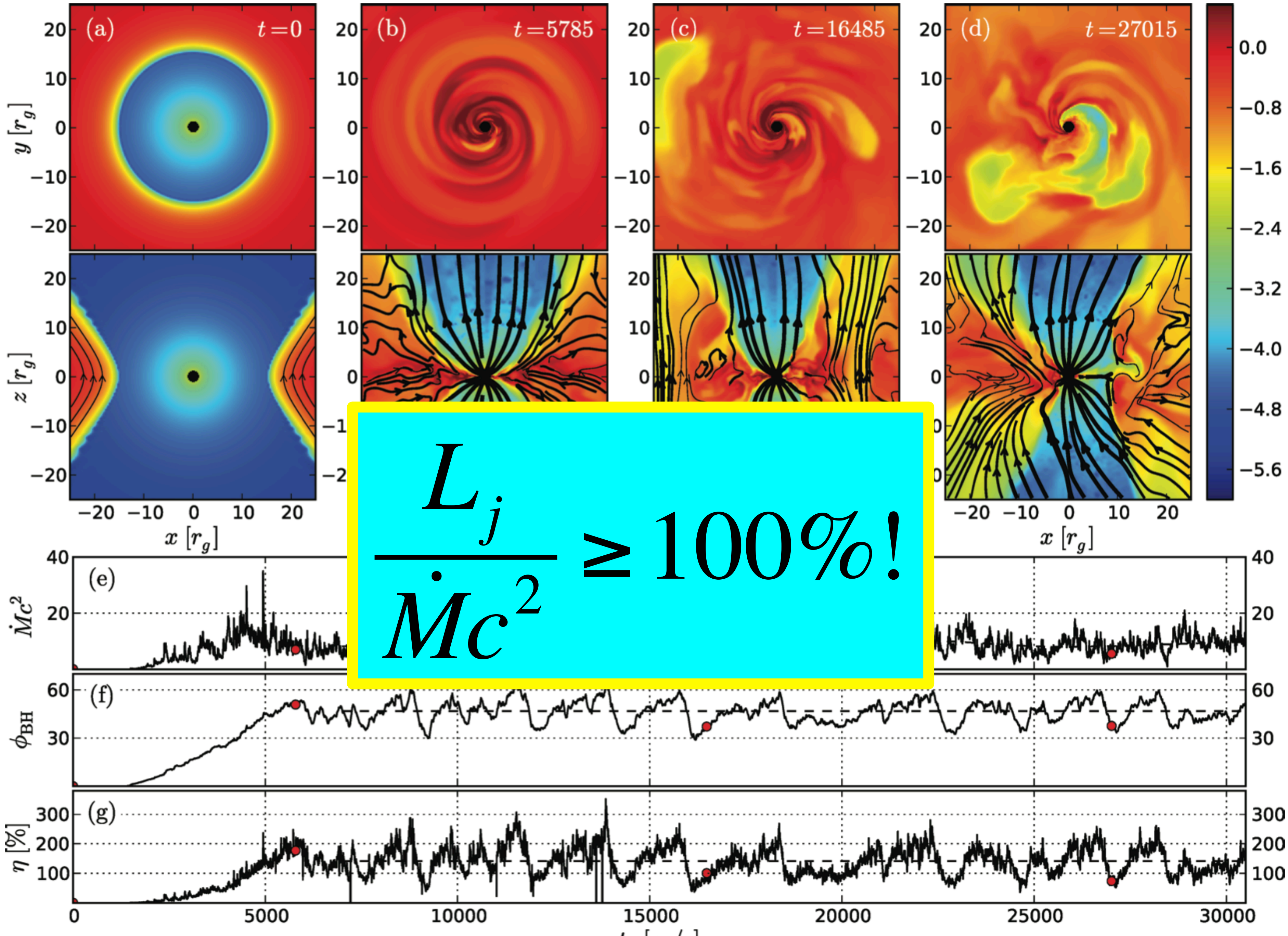
**B-flux saturation**

$$\dot{M} \sim 4\pi r_B^2 V \rho \sim 5\times 10^{35} \mathrm{erg\ s^{-1}} \times \left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10 M_\odot}\right)^2 \left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

$$p_a = \frac{GM\Sigma}{r^2} \sim \frac{GM\dot{M}}{2\pi r^3 v_r} \Leftrightarrow p_B = \frac{B^2}{8\pi}$$

Bisnovatyi-Kogan & Ruzmaikin 76
Narayan+ 03

$$B_H \sim \sqrt{\frac{4GM\dot{M}}{r^3 v_r}}\Bigg|_{r=r_H} \sim 4\times 10^7 \mathrm{G} \left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)^{1/2} \left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3/2}$$




$$\frac{L_j}{\dot{M}c^2} \geq 100\%!$$

Tchekhovskoy+ 11, McKinney+ 12

# Luminosity Function

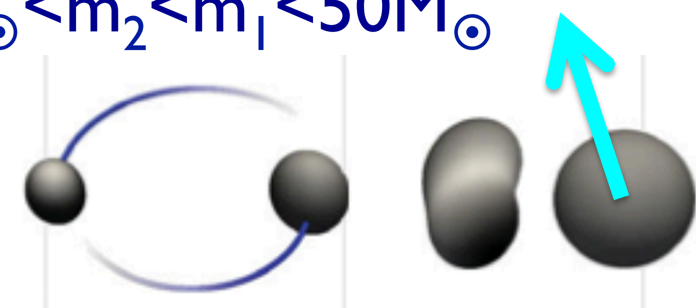
$$\frac{dN}{d\dot{M}} = N_{\rm BH} \int dm_1 \frac{dp(m_1)}{dm_1} \int dm_2 \frac{dp(m_2|m_1)}{dm_2} \int dv \frac{df(v)}{dv} \int dn \frac{d\xi(n)}{dn} \times h(m_1, m_2, v) \delta \left[ \dot{M}(n, m_1, m_2, v) - \dot{M} \right],$$

Agol & Kamionkowski 12
KI+ in prep.

**BH mass:** $m_1$: Salpeter, $m_2$: Flat, $5M_\odot < m_2 < m_1 < 50M_\odot$

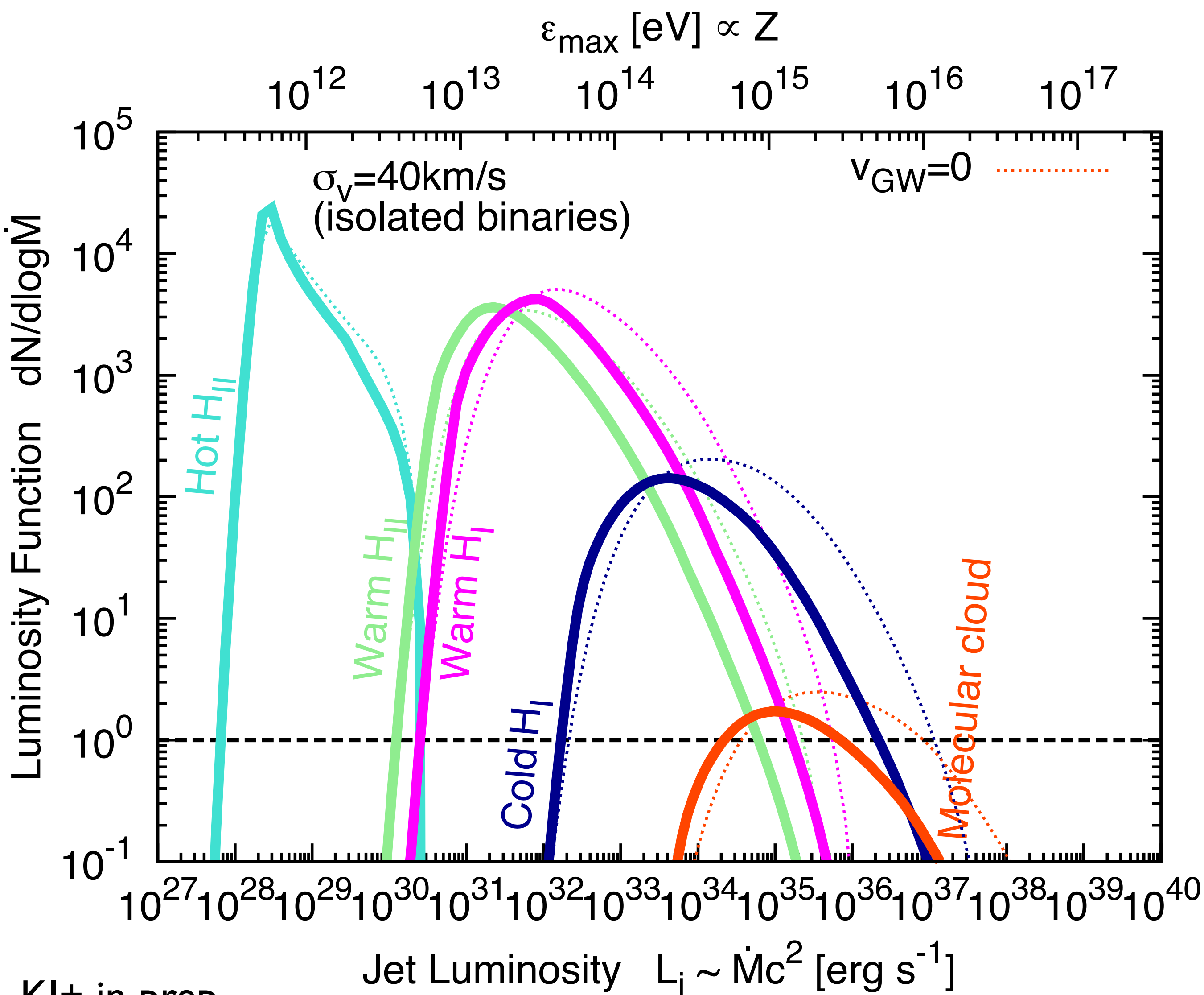
**Velocity:** Maxwell distribution
+ GW recoil + ISM sound velocity

**Density:** 5 phases of ISM



| Phase | $n_1$ [cm$^{-3}$] | $n_2$ [cm$^{-3}$] | $\beta$ | $\xi_0$ | $c_s$ [km s$^{-1}$] | $H_d$ |
|---|---|---|---|---|---|---|
| Molecular clouds | $10^2$ | $10^5$ | 2.8 | $10^{-3}$ | 10 | 75 pc |
| Cold $H_I$ | 10 | $10^2$ | 3.8 | 0.04 | 10 | 150 pc |
| Warm $H_I$ | 0.3 | – | – | 0.35 | 10 | 0.5 kpc |
| Warm $H_{II}$ | 0.15 | – | – | 0.2 | 10 | 1 kpc |
| Hot $H_{II}$ | 0.002 | – | – | 0.4 | 150 | 3 kpc |

# Luminosity Function

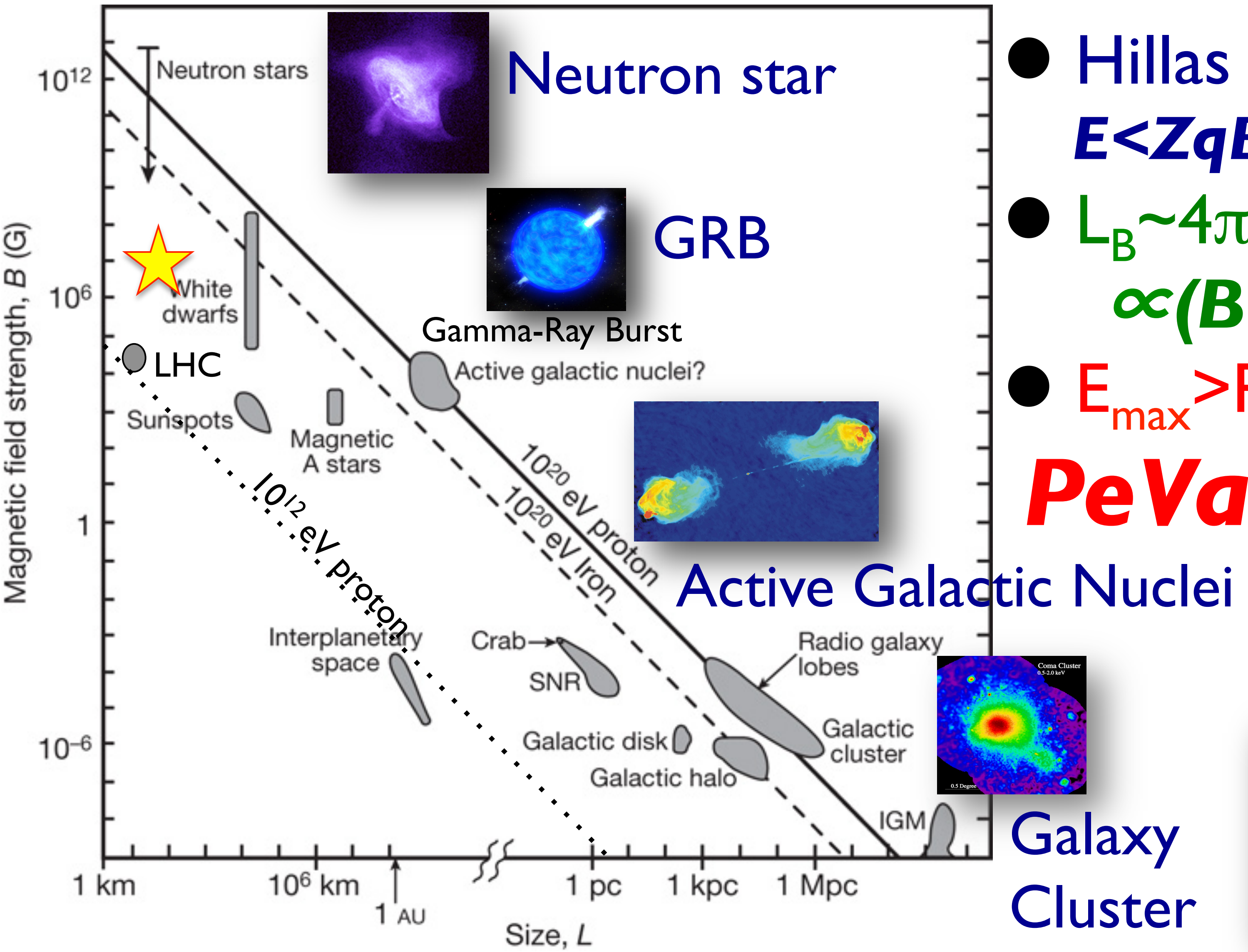



The most luminous BH jet is $\sim 10^{36}$ erg/s in cold $H_I$

$v_{GW}$ reduces $L_j$ by ~10

KI+ in prep.

# Particle Acceleration



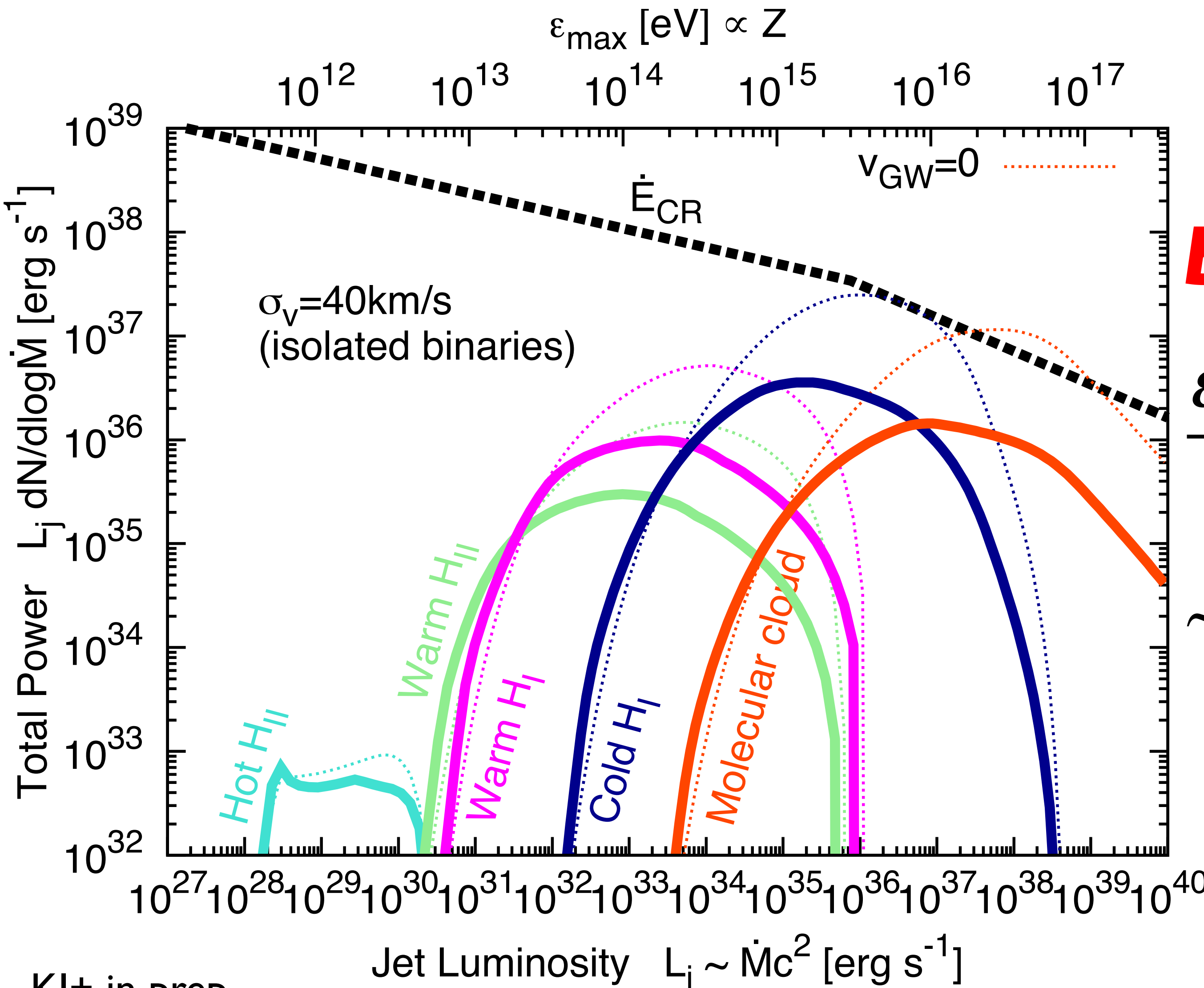

- Hillas condition
  ***E<ZqBR***
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$ Blandford 00, Waxman 04
- $E_{max}$>PeV

***PeVatron!!!***

Barkov+ 12
KI+ in prep.

Dark Matter?

# Total Power




KI+ in prep.

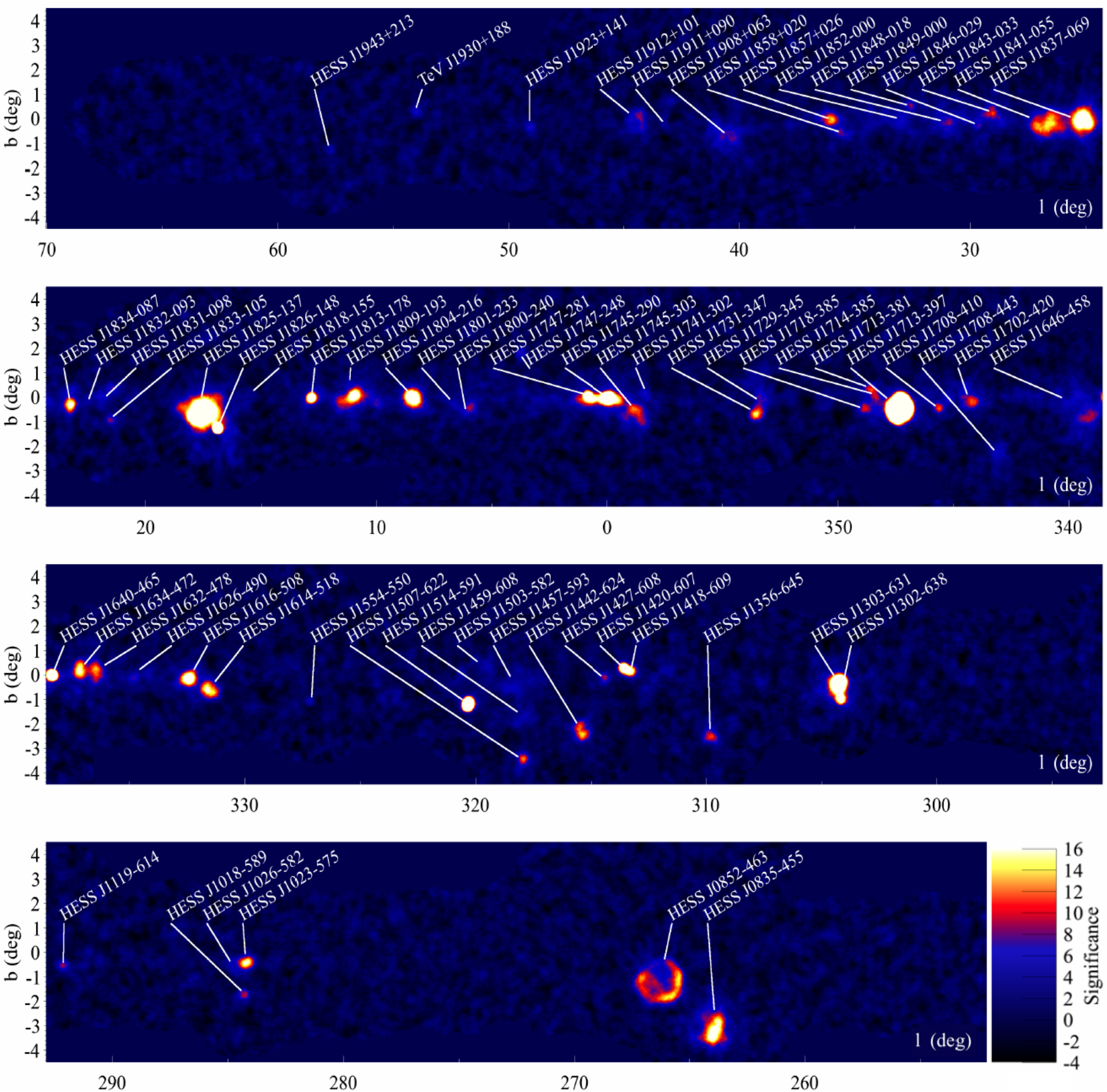
**BHs ⇔ Cosmic rays beyond PeV?**

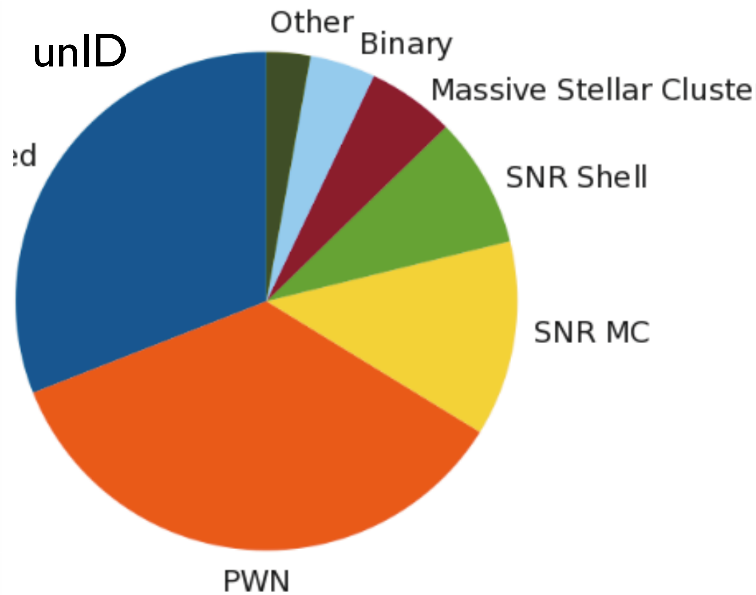
$$\frac{\varepsilon_{CR} E_{SN}}{100\,\mathrm{yr}} \sim 3\times 10^{40}\ \mathrm{erg\ s^{-1}}$$

**If leptonic ⇔ $e^{\pm}$ excess?**

# TeV Gamma-Ray Sky

HESS 1307.4690



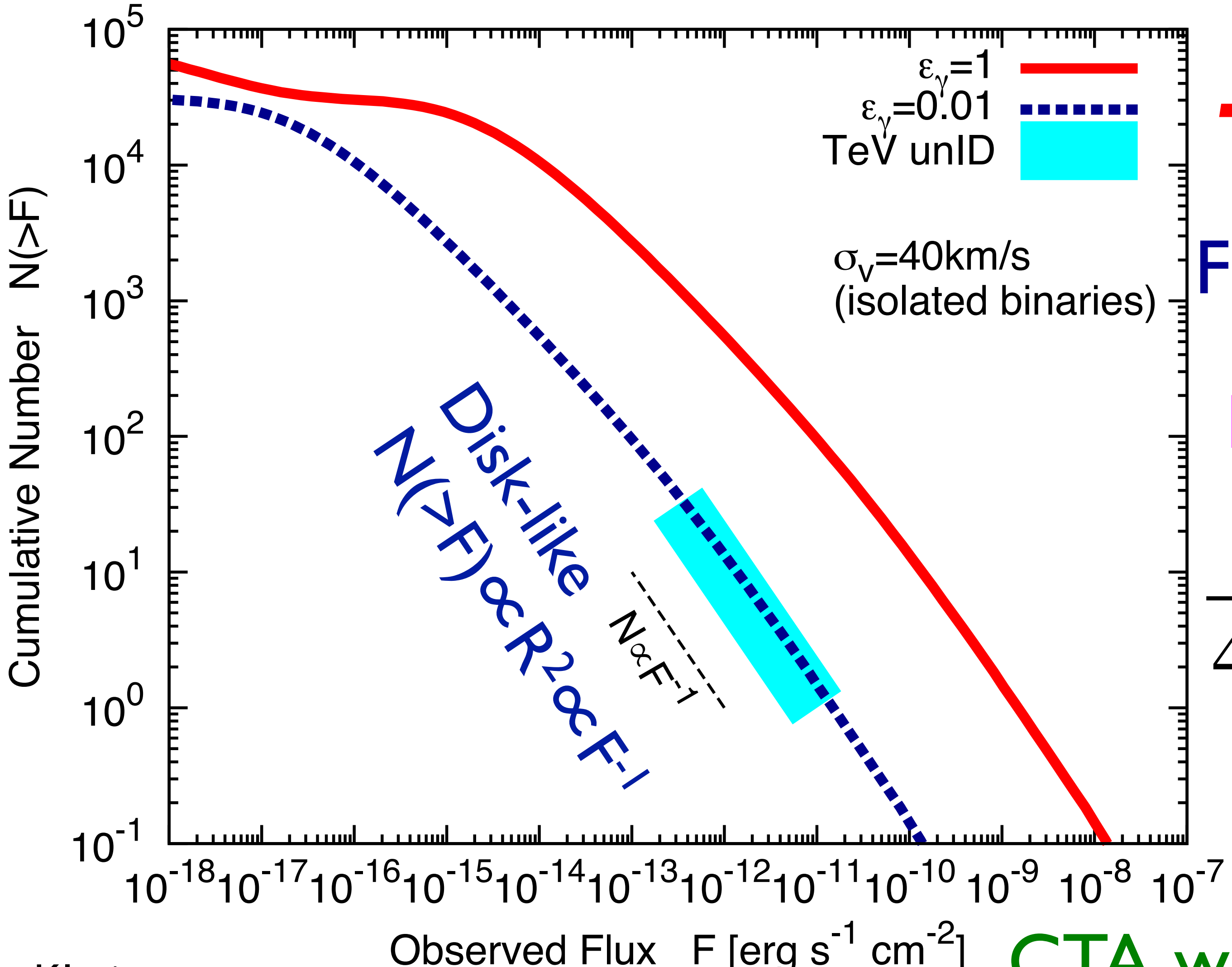




**unIDs dominate TeV γ-ray sky**

Spatially extended

$$R \sim \theta d \sim 3\mathrm{pc}\left(\frac{\theta}{0.2^\circ}\right)\left(\frac{d}{\mathrm{kpc}}\right)$$

# Log N – Log F




KI+ in prep.

**BHs ⇔ TeV unIDs?**

Flux dis. is similar

BH nebula size:

$$\frac{L_j}{4\pi r_h^2 \theta^2 c} \sim \rho V^2$$

$$\Rightarrow \; r_h \sim 3 \text{ pc}$$

CTA will see ~$10^3$ BHs

# Model Uncertainties

| | Number $N_{\rm BH}$ | Velocity $\sigma_v$ [km s$^{-1}$] | Spin $a_*^i$ | Disk $s$ | Duty cycle $\mathscr{D}$ | Total power $P_{\rm tot}$ [erg s$^{-1}$] |
|---|---|---|---|---|---|---|
| Isolated binary (fiducial) | $7 \times 10^4$ | 40 | 0 | 0 | 1 | $\sim 10^{37}$ |
| Stellar cluster | – | 200 | – | – | – | $\sim 10^{37} \times 10^{-2}$ |
| High spin | $10^8$ | – | 0.2 | – | – | $\sim 10^{37} \times 10^{3}$ |
| Wind | – | – | – | 1 | – | $\sim 10^{37} \times 10^{-1}$ |
| Feedback | – | – | – | 1 | $10^{-2}$ | $\sim 10^{37} \times 10^{-3}$ |

KI, Matsumoto, Teraki, Kashiyama & Murase in prep.

$$\dot{M}_{BH} \sim \dot{M}\left(\frac{20r_S}{r_{\rm disk}}\right)^s \text{ for } r_{\rm disk} > 20r_S$$

Blandford & Begelman 99
Yuan+ 16

$$\text{Duty cycle} \sim \frac{t_{\rm active}}{t_{\rm dormant}} \sim \frac{\text{Accretion time}@r_{\rm Bondi}}{\text{Nebula lifetime}} \sim 10^{-2}$$

***Uncertainties in total power ~ $\times 10^{\pm 3}$***

# Tip of Iceberg

# Contents

- **Gravitational wave**
  - BH-BH!!!
  - Galactic PeVatrons? TeV unIDs?

KI, Matsumoto, Teraki, Kashiyama & Murase in prep.

- **Heavy cosmic ray**
  - r-process cosmic rays
  - He & C hardening

Kyutoku+ 13, Kyutoku & KI 16
Takami+ 14

Ohira & KI 11, Ohira+ 16

- **Ultra-long GRB**
  - Collapsar? HE ν?
  - WD TDE

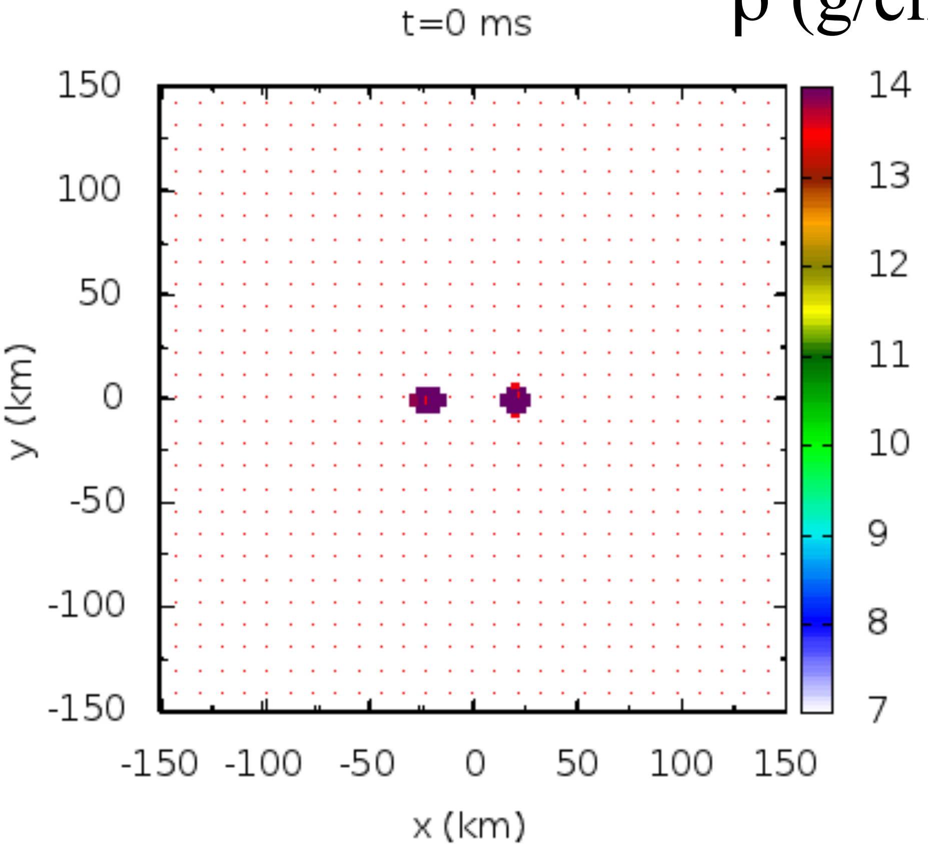
Suwa & KI 11
Matsumoto+ 15, 16
Murase & KI 13

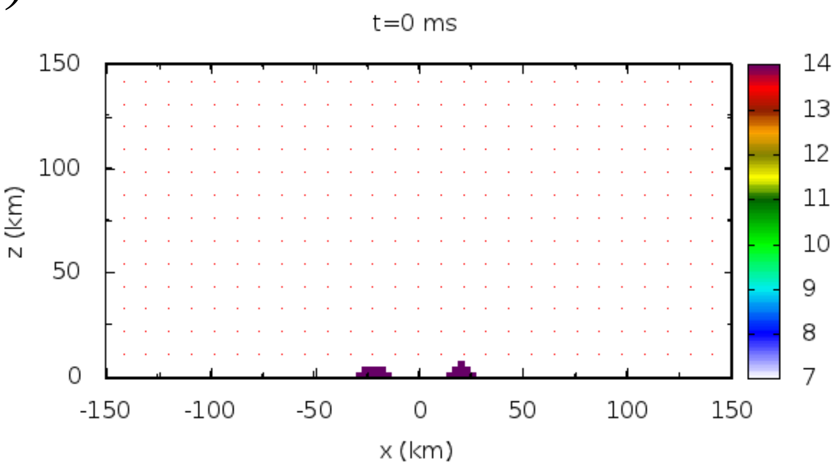
KI, Hotokezaka & Piran 16

# Merger of 1.3-1.4 $M_{sun}$ NS:

# EOS=APR4: stiff but relatively soft

ρ (g/cm³)



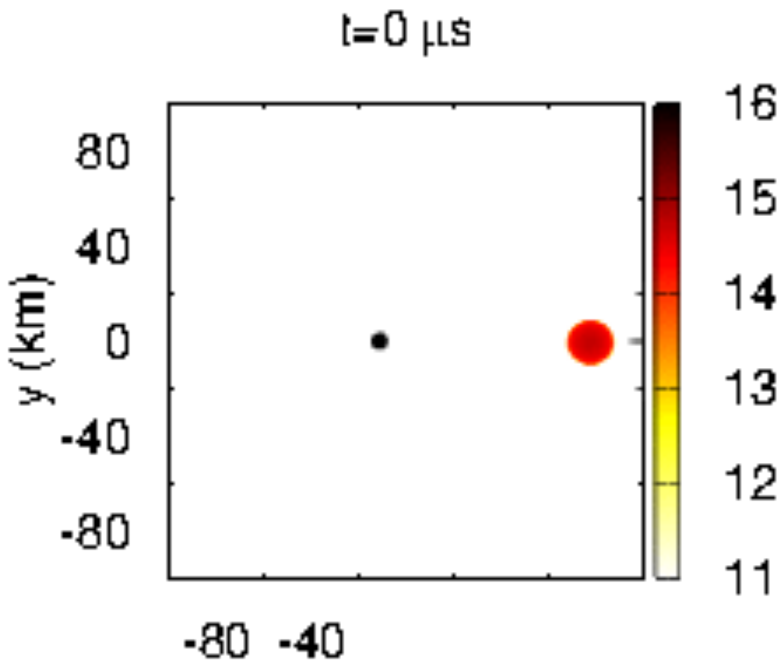



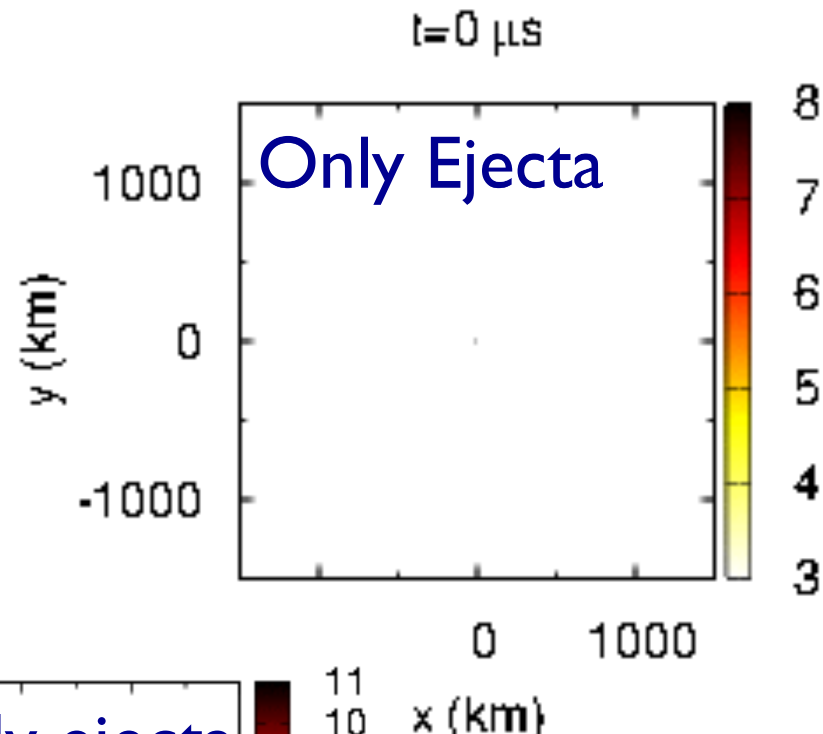

**Relatively wider view**

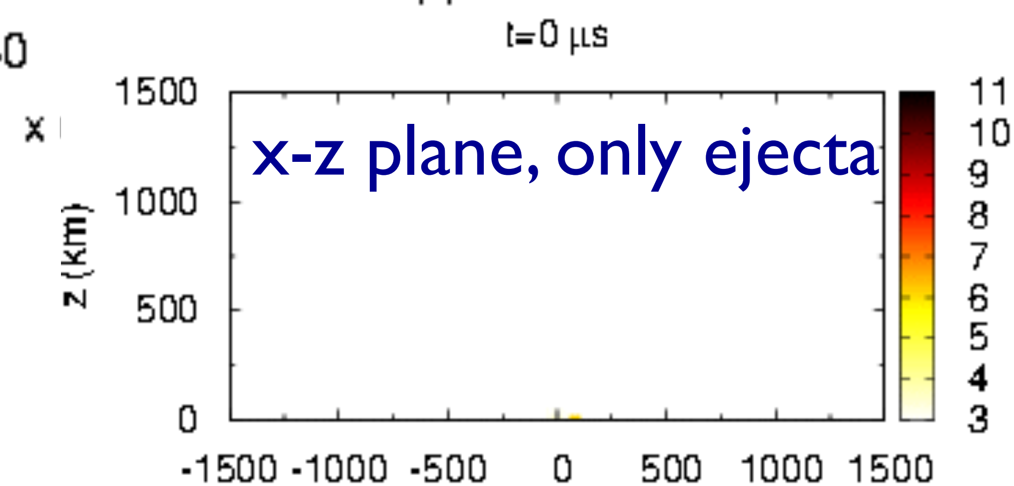
**Orbital plane**

***X-Z* plane**

# BH-NS Merger



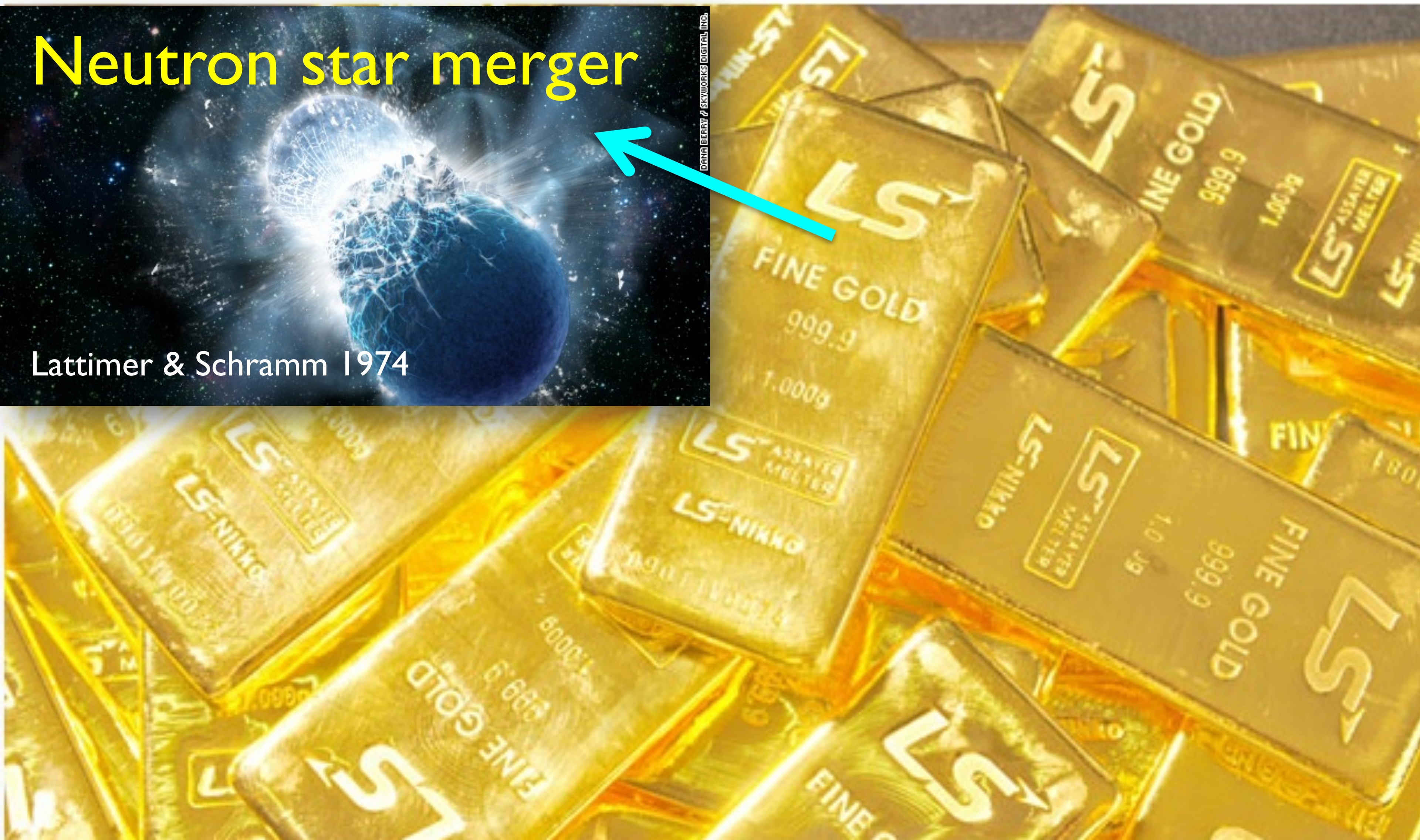




Full GR
Q=5
$\chi$=0.75
H4 EOS

Kyutoku, KI & Shibata 13
Kyutoku+ 15

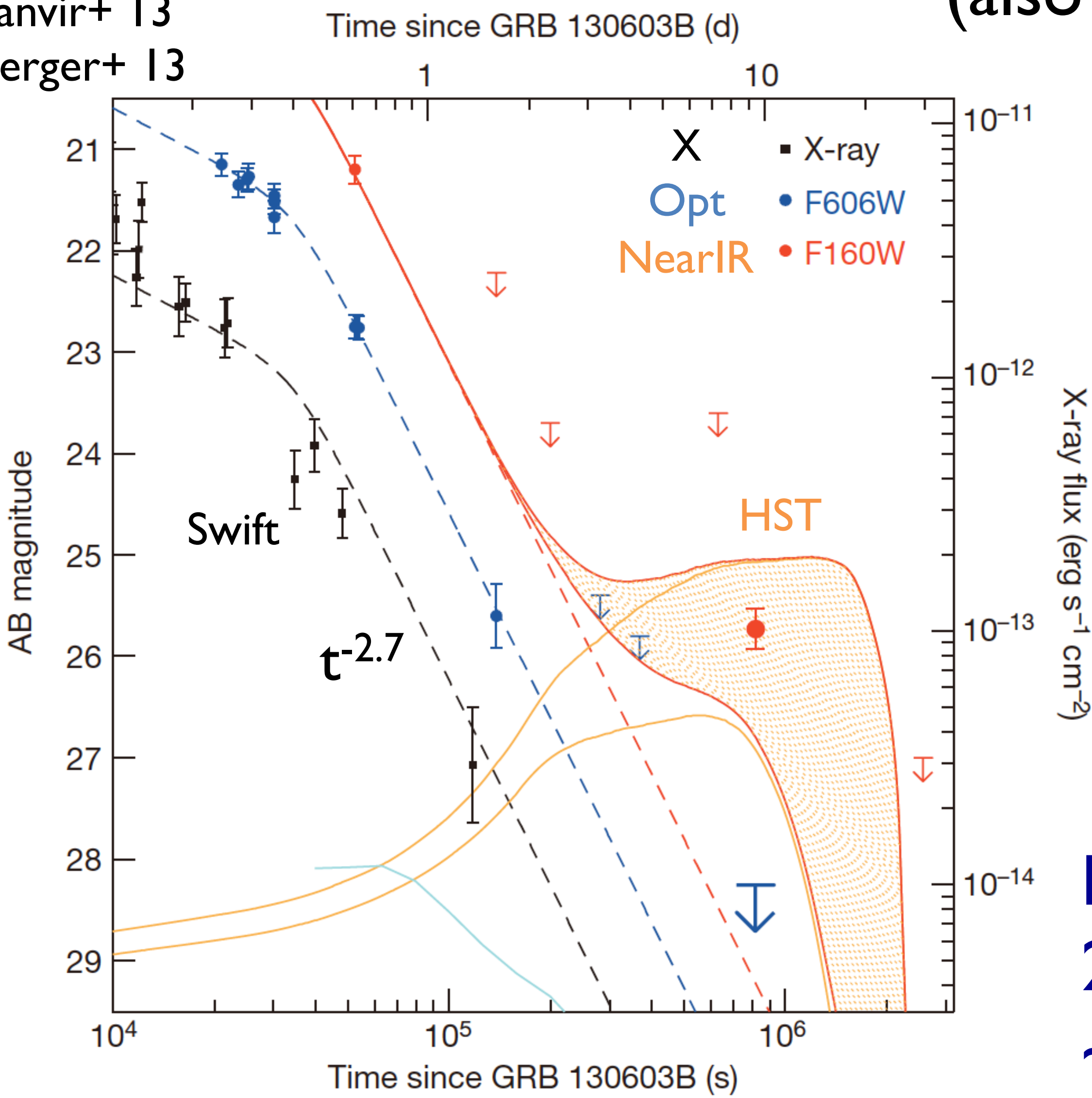
# R-Process Elements?



# Discovery of Macronova

(also known as kilonova)

Tanvir+ 13
Berger+ 13



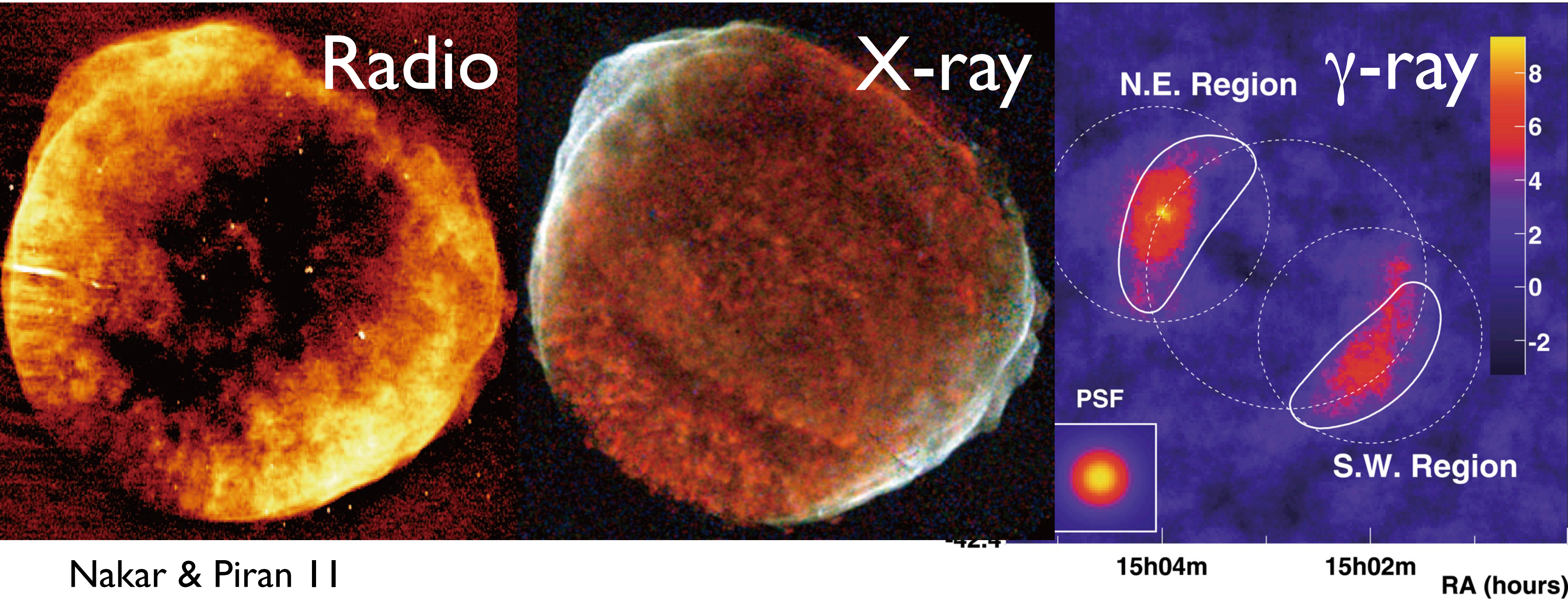

***Ejecta with***
***$\sim$0.01-0.1$M_\odot$***
***$\sim$0.1-0.3c***
***$\sim 10^{50}$-$10^{52}$erg***

***Radioactivity***
***$f \sim E/mc^2 \sim$3e-6***

Li & Paczynski 98
Kulkarni 05

$L \sim 10^{41}$erg/s @z~0.356
22-23 mag if @200Mpc
~10 days

# Like Supernova Remnant

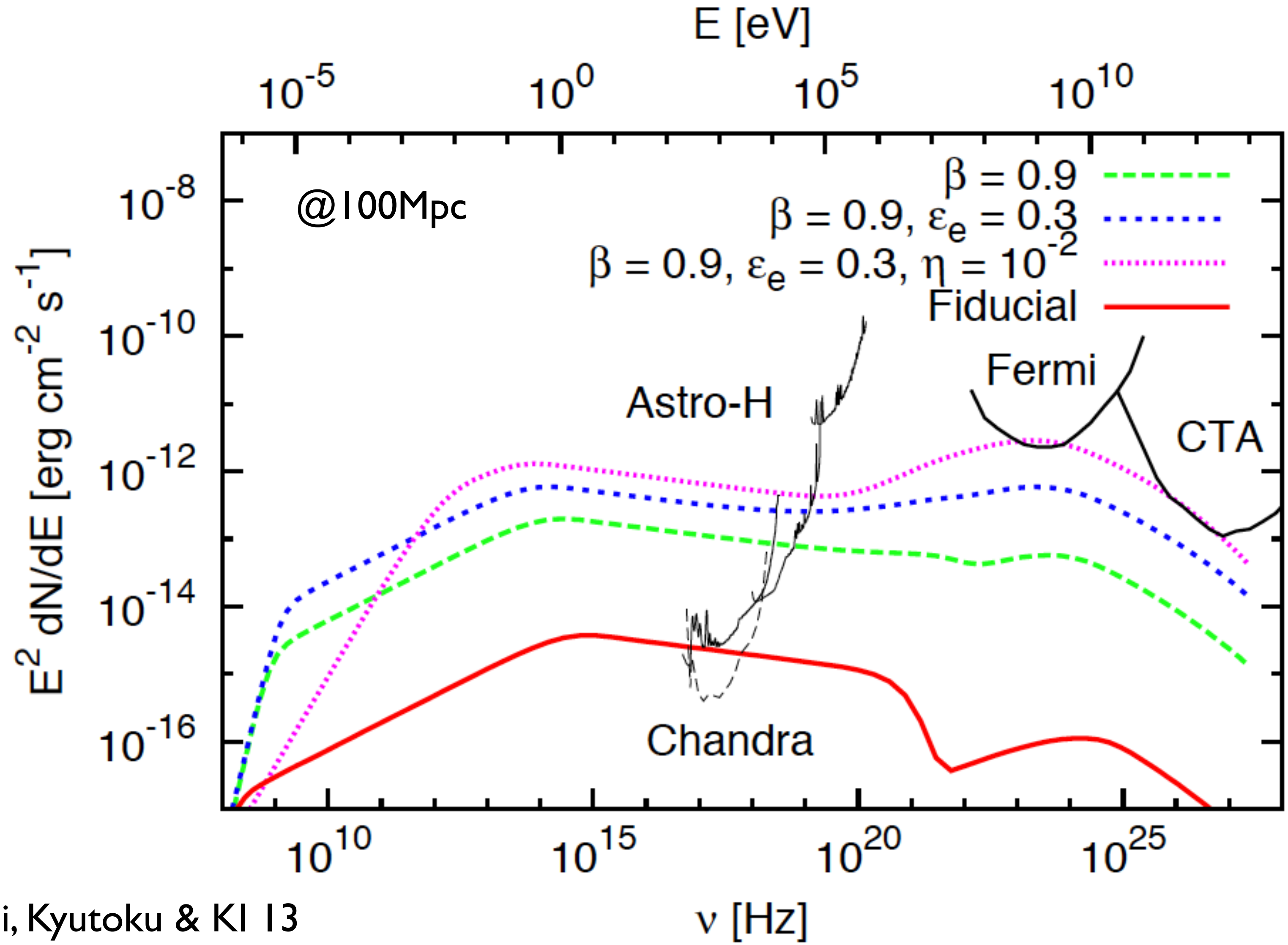



Nakar & Piran 11

NS merger remnant ~ Supernova remnant

⇒ ***High energy remnant for NS merger?***

# Merger Remnant Spectrum




Takami, Kyutoku & KI 13

# Cosmic Ray?

Similar to Supernova Remnant ⇒ Cosmic Ray

## *Maximum Energy*

$$\varepsilon_{\max} = 2\times10^{18}\ \text{eV}\ ZM_{ej,-2}^{1/3} v_{ave,0.3}^{2} \varepsilon_{B,-1}^{1/2} n_{0}^{1/6} \theta_{ej,1/5}^{2/3} \varphi_{ej,\pi}^{-1/3}$$

Larger than SNR due to large velocity

## *Energy Budget*

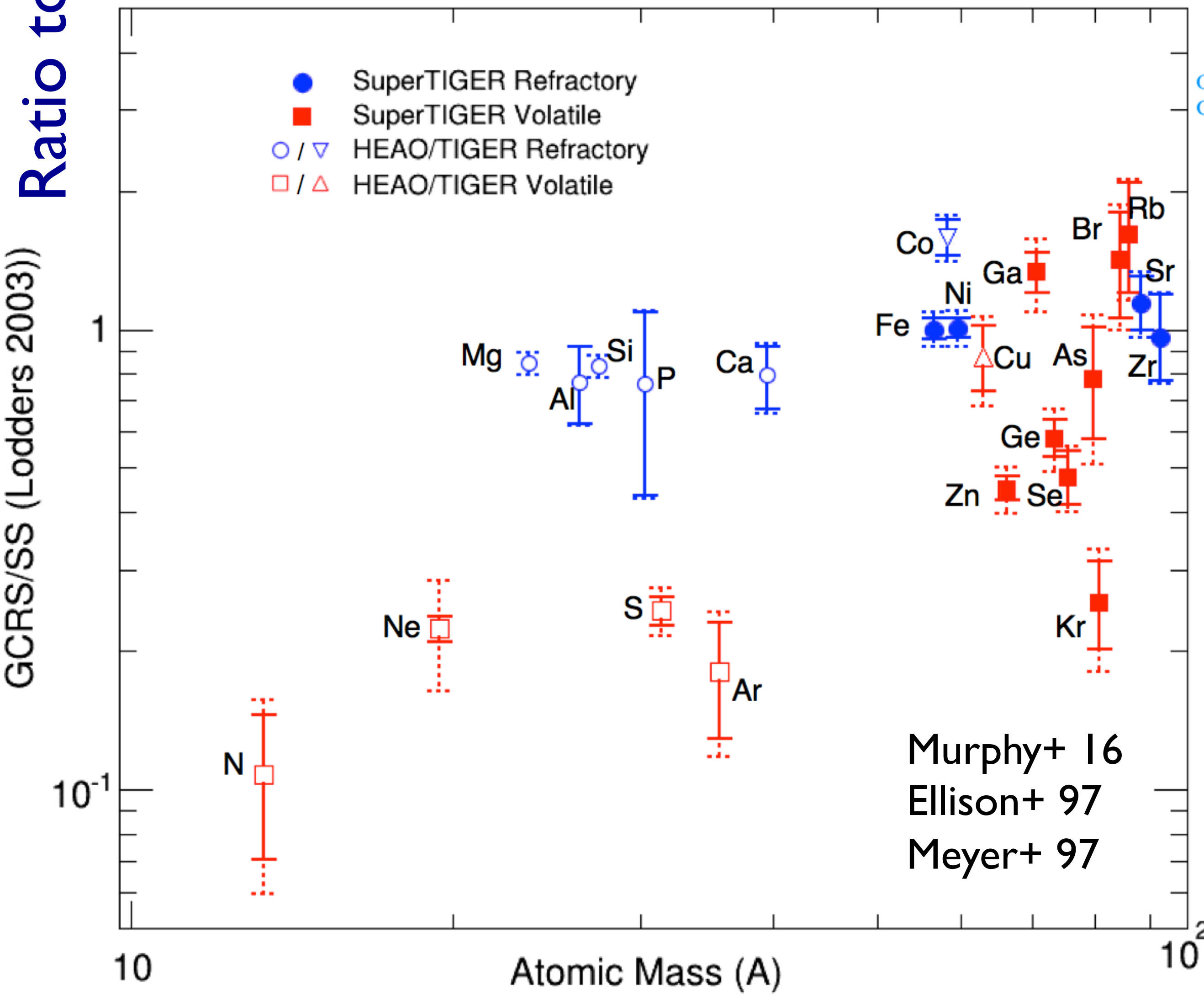
Kyutoku, KI & Shibata 13
Takami, Kyutoku & KI 13

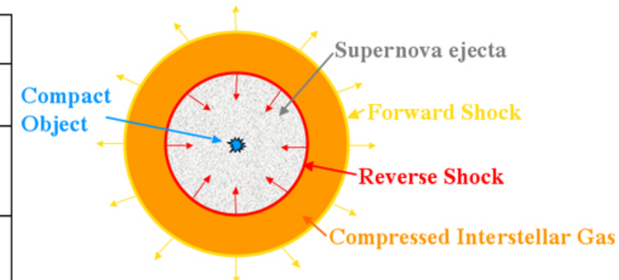
$10^{-4}$ $NS^2$/yr/galaxy ~ SN/100: Not small

Beyond knee CRs?
Ultra-high energy CRs with heavy elements?

# No R-Process Excess

Ratio to solar




No r-excess

⇒ We can say

$E_{CR}^{reverse} < 0.003\%\ E_{kin}$

or not an r-process site

Kyutoku & KI 16

# Energy Generation Rate

**r-CR**

Mass fraction — Ejecta mass — Event rate

$$\dot{E}_{r,\,\mathrm{NSM}} = \eta_{r/f}\varepsilon_{\mathrm{CR}}\frac{1}{2}v_{ej,NSM}^{2}\underline{X_{r,\,\mathrm{NSM}}M_{\mathrm{ej,\,NSM}}\mathfrak{R}_{\mathrm{NSM}}}$$

$$= \eta_{r/f}\varepsilon_{\mathrm{CR}}\times\underline{(0.2c)^{2}}\times\underline{10^{-6}M_{\odot}\mathrm{yr}^{-1}}$$

$$\sim 3\times10^{41}\mathrm{erg\ yr}^{-1}\left(\frac{\eta_{r/f}\varepsilon_{\mathrm{CR}}}{0.001\%}\right)$$

Same

**SN forward shock**

$$\dot{E}_{r,\,\mathrm{ISM}} = \varepsilon_{\mathrm{CR}}\frac{1}{2}v_{ej,SN}^{2}\underline{X_{r,\,\mathrm{ISM}}M_{\mathrm{ej,\,SN}}\mathfrak{R}_{\mathrm{SN}}}$$

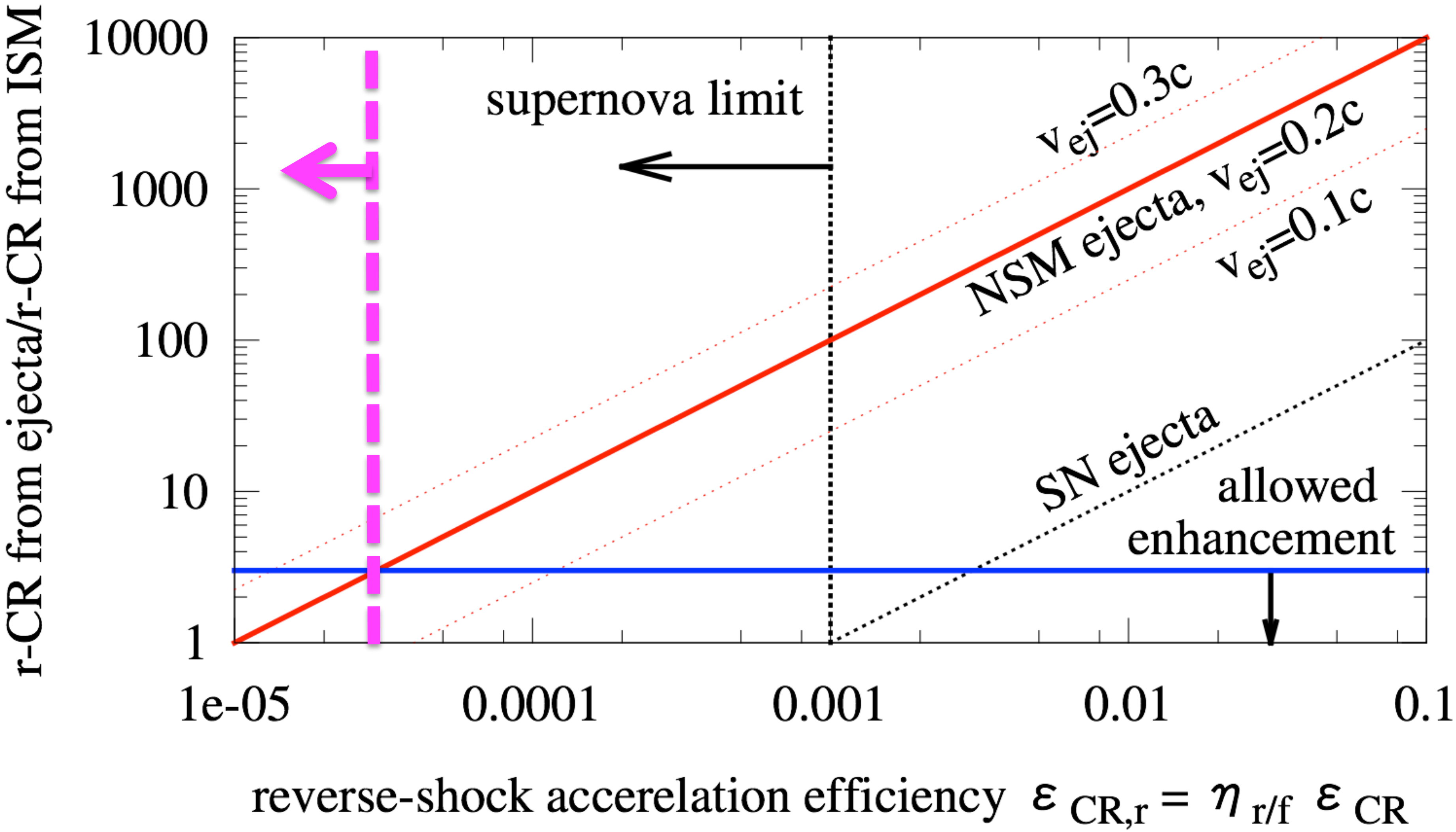
$$= \varepsilon_{\mathrm{CR}}\times\underline{(0.02c)^{2}}\times\underline{10^{-6}M_{\odot}\mathrm{yr}^{-1}}$$

$$\sim 3\times10^{41}\mathrm{erg\ yr}^{-1}$$

***Ratio is robust***

Kyutoku & KI 16

# Strong Constraints




Kyutoku & KI 16

# Energy Generation Rate

**Fe-CR**

Mass fraction — Ejecta mass — Event rate

$$\dot{E}_{\rm Fe,\,SN} = \eta_{r/f}\varepsilon_{\rm CR}\frac{1}{2}v_{ej,\,{\rm SN}}^2 \underline{X_{\rm Fe,\,SN}M_{\rm ej,\,SN}\mathfrak{R}_{\rm SN}}$$

$$= \eta_{r/f}\varepsilon_{\rm CR}\times(0.02c)^2\times 10^{-3}M_\odot{\rm yr}^{-1}$$

$$\sim 3\times 10^{44}\,{\rm erg\ yr}^{-1}\left(\frac{\eta_{r/f}\varepsilon_{\rm CR}}{0.1\%}\right)$$

Same

**SN forward shock**

$$\dot{E}_{\rm Fe,\,ISM} = \varepsilon_{\rm CR}\frac{1}{2}v_{ej,\,{\rm SN}}^2 \underline{X_{\rm Fe,\,ISM}M_{\rm ej,\,SN}\mathfrak{R}_{\rm SN}}$$

$$= \varepsilon_{\rm CR}\times(0.02c)^2\times 10^{-3}M_\odot{\rm yr}^{-1}$$

$$\sim 3\times 10^{44}\,{\rm erg\ yr}^{-1}$$

***Ratio is robust***

Kyutoku & KI 16

# Really R-Process?

**Yes?**

- Macronova with GRB 060614? — Yang+ 15
  - $M_{ejecta} \sim 0.1 M_\odot \Rightarrow$ BH-NS?
- Macronova with GRB 050709? — Jin+ 16
  - $M_{ejecta} \sim 0.05 M_\odot$, Wind signature?
- Deep-sea plutonium $^{244}$Pu ($t_{1/2} \sim 81$Myr) — Hotokezaka+ 15
- r-process in an ultrafaint dwarf galaxy — Ji+ 16

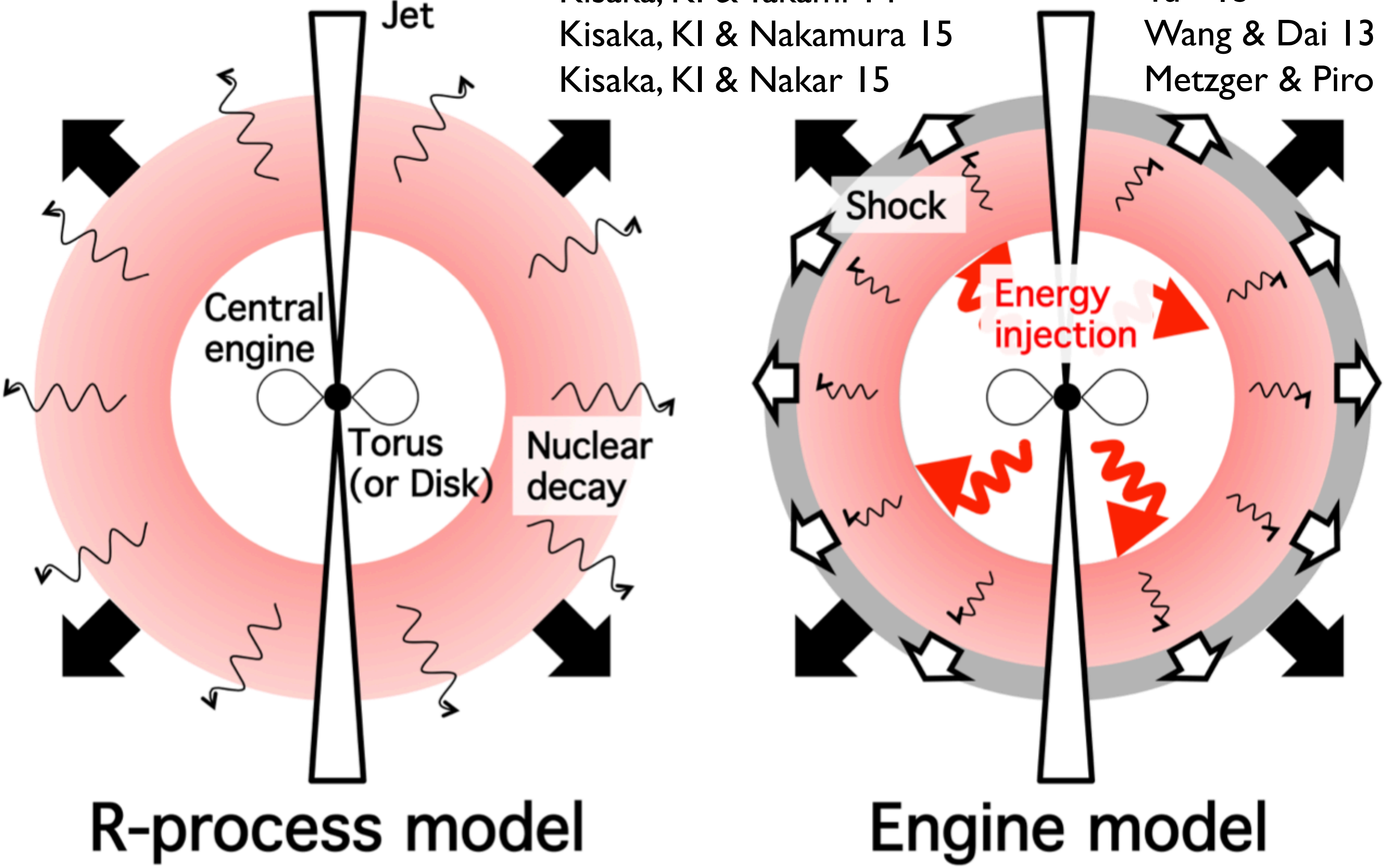
**No?**

- Required $M_{ejecta}$ is too large? — Grossmann+ 14, Kyutoku & KI 16
- r-process cosmic rays are unreasonably weak?

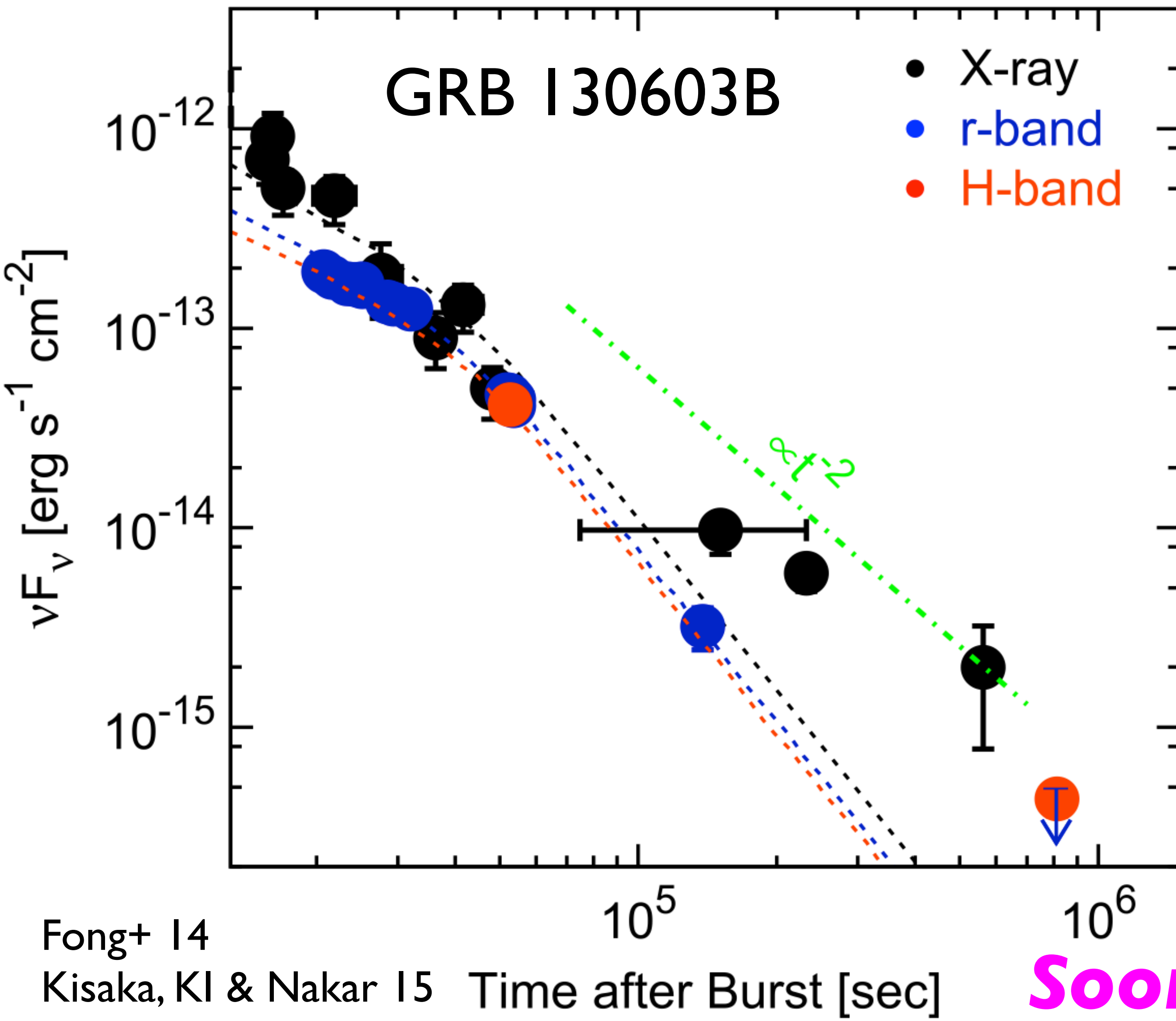
# Engine-Powered Macronova?

Kisaka, KI & Takami 14
Kisaka, KI & Nakamura 15
Kisaka, KI & Nakar 15

Yu+ 13
Wang & Dai 13
Metzger & Piro 14



# X-ray Powered?

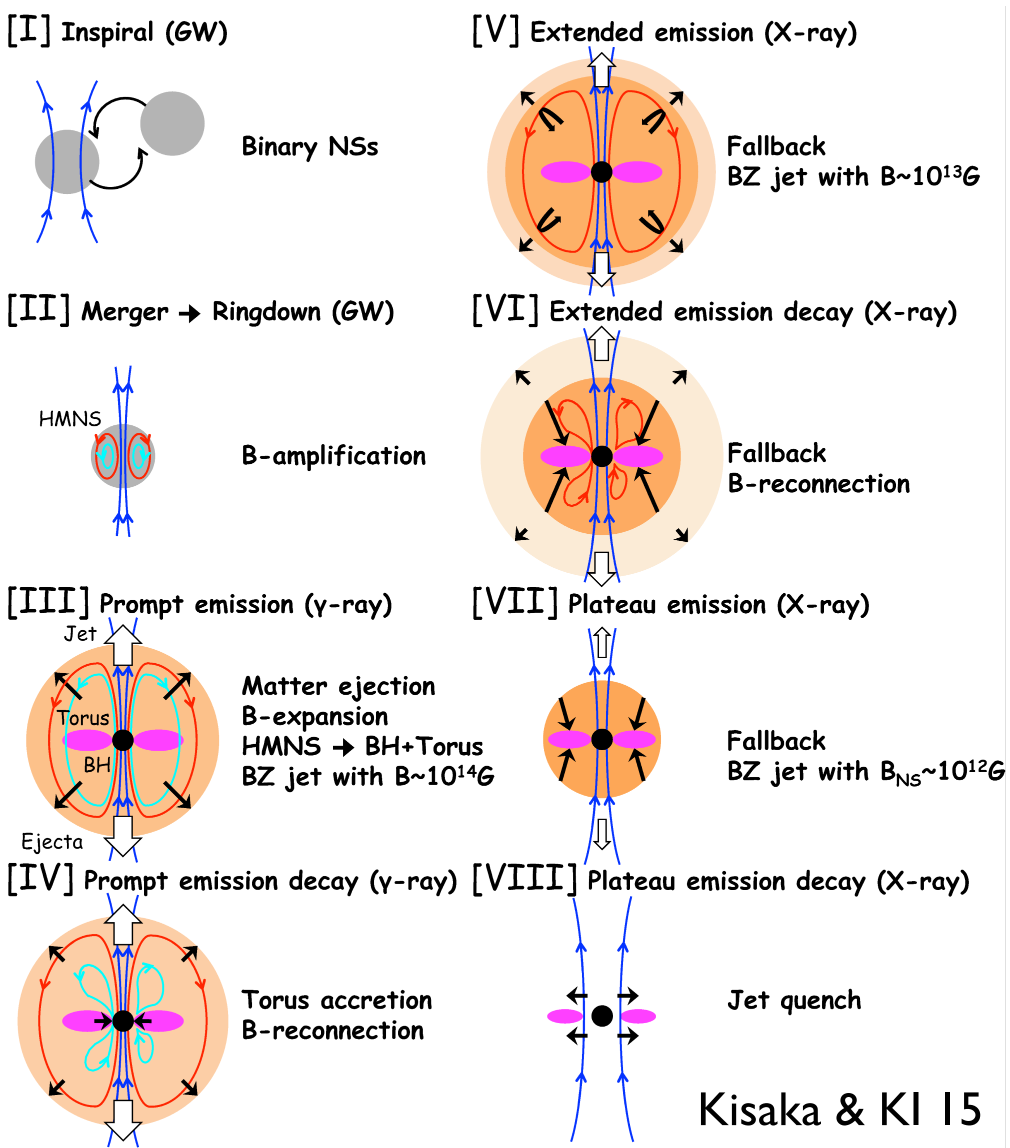


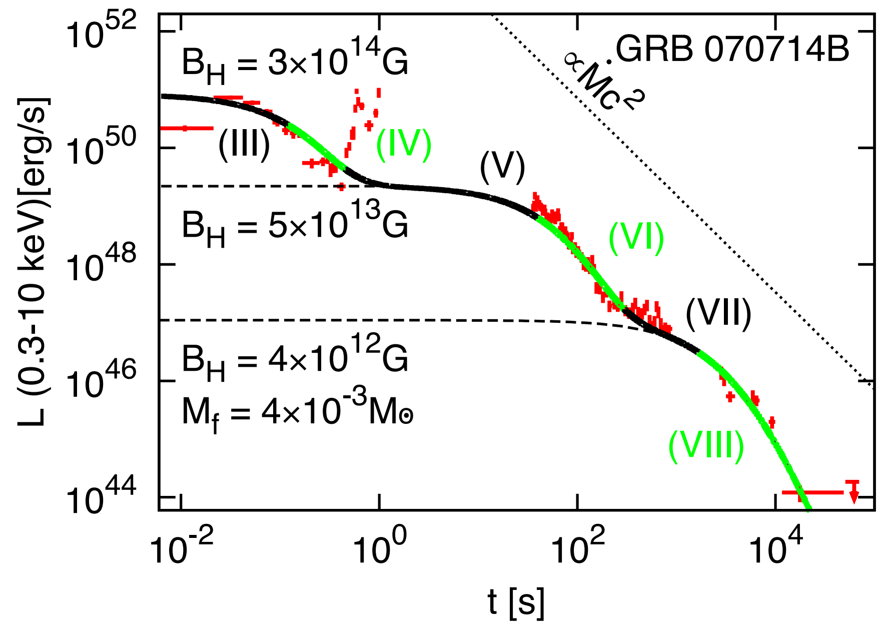

Fong+ 14
Kisaka, KI & Nakar 15

Macronova @IR
≈ X-ray excess
***Same origin?***
Required
$M_{ejecta} < 0.01 M_\odot$
⇔ r-process
model needs
$M_{ejecta} > 0.03 M_\odot$

***Soon GRB 160821B***

# Long-Lasting BH Jet




Fallback & Reconnection

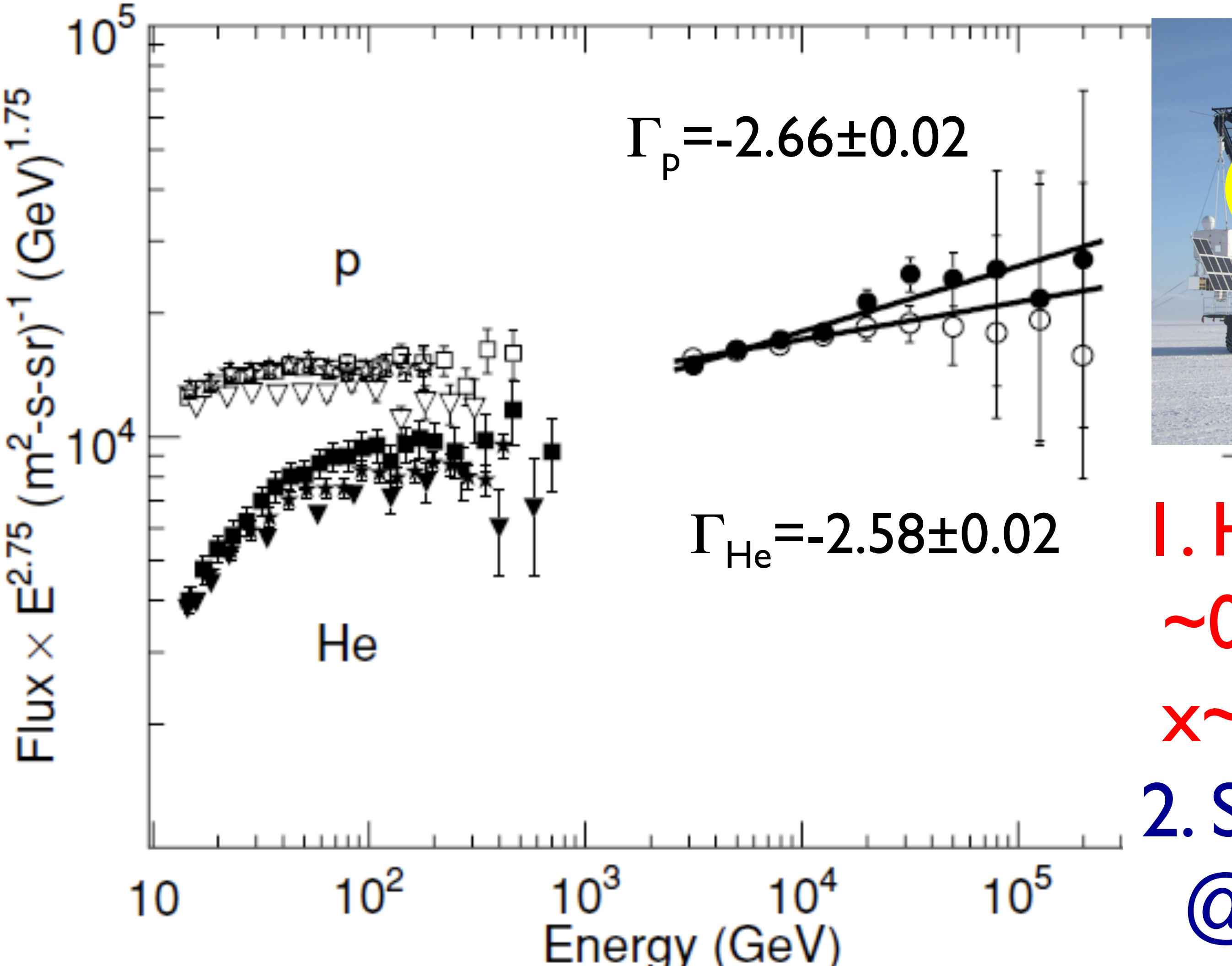
$L_{BZ} \propto B^2$

Prompt: $B \sim 10^{14}$G

Extended: $B \sim 10^{13}$G

Plateau: $B \sim 10^{12}$G

# CR Helium Hardenings



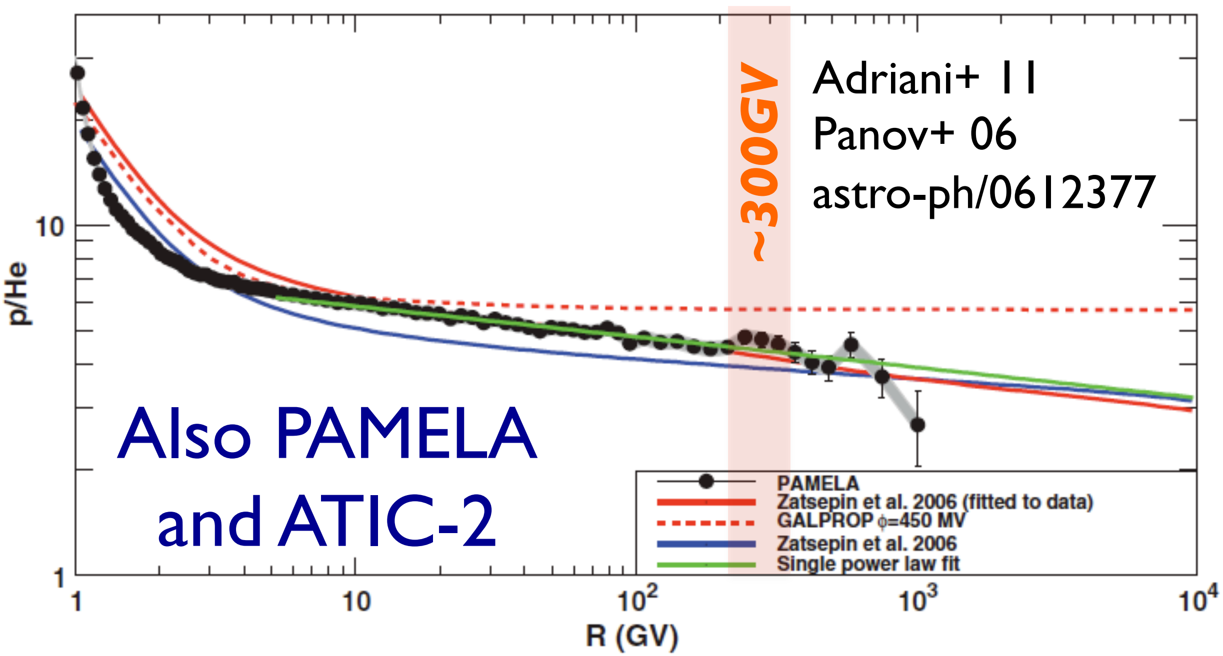

Ahn+ 10


1. He/p hardening
   ~0.2~$Y_\odot$ @GeV
   x~3 @100TeV
2. Spectral Break
   @~200GeV/n
   for all (p-Fe)

# p/He & Break

Two types of anomalies

**1. Proton/Helium Ratio**



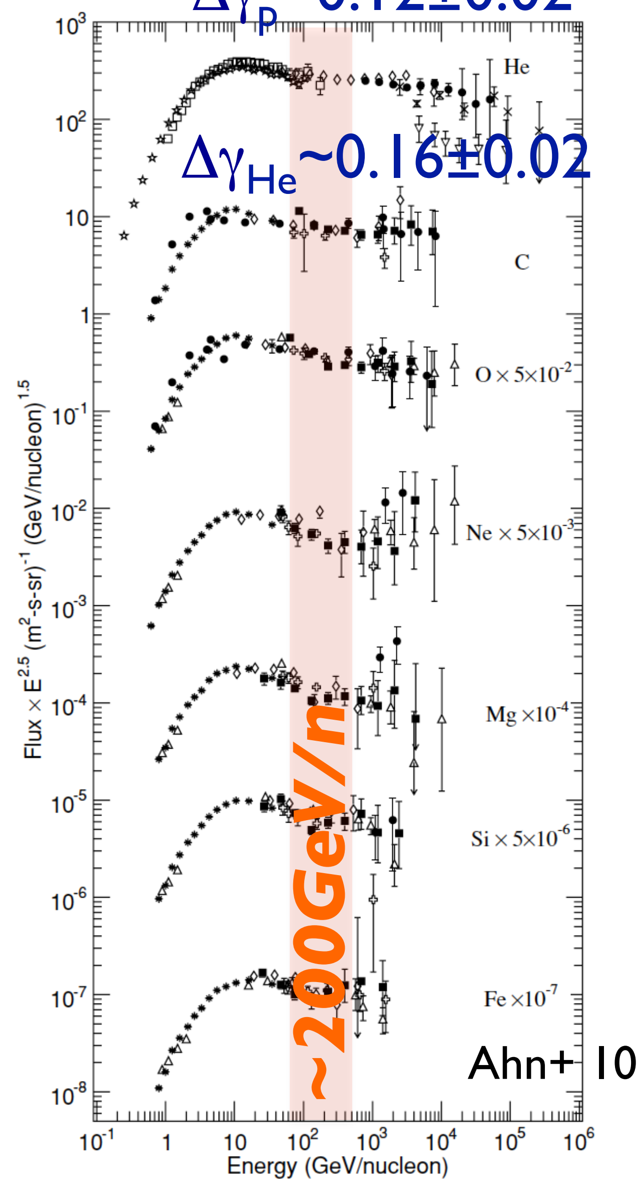

Also PAMELA and ATIC-2

p/He is continuous across break

**2. Break**

$\Delta\gamma_p \sim 0.12 \pm 0.02$

$\Delta\gamma_{He} \sim 0.16 \pm 0.02$

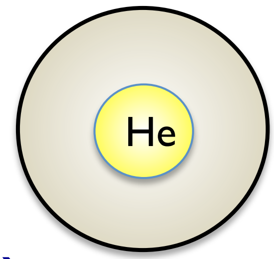


# Helium is Special

- He/p ~ **3×$Y_\odot$!** @100TeV
- Stellar nucleosynthesis never doubles the mean Y (∵ Schonberg-Chandrasekhar)

: Reason to invoke **Big Bang**

$M_{He}/M < q_{SC} \sim 0.1$

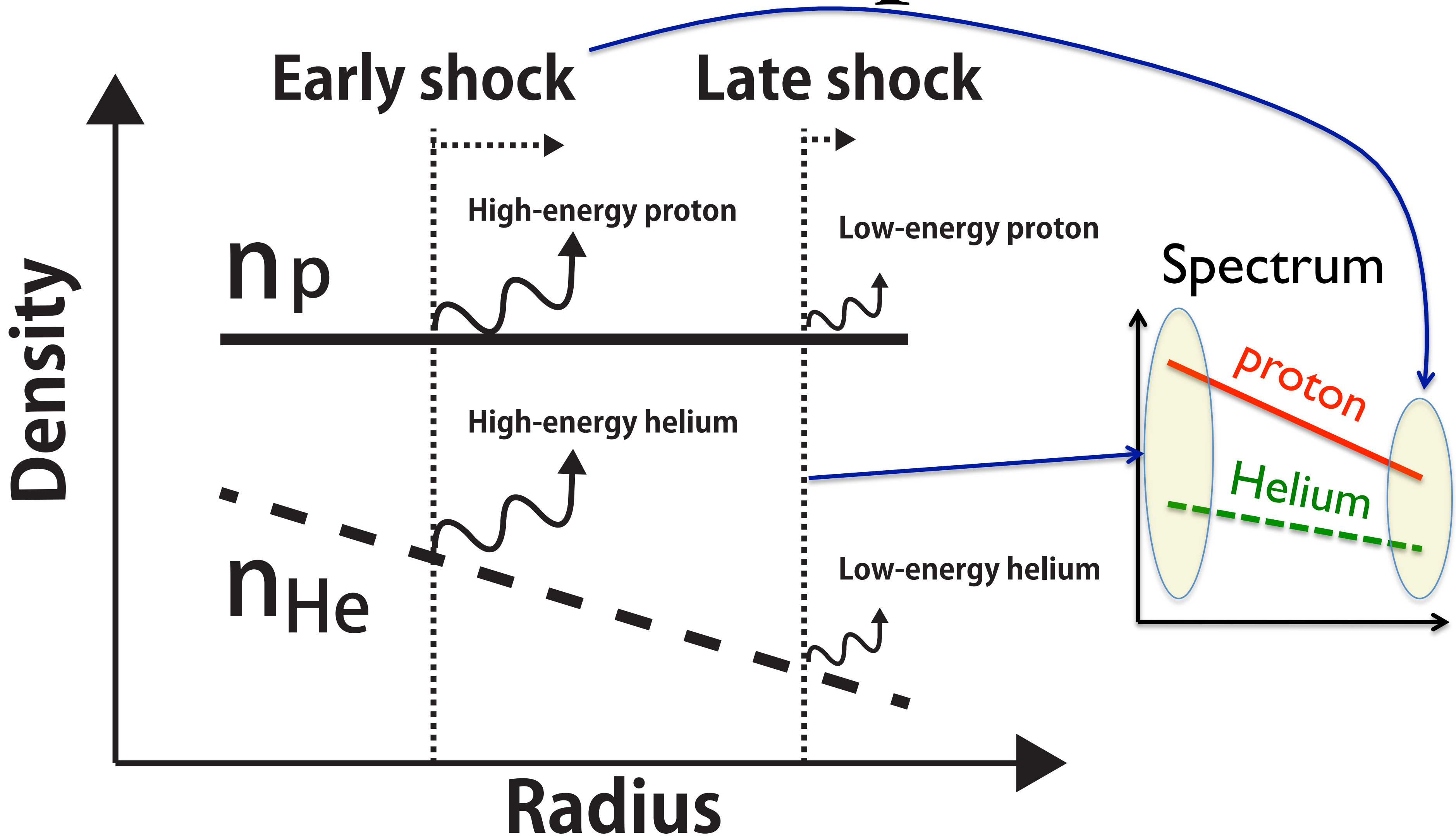



⇒ Chemical inhomogeneity

Ohira & KI 11
Ohira+ 16

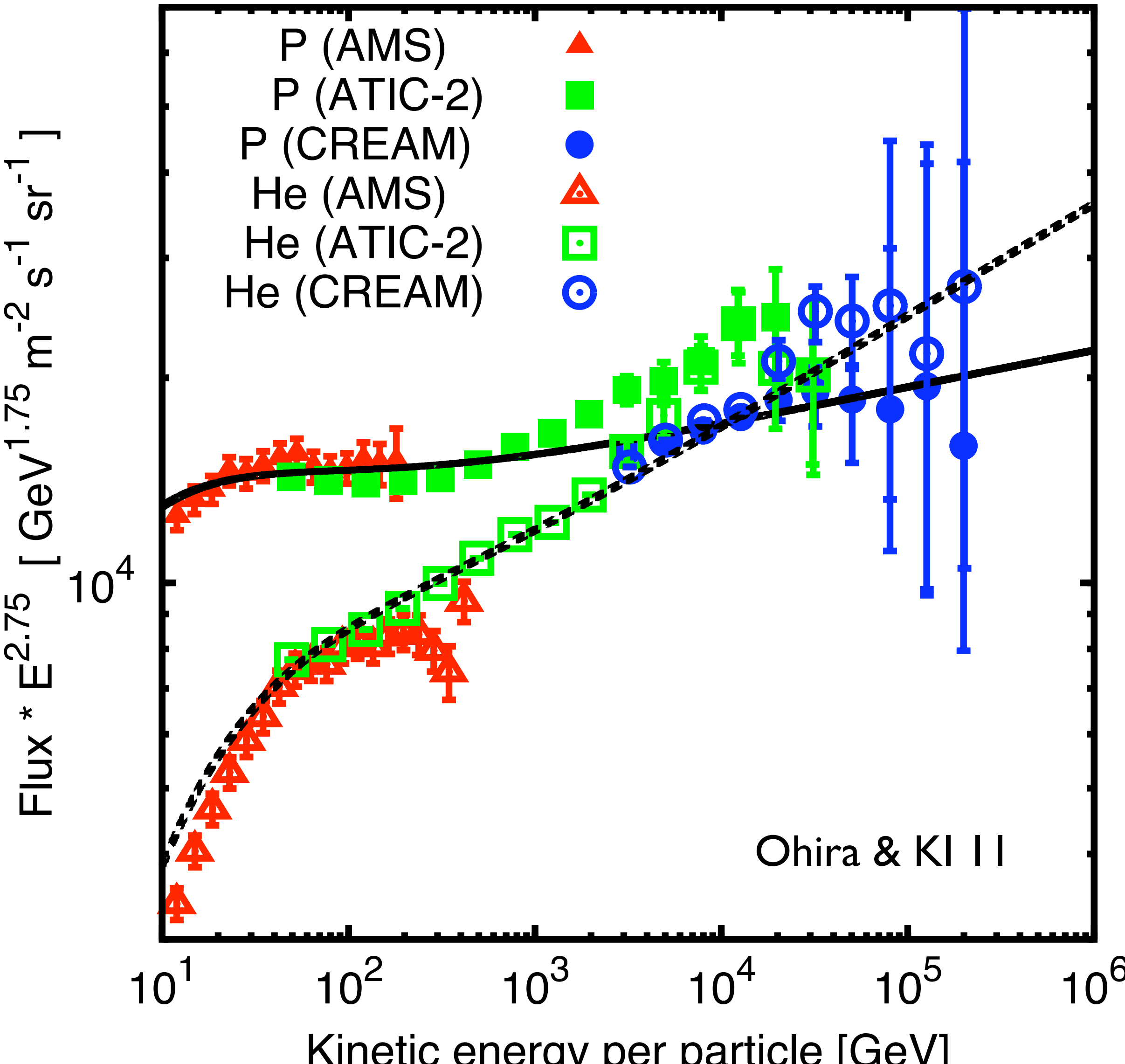
Ptuskin, Zirakashvili & Seo 13: Reverse shock

# Inhomo. + Escape Model




Ohira & KI 11

# Spectral Modeling




1. He/p hardening

$$n_p = \text{const}$$

$$n_{He} \propto R^{-\delta}$$

$\delta$~0.5-0.7

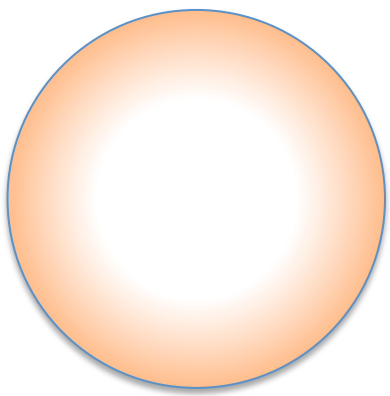
2. Concave spec. @~200GeV/n if T~$10^6$K

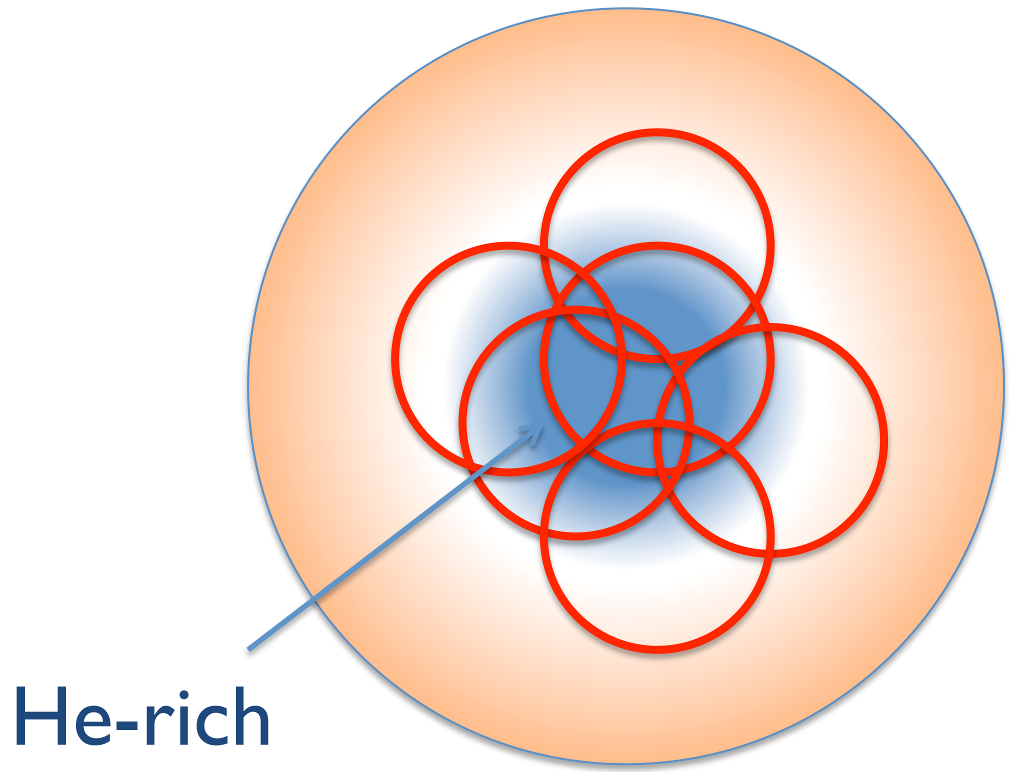
$$s_{obs} = s + \frac{\beta}{\alpha} + \gamma$$

$$s = 2\frac{M^2+1}{M^2-1}$$

# CR Origin ~ Superbubble?

see also Lemoine+ 98





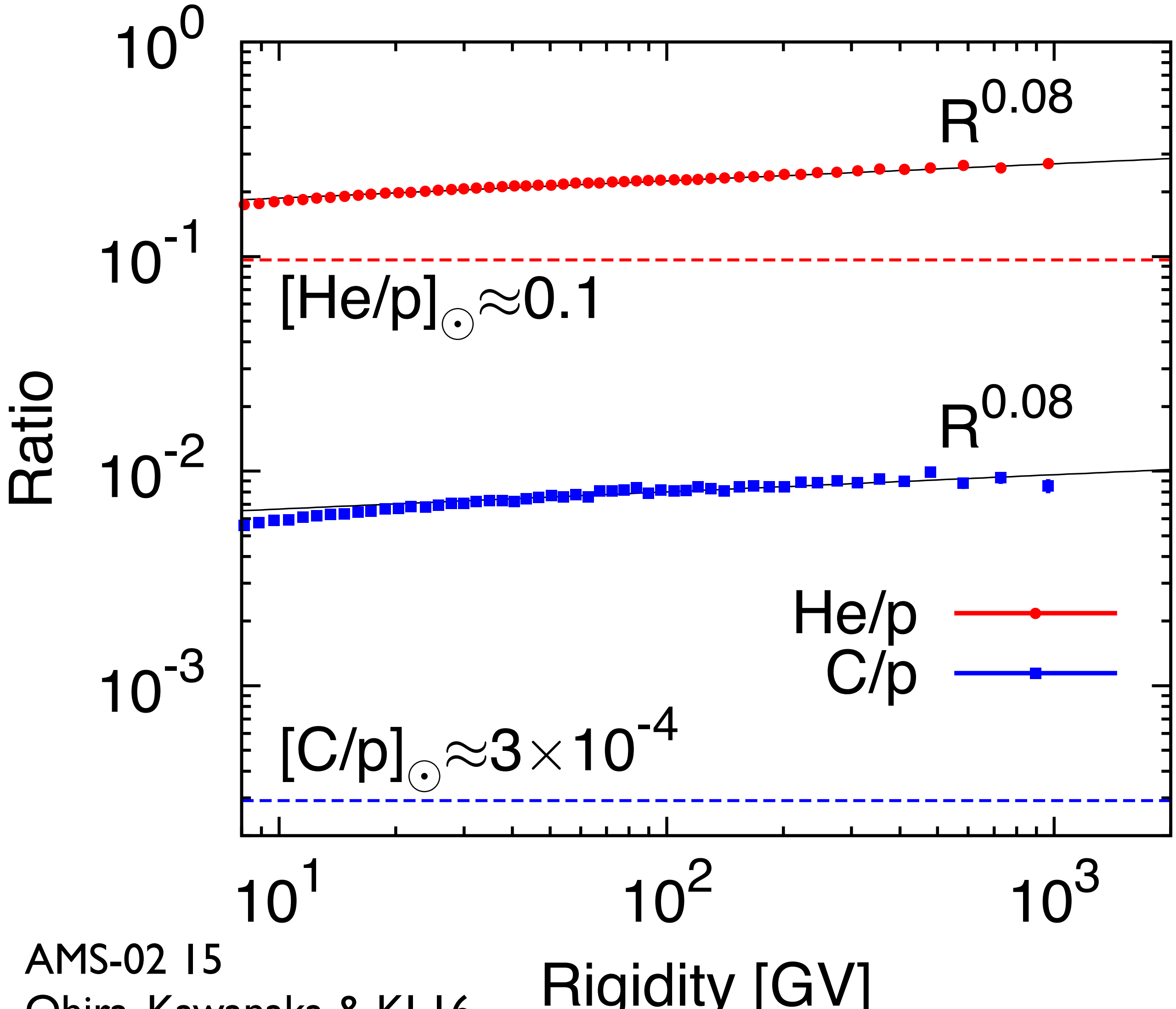

**Isolated SNR**
**(~Fermi SNR)**

not a main channel at PeV?

**Multiple SNR**
**Superbubble**

Heavy metals also show hardening

# He/p & C/p




He/p ≠ const
C/p ≠ const

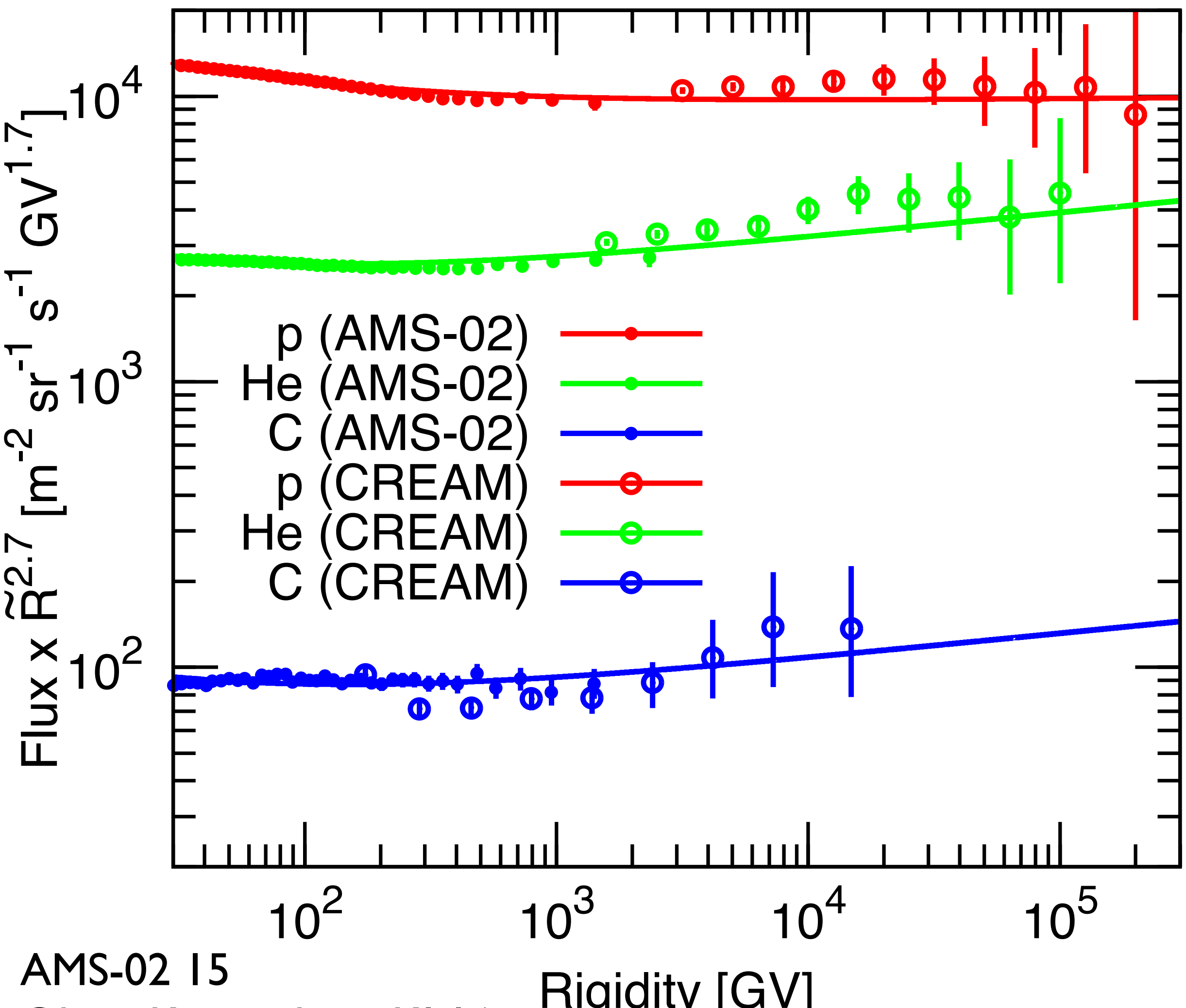
***He/p ∝ $R^{0.08}$***
***C/p ∝ $R^{0.08}$***

He/p>$[He/p]_\odot$
C/p>$[C/p]_\odot$

No break

AMS-02 15
Ohira, Kawanaka & KI 16

# Spectral Modeling




AMS-02 15
Ohira, Kawanaka & KI 16

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$$n_p = \text{const}$$

$$n_{He} \propto R^{-\delta}$$

δ~0.5-0.7

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# Contents

- ***Gravitational wave***
  - BH-BH!!!
  - Galactic PeVatrons? TeV unIDs?

KI, Matsumoto, Teraki, Kashiyama & Murase in prep.

- ***Heavy cosmic ray***
  - r-process cosmic rays
  - He & C hardening

Kyutoku+ 13, Kyutoku & KI 16
Takami+ 14

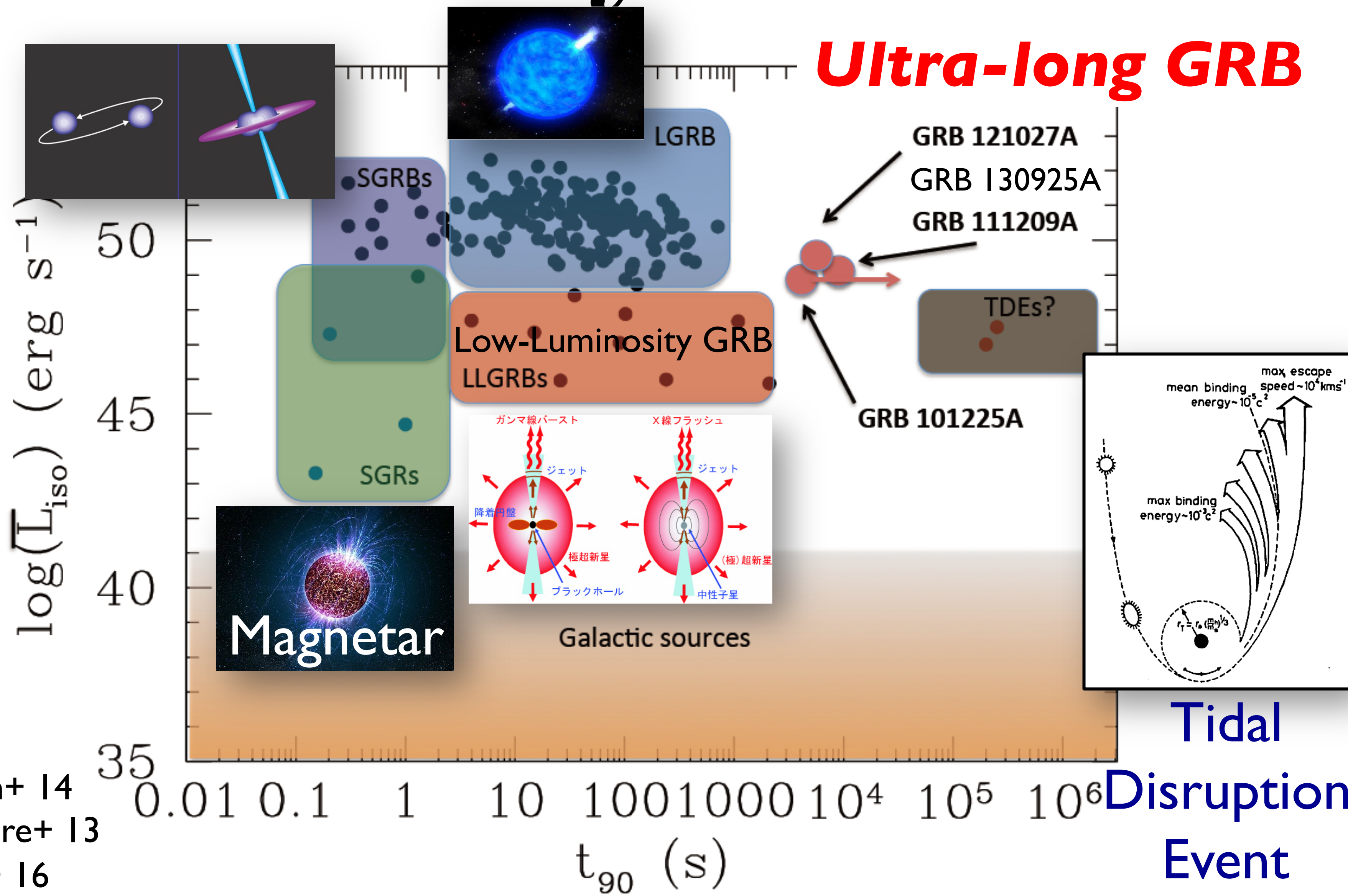
Ohira & KI 11, Ohira+ 16

- ***Ultra-long GRB***
  - Collapsar? HE ν?
  - WD TDE

Suwa & KI 11
Matsumoto+ 15, 16
Murase & KI 13

KI, Hotokezaka & Piran 16

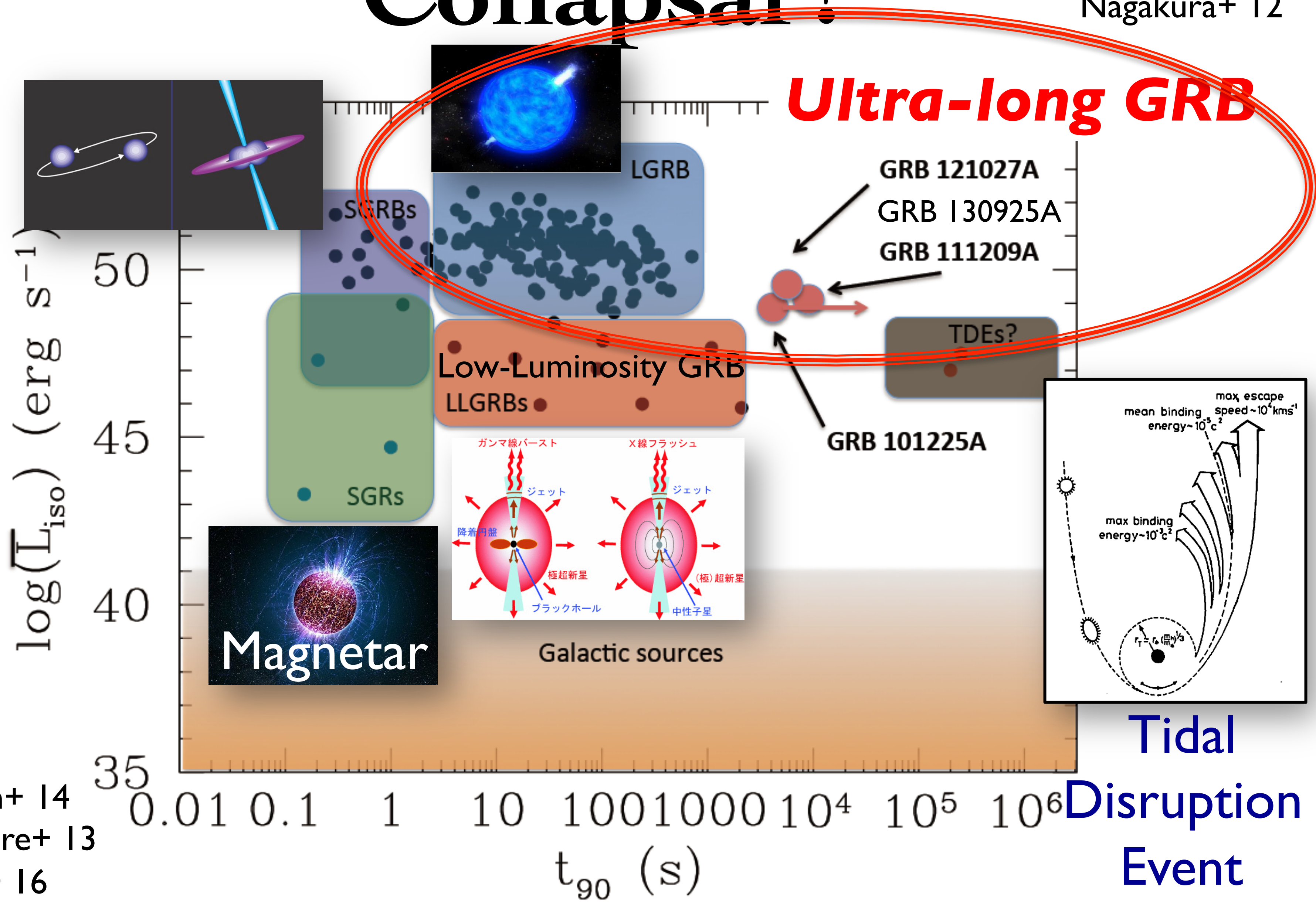
# Diversity of GRB




Levan+ 14
Gendre+ 13
Lien+ 16

Nakauchi+ 13
Kashiyama+ 13
Suwa & KI 11
Nagakura+ 12

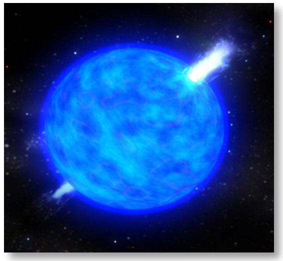
# Collapsar?



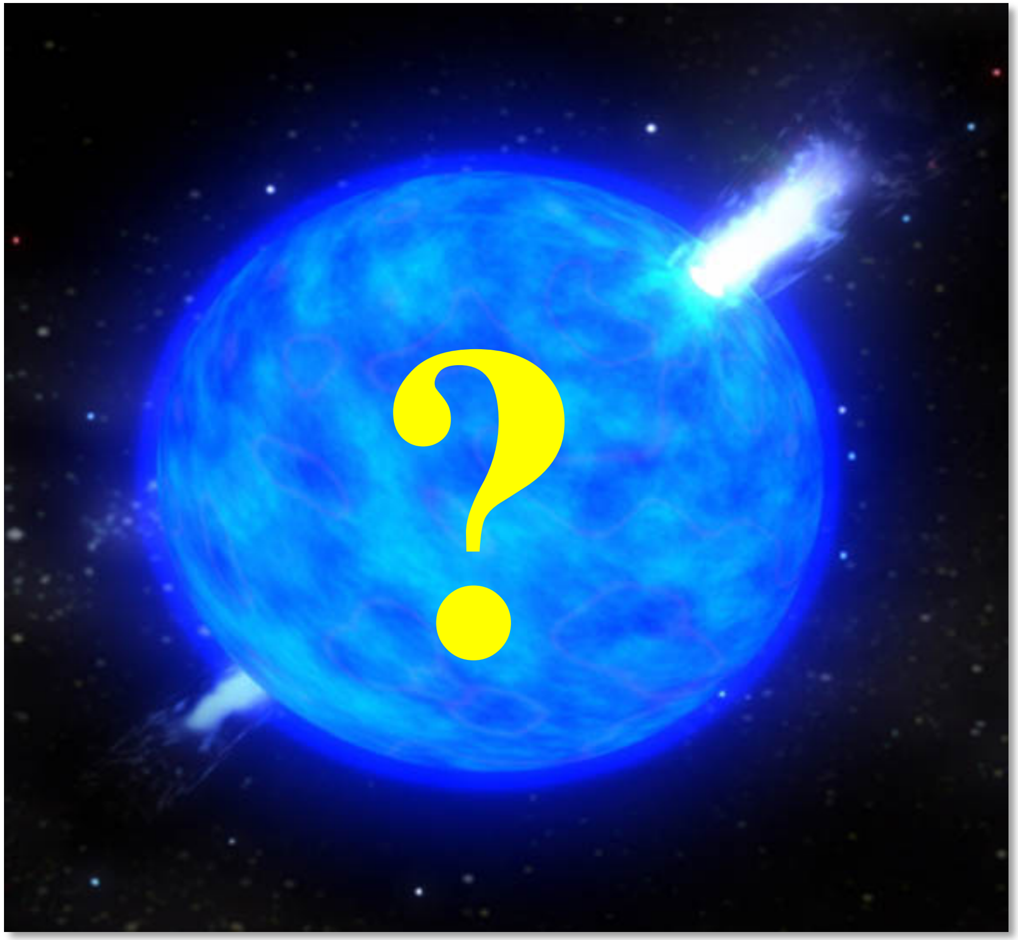

Levan+ 14
Gendre+ 13
Lien+ 16

# Pop III GRB?

**Present Day GRB**

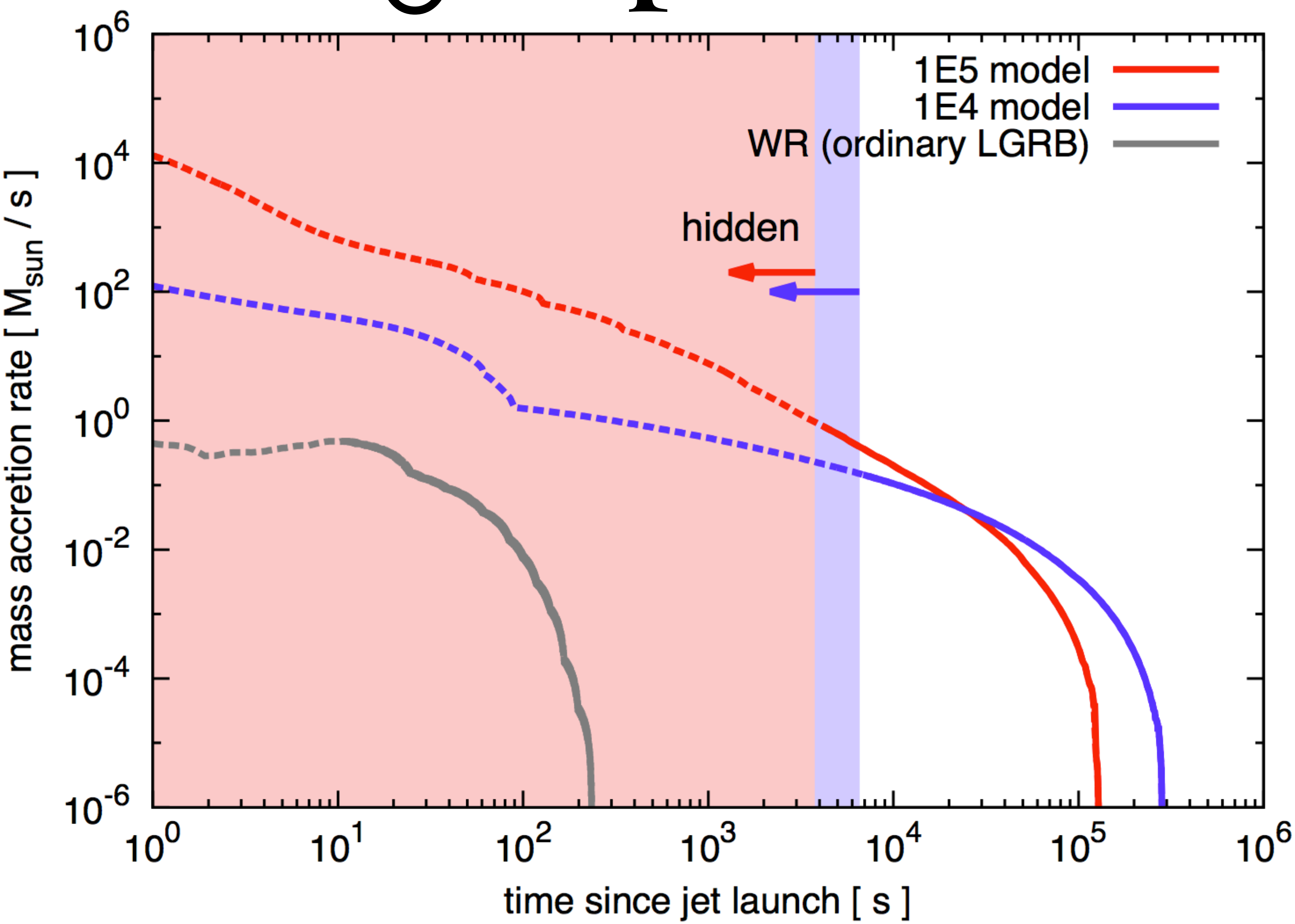


Komissarov & Barkov 10
Meszaros & Rees 10
Suwa & KI 11
Nagakura, Suwa & KI 12




**Envelope accretion ⇒ Ultra-long**

# GRB Jets can break out $10^5 M_\odot$ Supermassive Stars




Radiation pressure-dominated
⇒ Breakout

Total energy $\sim 10^{55\text{-}56}$ erg $\sim M_{halo}\, v_{esc}\, v_c$
⇒ Expel the host galaxy?

Matsumoto+ 15, 16

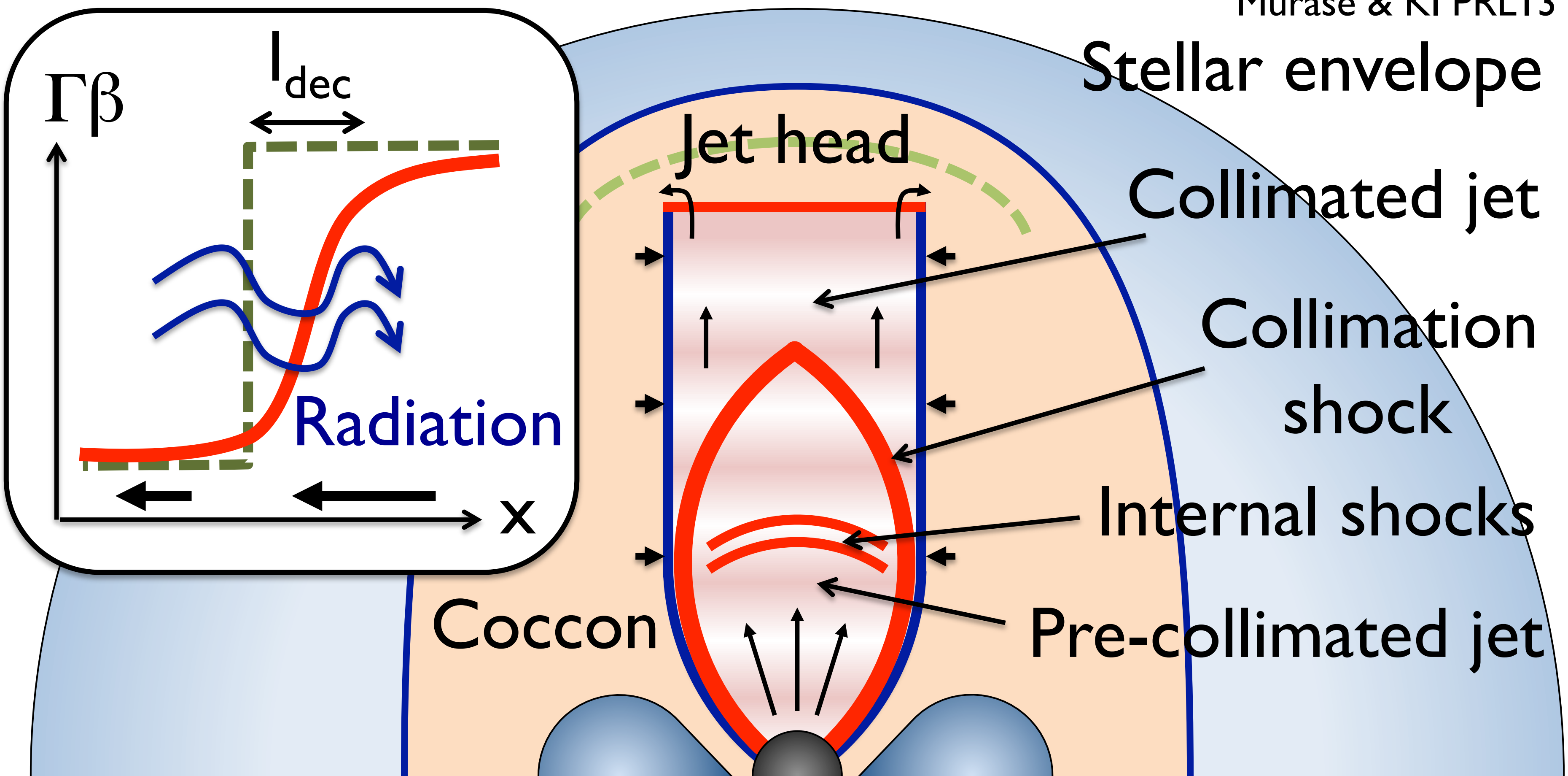
# HE ν?

Waxman's talk
Wang's talk
Meszaros's talk

## TeV-PeV ν from Low-power GRB Jets inside Stars

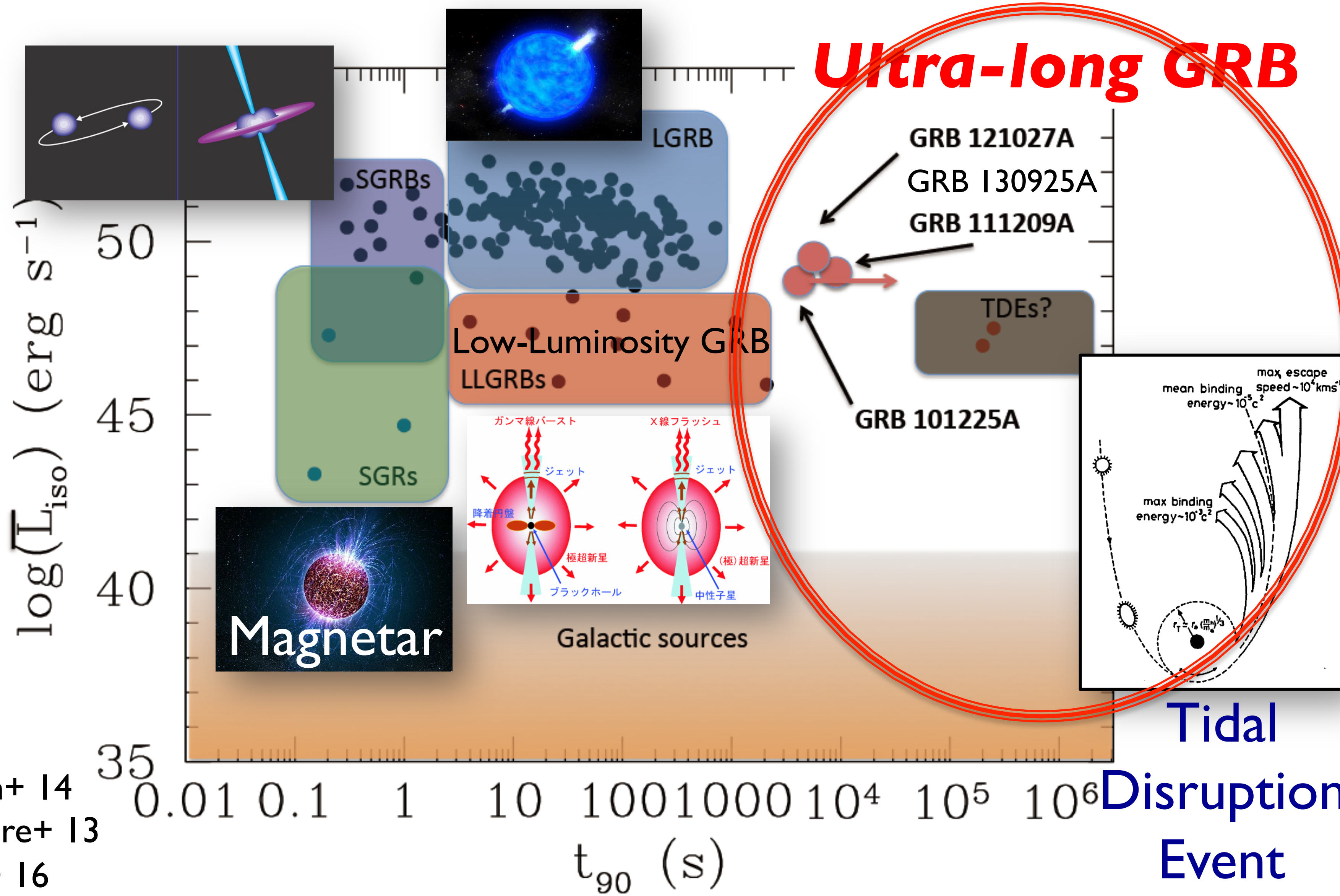
***Ultra-long GRB, Low-luminosity GRB***

Murase & KI PRL13



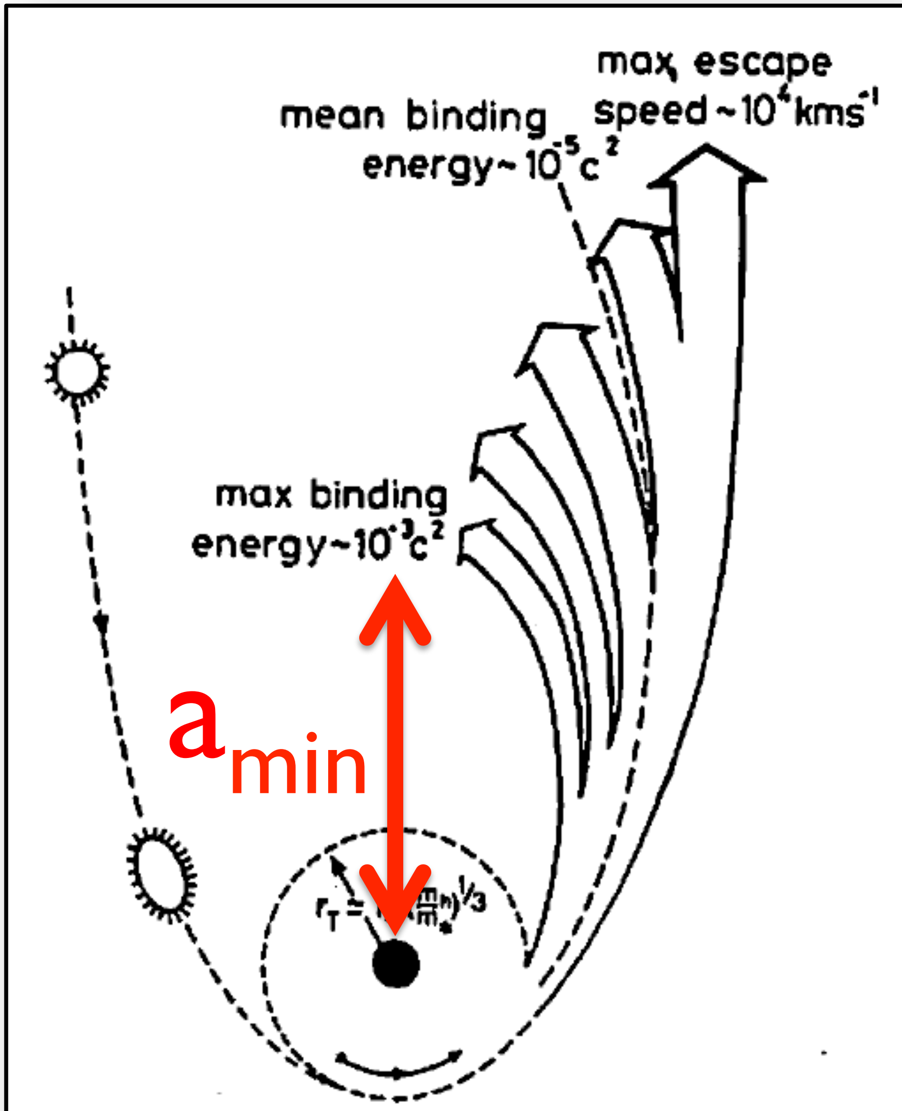
# TDE?

Levan+ 14
Gendre+ 13
MacLeod+ 14




Levan+ 14
Gendre+ 13
Lien+ 16

# White Dwarf TDE




$$a_{\min} \sim \left(\frac{M_{BH}}{M_*}\right)^{2/3} R_* \sim 10^{12}\,\mathrm{cm}\left(\frac{M_*}{M_\odot}\right)^{-1/3} \times \left(\frac{M_{BH}}{10^5 M_\odot}\right)^{2/3}\left(\frac{\rho_*}{10^6\,\mathrm{g\,cm^{-3}}}\right)^{-1/3}$$

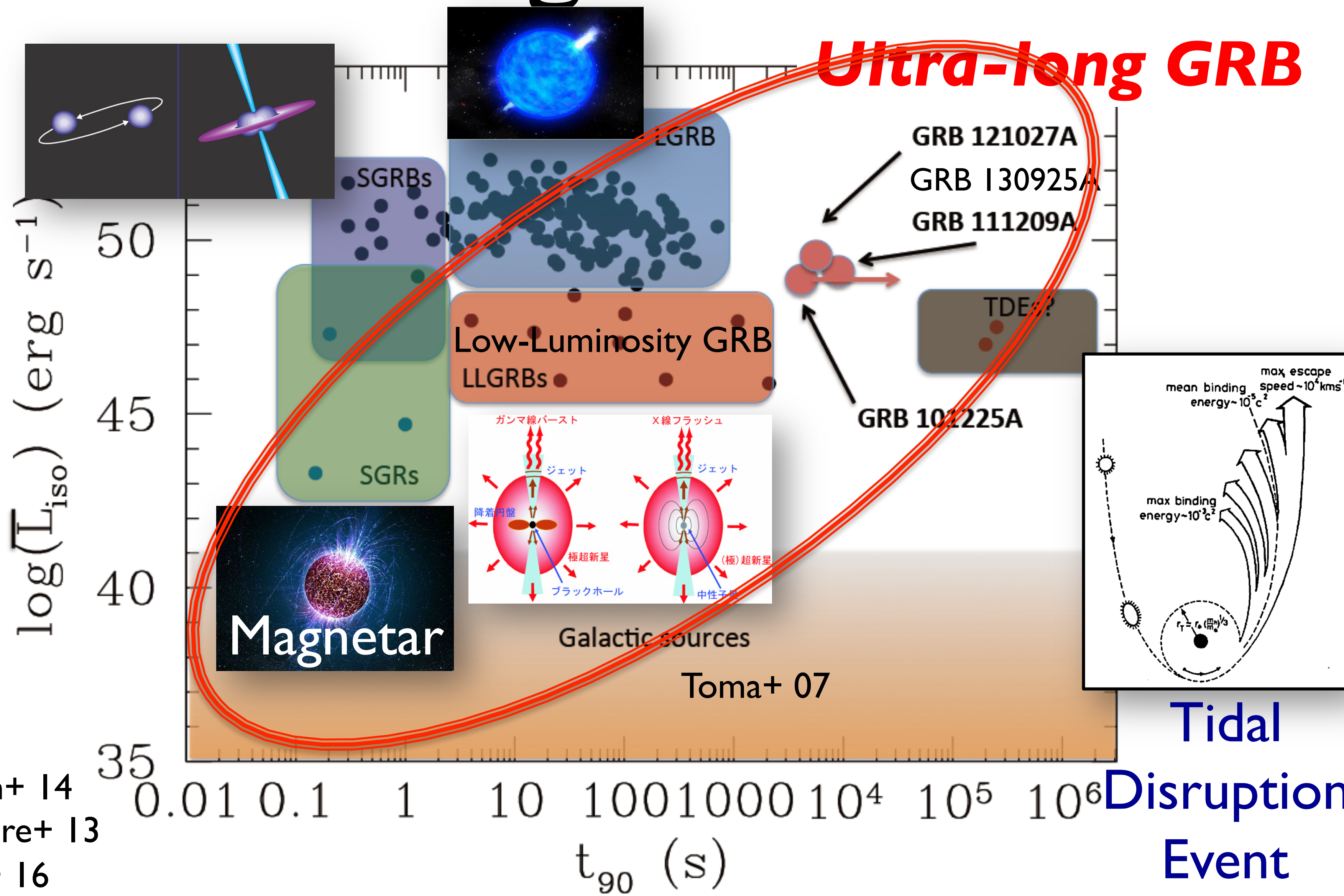
$$t_0 \sim 2\pi\sqrt{\frac{a_{\min}^3}{GM_{BH}}} \sim 4\times 10^3\,\sec\left(\frac{M_*}{M_\odot}\right)^{-1/2} \times \left(\frac{M_{BH}}{10^5 M_\odot}\right)^{1/2}\left(\frac{\rho_*}{10^6\,\mathrm{g\,cm^{-3}}}\right)^{-1/2}$$

Ultra-long duration requires WD density

Krolik & Piran 11

# Magnetar?

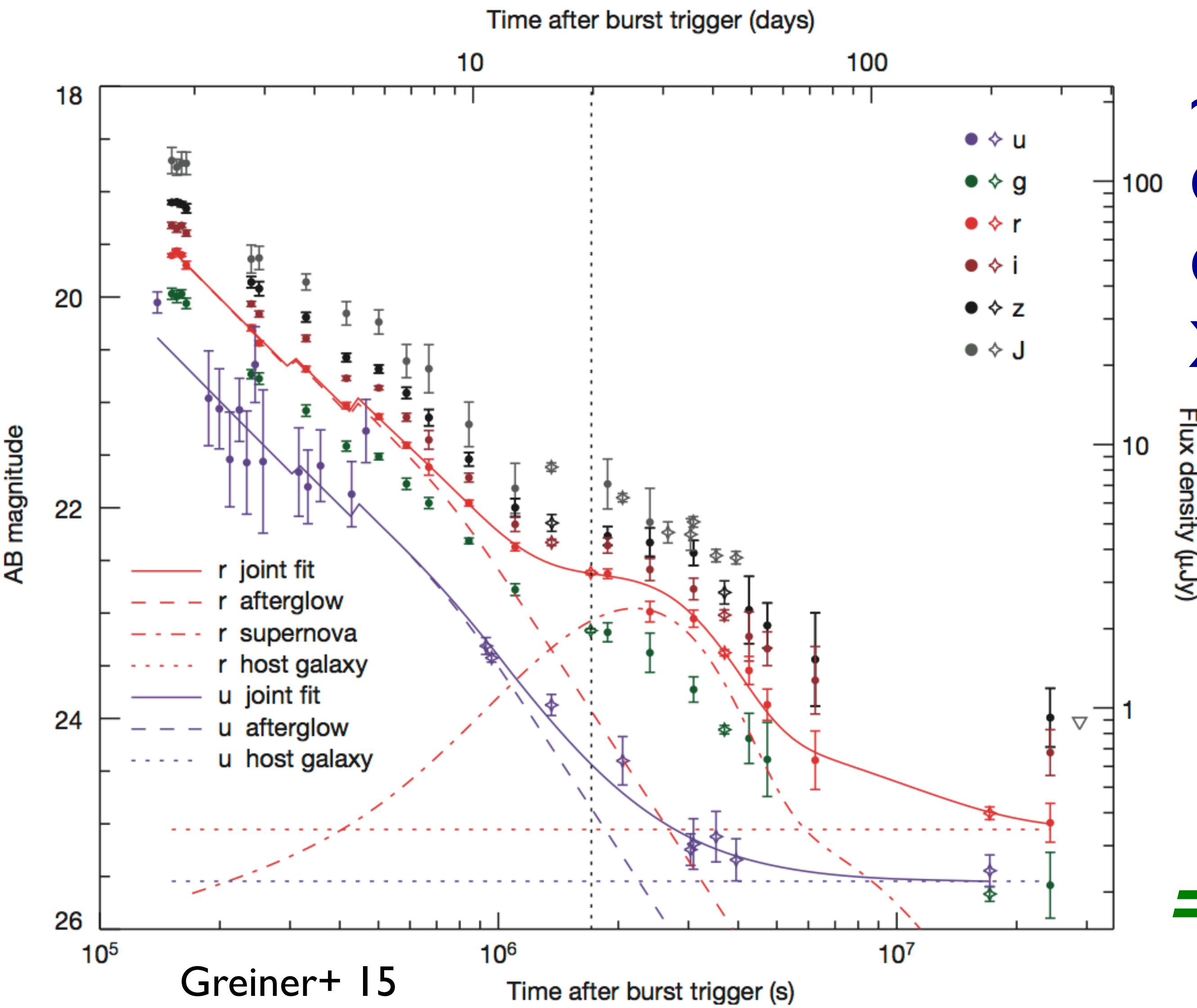
Greiner+ 15




Levan+ 14
Gendre+ 13
Lien+ 16

Tidal Disruption Event

# Bright SN 2011kl




Greiner+ 15

~10 days after GRB 111209

GROND multiband

X-shooter on VLT

***Supernova***

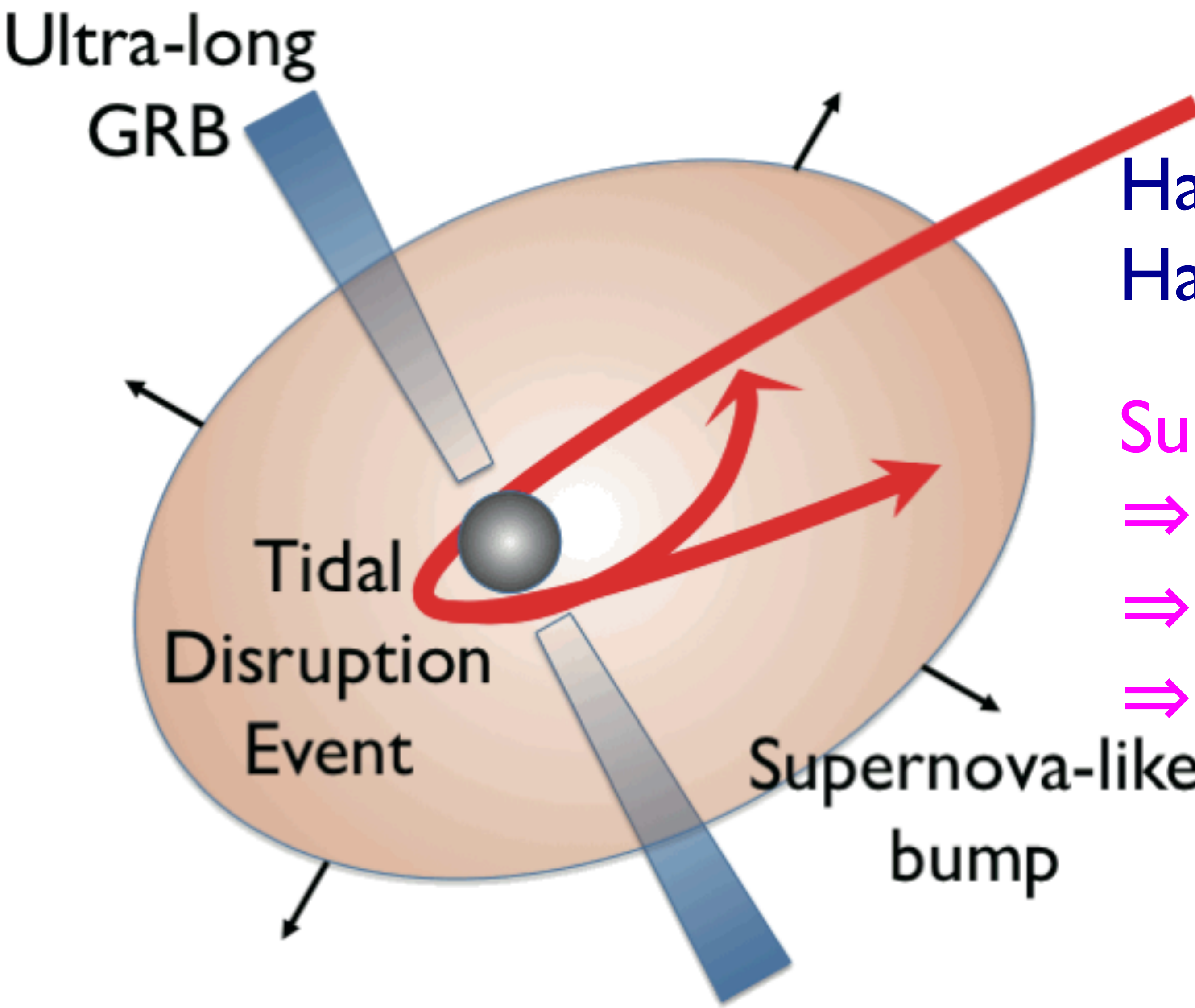
***⇒ TDE ×***

***No H line***

***⇒ BSG ×***

***⇒ Magnetar?***

# SN does not Exclude TDE

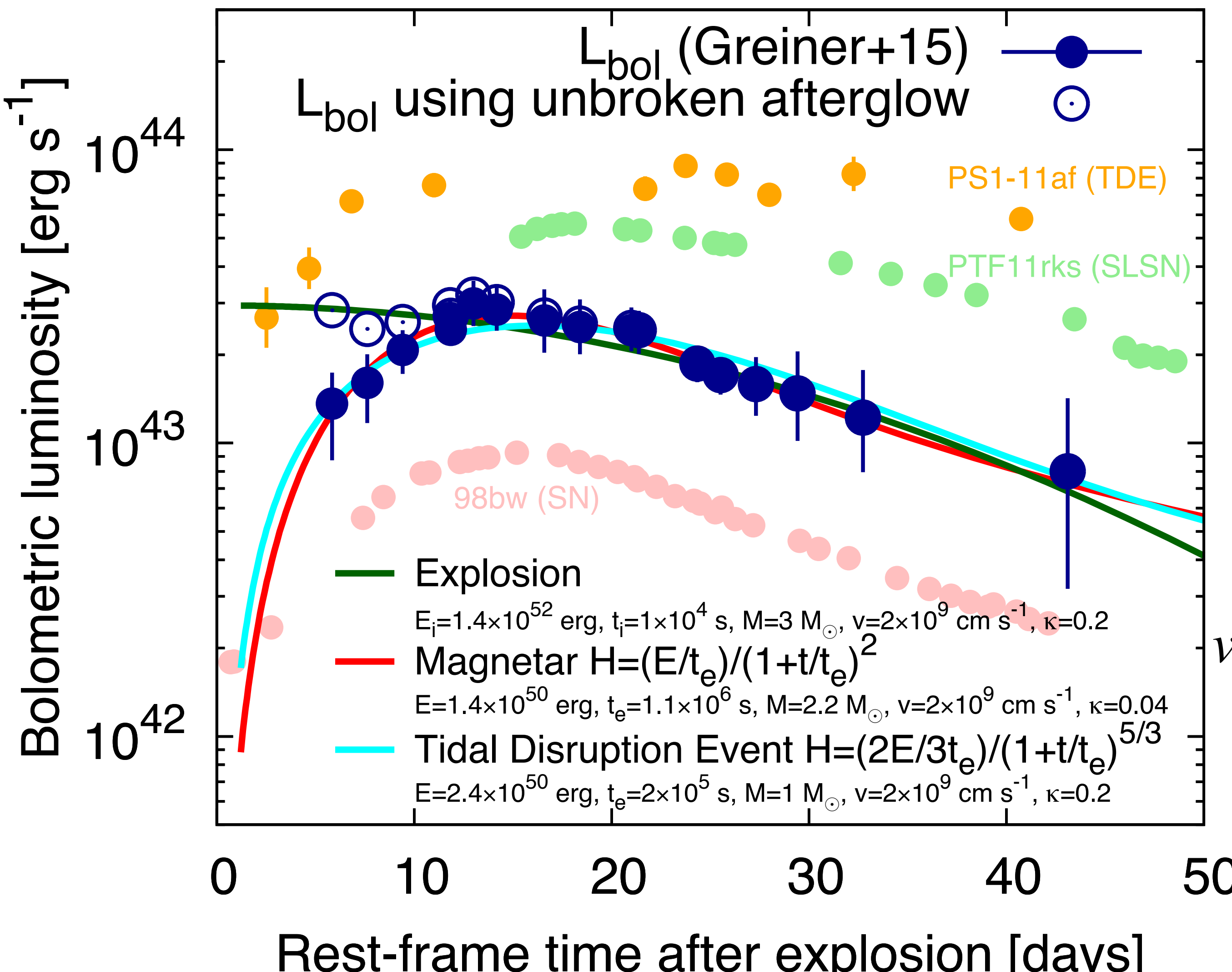



Half bound
Half unbound

Super-Eddington
⇒ Disk outflow, $\gamma$
⇒ E into Ejecta
⇒ SN-like bump

KI, Hotokezaka & Piran 16

# SN-like Light Curve




$$E \sim \frac{GM_{BH}(M_*/2)}{2a_{\min}} \sim 4\times10^{51}\,\mathrm{erg}$$

$$L \sim L_{Edd} \sim 10^{43}\,\mathrm{erg\ s^{-1}} \times \left(\frac{M_{BH}}{10^5 M_\odot}\right)$$

$$v_{\min} \sim \sqrt{\frac{GM_{BH}}{2a_{\min}}} \sim 2\times10^9\,\mathrm{cm\ s^{-1}}$$

KI, Hotokezaka & Piran 16

# Contents

Thank You

- **Gravitational wave**
  - BH-BH!!!
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Suwa & KI 11
Matsumoto+ 15, 16
Murase & KI 13

KI, Hotokezaka & Piran 16

# Backup

# Bondi Accretion

$$r_B \sim \frac{GM}{V^2} \sim 1\times 10^{15}\,\mathrm{cm}$$

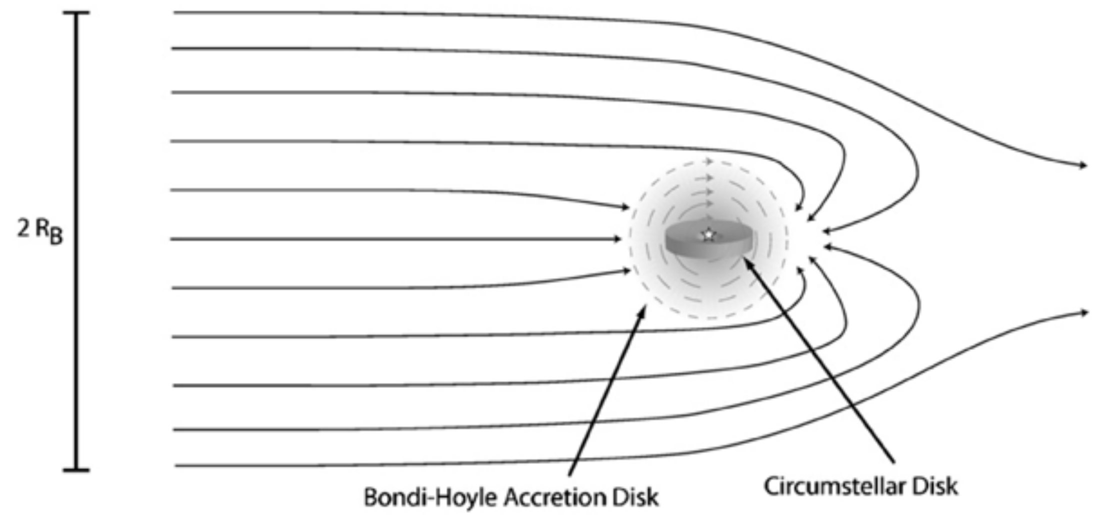
$$\times\left(\frac{M}{10M_\odot}\right)\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-2}$$

$$V = \sqrt{c_s^2 + v^2 + v_{\mathrm{GW}}^2}$$

$$\dot{M} \sim 4\pi r_B^2 V \rho$$

$$\sim 5\times 10^{35}\,\mathrm{erg\ s^{-1}}\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10M_\odot}\right)^2\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

$$\sim 4\times 10^{-4}\,\dot{M}_{\mathrm{Edd}}\left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10M_\odot}\right)\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$




Bondi & Hoyle 44

# ADAF (Hot, Thick Disk)

## Advection Dominated Accretion Flow

$$L_{\rm disk} \sim \alpha_{\rm QED} \frac{m_e}{m_p} \frac{\dot{M}c^2}{L_{\rm Edd}} \dot{M}c^2 \sim 10^{-13} L_{\rm Edd} \sim 10^{27} \,{\rm erg\ s^{-1}}$$

$$\frac{10^{27}\,{\rm erg\ s^{-1}}}{4\pi\,({\rm kpc})^2} \sim 10^{-17}\,{\rm erg\ s^{-1}\ cm^{-2}}$$

Nearby BH disks might be observable

Ichimaru 77, Narayan & Yi 94
Fujita, Inoue, Nakamura, Manmoto, Nakamura 98
Matsumoto et al. in preparation

# Luminosity Function

$$\frac{dN}{d\dot{M}} = N_{\rm BH}\int dm_1 \frac{dp(m_1)}{dm_1}\int dm_2 \frac{dp(m_2|m_1)}{dm_2}\int dv \frac{df(v)}{dv}\int dn \frac{d\xi(n)}{dn} \times h(m_1,m_2,v)\delta\left[\dot{M}(n,m_1,m_2,v)-\dot{M}\right],$$

Agol & Kamionkowski 12

## Mass function

$$\frac{dp(m_1)}{dm_1} = Cm_1^{-2.35}, \quad \frac{dp(m_2|m_1)}{dm_2} = \frac{1}{m_1 - M_{\rm min}}, \quad 5M_\odot \le m_2 \le m_1 \le 50M_\odot$$

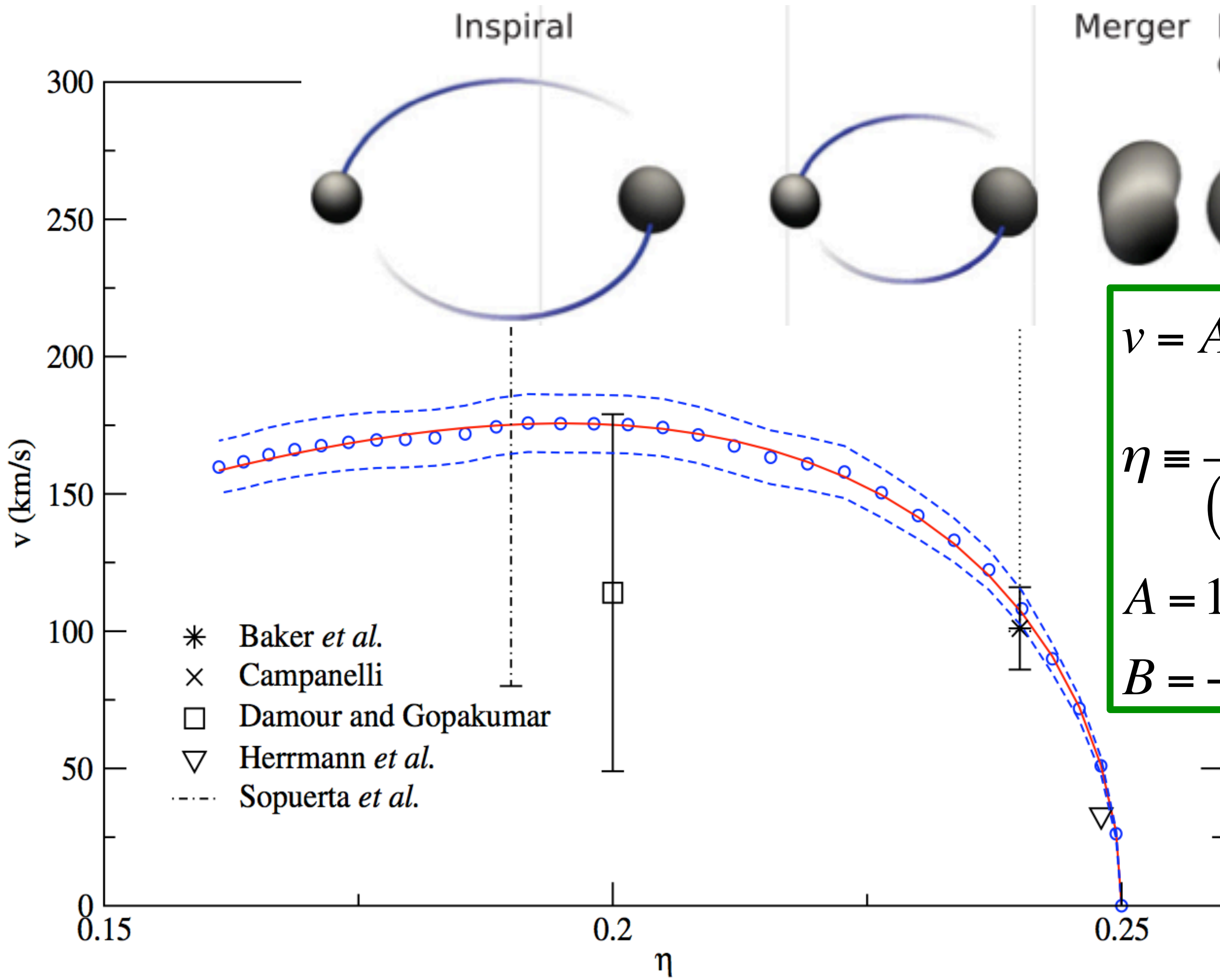
## Velocity distribution

$$\frac{df(v)}{dv} = \sqrt{\frac{2}{\pi}}\frac{v^2}{\sigma_v^3}\exp\left(-\frac{v^2}{2\sigma_v^2}\right)$$

$\sigma_v$~40km/s: isolated binary

$\sigma_v$~200km/s: stellar cluster

# GW Recoil Velocity




$$v = A\eta^2\sqrt{1-4\eta}\,(1+B\eta)$$

$$\eta \equiv \frac{M_1 M_2}{(M_1+M_2)^2}$$

$$A = 1.20\times 10^4\,\mathrm{km\ s^{-1}}$$

$$B = -0.93$$

Gonzalez+ 07
Fitchett 83

# Density Distribution

$$\frac{d\xi(n)}{dn} = D\xi_0 n^{-\beta}$$

Volume filling fraction

Scale height

| Phase | $n_1$ [cm$^{-3}$] | $n_2$ [cm$^{-3}$] | $\beta$ | $\xi_0$ | $c_s$ [km s$^{-1}$] | $H_d$ |
|---|---|---|---|---|---|---|
| Molecular clouds | $10^2$ | $10^5$ | 2.8 | $10^{-3}$ | 10 | 75 pc |
| Cold $H_I$ | 10 | $10^2$ | 3.8 | 0.04 | 10 | 150 pc |
| Warm $H_I$ | 0.3 | – | – | 0.35 | 10 | 0.5 kpc |
| Warm $H_{II}$ | 0.15 | – | – | 0.2 | 10 | 1 kpc |
| Hot $H_{II}$ | 0.002 | – | – | 0.4 | 150 | 3 kpc |

$$h(m_1, m_2, v) = \min\left(1, \frac{H_d}{H(v_z)}\right), \quad v_z^2 = \frac{1}{3}\left(v^2 + v_g^2\right)$$

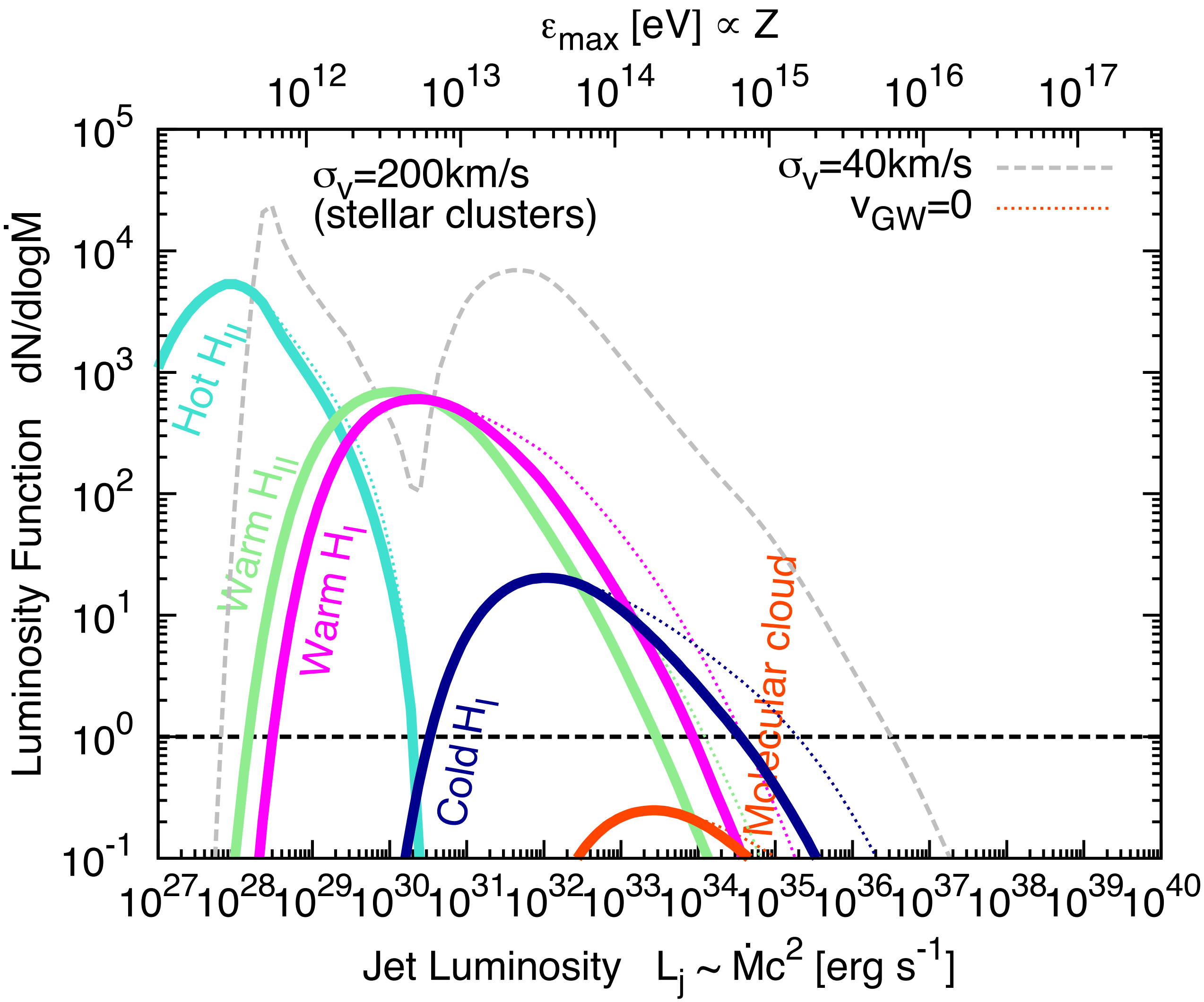
$$\frac{1}{2}v_z^2 = \Phi_z\left[H(v_z)\right], \quad \frac{\Phi_z(z)}{2\pi G} = K\left(\sqrt{z^2 + Z^2} - Z\right) + Fz^2$$

Z~180pc

K=48M$_\odot$/pc$^2$

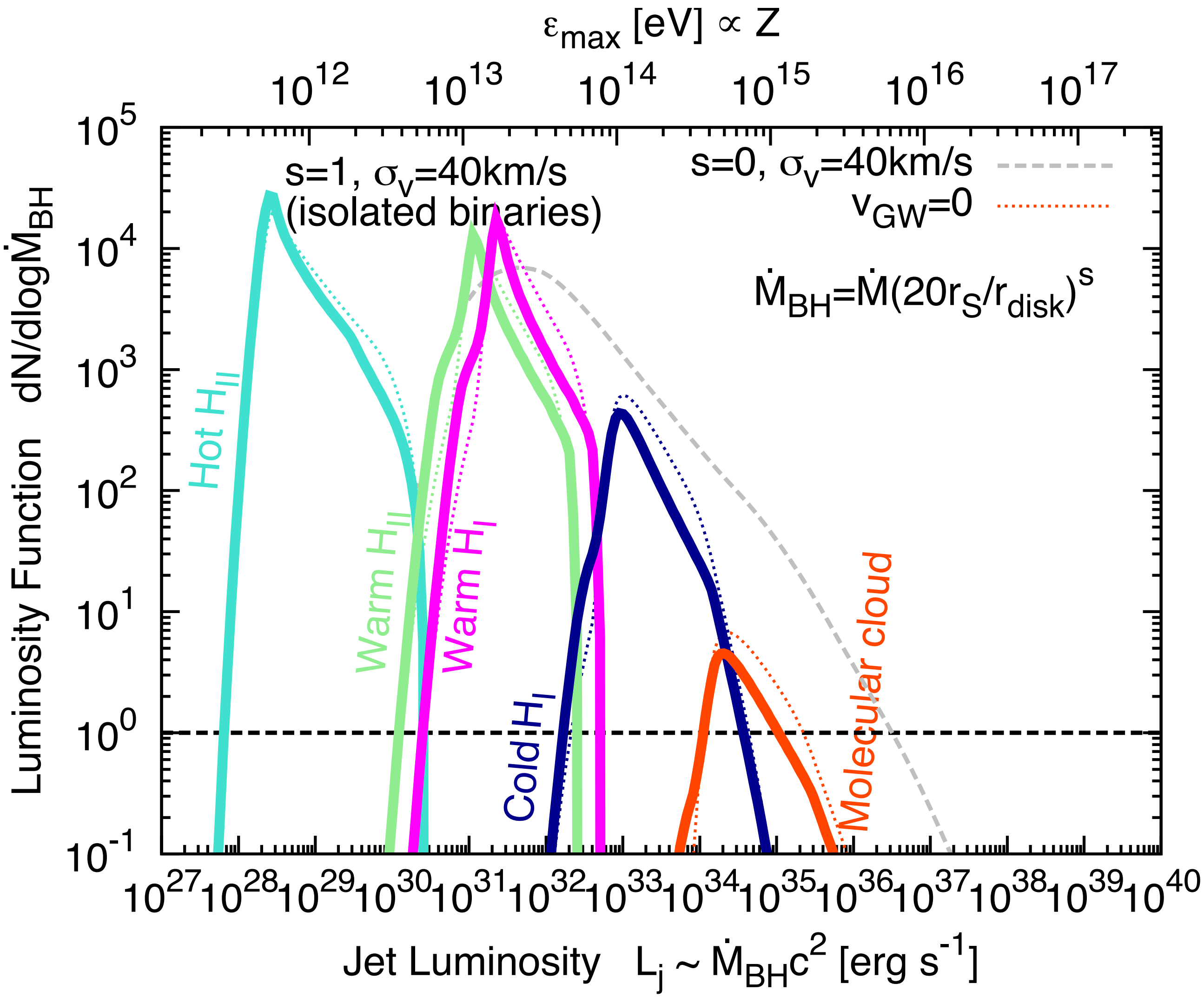
F=0.01M$_\odot$/pc$^3$

# Dependence on Binary Formation Scenario




$$\dot{M} \propto V^{-3} \sim \left( \frac{40 \text{ km s}^{-1}}{200 \text{ km s}^{-1}} \right)^3 \sim \frac{1}{100}$$

# Dependence on Accretion Disk Model

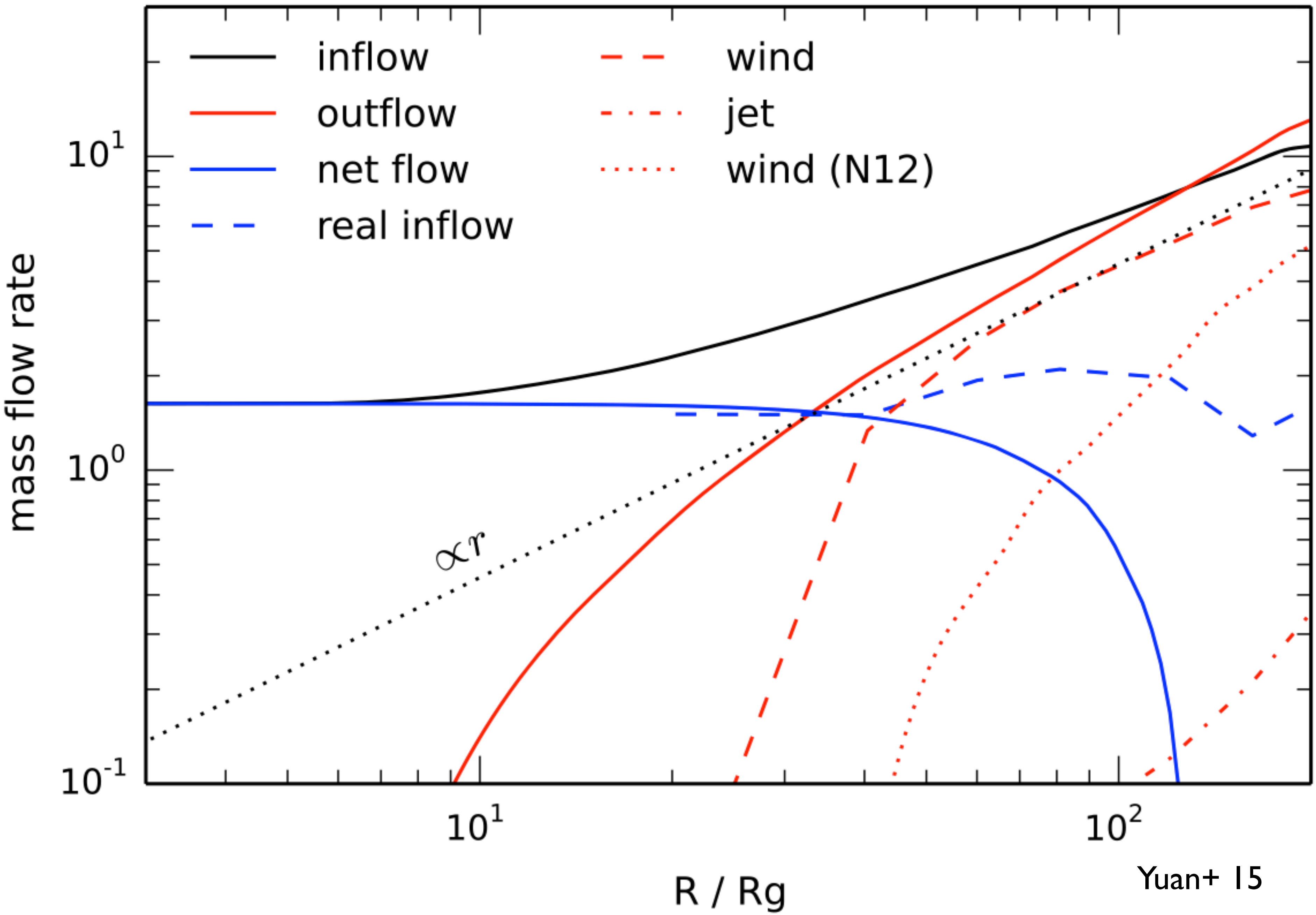



Adiabatic inflow-outflow solution (ADIOS)

$$\dot{M}_{\rm BH} \approx \dot{M}\left(\frac{20r_S}{r_{\rm disk}}\right)^s$$

Yuan+ 15

Most ISM does not accrete to BH

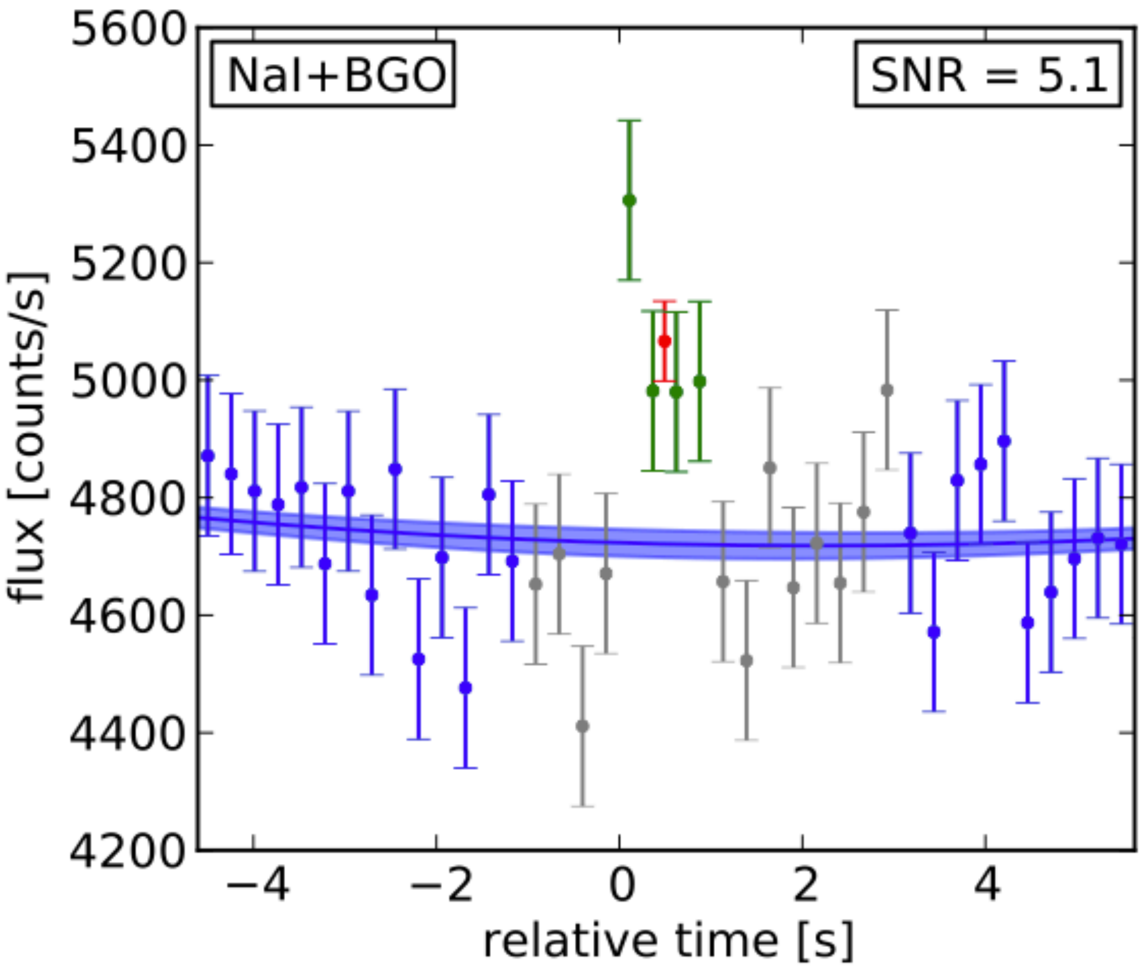


inflow
outflow
net flow
real inflow
wind
jet
wind (N12)
$\propto r$
mass flow rate
$10^1$
$10^0$
$10^{-1}$
$10^1$
$10^2$
R / Rg


Yuan+ 15

# Fermi γ-ray Burst Monitor

GBM detectors at 150914 09:50:45.797 +1.024s




>50keV

0.4s after GW

T~1sec

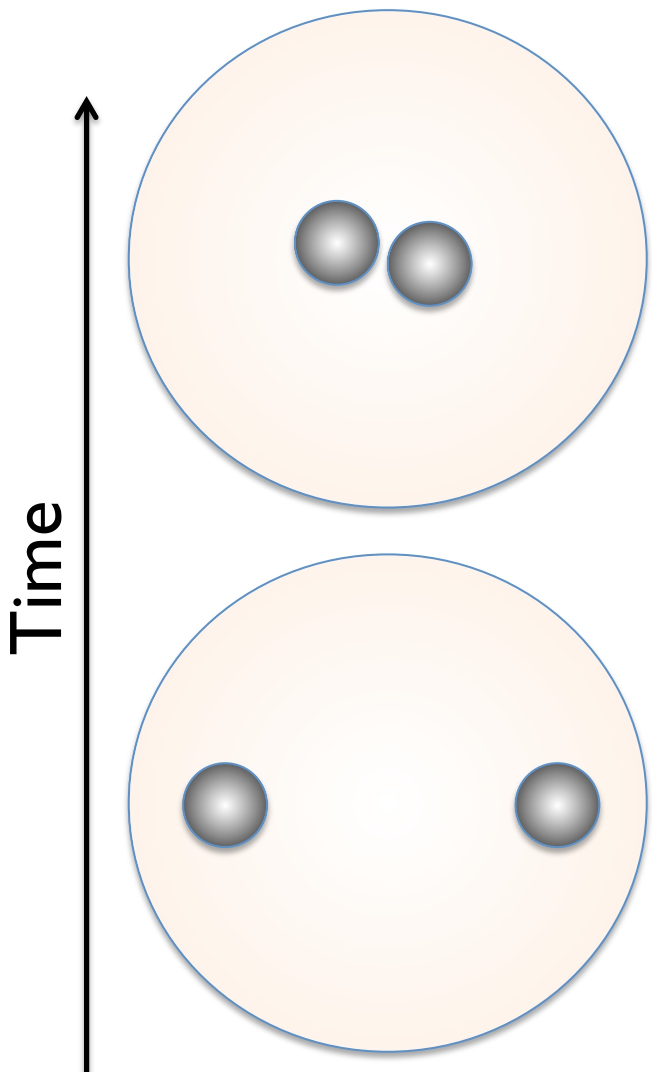
False alarm~0.0022

$L \sim 1.8^{+1.5}_{-1.0}$e49erg/s

***Short GRB!?***

Fermi+ 16

# No-Go?




$$t_{ff} \sim \frac{1}{\sqrt{G\rho}} \sim 1 \text{ sec}$$

$$\Rightarrow r \sim 10^9 \text{ cm}$$

$$t_m \sim \frac{5}{256} \frac{c^5 r^4}{G^3 M^2 \mu}$$

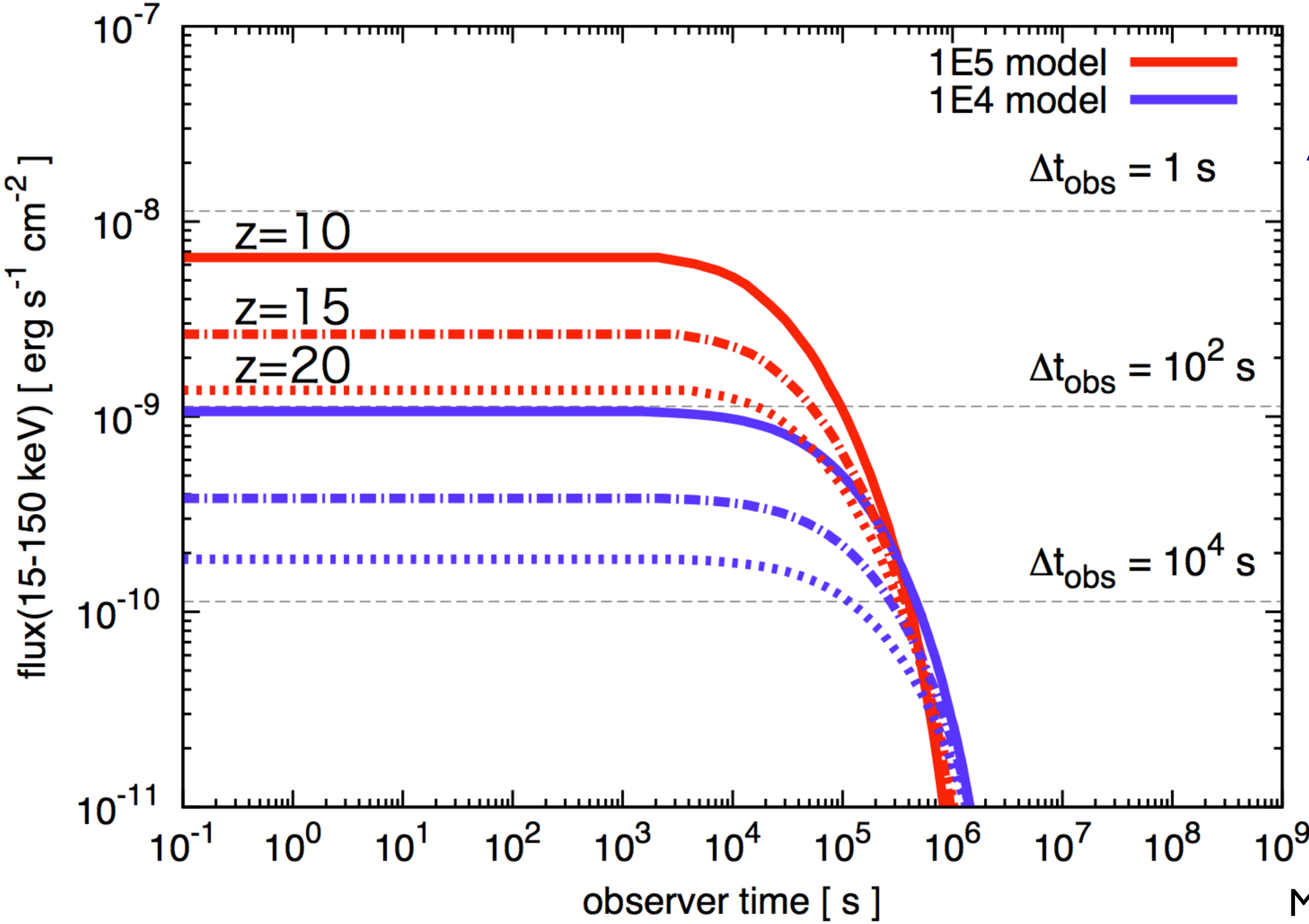
$$\sim 3 \times 10^3 \text{ sec}$$

$$L t_m \sim 3 \times 10^{52} \text{ erg}$$

$$> \frac{GMm}{r} \sim 2 \times 10^{52} \text{ erg} \left( \frac{m}{1 M_{sun}} \right)$$

Accretion occurred ⇒ Outflow ⇒ Unbound

# Observed Flux




Asuume
Swift BAT
Ep-Lp

Event rate
< 1/yr

Matsumoto+ 15

| Event | GW150914 | GW151226 | LVT151012 |
|---|---|---|---|
| Signal-to-noise ratio $\rho$ | 23.7 | 13.0 | 9.7 |
| False alarm rate FAR/yr$^{-1}$ | $< 6.0 \times 10^{-7}$ | $< 6.0 \times 10^{-7}$ | 0.37 |
| p-value | $7.5 \times 10^{-8}$ | $7.5 \times 10^{-8}$ | 0.045 |
| Significance | $> 5.3\,\sigma$ | $> 5.3\,\sigma$ | $1.7\sigma$ |
| Primary mass $m_1^{\rm source}/{\rm M}_\odot$ | $36.2^{+5.2}_{-3.8}$ | $14.2^{+8.3}_{-3.7}$ | $23^{+18}_{-6}$ |
| Secondary mass $m_2^{\rm source}/{\rm M}_\odot$ | $29.1^{+3.7}_{-4.4}$ | $7.5^{+2.3}_{-2.3}$ | $13^{+4}_{-5}$ |
| Chirp mass $\mathcal{M}^{\rm source}/{\rm M}_\odot$ | $28.1^{+1.8}_{-1.5}$ | $8.9^{+0.3}_{-0.3}$ | $15.1^{+1.4}_{-1.1}$ |
| Total mass $M^{\rm source}/{\rm M}_\odot$ | $65.3^{+4.1}_{-3.4}$ | $21.8^{+5.9}_{-1.7}$ | $37^{+13}_{-4}$ |
| Effective inspiral spin $\chi_{\rm eff}$ | $-0.06^{+0.14}_{-0.14}$ | $0.21^{+0.20}_{-0.10}$ | $0.0^{+0.3}_{-0.2}$ |
| Final mass $M_{\rm f}^{\rm source}/{\rm M}_\odot$ | $62.3^{+3.7}_{-3.1}$ | $20.8^{+6.1}_{-1.7}$ | $35^{+14}_{-4}$ |
| Final spin $a_{\rm f}$ | $0.68^{+0.05}_{-0.06}$ | $0.74^{+0.06}_{-0.06}$ | $0.66^{+0.09}_{-0.10}$ |
| Radiated energy $E_{\rm rad}/({\rm M}_\odot c^2)$ | $3.0^{+0.5}_{-0.4}$ | $1.0^{+0.1}_{-0.2}$ | $1.5^{+0.3}_{-0.4}$ |
| Peak luminosity $\ell_{\rm peak}/({\rm erg\,s}^{-1})$ | $3.6^{+0.5}_{-0.4} \times 10^{56}$ | $3.3^{+0.8}_{-1.6} \times 10^{56}$ | $3.1^{+0.8}_{-1.8} \times 10^{56}$ |
| Luminosity distance $D_{\rm L}/{\rm Mpc}$ | $420^{+150}_{-180}$ | $440^{+180}_{-190}$ | $1000^{+500}_{-500}$ |
| Source redshift $z$ | $0.09^{+0.03}_{-0.04}$ | $0.09^{+0.03}_{-0.04}$ | $0.20^{+0.09}_{-0.09}$ |
| Sky localization $\Delta\Omega/{\rm deg}^2$ | 230 | 850 | 1600 |

LIGO O1 16

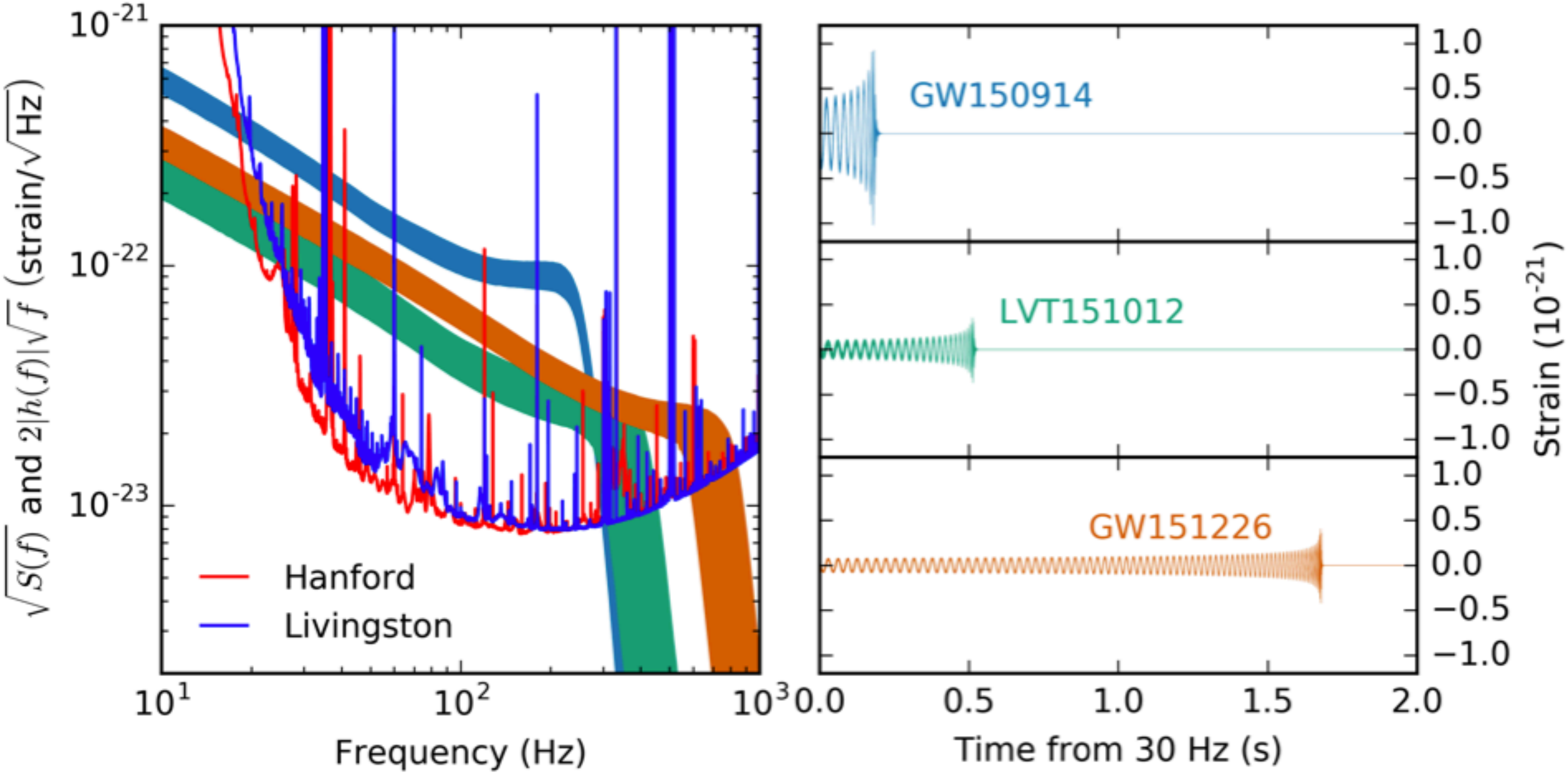



FIG. 1. Left: Amplitude spectral density of the total strain noise of the H1 and L1 detectors, $\sqrt{S(f)}$, in units of strain per $\sqrt{\text{Hz}}$, and the recovered signals of GW150914, GW151226 and LVT151012 plotted so that the relative amplitudes can be related to the SNR of the signal (as described in the text). Right: Time evolution of the waveforms from when they enter the detectors' sensitive band at 30 Hz. All bands show the 90% credible regions of the LIGO Hanford signal reconstructions from a coherent Bayesian analysis using a non-precessing spin waveform model [45].

LIGO O1 16

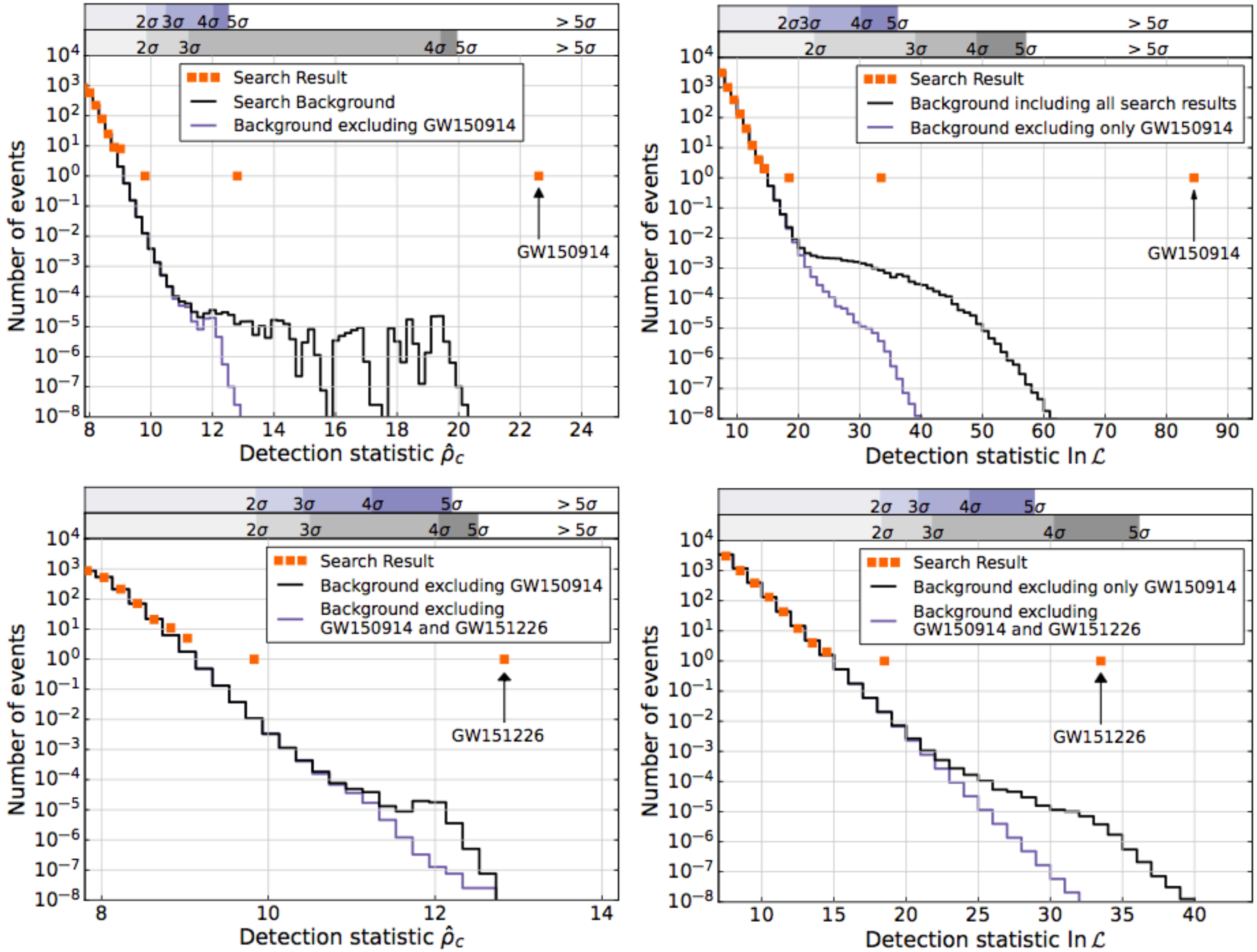
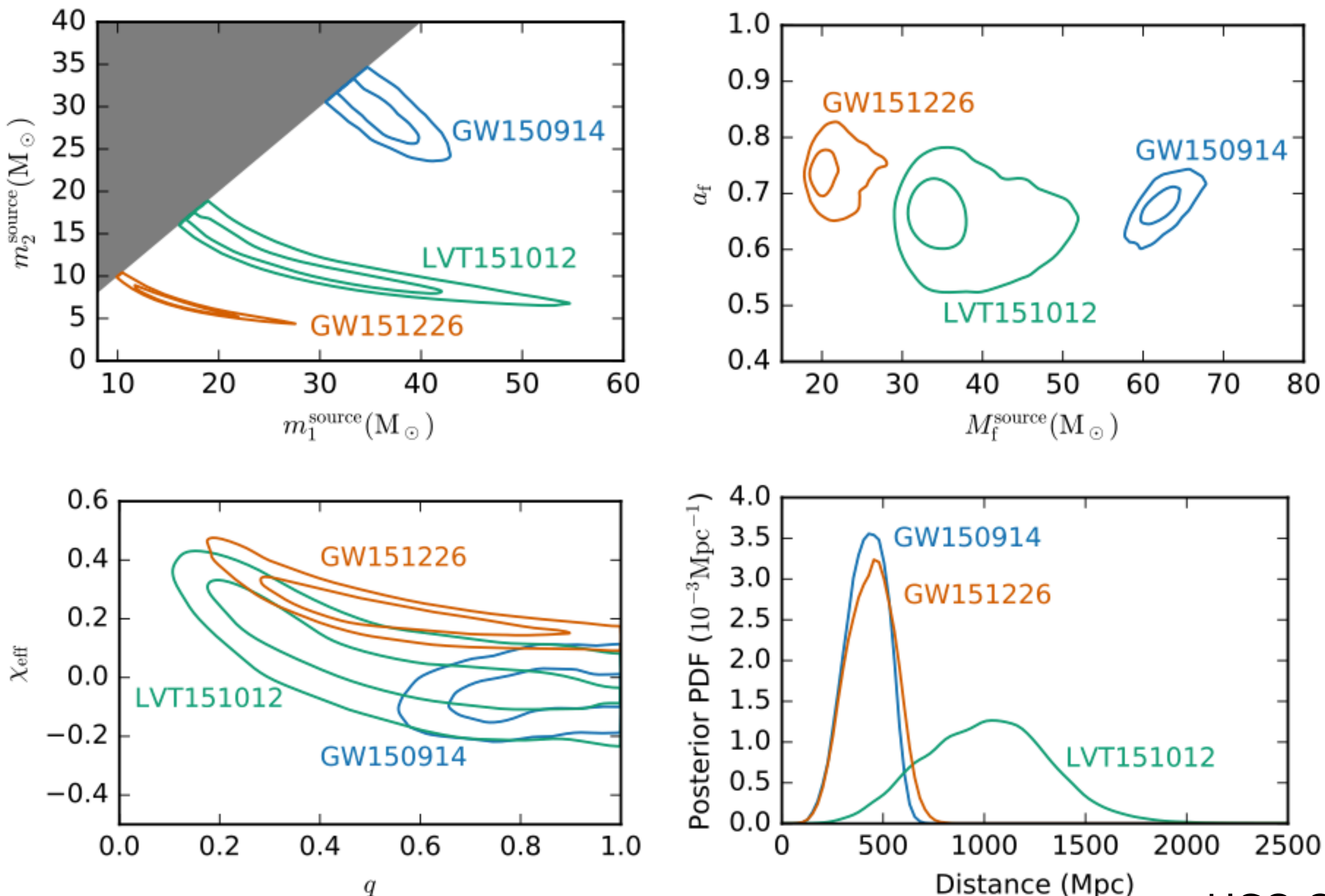


FIG. 3. Search results from the two analyses. The upper left hand plot shows the PyCBC result for signals with chirp mass $\mathscr{M} > 1.74 M_\odot$ (the chirp mass of a $m_1 = m_2 = 2M_\odot$ binary) and $f_{\rm peak} > 100$Hz while the upper right hand plot shows the GstLAL result. In both analyses, GW150914 is the most significant event in the data, and is more significant than any background event in the data. It is identified with a significance greater than $5\sigma$ in both analyses. As GW150914 is so significant, the high significance background is dominated by its presence in the data. Once it has been identified as a signal, we remove it from the background estimation to evaluate the significance of the remaining events. The lower plots show results with GW150914 removed from both the foreground and background, with the PyCBC result on the left and GstLAL result on the right. In both analyses, GW151226 is identified as the most significant event remaining in the data. GW151226 is more significant than the remaining background in the PyCBC analysis, with a significance of greater than $5\sigma$. In the GstLAL search GW151226 is measured to have a significance of $4.5\sigma$. The third most significant event in the search, LVT151012 is identified with a significance of $1.7\sigma$ and $2.0\sigma$ in the two analyses respectively. The significance obtained for LVT151012 is only marginally affected by including or removing background contributions from GW150914 and GW151226.




LIGO O1 16

FIG. 4. Posterior probability densities of the masses, spins and distance to the three events GW150914, LVT151012 and GW151226. For the two dimensional distributions, the contours show 50% and 90% credible regions. *Top left:* component masses $m_1^{\rm source}$ and $m_2^{\rm source}$ for the three events. We use the convention that $m_1^{\rm source} \geq m_2^{\rm source}$, which produces the sharp cut in the two-dimensional distribution. For GW151226 and LVT151012, the contours follow lines of constant chirp mass ($\mathcal{M}^{\rm source} = 8.9^{+0.3}_{-0.3}\,M_\odot$ and $\mathcal{M}^{\rm source} = 15.1^{+1.4}_{-1.1}\,M_\odot$ respectively). In all three cases, both masses are consistent with being black holes. *Top right:* The mass and dimensionless spin magnitude of the final black holes. *Bottom left:* The effective spin and mass ratios of the binary components. *Bottom right:* The luminosity distance to the three events.

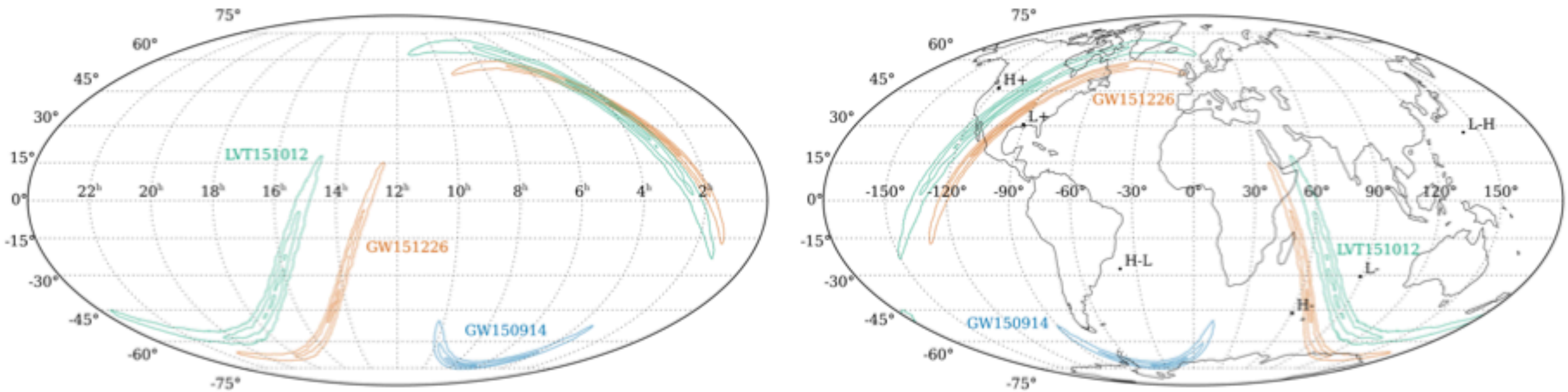



FIG. 5. Posterior probability distributions for the sky locations of GW150914, LVT151012 and GW151226 shown in a Mollweide projection. The left plot shows the probable position of the source in equatorial coordinates (right ascension is measured in hours and declination is measured in degrees). The right plot shows the localization with respect to the Earth at the time of detection. H+ and L+ mark the Hanford and Livingston sites, and H− and L− indicate antipodal points; H-L and L-H mark the poles of the line connecting the two detectors (the points of maximal time delay). The sky localization forms part of an annulus, set by the difference in arrival times between the detectors.

LIGO O1 16

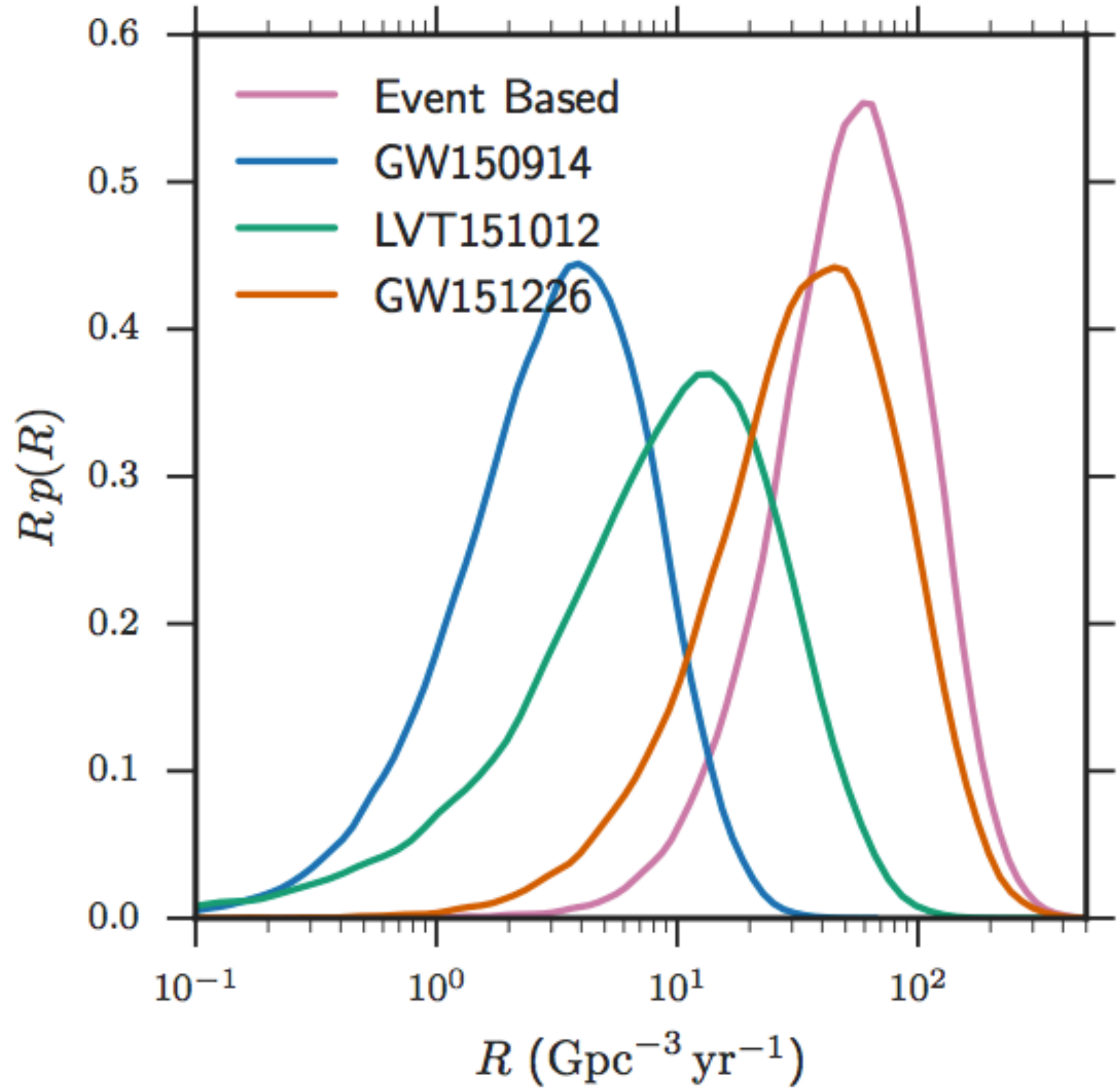



FIG. 9. The posterior density on the rate of GW150914-like BBH, LVT151012-like BBH, and GW151226-like BBH mergers. The event based rate is the sum of these. The median and 90% credible levels are given in Table II.

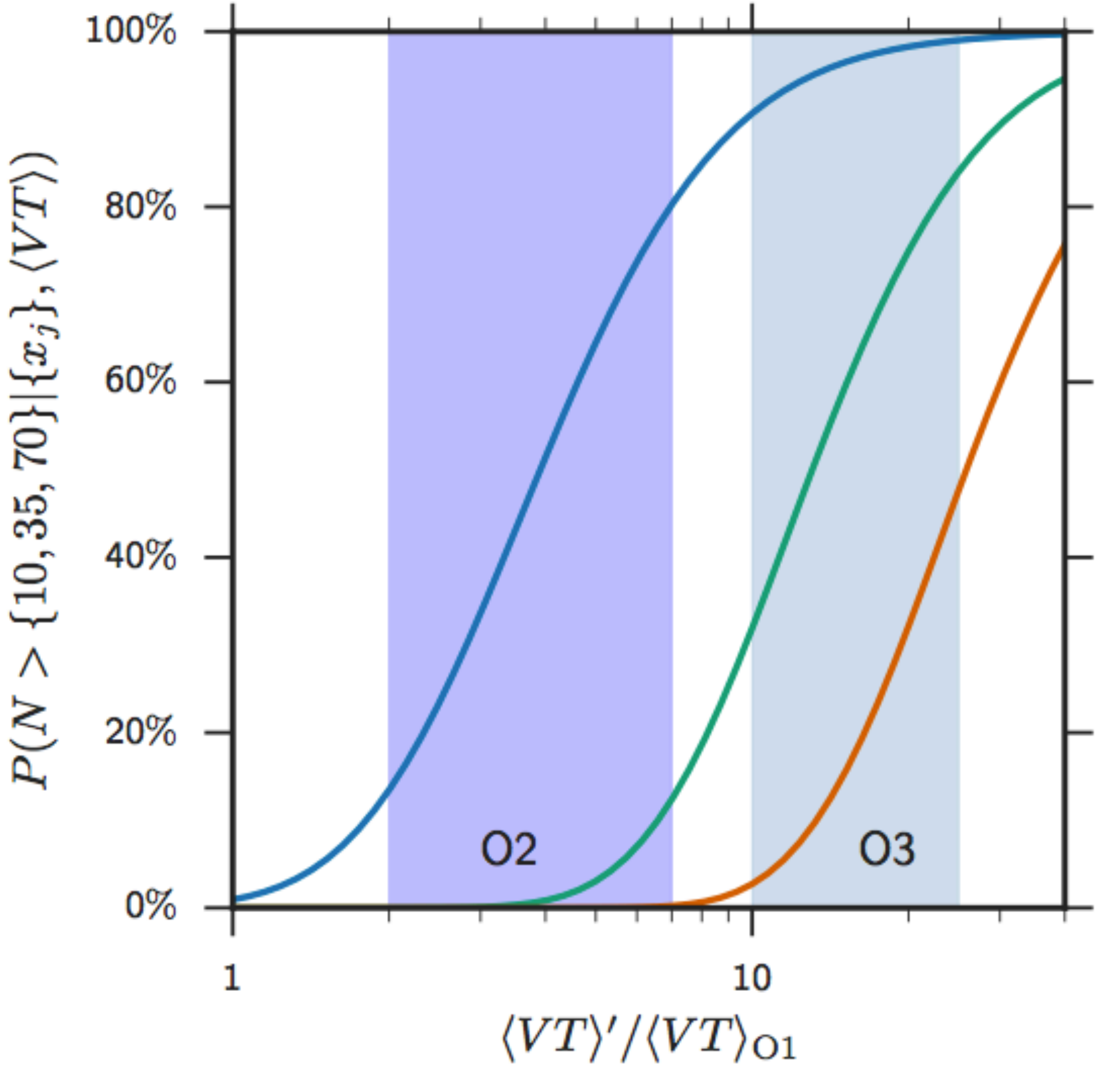
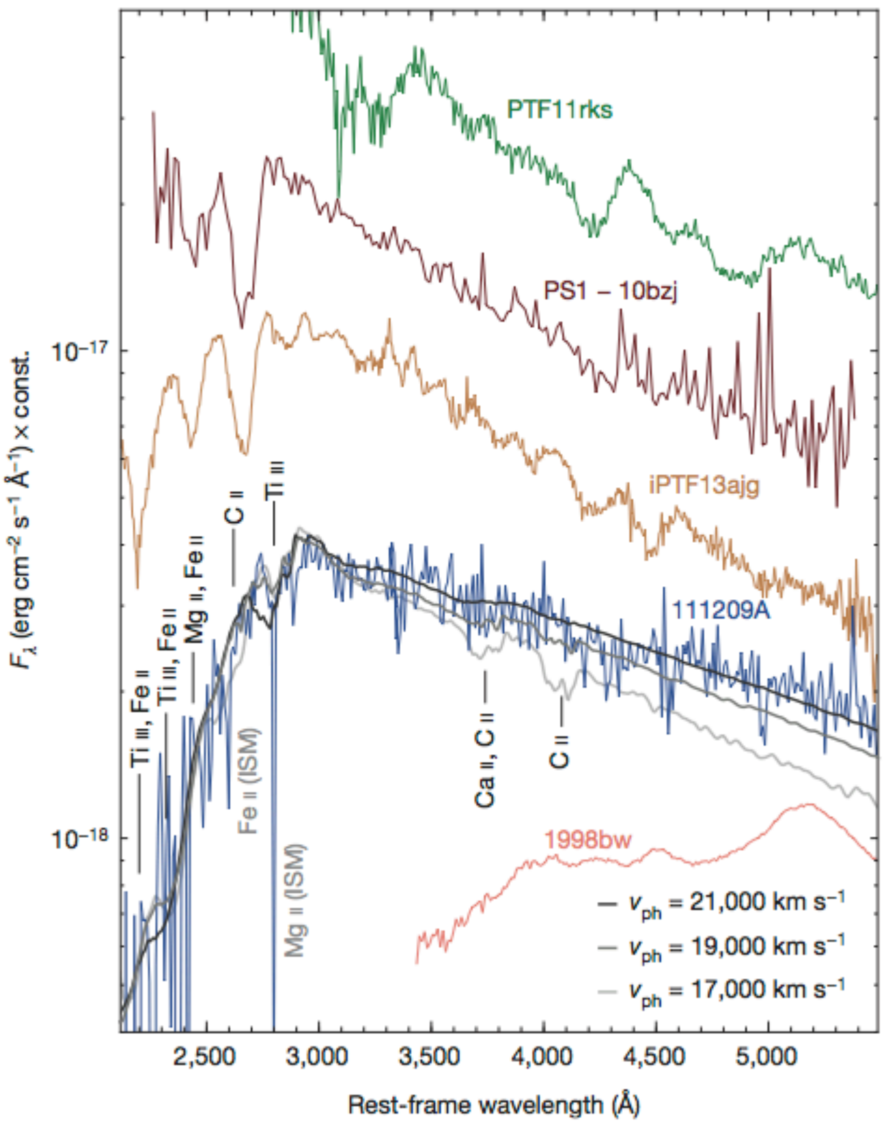



FIG. 12. The probability of observing $N > 10$, $N > 35$, and $N > 70$ highly significant events, as a function of surveyed time-volume. The vertical line and bands show, from left to right, the expected sensitive time-volume for the second (O2) and third (O3) advanced detector observing runs.

LIGO O1 16

# Spectrum




X-shooter spectrum
− GRB afterglow
− host galaxy

Supernova ⇒ TDE ×
No H line ⇒ BSG ×
⇒ Magnetar

No Ca II, C II lines
⇒ v>2e9 cm/s

Greiner+ 15

# Quantitatively Consistent

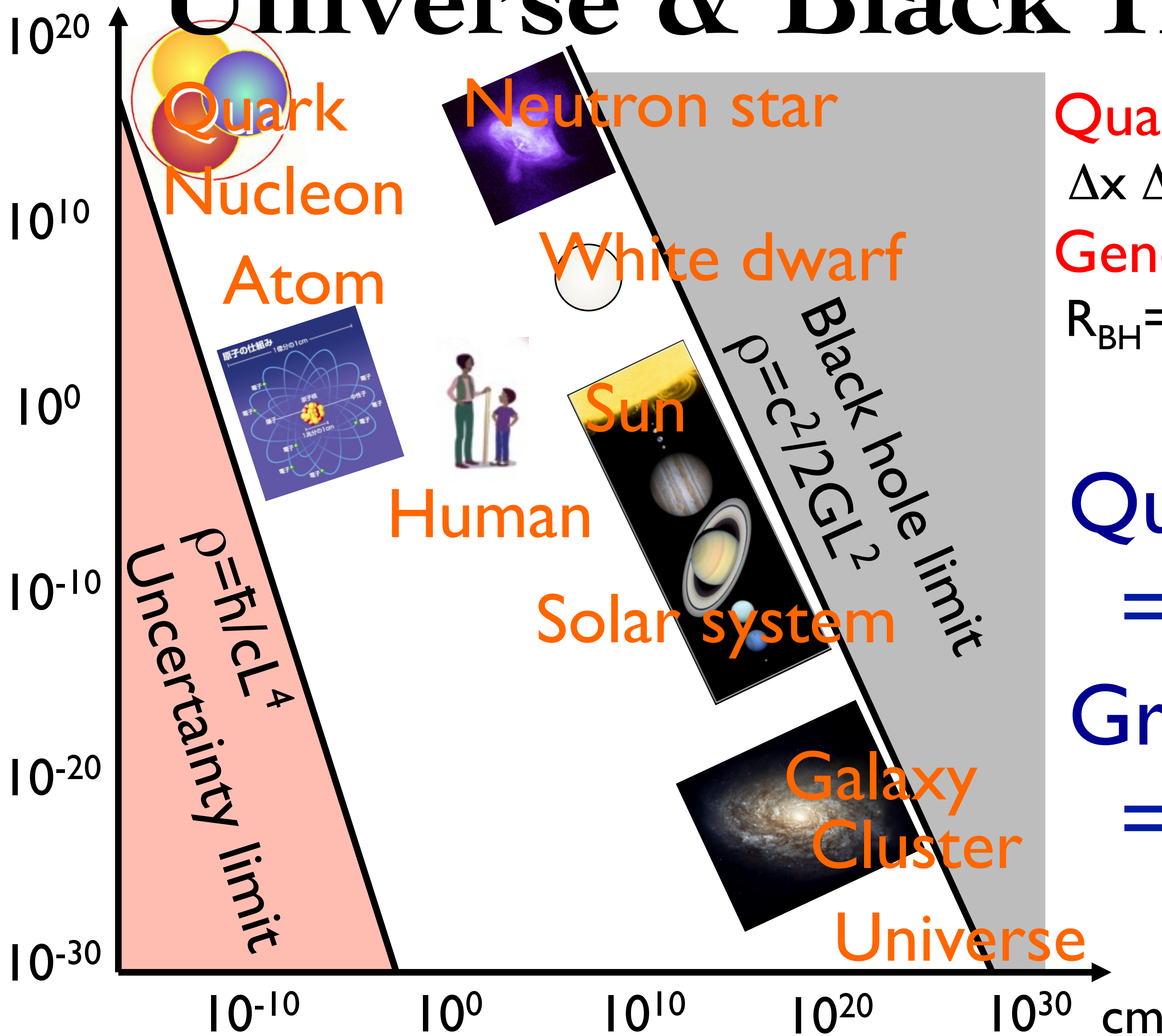
$$E \sim \frac{GM_{BH}\left(M_*/2\right)}{2a_{\min}} \sim 4\times10^{51}\,\mathrm{erg}$$

$$t_{circular} > 5-10\times t_0$$

$$L \sim L_{Edd} \sim 10^{43}\,\mathrm{erg\ s^{-1}}\left(\frac{M_{BH}}{10^5 M_8}\right)$$

$$v_{\min} \sim \sqrt{\frac{GM_{BH}}{2a_{\min}}} \sim 2\times10^{9}\,\mathrm{cm\ s^{-1}}$$

# Universe & Black Holes




Quantum mechanics

$\Delta x \, \Delta p \geq \hbar$

General relativity

$R_{BH}=2GM/c^2$

Quantum "ħ"

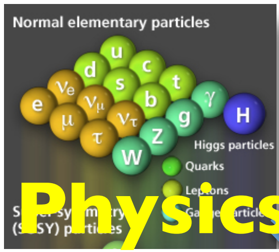
⇒ Particle

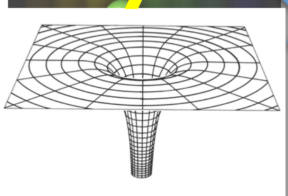
Gravity "G"

⇒ Universe

# Evolution to Black Holes

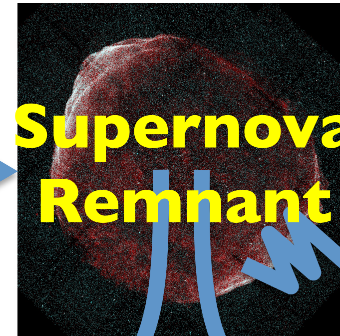
Gravity
Quantum



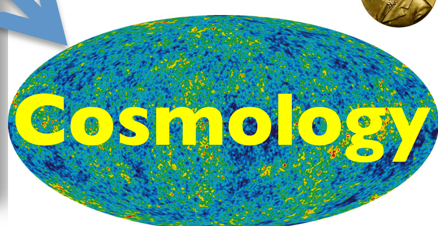




*Chandrasekhar*
*Bethe*

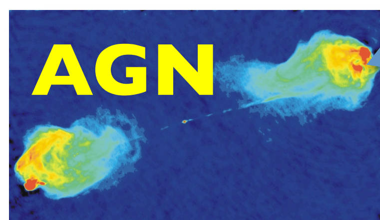

*Davis*
*Koshiba*



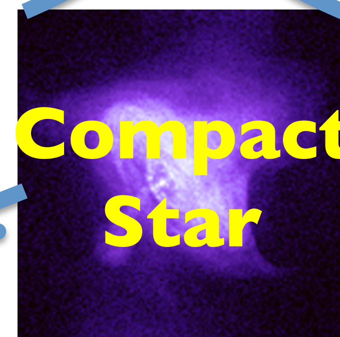

*W. A. Fowler*




*Penzias, Wilson*
*Mather, Smoot*
*Perlmutter, Riess,*
*Schmidt*

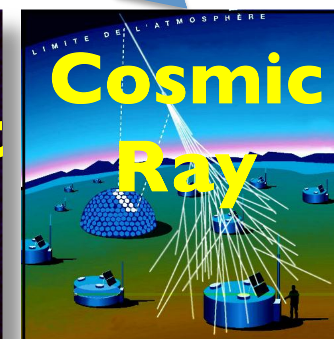




Active galactic nuclei
Massive black hole
at the center of galaxy




Black Hole
Neutron Star
White Dwarf

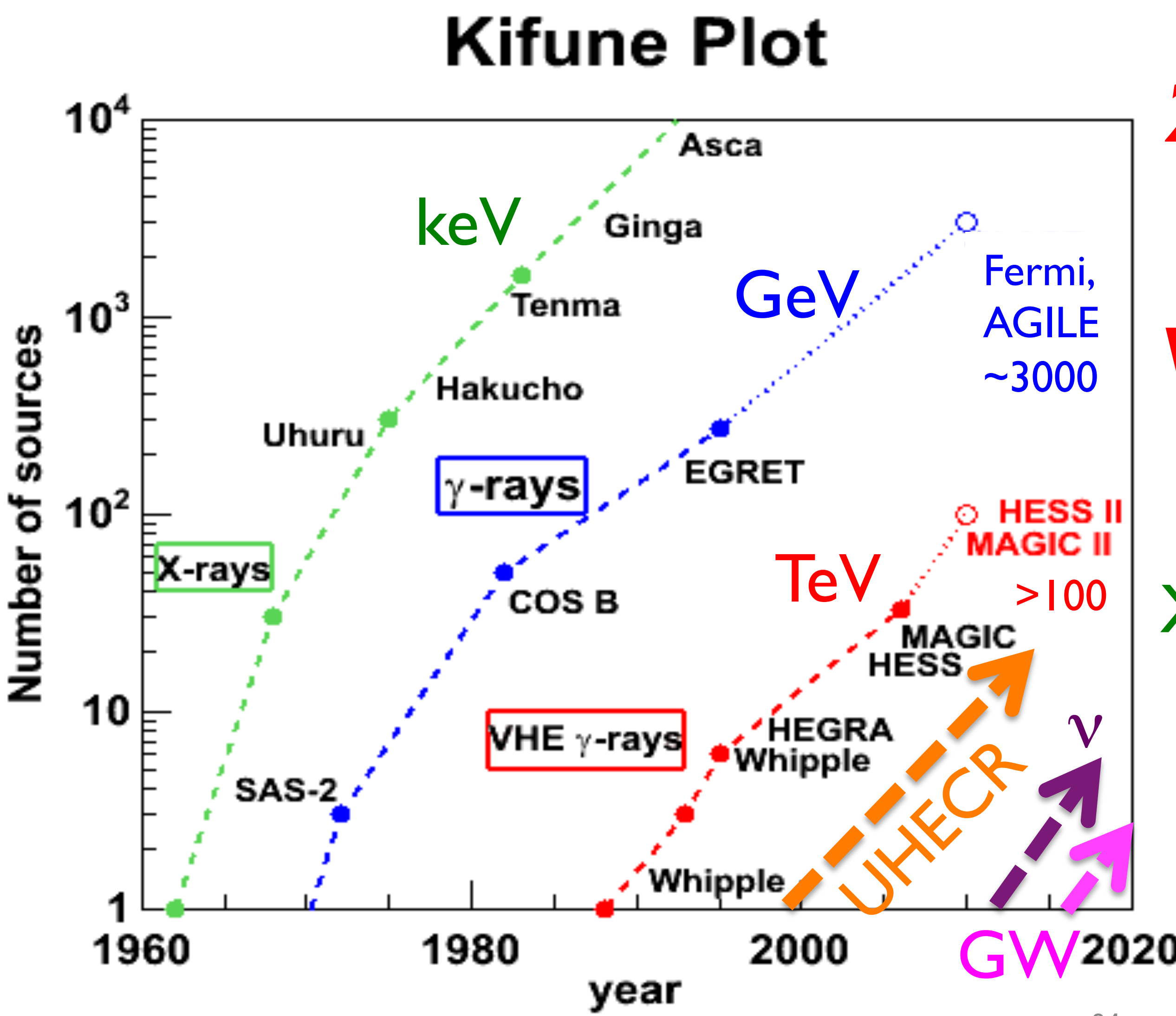
*Giacconi*
*Hewish*
*Hulse, Taylor*




*Hess*
*Anderson*
*Yukawa*
*Powell*
*Kajita*

## High Energy Universe

# Observational Revolution




**20th century: *Multi-wavelength***

μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

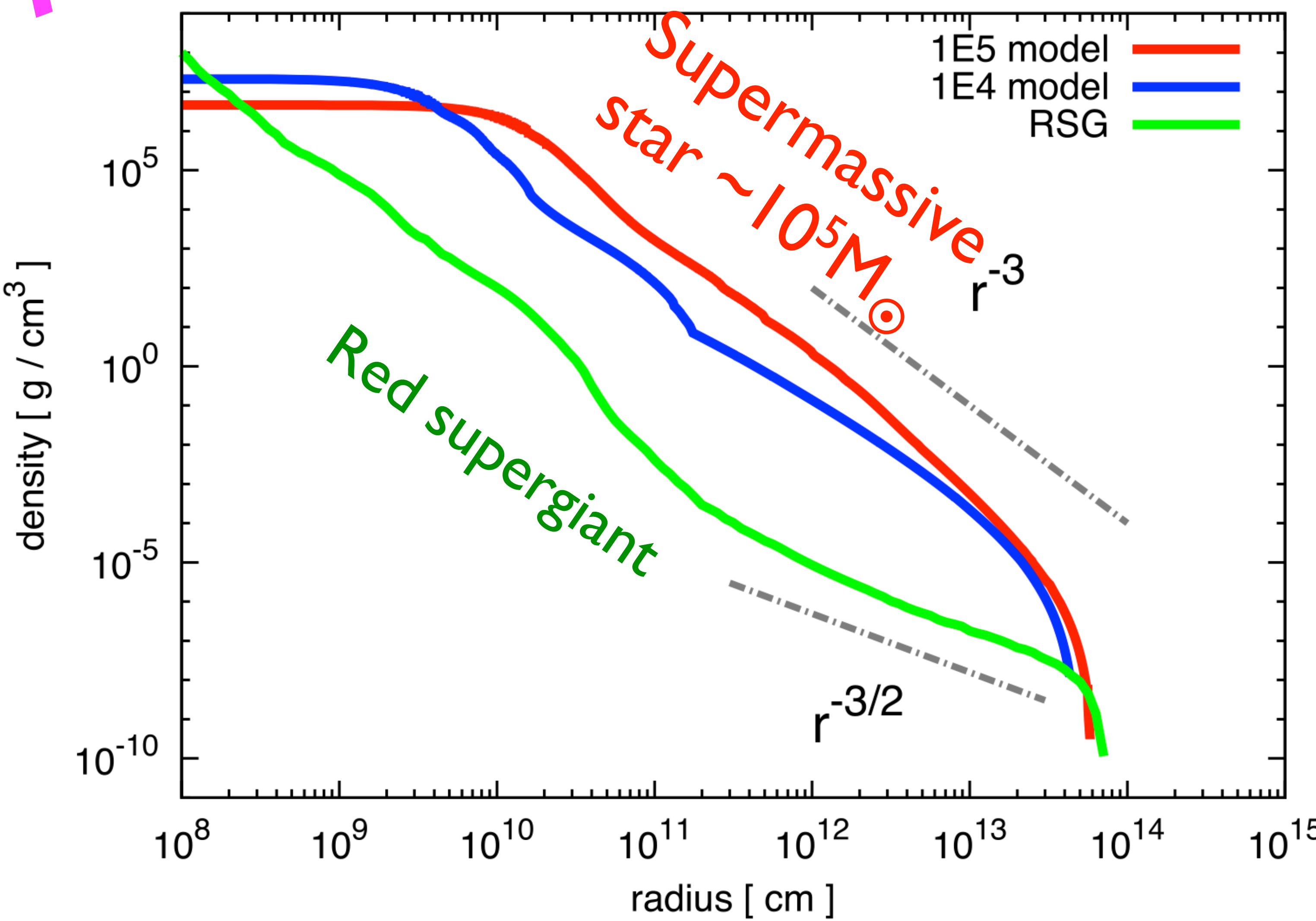
# of sources are increasing exponentially

# Multi-Messenger Era


**21th Century: Multi-Messenger Era**

# Direct Collapse BHs can Launch GRBs?

Poster 11



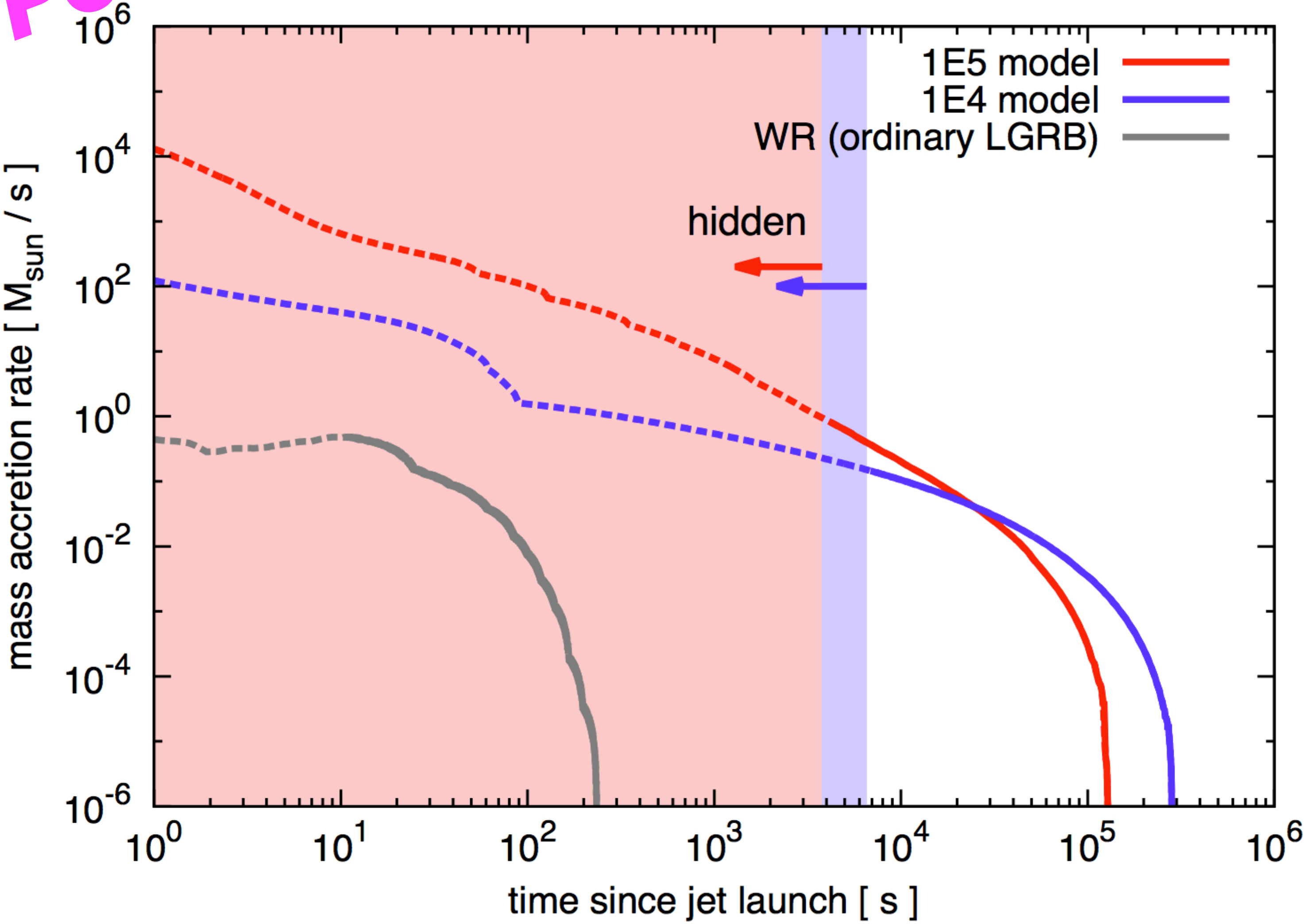

$10^9 M_\odot$ BH @z>6
Super-Edd. accretion?
or DCBH?

GRB jets break out the star?

Matsumoto+ 15

# GRB Jets can Break Out Supermassive Stars

Poster I I



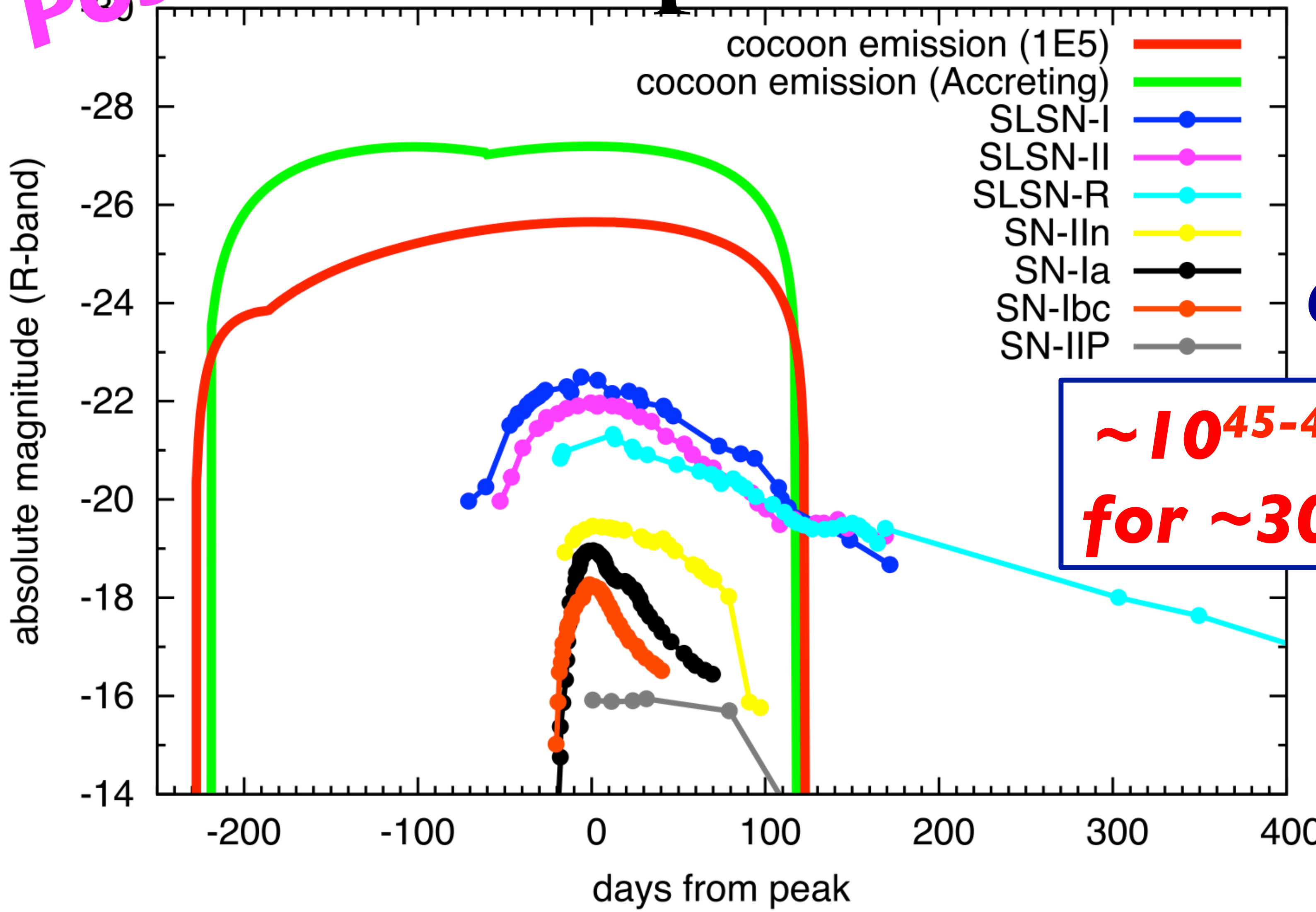

Radiation pressure-dominated ⇒ Breakout

Total energy ~$10^{55\text{-}56}$ erg ~$M_{halo}\, v_{esc}\, v_c$ ⇒ Expel the host galaxy?

Matsumoto+ 15

# Ultra-Luminous Supernova

Poster II




**Jet ⇒ Cocoon**

**~$10^{45\text{-}46}$ erg/s for ~300 days**