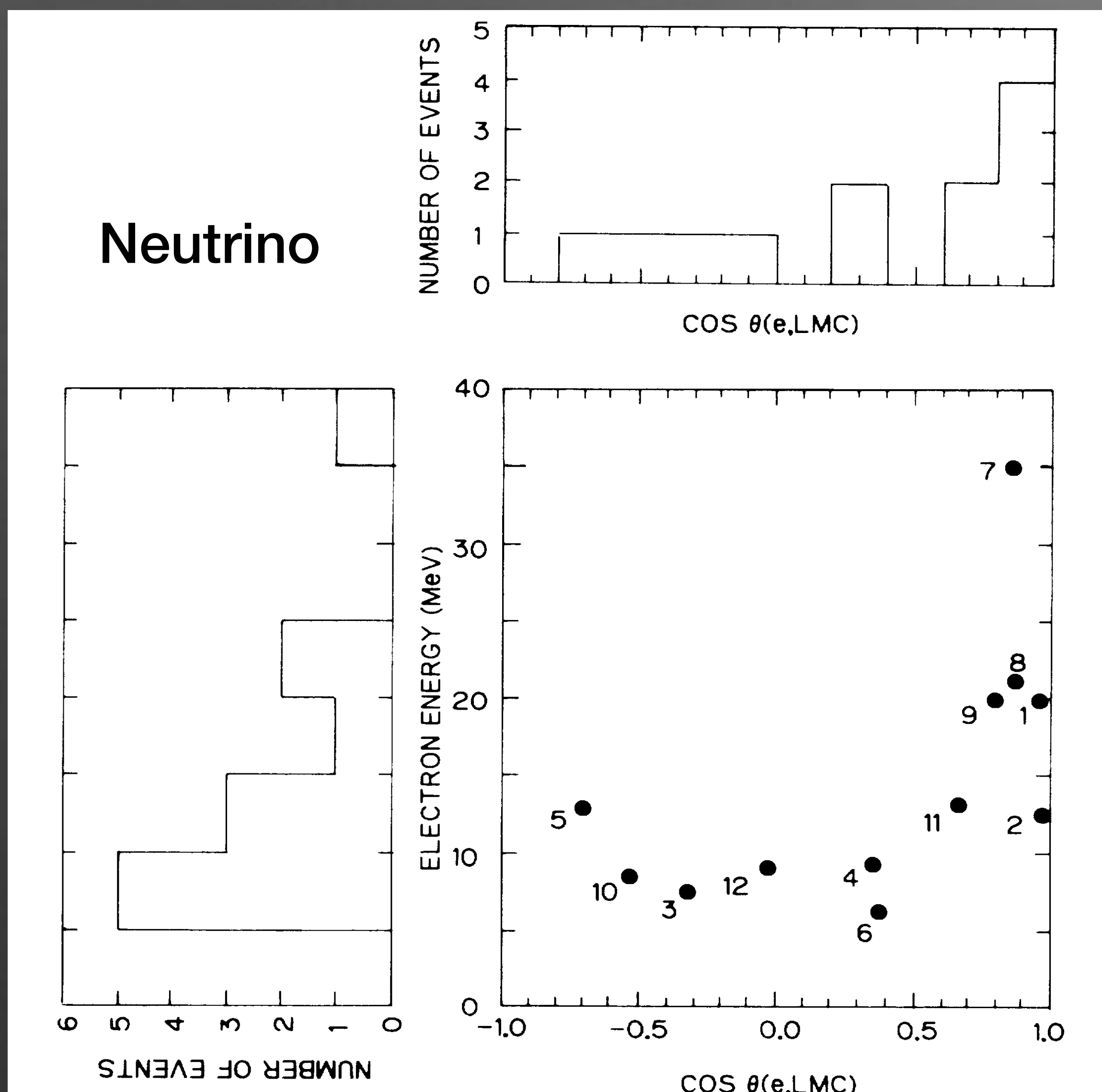
Multi-messenger Astrophysics of compact binary and core collapse

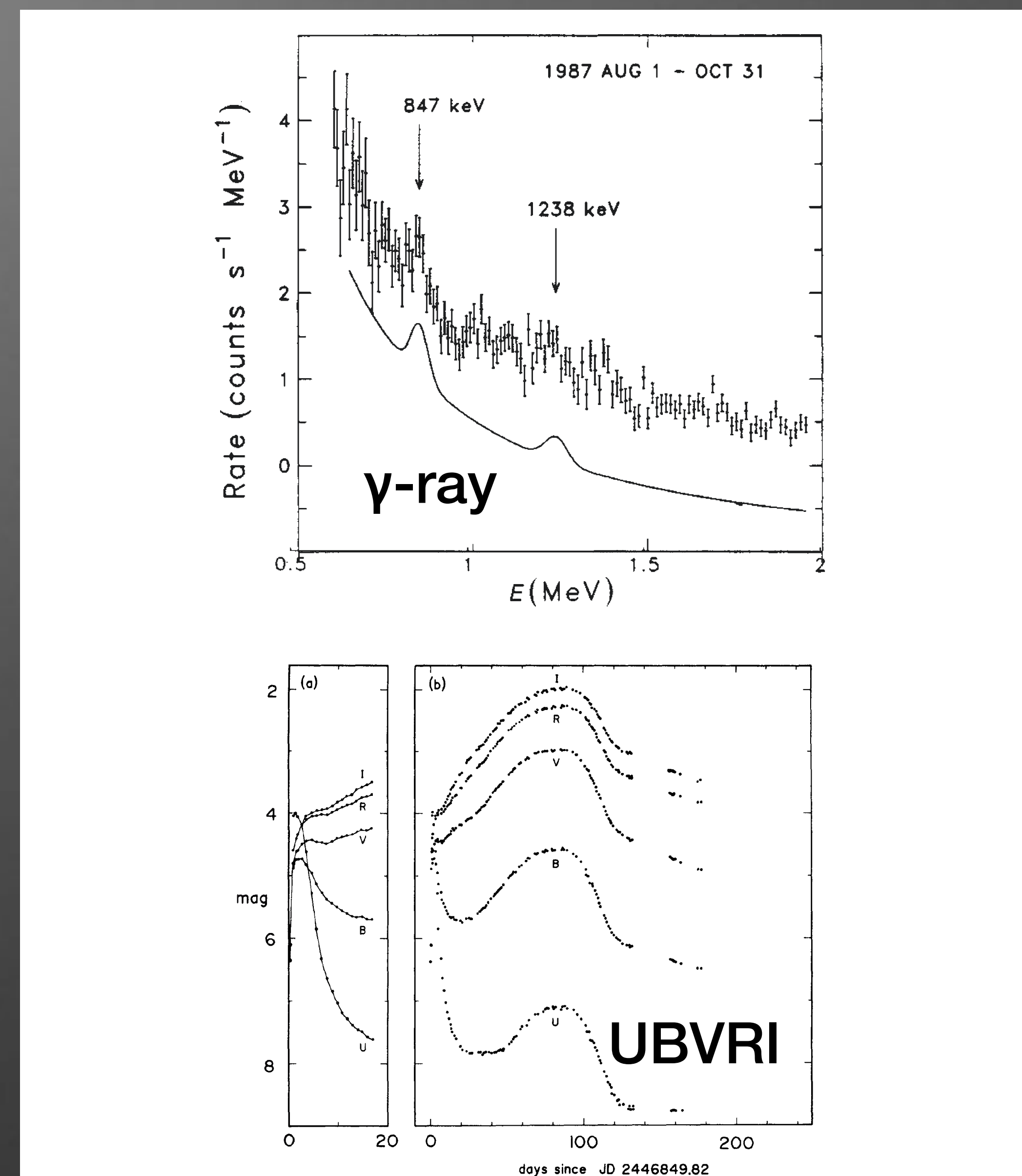
Kenta Hotokezaka
(RESCEU, U of Tokyo)

Collaborators:
E. Nakar (Tel Aviv), T. Piran (Hebrew), S. Nissanke (GRAPPA Amsterdam), K. Masuda (Osaka), A. T. Deller (Swinburne)
G. Hallinan, K. Mooley, M. M. Kasliwal, P. Beniamini (Caltech),
M. Shibata (AEI/YITP), M. Tanaka (Tohoku U.), D. Kato (Kyusyu U.),
H. Nagakura (Princeton)

The first multi-messenger Astrophysics: SN 1987A



Hirata et al. 1987, see also Bionta et al. 1987,

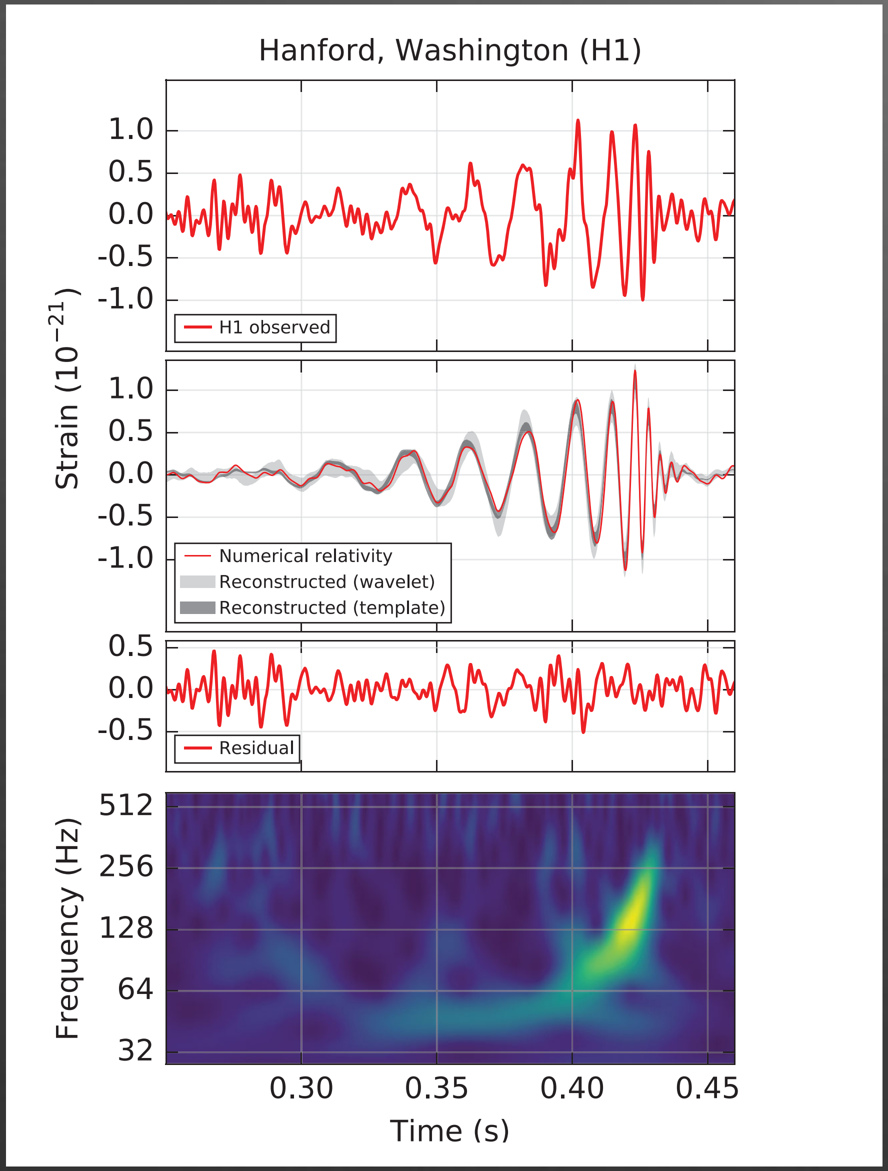


Matz et al. 1987 and Mario-Hurmy et al. 1988

This multi-messenger observation confirmed that the birth of a neutron star is responsible for a supernova. (I'll come back to this at the end of the talk)

Gravitational-wave Astronomy

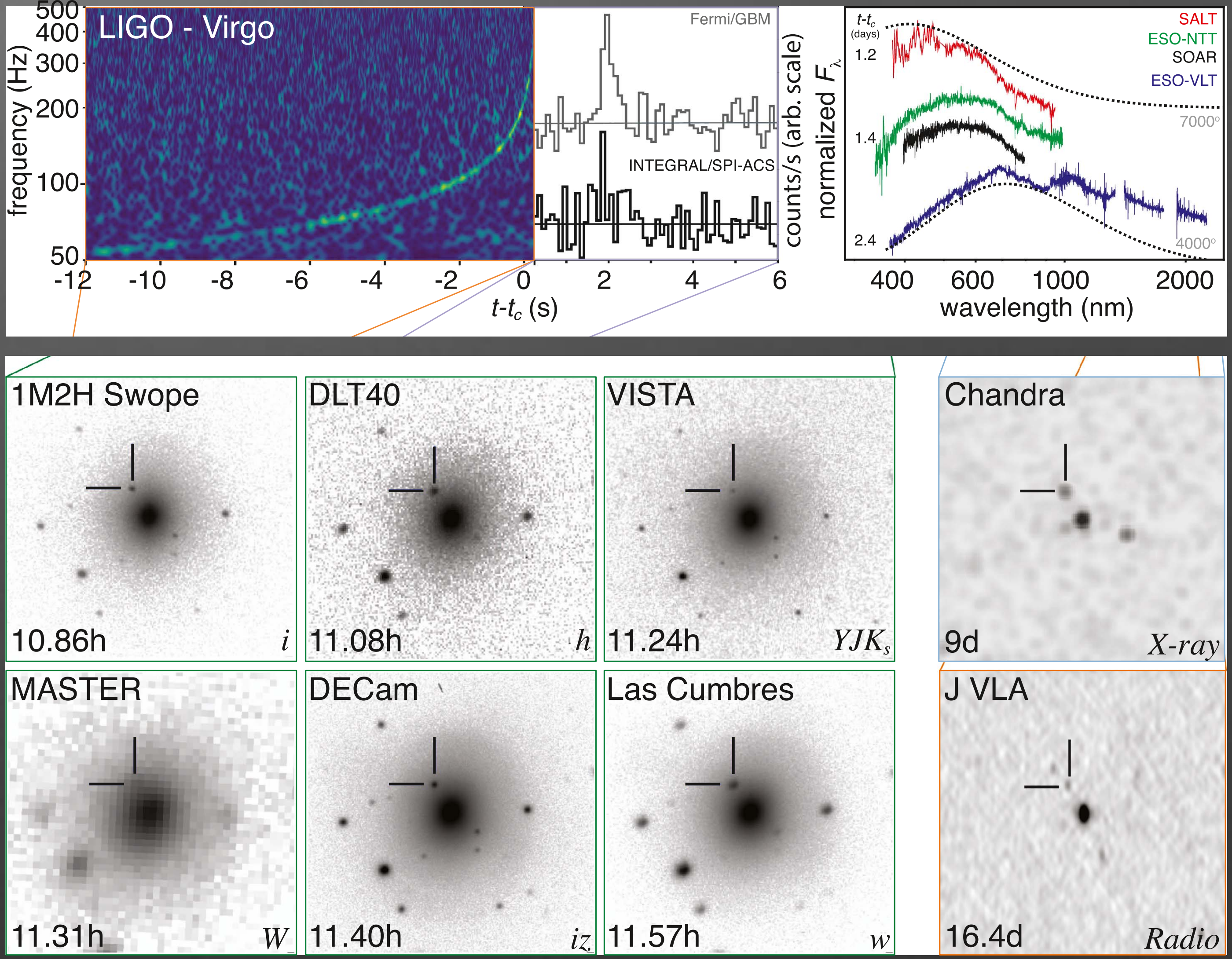
Binary Black Hole (BBH) merger
GW150914



The first GW detection

Abbott et al. 2016

Binary Neutron Star (BNS) merger
GW170817



The first GW & photon detection

Abbott et al. 2017

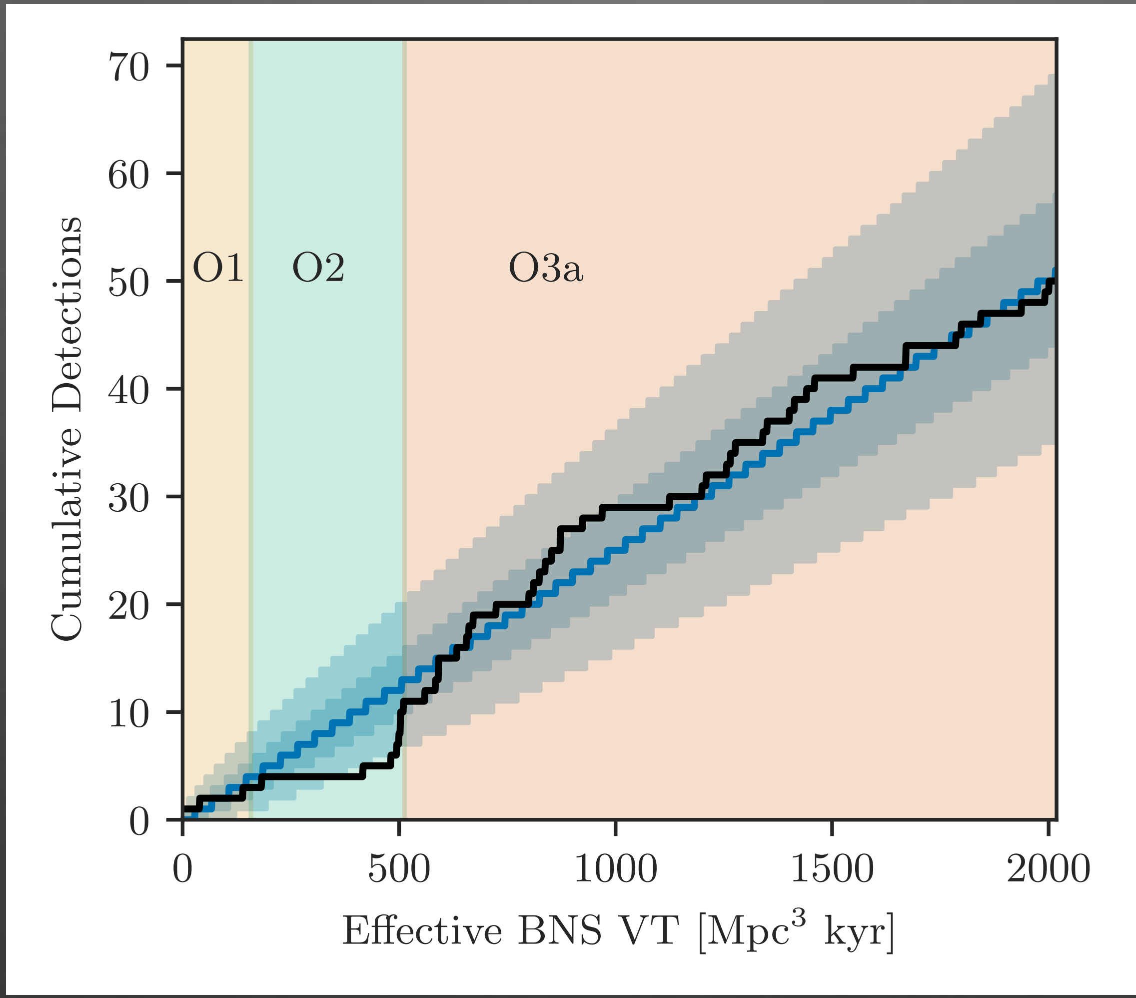
Outline

- A comment on Binary Black Holes: an astrophysical implication from new LIGO/Virgo catalogue (GWTC-2)
- Binary Neutron Star: what we have learned from multi-messenger observations of GW170817
- High energy (~100 MeV) neutrinos from core collapse supernovae and prospects with HyperKamiokande.

I will discuss very high energy gamma-rays from mergers in the CTA meeting next week.

Gravitational-Wave Transient Catalogue 2 (GWTC-2)

GWTC-2 contains 50 GW events detected by LIGO and Virgo since 2015 to O3a (Abbott et al 2020).



BBH merger rate:

99 $^{+138}_{-70}$ Gpc^{-3} yr^{-1} (2016) ⟶ 56 $^{+44}_{-27}$ (2018) ⟶ 23.9 $^{+14.9}_{-8.6}$ Gpc^{-3} yr^{-1} (2020)

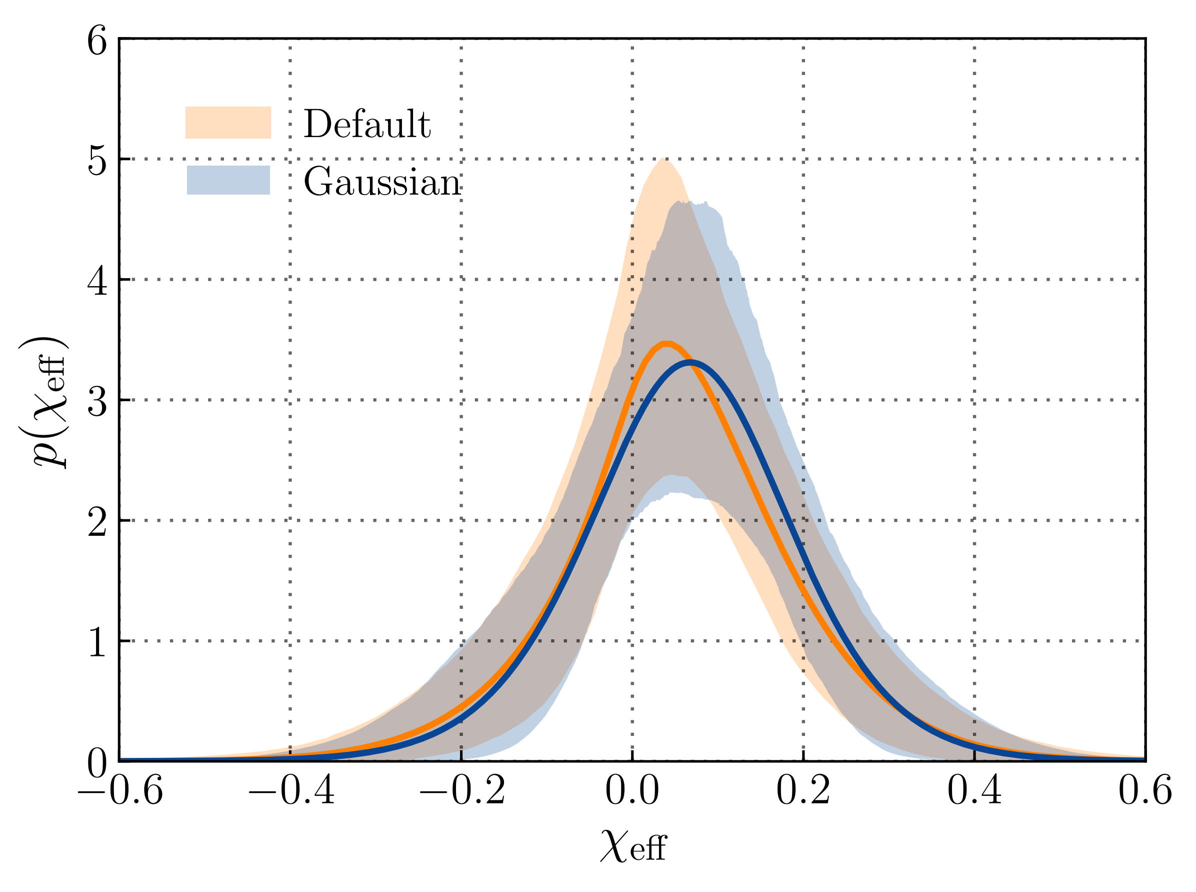
~ 2.4 Myr^{-1} in the Milky Way

=> We were lucky for BBHs.

Spin distribution indicates the field binary origin

Among 46 BBH mergers, 11 mergers have a positive χ_{eff} within a 90% credible interval. On the contrary, there is no event with a clear negative χ_{eff}. (Note that there is a bias, large χ_{eff} large observable volume)

In fact, the underlying spin distribution peaks at positive χ_{eff}.



(Abbott et al 2020)

Positive χ_{eff} means that the spin angular momenta and the orbital angular momentum are aligned, which is a very strong expectation of the field binary scenario.

Outline

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- Binary Neutron Star: what we have learned from multi-messenger observations of GW170817
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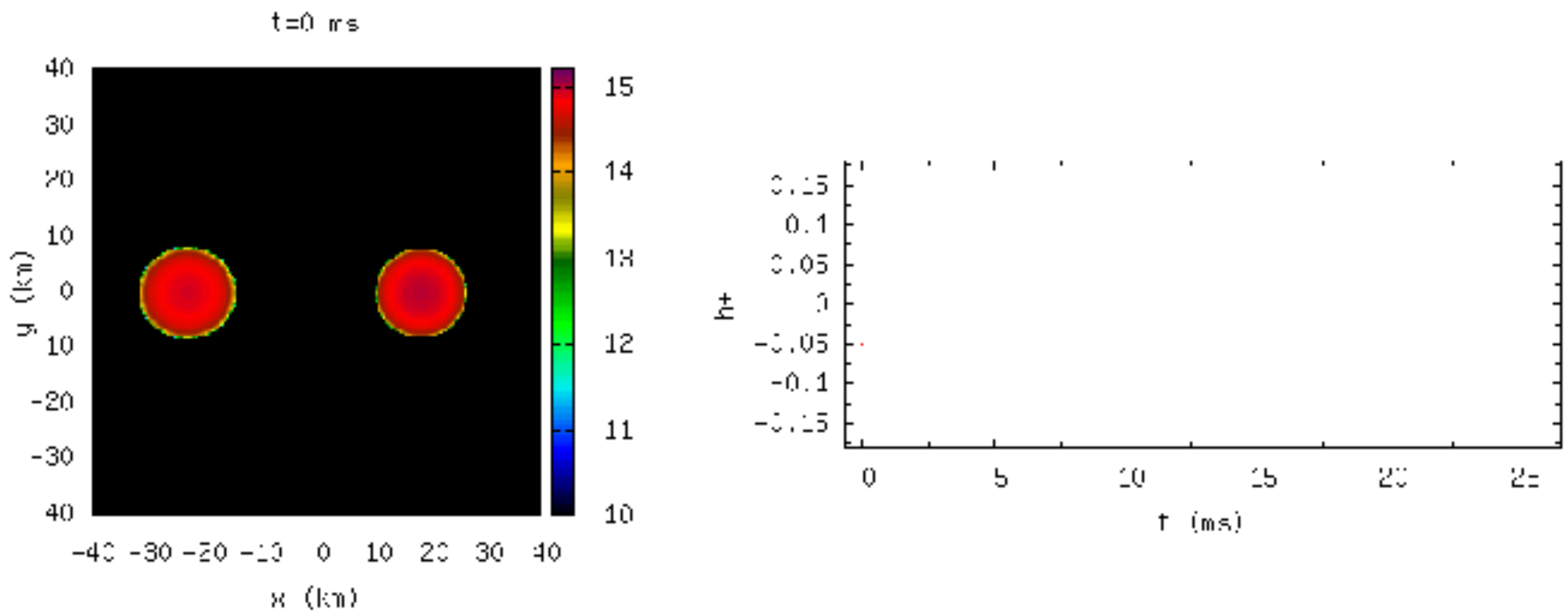
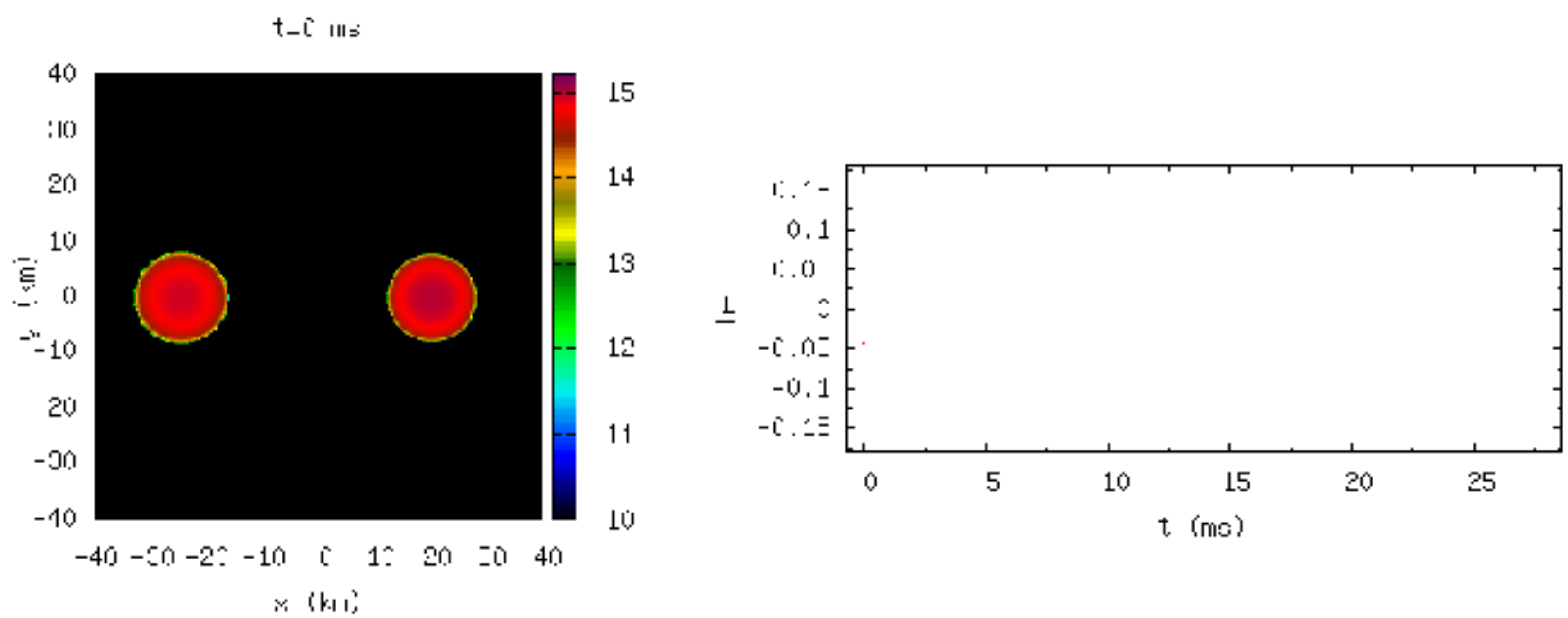
Neutron Star Merger

Propositions	Since GW170817
• One of the strongest GW emitters (Hulse & Taylor 1975)	○
• Standard cosmic siren (Schutz 1986)	○
• A site of heavy nucleosynthesis (Lattimer & Schramm 1974)	○
• Short GRB progenitors (Eichler et al 1988)	◌
• A laboratory of high-dense material (Flanagan & Hinderer 2008)	○
• Fast Radio Burst progenitors (Totani 2013)	?

EOS=APR, $M_{tot} = 2.7M_{sun}$

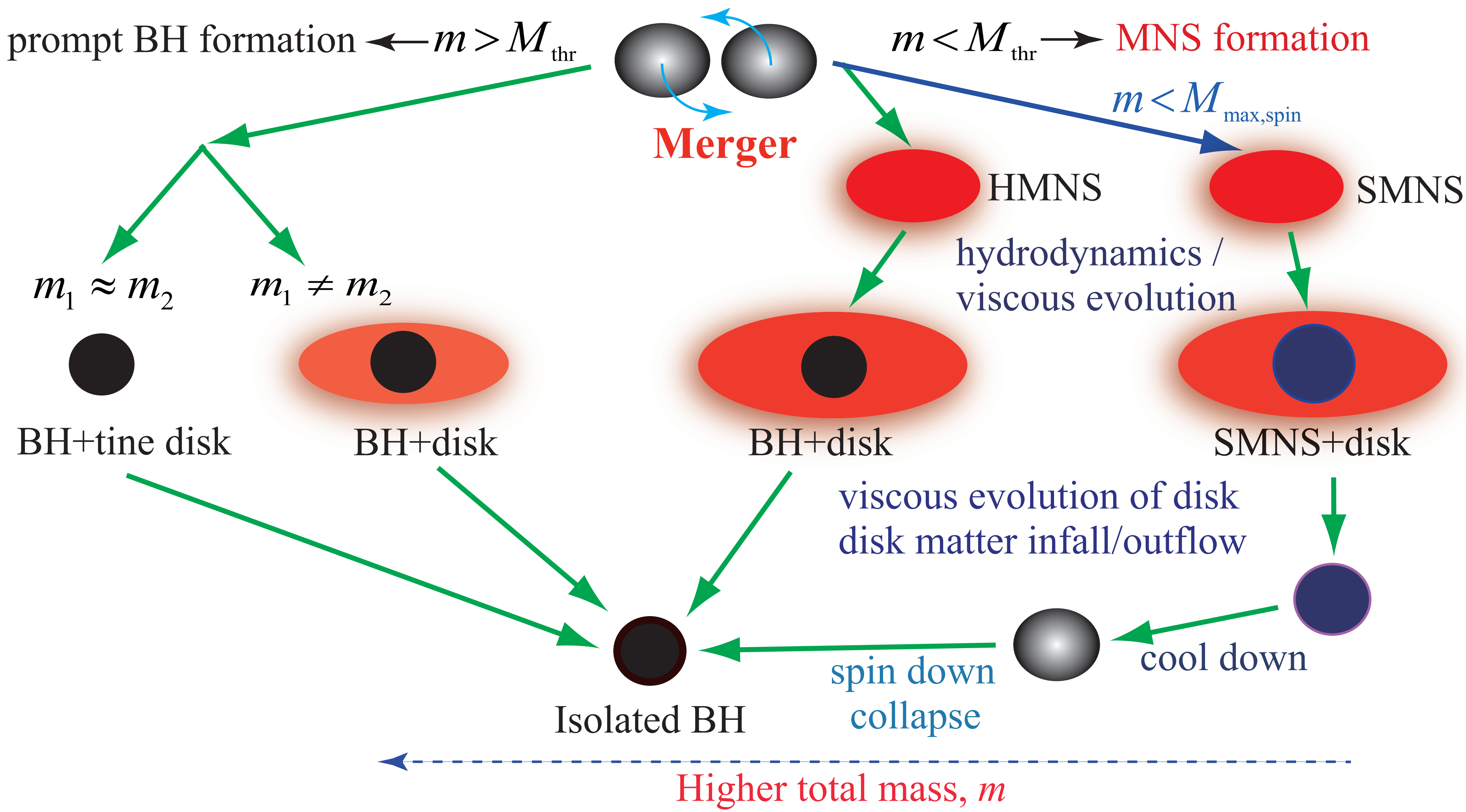


EOS=APR, $M_{tot} = 2.9M_{sun}$



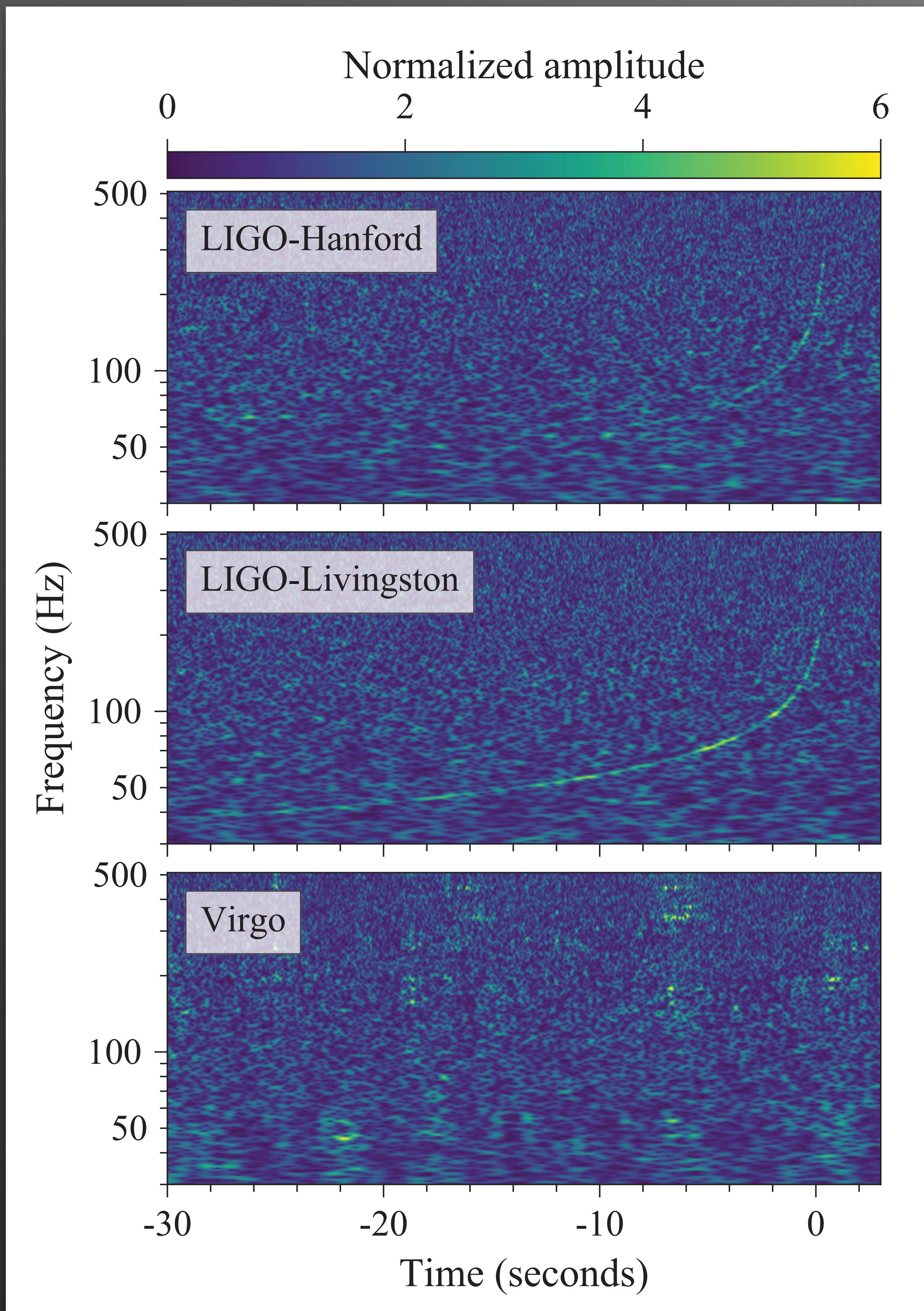
KH + 13

Variety in merger remnants

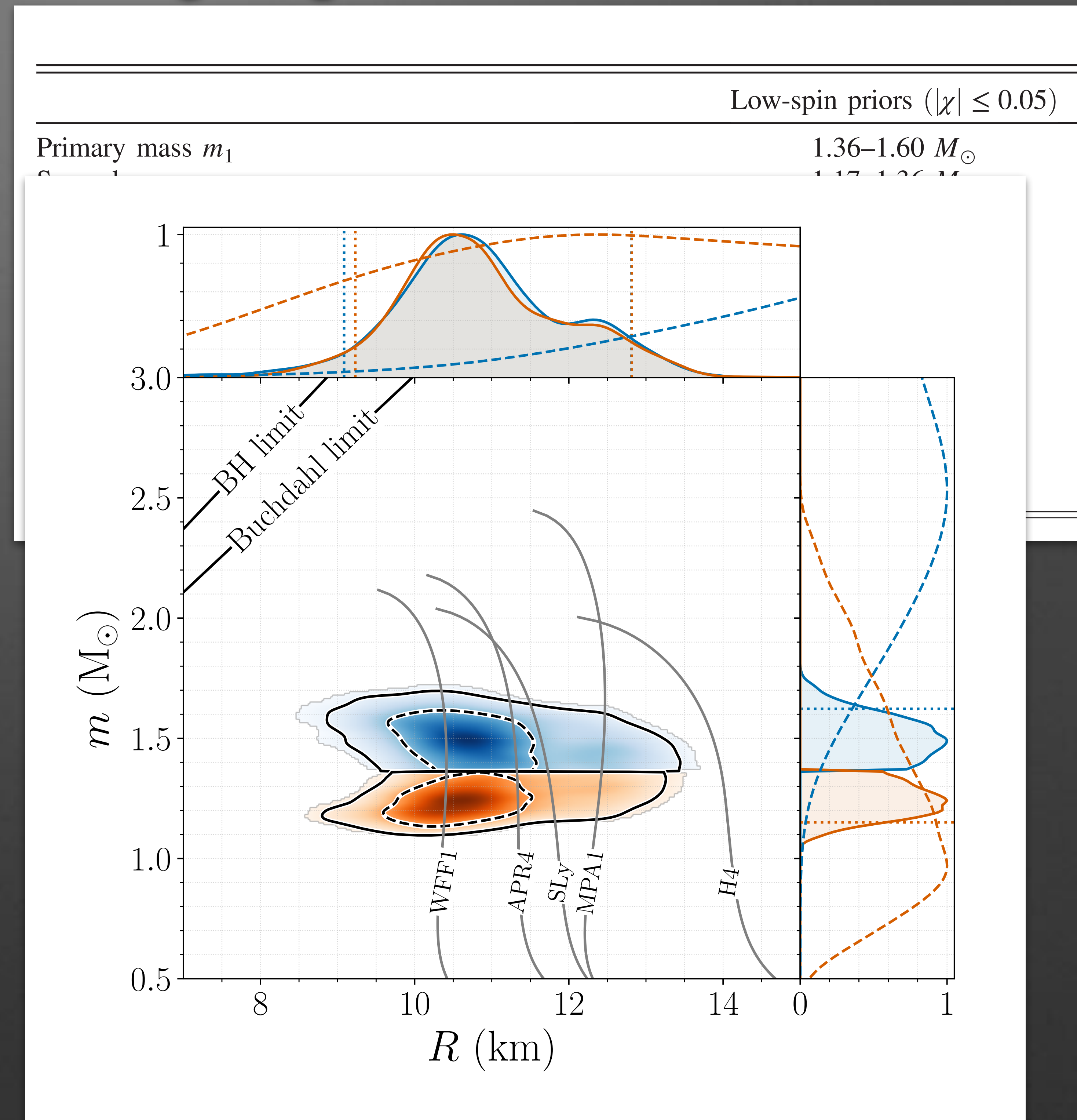


Shibata & KH 2019

The first binary neutron star merger: GW170817



High Signal-to-noise ratio ~ 30



Abbott et al 2017

Merger rate

Gravitational wave

$R_{GW} = 920^{+2220}_{-790}$ $Gpc^{-3}\ yr^{-1}$ (2018) ⟶ 320^{+490}_{-240} (2020)

We were also lucky for neutron star mergers.

=> ~ 32^{+49}_{-24} Myr^{-1} the Milky-Way Galaxy

Short GRBs

$R_{SGRB} = 6^{+2}_{-2}$ $Gpc^{-3}\ yr^{-1}$ (before a beaming correction, Wanderman & Piran 15)

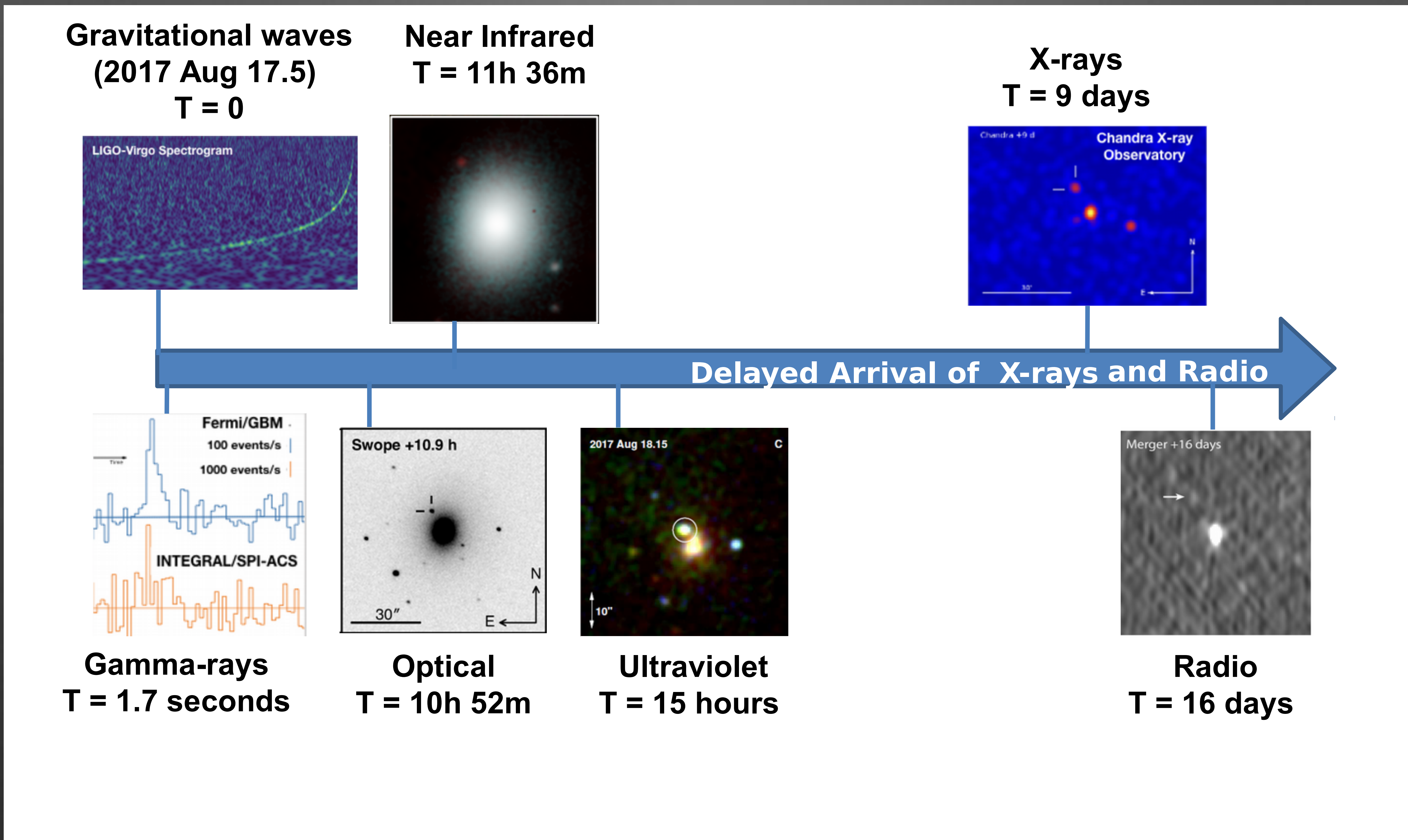
=> ~390^{+130}_{-130} $(f_b^{-1}/65)$ $Gpc^{-3}\ yr^{-1}$ (corresponding to a half-opening angle of 10^o)

R_{GW} ~ R_{SGRB} (corrected) suggests that all short GRBs can arise from mergers.

Galactic binary neutron stars (BNS)

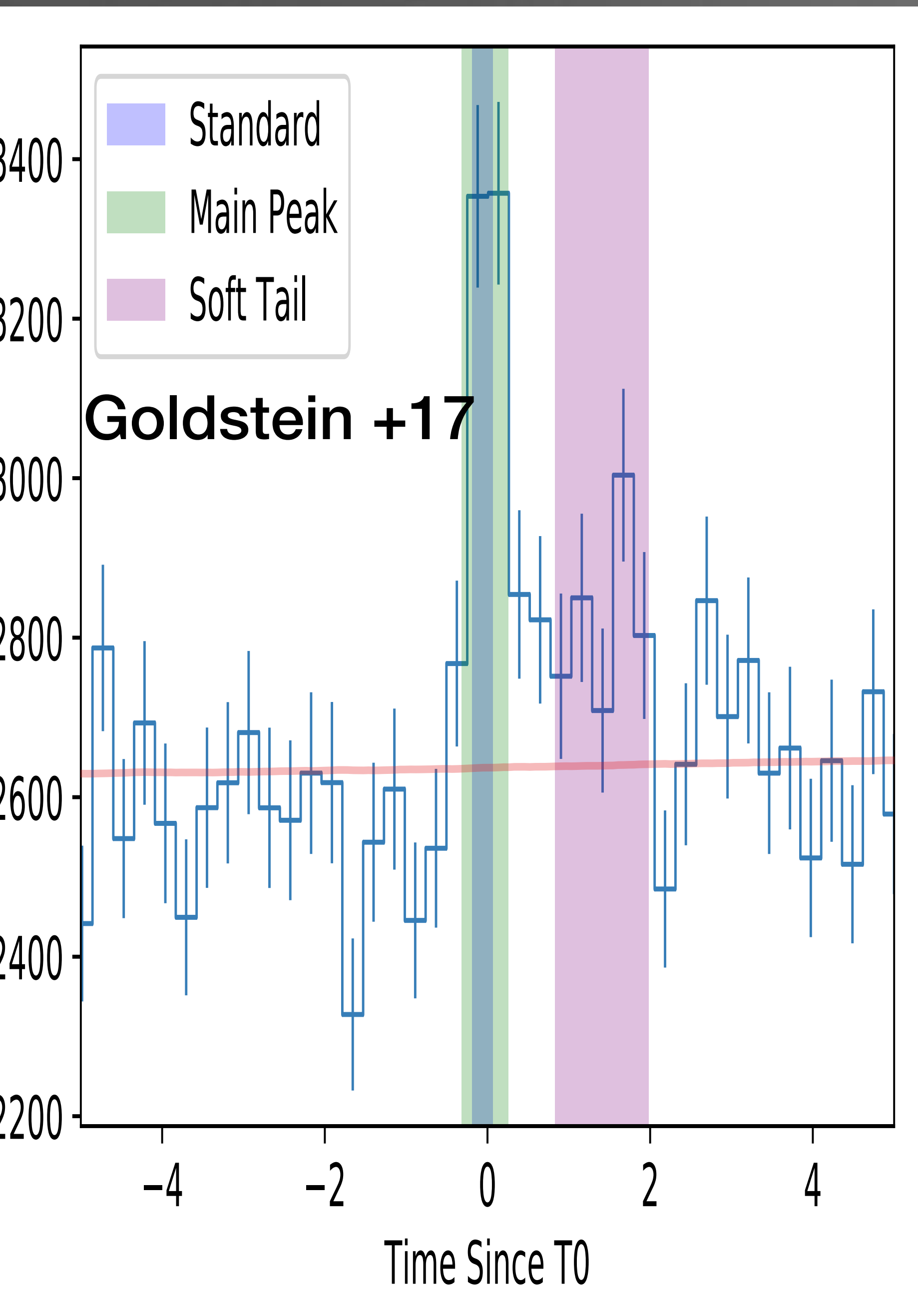
$R_{BNS} = 42^{+30}_{-10}$ Myr^{-1} (Pol, McLaughlin, & Lorimer 2019),
which is dominated by 5 systems, J1906+0746, B1913+16 (Hulse-Taylor),
J0737-3039A/B (the double), J1757-1854, J1946+2052 (the tightest)

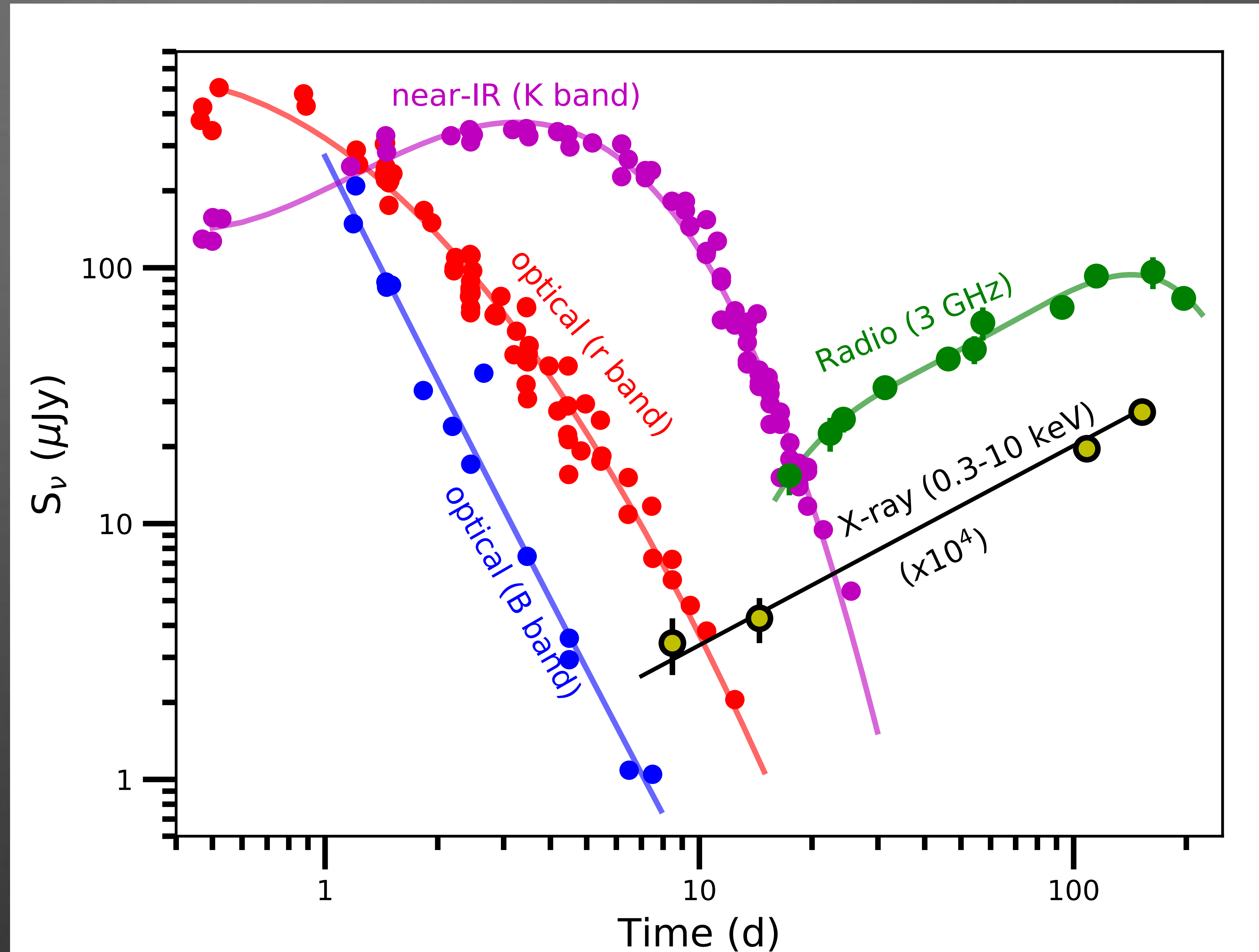
Follow-up observations of GW170817



Abbott et al., ApJL. 848, L12 (2017)

GW170817: GRB, Kilonova & Afterglow





GRB 170817 (X-γ)

Dissipation in the outflow:
L ~ 10^{46} - 10^{47} erg/s

Kilonova (uv-IR)

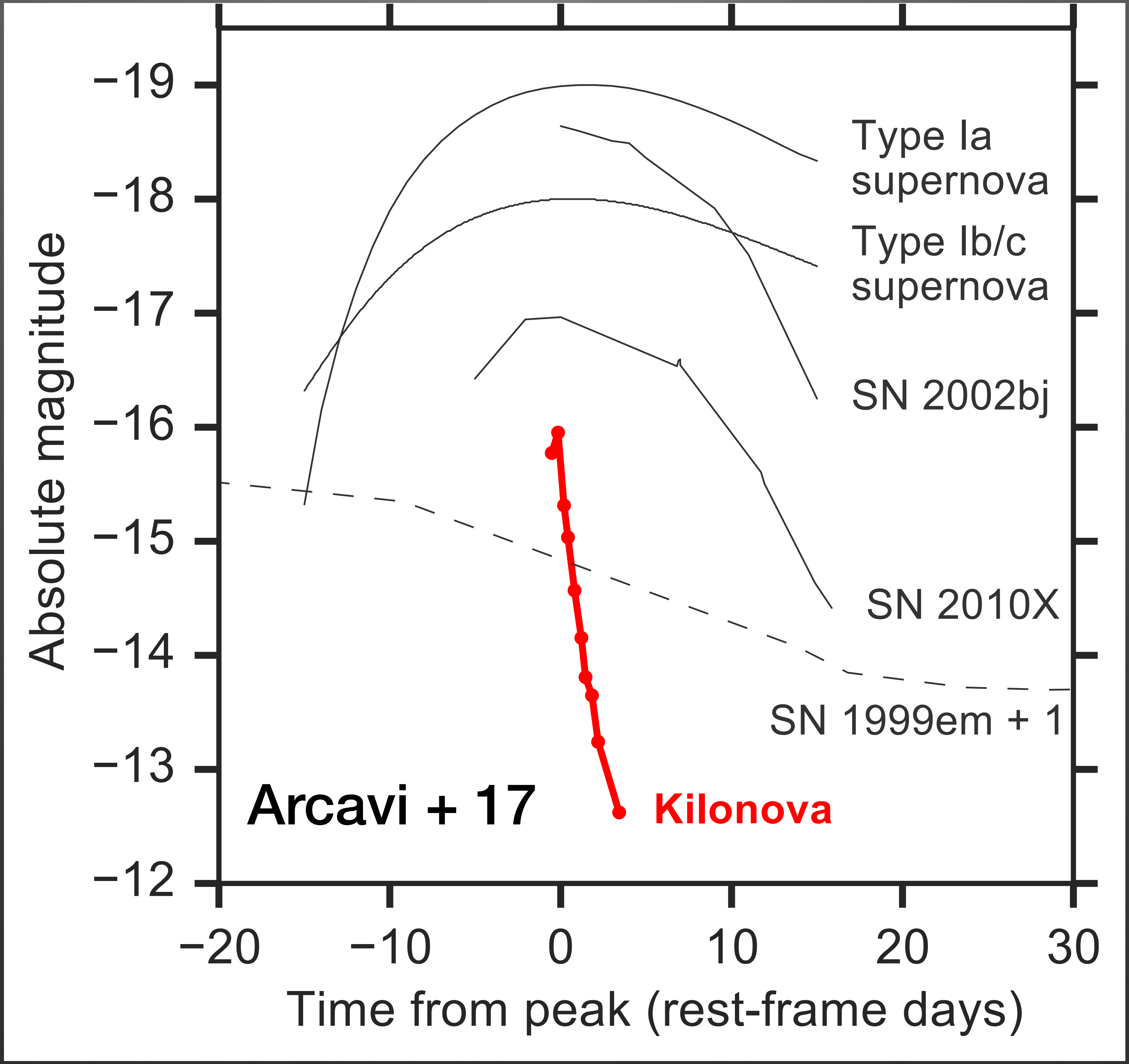
Radioactive decay:
~ 10^{38} - 10^{42} erg/s

Afterglow (radio-X)

Kinetic energy deposited
into the ISM: ~ 10^{38} - 10^{40} erg/s

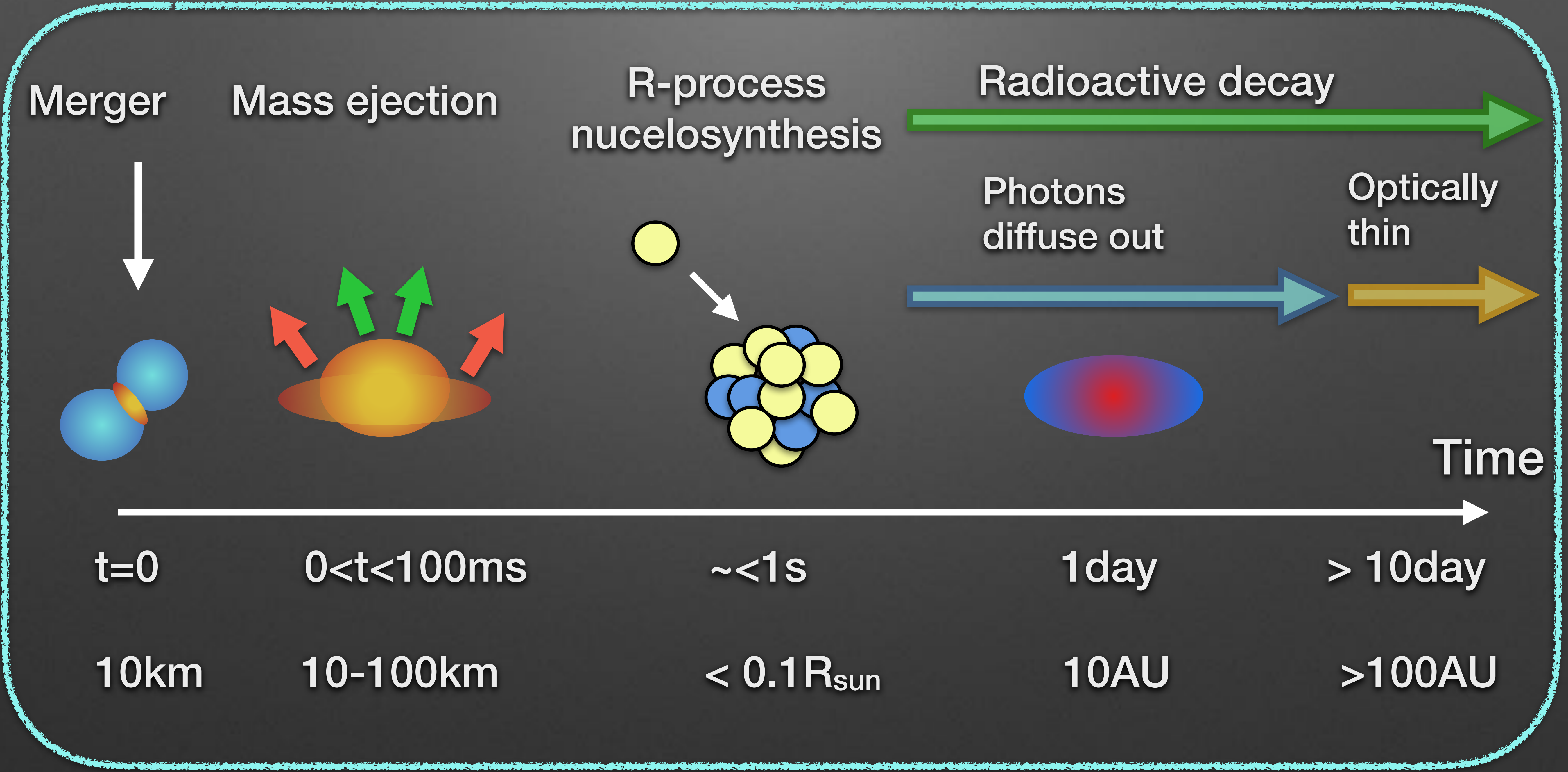
Kilonova in GW170817

Arcavi+17, Coulter+17, Lipunov+17, Soares-Santos+17, Tanvir+17, Valenti+17, Kasliwal+17,Drout+17, Evans+17, Utsumi+17



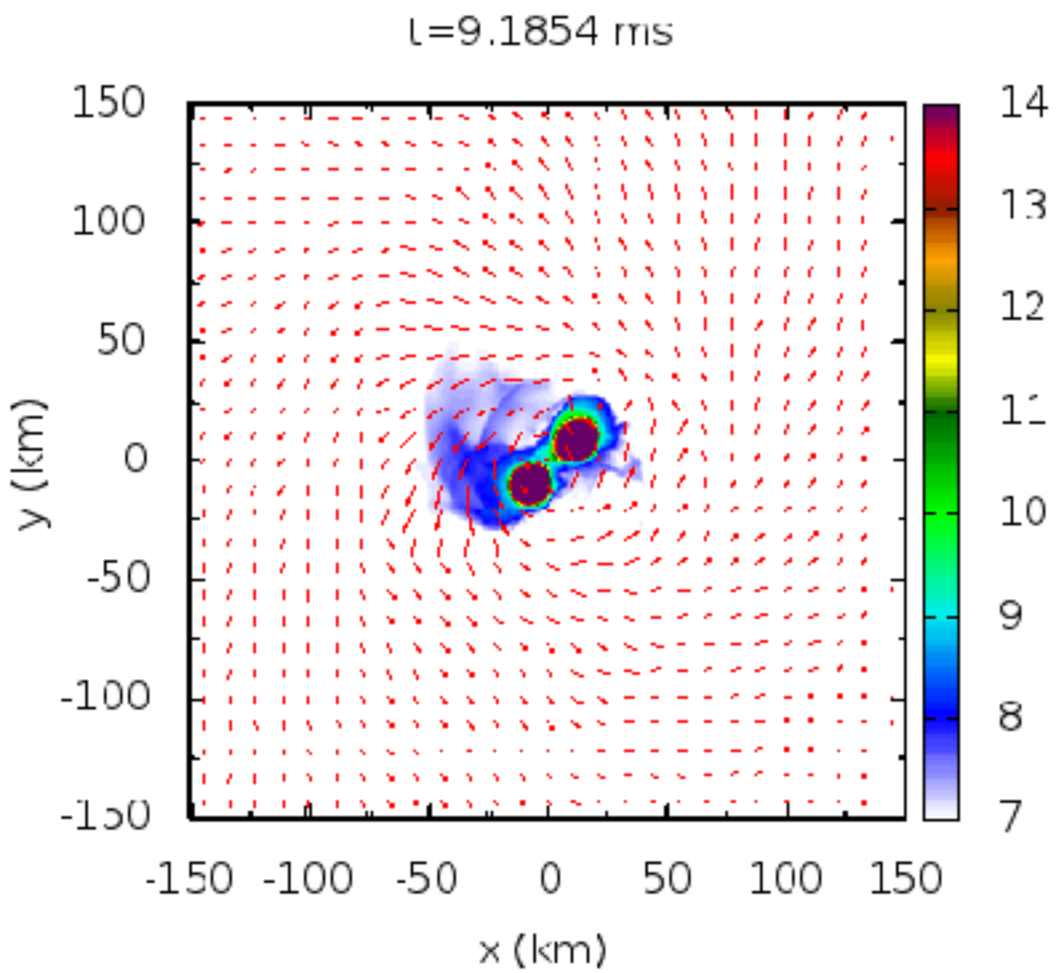
Basics of Kilonovae

Li & Paczynski 1998, Kulkarni 2005, Metzger + 2010

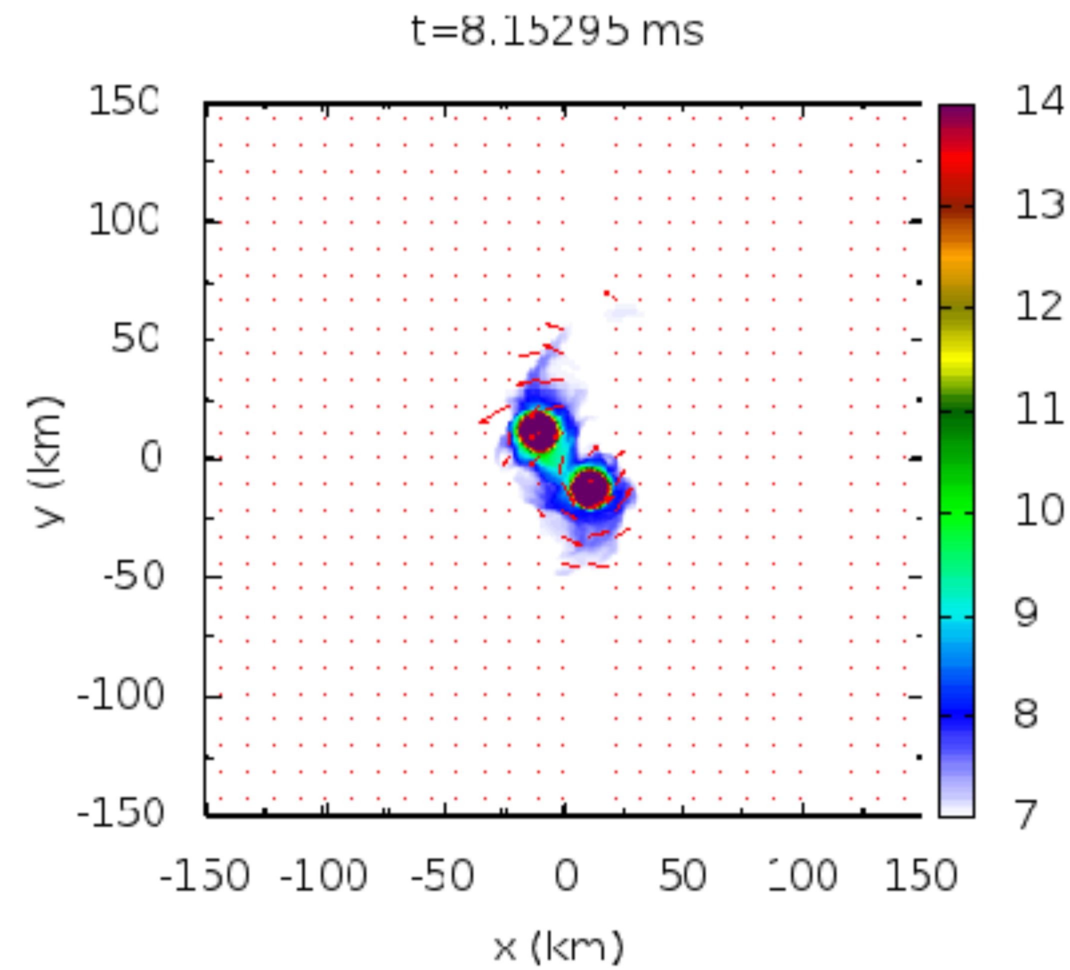


Dynamical mass ejection

1.5M_{sun} and 1.2M_{sun}



1.6M_{sun} and 1.3M_{sun}



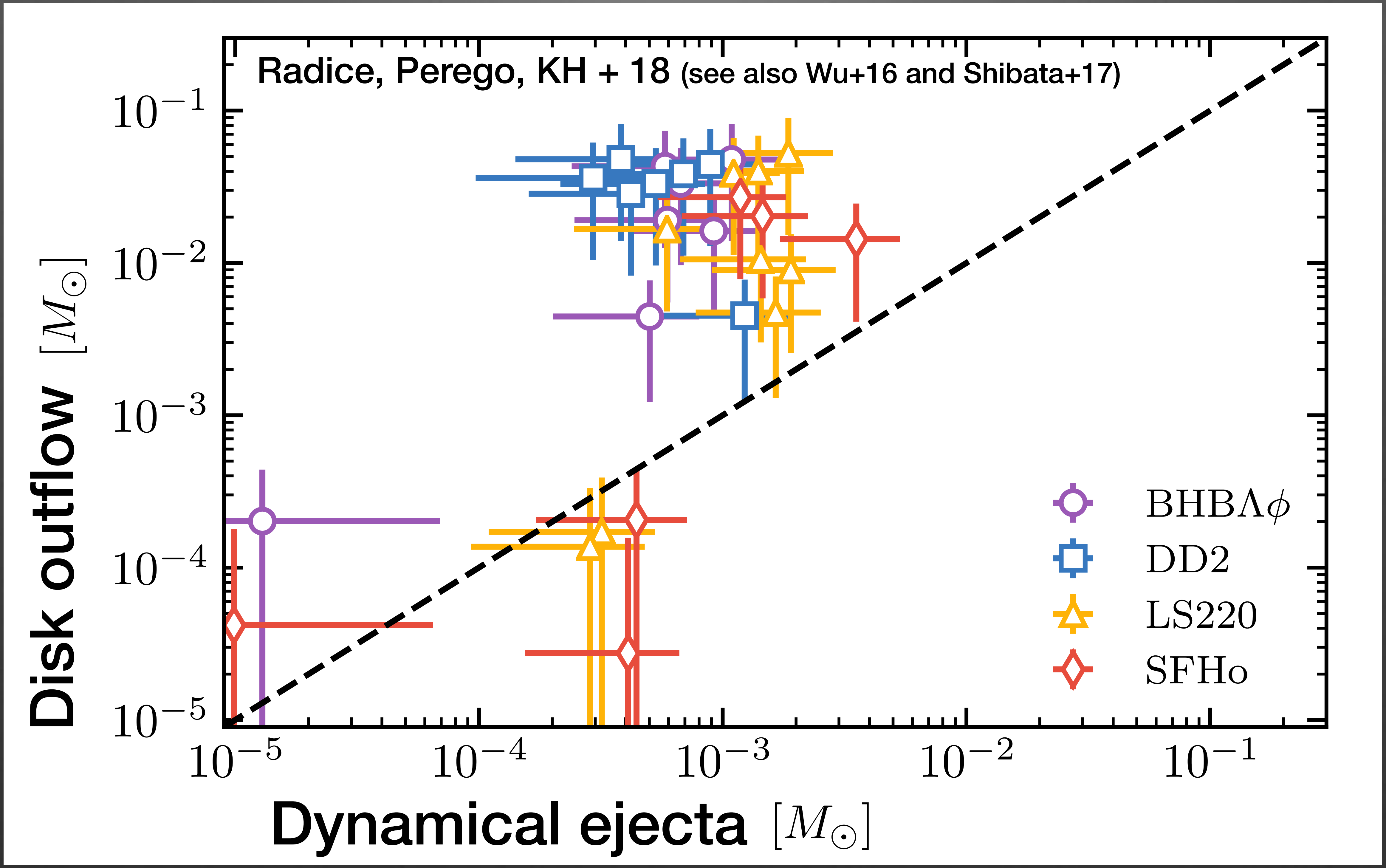
KH + 2013

HMNS formation:
- Tidal (cold) + shock (hot)
- Ejection lasts: ~ 5 ms
- Mass < 0.01Msun, v ~ 0.2c

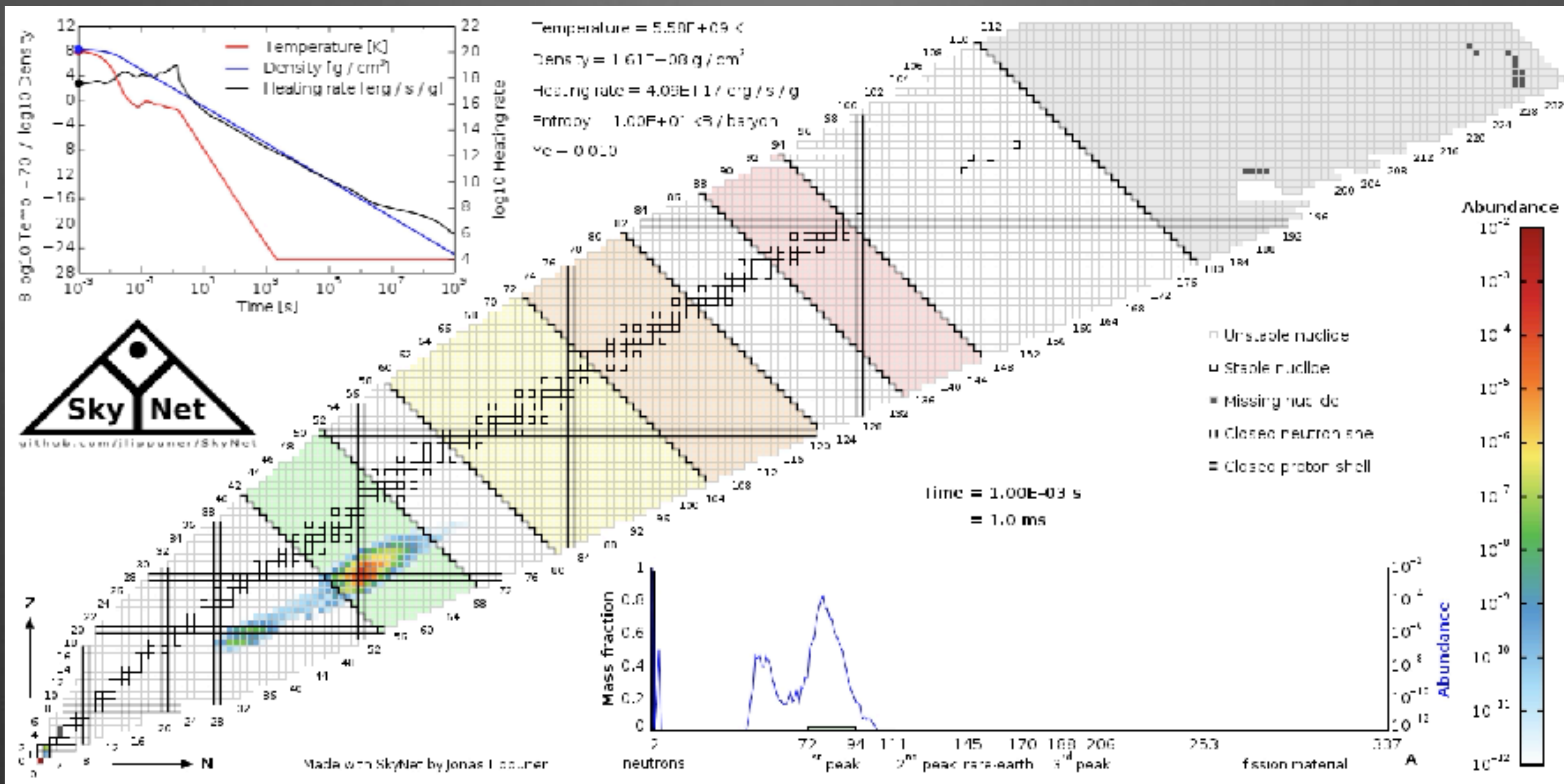
Prompt BH formation:
- Tidal (cold)
- Ejection lasts: ~ 1 ms
- Mass < 0.01Msun, v ~ 0.2c

Bauswein + 13, Piran + 13, Rosswog 2013, Kyutoku+15, Sekiguchi + 15, 16, Radice+16

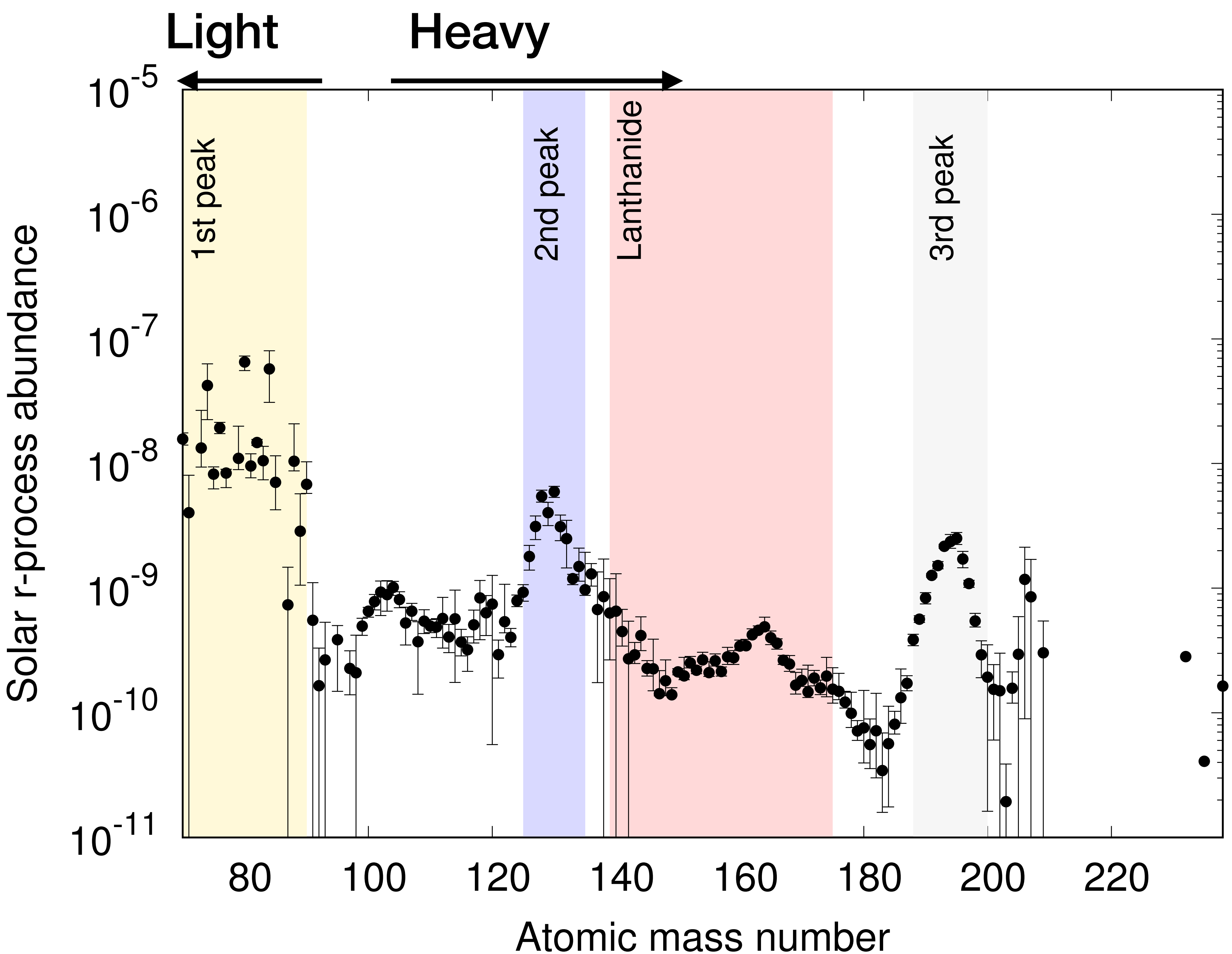
Dynamical ejection vs Disk outgflow



R-process nucleosynthesis in merger



Kilonova Emission depends on the composition

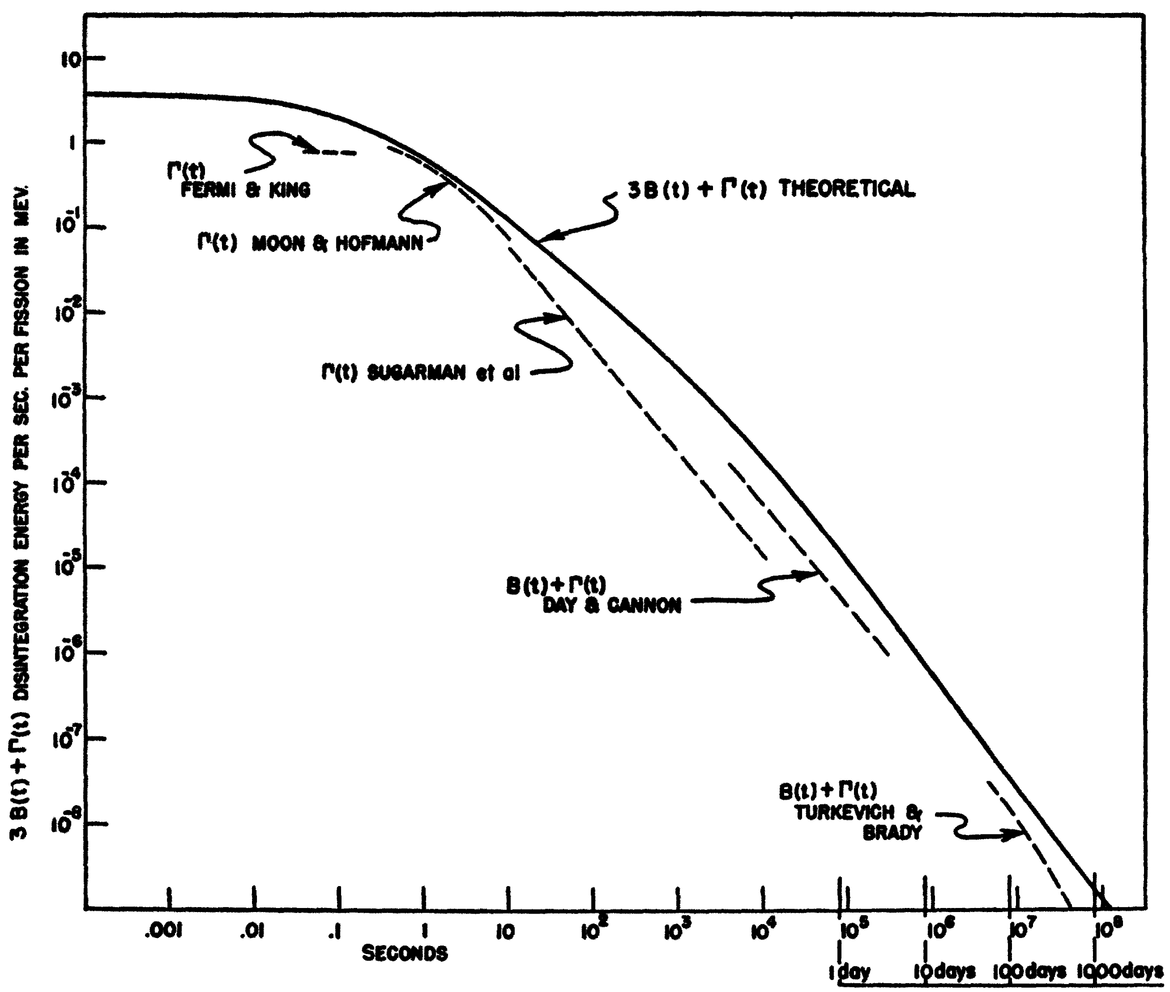


KH, Beniamini, Piran 18, Goriely 99

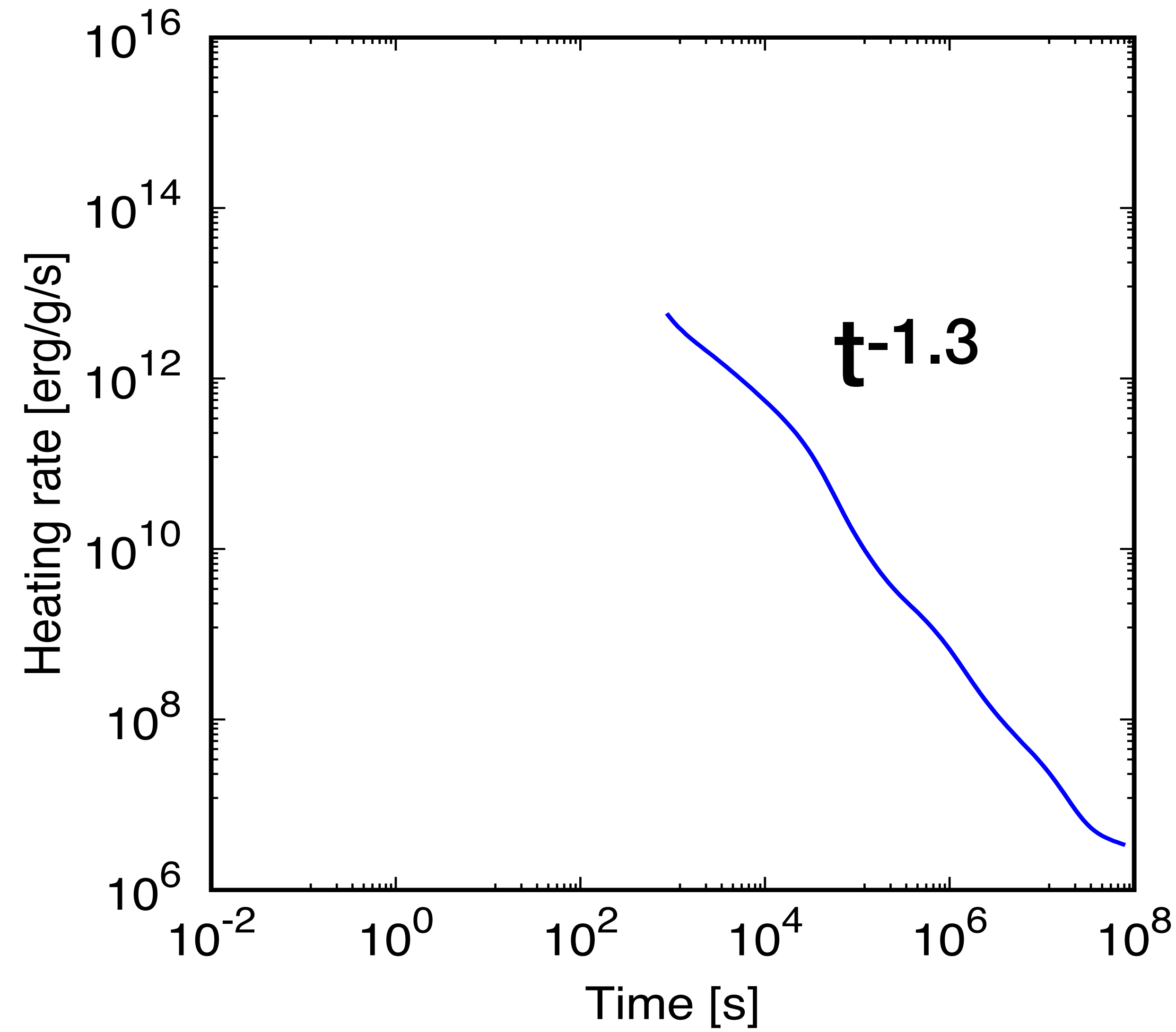
Heating rate of r-process

Way & Wigner 1948

KH & Nakar 2020



(a)



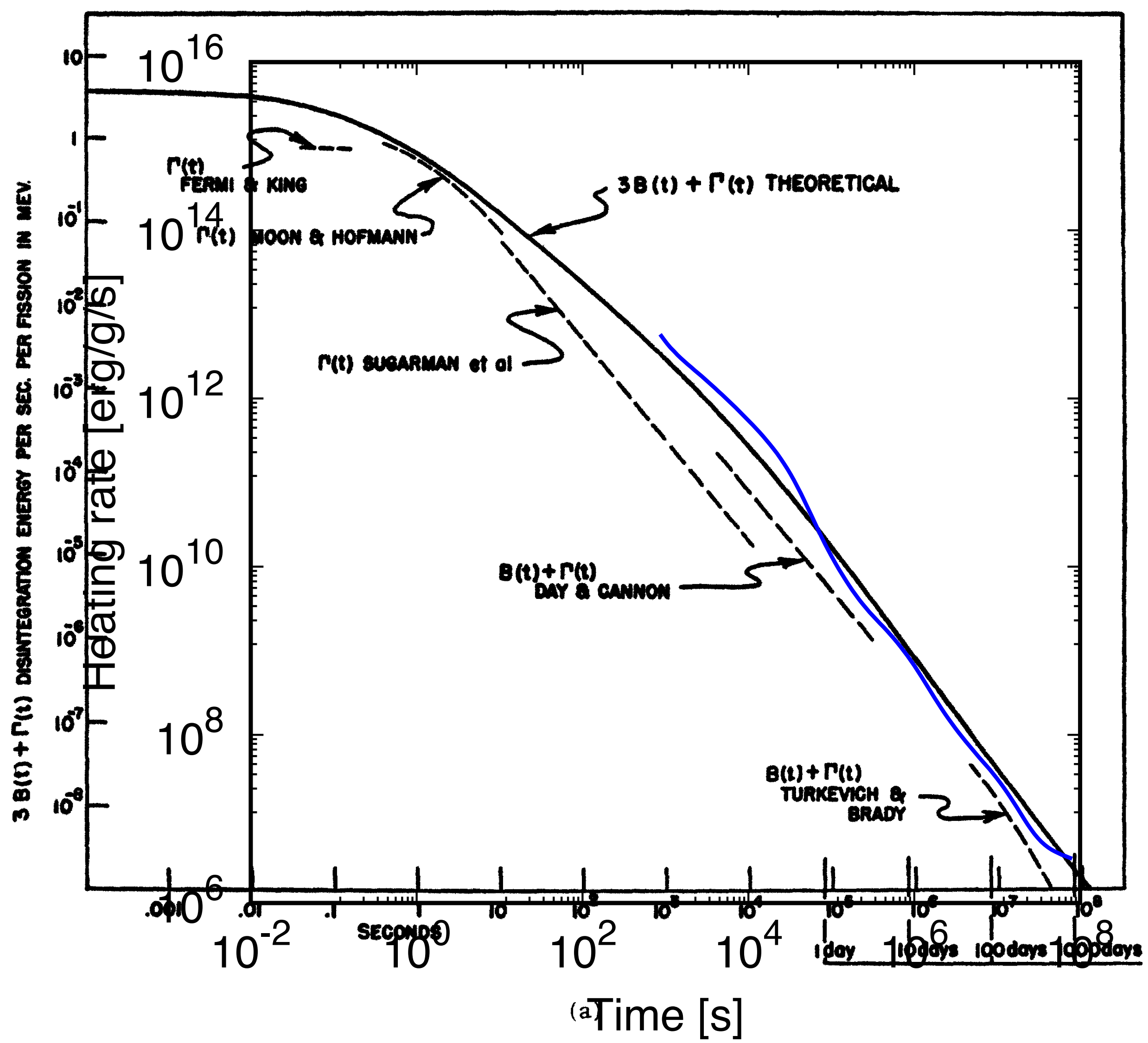
Heating rate of nuclear waste

Heating rate of r-process

Heating rate of r-process

Way & Wigner 1948

KH & Nakar 2020



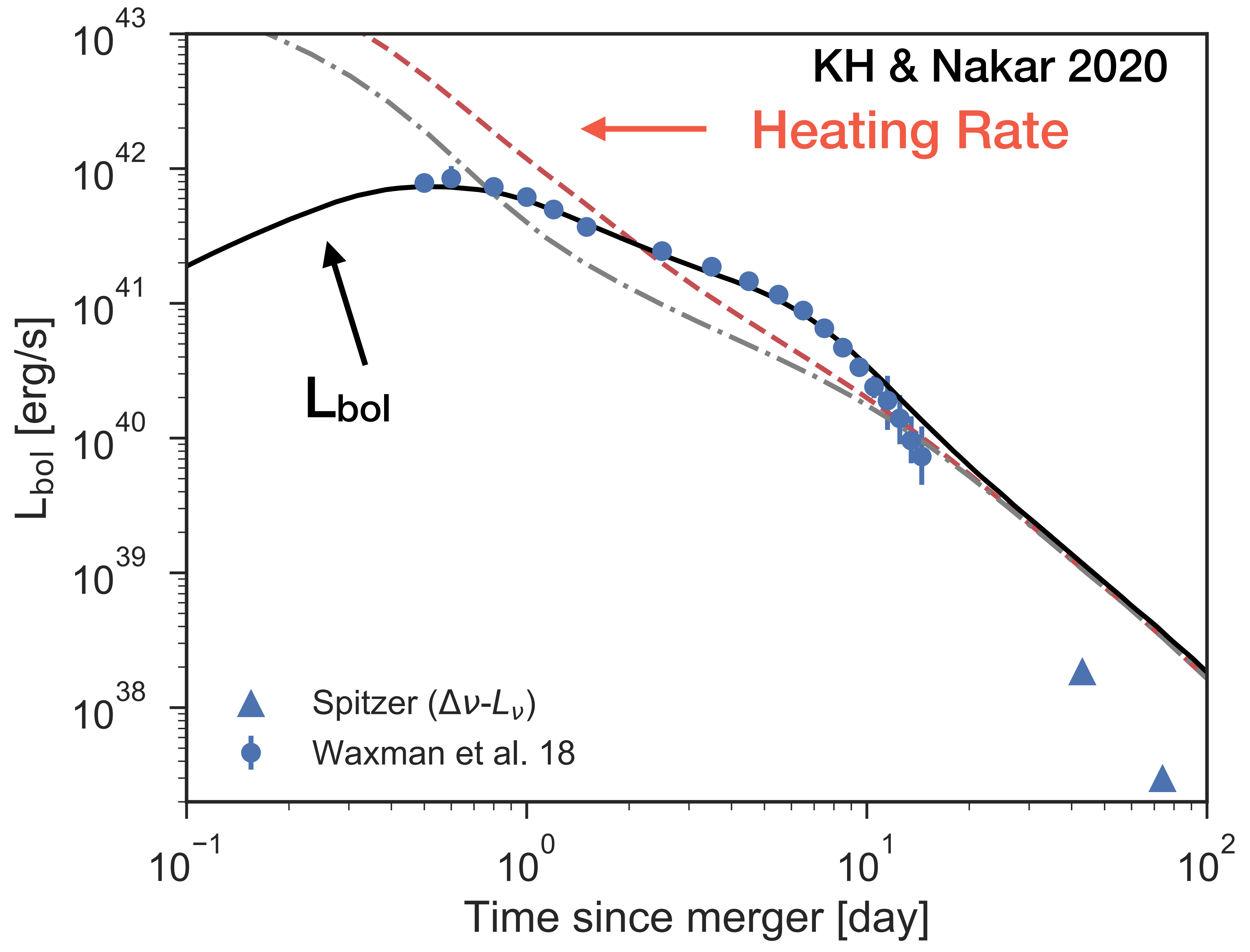
Heating rate of nuclear waste

Heating rate of r-process

This is somewhat a unique properties of the heating rates of many beta-decay chains.

Observation vs theory of Kilonova

Open code: https://github.com/hotokezaka/HeatingRate

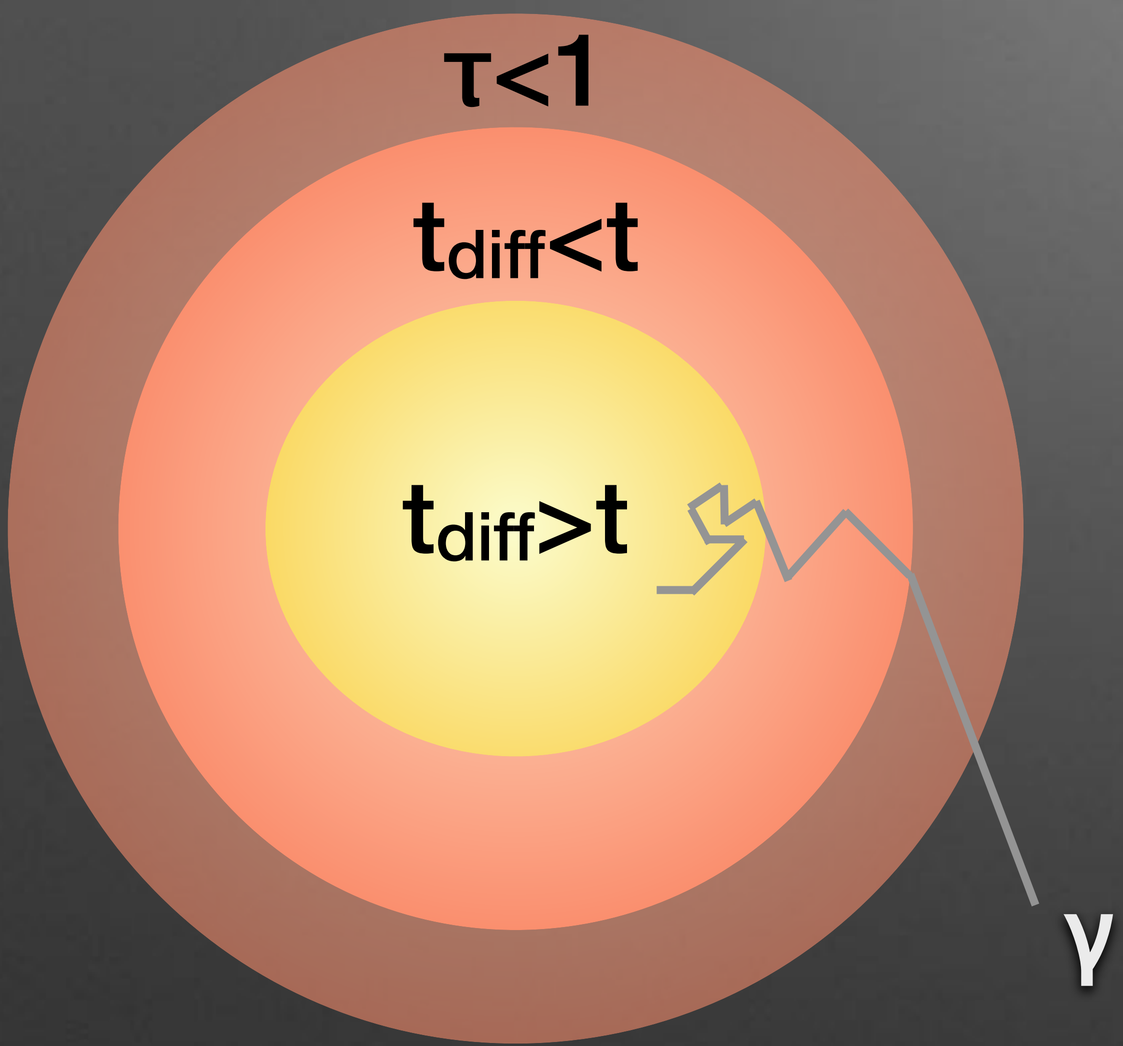


~0.05 Msun of r-process elements are required to power the kilonova GW170817.

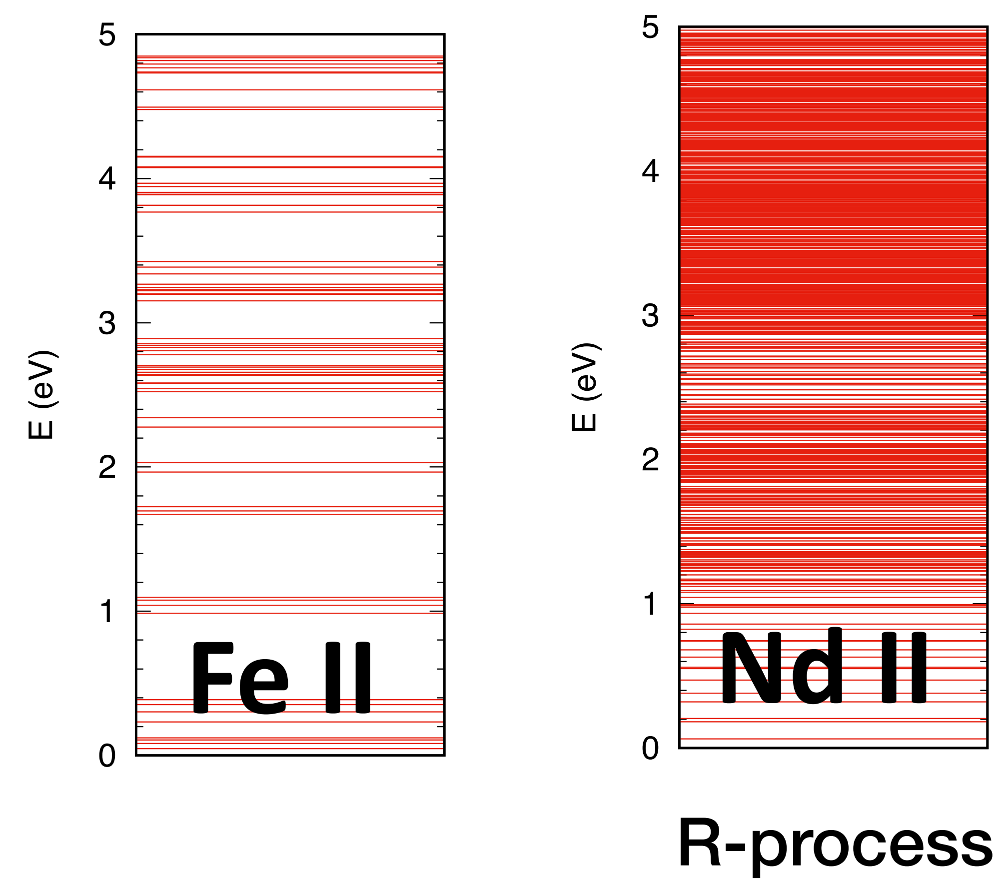
Radioactive heat => Photon Luminosity

Barnes & Kasen 13, Kasen + 13, Tanka & KH 13, Tanaka 17, Wollaeger + 18, Tanaka+19

Expanding Ejecta



Photons are blocked by atomic transitions

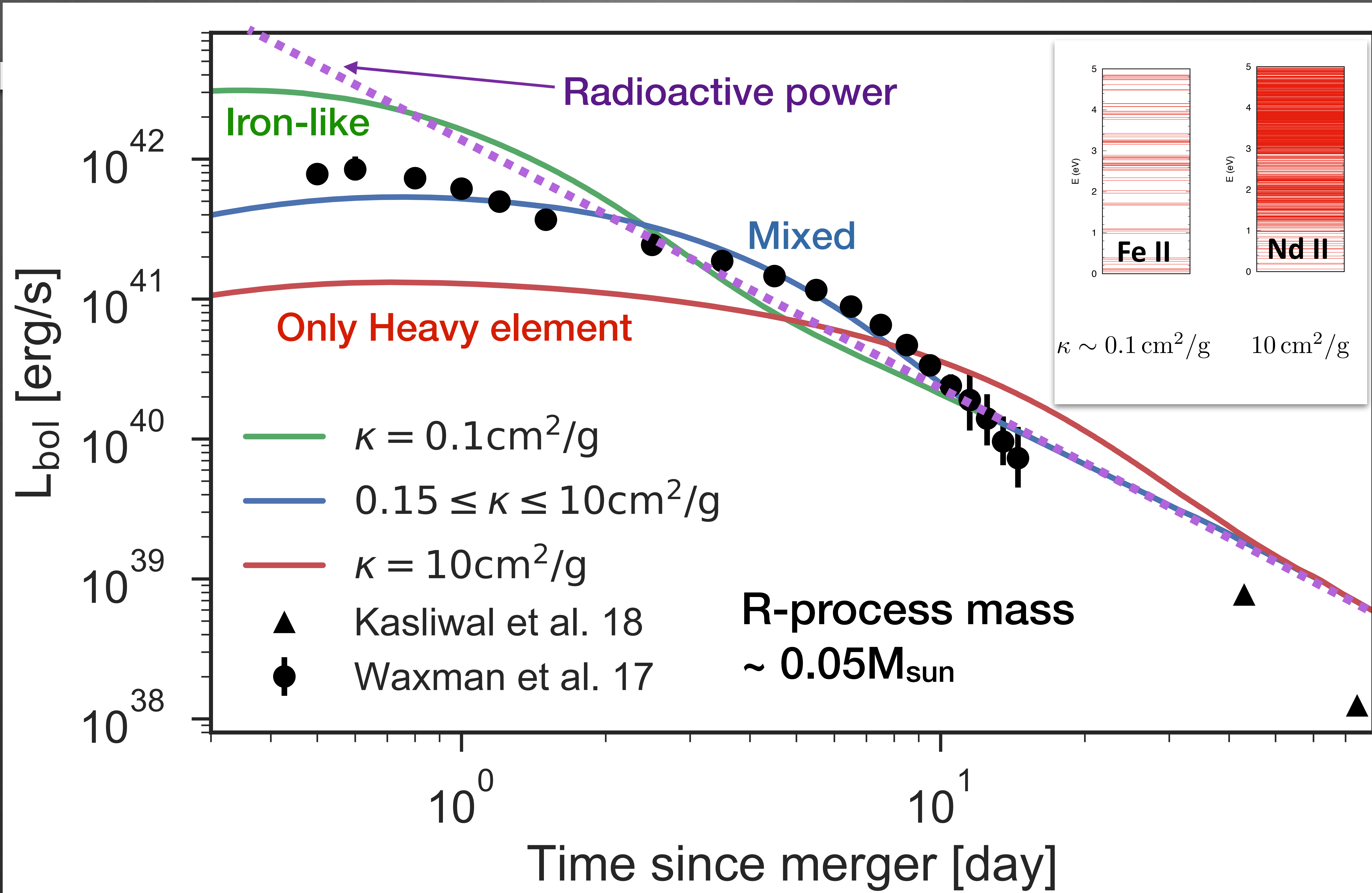


Opacity

$\kappa \sim 0.1\,\mathrm{cm}^2/\mathrm{g}$ $\quad 10\,\mathrm{cm}^2/\mathrm{g}$

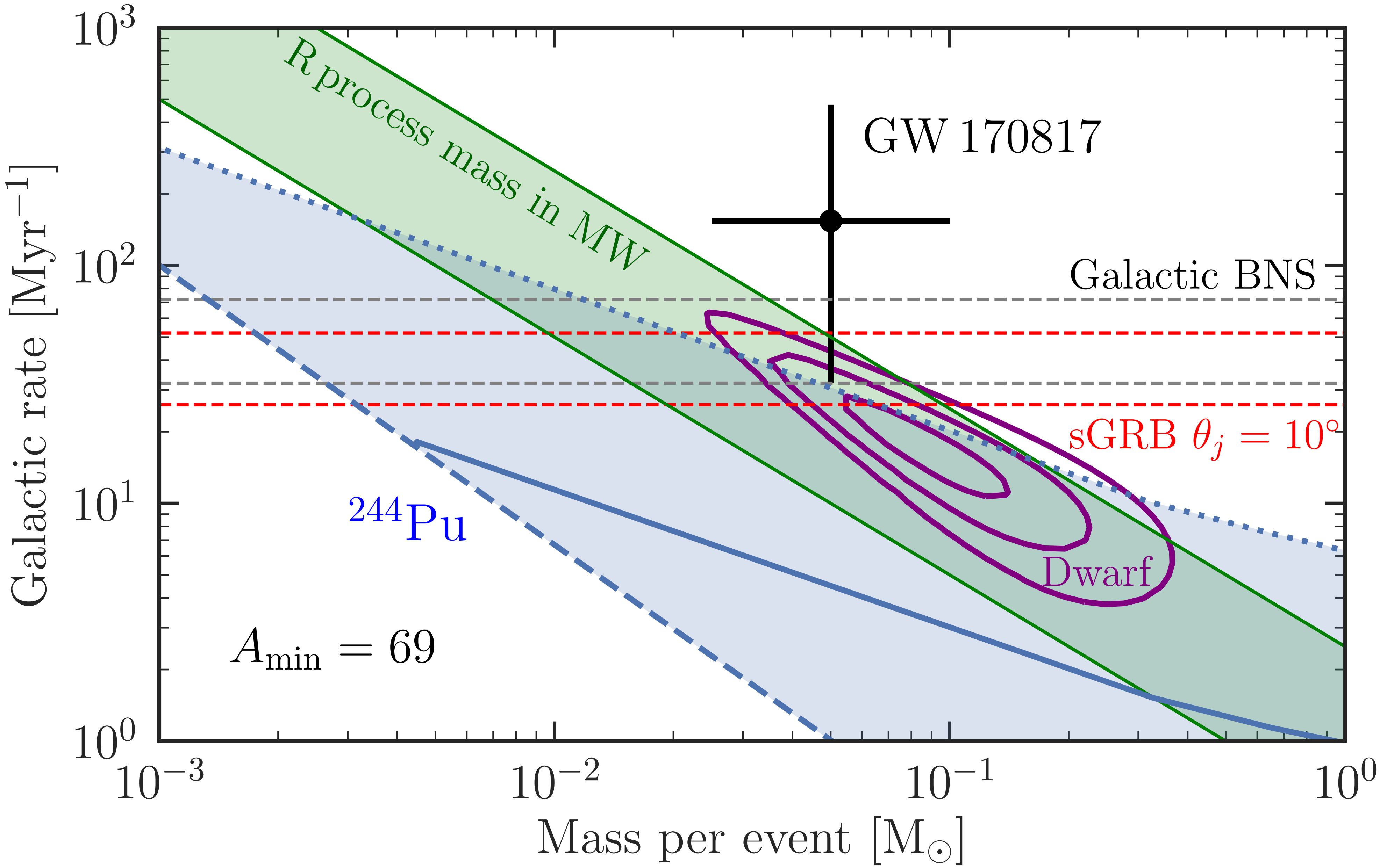
Kilonova GW170817: R-process heating matches the data

Open code: https://github.com/hotokezaka/HeatingRate



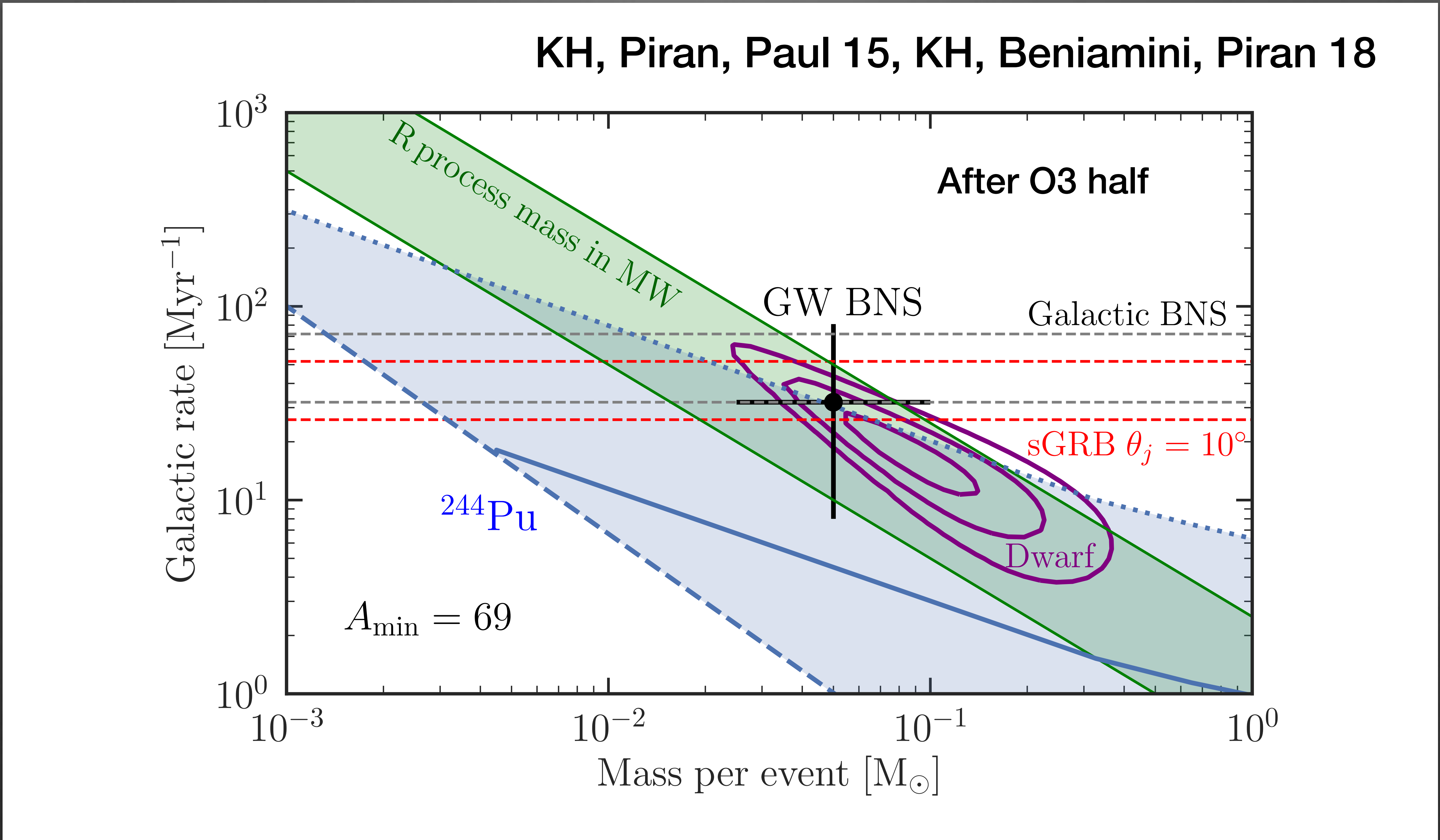
R-process mass budget from GWTC-1

KH, Piran, Paul 15, KH, Beniamini, Piran 18



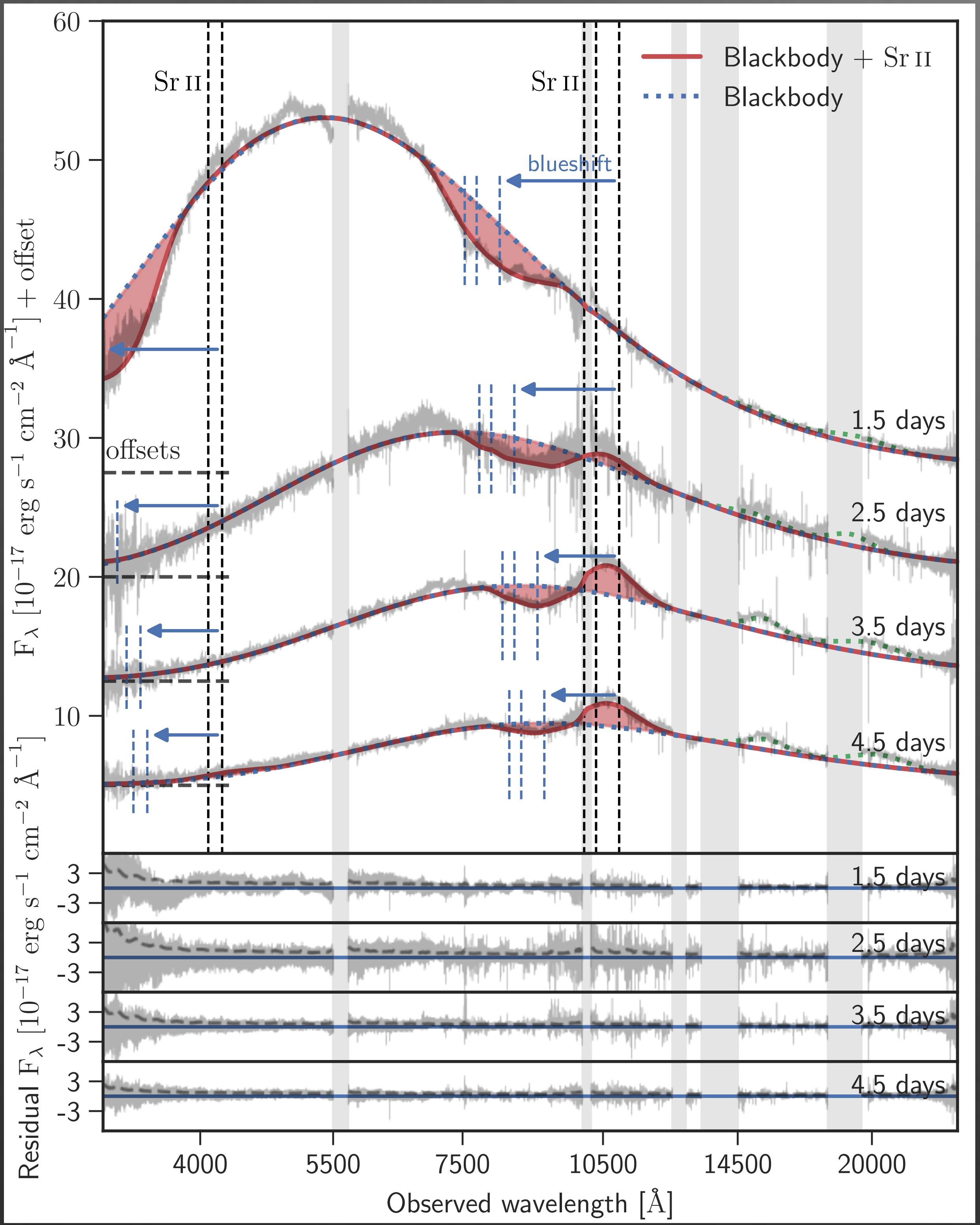
Ref: Goriely 1999, Lodders et al 2009, Wanderman & Piran 2015, Fong+2015, KH, Piran, Paul 2015, Beniamini, KH, Piran 2016, Pol, McLaughlin, Lorimer 2019, KH & Nakar 2020, LVC 2020

R-process mass budget from GWTC-2



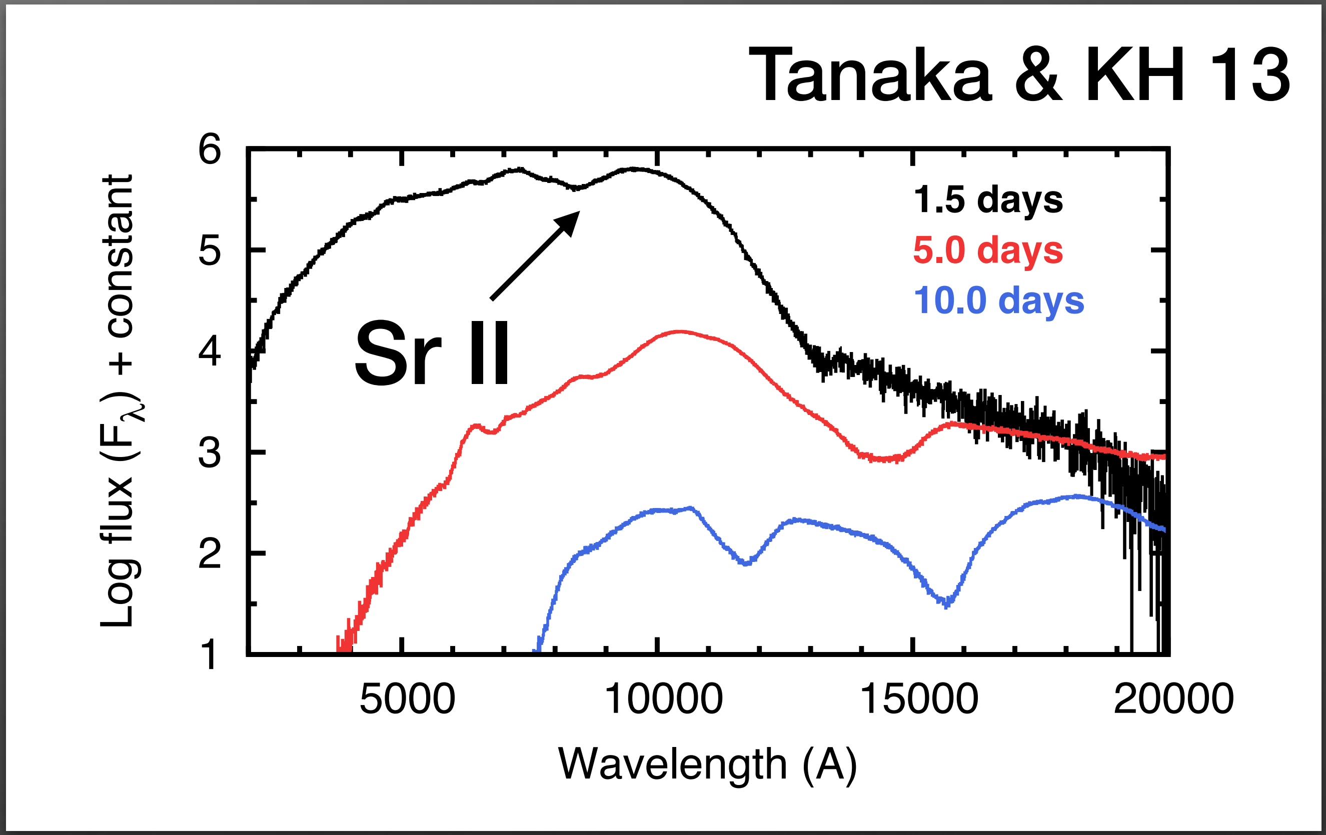
Ref: Goriely 1999, Lodders et al 2009, Wanderman & Piran 2015, Fong+2015, KH, Piran, Paul 2015, Beniamini, KH, Piran 2016, Pol, McLaughlin, Lorimer 2019, KH & Nakar 2020, LVC 2020

Sr lines in the kilonova spectrum



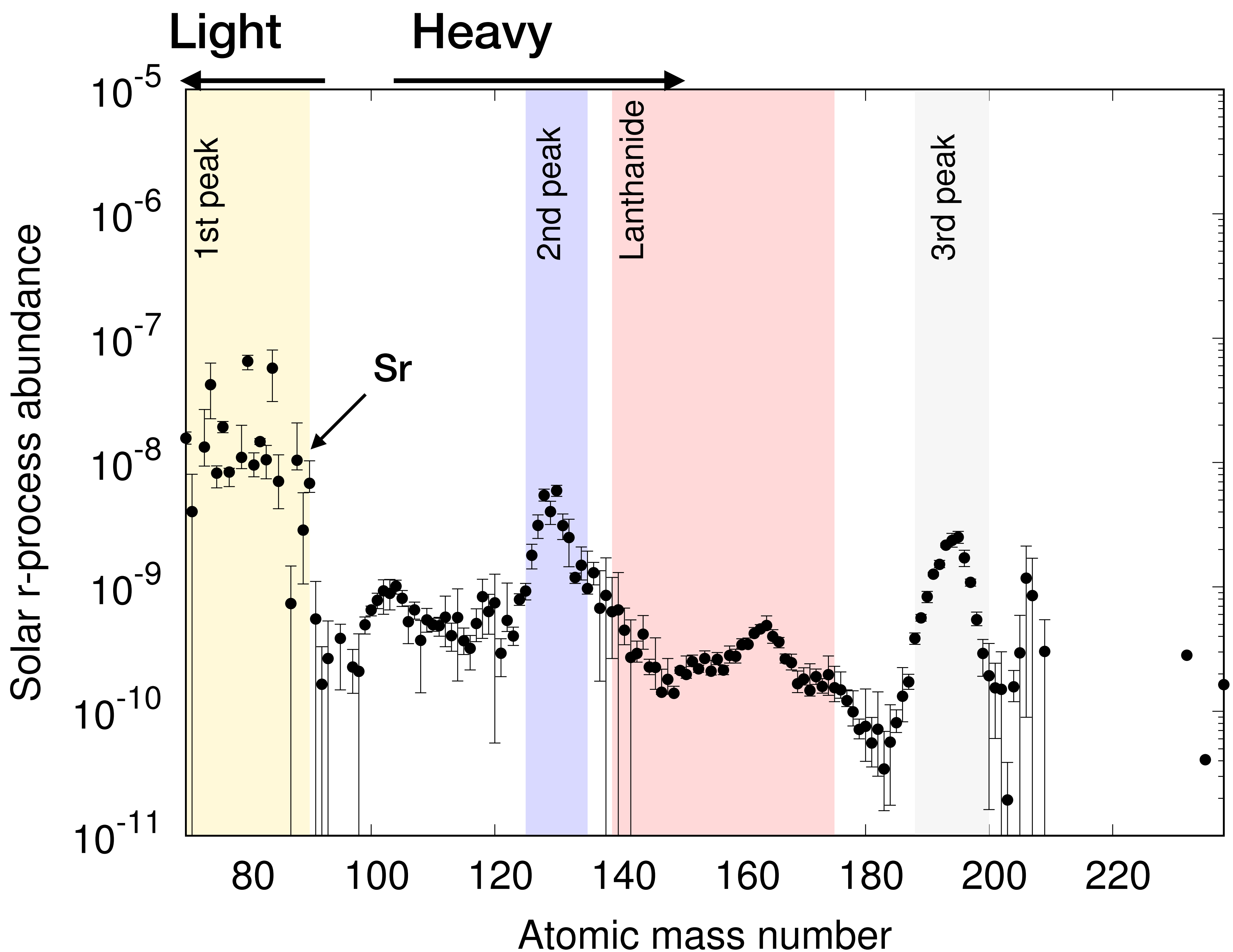
Watson et al 19

X-shooter spectra are explained by blackbody + Sr II lines.



- Sr lines are expected to be very strong.
- Heavy elements may be absent in the outer part of the ejecta.

Kilonova Emission depends on the composition

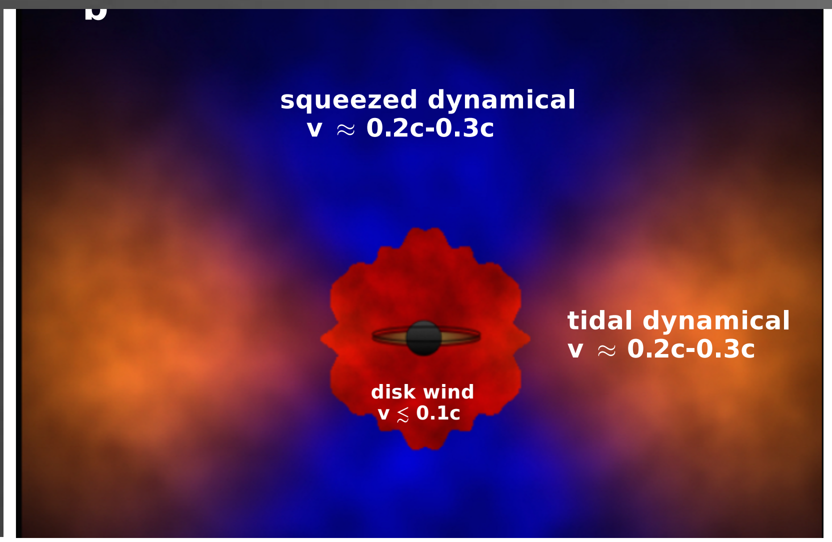


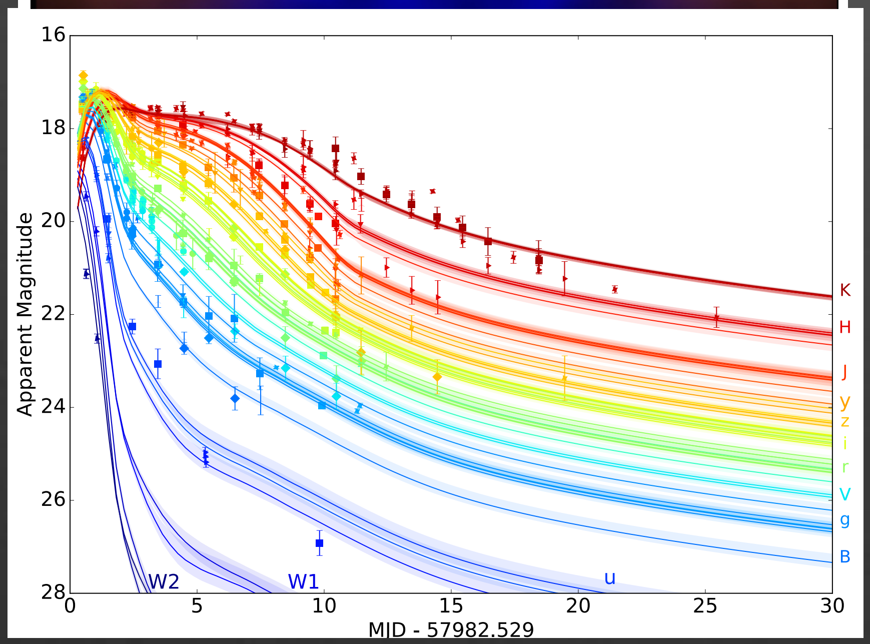
KH, Beniamini, Piran 18, Goriely 99

Proposed Scenarios for the GW170817 kilonvoa

Most of mass: lanthanide-rich

Kasen +17, Villar + 2017
Perego+2017

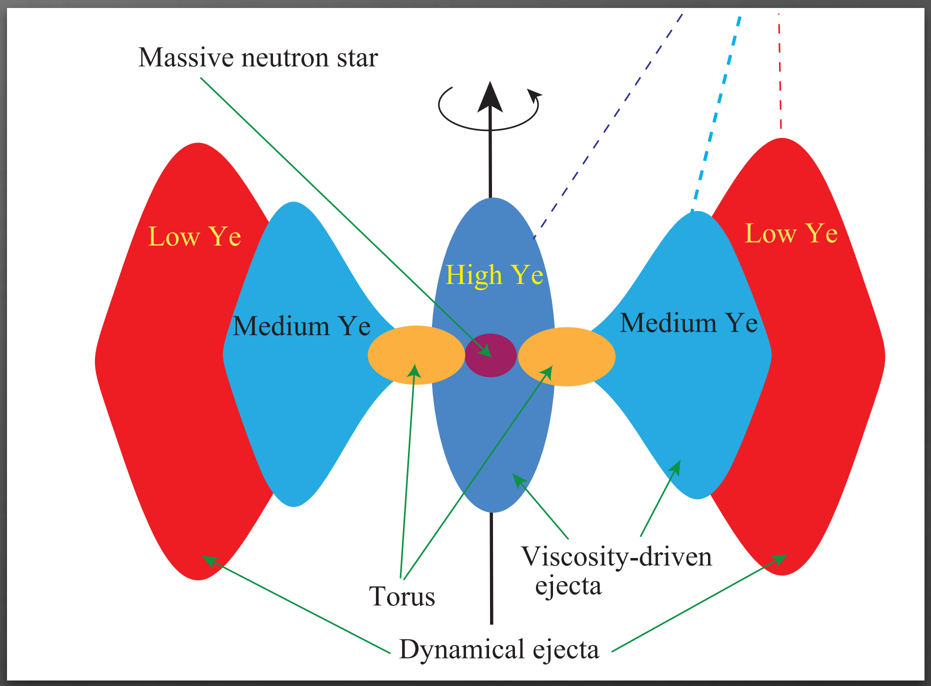


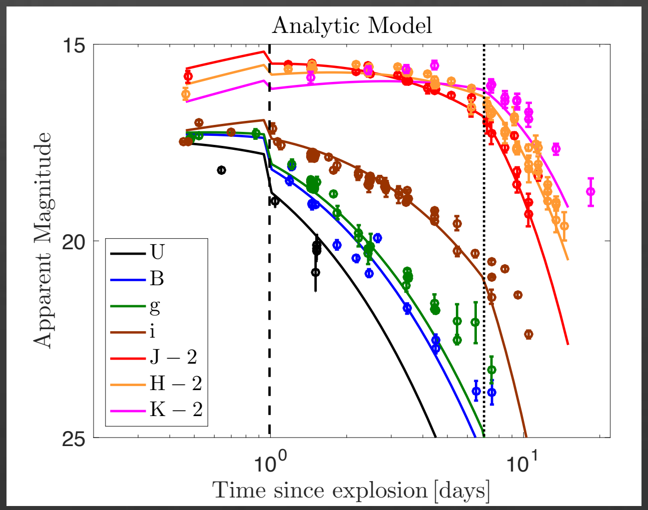


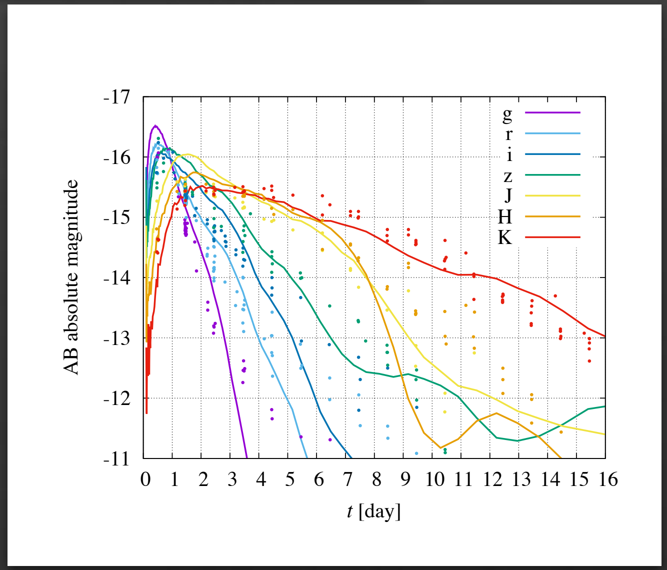
Remnant: short lived NS => BH

lanthanide-less

Waxman + 2017, Shibata..KH+17, Kawaguchi+18

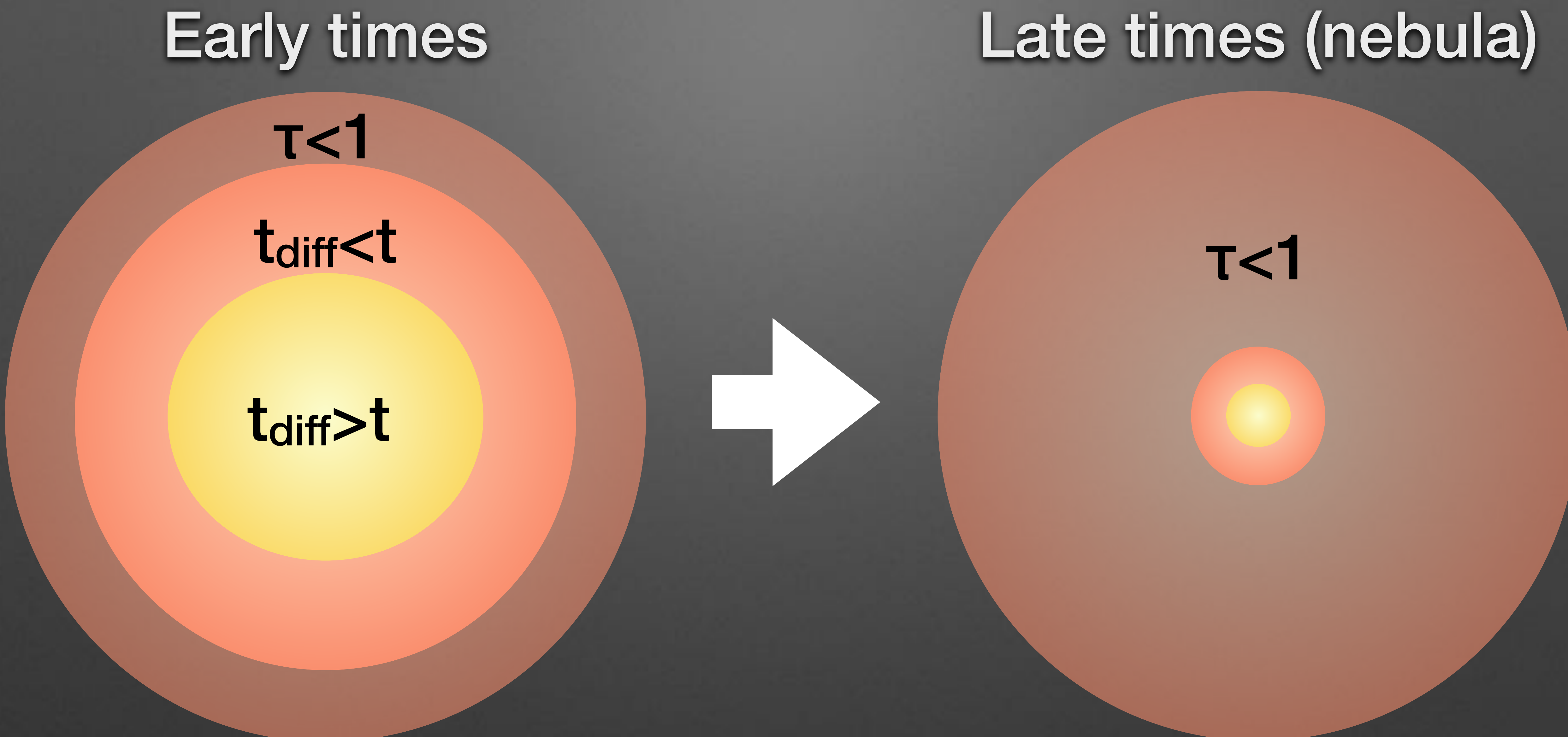






Long lived neutron star (~100 ms)

Kilonova Nebula

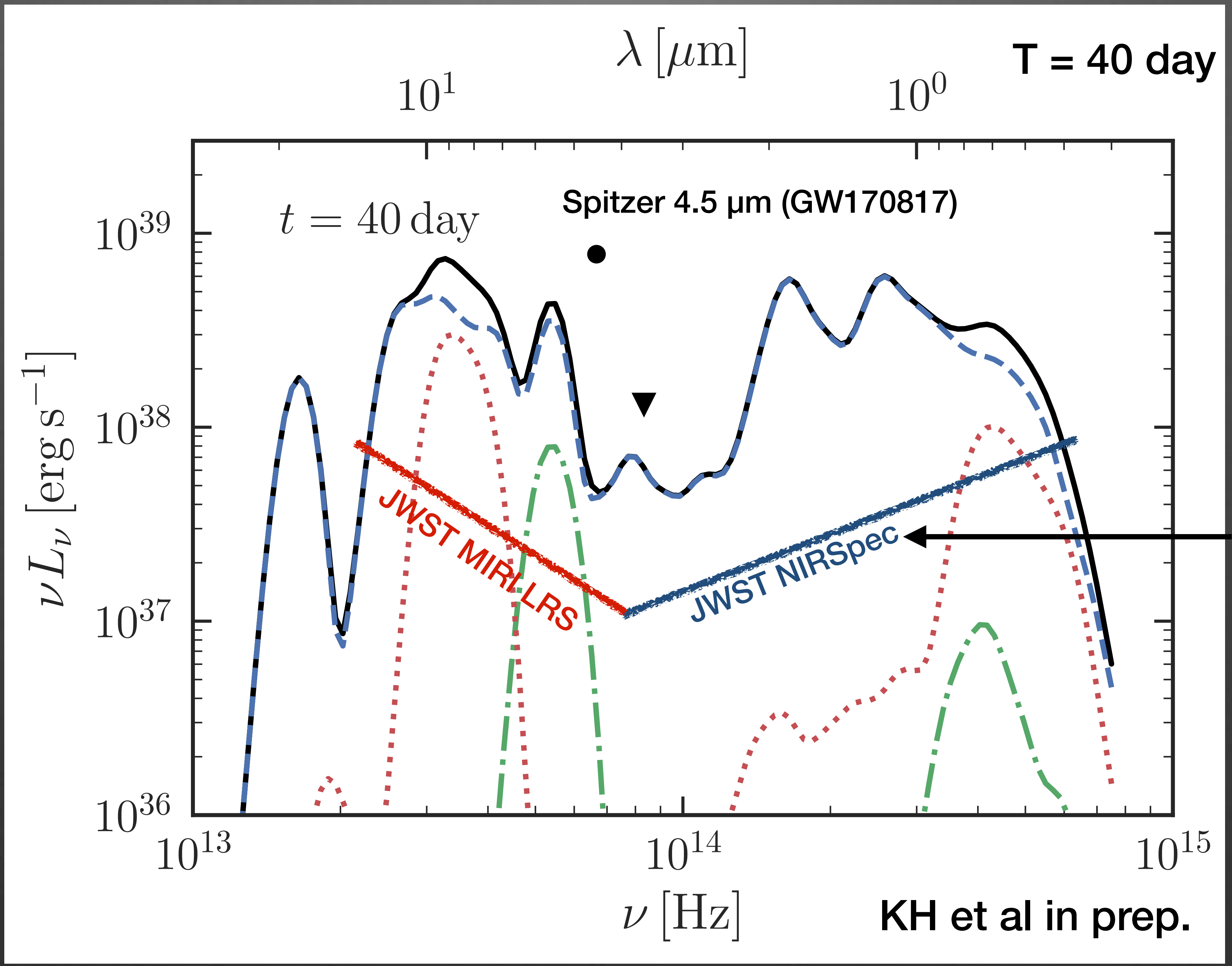


Nebular phase:

- Most of the ejecta can be seen. (inner parts have slower velocities)
- Photon luminosity ~ heating rate
- Photons are emitted directly by radiative de-excitations.

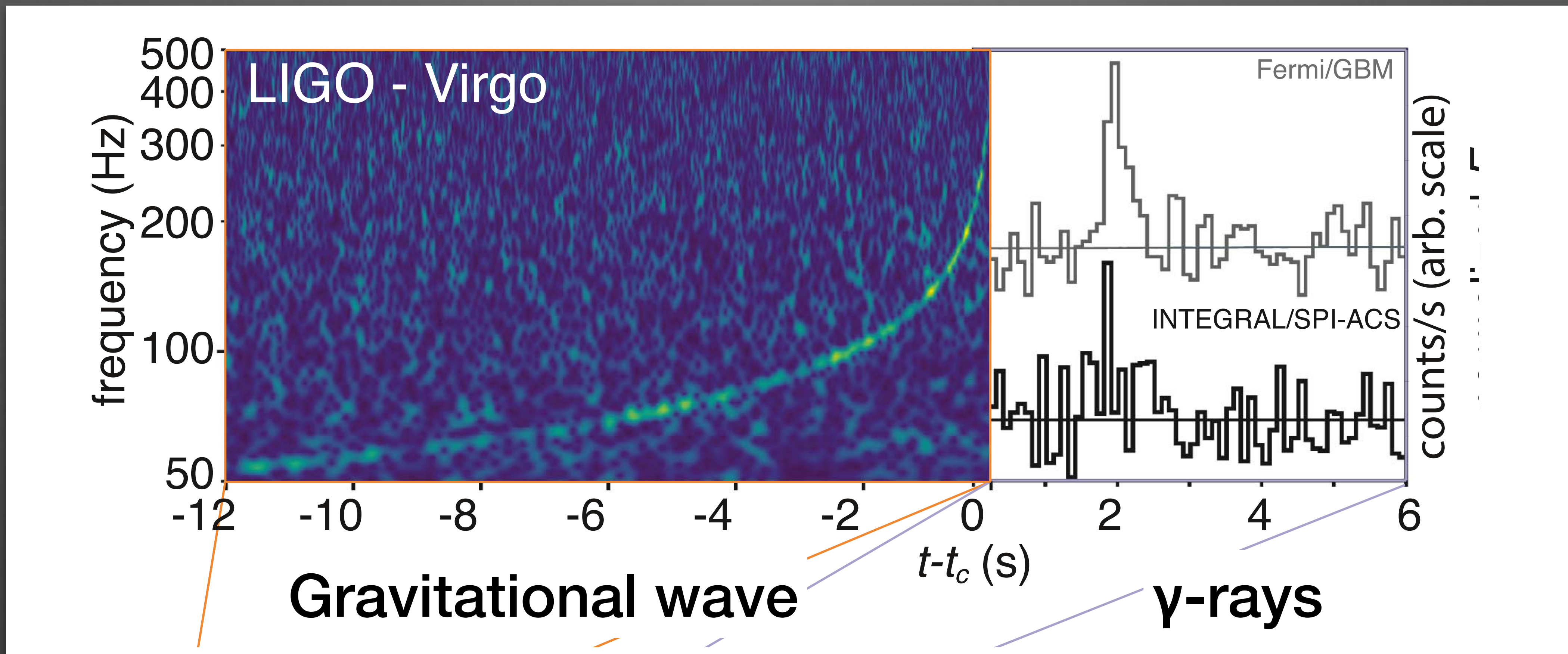
Future Prospects of Kilonova

When the ejecta becomes optically thin, we will see atomic emission lines.



James Webb Space Telescope will be extremely powerful to get kilonova spectra!!

A Gamma-Ray Burst after GW170817



Properties of γ-rays:

Similar to normal GRBs

1) Delay is ~1.7 sec and duration is ~2 sec.
2) Isotropic energy is ~ 10^{47} erg and spectral peak is ~200 keV.

Much less than normal GRBs

3) Off-axis short GRB => spectral peak < 10 keV

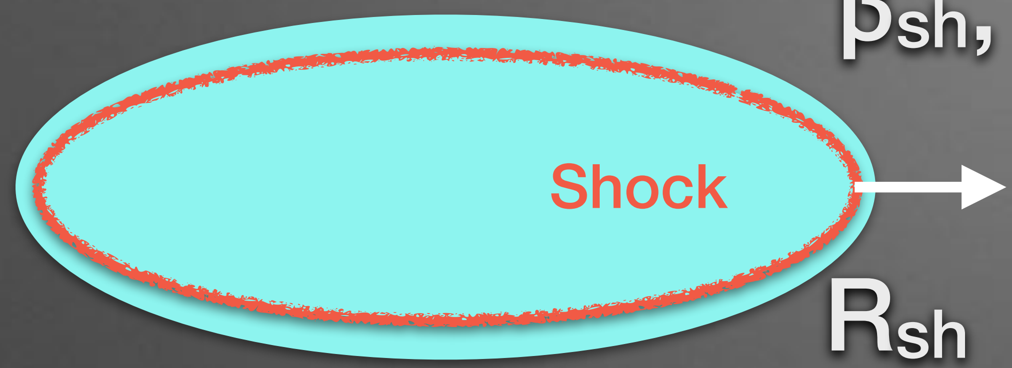
(e.g. Matsumoto+18)

On-axis mildly relativistic outflow

Kasliwal…KH+17, Gottlieb, Nakar, Piran, KH 17
Also Beloborodov + 19

Explosion (merger) at t=0

β_{sh}, $\Gamma_{sh}=(1-\beta_{sh}^2)^{-1/2}$



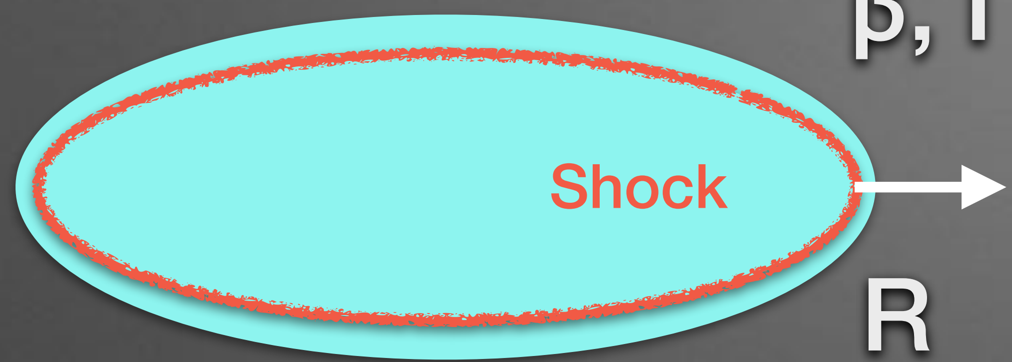
1. Duration: $T_{obs} \sim R_{sh}/2\Gamma_{sh}^2 c \sim 1$ sec. (observed)
2. γ-ray energy: $E \sim \Gamma_{sh} Mc^2 \sim 10^{47}$ erg (observed)
3. Optical depth: $\tau = \kappa M/4\pi R_{sh}^2 \sim 1$ (required)

On-axis mildly relativistic outflow

Kasliwal…KH+17, Gottlieb, Nakar, Piran, KH 17
Also Beloborodov + 19

Explosion (merger) at t=0

β, $\Gamma=(1-\beta^2)^{-1/2}$



1. Duration: $T_{obs} \sim R_{sh}/2\Gamma_{sh}^2 c \sim 1$ sec. (observed)

2. γ-ray energy: $E \sim \Gamma_{sh} Mc^2 \sim 10^{47}$ erg (observed)

3. Optical depth: $\tau = \kappa M/4\pi R_{sh}^2 \sim 1$ (required)

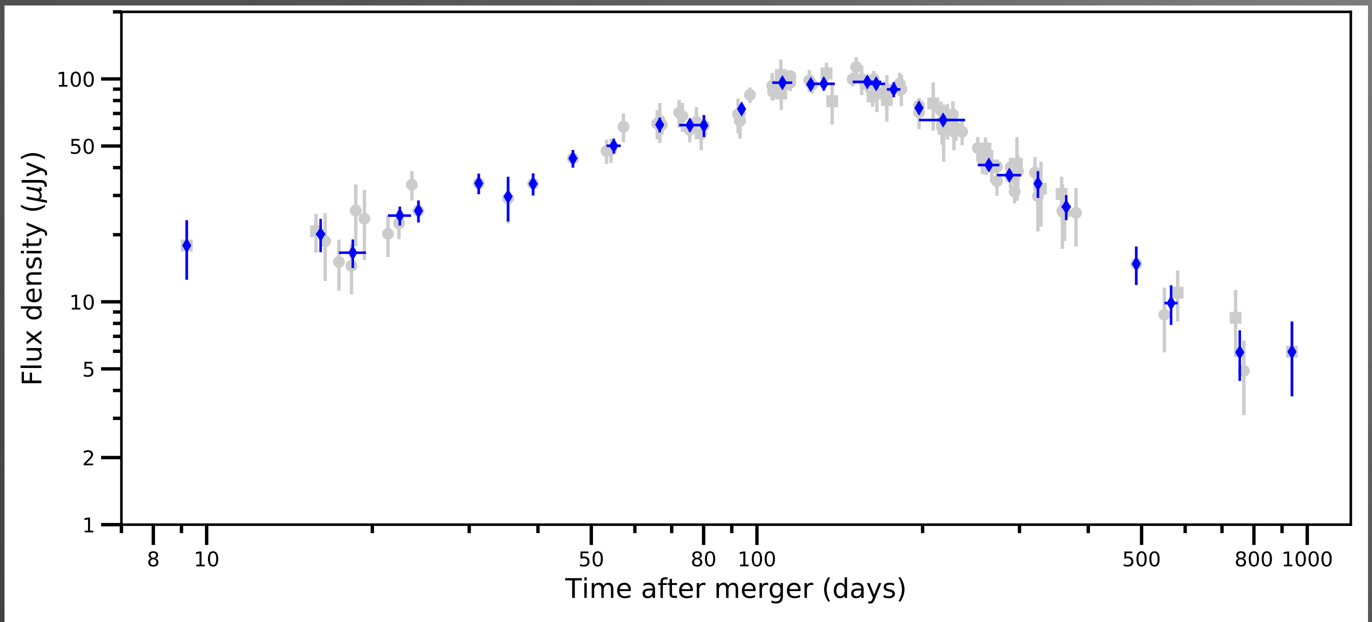
=> $R_{sh} \sim 10^{11}$-10^{12} cm, $\Gamma_{sh} \sim 3$-5, $M \sim 10^{-8}$-10^{-7} M_{sun}

Time delay: $\delta T = (1-\beta_{ej})R_{sh}/c \sim 1$ sec => $\beta_{ej} \sim 0.7 - 0.8$

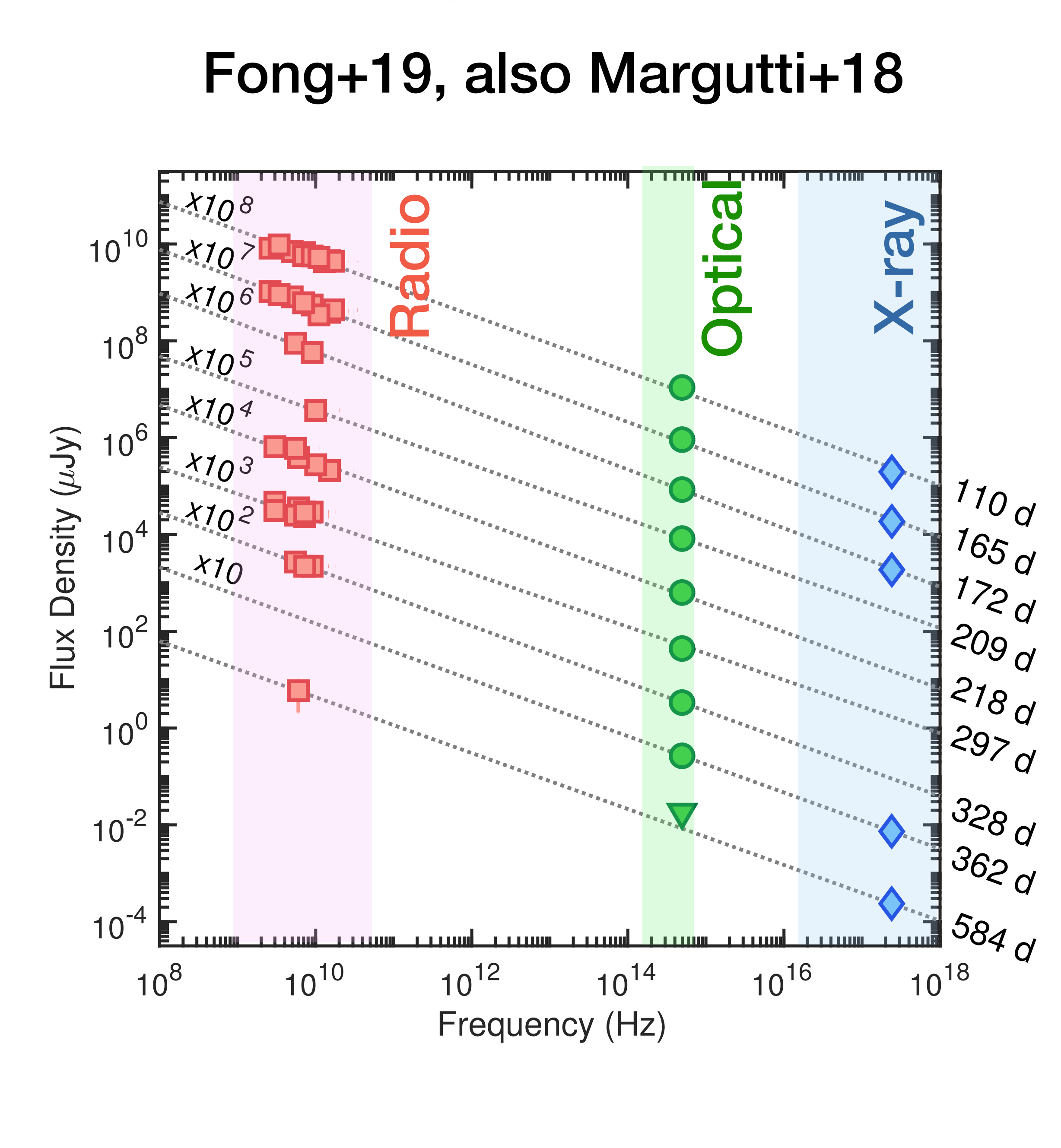
Merger simulations show a fast ejecta tail with ~0.8c and $10^{-7} M_{sun}$ (Kiuchi+17, KH+18)
But also see Ioka & Nakamura 2018 for off-axis jet considerations.

Late-time Afterglow across multi-wavelength

Light curve (Makhathini+2020)



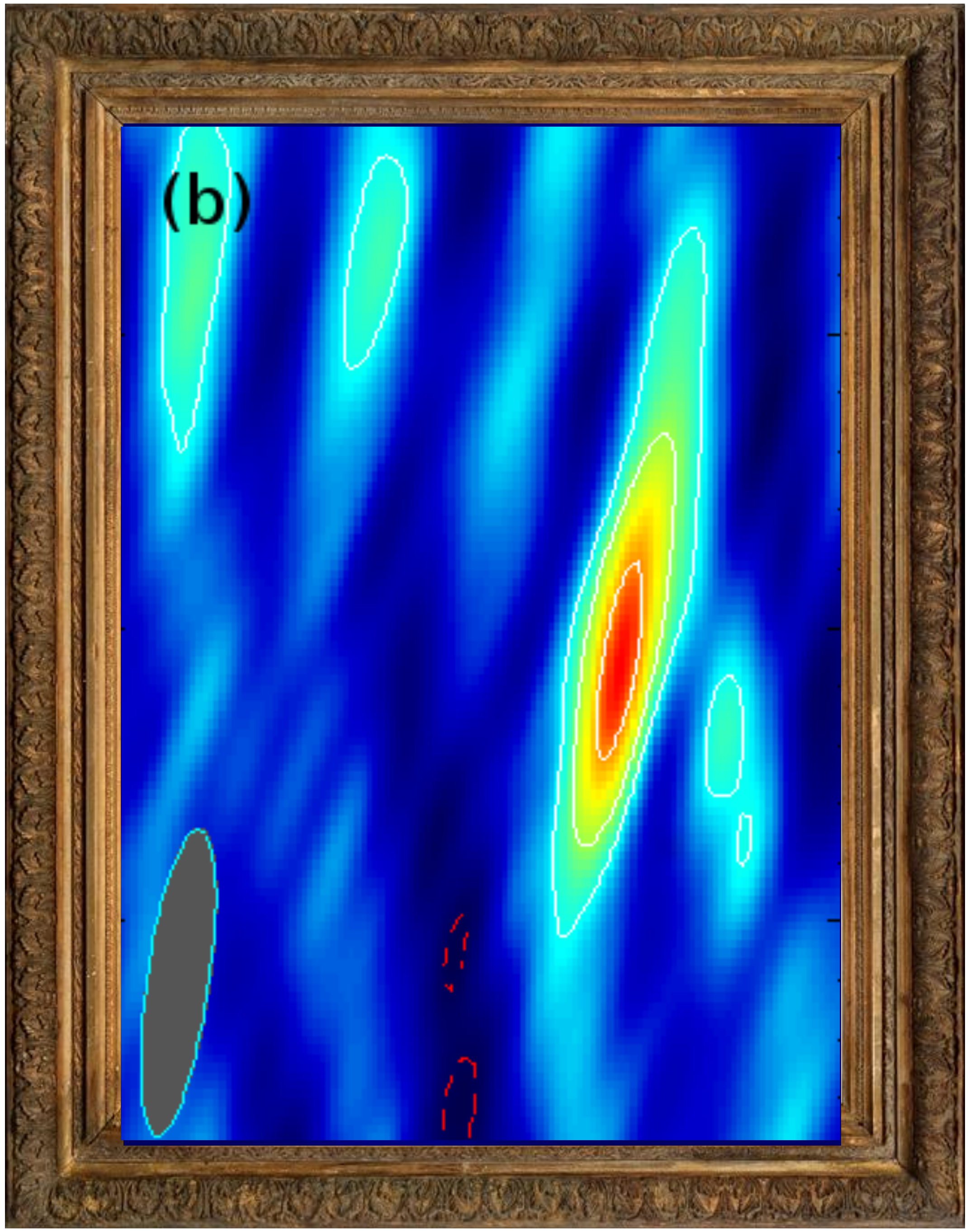
Spectrum

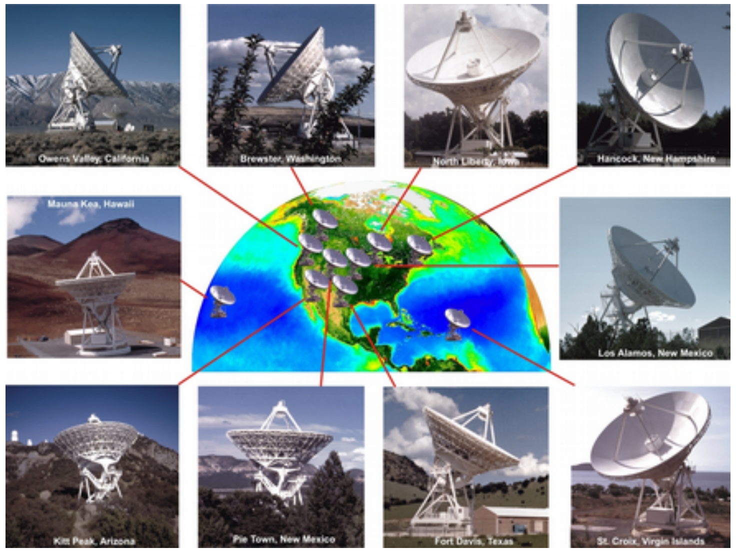


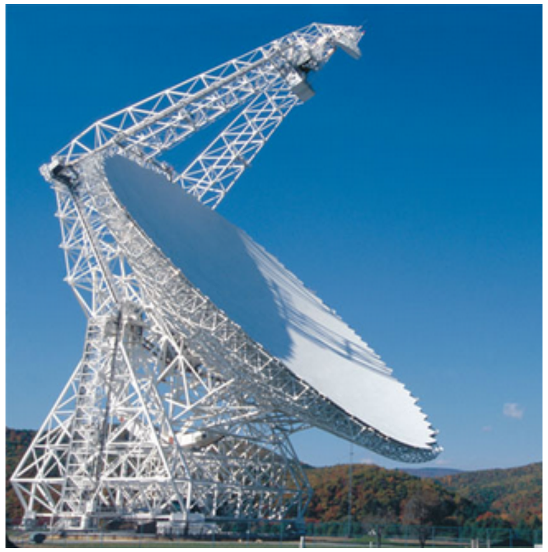
- The light curve rises and declines, which looks like an off-axis emission.
- The spectrum is a beautiful single power law, suggesting synchrotron emission.

Hallinan+17, Margutti+17,18, Troja+17,19, Haggard+17, Ruan+17,Lyman+18,Mooley+18

Imaging the afterglow with VLBI



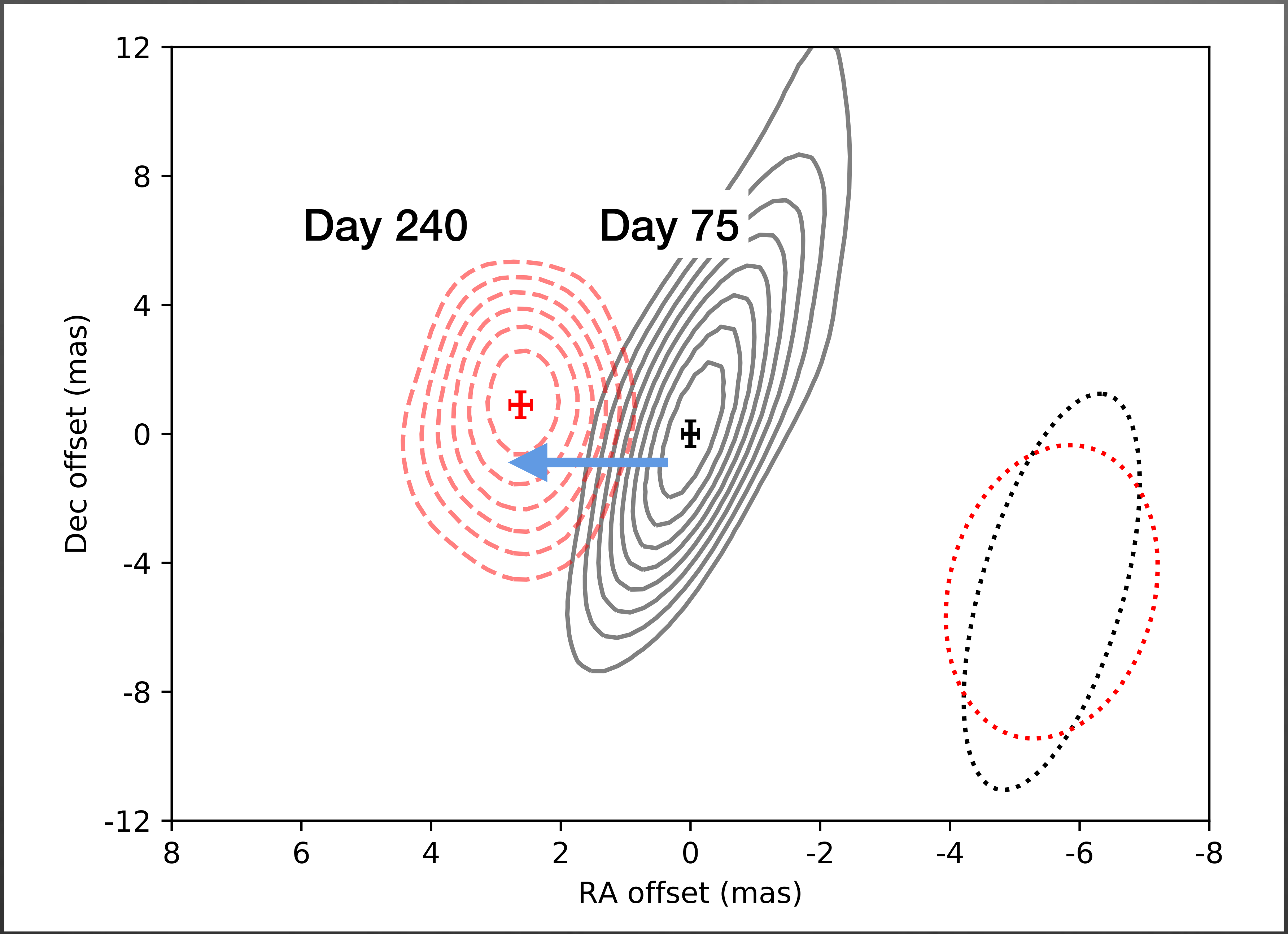




Two observations with the HSA
(75 d and 230 d post-merger)

Superluminal Jet in GW170817

VLBI resolve the motion of the radio source Mooley…KH (2018)



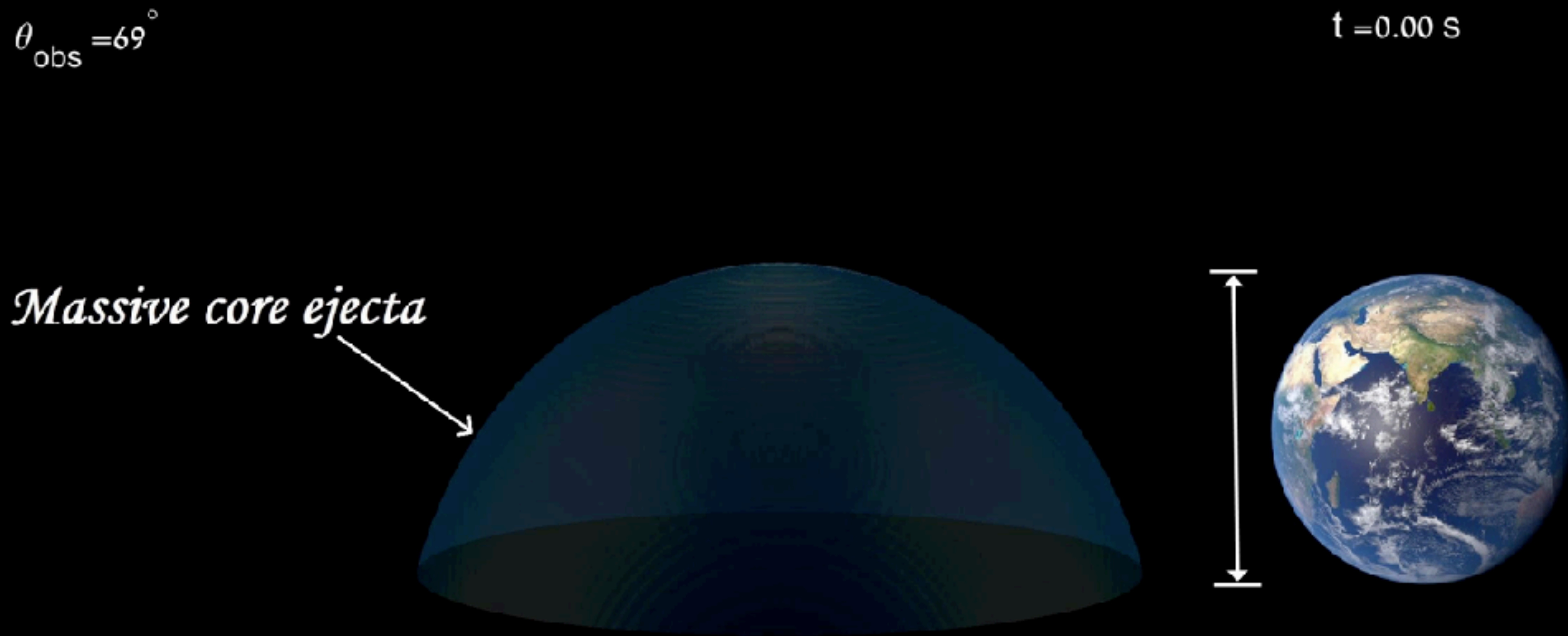
1, The source moved 2.7 mas in 155 day.

=> 2.7 mas ~ 0.5 pc (at 40Mpc)

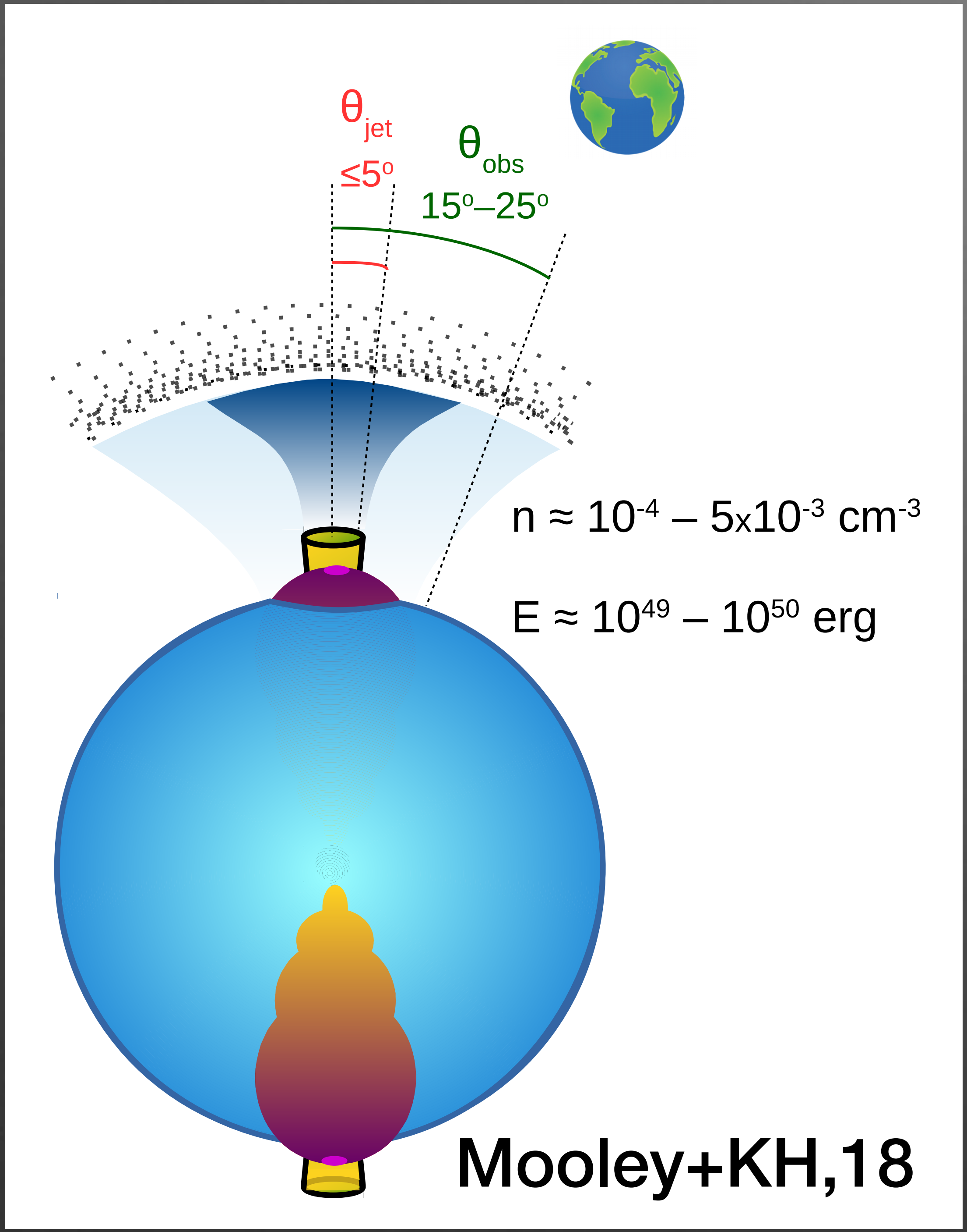
$$\beta_{\rm app} = 4.1 \pm 0.4$$

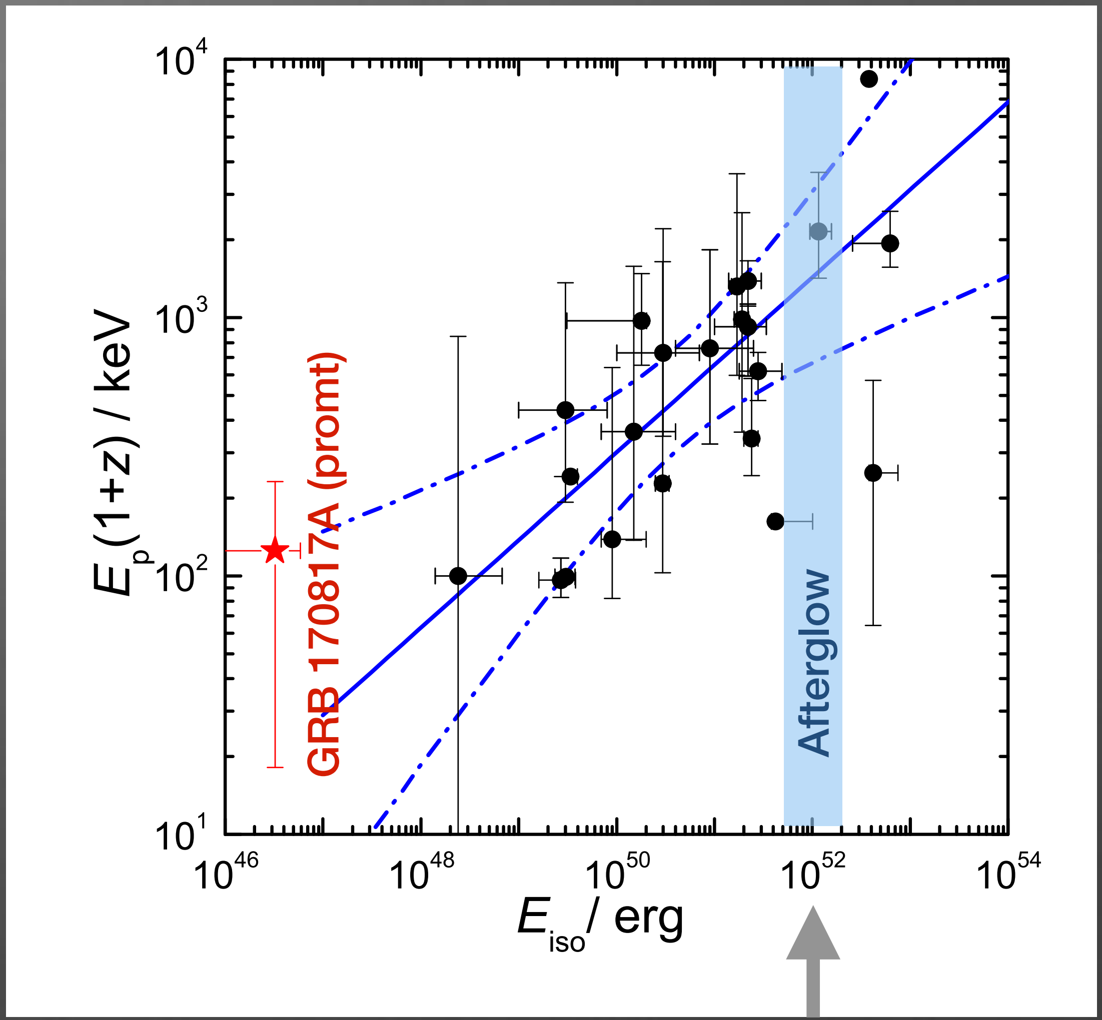
2, The source size is unresolved.
=> the emission region does not extend much.

- Very strong evidence for a jet in GW170817
- First time to see a superluminal motion of a “GRB” jet.


$\theta_{obs} = 69^\circ$
t =0.00 s
Massive core ejecta

Jet Parameters

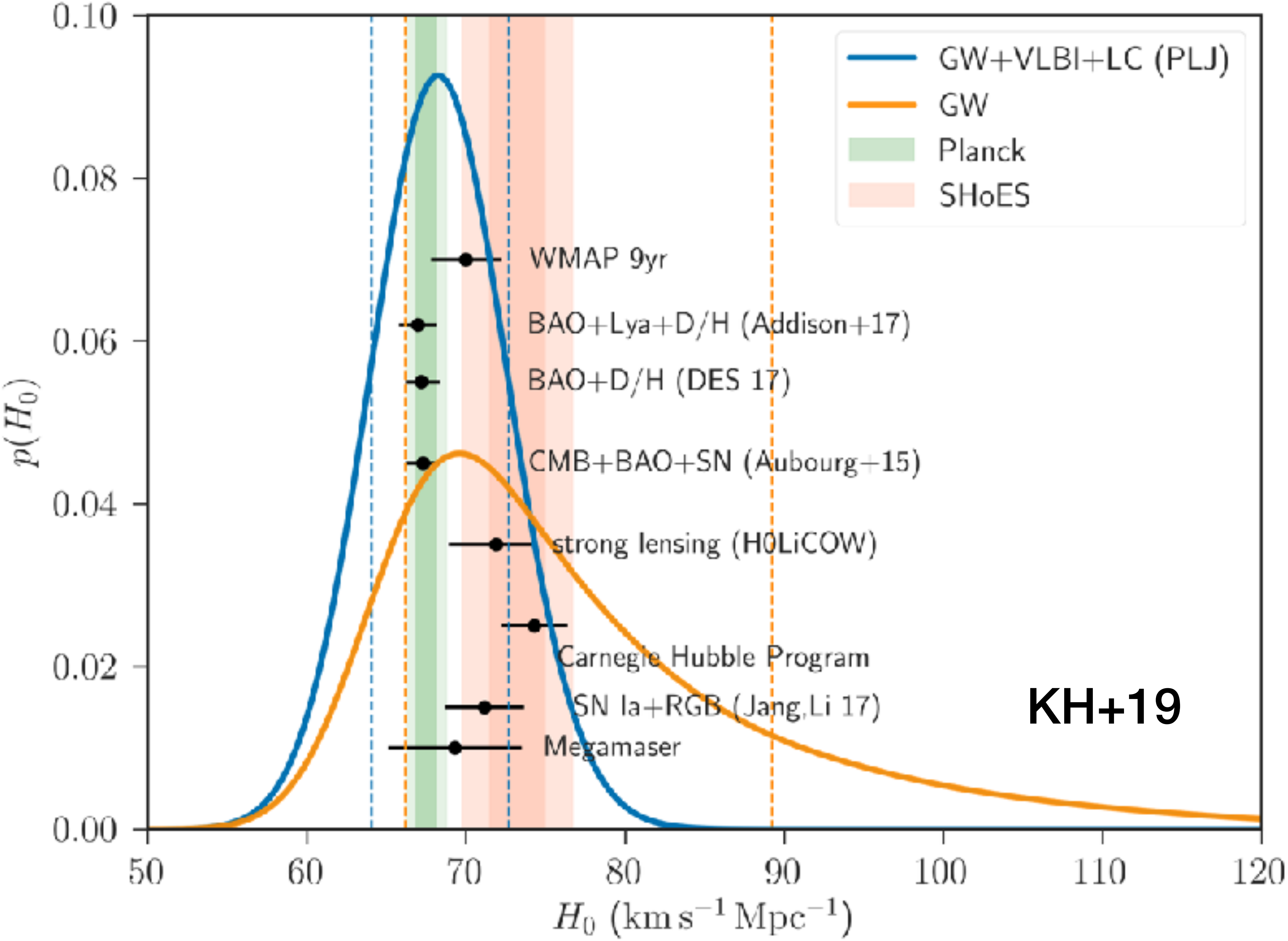




$E_{K,iso}$ inferred from VLBI
High end of E_{iso} of short GRBs

- We would have seen a strong GRB if we were on-axis.
- I'll talk about implications of these to CTA science in a meeting next week.

GW + light curve + VLBI => H0



$68.1^{+4.5}_{-4.3}$ km/s/Mpc

3-4% of a systematic uncertainty due to jet modeling

Outline

- A comment on Binary Black Holes: an astrophysical implication from new LIGO/Virgo catalogue (GWTC-2)
- Binary Neutron Star: what we have learned from multi-messenger observations of GW170817
- High energy (~100 MeV) neutrinos from core collapse supernovae and prospects with HyperKamiokande.

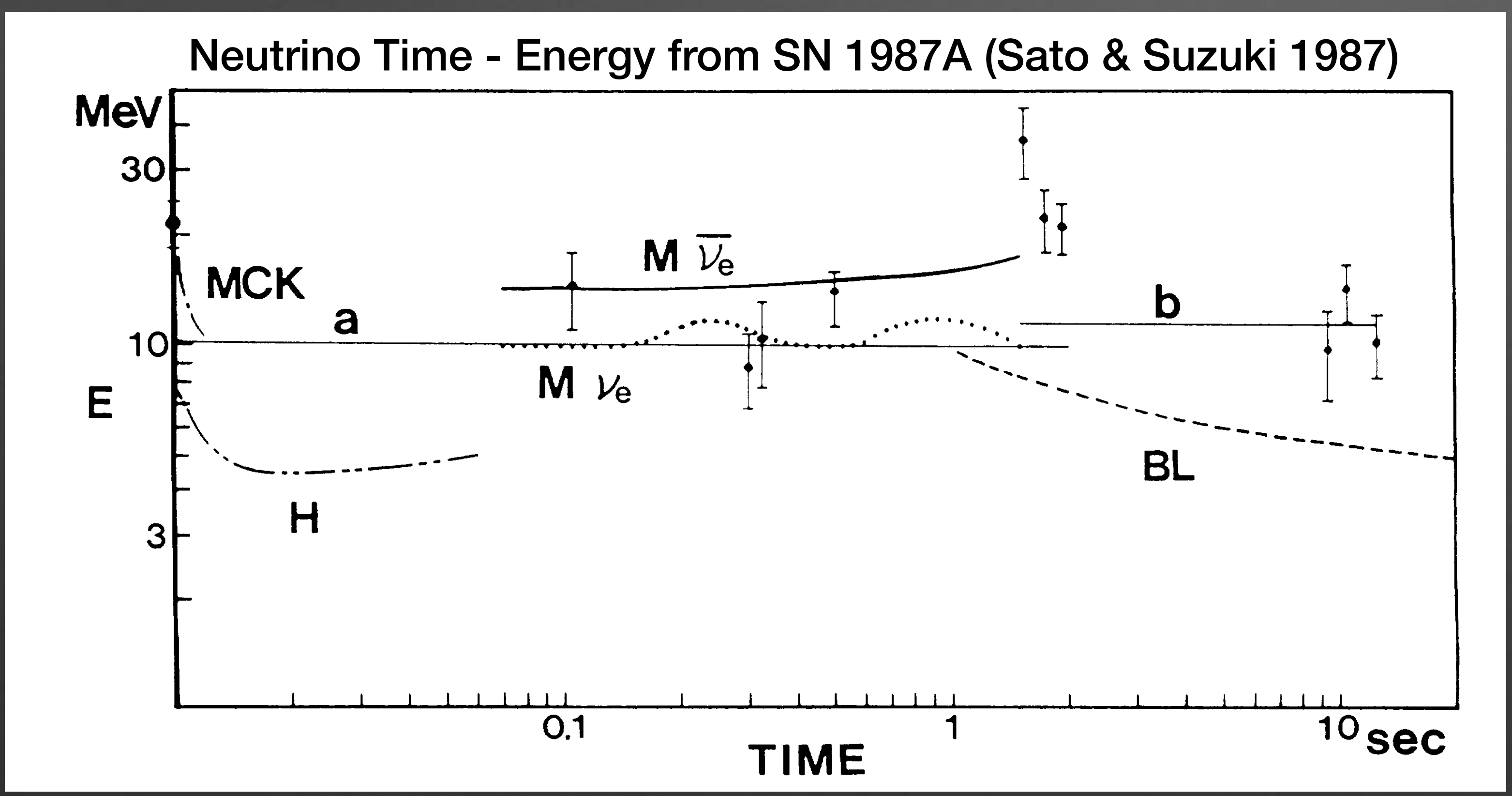
Looking forward to a Galactic supernova

Nagakura & KH 2020

Astrophysicists' dream is to get the ν_e ν_μ ν_τ spectra from a supernova.

(their antiparticles as well)

But it is widely accepted that obtaining ν_μ ν_τ and their anti-ν spectra from a supernova is very hard because they do not have enough energy to induce charged current interactions.



Kamiokande II & LMC

~ 10 neutrinos for 2 kt & 50 kpc

Hyper-Kamiokande & Galactic

~ 10^5 neutrinos for 200 kt & 5 kpc

A question: Is this true even if we have 10^5 ν_e type neutrinos?

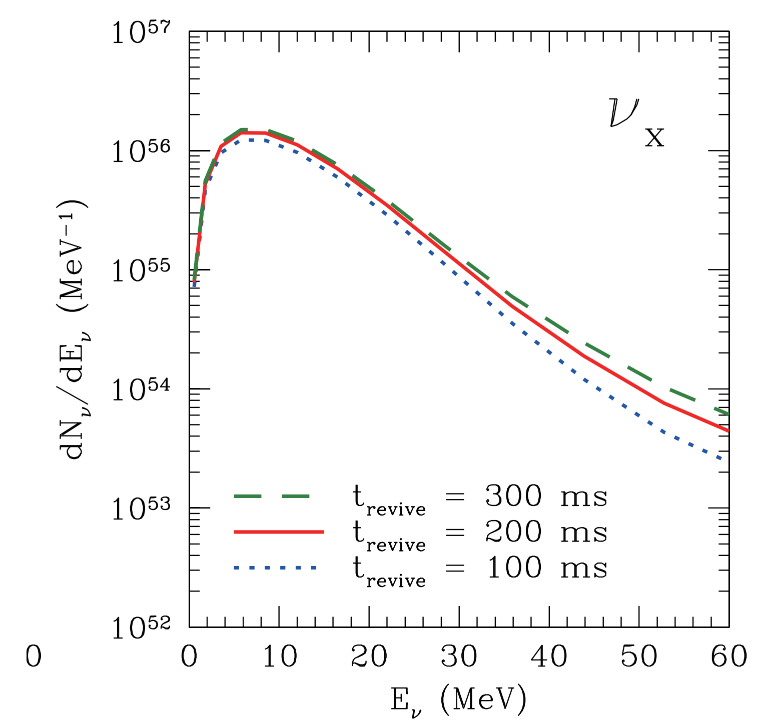
Looking forward to a Galactic supernova

Nagakura & KH 2020

Supernova ν_μ ν_τ and their anti-ν do not have enough energy to induce charged current interactions. Is this really true?

They need to be ν_μ with E>100MeV and ν_τ with E> 2GeV

Nakazato + 15



Supernova ν_μ ν_τ have quasi-thermal spectra with T ~ 5MeV.

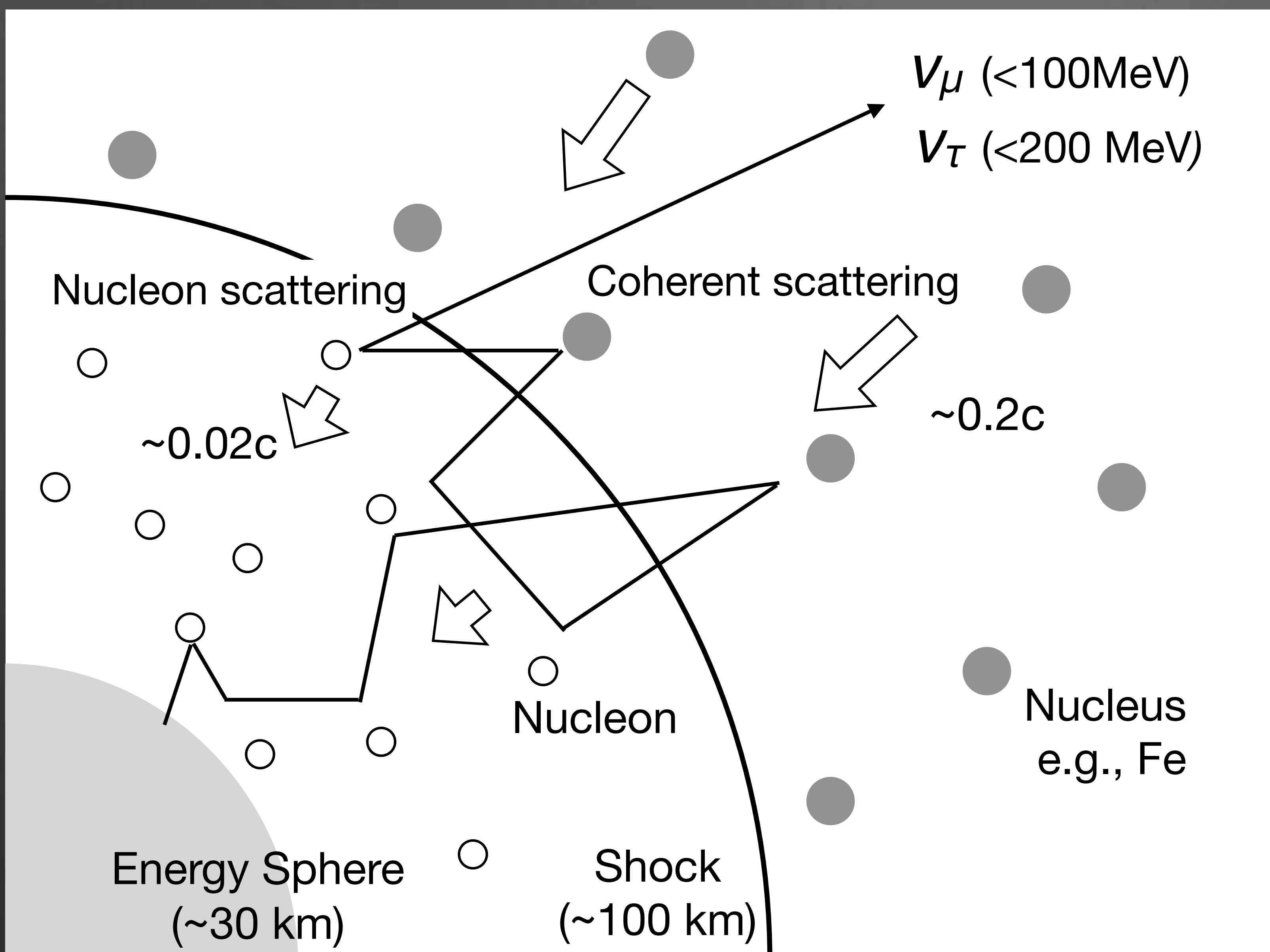
- ν_τ is impossible to induce CC interactions.
- ν_μ also seems to be impossible with a quasi-thermal spectrum.

Now the question we ask is "Are ν_μ and ν_τ always quasi-thermal during core collapse? "

“Non-thermal” ν_x in core collapse

Nagakura & KH 2020

When the supernova shock is ~ 100km, the collisional mean free path of ν_x is O(100km).
In such a situation, some of them cross the shock multiple times and then escape (first order Fermi Acceleration), which has been known since Kanzas & Ellison 81.
=> An observer can see accelerated neutrinos.



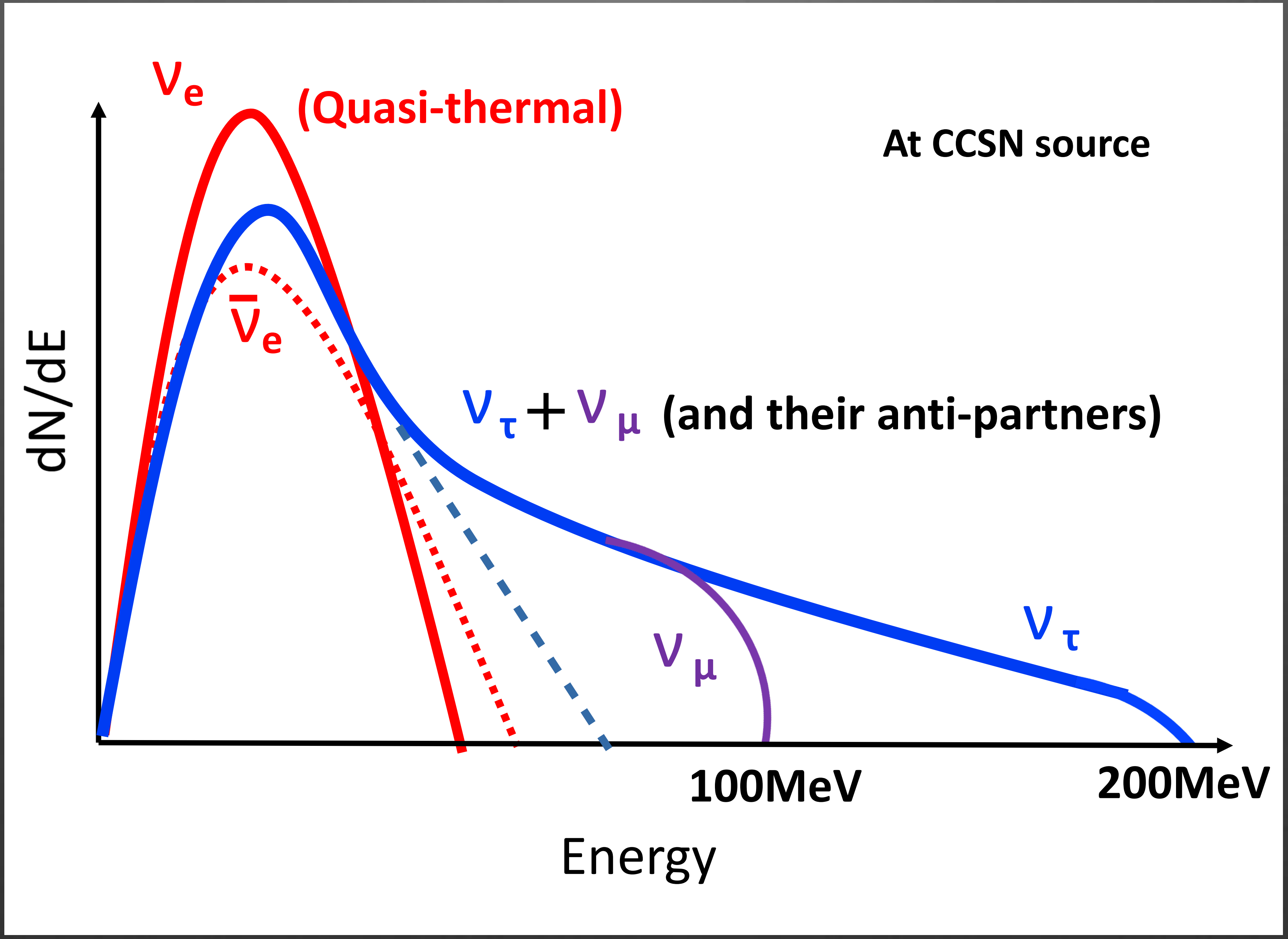
This acceleration occurs as long as the shock’s optical depth ~ 1.

Note that ν_e do not accelerate because CC interactions destroy them.

"Non-thermal" ν_x in core collapse

Nagakura & KH 2020

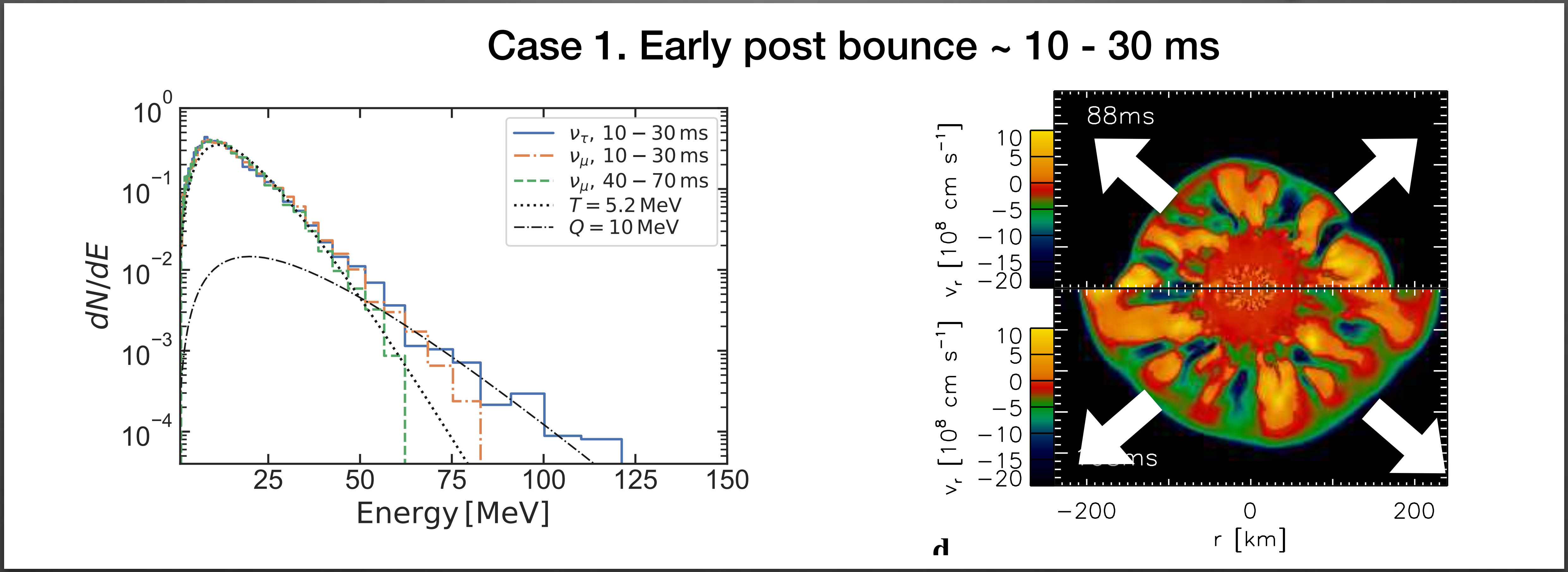
Are ν_μ and ν_τ always quasi-thermal during core collapse? No.



- Mu and tau have a significant non-thermal tail ~ E > 50MeV.
- The degeneracy between mu and tau is broken because CC interactions kick in at 100 MeV.

“Non-thermal” ν_x in core collapse

Nagakura & KH 2020

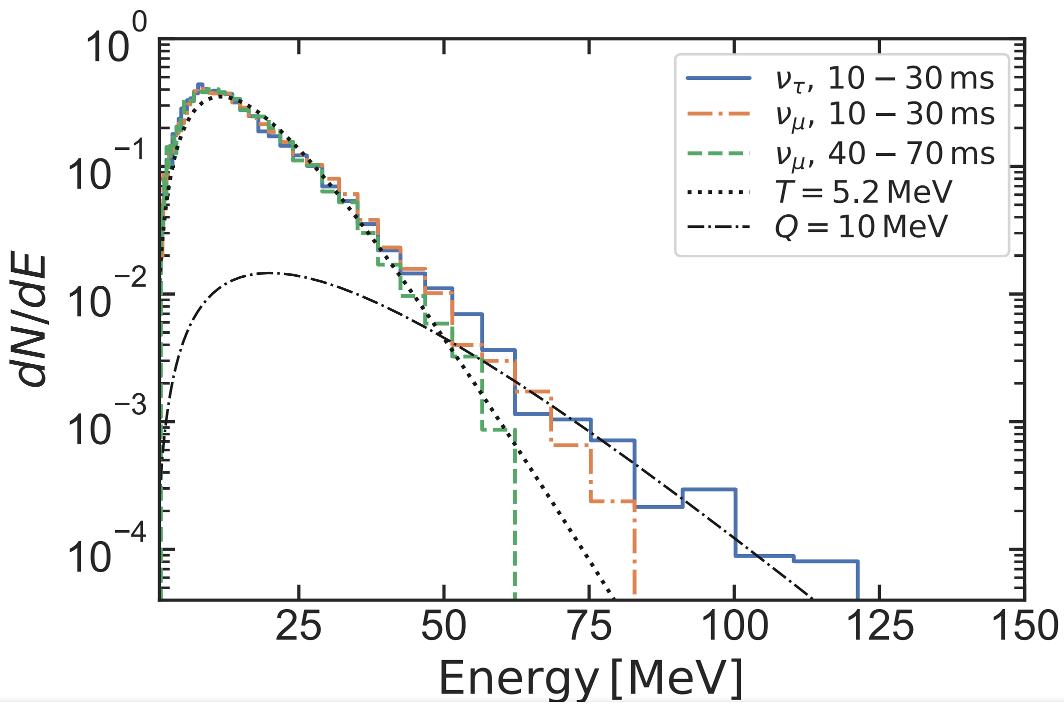


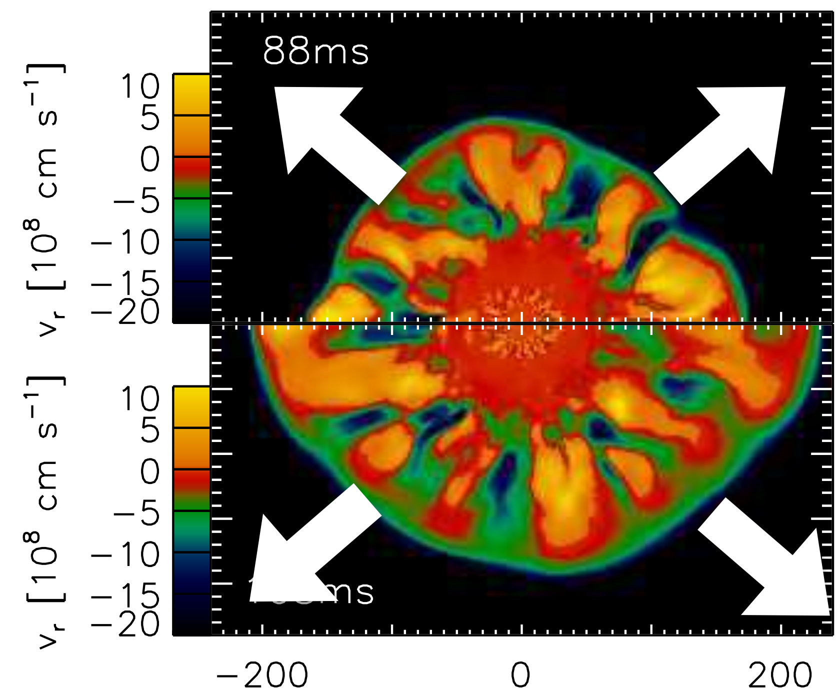
“Non-thermal” ν_x in core collapse

Nagakura & KH 2020

Case 1. Early post bounce ~ 10 - 30 ms

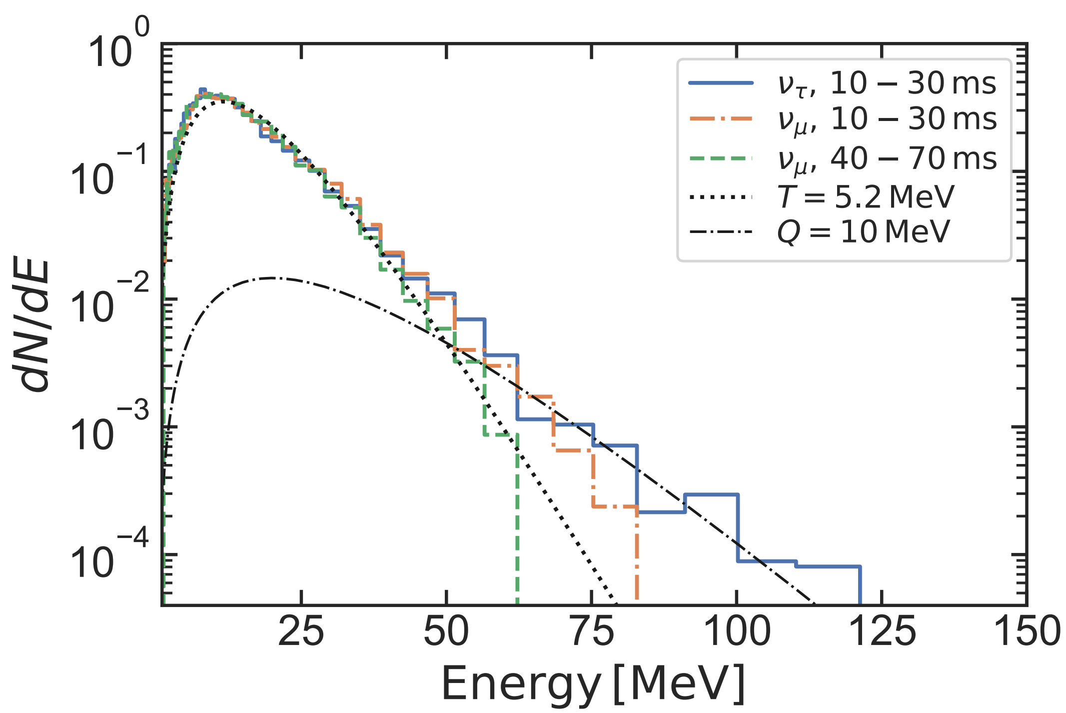
Buras+06

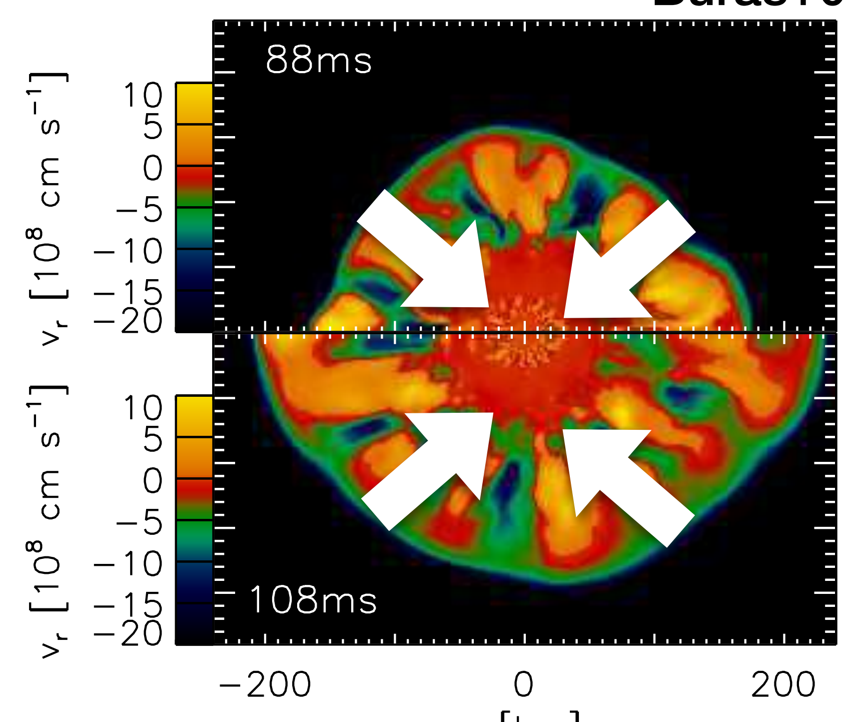




Case 2. Late failed Supernova ~ 100 ms

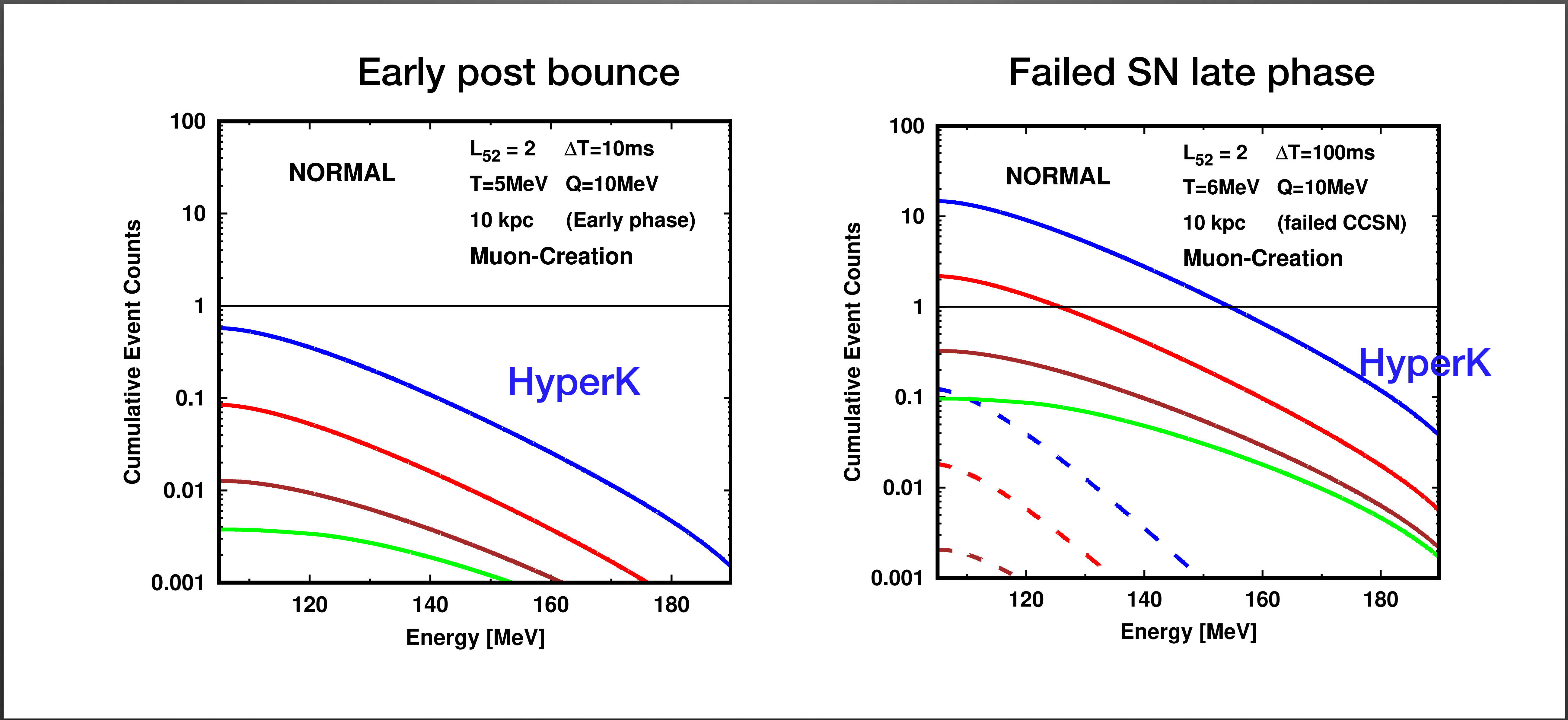
Buras+06





Observability: charged current interactions occur for ν_μ?

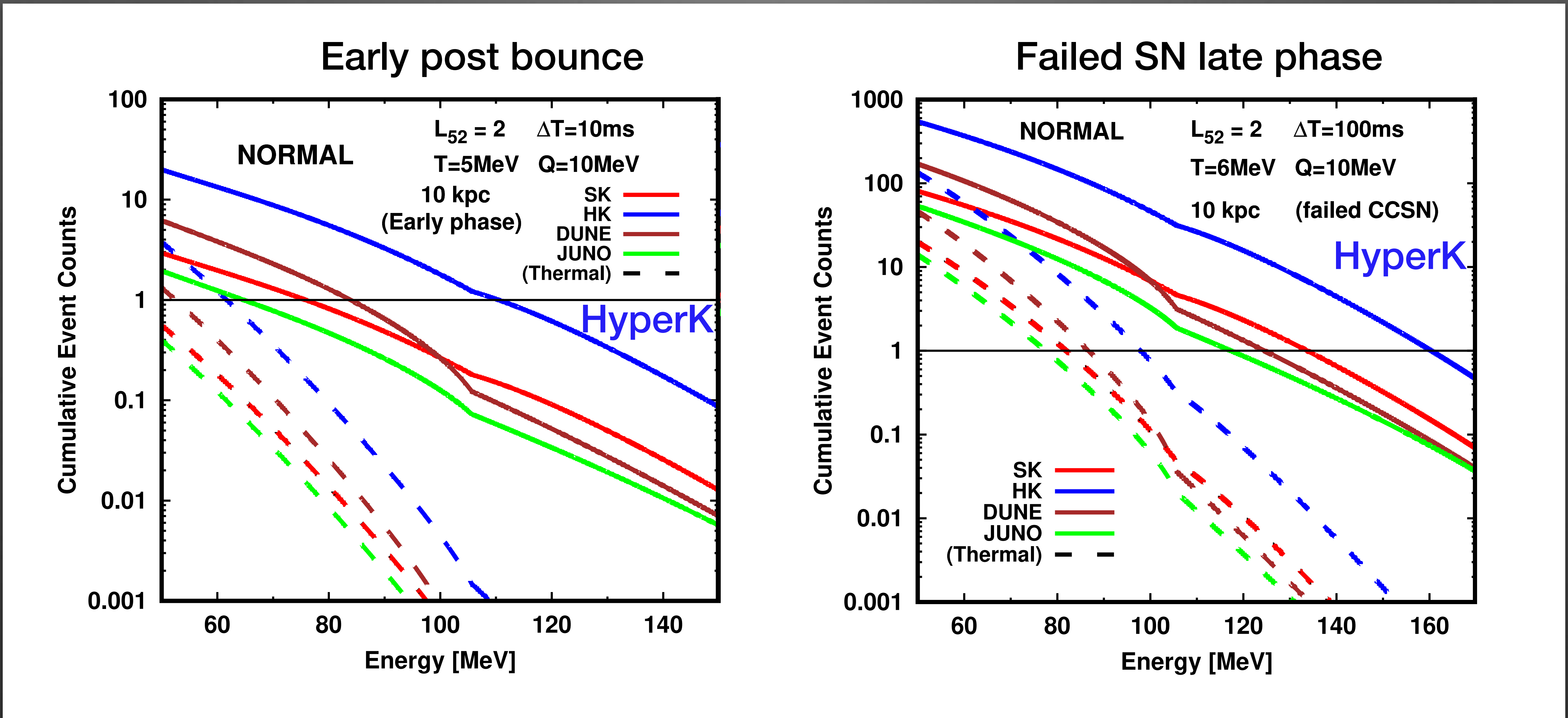
Nagakura & KH 2020



Muon production is not so promising but it can occur.

Observability: ν_e at higher energies

Nagakura & KH 2020



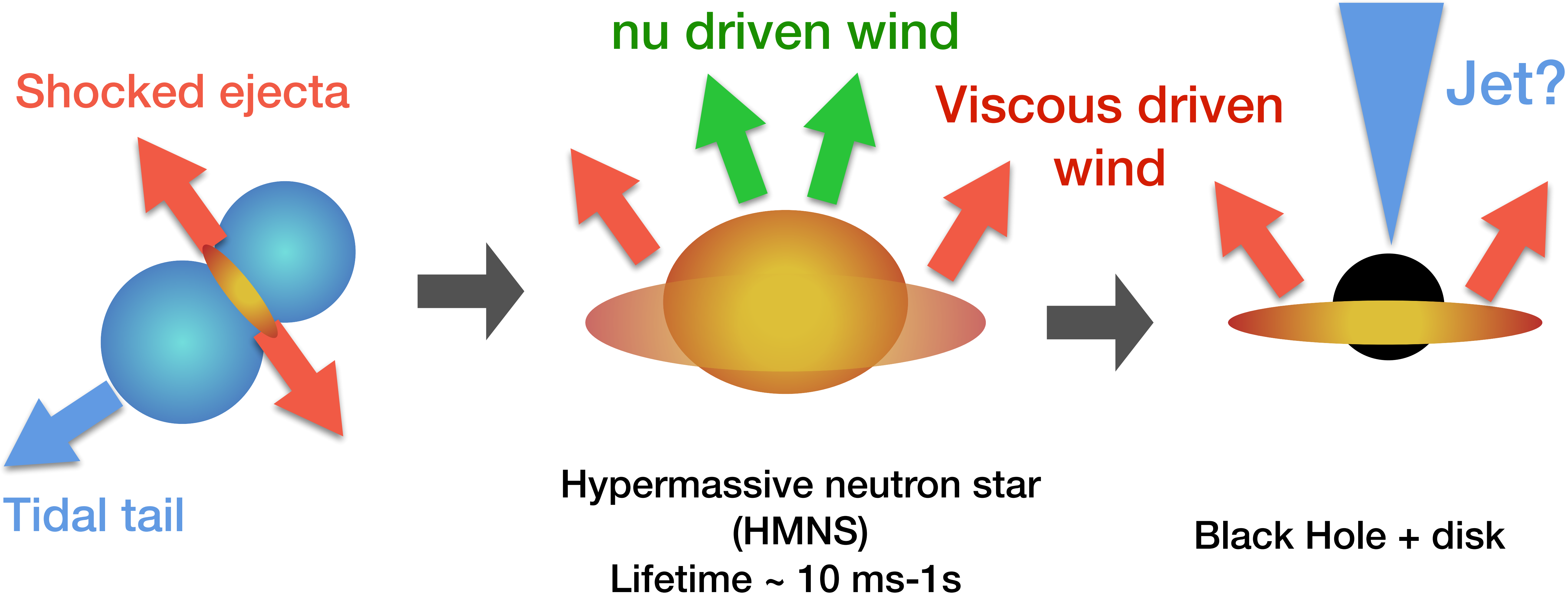
- HyperK will see neutrinos with E>80MeV in the first 50ms.
- This will be a clear signature that the shock is propagating in the scattering atmosphere ~ 100 km.
- These ν_e must originate from ν_x at the source.

Summary

- BBH spin distribution points to that field binaries are their dominant progenitors.
- The BNS merger rate is now just the one expected, ~30/Myr in the Milky Way.
- Kilonovae are optical-nIR emission of neutron star merger ejecta. Its heating rate ~ $t^{-1.3}$ (early) and $t^{-2.8}$ (late).
- The GW170817 light curve agrees with the r-process heating. It requires 0.05 Msun of r-process elements produced in GW170817.
- The estimated rate and mass of r-process elements from GW170817 are consistent with that all r-process elements are produced by mergers.
- GRB 170817A and its afterglow point to this merger launched a relativistic jet.
- The VLBI measurement of the superluminal motion of the jet in GW170817 provides the Lorentz factor, total energy, and viewing angle.
- The VLBI measurement can be used to improve the H0 measurement, ~ 68^{+5}_{-5} km/s/Mpc
- Mu and tau neutrino acceleration in supernovae occurs when the shock propagates in the scattering atmosphere. This produces high energy tail (~100 MeV) in the neutrino spectra and breaks the degeneracy between mu and tau. Hyper-Kamiokande will be very powerful to see these signatures.

Thank you !!!

Picture after GW170817



$M \sim 0.01 M_{sun}$
$v \sim 0.1\text{-}0.3c$

$M \sim 0.05 M_{sun}$
$v \sim 0.05\text{-}0.1c$

Outline

- Introduction
- Neutron Star Merger simulation
- R-process Kilonova
- Afterglow Jet
- Origin of binary black hole mergers