The birth of binary compact objects

Kazumi Kashiyama (Tohoku University / IPMU)

Self introduction

RESEARCH CENTER FOR
THE UNIVERSITY OF T
RESCEU
東北大学 理学部・理学研究科
TOHOKU
UNIVERSITY
HE PHYSICS AND
F THE UNIVERSE
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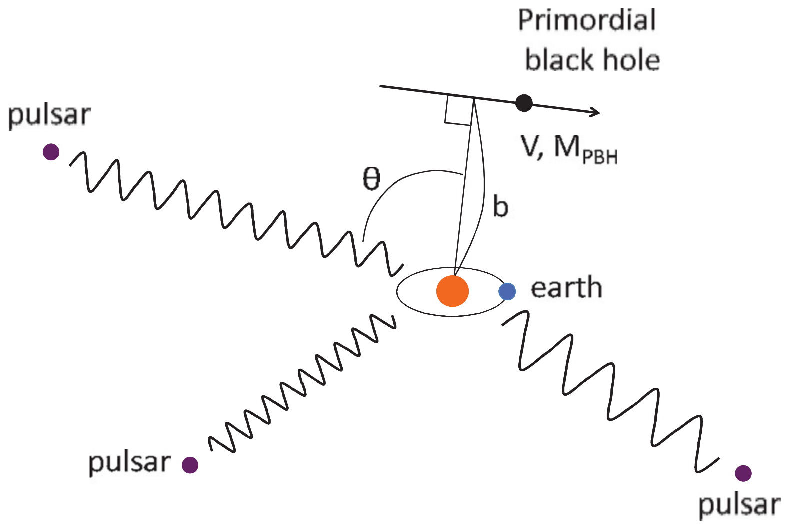

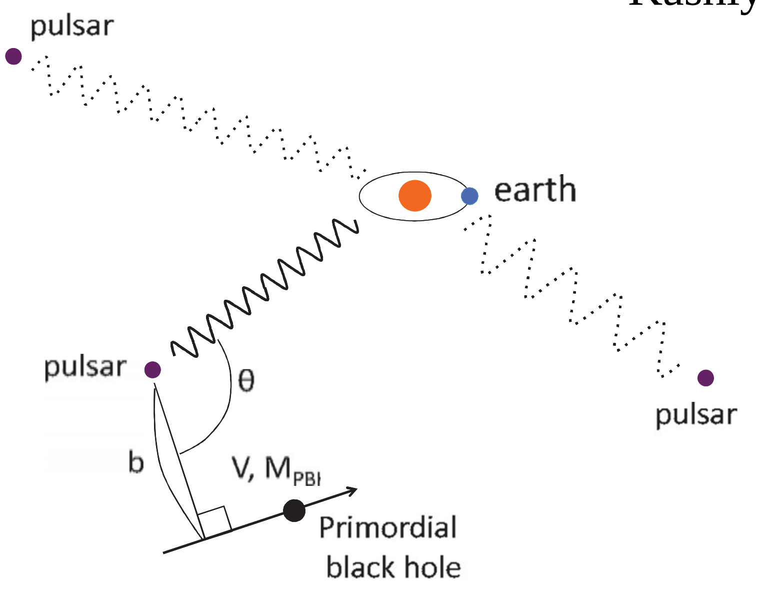

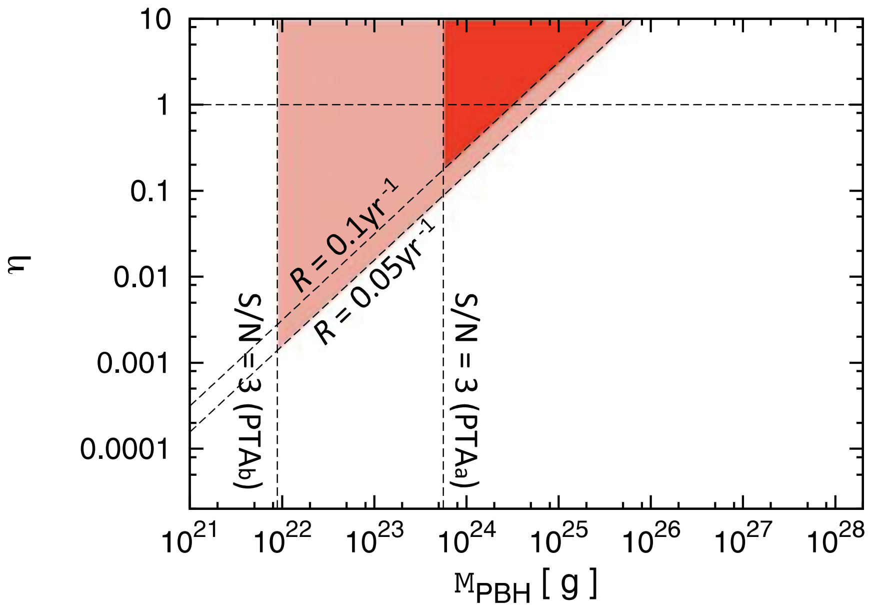

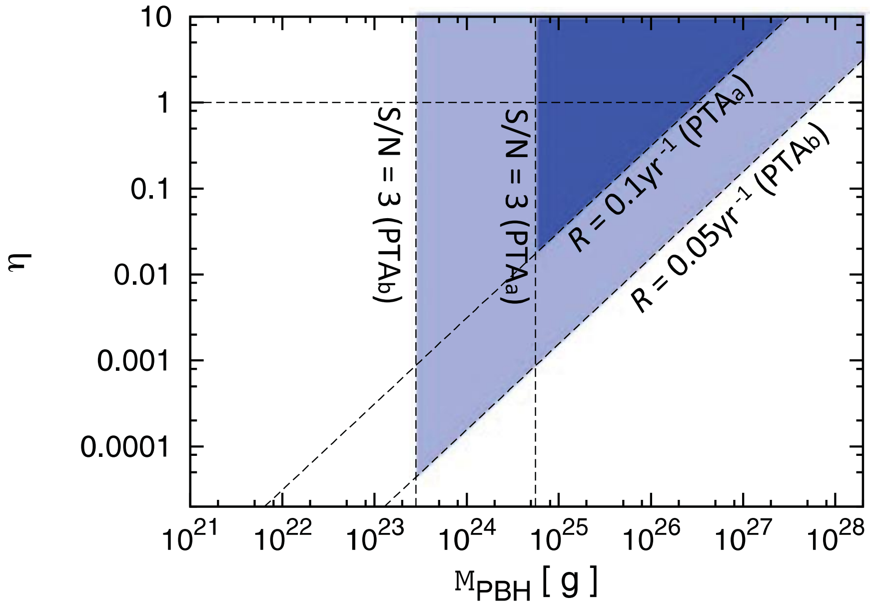

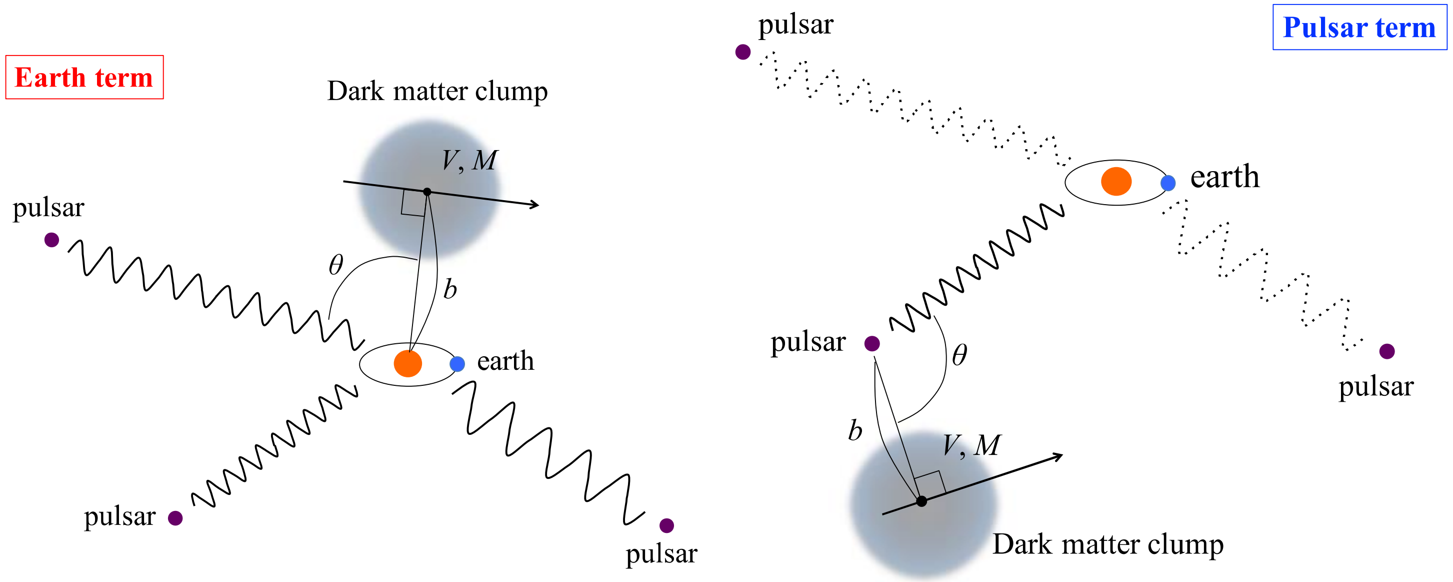

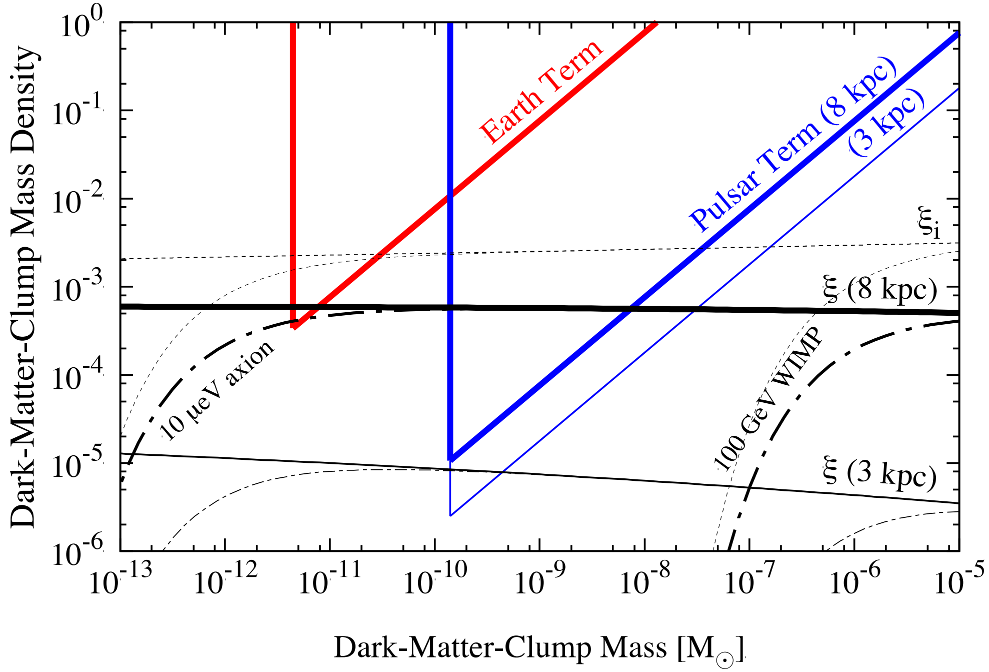

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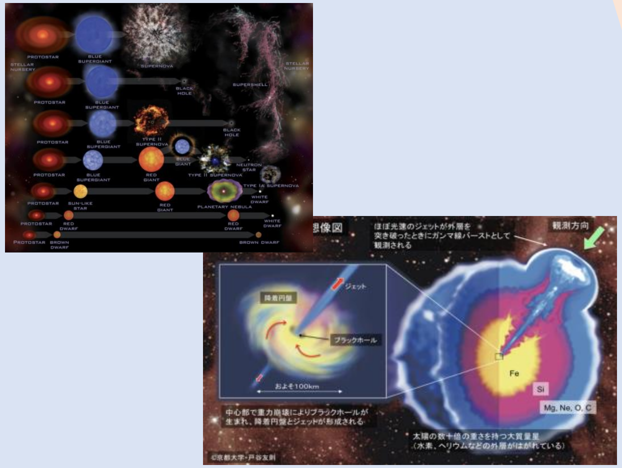
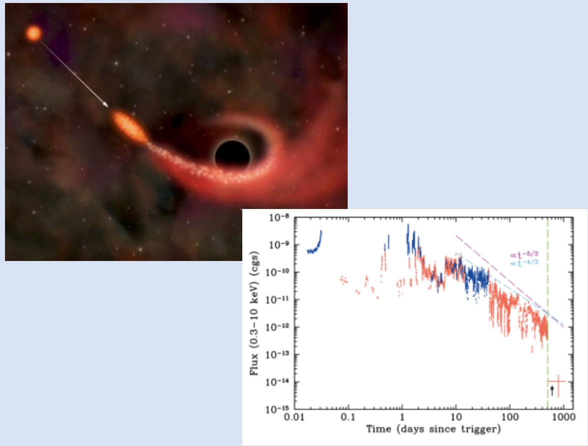
Multi-Messenger Time-Domain Astronomy

Explosive Death of Massive stars

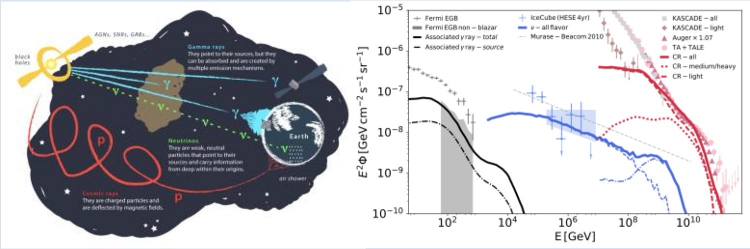


Compact Star Binary Mergers

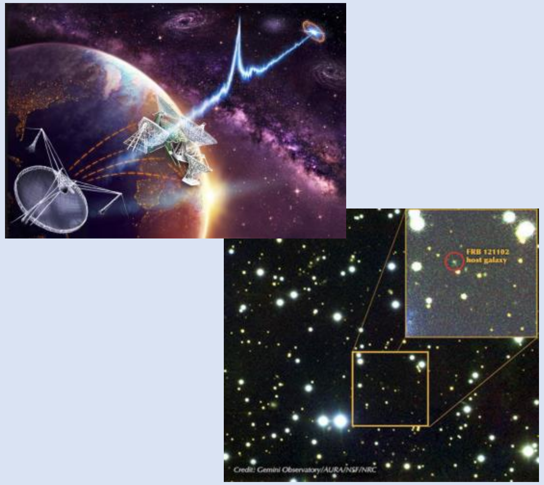
Growth of Supermassive Black hole



Origins of Cosmic Rays and Neutrinos



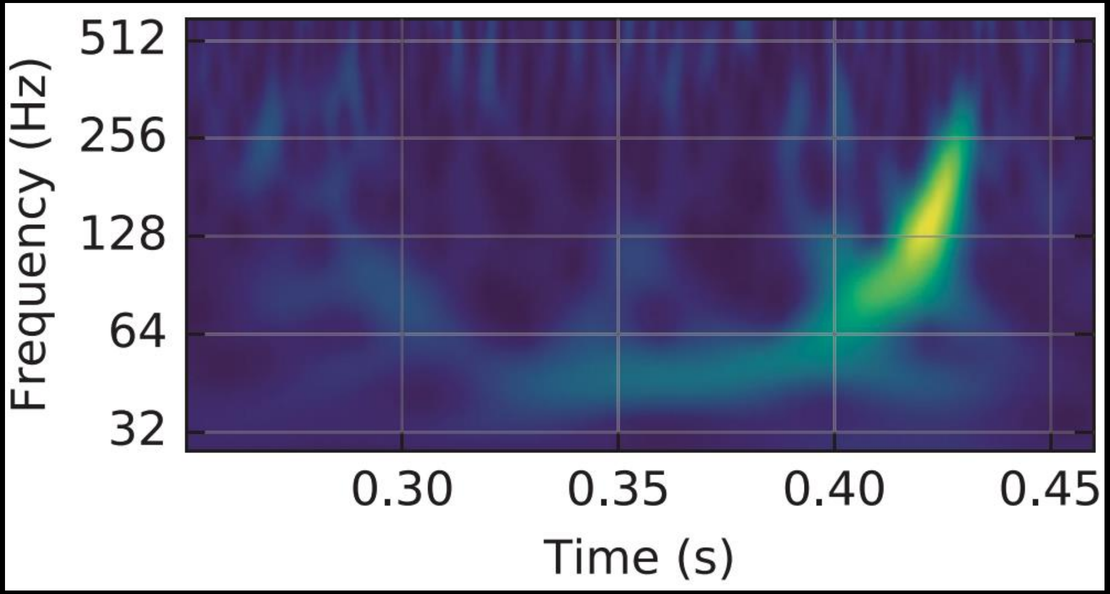
Origins of Fast Radio Bursts

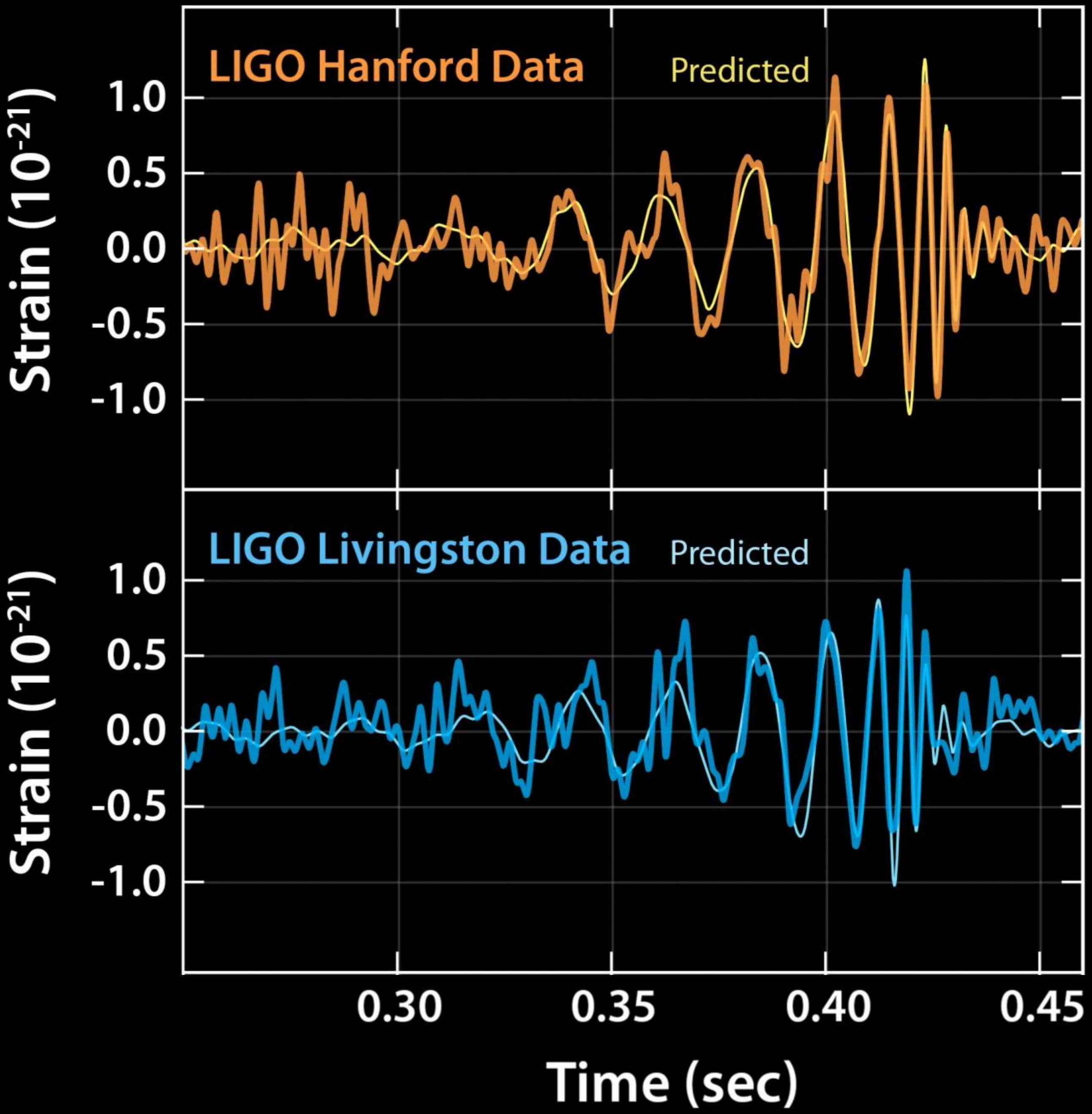


Gravitational wave astronomy and compact object binaries

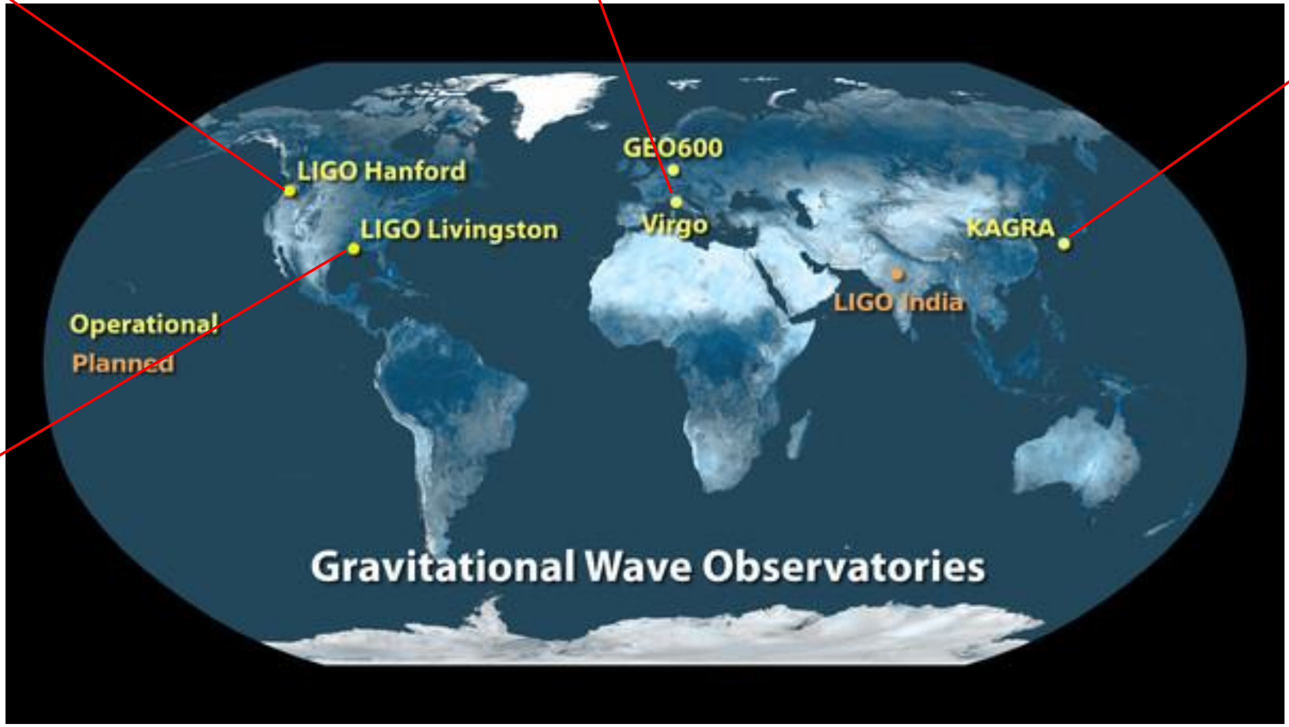
The first direct detection of GWs on Sep. 14, 2015

Image credit: Caltech/MIT/LIGO





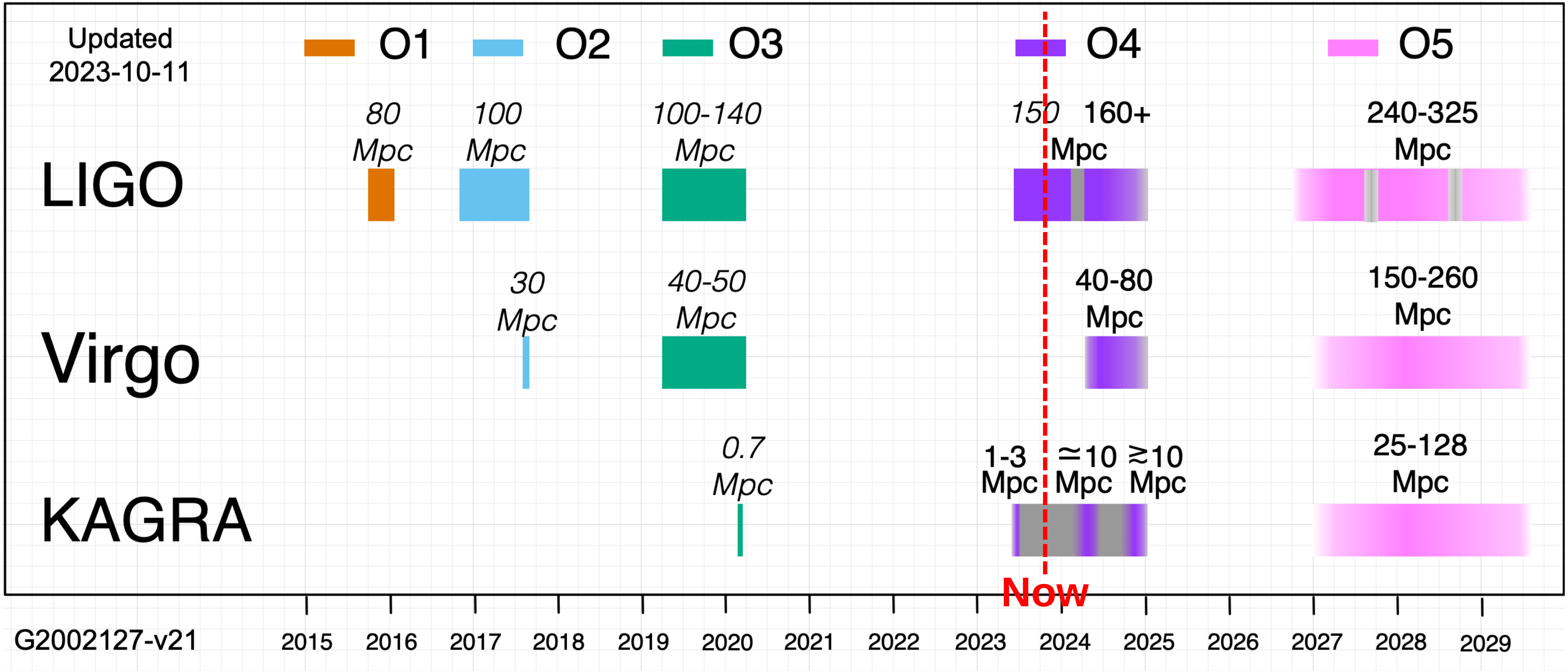
Gravitational-wave observatories



LIGO-Virgo-KAGRA (LVK) collaboration

Figure credit:
Caltech/MIT/LIGO Lab/ICRR

Observing Plan

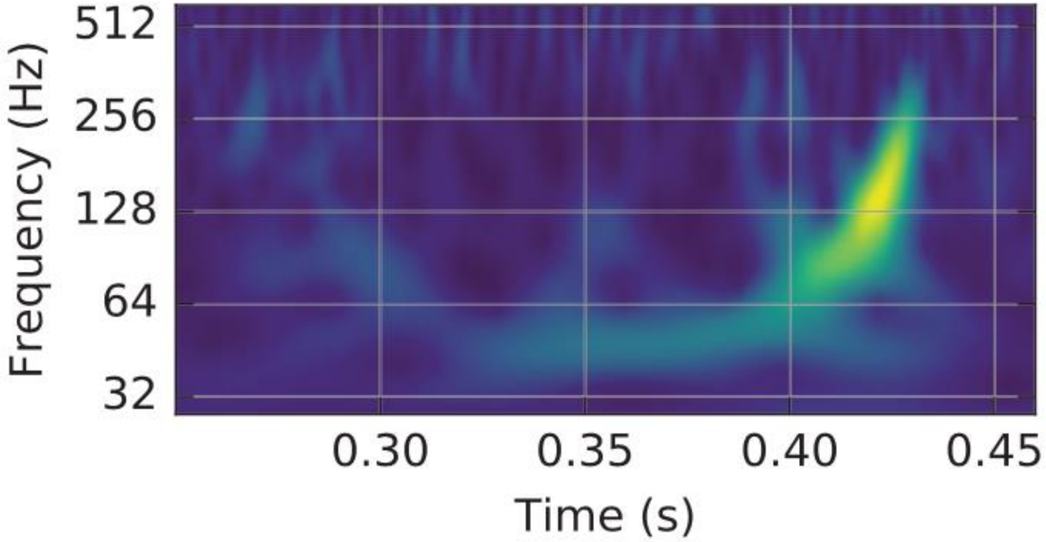


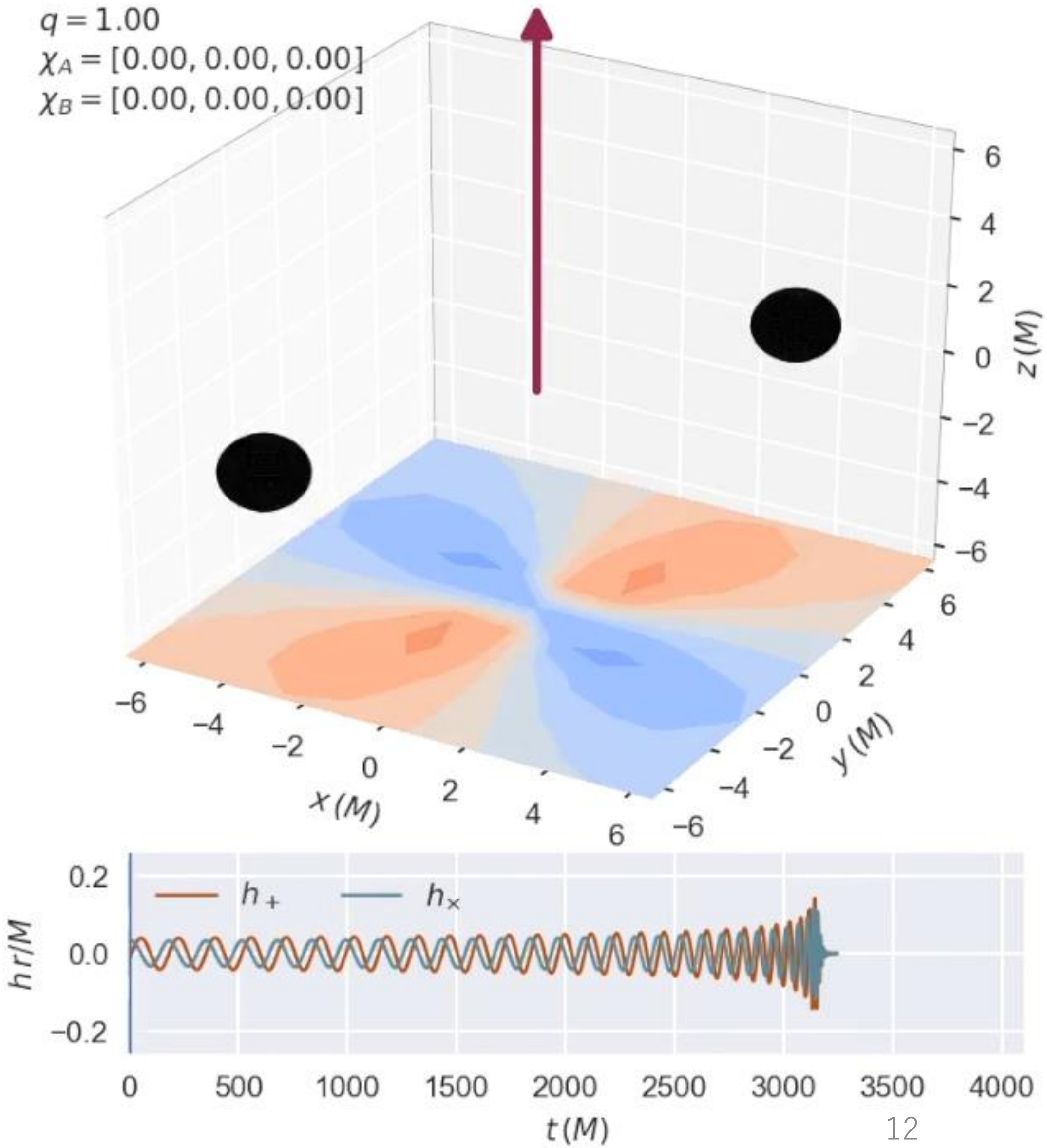
https://observing.docs.ligo.org/plan/

Compact binary coalescence (CBC)

- Signal with increasing frequency
- 3 categories
  - Binary Black Hole (BBH)
  - Binary Neutron Star (BNS)
  - Neutron Star-Black Hole (NSBH)
- Majority of events (>90%) are BBHs

Credit: Abbott+, PRL**116**, no.6, 061102 (2016).

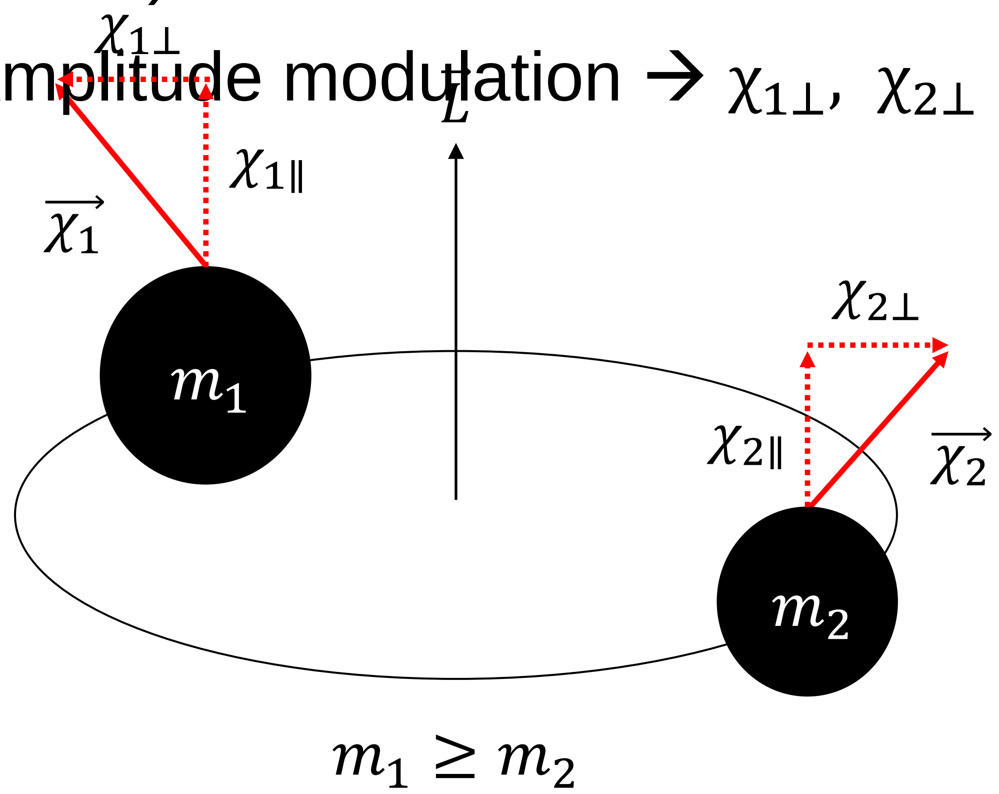


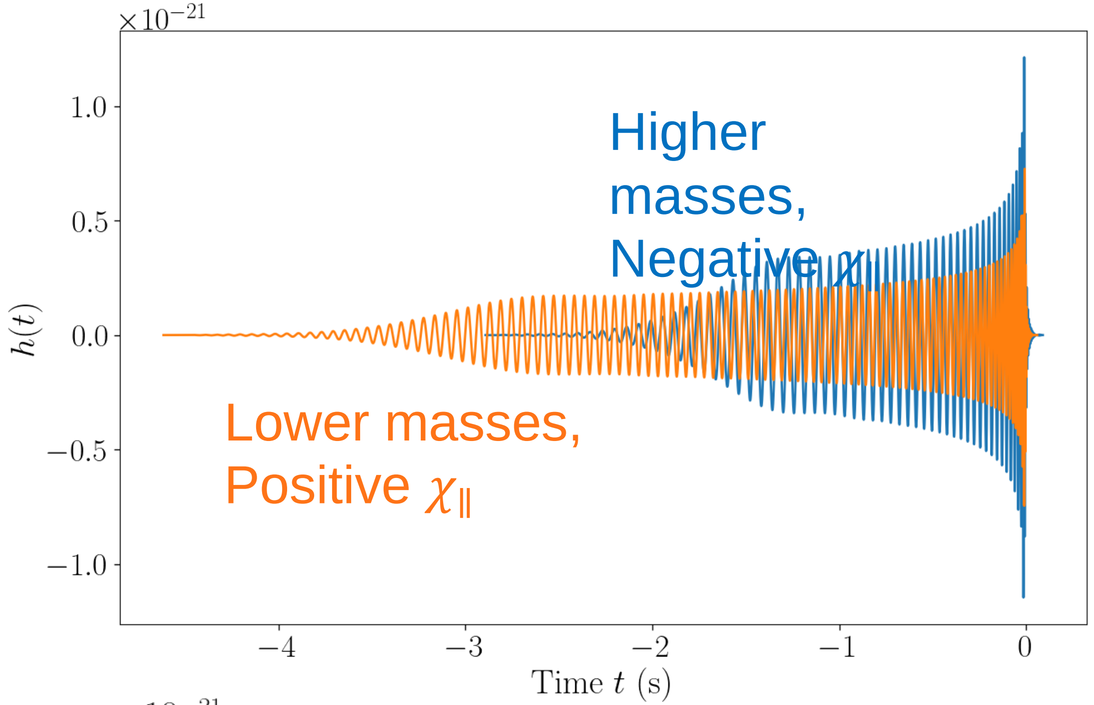


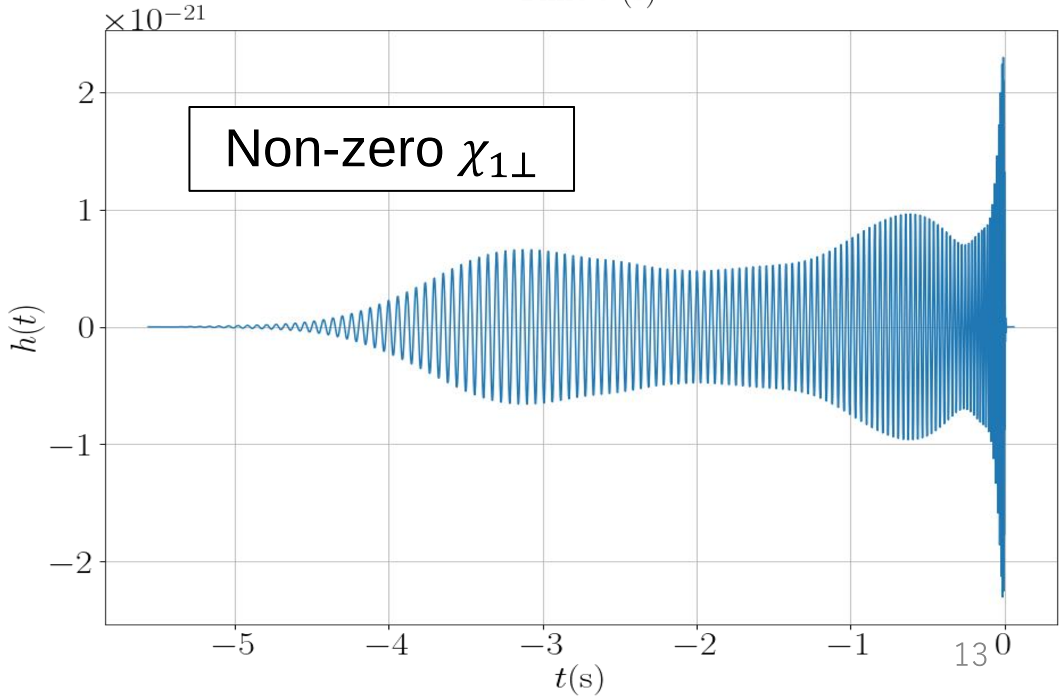
Credit: Vijay Varma et al., Binary Black Hole Explorer

CBC parameters

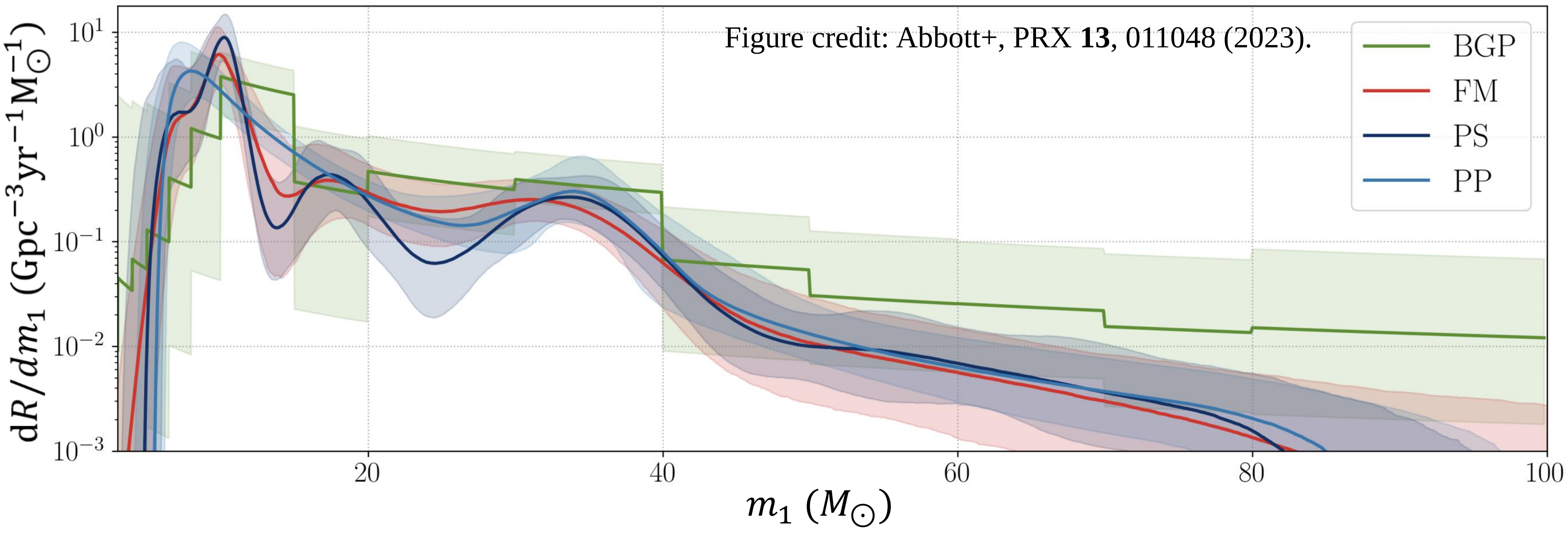
- Frequency evolution → m_1, m_2, $\chi_{1\parallel}$, $\chi_{2\parallel}$ (and tidal deformability for BNS, NSBH)
- Amplitude modulation → $\chi_{1\perp}$, $\chi_{2\perp}$







BBH distribution: Mass



- Local maxima at $m_1 \sim 10M_\odot$ and $m_1 \sim 35M_\odot$ (> 99% credibility)
- A few massive BBHs e.g. GW190521 ($m_1 = 85^{+21}_{-14}M_\odot$, $m_2 = 66^{+17}_{-18}M_\odot$)
  → Inconclusive evidence for pair-instability mass gap ($65 - 120M_\odot$).

Unequal-mass binaries

Reference: Abbott+, PRD **102**, no. 4, 043015 (2020), Abbott+, ApJL **896**, no.2, L44 (2020).

GW190412

- $m_1 = 30.1^{+4.6}_{-5.3} M_\odot$, $m_2 = 8.3^{+1.6}_{-0.9} M_\odot$
- Strong evidence of higher GW harmonics ($p \leq 6 \times 10^{-4}$)

GW190814

- $m_1 = 23.2^{+1.1}_{-1.0} M_\odot$, $m_2 = 2.59^{+0.08}_{-0.09} M_\odot$
- Strong evidence of higher GW harmonics ($p \leq 2.5 \times 10^{-4}$)
- The secondary mass is in "mass gap" between NS and BH.

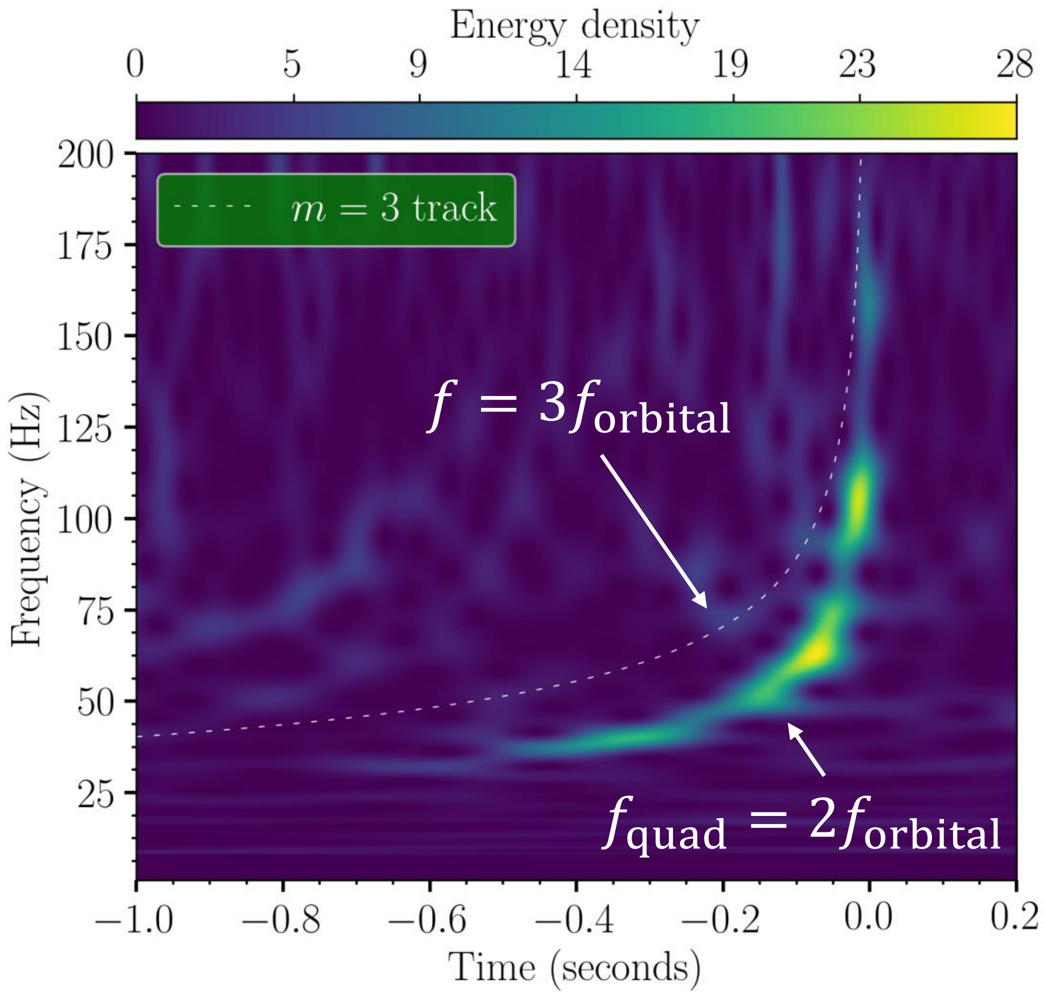
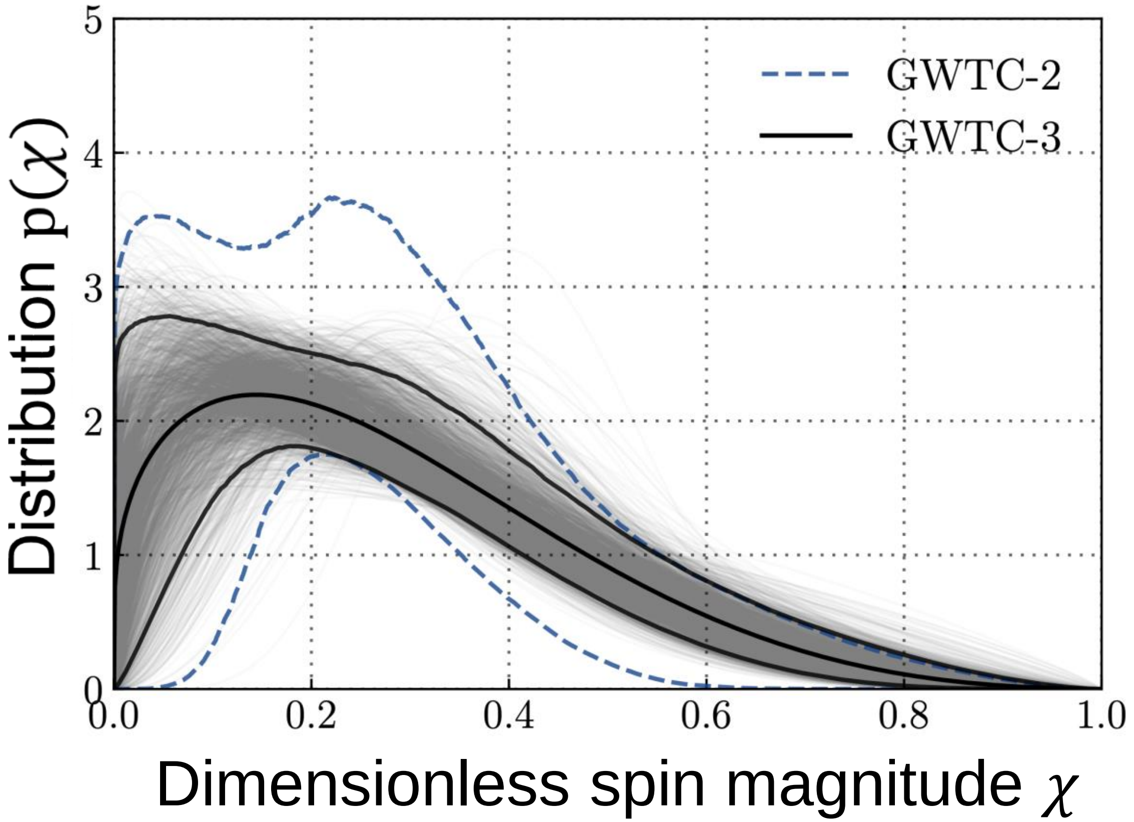
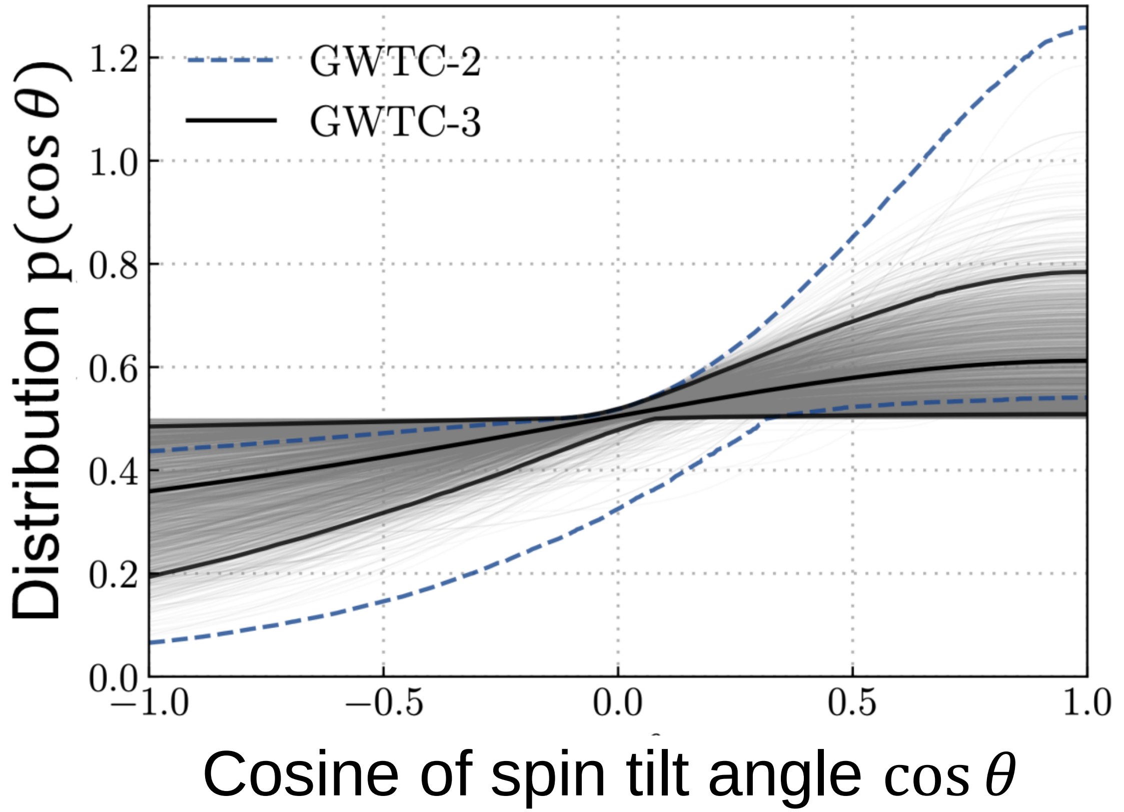


Figure: LIGO-Livingston data for GW190412

BBH distribution: Spin

Image credit: Abbott+, PRX **13**, 011048 (2023).





- Spin magnitude generally small ($\chi \lesssim 0.4$), but not-vanishing.
- Tilt angle has broad distribution, but $\cos\theta = 1$ preferred (but see Roulet et al 2021 about model dependence).

BBH distribution: Redshift

- Signal amplitude + masses
  → Luminosity distance
  → Redshift z

- Merger rate $\propto (1+z)^{\kappa}$, with $\kappa = 2.9^{+1.7}_{-1.8}$ (90% CI).

- Merger rate increases with redshift (at 99.6%).

- No evidence that mass distribution varies with redshift.

Image credit: Abbott+, PRX **13**, 011048 (2023).

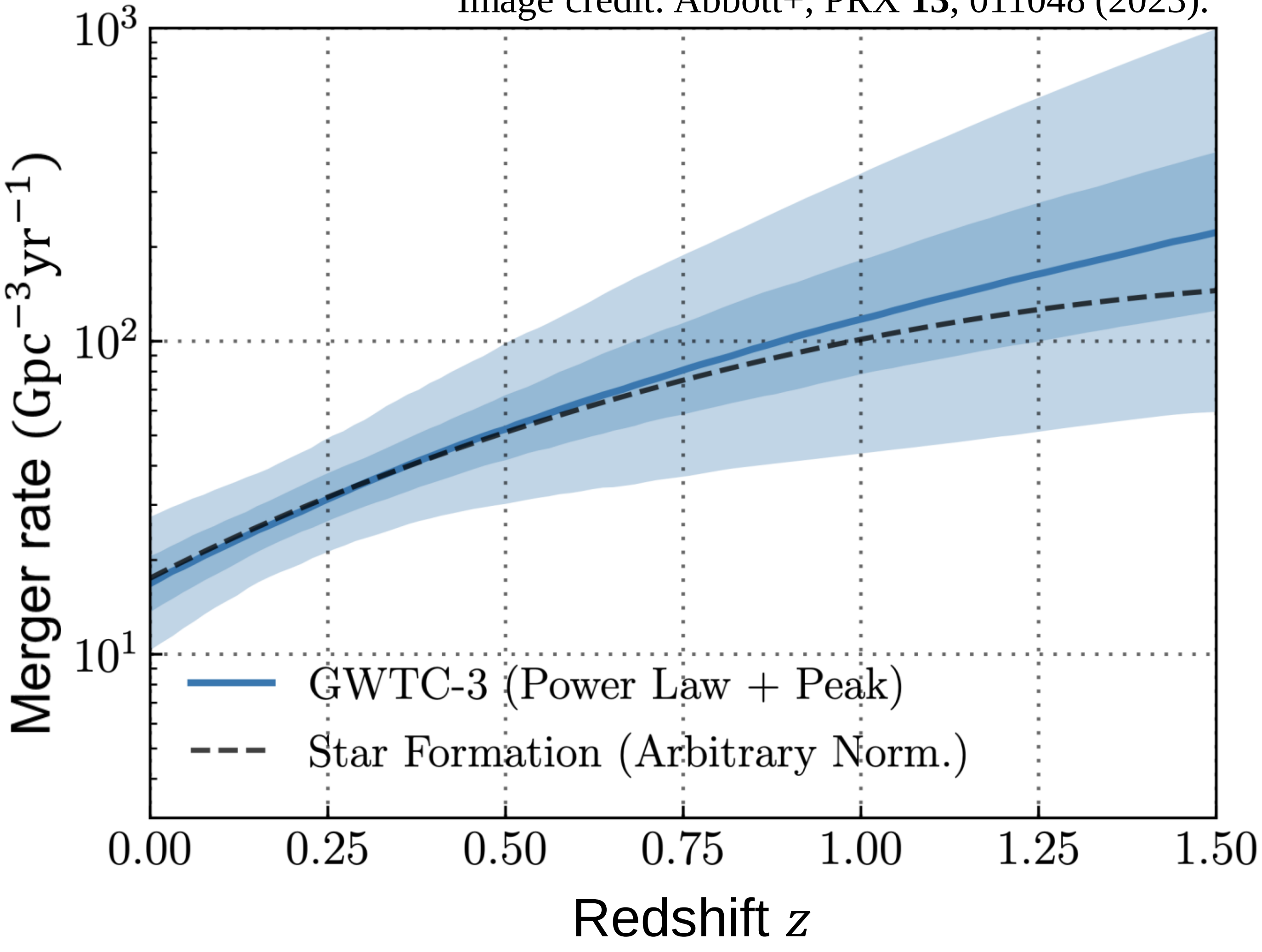


Figure: Redshift evolution of merger rate

GW170817: The first observed GWs from BNS

- First detection of binary neutron star in O2: $m_1 = (1.36 — 1.60) M_\odot, m_2 = (0.86 — 1.36) M_\odot$.
- Electromagnetic (EM) counterparts from radio to gamma rays
  → Multimessenger astronomy with GWs

Imaged credit:
Abbott+, PRL **119**, no.16, 161101 (2017),
Abbott+, ApJL **848**, no.2, L12 (2017).

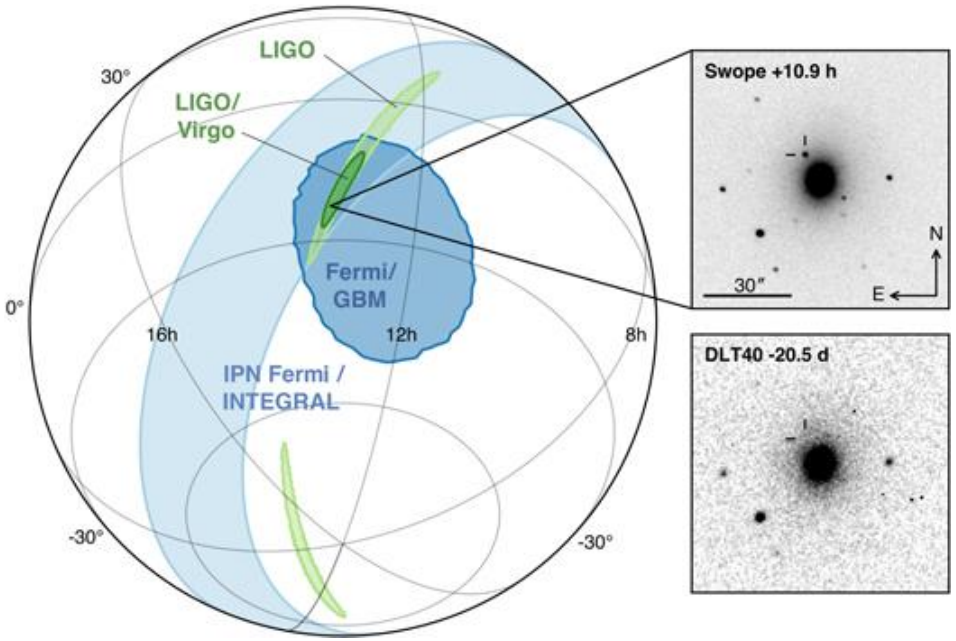


Figure:
Localization of GW, gamma-ray, and optical signal

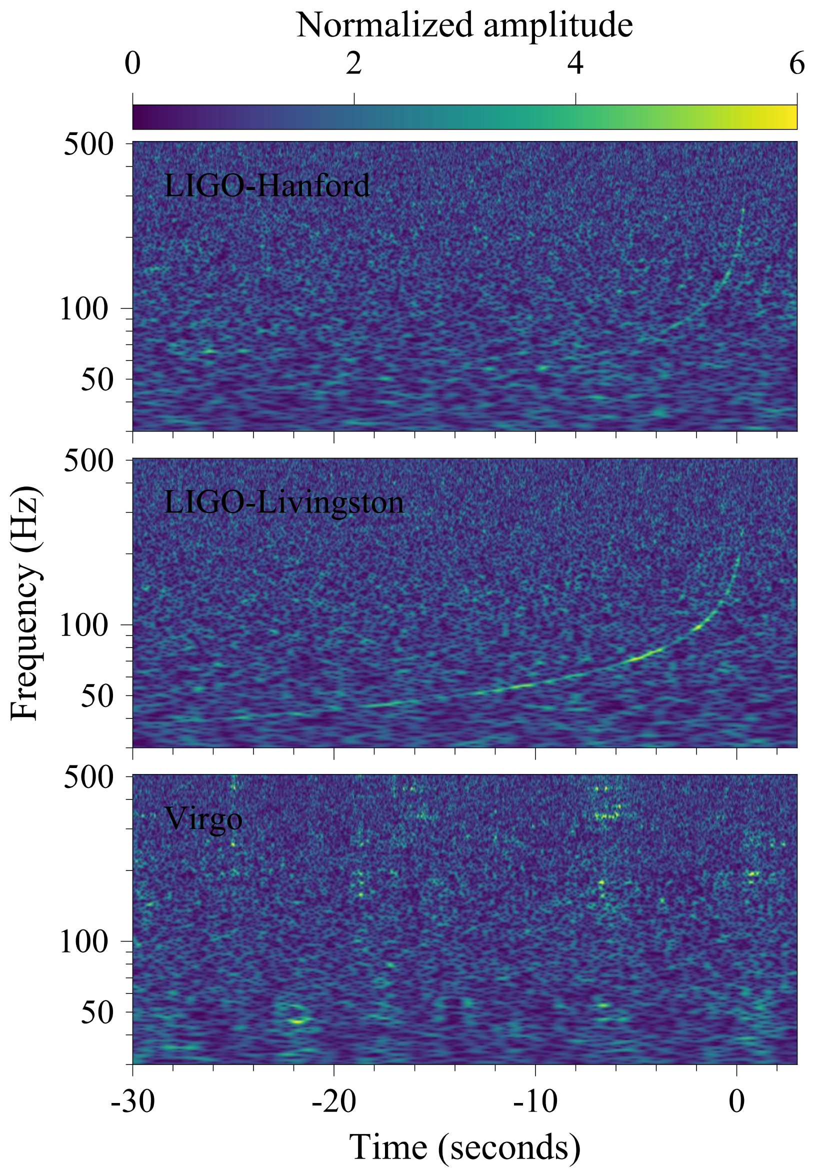


Figure: Time-frequency plot

GW170817: The first observed GWs from BNS

- Hubble constant measurement

$$cz = H_0 D_L$$

EM obs. (→ cz) GW obs. (→ D_L)

$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$$
$$(68.3\%,\ 1\sigma)$$

- sGRB observed ~1.7s after GWs
  → Speed of GWs Abbott+ ApJL 848 L13 2017

$$\left|\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}}\right| \leq O(10^{-15})$$

Figure credit: Abbott+, Nature **551**, 85 (2017).

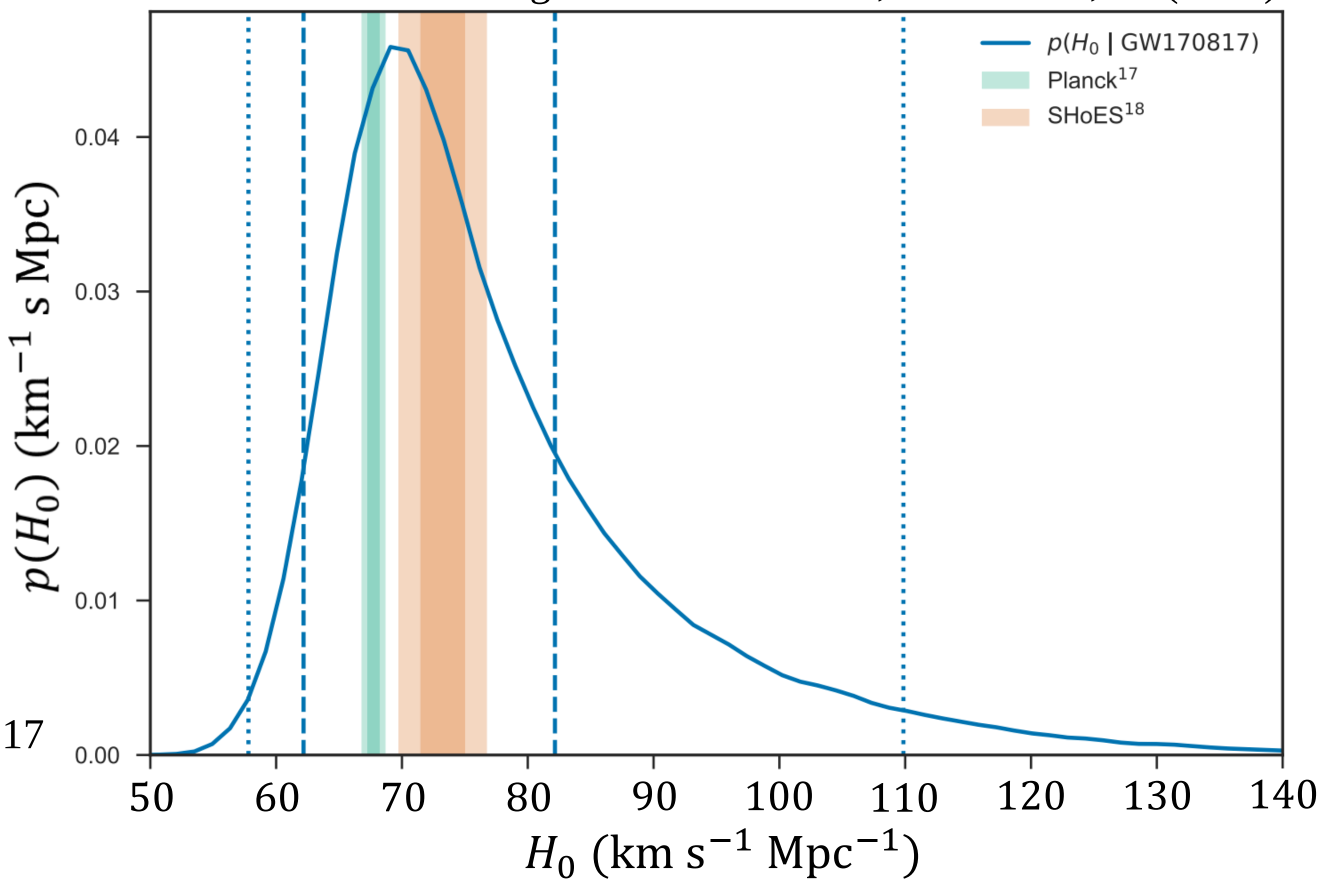
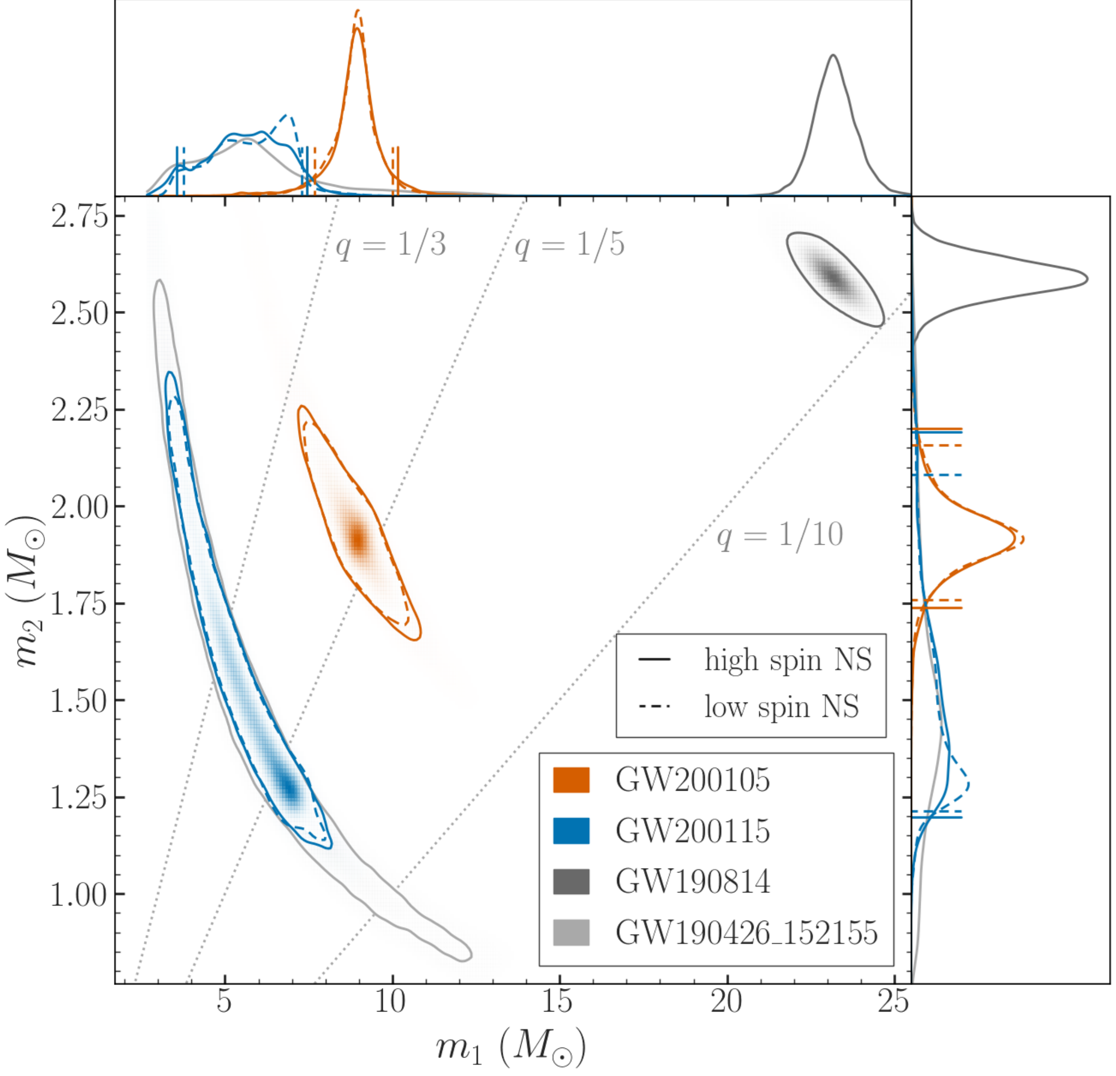


Figure: H_0 estimated with the joint observation of GW170817 and its electromagnetic counterpart

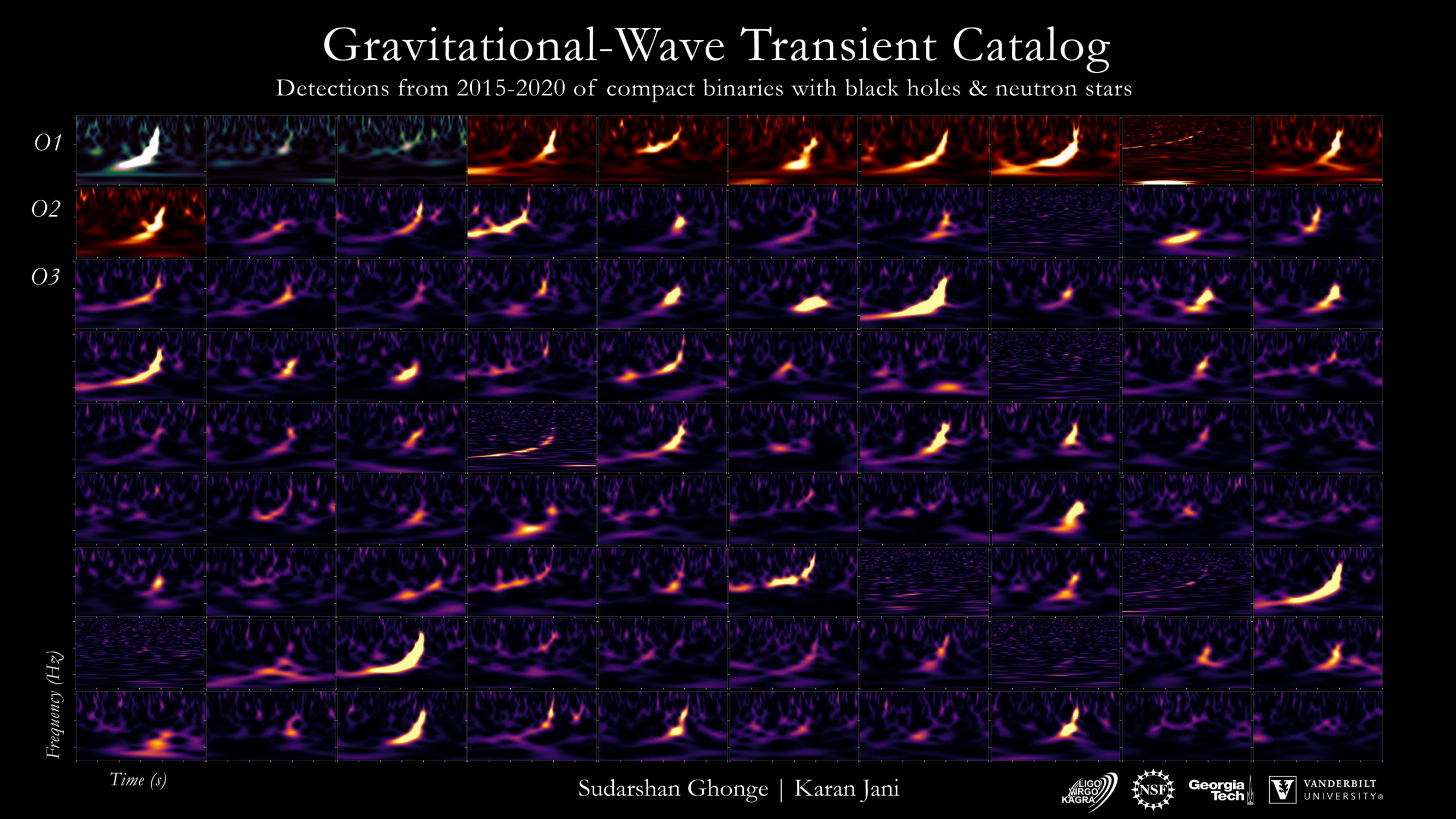
NSBH event candidates

Reference: Abbott+, ApJL **915**, no.1, L5 (2021).

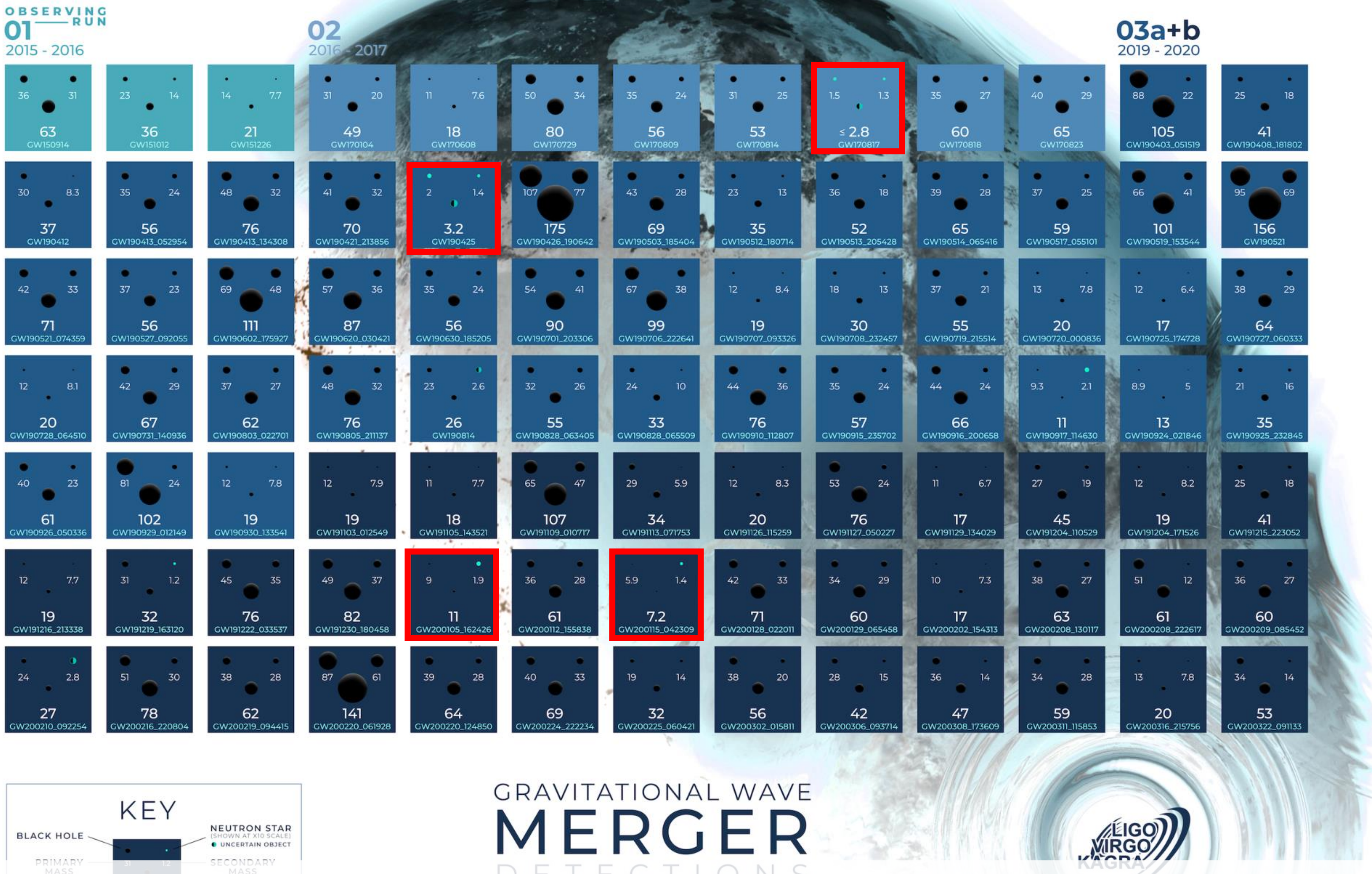


	m_1	m_2
GW200105	$8.9^{+1.2}_{-1.5} M_\odot$	$1.9^{+0.3}_{-0.2} M_\odot$
GW200115	$5.7^{+1.8}_{-2.1} M_\odot$	$1.5^{+0.7}_{-0.3} M_\odot$

- Masses consistent with neutron star-black hole (NSBH)
- GW200105 does not pass the GWTC3 event criteria.
- No direct evidence of secondary objects being neutron stars (No EM counterparts, no tidal information)



Gravitational-Wave Transient Catalog
Detections from 2015-2020 of compact binaries with black holes & neutron stars
O1
O2
O3
Frequency (Hz)
Time (s)
Sudarshan Ghonge | Karan Jani
LIGO VIRGO KAGRA
NSF
Georgia Tech
VANDERBILT UNIVERSITY



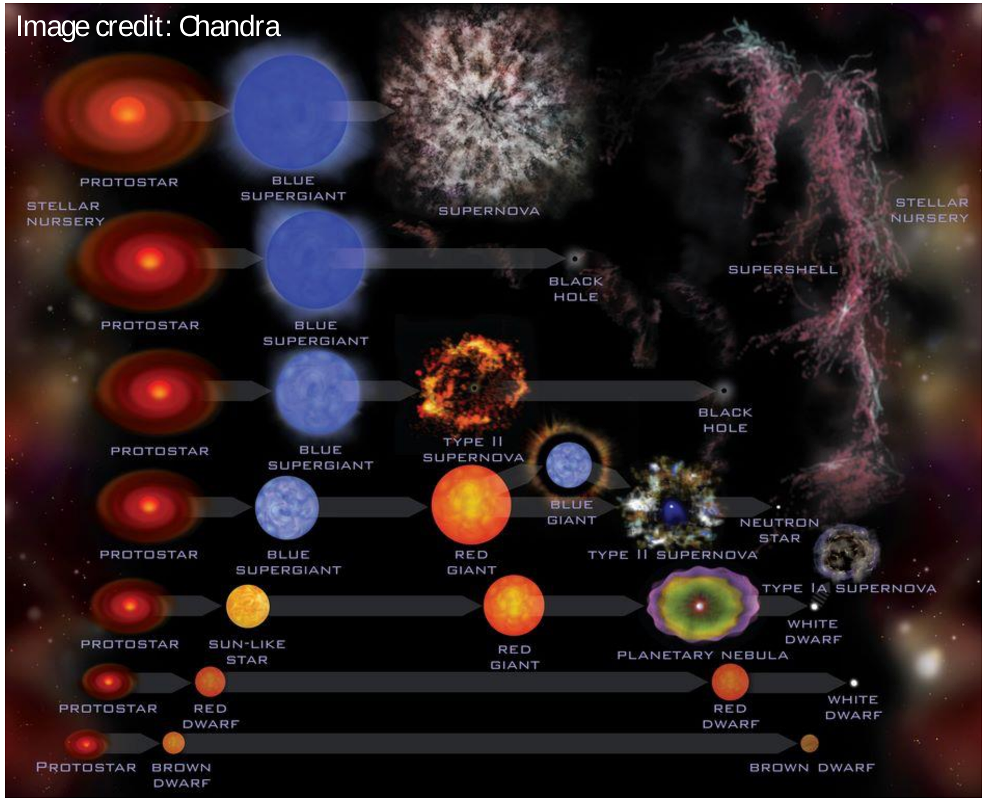
How, when, and where the progenitor system is formed?

What are the properties of the NSs at the binary formation?

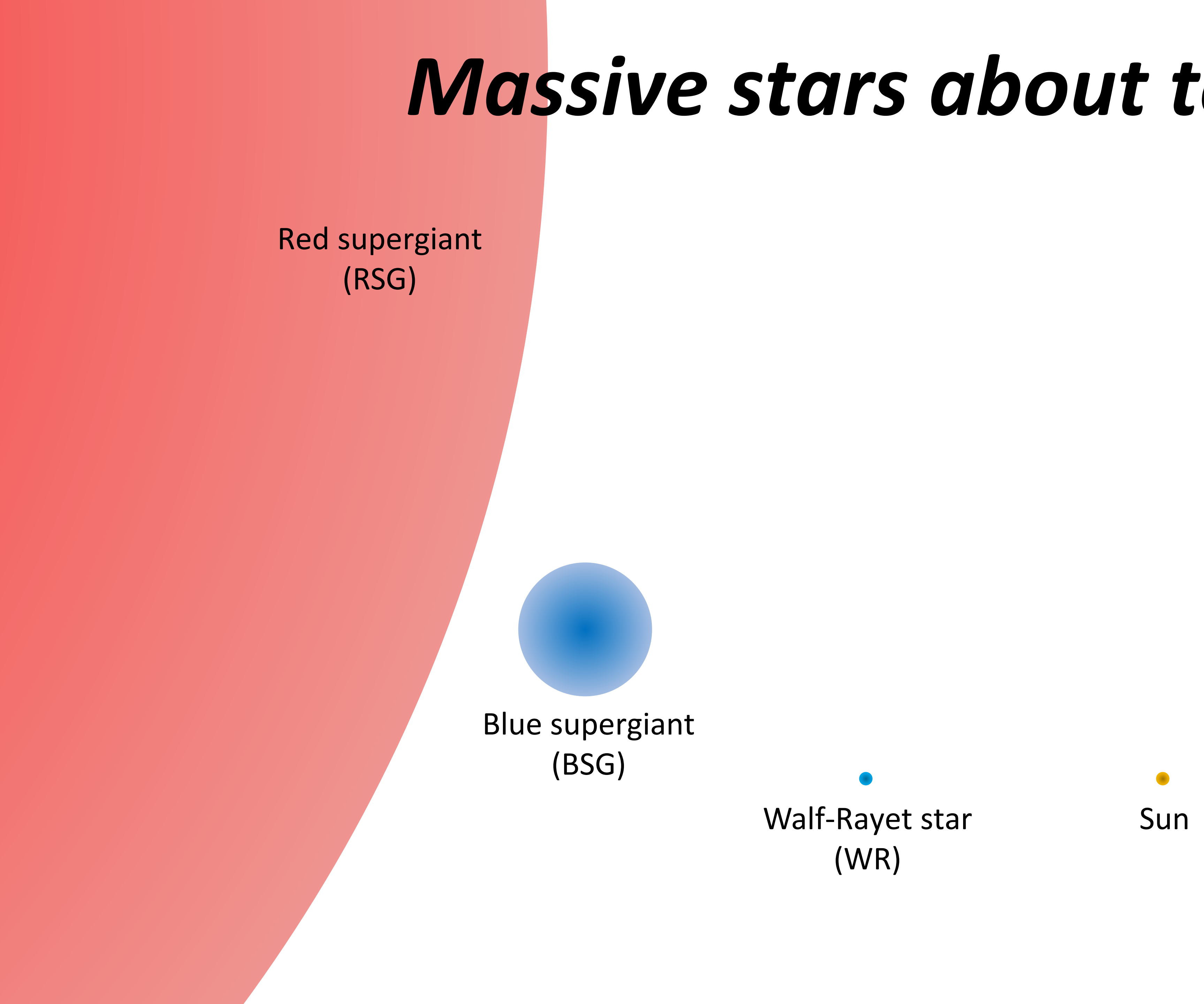
Time-domain astronomy and compact object formation

A Key Question of Multi-Messenger Time-Domain Astronomy

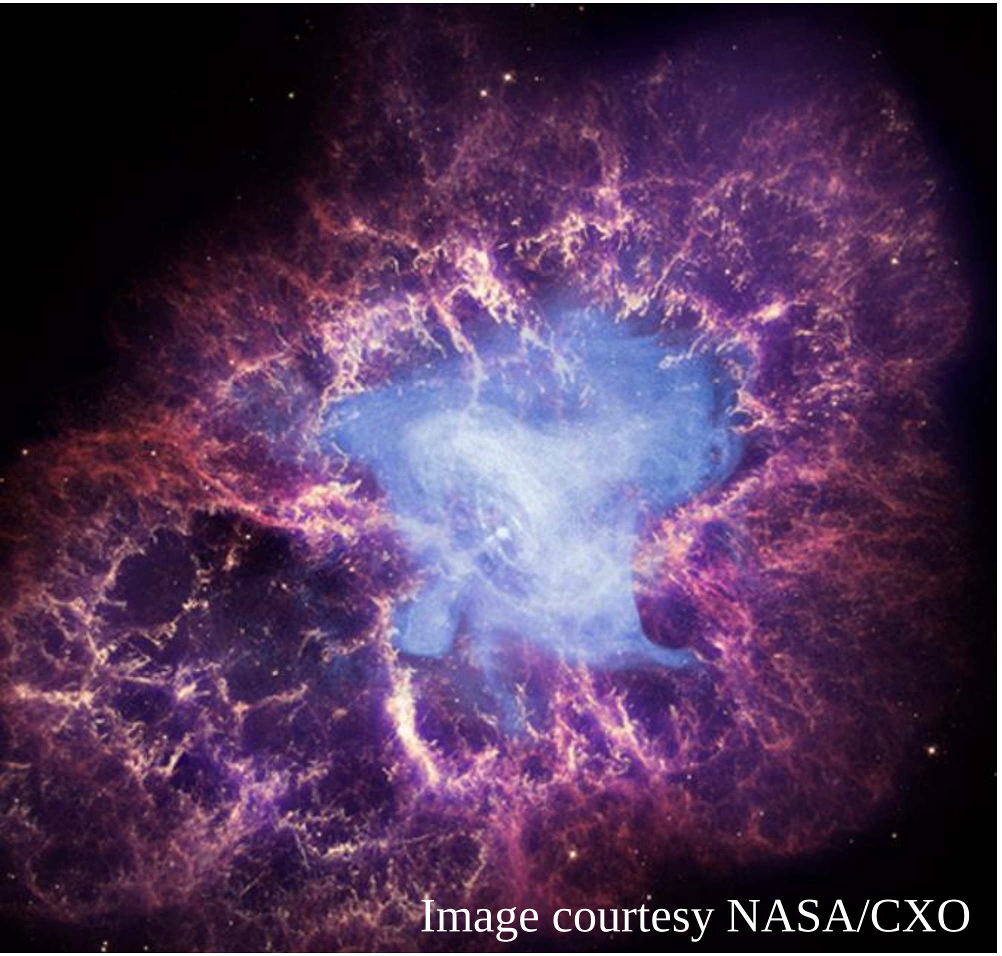
What kind of massive star (RSG, BSG, WR) produces
what kind of compact object (NS or BH? B field, rotation, disk?)
and what kind of explosive transient (SN, GRB, FRB or else) ?



Massive stars about to die



Messier 1 : the 1st NS detected



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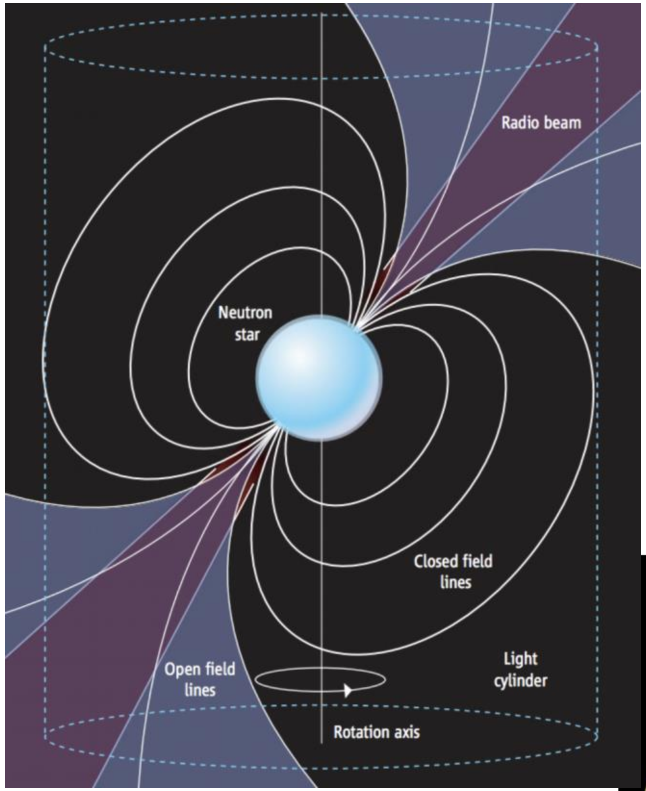
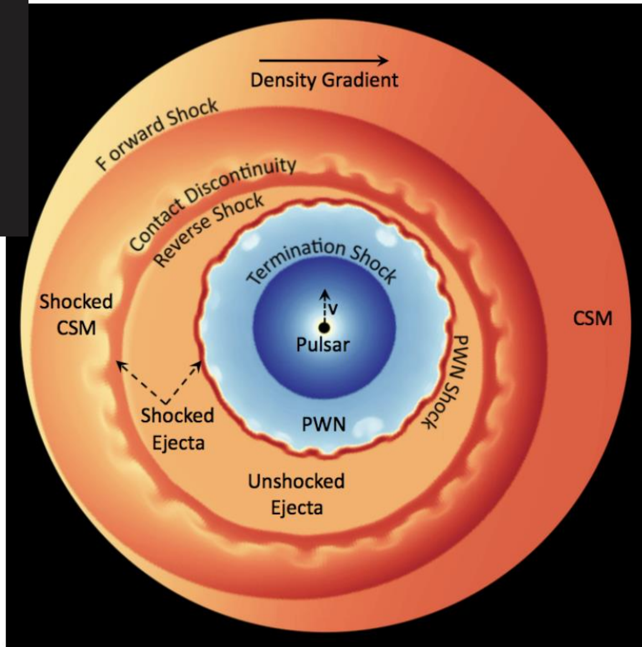
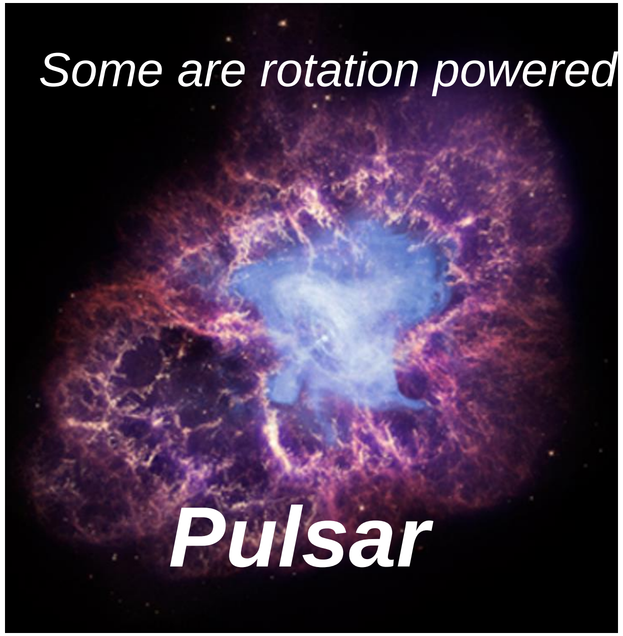
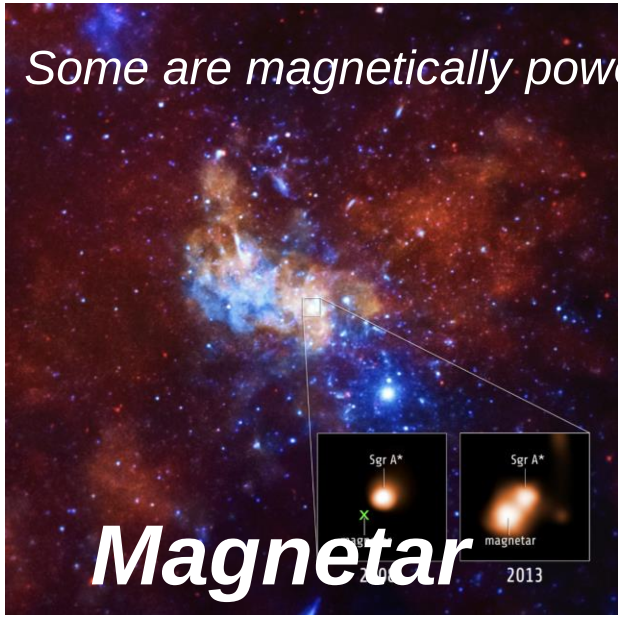
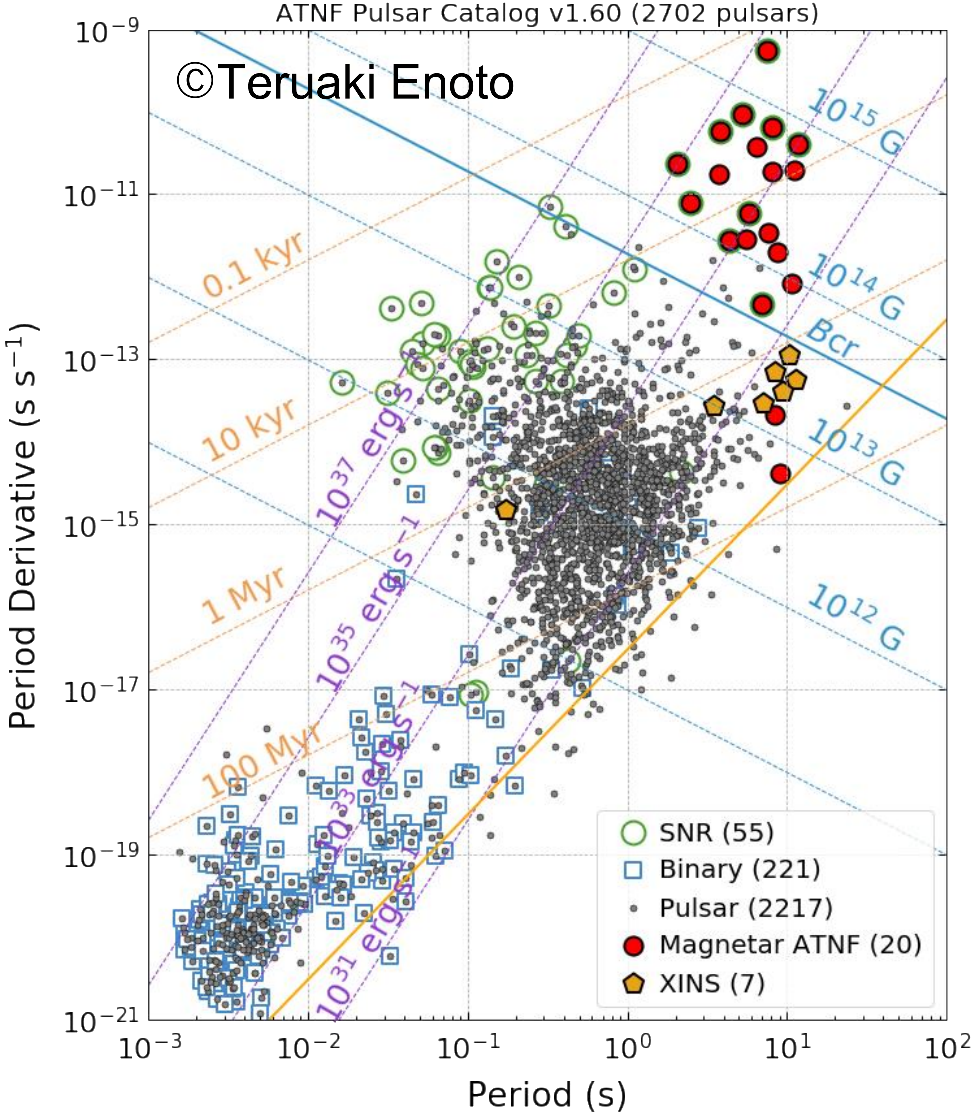


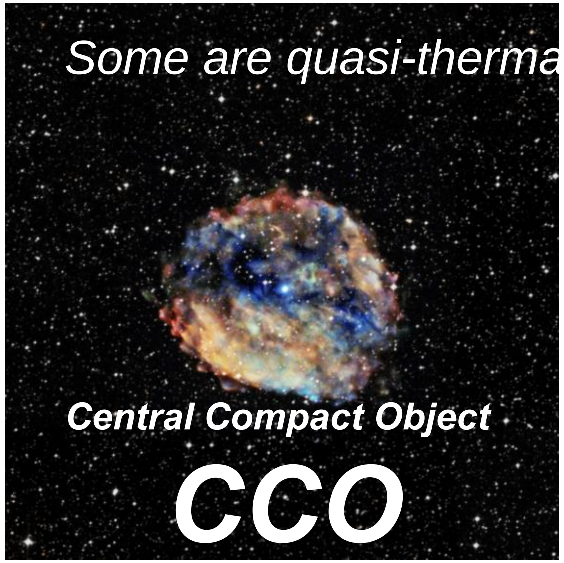


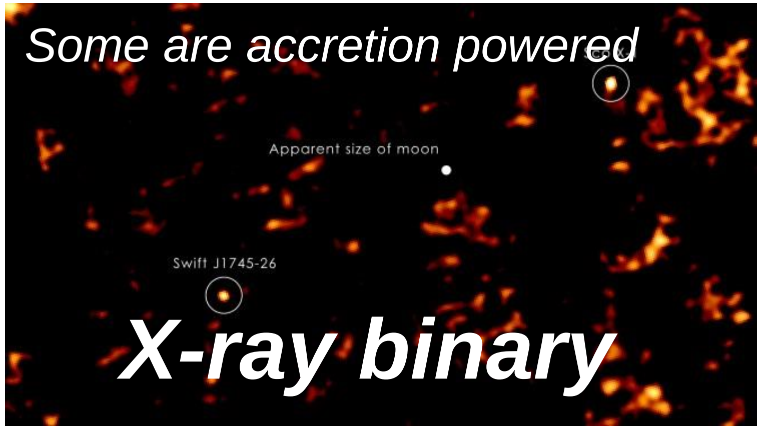
Known knowns about NSs





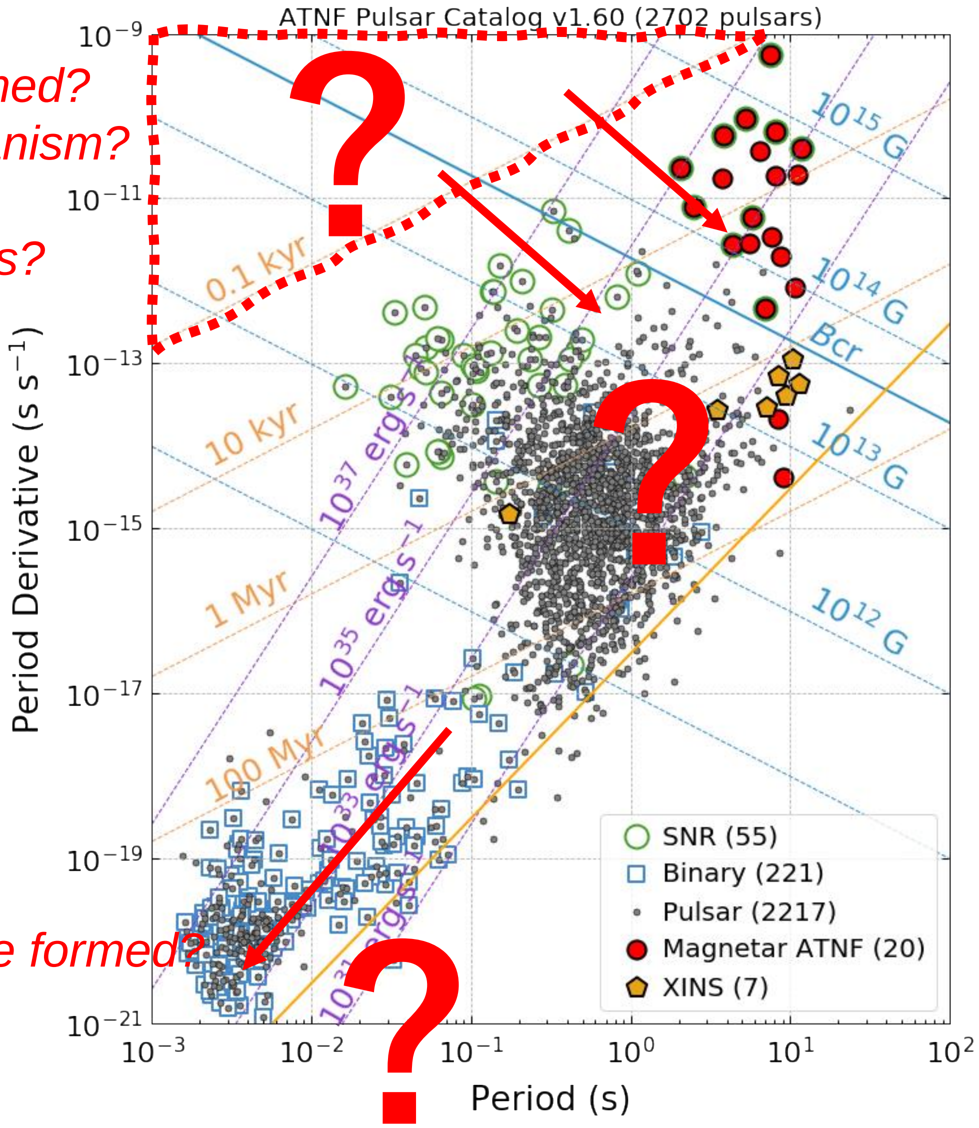






- **Known unknowns about NSs**

How and when NSs are formed?
Supernova explosion mechanism?
How the trifurcation of pulsar/magentar/CCO occurs?

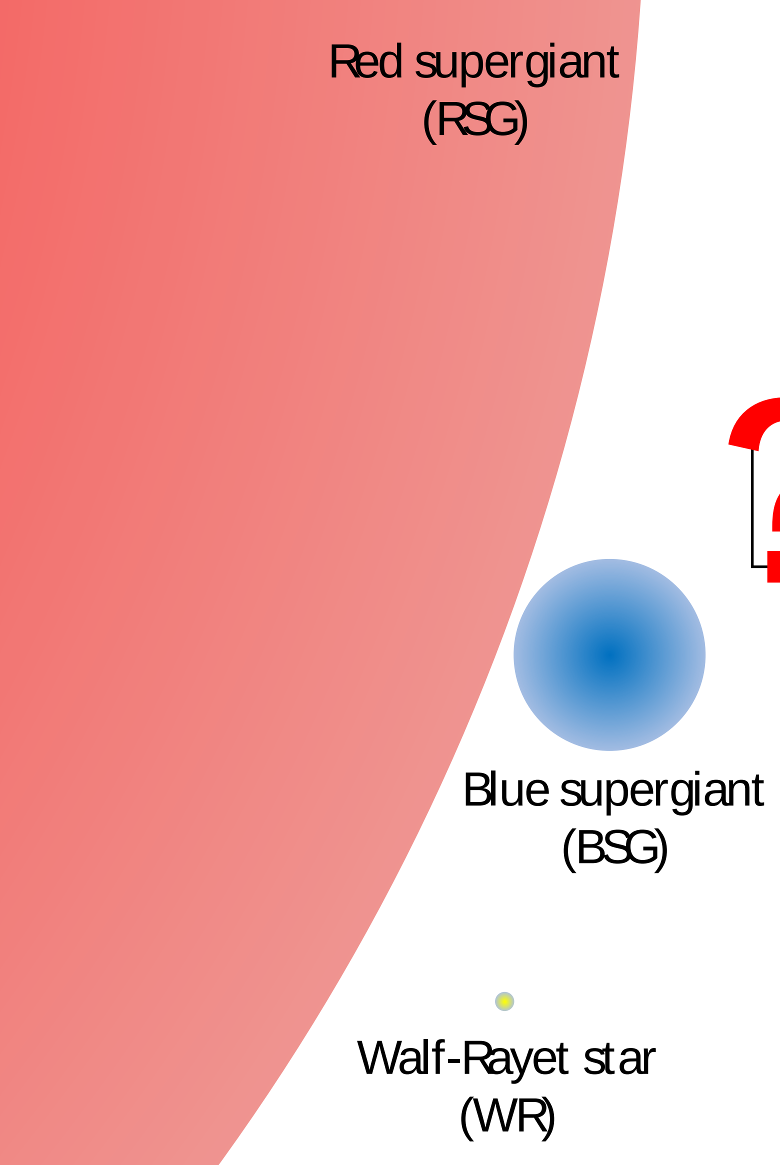


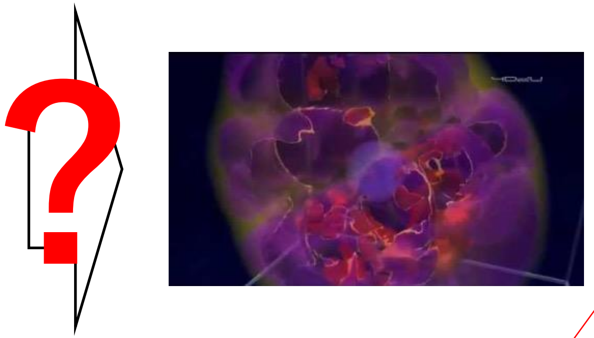
Particle acceleration & emission mecha

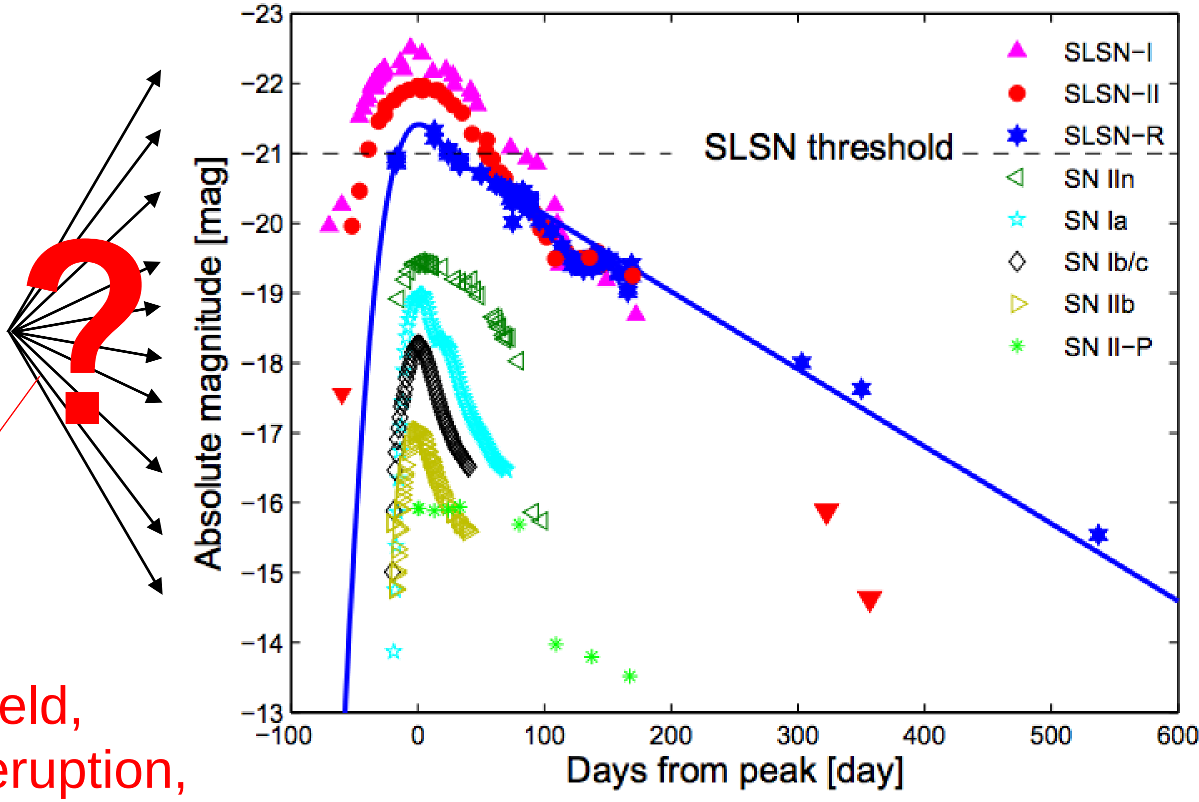
- *Coherent radio emission?*
- *Magnetar flare?*
- *When an NS can be an FRB source*
- *NSs are pevatrons?*

How and when binary NSs are formed?
Ultraluminous X-ray pulsars?
Short gamma-ray bursts?

Diversity in NS formation and associated transients

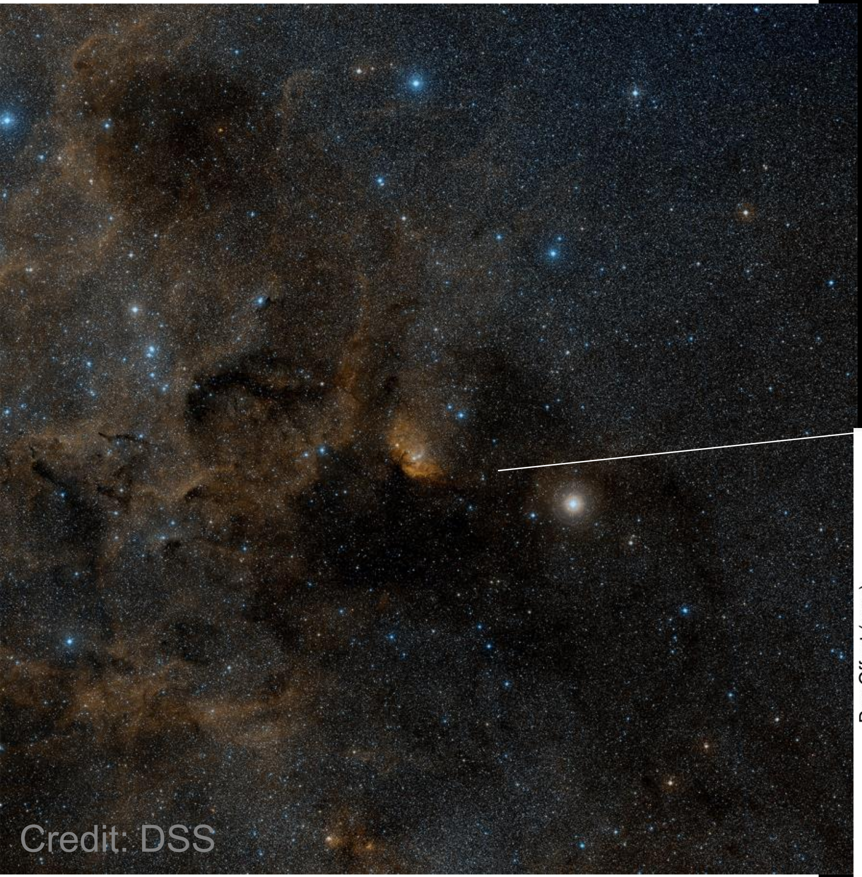


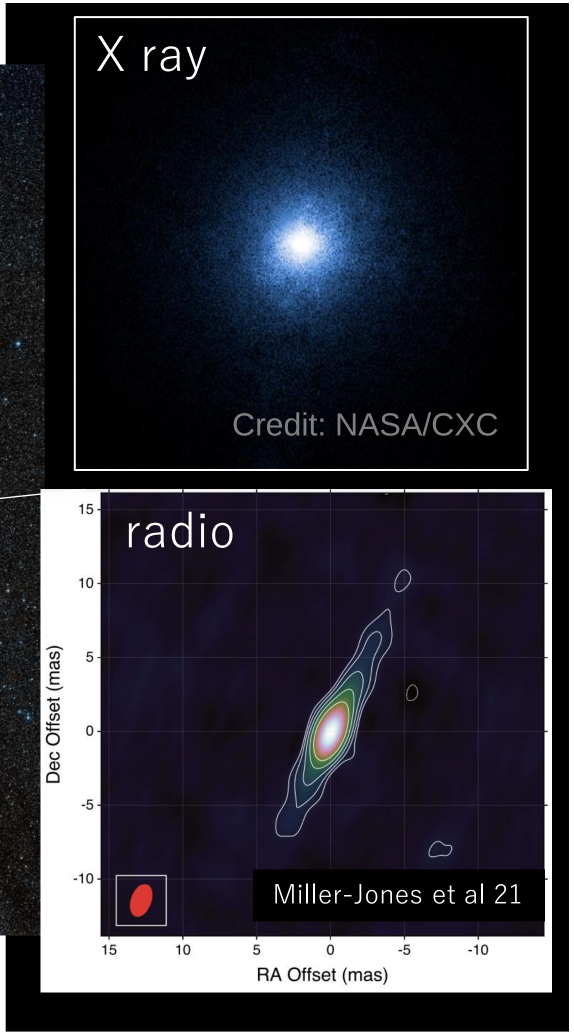




rotation, magnetic field,
pre-collapse mass eruption,
single or binary, …

Cygnus X-1 : the 1st BH detected





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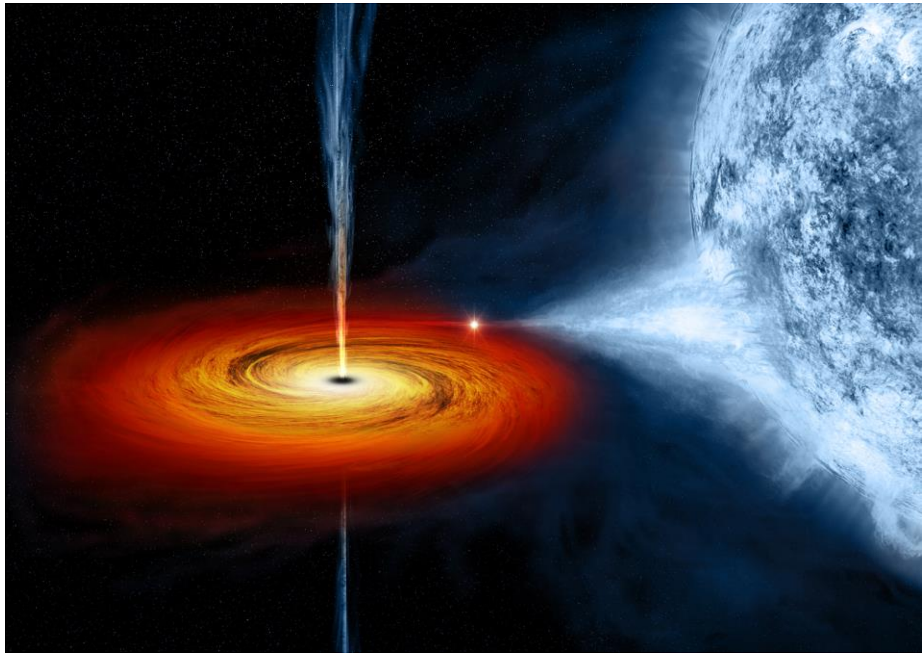
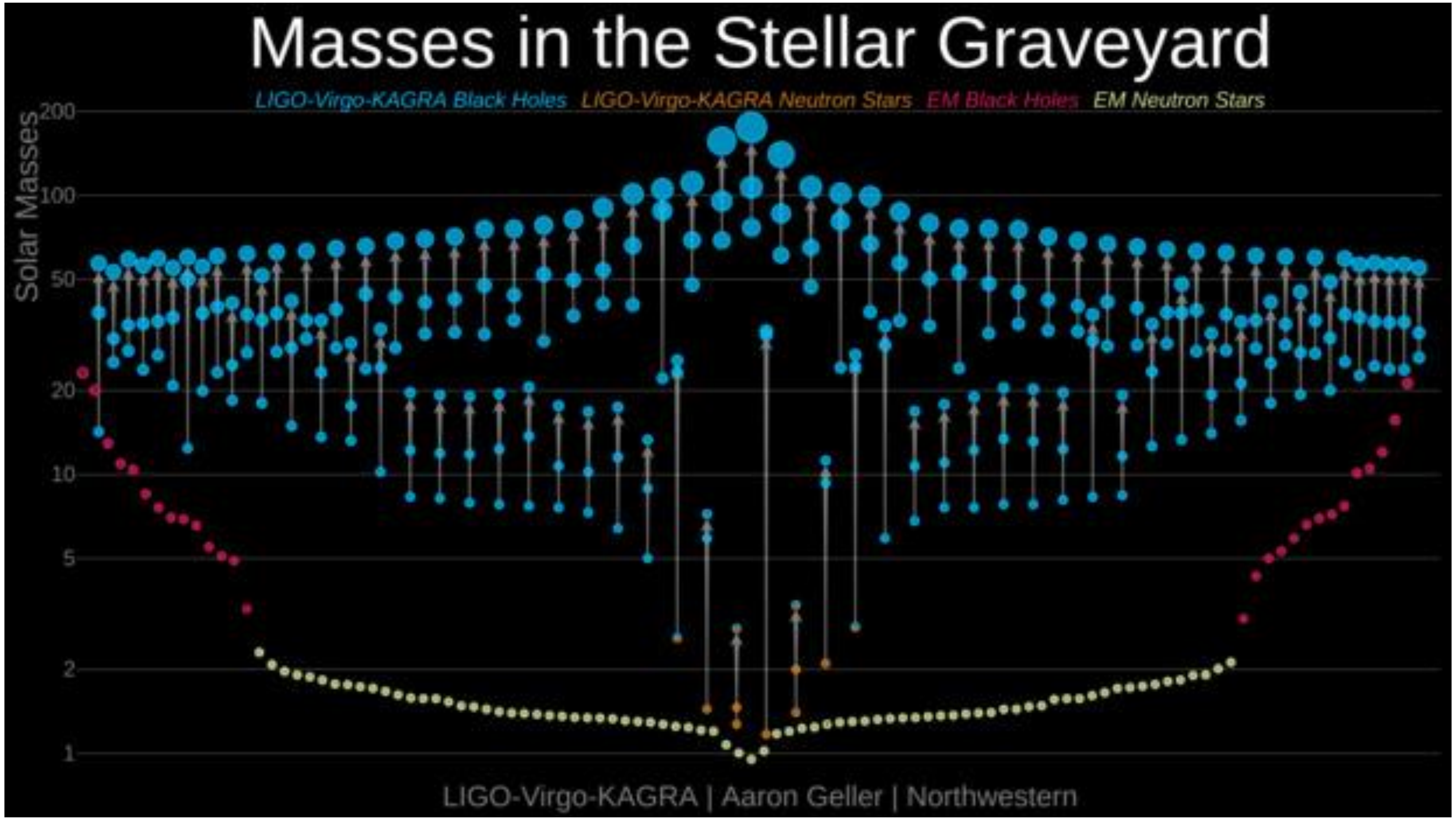
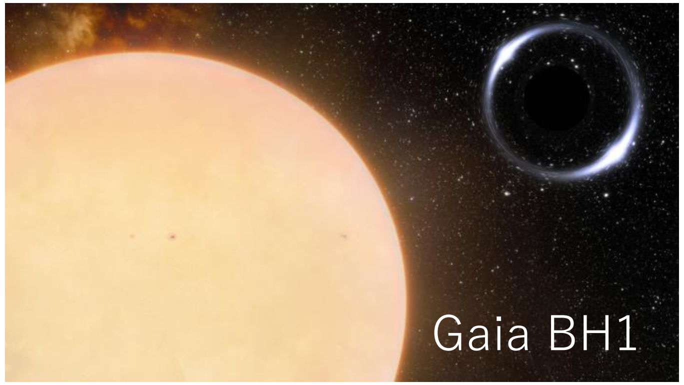
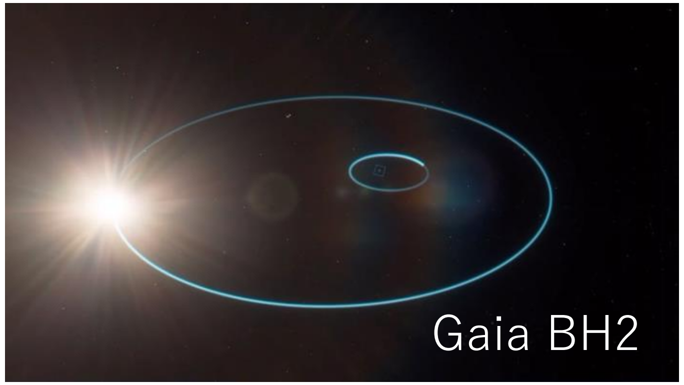


Known knowns about BHs







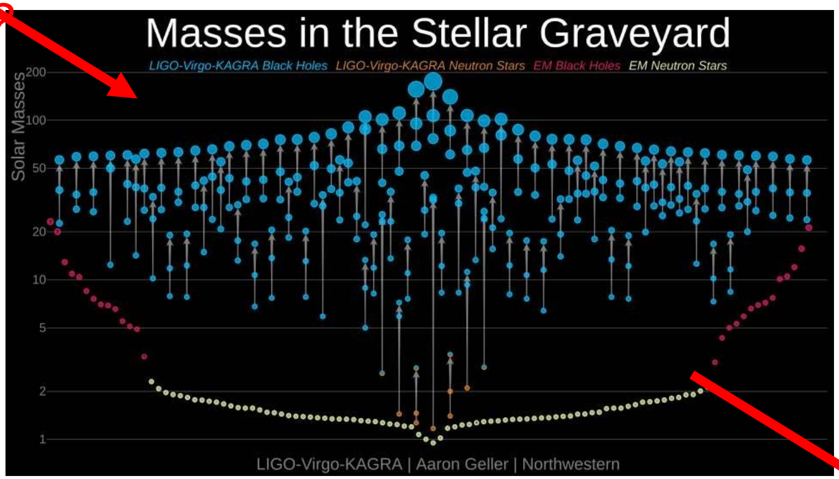
- **Known unknowns about BH**

?

How and when (binary) BHs are formed?
Associated with energetic transients?

?

Mass and spin distribution?
Ultraluminous X-ray sources = intermediate B



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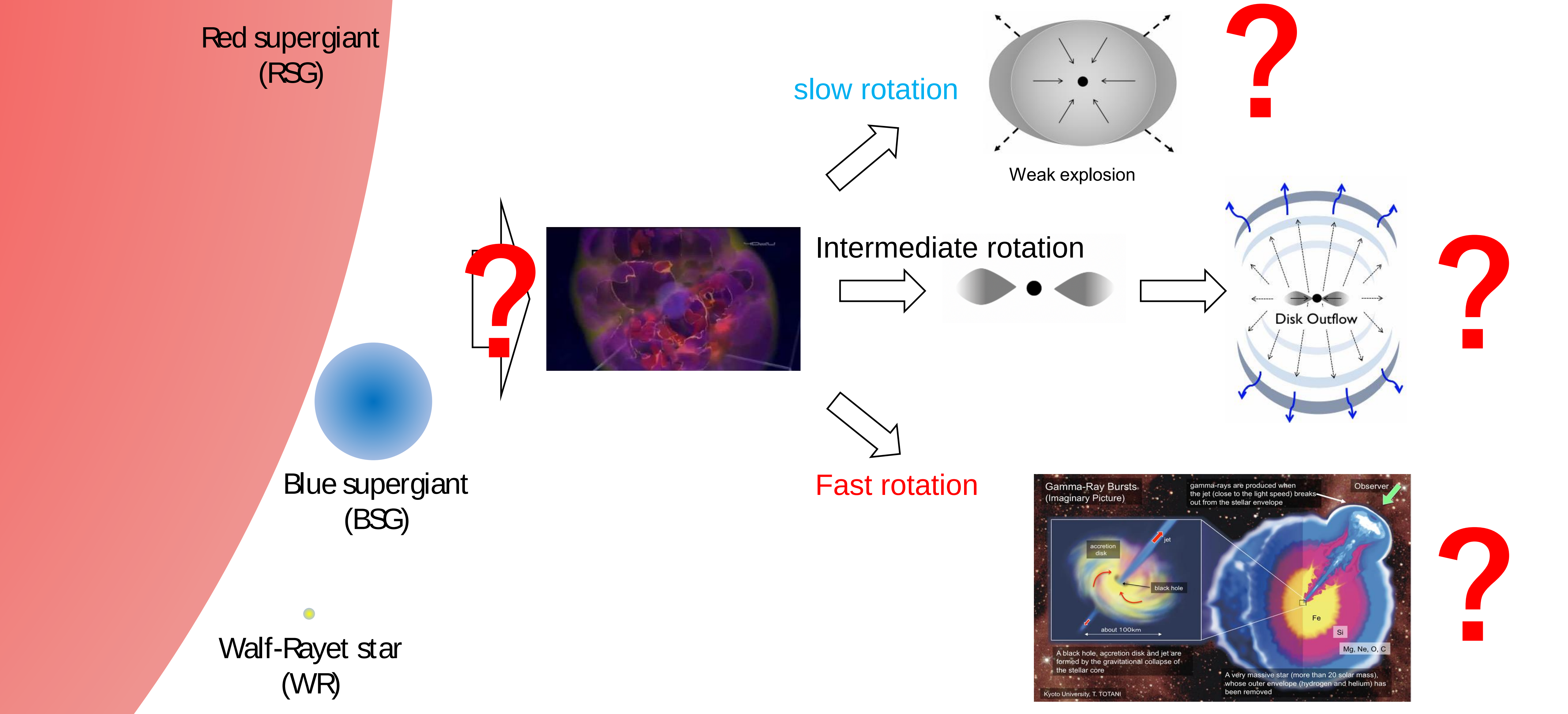
“Floating” BHs in the Galaxy
How are they?
Where they are?

time

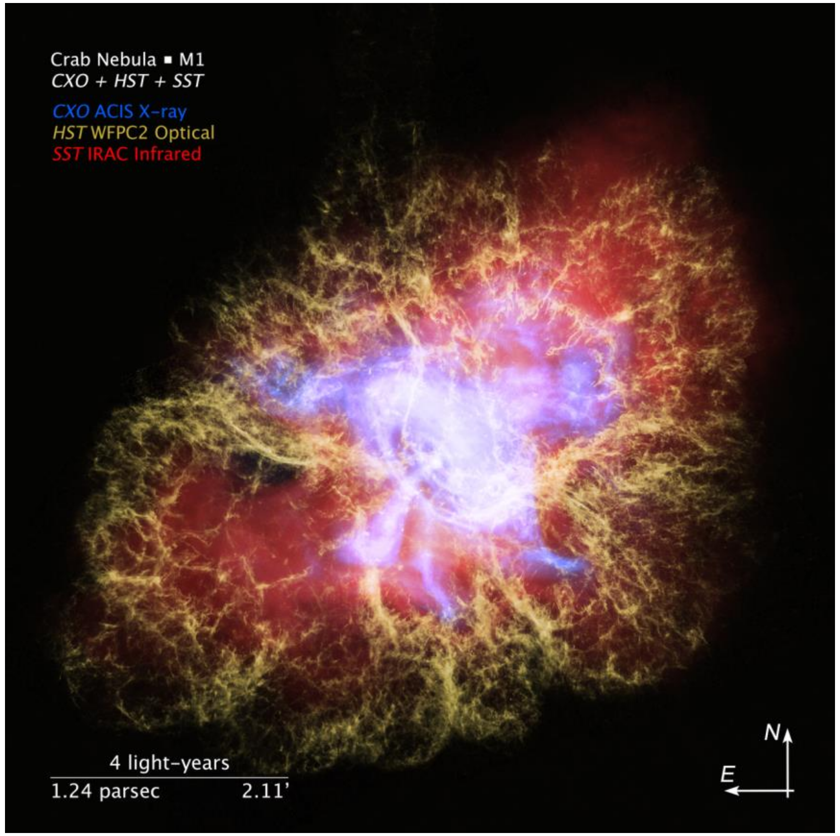
Diversity in BH formation and associated transients



平安人は見た

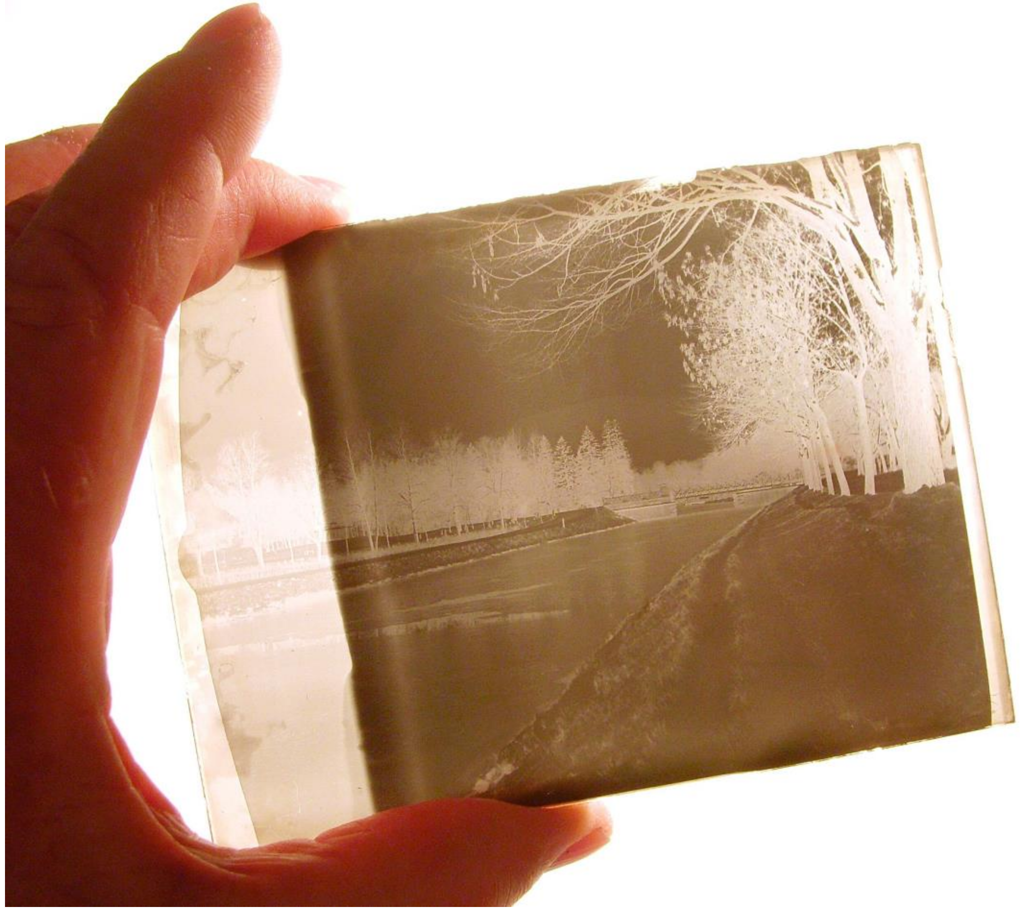
後冷泉院 天喜二年 四月中旬以降 丑時
客星觜参度 見東方 孛天関星 大如歳星
「明月記」

“かに超新星” SN1054の今の姿

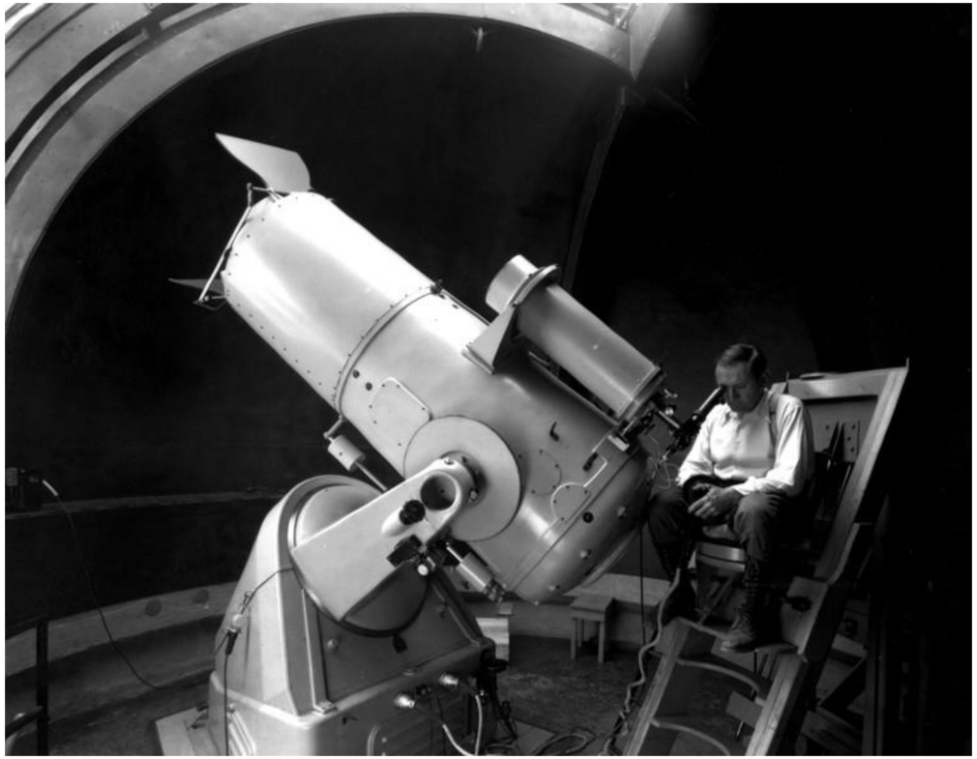


Credit : NASA, ESA, J. DePasquale (STScI), and R. Hurt (Caltech/IPAC)

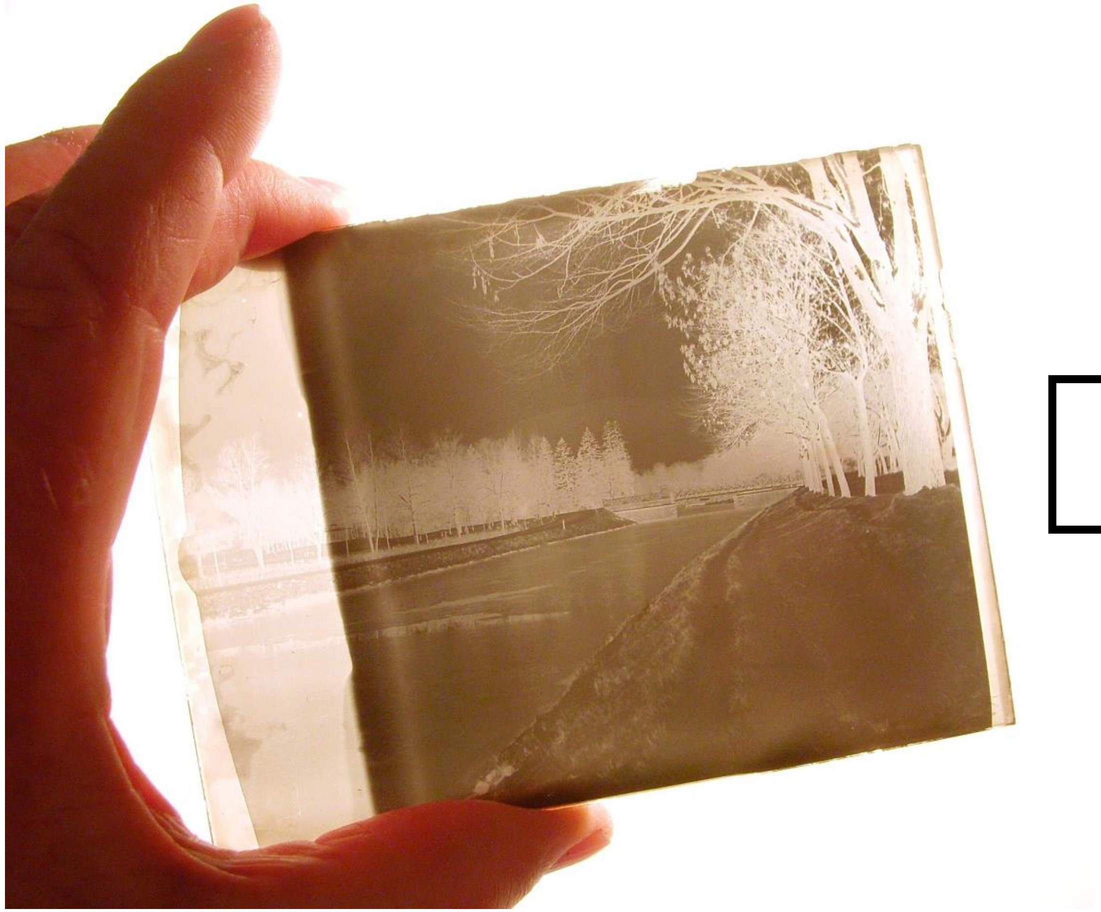

後冷泉院天喜二年四月中旬以後丑時客星出觜参度見東方孛天関星大如歳星

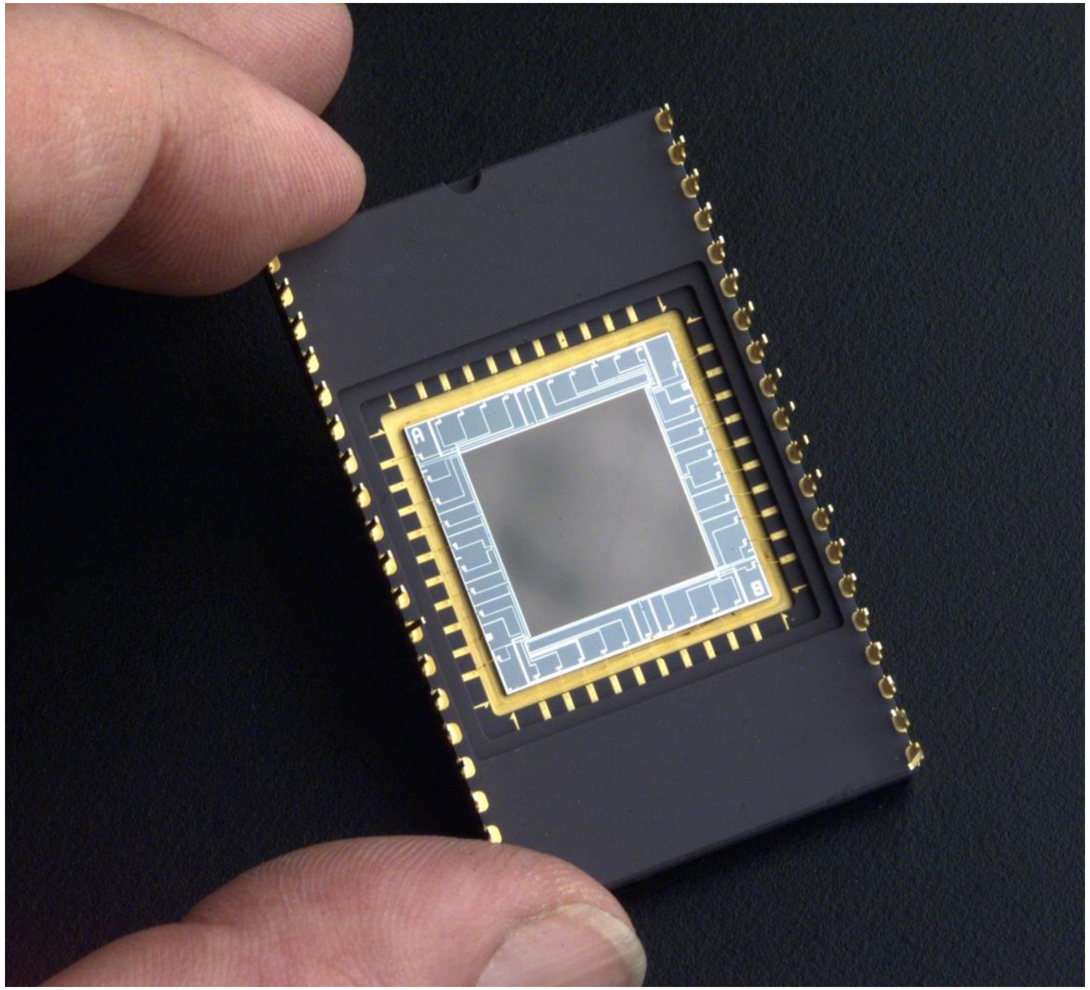


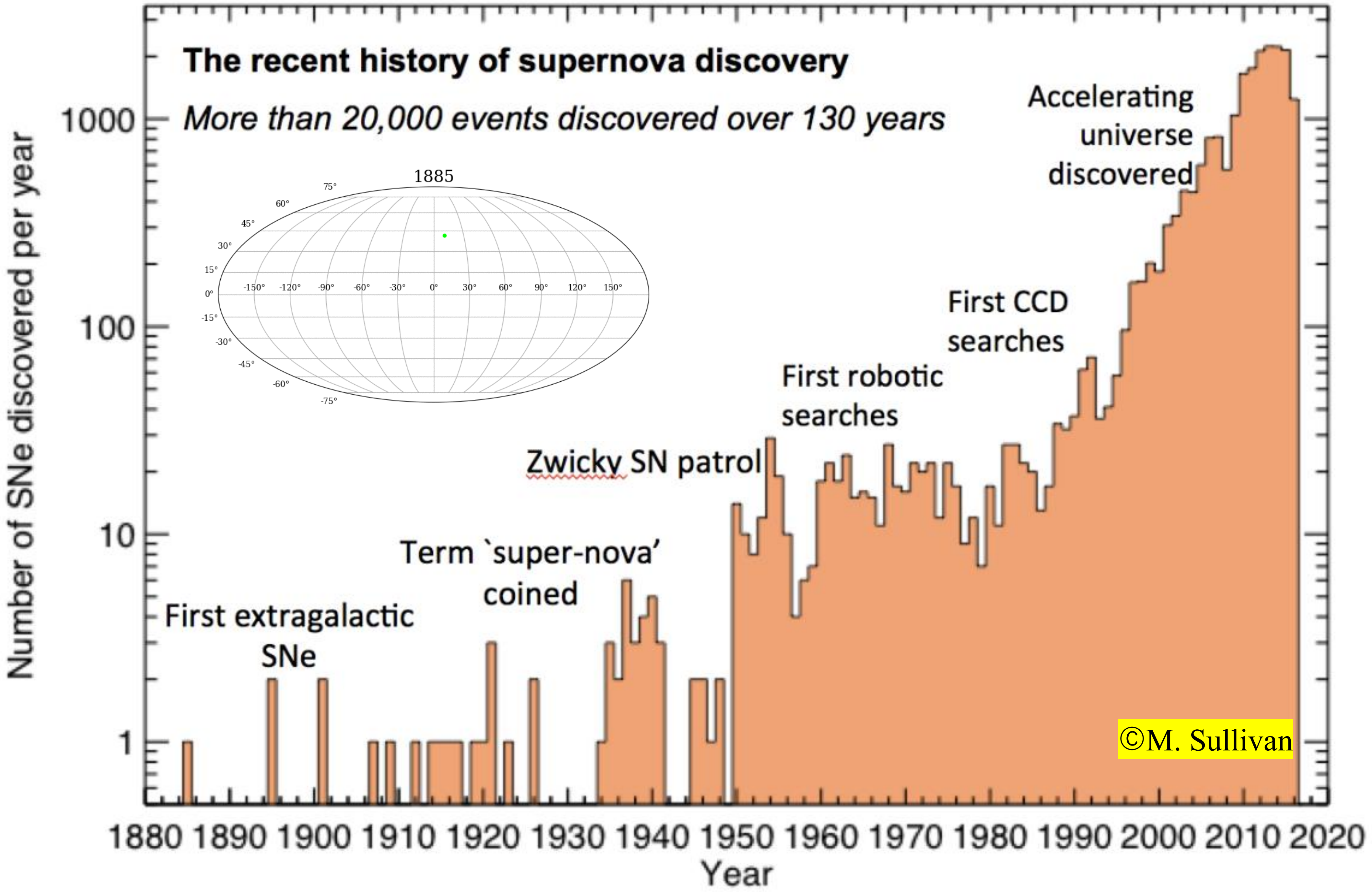
Zwicky SN patrol



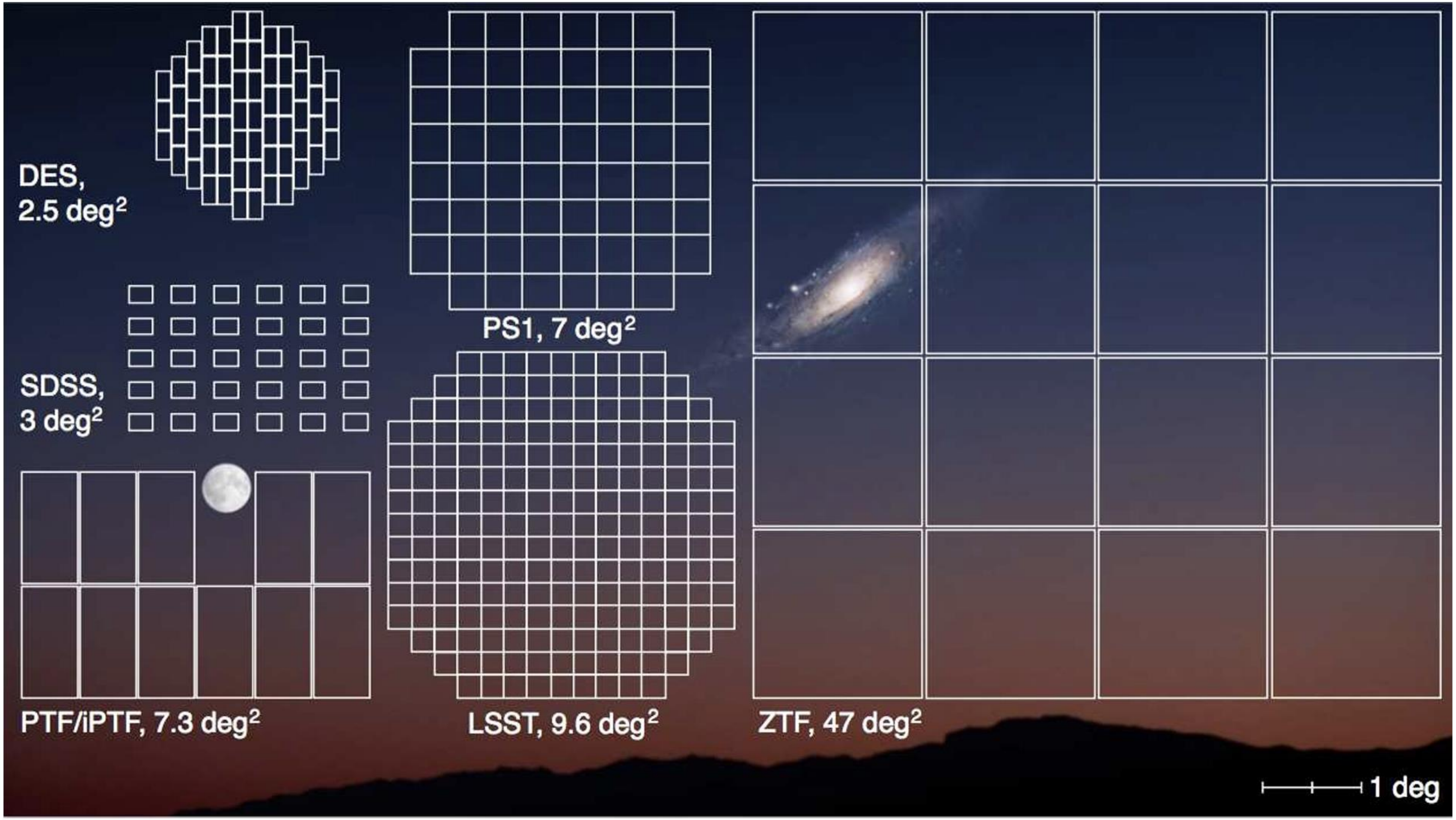
Credit: Palomar Observatory/Caltech



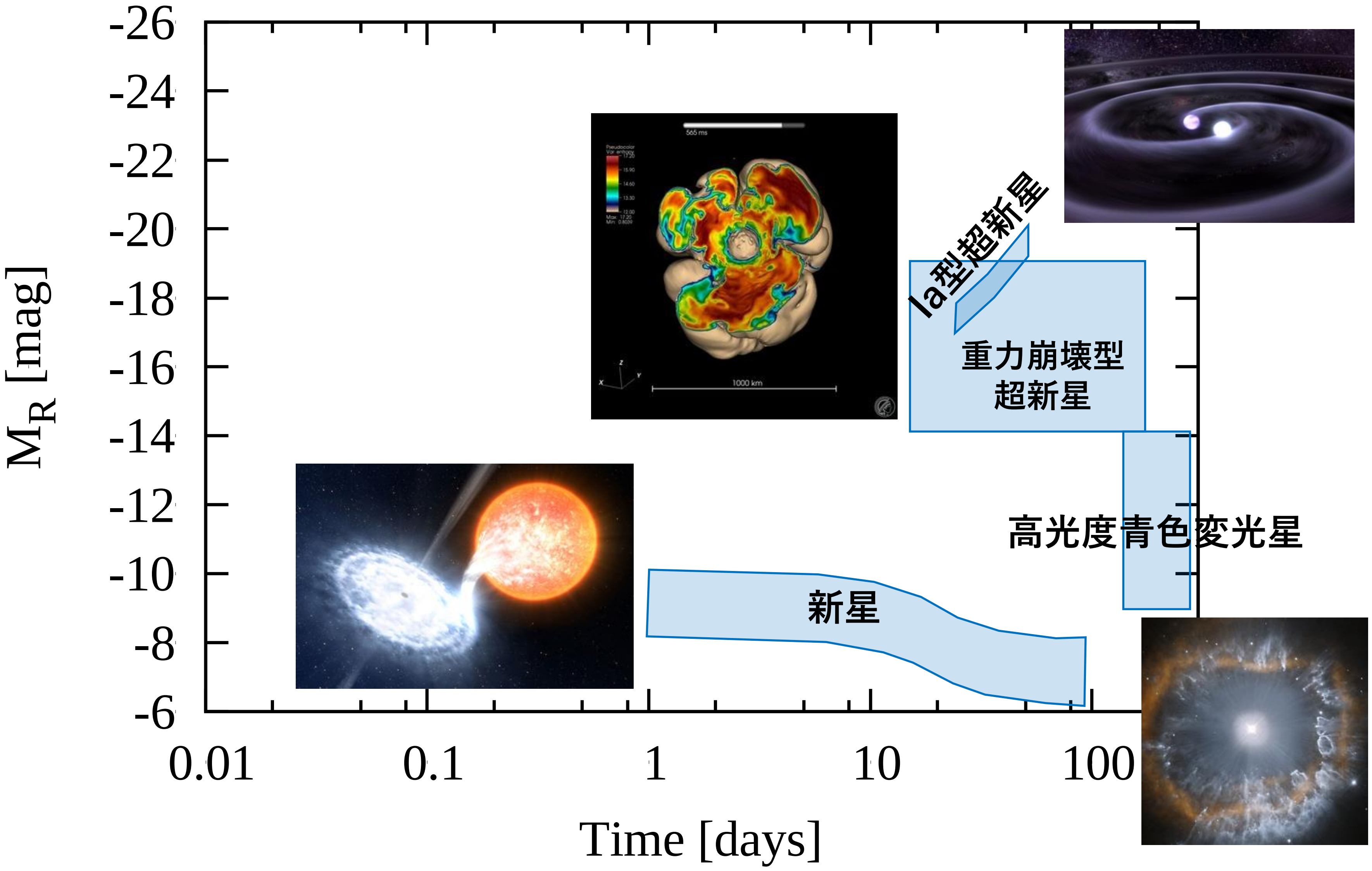




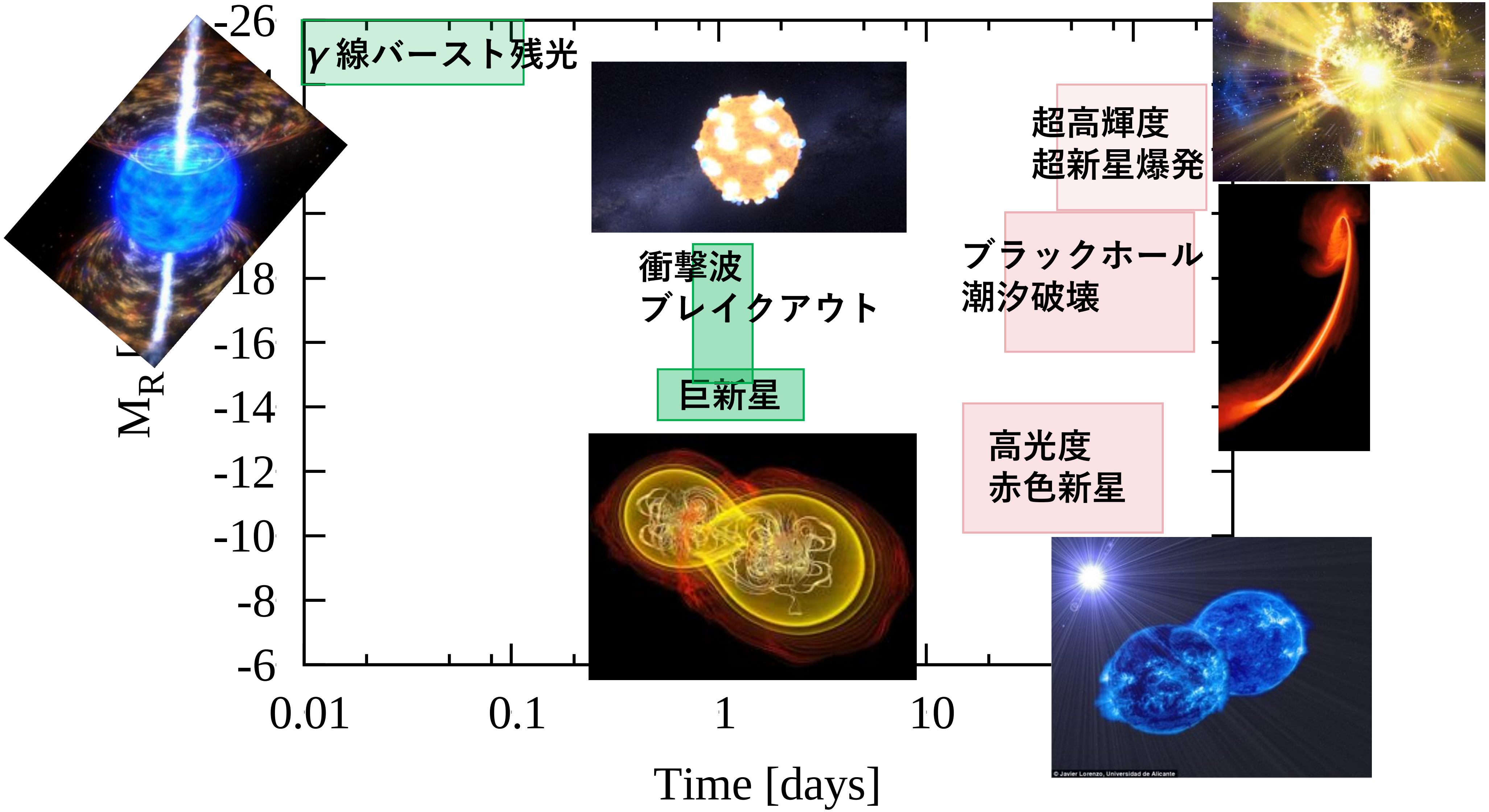
The recent history of supernova discovery
More than 20,000 events discovered over 130 years
1885
First extragalactic SNe
Term `super-nova' coined
Zwicky SN patrol
First robotic searches
First CCD searches
Accelerating universe discovered
©M. Sullivan
Number of SNe discovered per year
Year


DES,
2.5 deg²
PS1, 7 deg²
SDSS,
3 deg²
PTF/iPTF, 7.3 deg²
LSST, 9.6 deg²
ZTF, 47 deg²
1 deg

可視光突発天体動物園（数10年前）

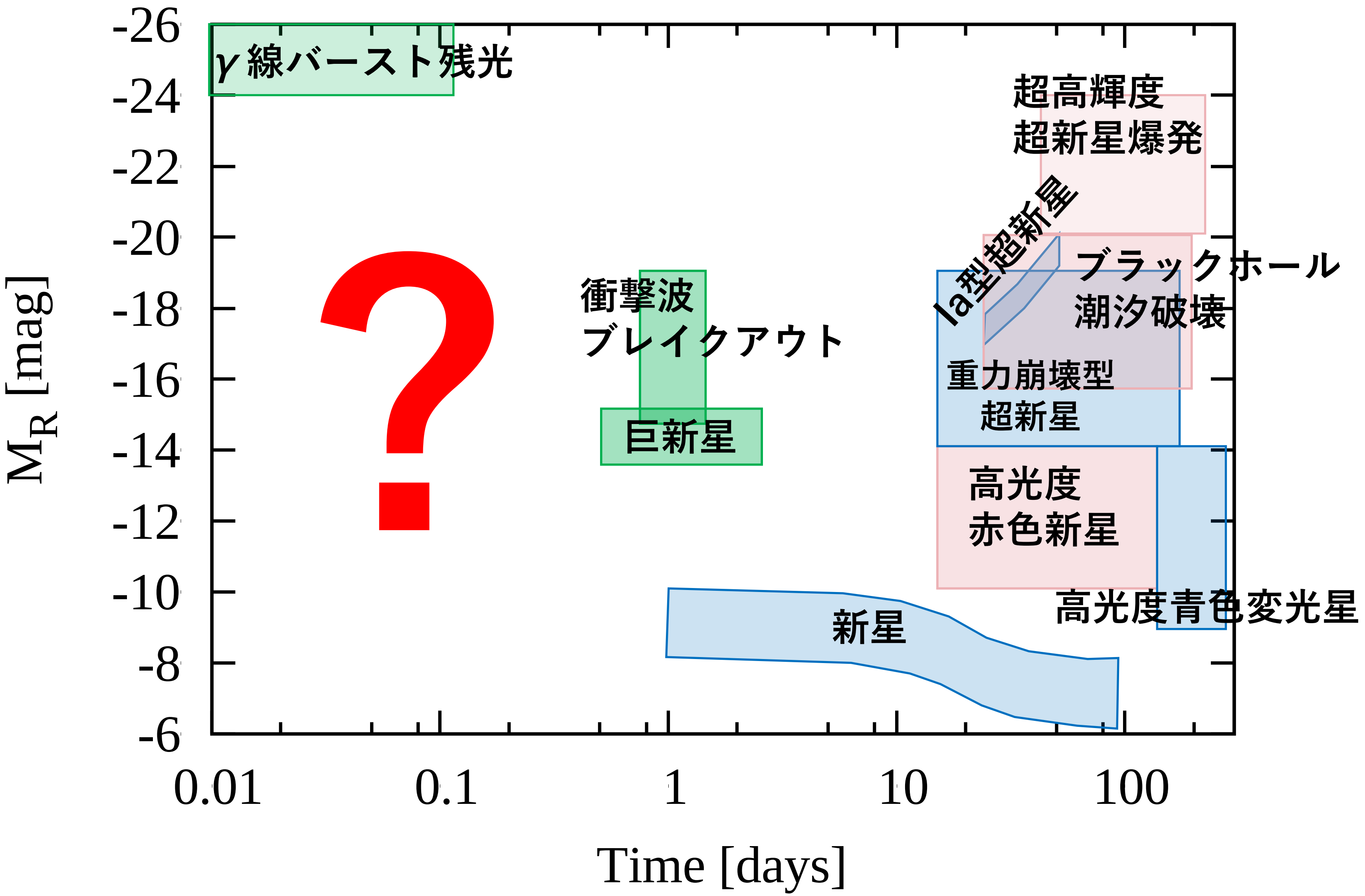


可視光突発天体動物園（現在）



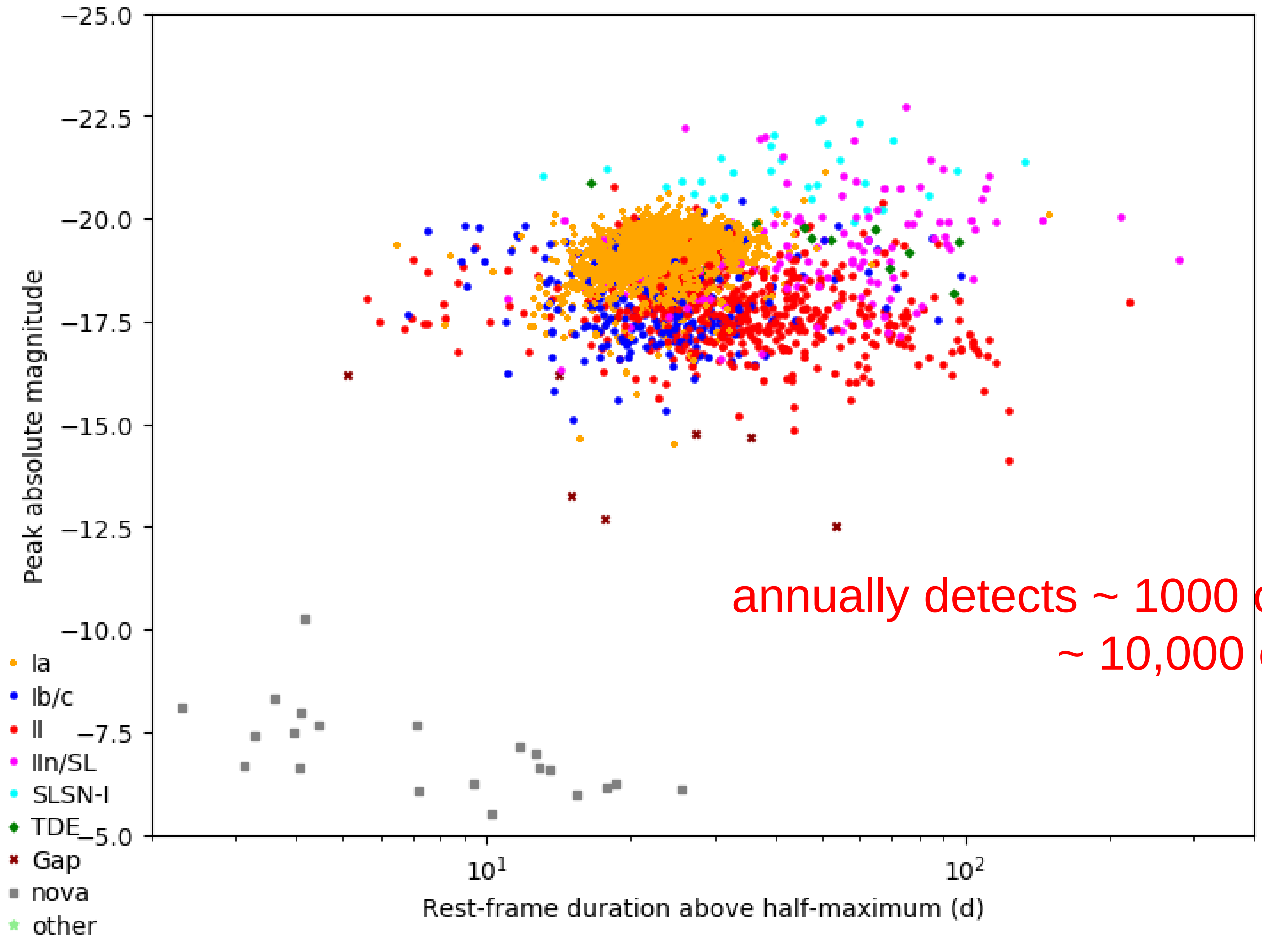
遠くのレアで明るい天体 or 近くの暗い天体 or 速い天体の発見が相次ぐ

突発天体動物園（近未来）



より深く、より速く、より広く

e.g., The ZTF Bright Transient Survey



annually detects ~ 1000 of bright extragalactic transients
~ 10,000 of not-so-bright transients

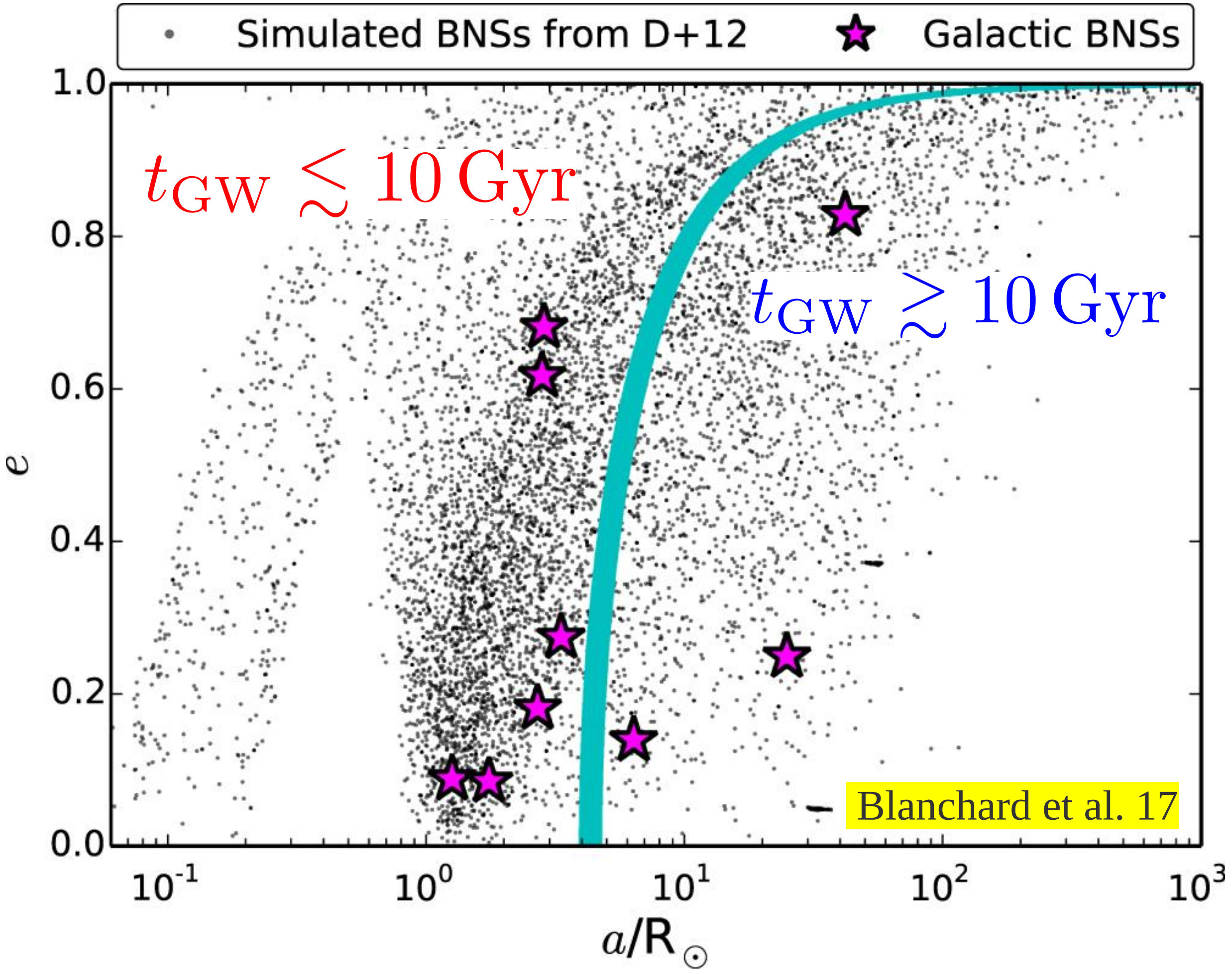
- SN rate ~ 1/100 yr^{-1} gal^{-1}
- BNS rate ~ 1/10^5 yr^{-1} gal^{-1}

~1/1000 of them would be related to births of compact binary objects, but which one?

The birth of binary compact objects

1. ultra-stripped supernovae

It takes time for a BNS /NS-BH merger

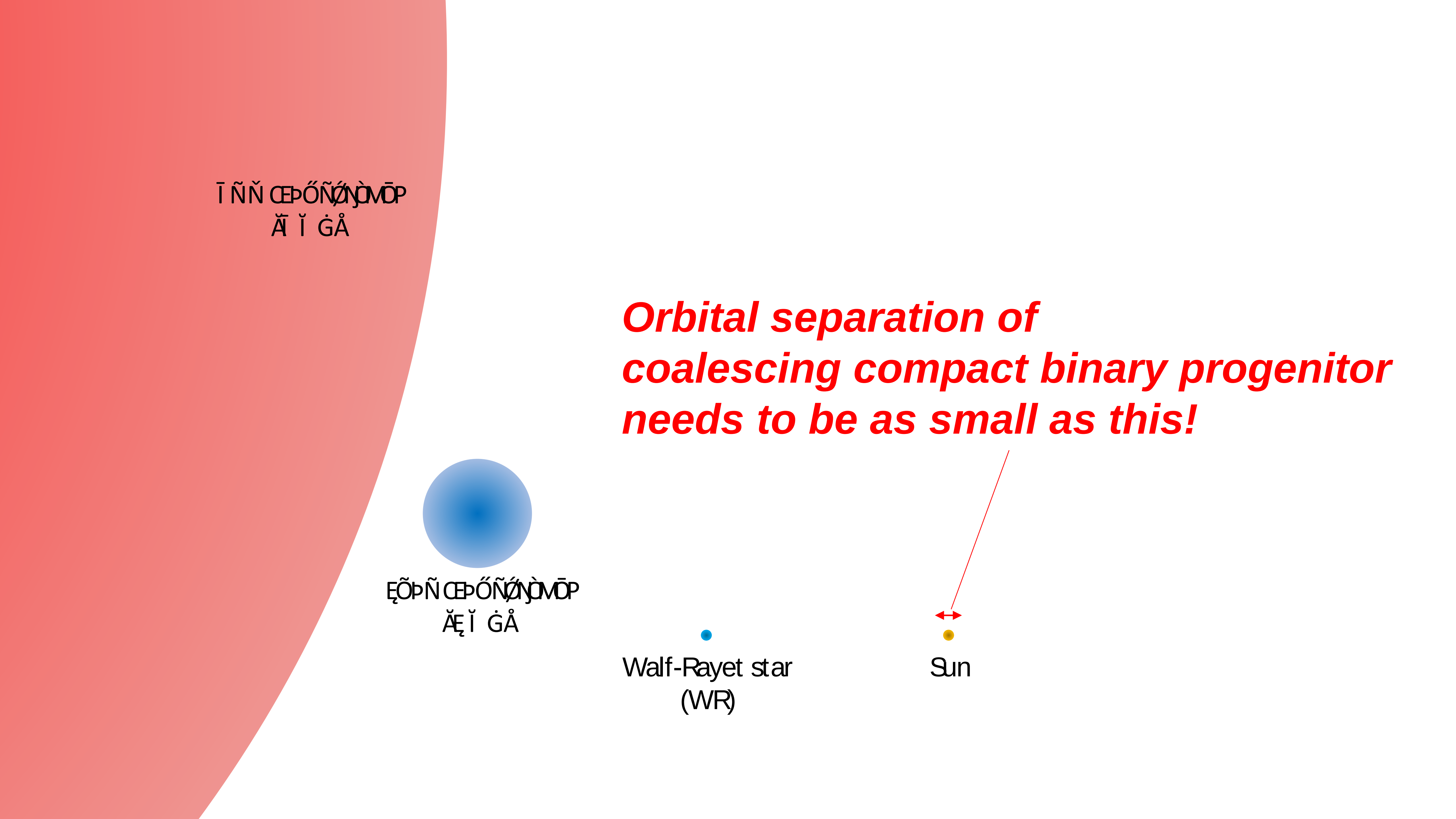


c.f.,

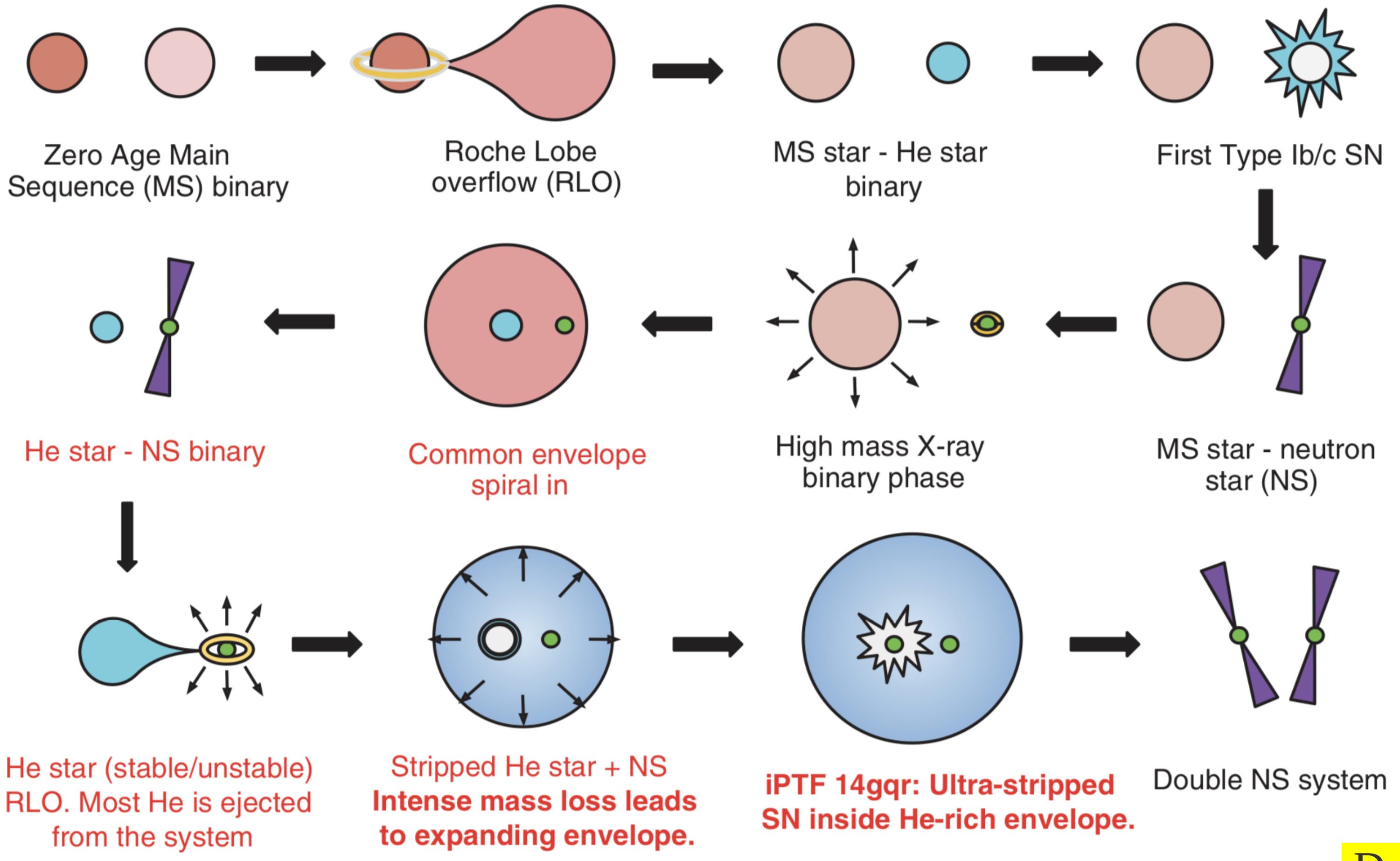
$$t_{\rm gw} \sim 0.16\,{\rm Gyr}\, a_{11}^4 \left(\frac{\mu}{0.7\,M_\odot}\right)^{-1} \left(\frac{m}{2.8\,M_\odot}\right)^{-2} (1-e^2)^{7/2}$$

$$P_{\rm orb} \sim 0.1\,{\rm day}\, a_{11}^{3/2} \left(\frac{m}{2.8\,M_\odot}\right)^{-1/2}$$

To merge within a cosmological time, the orbital separation at birth needs to be comparable to the solar radius

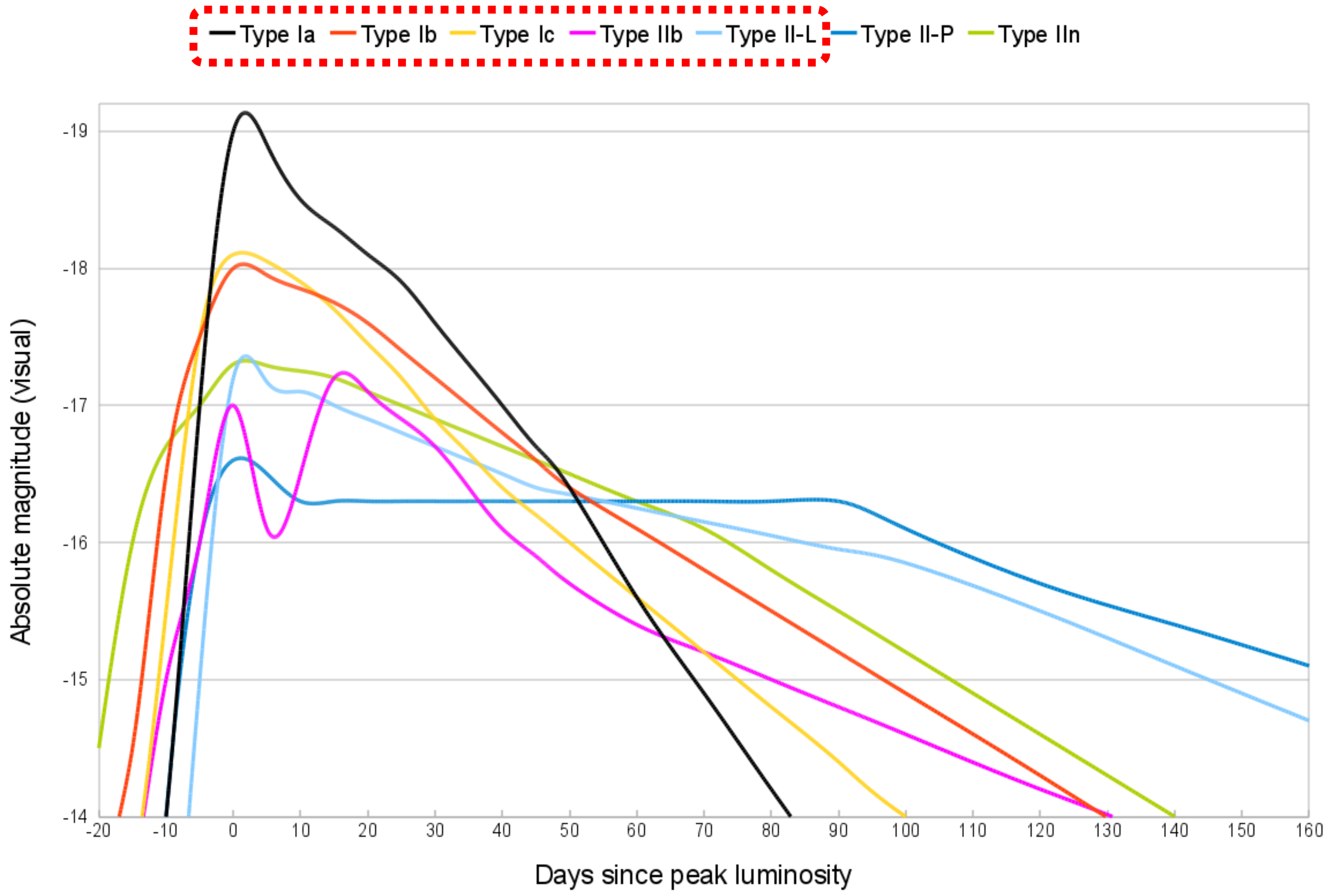

Orbital separation of
coalescing compact binary progenitor
needs to be as small as this!
Walf-Rayet star
(WR)
Sun

Binary neutron star (BNS) formation and ultra-stripped supernovae (USSNe)



De et al. 18

SN light curves powered by ^{56}Ni decay



$$\dot{Q}(t) = f_{\rm dep} \cdot (M_{\rm Ni}\ \ q_{\rm Ni}(t))$$

$$q_{\rm Ni}(t) = \epsilon_{\rm Ni} \cdot e^{-t/\tau_{\rm Ni}} + \epsilon_{\rm Co} \cdot e^{-t/\tau_{\rm Co}}$$

where $\epsilon_{\rm Ni} = 3.22 \times 10^{10}$ erg g^{-1} s^{-1} and $\epsilon_{\rm Co} = 6.78 \times 10^{9}$ erg g^{-1} s^{-1} are the specific decay energy of ^{56}Ni and ^{56}Co, and $\tau_{\rm Ni} = 8.8$ day and $\tau_{\rm Co} = 113.6$ day are the mean lifetimes of ^{56}Ni and ^{56}Co, respectively.

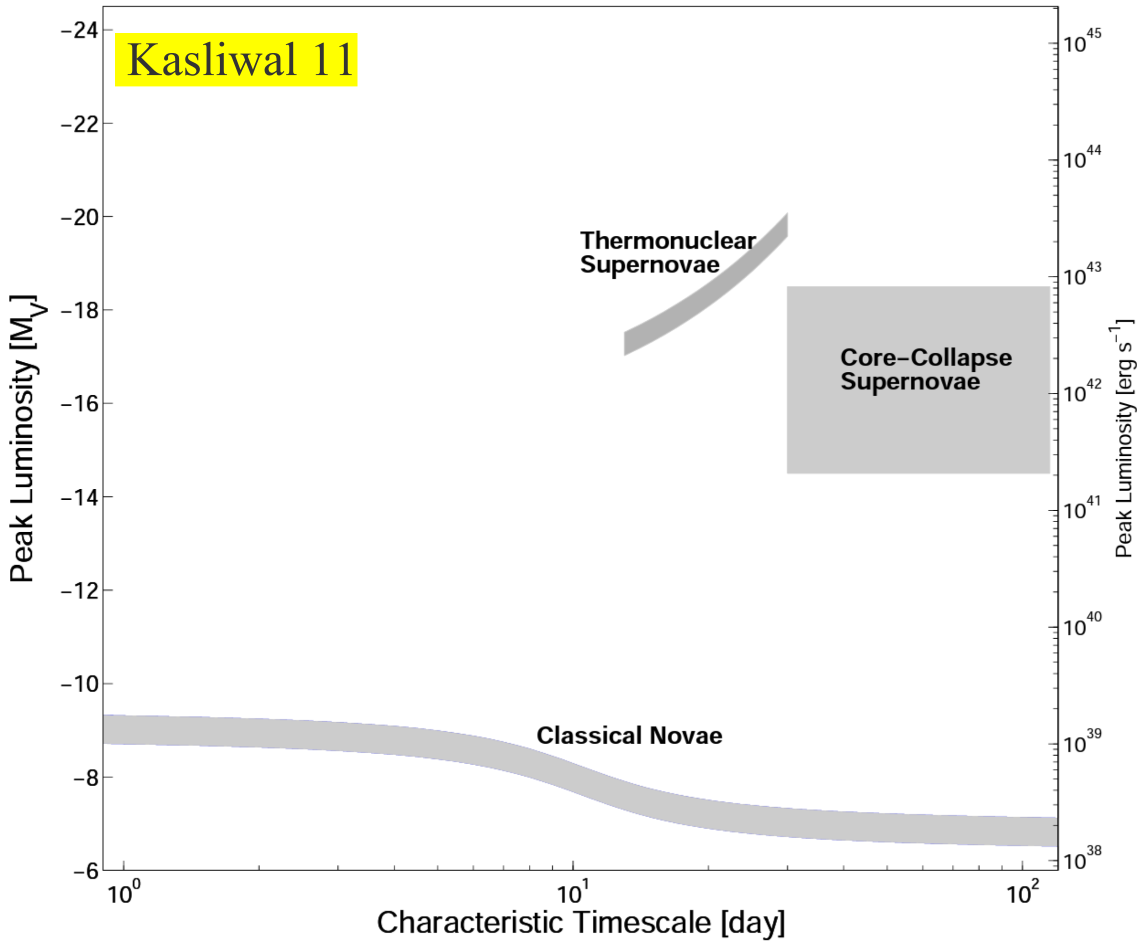
$$L_{\rm opt,peak} \sim 7.8 \times 10^{41}\,{\rm erg\,s^{-1}}\,M_{^{56}{\rm Ni},-2}$$

$$t_{\rm opt,peak} \approx (3\kappa_{\rm sc} M_{\rm ej}/4\pi c v_{\rm ej})^{1/2}$$
$$\sim 6.5\,{\rm day}\,\kappa_{{\rm sc},-0.7}^{1/2} M_{{\rm ej},-1}^{1/2} v_{{\rm ej},9}^{-1/2}$$

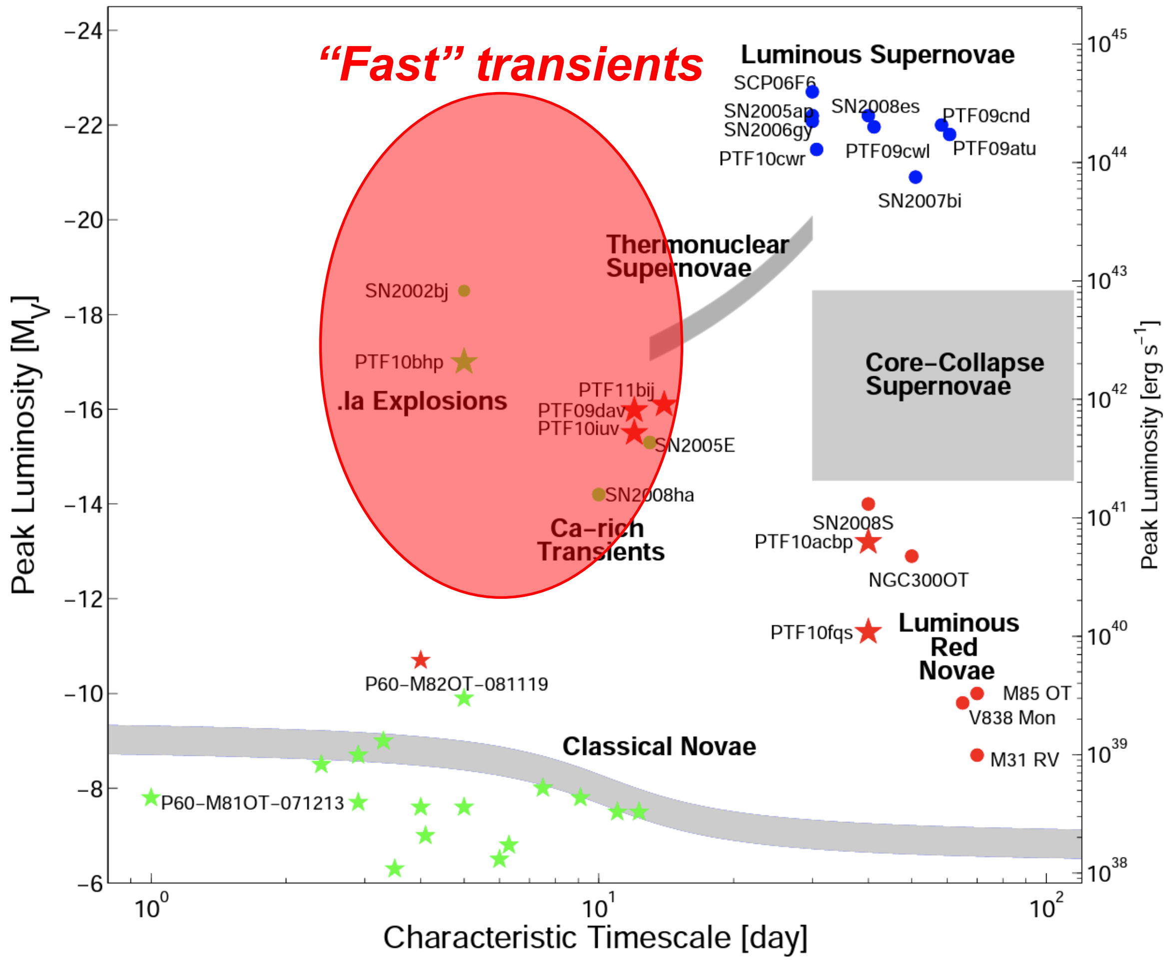
ultra-stripped → low ejecta mass → "fast" light curve

A frontier of the time-domain astronomy

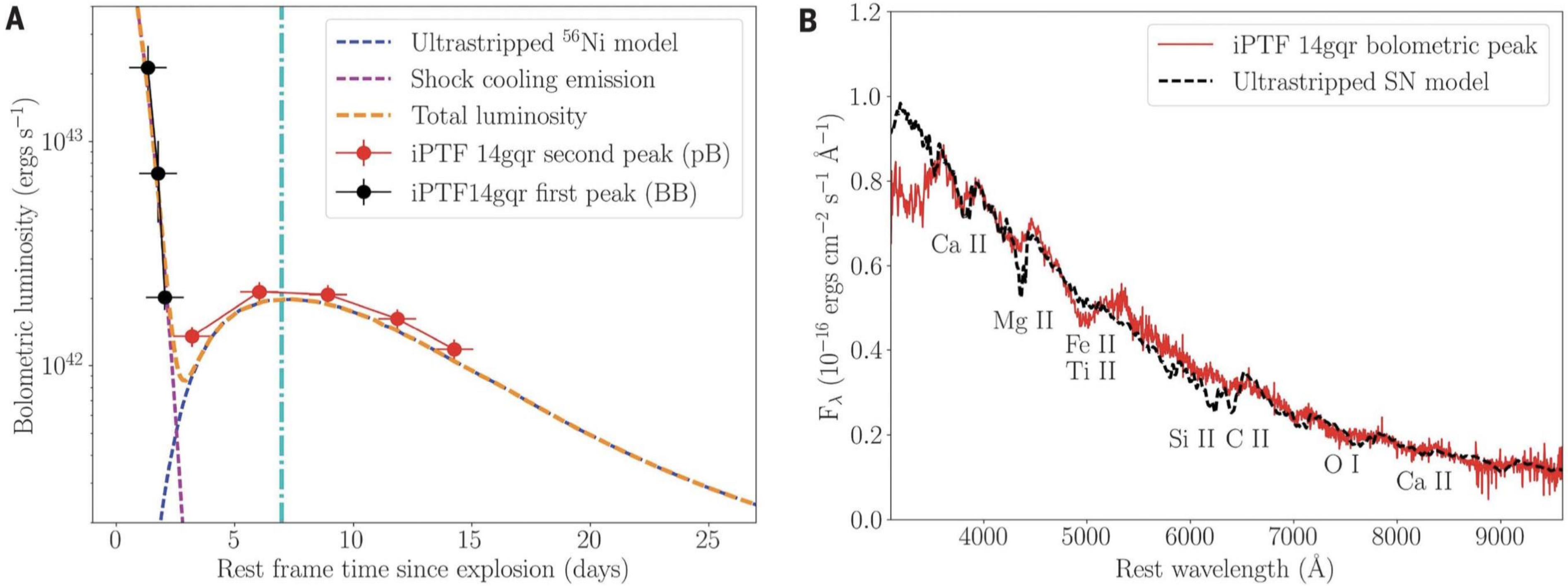
before ~ 2005



after ~2010

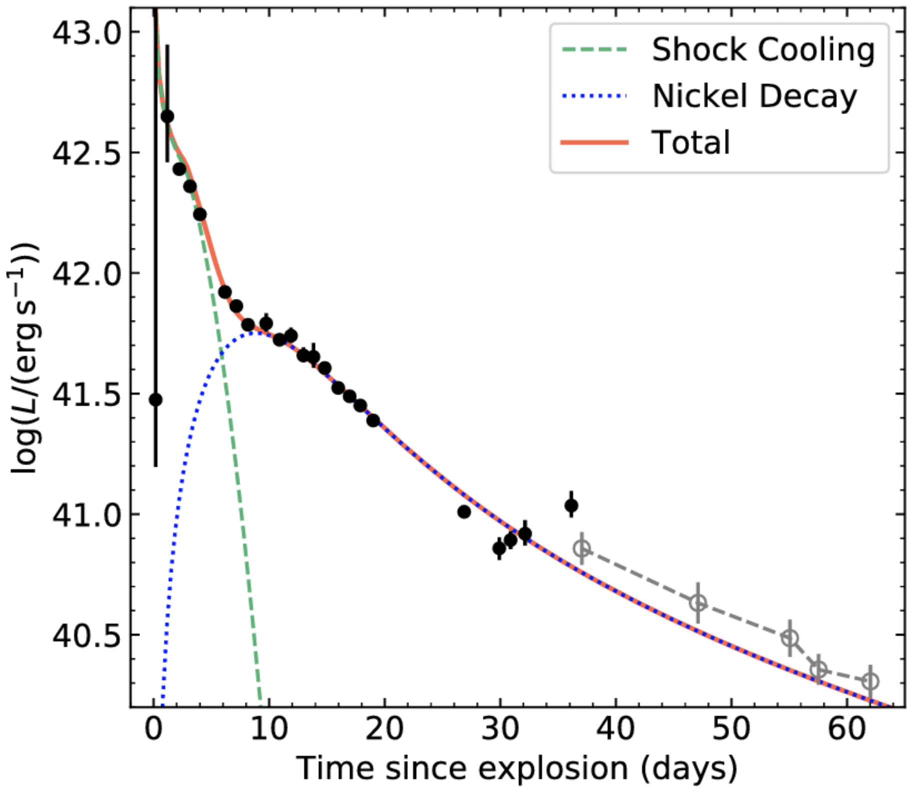


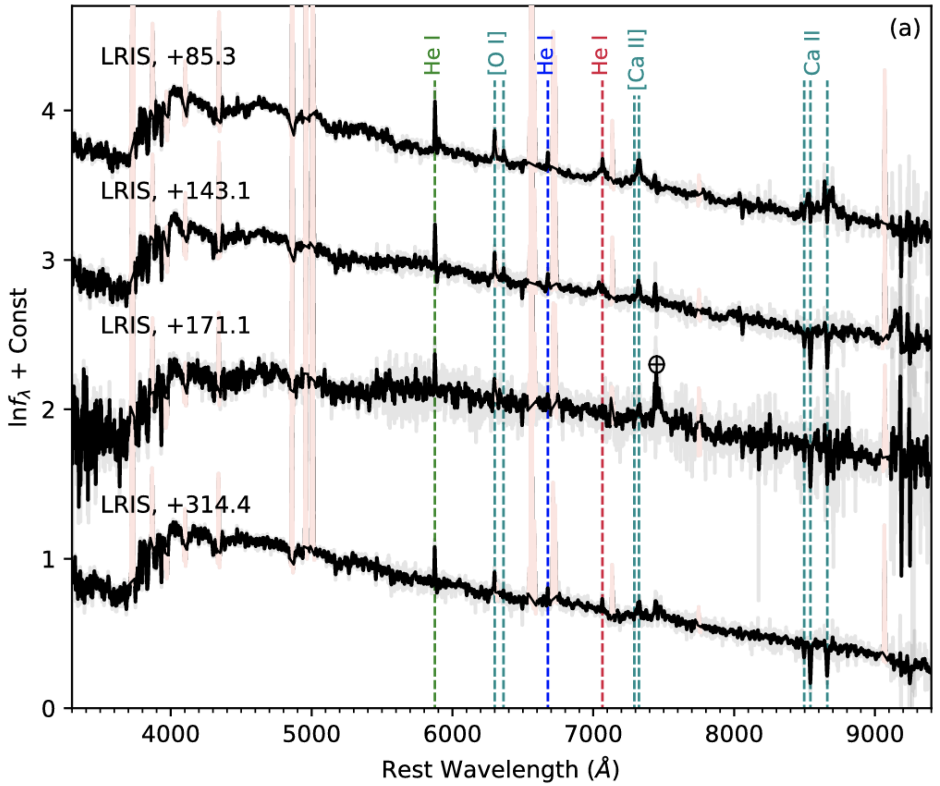
e.g., iPTF 14gqr



*E*ŒÕ Š ČŔĈĆ^DĆ ÑØÑÆ*M*ÑÓ Š ĆBČ *M*ŒÞÕÆ*M*ÍÒ Š ĆBĆD *M*ŒÞÕ De et al. 18

e.g., SN2019edg

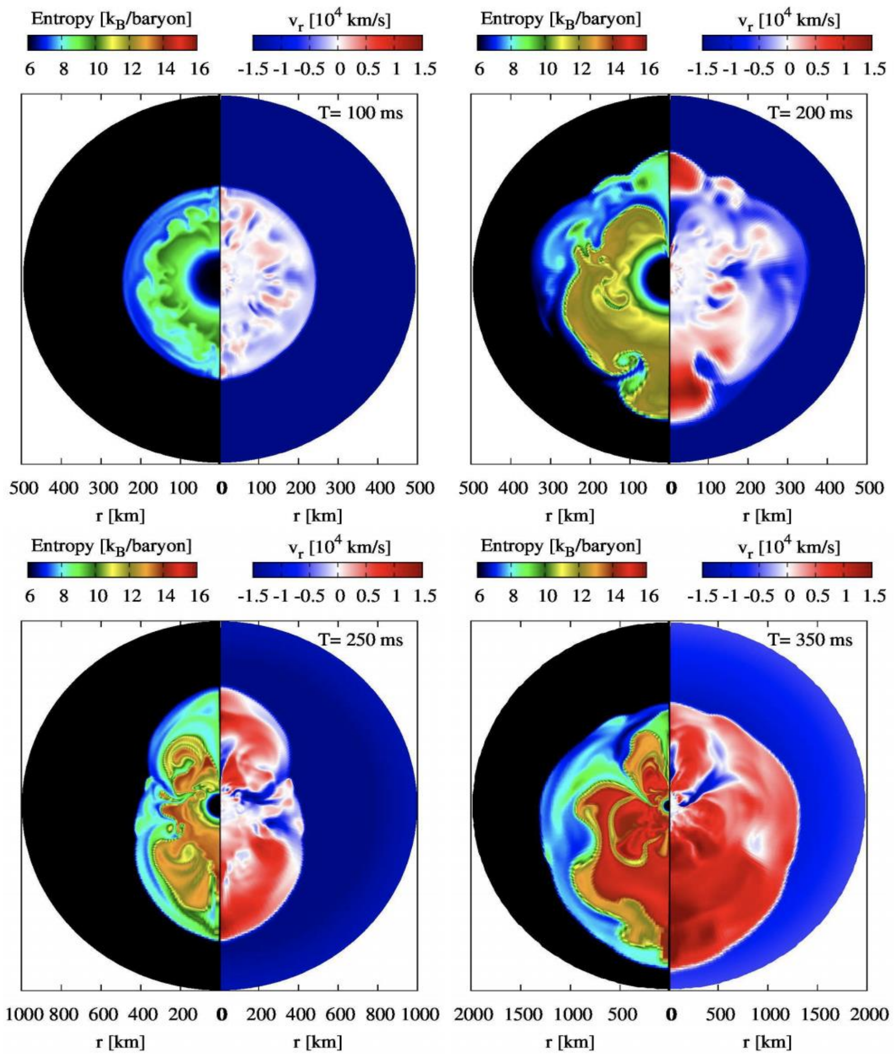




E_{sn} ~ 1.3x10^{50} erg, M_{ej} ~ 0.3 M_{sun}, M_{Ni} ~ 0.017 M_{sun} Yao et al. 20

Note that USSN rate ~ 10^{-3} yr^{-1}gal^{-1} >> *BNS merger rate* ~ 10$^{-(4-5)}$ yr^{-1}gal^{-1}

USSN explosion



Suwa et al. 15

Axisymmetric hydrodynamics simulations with spectral neutrino transport

"successful explosions driven by neutrino heating"

$$E_{sn} \sim 10^{50}\ \text{erg},\ M_{ej} = \text{a few} \times 0.1\ M_{sun}$$

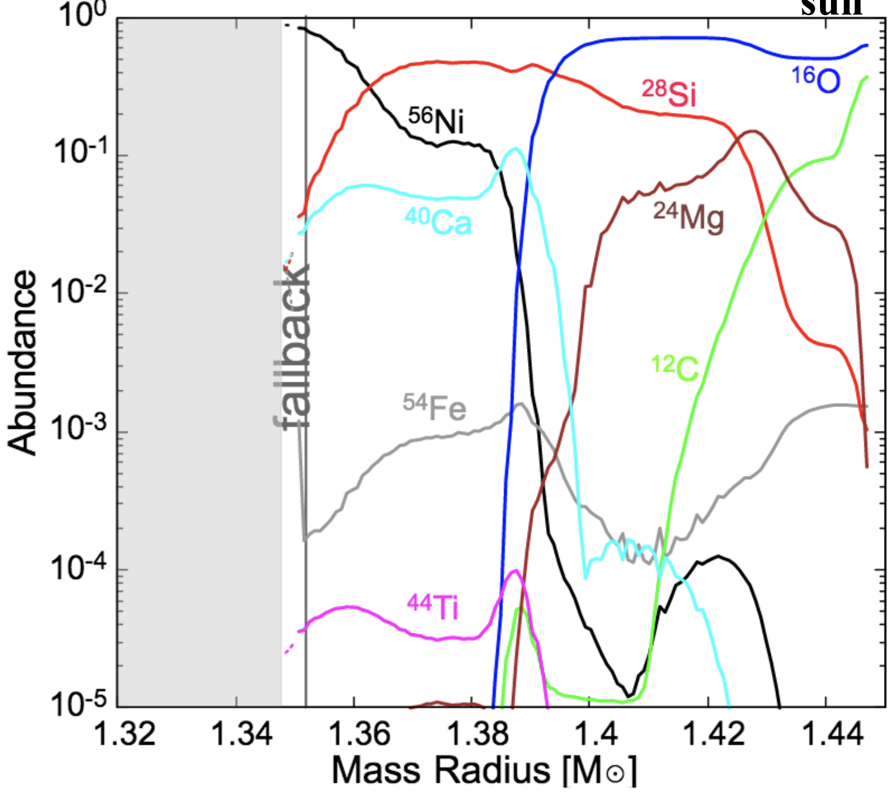
- The explosion energy and ejecta mass are broadly consistent with those inferred from the observations.
- How about the Ni mass?

Explosive nucleosynthesis in USSNe

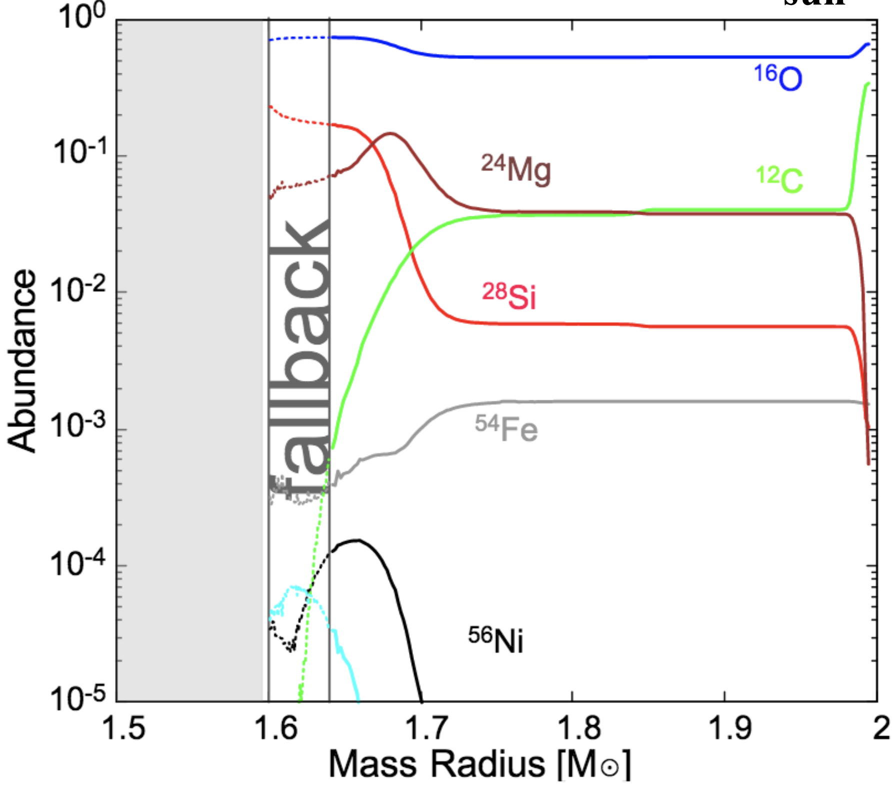
Long-term explosion simulations of ultra-stripped progenitors with various masses based on results of Suwa et al.15, and consistently calculate the nucleosynthesis and the SN light curves.

Sawada et al. 22

CO core mass = 1.45 M_{sun}



CO core mass = 2.0 M_{sun}

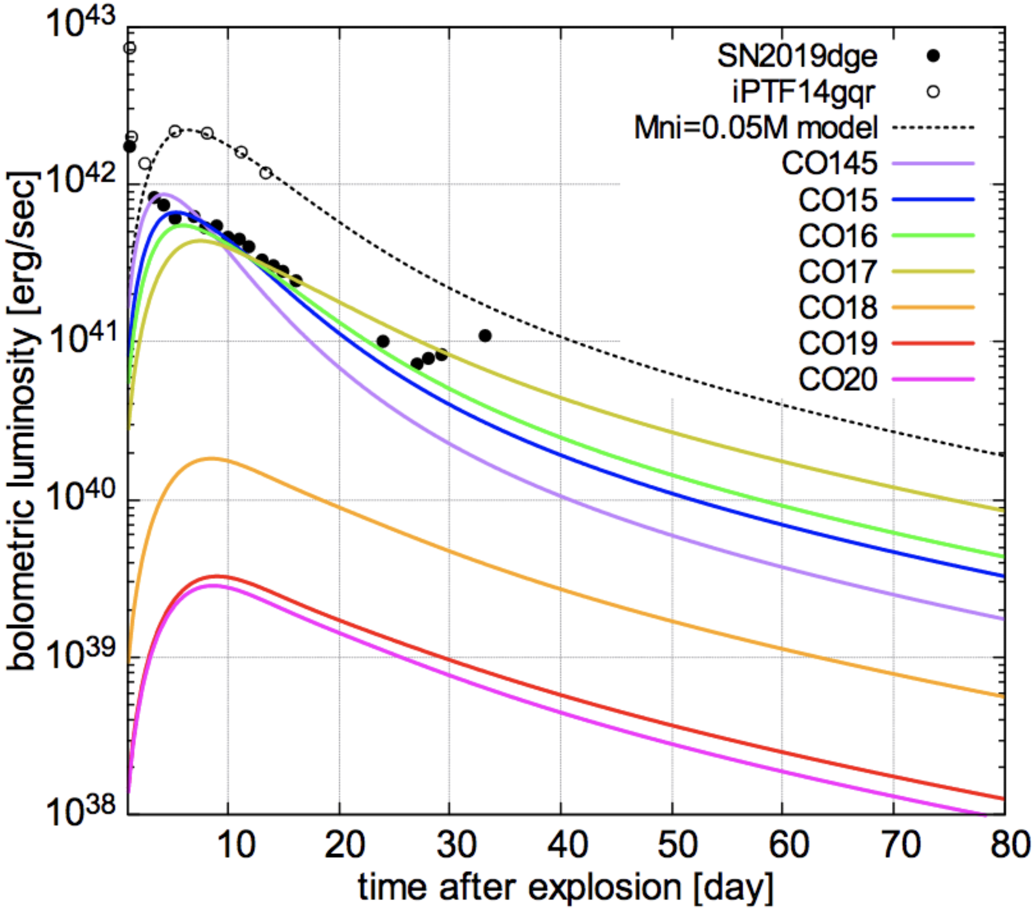


$M_{Ni} \sim 0.017\ M_{sun}$

$M_{Ni} \sim 10^{-4}\ M_{sun}$

^{56}Ni problem (also) in USSNe?

Sawada et al. 22



✓ ***SN2019dge-like event***

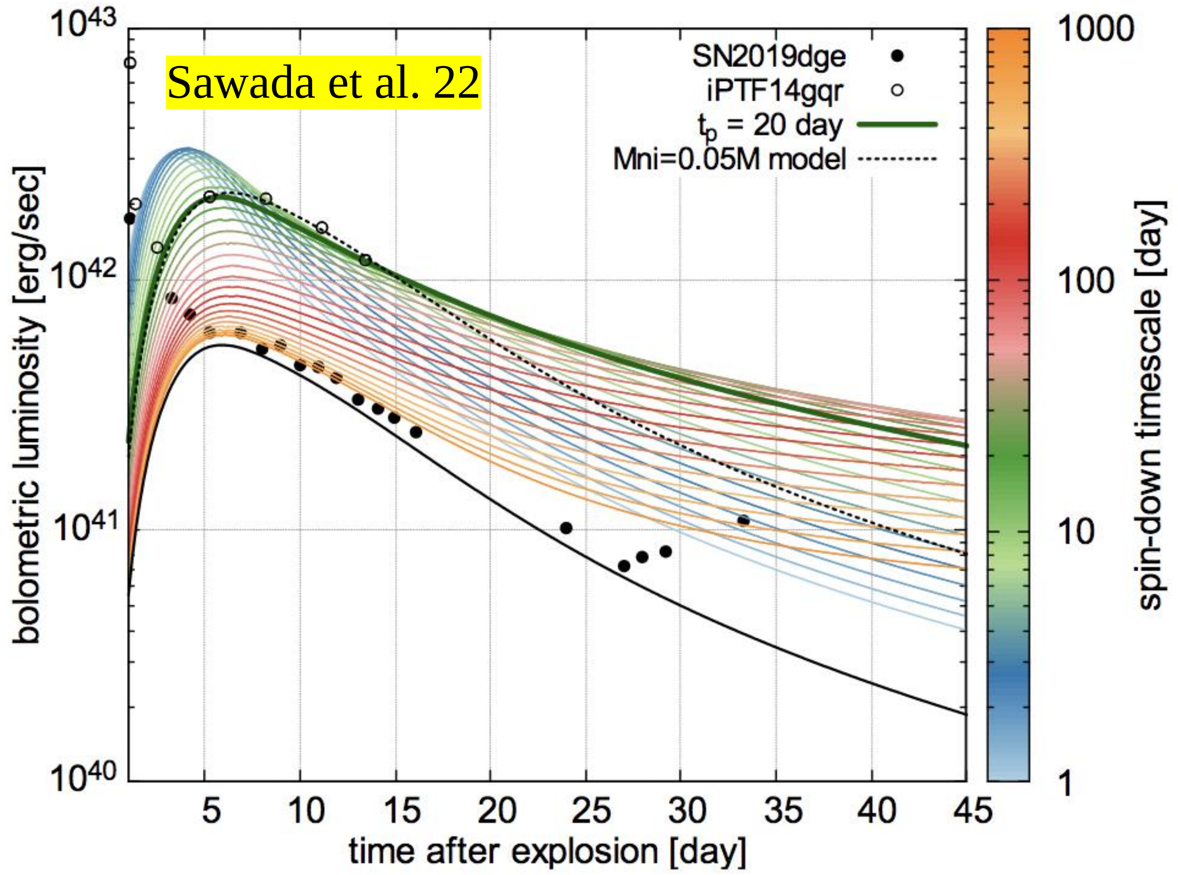
- $M_{\mathrm{Ni,obs}}$ ~ 0.017 M_{sun}
- Everything is consistent with the "standard" model
- (except for the bump at ~ month?)

✓ ***iPTF14gqr-like event***

- $M_{\mathrm{Ni,obs}}$ ~ 0.05 M_{sun}
- No model can synthesize and eject such a large amount of ^{56}Ni.

- The models are not good enough?
- Or an alternative energy source?

An additional energy source = the newborn NS spin-down luminosity?



$$\dot{Q}_{\rm p}(t) = \frac{E_p}{t_p}\frac{1}{(1+t/t_p)^2},$$

$$E_p = 2 \times 10^{50} P_{10}^{-2}\ \mathrm{erg}, \quad t_p = 0.44\, B_{14}^{-2} P_{10}^{2}\ \mathrm{yr}$$

✓ *iPTF14gqr is compatible with an USSN with an NS with B ~ 10^{15} G and P ~ 0.1 sec.*

✓ *Magnetar formation is common in USSNe?*

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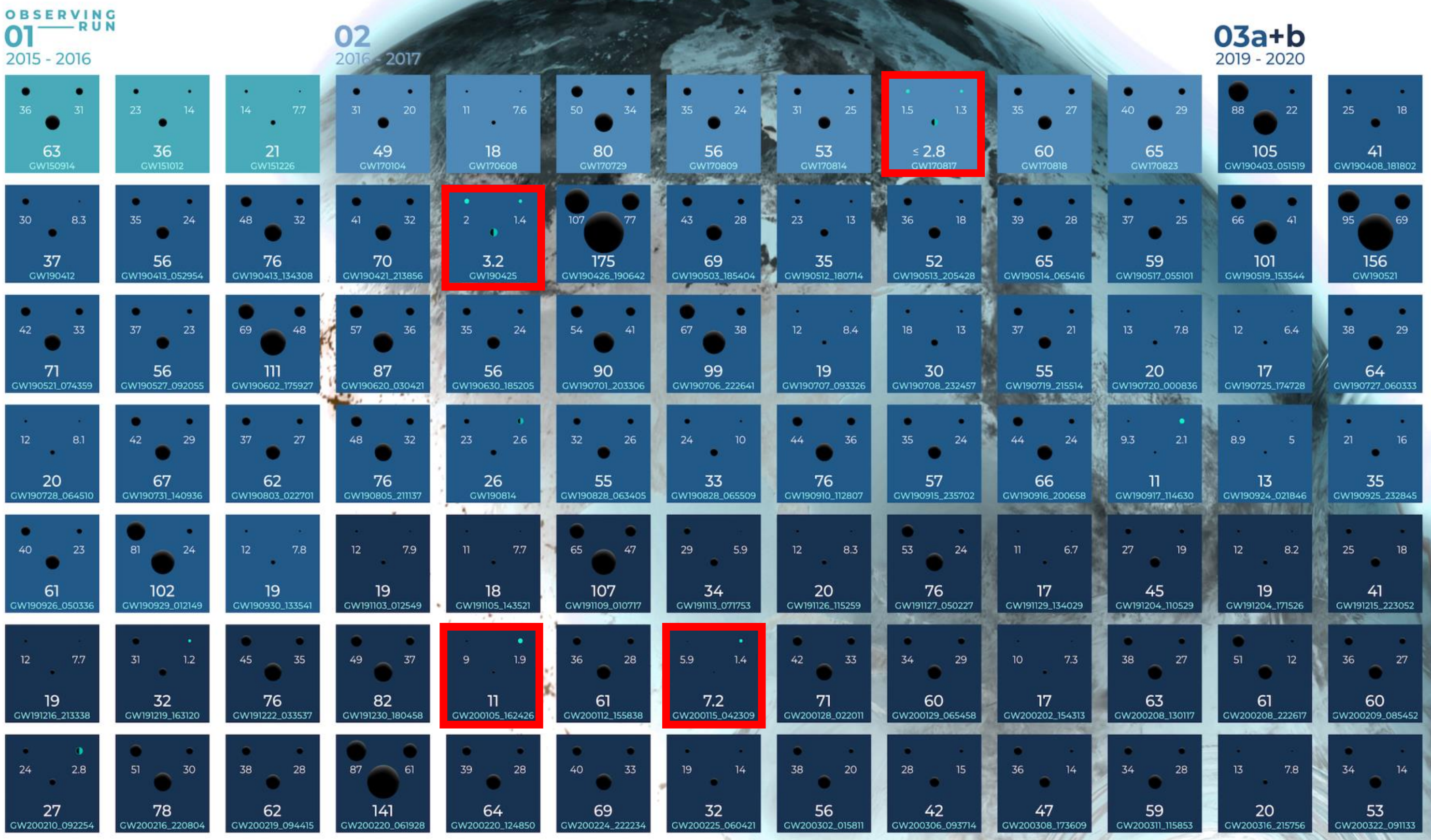
2. X-raying?

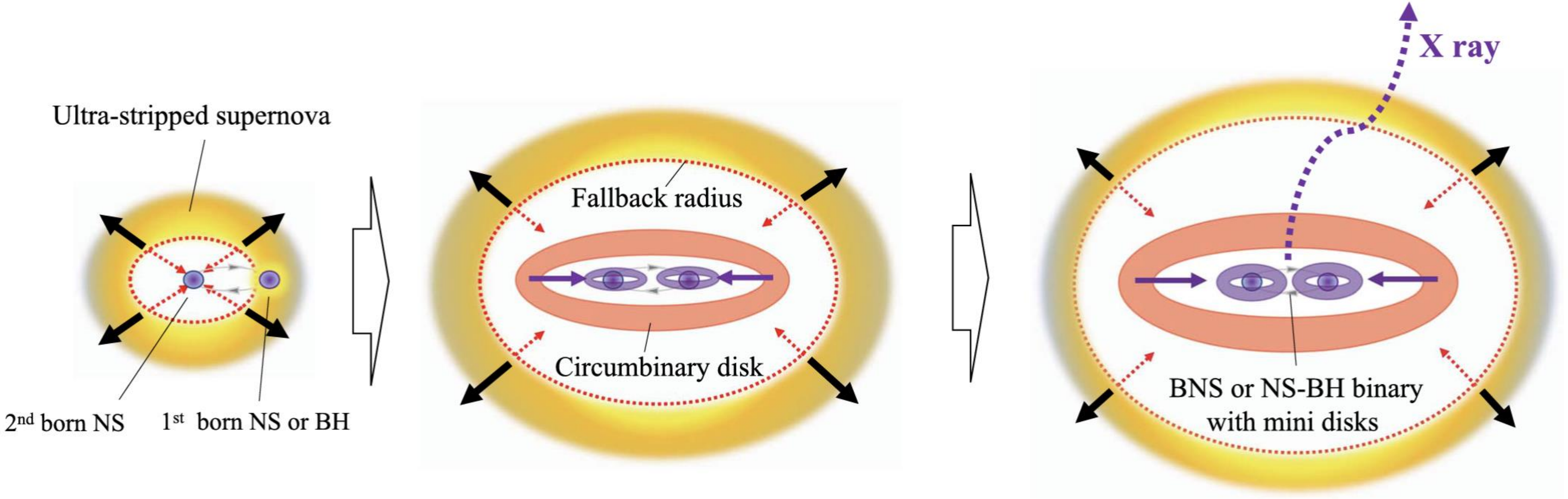


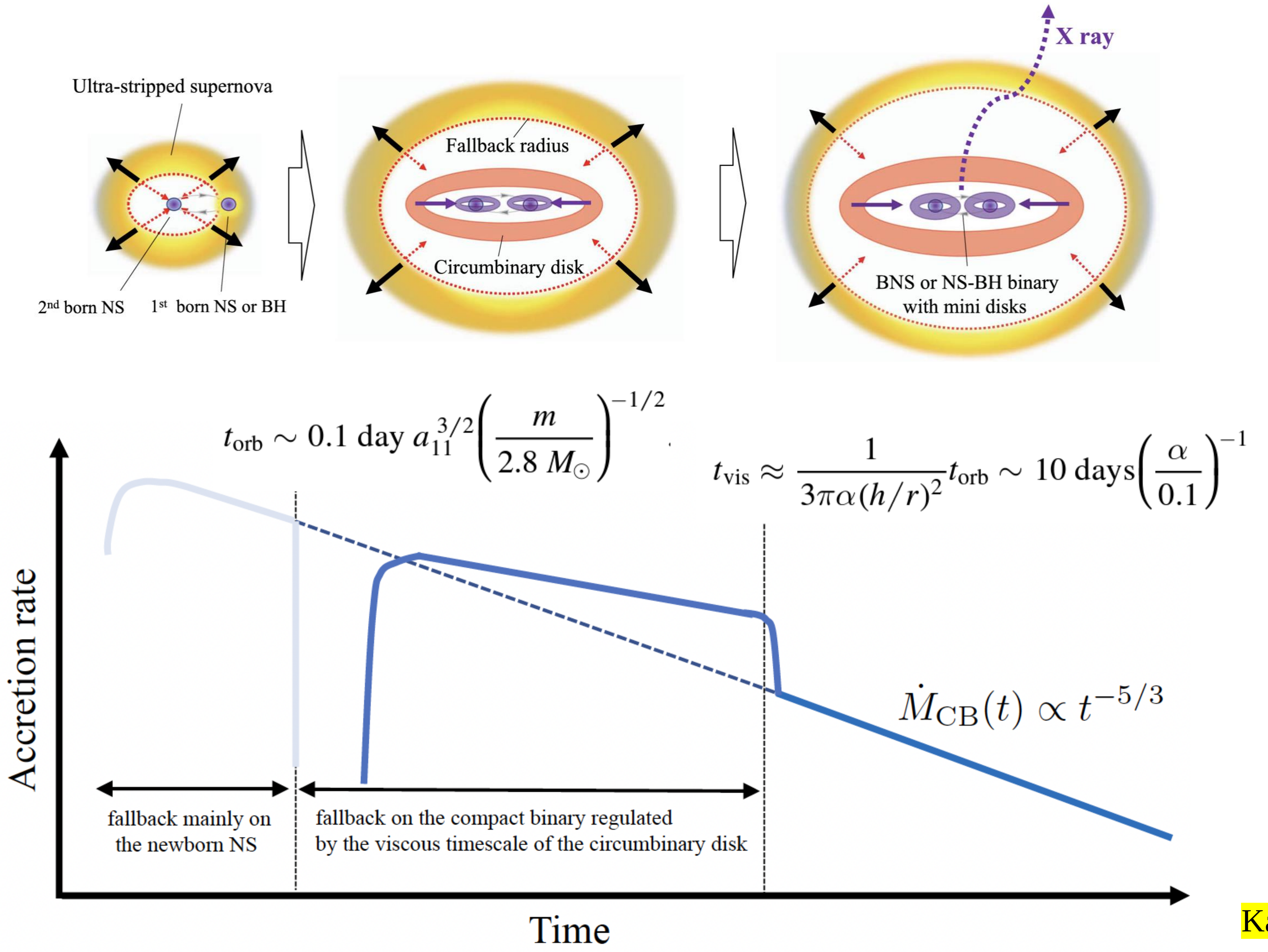
How, when, and where the progenitor system is formed?
What are the properties of the NSs at the binary formation?

OK, probably they are born with USSNe.
But what are the smoking gun?

Fallback accretion onto the newborn BNS

Kashiyama et al. 22



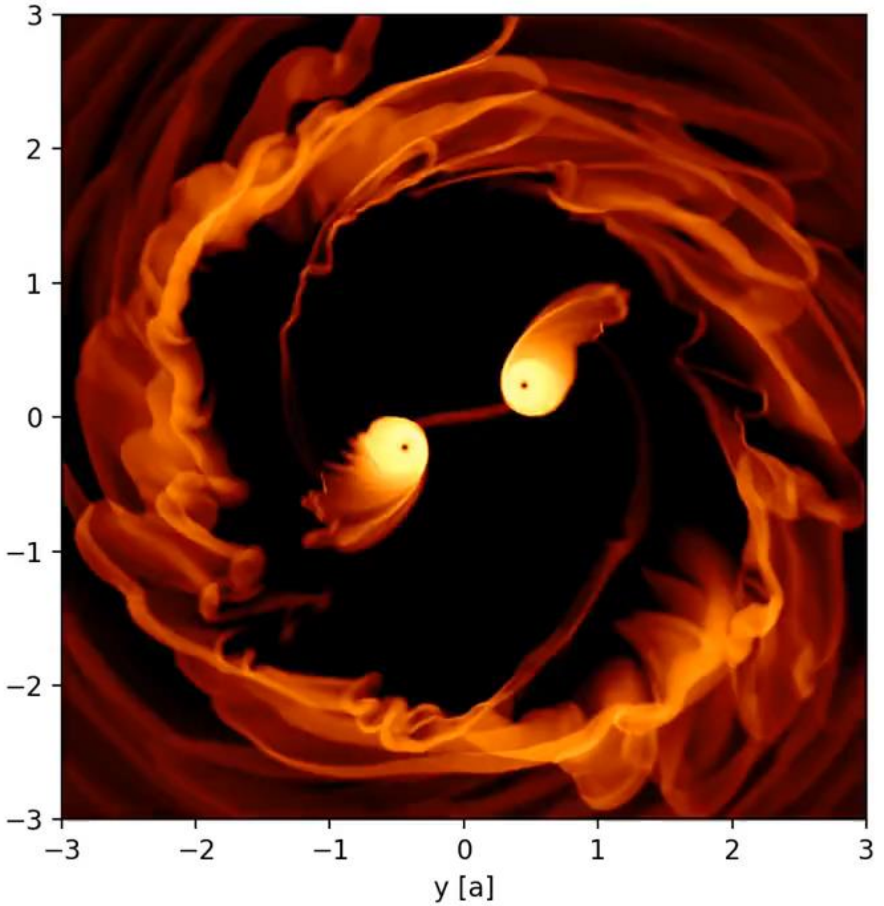


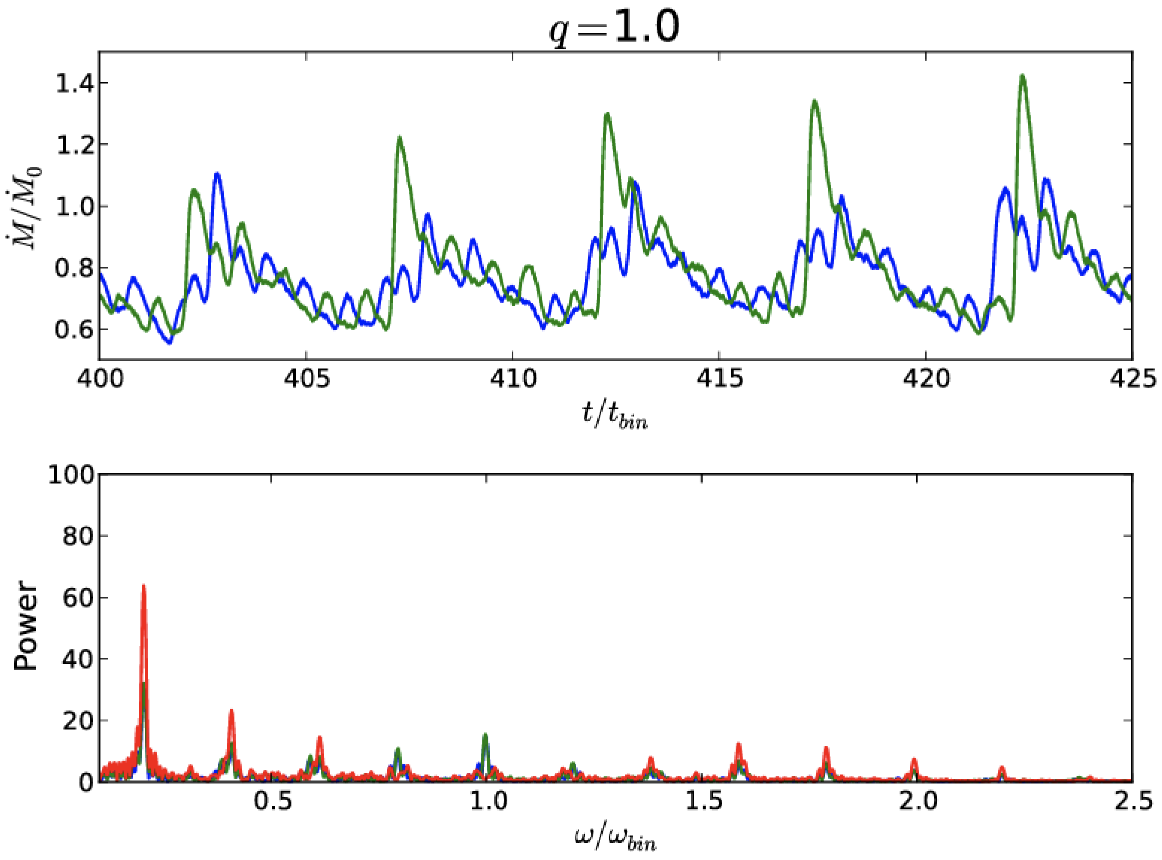
Kashiyama et al. 22

Accretion onto binary → orbital modulation

dr. Jordy Davelaar @jordydavelaar · 1月27日

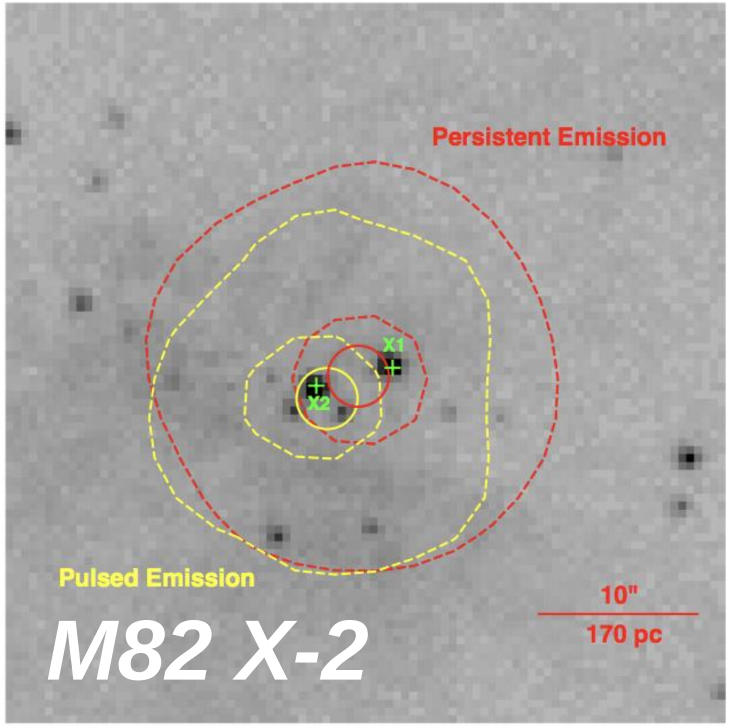
This week we started a new project led by grad student Luke Krauth at Columbia to study hydro simulations of binary black holes. The first test simulation we ran looks already stunning! Material from a larger circumbinary disk plunges to the black holes rotating in the center



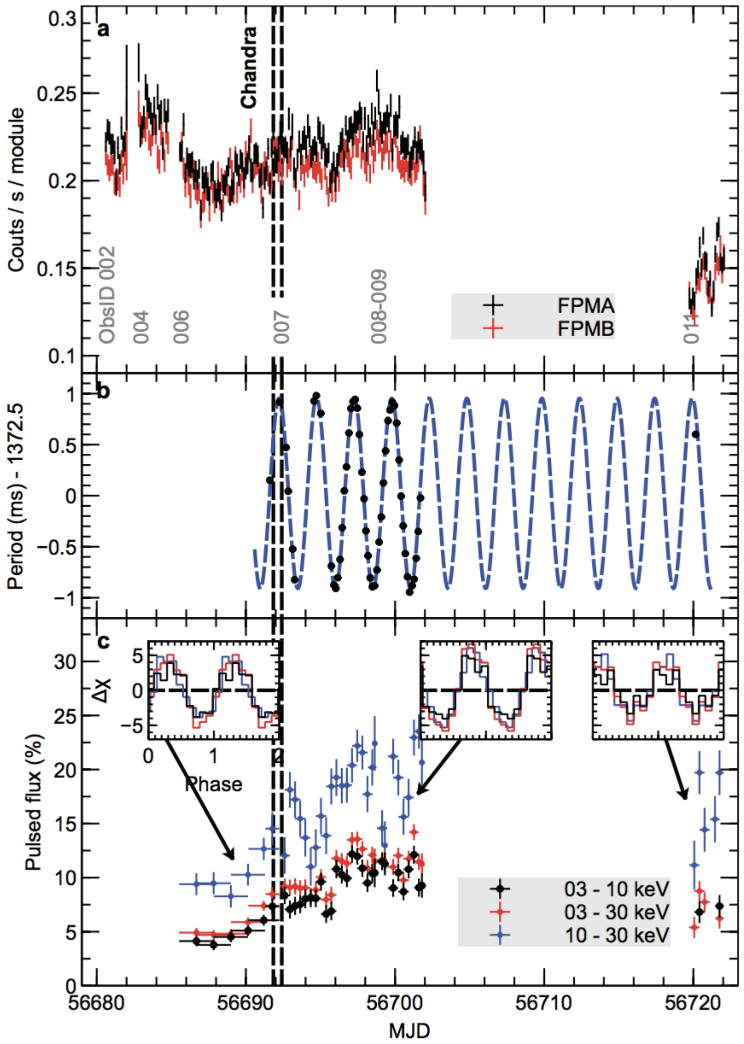


Farris et al. 14

Super-Eddington accretion onto NS → ULX pulsar



Bachetti et al. 14



$$L_X \sim 10^{40}\,\mathrm{erg\,s^{-1}} \sim 100\,L_{\rm Edd}$$

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♫śŉ╜ ◘ŕ ◘ź YÈƵƐ ℓśľ
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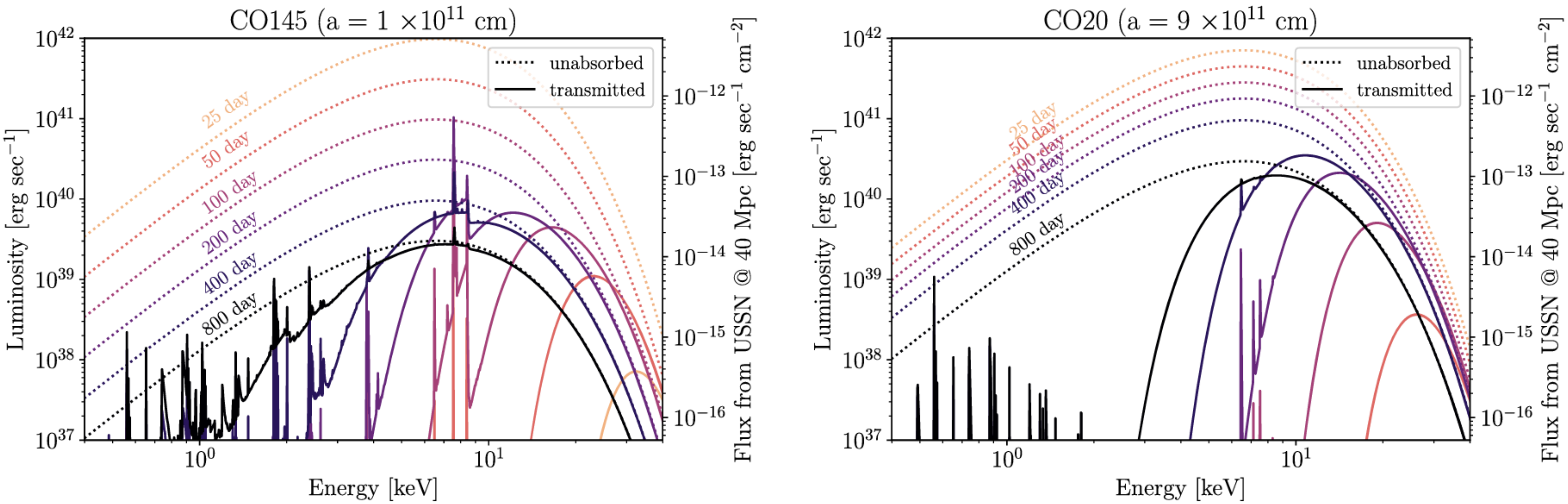
X-raying the birth of BNSs and NS-BHs?

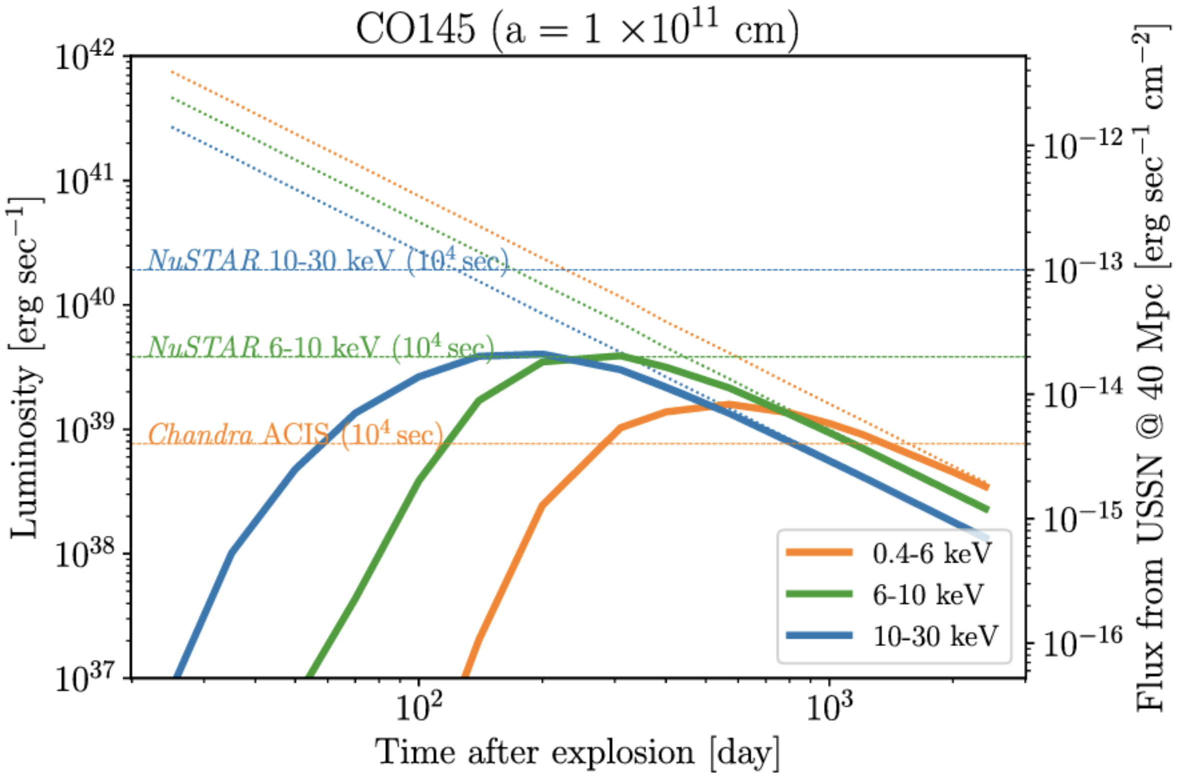
Kashiyama et al. 22

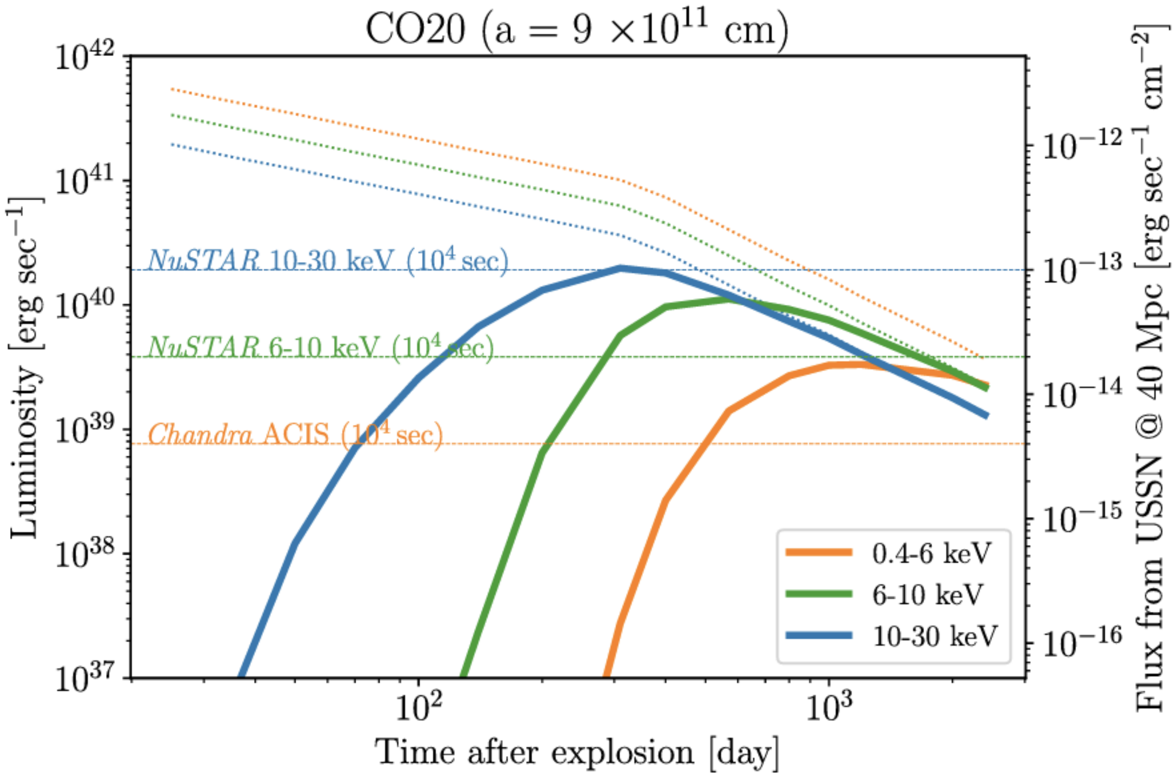


A fraction of the X-rays can emerge through the USSN ejecta ~100–1000 days after the explosion!

X-raying the birth of BNSs and NS-BHs?

Kashiyama et al. 22





We encourage follow-up observations of USSNe within ~100 Mpc and ~100–1000 days after the explosion using Chandra, XMM Newton, and NuSTAR.

The birth of binary compact objects

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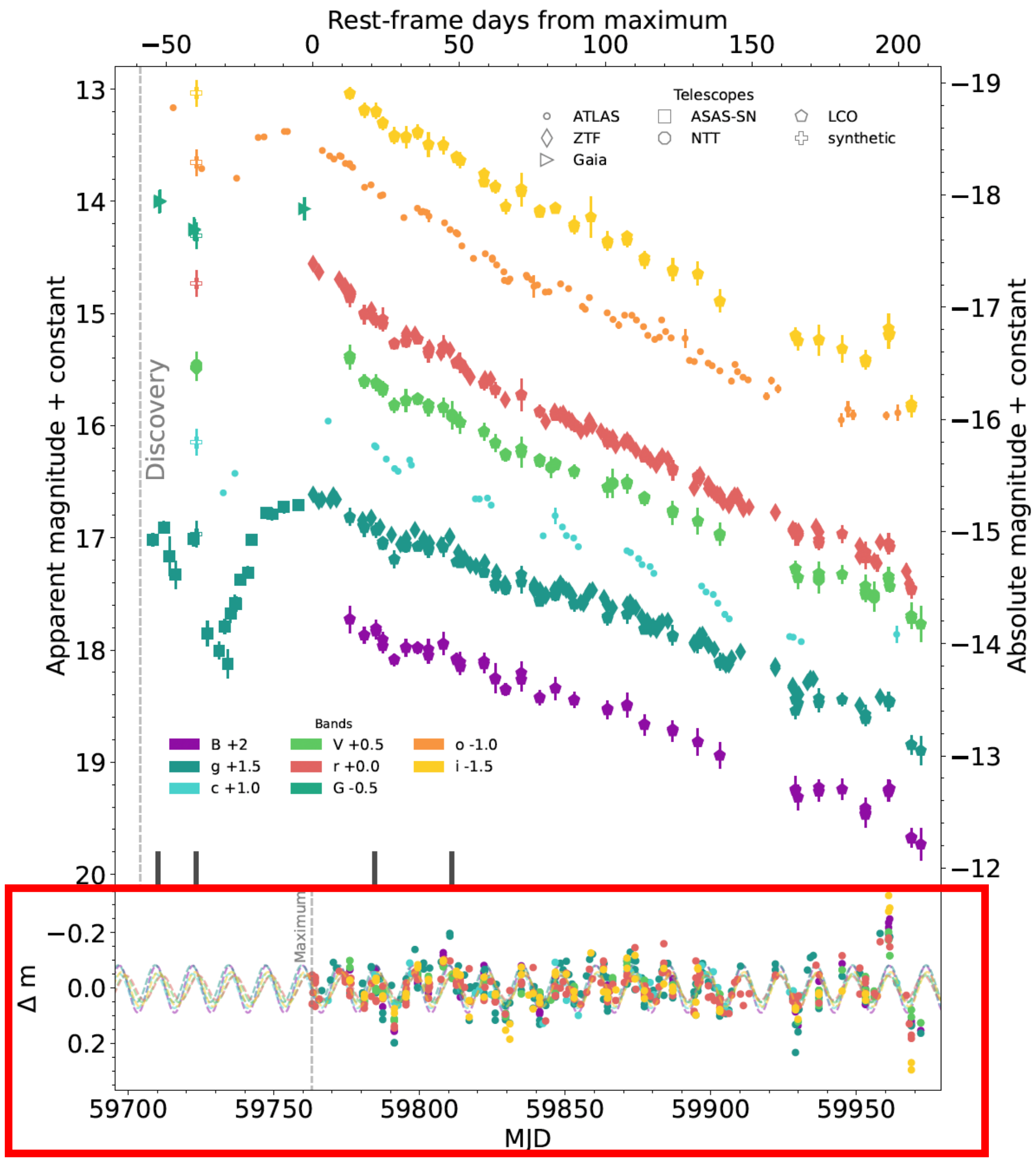
SN 2022jli

Moore et al. 23; Chen et al. 23



- Stripped envelop (type Ic) SN
- host Gal. = NGC 157 (z = 0.055, D = 22.5 ± 2 Mpc)
- An extreme early excess fades over ~ 25 days, followed by a rise to a peak luminosity of ~$10^{42.1}$ erg s^{-1}.

  → an ejecta mass of M_{ej} ~ 1 $M_\odot$ powered by ^{56}Ni

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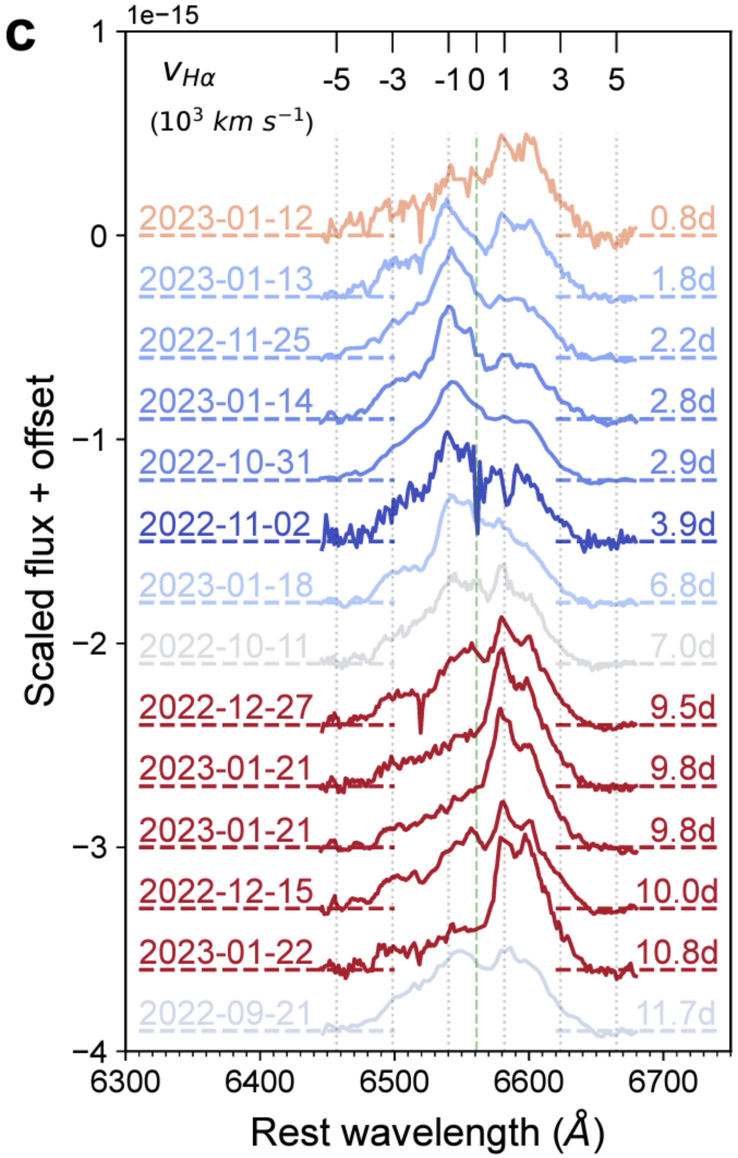
SN 2022jli

Moore et al. 23; Chen et al. 23



- Stripped envelop (type Ic) SN
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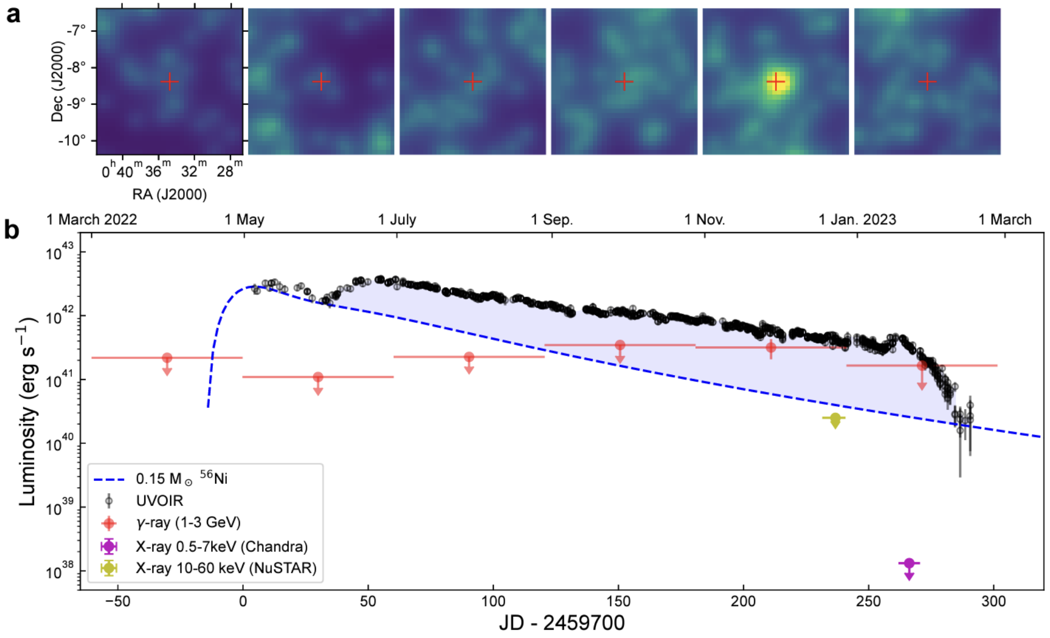
- *The light curve at and after the 2nd peak shows a periodic undulation with a period of 12.4 days and an amplitude of ~1% sharply fading out at ~ 270 days*
- *Narrow Hα line emission synchronously undulates*

SN 2022jli

Moore et al. 23; Chen et al. 23



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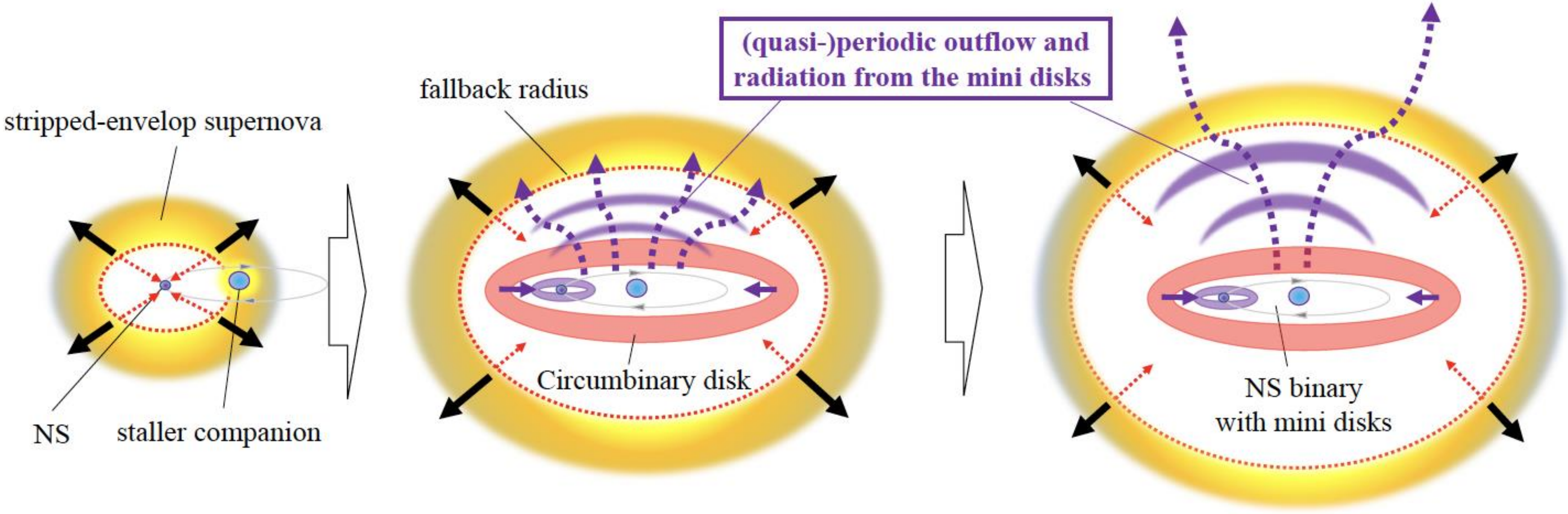
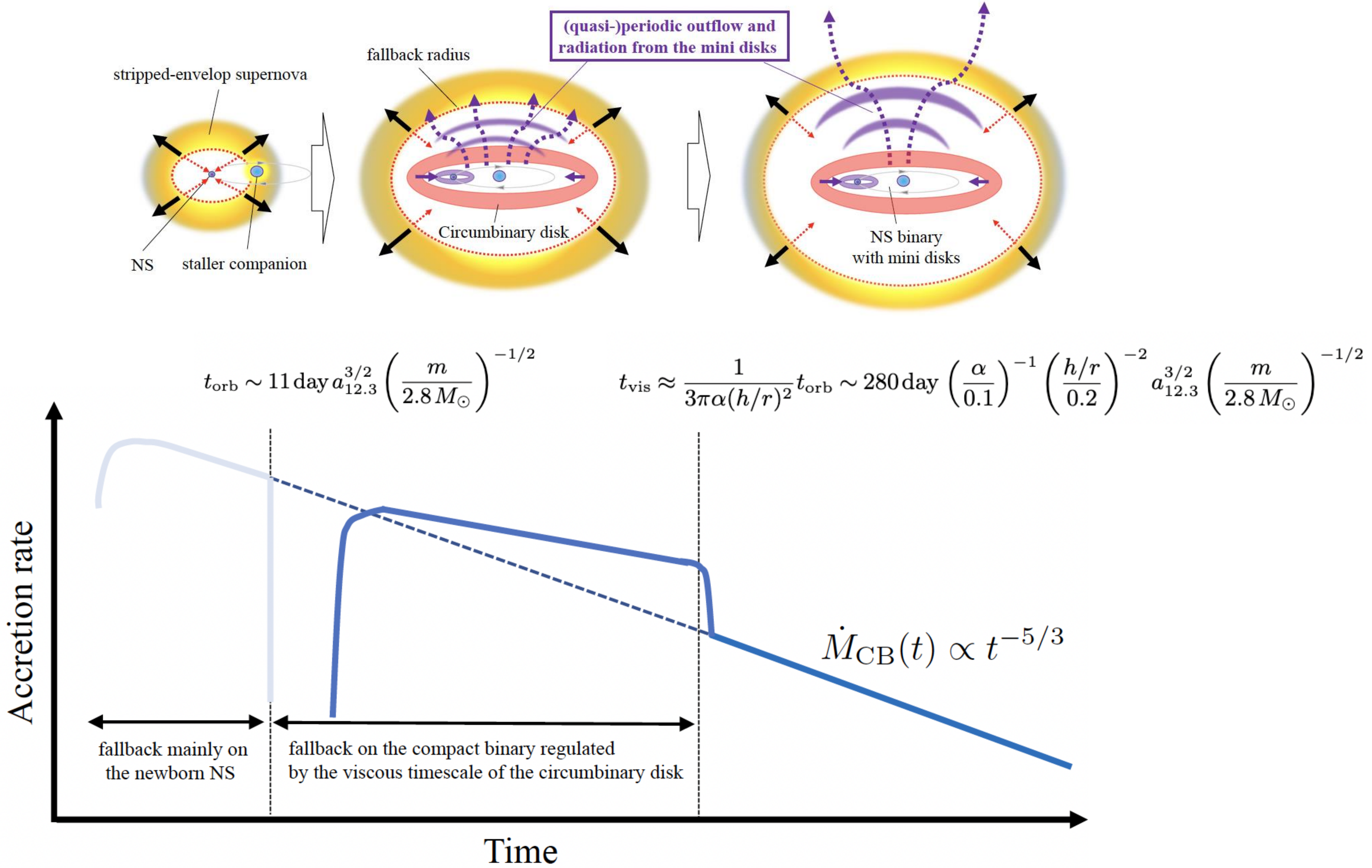
- *The light curve at and after the 2nd peak shows a periodic undulation with a period of 12.4 days and an amplitude of ~1% sharply fading out at ~ 270 days*
- *Narrow Hα line emission synchronously undulates*
- *Fermi-LAT detected a gamma-ray counterpart in the 1-3 GeV energy band with a luminosity of L_γ = 3.1 × 10^{41} erg s^{-1} at around 200 days after the discovery!*

Or the birth of a NS binary with fallback accretion?

Kashiyama et al. in prep





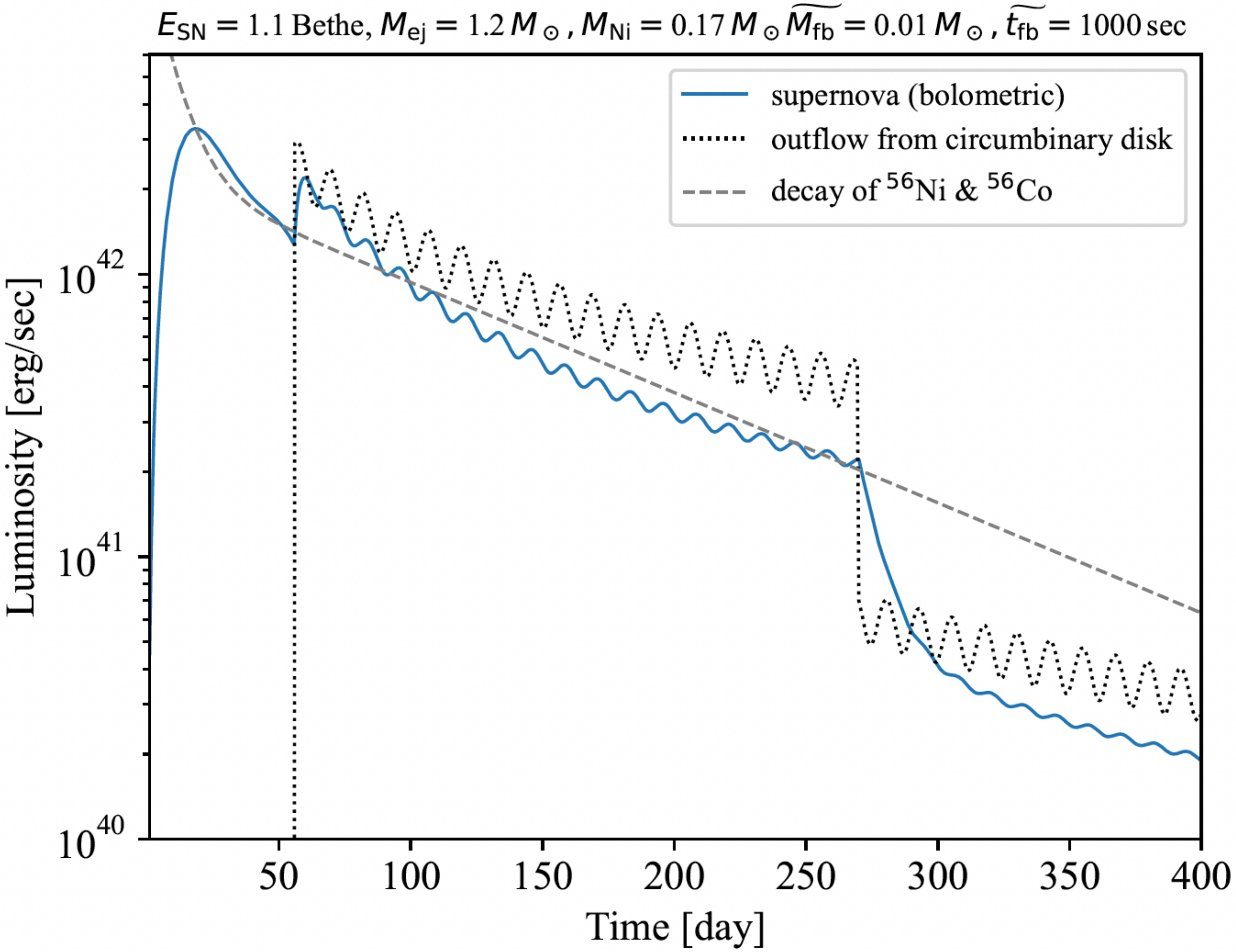
stripped-envelop supernova
NS
staller companion
fallback radius
(quasi-)periodic outflow and radiation from the mini disks
Circumbinary disk
NS binary with mini disks
$t_{\rm orb} \sim 11\,{\rm day}\,a_{12.3}^{3/2}\left(\frac{m}{2.8\,M_\odot}\right)^{-1/2}$
$t_{\rm vis} \approx \frac{1}{3\pi\alpha(h/r)^2}t_{\rm orb} \sim 280\,{\rm day}\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{h/r}{0.2}\right)^{-2}a_{12.3}^{3/2}\left(\frac{m}{2.8\,M_\odot}\right)^{-1/2}$
Accretion rate
$\dot{M}_{\rm CB}(t) \propto t^{-5/3}$
fallback mainly on the newborn NS
fallback on the compact binary regulated by the viscous timescale of the circumbinary disk
Time

Optical echo of the birth of a NS binary?

A toy model

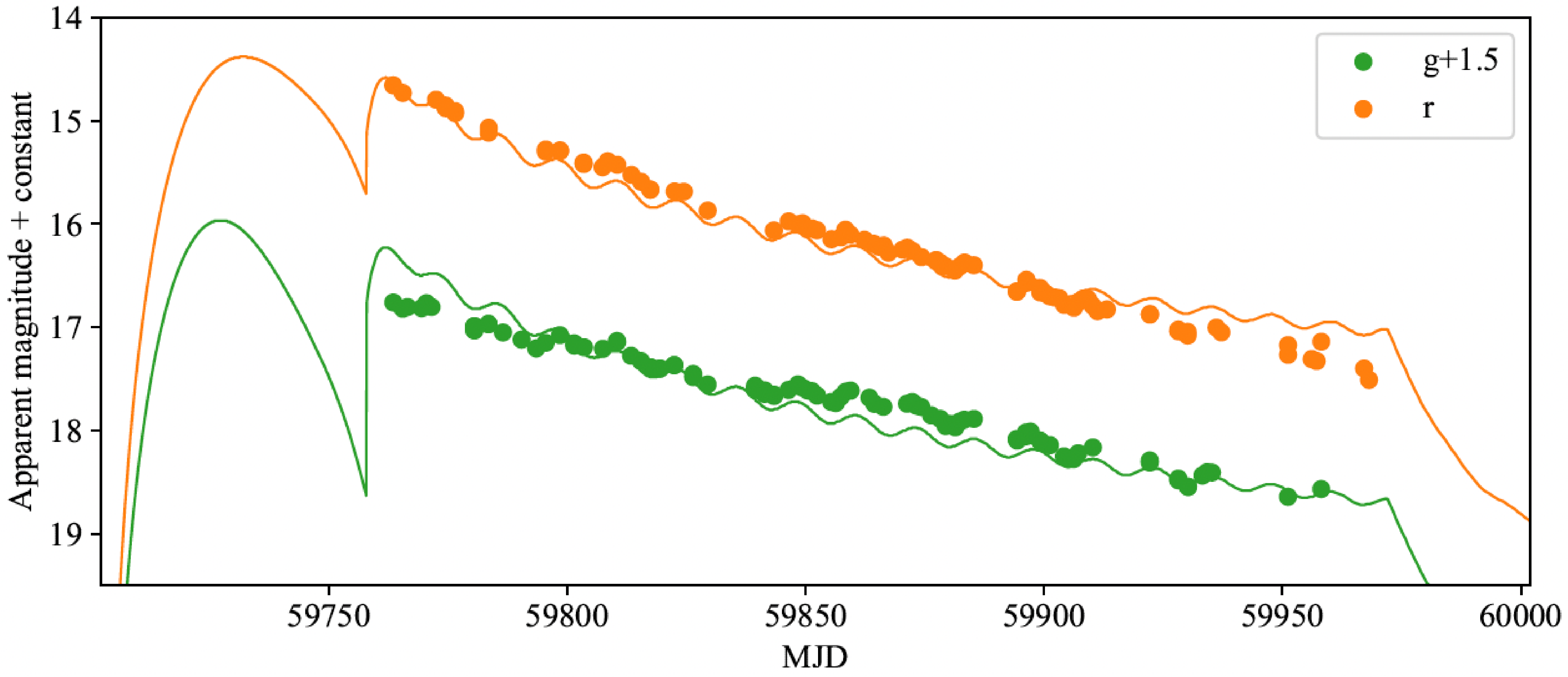
$$\dot{M}_{\rm CB}(t) \approx \begin{cases} \frac{\widehat{M_{\rm fb}}}{\tilde{t}_{\rm fb}} \left(\frac{t}{\tilde{t}_{\rm fb}}\right)^{-p} & (t_{\rm orb} \lesssim t \lesssim t_{\rm vis}) \\ \dot{M}_{\rm fb}(t) & (t_{\rm vis} \lesssim t) \end{cases}$$

$$L_{\rm CB}(t) = \eta \dot{M}_{\rm CB}(t) c^2 \times \left[1 + \mathcal{C} \sin\left(2\pi \frac{t}{t_{\rm orb}} + \phi\right)\right]$$



Kashiyama et al. in prep

Optical echo of the birth of a NS binary?



Kashiyama et al. in prep

Summary and discussion

- *USSNe may accompany formation of BNSs and NS-BHs that merges within a cosmological timescale.*

- *The USSN explosion can be solely explained by the standard neutrino mechanism, while there may be diverse energy sources for the USSN emission.*

- *X-ray follow-up observations of USSNe within ~100 Mpc and ~100–1000 days after the explosion could detect binary ULXs with time variations representing the properties of the nascent compact binary, e.g., the orbital motion of the binary, the spin of the NS, and/or the quasiperiodic oscillation of the mini disks.*

- *Periodic modulation observed in a SESN 2022jli light curve can be the signature of formation of a NS binary which would NOT merge within a cosmological timescale.*