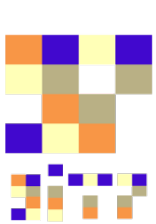
Black Hole Systems as Multi-Messenger Sources

Kunihito Ioka

(Center for Gravity Physics,

YITP, Kyoto U.)



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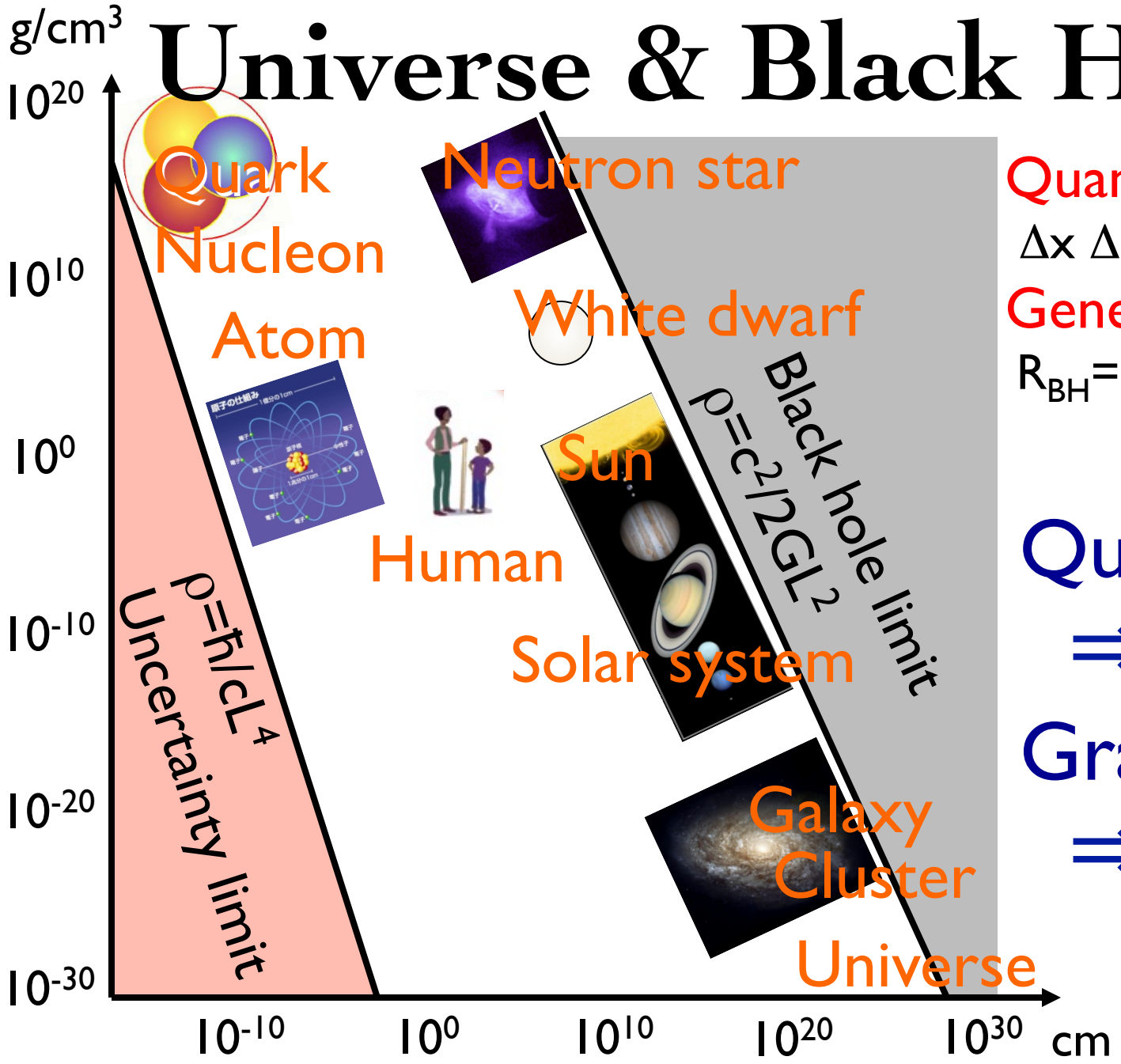
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

Universe & Black Holes



Quantum mechanics

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

General relativity

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

Quantum "ħ"

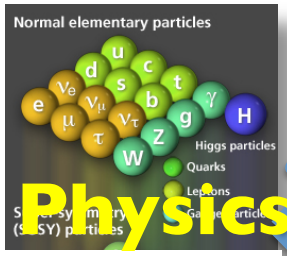
⇒ Particle

Gravity "G"

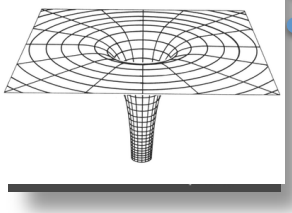
⇒ Universe

Evolution to Black Holes

Gravity
Quantum

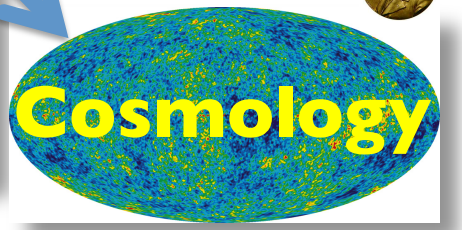


Physics



Star

Chandrasekhar
Bethe



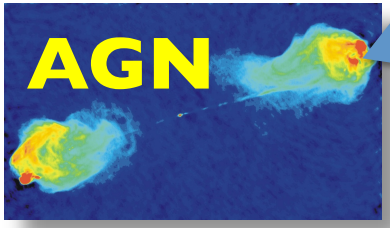
Cosmology

Supernova
GRB

Davis
Koshiba

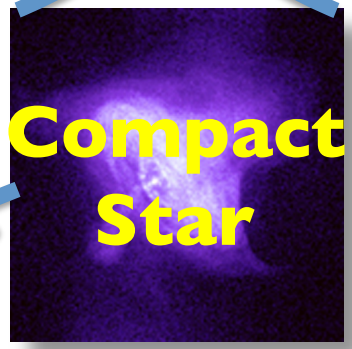
Supernova Remnant

W. A. Fowler



AGN

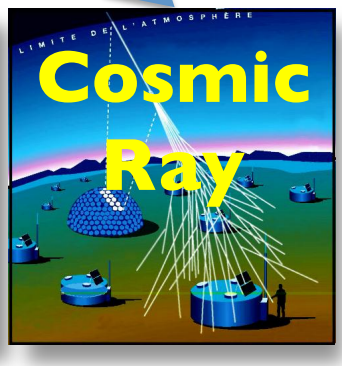
Active galactic nuclei
Massive black hole
at the center of galaxy



Compact Star

Black Hole
Neutron Star
White Dwarf

Giacconi
Hewish
Hulse, Taylor



Cosmic Ray

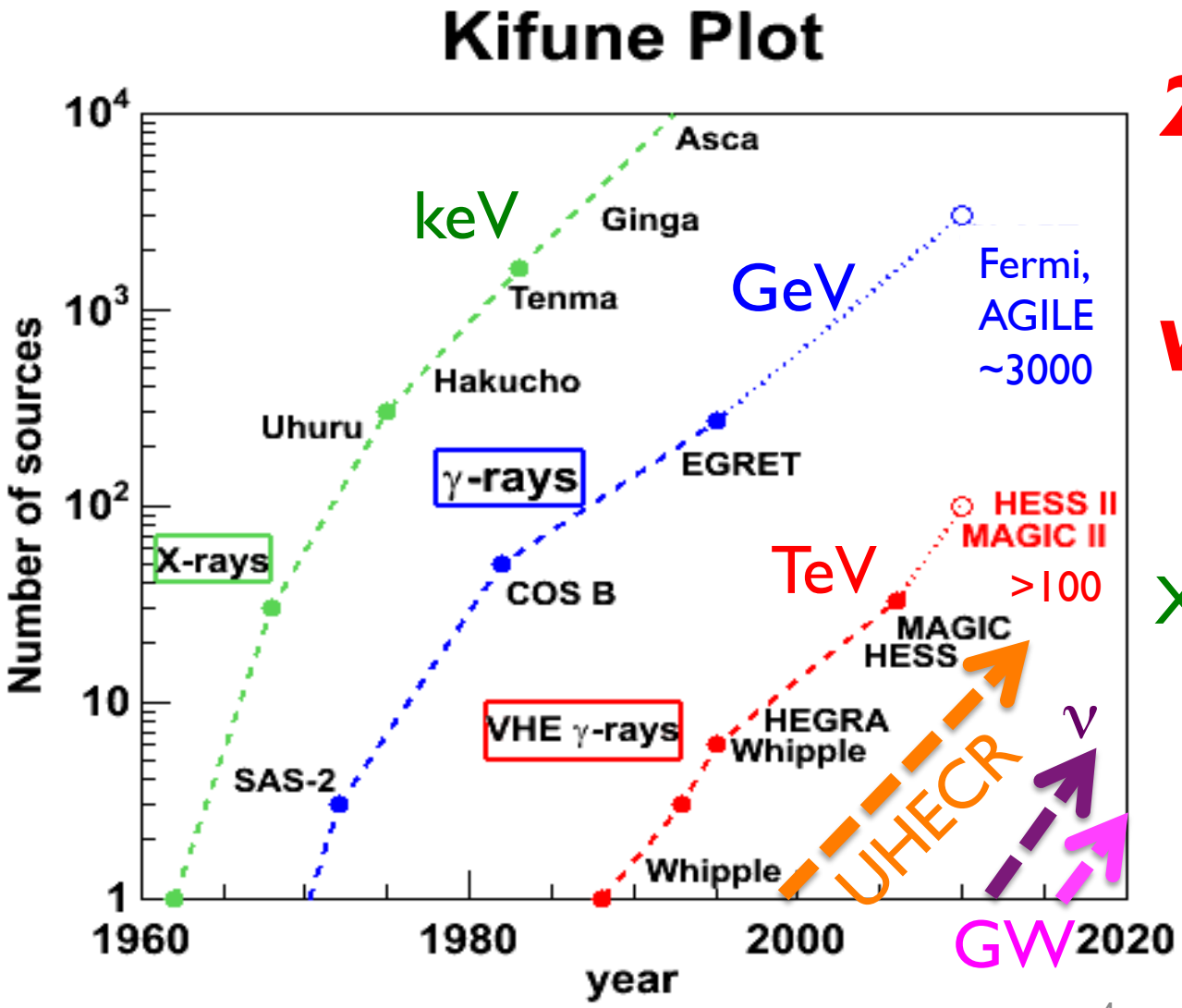
Hess
Anderson
Yukawa
Powell
Kajita

Computer

Penzias, Wilson
Mather, Smoot
Perlmutter, Riess,
Schmidt

High Energy Messengers

Observational Revolution

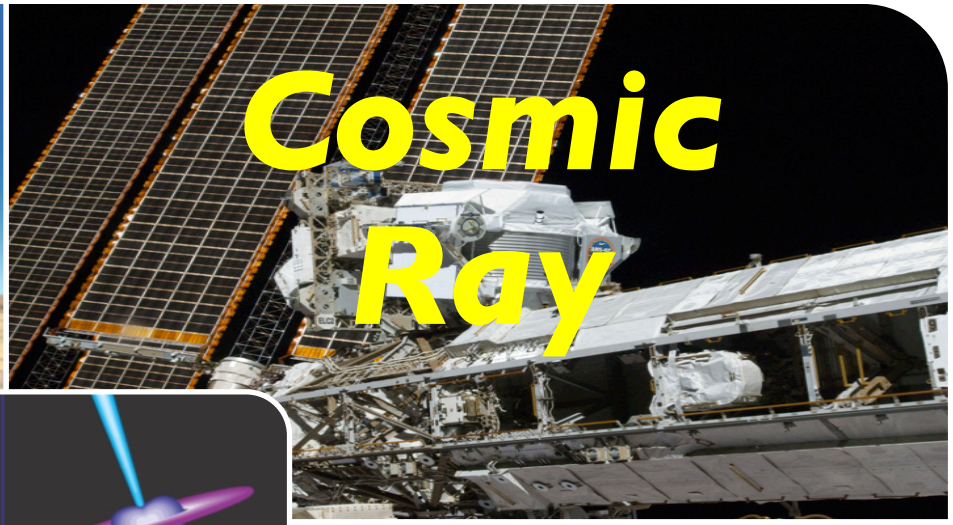


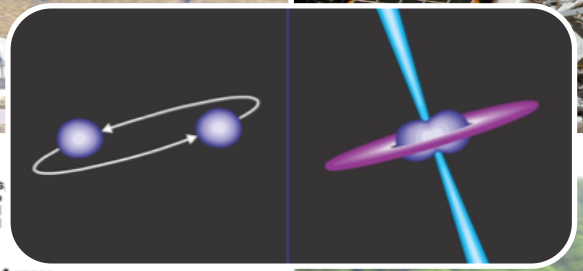
20th century: Multi-wavelength

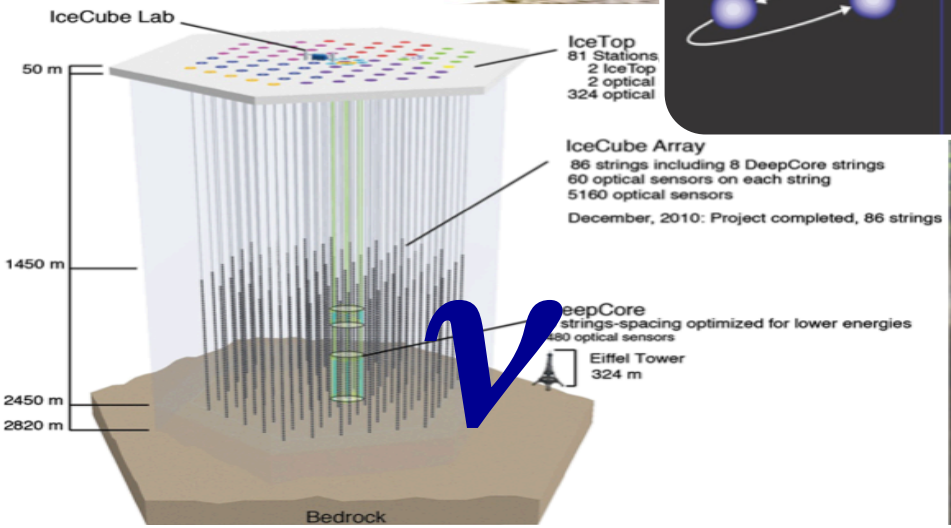
μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

# of sources are increasing exponentially

Multi-Messenger Era







21th Century: Multi-Messenger Era

Contents

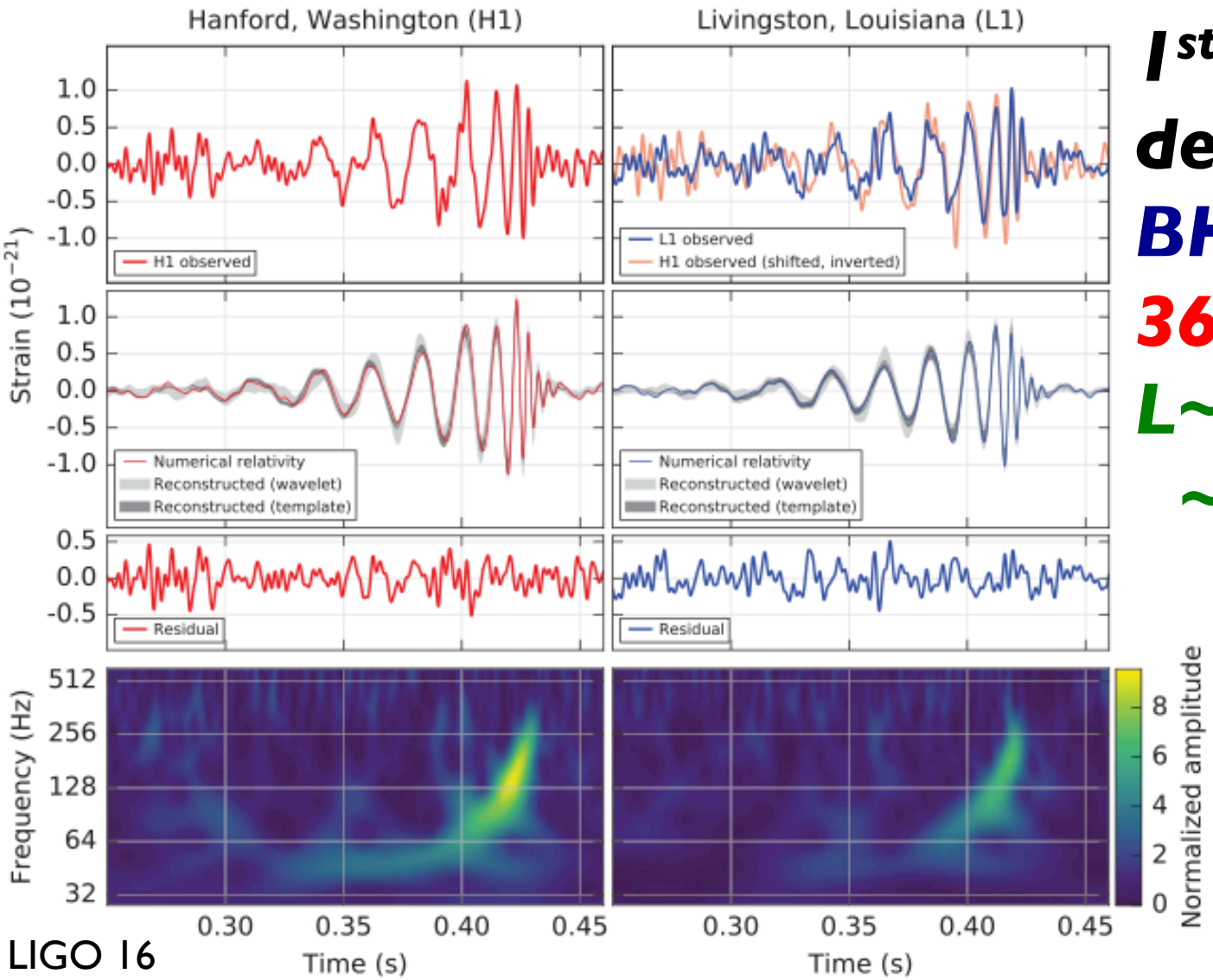
- ***BH-BH***
  - Gravitational waves!!!
  - Galactic PeVatrons? TeV unIDs? — KI, Matsumoto, Teraki, Kashiyama & Murase in prep.
- ***BH/NS-NS***
  - Macronovae? — Kyutoku+ 13, 15, Kyutoku & KI 16
  - Long-lasting short GRBs? — Kisaka+ 15, 16, Kisaka & KI 15
- ***Supermassive BH***
  - Ultra-long GRBs? — KI, Hotokezaka & Piran 16
  - Direct collapse BH jets? — Matsumoto+ 15, 16

We Did It!

@YITP
midnight

Champagne

GW150914



LIGO 16

1st direct detection

BH-BH

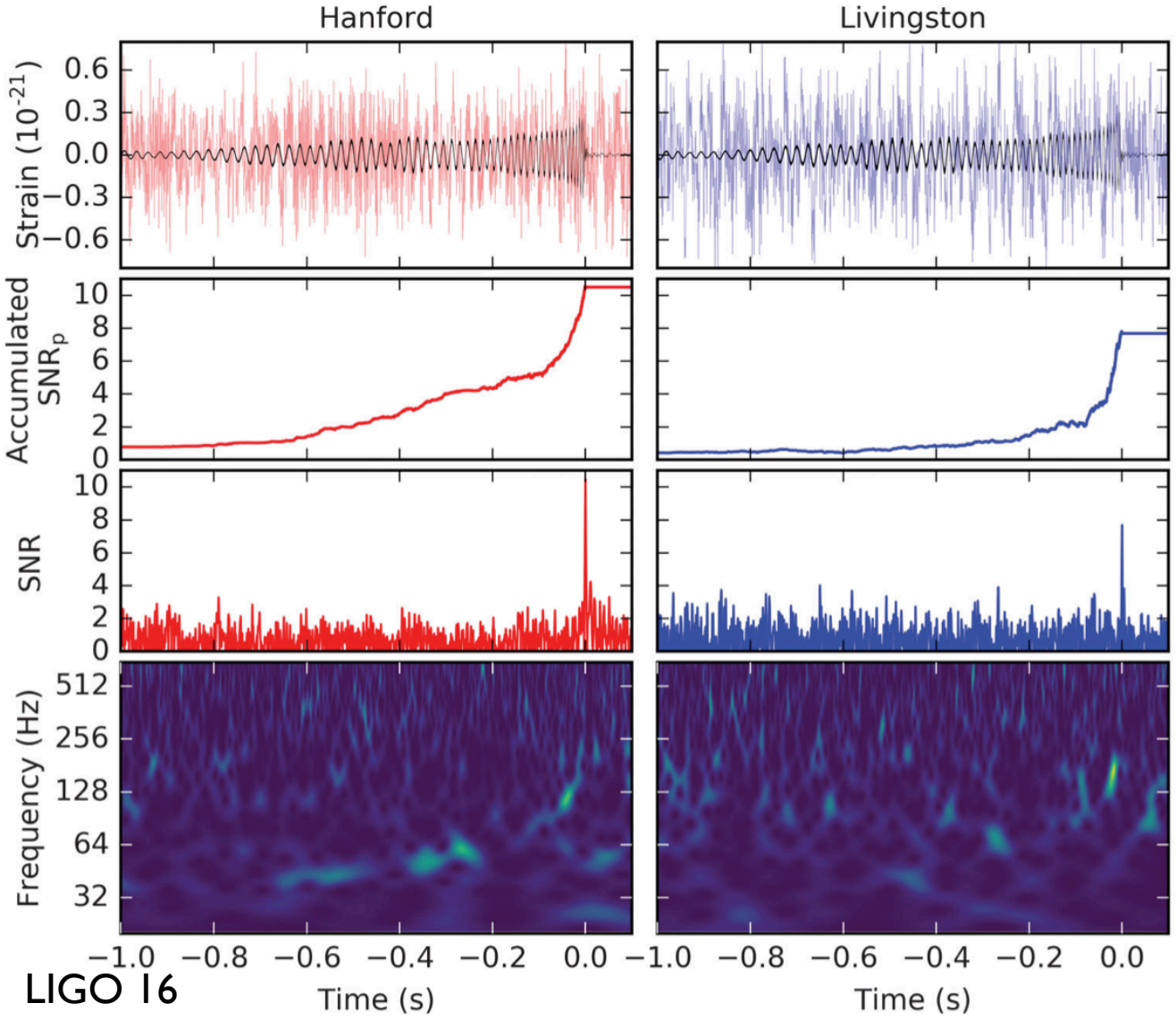
$36M_\odot+29M_\odot$

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

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

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

GW151226



2nd event

BH-BH

$14.2M_\odot$

$+7.5M_\odot$

$L \sim 170M_\odot c^2/s$

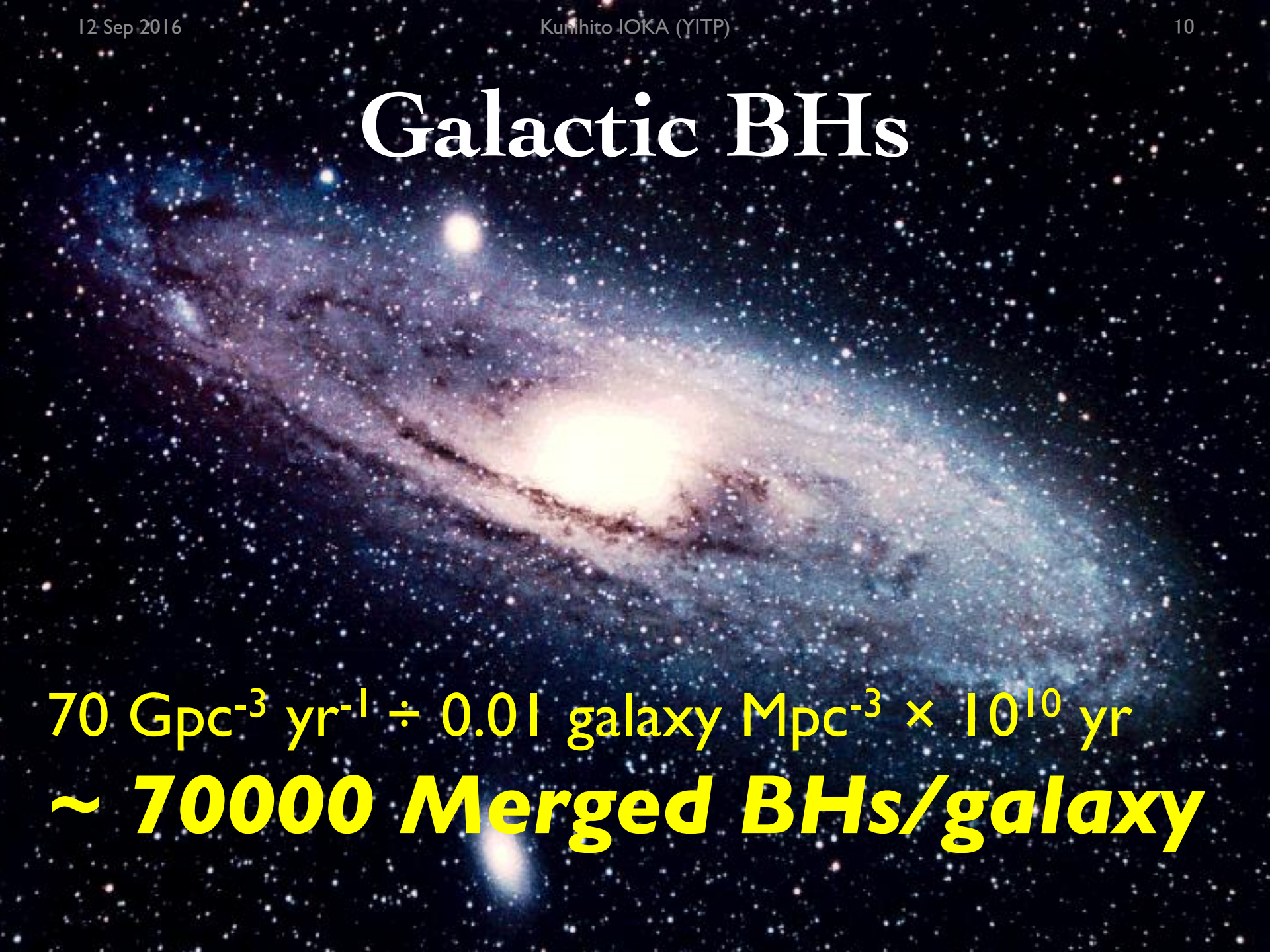
$a_{1or2} > 0.2$

LVT151012

R_{GW}~9-240 events

$Gpc^{-3}\ yr^{-1}$

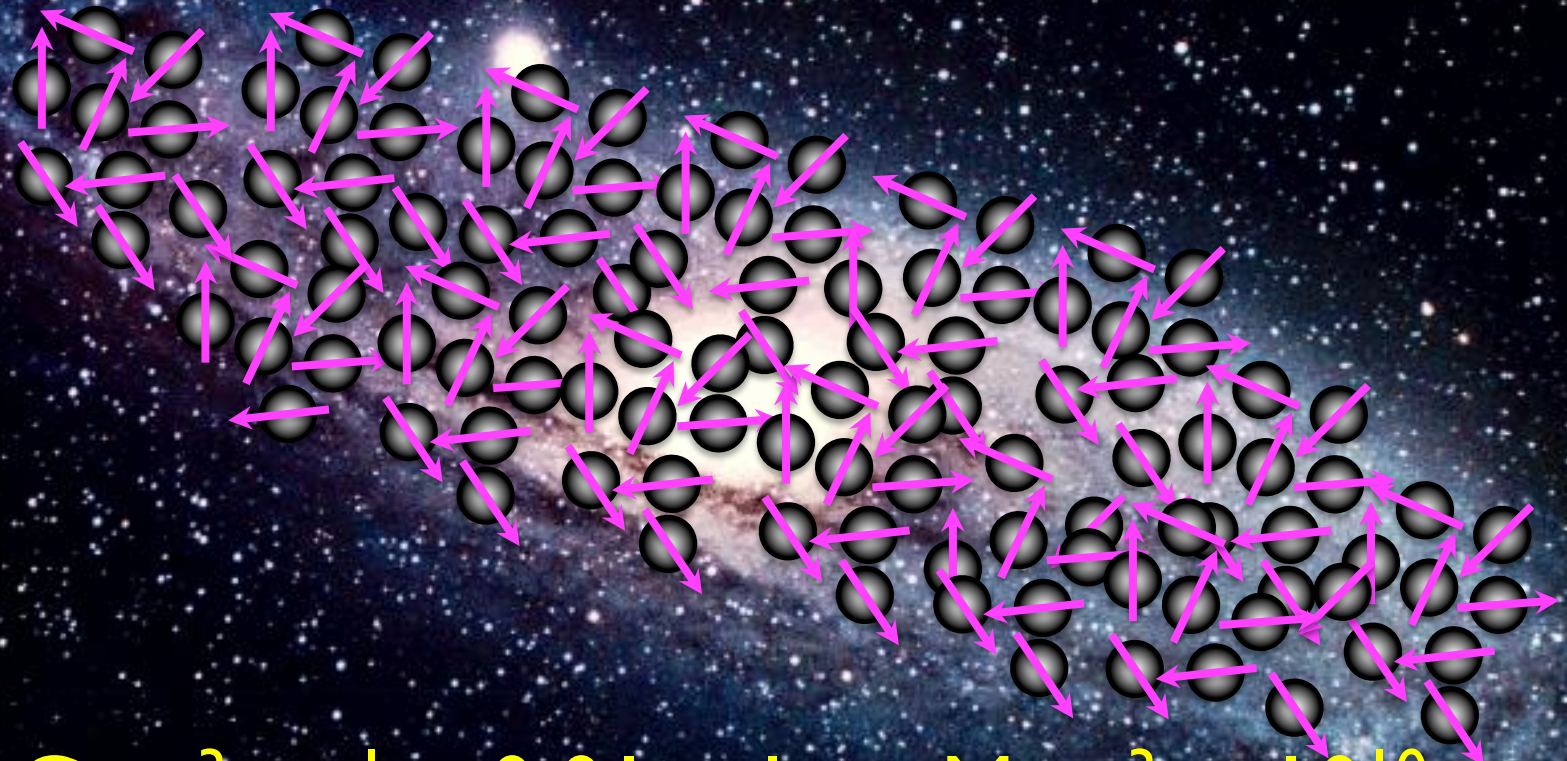
Galactic BHs



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

~ 70000 Merged BHs/galaxy

Galactic BHs



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

$\sim$ 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

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

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

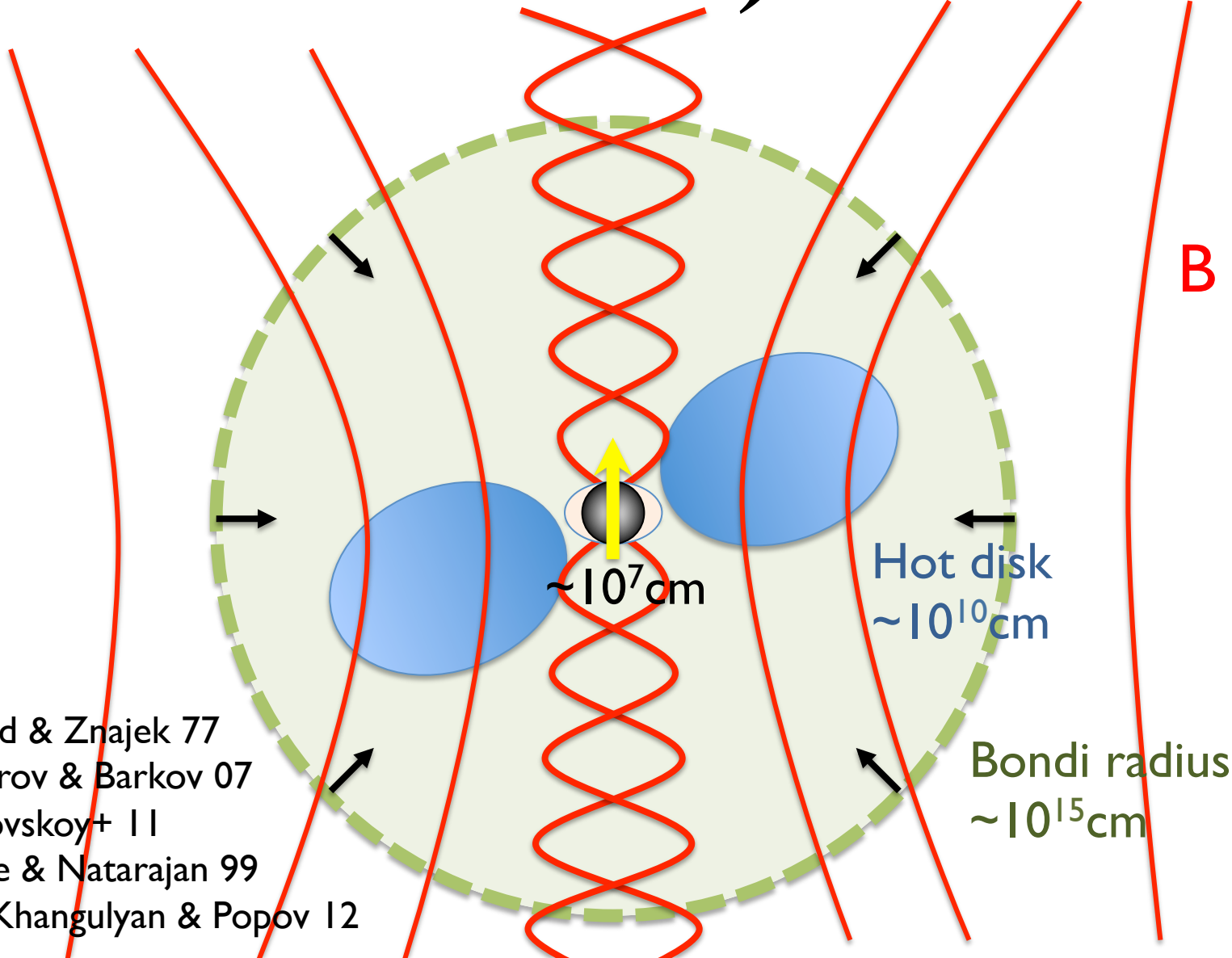
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7\times 10^4\ {\rm BHs} \times 1\times 10^{54}\,{\rm erg}$$

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

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

Comparable to supernovae ever happened!

Blandford-Znajek Effect

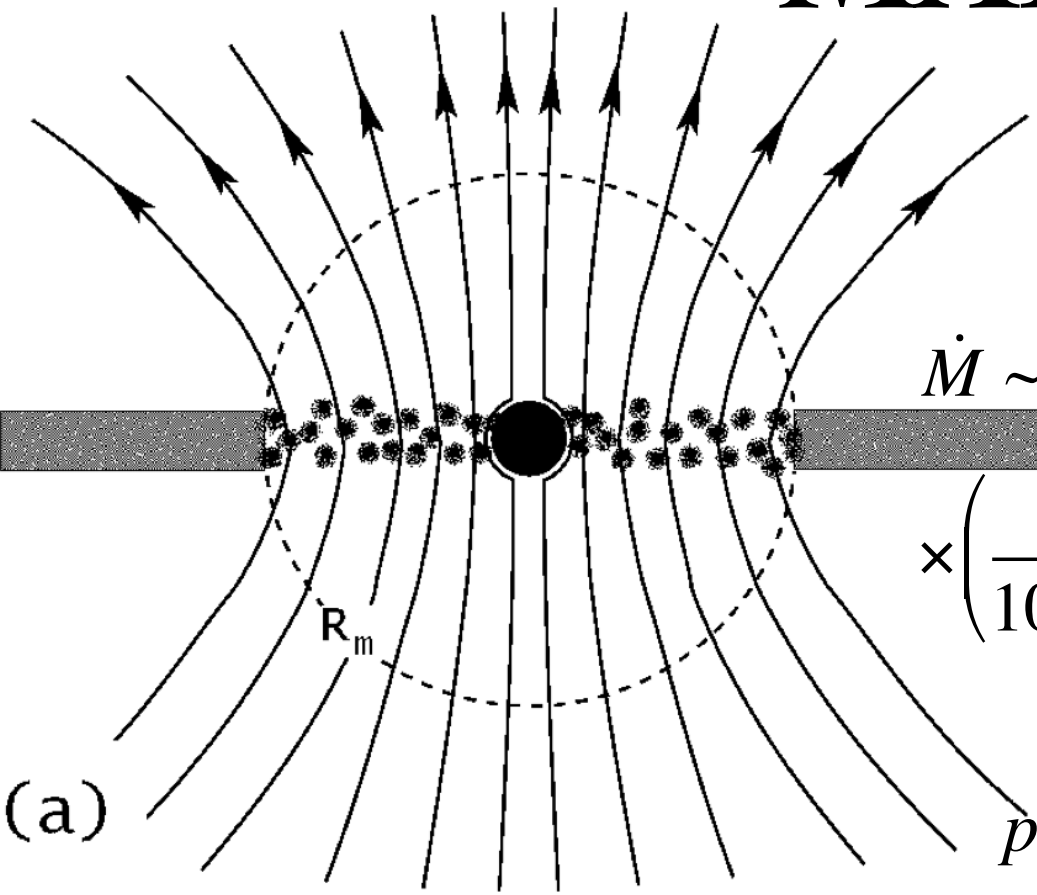


Blandford & Znajek 77
Komissarov & Barkov 07
Tchekhovskoy+ 11
Armitage & Natarajan 99
Barkov, Khangulyan & Popov 12

MAD

Magnetically Arrested Disk

B-flux saturation

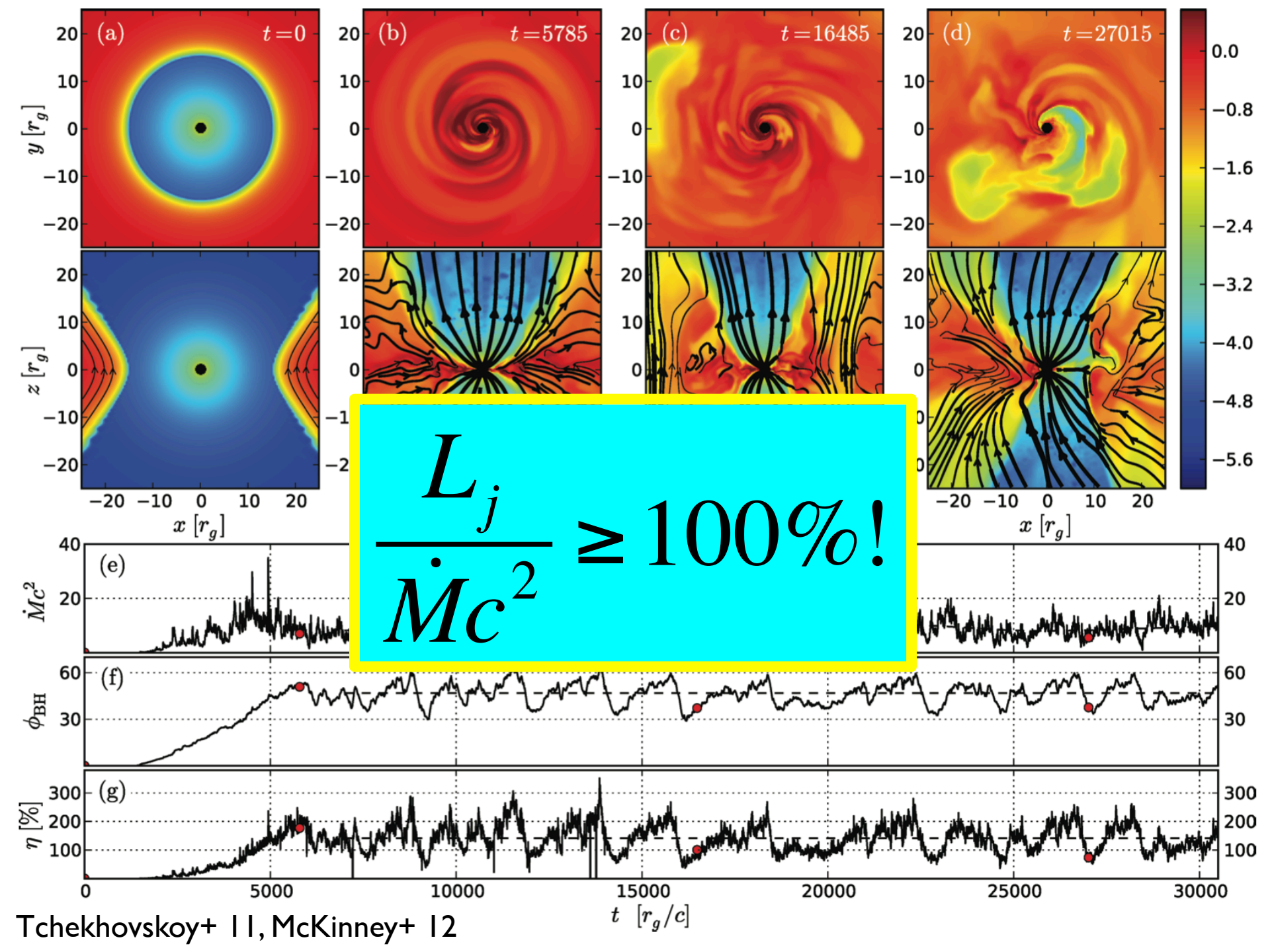


$$\dot{M} \sim 4\pi r_B^2 V \rho \sim 5\times 10^{35}\,\mathrm{erg\ s^{-1}} \times \left(\frac{n}{10\ \mathrm{cm^{-3}}}\right)\left(\frac{M}{10M_\odot}\right)^2\left(\frac{V}{10\ \mathrm{km\ s^{-1}}}\right)^{-3}$$

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

Bisnovatyi-Kogan & Ruzmaikin 76
Narayan+ 03

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



Tchekhovskoy+ 11, McKinney+ 12

Luminosity Function

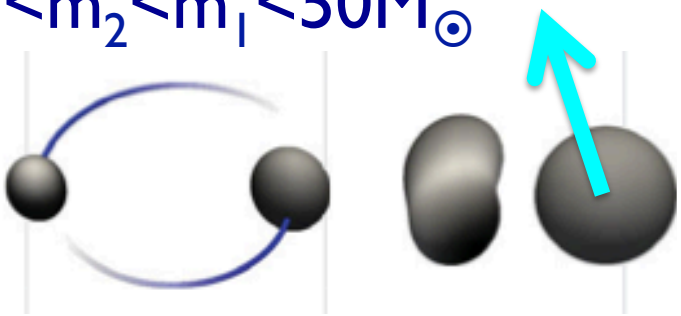
$$\frac{dN}{d\dot{M}} = N_{\rm BH}\int dm_1 \frac{dp(m_1)}{dm_1}\int dm_2 \frac{dp(m_2|m_1)}{dm_2}\int dv \frac{df(v)}{dv}\int dn \frac{d\xi(n)}{dn}$$
$$\times h(m_1,m_2,v)\delta\left[\dot{M}(n,m_1,m_2,v)-\dot{M}\right],$$

Agol & Kamionkowski 12
KI+ in prep.

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

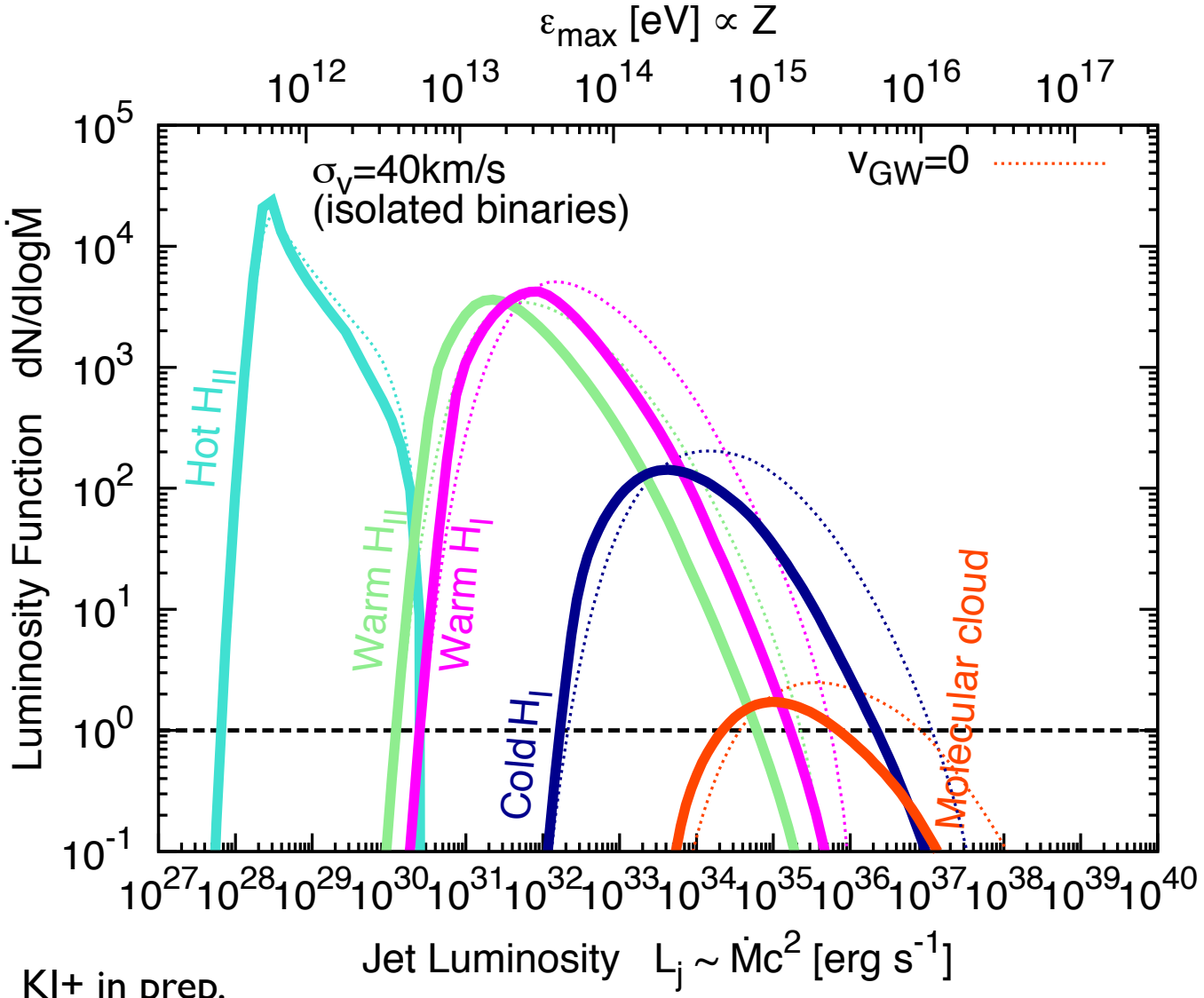
Velocity: Maxwell distribution
+ GW recoil + ISM sound velocity

Density: 5 phases of ISM



Phase	n_1 [cm^{-3}]	n_2 [cm^{-3}]	β	ξ_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

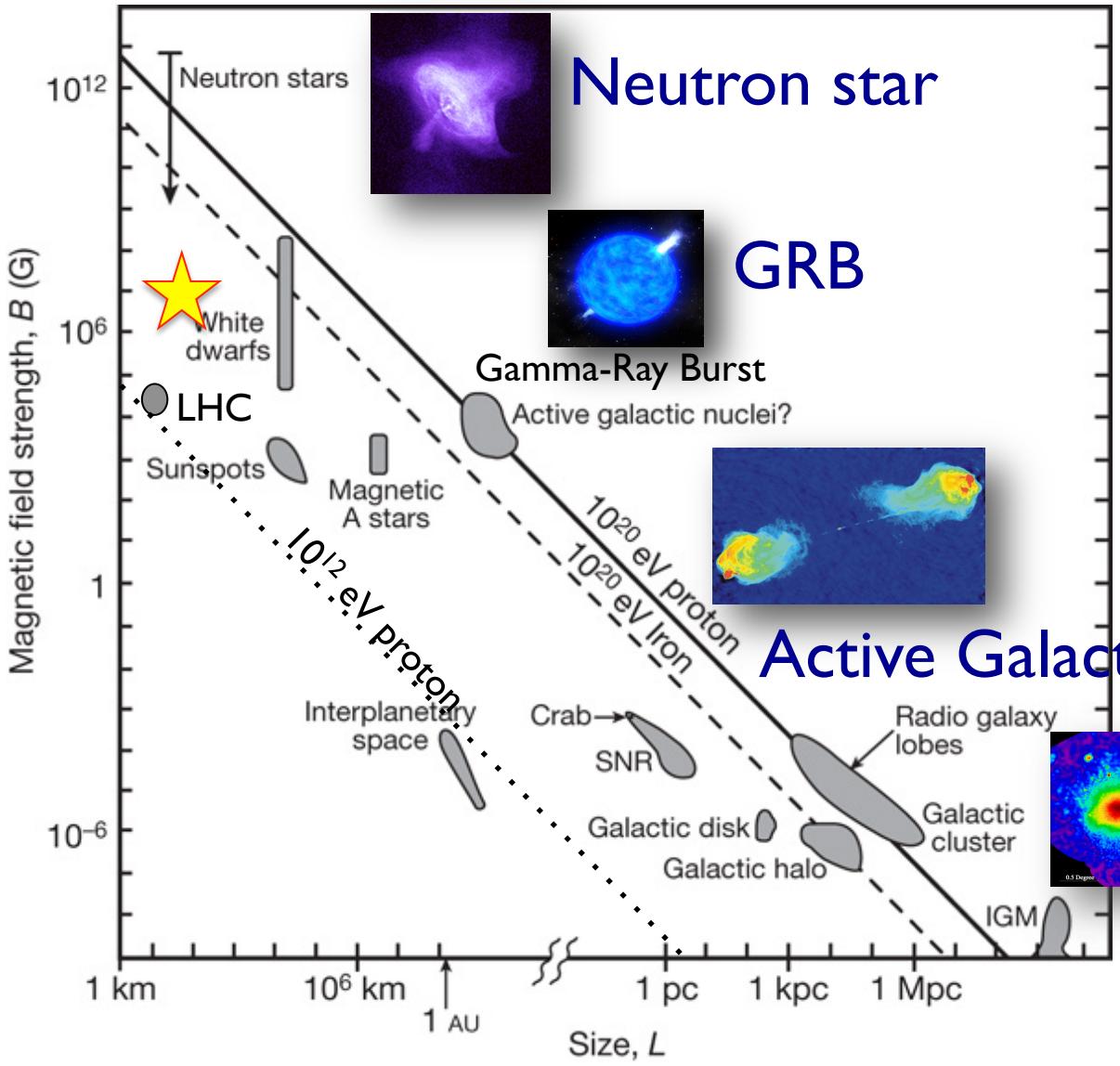


The most luminous BH jet is ~10^{36} erg/s in cold H_I

v_{GW} reduces L_j by ~10

KI+ in prep.

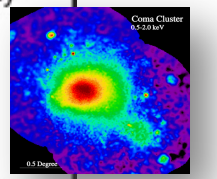
Particle Acceleration



Neutron star

GRB

Active Galactic Nuclei



Galaxy Cluster

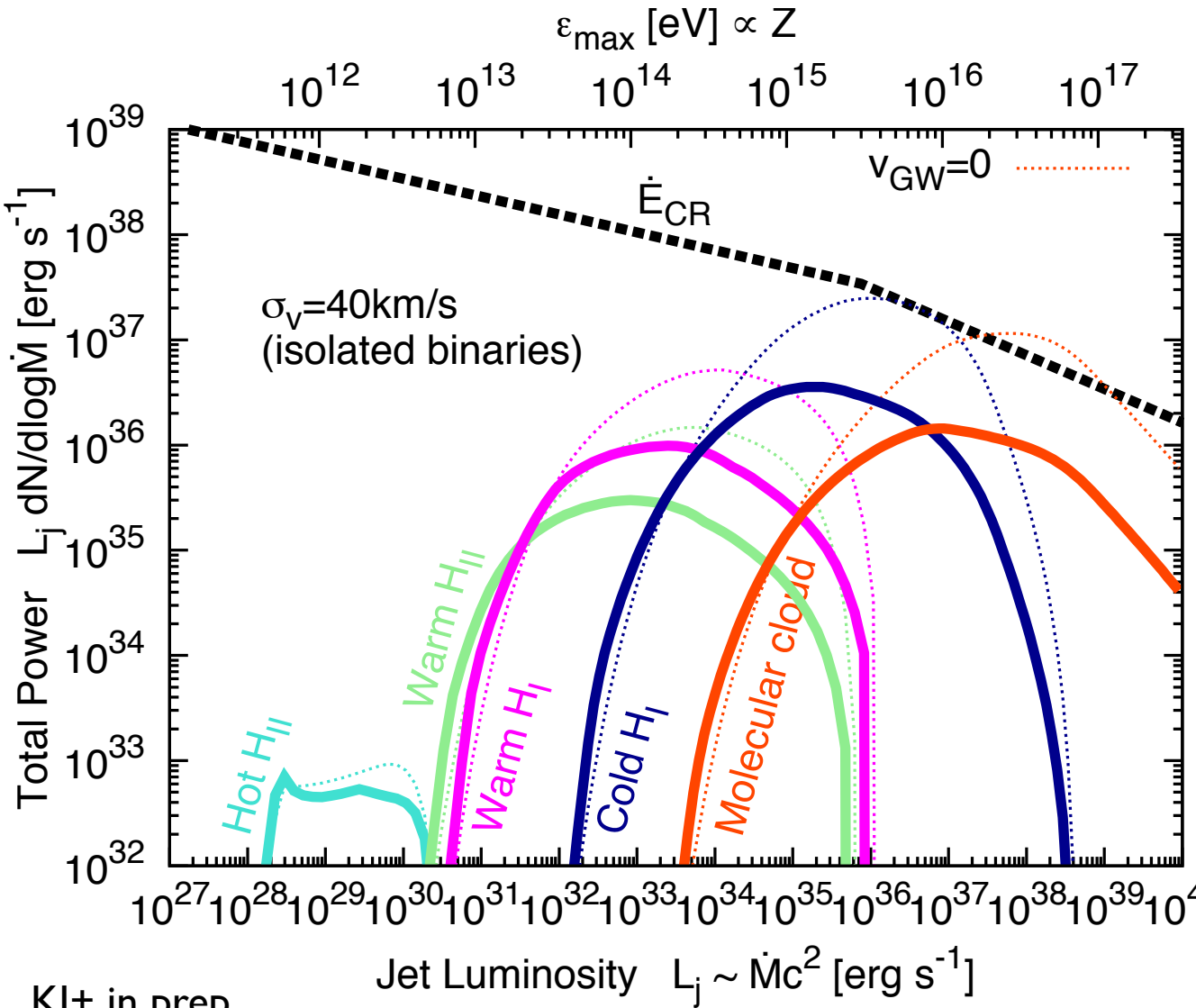
- Hillas condition
  E<ZqBR
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$ Blandford 00
  Waxman 04
- E_{max}>PeV

PeVatron!!!

Barkov+ 12
KI+ in prep.

Dark Matter?

Total Power



BHs ⇔ Cosmic rays beyond PeV?

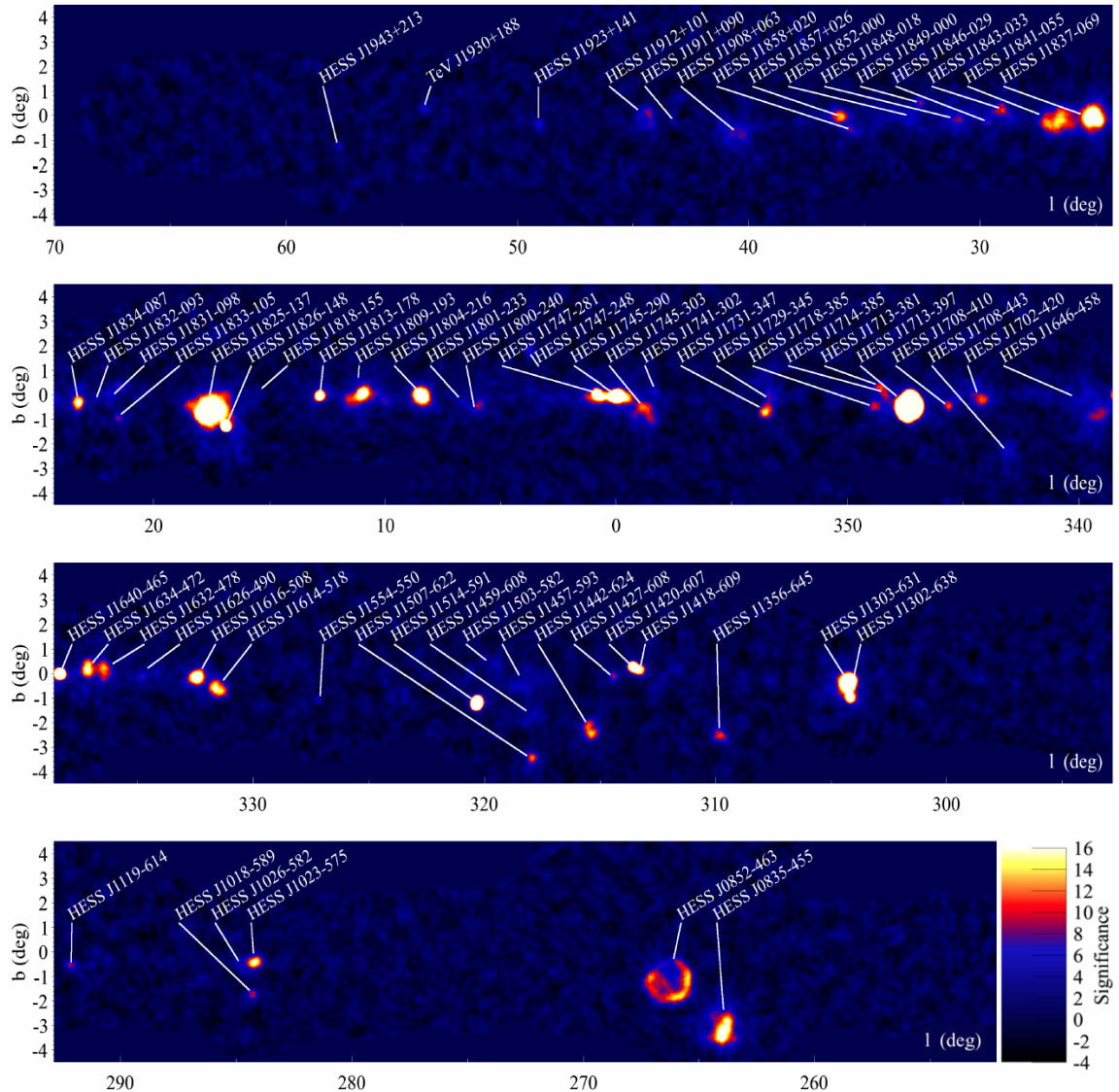
$$\frac{\varepsilon_{CR} E_{SN}}{100\,\mathrm{yr}} \sim 3\times10^{40}\ \mathrm{erg\ s^{-1}}$$

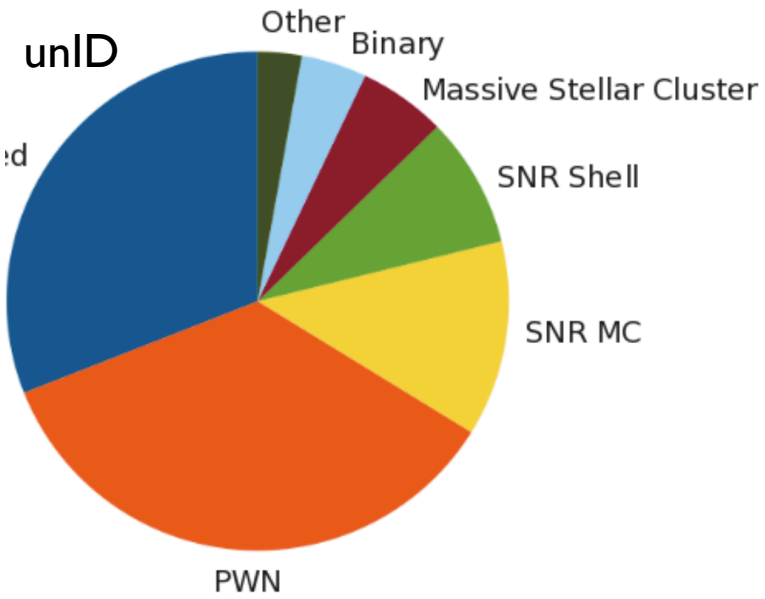
If leptonic ⇔ $e^{\pm}$ excess?

KI+ in prep.

TeV Gamma-Ray Sky

HESS J1307.4690



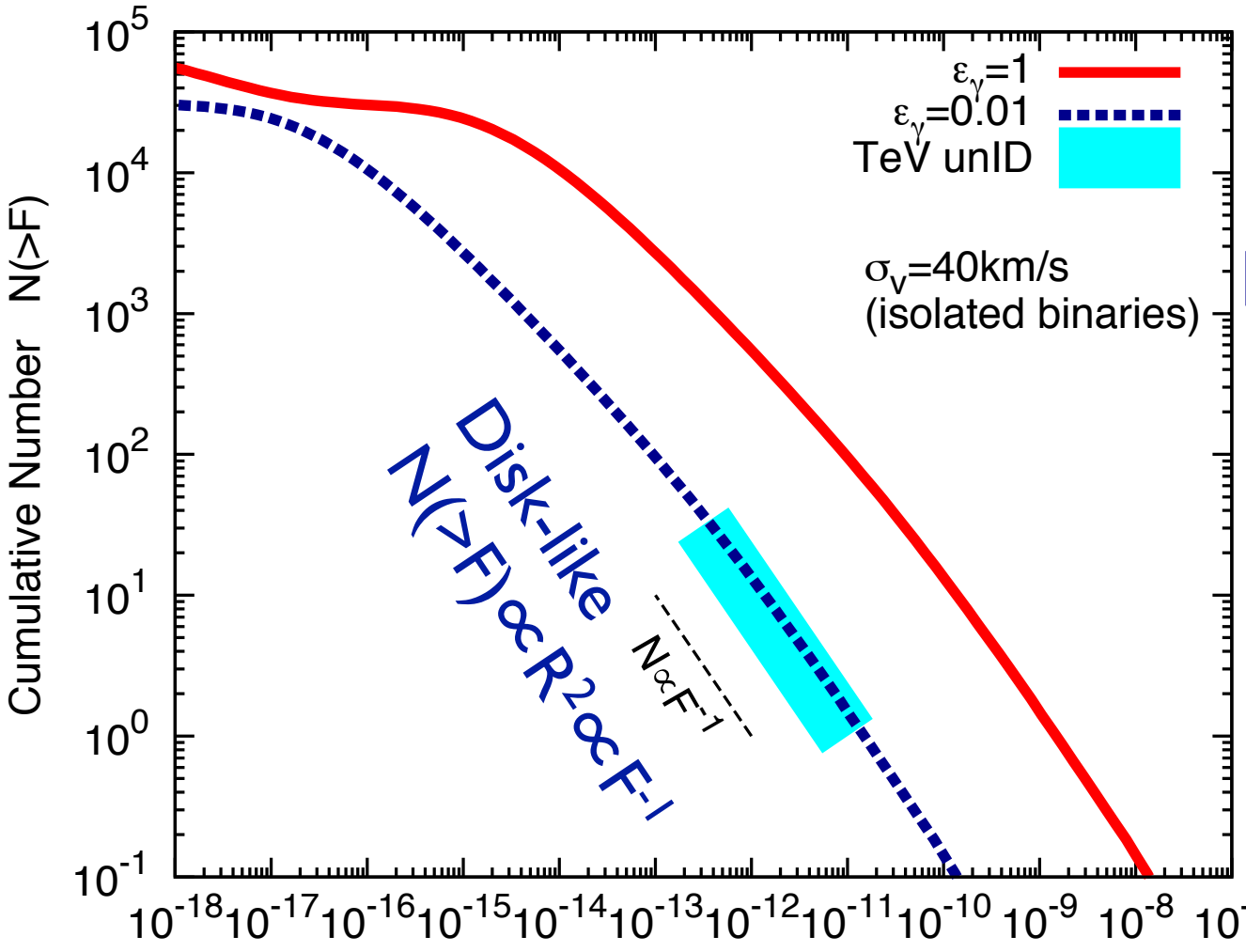


unIDs dominate TeV γ-ray sky

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



BHs ⇔ TeV unIDs?

Flux dis. is similar

BH nebula size:

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

$$\Rightarrow\ r_h \sim 3\ \mathrm{pc}$$

KI+ in prep.

CTA can see ~10^3 BHs

Tip of Iceberg

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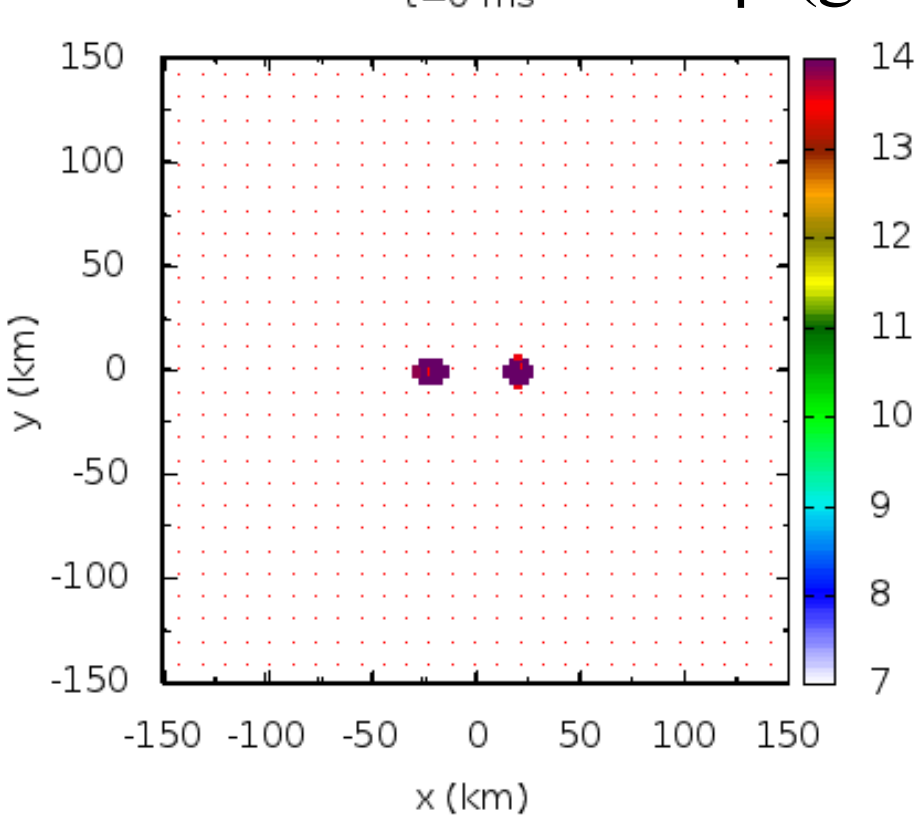
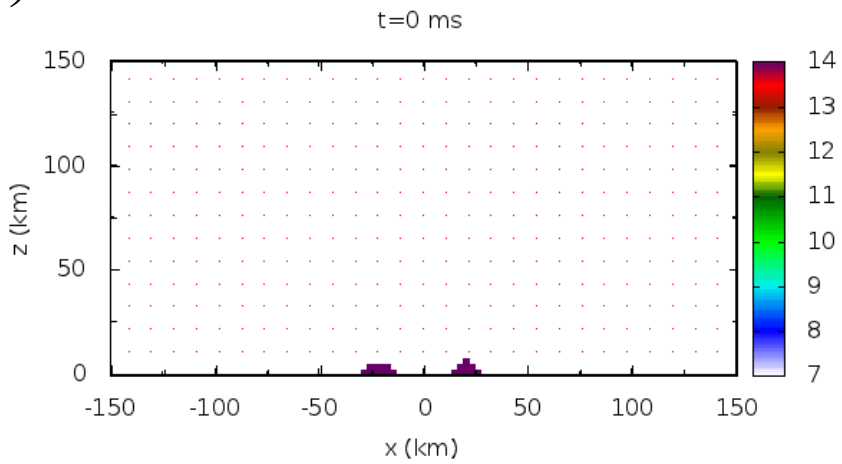
Merger of 1.3-1.4 M_{sun} NS:
EOS=APR4: stiff but relatively soft

ρ (g/cm^3)





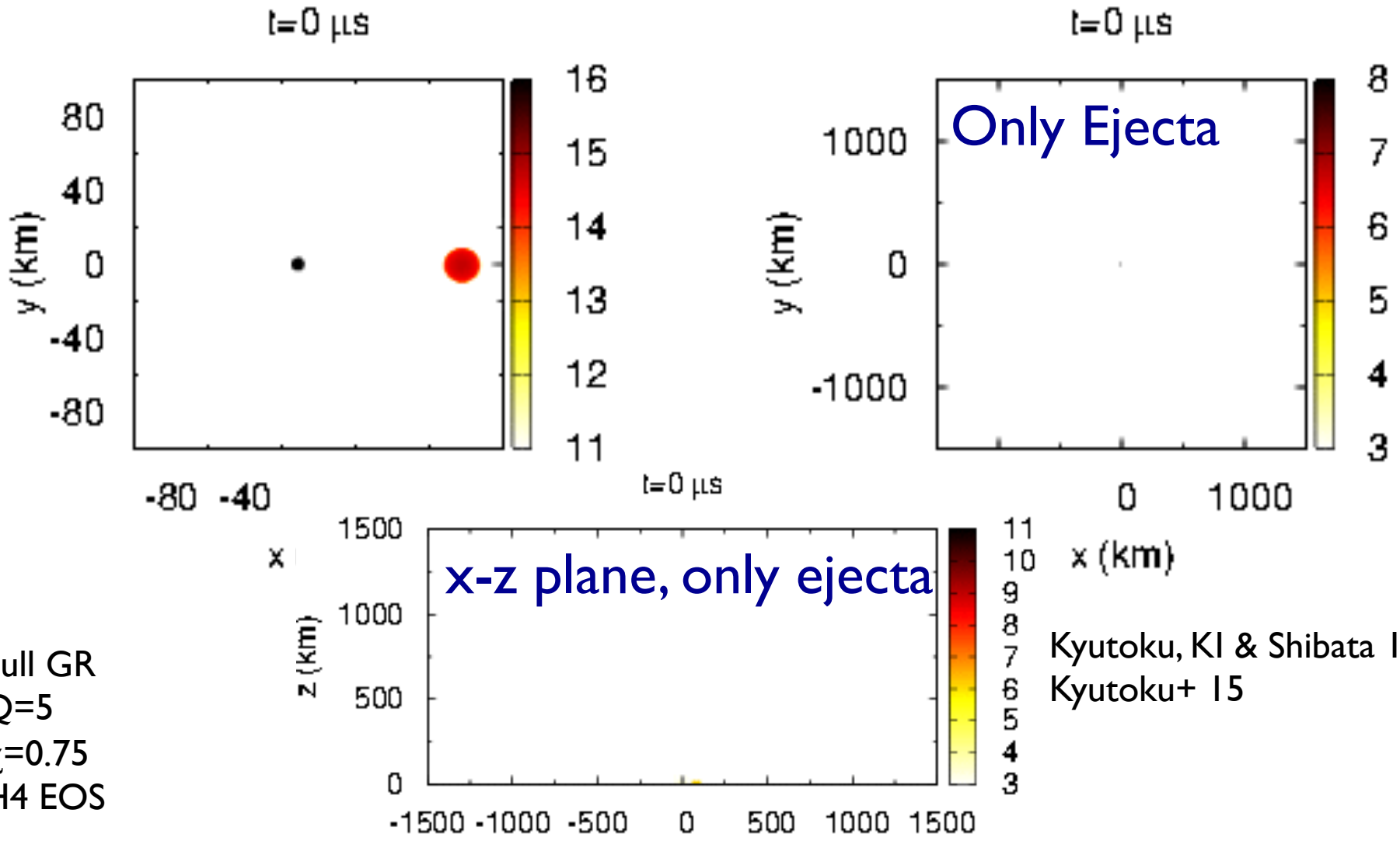
Relatively wider view

Orbital plane

***X-Z* plane**

©Shibata, Hotokezaka

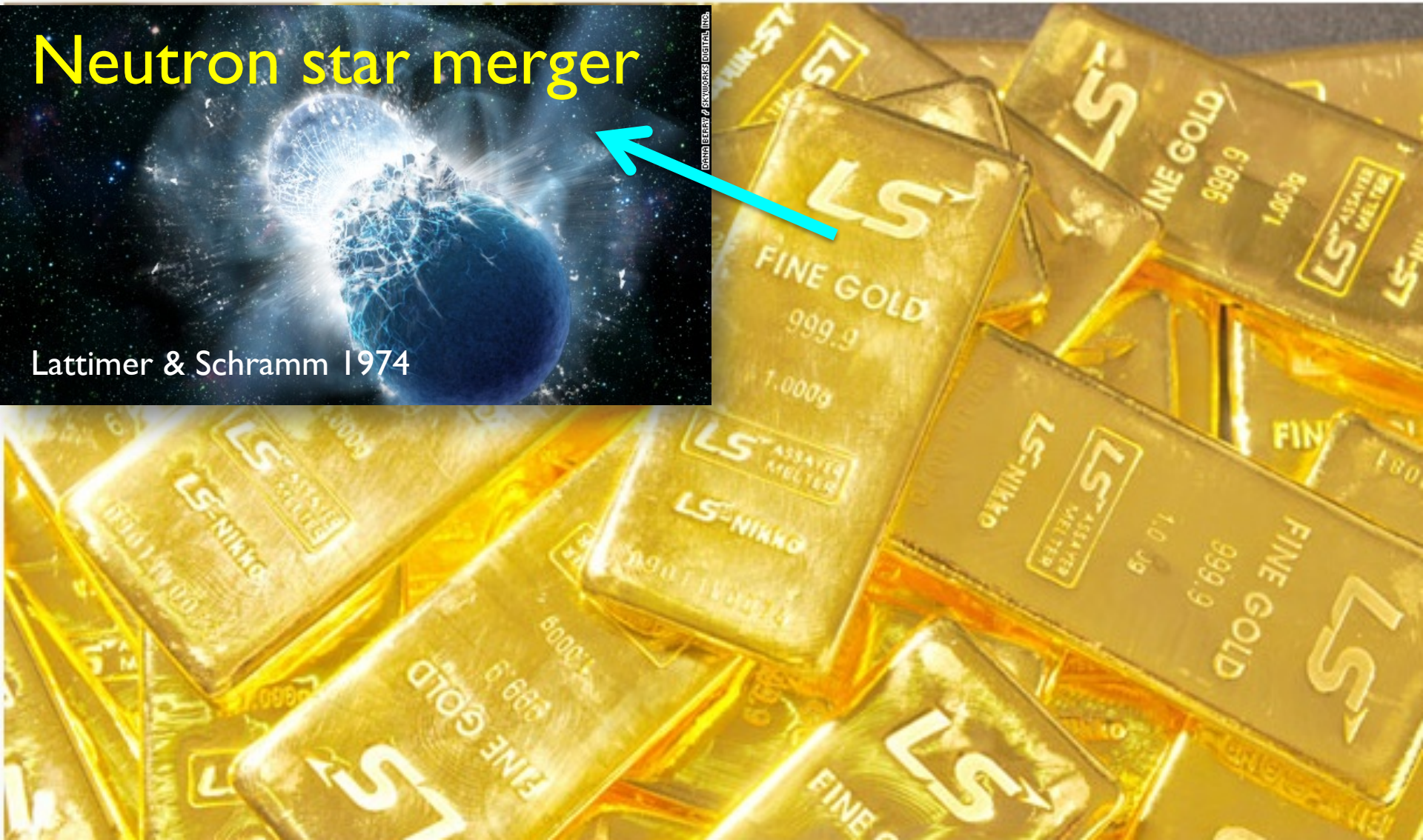
BH-NS Merger



Full GR
Q=5
χ=0.75
H4 EOS

Kyutoku, KI & Shibata 13
Kyutoku+ 15

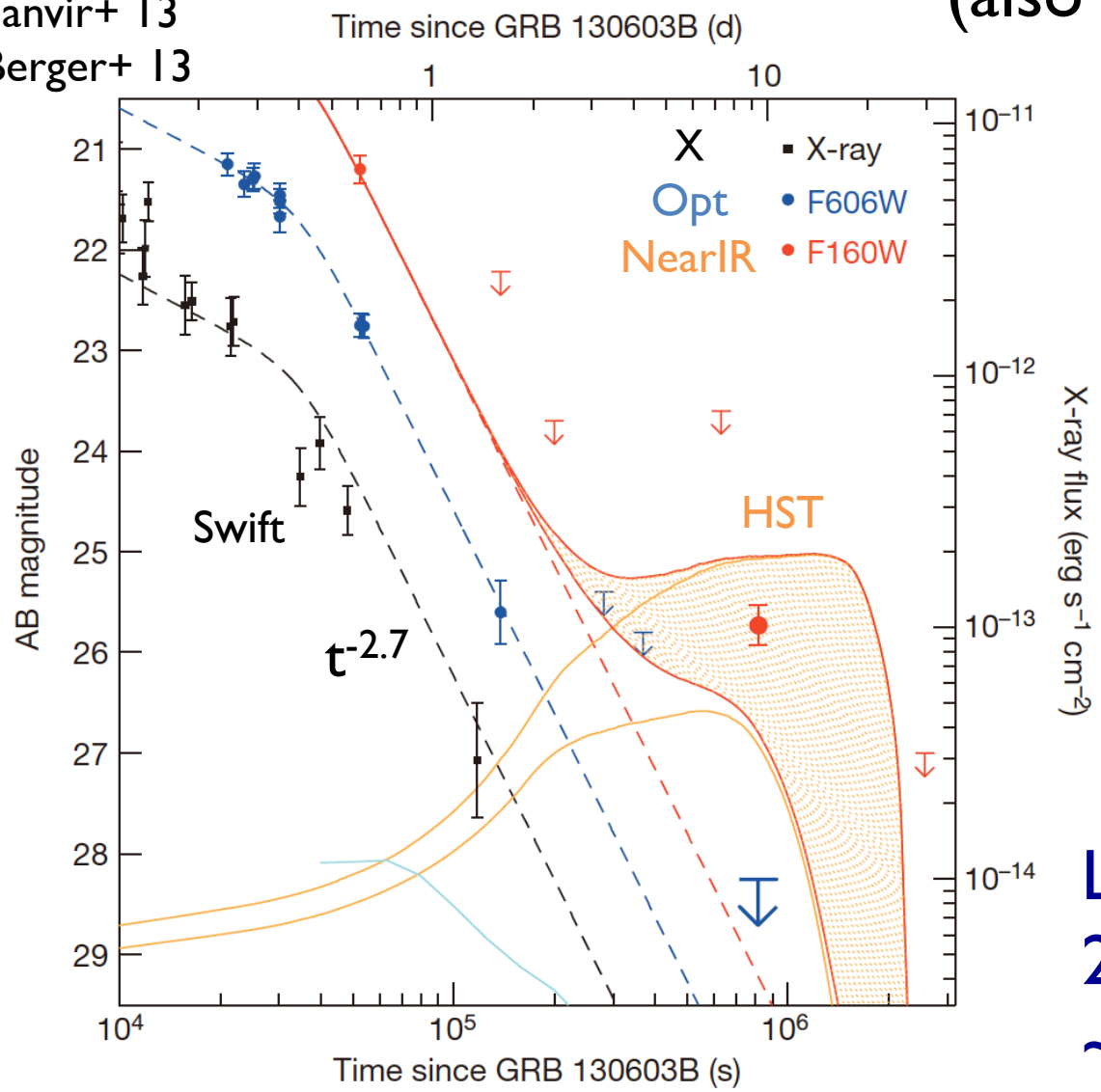
R-Process Elements?



Discovery of Macronova

(also known as kilonova)

Tanvir+ 13
Berger+ 13



Ejecta with
~0.01-0.1$M_\odot$
~0.1-0.3c
~10^{50}-10^{52}erg
Radioactivity
f~E/mc^2~3e-6

Li & Paczynski 98
Kulkarni 05

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

Really R-Process?

Yes?

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

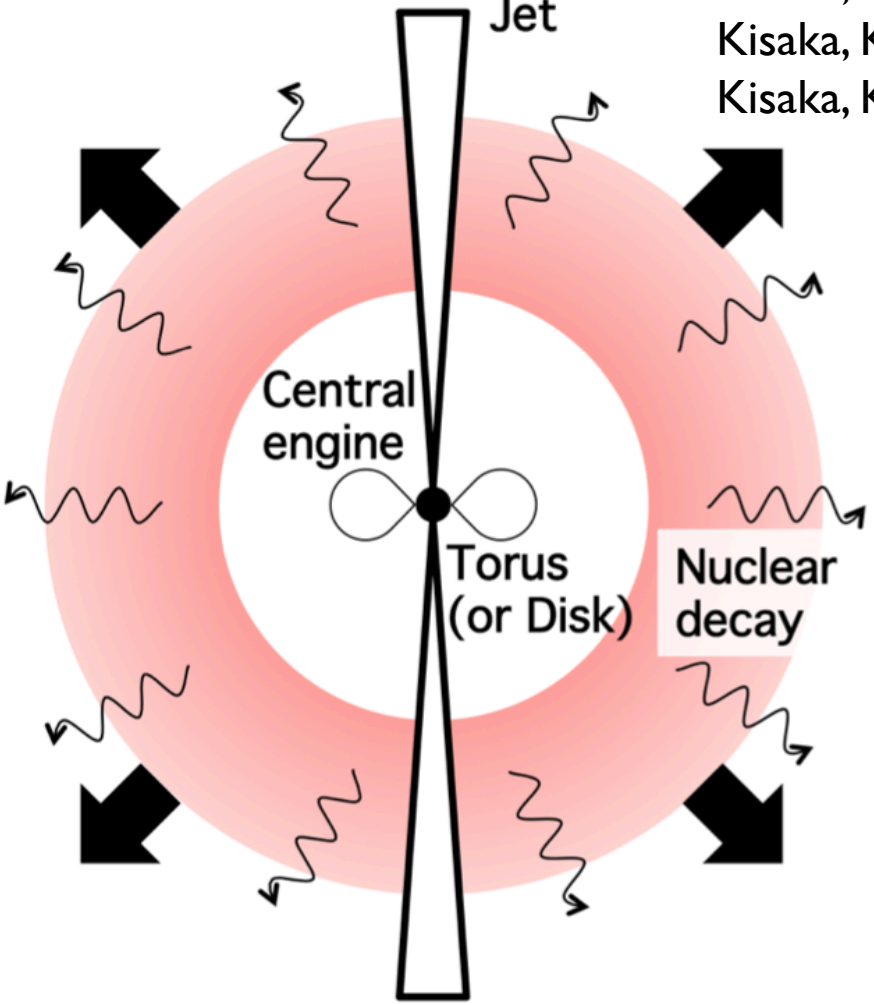
No?

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

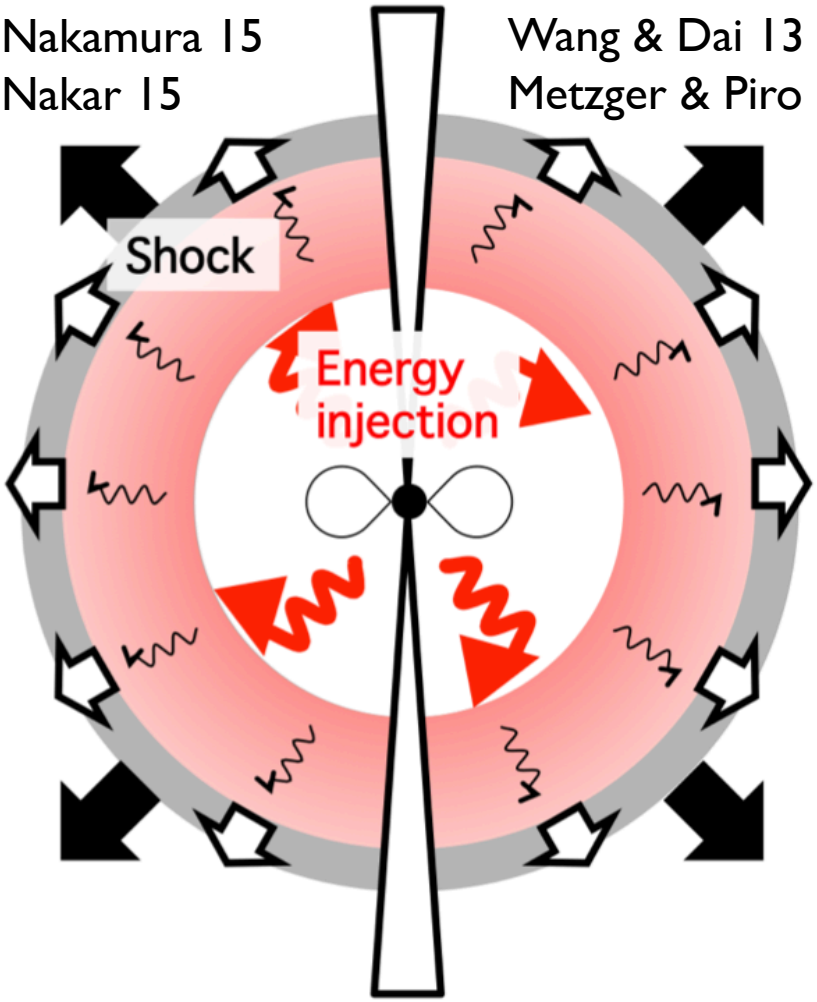
Engine-Powered Macronova?

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

Yu+ 13
Wang & Dai 13
Metzger & Piro 14



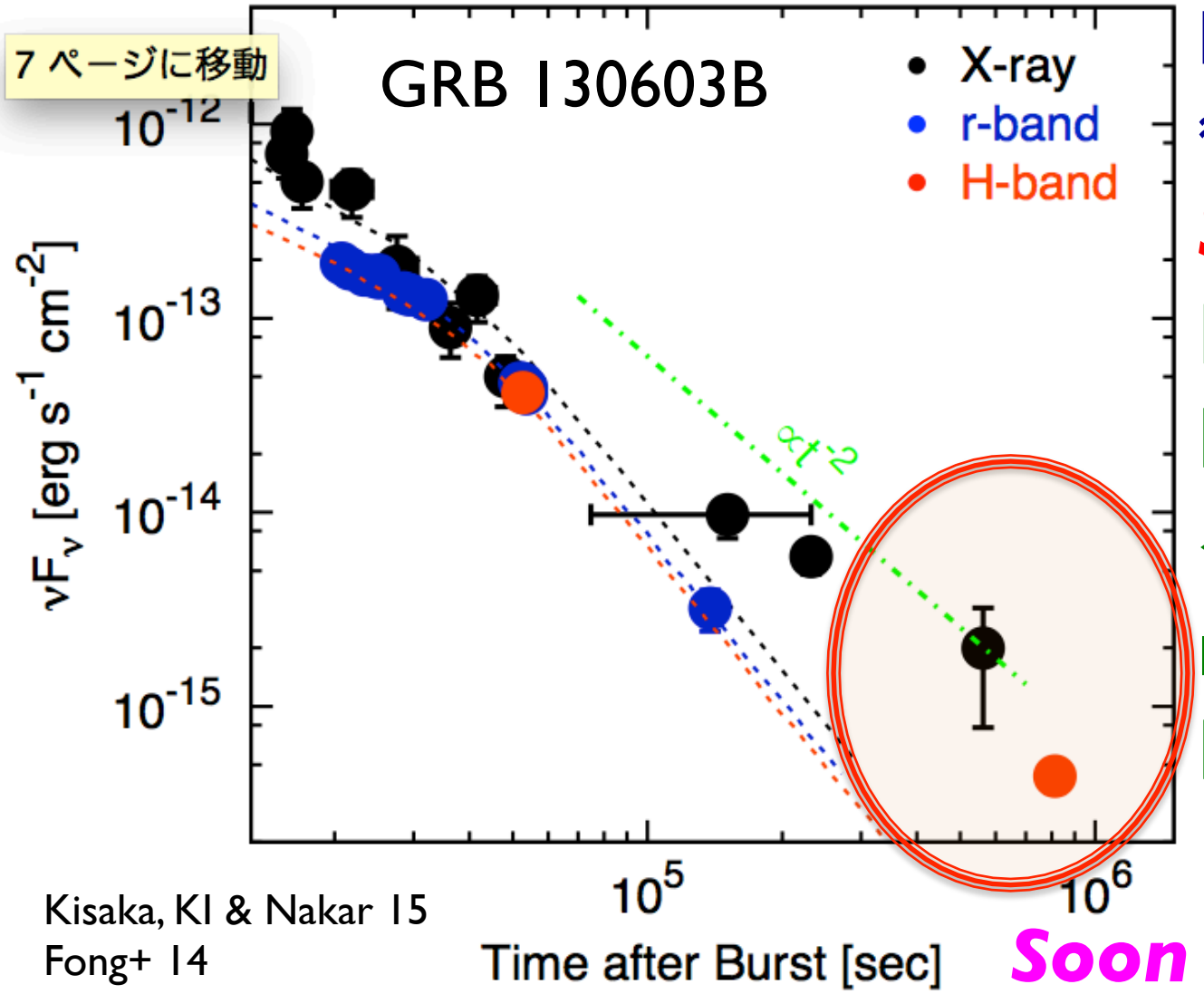
R-process model



Engine model

X-ray Powered?

7 ページに移動



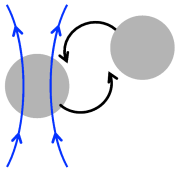
Macronova @IR
≈ X-ray excess
Same origin?
Required
$M_{ejecta}<0.01M_\odot$
⇔ r-process
model needs
$M_{ejecta}>0.03M_\odot$

Kisaka, KI & Nakar 15
Fong+ 14

Soon GRB 160821B

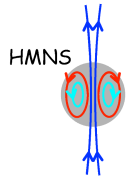
Long-Lasting BH Jet

[I] Inspiral (GW)



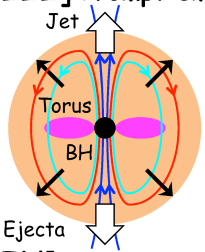
Binary NSs

[II] Merger → Ringdown (GW)



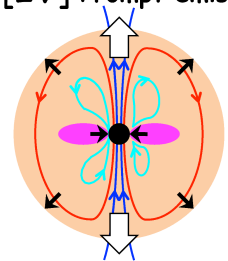
B-amplification

[III] Prompt emission (γ-ray)



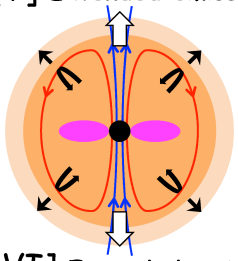
Matter ejection
B-expansion
HMNS → BH+Torus
BZ jet with $B\sim10^{14}G$

[IV] Prompt emission decay (γ-ray)



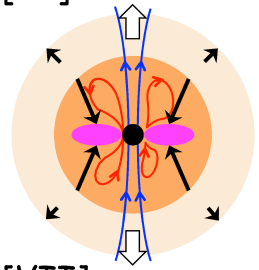
Torus accretion
B-reconnection

[V] Extended emission (X-ray)



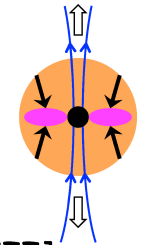
Fallback
BZ jet with $B\sim10^{13}G$

[VI] Extended emission decay (X-ray)



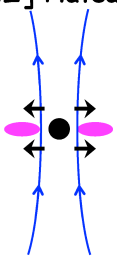
Fallback
B-reconnection

[VII] Plateau emission (X-ray)

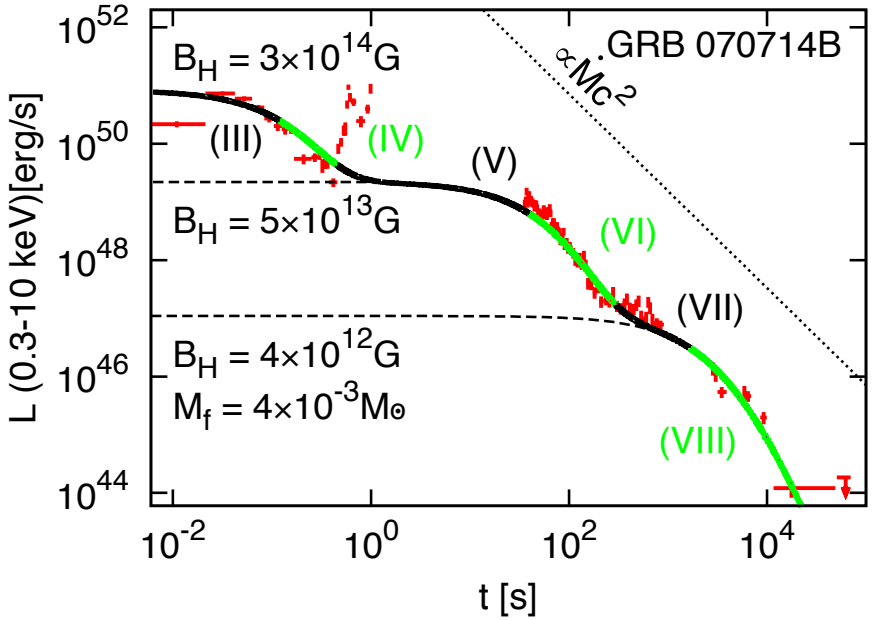


Fallback
BZ jet with $B_{NS}\sim10^{12}G$

[VIII] Plateau emission decay (X-ray)



Jet quench



Fallback & Reconnection

$L_{BZ} \propto B^2$

Kisaka & KI 15
Lee & Ramirez-Ruiz 07

Prompt: $B\sim10^{14}G$

Extended: $B\sim10^{13}G$

Plateau: $B\sim10^{12}G$

Contents

- ***BH-BH***
  - Gravitational waves!!!
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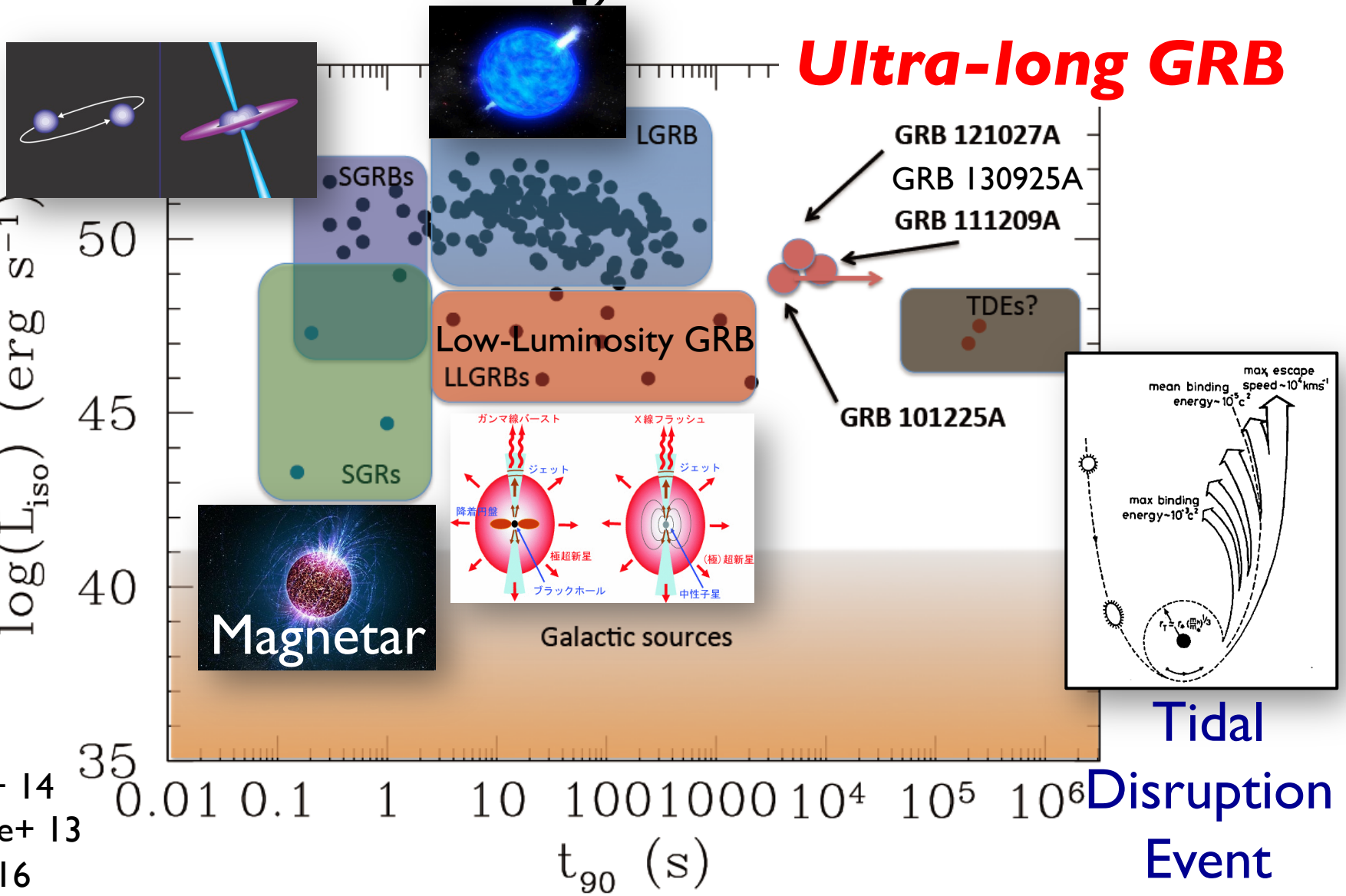
- ***BH/NS-NS***
  - Macronovae? — Kyutoku+ 13, 15, Kyutoku & KI 16
  - Long-lasting short GRBs? — Kisaka+ 15, 16, Kisaka & KI 15
- ***Supermassive BH***
  - Ultra-long GRBs? — KI, Hotokezaka & Piran 16
  - Direct collapse BH jets? — Matsumoto+ 15, 16

Diversity of GRB

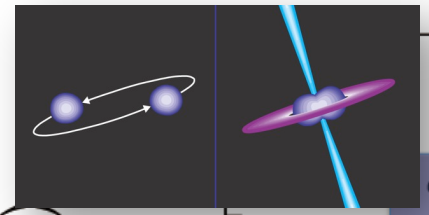


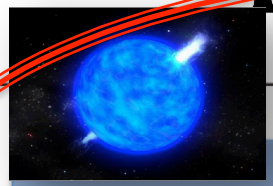
Tidal Disruption Event

Levan+ 14
Gendre+ 13
Lien+ 16

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

Collapsar?





Ultra-long GRB

LGRB

SGRBs

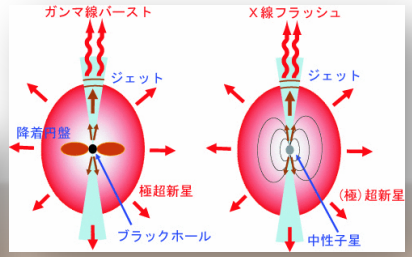
GRB 121027A
GRB 130925A
GRB 111209A

TDEs?

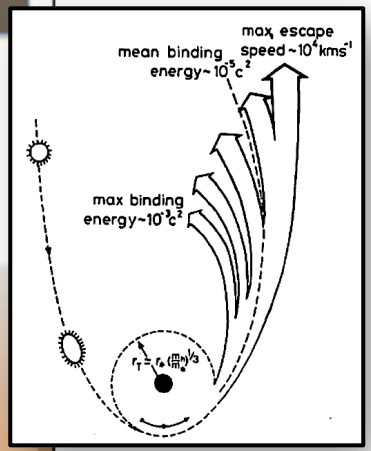
Low-Luminosity GRB
LLGRBs

GRB 101225A

SGRs



Galactic sources



Tidal Disruption Event

$\log(L_{iso})$ (erg s^{-1})

50
45
40
35

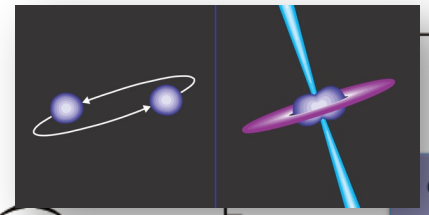
0.01 0.1 1 10 100 1000 10^4 10^5 10^6

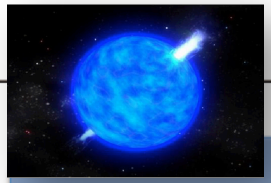
t_{90} (s)

Levan+ 14
Gendre+ 13
Lien+ 16

TDE?

Levan+ 14
Gendre+ 13
MacLeod+ 14



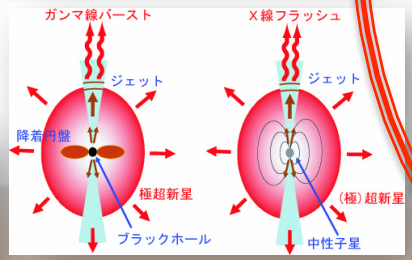


LGRB

SGRBs

SGRs

Low-Luminosity GRB
LLGRBs



Magnetar

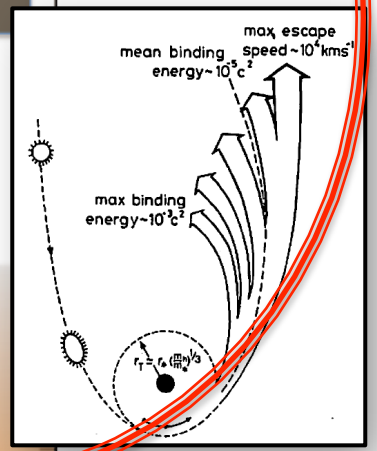
Galactic sources

Ultra-long GRB

GRB 121027A
GRB 130925A
GRB 111209A

TDEs?

GRB 101225A



Tidal Disruption Event

$\log(\overline{L}_{iso})$ (erg s^{-1})

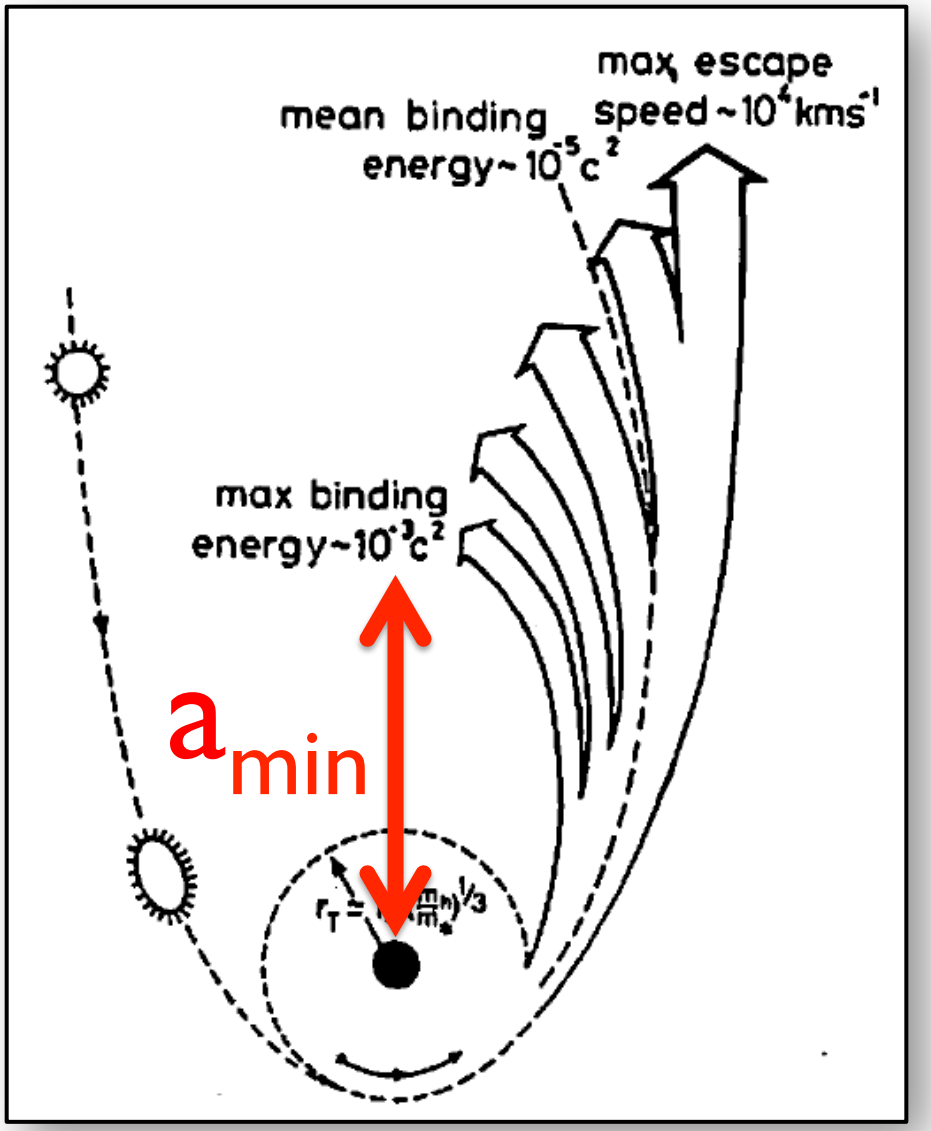
50
45
40
35

0.01 0.1 1 10 100 1000 10^4 10^5 10^6

t_{90} (s)

Levan+ 14
Gendre+ 13
Lien+ 16

White Dwarf TDE



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

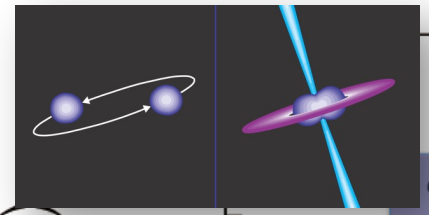
$$t_0 \sim 2\pi\sqrt{\frac{a_{\rm min}^3}{GM_{BH}}} \sim 4\times 10^3\,{\rm sec}\left(\frac{M_*}{M_\odot}\right)^{-1/2} \times \left(\frac{M_{BH}}{10^5 M_\odot}\right)^{1/2} \left(\frac{\rho_*}{10^6\,{\rm g\,cm^{-3}}}\right)^{-1/2}$$

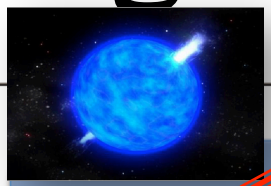
Ultra-long duration requires WD density

Krolik & Piran 11

Magnetar?

Greiner+ 15





Ultra-long GRB

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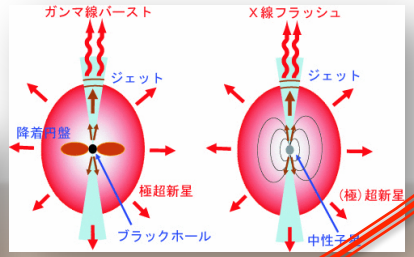
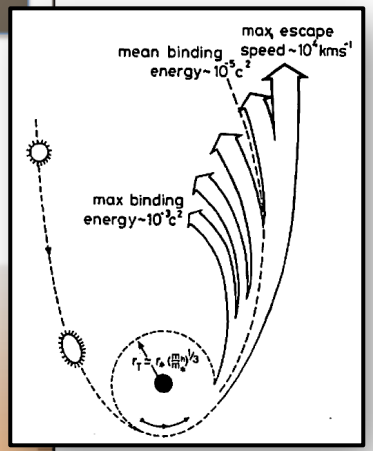


Galactic sources

Toma+ 07



Tidal Disruption Event

$\log(\overline{L}_{iso})$ (erg s^{-1})

50

45

40

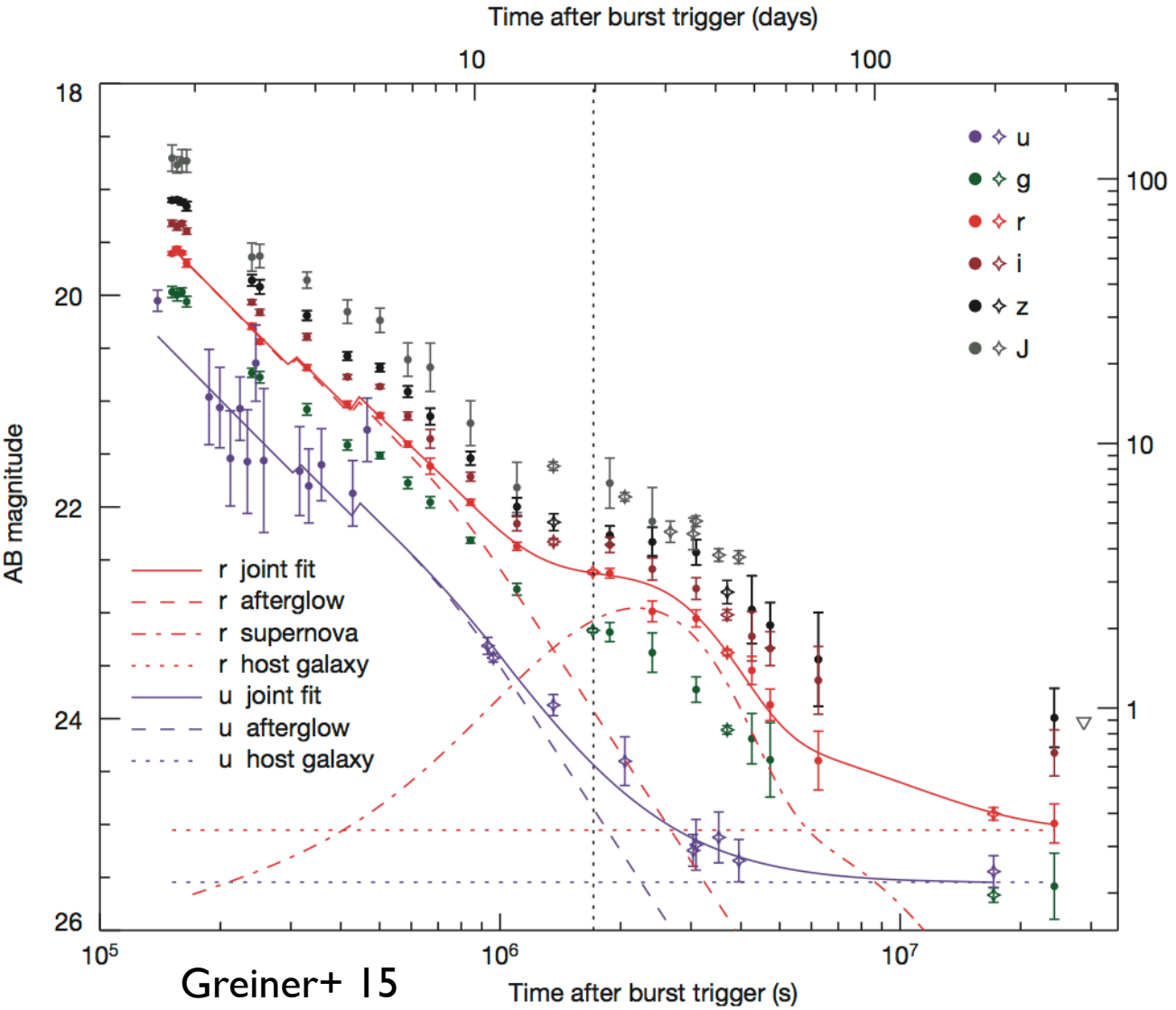
35

0.01 0.1 1 10 100 1000 10^4 10^5 10^6

t_{90} (s)

Levan+ 14
Gendre+ 13
Lien+ 16

Bright SN 2011kl

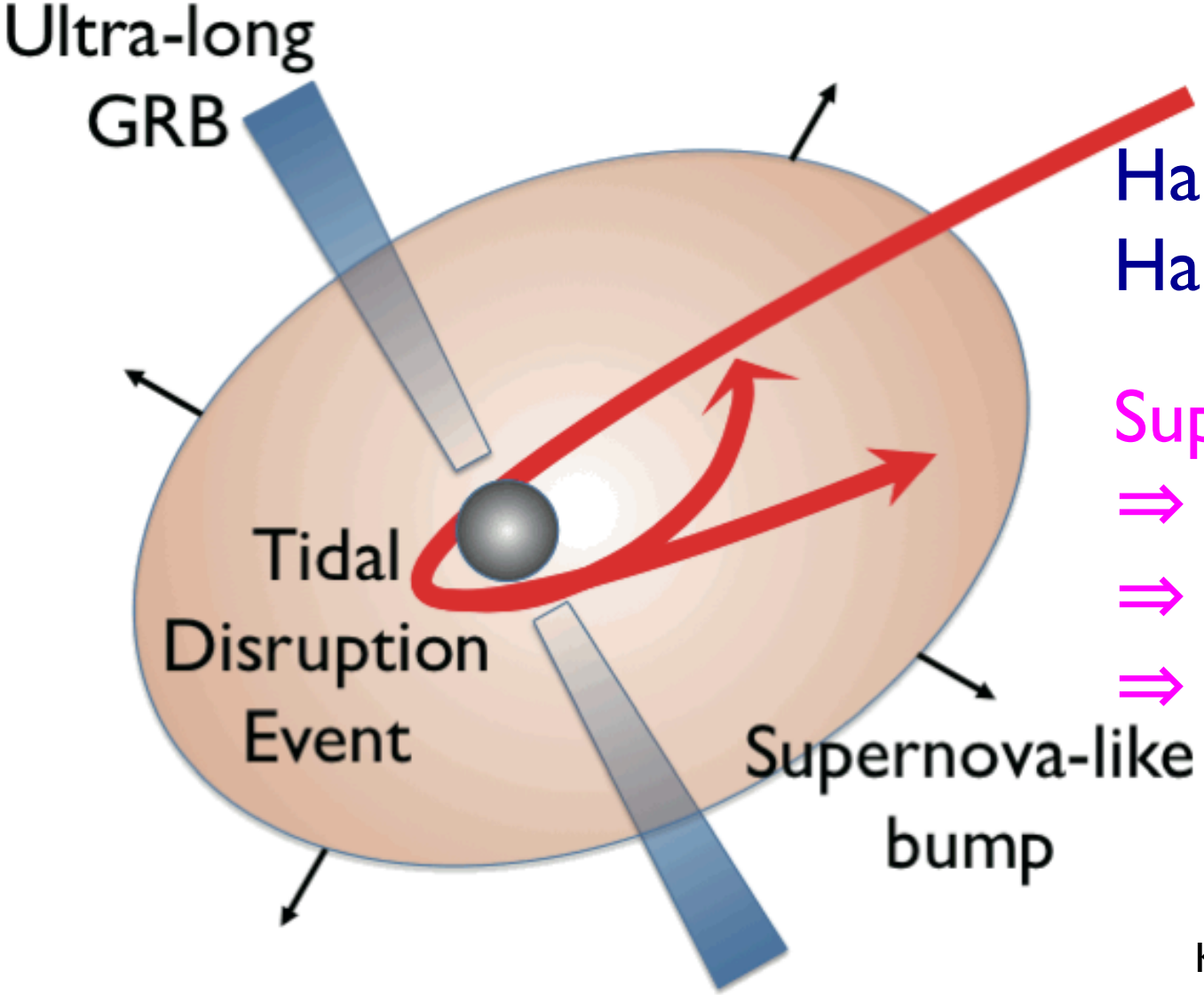


Greiner+ 15

~10 days after
ul-GRB 111209
GROND multiband
X-shooter on VLT

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

SN does not Exclude TDE

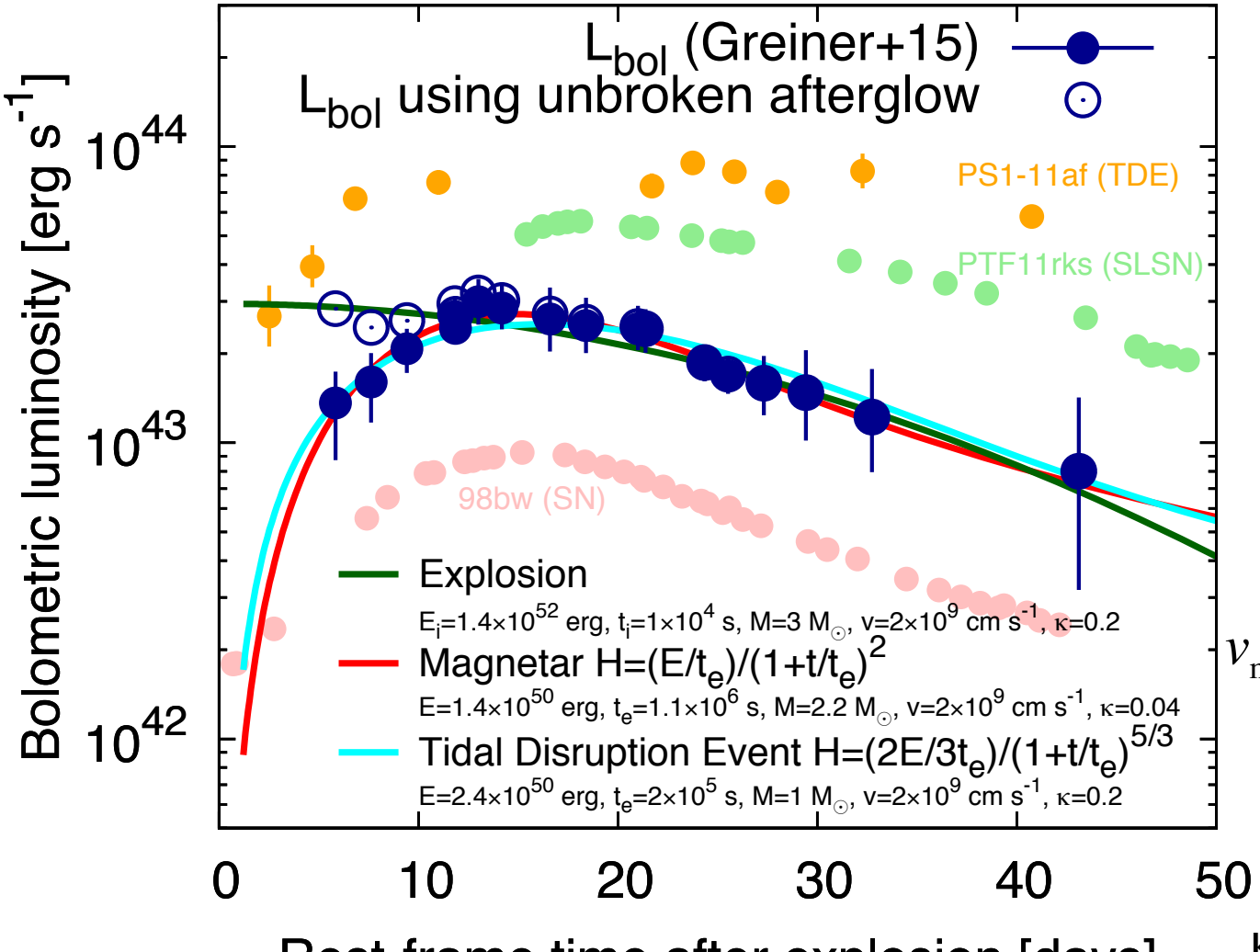


Half bound
Half unbound

Super-Eddington
⇒ Disk outflow, γ
⇒ E into Ejecta
⇒ SN-like bump

KI, Hotokezaka & Piran 16

SN-like Light Curve



$$E \sim \frac{GM_{BH}\left(M_*/2\right)}{2a_{\min}}$$

$$\sim 4\times10^{51}\,\mathrm{erg}$$

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

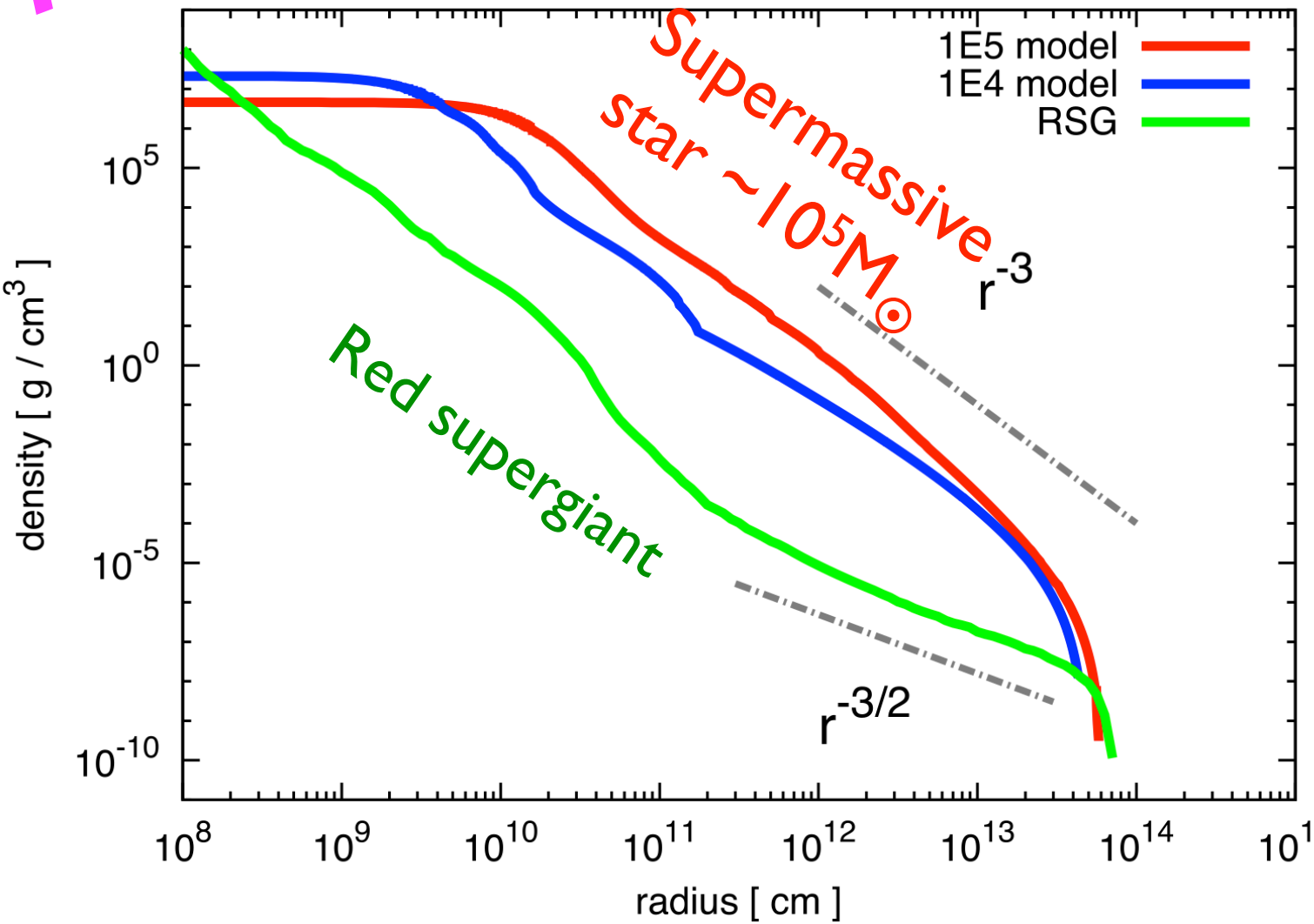
$$v_{\min} \sim \sqrt{\frac{GM_{BH}}{2a_{\min}}}$$

$$\sim 2\times10^{9}\,\mathrm{cm\ s^{-1}}$$

KI, Hotokezaka & Piran 16

Direct Collapse BHs can Launch GRBs?

Poster 11



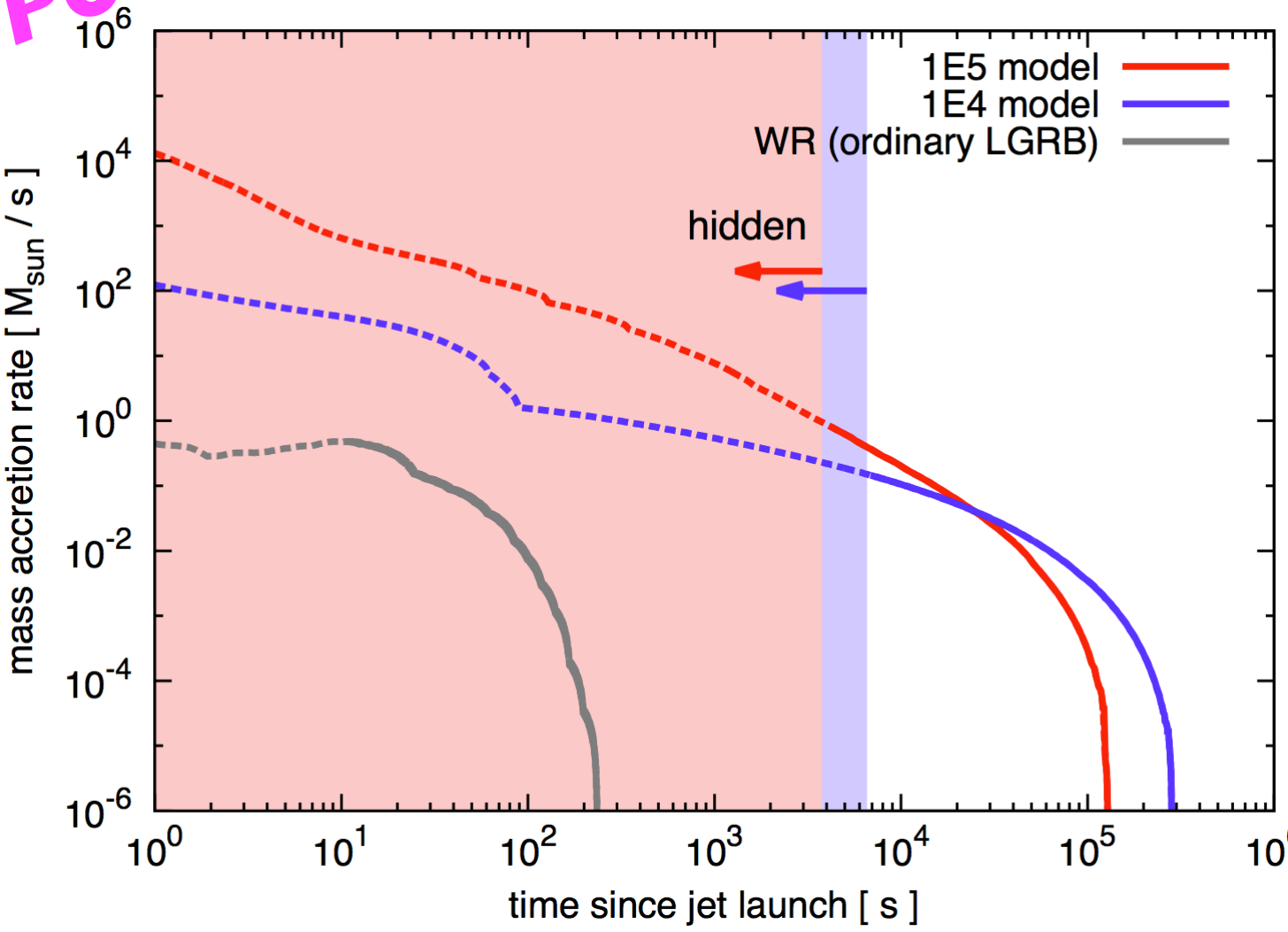
$10^9 M_\odot$ BH @z>6 Super-Edd. accretion? or DCBH?

GRB jets break out the star?

Matsumoto+ 15

GRB Jets can Break Out Supermassive Stars

Poster!!



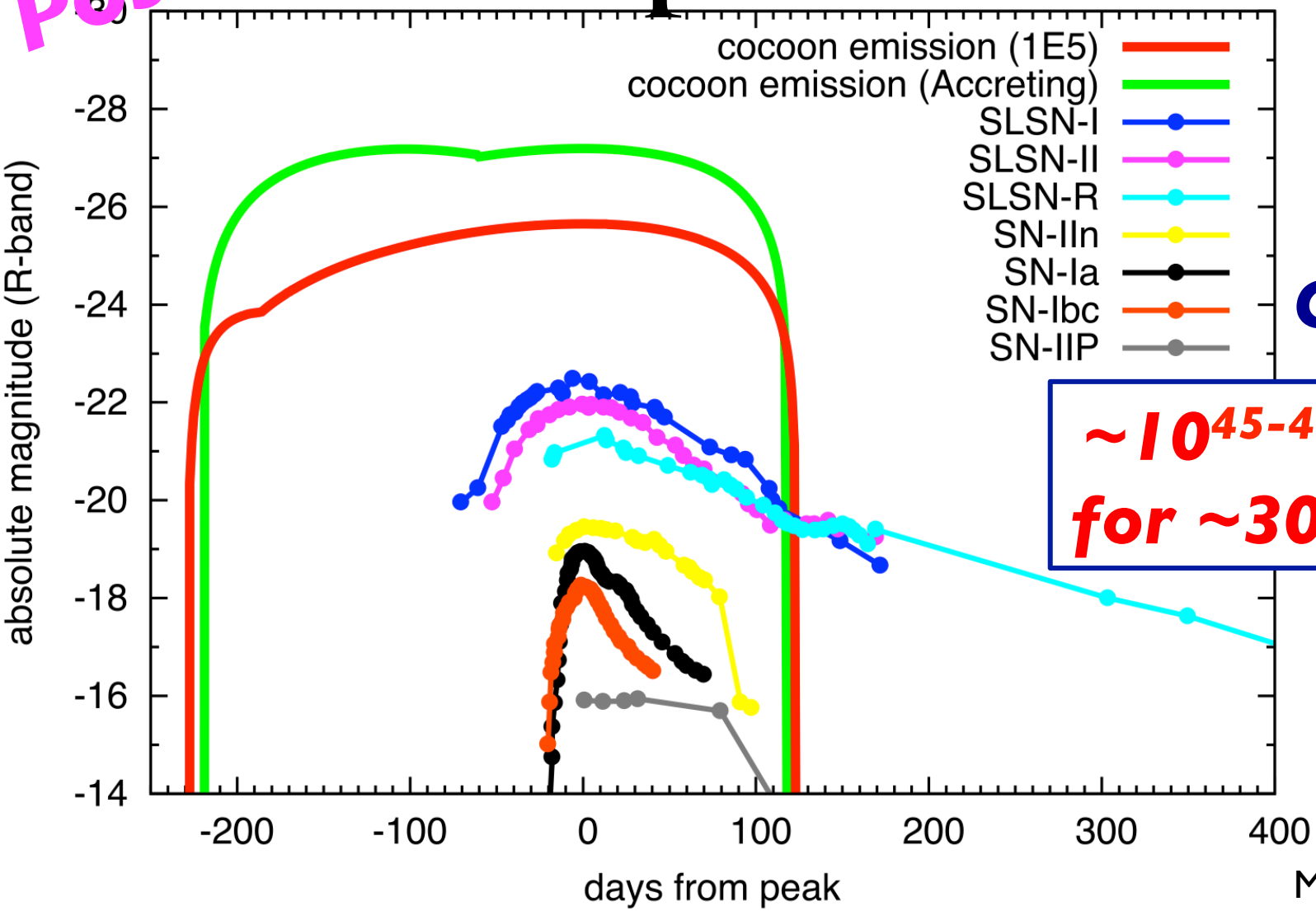
Radiation pressure-dominated
⇒ Breakout

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

Matsumoto+ 15

Ultra-Luminous Supernova

Poster 11



Jet ⇒ Cocoon

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

Matsumoto+ 16

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