# *NS-NS merger*

Event GW170817:

Abbott et al. PRL 119, 161101 (2017)

Summary of GW170817

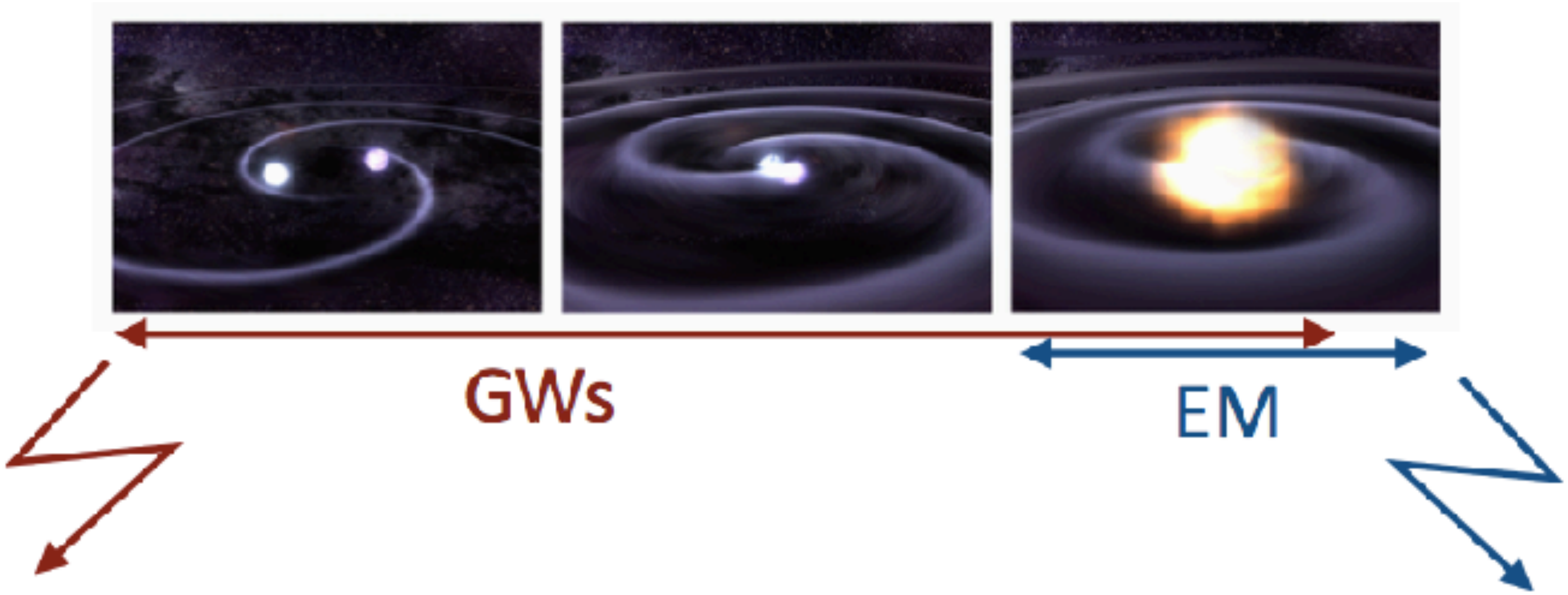
https://www.ligo.org/science/Publication-GW170817BNS/index.php

Electromagnetic Counterpart to GW170817

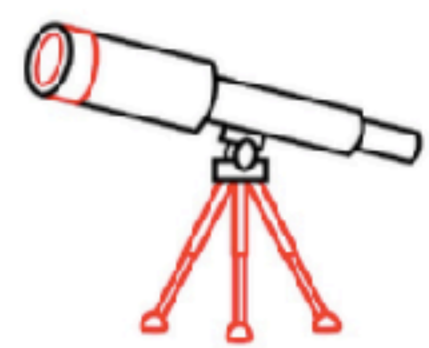
https://dcc.ligo.org/public/0145/P1700294/007/ApJL-MMAP-171017.pdf

# double neutron stars and GW

courtesy of S. Nissake







2017-2019 (LIGO+Virgo+...):

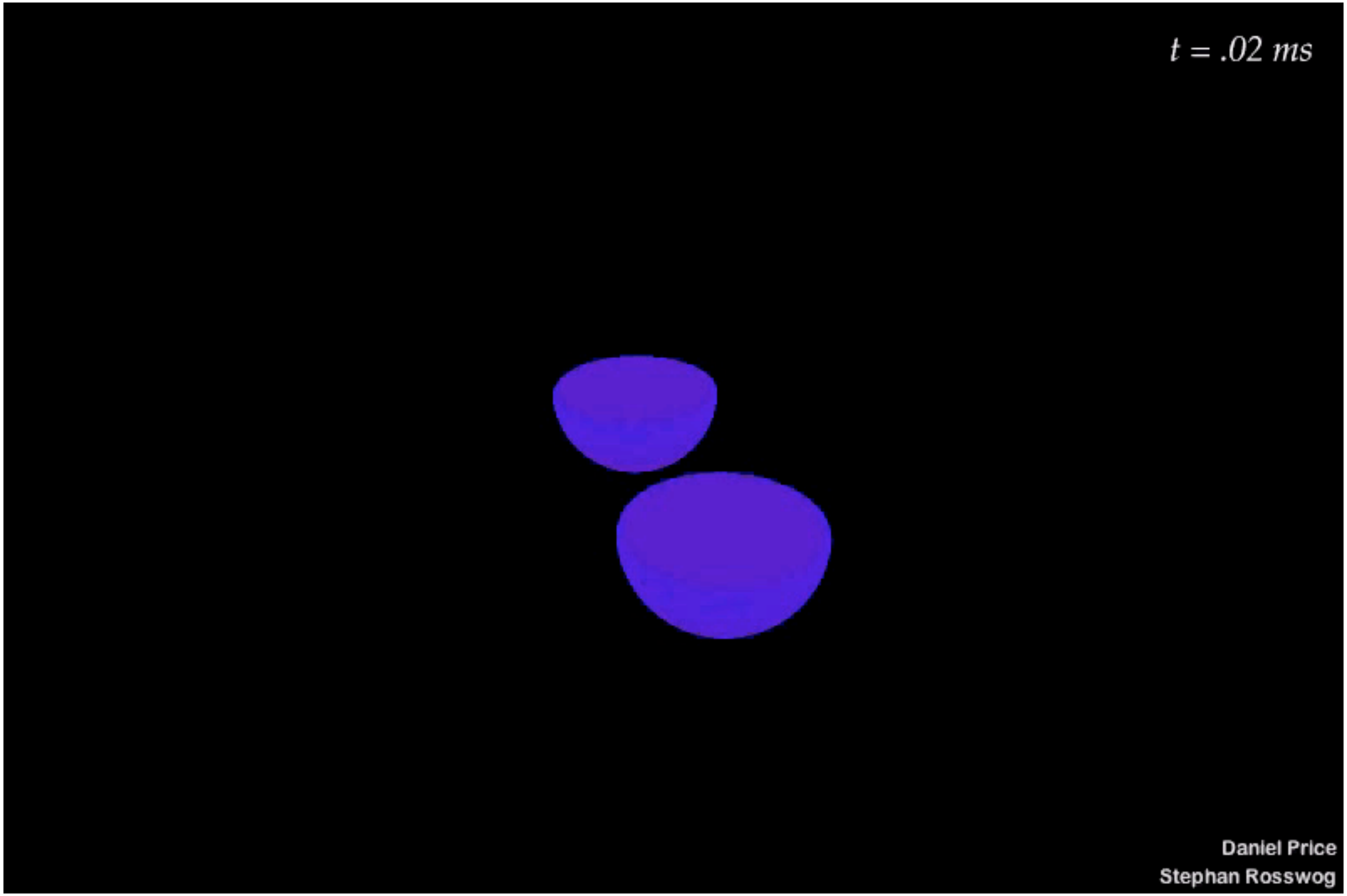
NS-NS: 0.007-100 year$^{-1}$

BH-BH: few to tens year$^{-1}$(mean)

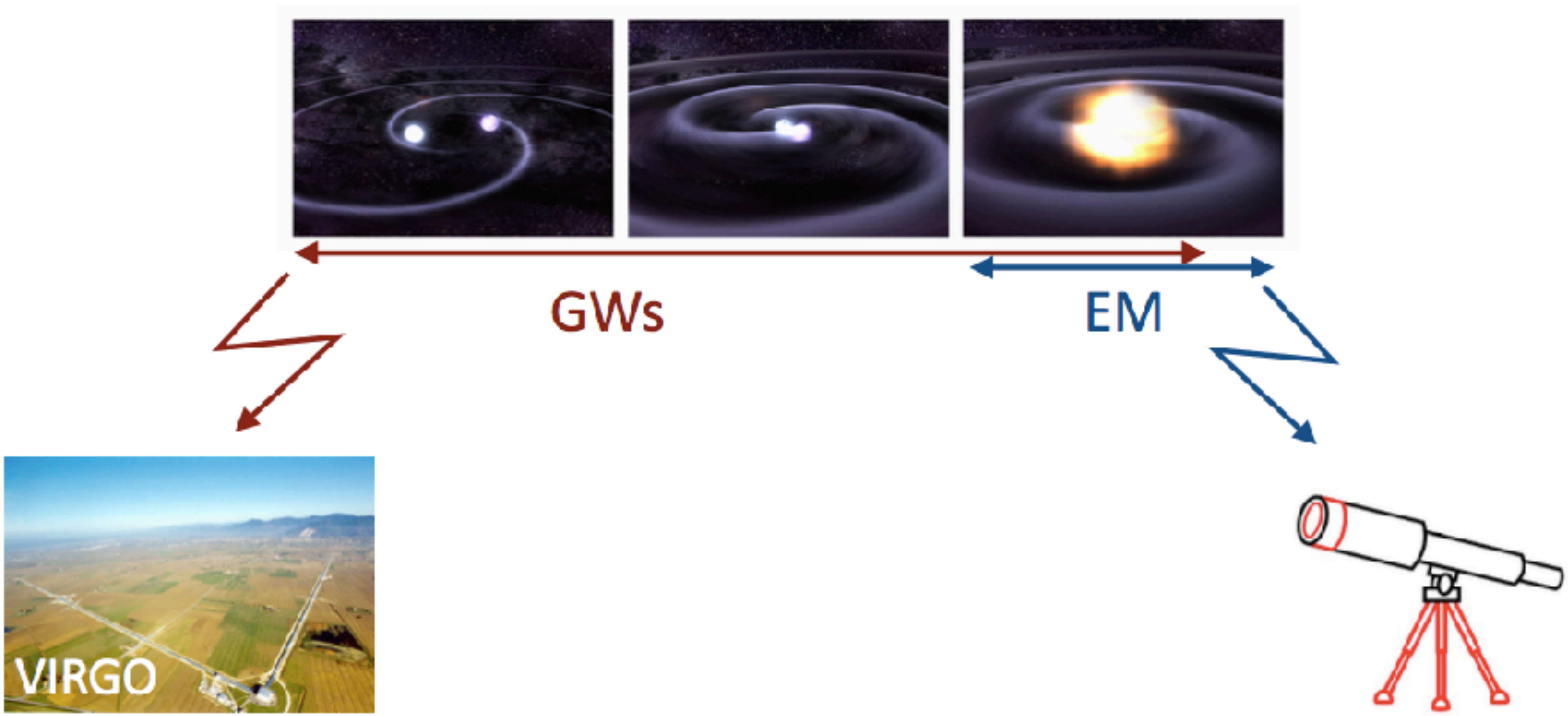
[LIGO Scientific and Virgo Collaborations (LVC),
Living Reviews in Relativity 19, 1, 2016 and PRX 6, 041015, 2016]

2017+:

Wide-field high-energy,
optical, radio telescopes
(BlackGEM, LOFAR, SKA)


t = .02 ms
Daniel Price
Stephan Rosswog

courtesy of S. Nissake




Extract sources' dynamic and fundamental (masses, spins) parameters

Extract sources' environment and energetics

# Why should we care about EM counterparts? (some motivation)

courtesy of S. Nissake

1. Strong field gravity astrophysics
   Physical processes in strongly curved space-times

2. Stellar Evolution
   Understanding the fate of compact binary stellar systems?

3. Cosmic Enrichment
   Sites of r-process nucleosynthesis

4. Cosmological Probes
   Measuring the expansion history of the Universe

# *r-processes*

rapid neutron capture process :

is a set of reactions in nuclear astrophysics that are responsible for the creation (nucleosynthesis) of approximately half the atomic nuclei heavier than iron. This process entails a succession of *rapid* neutron captures (hence the name) by heavy seed nuclei, typically beginning with $^{56}Fe$.

rapid…w.r.t. radioactive decay: presence of large neutron flux: supernovae or…NS-NS merger!

e.g. gold and platinum !

# Two Types of Matter Outflows

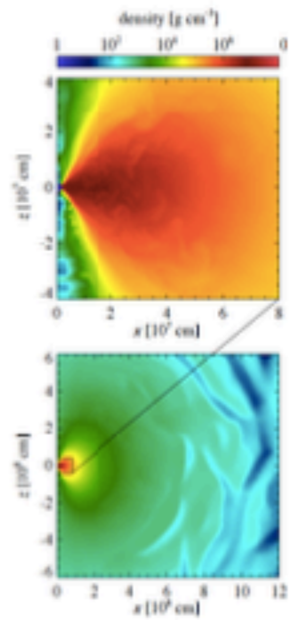
courtesy of S. Nissake

## 1. Tidal Tails + Disk Winds

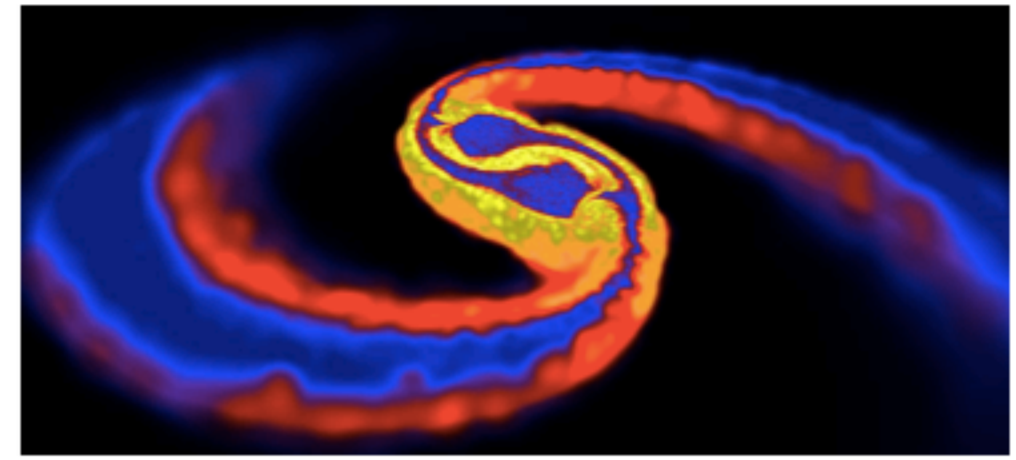
$M_{ej} \approx 10^{-4}$ - 0.01 $M_\odot$

$E \approx 10^{49}$- $10^{50}$ ergs

$v \approx$ 0.1-0.3c



[Fernandez & Metzger 2013]



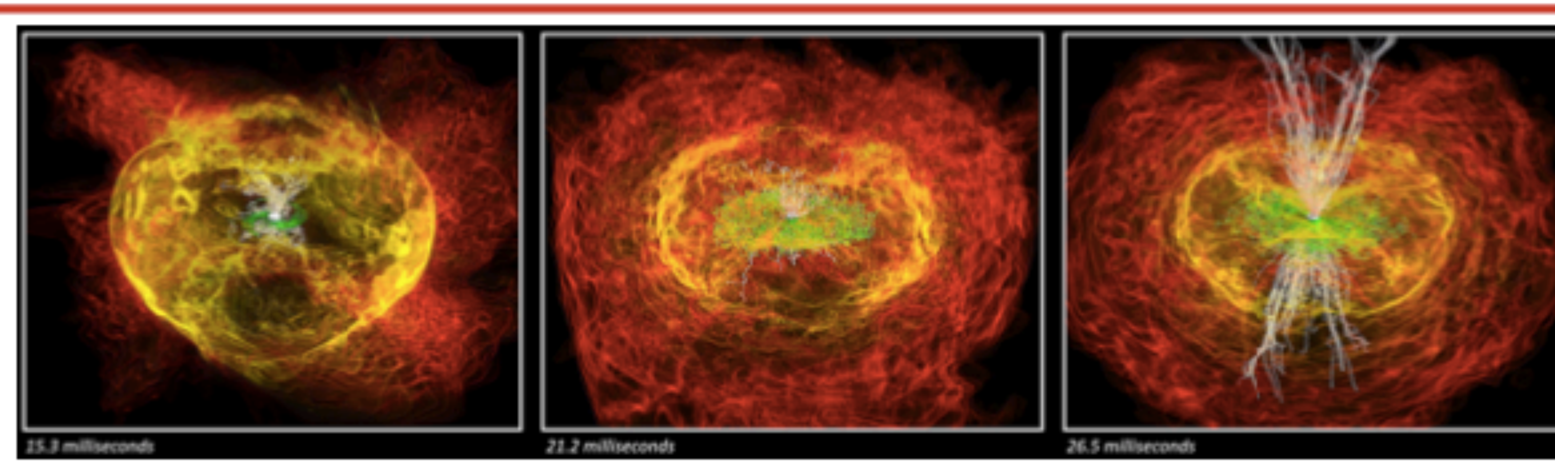
[Rosswog 2012, 2013, 2015]

## 2. Ultra-relativistic Jet

$M_{ej} \approx 10^{-6}$ $M_\odot$

$E \approx 10^{49}$- $10^{51}$ ergs

$\Gamma \approx 100$

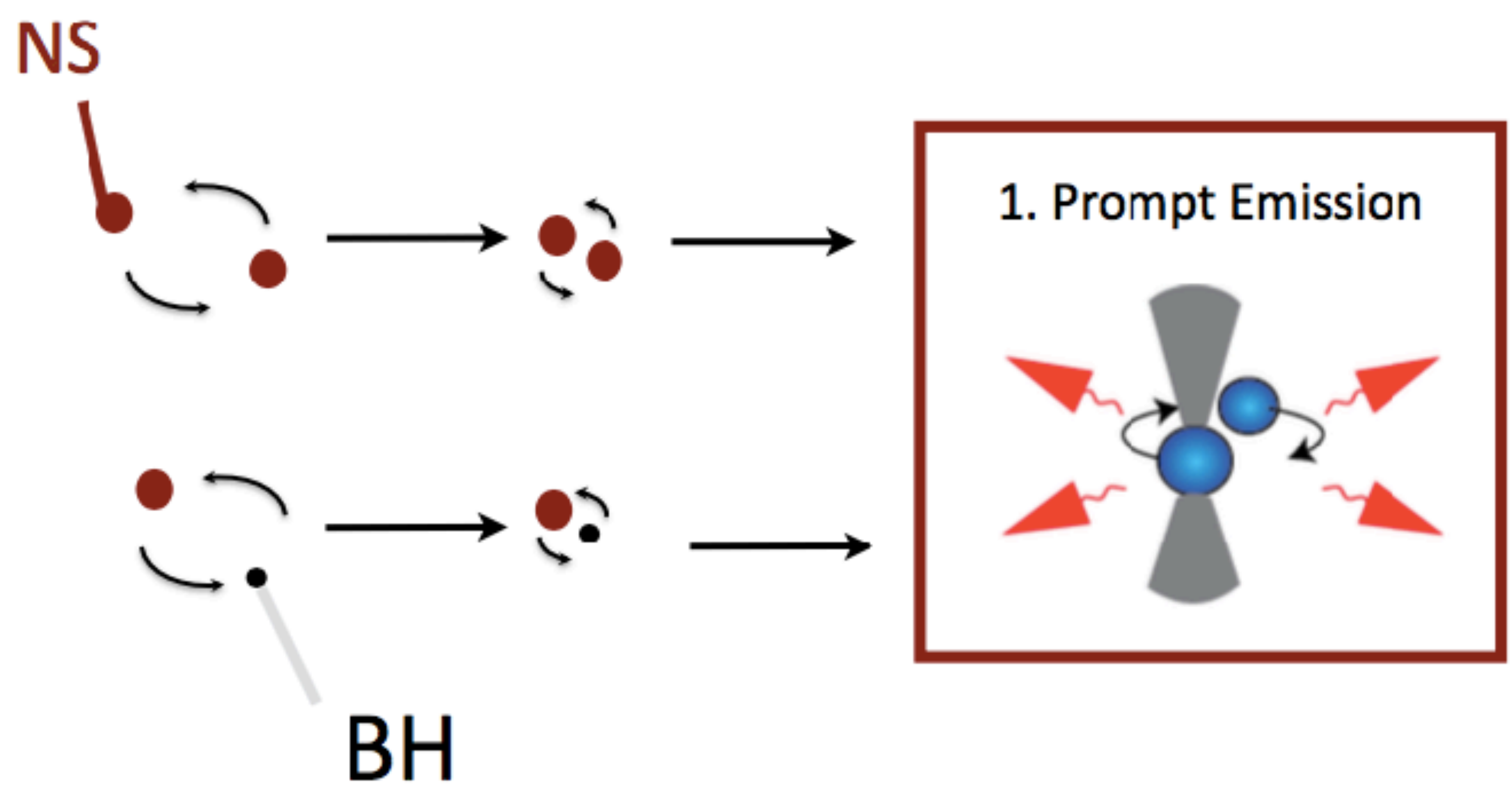



[Rezzolla et al. 2011]

[see e.g., Rezzolla et al. 2010, 2014, Palenzuela et al, 2010, 2011, Hotokezaka et al., 2012, 2014, Rosswog et al. 2012, Piran et al. 2013, Bauswein et al. 2013, Foucart et al. 2014, Nagakura et al., 2014, Bernuzzi et al. 2013, Kyutoku et al. 2014, Fernandez et al. 2014, Paschalidis et al. 2015, Ruiz et al. 2016, Radice et al. 2016 ...]

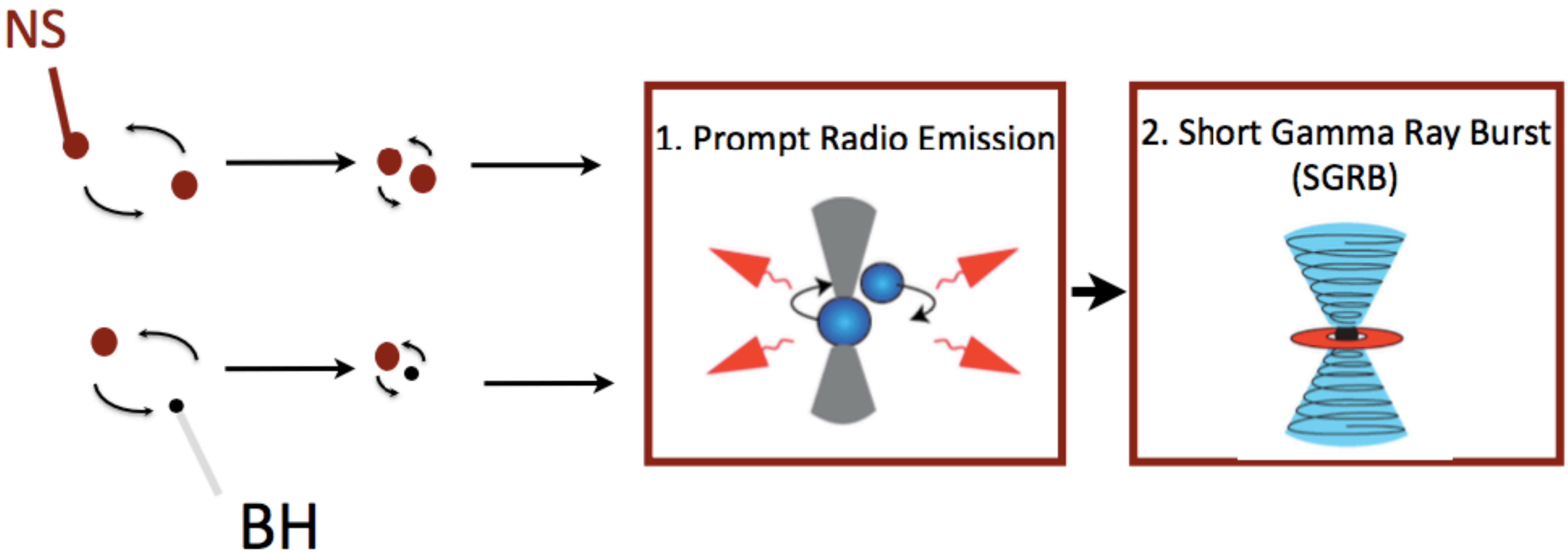
(cf. Supernova: $10^{51}$ ergs)

# Two Types of Outflows ⇒ Four+ EM counterparts



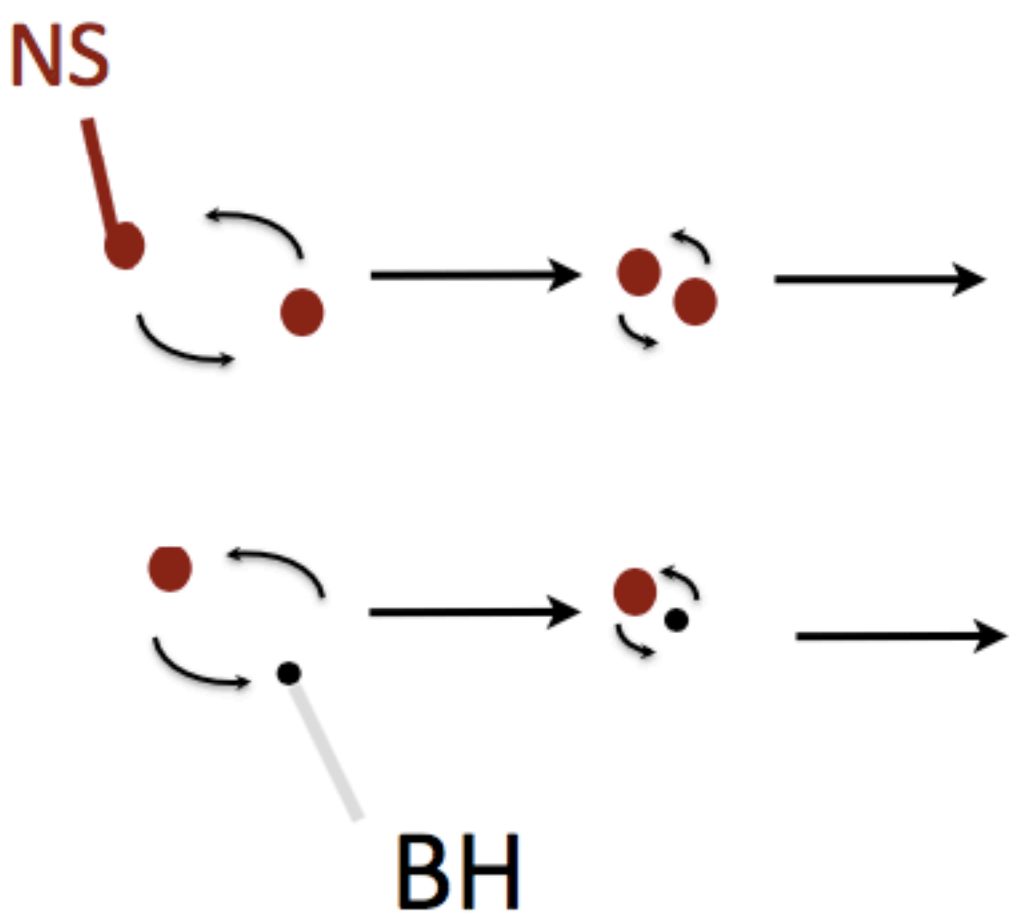

[e.g., Hansen & Lyutikov (2001), Moortgat and Kuipjers (2002,5,6), Postnov and Pshirkov (2010), Chu et al (2015, Tsang et al. (2011, Mingarelli et al. (2014), Lai et al. (2012, 2017), Coward et al. (2011,12,13), ...)]

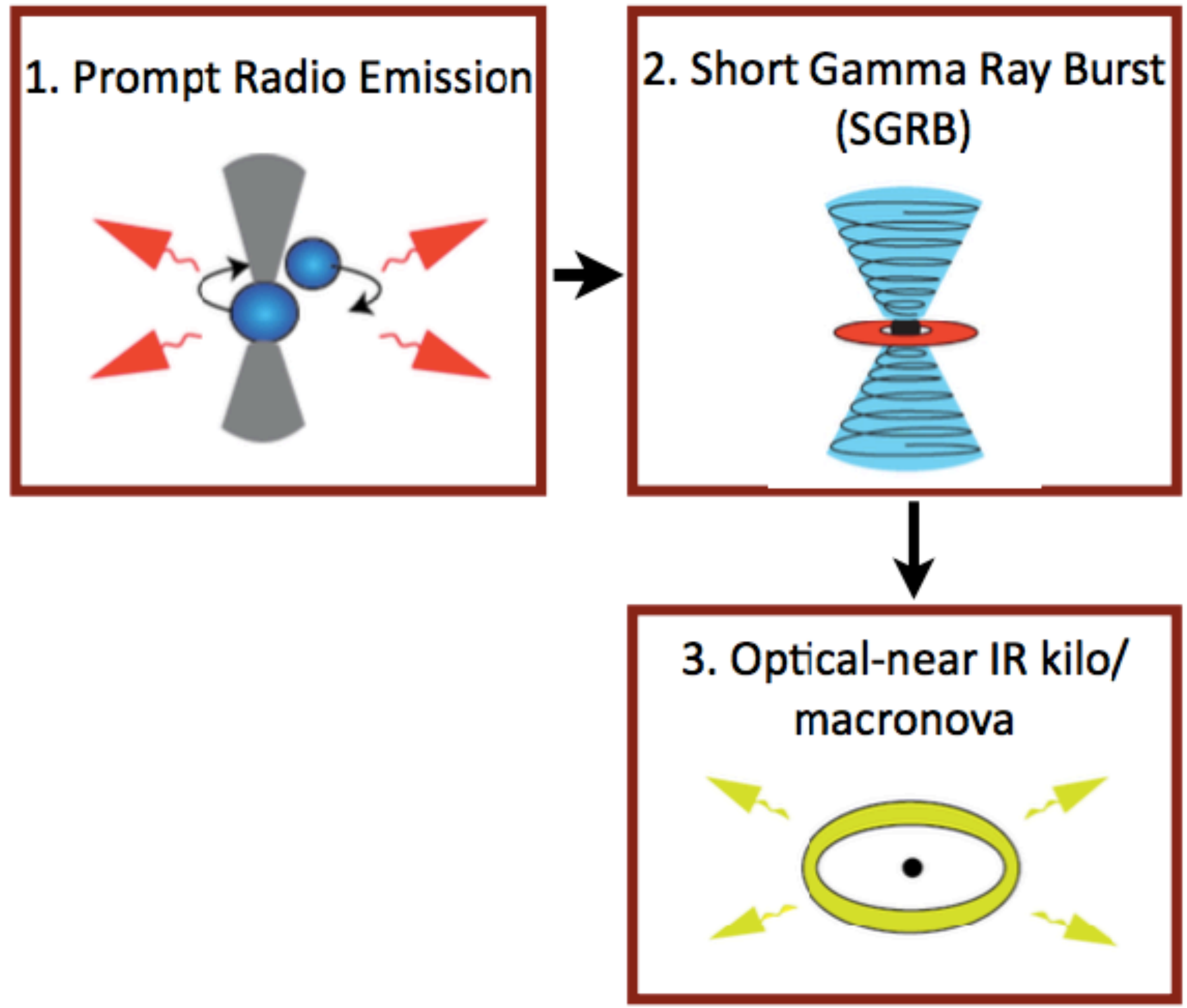
# Four or more EM counterparts




[see e.g. reviews by Nakar et al. 2007, Berger 2014 and simulations by Rezzolla et al. 2011, Siegel and Ciolfi 2016, ... Piran and Nakar 2016]

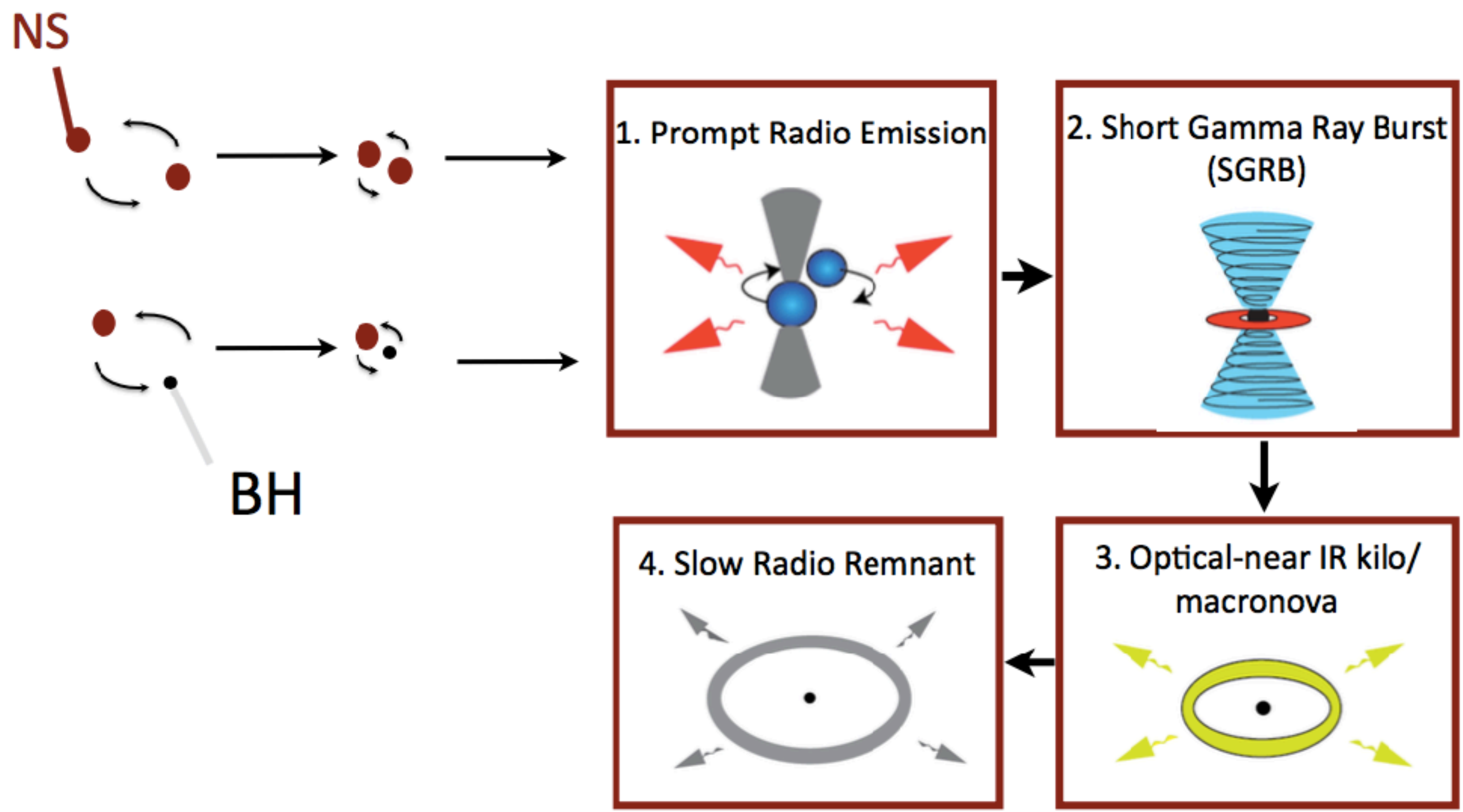
# Four or more EM counterparts



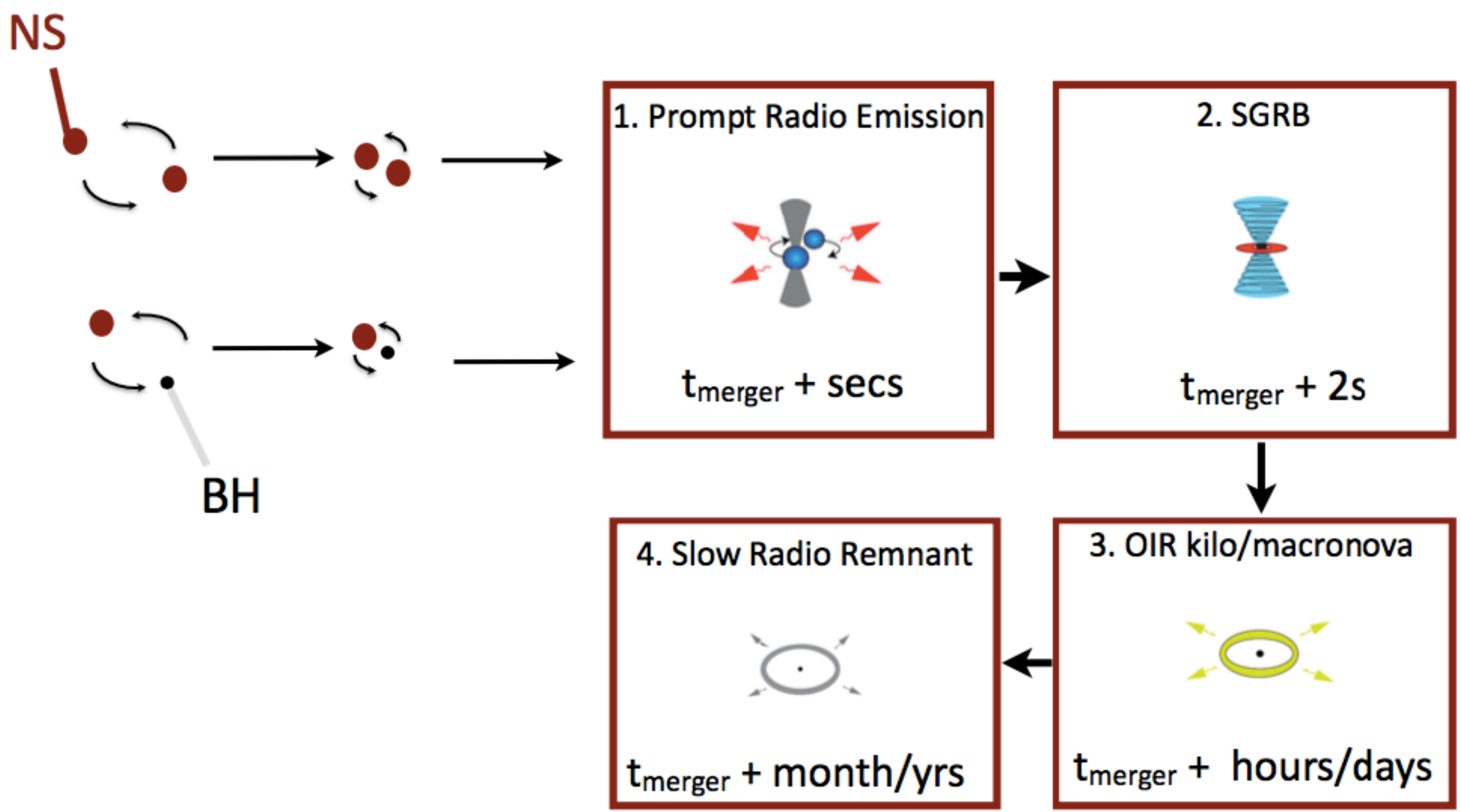

[e.g., macronova: Li and Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Metzger & Berger 2012, ...Rosswog 2012, Piran et al. 2012, Barnes et al. 2013, Grossman et al. 2013, Tanaka et al. 2013, Korobkin et al. 2012, Zhang et al., 2014, Fernandez et al. 2013, Metzger et al. 2014, Kasen et al. 2015, Wollaeger, Korobkin et al. 2017, Fontes et al. 2017, review in LRR by Metzger 2017]

# Four or more EM counterparts

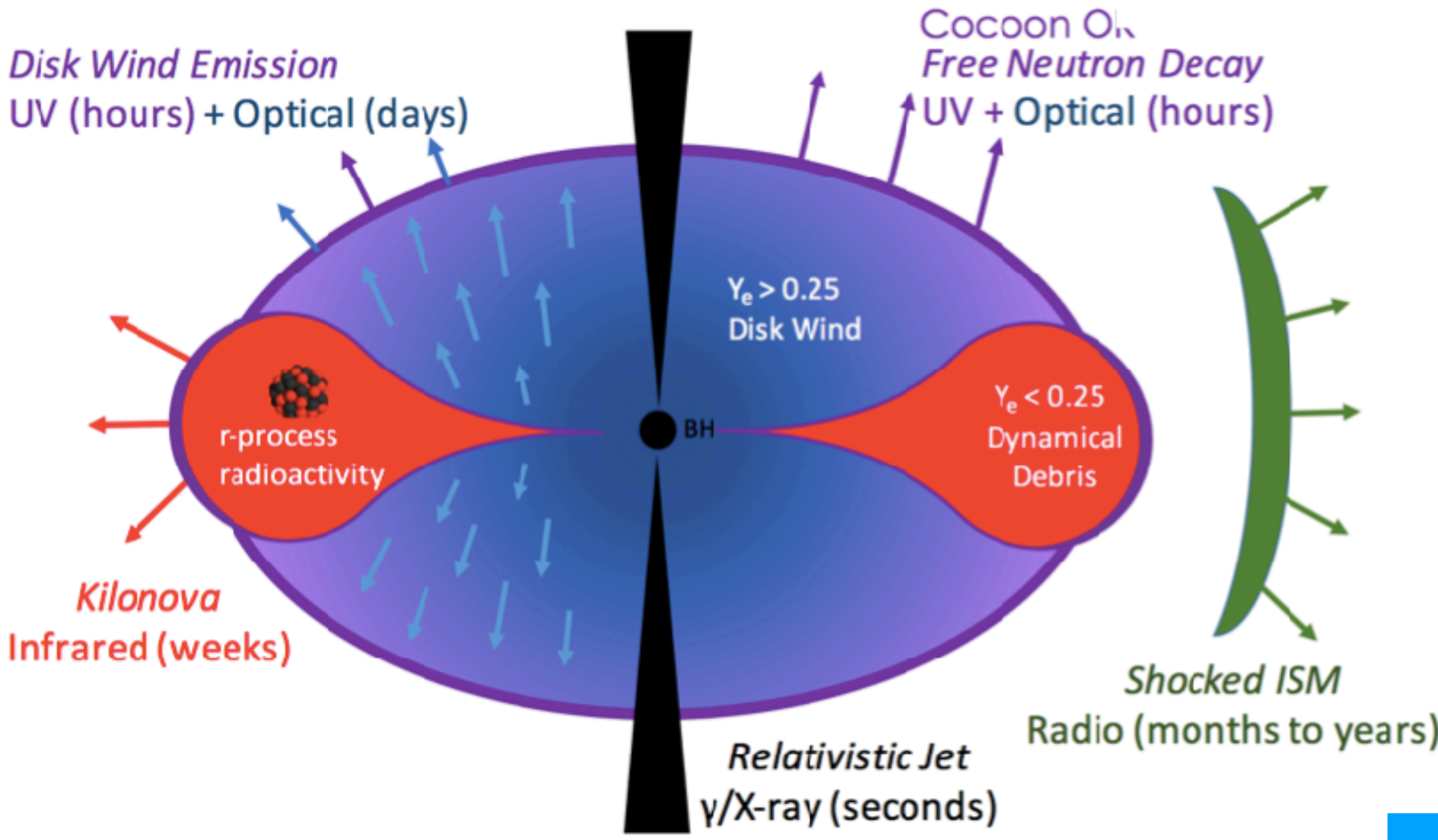



[e.g., Nakar and Piran 2011, Hotokezaka and Piran 2015, Hotokezaka, Nissanke et al. 2016]

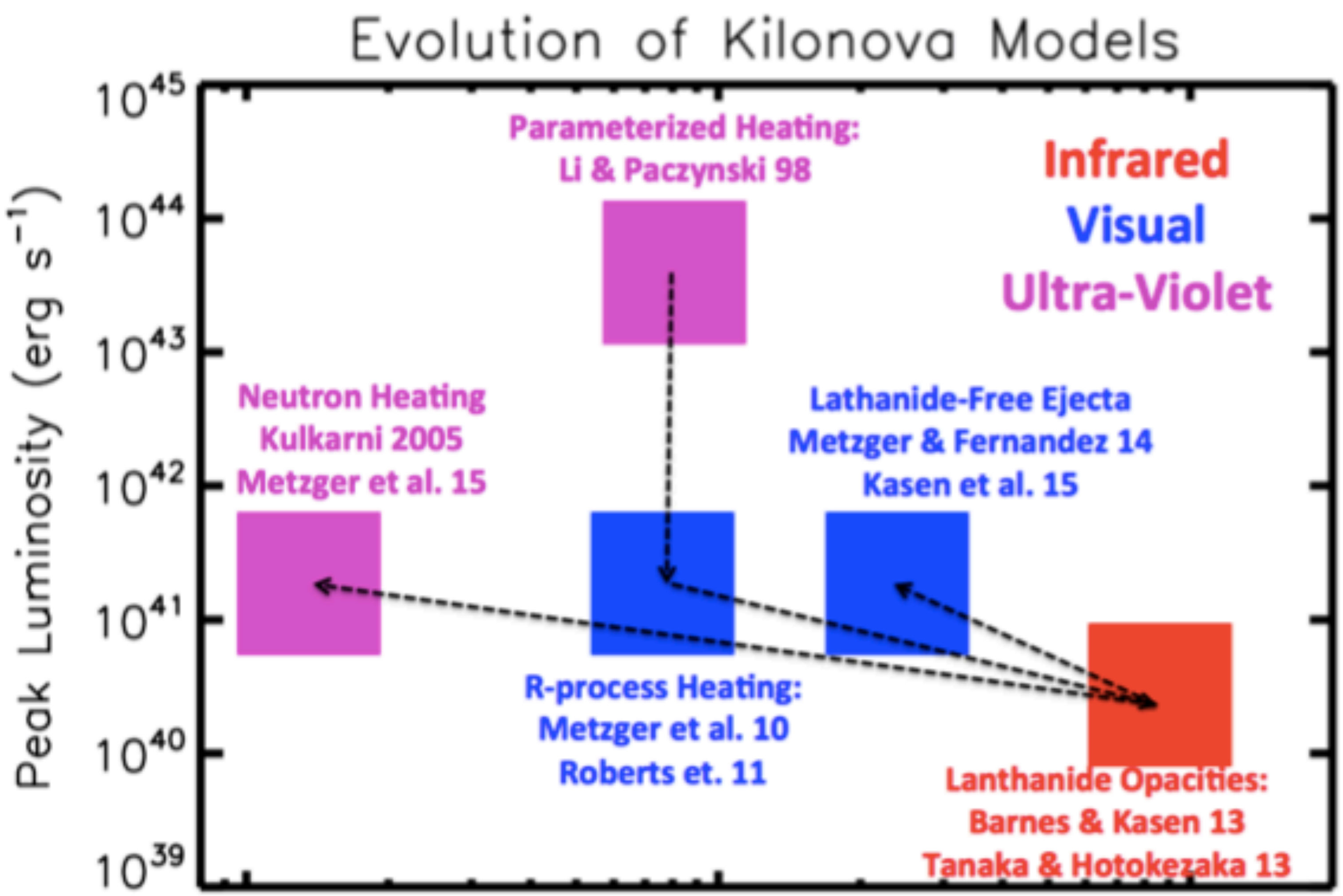
# 1/3: Different EM observable timescales



# Post-merger physics and BH formation requires full multi-wavelength picture




[fig. courtesy of Kasliwal]



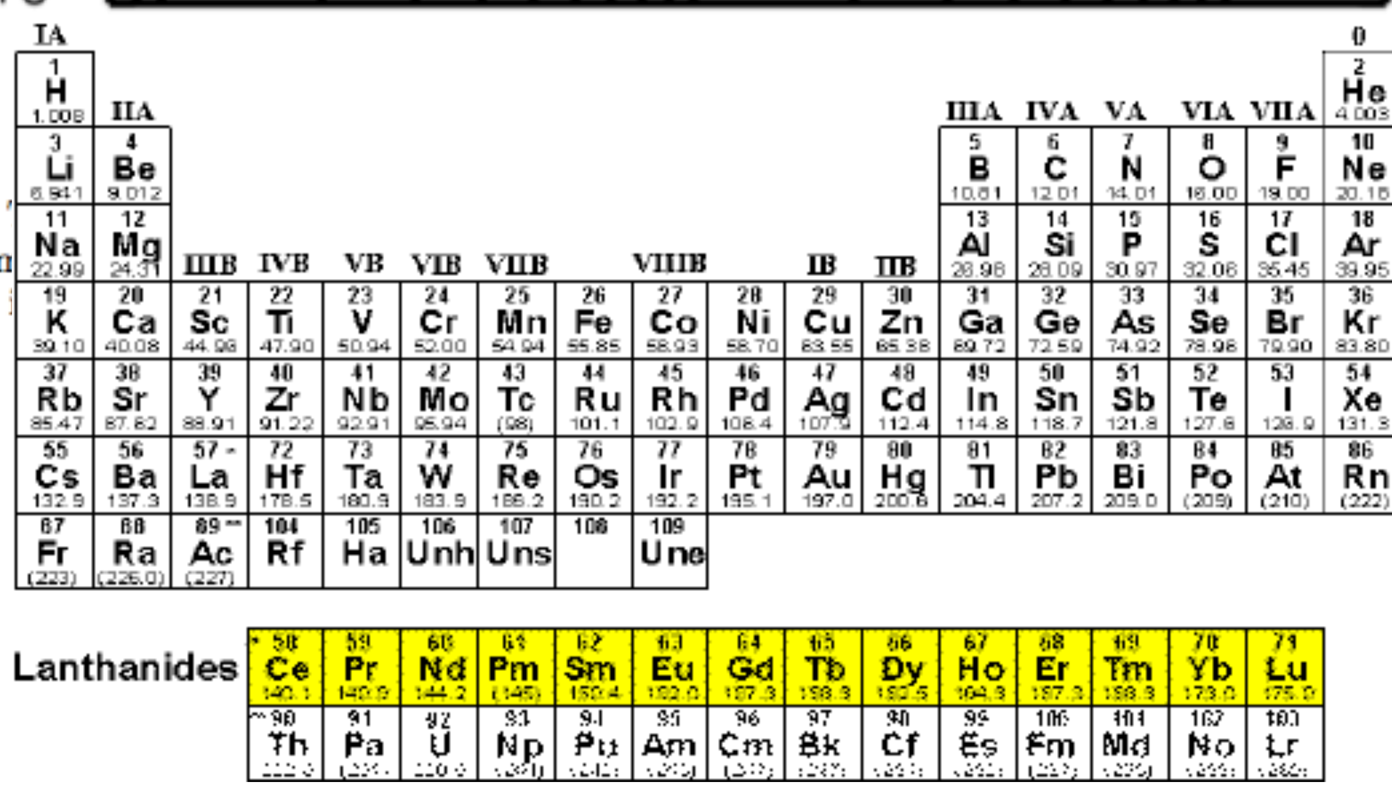




**Fig. 1** ... nd
peak tin ... as
marked i

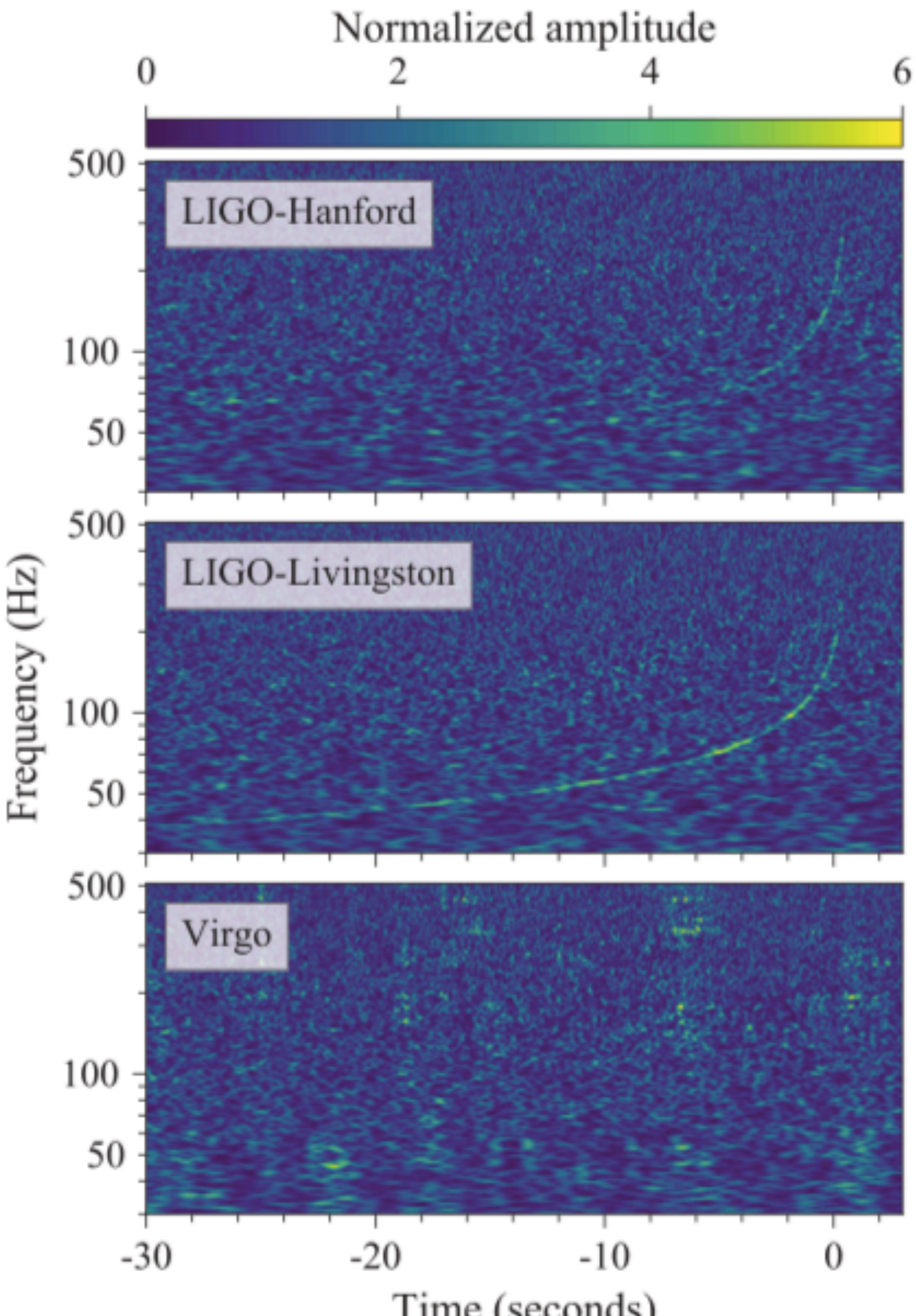
GW170817
in Gravitational waves

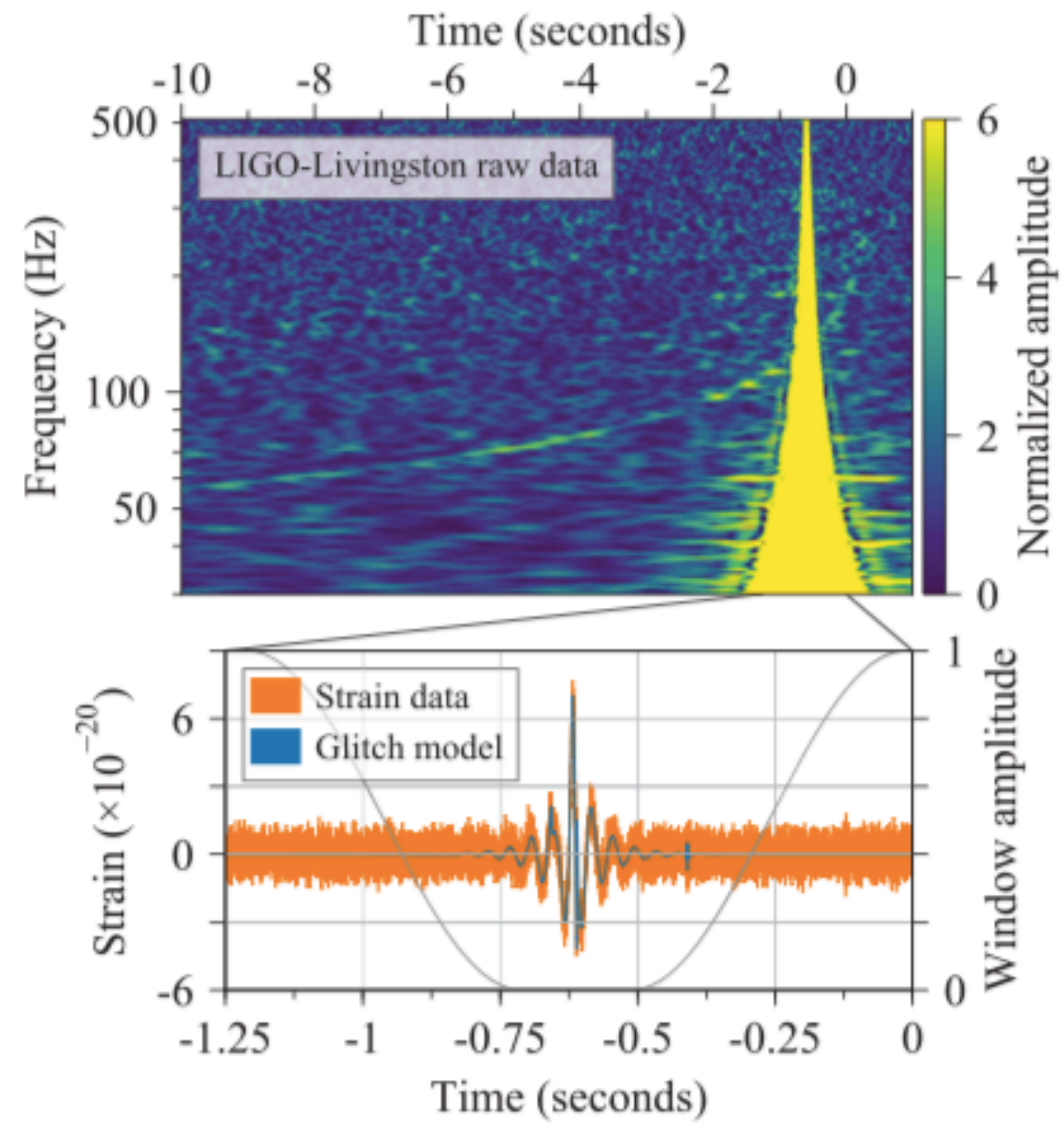
https://www.ligo.org/detections/GW170817.php

# GW170817

12:41:20 UTC

alert sent out based on single-detector analysis

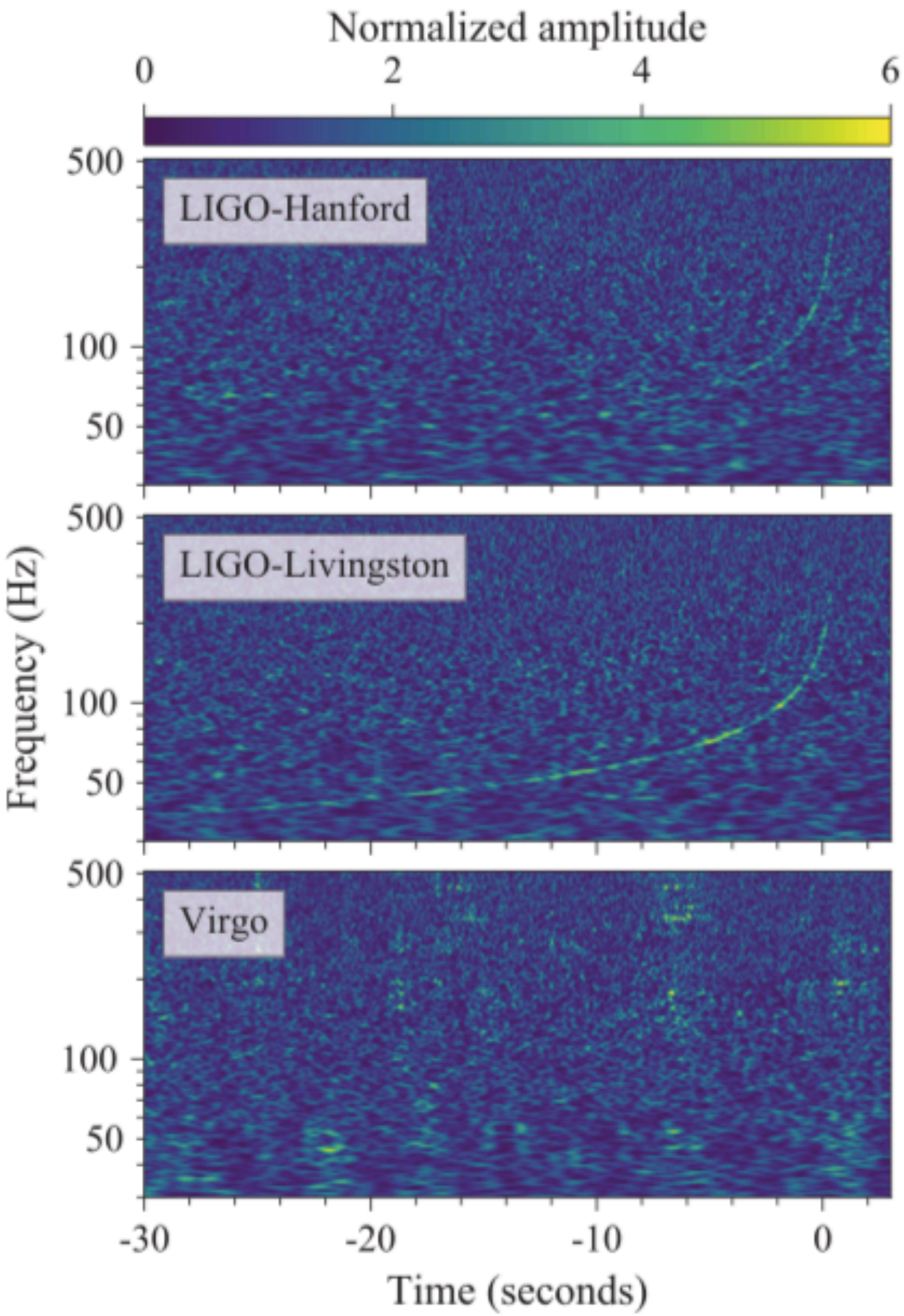



glitch in Livingston

# GW170817

12:41:20 UTC
alert sent out based
on single-detector analysis



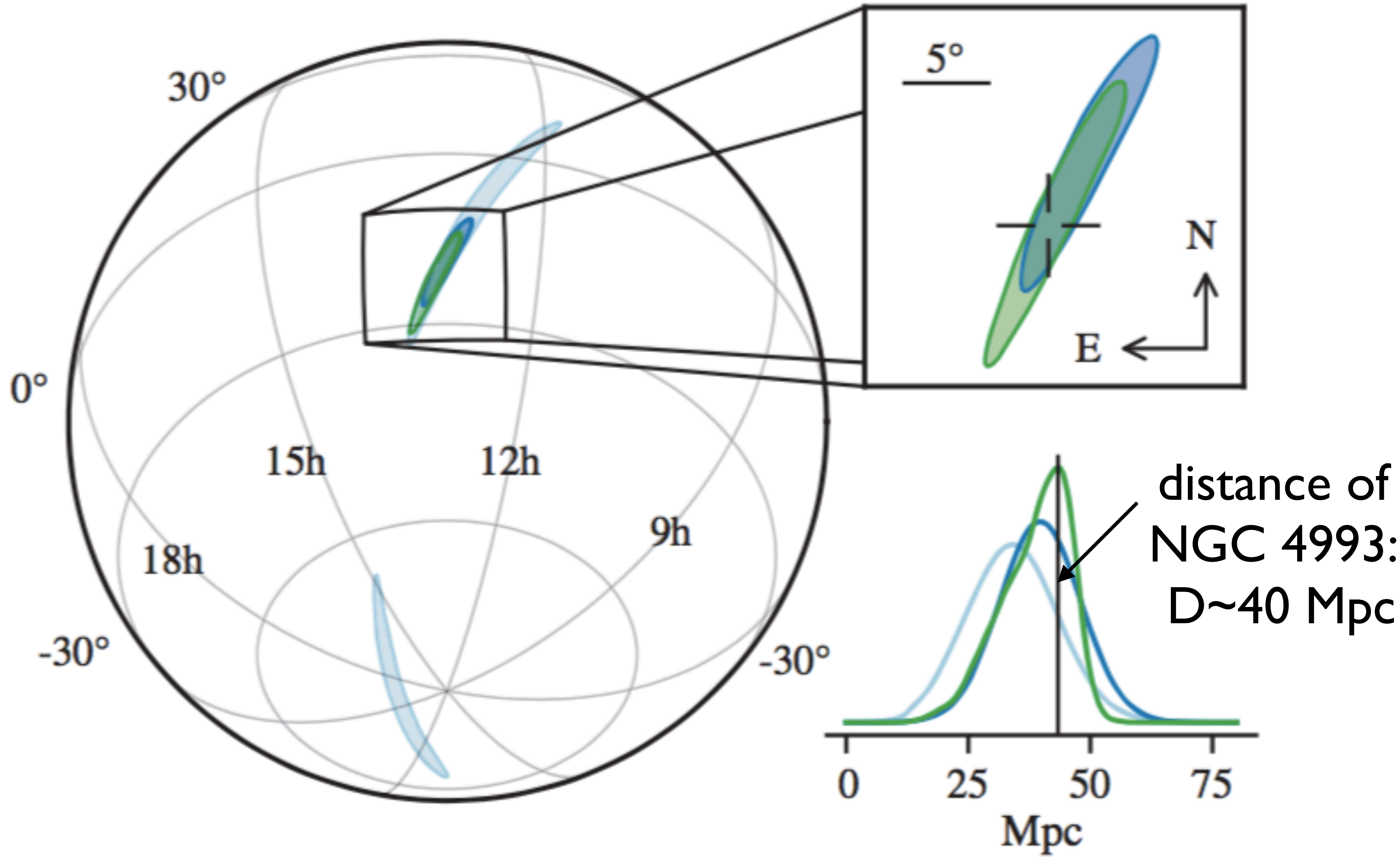

The signal lasted ~100 s

The signal was match filtered with the expected gravitational wave signal from merging neutron stars…

…Yielding a detection with combined signal-to-noise ratio ~32: the loudest signal so far.

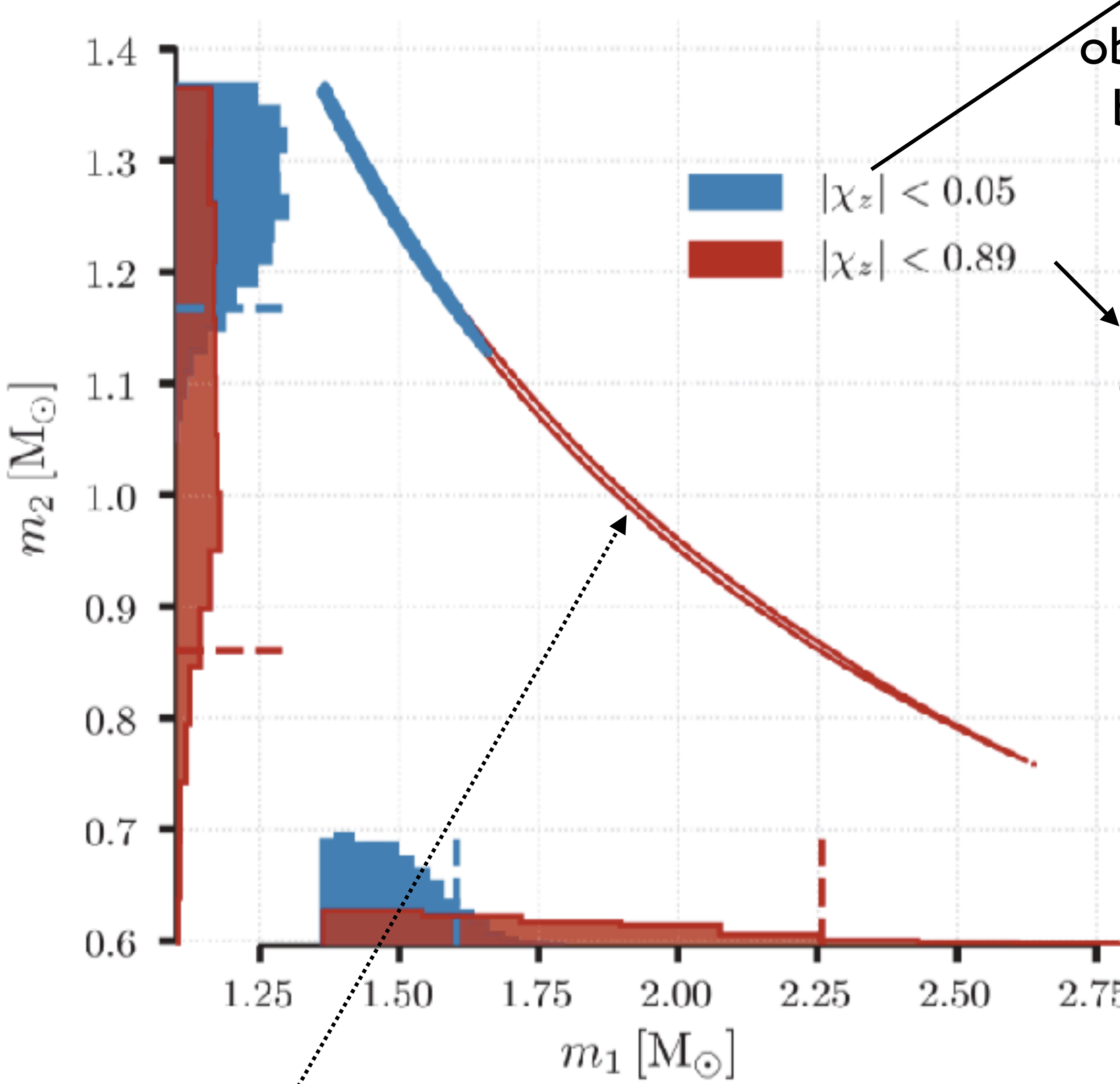
LIGO alone: 190 deg$^2$

LIGO+ VIRGO alone: 31 deg$^2$ —-> refined analysis 28 deg$^2$




This exploited the existence of "blind spots in the VIRGO detector"

# Masses



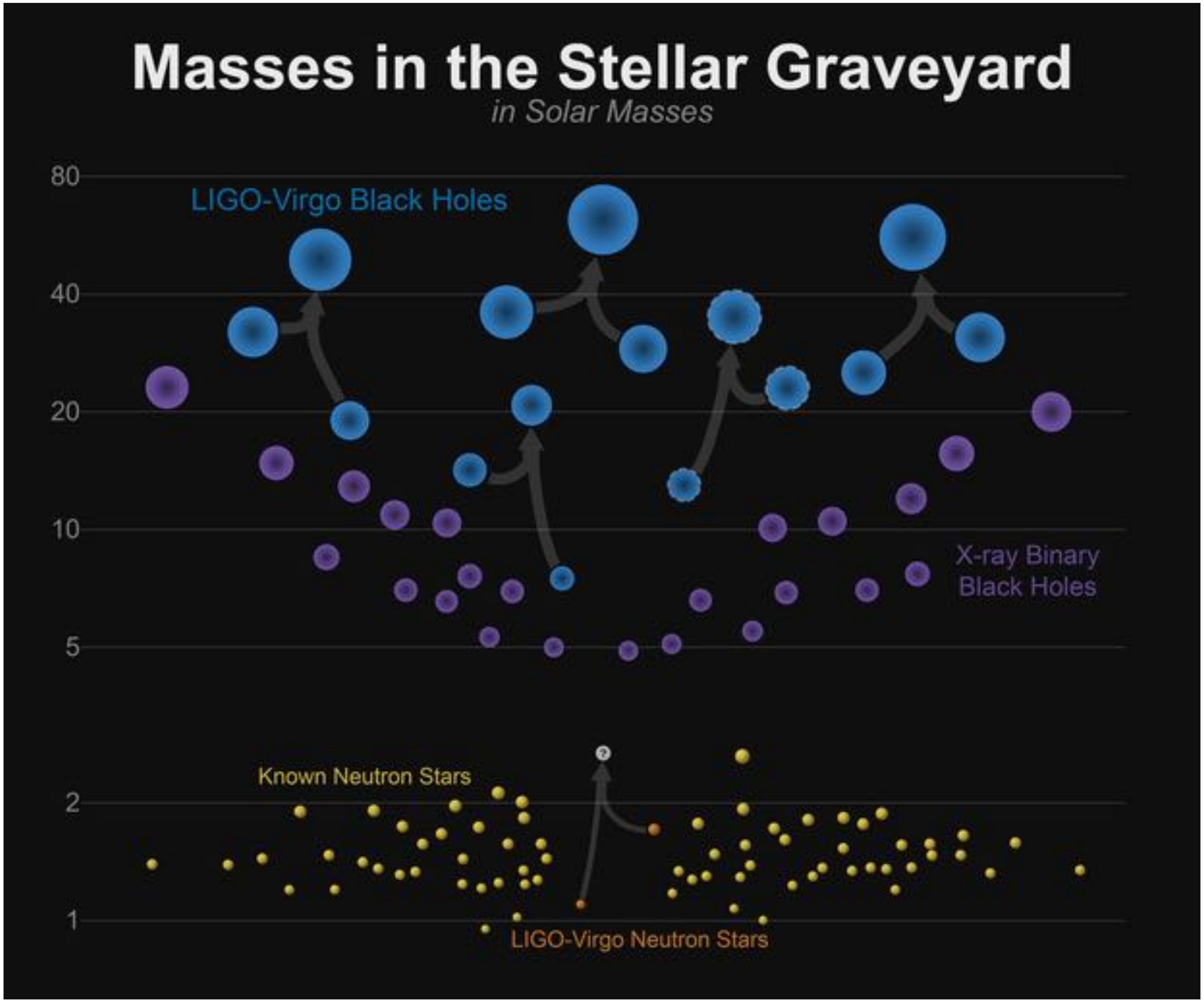

consistent with observed population of binary neutron stars

from possible equation of state

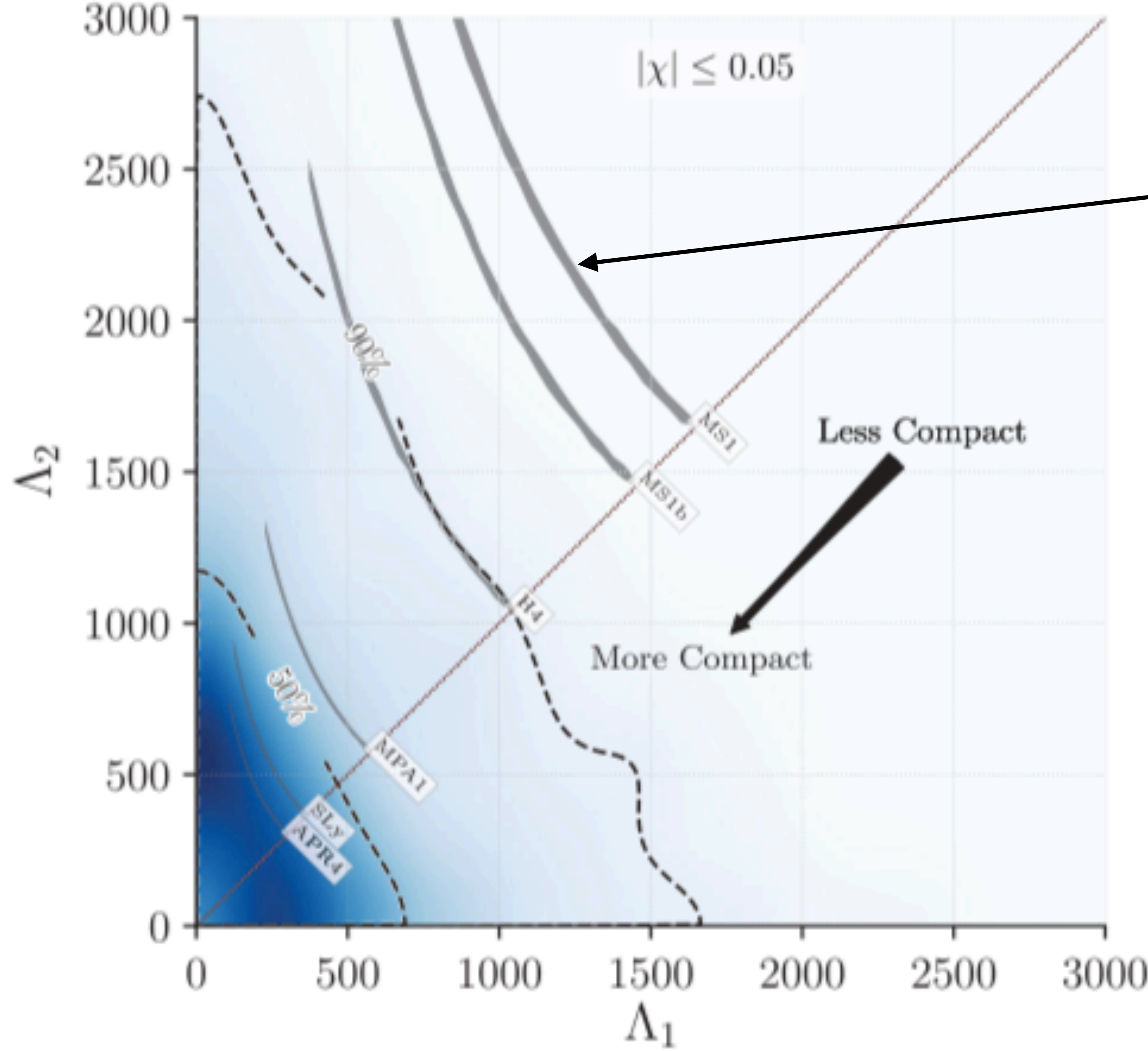
masses are degenerate with $\chi_\mathrm{z}$ the orbit-aligned spin, which is the dimensionless component of spin in the direction of the orbital axis.

chirp mass $\mathcal{M} = (m_1 m_2)^{3/5}(m_1 + m_2)^{-1/5}$

masses consistent with known NS
but remnant unconstrained



Upper limit that disfavour less compact NS in agreement with X-ray observations of Mass and Radii




representative predictions from EOS

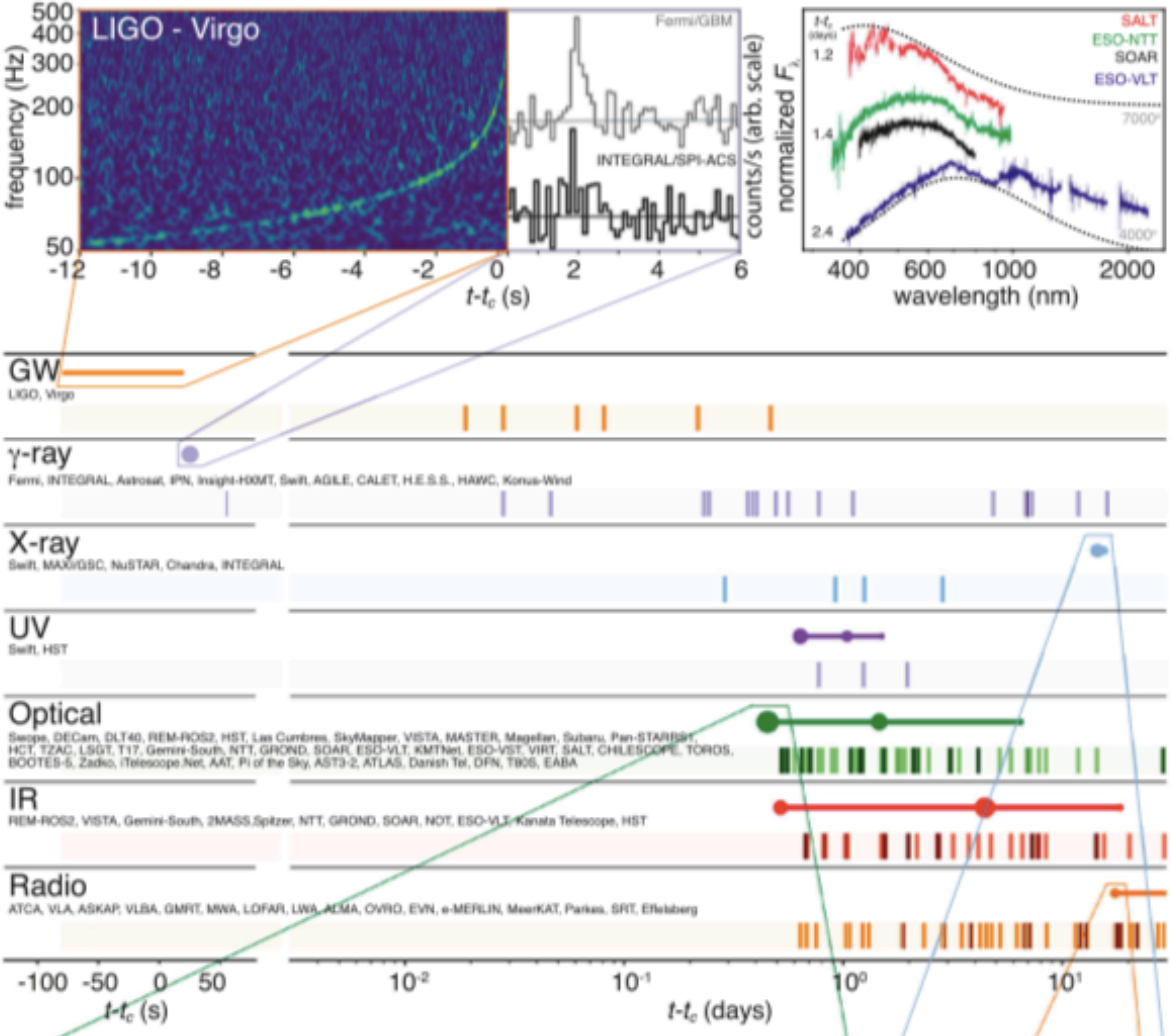
deformability=ration of induced quadrupole moment to the external tidal field

GW170817

+

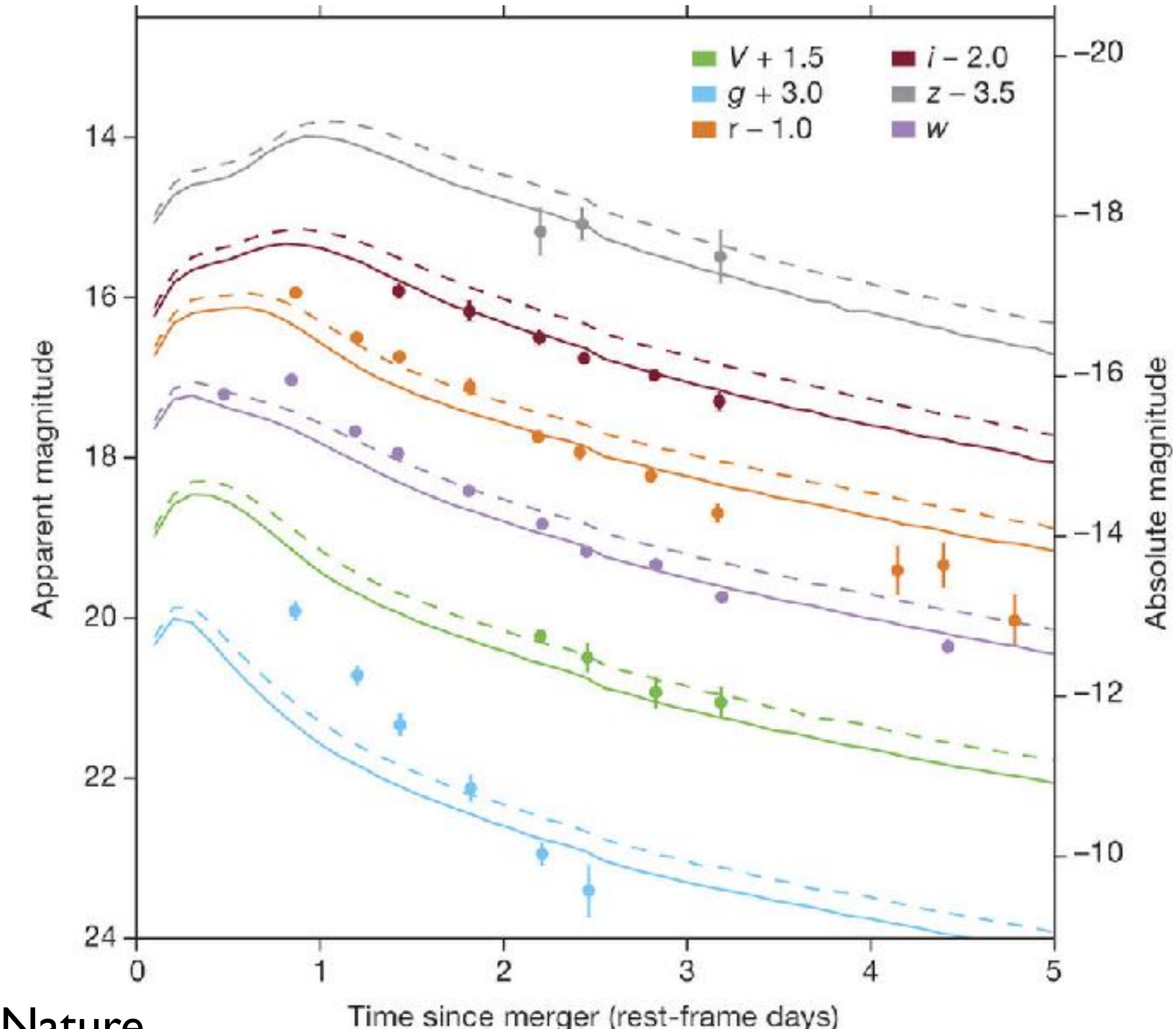
Electromagnetic counter parts

https://www.youtube.com/watch?v=EAyk2OsKvtU



LIGO - Virgo
frequency (Hz)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
t-t_c (s)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (s)
t-t_c (days)

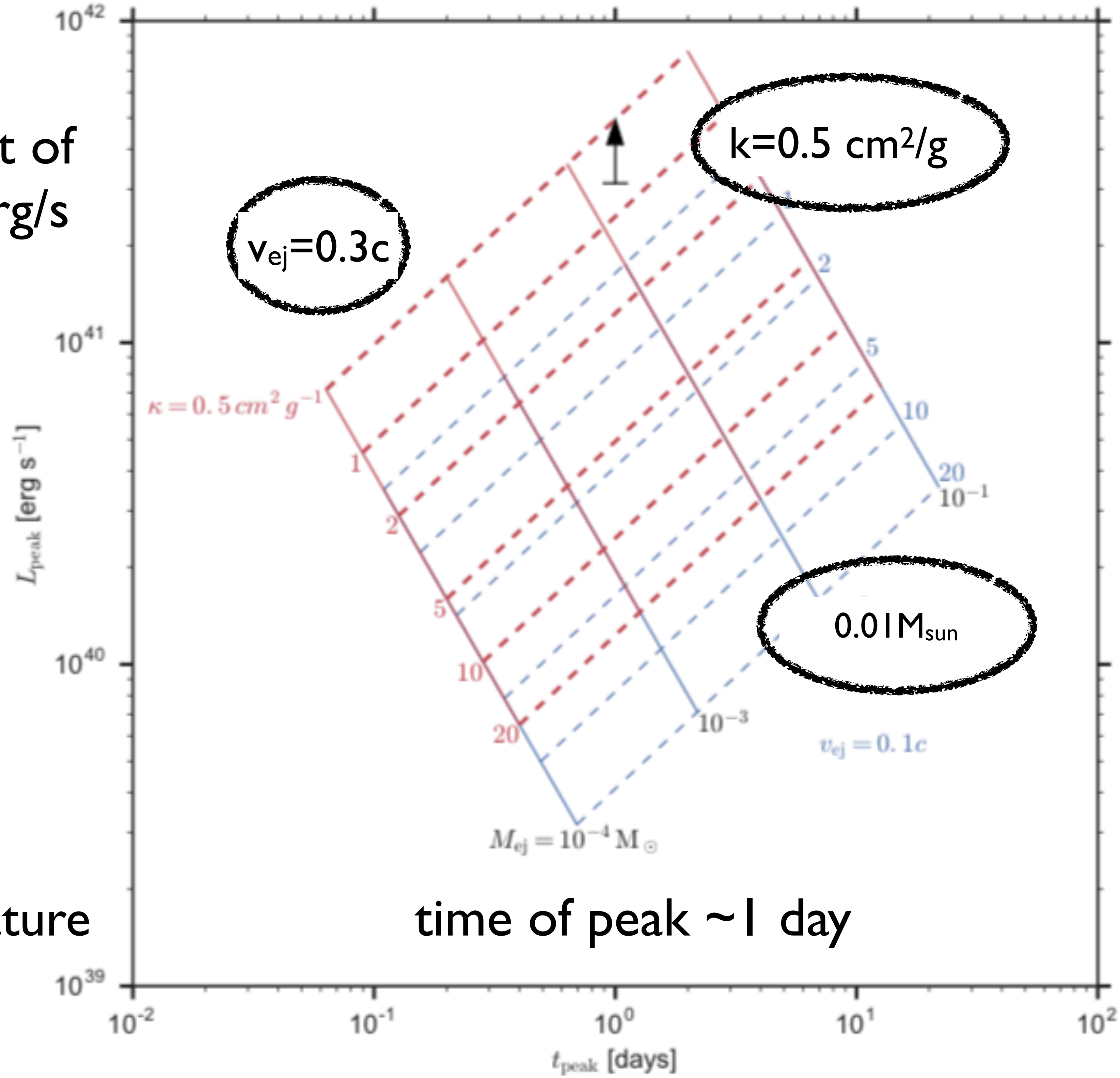
# kilonova lightcurve




Arcavi + 17, Nature

# the kilonova's at peak

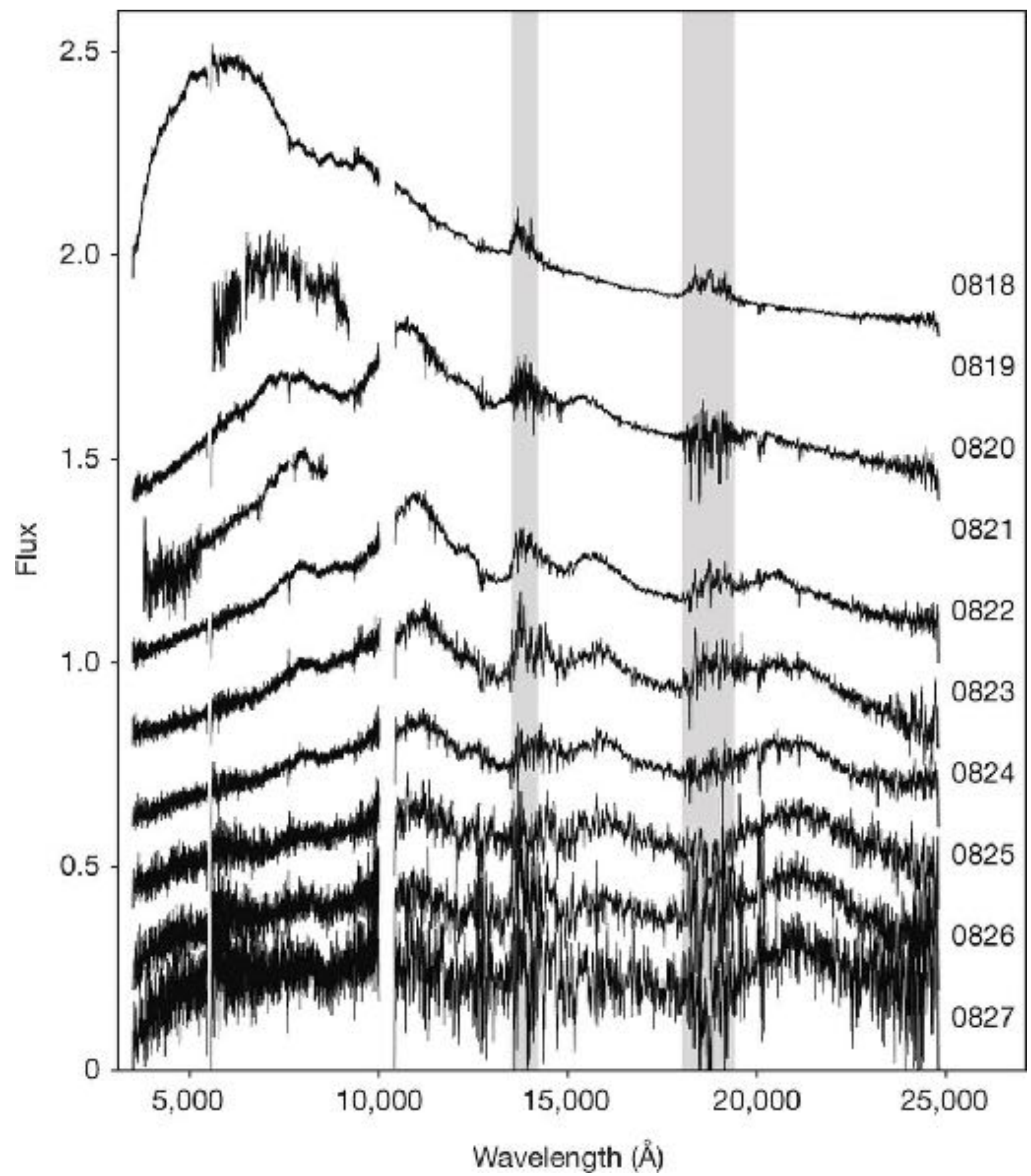
lower limit of
~3 $10^{41}$ erg/s




Arcavi + 17, Nature

# spectroscopic follow-up
# to confirm the kilonova hypothesis

fit to data reveals presence of high-opacity lanthanides




Pian, E. + 2017

For an easy reading on the debate about kilonova nuclear composition see:

https://www.nature.com/articles/nature24153

and follow the reference these for more details:


Arcavi, I. *et al. Nature* **551**, 64–66 (2017).

Pian, E. *et al. Nature* **551**, 67–70 (2017).

Smartt, S. J. *et al. Nature* **551**, 75–79 (2017).

# Importance

a few examples

**Test of general relativity strong regime:**

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Astrophys. J. Lett. 848, L13 (2017);

**Cosmology:** combining the GW luminosity distance and the redshift of the host galaxy===>cosmological parameter, e.g. Hubble constant

B. P. Abbott et al. Nature (London), in press (2017), DOI: 10.1038/ nature24471.

**Study the NS equation of state and structure**

**Unveil the origin of short gamma- ray bursts**

**Settle the origin of elements heavier than iron by r-processes**

# Exercise time!

Let's build our Kilonova light curve, following

*One-zone Arnett Model of Radioactive Transients*

Arnett 80,82

Text of problems at

http://www.ictp-saifr.org/wp-content/uploads/2014/05/problem_set.pdf

courtesy of D. Kasen

A cloud with mass M and total energy $E_o$ (mostly internal)

The equation describing its evolution is energy conservation:

volume

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} + \dot{\epsilon} - L(t)$$

Escaping luminosity (erg/s)

E internal energy

pressure

heating rate (erg/s) due to radioactive decay

A cloud with mass M and total energy $E_o$ (mostly internal)

The equation describing its evolution is energy conservation:

volume

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} + \dot{\epsilon} - L(t)$$

Escaping luminosity (erg/s)= observed lightcurve

E internal energy

pressure

heating rate (erg/s) due to radioactive decay

A cloud with mass M  and total energy $E_o$

The equation describing is evolution is energy conservation:

volume

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} + \dot{\epsilon} - L(t)$$

Escaping luminosity (erg/s)

E internal energy

pressure

heating rate (erg/s) due to radioactive decay

Let's assume:

- Spherical symmetry
- "One zone" model:  homogeneous in thermo- and dynamical properties
- Free expansion of the cloud : $v = \sqrt{2E_o/M} \to V(t) = V_0\,(t/t_o)^3$

where $V_o = 4\pi/3R_o^3$ and $t_0 = R_0/v$

- radiation dominated cloud $u = aT^4 = E/V = 3p \qquad E = uV$
- Radiative diffusion: $L(R) \approx 4\pi R^2 \frac{c}{3\kappa\rho}\frac{u(R)}{R} \quad \propto u(R)R^4$

# Adiabatic case: how do T, u evolve with t and R ?

$$\dot{X} = \frac{dX}{dt}$$

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} \cancel{+\dot{\epsilon}} \cancel{- L(t)}$$

$$u\dot{V} + \dot{u}V = -(1/3)\ u\dot{V}$$

$$\frac{\dot{u}}{u} = -\frac{4}{3}\frac{\dot{V}}{V}$$

$$\dot{V} = \frac{3V}{t}$$

integration

$$\frac{\dot{u}}{u} = -\frac{4}{t}$$

$$\log\frac{u}{u_o} = -4\log\frac{t}{t_o}$$

$$R = vt$$

$$e^{\log x} = x$$

$$u = aT^4$$

$$uR^4 = u_o R_o^4$$

$$T \propto R^{-1}$$

# Diffusion limited case (no source of energy)

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} + \cancel{\dot{e}} - L(t)$$

diffusion timescale in a static medium:

$$t_\mathrm{d} = \frac{R_o}{c/\tau} = \frac{3Mk}{4\pi R_o c} \approx 10^{15}\ \mathrm{s} \approx 30\ \mathrm{Myr}$$

!!!
optically thick

Ro =10 km, M =0.01 $M_{sun}$, k = 0.1 $cm^2$/g

# Diffusion limited case (no source of energy)

$$\dot{X} = \frac{dX}{dt}$$

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} \cancel{+\dot{e}} - L(t)$$

Please, derive

- the light curve L(t)
- the peak luminosity $L_p$
- the peak timescale $t_p$
- evaluate $L_p$ and $t_p$ assuming GW170817: i.e.

v=0.3 c, Ro =10 km, M =0.01 $M_{sun}$, k = 0.1 $cm^2$ /g

(k=gas opacity)

# Diffusion limited case (no source of energy)

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} \cancel{+\dot{e}} - L(t)$$

suggestions:

since $L \propto \chi$ solve for $\chi = uR^4$ instead, starting from:

$$\dot{\chi} = \dot{u}R^4 + u\dot{R}^4$$

$$\mathrm{NOTE:}\ \ u\dot{R}^4 = \frac{4uR^4}{t}$$

# solution

$$\dot{\chi} = \dot{u}R^4 + u\dot{R}^4$$

$$\frac{dE(t)}{dt} = -p\frac{dV}{dt} + \cancel{\dot{\epsilon}} - L(t) \quad \Longrightarrow \quad \dot{u} = -\frac{4u}{t} - \frac{L}{V}$$

$$\dot{\chi} = -\cancel{\frac{4uR^4}{t}} - \frac{LR^4}{V} + \cancel{\frac{4uR^4}{t}} = -\frac{LR^4}{V}$$

- Radiative diffusion: $L(R) \approx 4\pi R^2 \frac{c}{3\kappa\rho}\frac{u(R)}{R}$ $\qquad \chi = uR^4$

$$\frac{\dot{\chi}}{\chi} = -\frac{t}{t_{\rm d}t_o} \quad \Longrightarrow \quad \chi = \chi_0 e^{-\frac{t^2-t_0^2}{2t_{\rm p}}} \qquad \text{with } t_{\rm p} = t_{\rm d}t_o$$

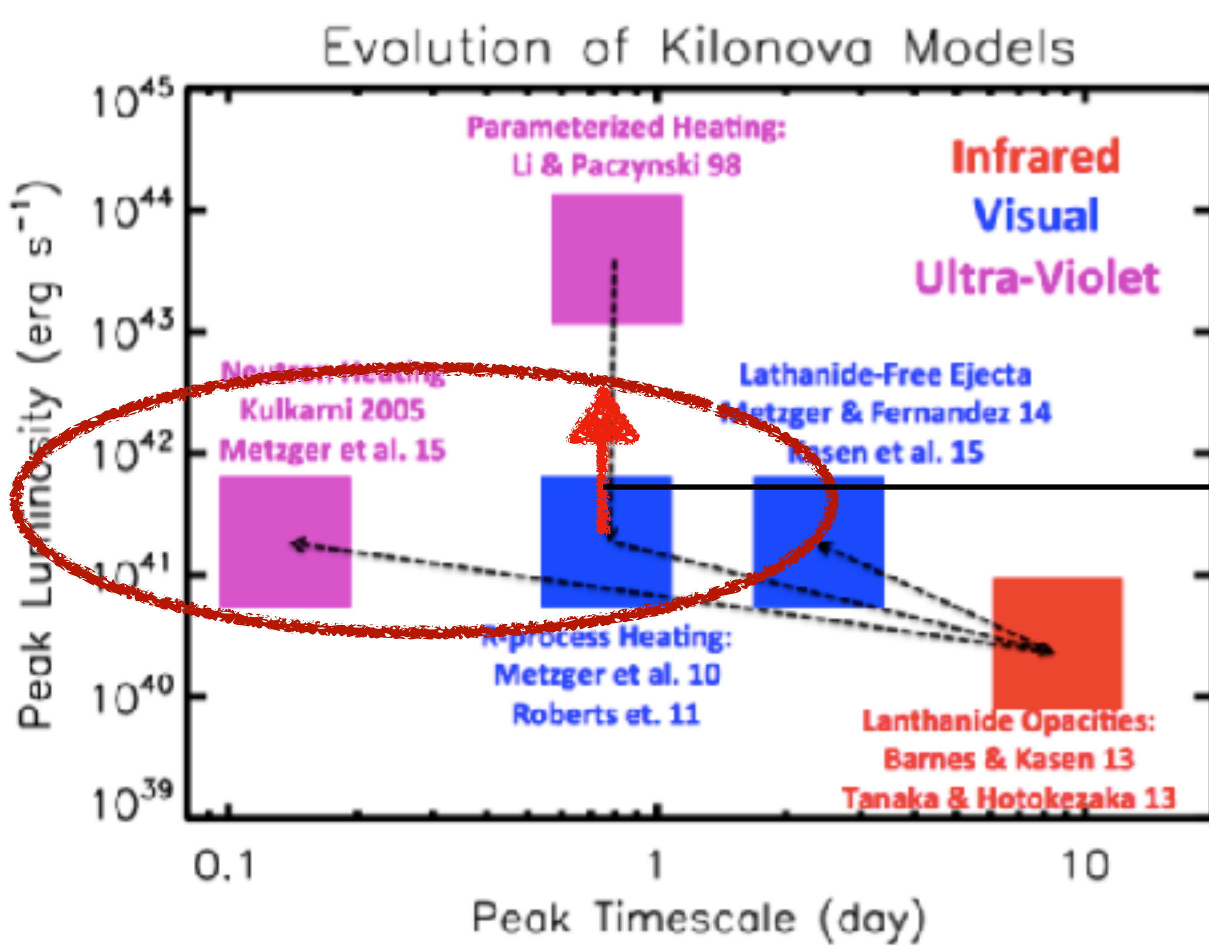
<u>lightcurve</u>: $$L = L_\mathrm{p} \times e^{\frac{1}{2}\frac{t^2 - t_o^2}{t_\mathrm{p}^2}}$$

Peak Luminosity:

$$L_\mathrm{p} = \frac{4\pi}{3}\frac{E_o R_o c}{M k} = \frac{1}{3}\frac{4\pi G M_{NS} c}{k} \approx L_\mathrm{edd}$$

$$\text{if } E_o \approx \frac{G M_\mathrm{NS} M}{R_o}$$

~$10^{38}$ erg/s : too dim. need for radioactive decay




GW170817

$$L = L_{\mathrm{p}} \times e^{\frac{1}{2}\frac{t^2 - t_o^2}{t_{\mathrm{p}}^2}}$$

## Timescale:

$$t_{\mathrm{p}} = \sqrt{t_{\mathrm{d}} t_{\mathrm{o}}} \approx \sqrt{10^{15} \times 3 \times 10^{-4}} \approx 3.5\ \mathrm{d}$$

$\boxed{\text{that's OK!}}$