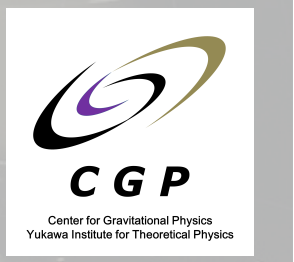
Recent Progresses in Gravitational Wave Astrophysics

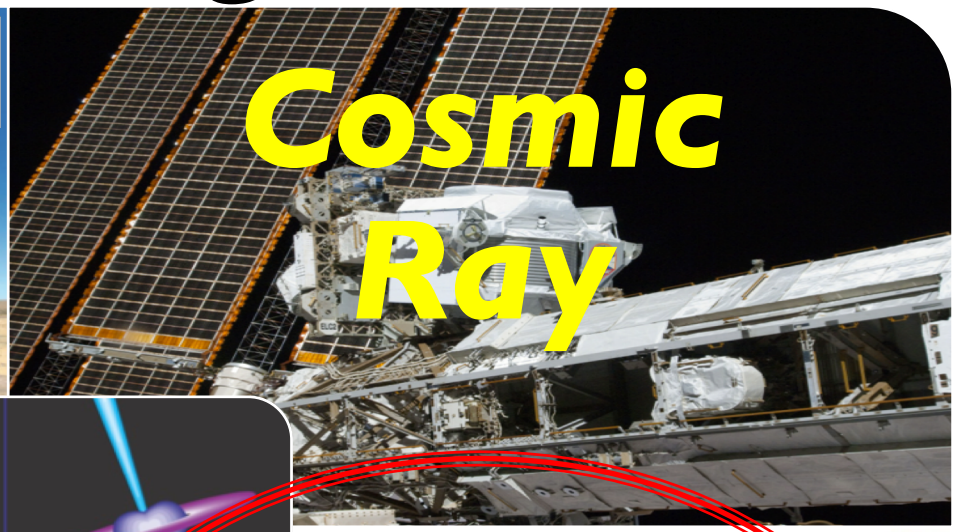
井岡 邦仁 ***Kunihito IOKA***

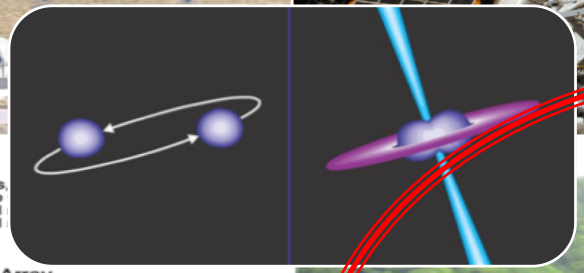
(Center for Gravitational Physics, YITP, Kyoto U)

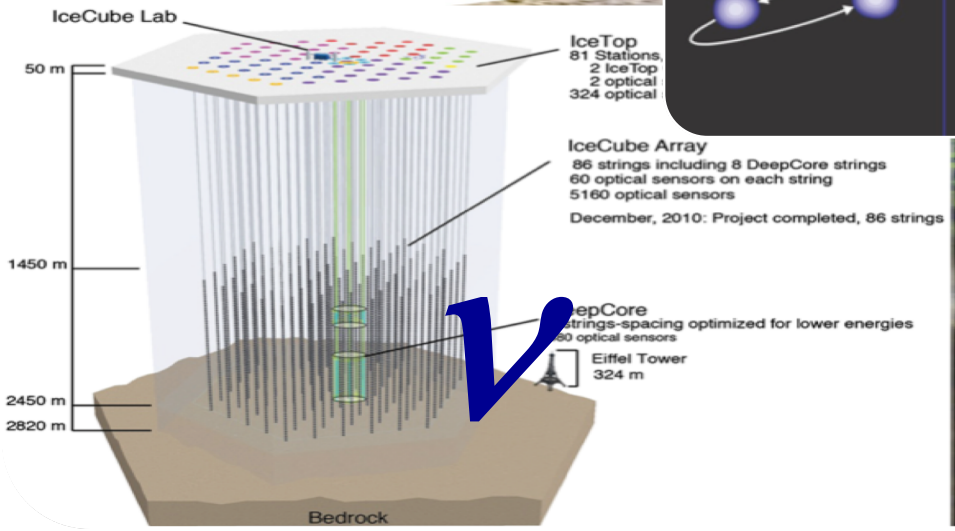
YITP
YUKAWA INSTITUTE FOR THEORETICAL PHYSICS



Multi-Messenger Era

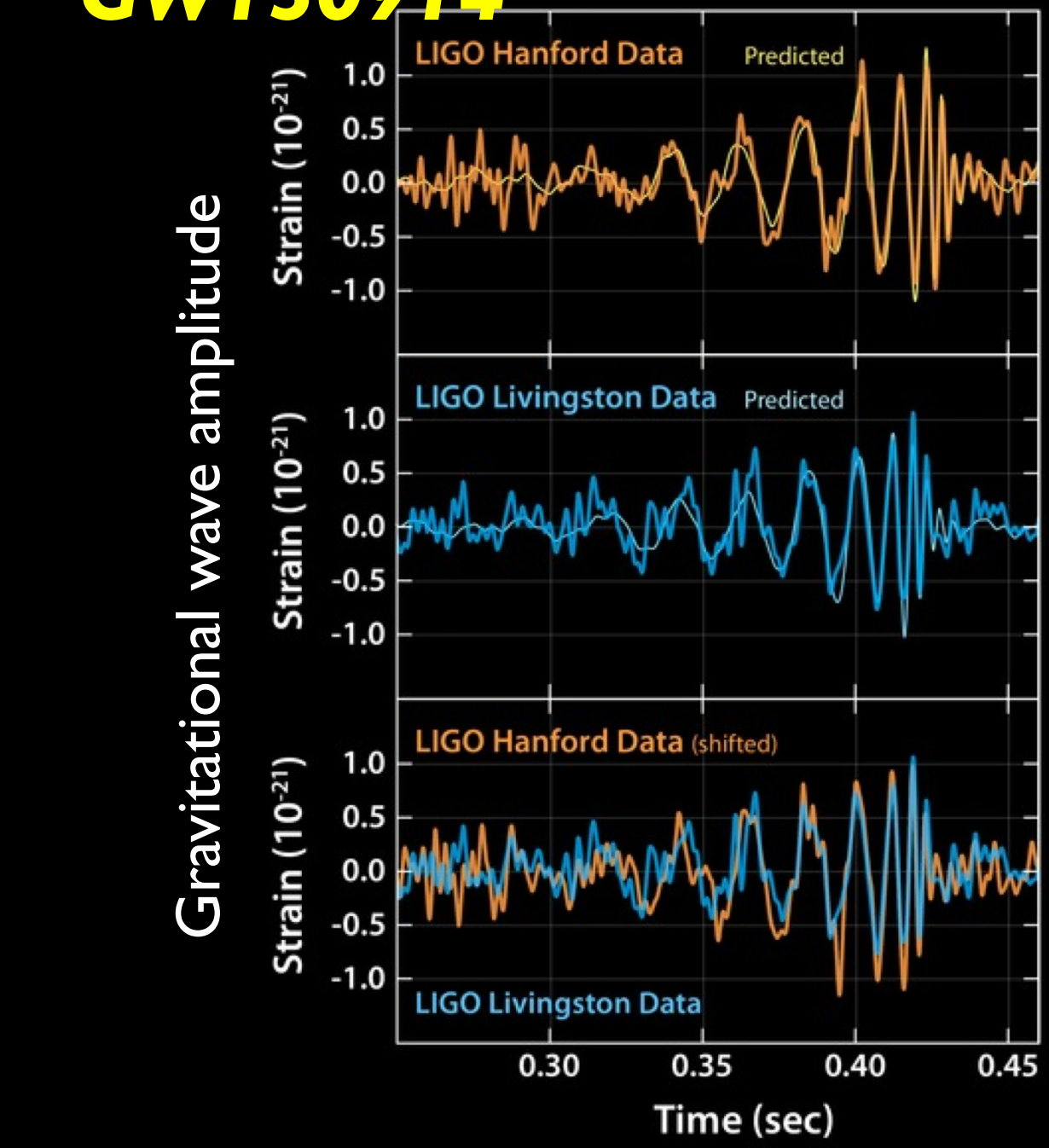




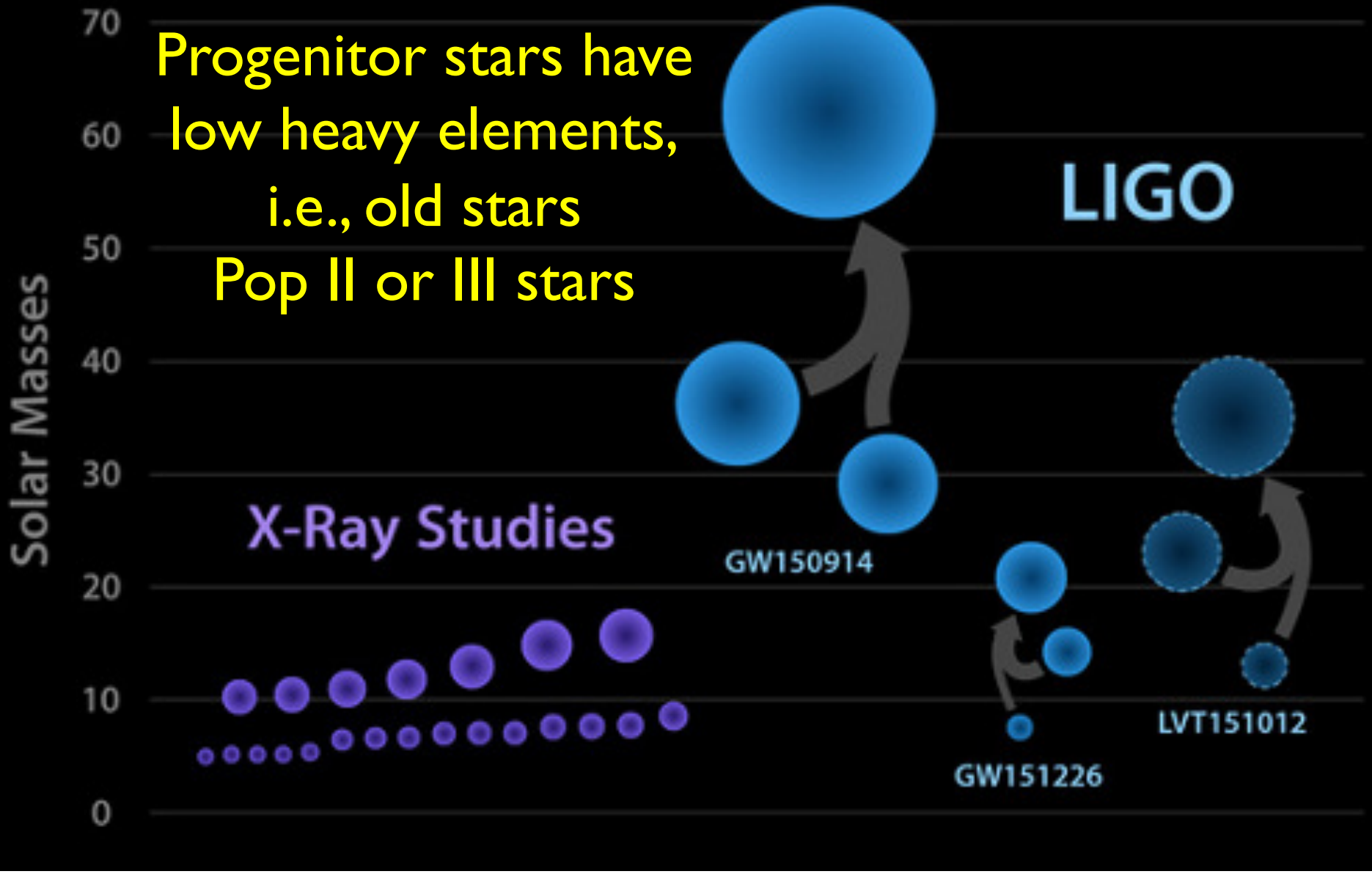


21th Century: Multi-Messenger Era

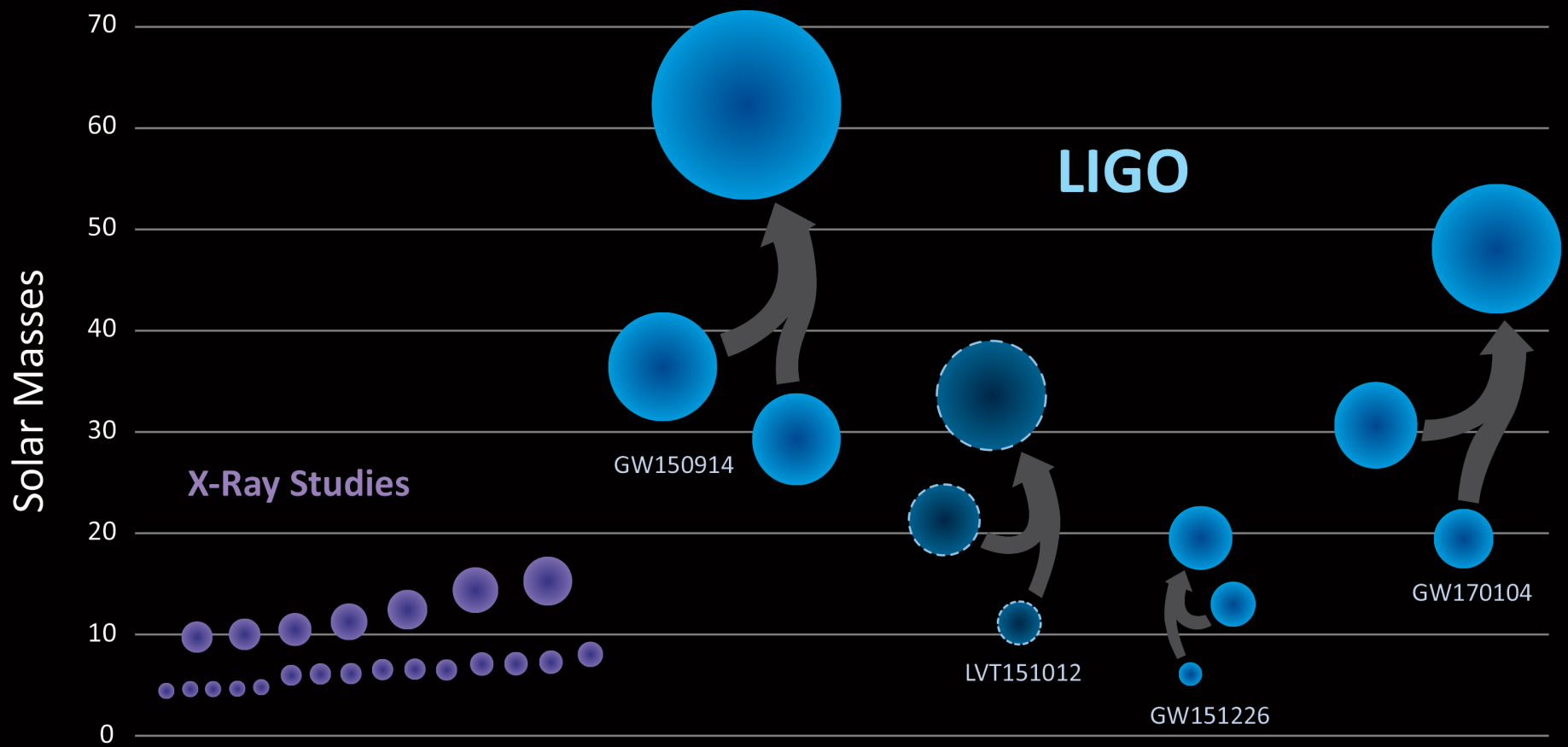
GW150914


Gravitational wave amplitude
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

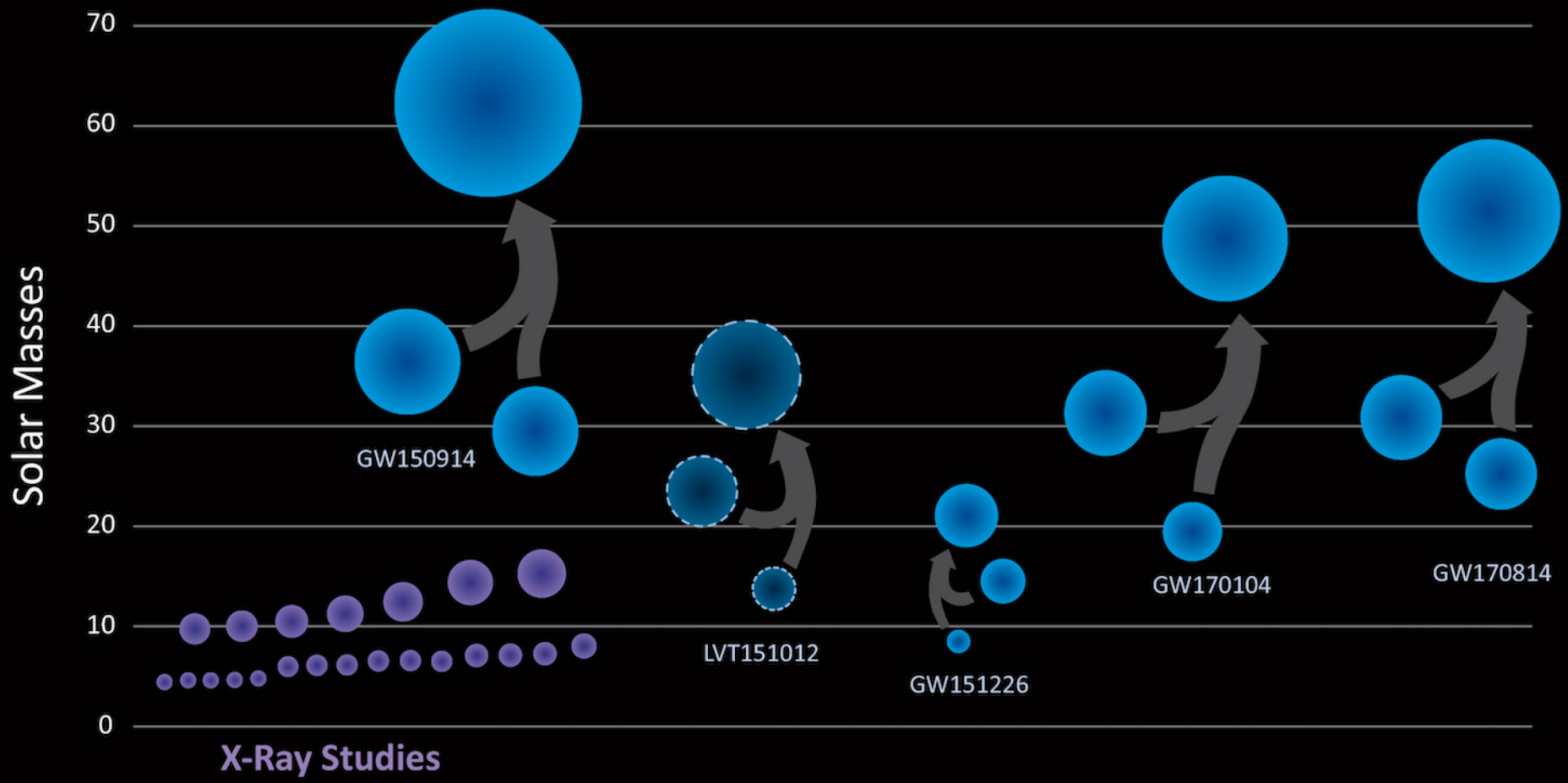
Black Holes of Known Mass



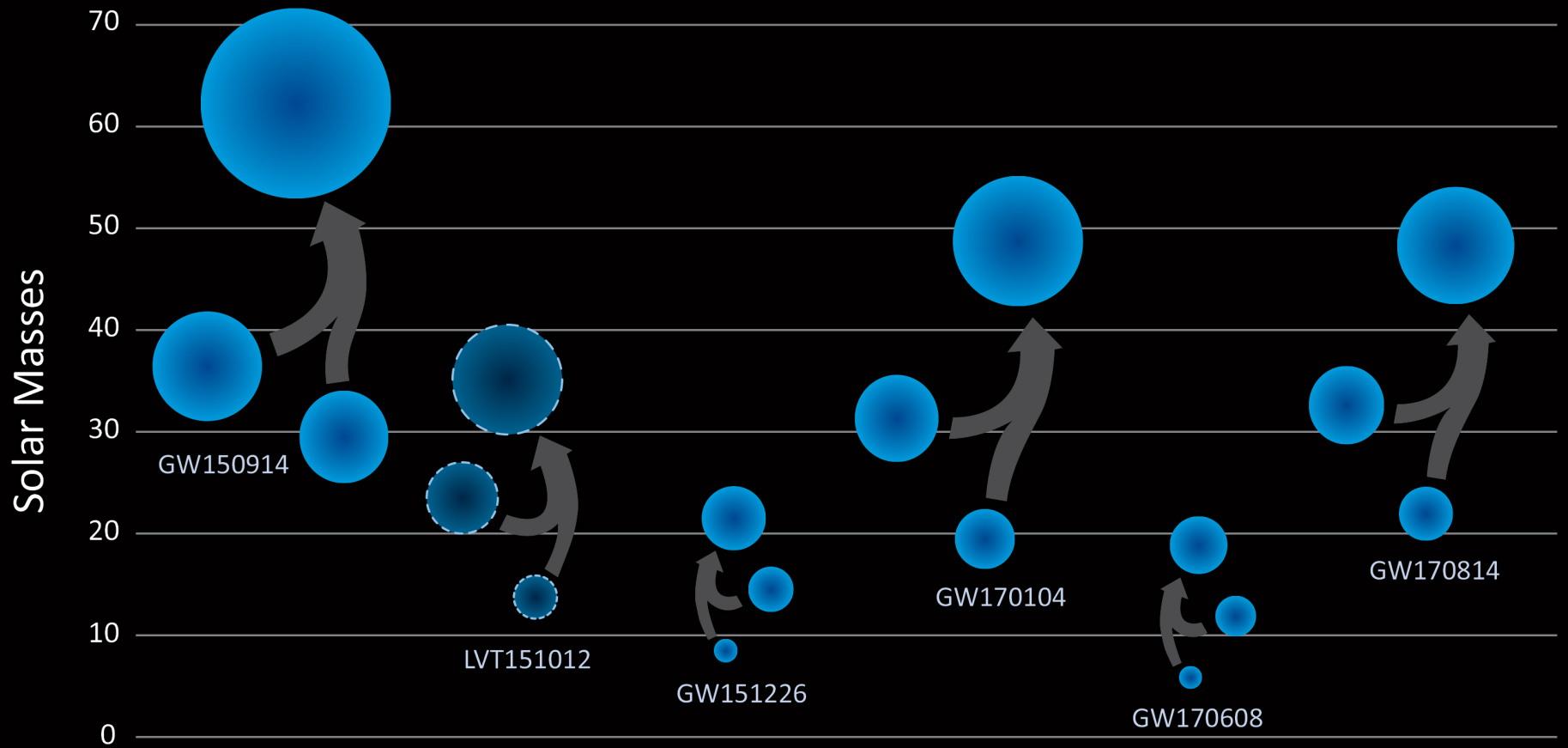
Black Holes of Known Mass

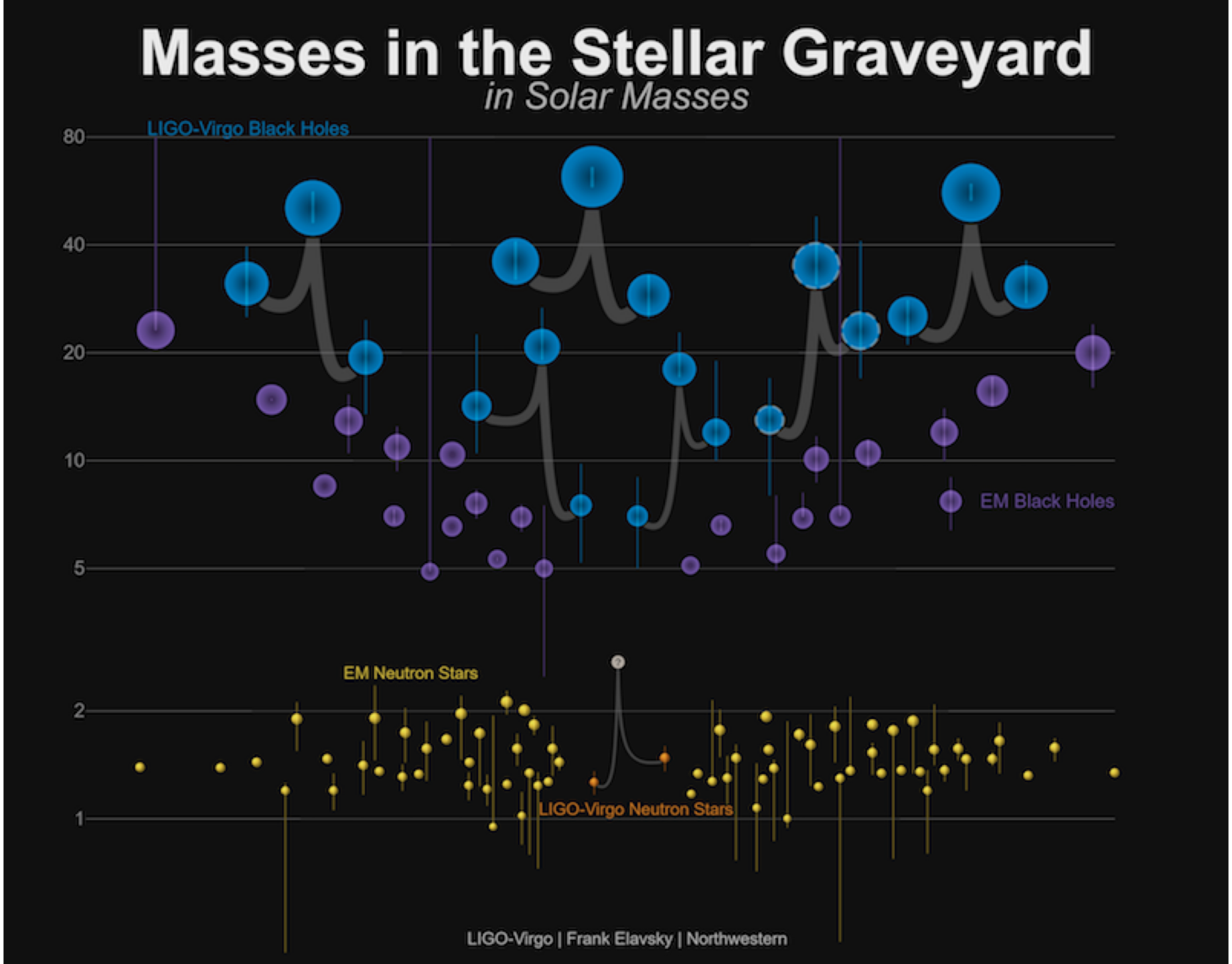


Black Holes of Known Mass

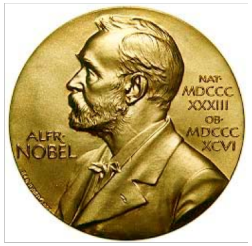


Black Holes of Known Mass

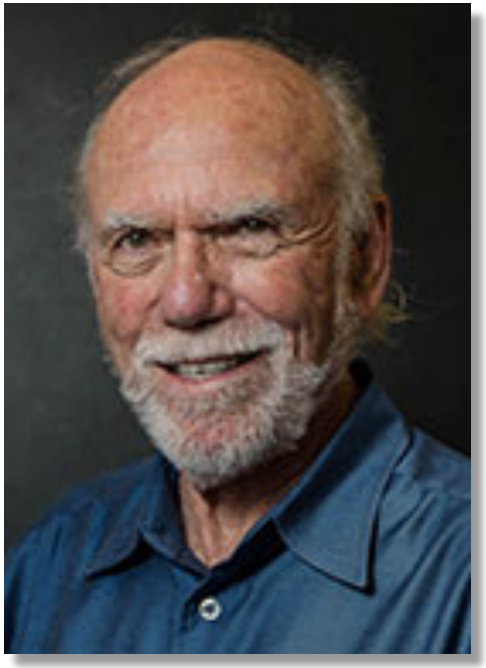



Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

The Nobel Prize in Physics 2017



Rainer Weiss



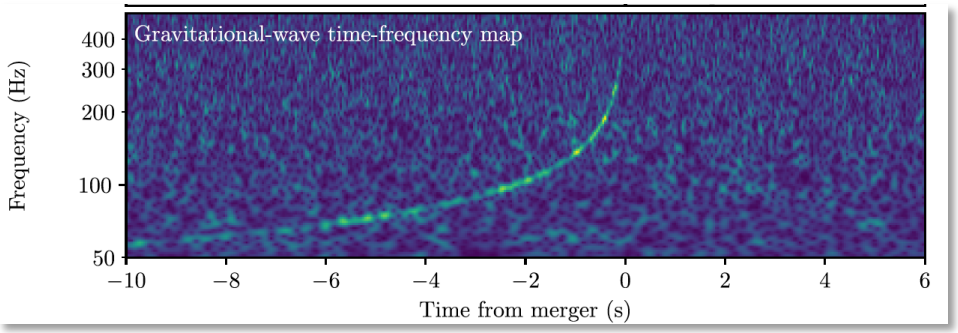
Barry C. Barish

Kip S. Thorne

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

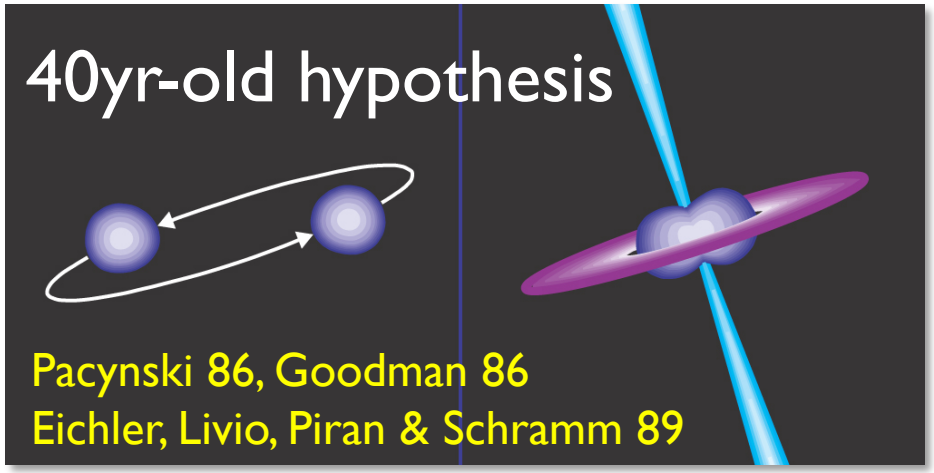
GW170817

1st GW from NS²



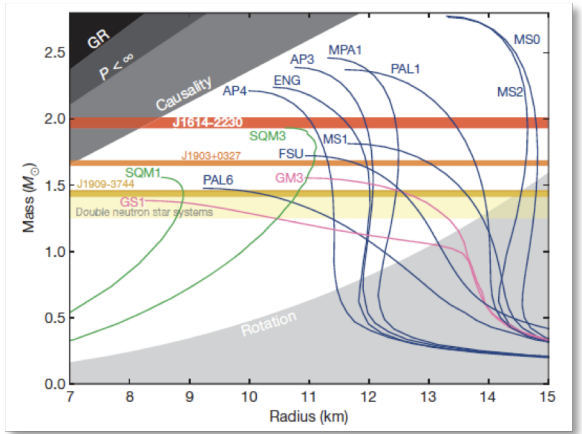
~100 sec chirp ⇒ NS-NS

NS² = Short GRB?

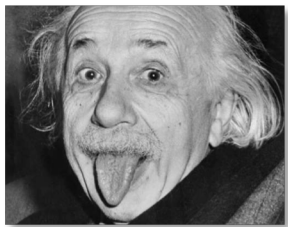


R-process elements

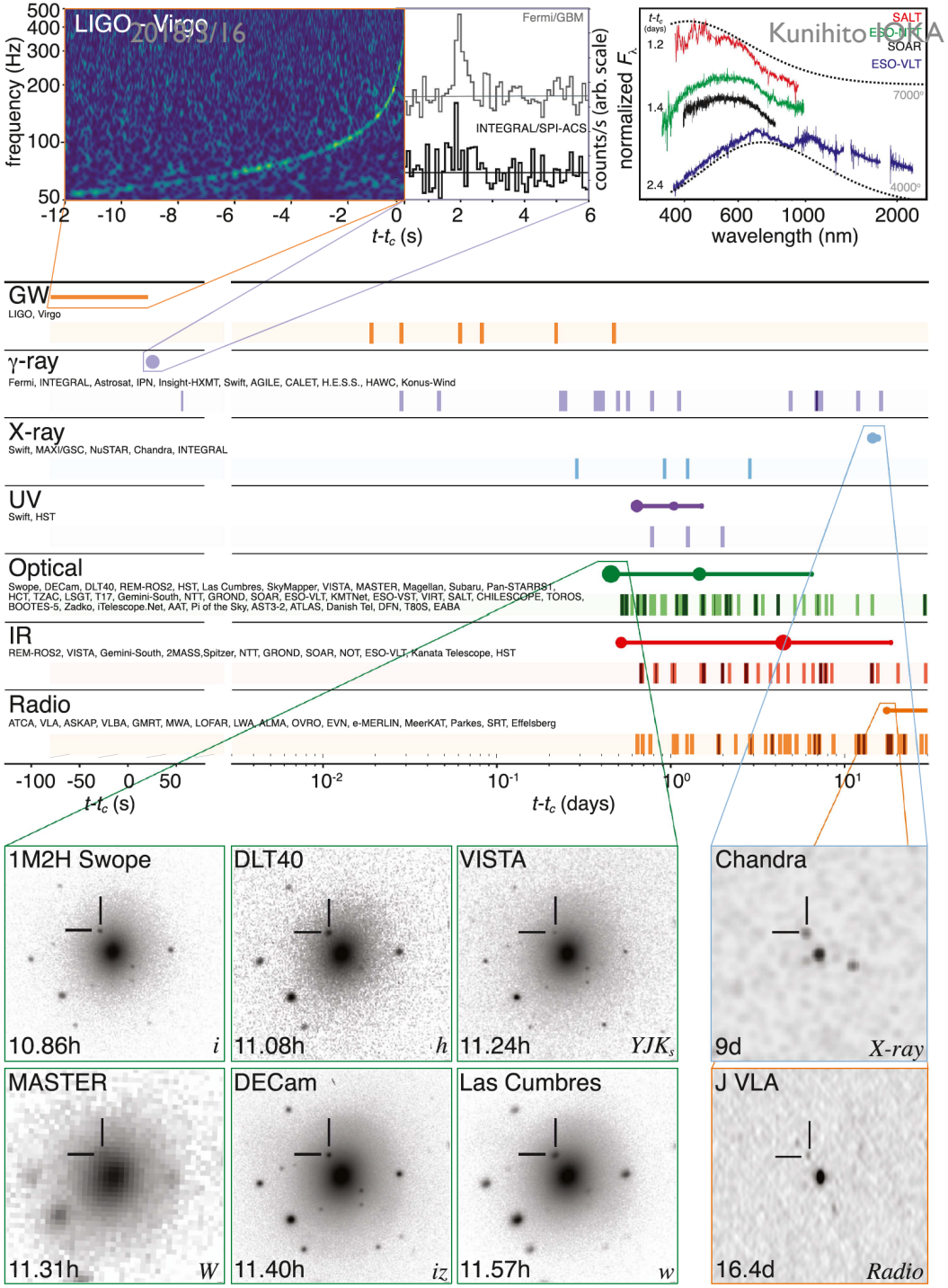
Equation of state



Relativity,
Cosmology,
…



New Era of Multi-Messenger



Follow-up observations

>3000 people

γ-ray: ~1.734 ± 0.054 sec

⇒ sGRB 170817A

UV-Opt-IR: 10.86 hr

⇒ Macronova/Kilonova

X, radio: ~10 day

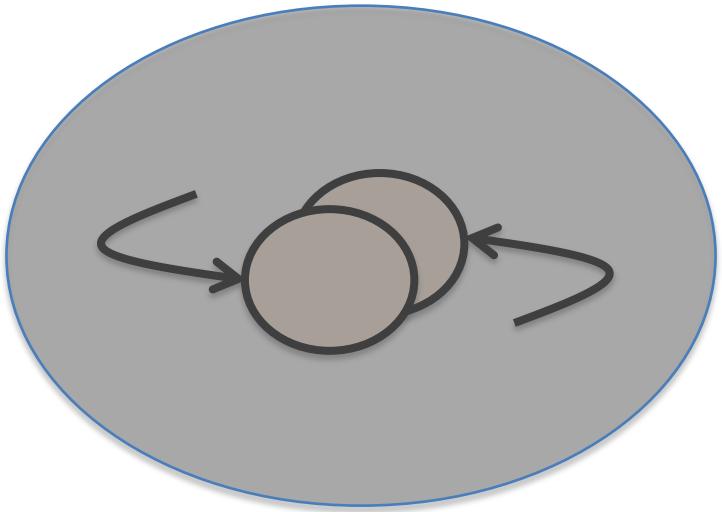
⇒ Afterglow

LVC-EM 17

Band: GCN circ., Circles ∝ brightness

Before GW170817

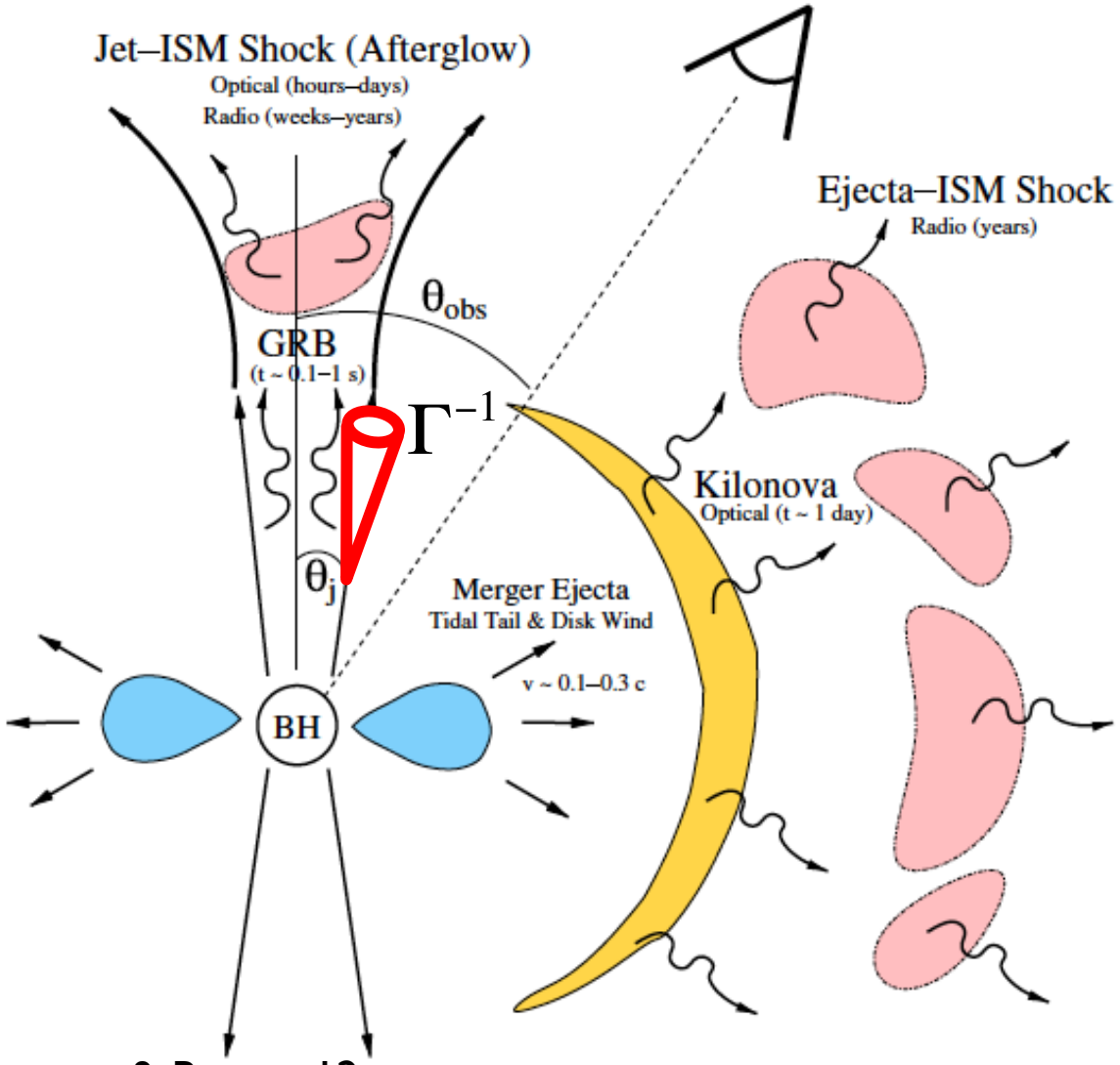
Optically Thick



Optical depth

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

EM Counterparts



Metzger & Berger 12

GRB was thought to be too faint

On-axis fraction

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

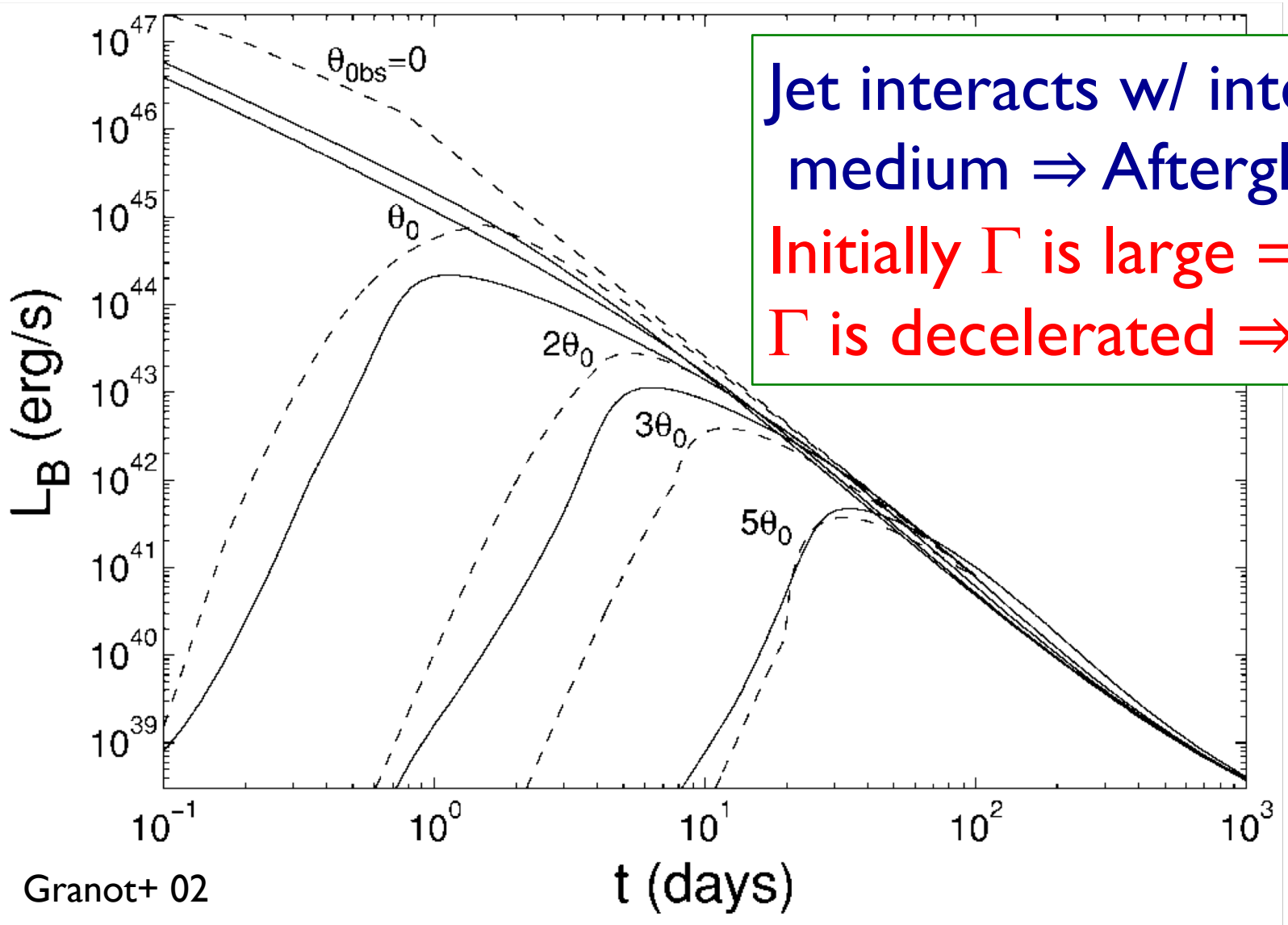
Off-axis energy

$$E_{\rm iso} \propto \delta^3 \propto \theta_{\rm v}^{-6}$$

(point source case)

$$\delta \equiv \frac{1}{\Gamma(1-\beta\cos\theta_{\rm v})}$$

Off-Axis Afterglow



Granot+ 02

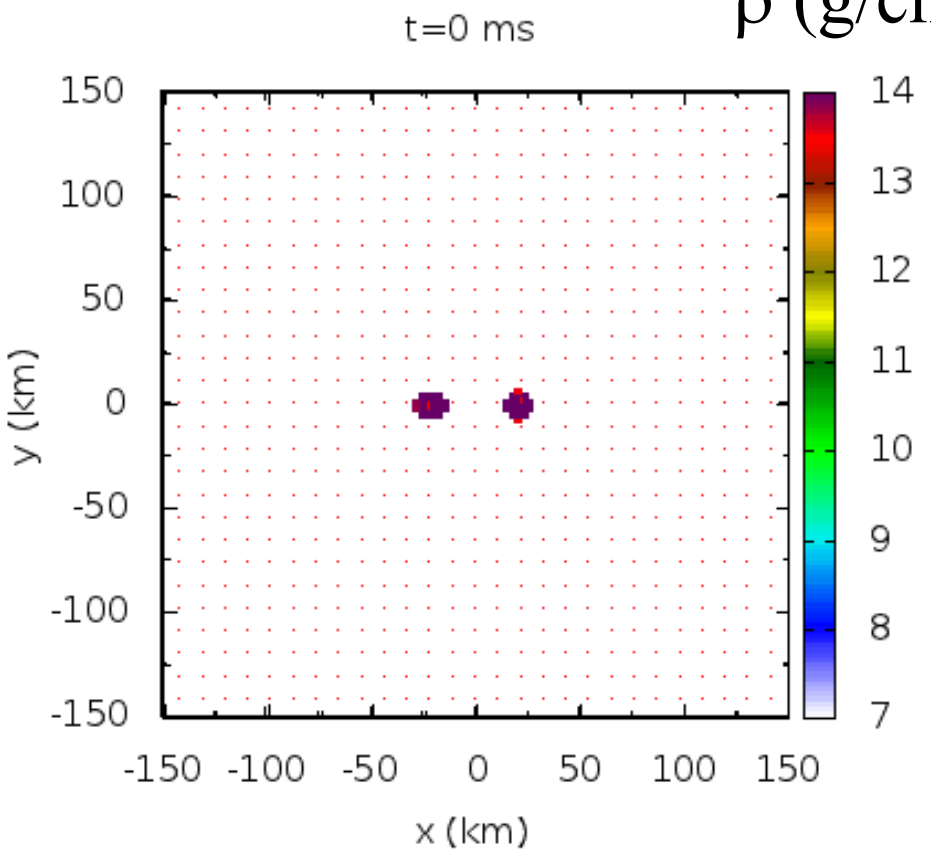
Jet interacts w/ interstellar medium ⇒ Afterglow

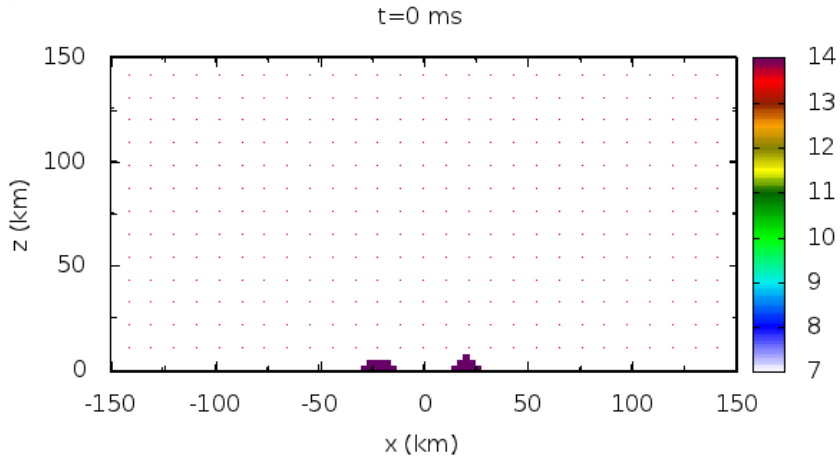
Initially Γ is large ⇒ Faint

Γ is decelerated ⇒ θ_{obs}~0

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

ρ (g/cm^3)





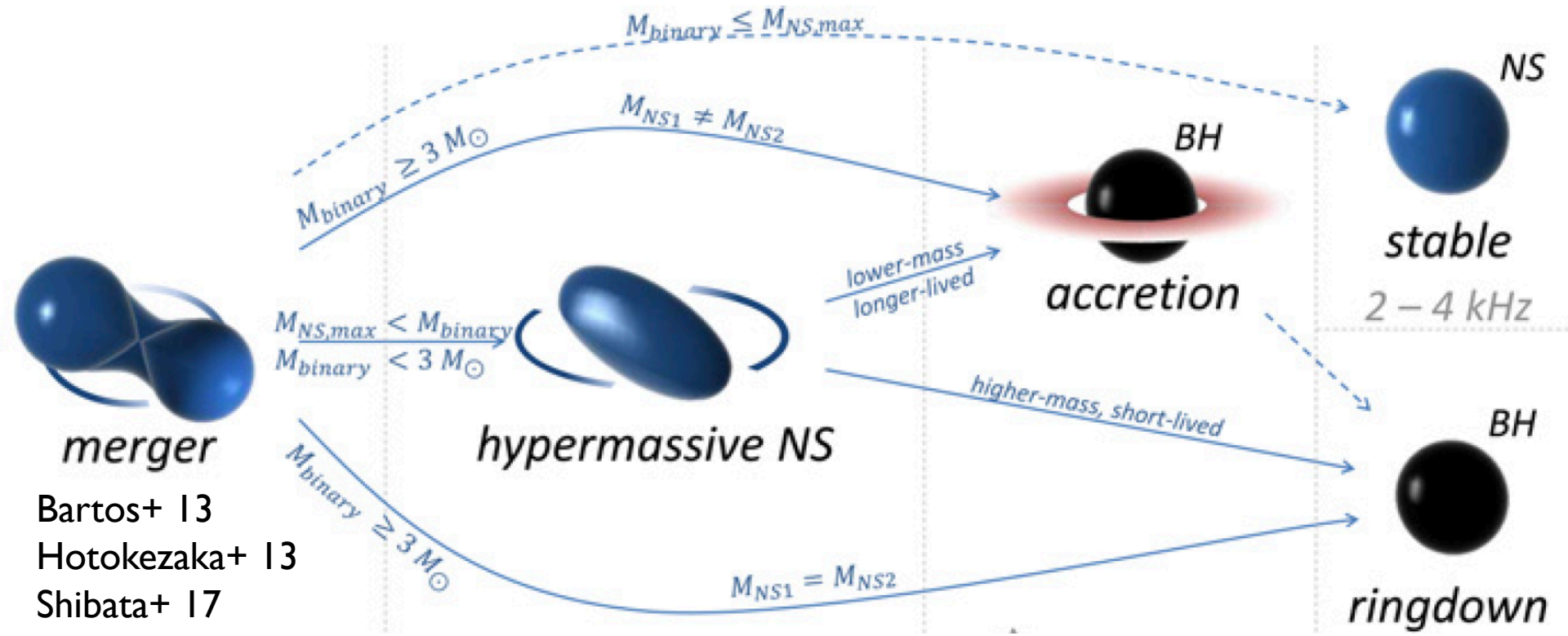
Relatively wider view

Orbital plane

***X-Z* plane**

©Shibata, Hotokezaka

Final Fates of Mergers



Bartos+ 13
Hotokezaka+ 13
Shibata+ 17

$2M_\odot$ neutron stars

PSR J1614-2230 ($M = 1.928^{+0.017}_{-0.017} M_\odot$)

PSR J0348+0432 ($M = 2.01^{+0.04}_{-0.04} M_\odot$)

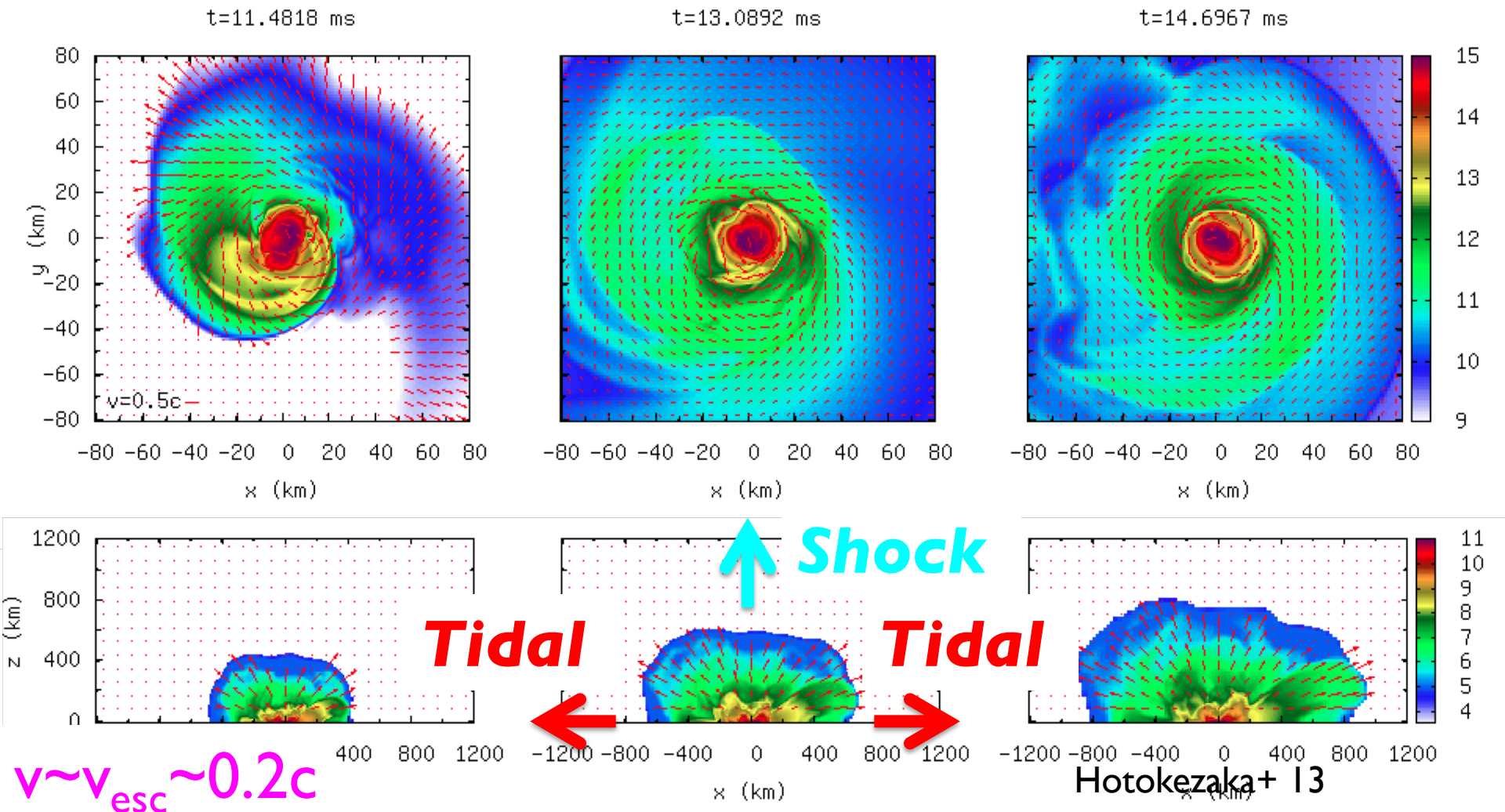
Demorest+ 10, Antoniades+ 13, Fonseca+ 16

$M_{tot} < \sim 2.8 M_\odot$

$\Rightarrow$ HMNS/MNS

$\leftrightarrow$ 2.73~2.78 $M_\odot$ (90%)

Dynamical Ejecta



$v \sim v_{esc} \sim 0.2c$

$M < 0.01 M_\odot$

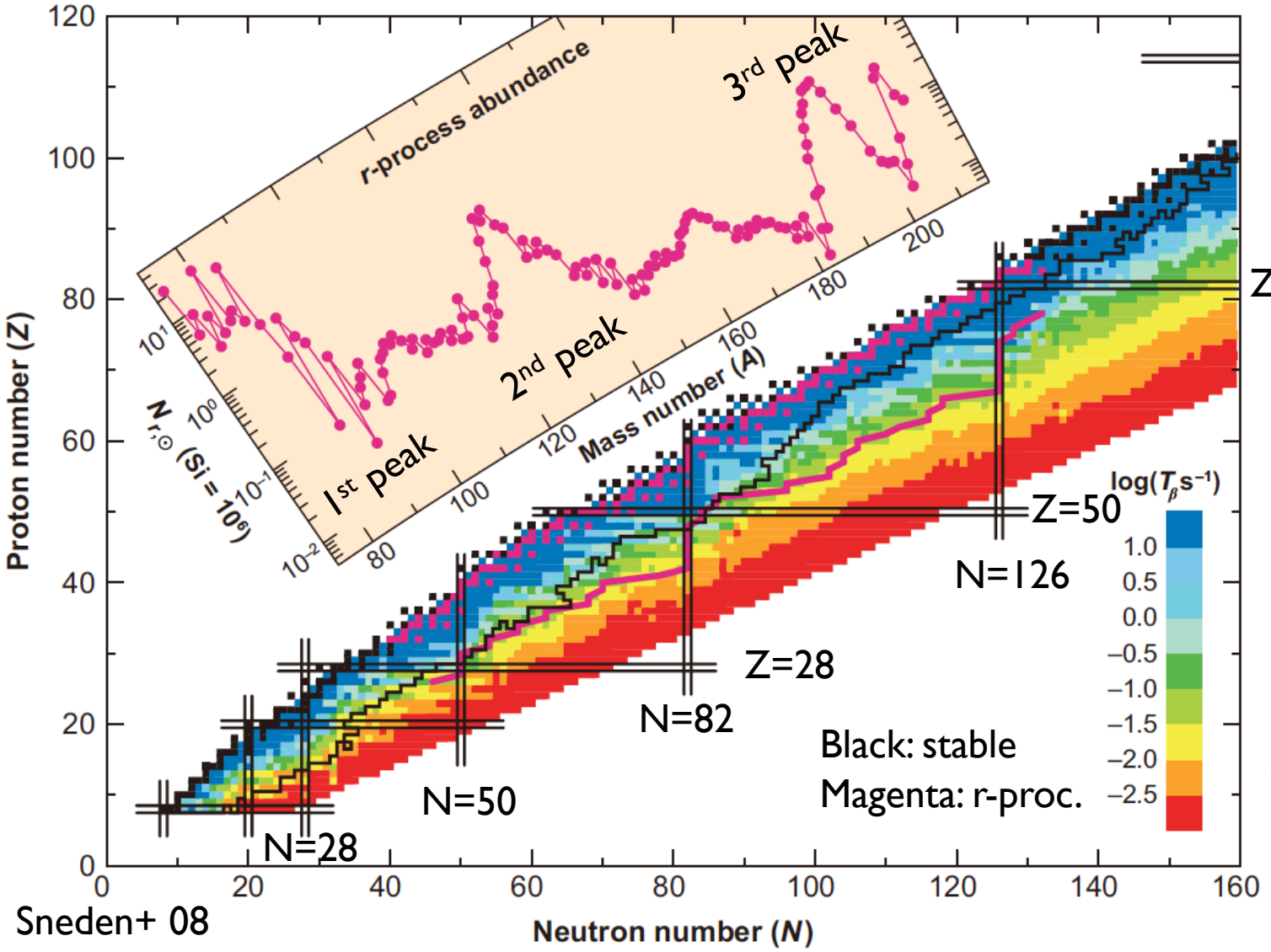
Quasi-spherical

Hotokezaka+ 13

Bauswein+ 13,

Sekiguchi+ 15, many others

r-Process Nucleosynthesis



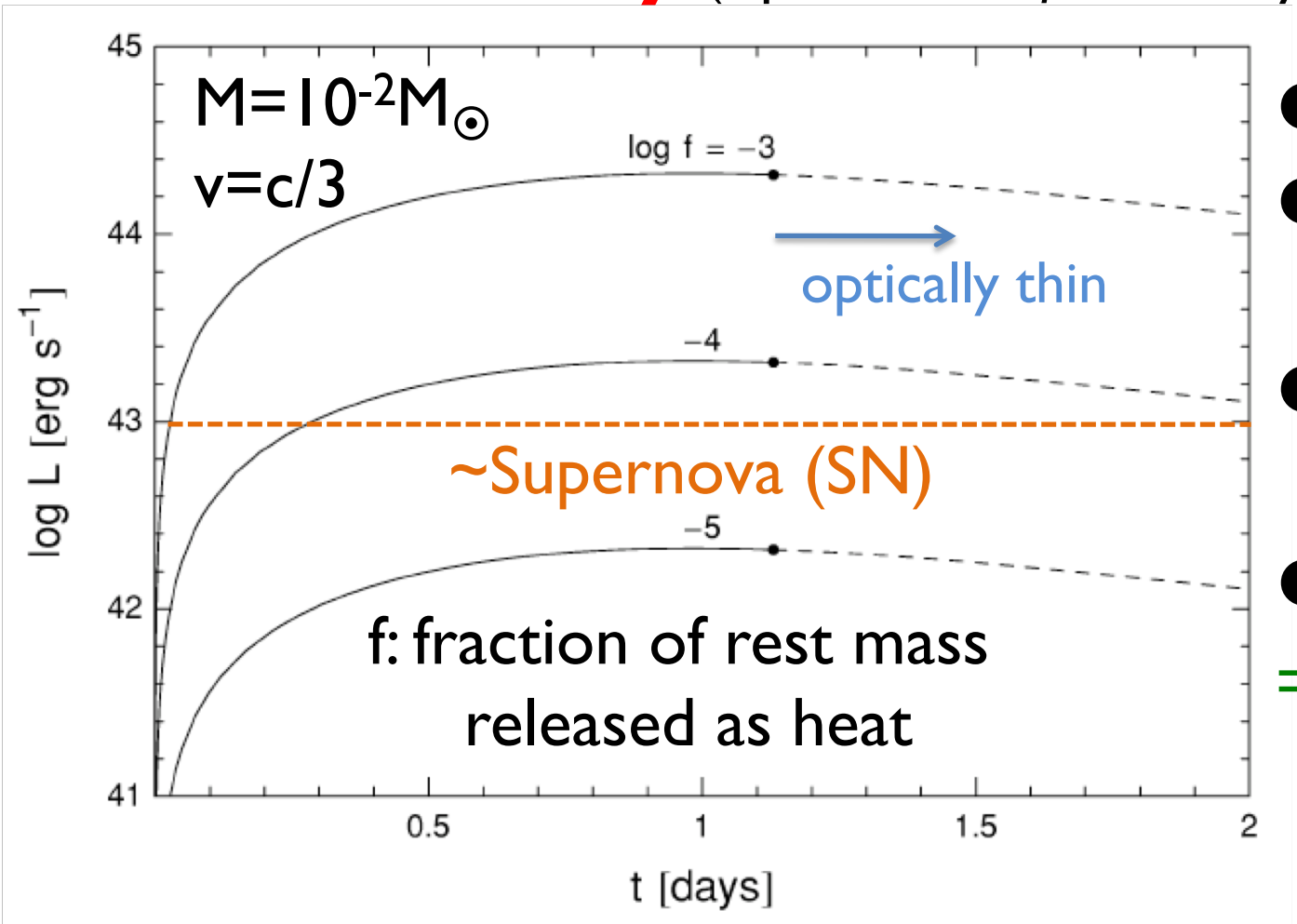
Sneden+ 08

Neutron-rich ejecta

Neutron -capture >> β-decay

Macronova/Kilonova

Radioactivity (r-process → β-, α-decay, fission, …)



- ≈Supernova
- $t_{diffusion} \propto (\kappa M/v)^{1/2}$
- $T \propto (f^2/Mv)^{1/8}$
  ~ IR-Opt
- f~3x10^{-6}

⇒ Faint SN

Li & Paczynski 98
Kulkarni 05
Metzger+ 10

Macronova Characteristic

Duration
(~Optically thin)

$$t_c = \left(\frac{3\kappa M}{4\pi V^2}\right)^{1/2}$$

~10days for SN

$$= 1.13 \text{ days } \left(\frac{M}{0.01\ M_\odot}\right)^{1/2} \left(\frac{3V}{c}\right)^{-1} \left(\frac{\kappa}{\kappa_e}\right)^{1/2}.$$

~0.1cm²/g

Luminosity

$$\frac{f\left(0.01 M_{\rm sun}\right)c^2}{\left(1{\rm day}\right)} \approx 10^{42} {\rm erg\ s^{-1}} f_{-5}$$

$$f \sim \frac{\rm MeV}{\rm 100GeV} \sim 10^{-5}$$

$$\approx -16\ {\rm mag}_{bol} \approx 10^3 L_{nova}$$

kilonova

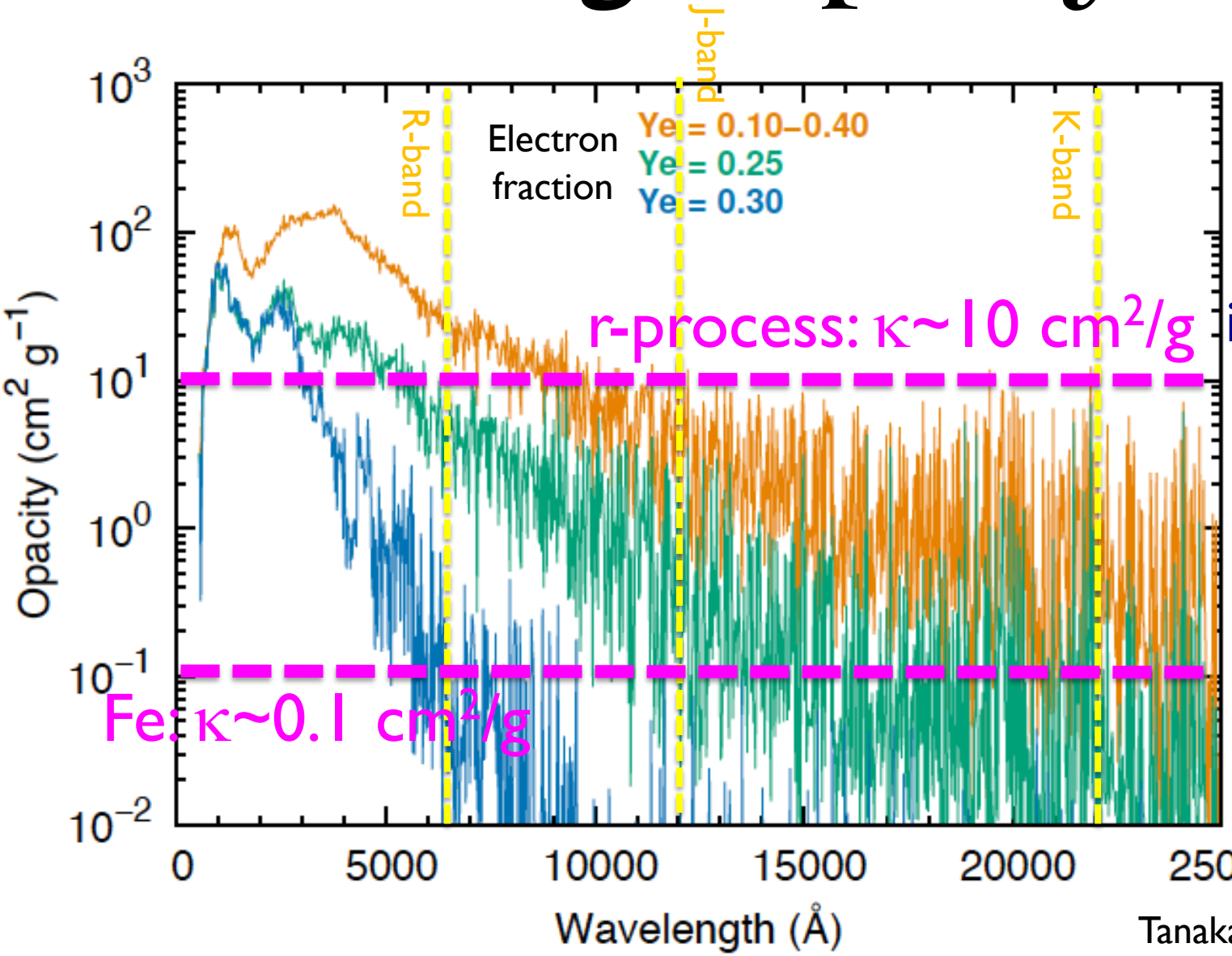
Temperature

$$T_{\rm peak} \simeq \left(\frac{L_{\rm peak}}{4\pi R_{\rm peak}^2 \sigma}\right)^{1/4}$$

UV-Opt

$$\approx 1.4 \times 10^4\,{\rm K} \left(\frac{f}{10^{-6}}\right)^{1/4} \left(\frac{v}{0.1c}\right)^{-1/8} \left(\frac{M_{\rm ej}}{10^{-2}\,{\rm M}_\odot}\right)^{-1/8}$$

Large Opacity



r-process elements/ Lanthanides increase the opacity κ larger than ~0.1 cm^2/g

⇒ t~10day

$L\sim10^{41}$erg/s

T~Infrared

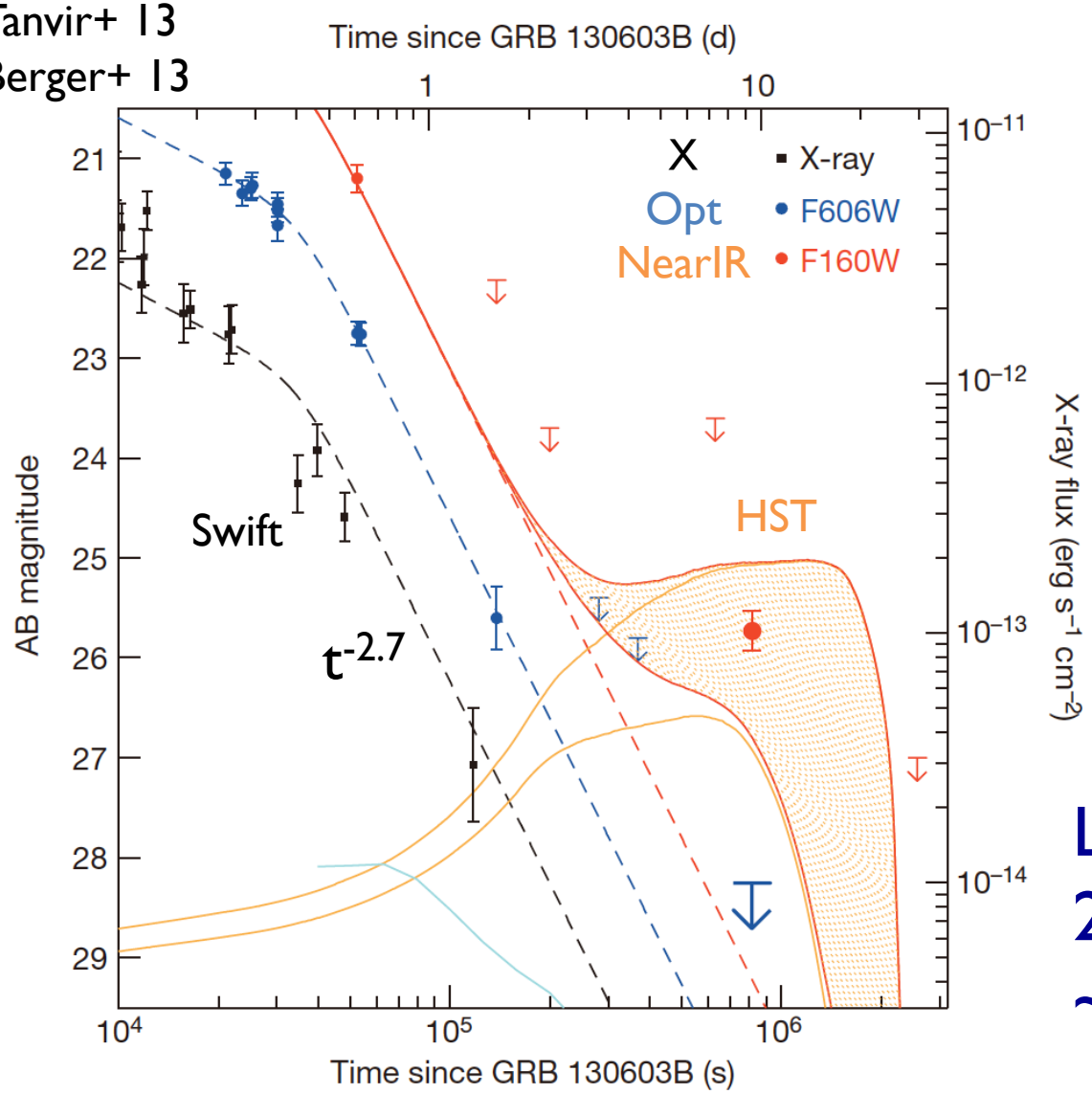
Tanaka+ 17

Kasen+ 13

Tanaka & Hotokezaka 13

GRB 130603B Macronova

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
< Supernova

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

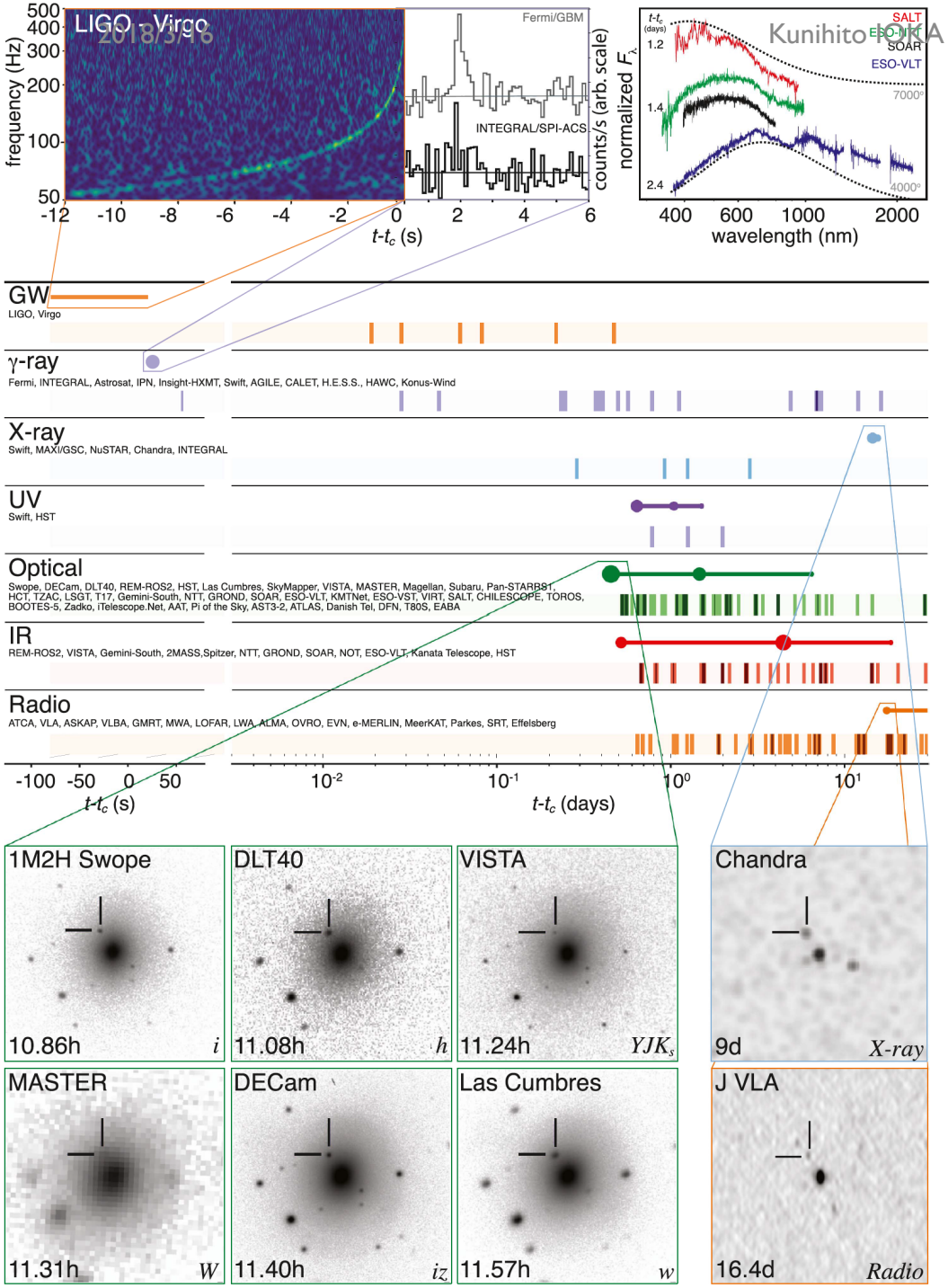
Galactic Abundance

- ***Galactic r-process rate***
  ~ 10^{-6} $M_\odot$/yr
- ***Ejected mass***
  ~ 0.01 $M_\odot$/event
- ***Event rate***
  ~ 10^{-4} events/yr/galaxy
  ~ 10^{3} events/Gpc^3/yr
- $X_{Lanthanide}$ ~ 0.03

NS^2 = r-process origin?

After GW170817

New Era of Multi-Messenger



Follow-up observations

>3000 people

γ-ray: ~1.734±0.054 sec

⇒ sGRB 170817A

UV-Opt-IR: 10.86 hr

⇒ Macronova/Kilonova

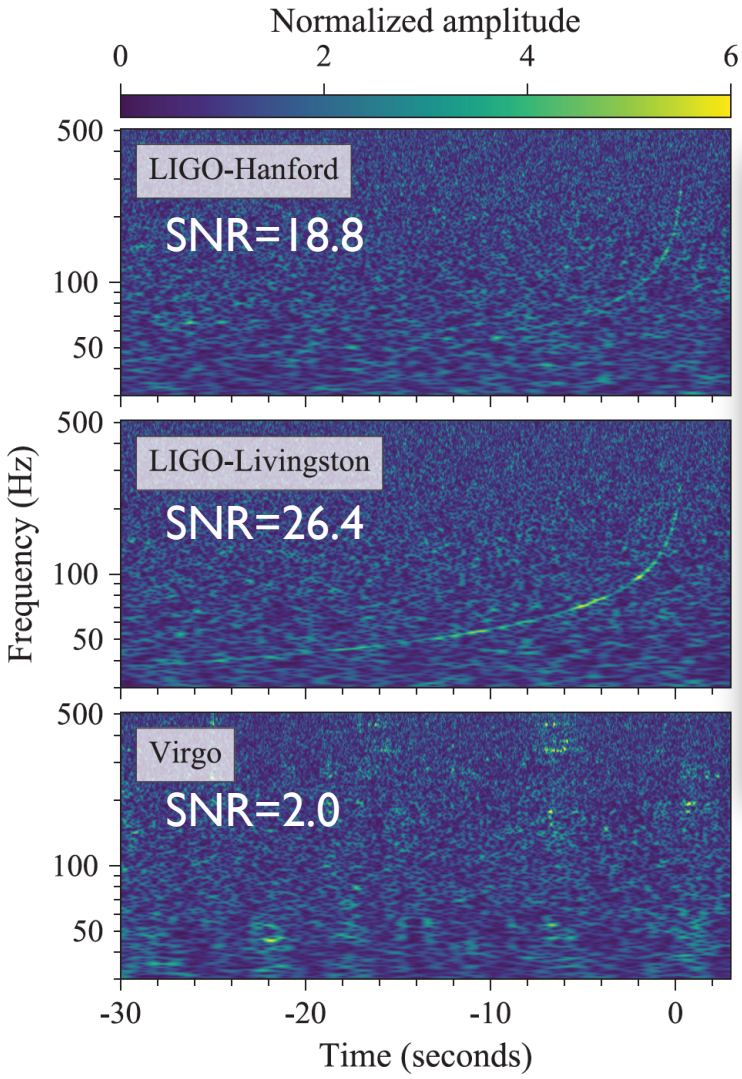
X, radio: ~10 day

⇒ Afterglow

LVC-EM 17

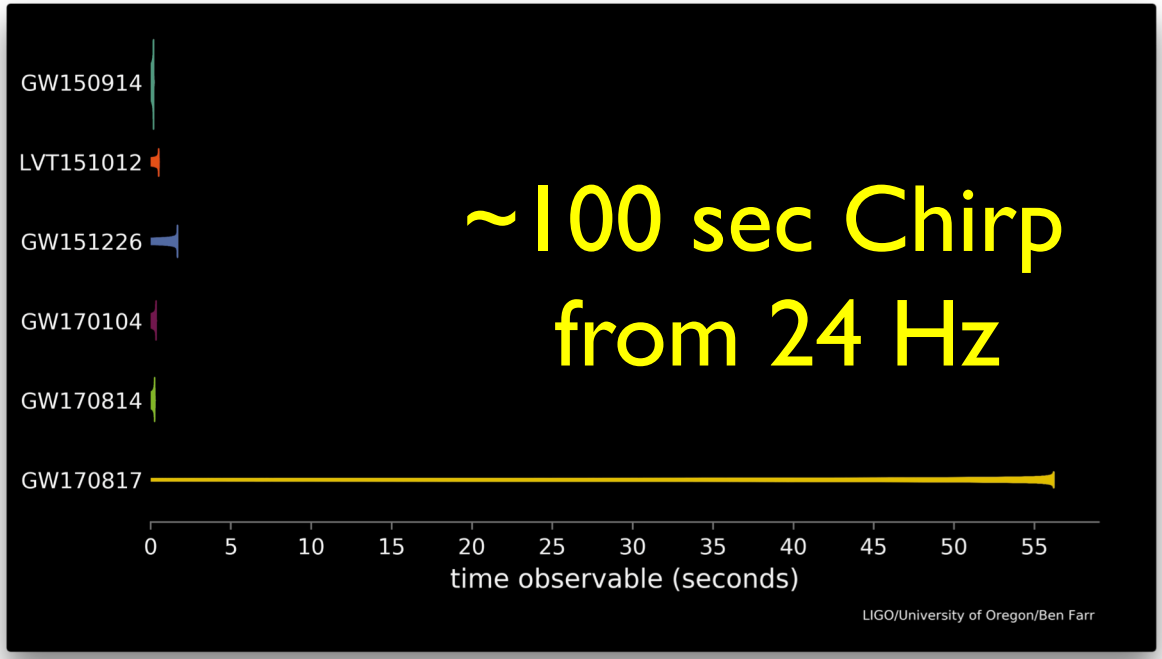
Band: GCN circ., Circles ∝ brightness

GW170817



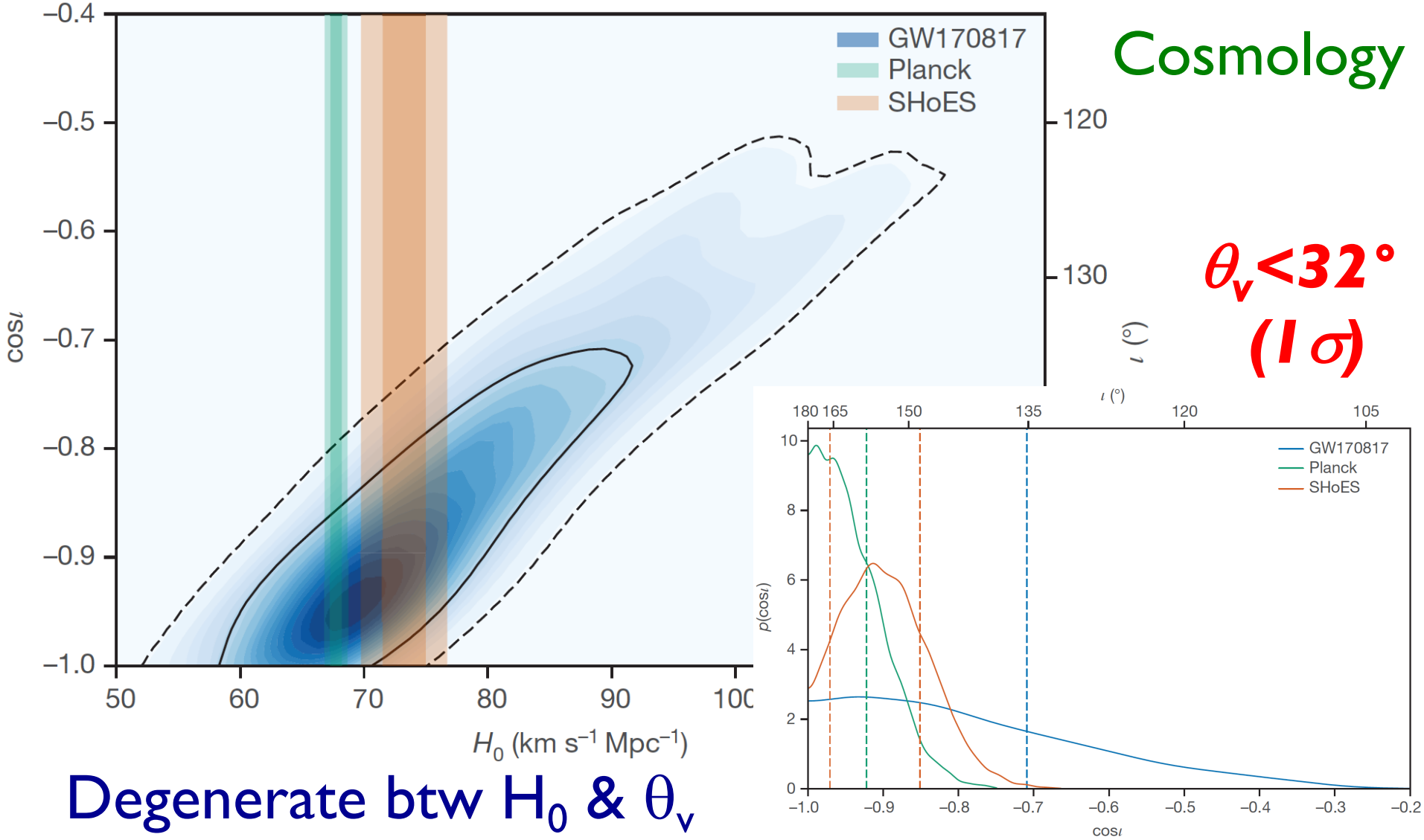
LVC 17

Discovery of an NS-NS merger!



O2: 30 Nov. 2016 – 25 Aug. 2017
Virgo from 1 Aug. 2017
SNR=32.4 (loudest yet) w/ matched filtering
False alarm <1/8e4 yr (within 5.9 day)

Viewing Angle & H_0

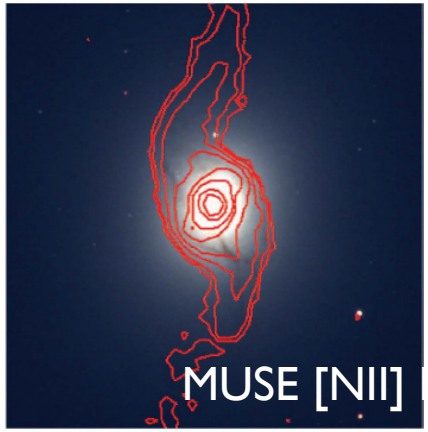


Cosmology

θ_v<32° (1σ)

Degenerate btw H_0 & θ_v

Host Galaxy NGC 4993



Property (1)	SGRB SF Median (2)	SGRB Ell. Median (3)	SGRB Total Median (4)	NGC 4993 (5)
Stellar Mass ($\log(M_*/M_\odot)$)	9.65 (0.90)	10.85 (0.33)	10.10 (0.72)	10.65
Rest-frame B-band Luminosity (L_B/L^*)	0.70 (1.00)	1.0 (0.80)	0.85 (0.94)	4.2
Star Formation Rate ($M_\odot$ yr^{-1})	1.1 (0)	$\lesssim$0.2 (0)	$\lesssim$0.5 (0)	0.01
Stellar Population Age (Gyr)	0.26 (1.00)	1.3 (1.00)	0.50 (1.00)	11.2
Projected Physical Offset δR (kpc)	5.5 (0.27)	20.7 (0.17)	6.9 (0.24)	2.1
Fractional Flux	0.14 (0.75)	0.21 (0.80)	0.19 (0.76)	0.54

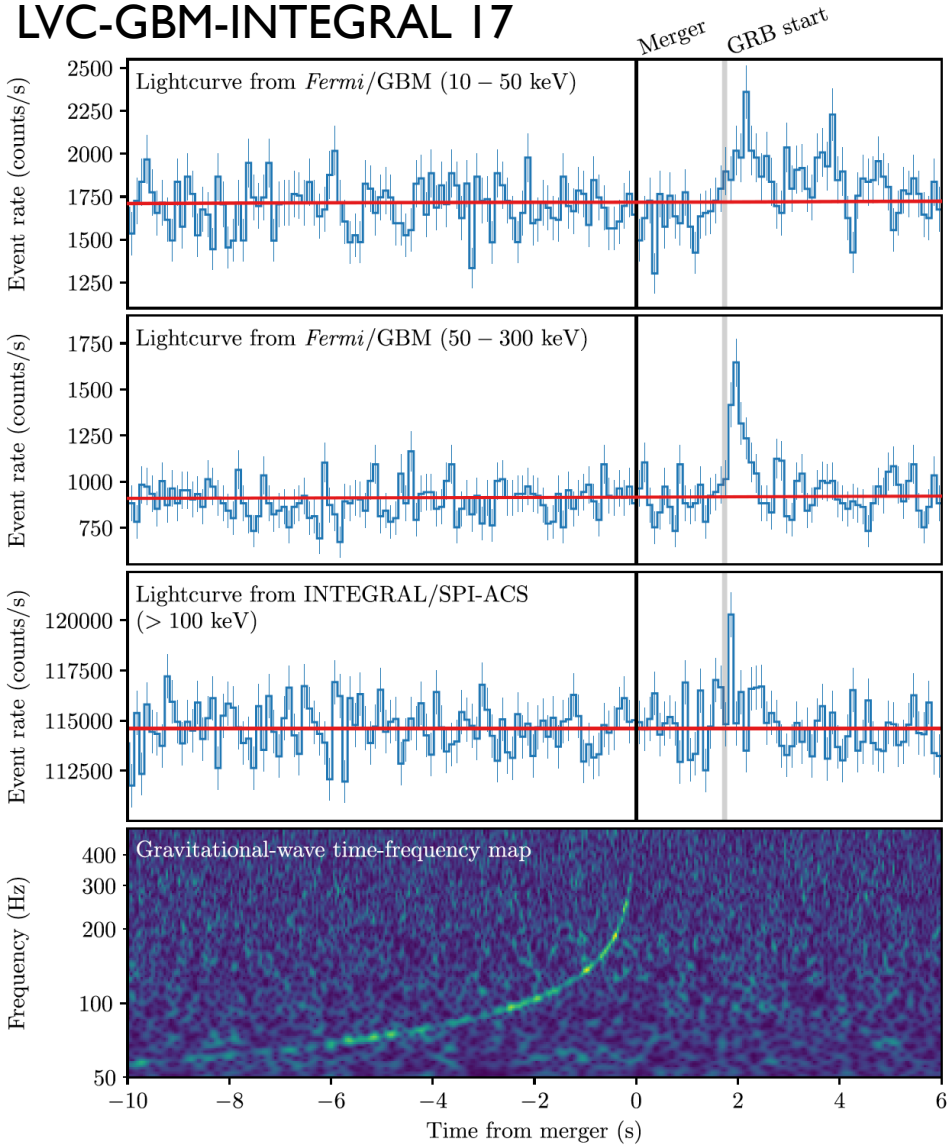
d_{GW}=40+8-14 Mpc
z_{GW}=0.008+0.002-0.003
$z=0.009783 \pm 0.000023$
in a group of galaxies
Typical S0 galaxy
Bulge dominated
$M_* \sim 10^{10.5\text{-}11}\ M_\odot$
Low SFR ~ $0.01 M_\odot$/yr
Spiral dust: dry merger?
Weak active nucleus
$Z \sim 0.9 Z_\odot$

2kpc away in r_{eff}~3kpc
Very old t_*~11.2 Gyr
Kick is small <200 km/s
Low extinction: in front

Hjorth+, Levan+, Pan+, Blanchard+, Im+, Fong+ 17

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

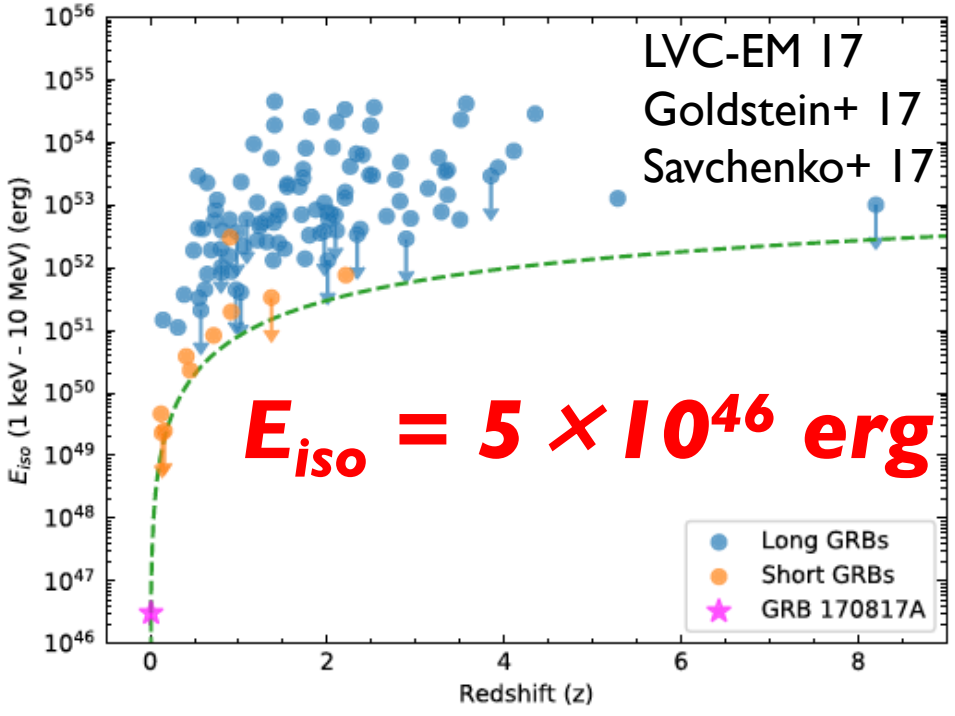


3 (of 12) GBM NaI detectors

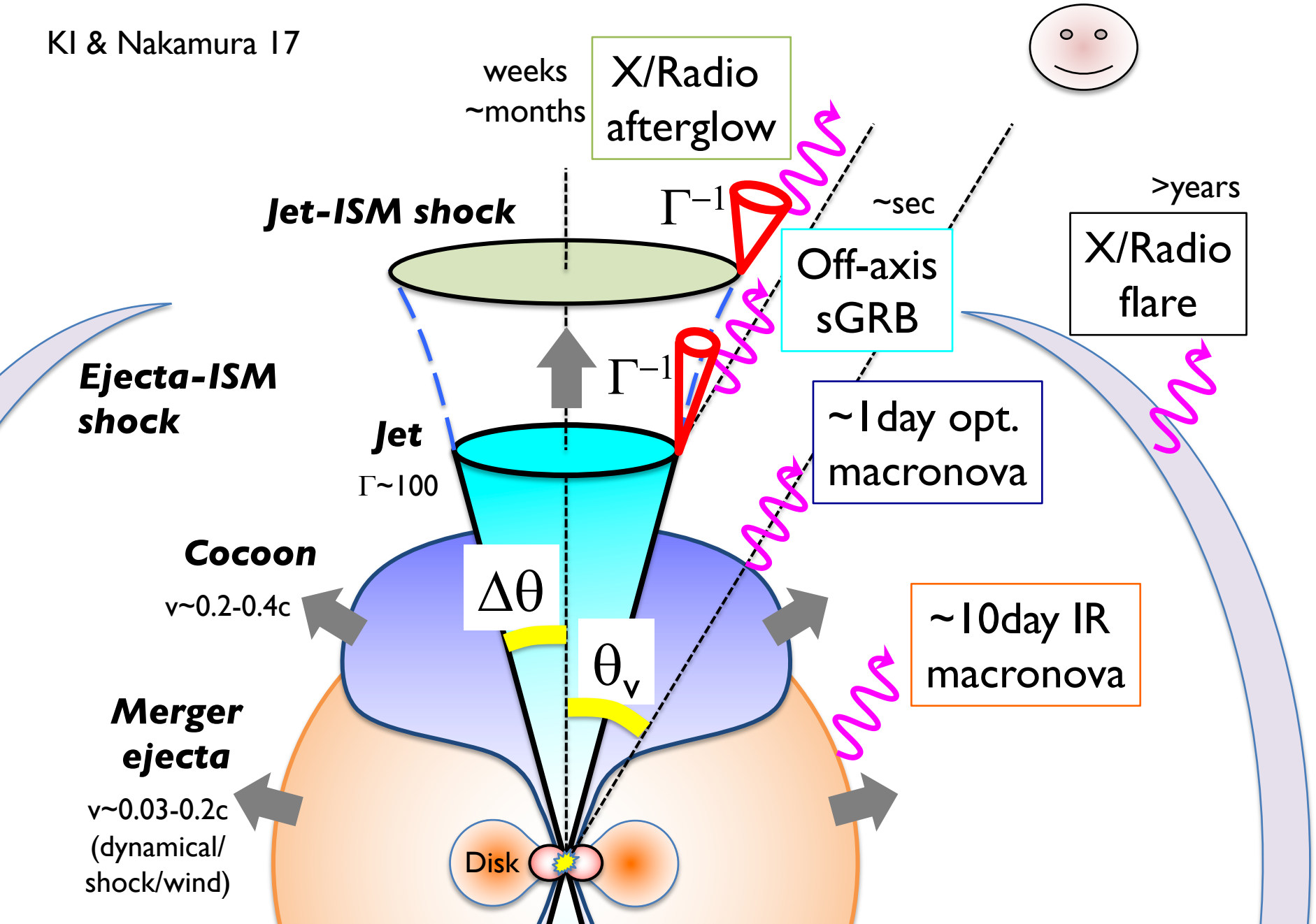
T_0=1.74±0.05 sec (68%)

T_{90}=2.0±0.5 sec

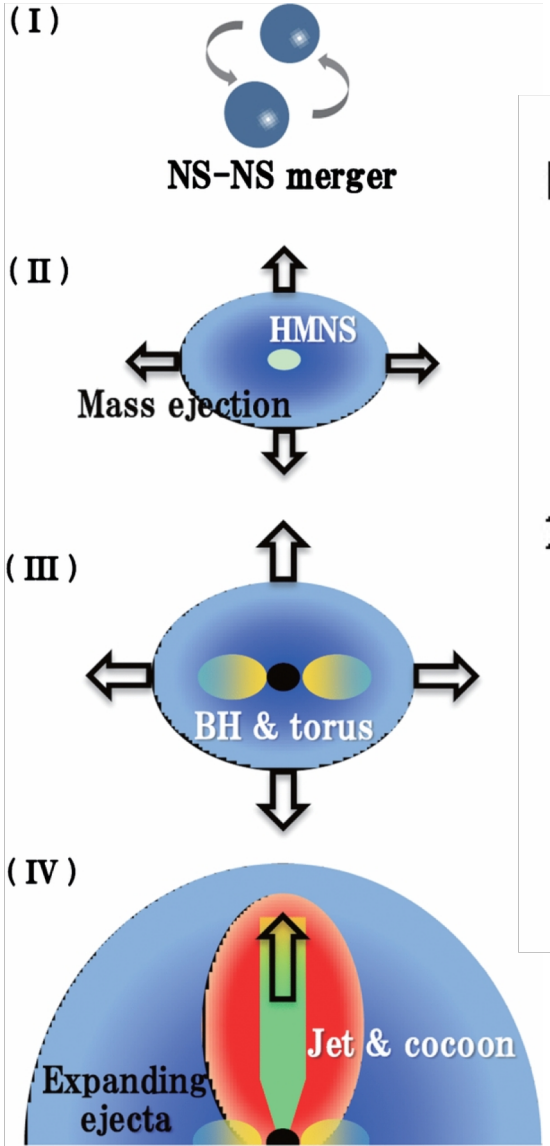
Weak but Detected



KI & Nakamura 17

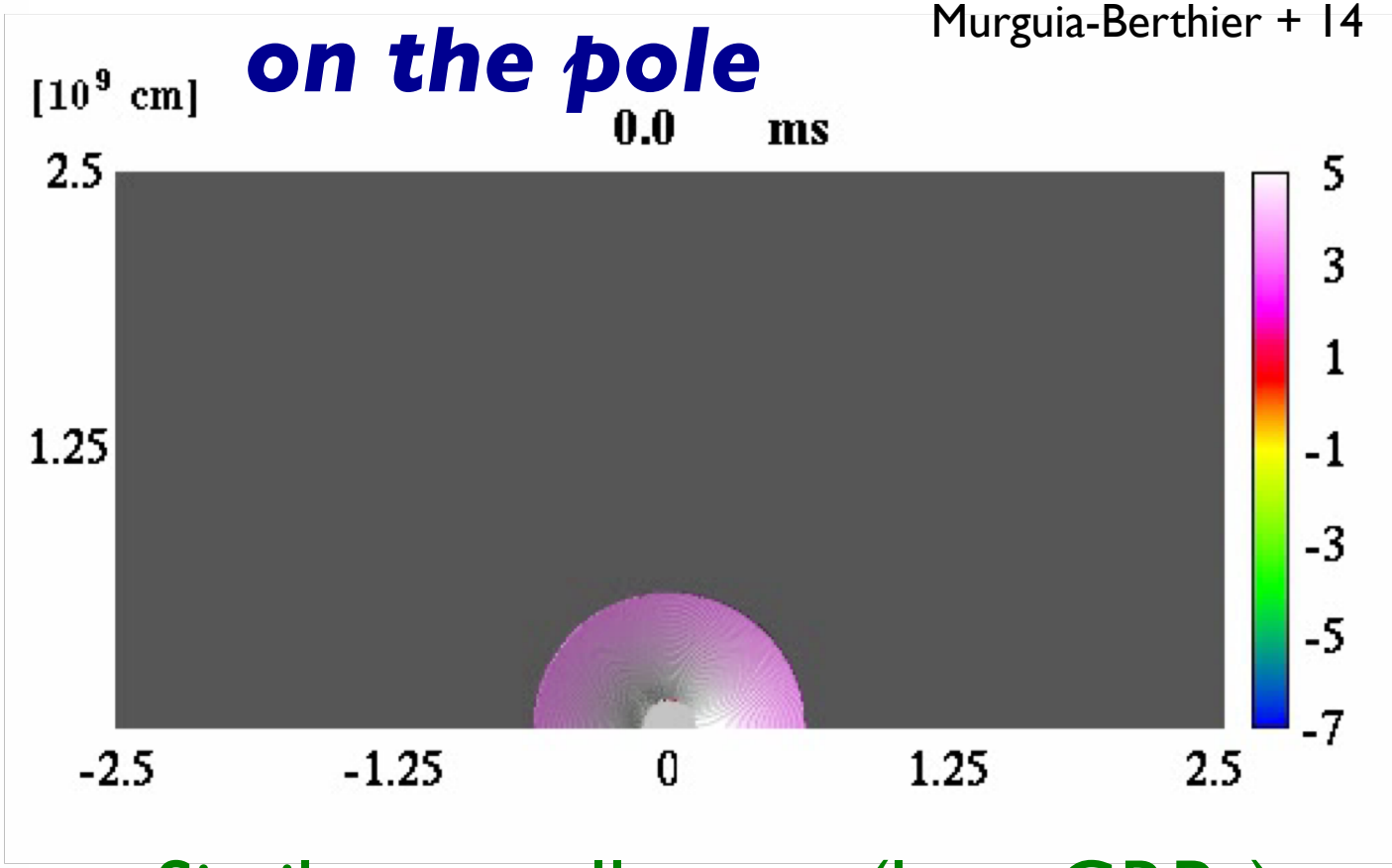


Jet Breakout from Ejecta



Ejecta is also on the pole

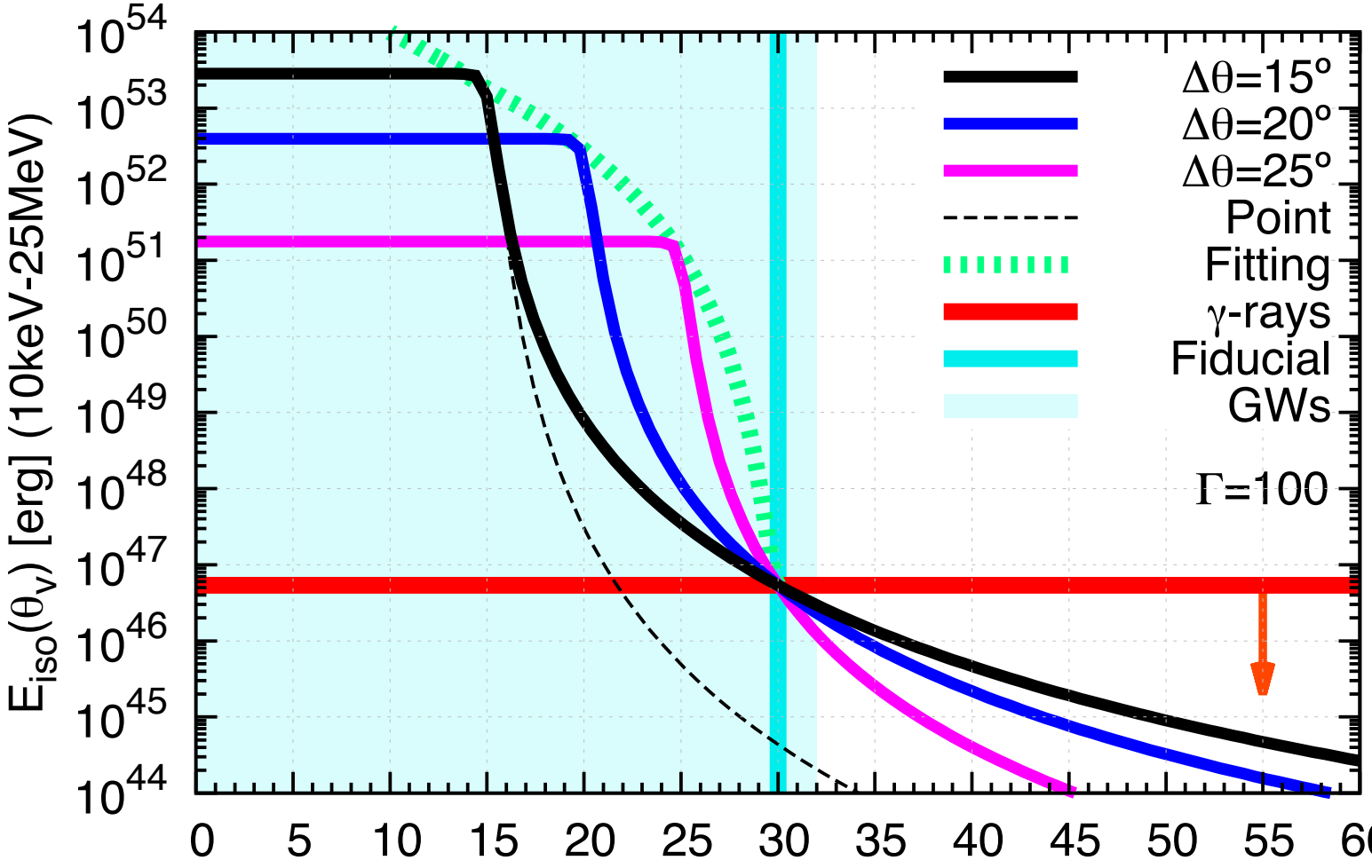
Nagakura+ 14
Murguia-Berthier + 14



Similar to collapsars (long GRBs)

Weak jet ~10^{46} erg/s cannot break out

Off-Axis Jet



$\theta_v \sim \Delta\theta$

⇒ Point approx. is bad

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

↓

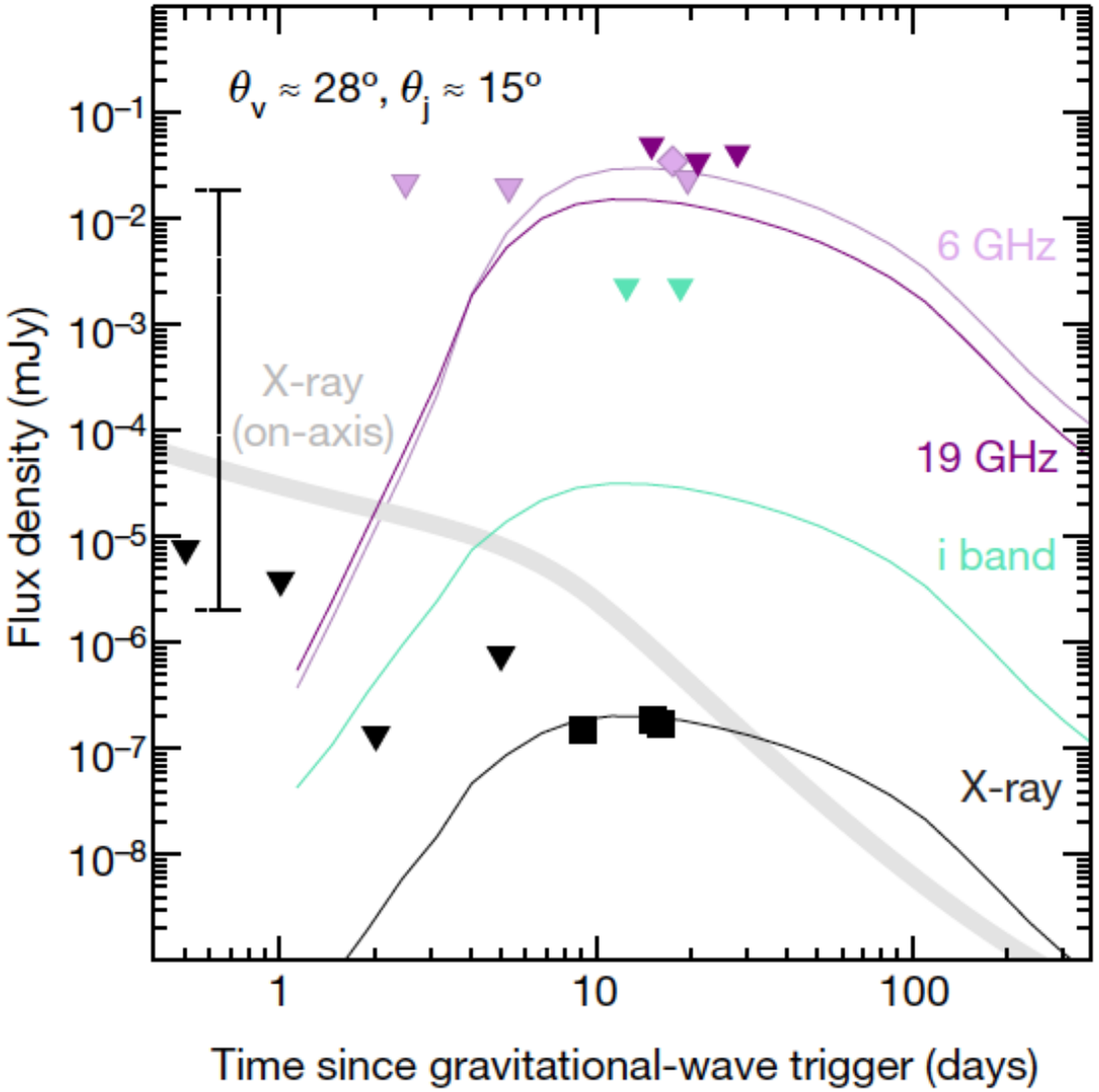
$E_{iso} \propto \theta_v^{-4}$

KI & Nakamura 17, 01
Yamazaki, KI & Nakamura 02, 03, 04

LVC-GBM-INTEGRAL 17
Granot+ 17, Kasliwal+ 17

Kasliwal+ 17
Gottlieb+ 17
Bromberg+ 17

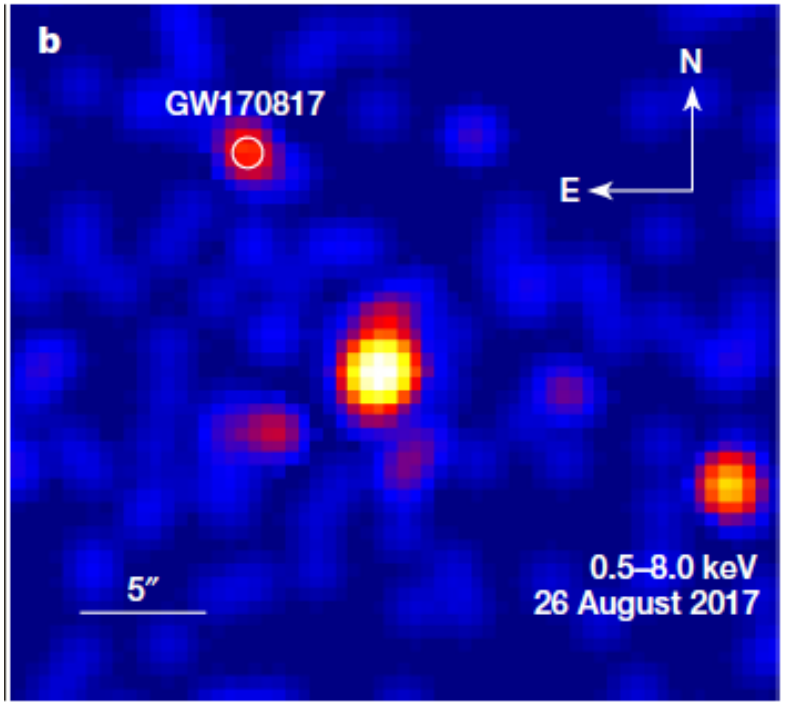
X-ray Afterglow



Chandra 50ks

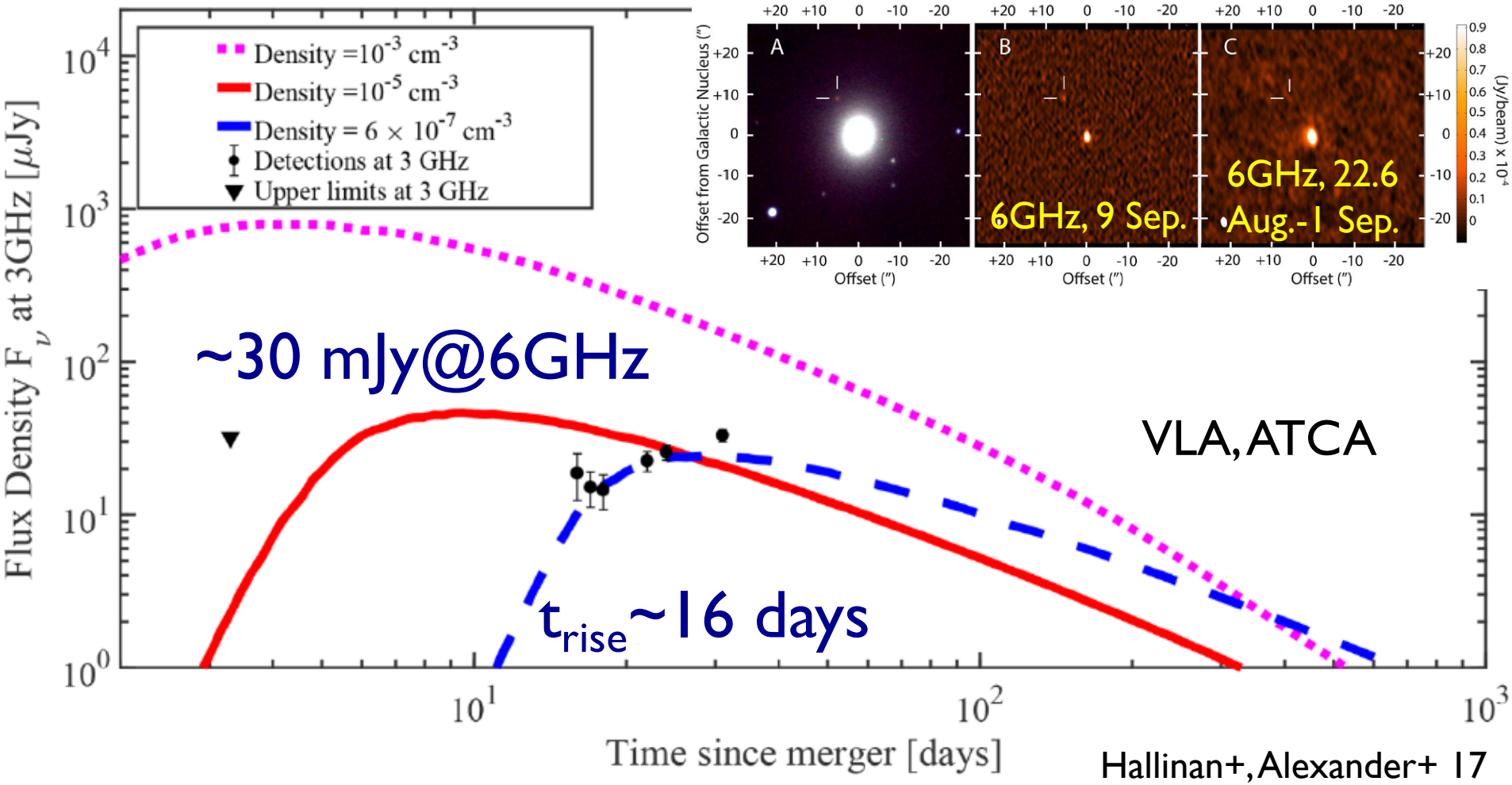
t_{rise}~9 day

$L_{X,iso}$~1.1e39 erg/s



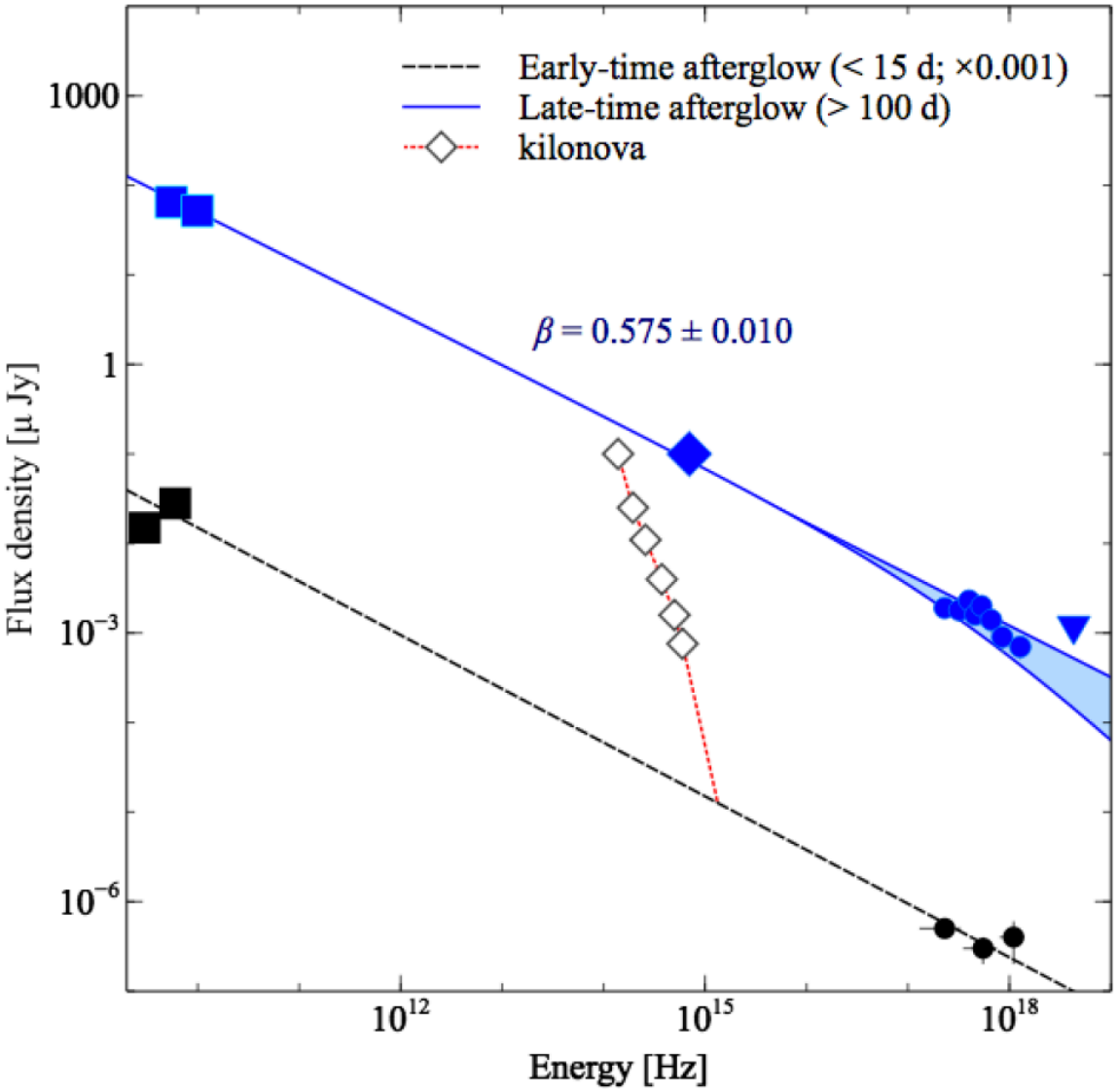
Troja+, Margutti+, Haggard+ 17

Radio Afterglow



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

Afterglow Spectrum



Consistent with a single power-law ⇒ Synchrotron $\nu_m < \nu < \nu_c$

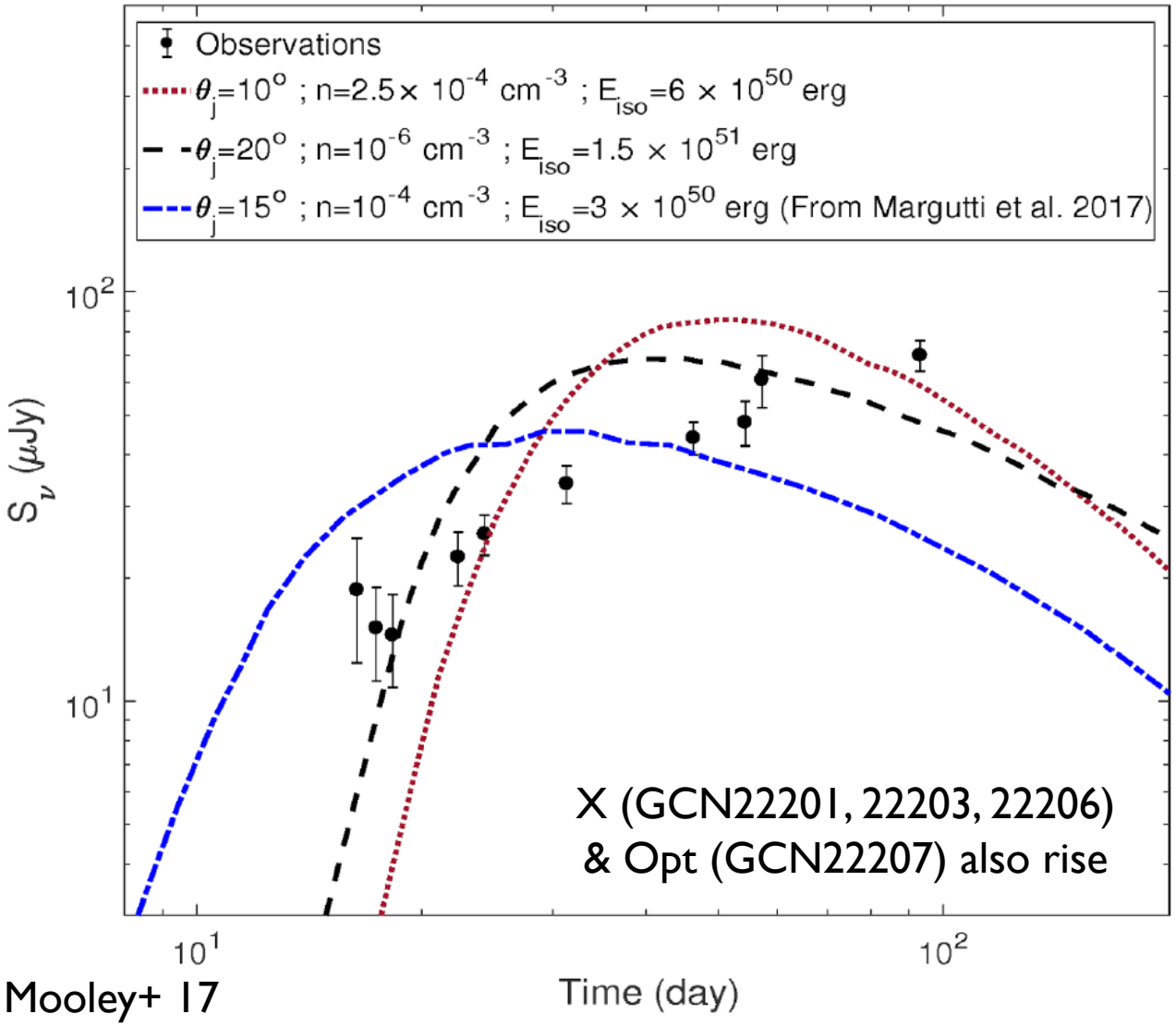
$$F_\nu(t) \propto \nu^{0.6} t^{0.7}$$

⇨ e spectrum:

$$p \approx 2.2$$

Troja+ 18, Marugutti+ 18, Ruan+ 18, D'Avanzo+ 18, Lyman+ 18,

Rising Afterglow



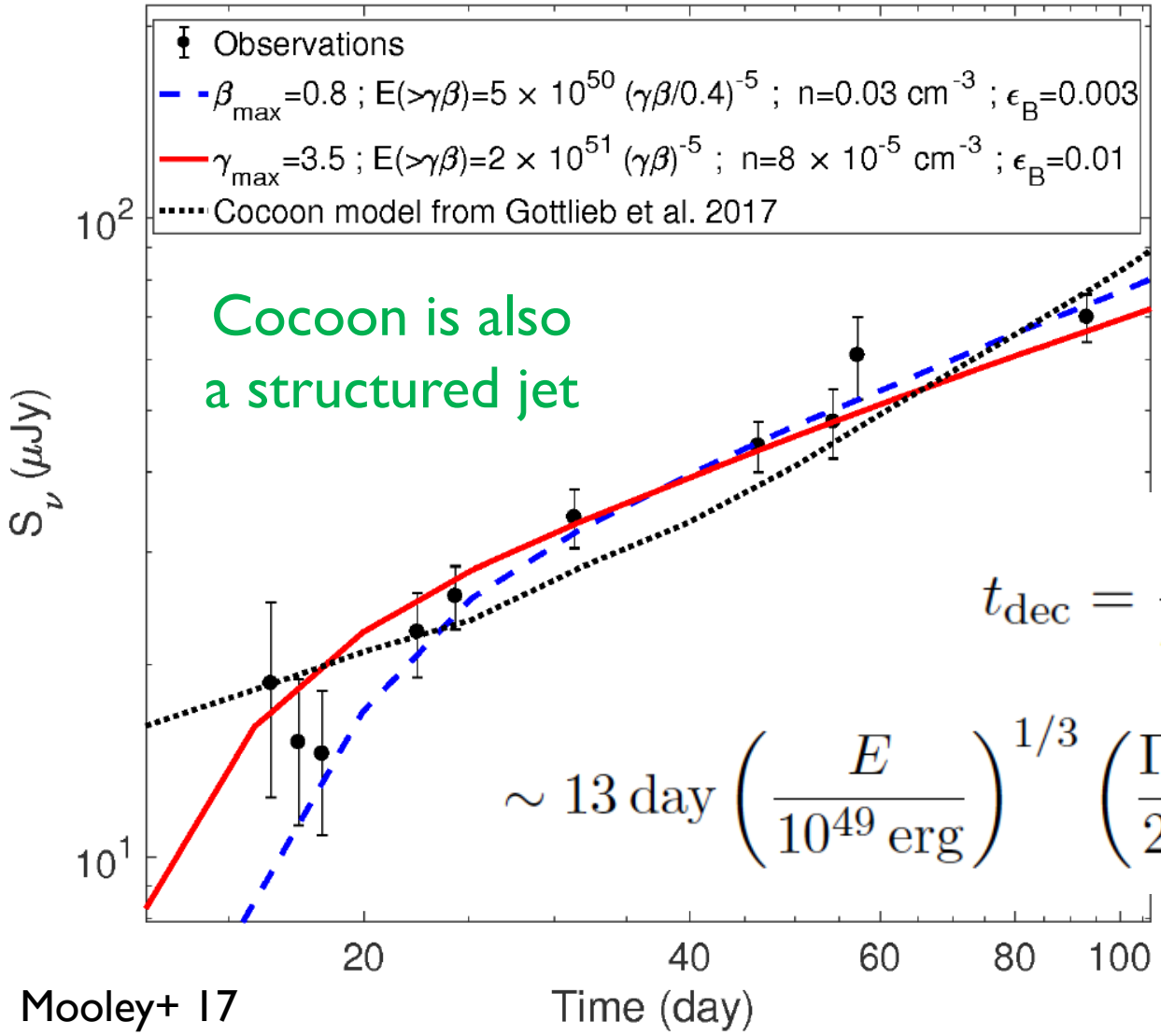
Mooley+ 17

Rising up to ~100d

Inconsistent with a simple jet

Energy injection radial or polar: Structured jet or cocoon?

Cocoon Afterglow?



Mooley+ 17

Cocoon or
Ejecta tail
interact w/ ISM

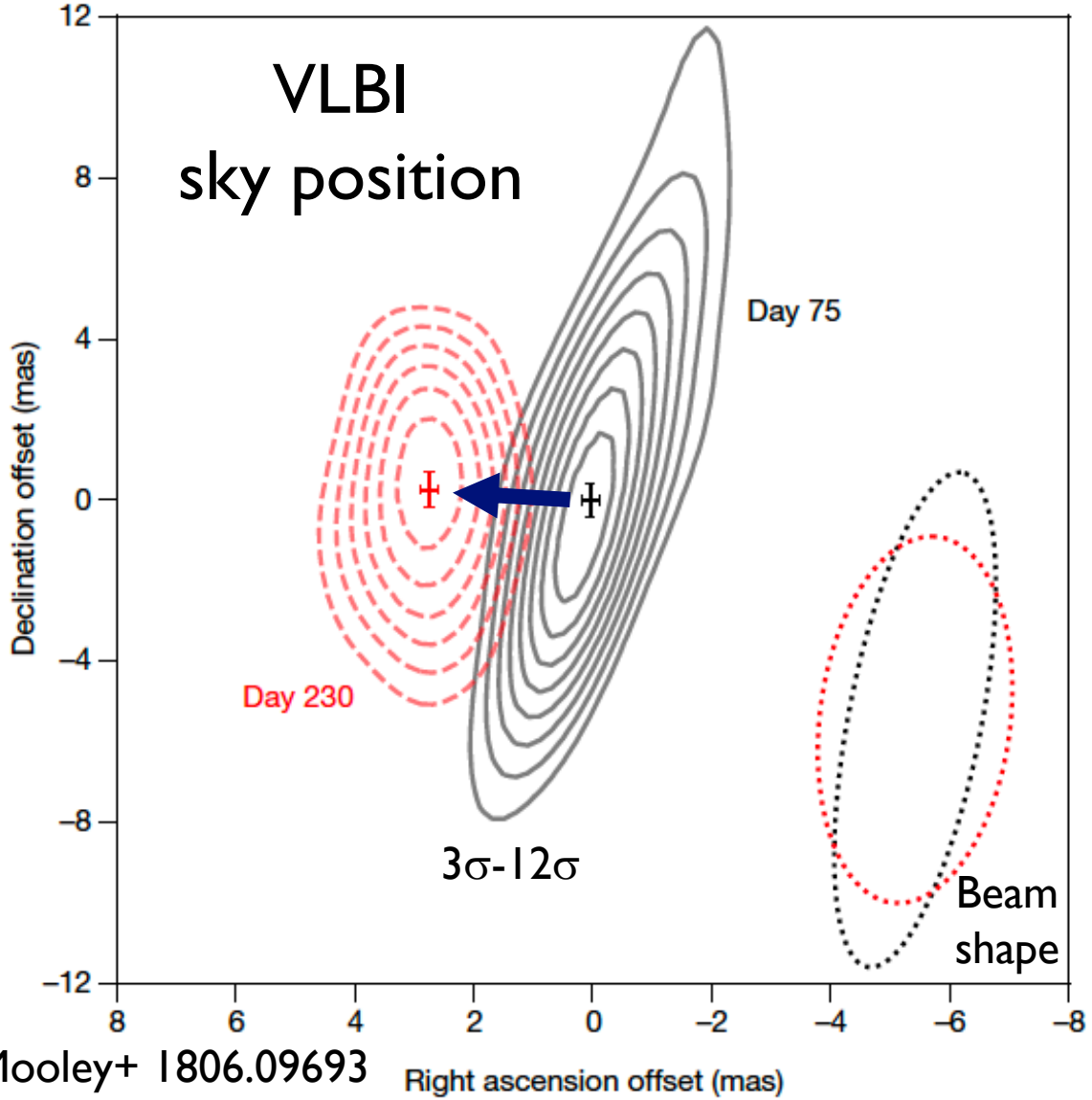
Rise time~
Deceleration time

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

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

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

Superluminal Motion



Mooley+ 1806.09693

v_{app}~4.1 ±0.5 c!

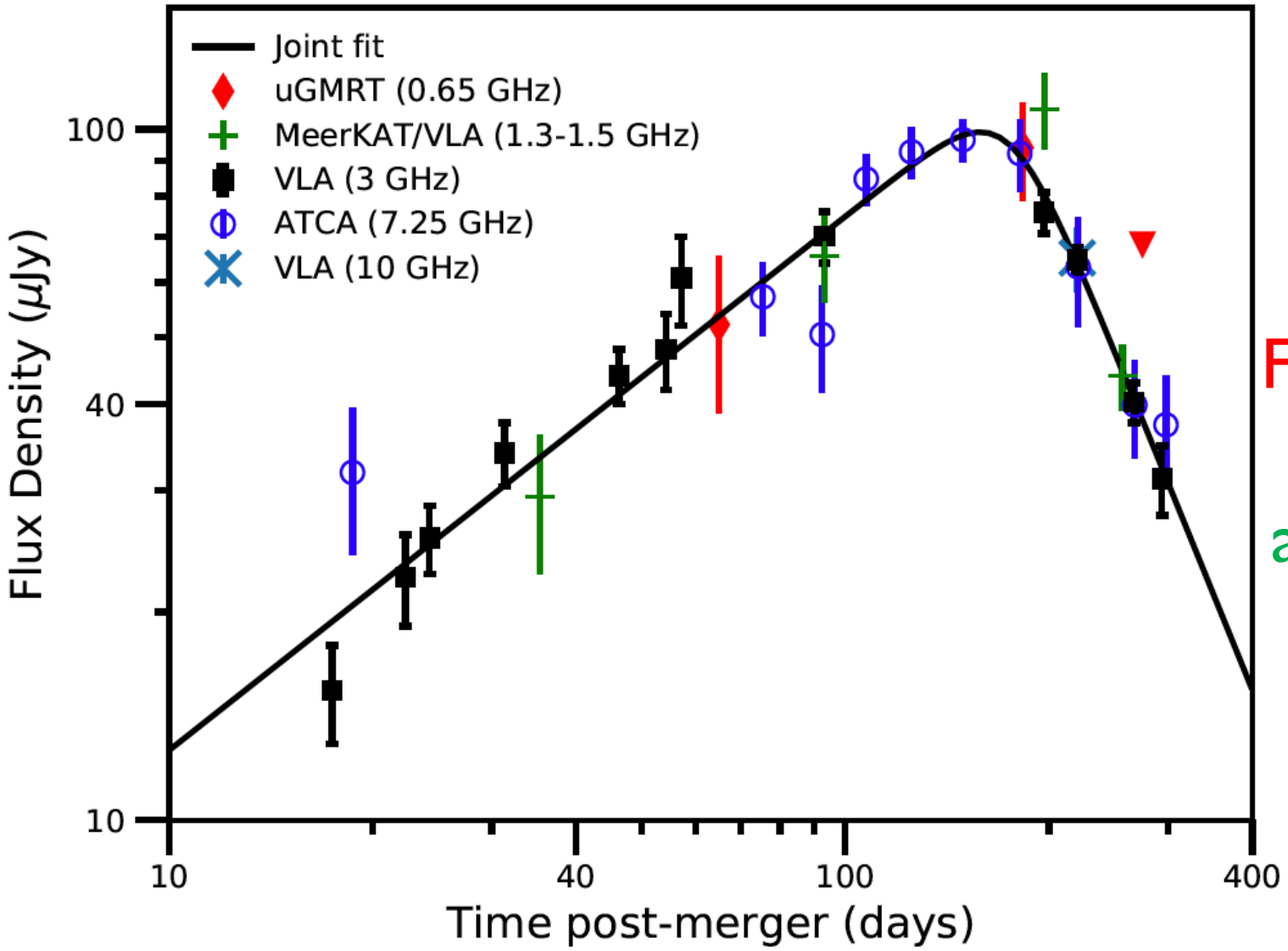
Unresolved

R<0.2pc(1mas),
<2pc(10mas)

Not consistent with a spherical source

Γ~4 at t~t_{peak}

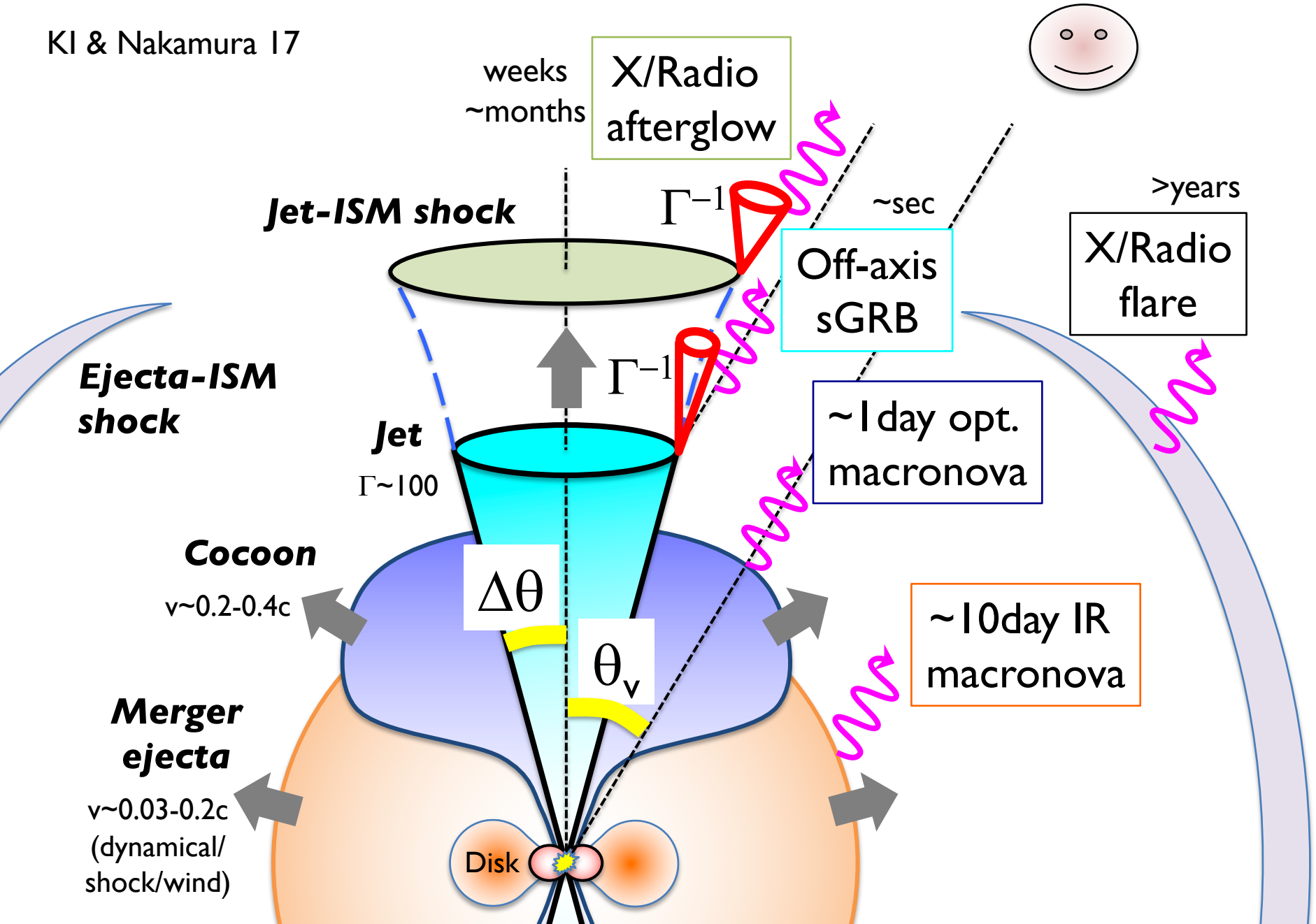
Turnovers in Afterglows



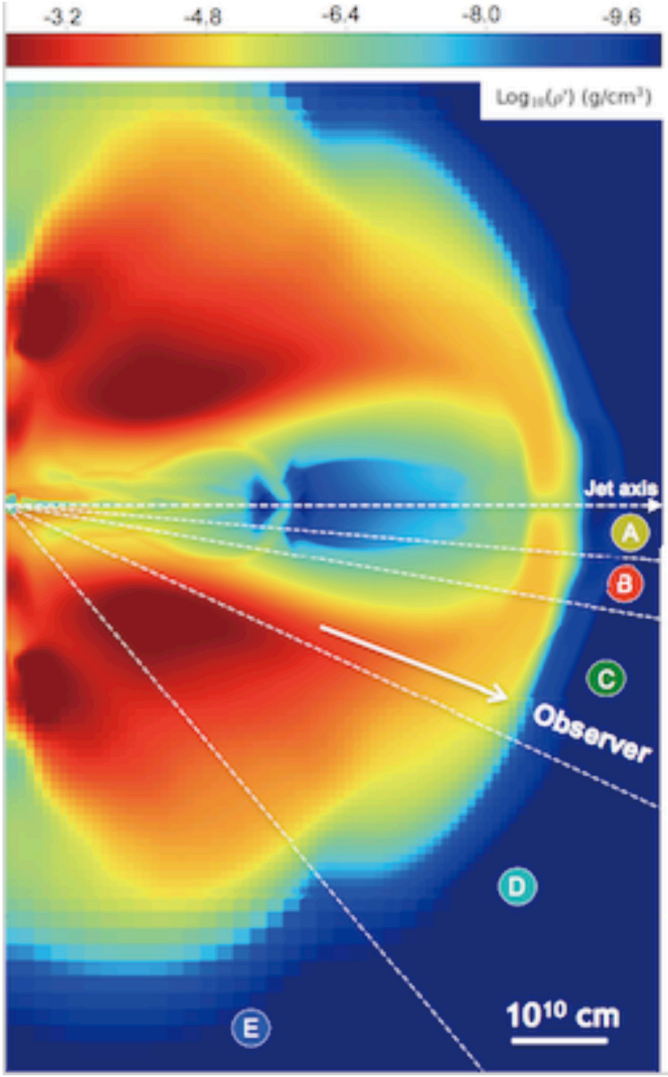
Afterglow theory predicts $F_\nu \sim t^{-p}\ \nu^{-(p-1)/2}$ for a jet as observed ($p \sim 2.2$)

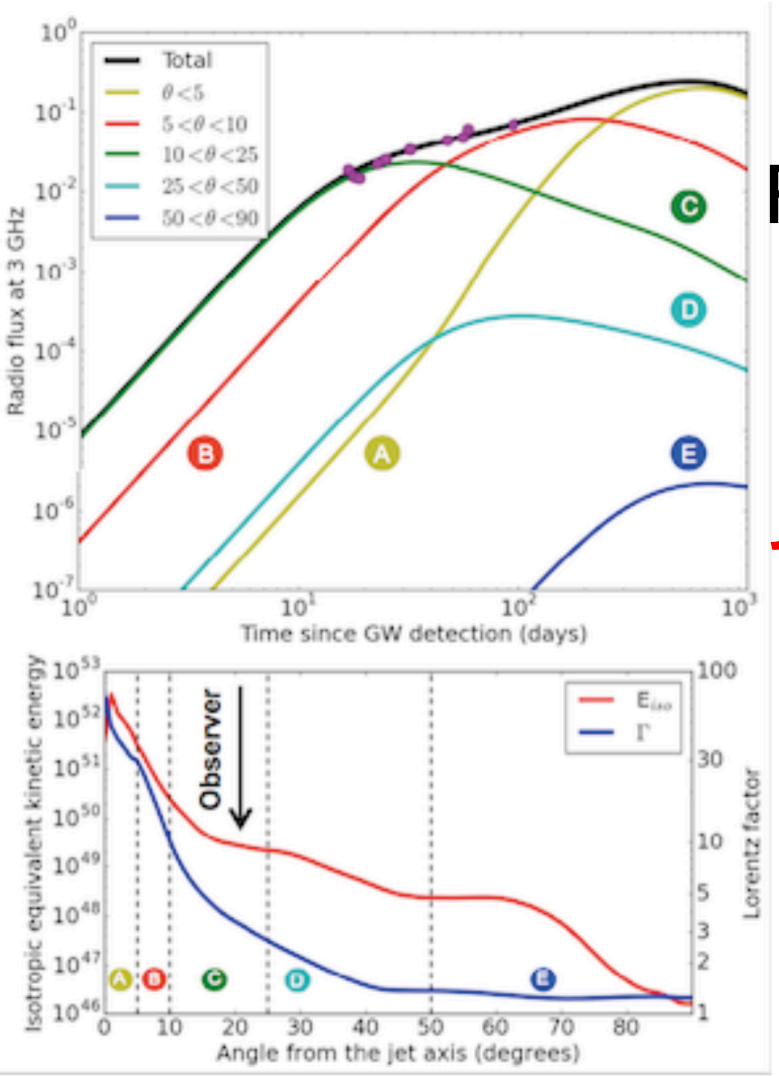
Mooely+ 18

KI & Nakamura 17



Structured Jet?





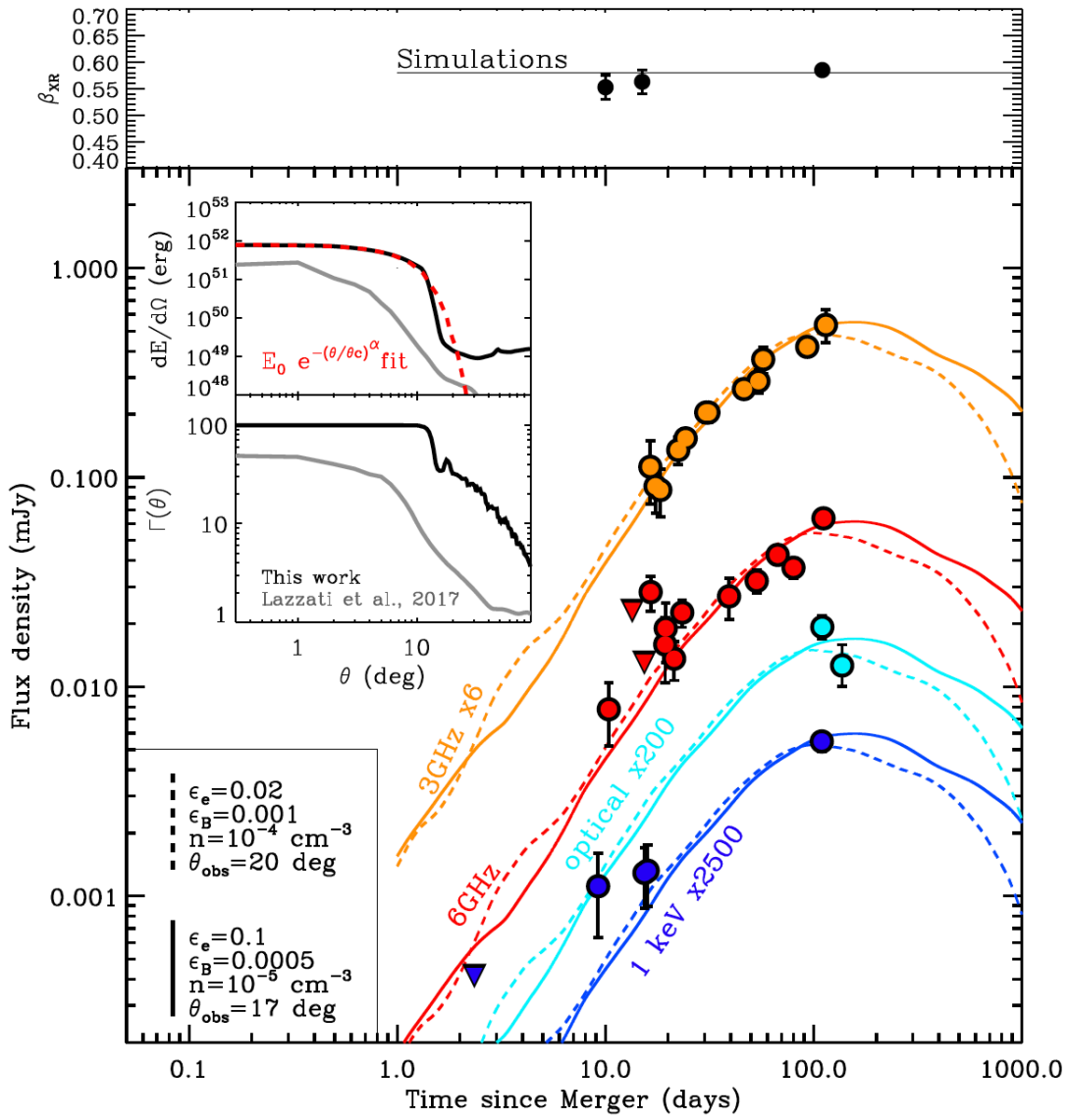
Polar energy injection

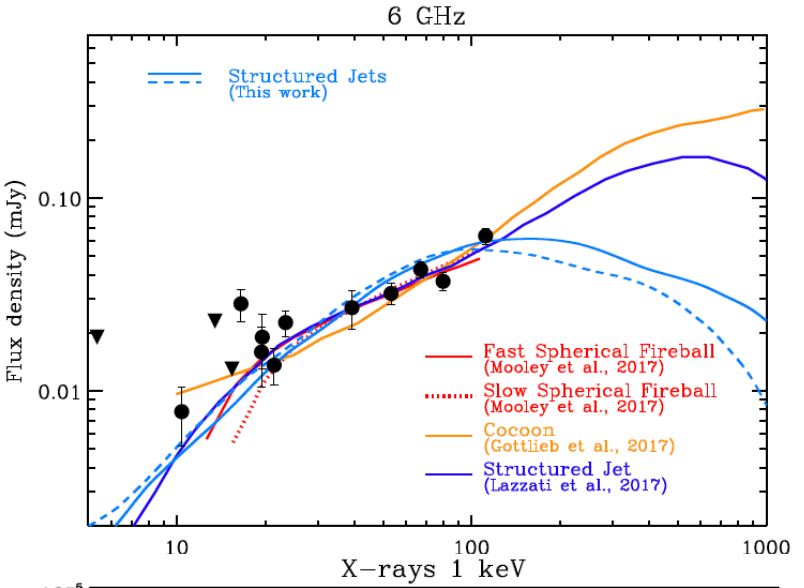
Jet+Coccon or Intrincially structured?

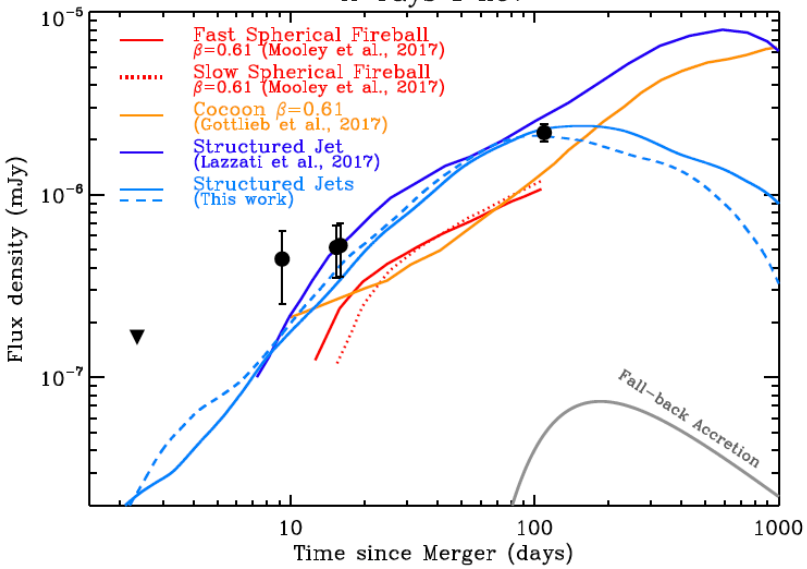
Lazzati+ 17

Structured Jet?

Margutti+ 18
Lazzati+ 17
D'Avanzo+ 18
Lyman+ 18

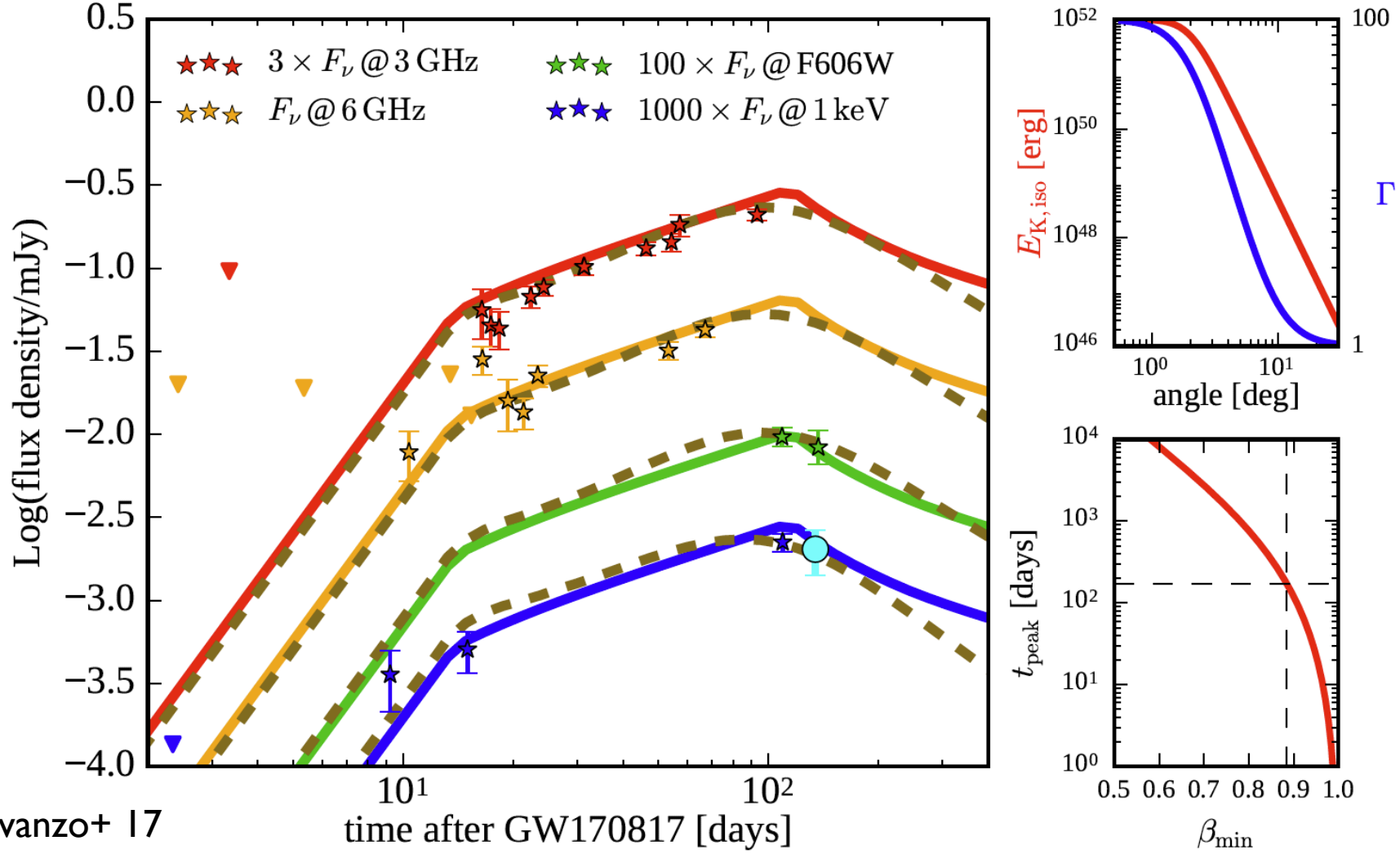






Power-Law Jet?

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



D'Avanzo+ 17

Gaussian Jet?

$$E(\theta) = E_0(-\theta^2/2\,\theta_c^2)$$

Troja+ 18

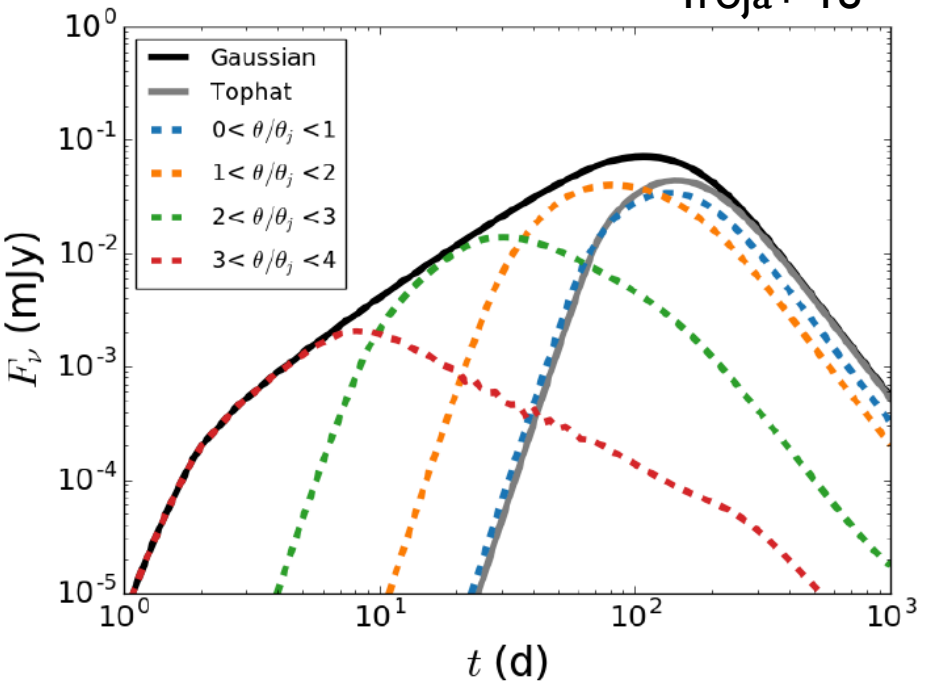


Table 2. Constraints on the Gaussian jet and Cocoon model param
distribution with symmetric 68% uncertainties (ie. the 16% and 84% q

	Jet		Jet+GW+Planck			
Parameter	Med.	Best-fit	Med.	Best-fit		
θ_v	$0.51^{+0.20}_{-0.22}$	0.79	$0.32^{+0.13}_{-0.13}$	0.51		
$\log_{10} E_0$	$52.50^{+1.6}_{-0.79}$	54.39	$52.73^{+1.30}_{-0.75}$	56.93	$52.52^{+1.4}_{-0.71}$	56.93
θ_c	$0.091^{+0.037}_{-0.040}$	0.146	$0.057^{+0.025}_{-0.023}$	0.079	$0.076^{+0.026}_{-0.027}$	0.079
θ_w	$0.55^{+0.65}_{-0.22}$	0.63	$0.62^{+0.65}_{-0.37}$	0.44	$0.53^{+0.70}_{-0.24}$	0.44
$\log_{10} n_0$	$-3.1^{+1.0}_{-1.4}$	-3.8	$-3.8^{+1.0}_{-1.3}$	-6.4	$-3.24^{+0.91}_{-1.3}$	-6.4
p	$2.155^{+0.015}_{-0.014}$	2.159	$2.155^{+0.015}_{-0.014}$	2.170	$2.155^{+0.015}_{-0.014}$	2.170
$\log_{10} \epsilon_e$	$-1.22^{+0.45}_{-0.80}$	-0.73	$-1.51^{+0.53}_{-0.89}$	-1.37	$-1.31^{+0.46}_{-0.78}$	-1.37
$\log_{10} \epsilon_B$	$-3.38^{+0.81}_{-0.45}$	-3.50	$-3.20^{+0.92}_{-0.58}$	-1.27	$-3.33^{+0.82}_{-0.49}$	-1.27
$\log_{10} E_{tot}$	$50.26^{+1.7}_{-0.69}$	52.72	$50.16^{+1.1}_{-0.67}$	54.75	$50.19^{+1.41}_{-0.65}$	54.75

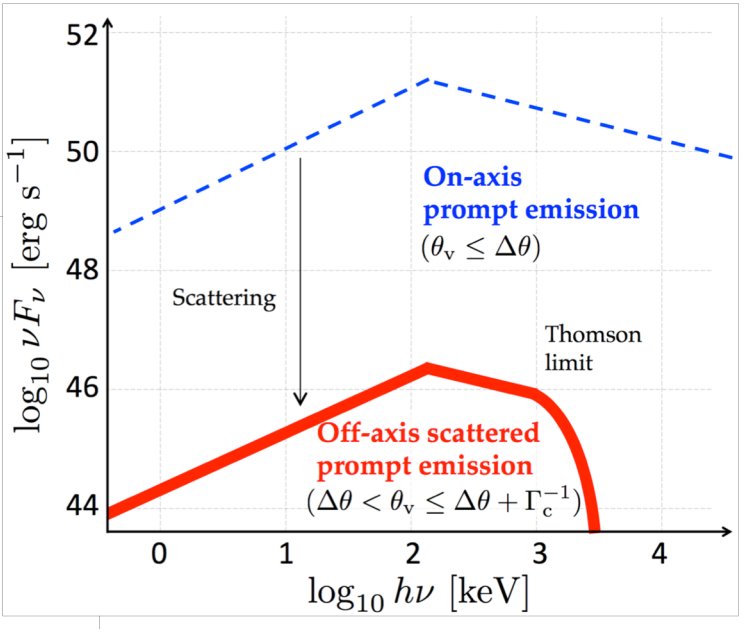
$\log_{10} u_{\rm min}$	$-2.2^{+1.3}_{-1.9}$	-2.9
$\log_{10} E_{\rm inj}$	$54.7^{+1.6}_{-2.7}$	52.4
k	$5.62^{+0.93}_{-1.1}$	5.3
$\log_{10} M_{\rm ej}$	$-7.6^{2.1}_{-1.7}$	-9.5
$\log_{10} n_0$	$-5.2^{+2.2}_{-2.0}$	-6.5
p	$2.156^{+0.014}_{-0.014}$	2.157
$\log_{10} \epsilon_e$	$-1.33^{+0.93}_{-1.3}$	-0.36
$\log_{10} \epsilon_B$	$-2.5^{+1.5}_{-1.1}$	-0.4
$\log_{10} E^*_{tot}$	$52.84^{+0.97}_{-1.3}$	51.00

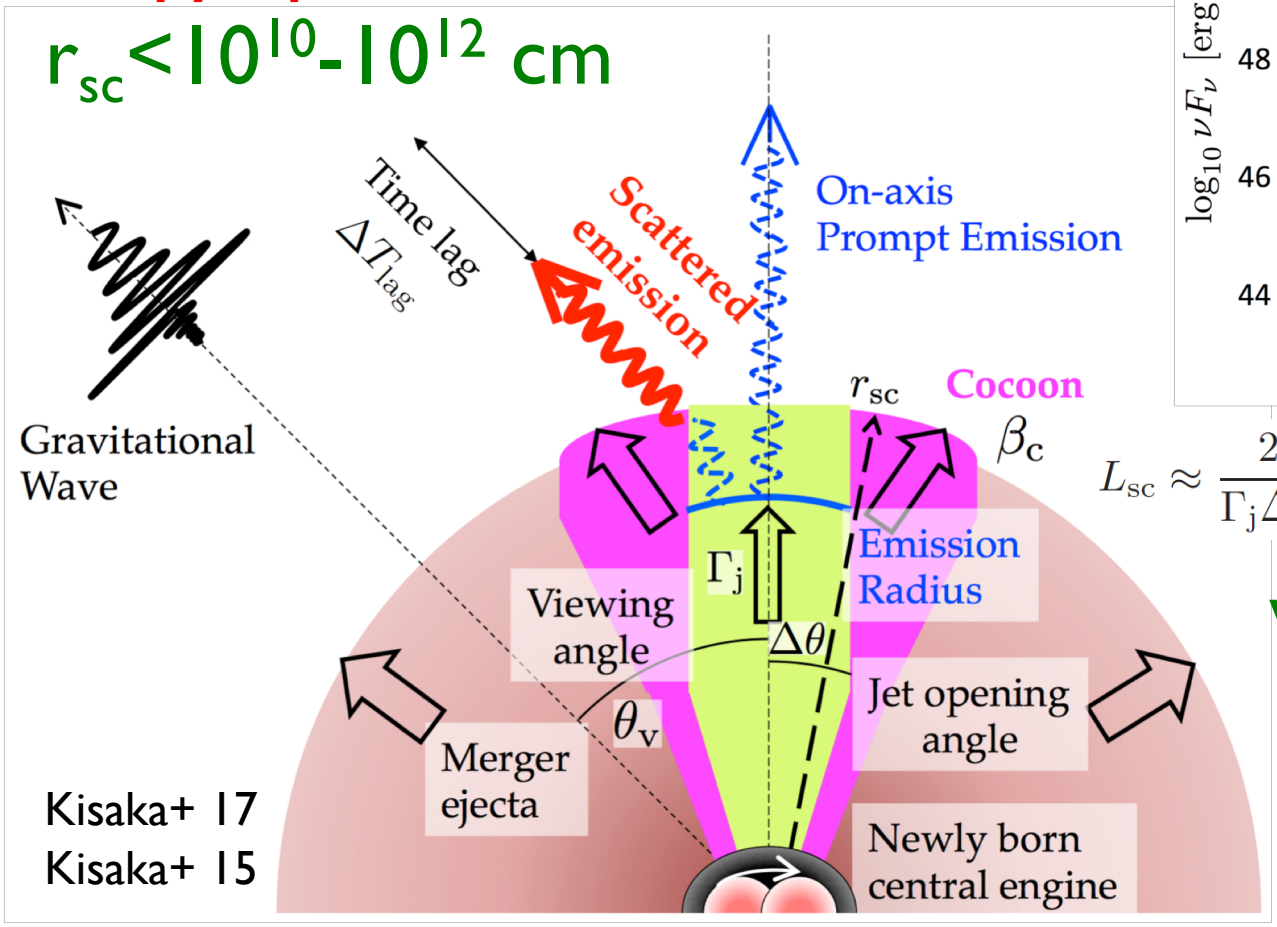
Scattered sGRB

Thompson scattering by cocoon

Copy spectrum w/ ~MeV cutoff

r_{sc}<10^{10}-10^{12} cm





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

Wide angle

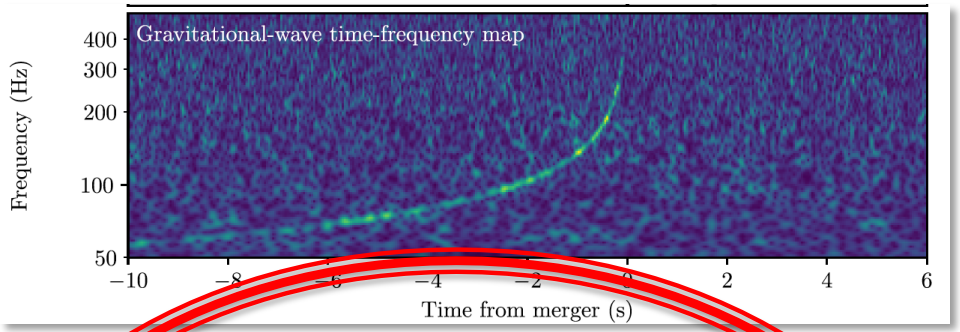
$$\Delta\theta_{sc} \approx \frac{1}{\Gamma_c}.$$

Kisaka+ 17

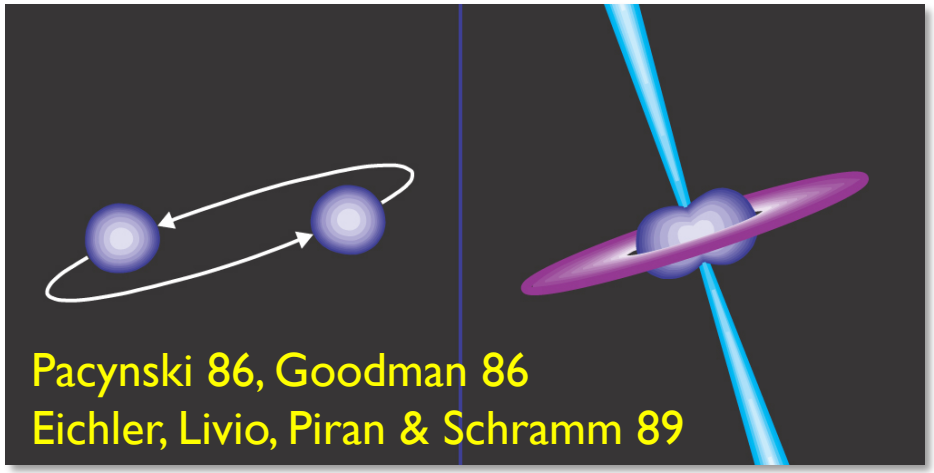
Kisaka+ 15

GW170817

1st GW from NS²

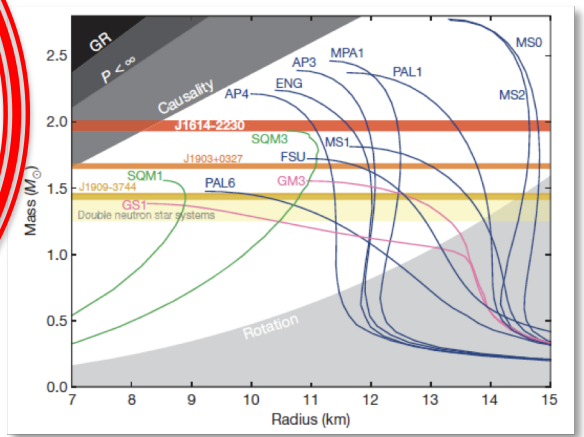


NS² = Short GRB?

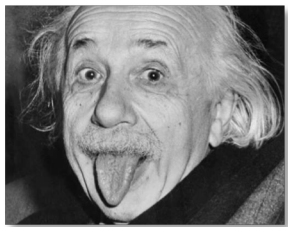


R-process elements

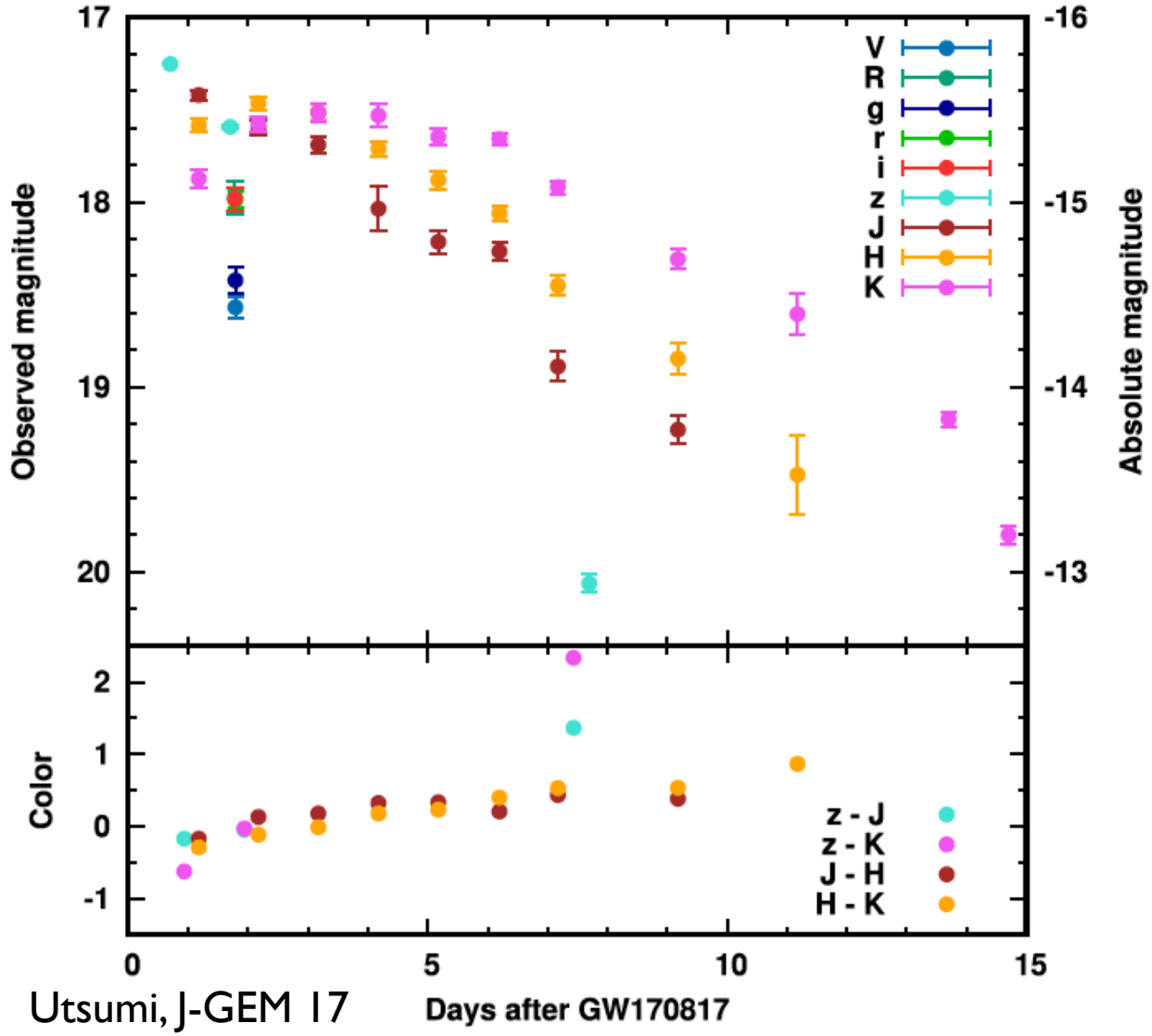
Equation of state



Relativity,
Cosmology,
…



Macronova/Kilonova



Utsumi, J-GEM 17

Blue macronova

~1 day opt.

T~7000K

L~7e41 erg/s

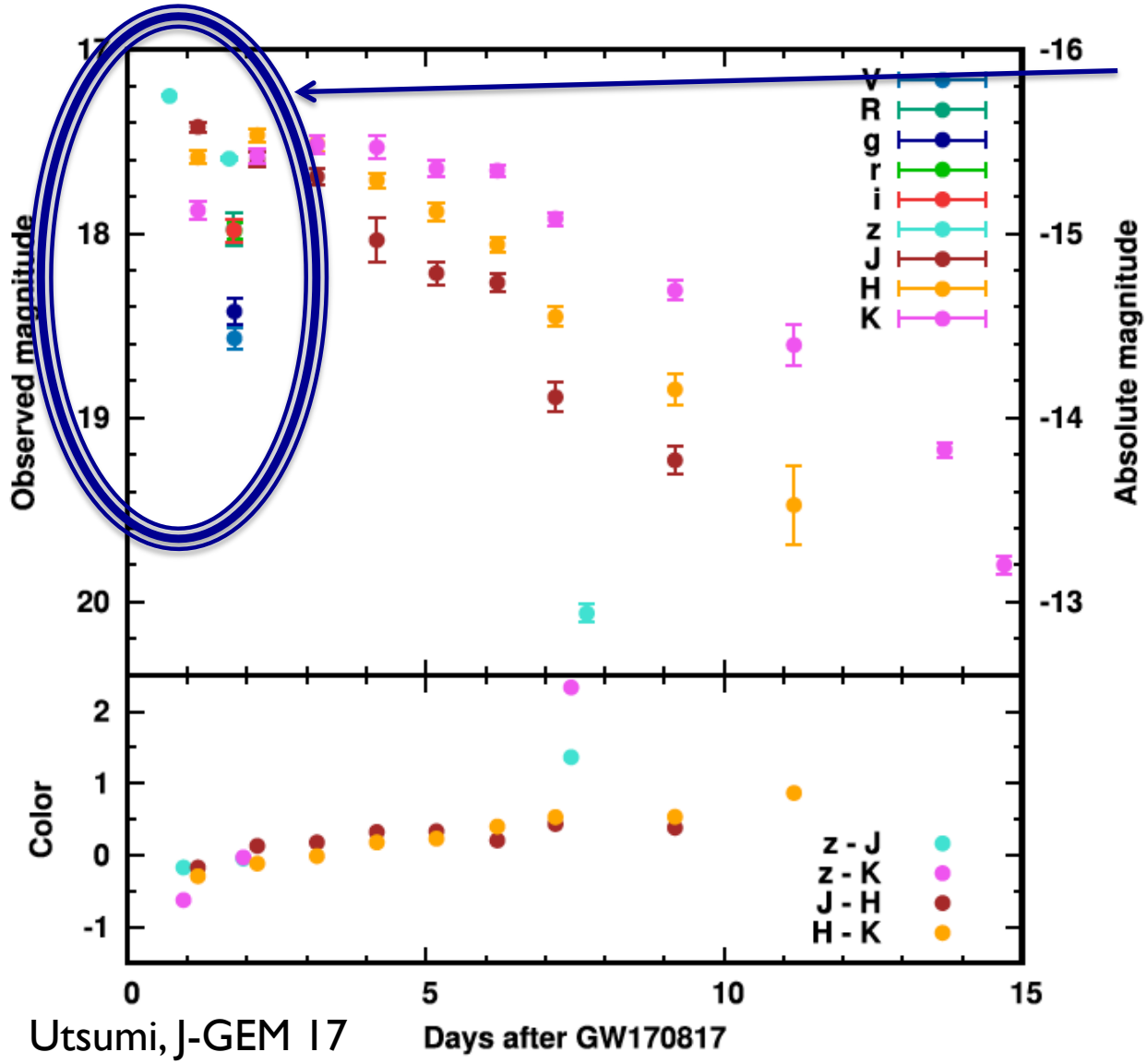
Red macronova

~10 day IR

T~2000K

L~4e40 erg/s

Macronova/Kilonova



Utsumi, J-GEM 17

Blue macronova

~1 day opt.

T~7000K

L~7e41 erg/s

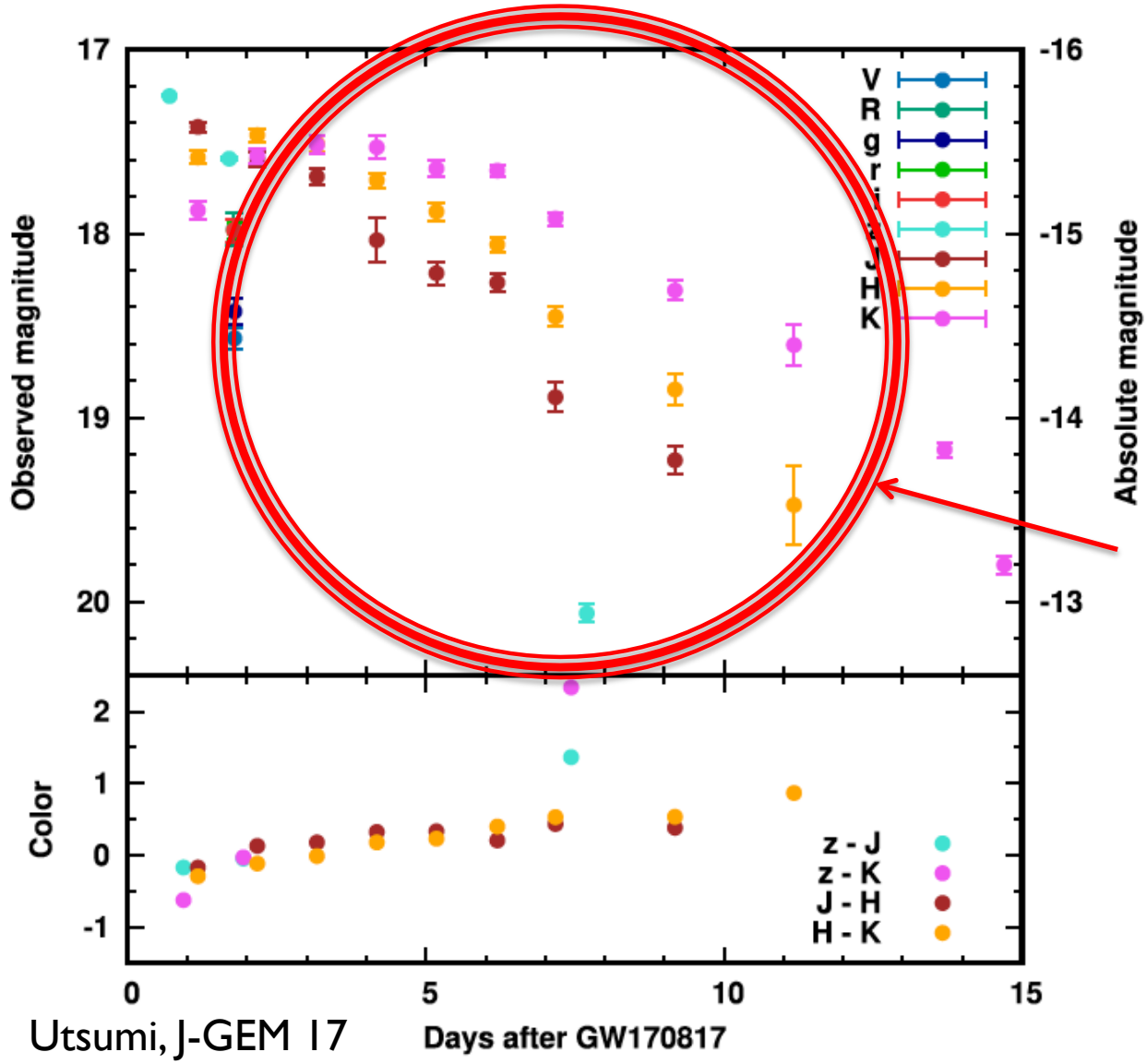
Red macronova

~10 day IR

T~2000K

L~4e40 erg/s

Macronova/Kilonova



Utsumi, J-GEM 17

Blue macronova

~1 day opt.

T~7000K

L~7e41 erg/s

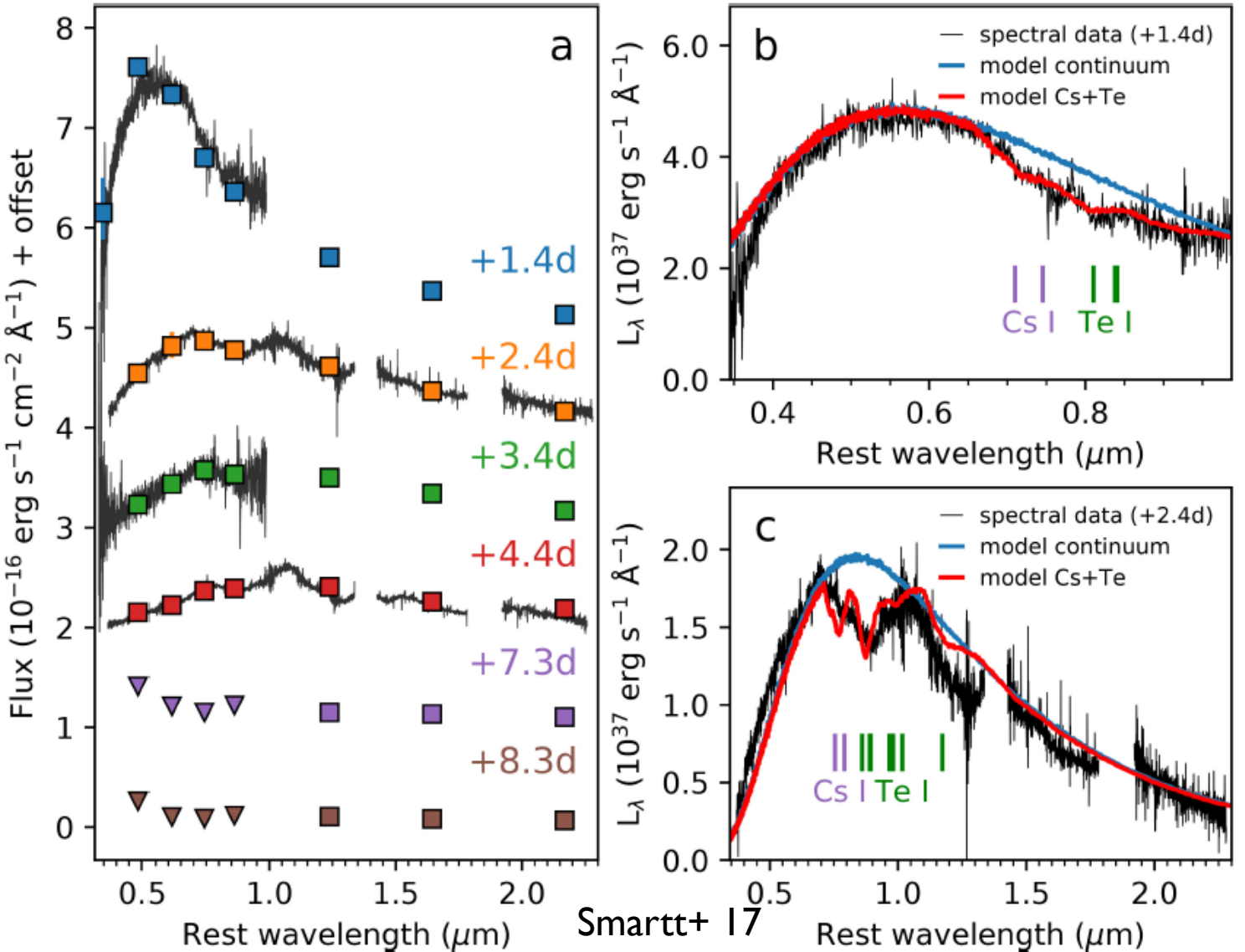
Red macronova

~10 day IR

T~2000K

L~4e40 erg/s

Macronova Spectrum



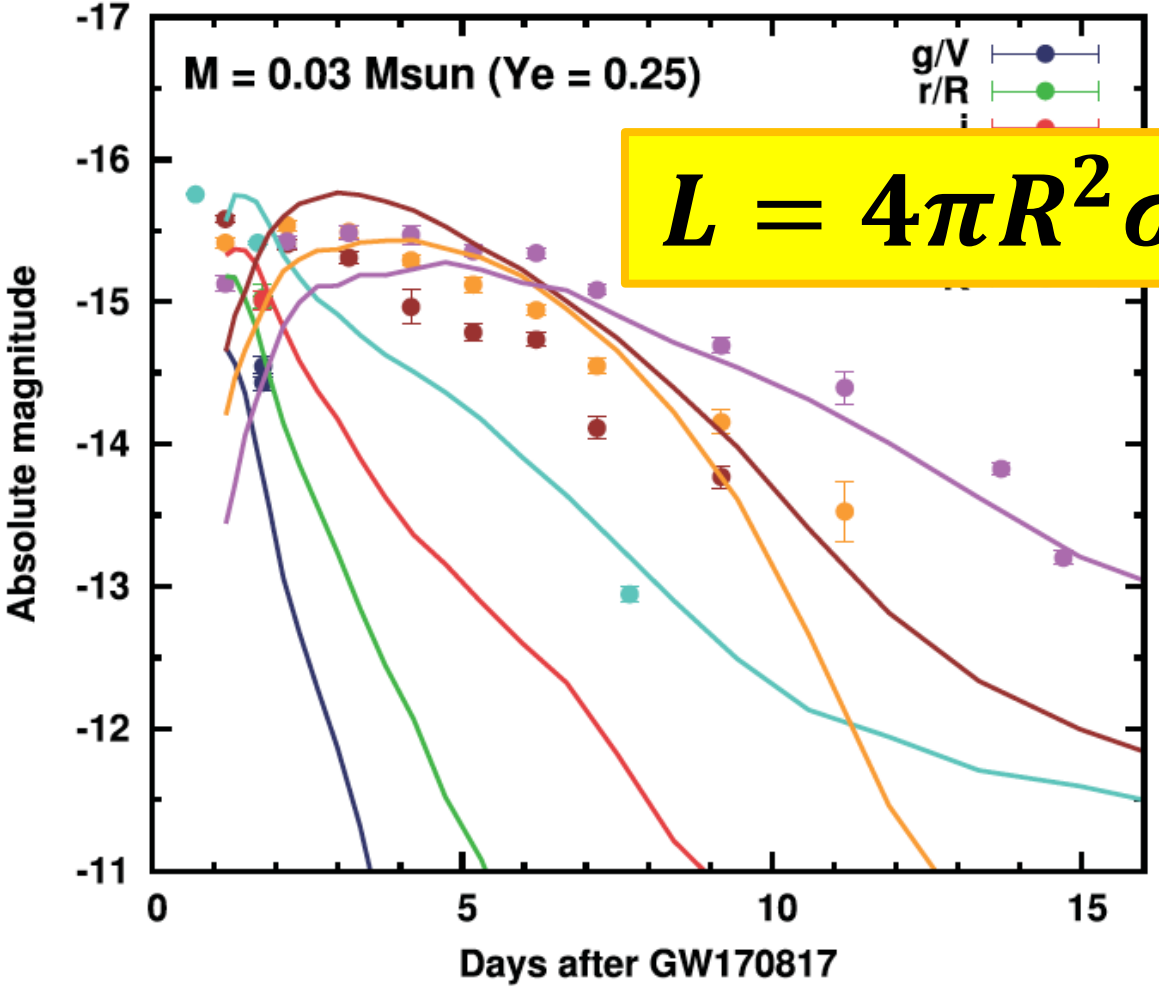
Smartt+ 17

~1 day
Black body

> 3-4 days
Lines

Not dust
cf. Takami+ 14
Gall+ 17

Macronova Modelings



$$L = 4\pi R^2 \sigma T^4$$

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, …

Blue macronova

v~0.3c

$M \sim 0.02 M_\odot$

$\kappa \sim 0.3\ cm^2/g$

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

Red macronova

v~0.1-0.2c

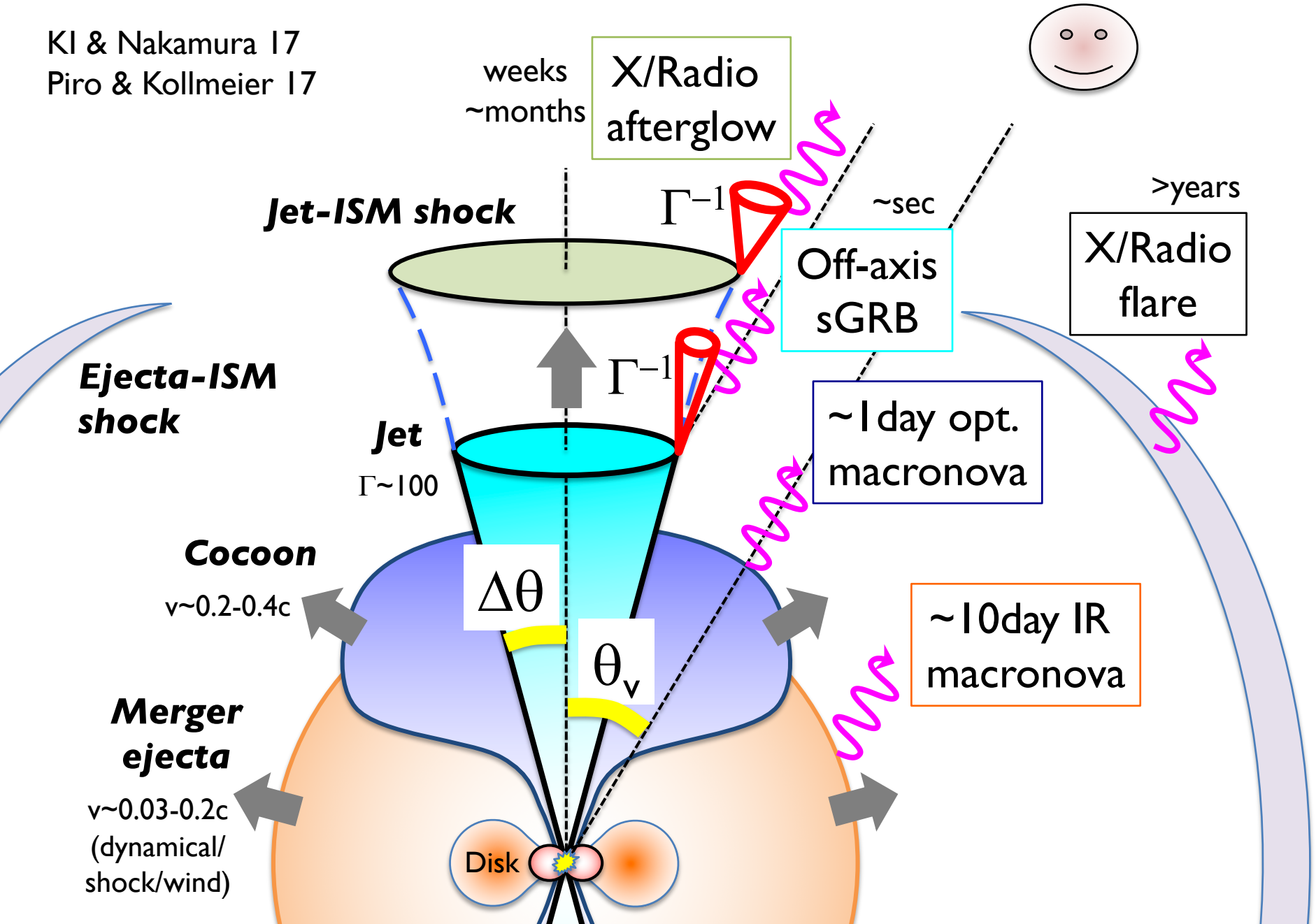
$M \sim 0.03 M_\odot$

$\kappa \sim 3\ cm^2/g$

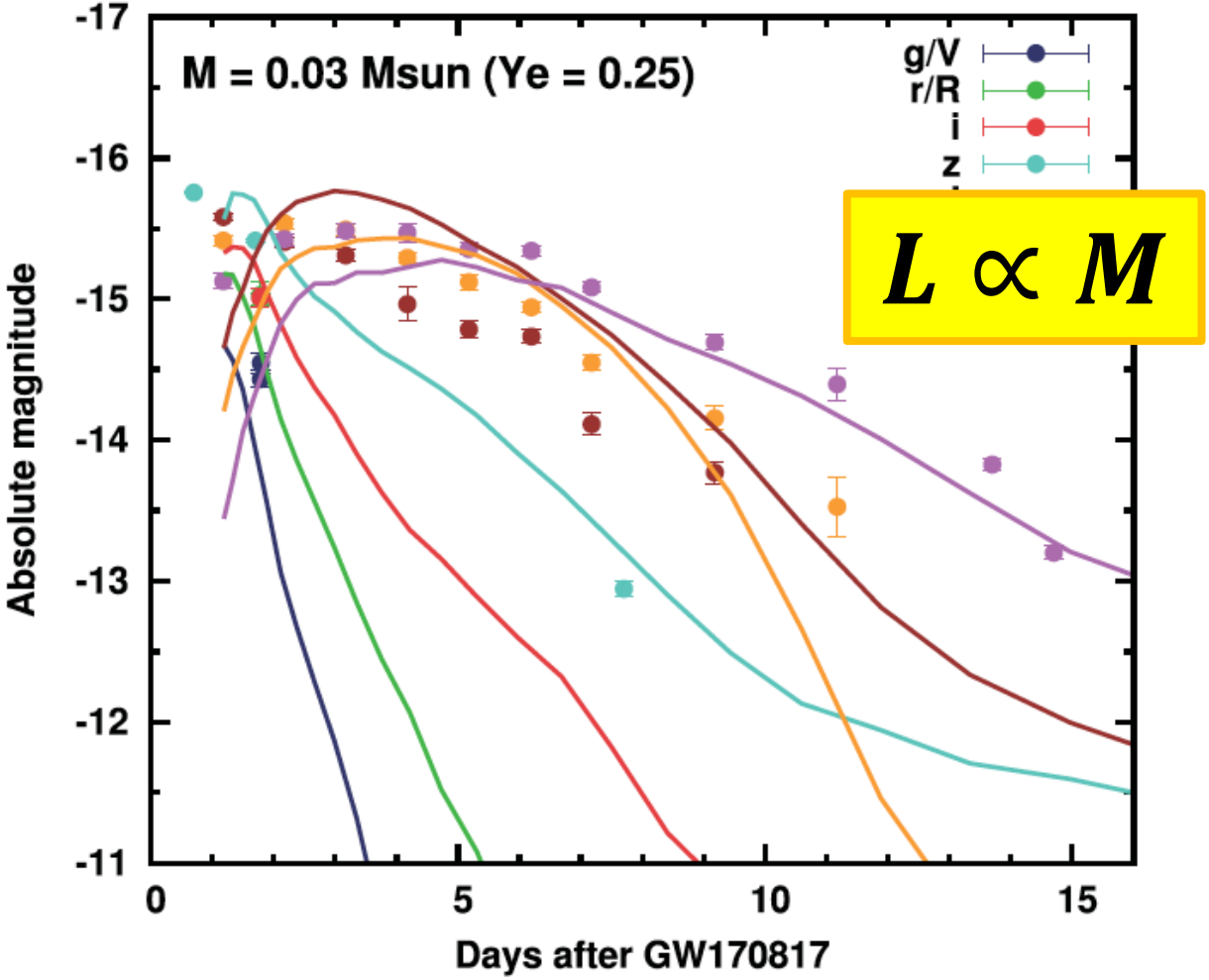
$(X_{Lan} \sim 10^{-2})$

Polar or Radial

KI & Nakamura 17
Piro & Kollmeier 17



Macronova Modelings



$L \propto M$

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, …

Blue macronova

v~0.3c

$M \sim 0.02 M_\odot$

$\kappa \sim 0.3$ cm^2/g

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

Red macronova

v~0.1-0.2c

$M \sim 0.03 M_\odot$

$\kappa \sim 3$ cm^2/g

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

Polar or Radial

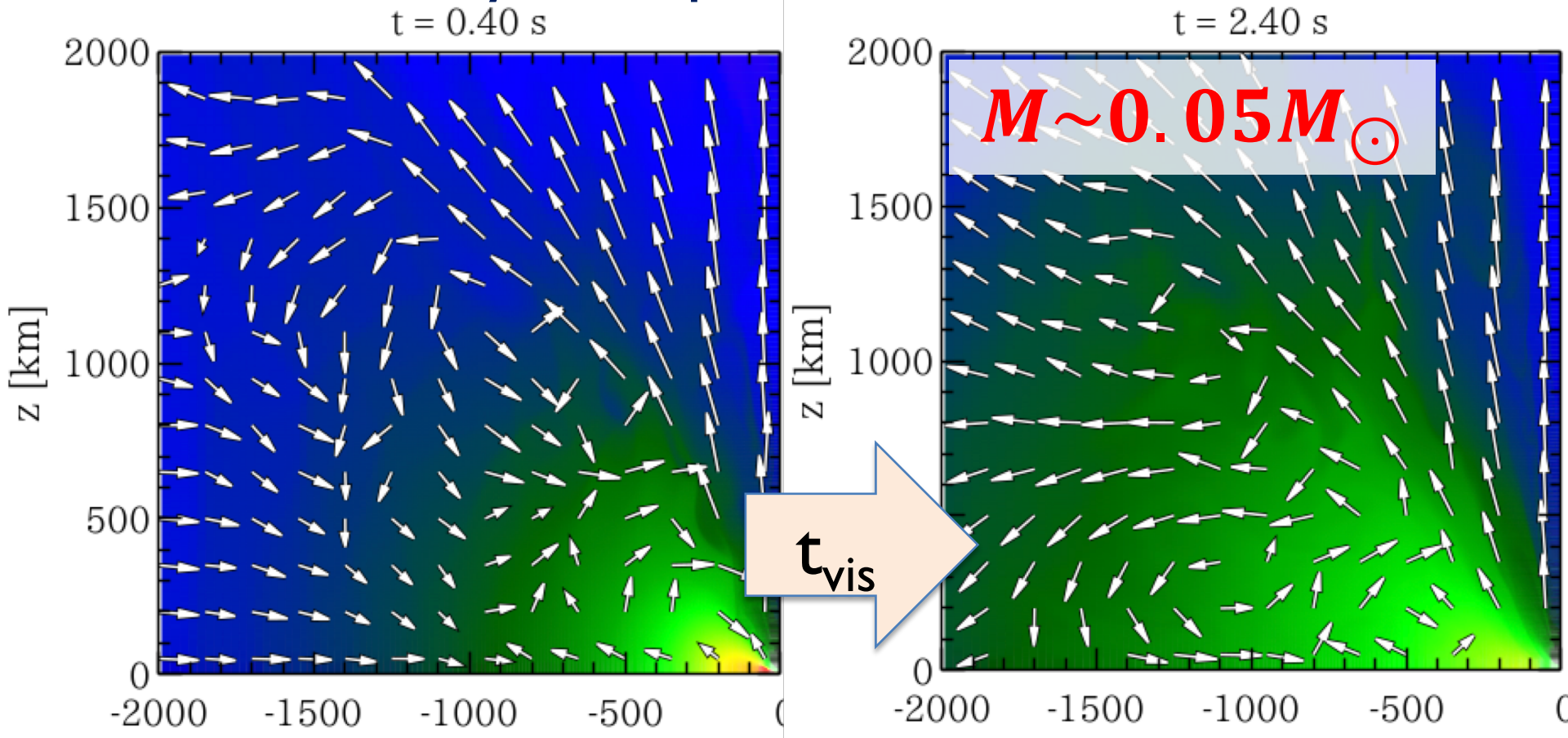
Galactic Abundance

- ***Galactic r-process rate***
  ~ 10^{-6} $M_\odot$/yr
- ***Ejected mass***
  ~ 0.01 $M_\odot$/event
  ~0.03 $M_\odot$ (red)
  + 0.02 $M_\odot$ (blue)
- ***Event rate***
  ~ 10^{-4} events/yr/galaxy
  ~ 10^3 events/Gpc^3/yr
  ~1540^{+3200}_{-1220}/Gpc^3/yr
- $X_{\mathrm{Lanthanide}}$ ~ 0.03
  $X_{Lanthanide} < 0.01$

NS^2 = r-process origin?

Viscous Disk Outflow?

Viscosity ⇒ Expand disk ⇒ Outflow

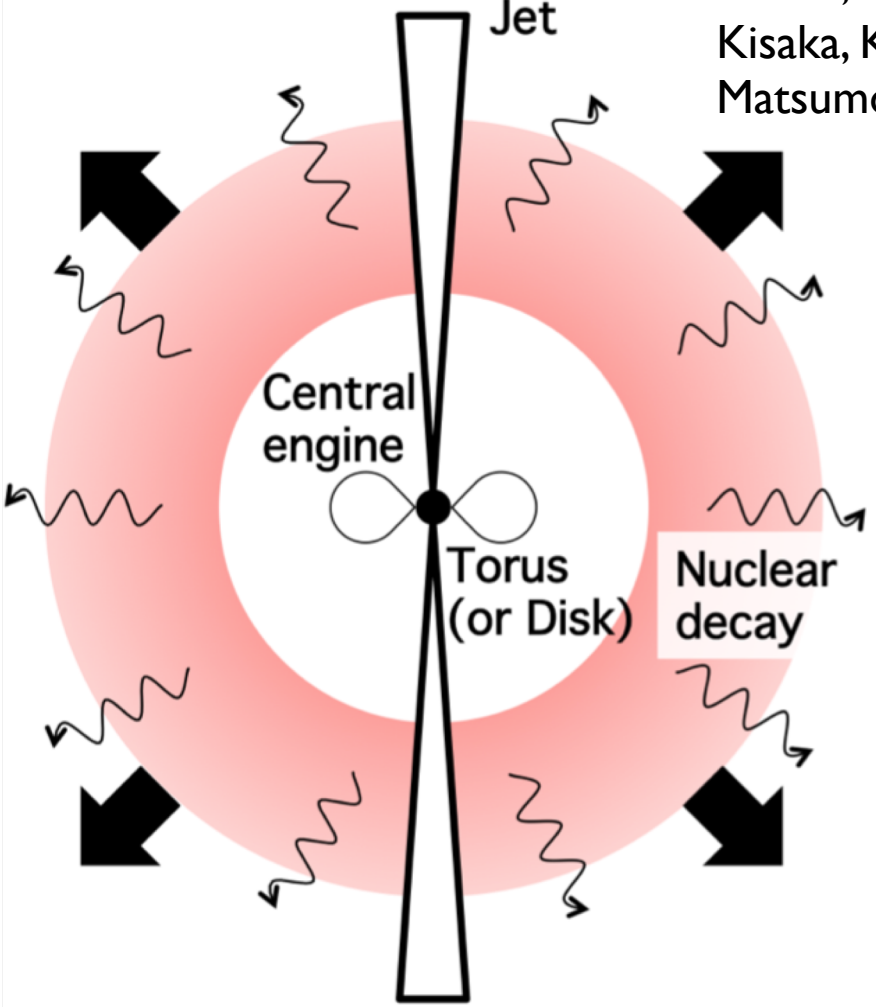


⇒ Low $v \sim v_{esc} \sim 0.05$-$0.1\ c$ & Late-time >~2s

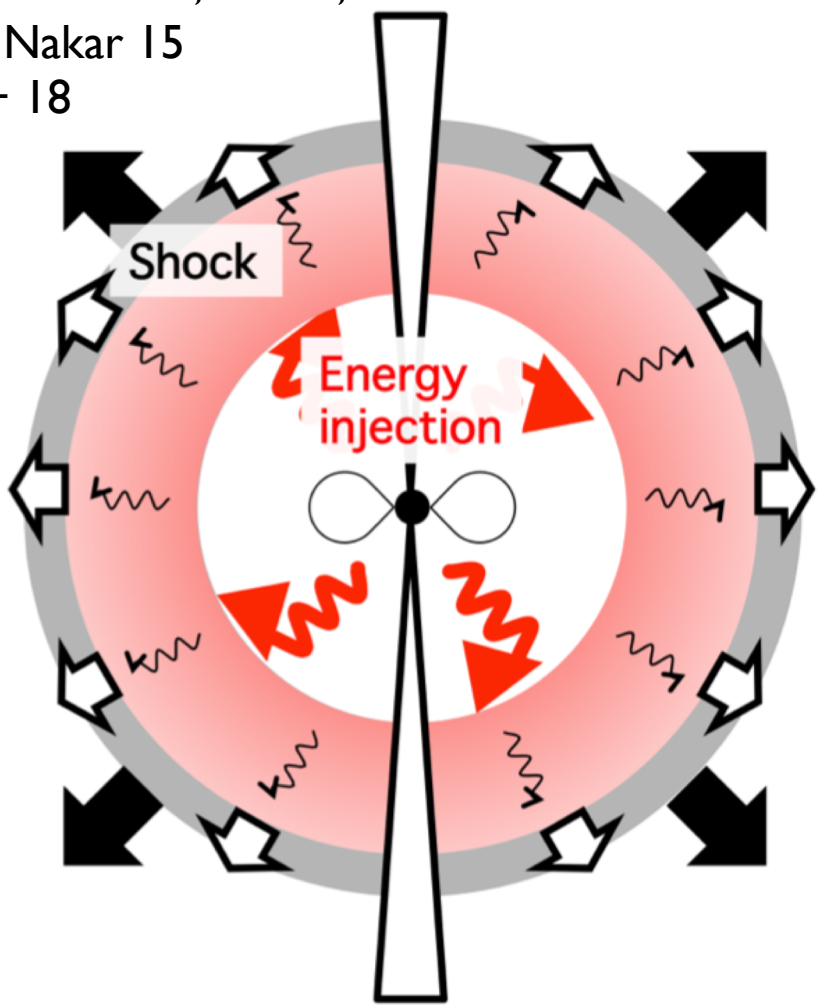
Fernandez & Metzger 13-15, Just+ 15, Siegel & Metzger 17, Shibata+ 17, Fujibayashi+ 18

Engine-Powered Macronova?

Kisaka, KI & Takami 14, Kisaka, KI & Nakamura 15
Kisaka, KI & Nakar 15
Matsumoto+ 18



R-process model

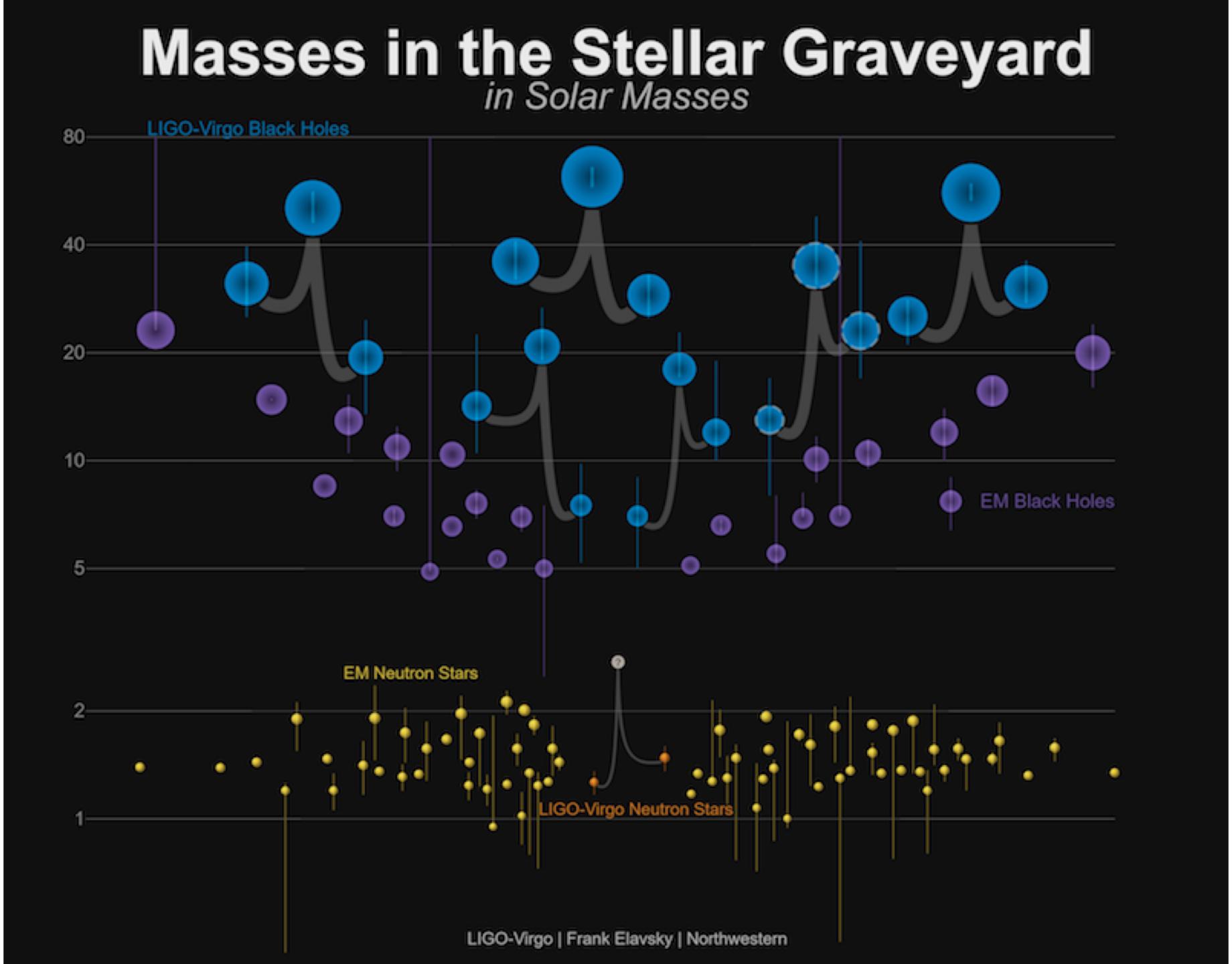


Engine model

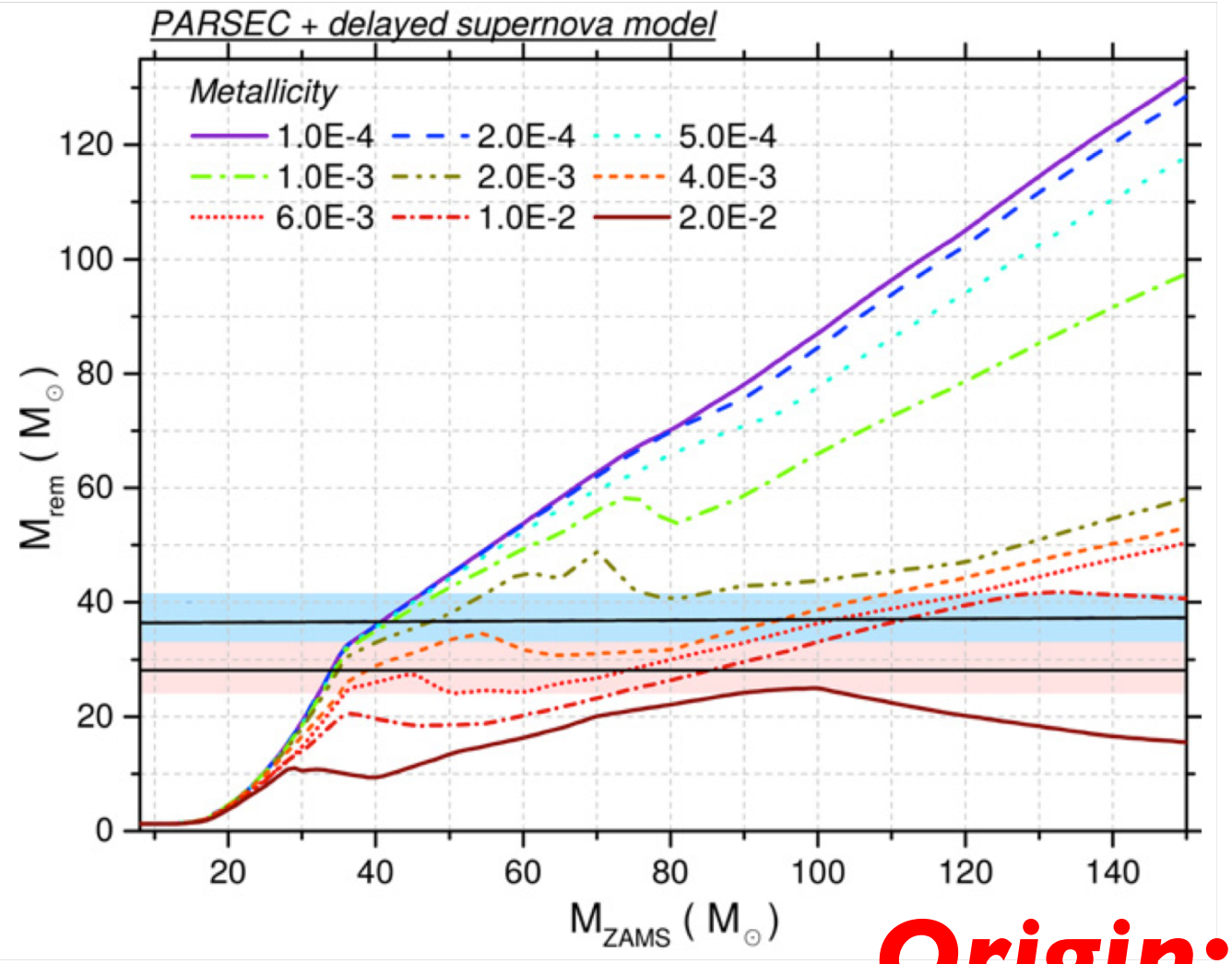
New Problems

- ***sGRB 170817A (gamma)***
  - Jet, Cocoon breakout, or Scattering?
- ***Afterglow (X, opt, radio)***
  - ***Jet is verified***, Jet structure?
- ***Macronova/Kilonova (UV, opt, IR)***
  - Radioactive energy or Central engine?
  - r-process abundance & pattern?

Great Progress!!


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Low Metallicity



Heavy elements like C should be little in the star

Otherwise stellar wind
⇒ mass loss
⇒ too small M

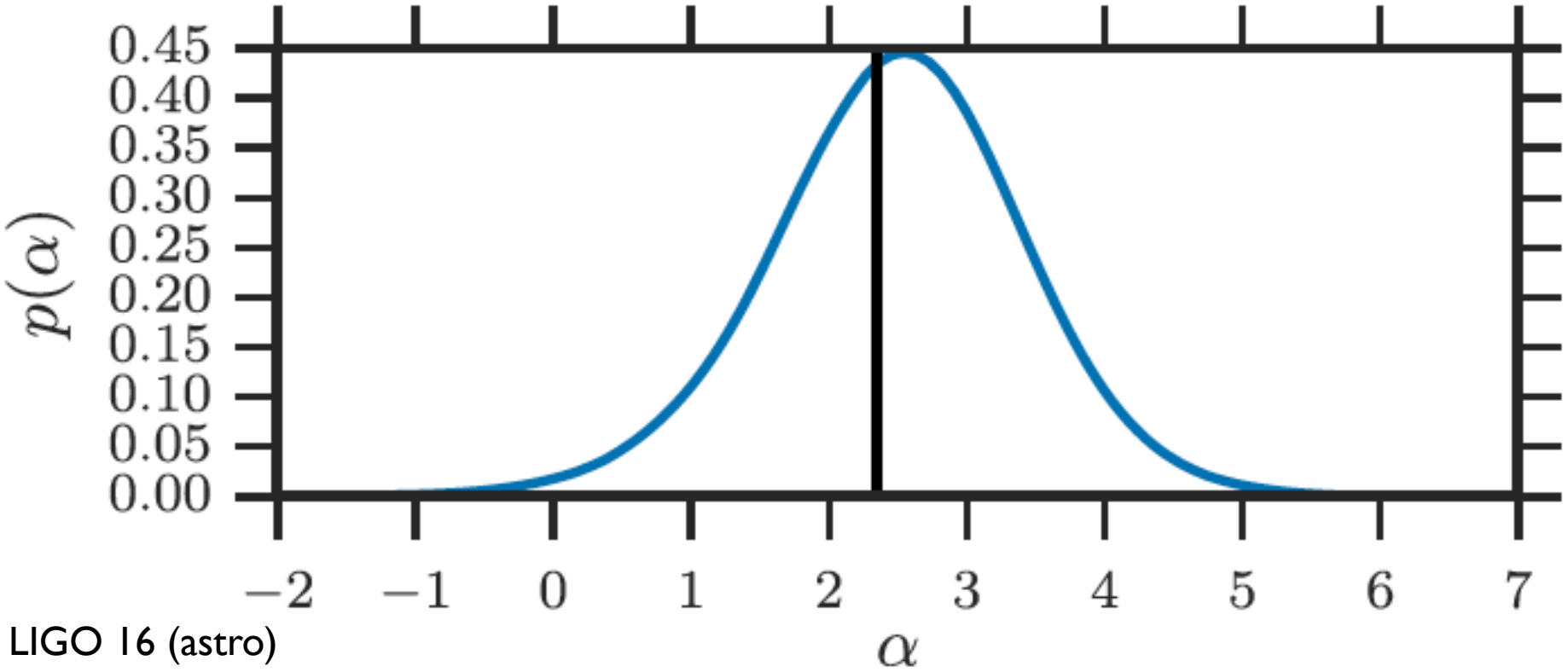
Origin: Old stars

LIGO(astro) 16

Mass Function

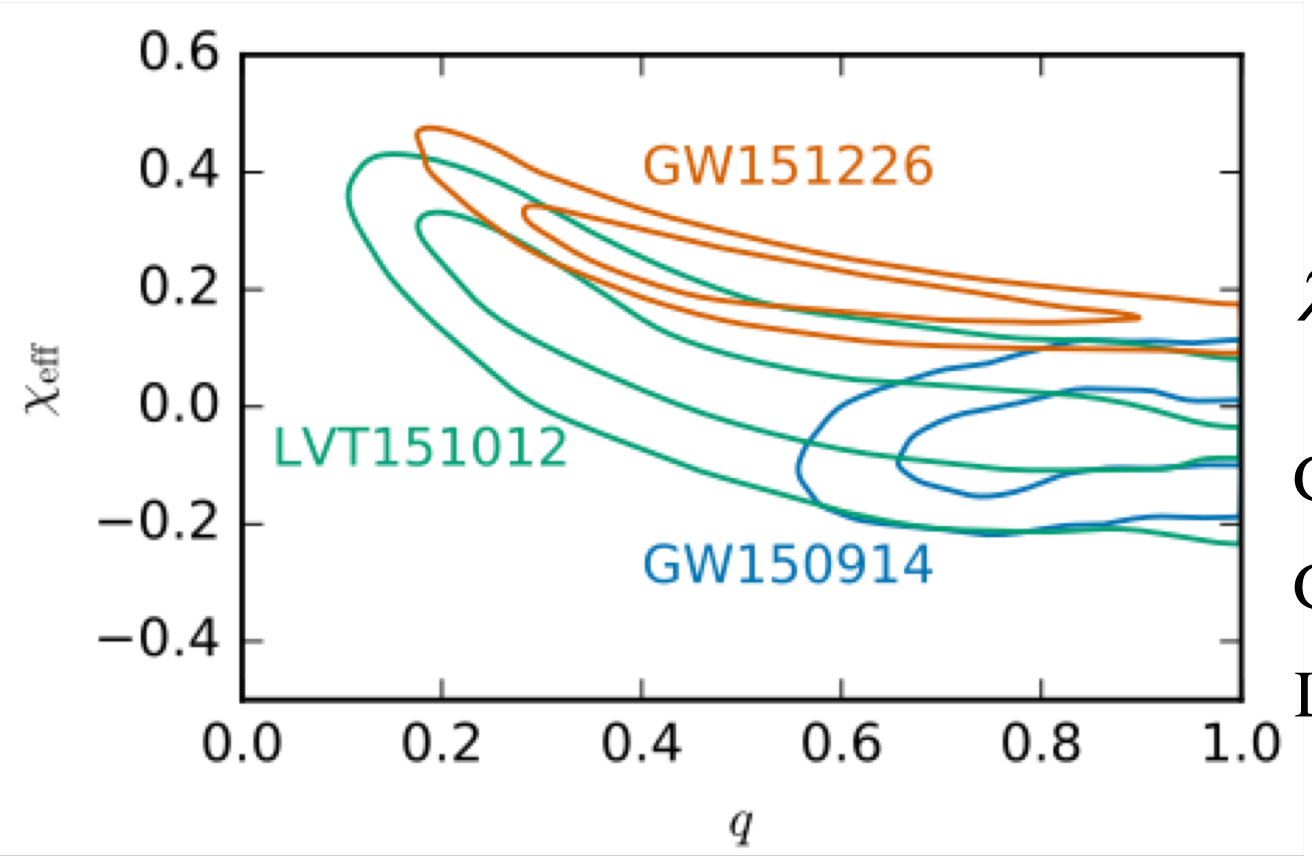
~ Salpeter mass function

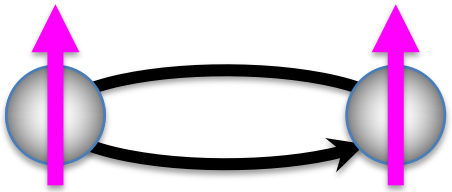
$$p(m_1) \propto m_1^{-\alpha},\ \alpha \sim 2.5^{+1.5}_{-1.6}$$



LIGO 16 (astro)

Low Spin?





$$\chi_{\rm eff} \equiv \frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2$$

GW150914: $-0.06^{+0.14}_{-0.14}$

GW151226: $0.21^{+0.20}_{-0.10}$

LVT151012: $0.0^{+0.3}_{-0.2}$

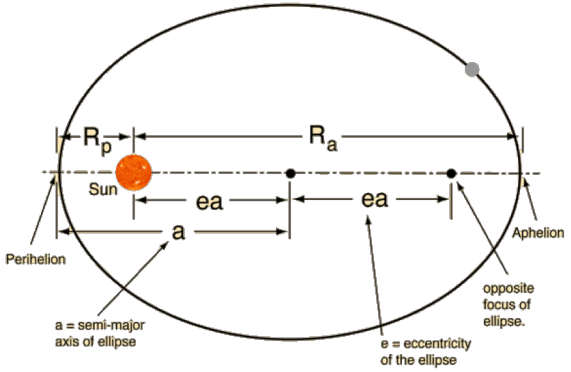
The Sun (P~26 days) ⇒ χ~0.2

Typical O star (R~10^{12}cm, v~100km/s) ⇒ χ~30

Very Close Binary

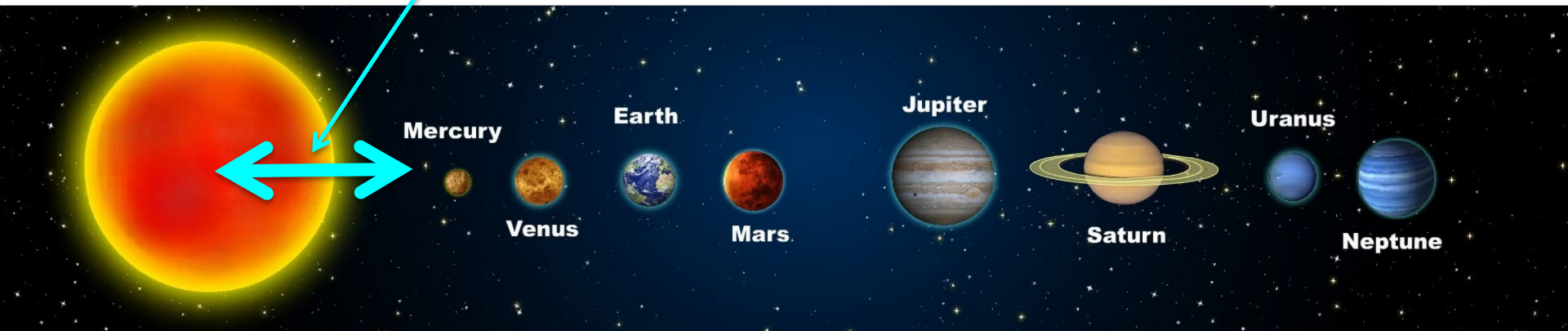
GW coalescence time

$$t_{GW} \cong \frac{5}{256}\frac{a}{c}\frac{c^2 a}{Gm_1}\frac{c^2 a}{Gm_2}\frac{c^2 a}{GM}\left(1-e^2\right)^{7/2}$$



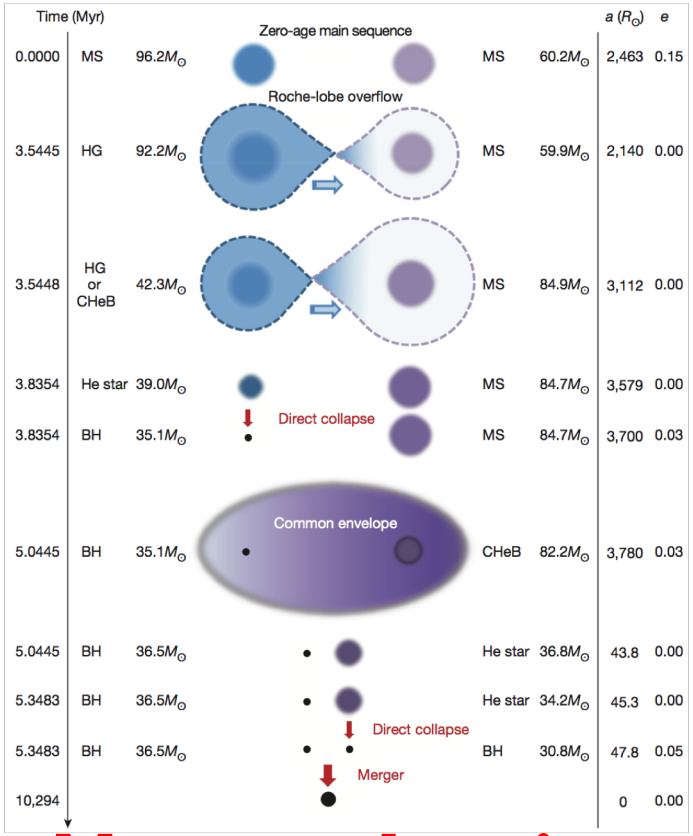
$$\approx 10^{10}\,\mathrm{yr}\left(\frac{a}{3\times10^{12}\,\mathrm{cm}}\right)^4\left(\frac{m_1}{30M_\odot}\right)^{-3}\left(\frac{2/q}{1+q}\right)\left(1-e^2\right)^{7/2}$$

closer than Mercury for $t_{GW}<t_H$!



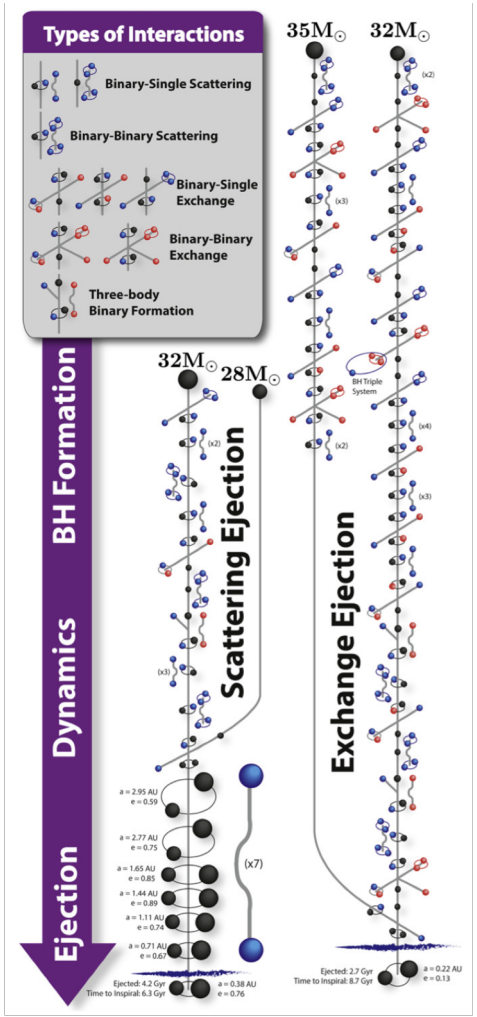
What is the Origin?

Isolated binary



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

Stellar cluster



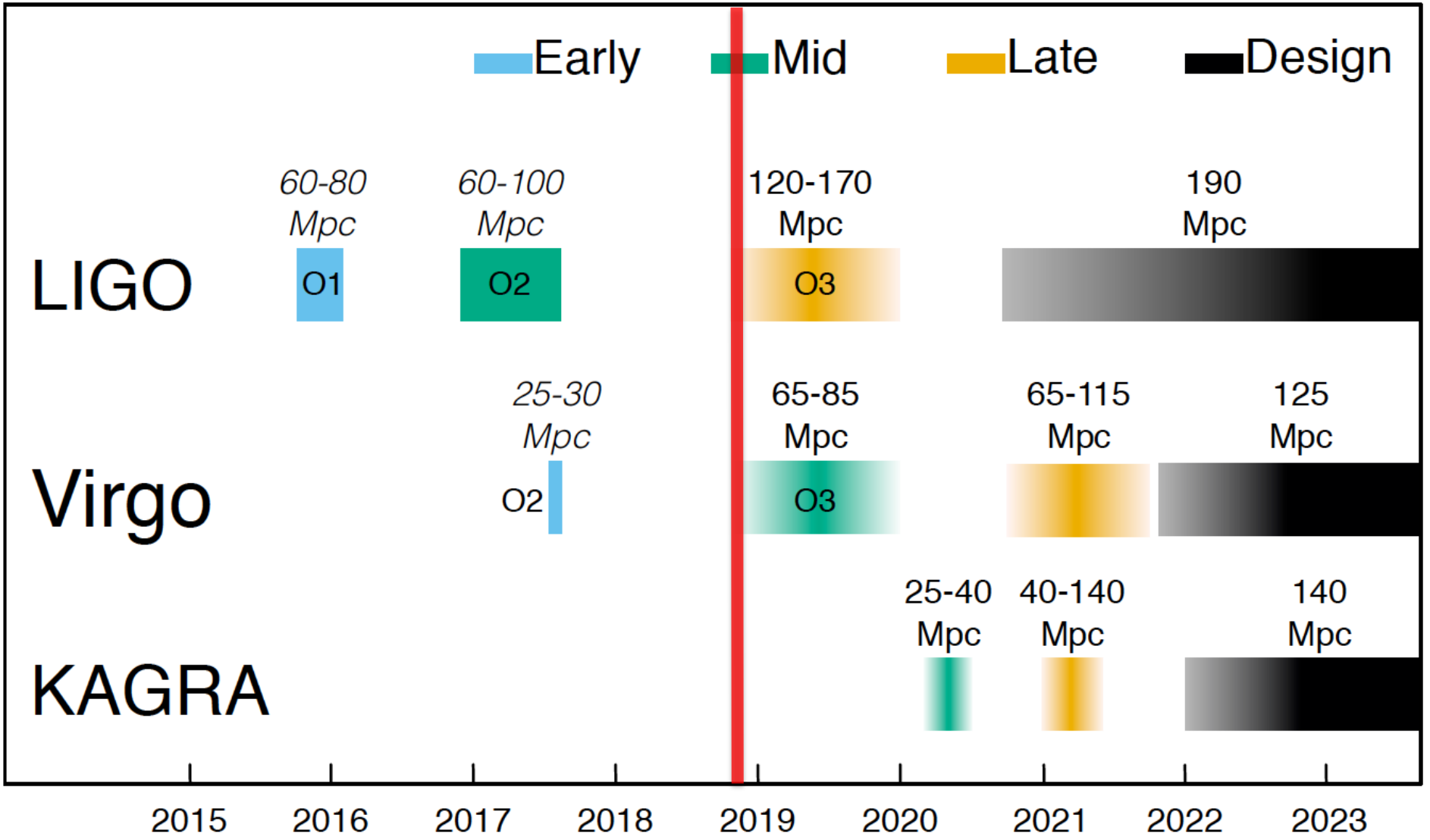
Rodriguez+ 16
O'Leary+ 16

Antonini & Rasio 16
Bartos+ 16
Stone+ 16

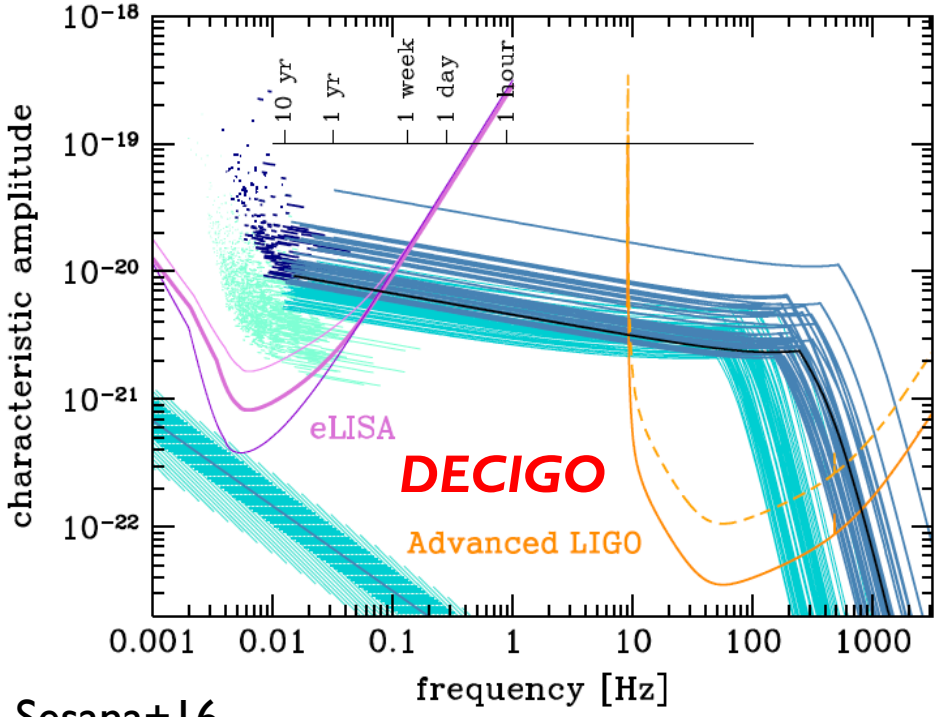
Sasaki+ 16
Bird+ 16
Binnilov+ 16
Carr+ 16
Kawasaki+ 16

Near galactic nuclei
Primordial black hole

Future GW Observations



Space GW Observatories



Sesana+16

Low frequency band

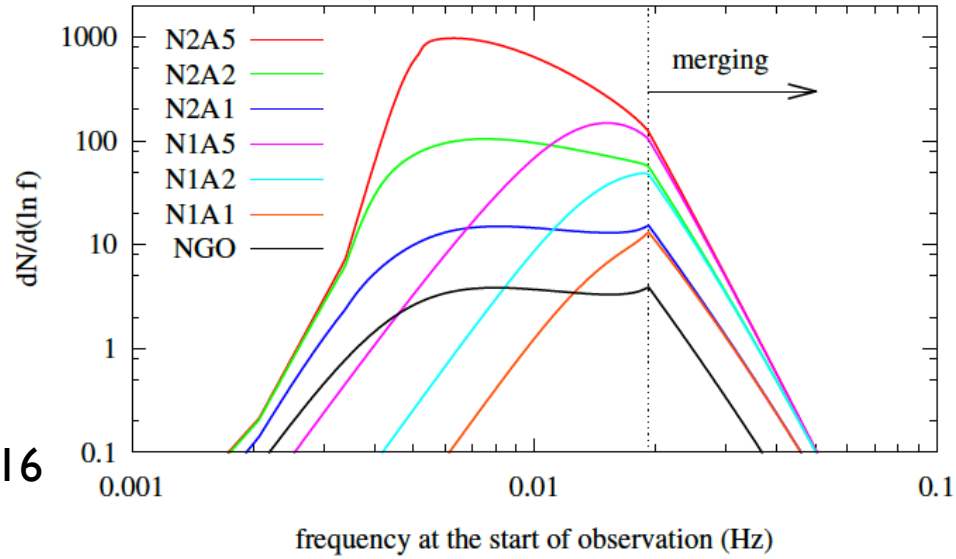
LISA ~0.01Hz

DECIGO ~0.1Hz

→ Ground ~100Hz

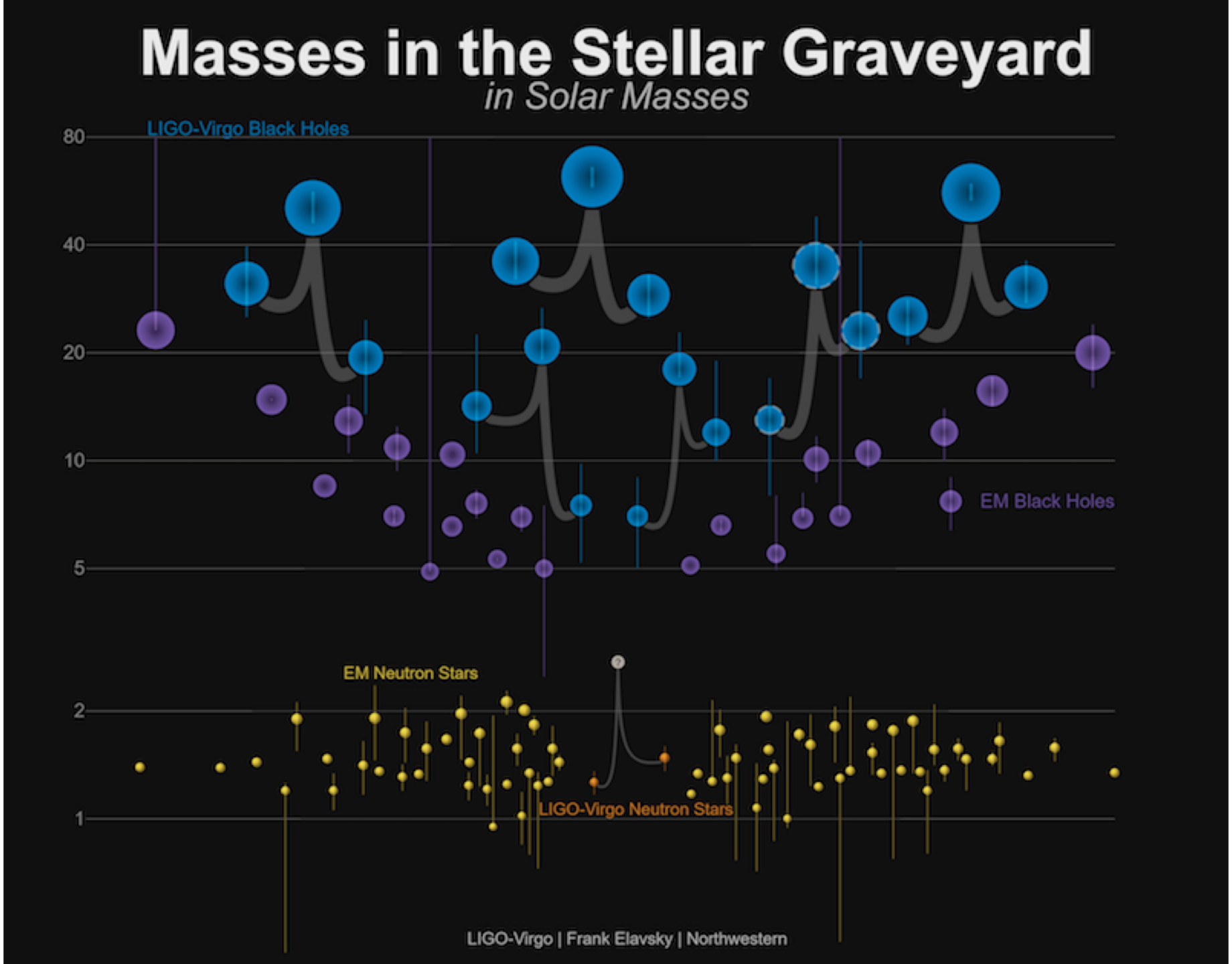
Guaranteed sources

Good localization



Kyutoku & Seto 16

Seto 16


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Thank You