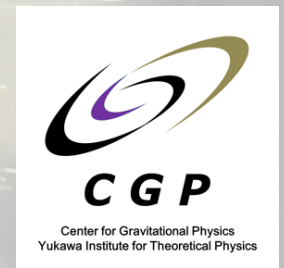


Multi-Messenger Astrophysics in the Gravitational Wave Era

Kunihito Ioka

(Center for Gravitational Physics, YITP, Kyoto U)



Multi-Messenger Era

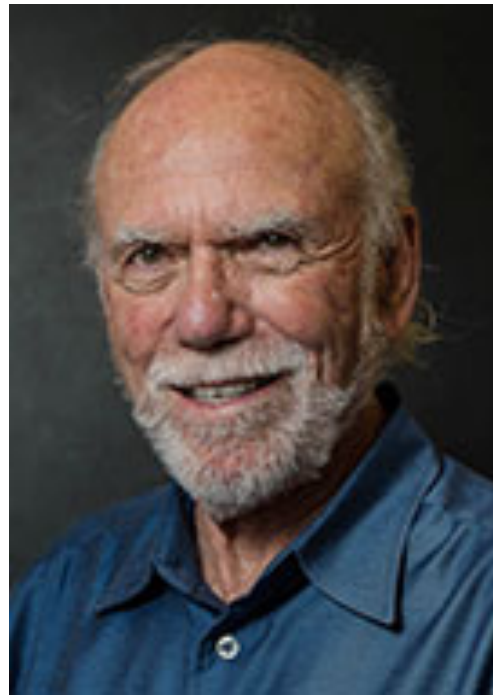


21st Century: Multi-Messenger Era

The Nobel Prize in Physics 2017



Rainer Weiss



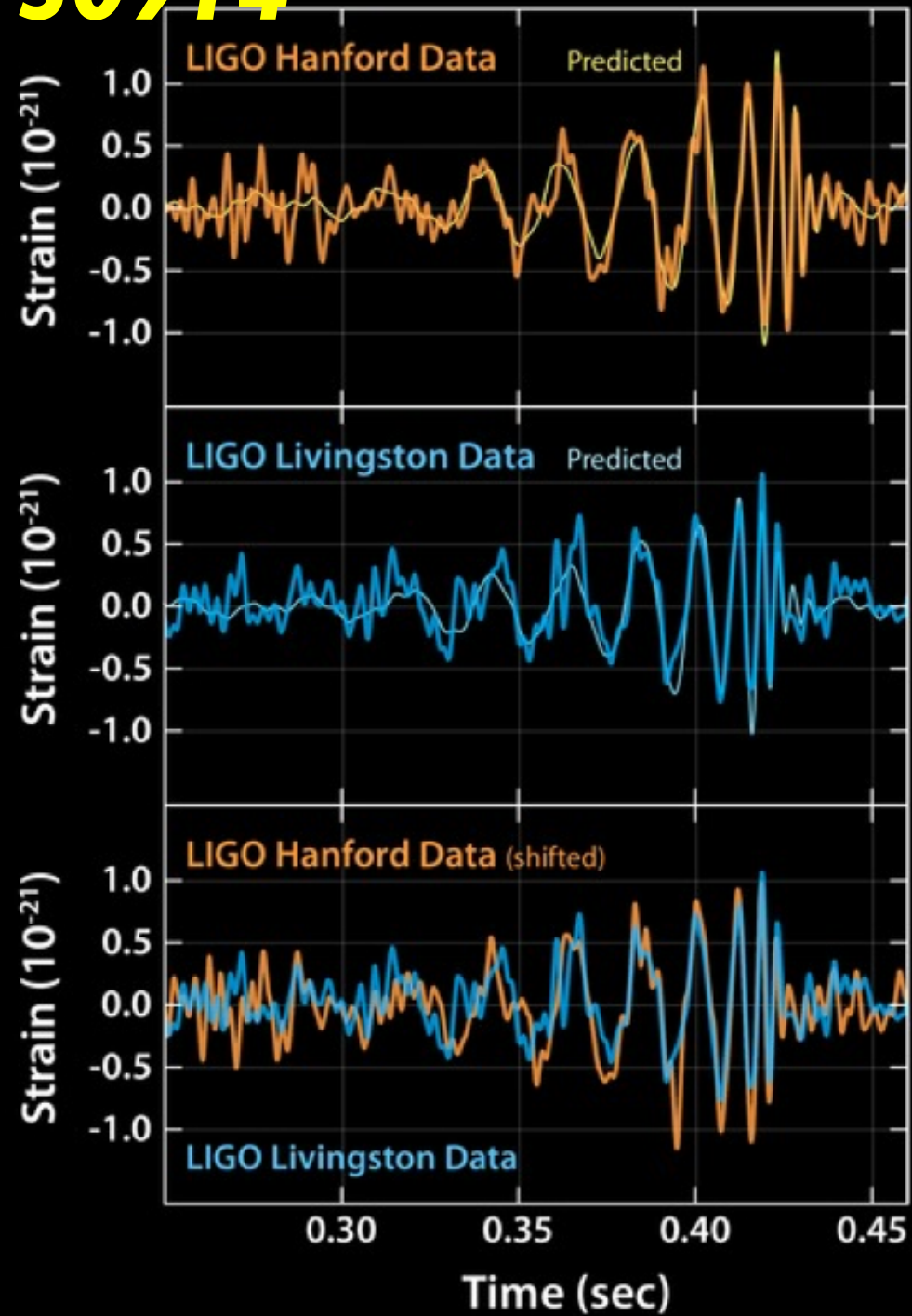
Barry C. Barish



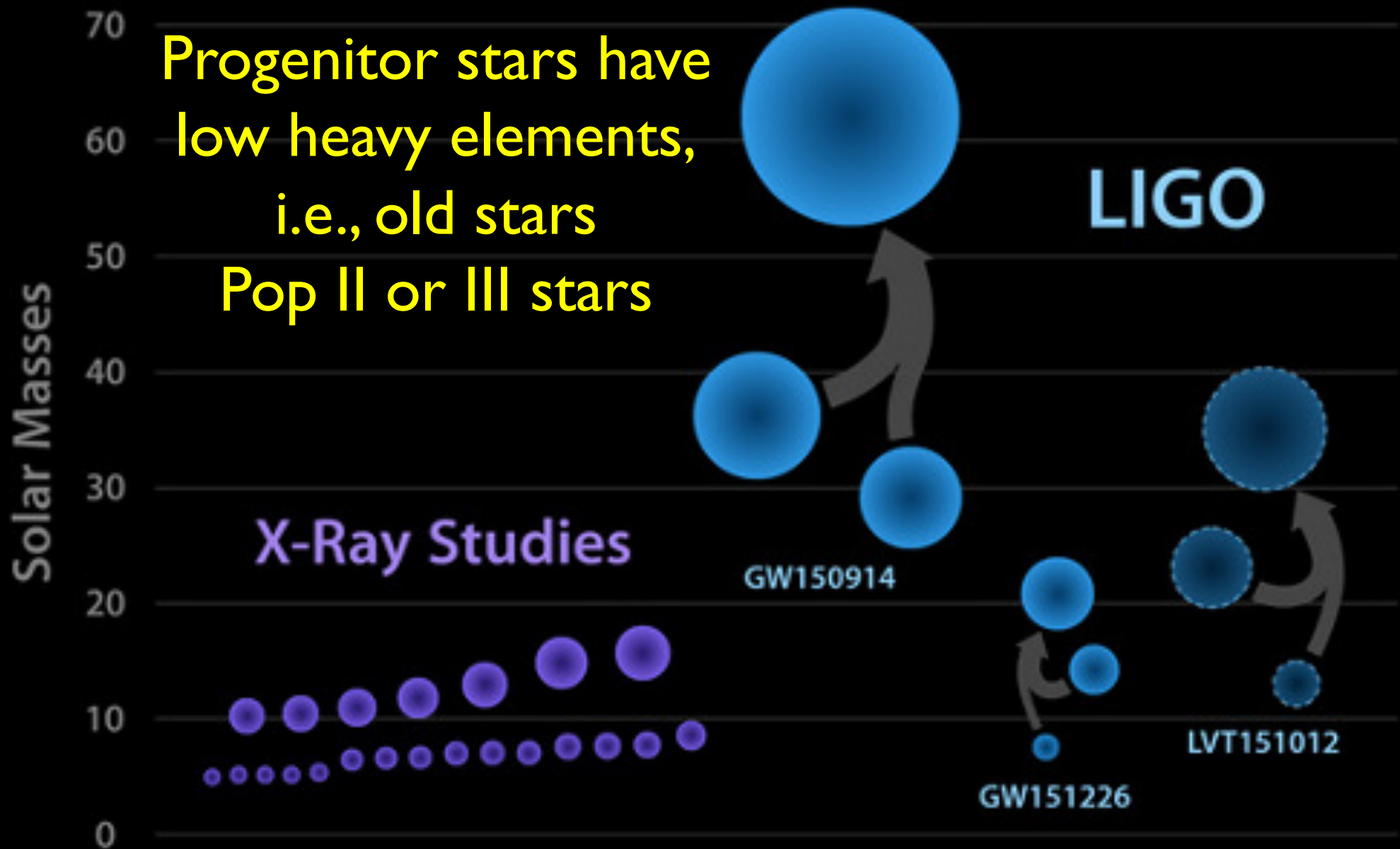
Kip S. Thorne

*for decisive contributions to the LIGO detector
and the observation of gravitational waves*

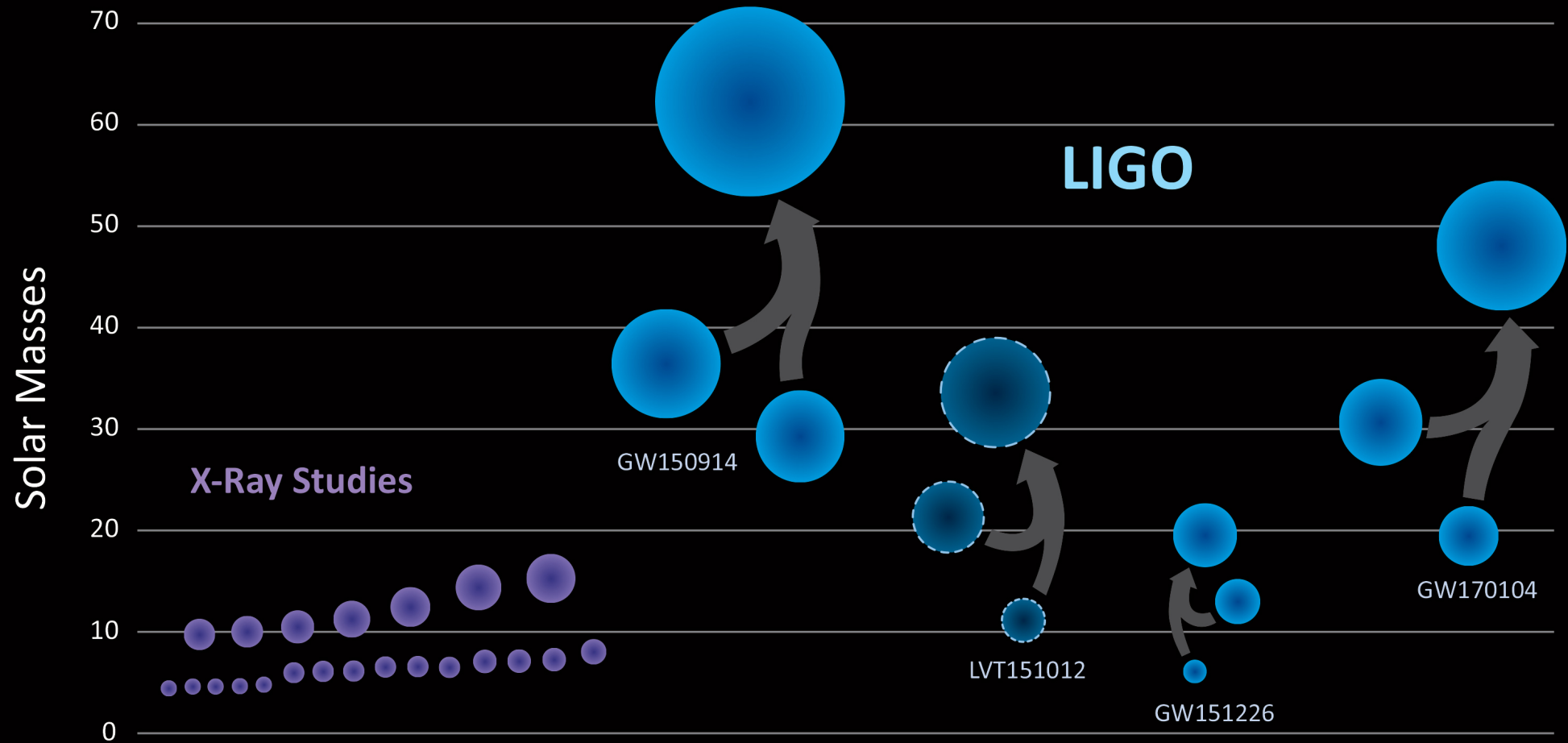
Gravitational wave amplitude



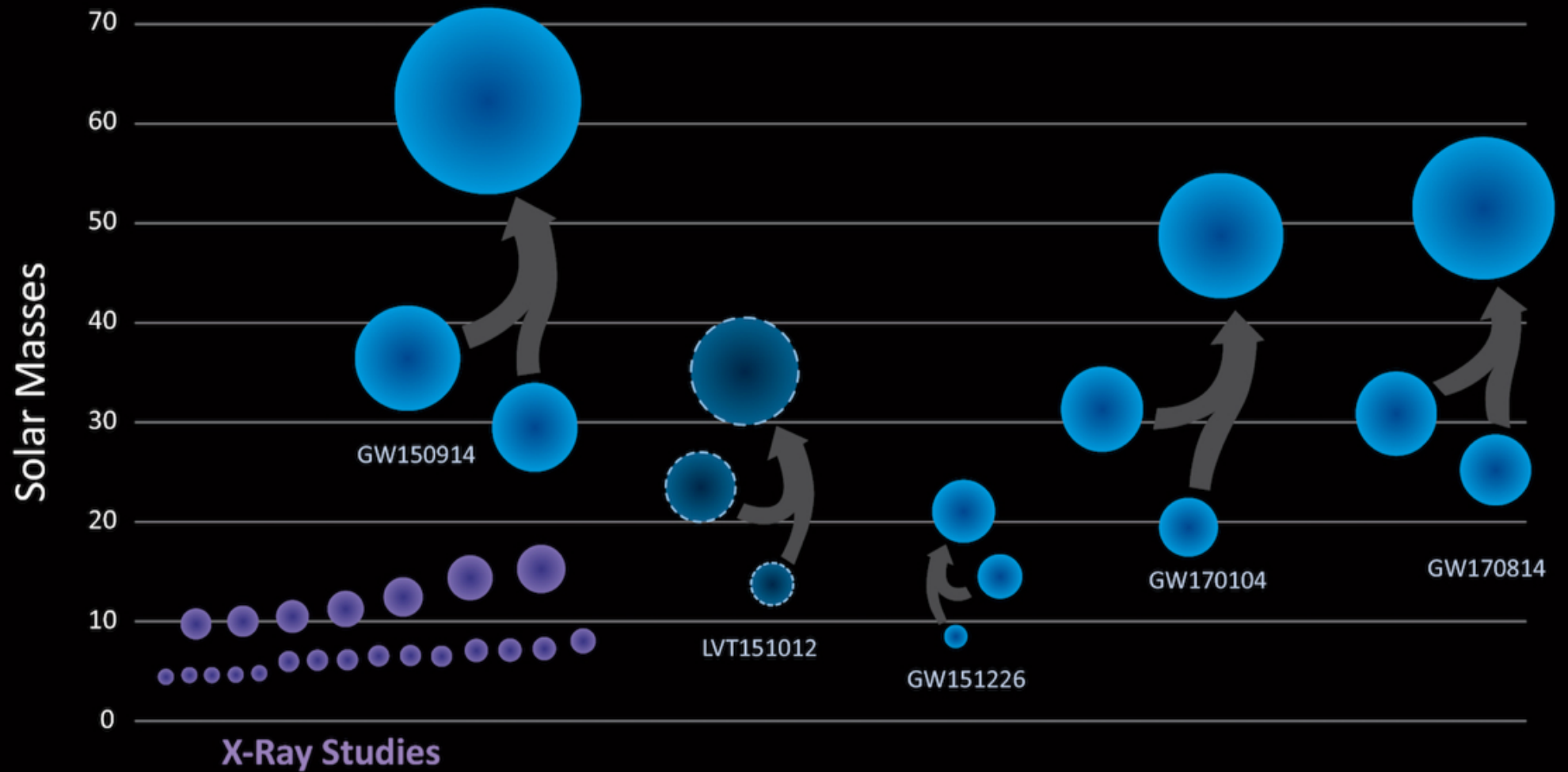
Black Holes of Known Mass



Black Holes of Known Mass



Black Holes of Known Mass

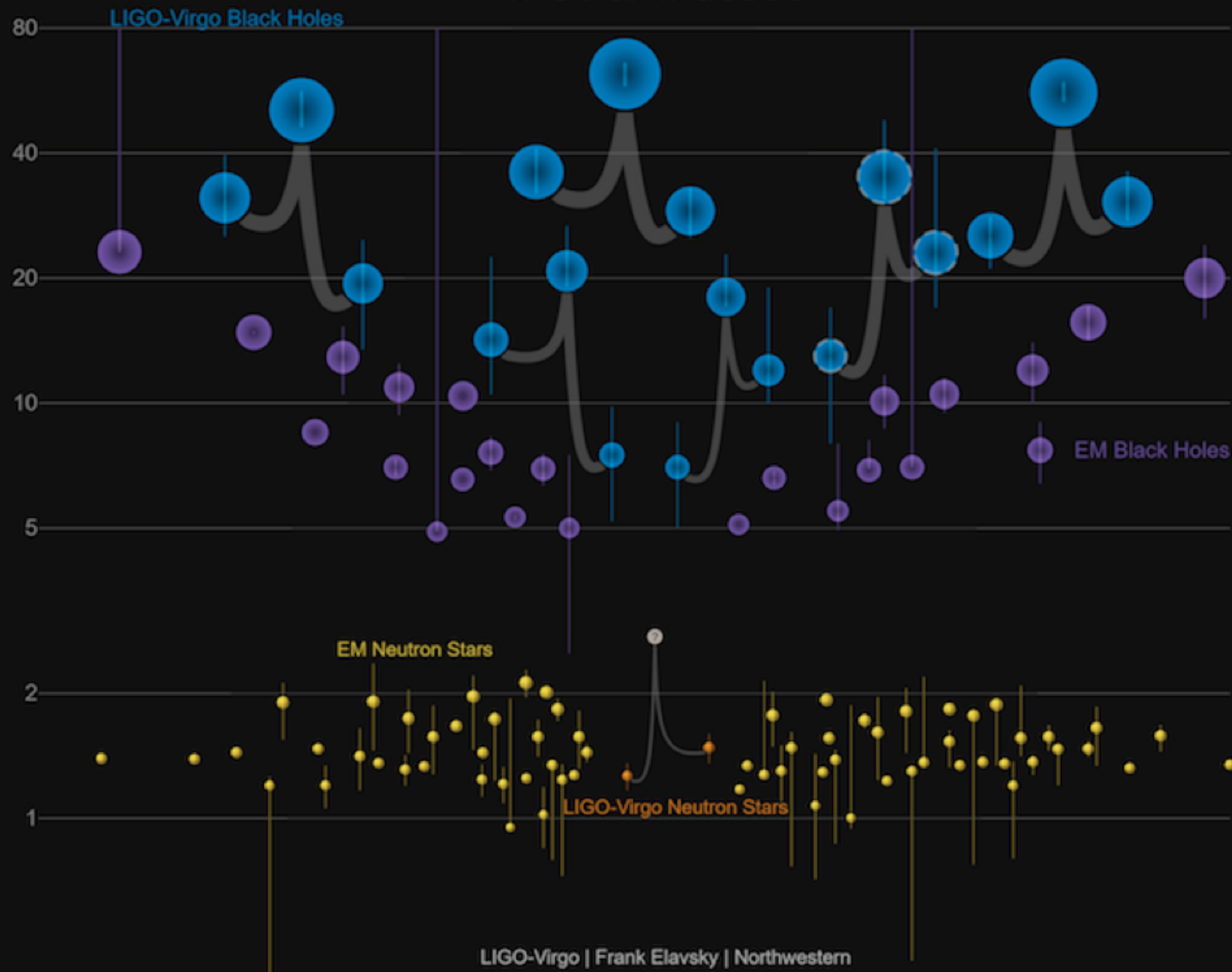


Black Holes of Known Mass



Masses in the Stellar Graveyard

in Solar Masses

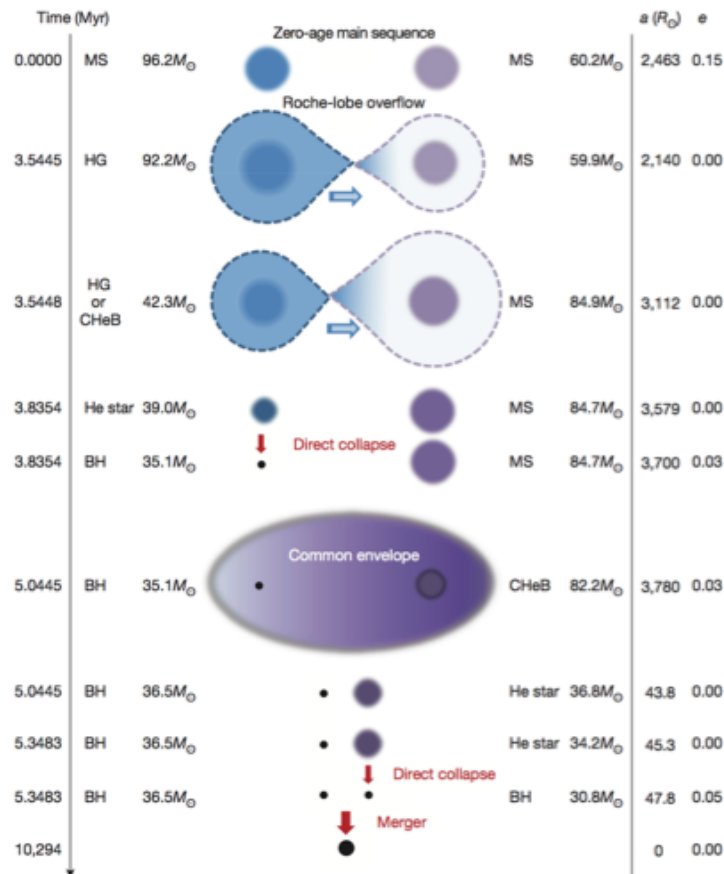


Evolution to Black Holes



What is the Origin?

Isolated binary



Near galactic nuclei Primordial black hole

Postnov & Yungelson 14
Belczynski+ 16
van den Heuvel+ 17
Mandel & de Mink 16
Kinugawa+ 16

Rodriguez+ 16
O'Leary+ 16

Antonini & Rasio 16

Bartos+ 16

Stone+ 16

Sasaki+ 16

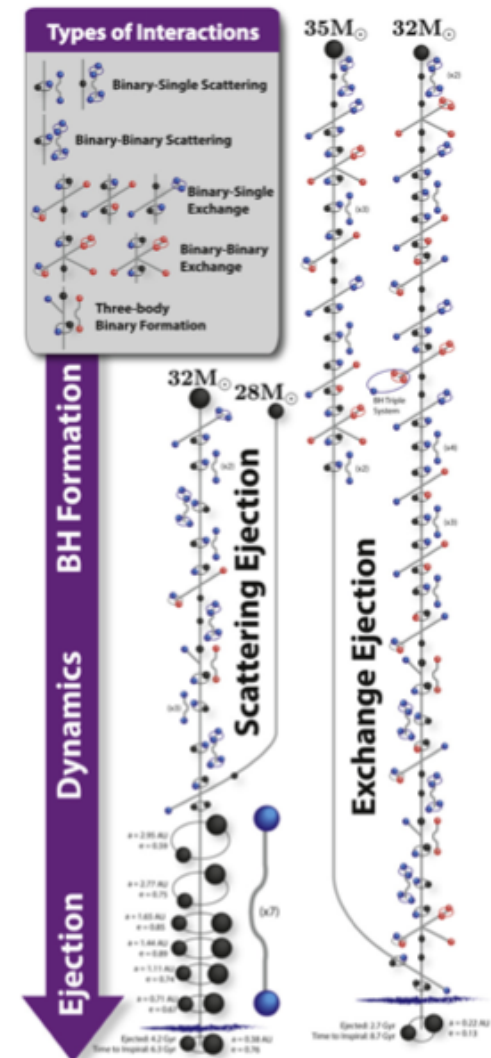
Bird+ 16

Binnikov+ 16

Carr+ 16

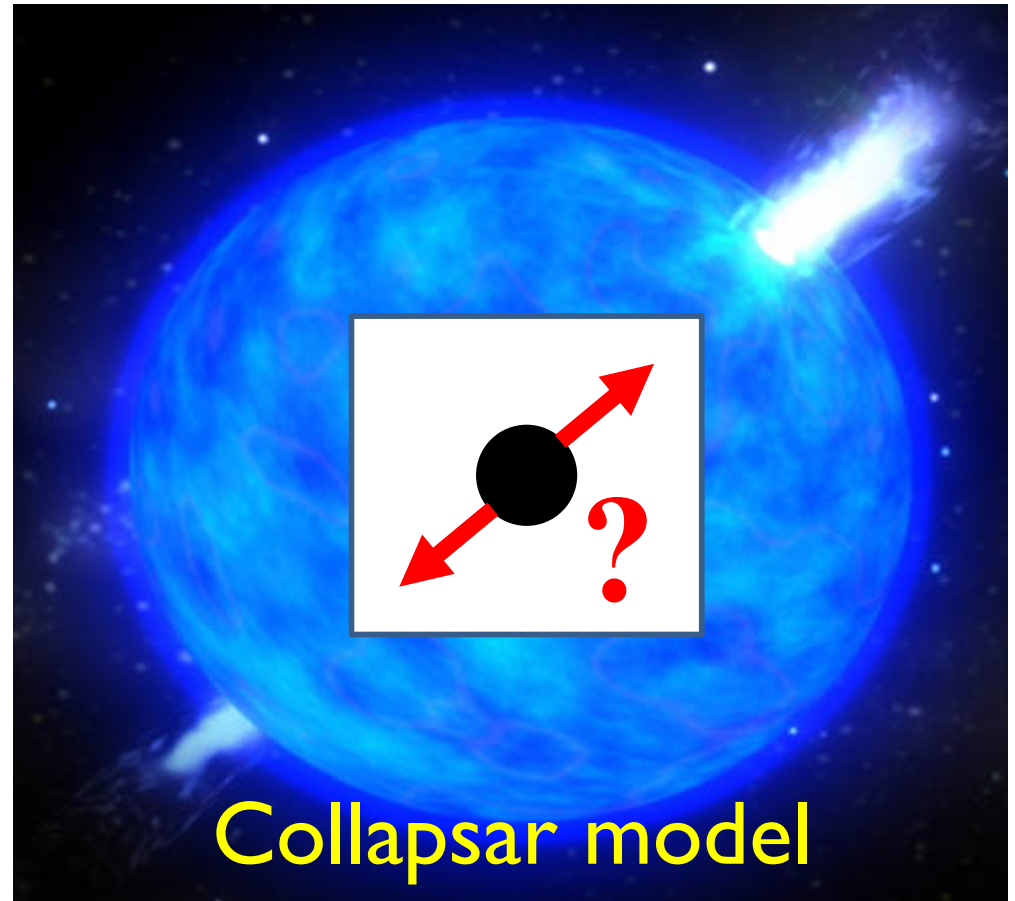
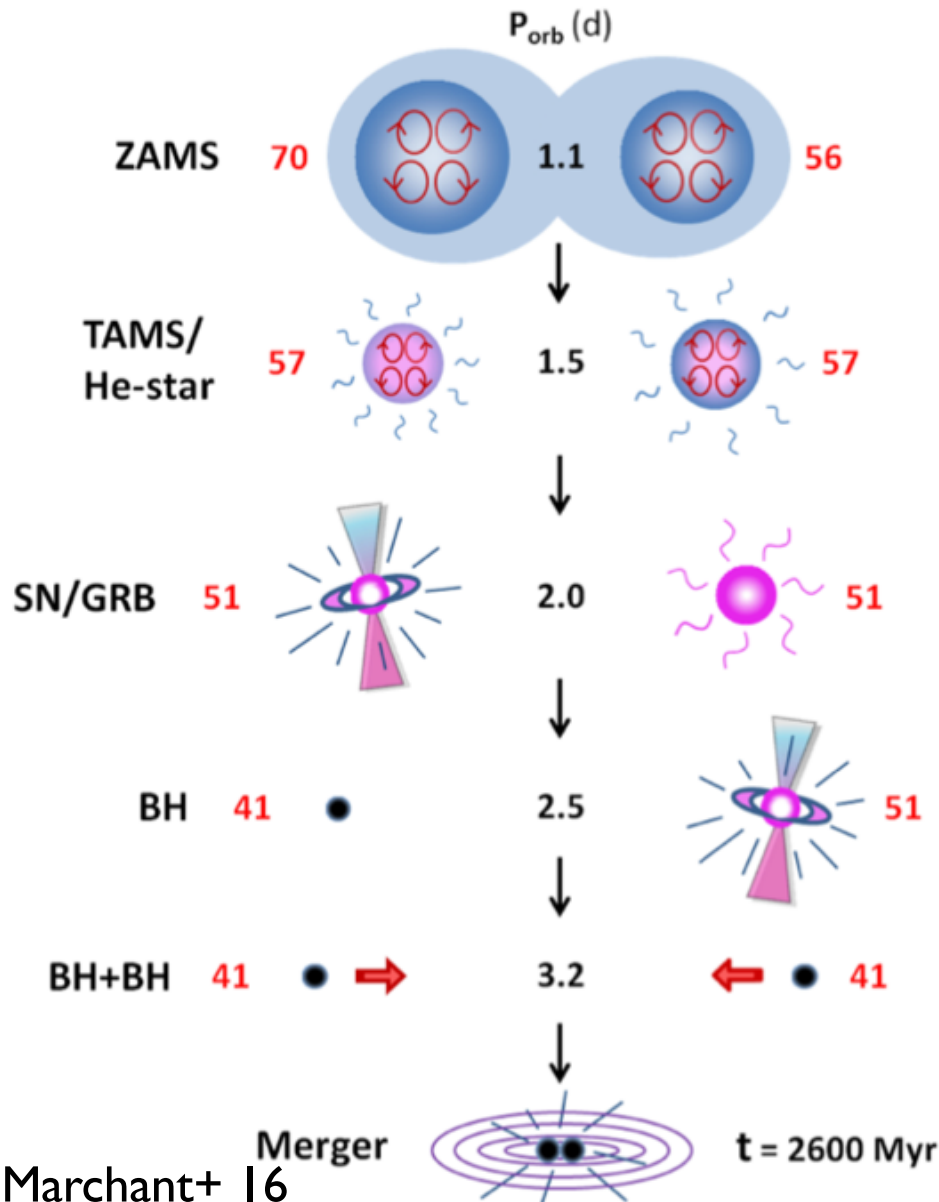
Kawasaki+ 16

Stellar cluster



Gamma-Ray Bursts?

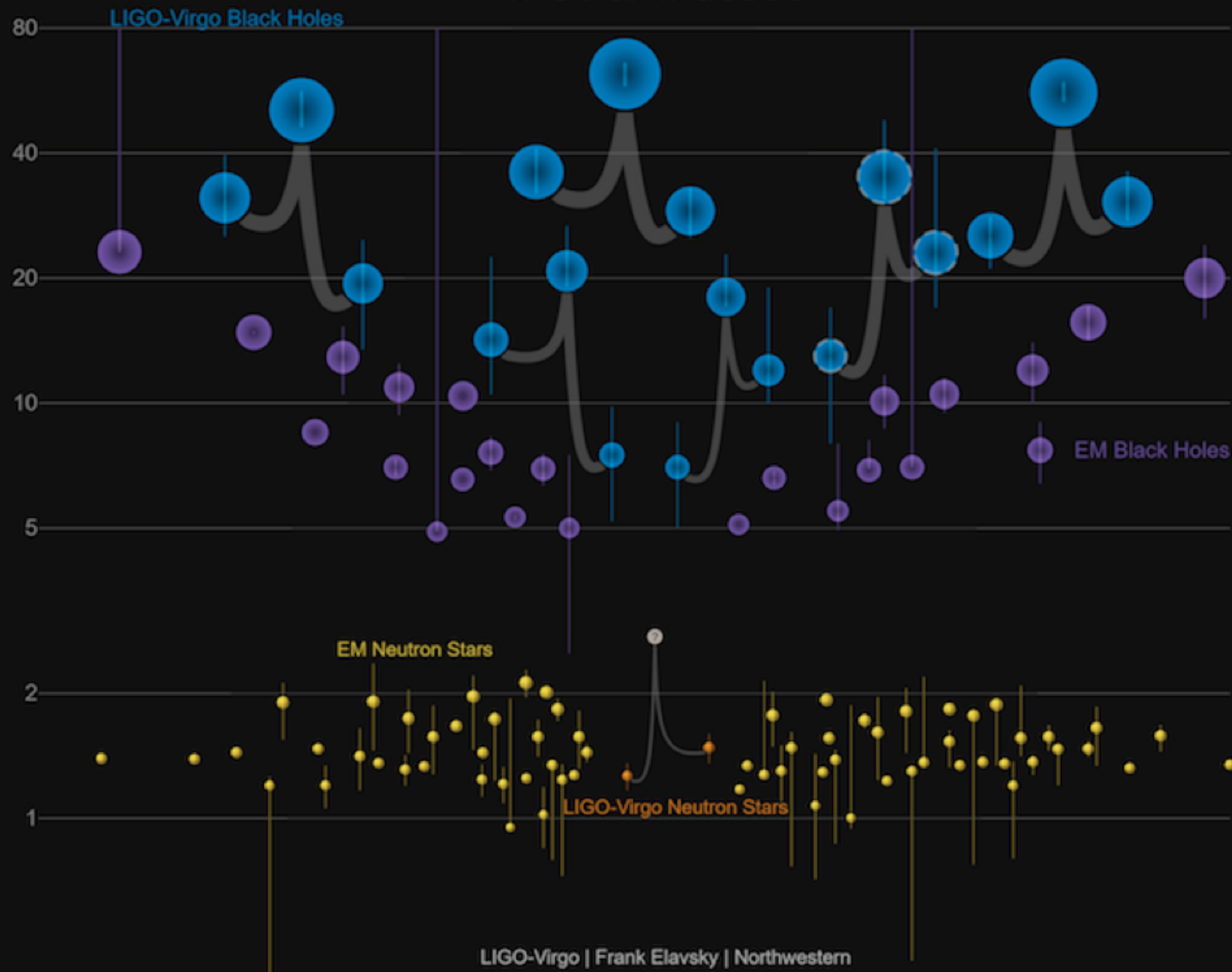
~ BH formation



GW rate ~ GRB rate

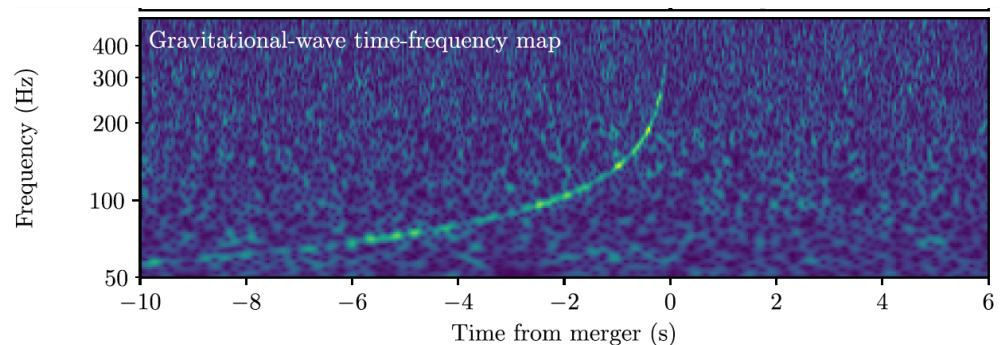
Masses in the Stellar Graveyard

in Solar Masses



GW170817

1st GW from NS²

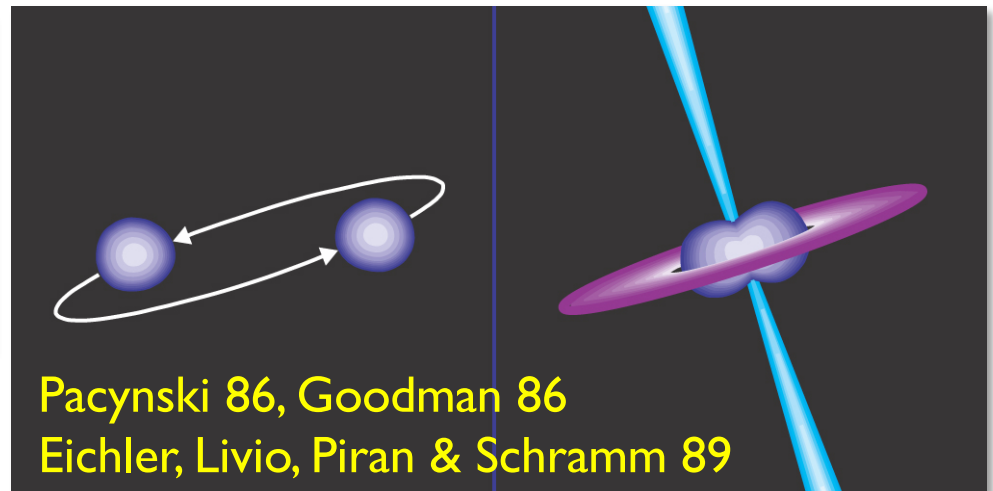


~100 sec chirp \Rightarrow NS-NS

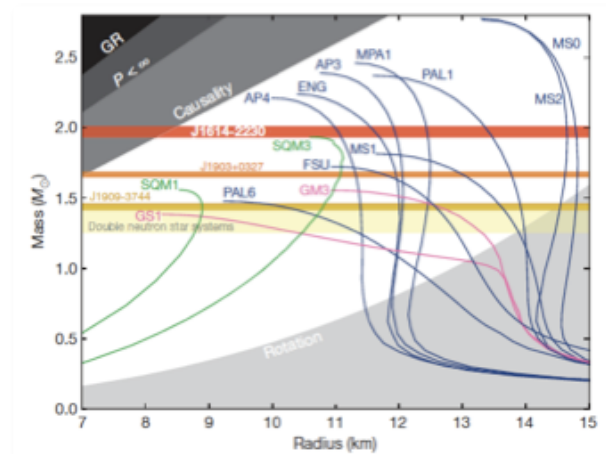
R-process elements



NS² = Short GRB?

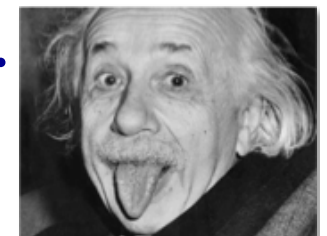


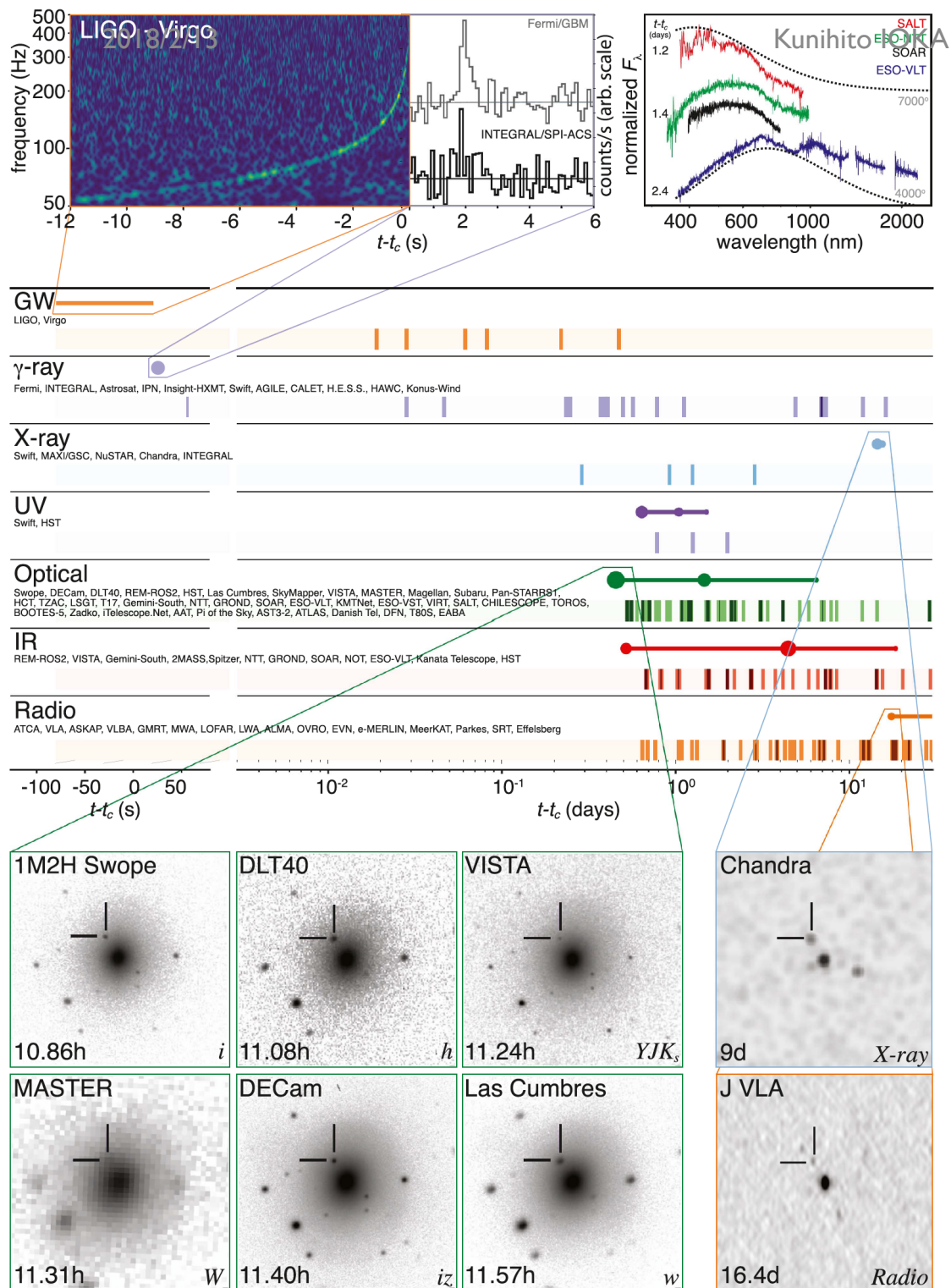
Equation of state



**Relativity,
Cosmology,**

...





New Era of¹⁵ Multi-Messenger

Follow-up observations
>3000 people

γ -ray: $\sim 1.734 \pm 0.054$ sec
 \Rightarrow sGRB 170817A

UV-Opt-IR: 10.86 hr

\Rightarrow Macronova/kilonova

X, radio: ~ 10 day

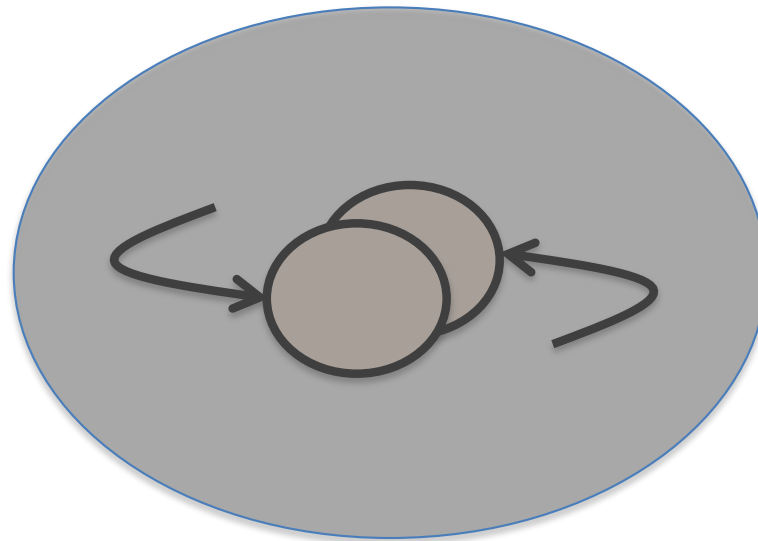
\Rightarrow Afterglow

LVC-EM 17

Band: GCN circ., Circles \propto brightness

Before
GW170817

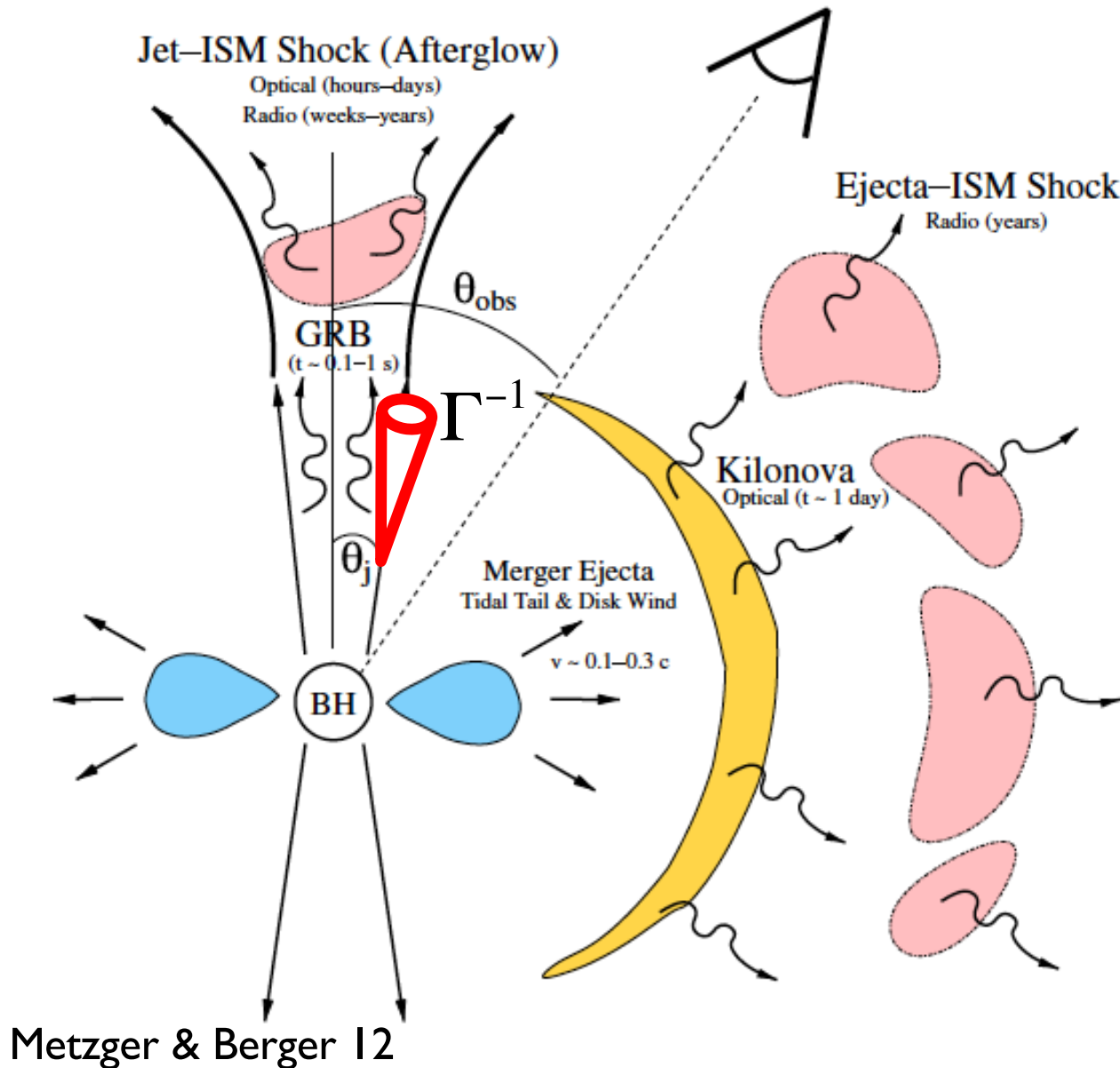
Optically Thick



Optical depth

$$\tau \sim 10^{14} \left(\frac{M}{10^{-6} M_{\odot}} \right) \left(\frac{r}{10^6 \text{ cm}} \right)^{-2}$$

EM Counterparts



GRB was thought
to be too faint

On-axis fraction

$$\frac{2\pi(\Delta\theta)^2}{4\pi} \sim 0.01 \ll 1$$

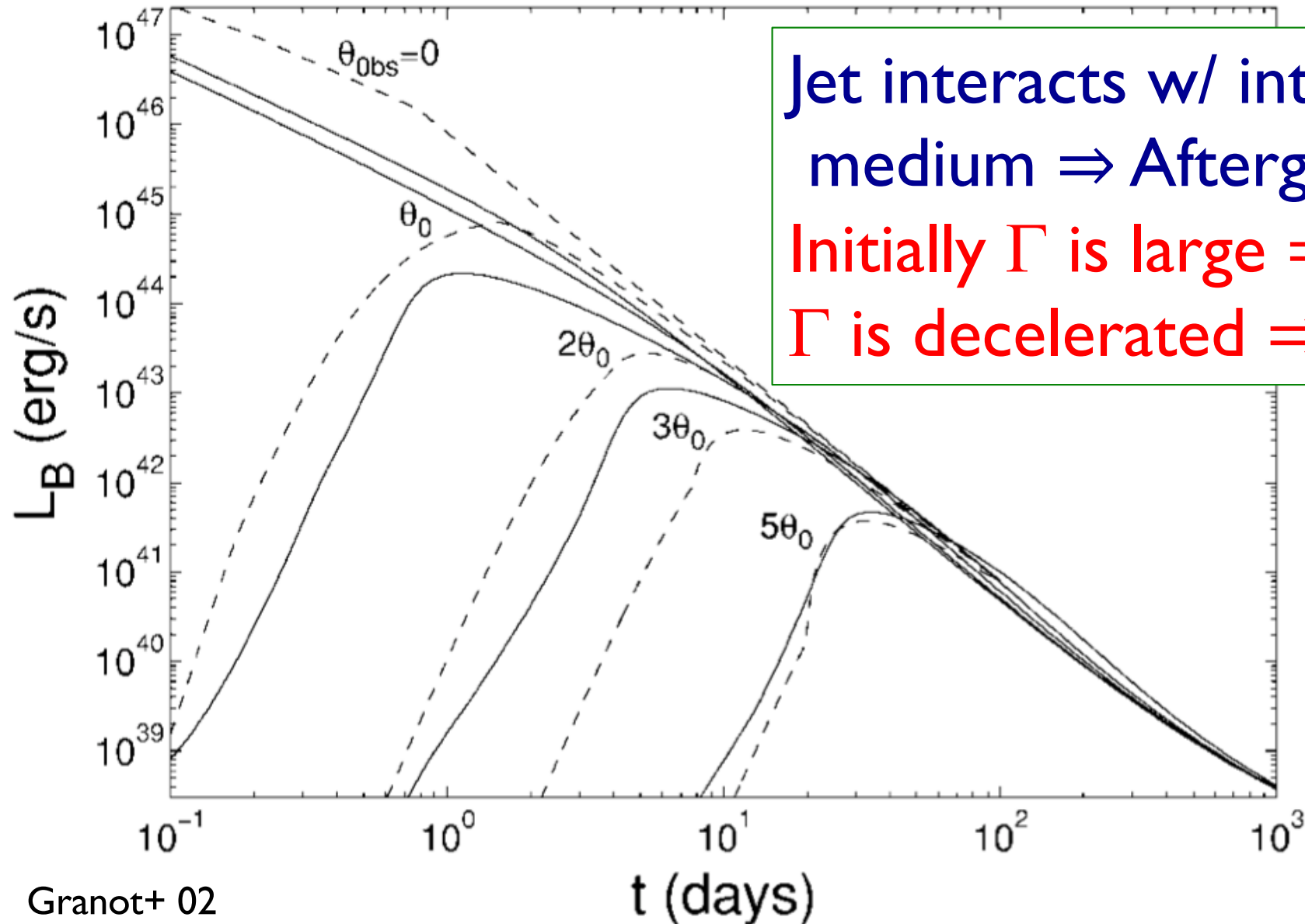
Off-axis energy

$$E_{\text{iso}} \propto \delta^3 \propto \theta_v^{-6}$$

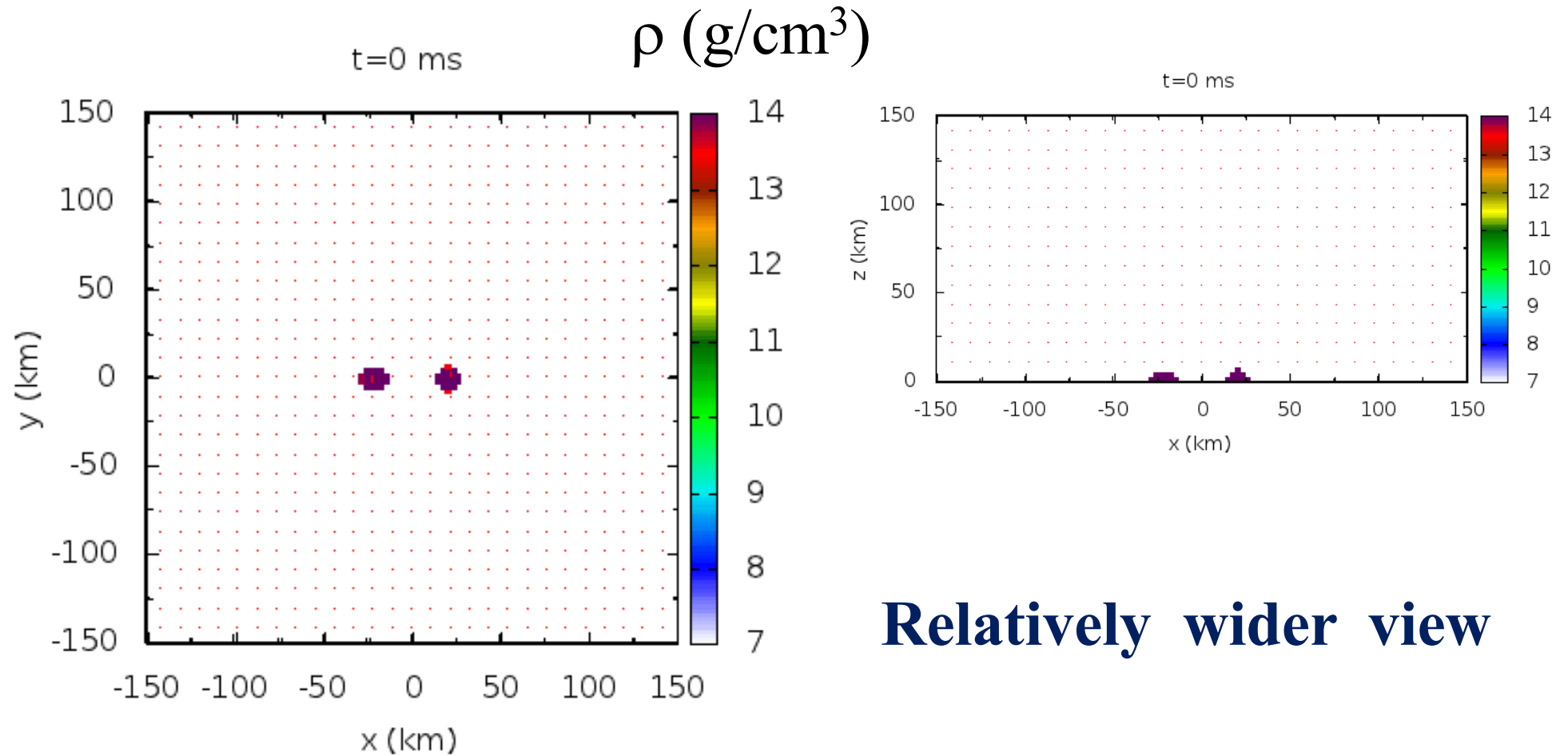
(point source case)

$$\delta \equiv \frac{1}{\Gamma(1 - \beta \cos \theta_v)}$$

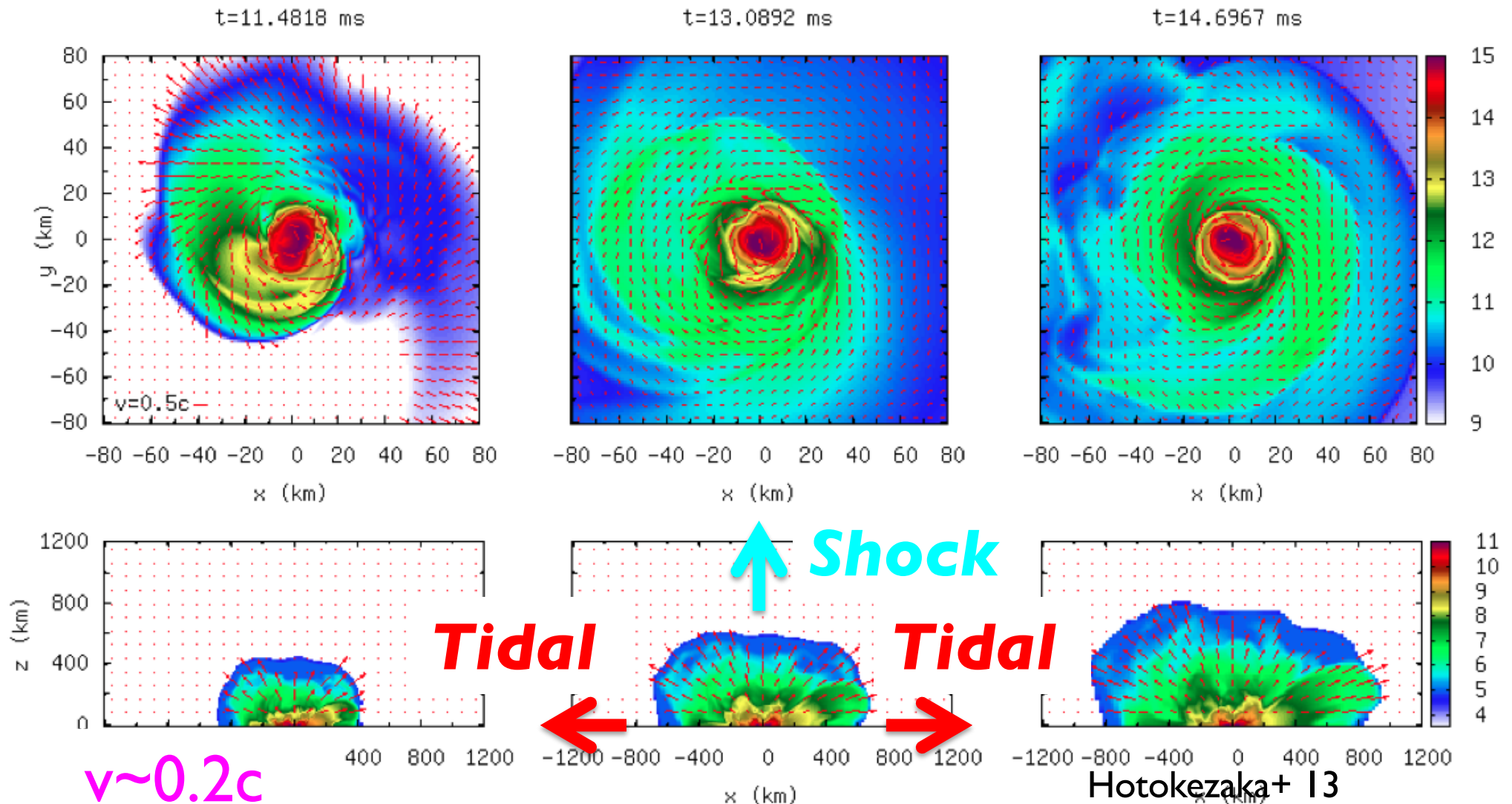
Off-Axis Afterglow



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



Dynamical Ejecta

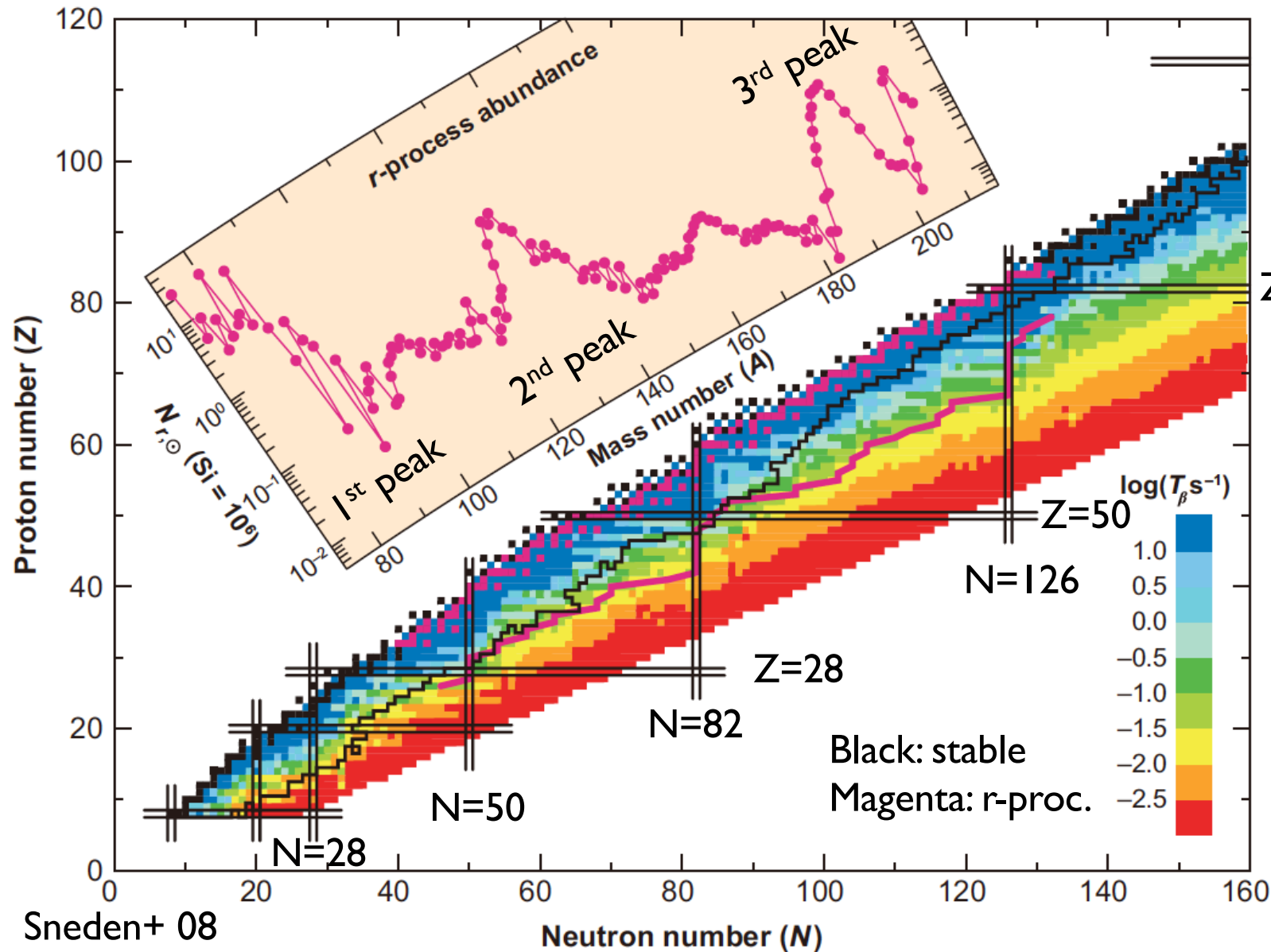


$v \sim 0.2c$
 $M < 0.01 M_{\odot}$

Quasi-spherical

Hotokezaka+ 13
 Bauswein+ 13,
 Sekiguchi+ 15, many others

r-Process Nucleosynthesis



Neutron-rich ejecta

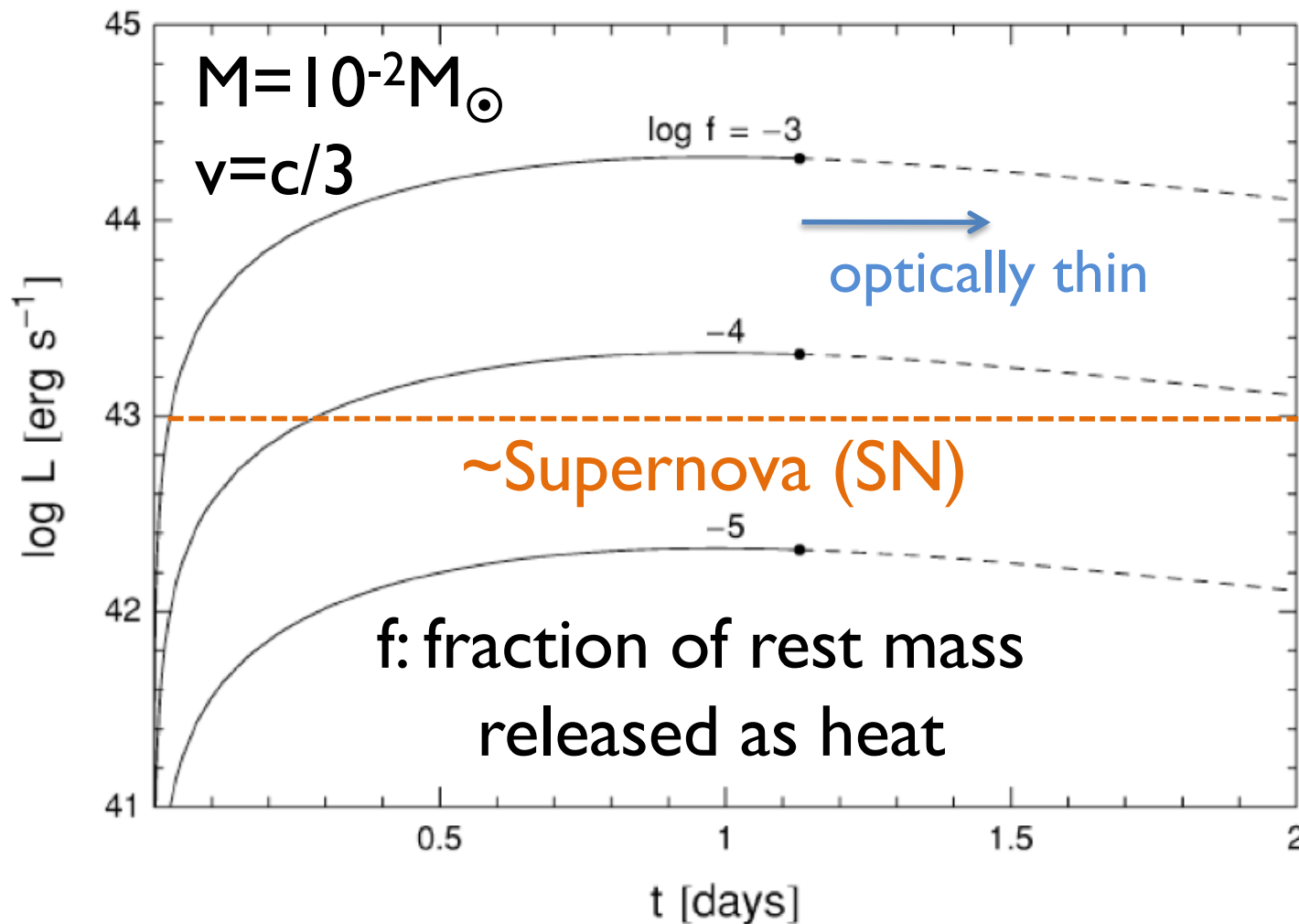
Neutron-capture
>>

β -decay

Y_e is changed by ν from a hypermassive neutron star

Macronova/Kilonova

Radioactivity (r-process \rightarrow β -, α -decay, fission, ...)



● \approx Supernova

● $t_{\text{diffusion}} \propto (\kappa M/v)^{1/2}$

● $T \propto (f^2/Mv)^{1/8}$

\sim IR-Opt

● $f \sim 3 \times 10^{-6}$

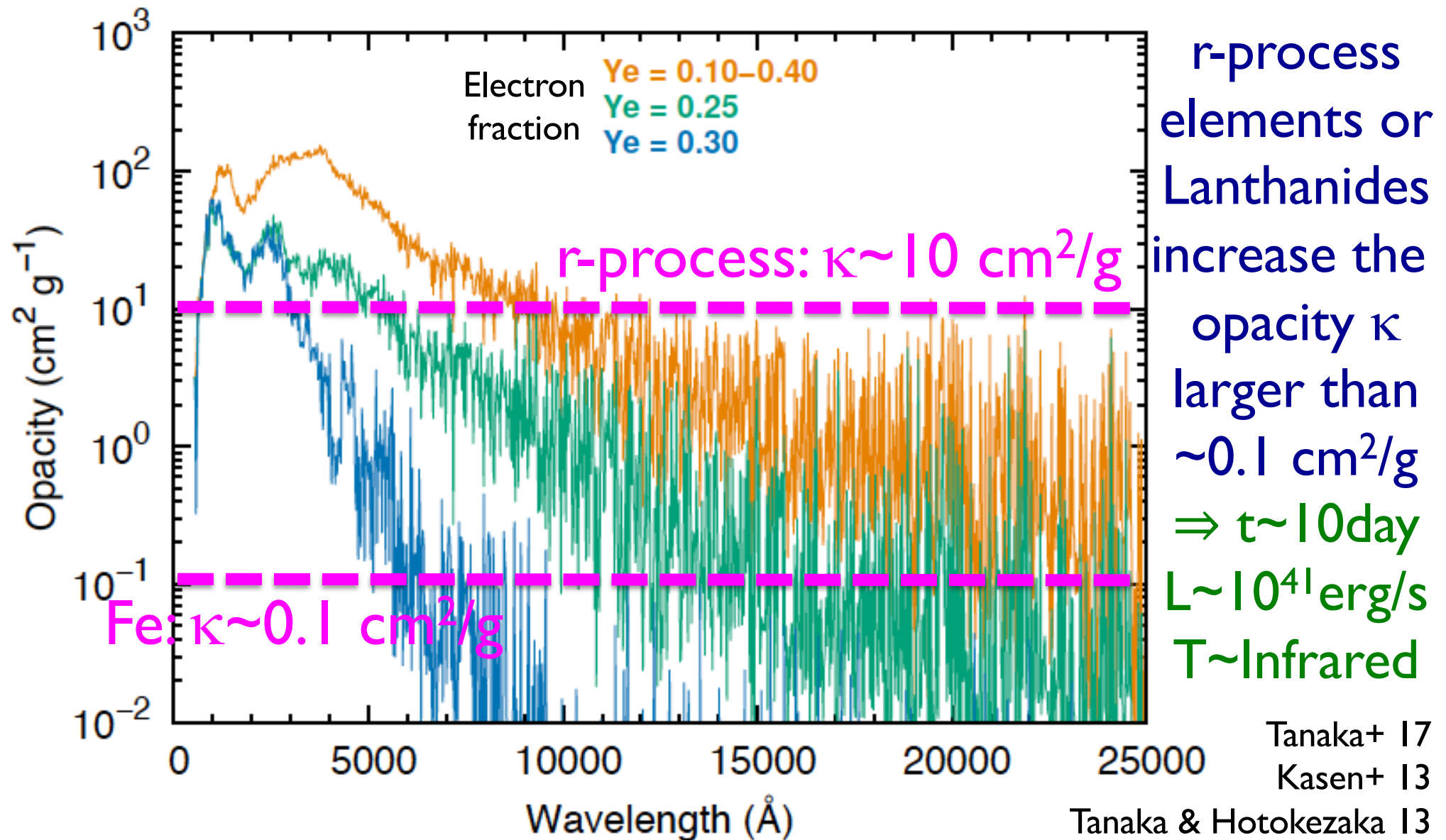
\Rightarrow **Faint SN**

Li & Paczynski 98

Kulkarni 05

Metzger+ 10

Large Opacity



Galactic Abundance

- **Galactic *r*-process rate**

$$\sim 10^{-6} M_{\odot}/\text{yr}$$

- **Ejected mass**

$$\sim 0.01 M_{\odot}/\text{event}$$

- **Event rate**

$$\sim 10^{-4} \text{ events/yr/galaxy}$$

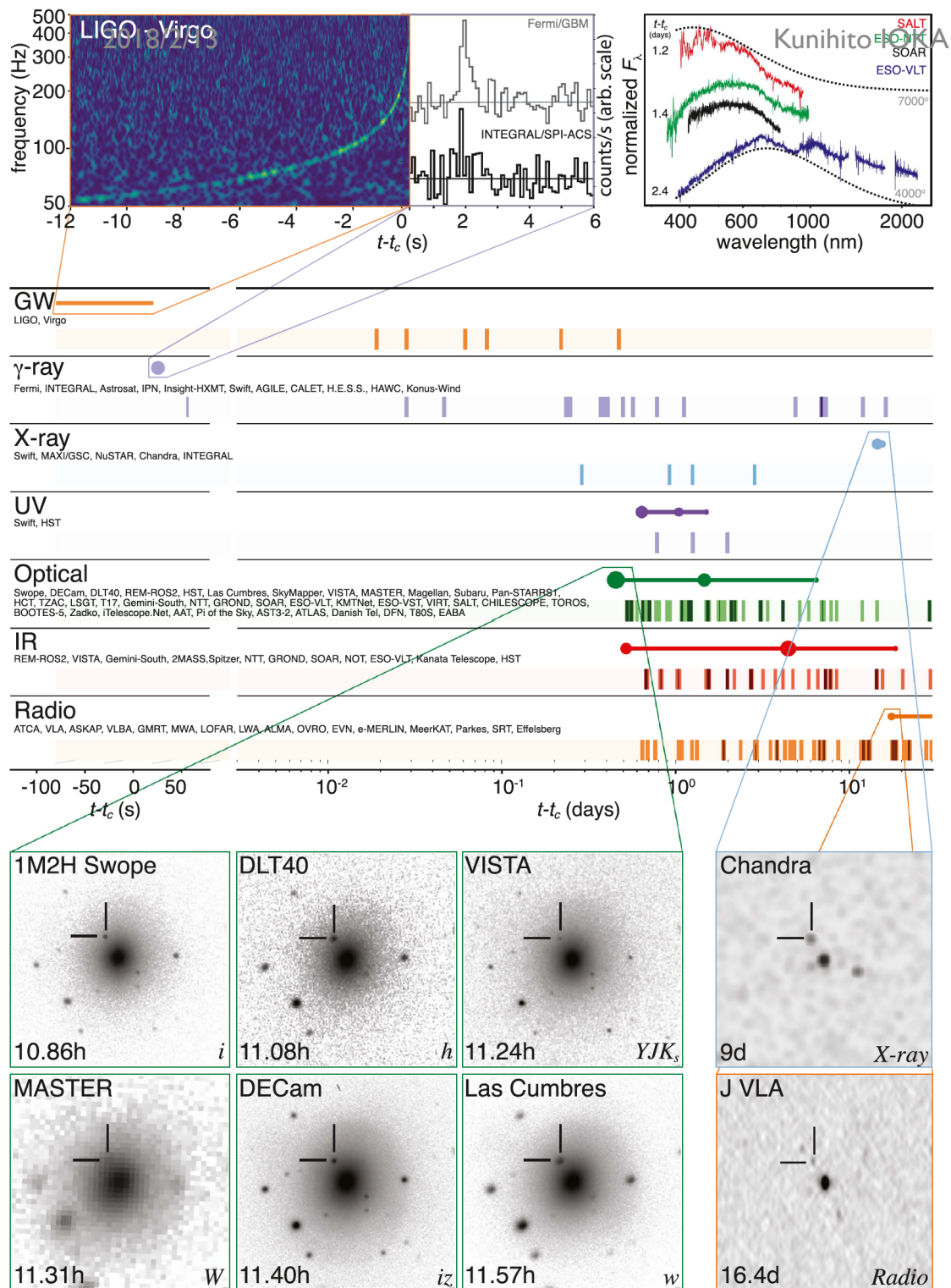
$$\sim 10^3 \text{ events/Gpc}^3/\text{yr}$$

- $X_{\text{Lanthanide}} \sim 0.03$

NS² = r-process origin?

After

GW170817



New Era of Multi-Messenger ²⁷

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>3000 people

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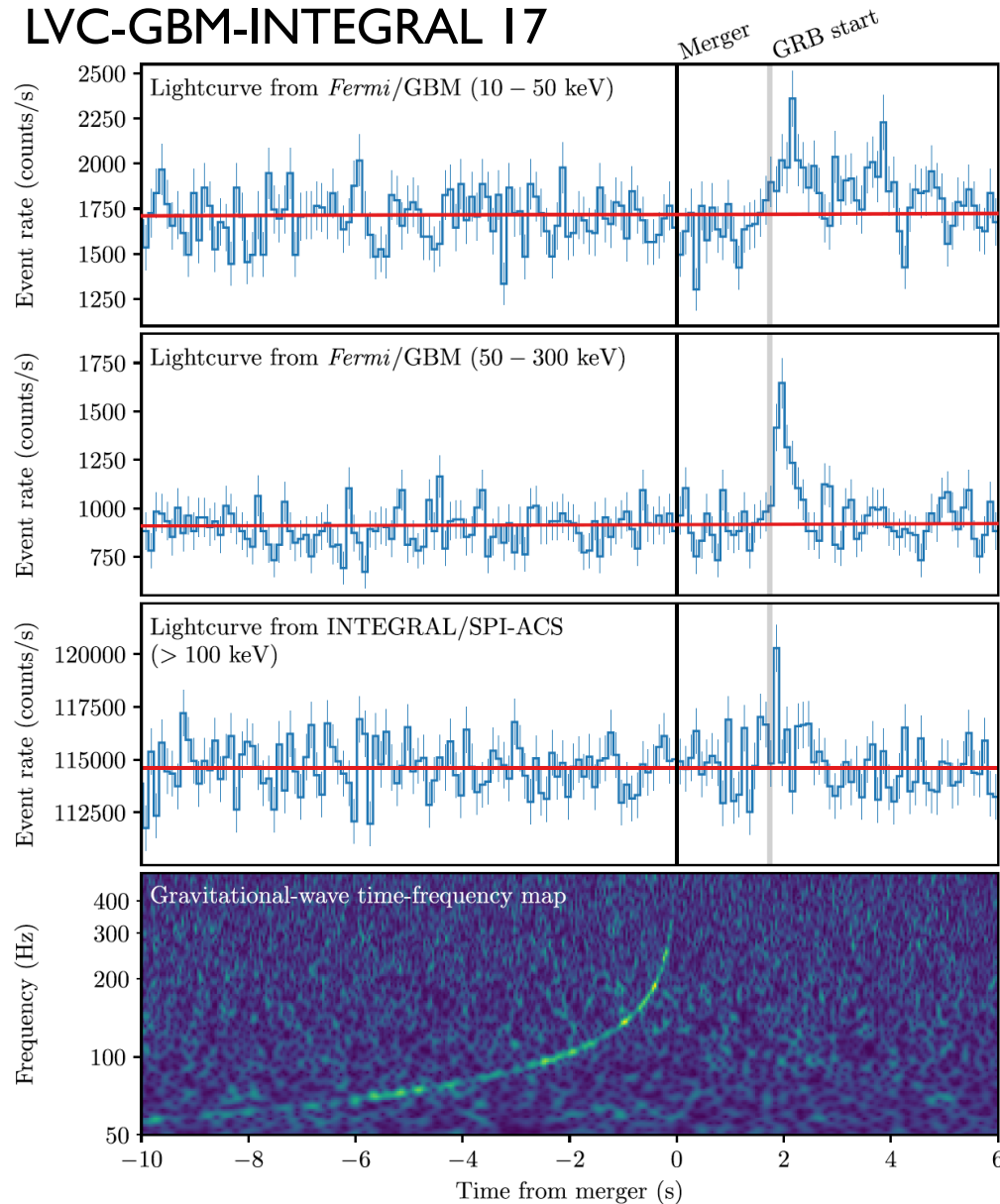
\Rightarrow Afterglow

LVC-EM 17

Band: GCN circ., Circles \propto brightness

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

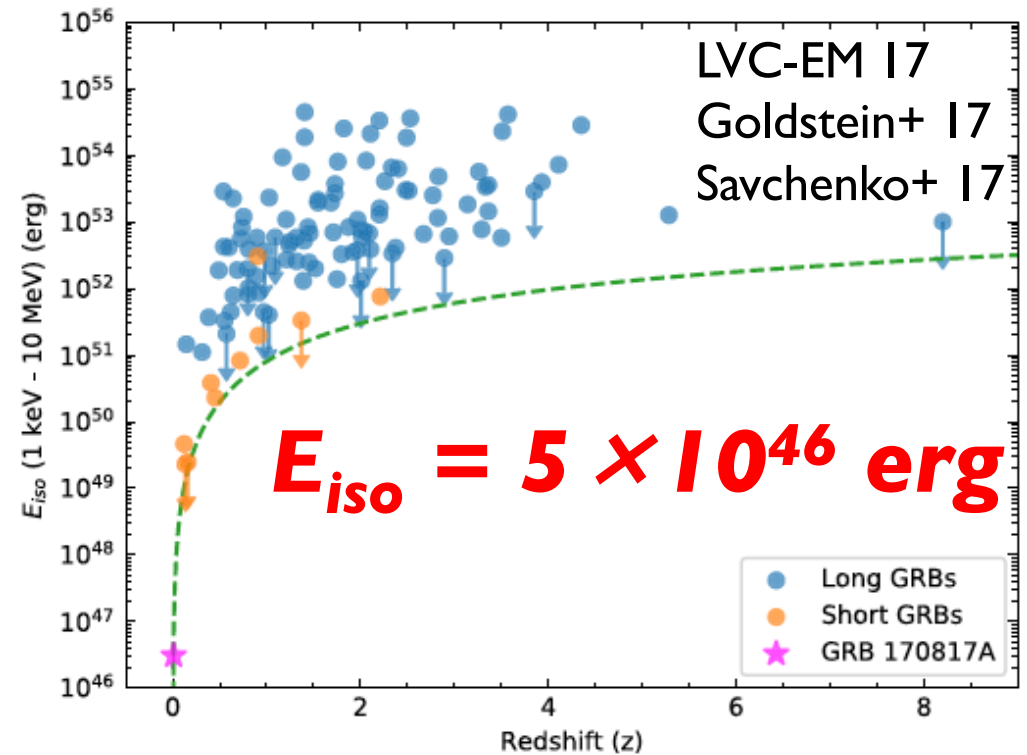


3 (of 12) GBM NaI detectors

$T_0 = 1.74 \pm 0.05$ sec (68%)

$T_{90} = 2.0 \pm 0.5$ sec

Weak but Detected

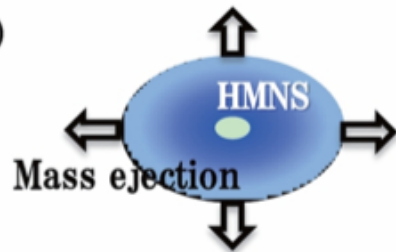


Successful or Failed Jet?

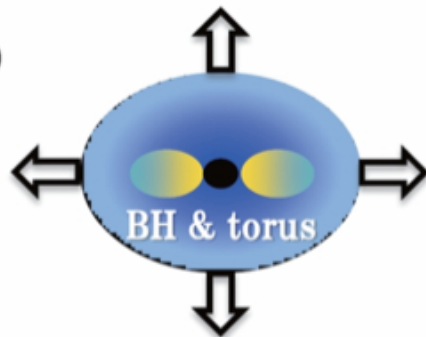
(I)



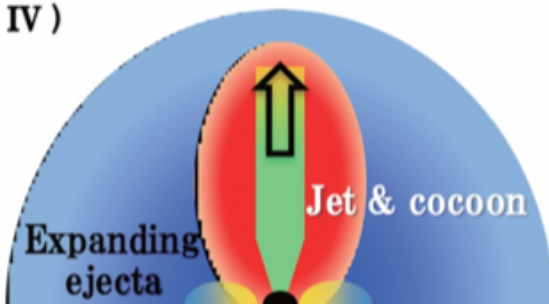
(II)



(III)



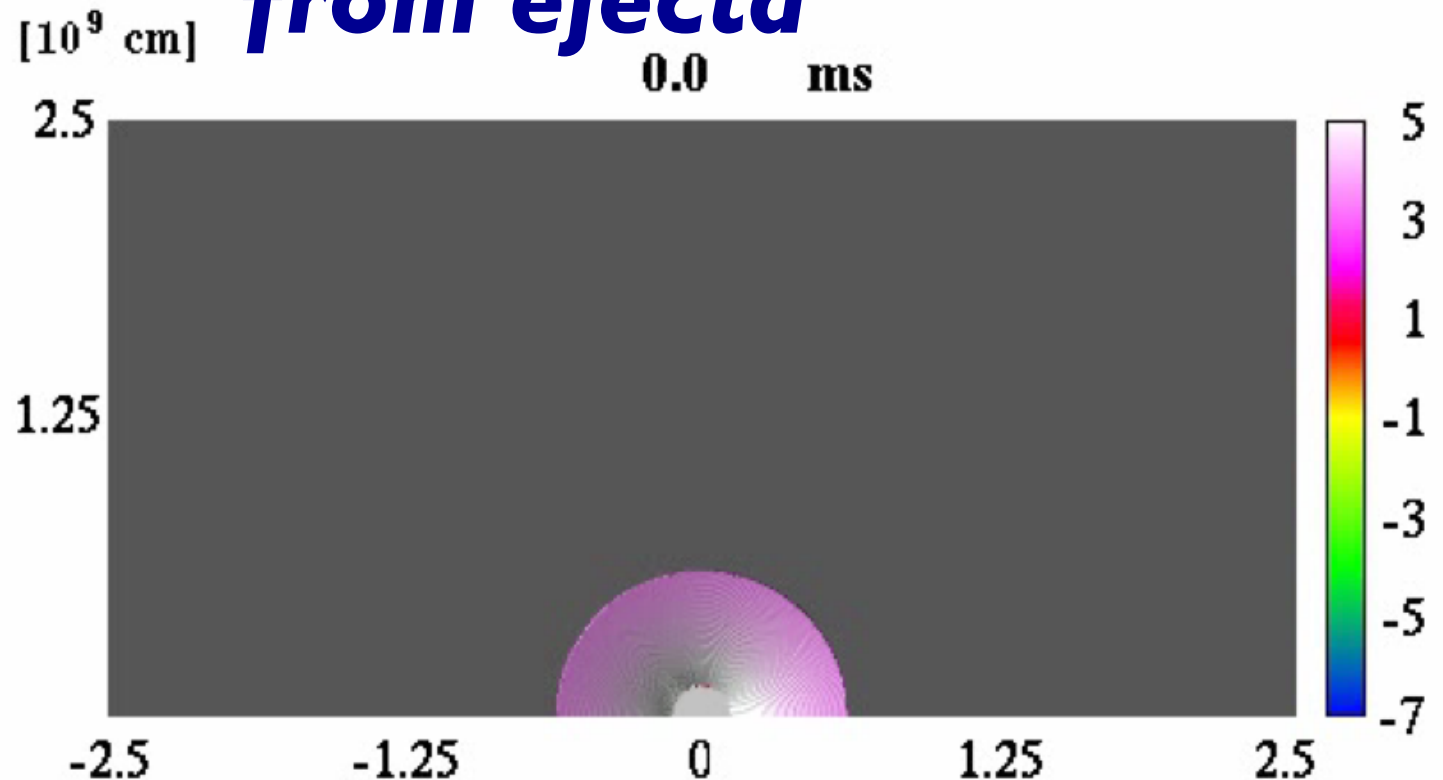
(IV)



***Jet breakout
from ejecta***

Nagakura+ 14

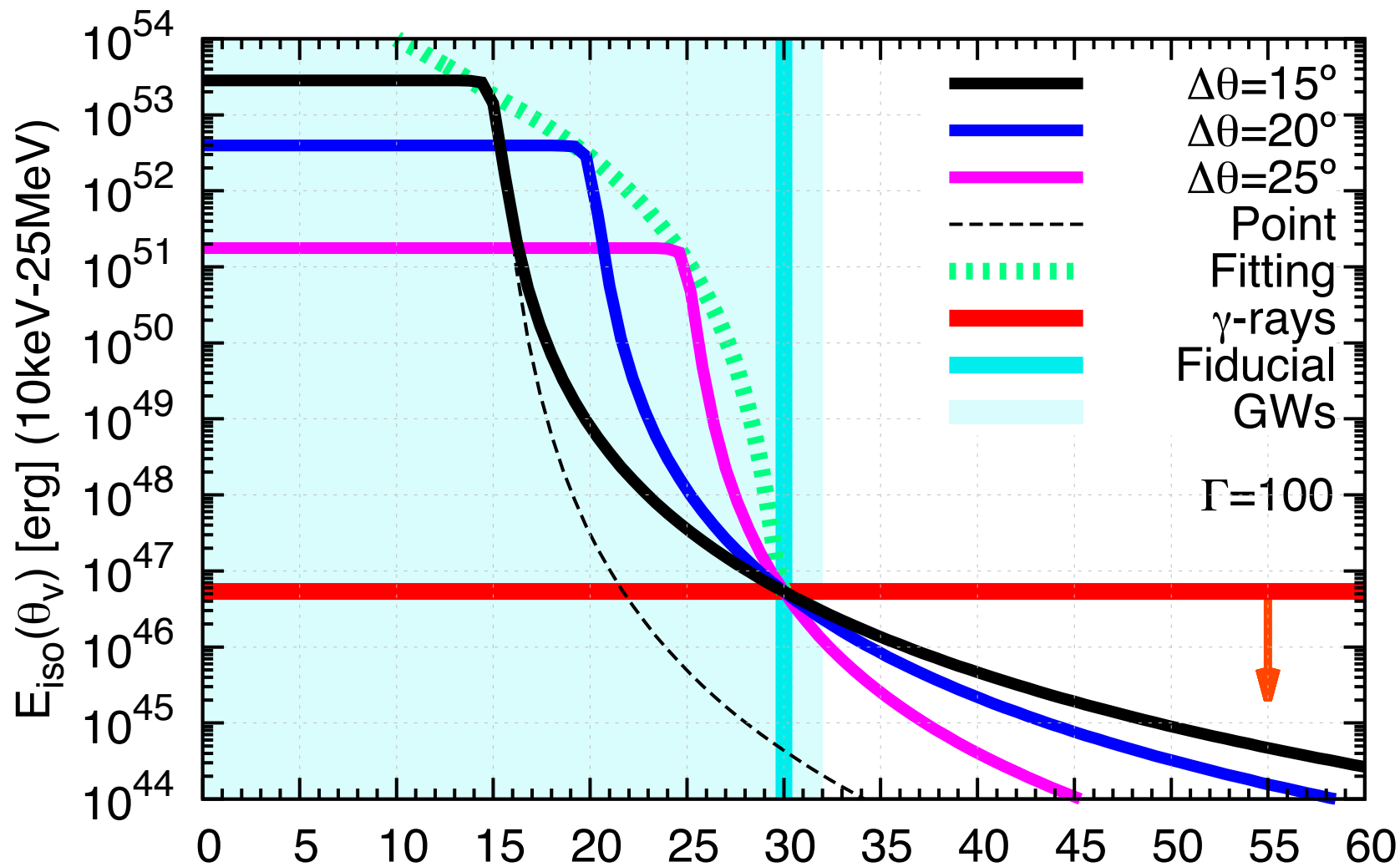
Murguia-Berthier + 14



Similar to collapsars (long GRBs)

Weak jet $\sim 10^{46}$ erg/s cannot break out

Off-Axis Jet



$\theta_v \sim \Delta\theta$
 \Rightarrow **Point approx. is bad**

$$E_{\text{iso}} \propto \theta_v^{-6}$$

↓

$$E_{\text{iso}} \propto \theta_v^{-4}$$

KI & Nakamura 17, 01

Viewing angle θ_v of the jet

LVC-GBM-INTEGRAL 17

Yamazaki, KI & Nakamura 02, 03, 04

Granot+ 17, Kasliwal+ 17

Kasliwal+ 17
Gottlieb+ 17
Bromberg+ 17

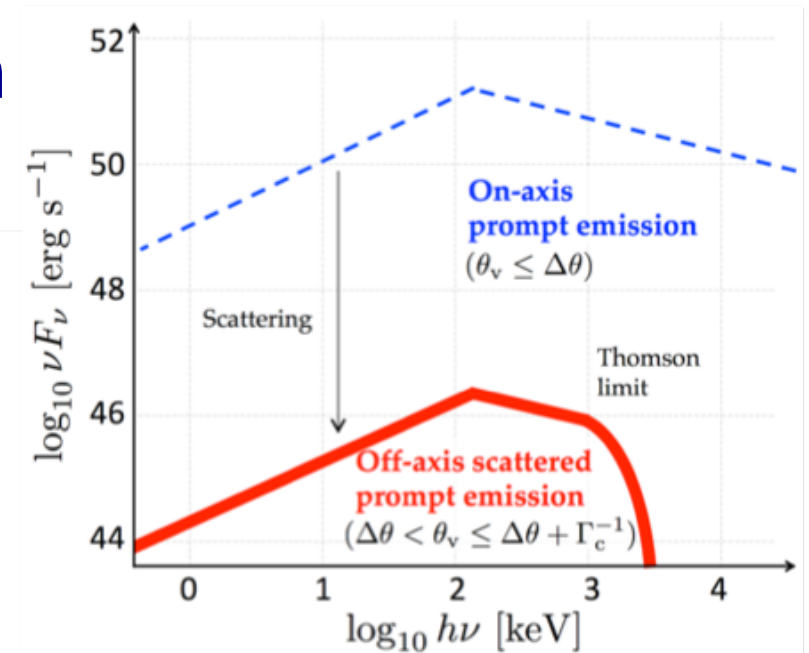
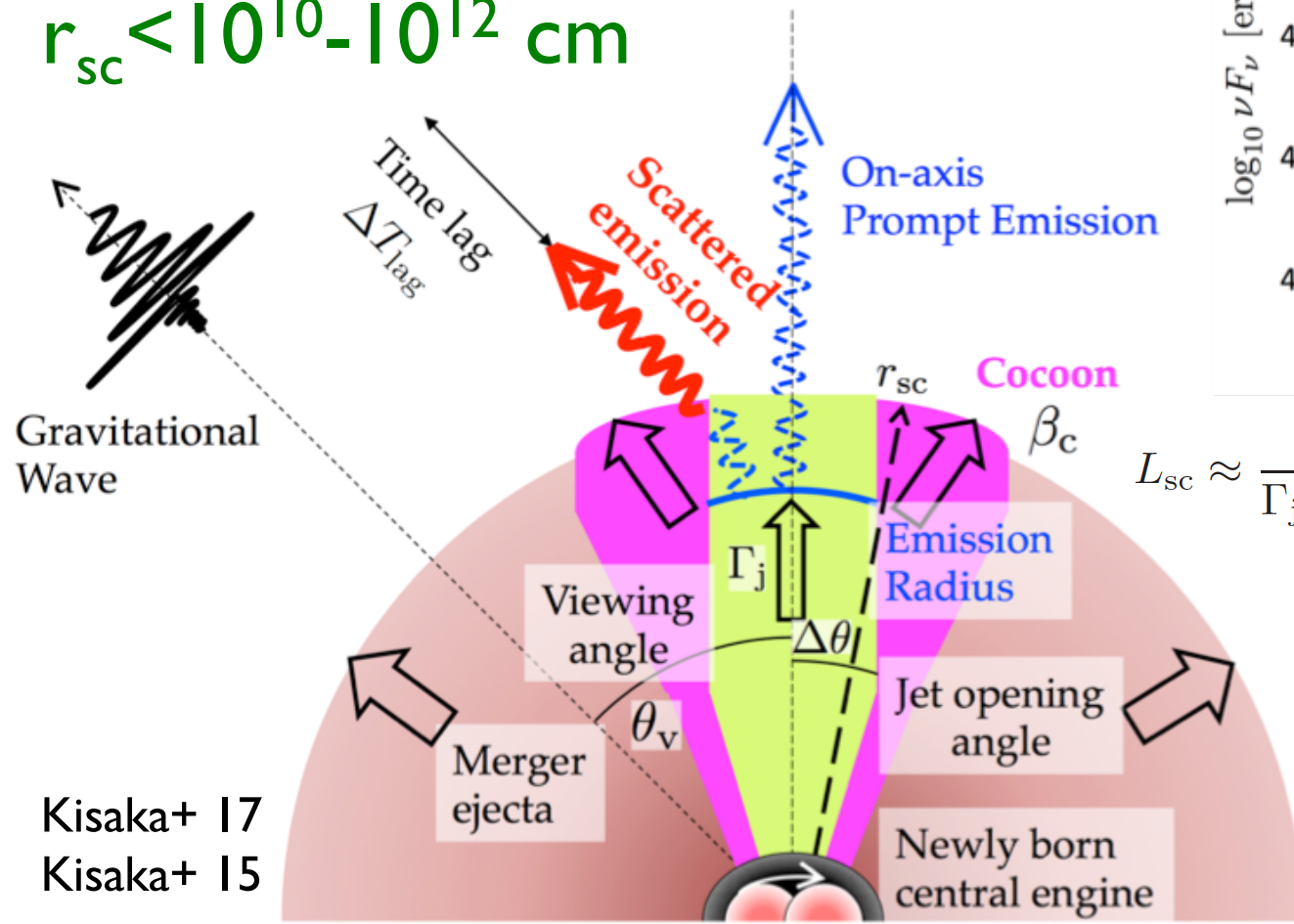


Scattered sGRB

Thompson scattering by cocoon

Copy spectrum w/ $\sim \text{MeV}$ cutoff

$r_{\text{sc}} < 10^{10} - 10^{12} \text{ cm}$



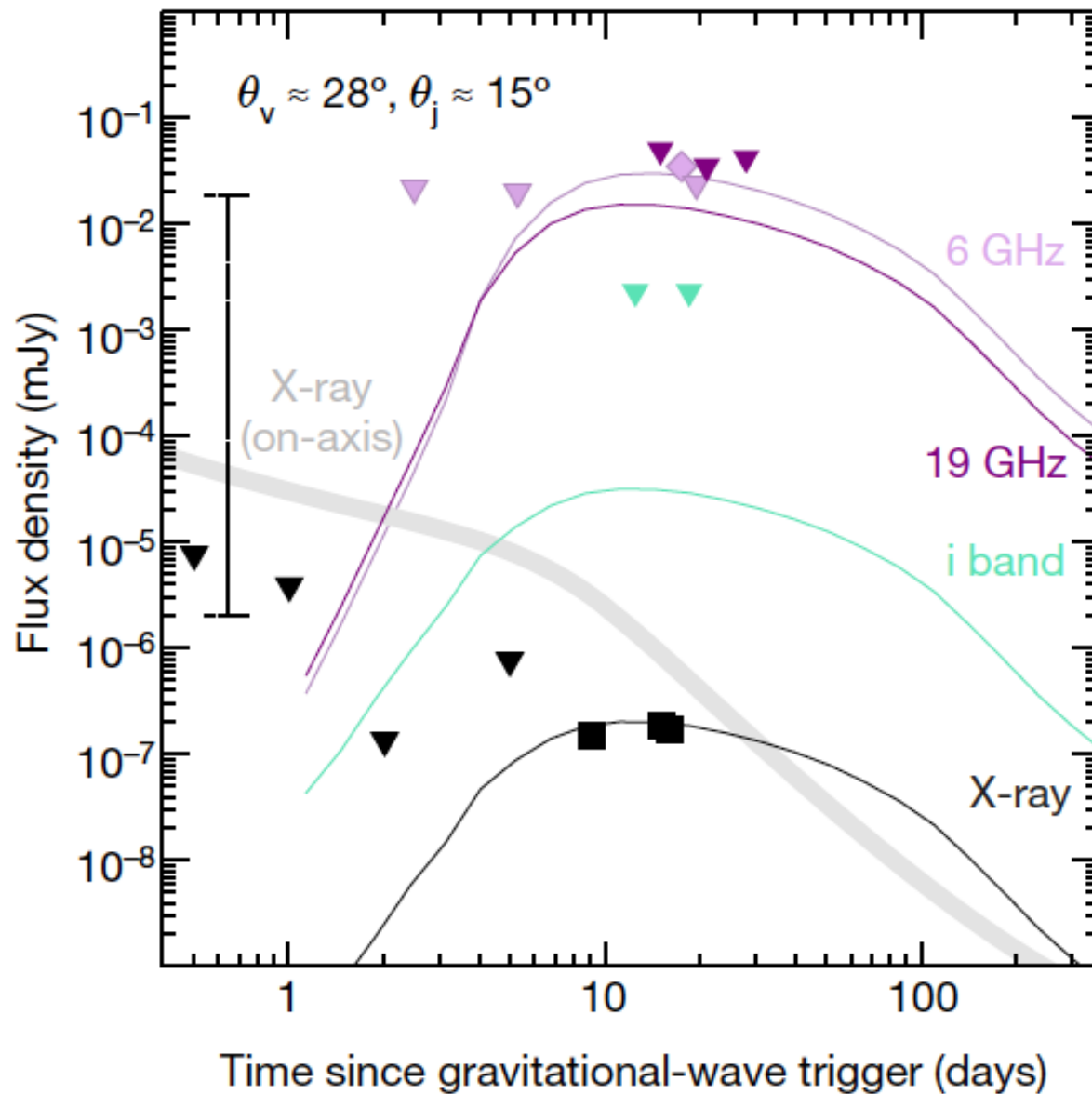
$$L_{\text{sc}} \approx \frac{2}{\Gamma_j \Delta\theta} \times \frac{t_{\text{dur}}}{T_{\text{dur,sc}}} \times \Gamma_c^2 \times \epsilon_{\text{sc}} \times \frac{\Delta\theta^2}{2} L_{\text{iso}}$$

Wide angle

$$\Delta\theta_{\text{sc}} \approx \frac{1}{\Gamma_c}$$

Kisaka+ 17
Kisaka+ 15

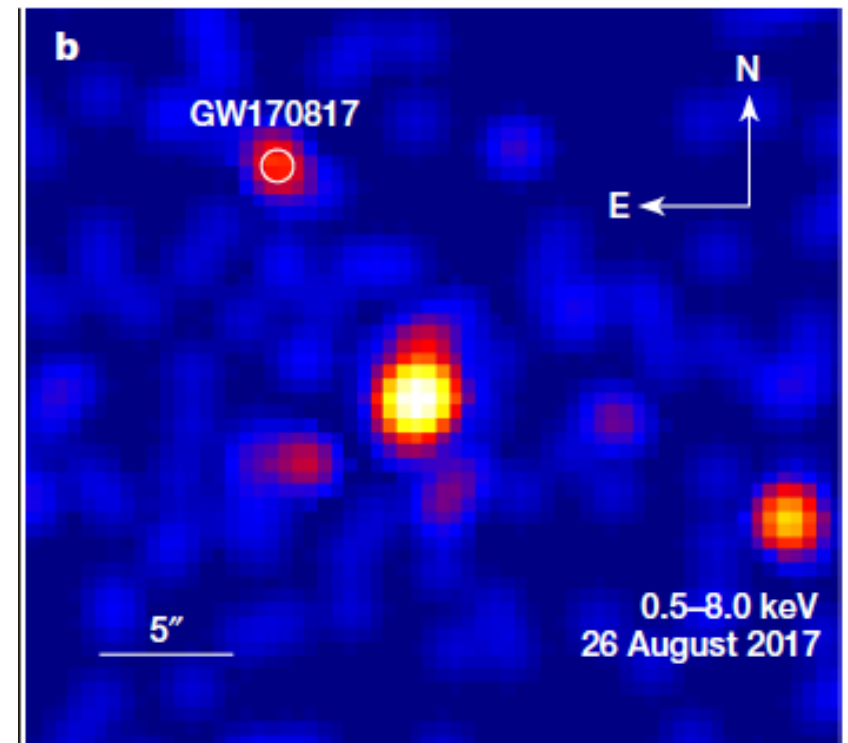
X-ray Afterglow



Chandra 50ks

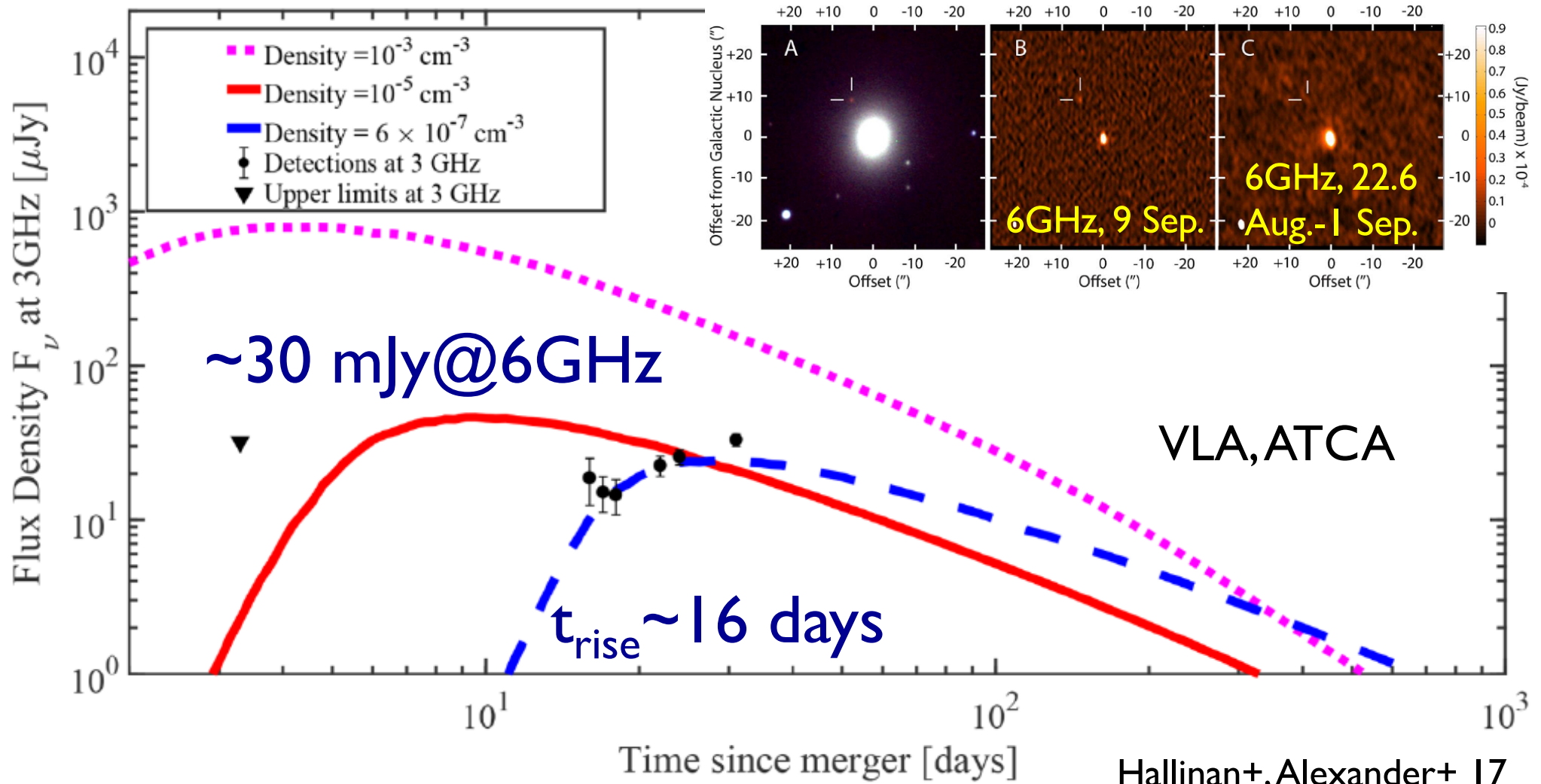
$t_{\text{rise}} \sim 9$ day

$L_{\text{X,iso}} \sim 1.1 \text{e}39 \text{ erg/s}$



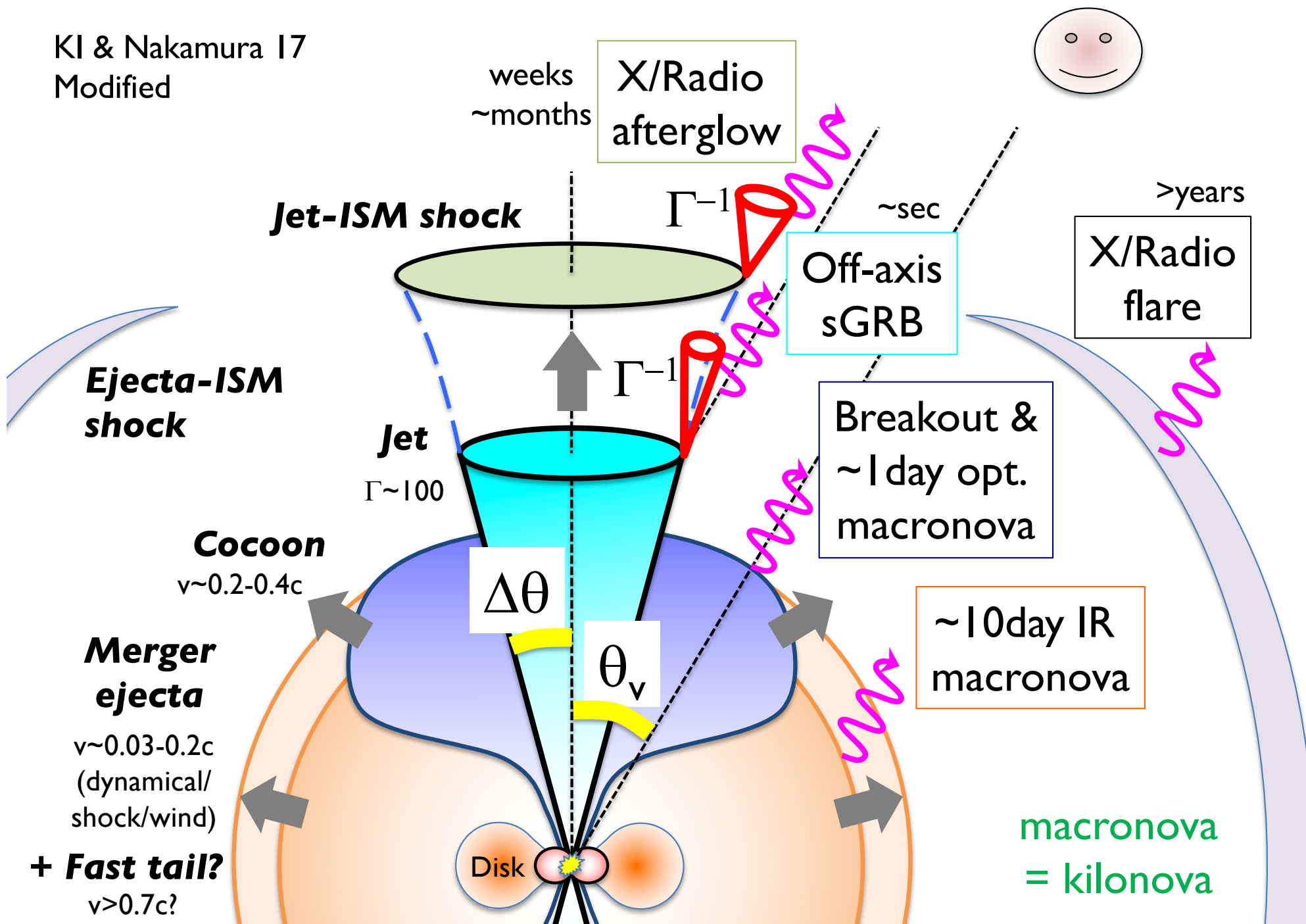
Troja+, Margutti+, Haggard+ 17

Radio Afterglow

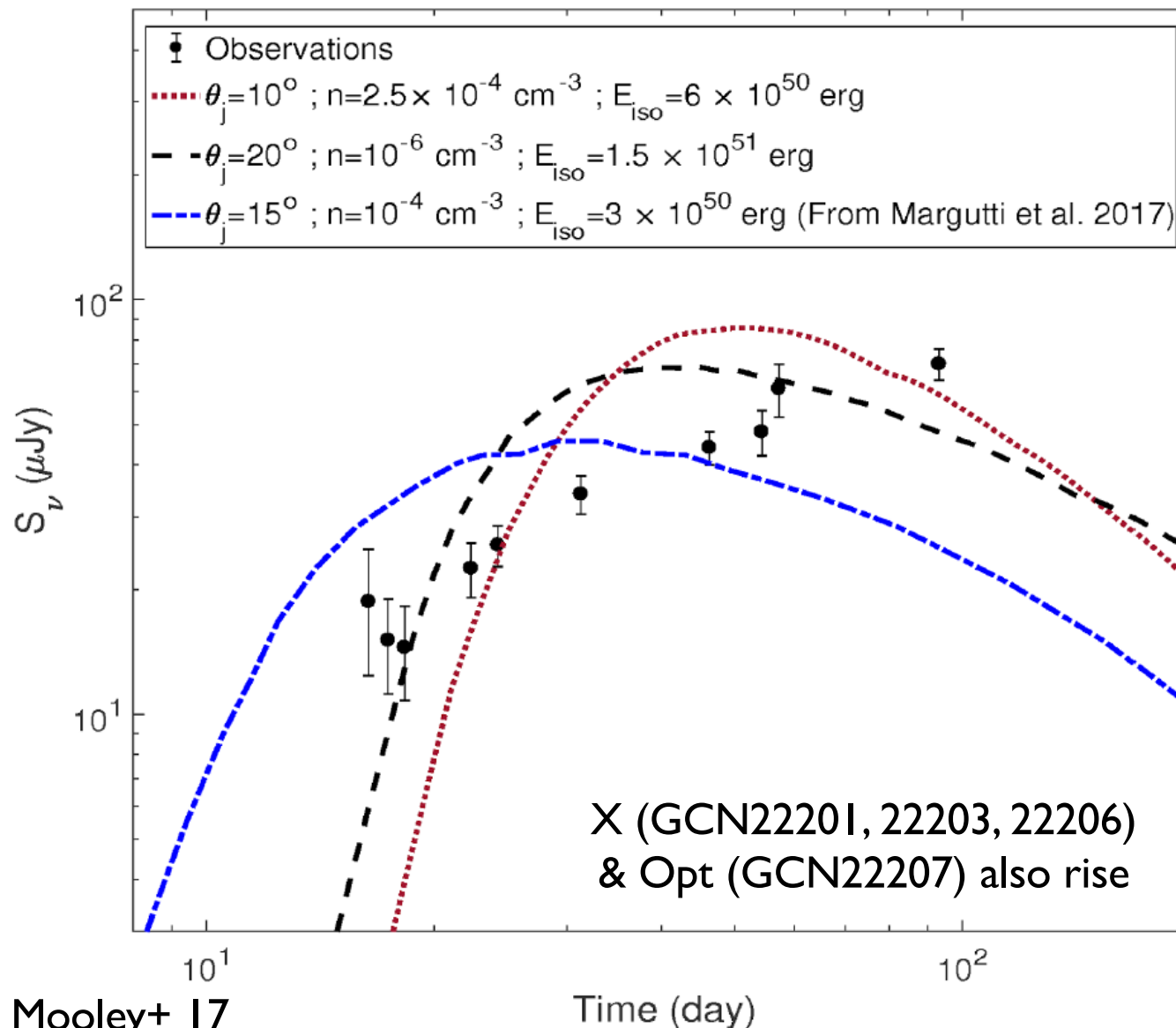


X/Radio ratio \sim Synchrotron $p=2.2$ ($\nu_m < \nu < \nu_c$)

KI & Nakamura 17
Modified



Rising Afterglow



**Rising
up to $\sim 100\text{d}$**

Inconsistent
with a simple jet

Energy injection
radial or polar:
Structured jet
or cocoon?

Margutti+ 18

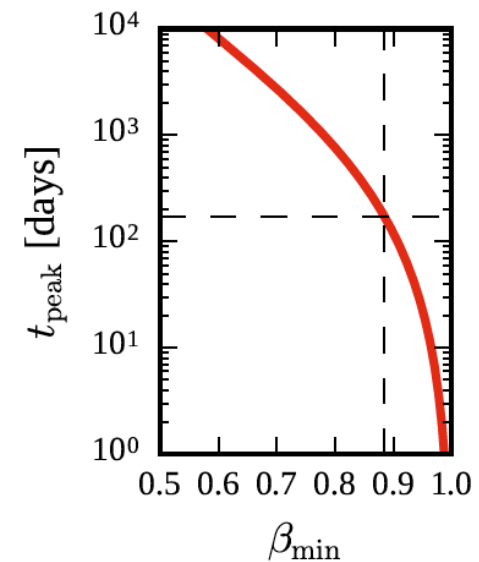
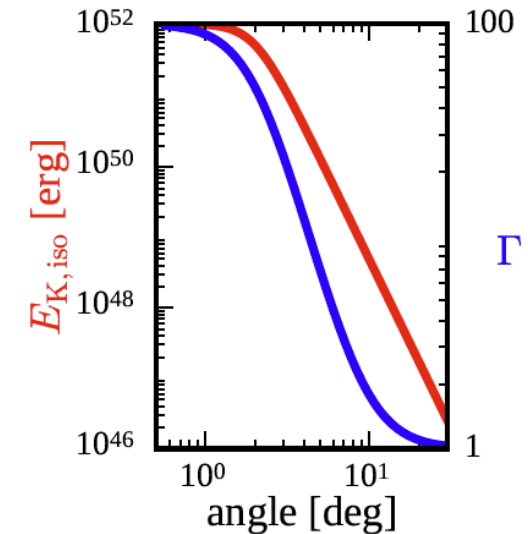
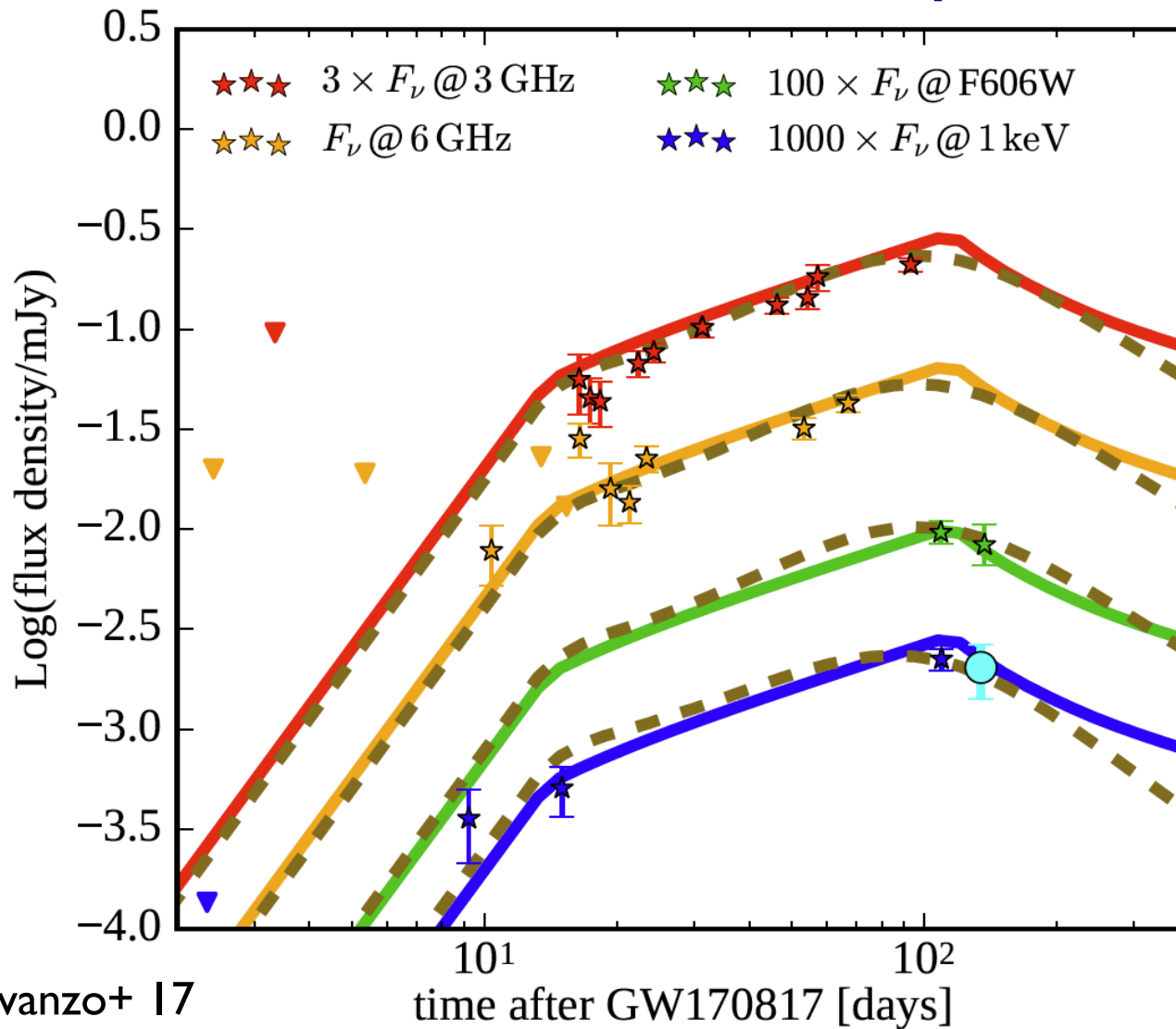
Lazzati+ 17

D'Avanzo+ 18

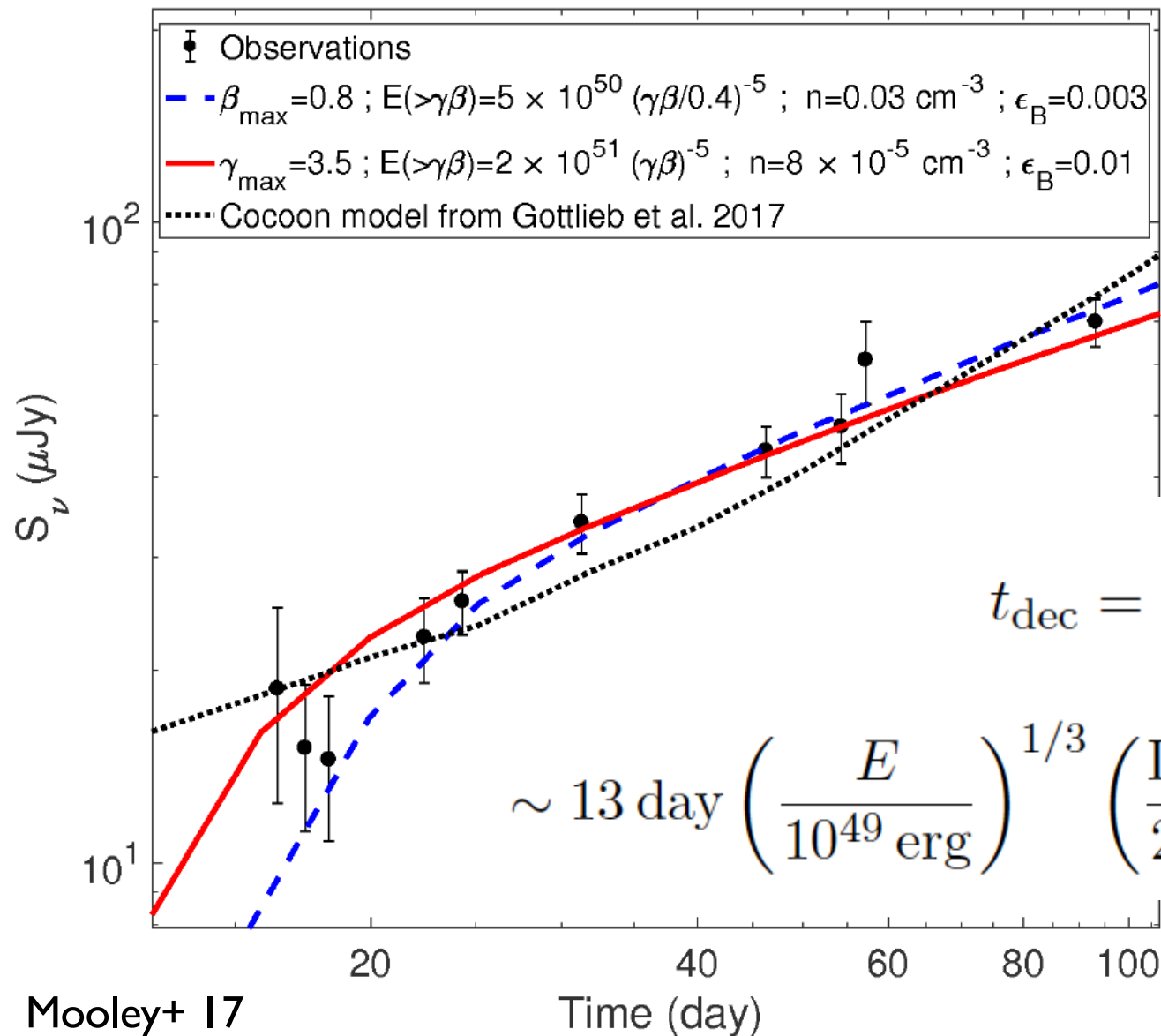
Lyman+ 18

Structured Jet?

$$F_\nu(t) \propto \nu^{0.6} t^{0.7} \Rightarrow \text{e spectrum: } p \approx 2.2$$



Cocoon/Ejecta Afterglow?



Cocoon or
Ejecta tail
interact w/ ISM

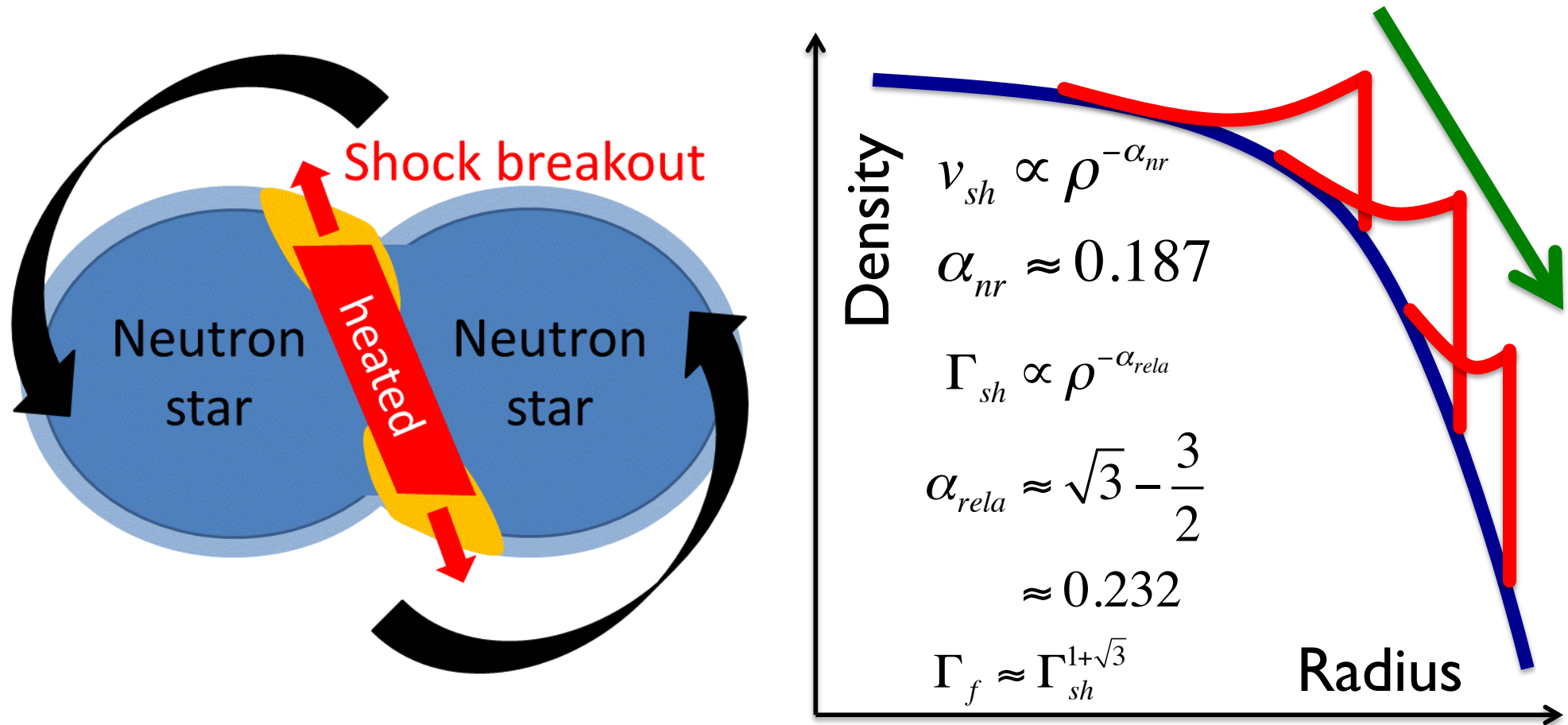
Rise time~
Deceleration time

$$t_{\text{dec}} = \frac{1}{4\Gamma^2 c} \left(\frac{3E}{4\pi n m_p c^2 \Gamma^2} \right)^{1/3}$$

$$\sim 13 \text{ day} \left(\frac{E}{10^{49} \text{ erg}} \right)^{1/3} \left(\frac{\Gamma}{2} \right)^{-8/3} \left(\frac{n}{10^{-3} \text{ cm}^{-3}} \right)^{-1/3}$$

X (GCN22201, 22203, 22206)
& Opt (GCN22207) also rise

Merger Shock Breakout

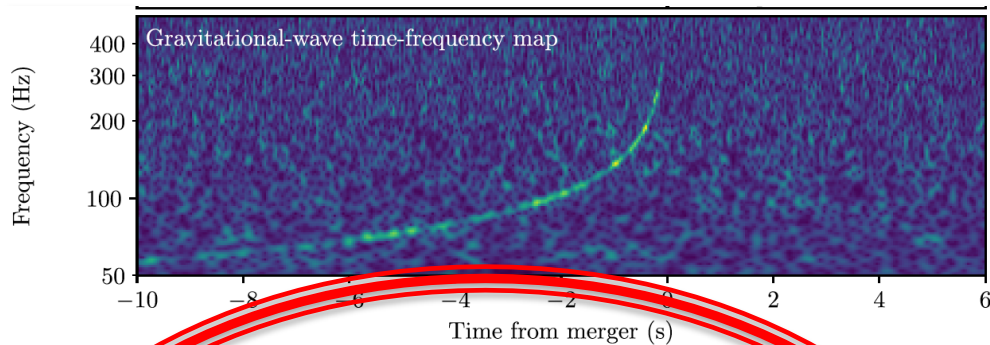


Kyutoku, KI & Shibata 14
Sakurai 60, Johnson & McKee 71

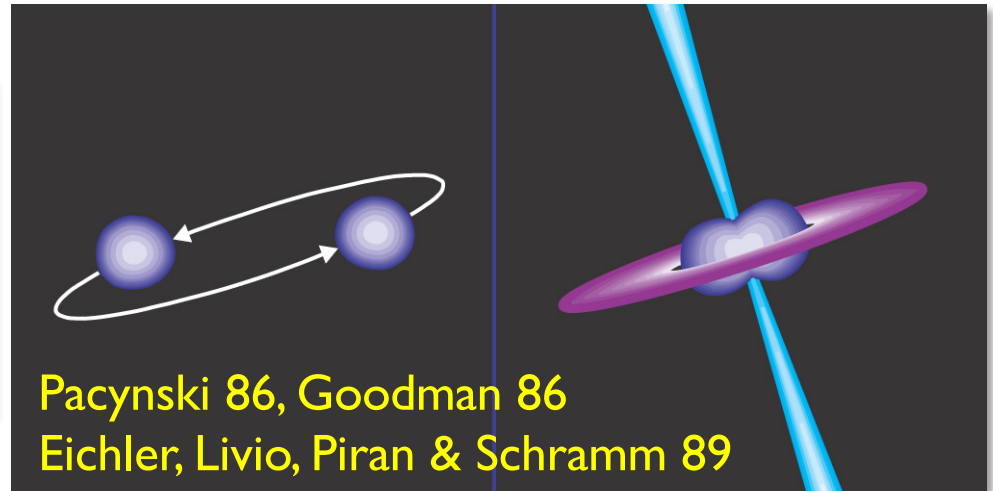
Shock acceleration @surface
up to $\sim 10^{-5} M_{\odot}$ but uncertain

GW170817

1st GW from NS²



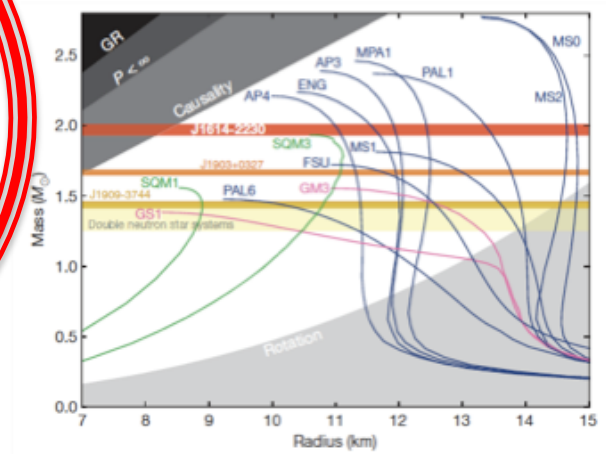
NS² = Short GRB?



R-process elements

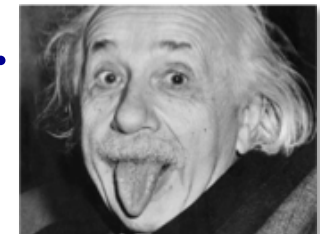


Equation of state

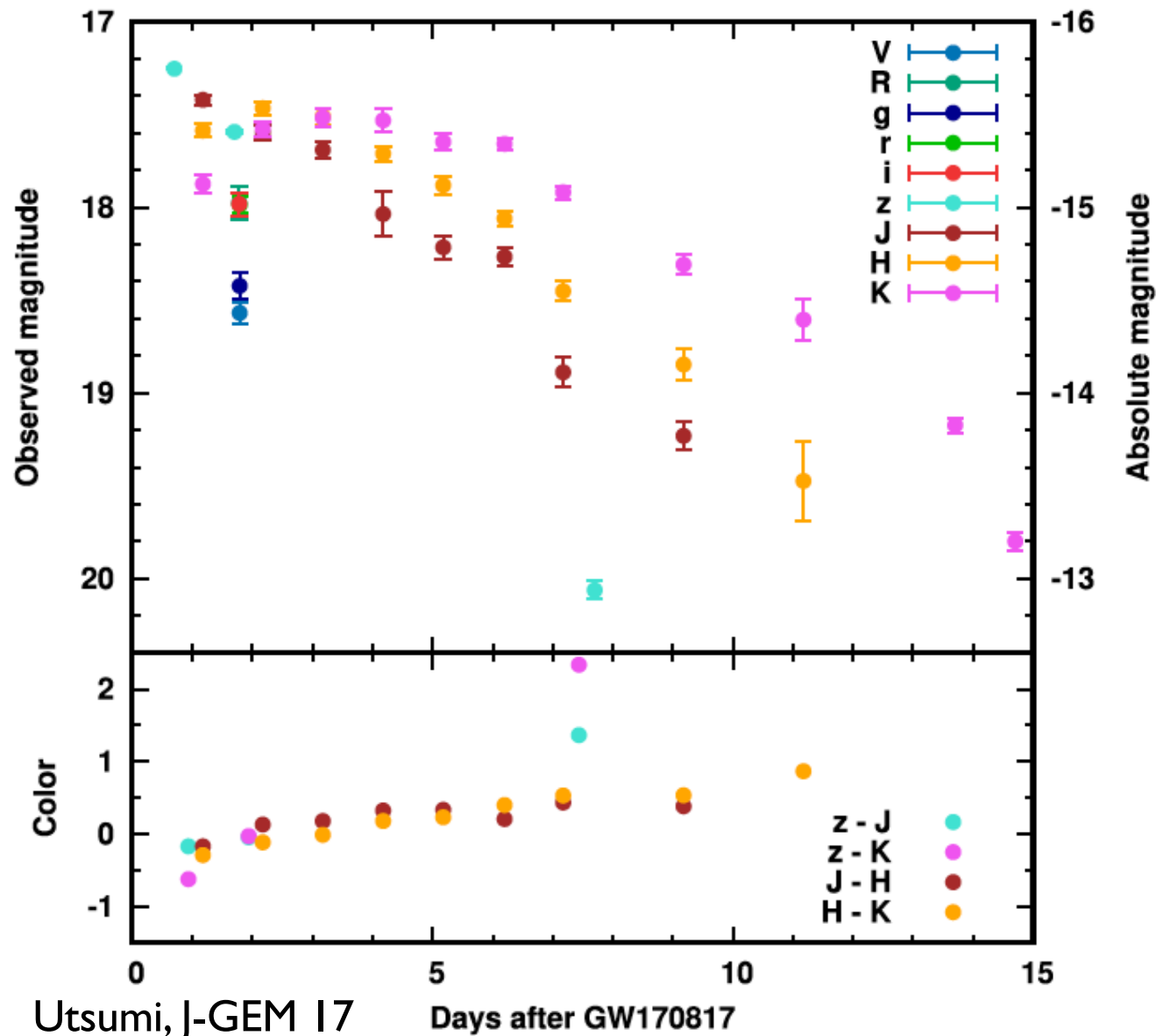


Relativity,
Cosmology,

...



Macronova/Kilonova



Blue macronova

~1 day opt.

$T \sim 7000\text{K}$

$L \sim 7e41 \text{ erg/s}$

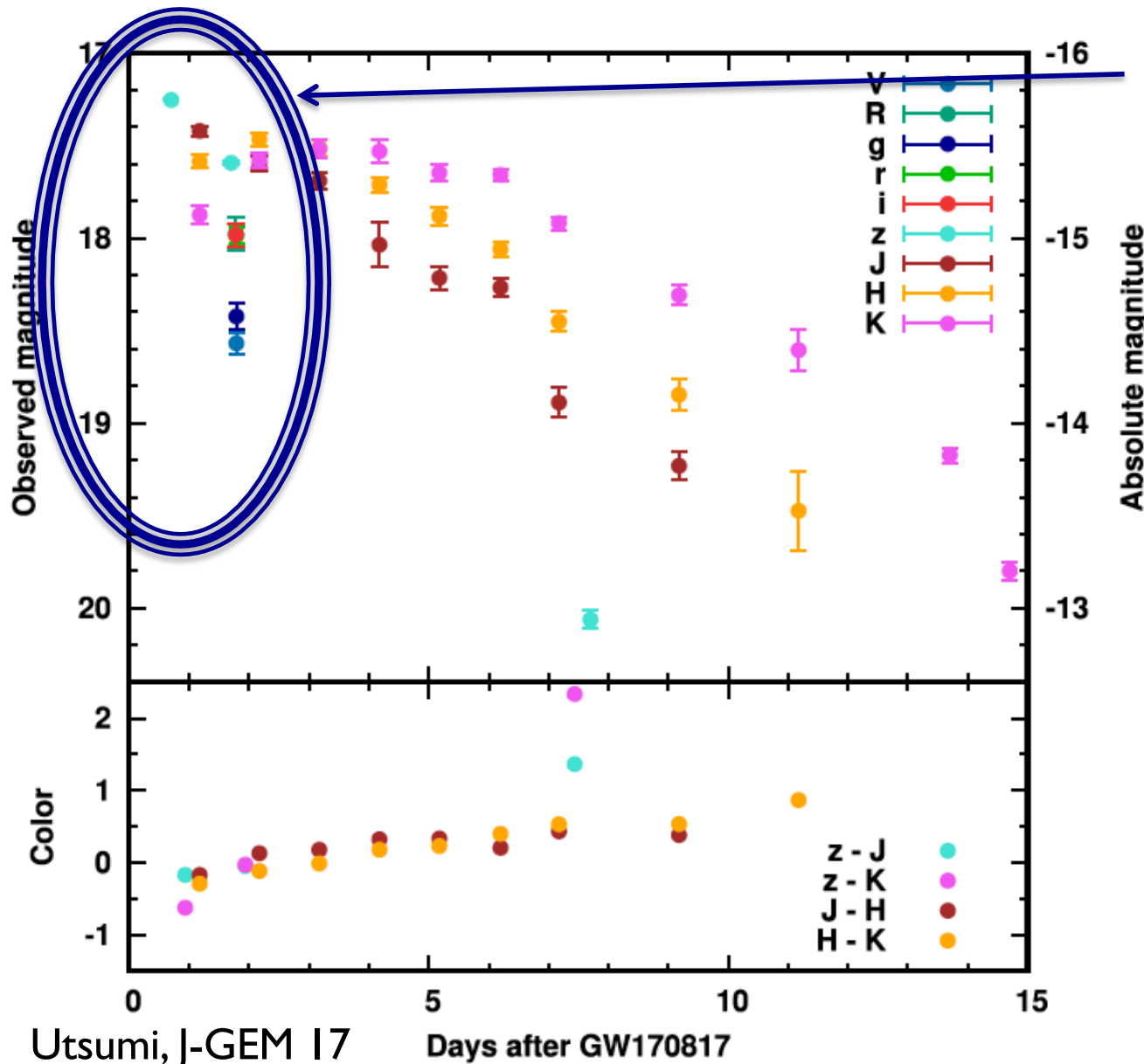
Red macronova

~10 day IR

$T \sim 2000\text{K}$

$L \sim 4e40 \text{ erg/s}$

Macronova/Kilonova



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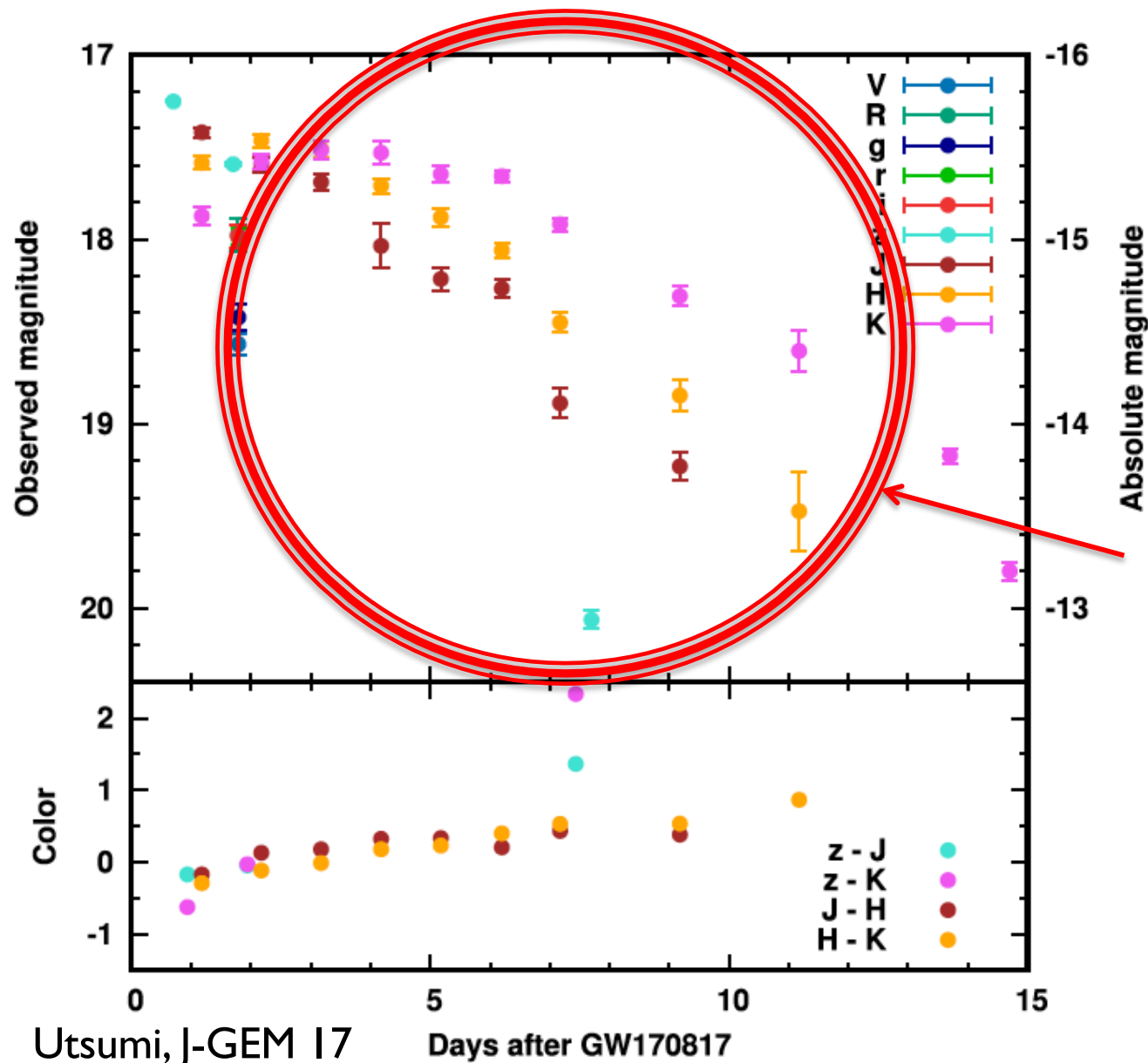
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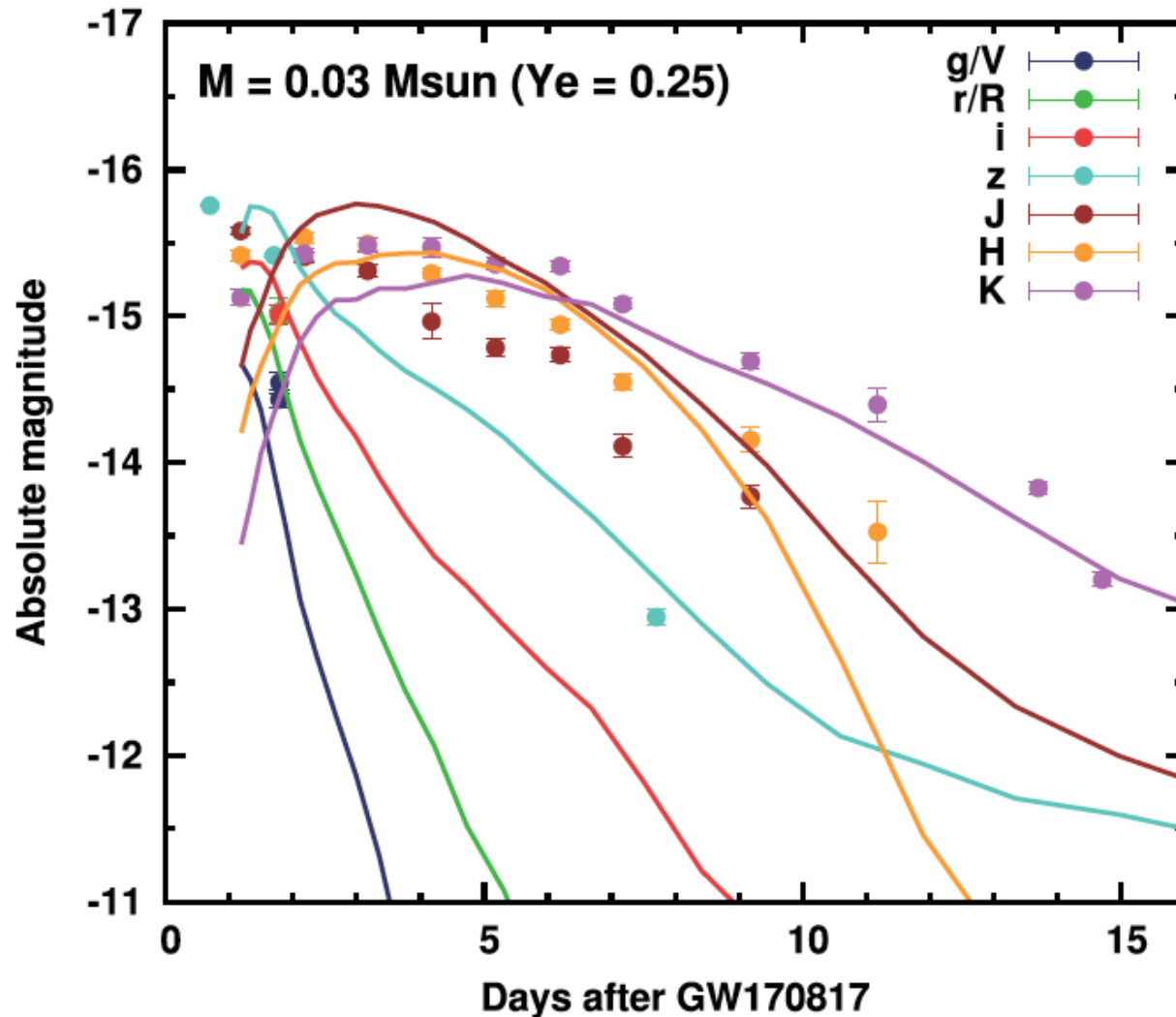
Red macronova

~10 day IR

$T \sim 2000\text{K}$

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Macronova Modelings



Blue macronova

$v \sim 0.3c$

$M \sim 0.02 M_{\odot}$

$\kappa \sim 0.3 \text{ cm}^2/\text{g}$

$(X_{\text{Lan}} \sim 10^{-4})$

Red macronova

$v \sim 0.1-0.2c$

$M \sim 0.03 M_{\odot}$

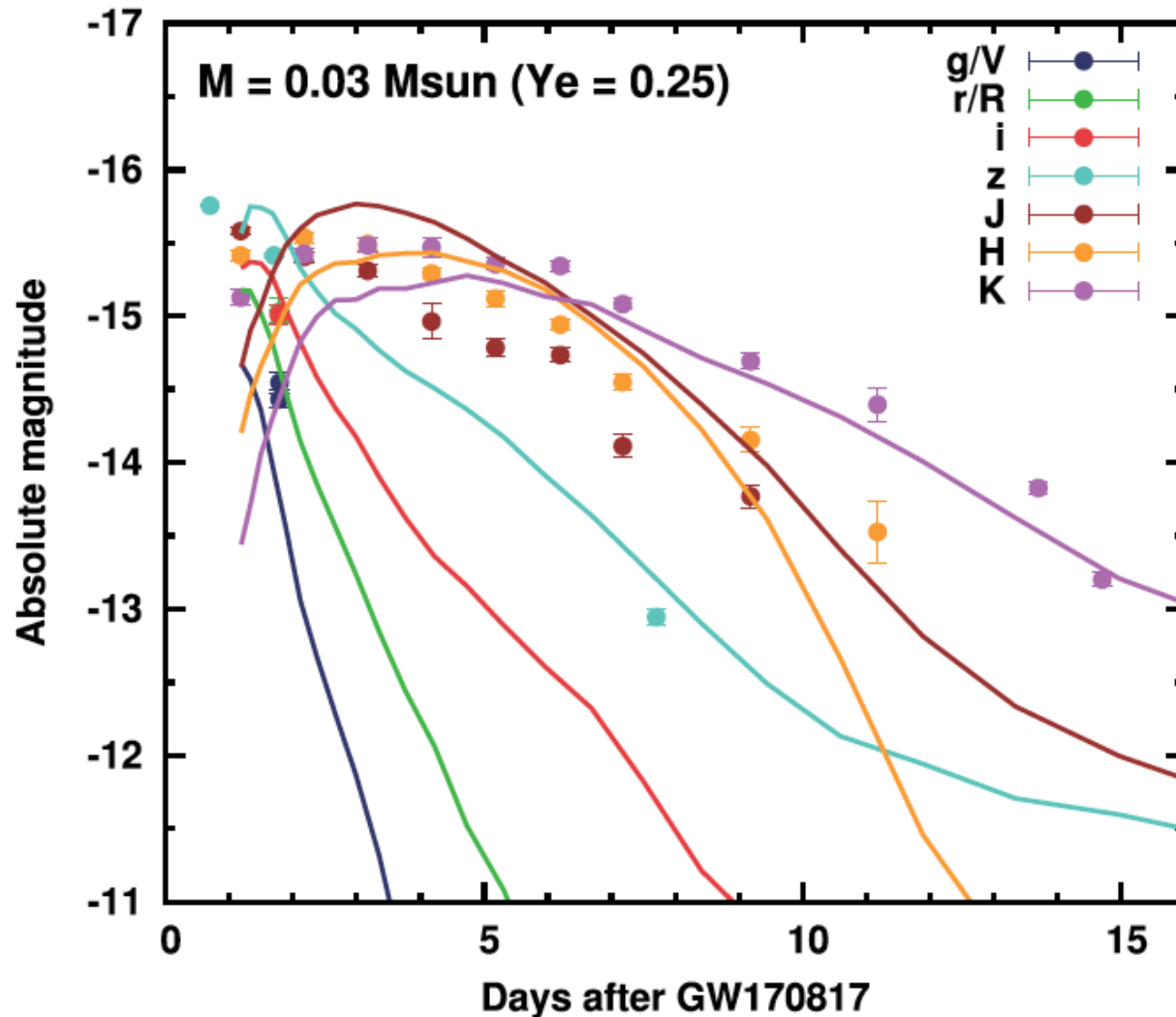
$\kappa \sim 3 \text{ cm}^2/\text{g}$

$(X_{\text{Lan}} \sim 10^{-2})$

Polar or Radial

J-GEM 17, Tanaka+ 17, Utsumi+ 17, Tominaga+ 17, Arcavi+ 17, Drout+ 17, Cowperthwaite+ 17, Villar+ 17, Kasliwal+ 17, Kasen+ 17, Smartt+ 17, Kilpatrick+ 17, Pian+ 17, Chornock+ 17, Coulter+ 17, Evans+ 17, ...

Macronova Modelings



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Polar or Radial

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Galactic Abundance

- **Galactic *r*-process rate**

$$\sim 10^{-6} M_{\odot}/\text{yr}$$

- **Ejected mass**

$$\sim 0.01 M_{\odot}/\text{event}$$

$$\sim 0.03 M_{\odot} \text{ (red)}$$

$$+ 0.02 M_{\odot} \text{ (blue)}$$

- **Event rate**

$$\sim 10^{-4} \text{ events/yr/galaxy}$$

$$\sim 10^3 \text{ events/Gpc}^3/\text{yr}$$

$$\sim 1540^{+3200}_{-1220} / \text{Gpc}^3/\text{yr}$$

- $X_{\text{Lanthanide}} \sim 0.03$

$$X_{\text{Lanthanide}} < 0.01$$

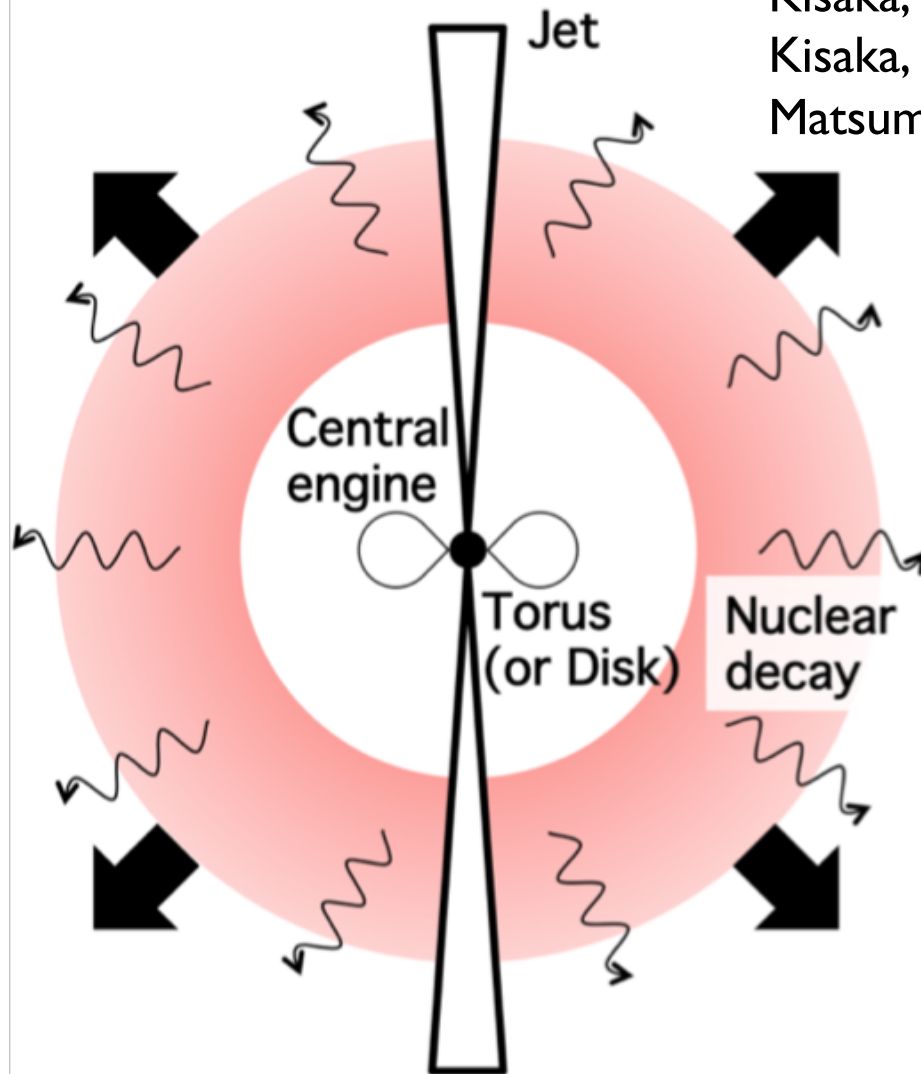
NS² = r-process origin?

Engine-Powered Macronova?

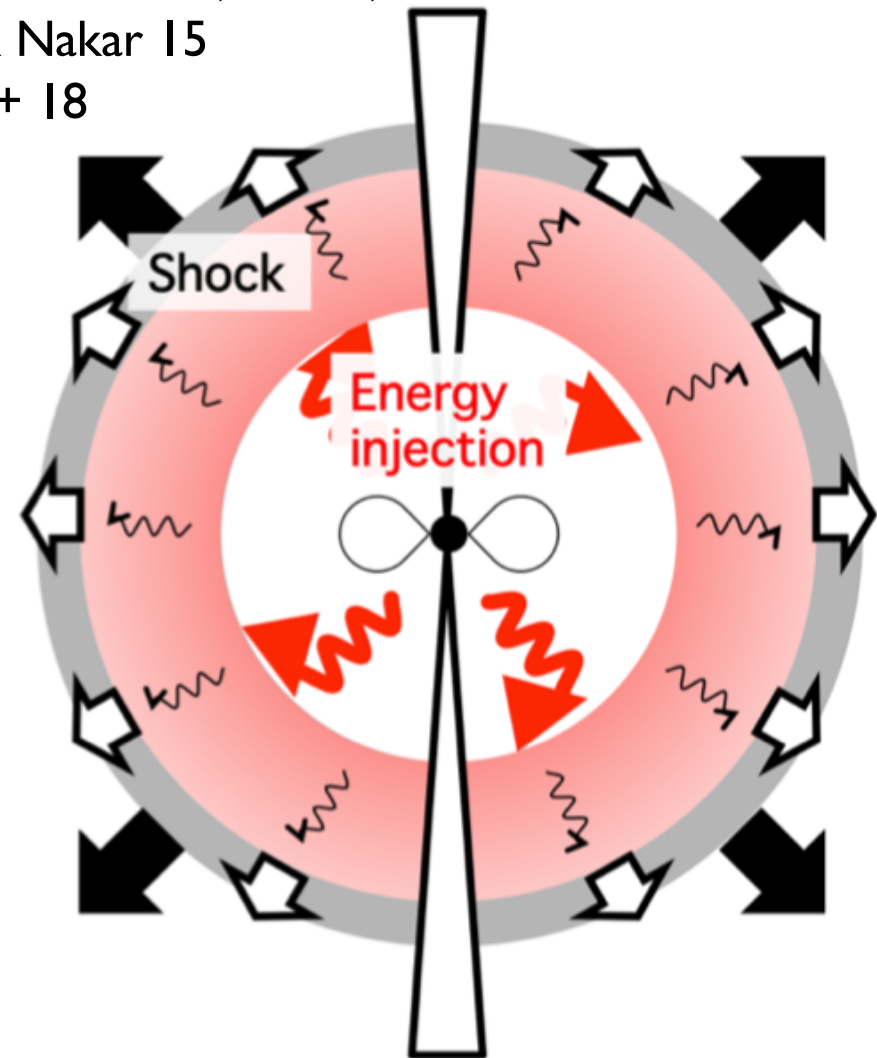
Kisaka, KI & Takami 14, Kisaka, KI & Nakamura 15

Kisaka, KI & Nakar 15

Matsumoto+ 18

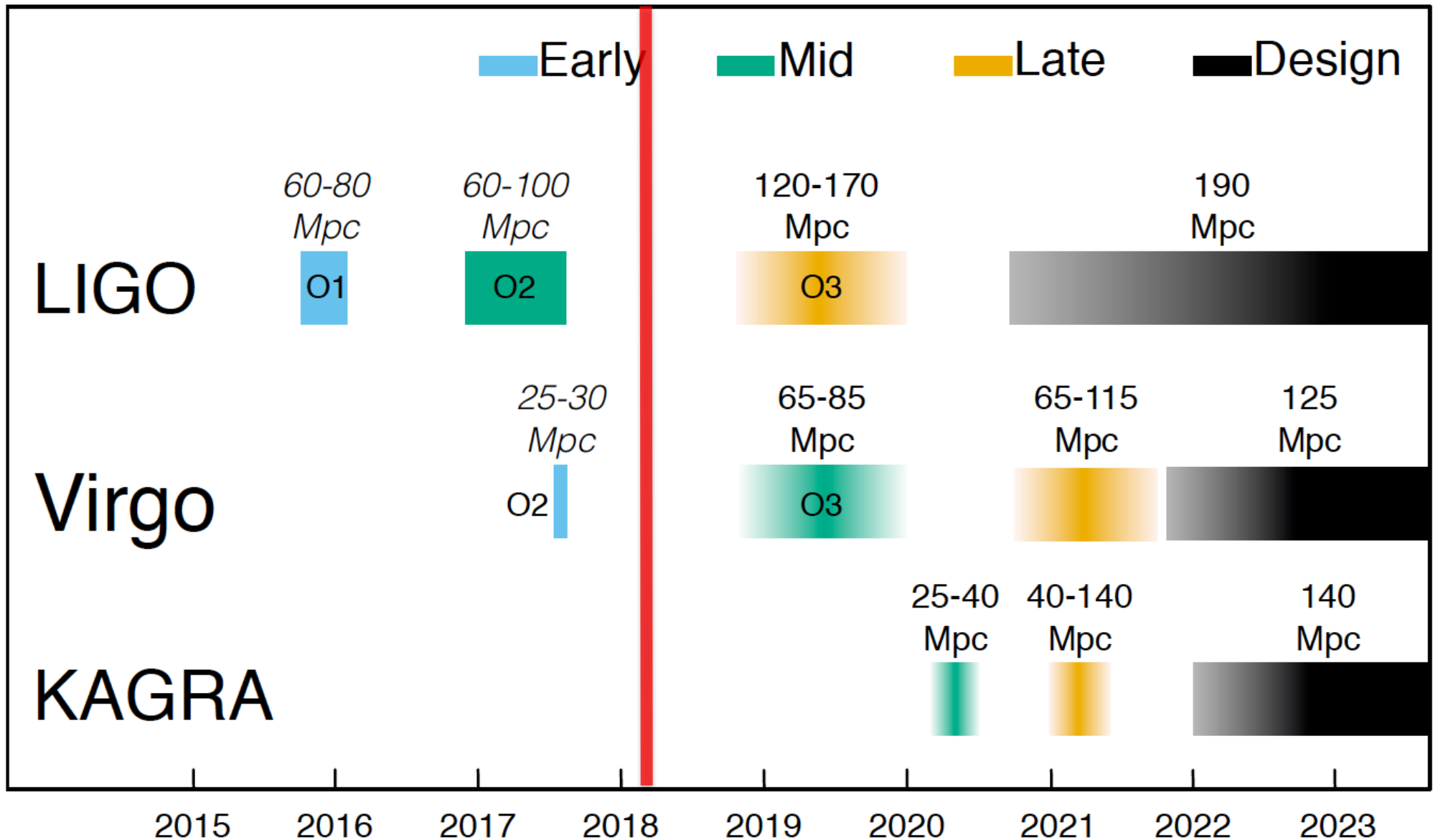


R-process model



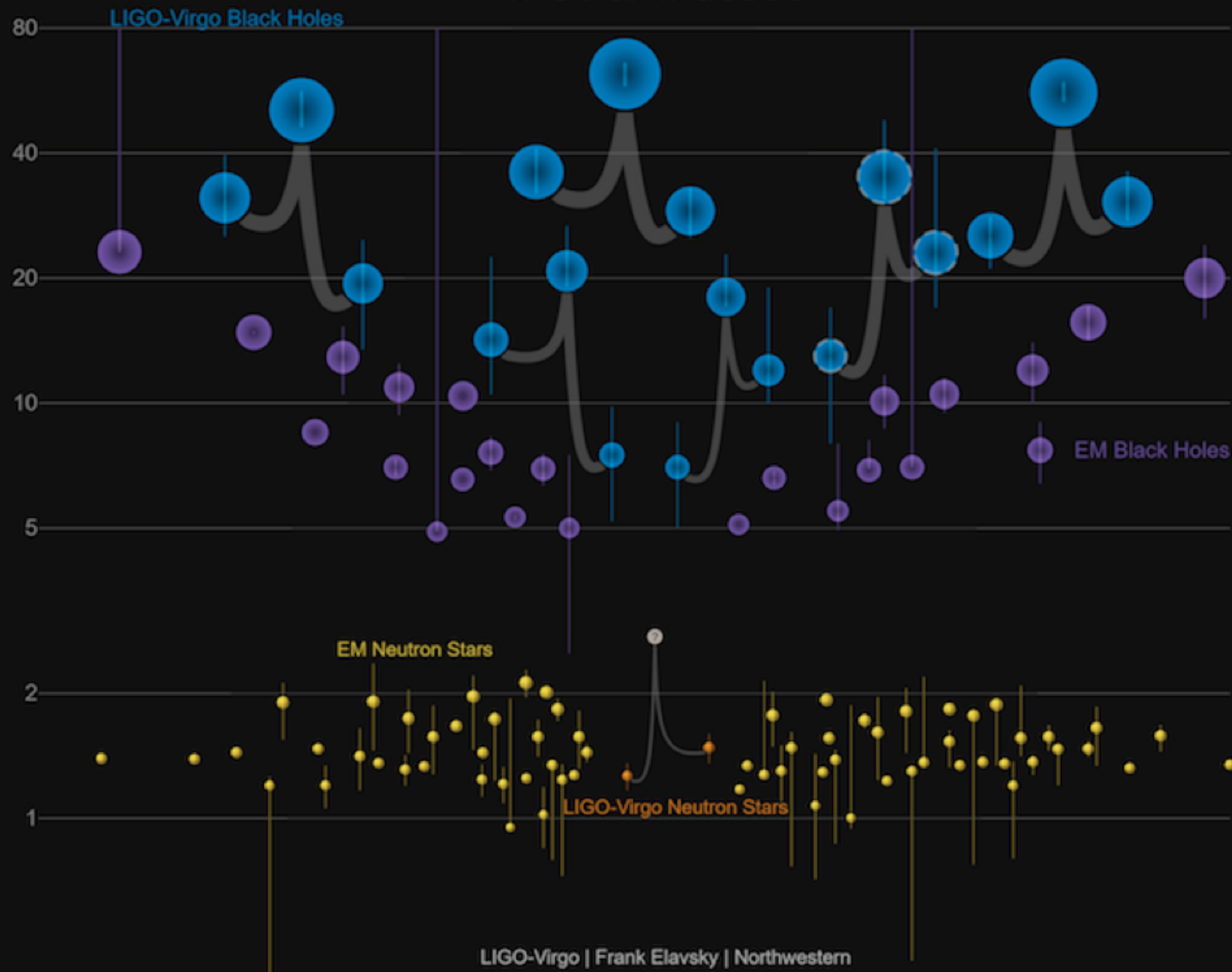
Engine model

Future GW Observations



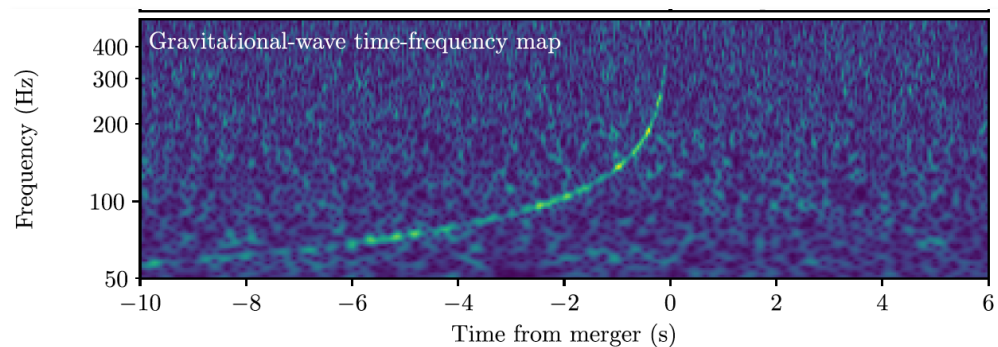
Masses in the Stellar Graveyard

in Solar Masses

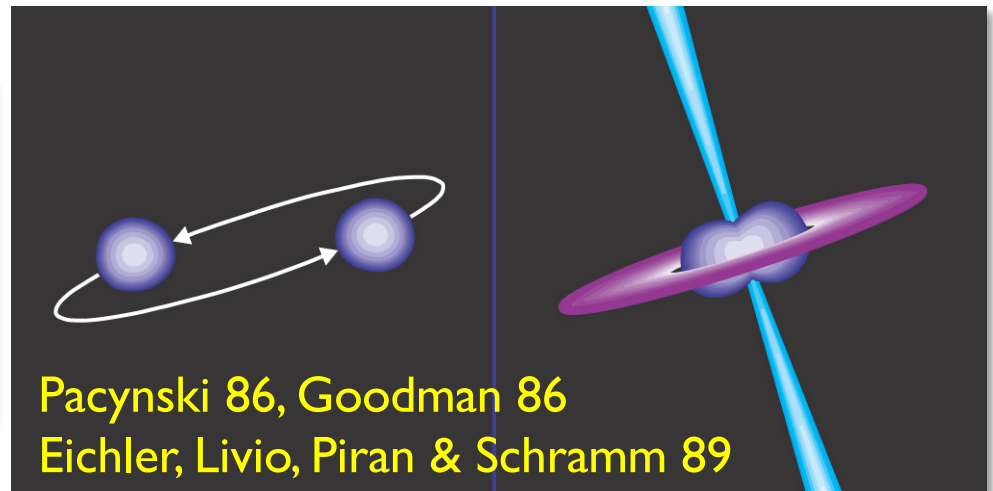


GW170817

1st GW from NS²



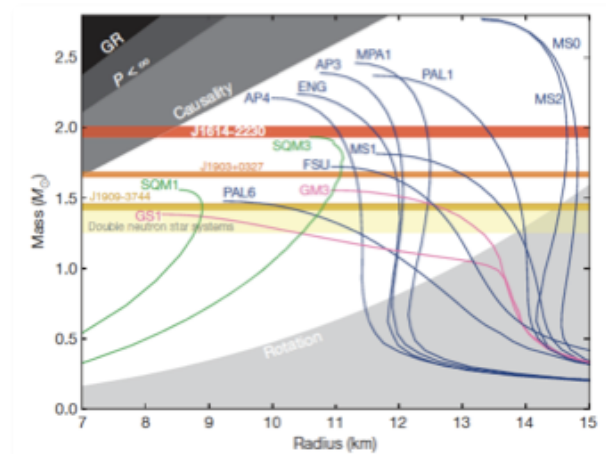
NS² = Short GRB?



R-process elements

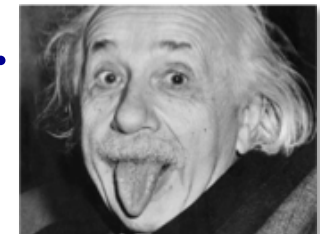


Equation of state



Relativity,
Cosmology,

...



Thank

You