# Black Holes in Short GRBs, Macronovae & GW150914

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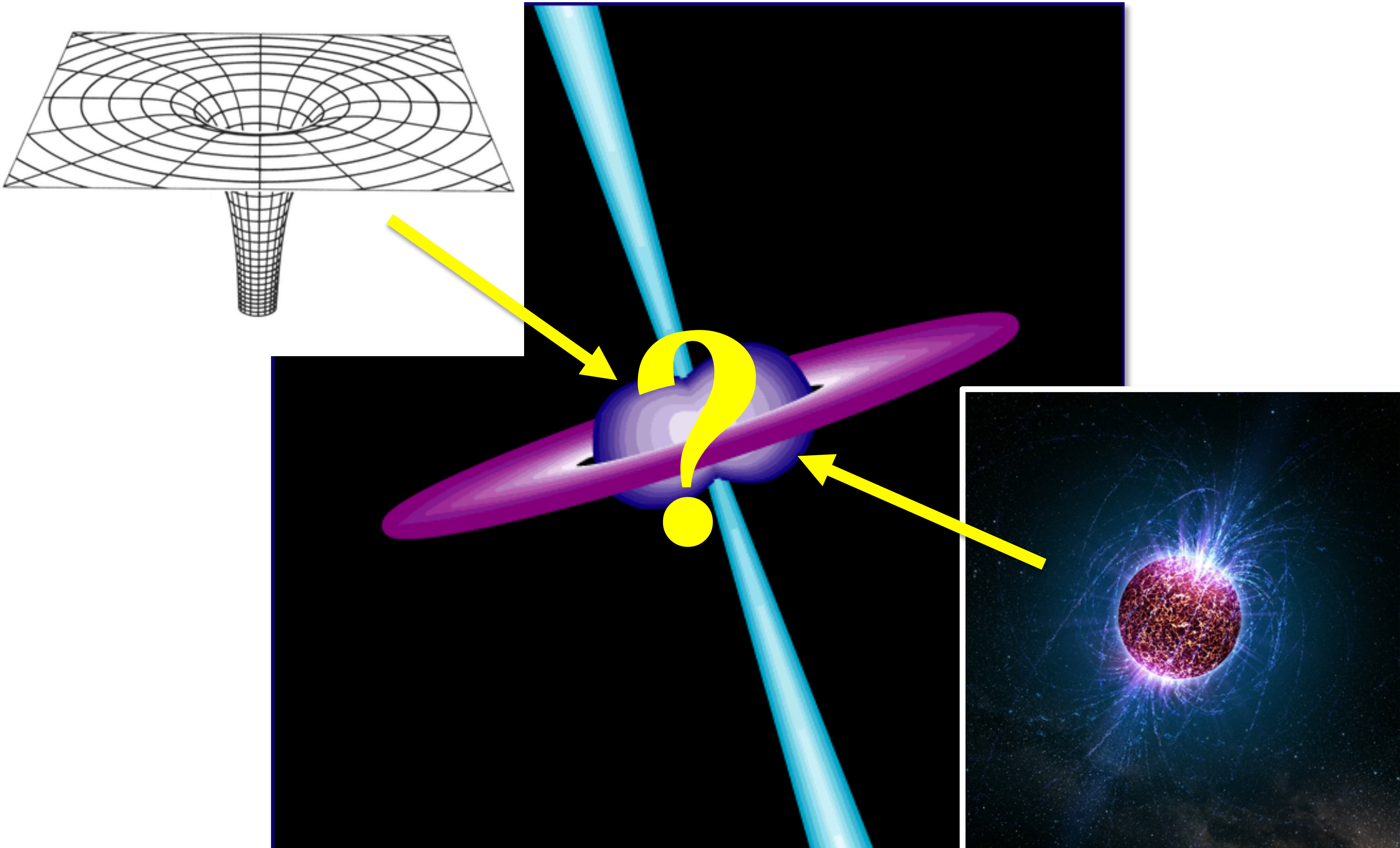
KYOTO UNIVERSITY KYOTO JAPAN FOUNDED 1897

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

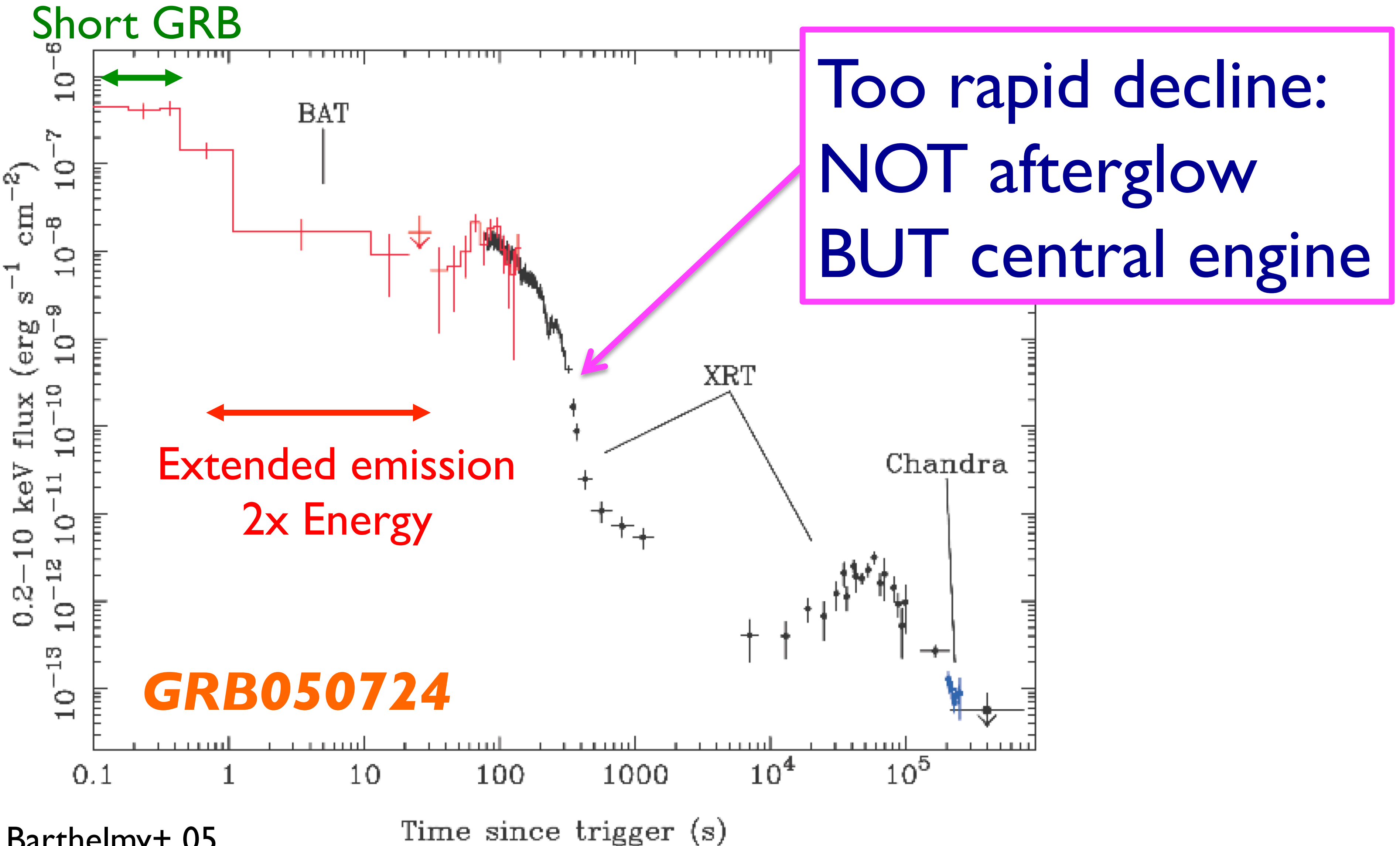
# Contents

- ***BH in long-lasting short GRBs***
  – BH v.s. Neutron star
- ***BH in macronovae***
  – BH v.s. R-process radioactivity
- ***BH in GW150914***
  – Galactic BHs as high-energy sources
  – Fermi GBM event

# Black Hole or Neutron Star?

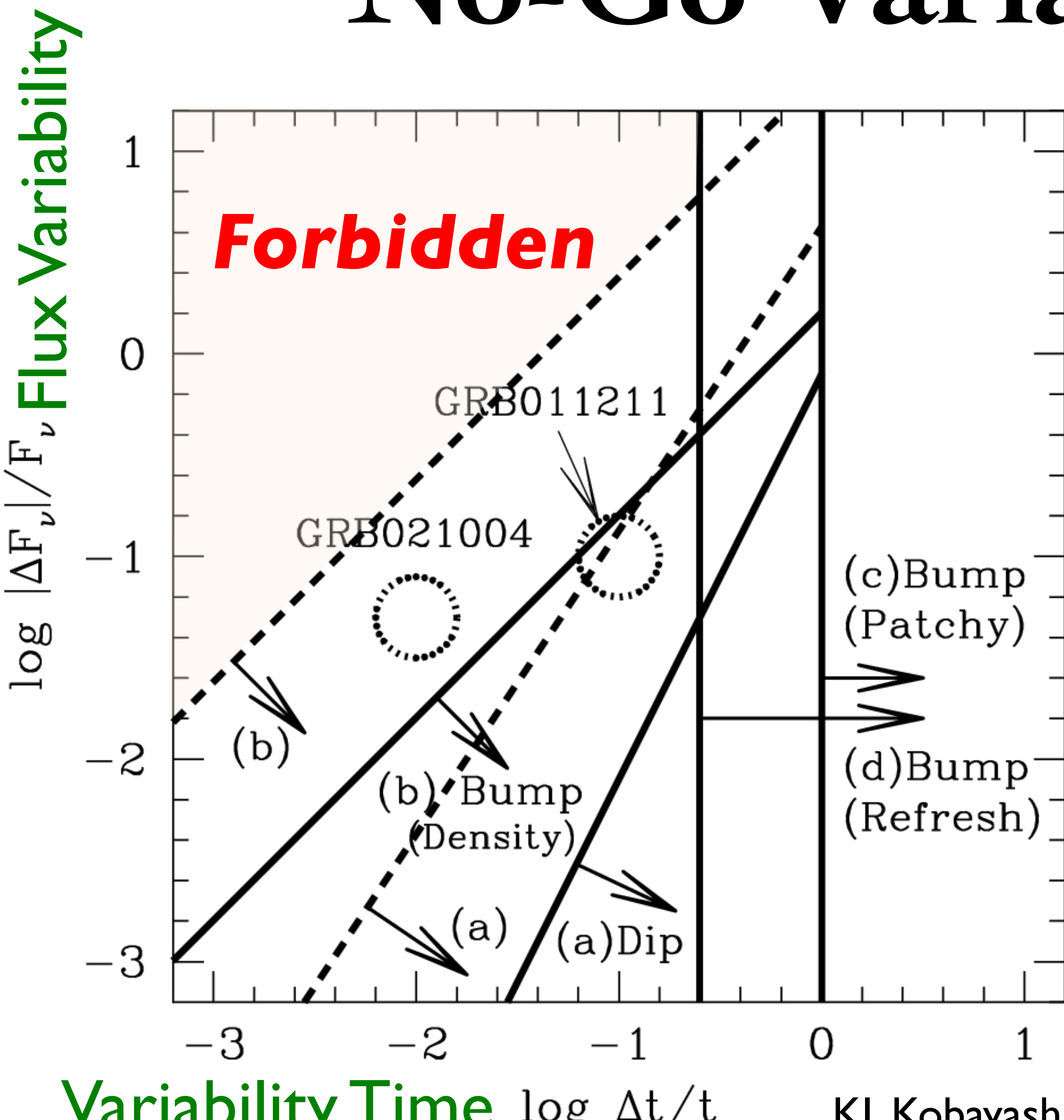


# Short GRBs are Not Short

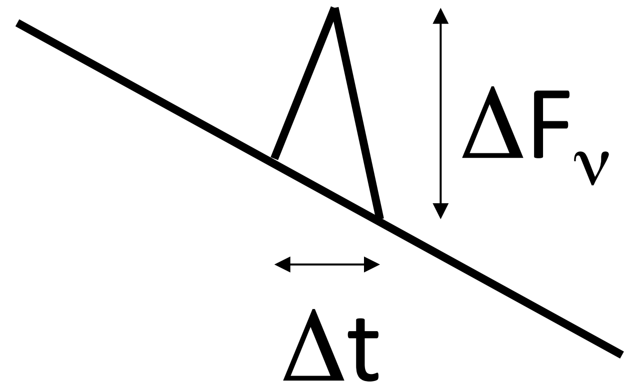



Barthelmy+ 05

# No-Go Variability




KI, Kobayashi & Zhang 05

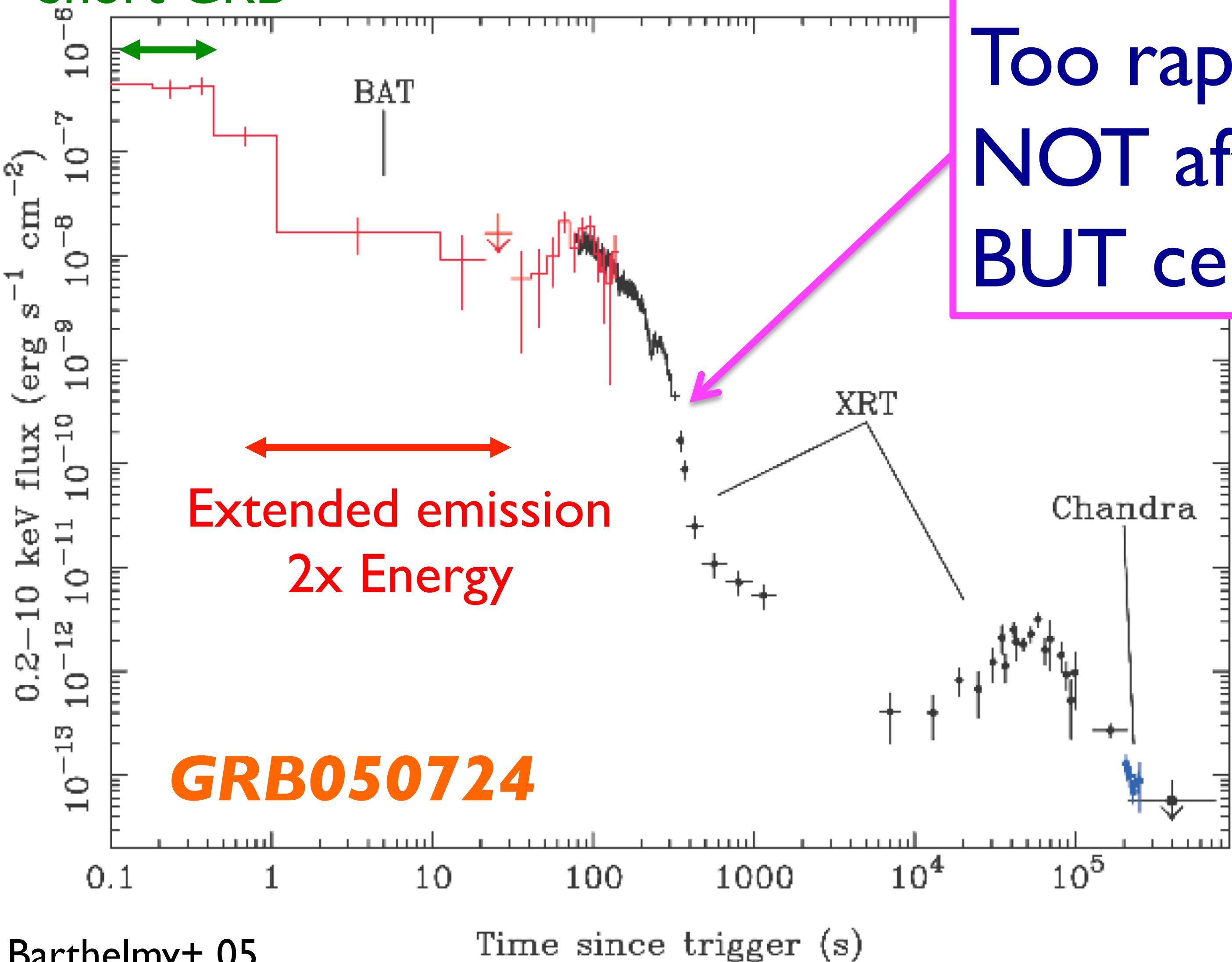



A short & large variability is NOT allowed by an afterglow

⇒ Central engine

# Short GRBs are Not Short

Short GRB




Extended emission
2x Energy

***GRB050724***

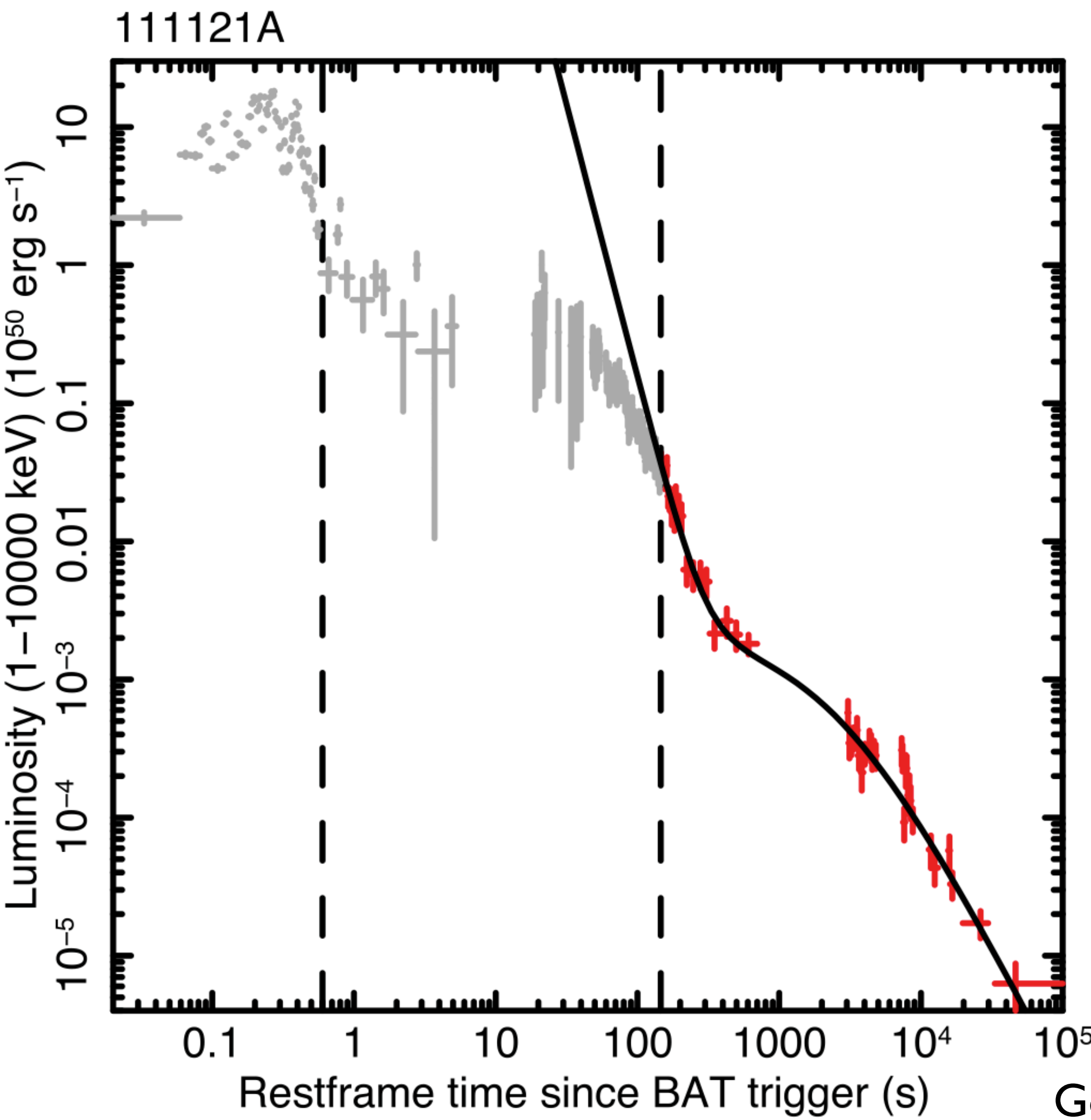
Too rapid decline:
NOT afterglow
BUT central engine

***~100 s >> $t_{vis}$ ~ 0.1 s***

***⇒ Not BH but NS? Magnetar?***

Barthelmy+ 05

# Plateau Emission




**$t \sim 10000$ s!**

$$\gg t_{\rm acc} \sim \frac{1}{\alpha}\frac{r}{c_s}\frac{r}{h}$$

$$\sim 0.1\,{\rm s}\left(\frac{\alpha}{0.1}\right)^{-1}$$

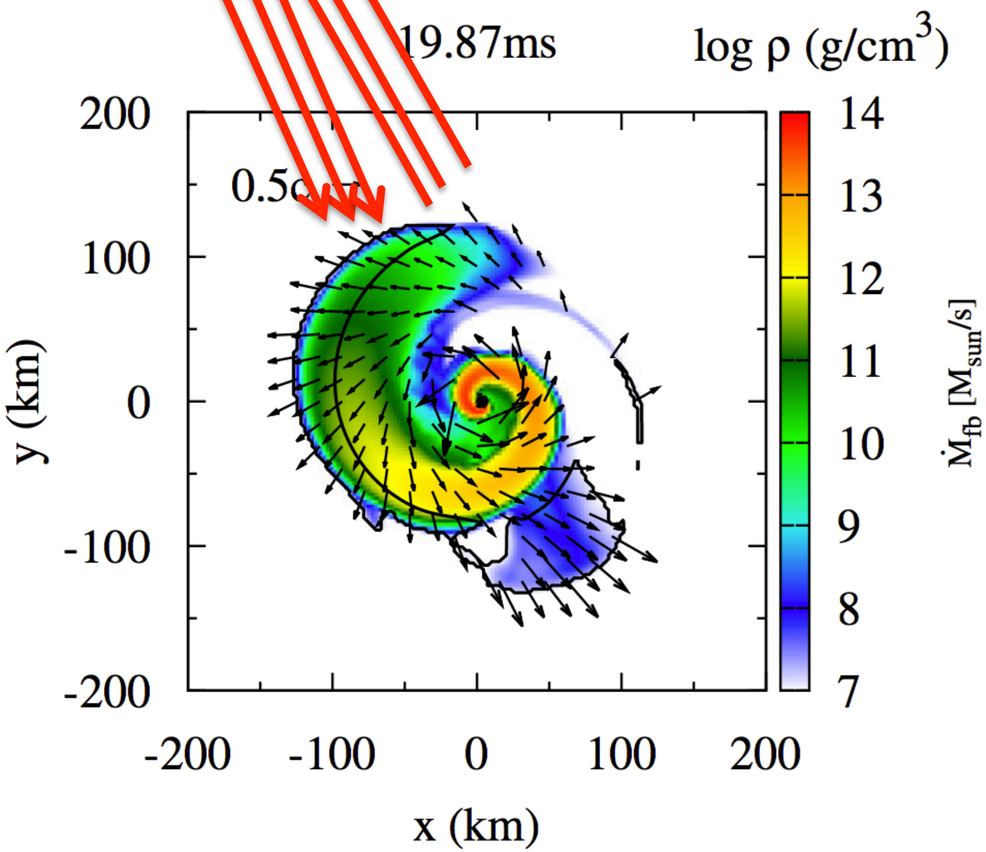
$$\times\left(\frac{r}{10^6\,{\rm cm}}\right)\left(\frac{r}{10h}\right)$$

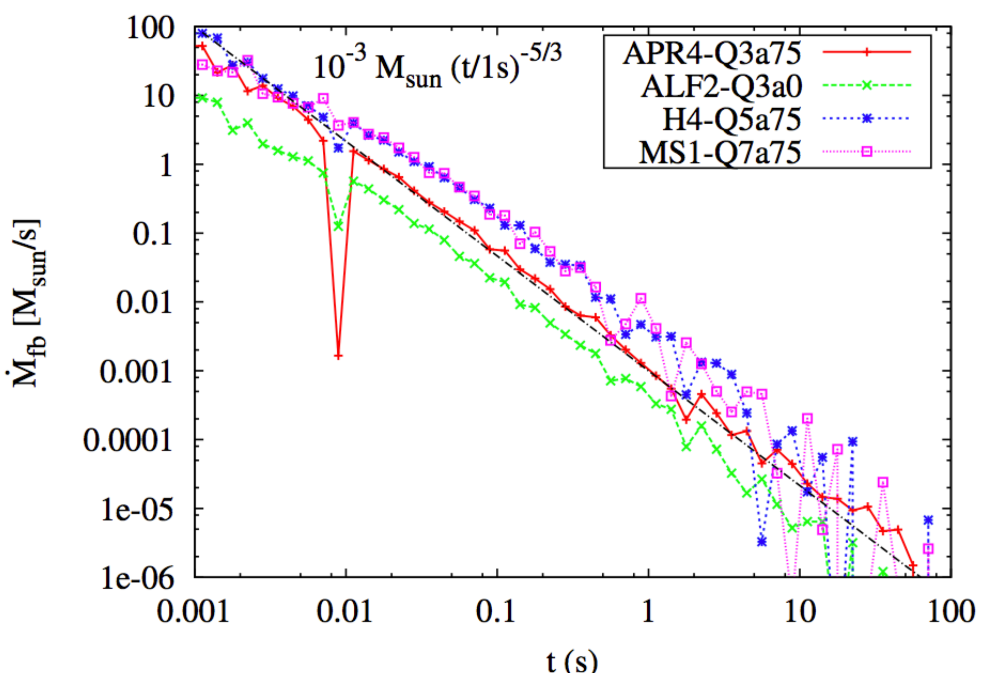
$\Rightarrow$ Neutron star?

Gompertz+ 13, 14; Rowlinson+ 13; Li+ 15

# Fallback

## ***NS merger ⇒ Ejecta ⇒ Fallback***

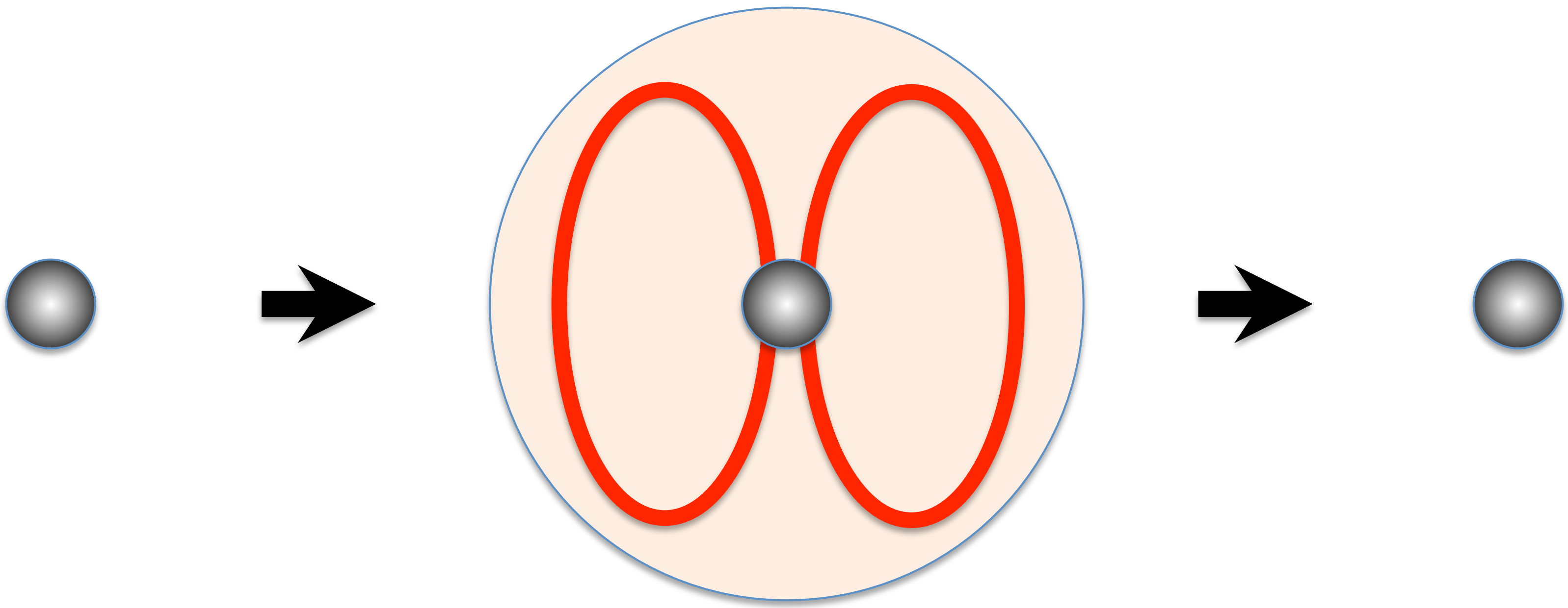



Kyutoku+ 15
Rosswog 07

***Merger ejecta fall back much later***

# Magnetic Field Topological Evolution

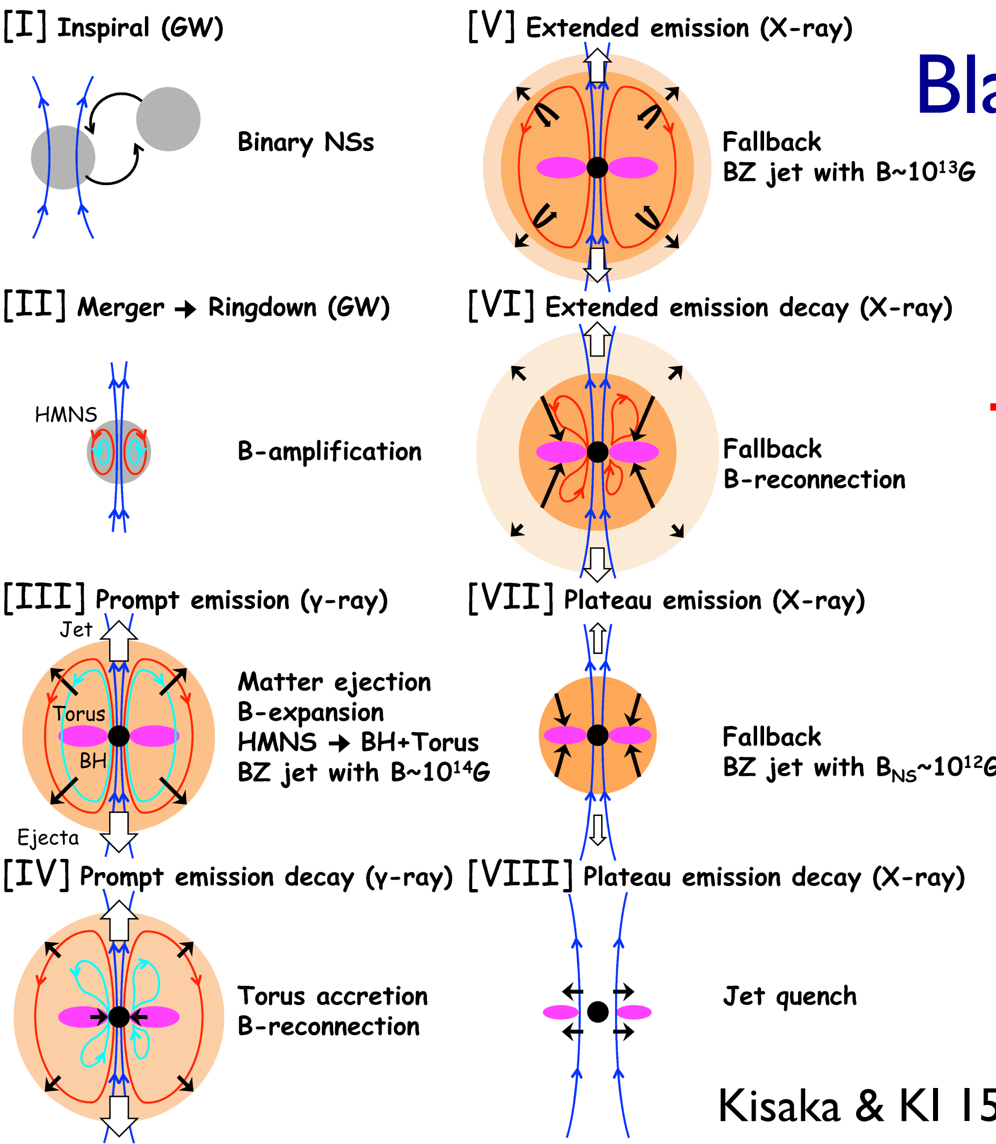


Mass ejection
⇔ $B_p$-increase

Mass fallback
⇔ $B_p$-decrease

Kisaka & KI 15

# Black Hole Jet



Kisaka & KI 15

## Blandford-Znajek luminosity

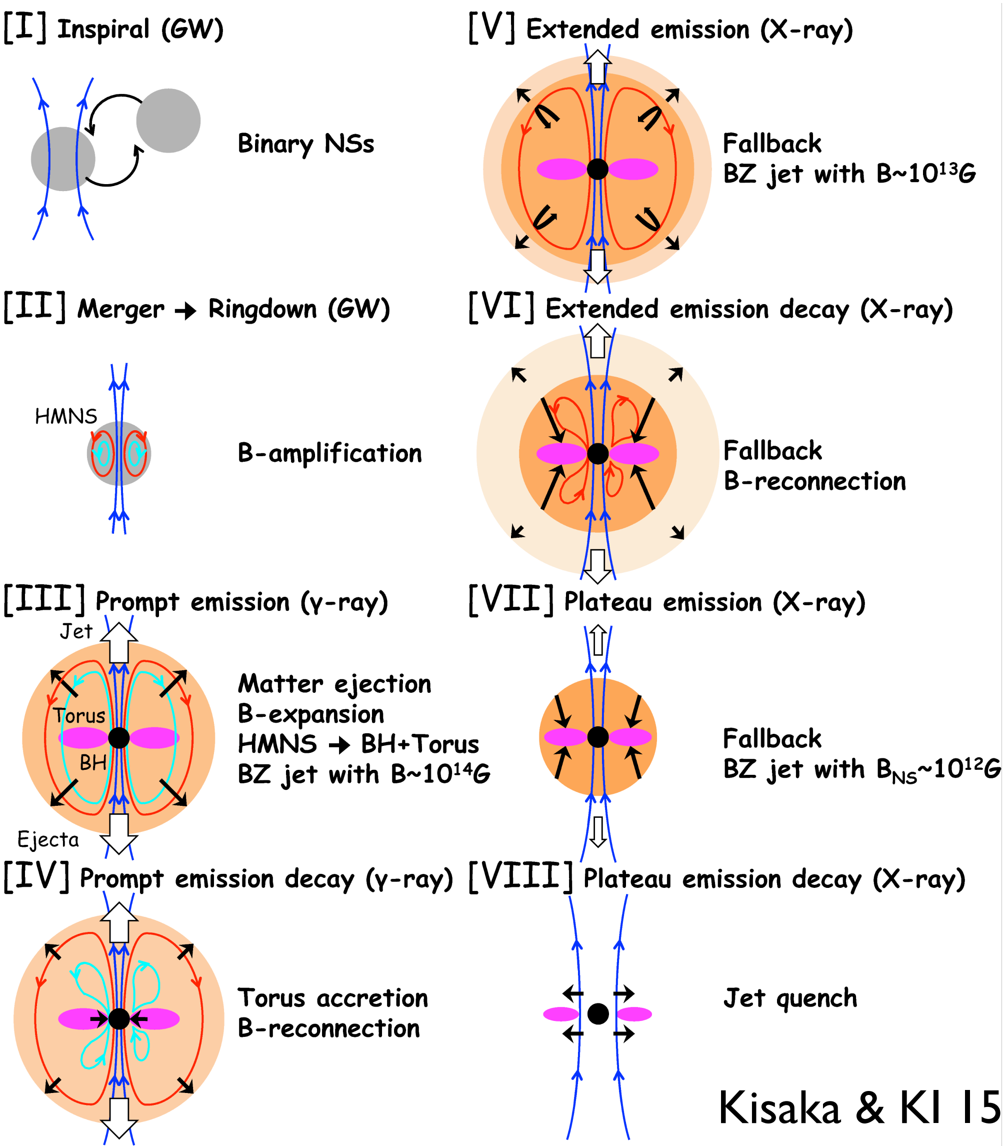
$$L_{\rm jet} \propto B^2_{\rm large\text{-}scale\ poloidal}$$

## Topological evolution of B

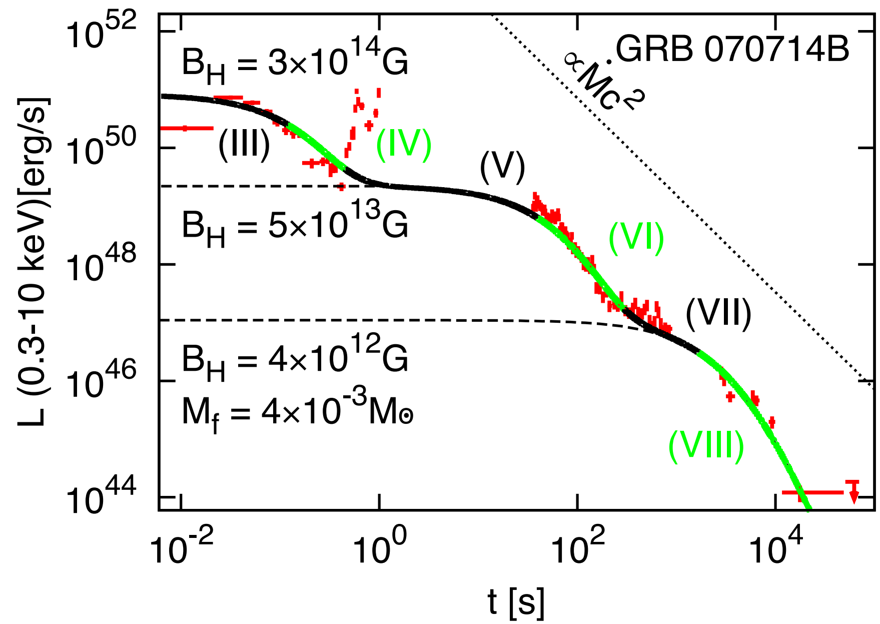
***Initial $B_p$~$10^{12}$G***
*(whatever happens)*
***Final $B_p$~$10^{12}$G***

Mass ejection ⇔ $B_p$-increase
Fallback ⇔ $B_p$-decrease

# Black Hole Jet




Kisaka & KI 15



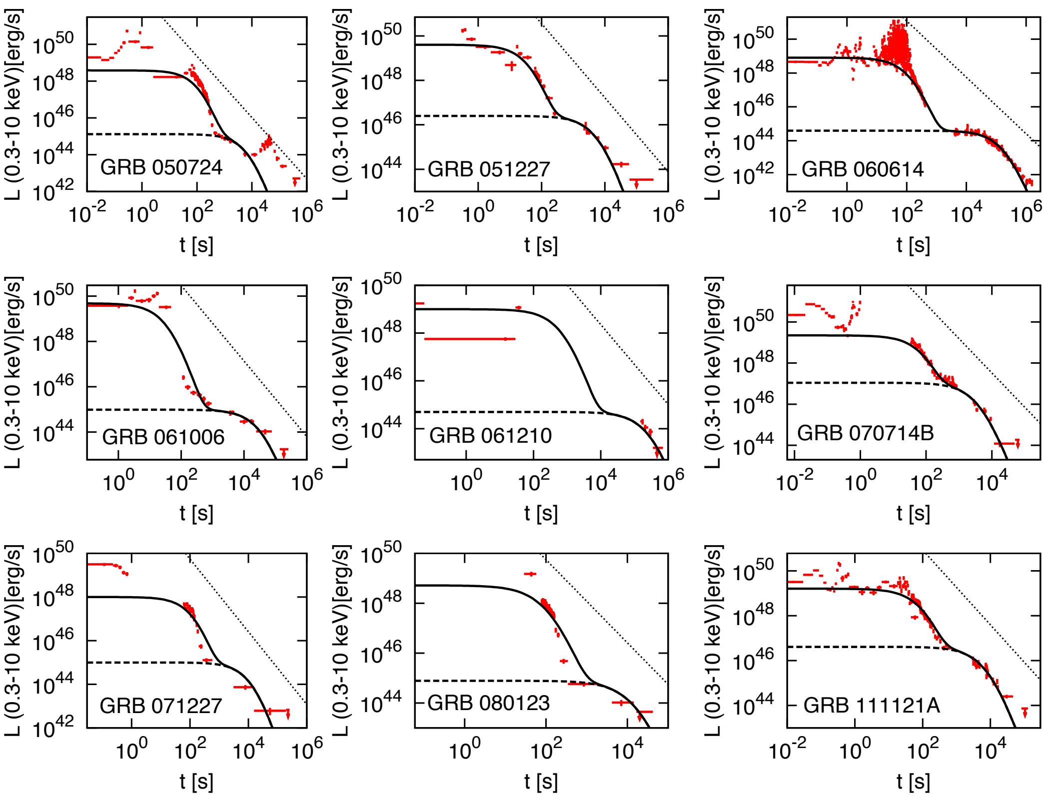

$L_{jet} \propto B^2$

Prompt: B~$10^{14}$G

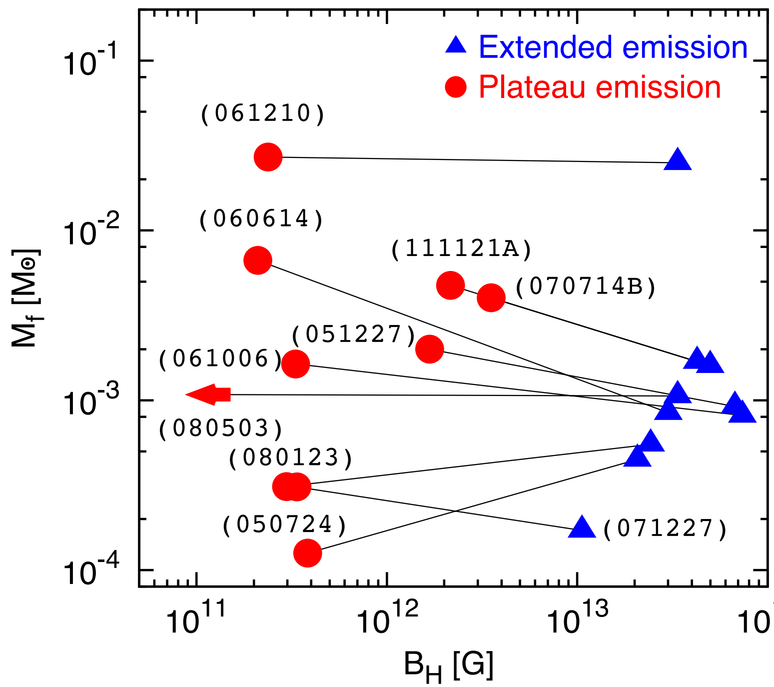
Extended: B~$10^{13}$G

Plateau: B~$10^{12}$G

# Black Hole Jet




Kisaka & KI 15




**Luminosity & Duration**

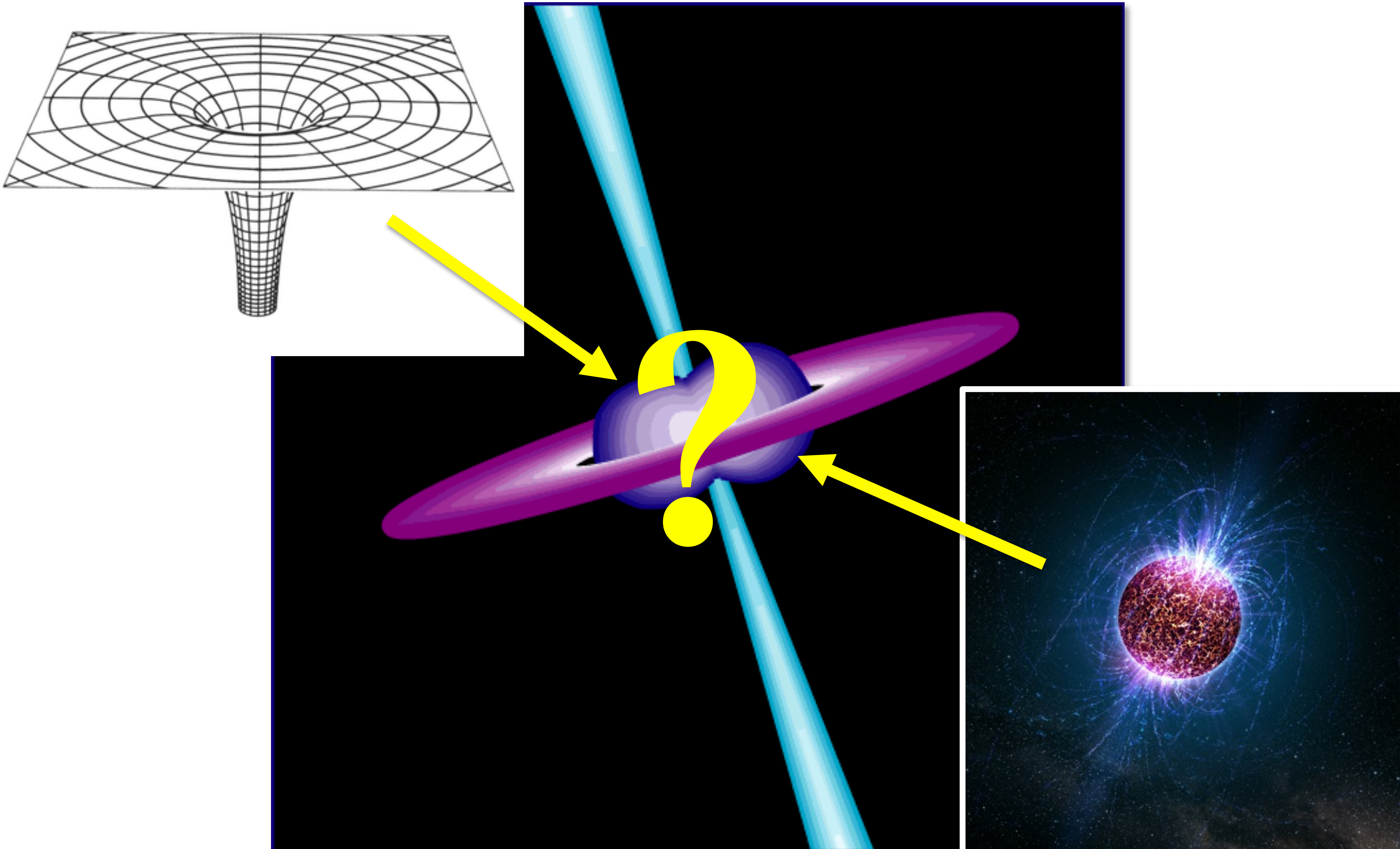
**⇔ $M_{\rm fallback}$ & B**

**($P_{\rm fallback}$~$P_B$ ⇒ Duration)**

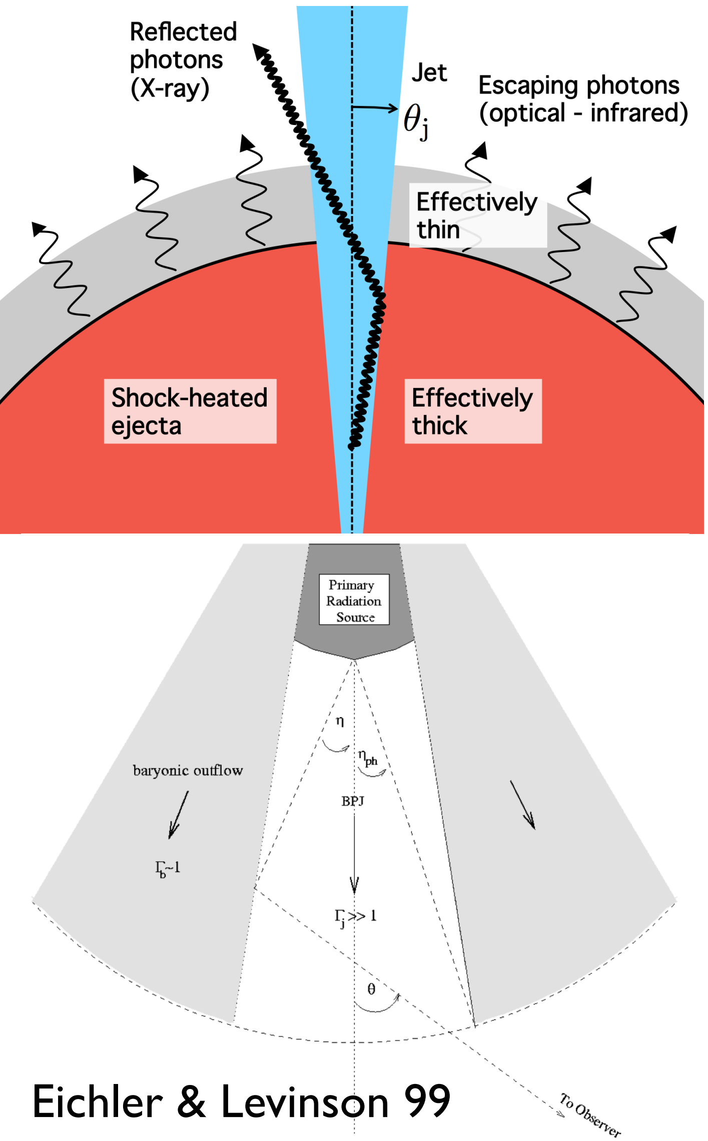
$$L \sim 10^{46} \left( \frac{B}{10^{12}\,{\rm G}} \right)^2 {\rm erg\,s^{-1}}$$

$$T \sim 10^4 \left( \frac{M_f}{10^{-3} M_\odot} \right)^{3/5} \left( \frac{B}{10^{12}\,{\rm G}} \right)^{-6/5} {\rm s}$$

# Black Hole or Neutron Star?

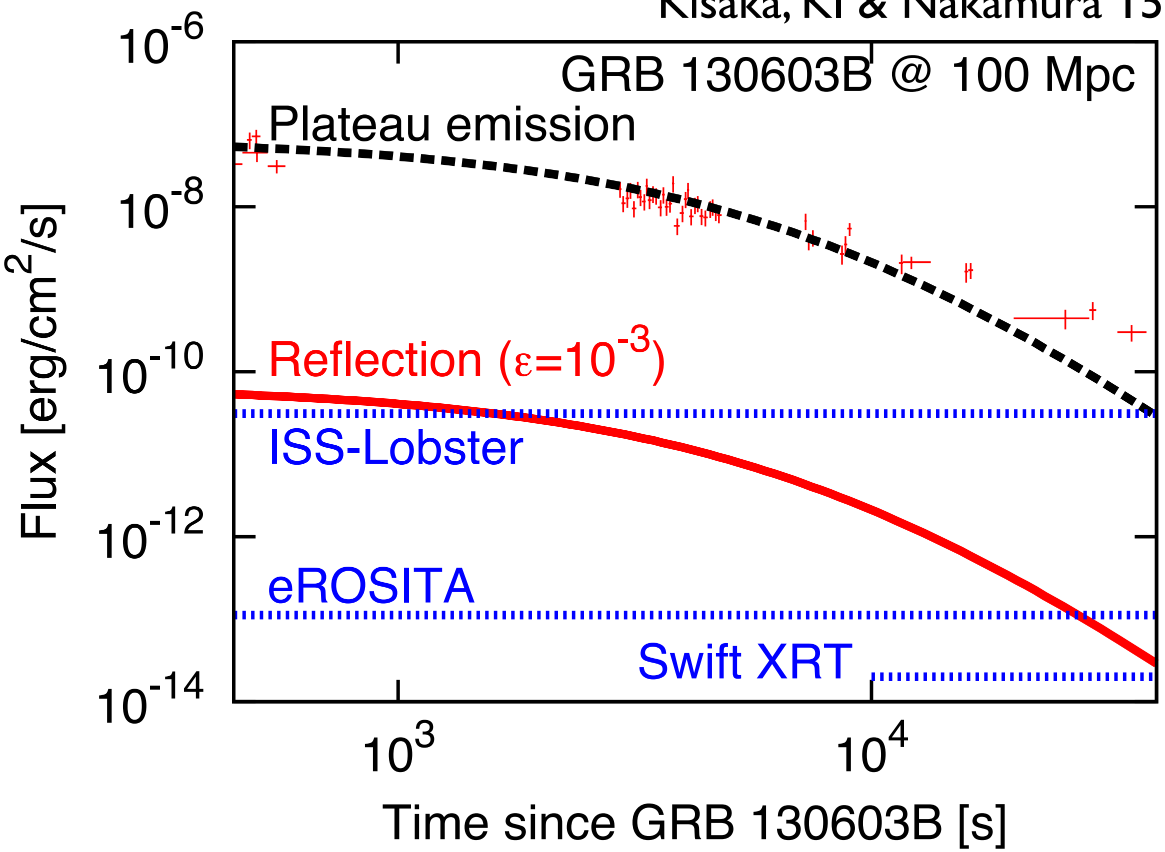


# Scattering Plateau X-ray




Eichler & Levinson 99

Kisaka, KI & Nakamura 15




X-ray localization ⇒ Opt/IR

***Wide-field X-ray follow-up***

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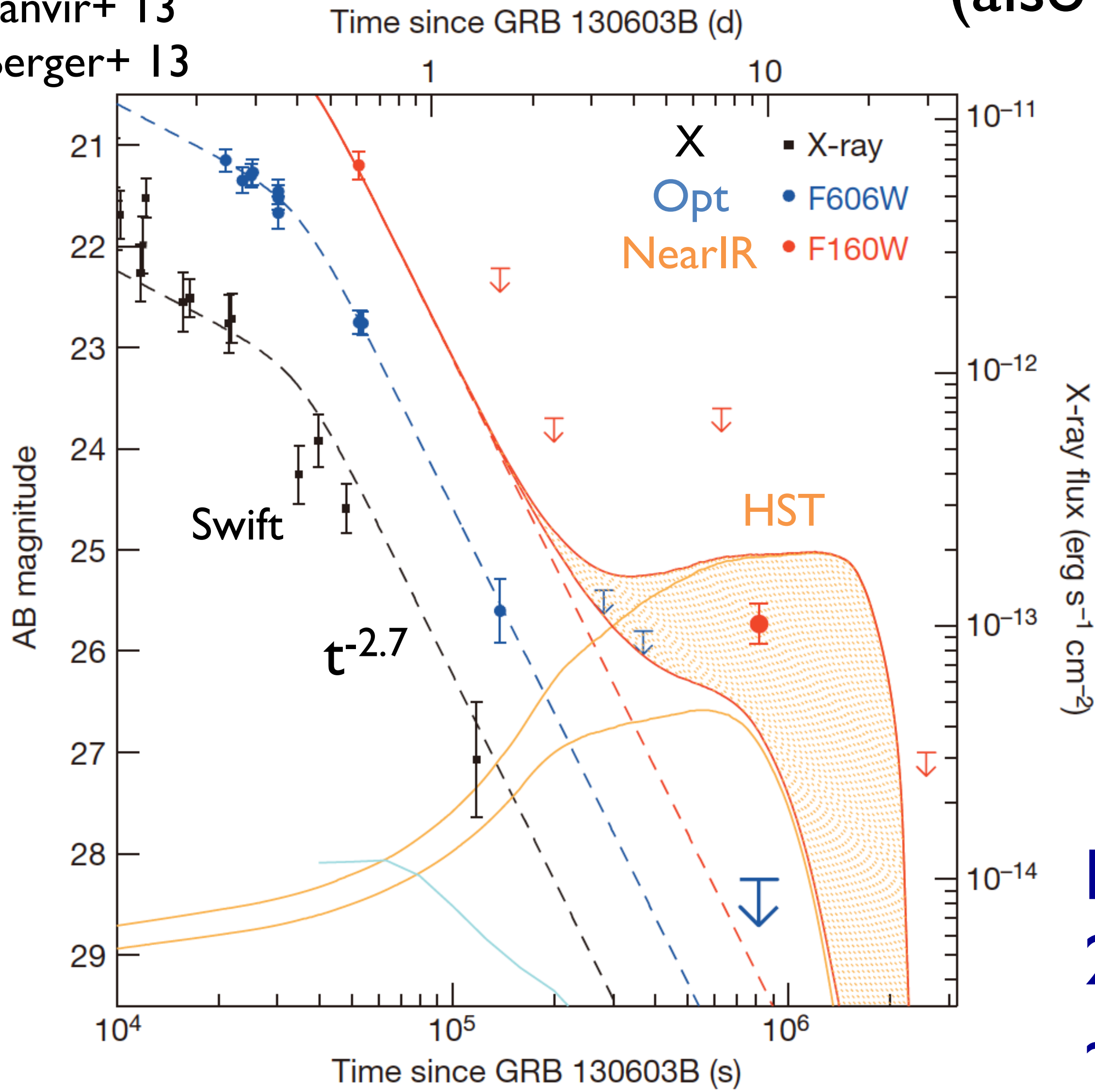
# Discovery of Macronova

(also known as kilonova)

Tanvir+ 13
Berger+ 13




***Ejecta with***
***~0.01-0.1M$_\odot$***
***~0.1-0.3c***
***~$10^{50}$-$10^{52}$erg***

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

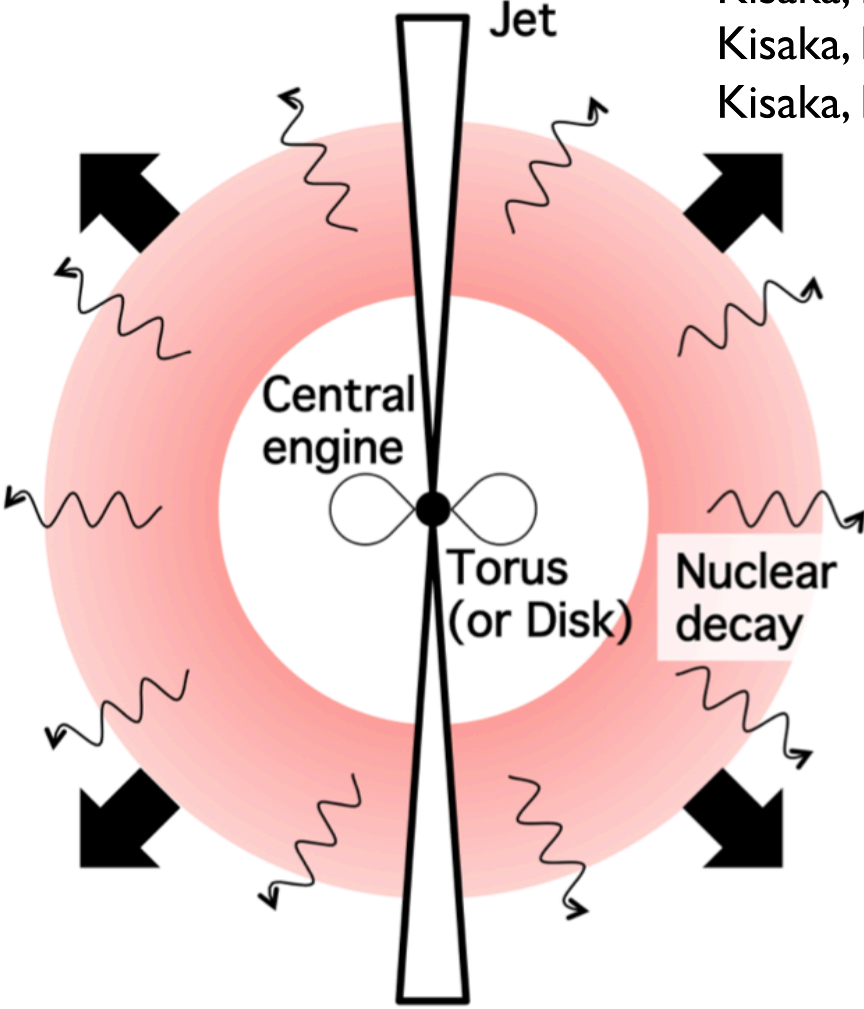
Li & Paczynski 98
Kulkarni 05

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

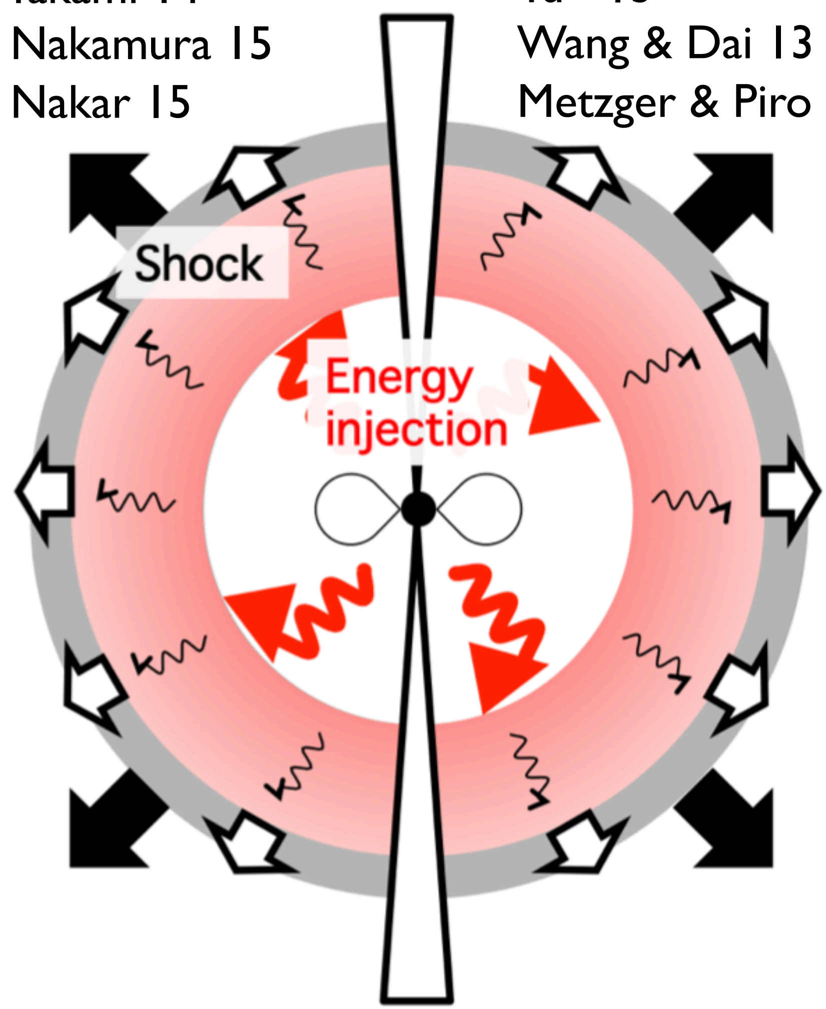
# Engine-Powered Macronova?

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

Yu+ 13
Wang & Dai 13
Metzger & Piro 14

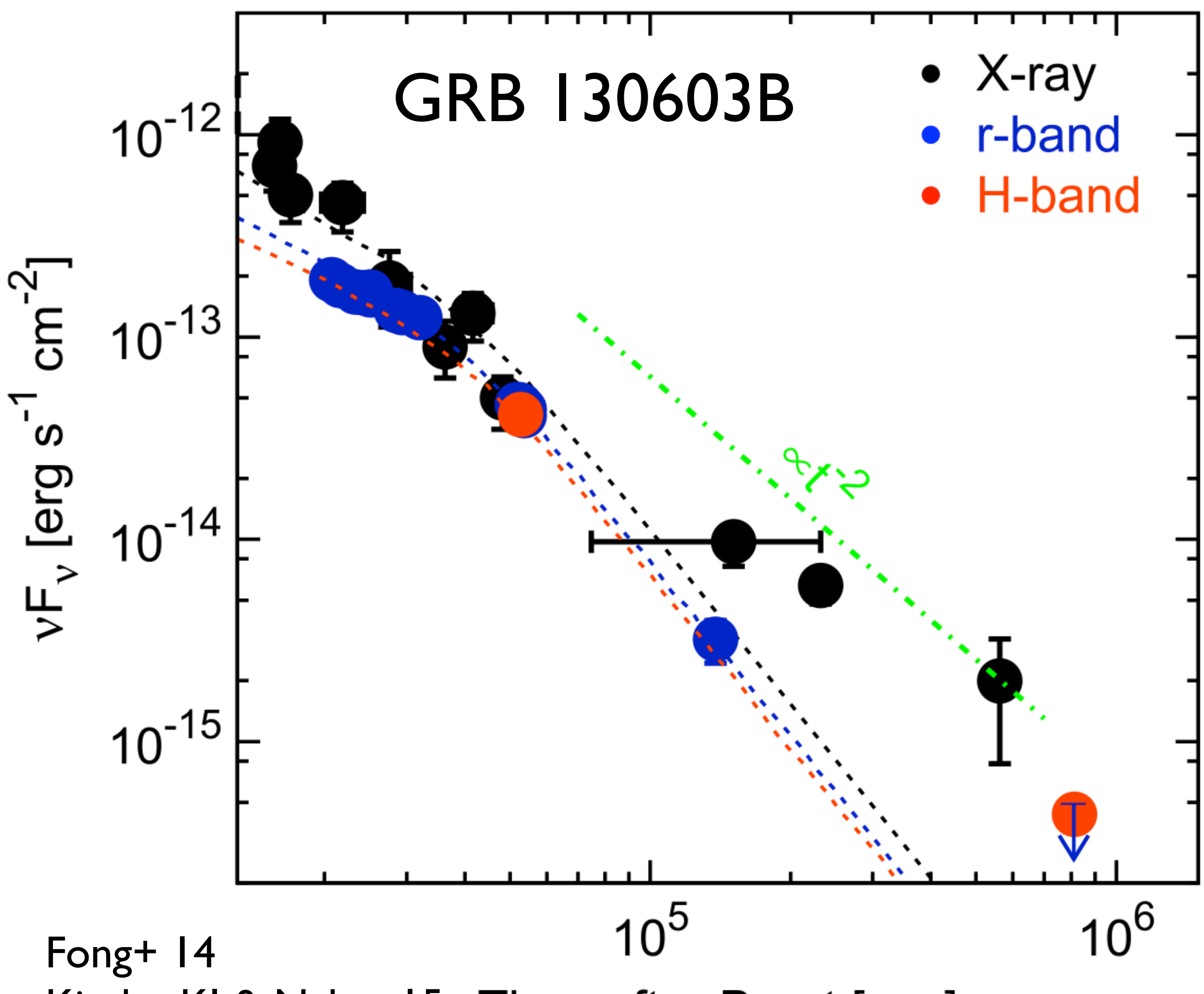



R-process model




Engine model

# X-ray Powered?



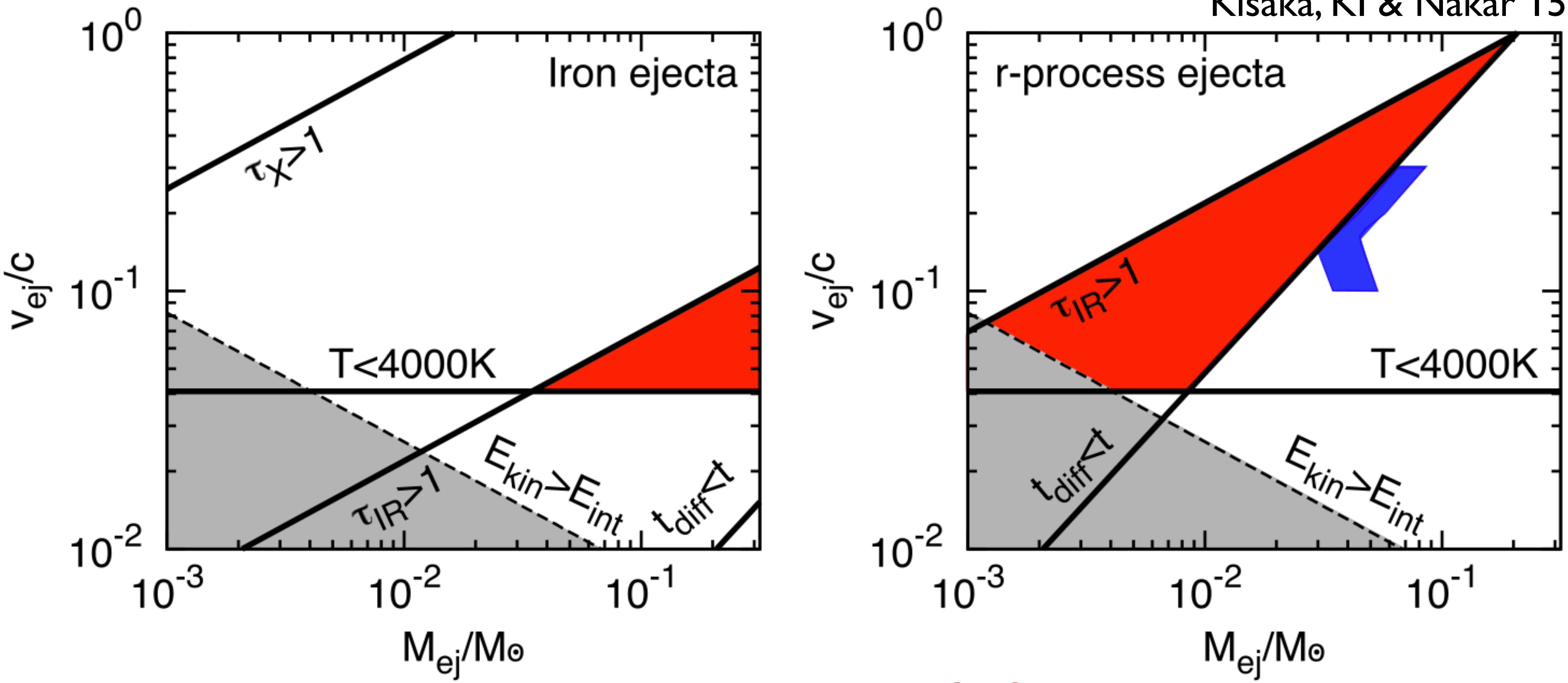

Fong+ 14
Kisaka, KI & Nakar 15

Macronova @IR
≈ X-ray excess
***Same origin?***

*X-ray*
*⇒ Ejecta*
*⇒ Thermalized*
*⇒ Infrared*
*as reprocessed*

# Required Ejecta Mass

Kisaka, KI & Nakar 15



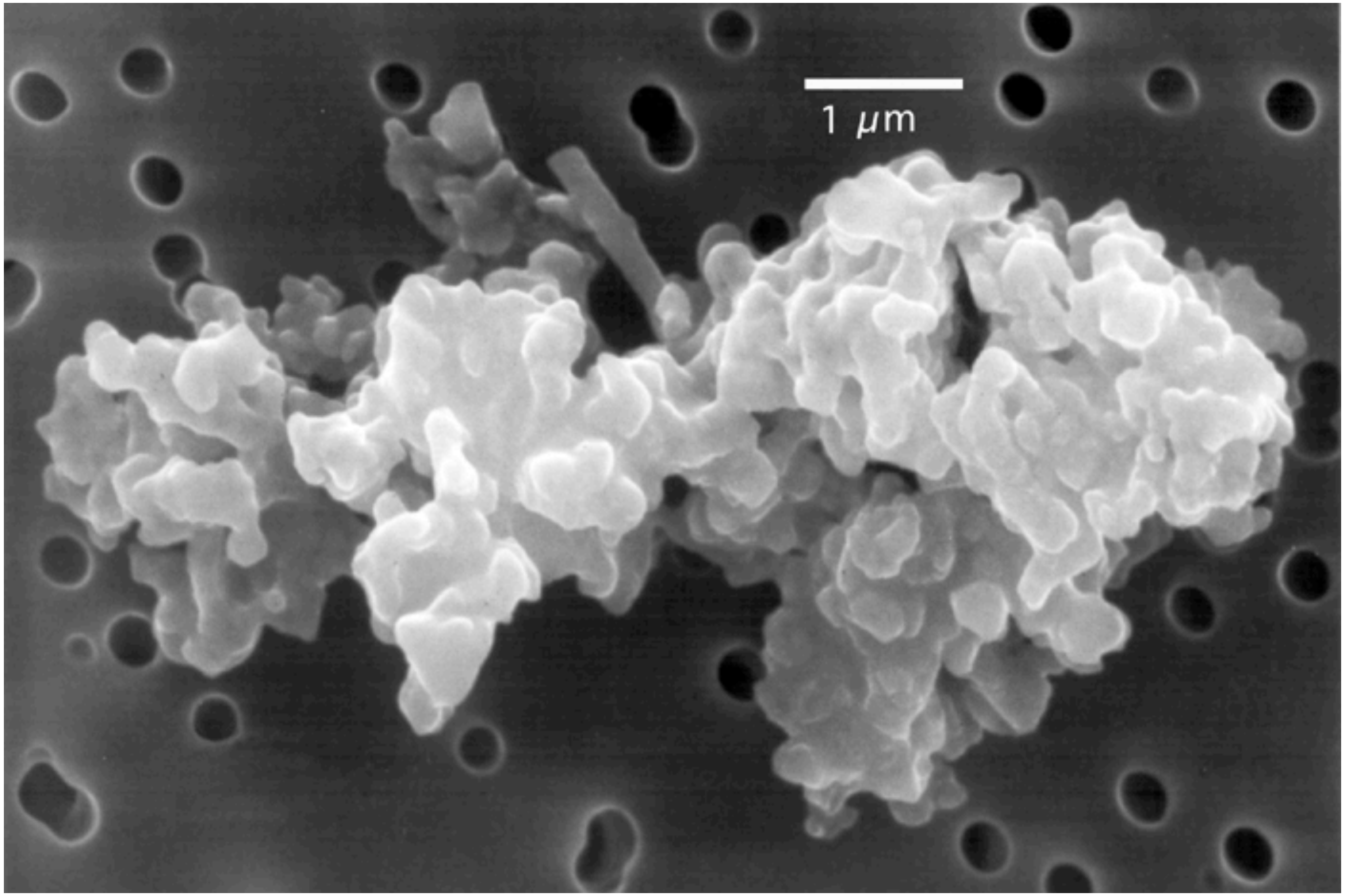

Required $M_{ejecta} < 0.01 M_\odot$

⇔ R-process model: $M_{ejecta} > 0.03 M_\odot$

Only Fe ⇒ large $M_{ejecta}$

# Cosmic Dust?

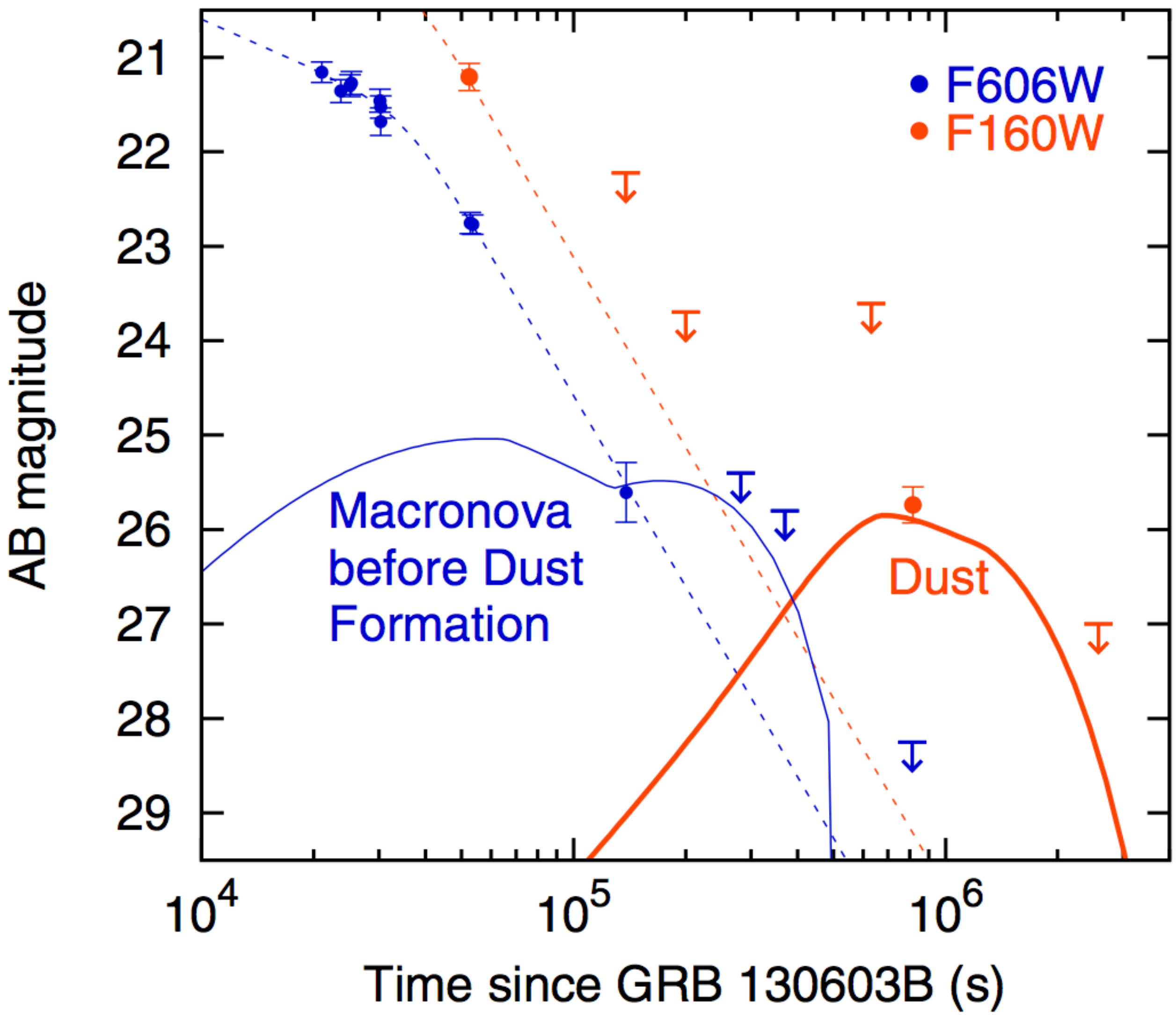
Takami, Nozawa & KI 14




$$\kappa_{geometrical} = \frac{\pi r_{dust}^2}{m_{dust}} \sim \frac{\pi \left(N^{1/3} r_A\right)^2}{N m_A} \sim 10^6 N^{-\frac{1}{3}} \text{ cm}^2 \text{ g}^{-1}$$

If $2\pi r_{dust}/\lambda < 1$, $\kappa \propto \lambda^{-1}$

# Lightcurve of Dust Model

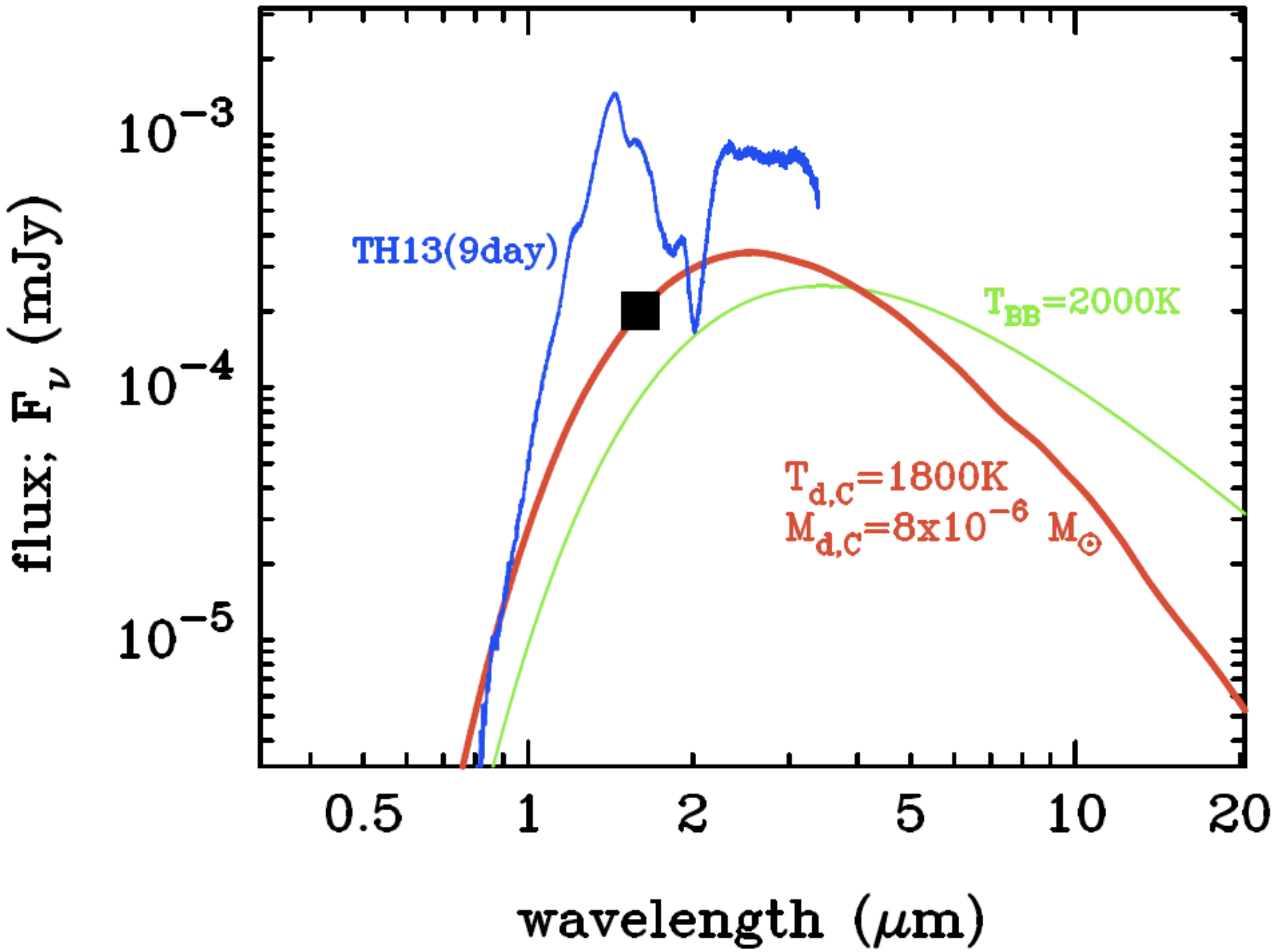



Initially κ~0.1 $cm^2/g$
Optical-UV
t~day
like original model

Dust formation
⇒ κ~10 $cm^2/g$
Infrared-Optical
t~10day

Takami, Nozawa & KI 14

# Macronova Spectrum




Featureless even without broad lines

Not black-body
$Q \propto \lambda^{-1}$

Takami, Nozawa & KI 14

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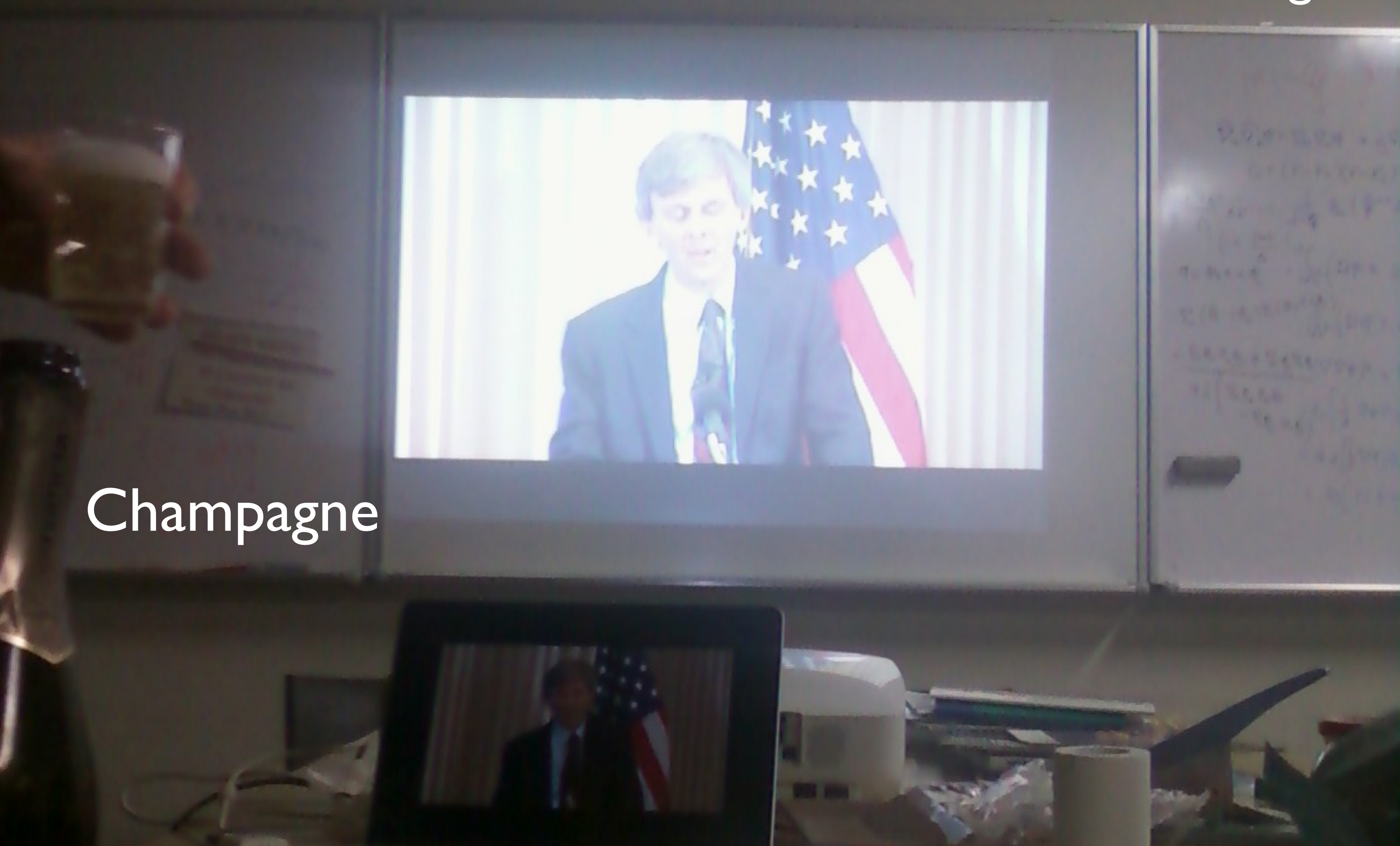
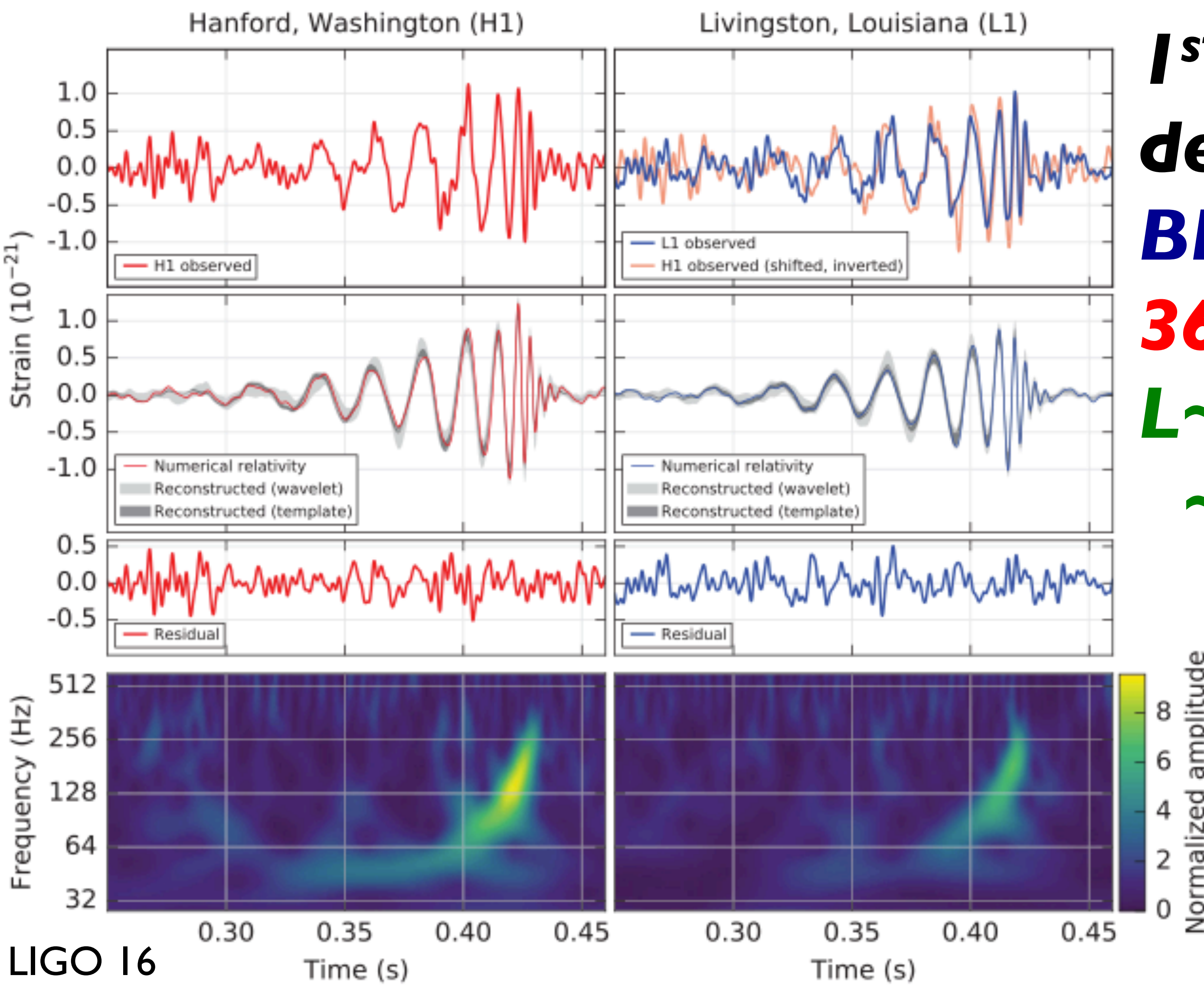
# We Did It!

@YITP
midnight



Champagne

# GW150914




LIGO 16

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

**BH-BH**

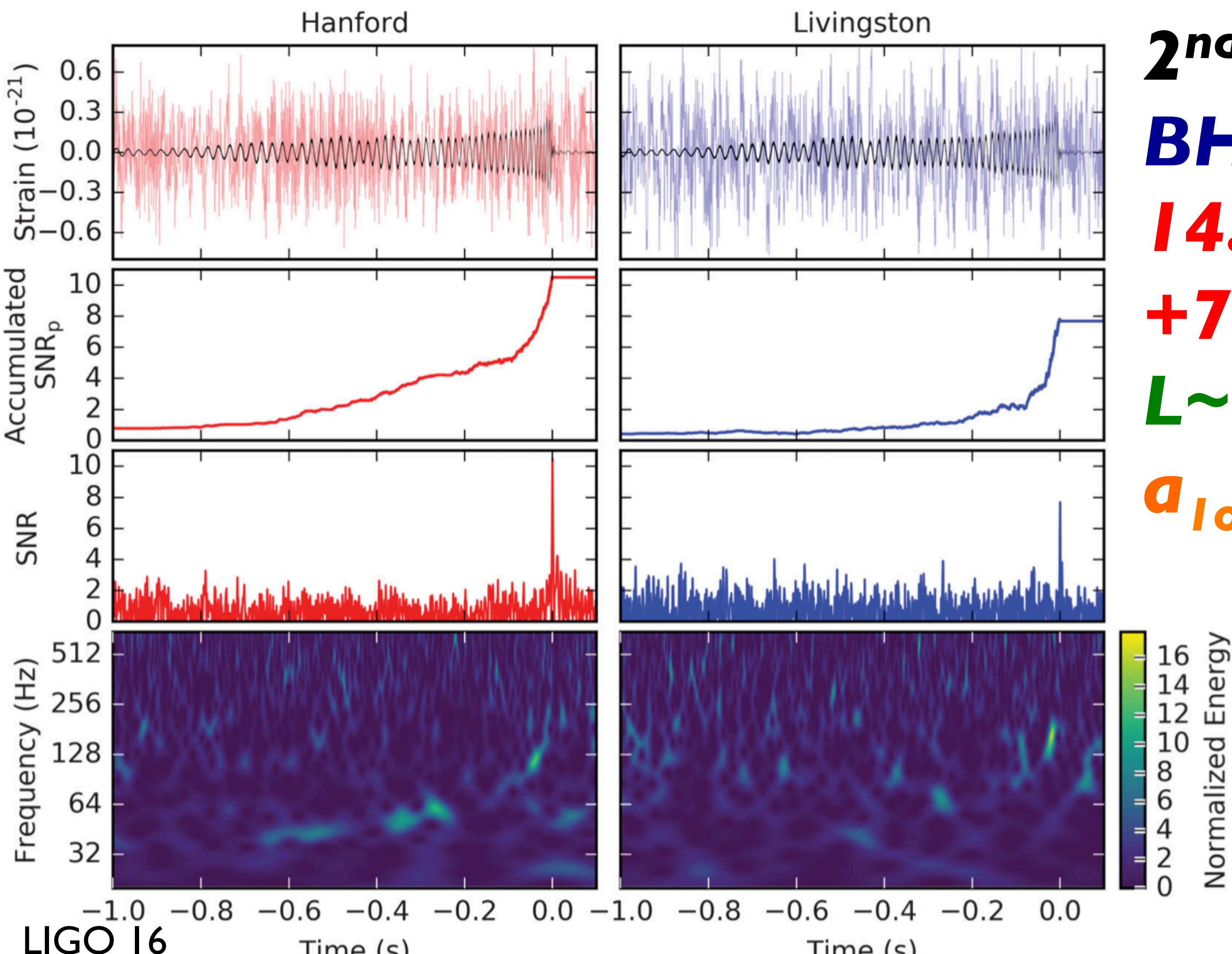
**$36M_\odot+29M_\odot$**

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

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

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

# GW151226




LIGO 16

**2nd event**

**BH-BH**

**14.2M⊙ +7.5M⊙**

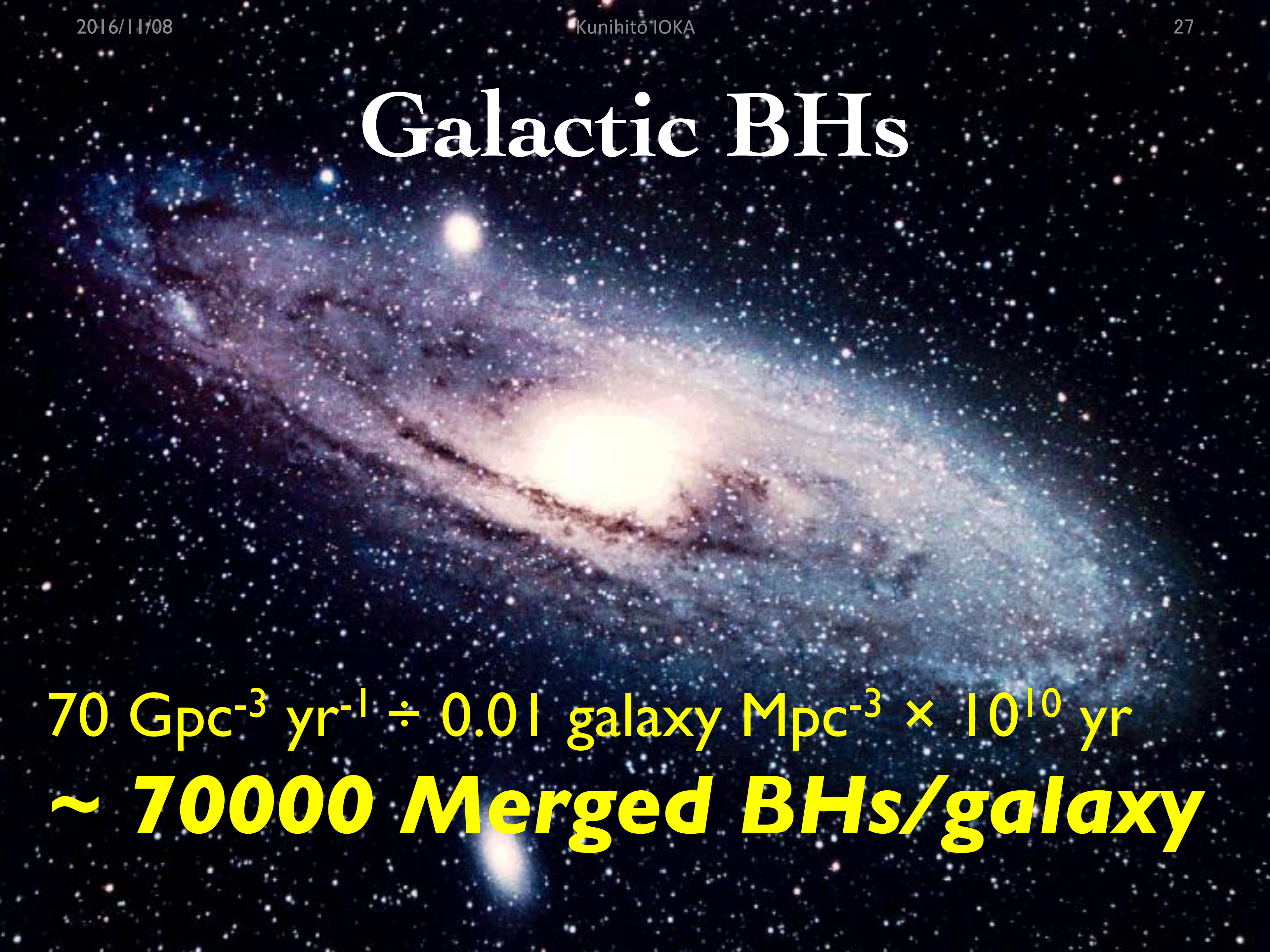
**L~170M⊙c²/s**

**a$_{1or2}$ > 0.2**

LVT151012

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

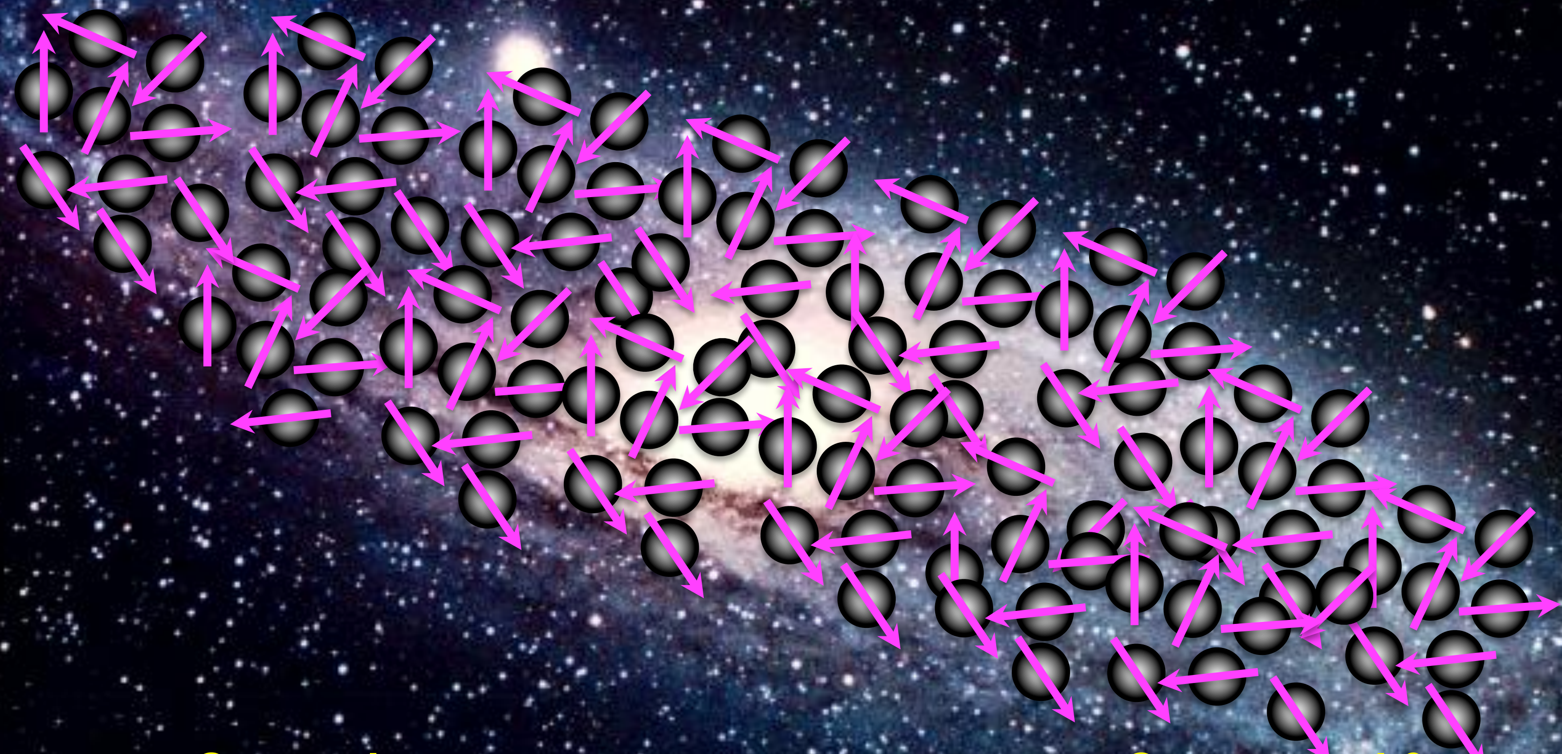
# Galactic BHs



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

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

# Galactic BHs



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

***~ 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

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

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

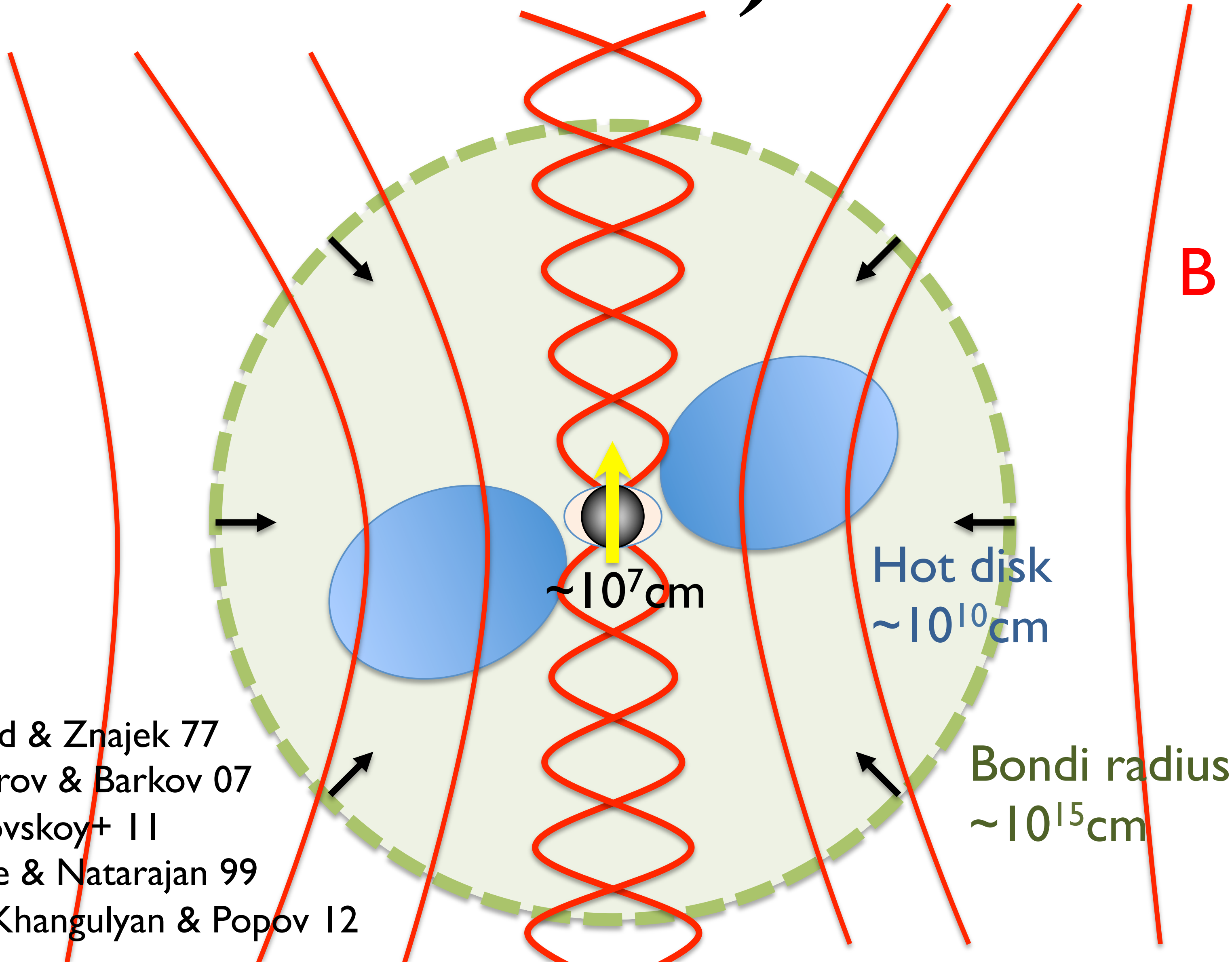
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7 \times 10^4 \ {\rm BHs} \times 1 \times 10^{54}\,{\rm erg}$$

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

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

**Comparable to supernovae ever happened!**

# Blandford-Znajek Effect




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

# 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.

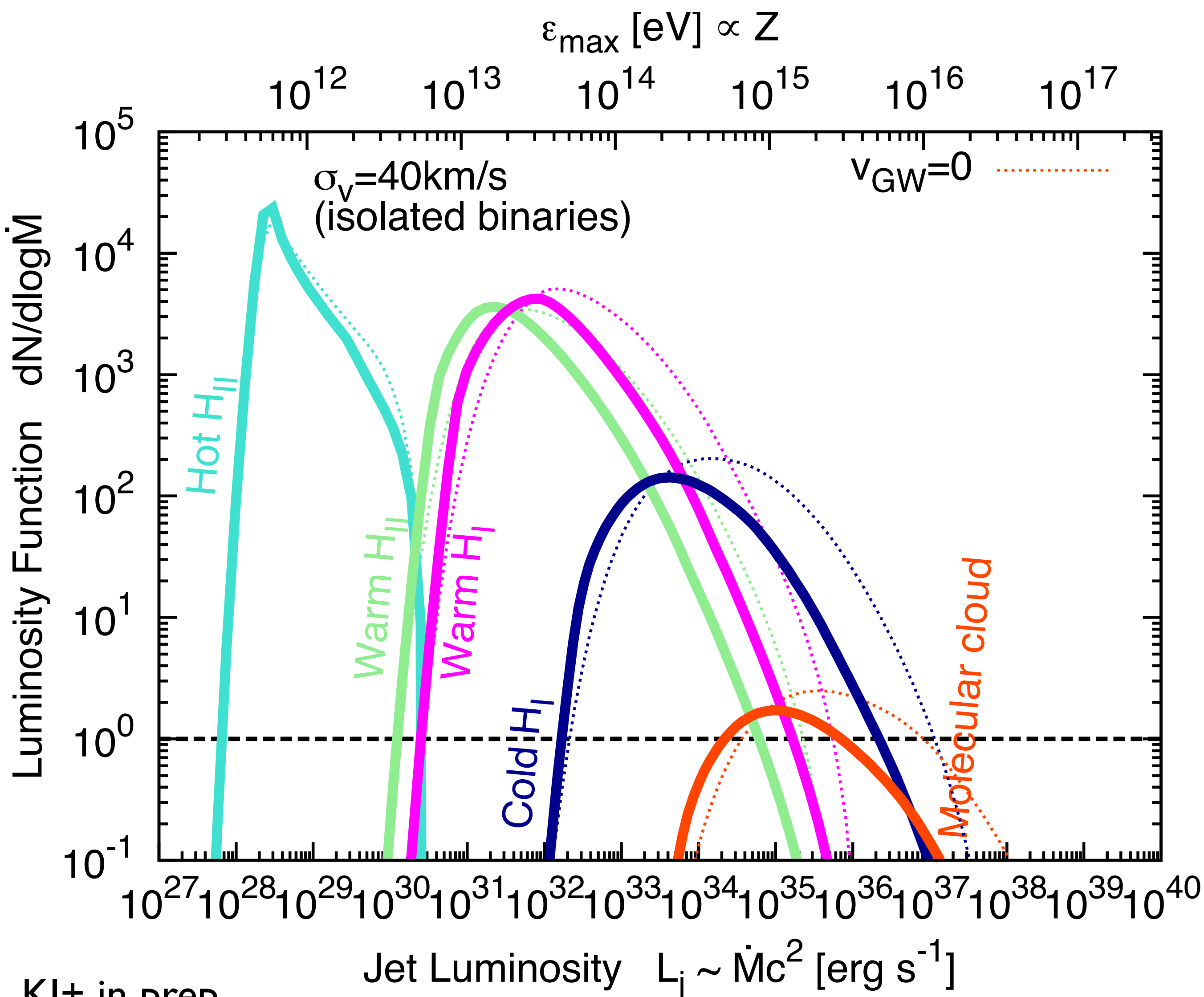
**BH mass:** $m_1$: Salpeter, $m_2$: Flat, $5M_\odot < m_2 < m_1 < 50M_\odot$

**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

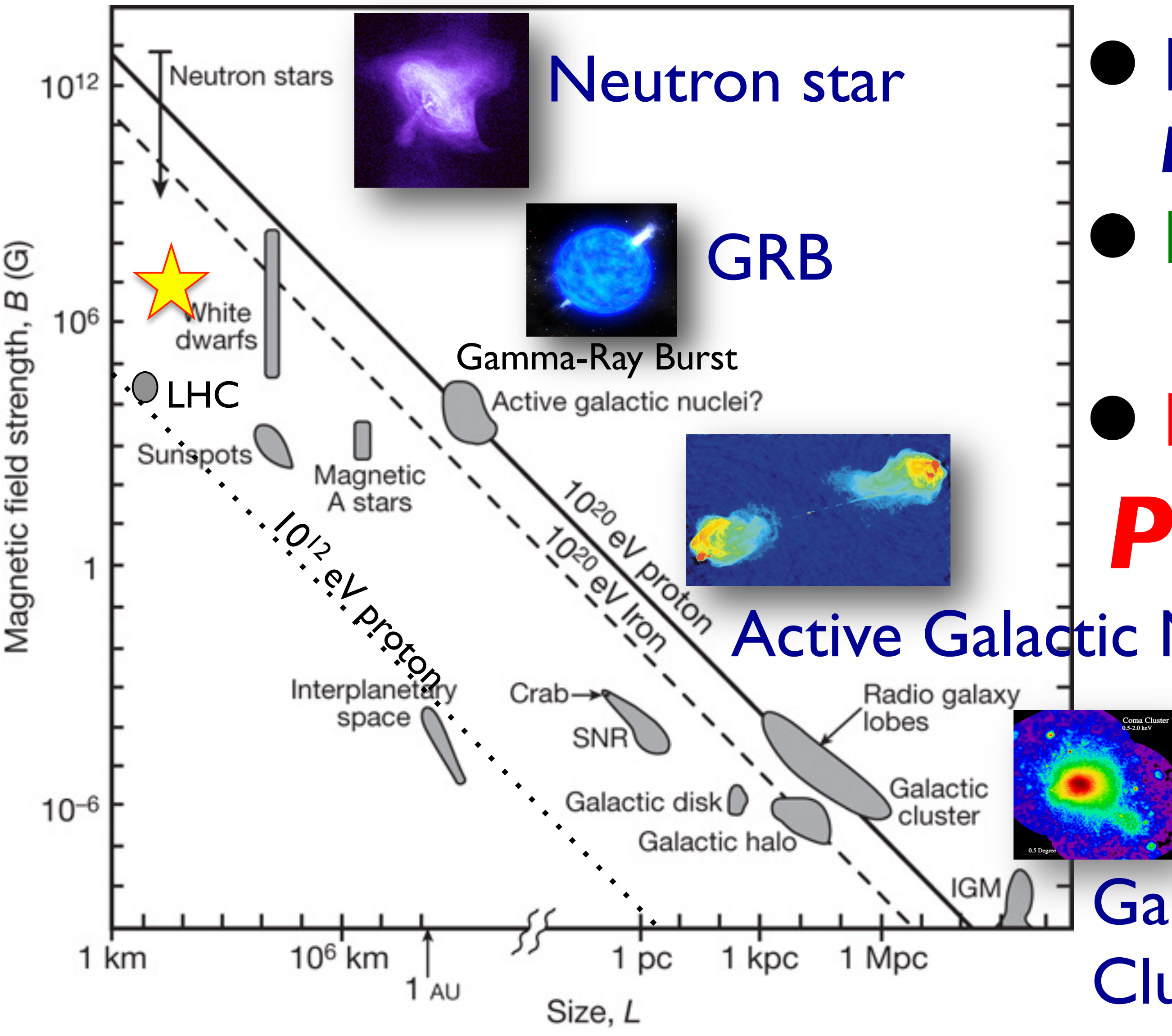



The most luminous BH jet is $\sim 10^{36}$ erg/s in cold $H_I$

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

KI+ in prep.

# Max Acceleration Energy



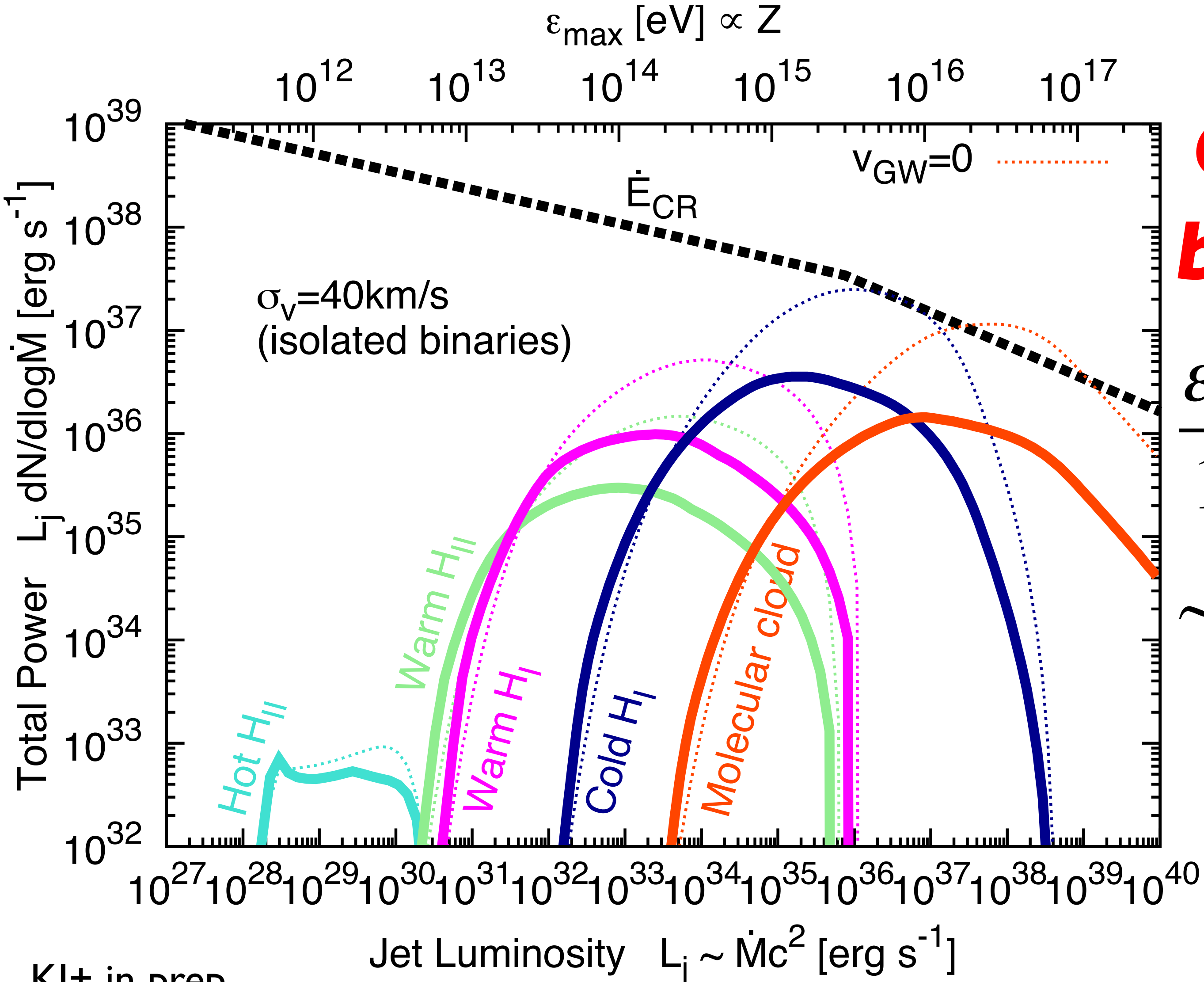

- Hillas condition
  ***E<ZqBR***
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\boldsymbol{\propto (BR)^2}$ Blandford 00 Waxman 04
- $E_{max}$>PeV

***PeVatron!!!***

Barkov+ 12
KI+ in prep.

Dark Matter?

# Total Power




KI+ in prep.

**BHs ⇔ Cosmic rays beyond PeV?**

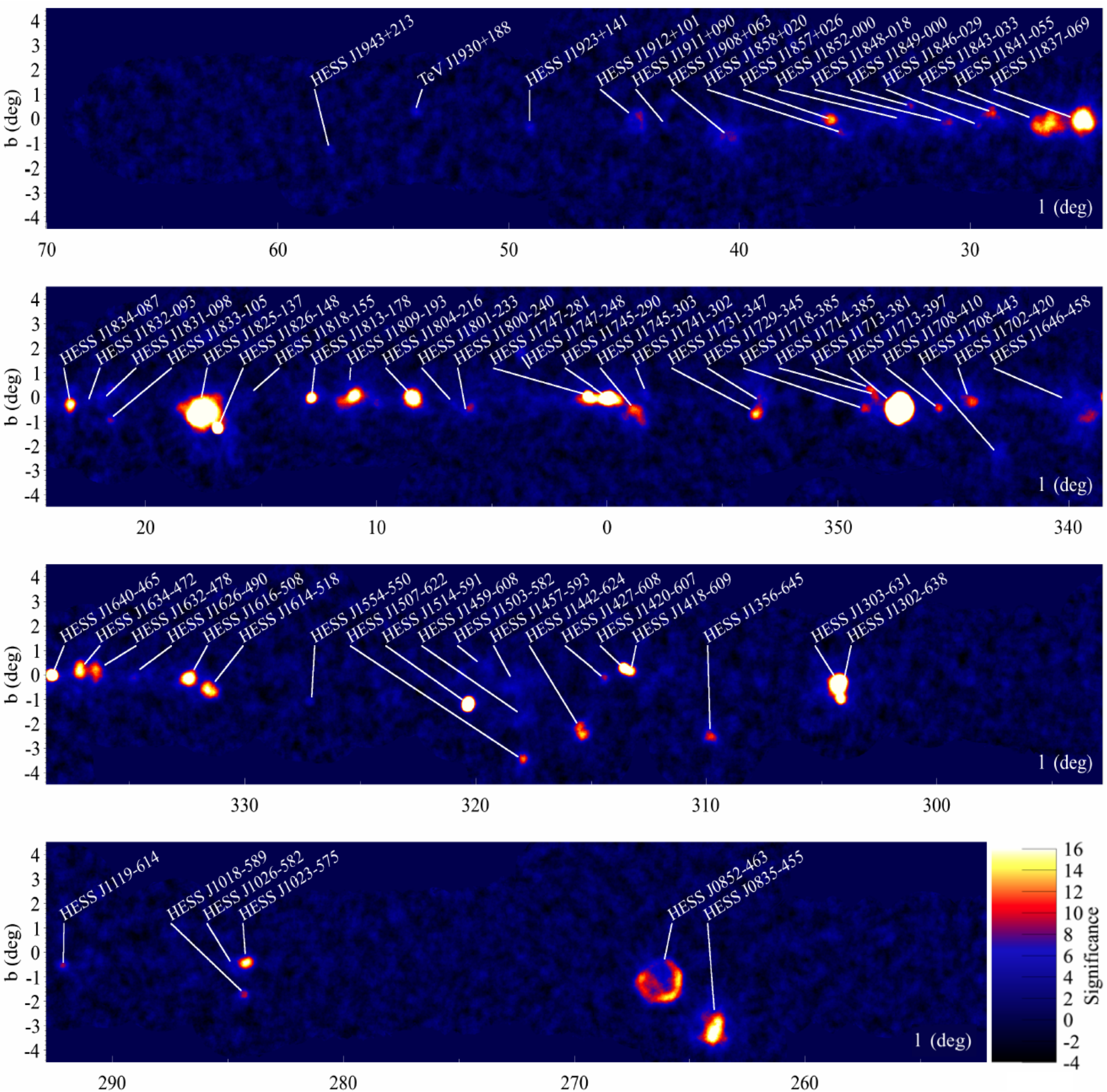
$$\frac{\varepsilon_{CR} E_{SN}}{100\mathrm{yr}}$$

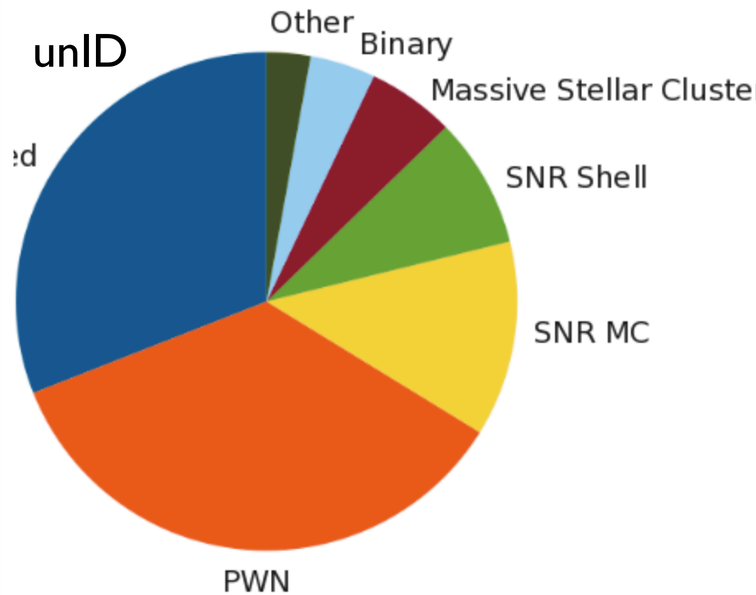
$$\sim 3\times10^{40}\ \mathrm{erg\ s^{-1}}$$

If leptonic ⇔ $e^{\pm}$ excess?

# TeV Gamma-Ray Sky

HESS 1307.4690



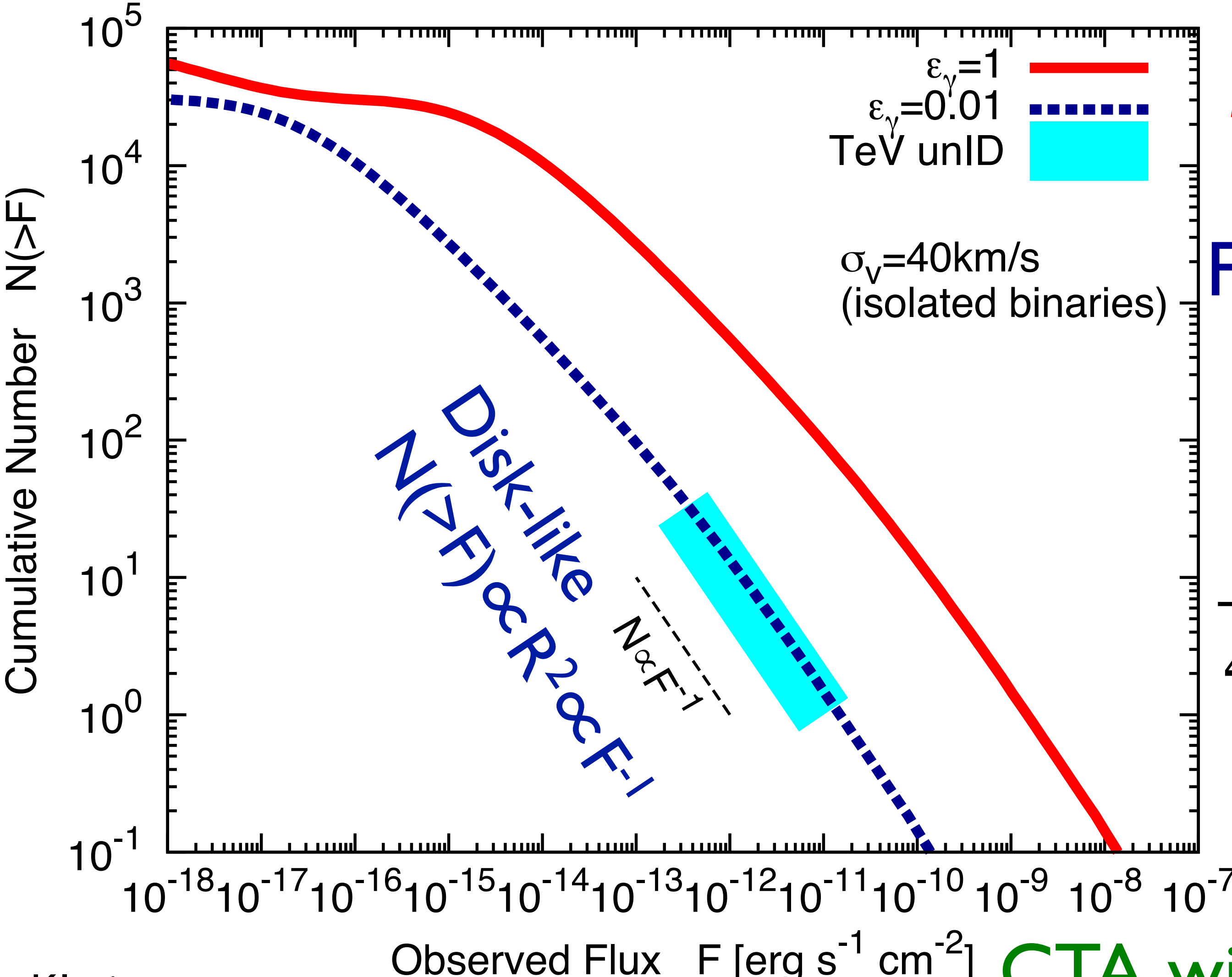




***unIDs dominate TeV γ-ray sky***

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




**BHs ⇔ TeV unIDs?**

Flux dis. is similar

BH nebula size:

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

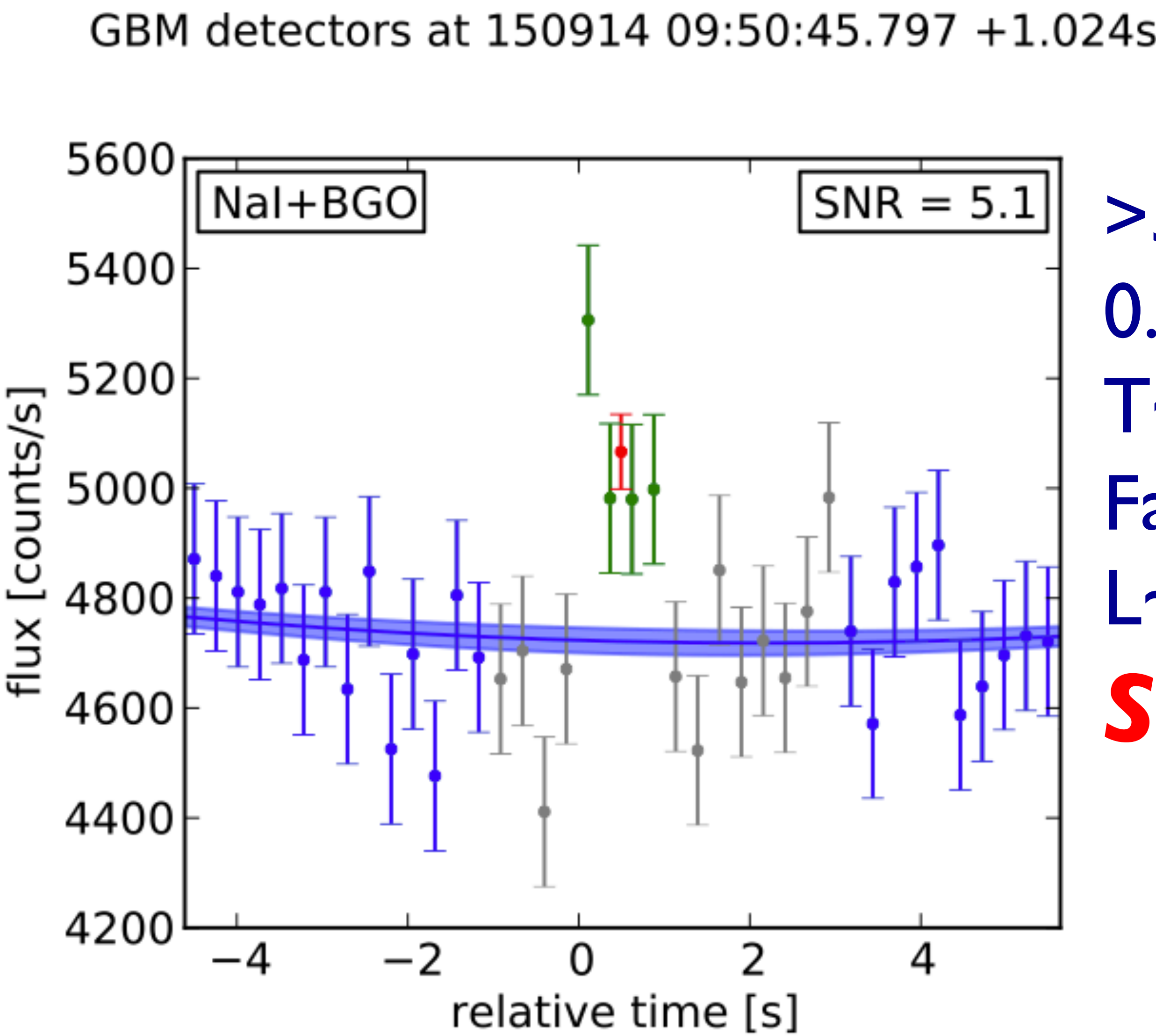
$$\Rightarrow \; r_h \sim 3 \text{ pc}$$

KI+ in prep.

CTA will see ~300 BHs

# Tip of Iceberg

# Fermi γ-ray Burst Monitor




>50keV

0.4s after GW

T~1sec

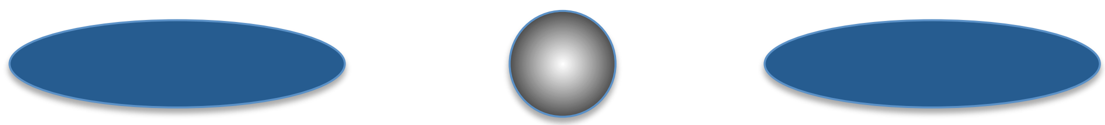
False alarm~0.0022

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

***Short GRB!?***

Fermi+ 16

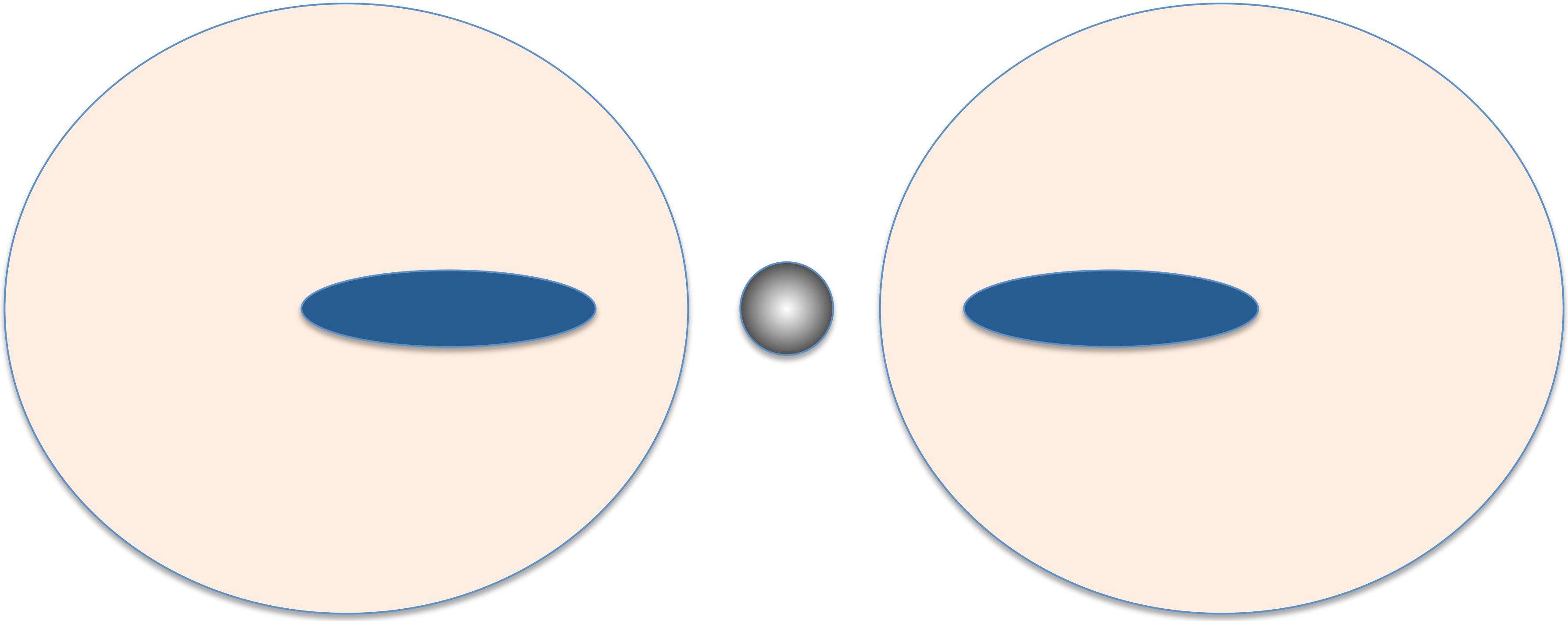
# Dead Disk



Cold neutral disk
No MRI, No accretion
Accretion only at merger

Perna+ 15

# Dead Disk Evaporation



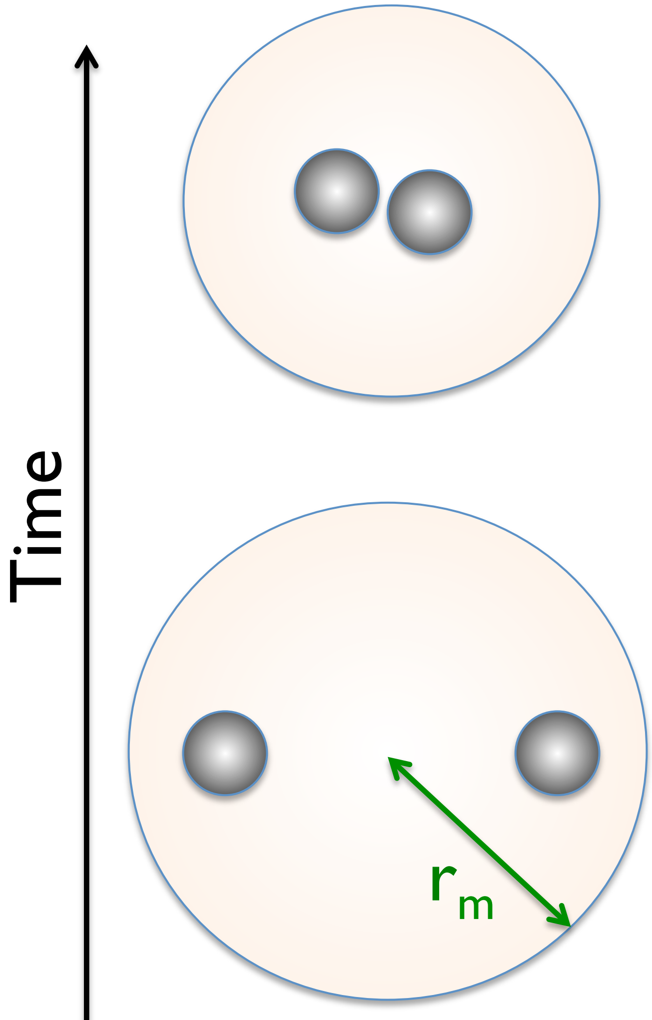
***ISM accretion ⇒ Hot disk ⇒ Evaporation***

$$\dot{M}_{\rm eva} \sim 2\pi r^2 n_i v_i m_p \sim 1\times 10^{15}\,{\rm g\,s^{-1}} \left(\frac{r}{10^{12}\,{\rm cm}}\right)^{-5/2} \left(\frac{M}{60M_\odot}\right)^4 \left(\frac{n}{1\,{\rm cm^{-3}}}\right)^{5/2} \left(\frac{V}{40\,{\rm km\,s^{-1}}}\right)^{-9/2}$$

$t_{eva} \sim 10^6$ yr for $M_{dead\ disk} \sim 10^{-5} M_\odot$

KI+ in prep.

# No-Go?




Going back time
by say $t_b$~1000 sec

$$r_m \sim 10^{10}\,\mathrm{cm}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{2/3}$$

$$\frac{E_{\mathrm{binding}}}{M_m c^2} = \frac{GMM_m/r_m}{M_m c^2}$$

$$\sim 10^{-3}\left(\frac{t_b}{10^3\,\mathrm{sec}}\right)^{-2/3}$$

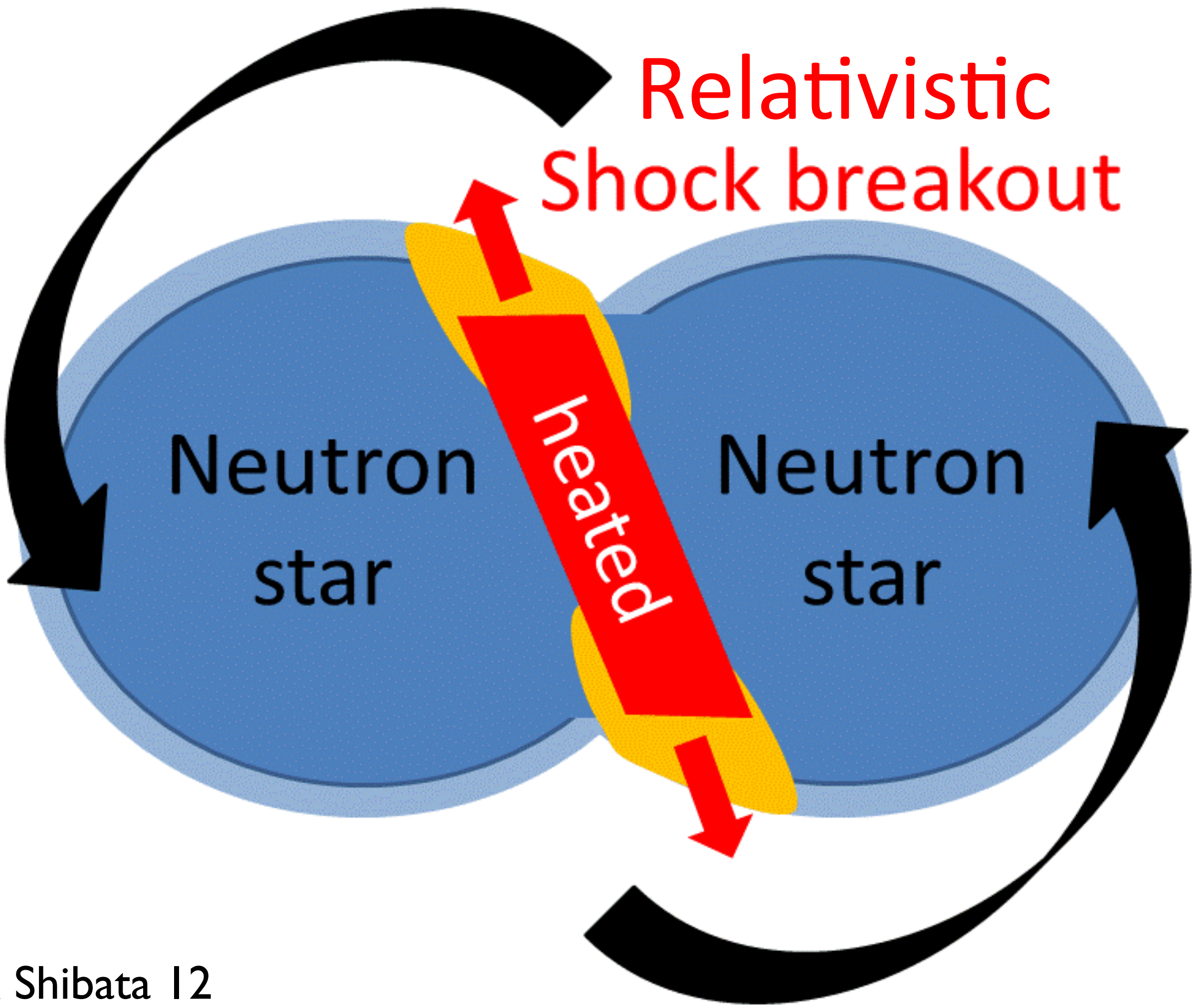
Accretion occurred ⇒ Outflow ⇒ Unbound

# Contents

- ***BH in long-lasting short GRBs***
  - BH v.s. Neutron star
- ***BH in macronovae***
  - BH v.s. R-process radioactivity
- ***BH in GW150914***
  - Galactic BHs as high-energy sources
  - Fermi GBM event

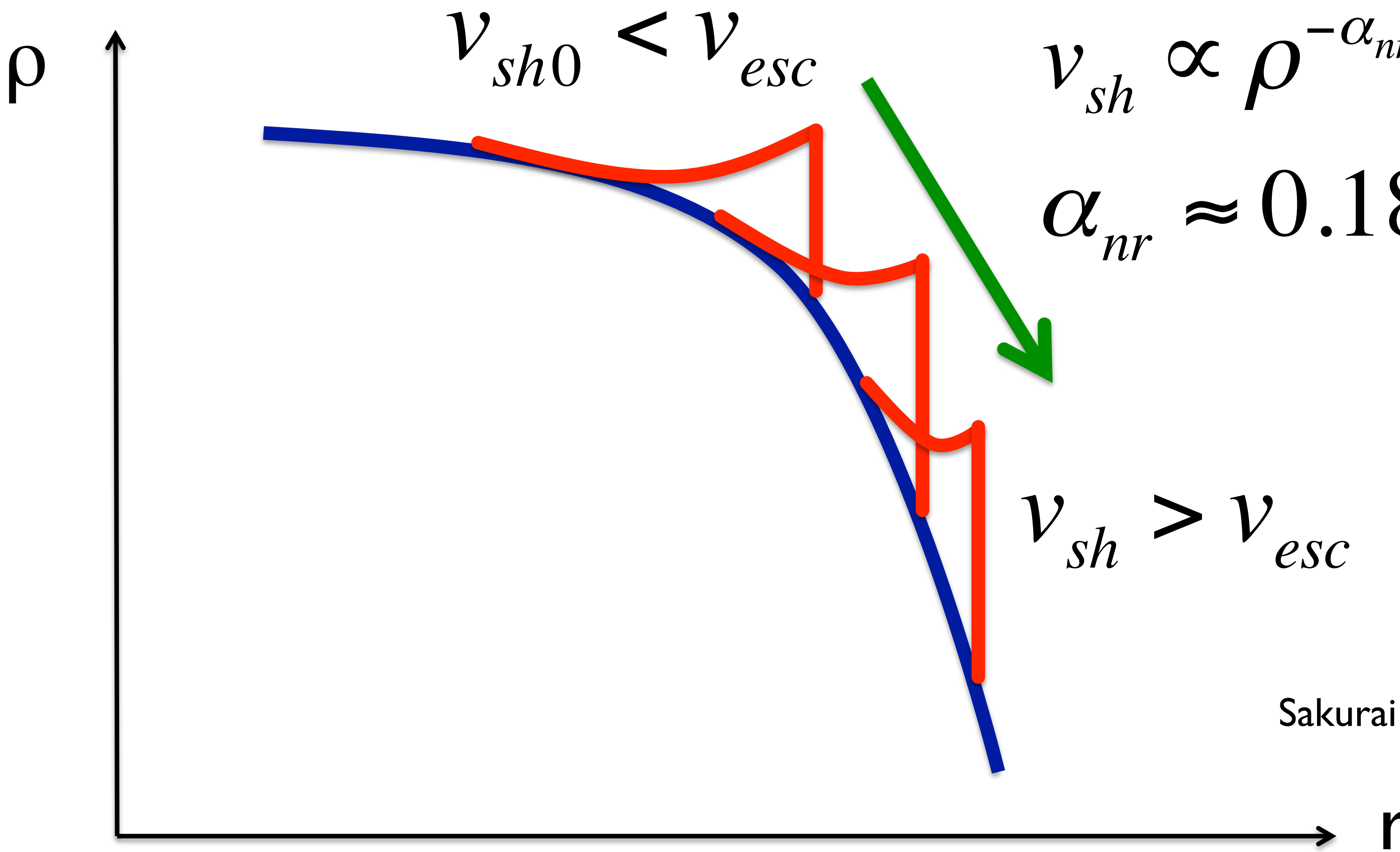
# Thank You

# Relativistic Shock Breakout




Kyutoku, KI & Shibata 12

# Shock Acceleration

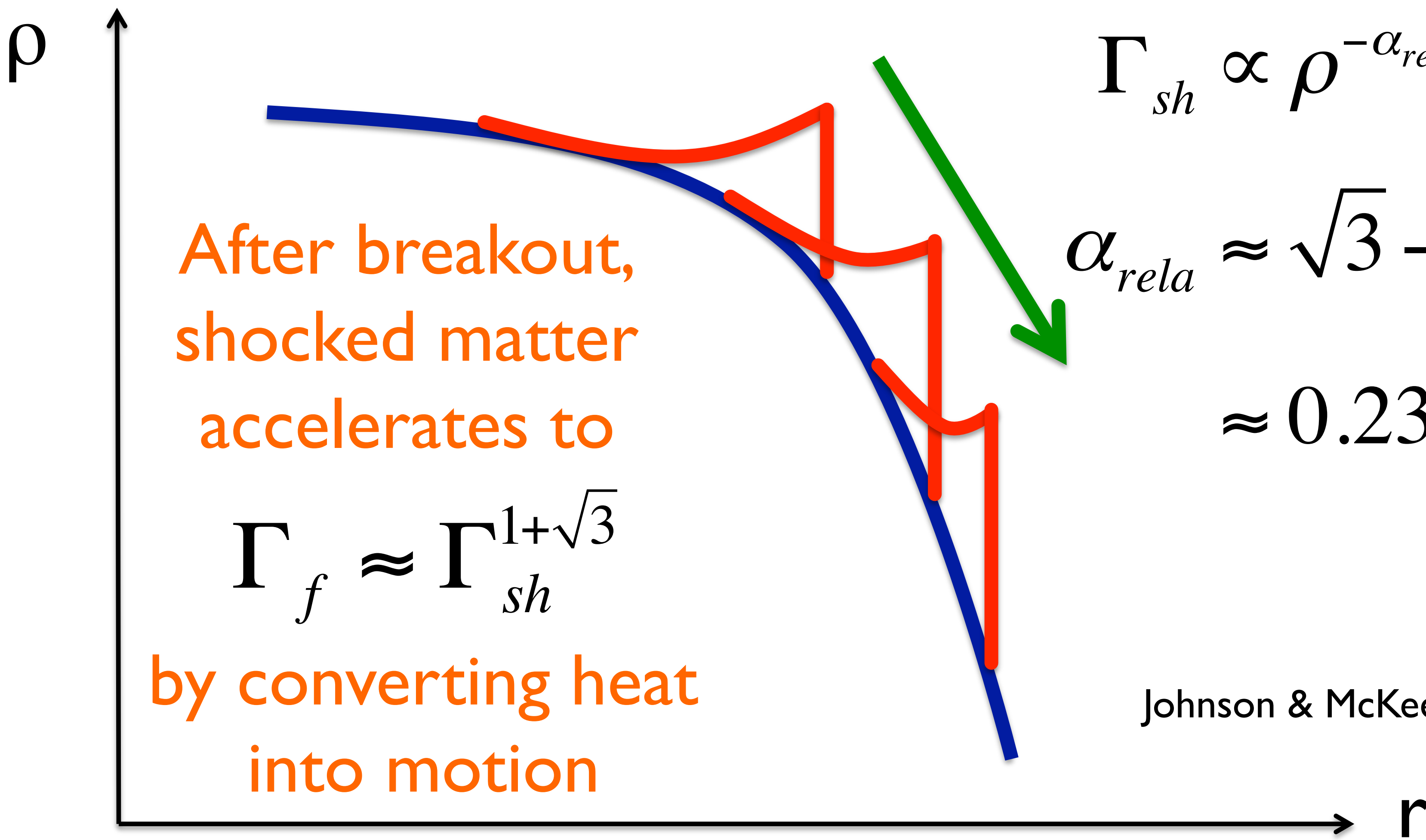



$$v_{sh} \propto \rho^{-\alpha_{nr}}$$

$$\alpha_{nr} \approx 0.187$$

Sakurai 60

# Relativistic Shock Acceleration




After breakout, shocked matter accelerates to

$$\Gamma_f \approx \Gamma_{sh}^{1+\sqrt{3}}$$

by converting heat into motion

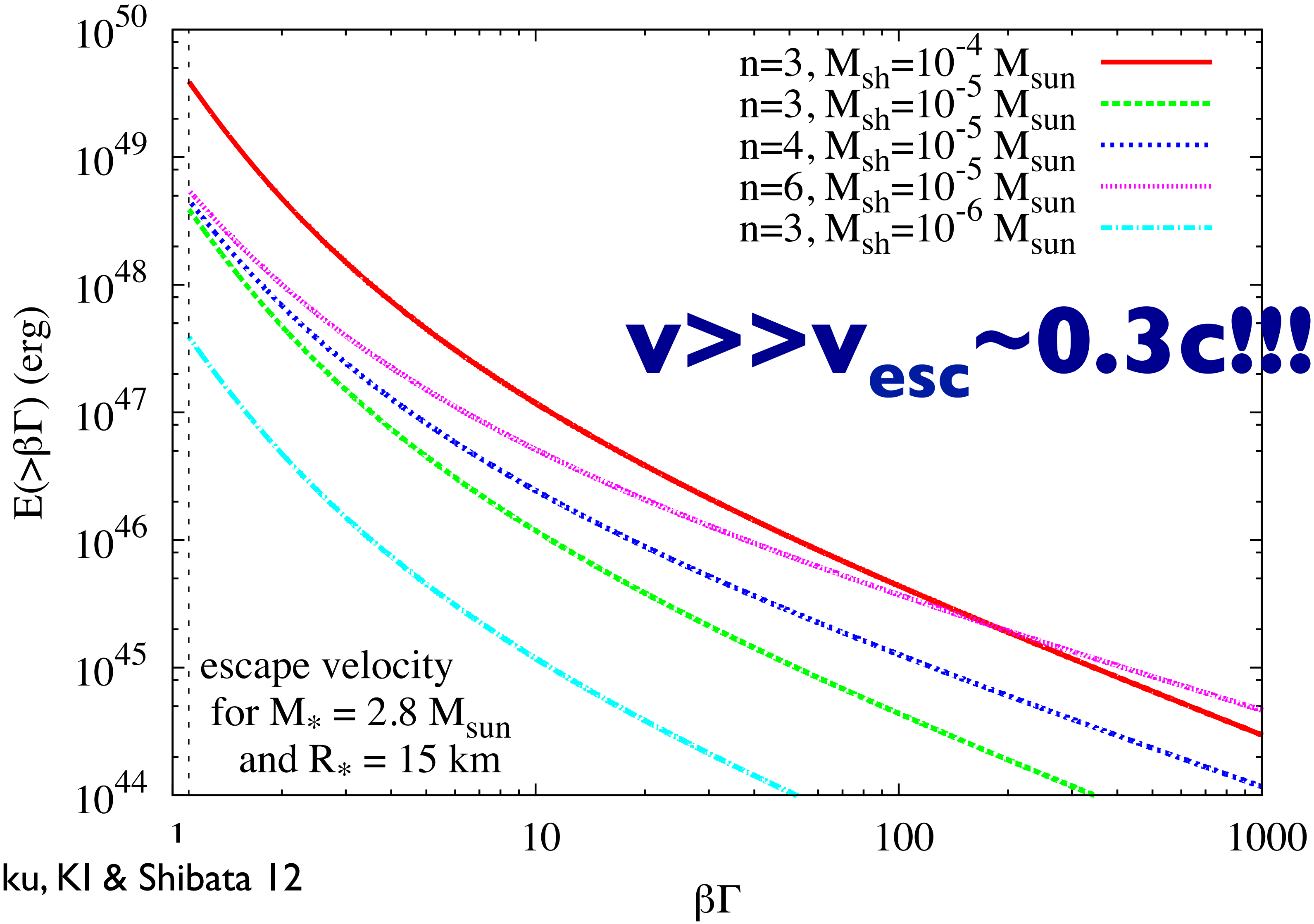
$$\Gamma_{sh} \propto \rho^{-\alpha_{rela}}$$

$$\alpha_{rela} \approx \sqrt{3} - \frac{3}{2}$$

$$\approx 0.232$$

Johnson & McKee 71

# Relativistic Outflow

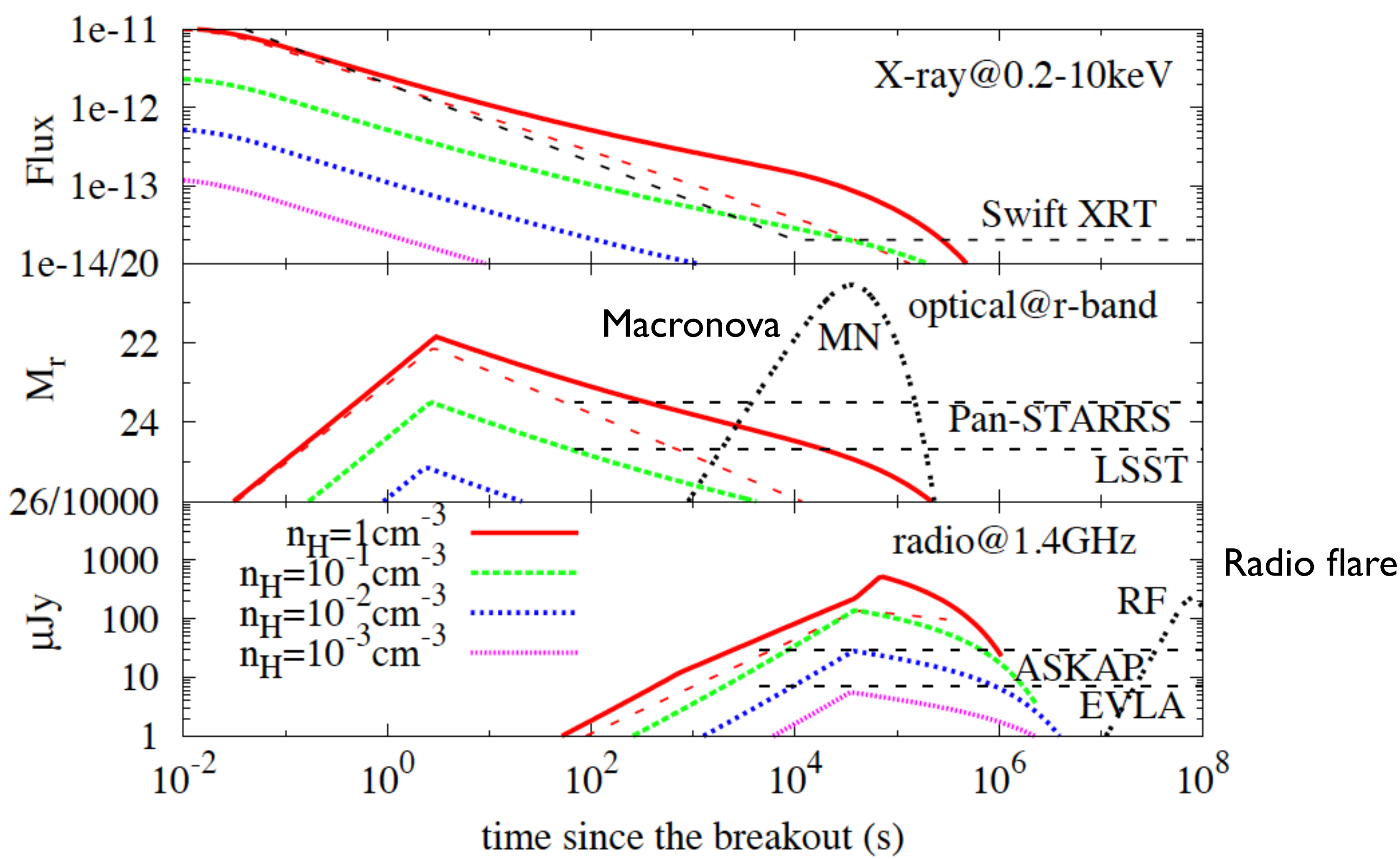



**$v \gg v_{esc} \sim 0.3c$!!!**

Kyutoku, KI & Shibata 12

# Early & High-Energy

Kyutoku, KI & Shibata 12



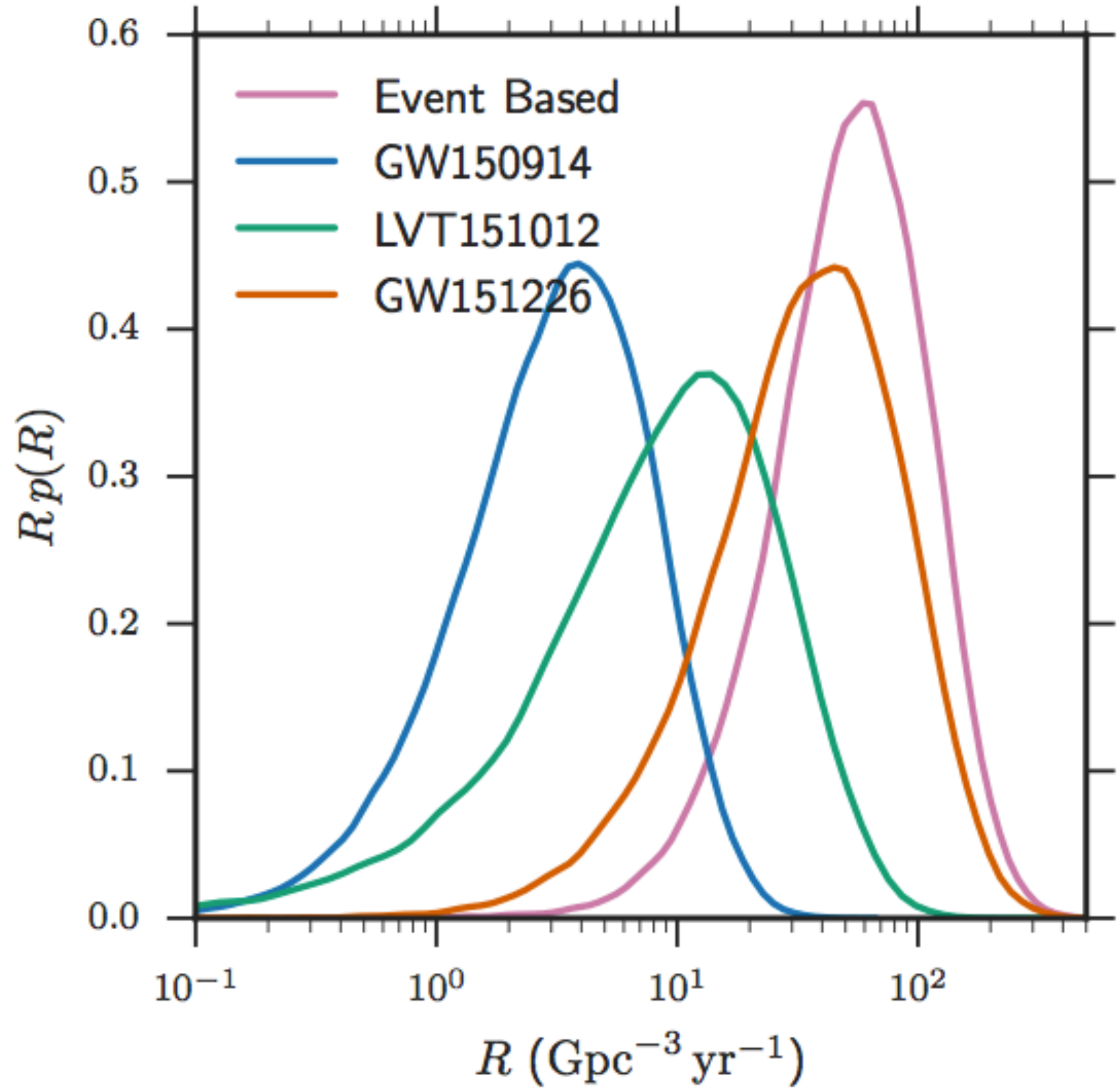



FIG. 9. The posterior density on the rate of GW150914-like BBH, LVT151012-like BBH, and GW151226-like BBH mergers. The event based rate is the sum of these. The median and 90% credible levels are given in Table II.

LIGO O1 16

# Really r-Process?

***Yes?***

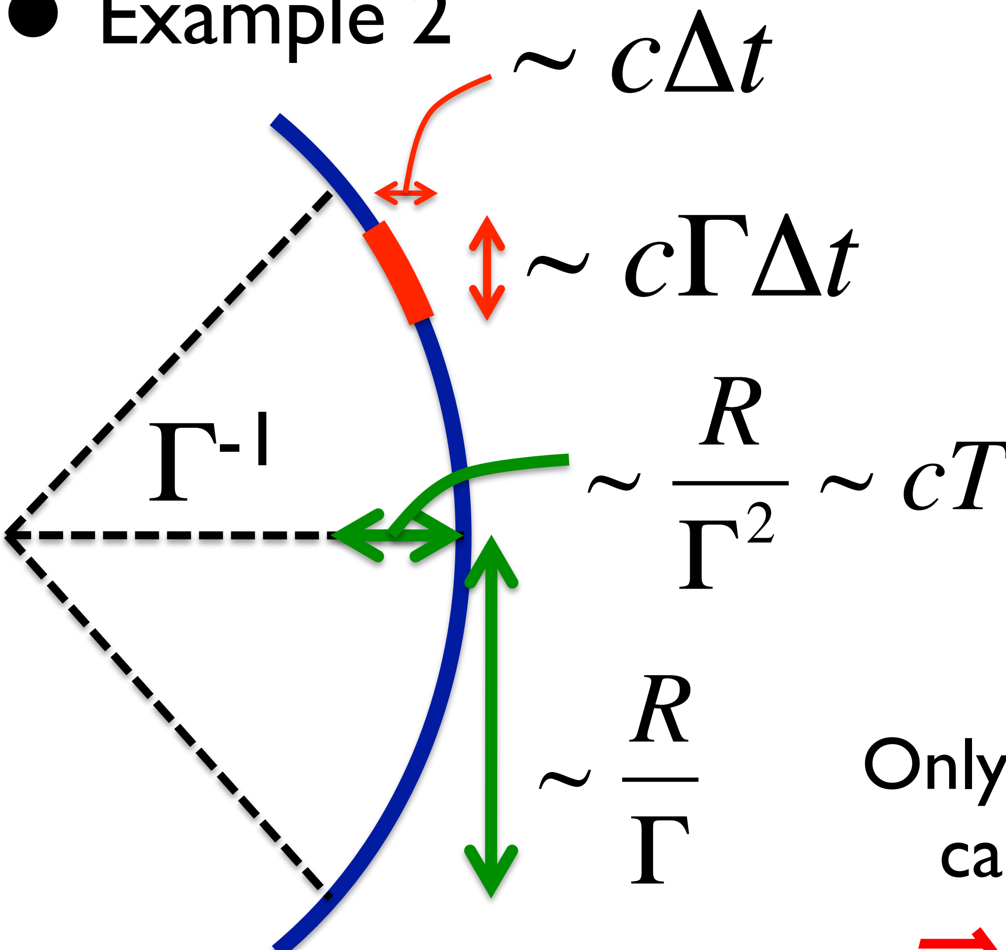
- Macronova with GRB 060614? — Yang+ 15
  - $M_{ejecta} \sim 0.1 M_\odot \Rightarrow$ BH-NS? — Jin+ 16
- Macronova with GRB 050709?
  - $M_{ejecta} \sim 0.05 M_\odot$, Wind signature?
- Deep-sea plutonium $^{244}Pu$ ($t_{1/2} \sim 81$ Myr) — Hotokezaka+ 15
- r-process in an ultra-faint dwarf galaxy —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

***No?***

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

# External Shock Variability

- Example 2




Ratio of surface area

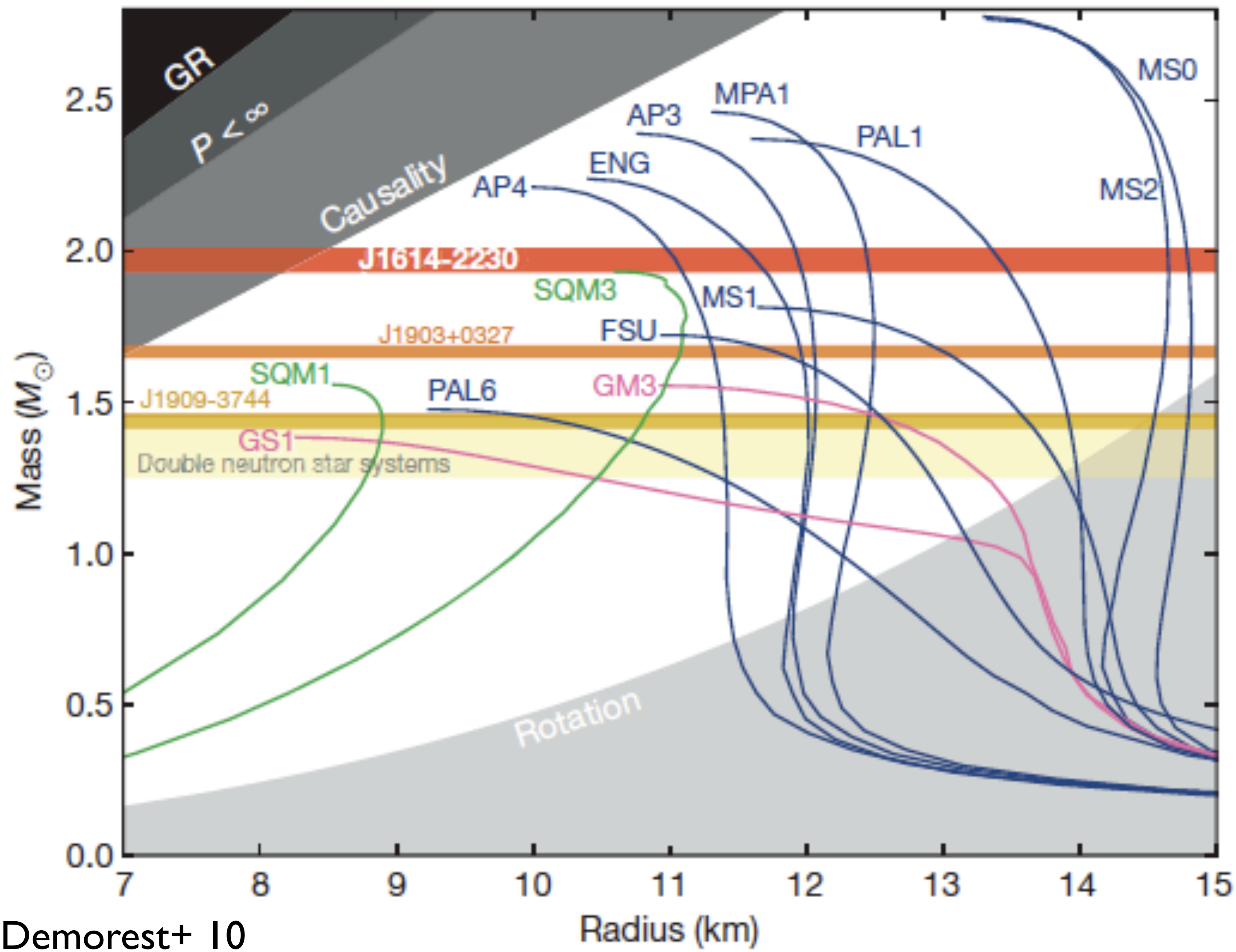
$$\frac{N(c\Gamma\Delta t)^2}{(R/\Gamma)^2} \sim N\left(\frac{\Delta t}{T}\right)^2$$

$$\sim \frac{1}{N} < 10\%$$

Only a fraction of the surface can emit for variable LC

⇒ ***Low efficiency***

# Max Mass of Neutron Star




Demorest+ 10

**$2M_\odot$**

msec NS + $0.5M_\odot$ WD

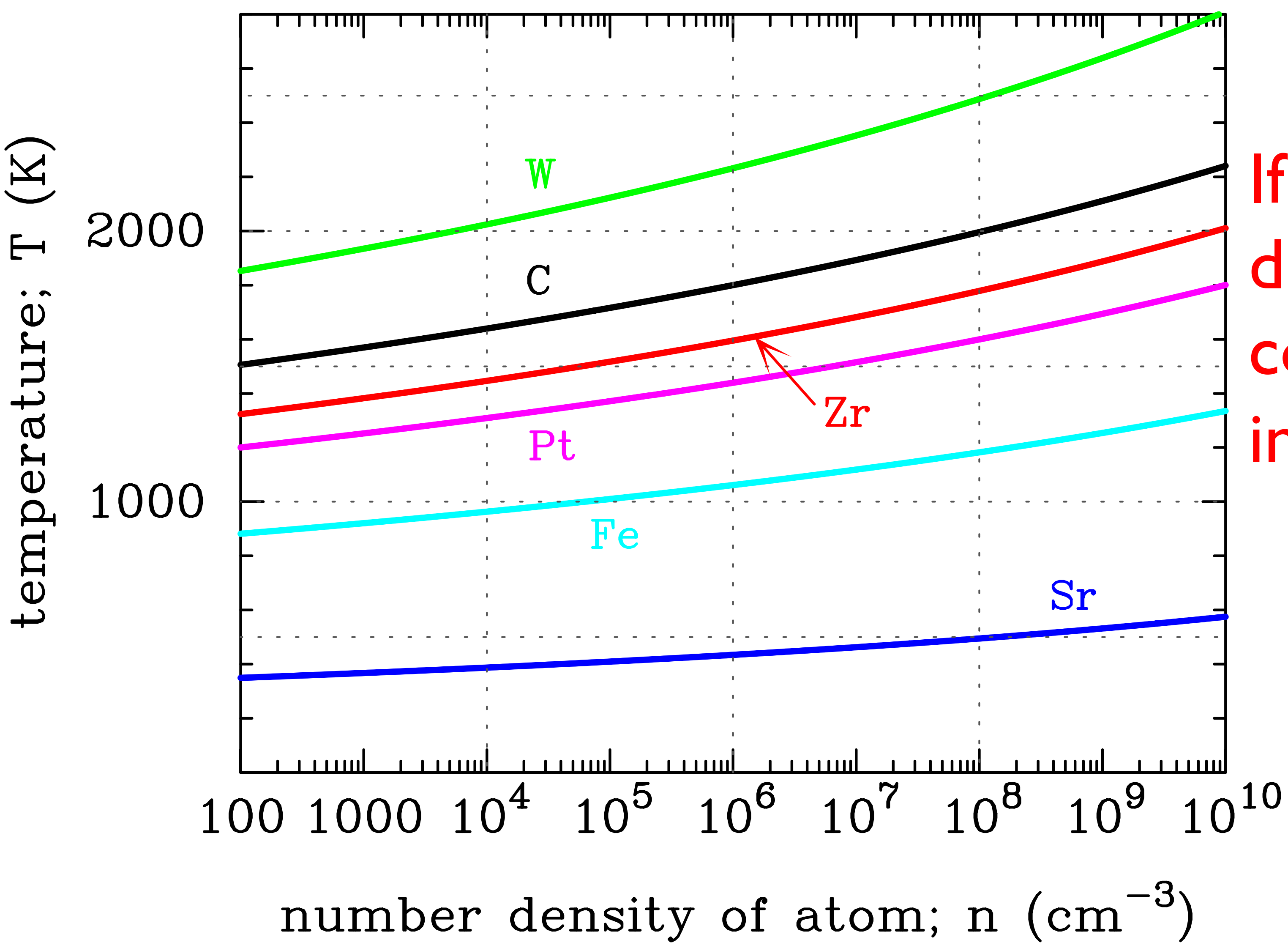
Shapiro delay

~$(1.97 \pm 0.04) M_\odot$

***Stiff EOS***

(Hyperon? 3-body? quark?)

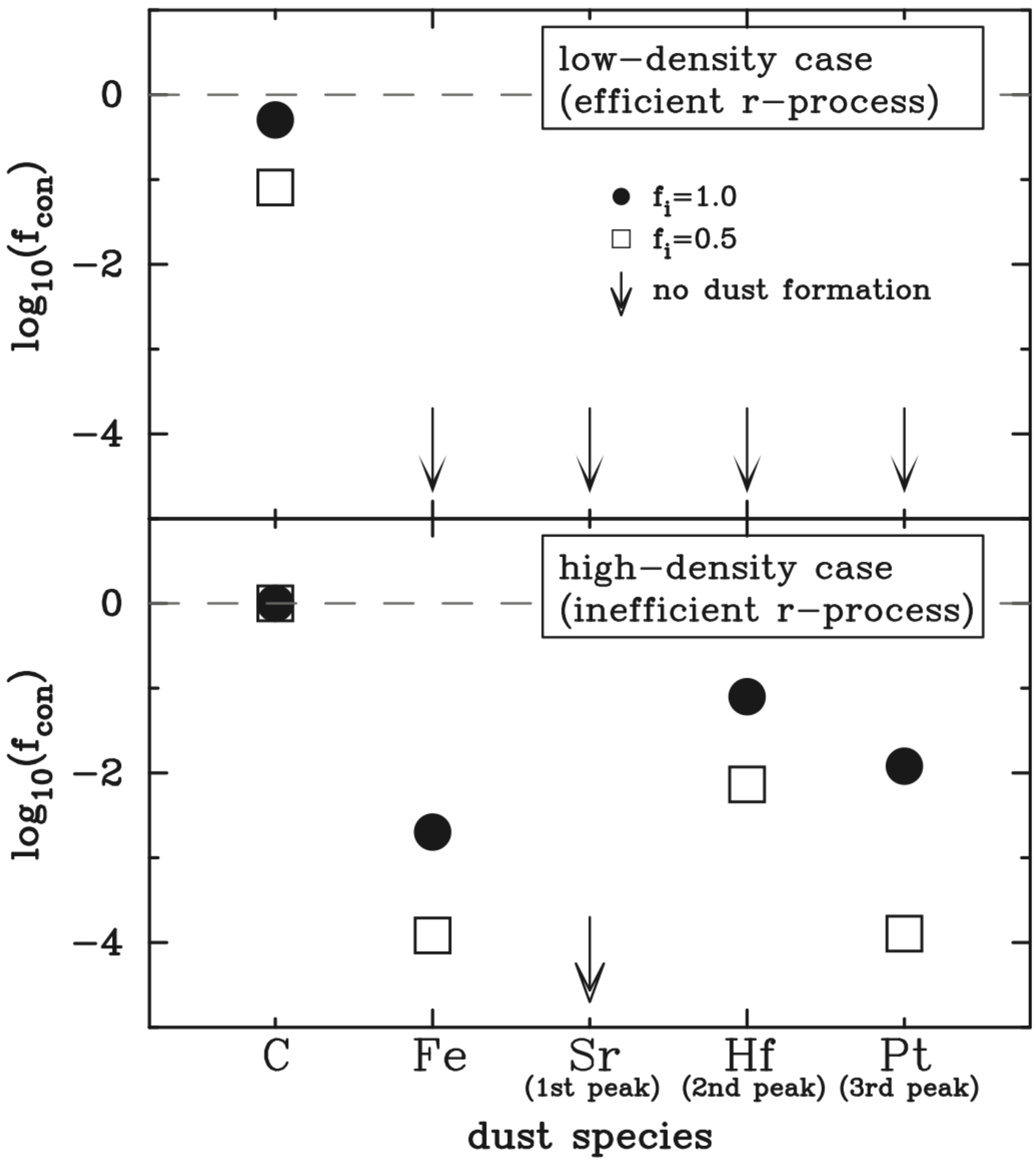
# Condensation Temperature




If T<2000K, dusts can condensate in principle

©Nozawa

# Dust Yield




r-process dusts are not formed

***Carbon dusts are possible!***

Iron dusts may be formed but at t>10 days

Takami, Nozawa & KI 14

# Density

Photons diffuse out when $\rho\kappa_r r \sim \dfrac{c}{v}$

$$t_{\rm diff} \sim \frac{\ell_{\rm mfp}}{c}\left(\frac{r}{\ell_{\rm mfp}}\right)^2 \sim \frac{r^2\rho\kappa}{c}$$

$$\ell_{\rm mfp} = (\rho\kappa)^{-1}$$

$$t_{dyn} \sim \frac{r}{v}$$

v=0.2c

**Density at ~7 days**

$$\rho_e \sim \frac{1}{\kappa_\gamma r_e}\frac{c}{v} \sim 1.4\times 10^{-16}\,{\rm g\,cm^{-3}}\left(\frac{\kappa_\gamma}{10\ {\rm cm^2\ g^{-1}}}\right)^{-1}$$

# Expected Dust Size

Once $T<T_{condense}$, colliding dusts stick together

$$\tau_{\rm N} \sim \rho_e \kappa_{\rm N} v_{\rm N} t \sim 200 \left( \frac{\kappa_\gamma}{10 \ {\rm cm}^2 \ {\rm g}^{-1}} \right)^{-1} \left( \frac{N}{12} \right)^{-3/2}$$

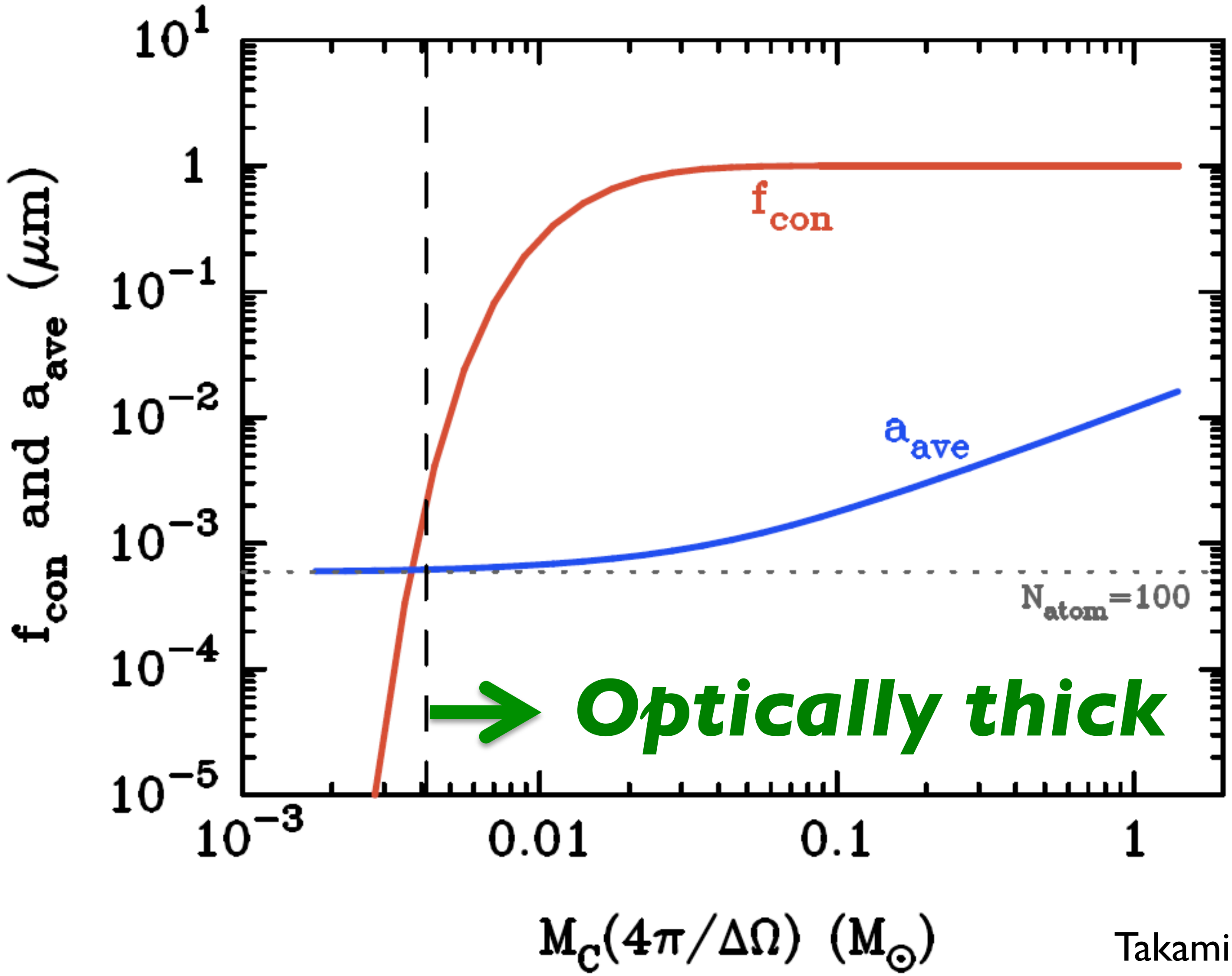
$$v_{\rm N} = \sqrt{2k_B T/m_N}, \kappa_{\rm N} = \pi r_{\rm N}^2/m_{\rm N}, r_{\rm N} = 10^{-8} \ {\rm cm}, \ m_{\rm N} = N m_p$$

If $\kappa$~0.1cm$^2$/g without r-process, the density can be large

$$\tau_{\rm N} \sim \rho_e \kappa_{\rm N} v_{\rm N} t \sim 20000 \left( \frac{\kappa_\gamma}{0.1 \ {\rm cm}^2 \ {\rm g}^{-1}} \right)^{-1} \left( \frac{N}{12} \right)^{-3/2}$$

Heavy elements are difficult to form dusts

# Metallicity Dependence




Dust is formed if $M > 0.01 M_\odot \times (4\pi/\Delta\Omega)$

Takami, Nozawa & KI 14

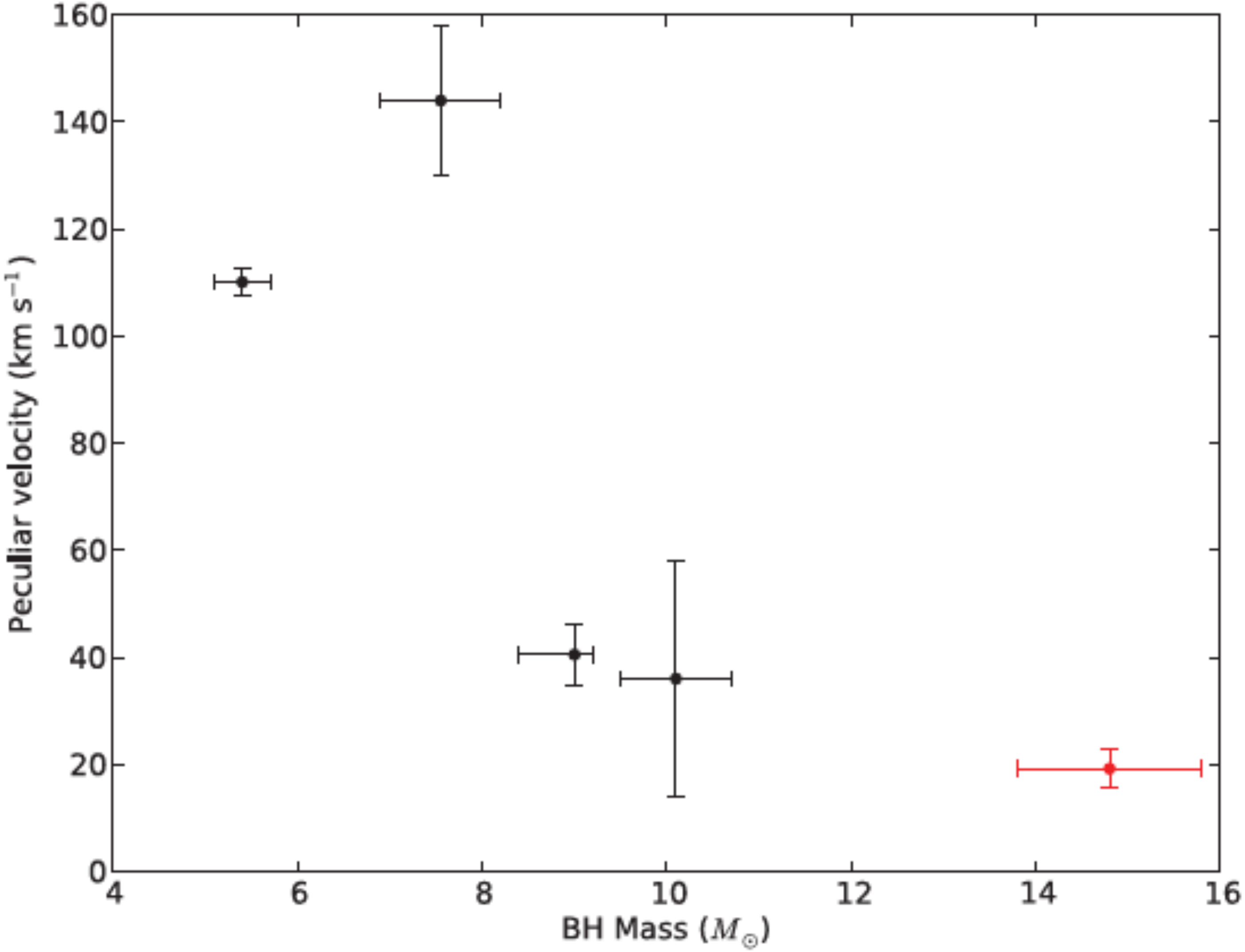



**Figure 3.** Inferred peculiar velocity as a function of black hole mass. Black points denote low-mass X-ray binaries, and the red point represents the high-mass X-ray binary Cygnus X-1. A larger sample is required to make robust inferences about any potential correlation between black hole (or companion) mass and natal kicks.

Miller-Jones 14

# Swift/XRT data of GRB 160821B