DZA Deutsches Zentrum für Astrophysik

KAT Komitee für Astro Teilchen Physik

RDS

Multi-Messenger
Astrophysics 2024

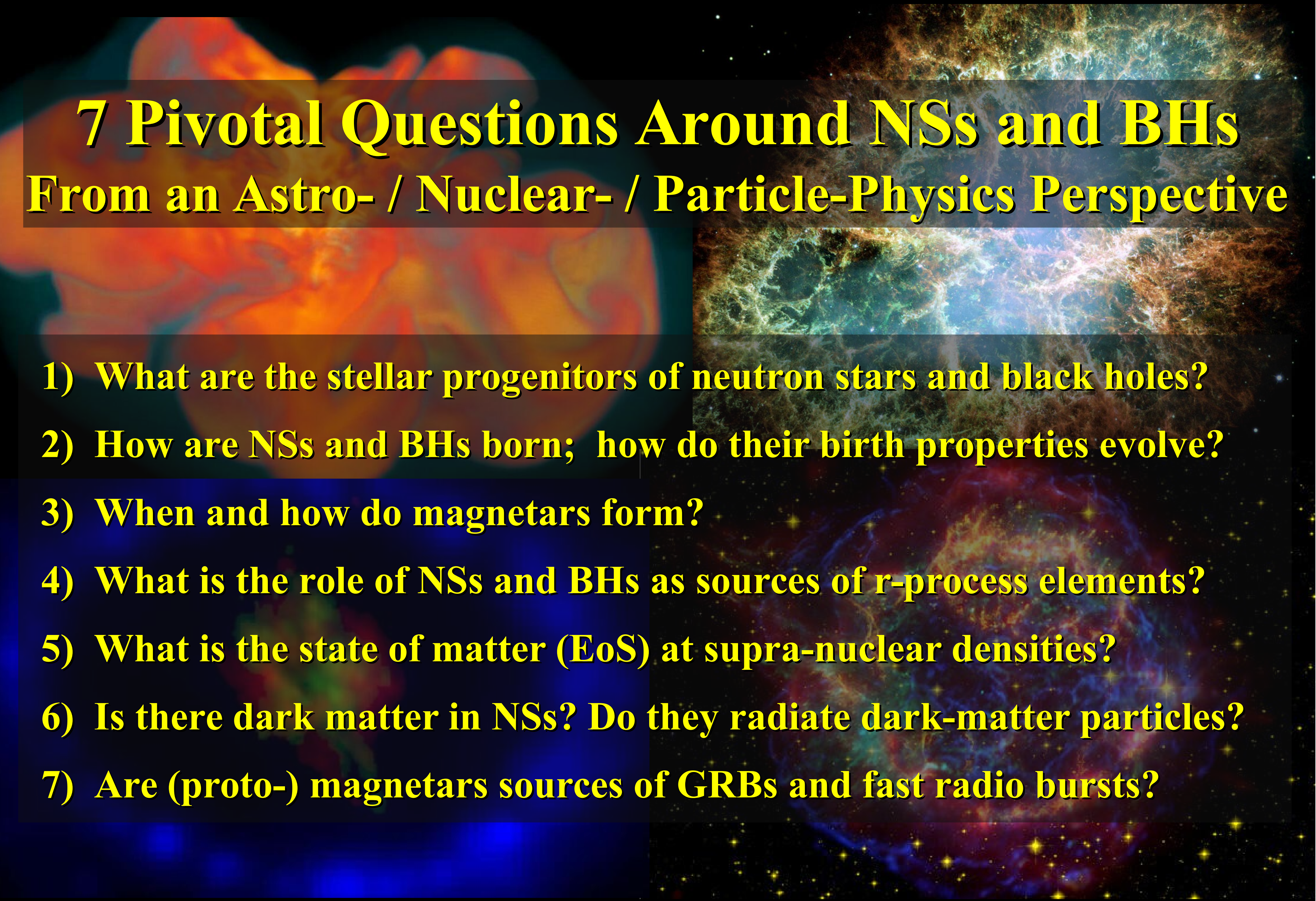
Multi-Messenger Astrophysics 2014
DZA Deutsches Zentrum für Astrophysik, Görlitz
March 26–27 , 2024

Neutron Stars and Black Holes as Remnants of Stellar Death

Multi-Messenger Objects par Excellence

Hans-Thomas Janka
Max Planck Institute for Astrophysics
Garching, Germany

D. Milisavljevic et al.,
JWST Survey of Cas A



7 Pivotal Questions Around NSs and BHs

From an Astro- / Nuclear- / Particle-Physics Perspective

1) What are the stellar progenitors of neutron stars and black holes?
2) How are NSs and BHs born; how do their birth properties evolve?
3) When and how do magnetars form?
4) What is the role of NSs and BHs as sources of r-process elements?
5) What is the state of matter (EoS) at supra-nuclear densities?
6) Is there dark matter in NSs? Do they radiate dark-matter particles?
7) Are (proto-) magnetars sources of GRBs and fast radio bursts?

NSs & BHs: Multi-Messenger Sources

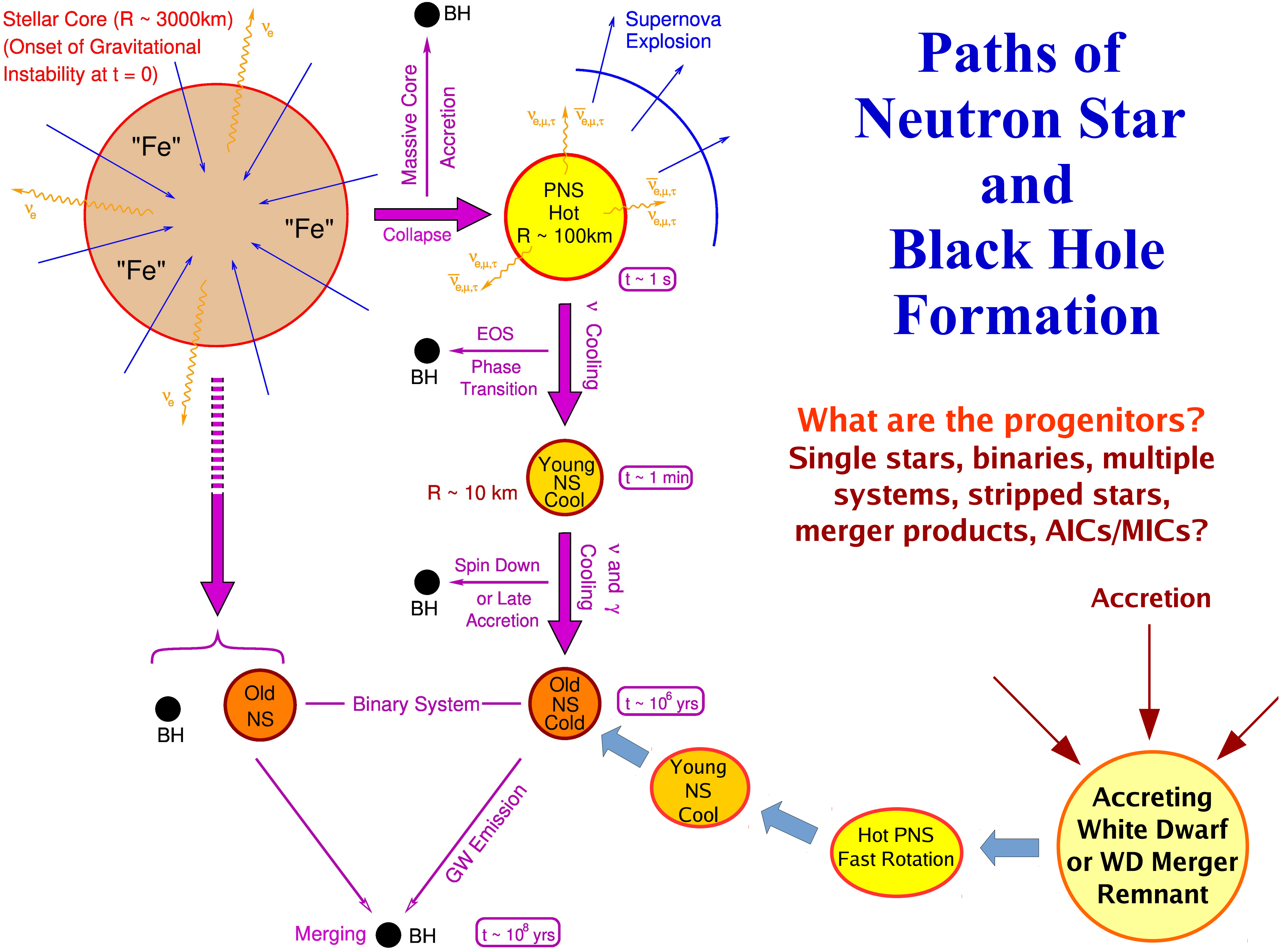
- Neutrinos (MeV and high-energy)
- Gravitational waves (burst signals and inspiral signals)
- Electromagnetic emission (from radio to gamma rays)
- High-energy particles (in jets and collimated outflows; electrons and positrons in magnetosphere; cosmic rays in shocks)

Answering the pivotal questions will not be possible with information from single channels.
Multi-messenger signals are indispensable!

Paths of Neutron Star and Black Hole Formation

What are the progenitors?

Single stars, binaries, multiple systems, stripped stars, merger products, AICs/MICs?



Stellar Core (R ~ 3000km)
(Onset of Gravitational
Instability at t = 0)

ν_e

"Fe"

"Fe"

"Fe"

Collapse

Massive Core Accretion

BH

Supernova
Explosion

PNS
Hot
R ~ 100km

$\nu_{e,\mu,\tau}$ $\bar{\nu}_{e,\mu,\tau}$

t ~ 1 s

ν Cooling

EOS
Phase
Transition

BH

Young
NS
Cool

R ~ 10 km

t ~ 1 min

ν and γ Cooling

Spin Down
or Late
Accretion

BH

Old
NS
Cold

$t \sim 10^6$ yrs

Binary System

Old
NS

BH

GW Emission

Merging

BH

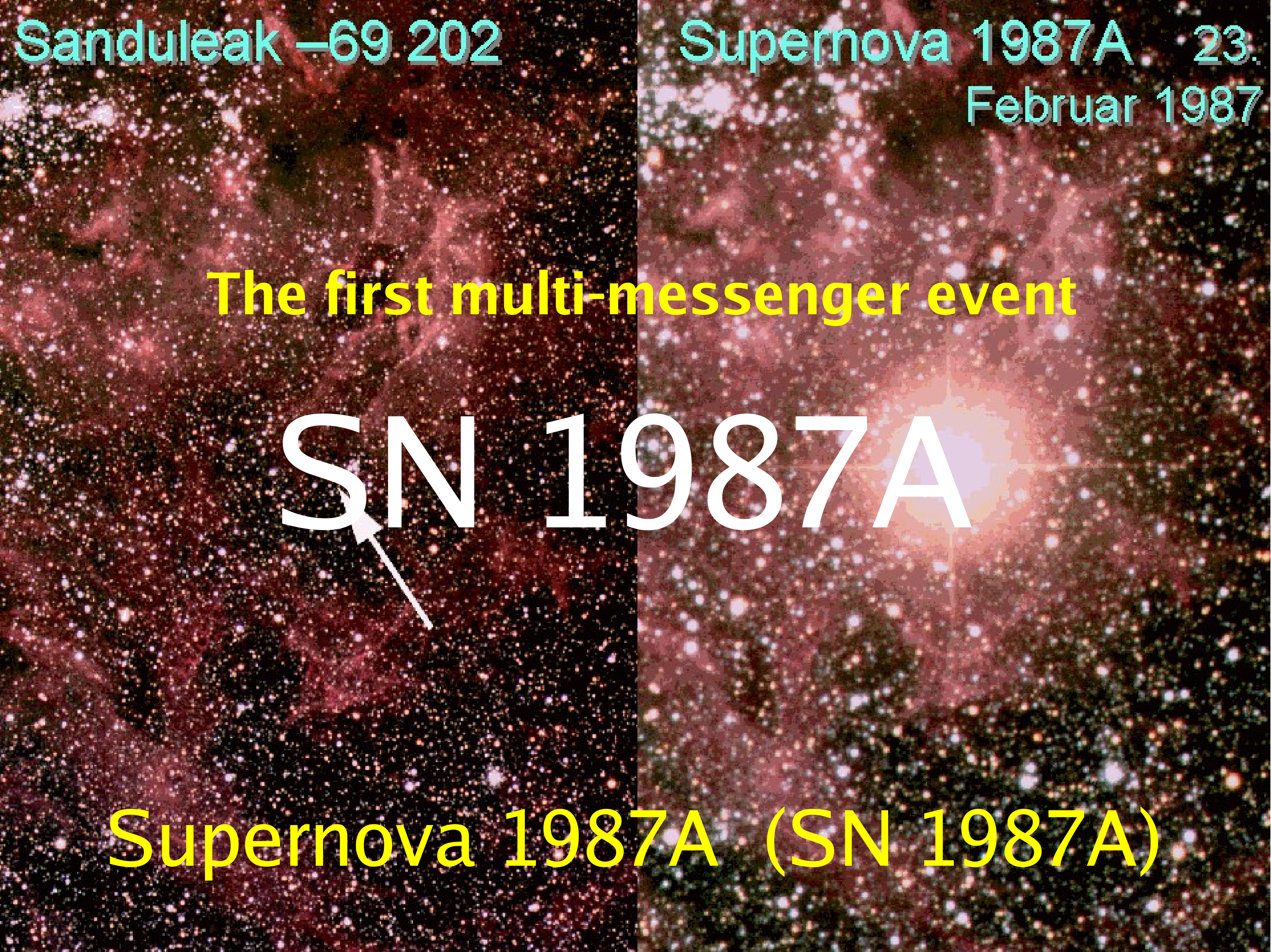
$t \sim 10^8$ yrs

Accretion

Accreting White Dwarf or WD Merger Remnant

Hot PNS
Fast Rotation

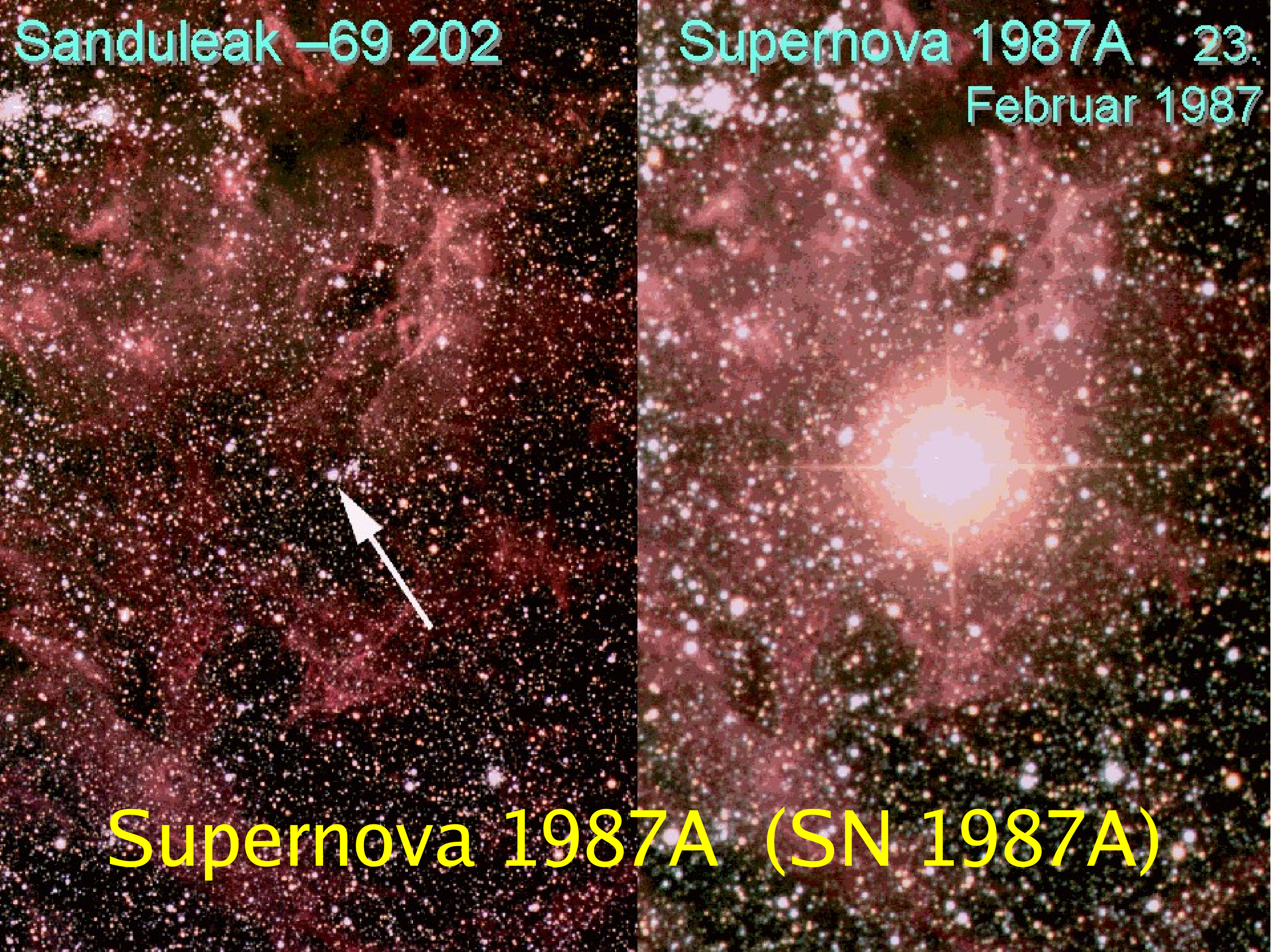
Young
NS
Cool



The first multi-messenger event

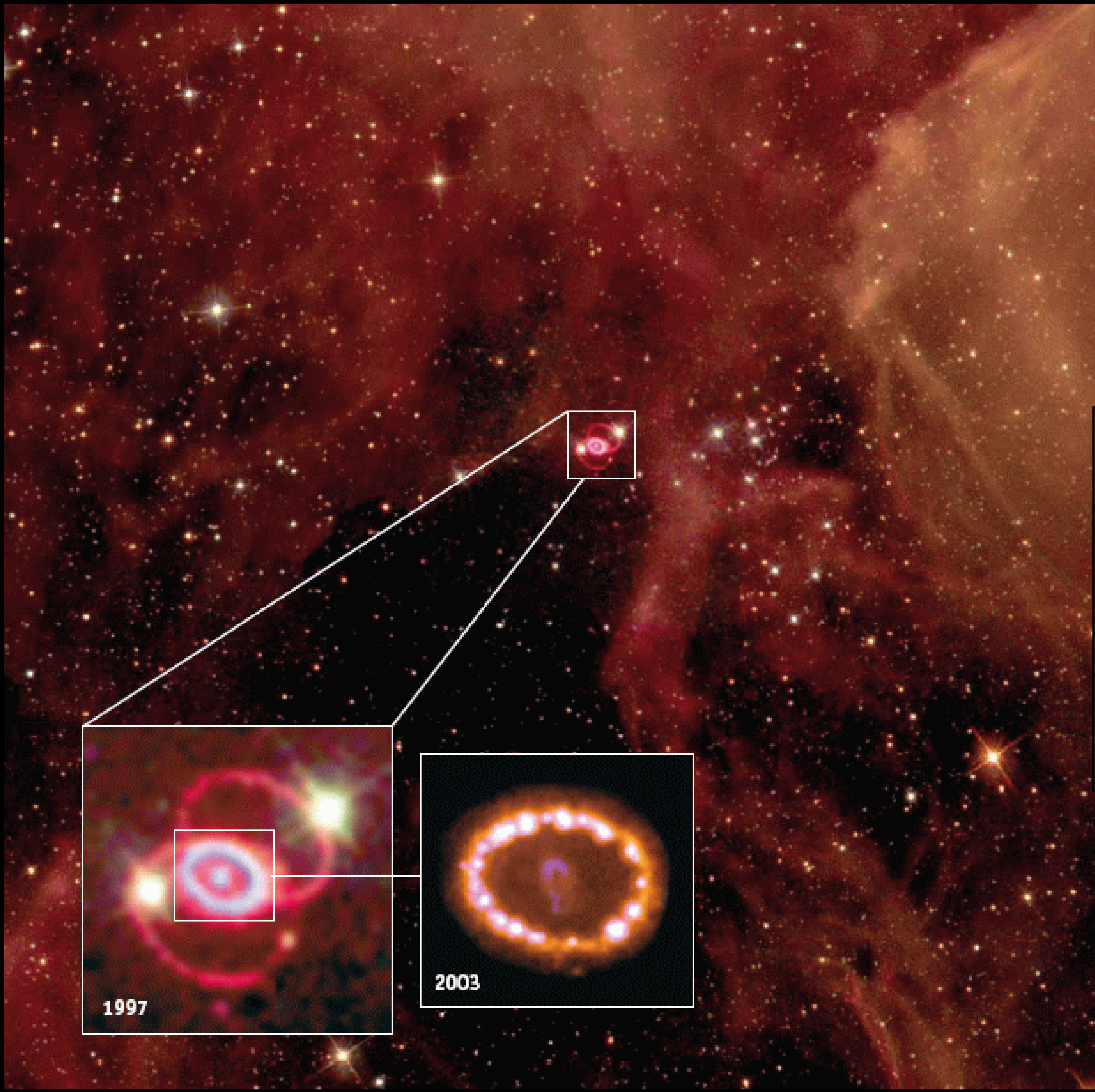
SN 1987A

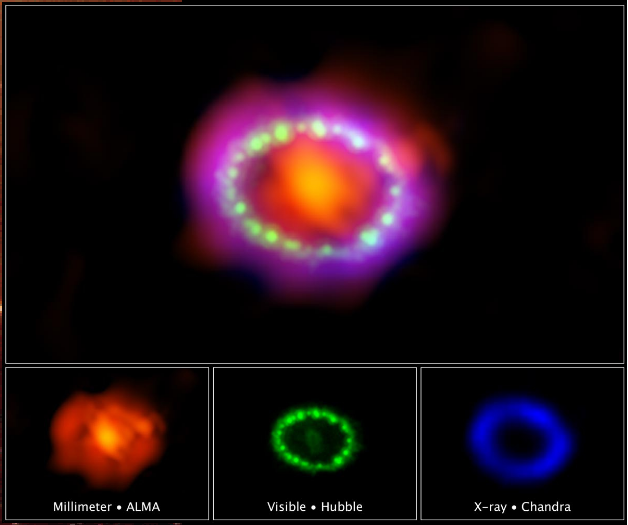
Supernova 1987A (SN 1987A)



Supernova 1987A (SN 1987A)

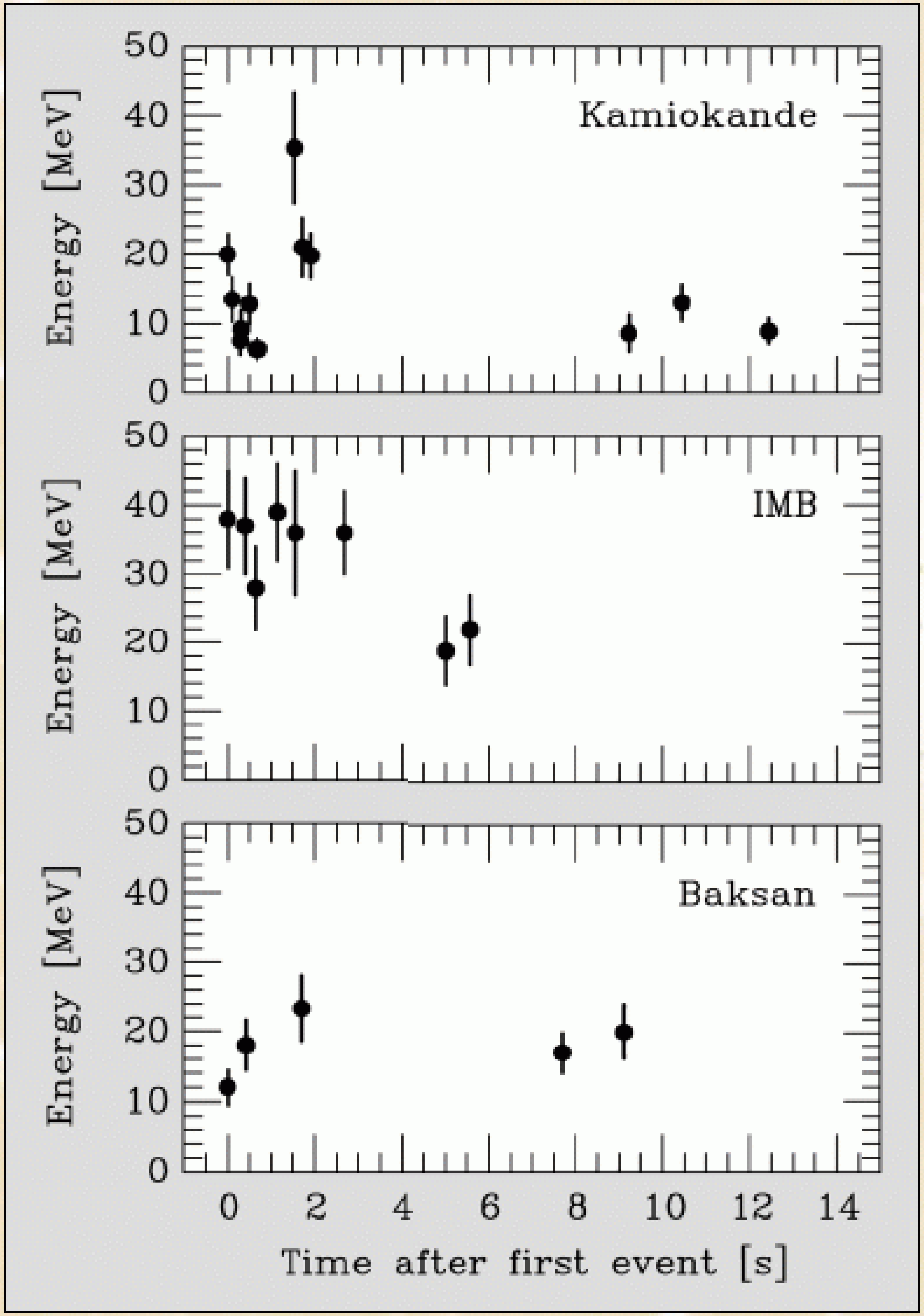
Supernova 1987A aging





ALMA: radio, red
Hubble: visible, green
Chandra: X-ray, blue

Neutrino Burst of Supernova 1987A



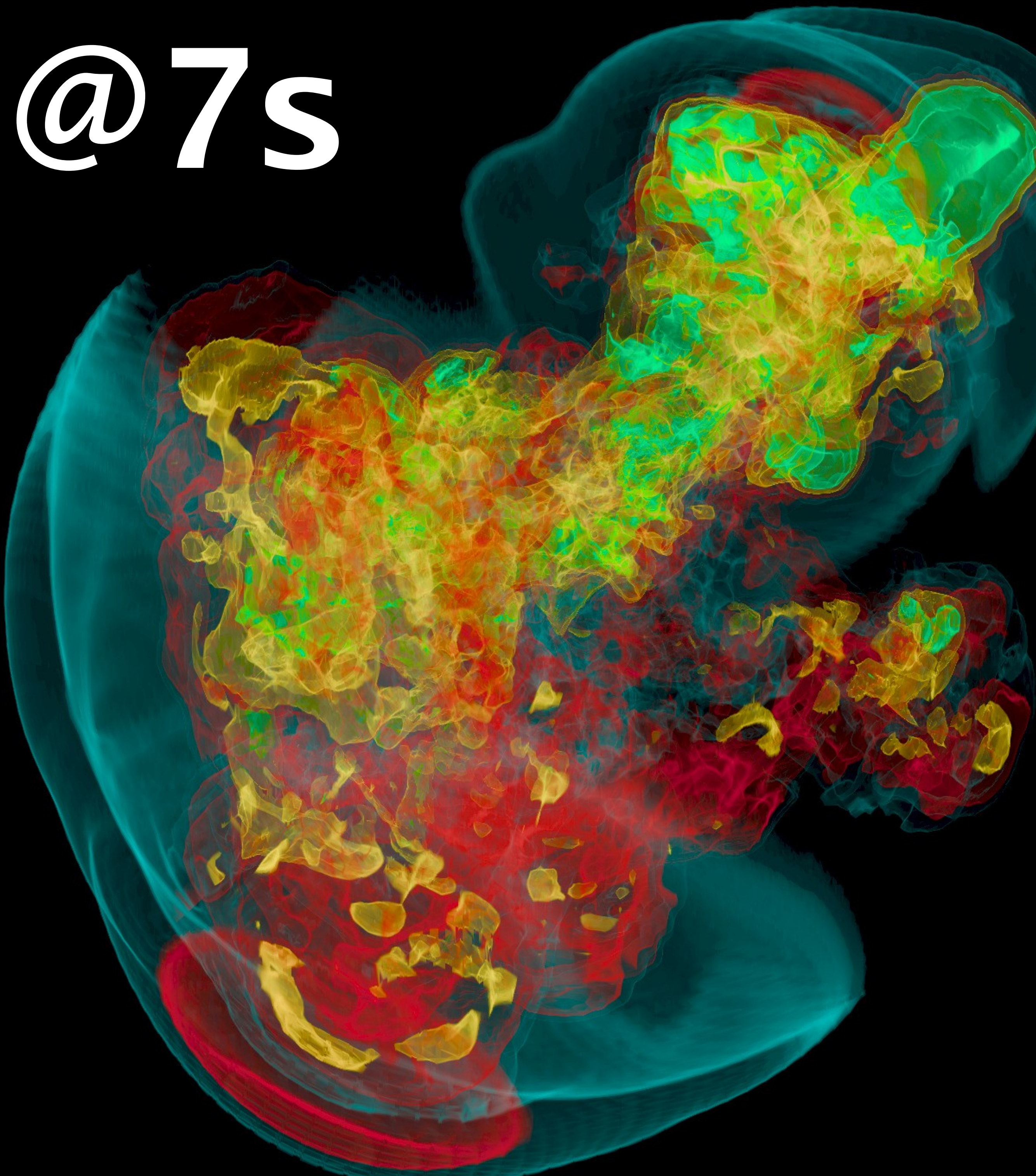
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

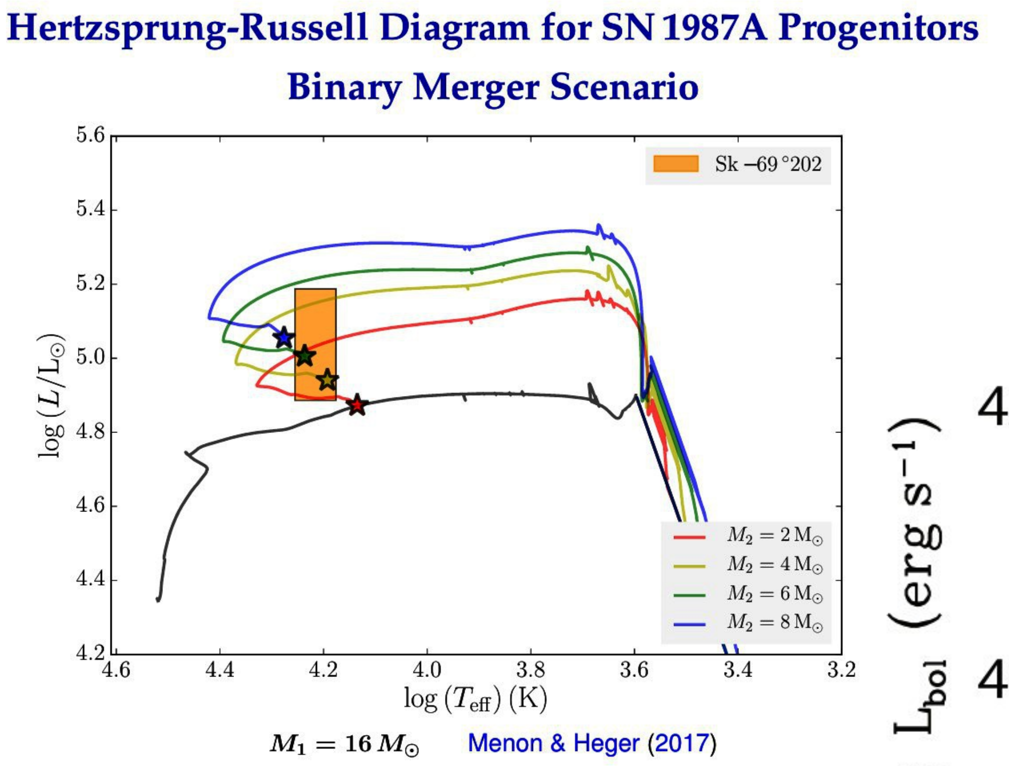
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

@7s

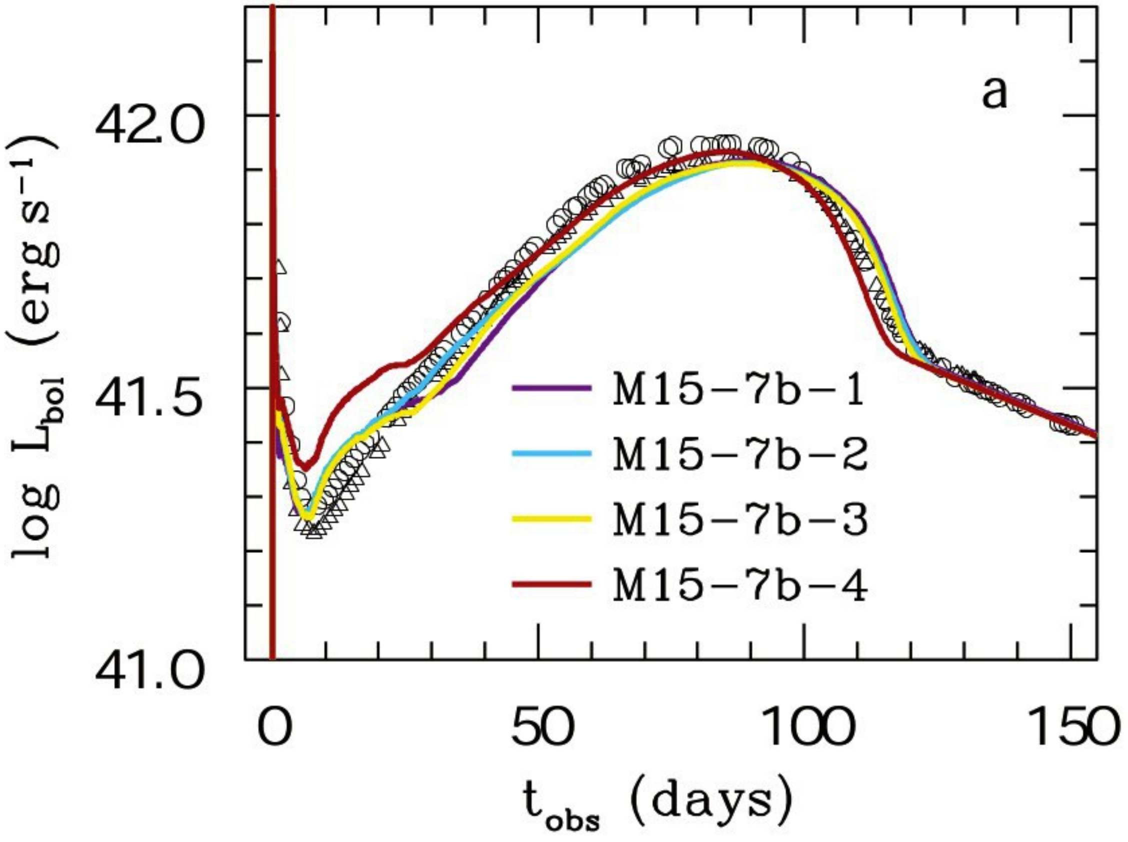


Binary-Star Models for SN1987A: Bolometric Light Curves From 3D Explosions

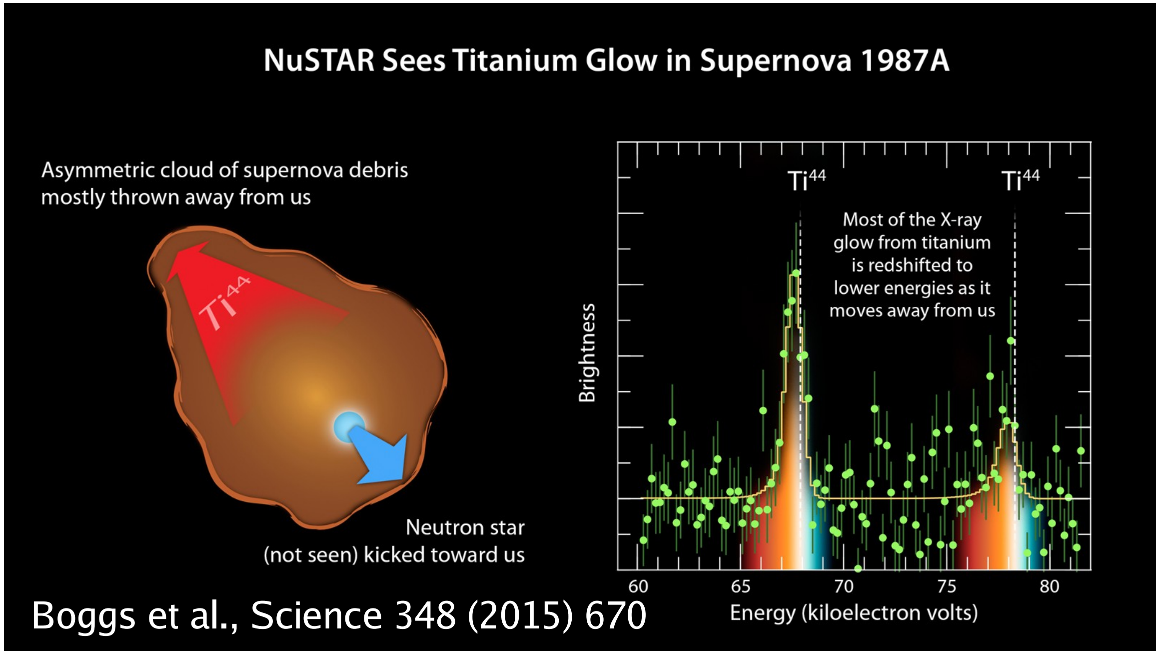


Menon & Heger (2017);
Binary merger progenitors, following an original suggestion by Podsiadlowski and coworkers (1990ff)

Utrobin et al., ApJ 914 (2021) 4



SN 1987A: Gamma-Ray Lines of ^{44}Ti & ^{56}Co

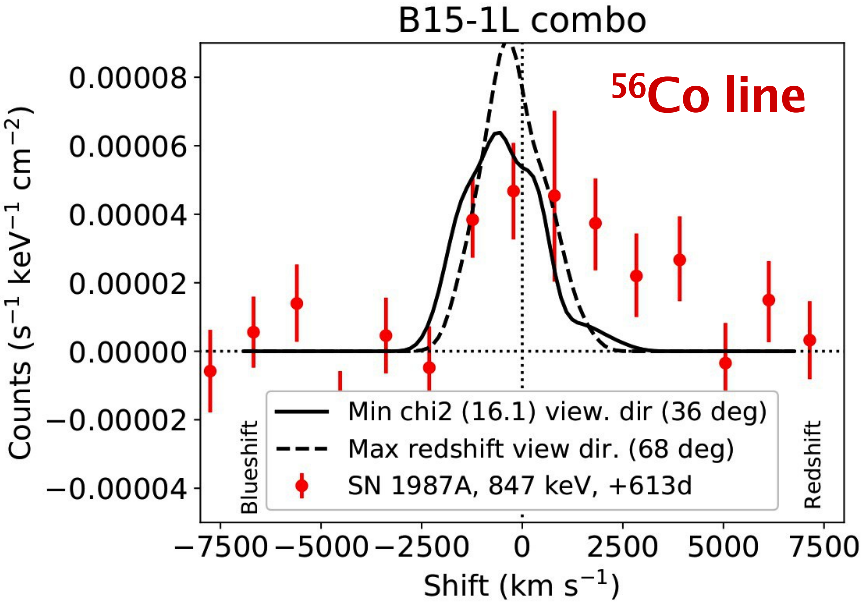


Boggs et al., Science 348 (2015) 670

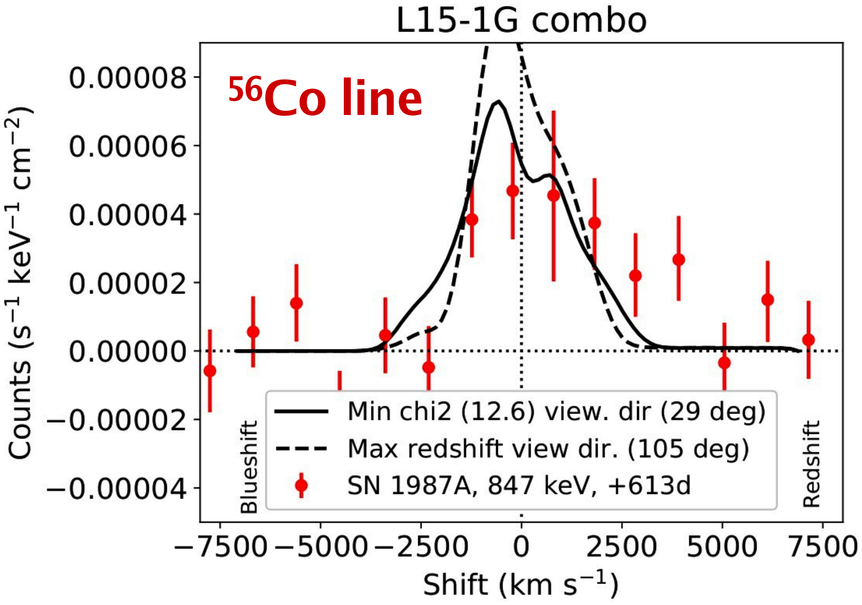
Redshifted ^{44}Ti lines suggest that NS in SN 1987A is likely to have fairly high kick towards us.

(Boggs et al., Science 2015)

v_{ns} ~100 km/s: Incompatible



v_{ns} ~300 km/s: Better fit!



Jerkstrand et al., MNRAS 494 (2020) 2471

State-of-the-art Proto-NS Cooling Models Versus SN1987A Neutrinos

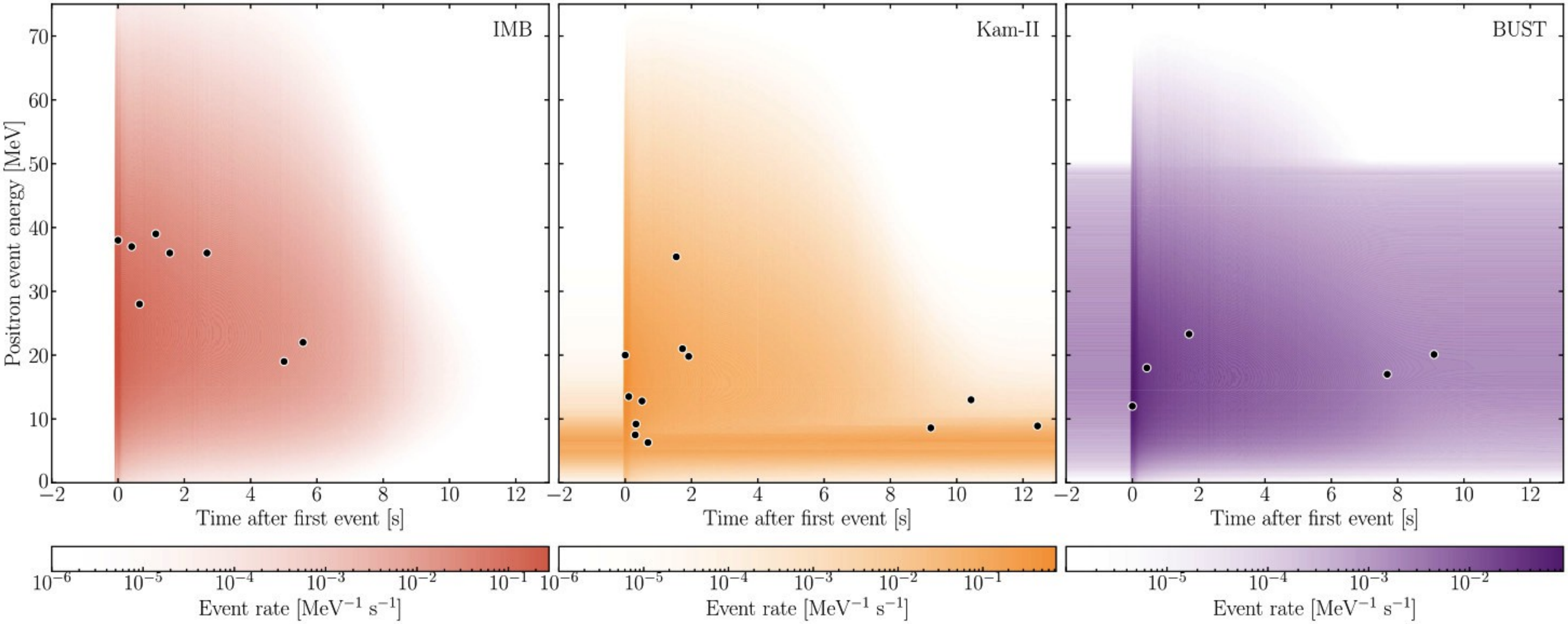
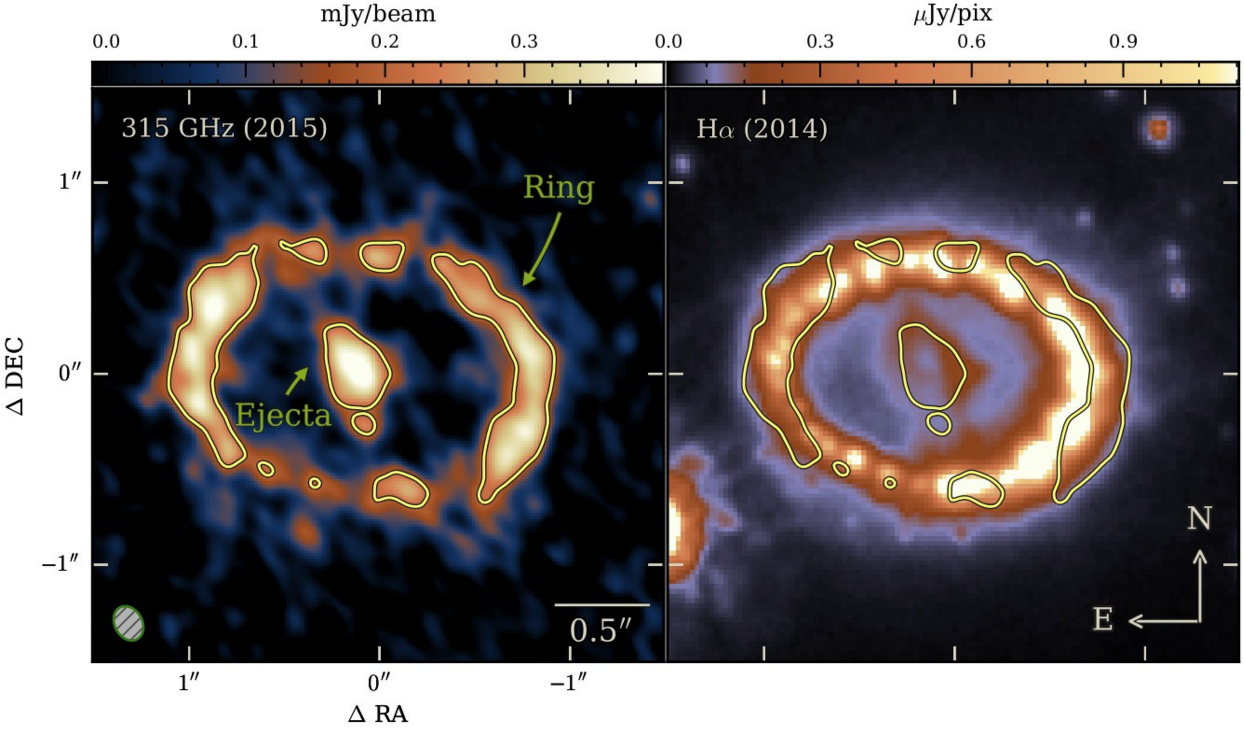


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

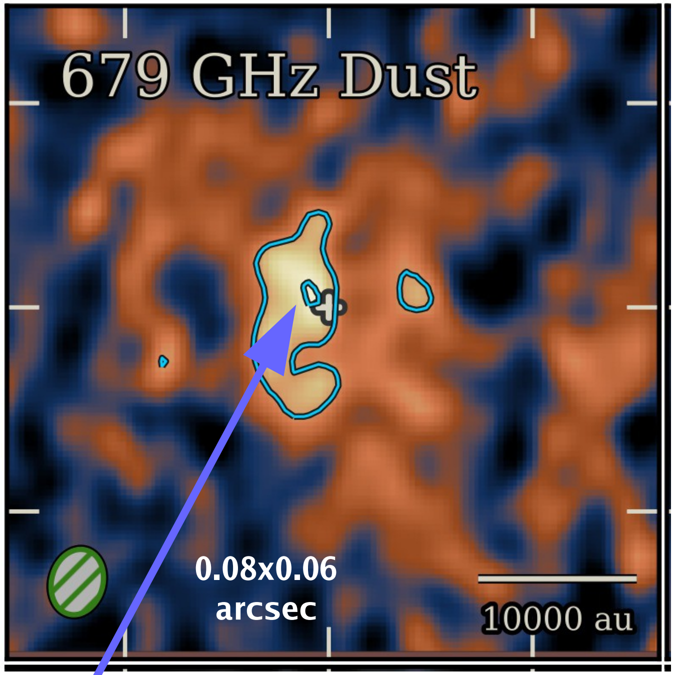
(M. Heinlein, Master Thesis, TUM 2022;
Fiorillo, Heinlein, et al., PRD 108 (2023) 083040)

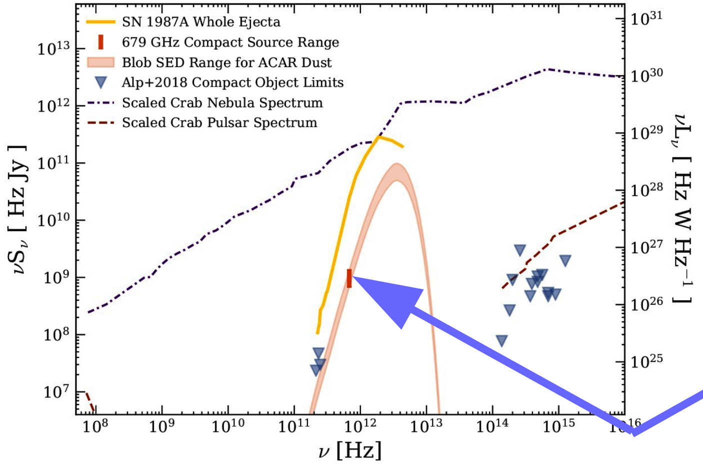
A Compact Object in SN1987A?

High angular resolution ALMA images of dust and molecules in the ejecta of SN 1987A show blob of heated, IR emitting dust



Beam resolution limits clump size— assuming a distance of 51.4±1.2 kpc (Panagia 1999): Band 9 beam FWHM of 0.08x0.06 arcsec corresponds to physical scale of 4125x3230 au.





5-sigma hot "blob" north-east of ejecta center:

Compact source would be compatible with recent limits by Alp et al. (ApJ 864 (2018) 174).

Luminosity can be explained by energy input from a thermally cooling NS (or, less likely, accretion by BH)

(Cigan et al., ApJ 886 (2019) 51; Page et al., ApJ 898 (2020) 125)

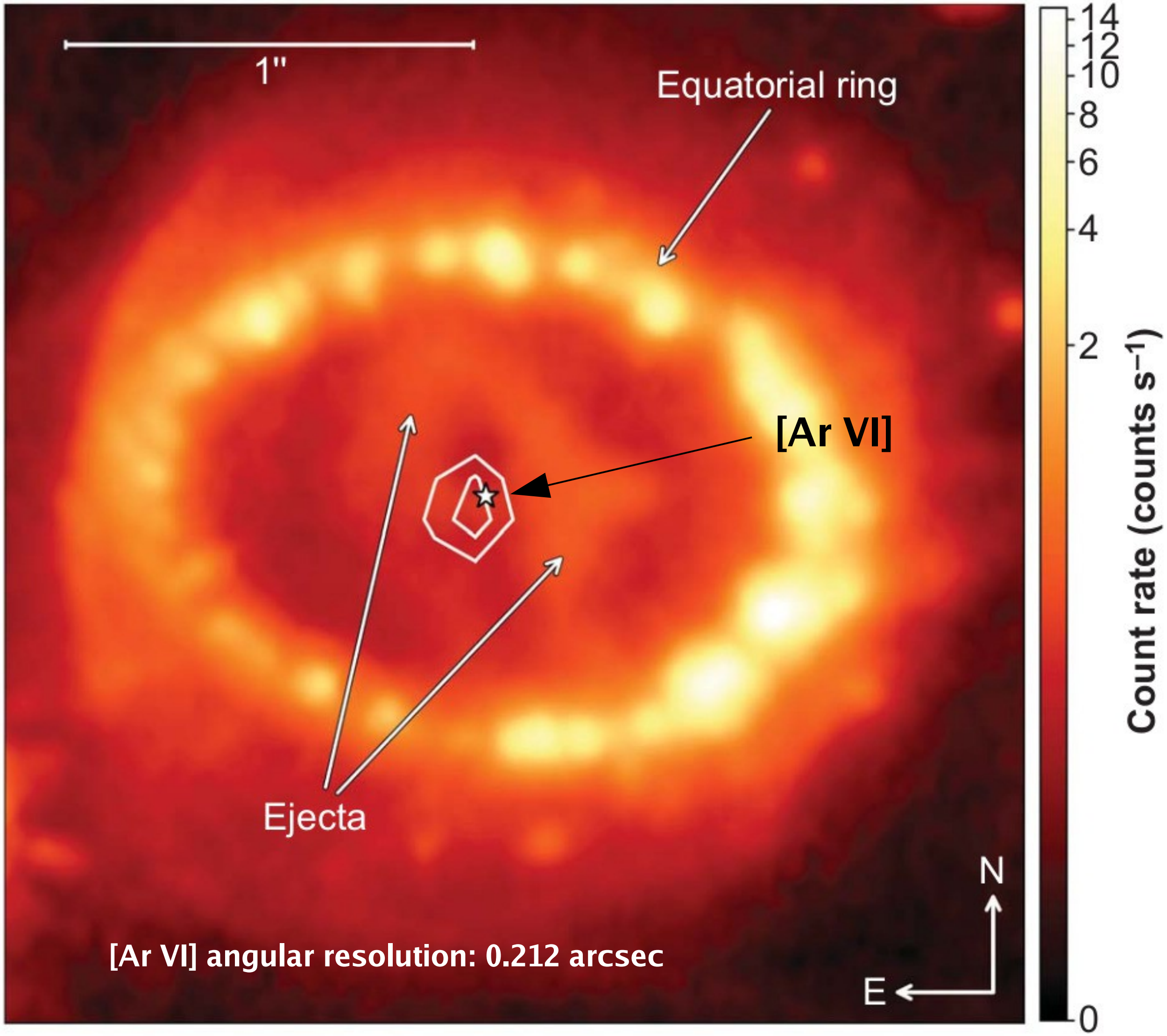
A Compact Object in SN1987A?

JWST observes emission lines due to ionizing radiation from a compact object in the remnant of SN 1987A.

[Ar II] and [Ar VI] emission peaks (spatially unresolved).

Positions of emission maxima spatially coincide with each other and with the center of the equatorial ring (assumed to be the explosion site).

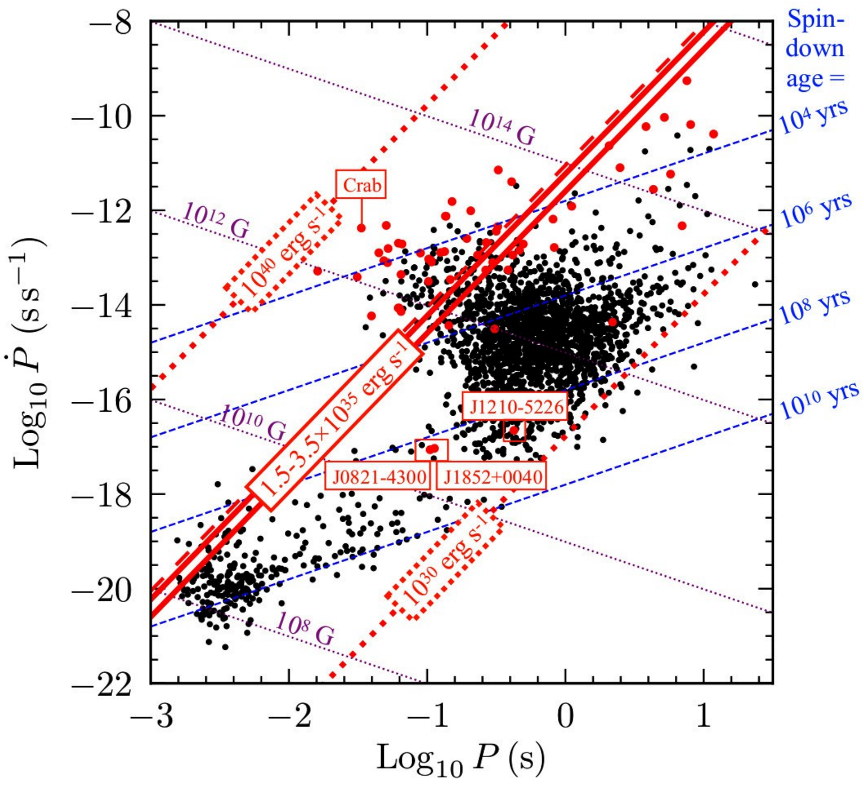
Emission peak not perfectly coincident with position of the hot blob on the ALMA images.

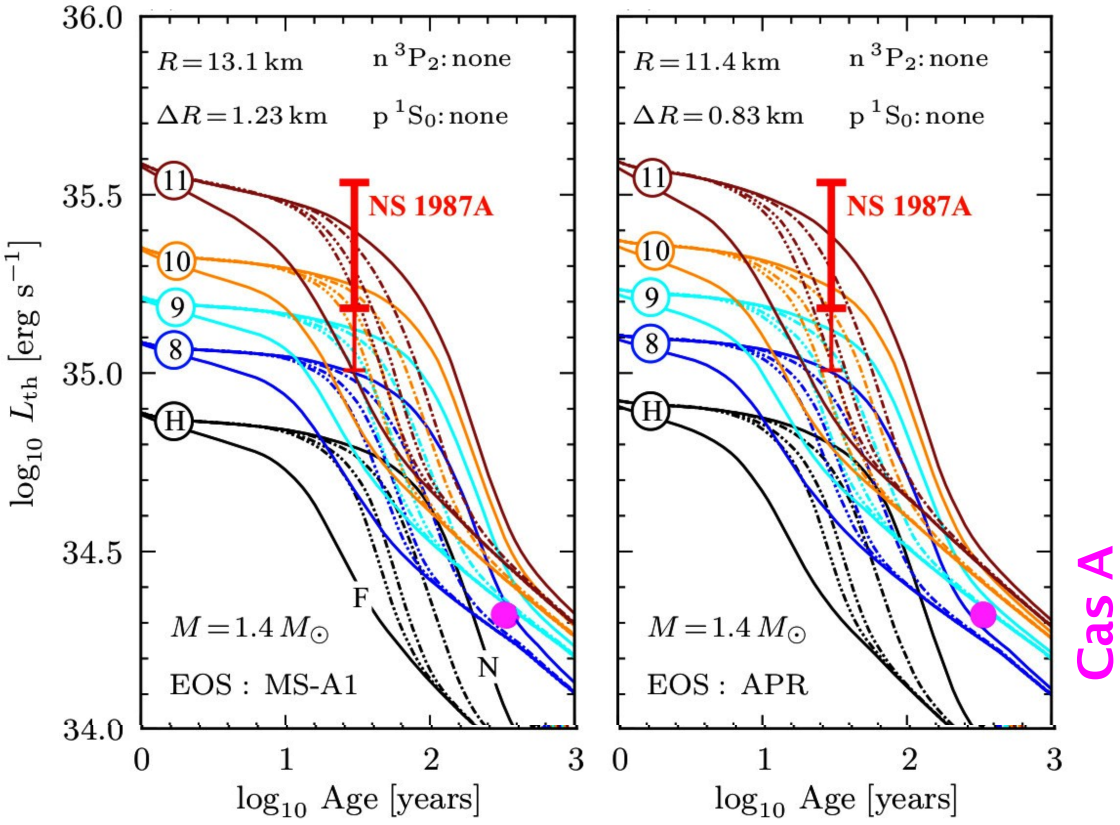


[Ar VI] angular resolution: 0.212 arcsec

A Compact Object in SN1987A?

High angular resolution ALMA images of dust and molecules in the ejecta of SN 1987A: Thermally cooling neutron star or PWN?

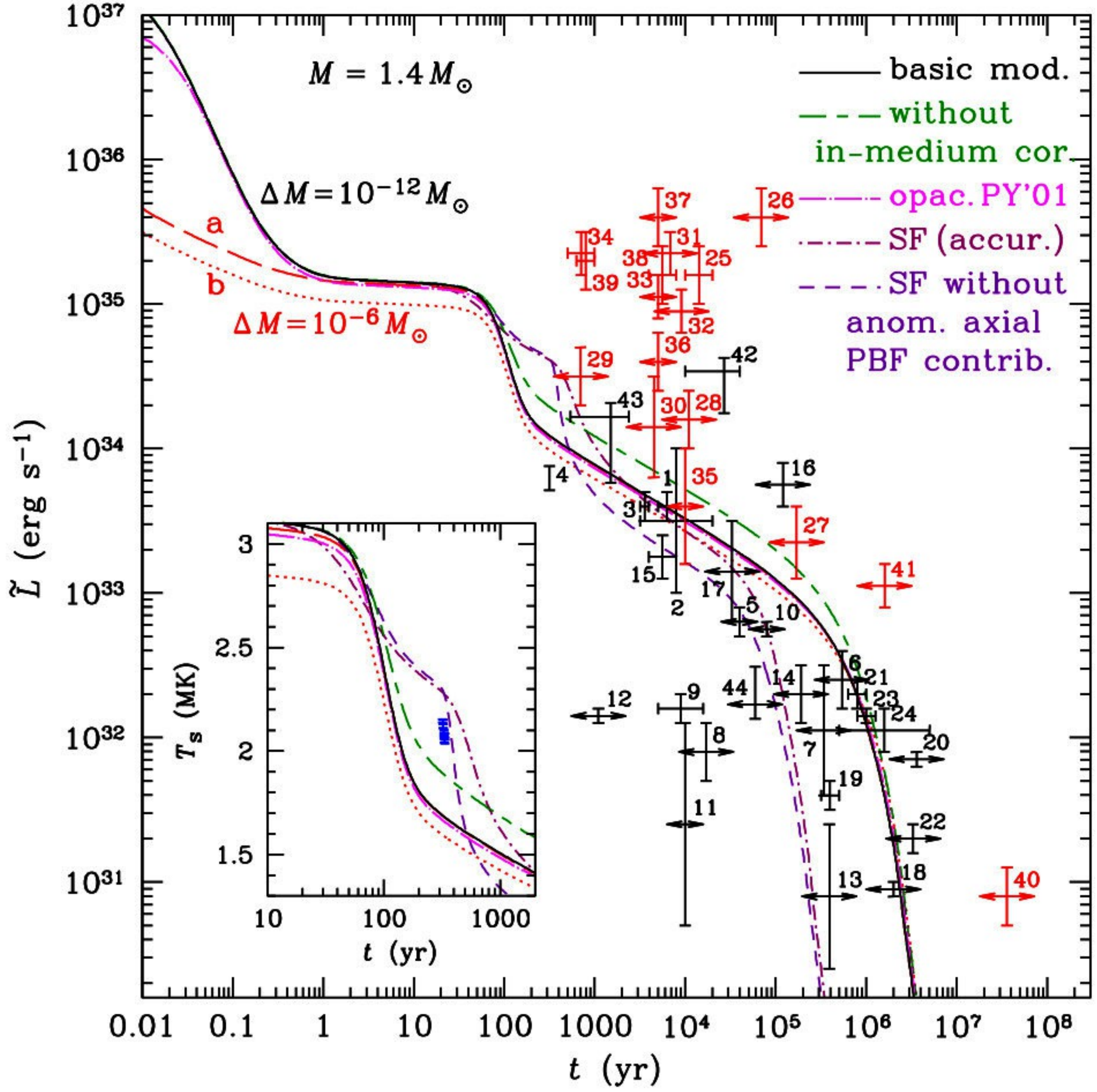




Luminosity can be explained by energy input from a thermally cooling NS (or, less likely, accretion by BH)

(Page et al., ApJ 898 (2020) 125)

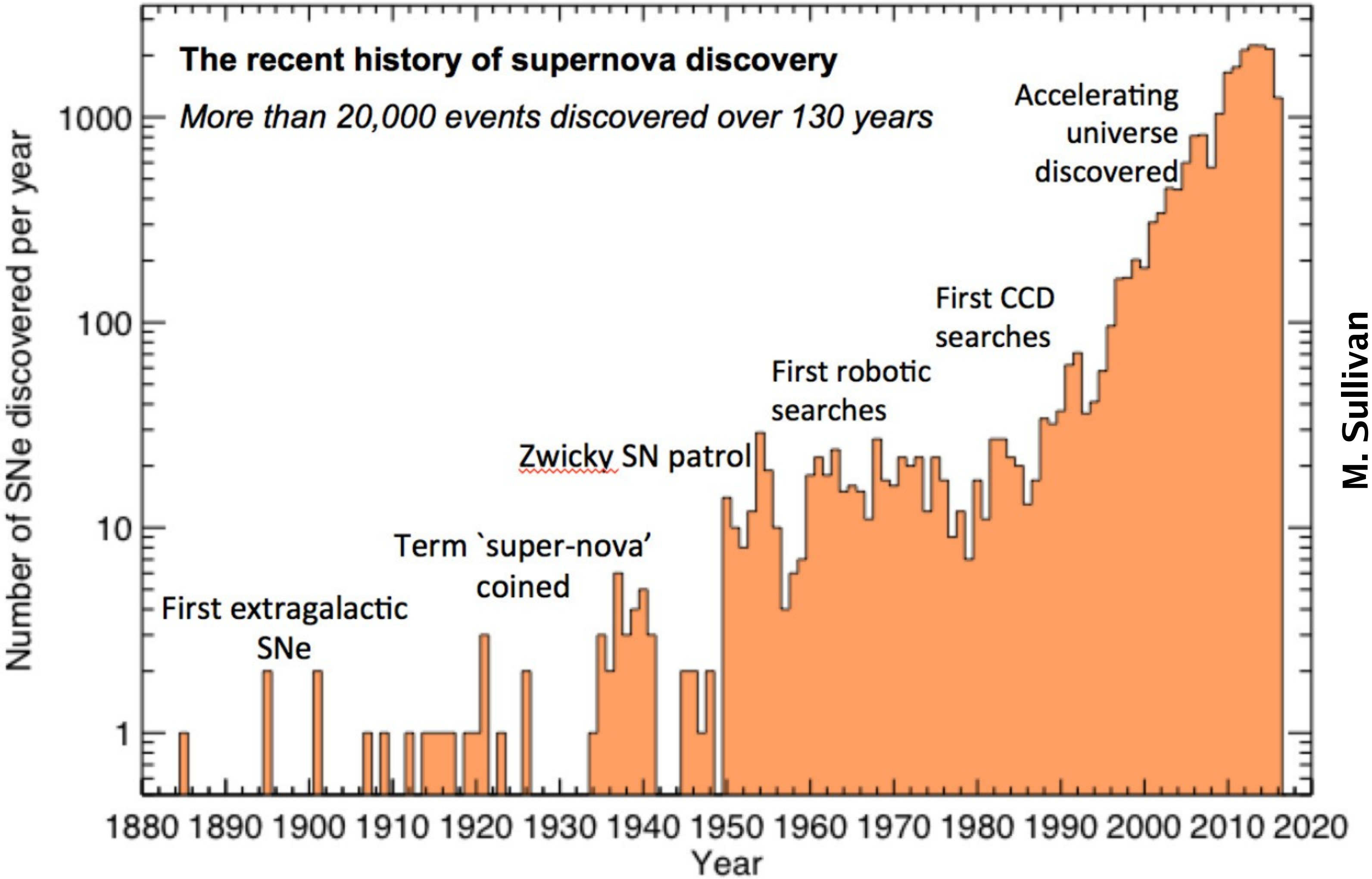
Long-Time Cooling of Neutron Stars and Magnetars



Potekhin & Chabrier, A&A 609 (2018) A74

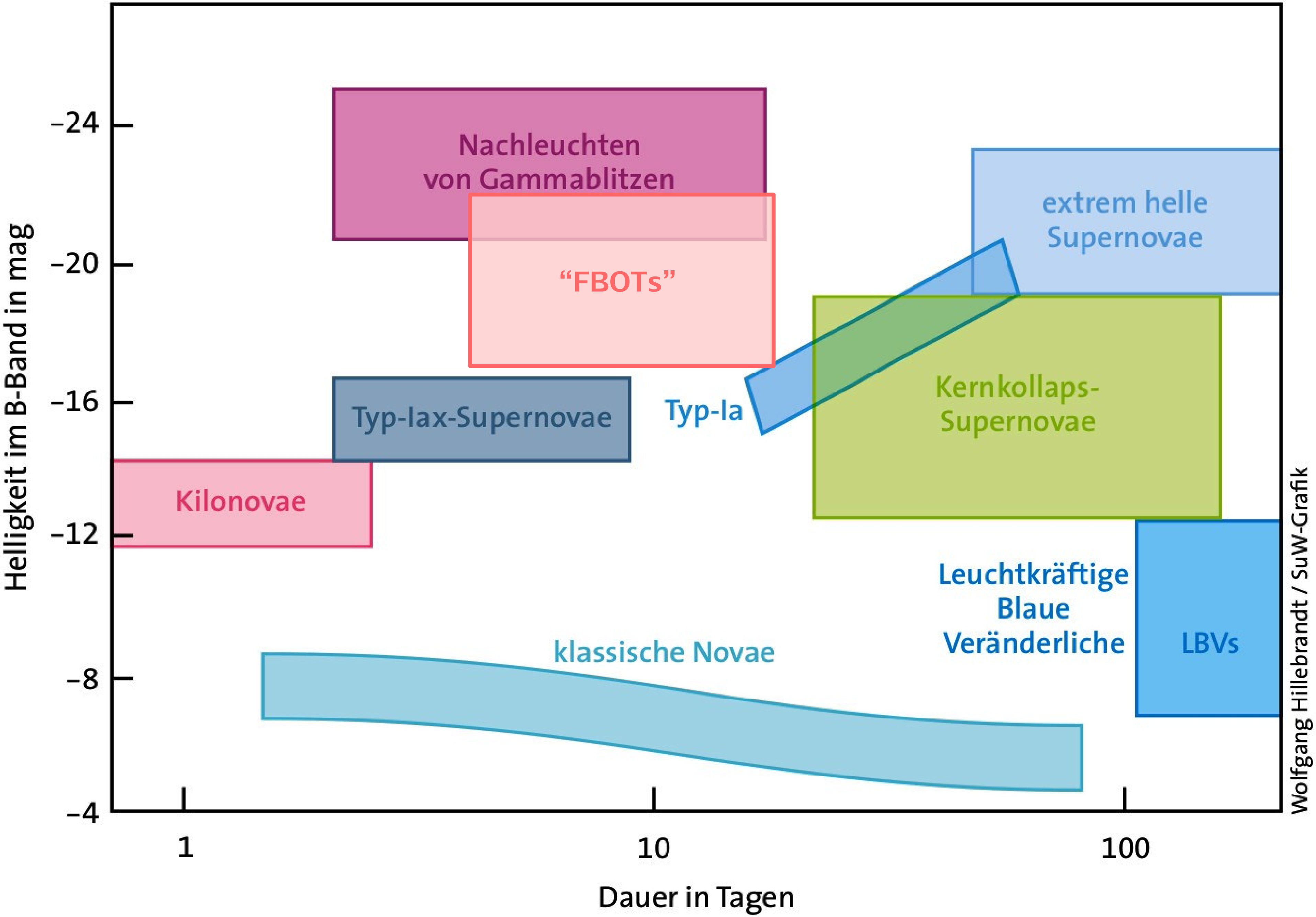
Supernova Discoveries

Number of detected SNe has increased exponentially due to robotic search; will sky-rocket by new transient surveys, e.g. synoptic astronomical survey (Legacy Survey of Space and Time; LSST) of Vera C. Rubin Observatory.

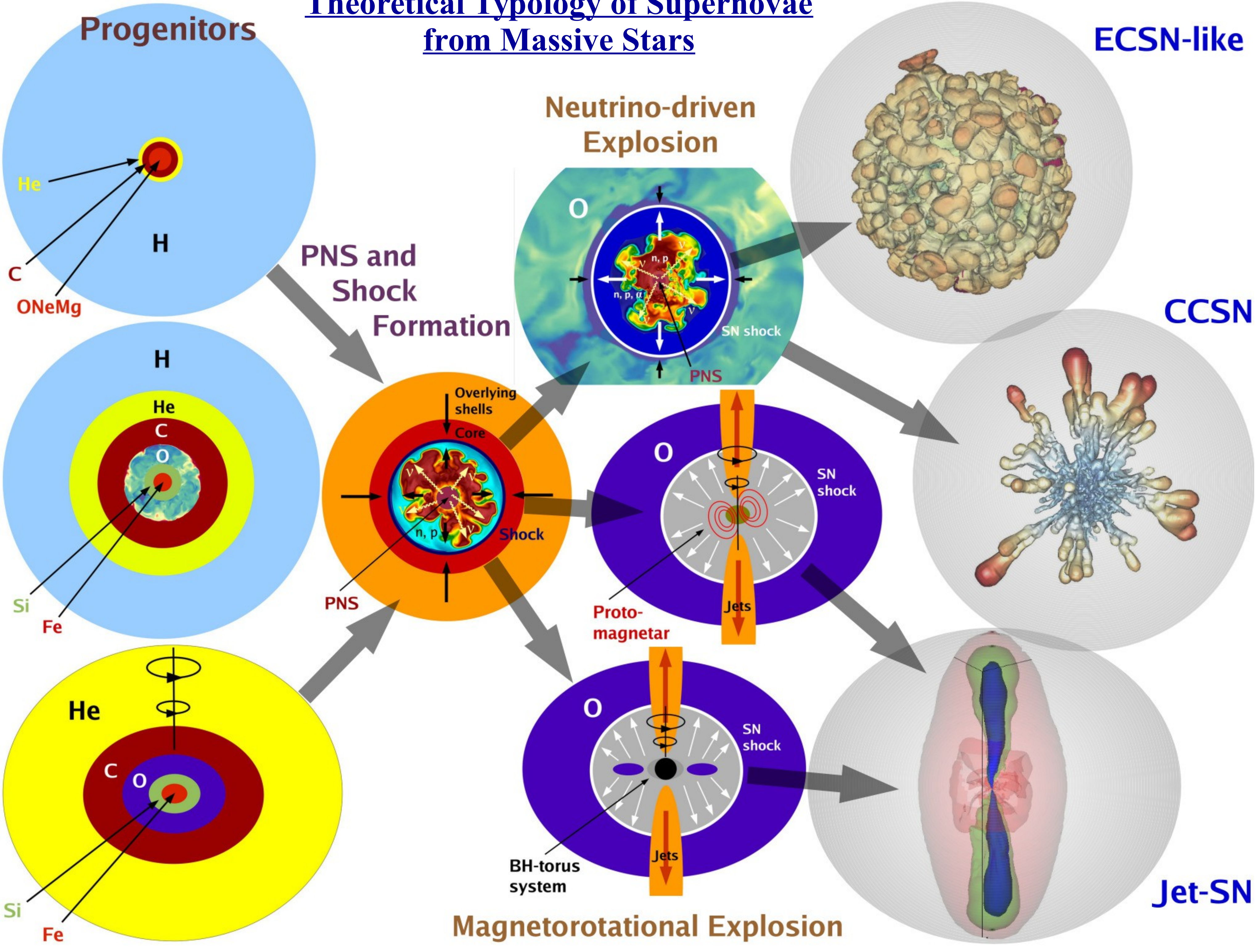


M. Sullivan

The Puzzling Zoo of Supernova-like Transients

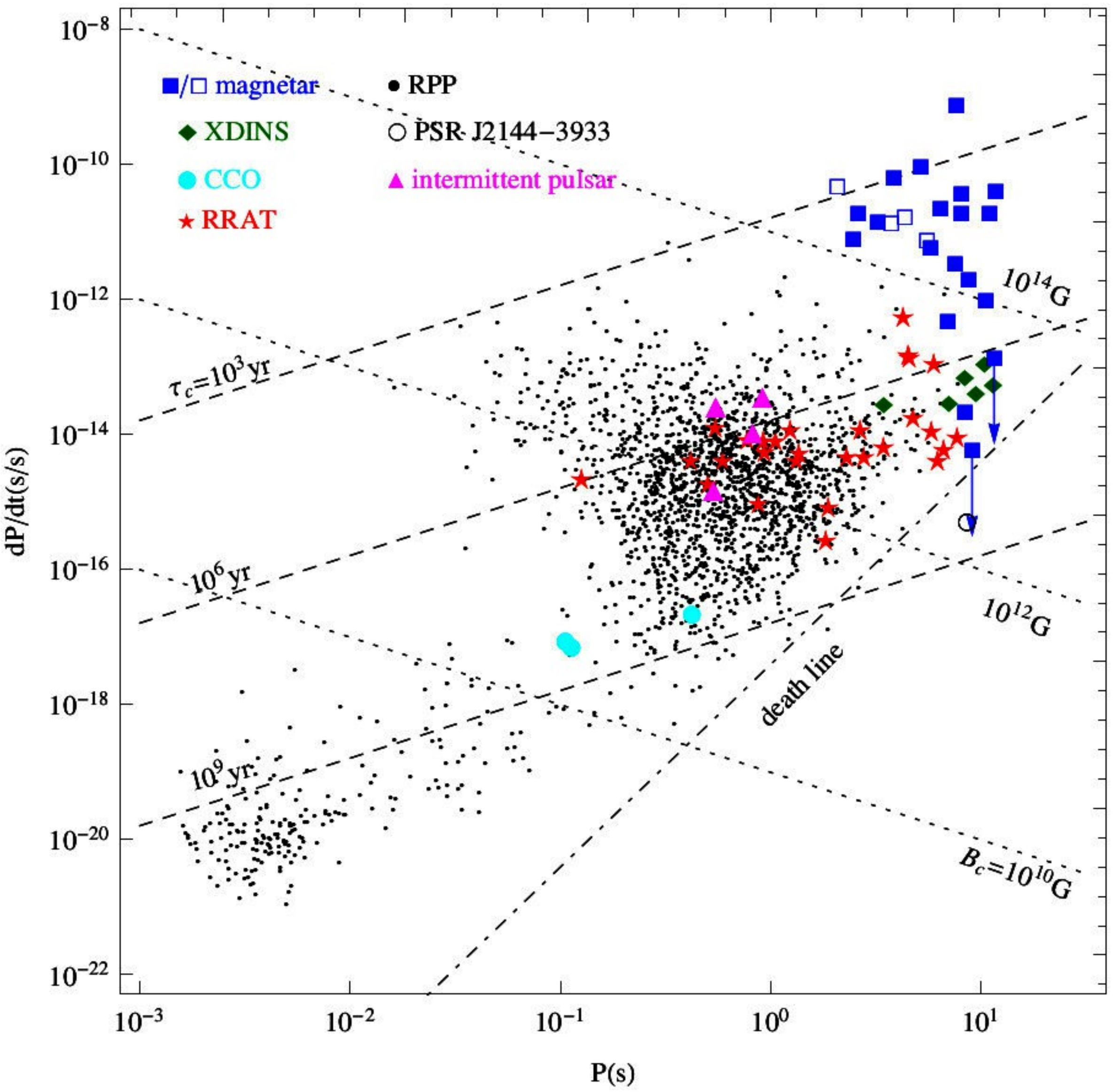


Theoretical Typology of Supernovae from Massive Stars



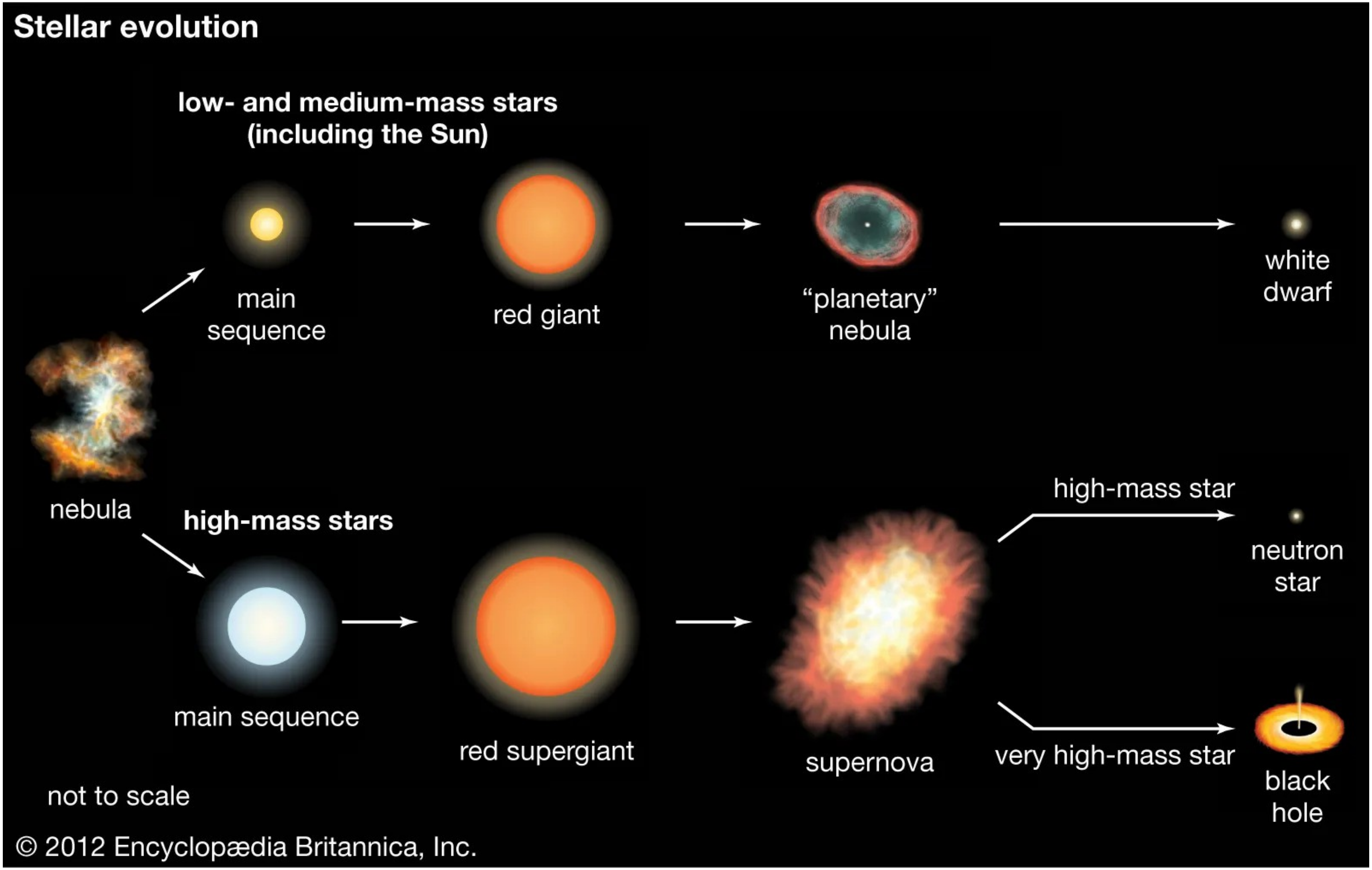
HTJ & A. Bauswein, in Handbook of Nuclear Physics (Springer-Nature, 2023); arXiv:2212.07498

Demographic View of Pulsars



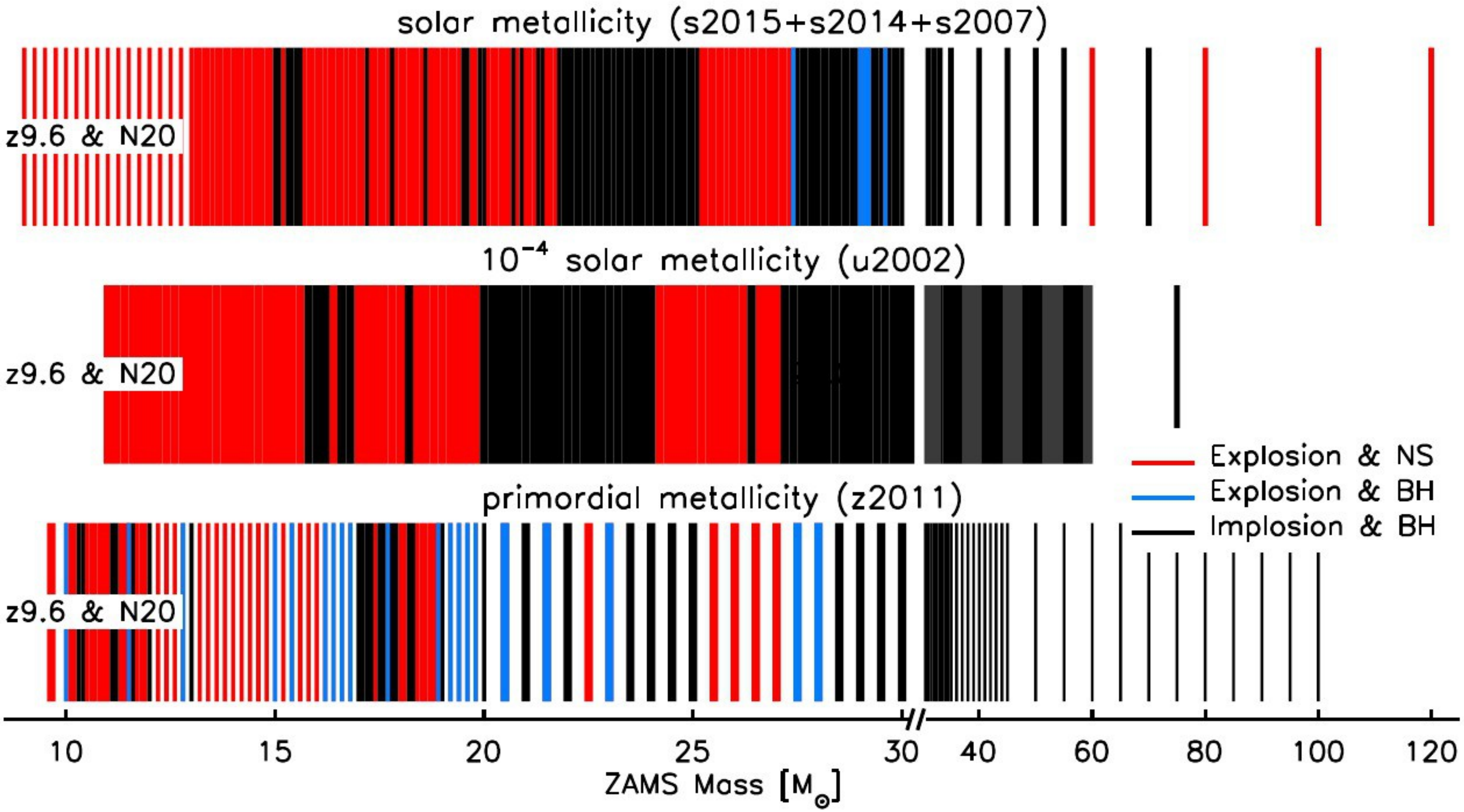
Zhou X., Tong, H., et al., arXiv:1809.05494

The Textbook Picture



Neutrino-driven Explosions: Variations with Metallicity and ZAMS Mass

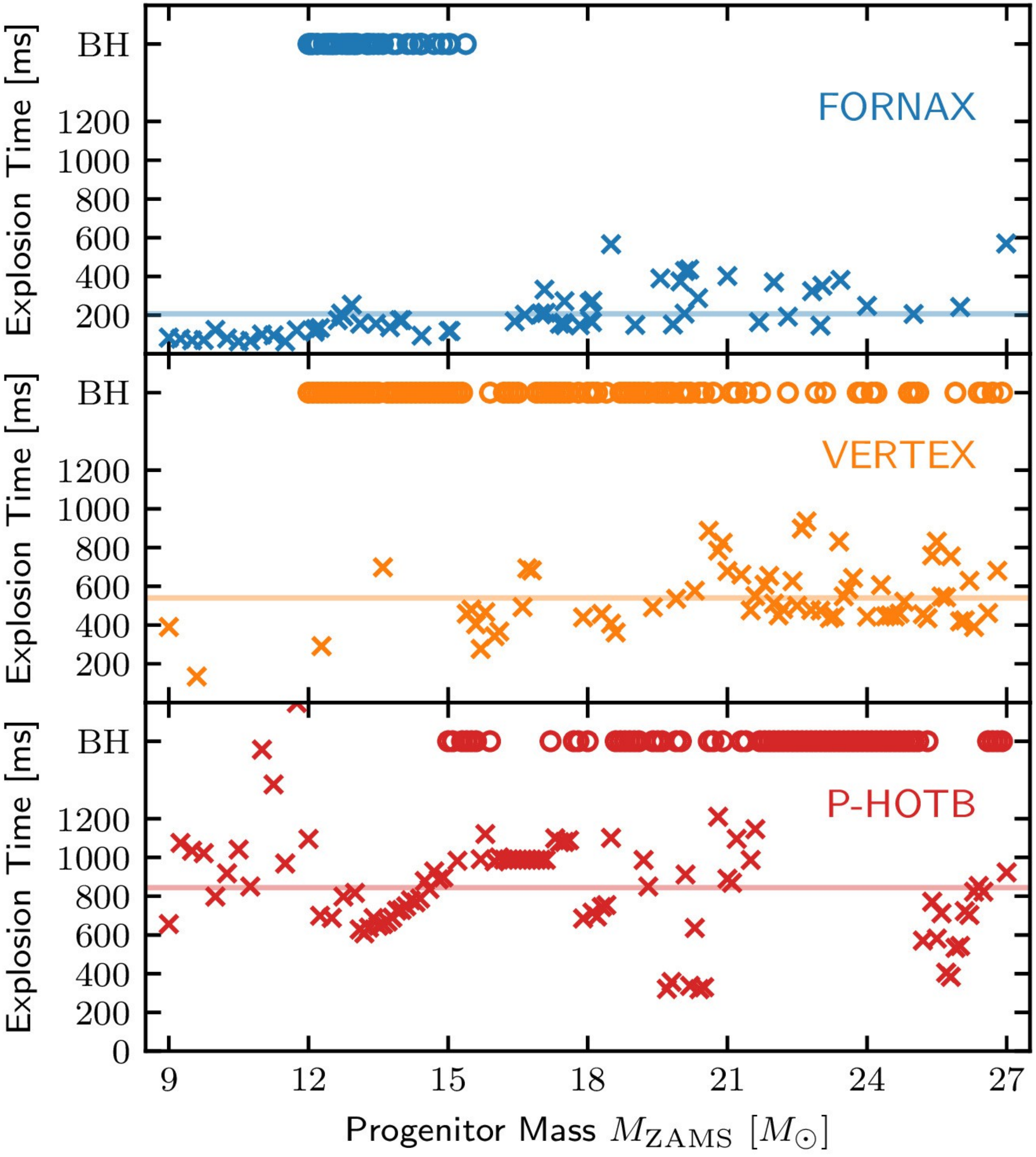
"Explodability" (NS vs. BH formation) prediction by simple "neutrino engine" treatments; depends on strength of engine.



(Ertl, PhD Thesis 2016; Janka, Handbook of Supernovae, arXiv:1702.08825)

The Explodability Puzzle

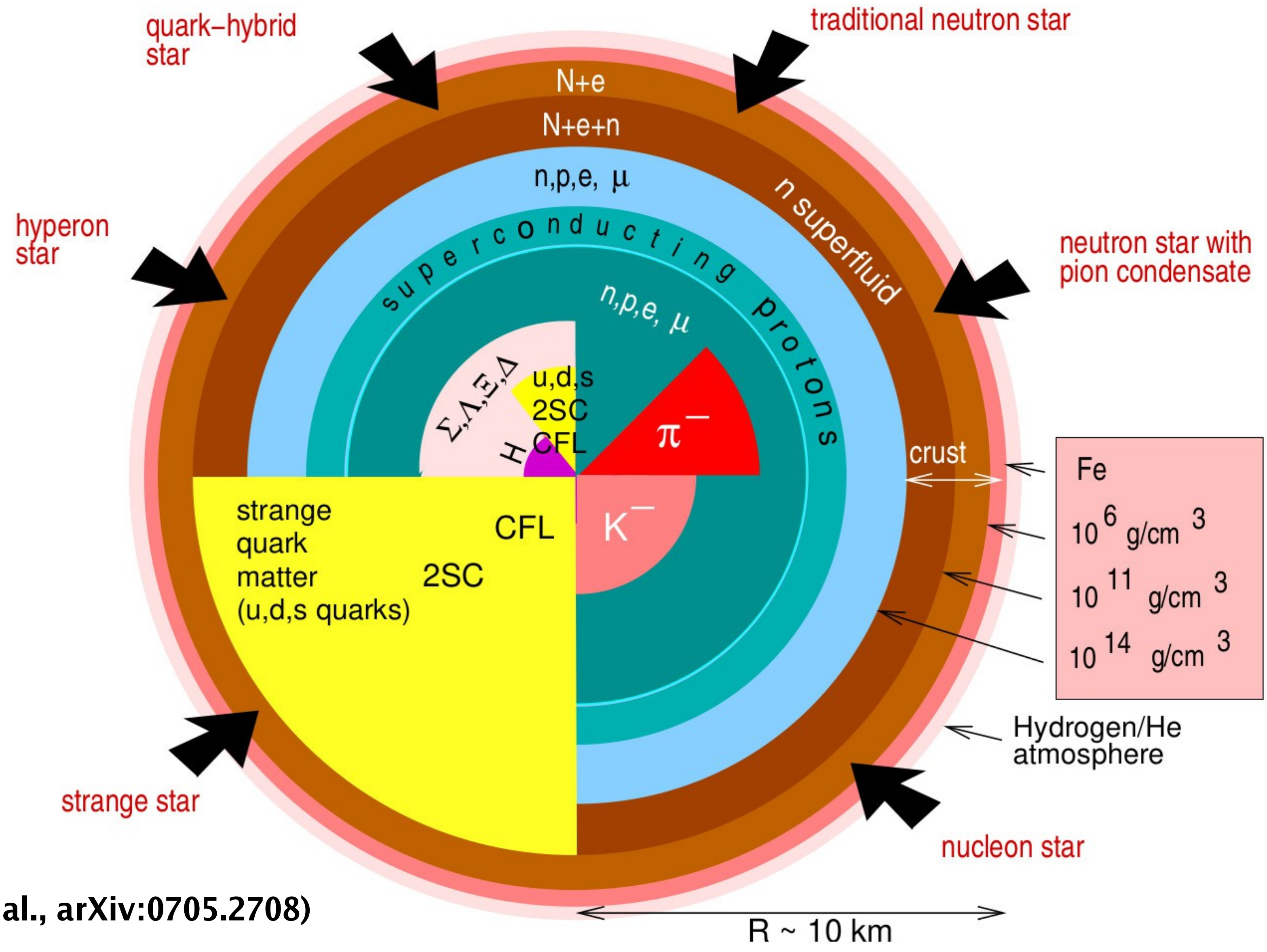
"Explodability" predictions from different simulations and treatments not yet converged.



(R. Glas, R. Bollig, THJ, in preparation)

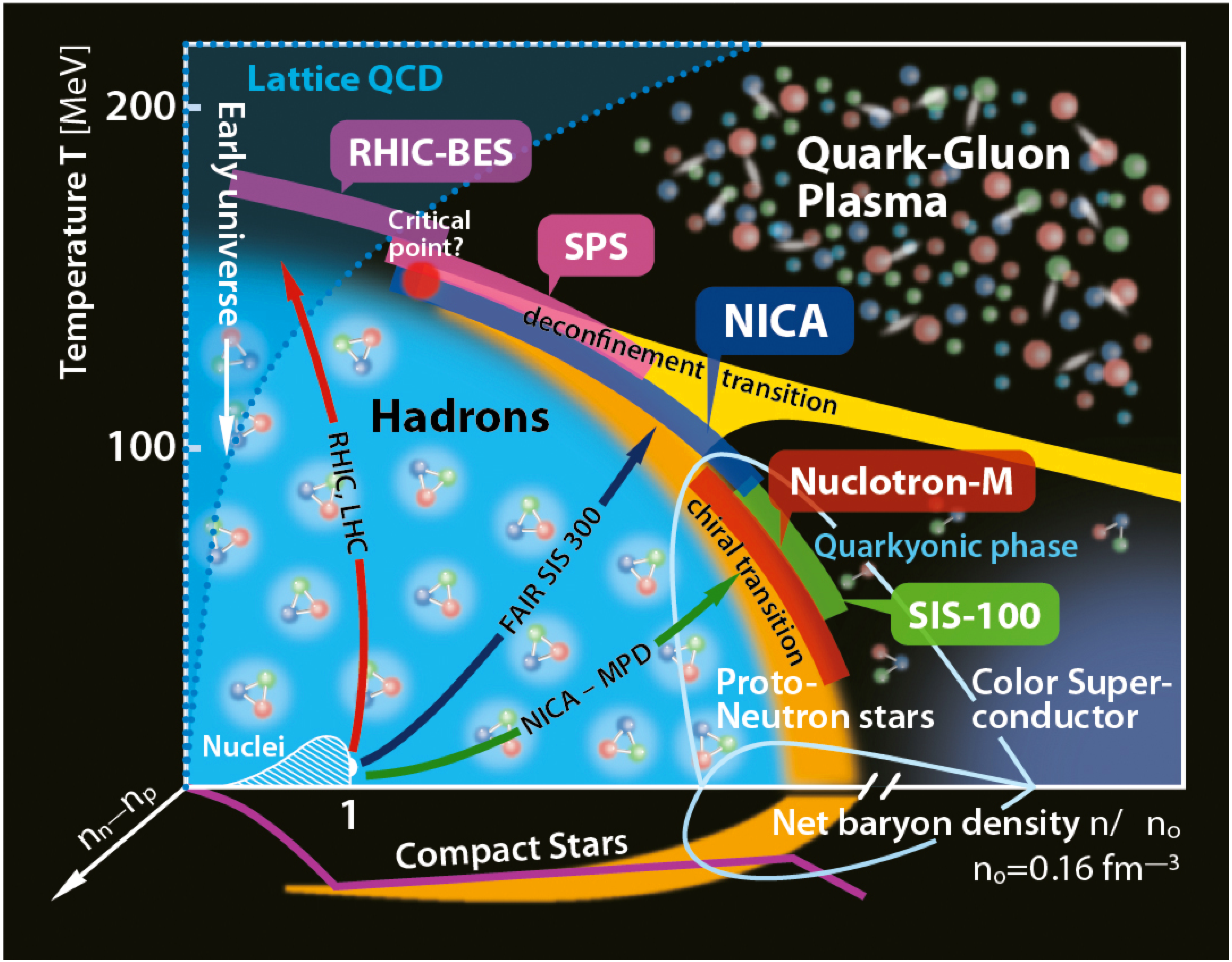
The NS-Matter Puzzle

Physics of matter inside compact stellar remnants remains an enigma.
Do the supra-nuclear cores of NSs contain mainly neutrons?



(F. Weber et al., arXiv:0705.2708)

NSs and Proto-NSs are Unique Laboratories of Nuclear Physics

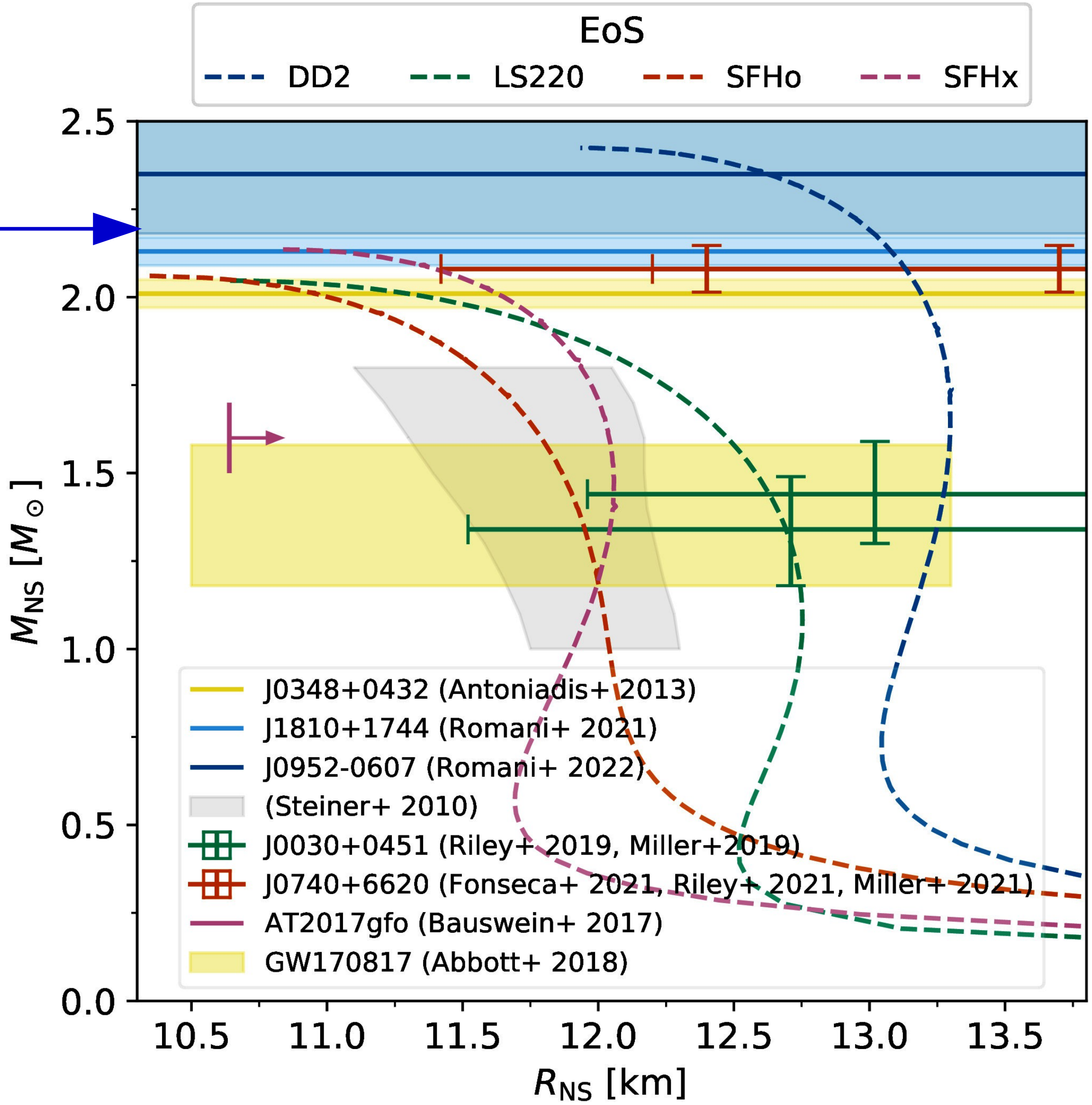


(GSI Darmstadt)

Multi-Wavelength and Multi-Messenger Astrophysics of Binaries Yield Bounds on NS Masses and Radii

GW170817 & Kilonova AT2017gfo

(Rezzolla+ 2017; Maragalit & Metzger 2017)



(Adapted from: M. Heinlein, Master Thesis, TUM, 2022)

MM Signals from NS+NS/BH Mergers

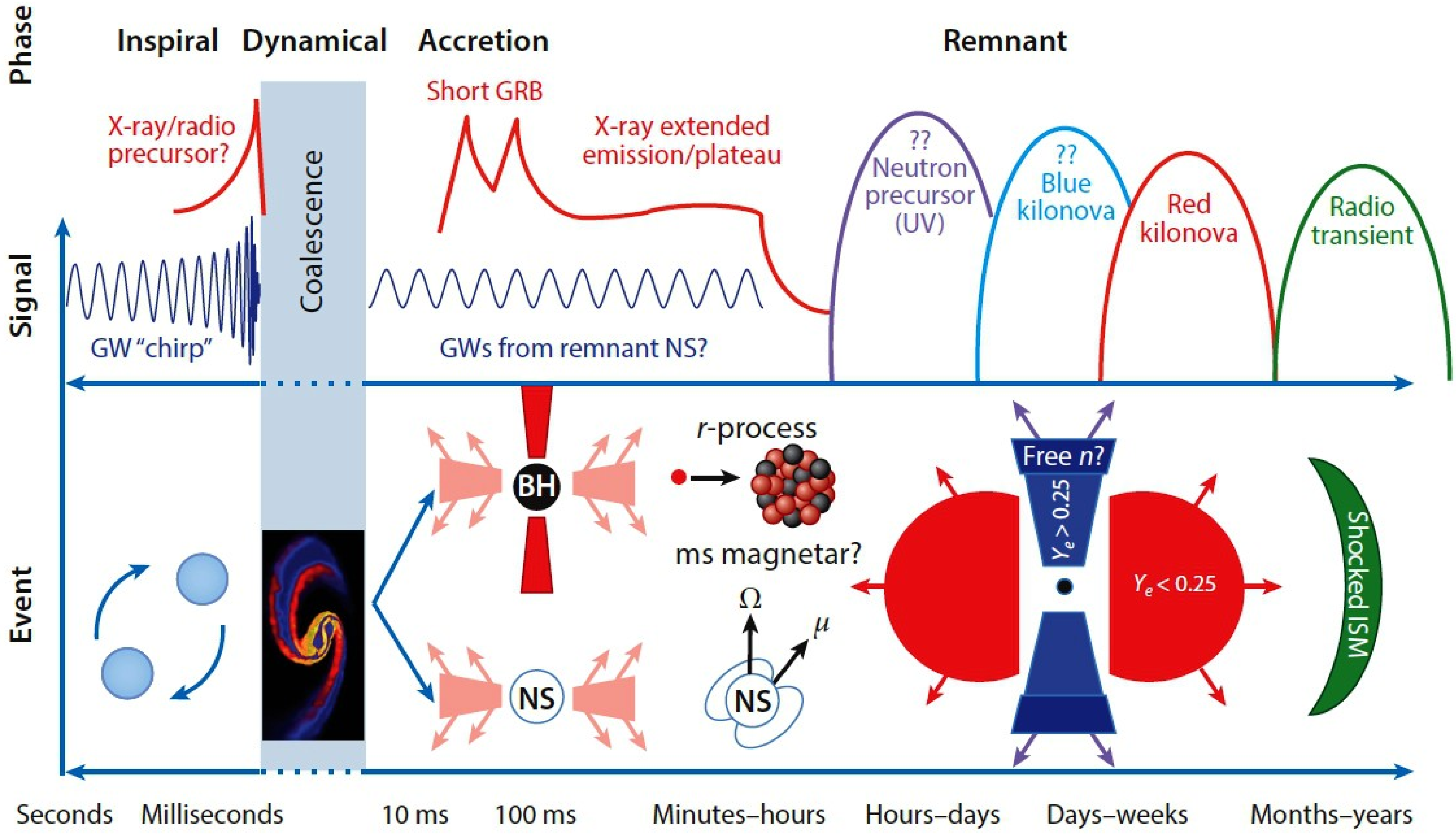
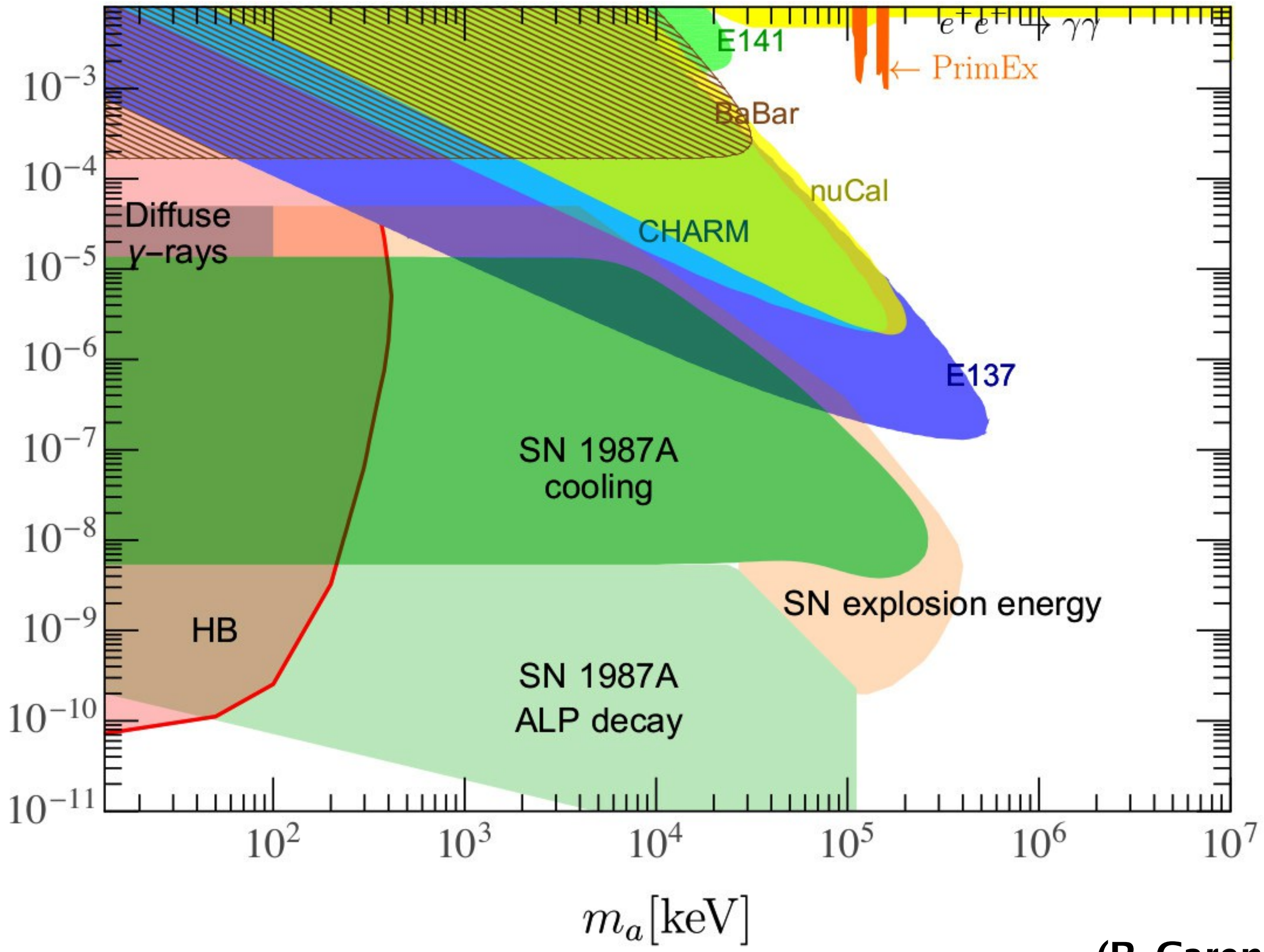


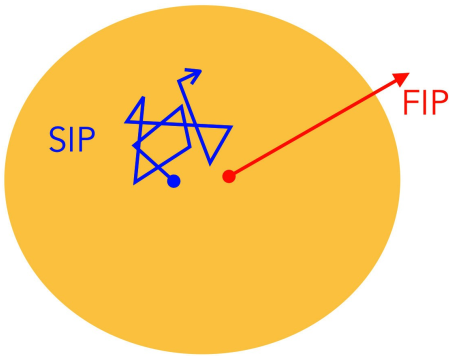
Figure 1

Phases of a neutron star (NS) merger as a function of time, showing the associated observational signatures and underlying physical phenomena. Abbreviations: BH, black hole; GRB, γ-ray burst; GW, gravitational wave; ISM, interstellar medium; n, neutron; UV, ultraviolet; Y_e, electron fraction. Coalescence inset courtesy of D. Price and S. Rosswog (see also Reference 15).

Fernández & Metzger, ARNPS (2016)

NSs and Proto-NSs are Unique Laboratories of Particle Physics





Hot proto-NSs might radiate large numbers of feebly interacting dark matter particles (FIPSs; e.g., dark photons, axions, ALPs).

Matter-affected dark matter fields could modify nucleon masses in NS interiors and thus affect macroscopic and microscopic properties of NSs.

(P. Carenza, talk @ CERN, Oct. 2022)

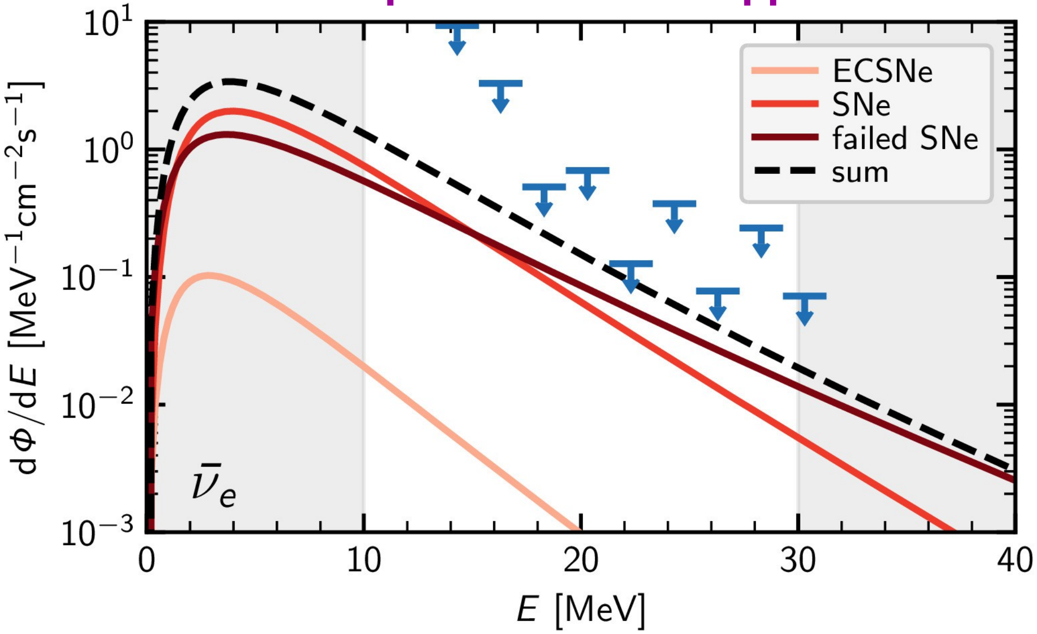
Diffuse Supernova Neutrino Background: An Upcoming Multi-Messenger Opportunity

Differential number flux [$\mathrm{MeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$] of (anti-)neutrinos arriving on Earth with energy E:

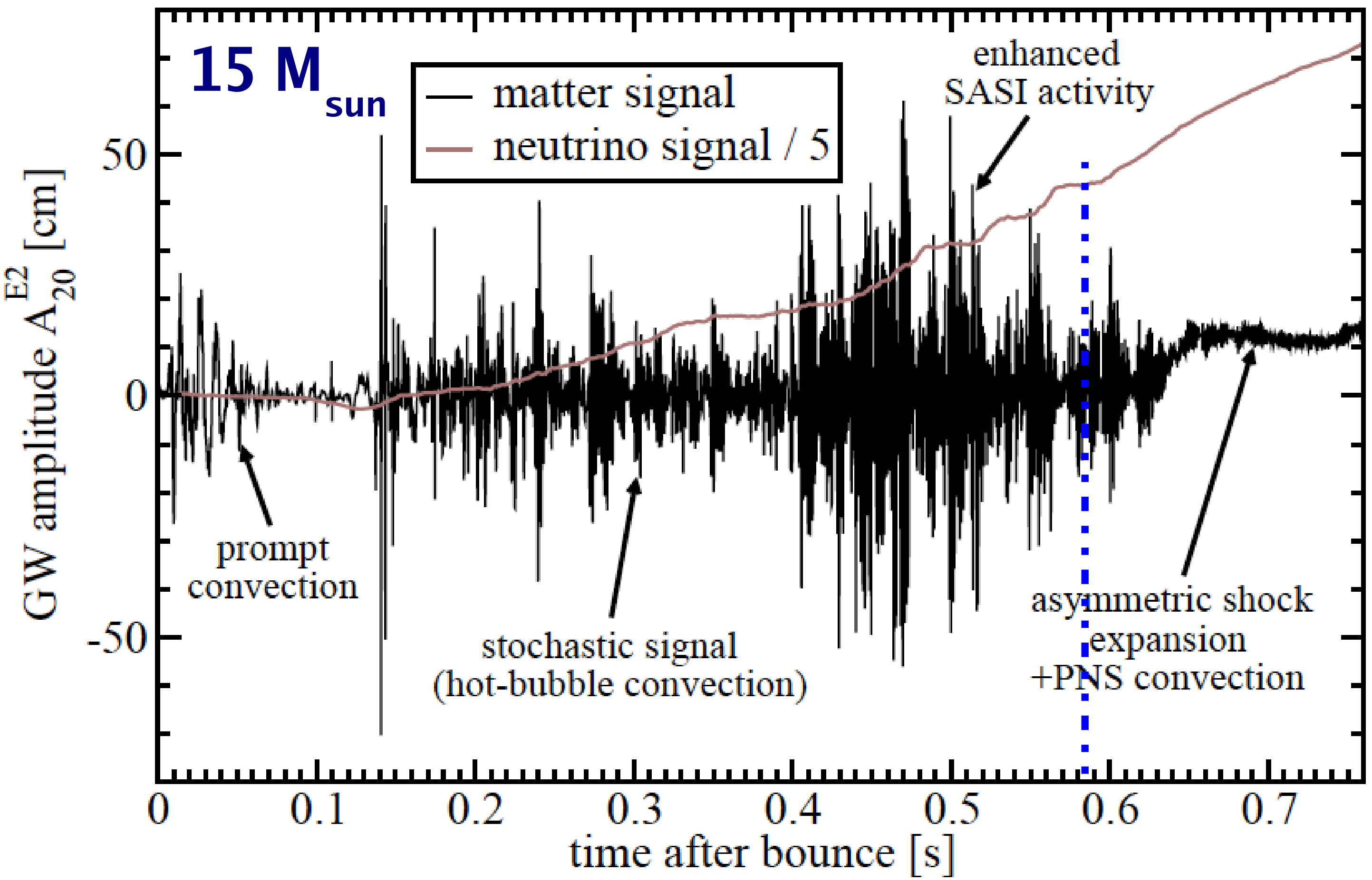
$$\frac{\mathrm{d}\Phi}{\mathrm{d}E} = c \int \frac{\mathrm{d}N_{\mathrm{CC}}}{\mathrm{d}E'} \frac{\mathrm{d}E'}{\mathrm{d}E} R_{\mathrm{CC}}(z) \left|\frac{\mathrm{d}t}{\mathrm{d}z}\right| \mathrm{d}z$$

- **Supernova neutrino number spectrum [MeV^{-1}], time-integrated and IMF-folded; cosmological redshift $E' = (1+z)E$**
- **Cosmic core-collapse rate density [$\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$] (may be linked to star formation rate)**
- **Cosmological volume factor (e.g., ΛCDM)**
- **1st and 2nd factor contain large uncertainties**
- **SuperKamiokande-Gd and JUNO are likely to measure DSNB in the coming years!**

Data: SuperKamiokande upper limits



Gravitational Waves from SN Explosions



(Müller, THJ, & Marek, ApJ 766 (2013) 43)

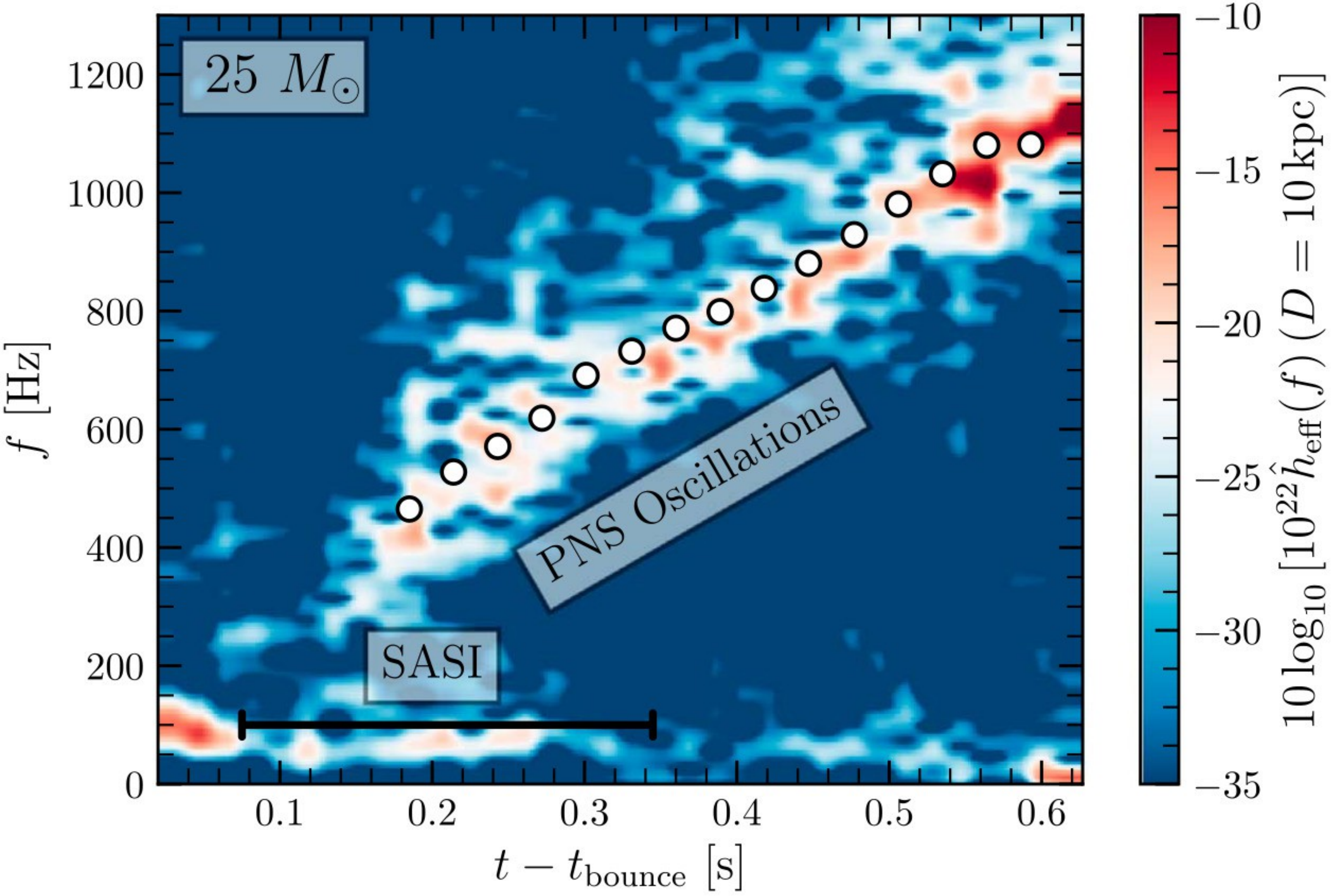
$$h = \frac{1}{8}\sqrt{\frac{15}{\pi}}\sin^2\Theta\frac{A_{20}^{\mathrm{E2}}}{R}$$

$$h_\nu = \frac{2G}{c^4 R}\int_0^t L_\nu(t')\alpha_\nu(t')\,dt'$$

$$\alpha_\nu = \frac{1}{L_\nu}\int \pi\sin\theta\,(2|\cos\theta| - 1)\,\frac{dL_\nu}{d\Omega}d\Omega$$

Gravitational Waves from SN Explosions

GW spectrograms reveal different signal contributions



(Radice, Morozova, Burrows, Vartanyan & Nagakura, ApJL 876 (2019) L9)

Frequency of neutron star surface gravity-modes (Müller et al., ApJ 766 (2013) 43):

$$f_{\mathrm{g}} \approx \frac{1}{2\pi}\frac{GM_{\mathrm{by}}}{R^2}\sqrt{1.1\frac{m_{\mathrm{n}}}{\langle E_{\bar{\nu}_{\mathrm{e}}}\rangle}}\left(1-\frac{GM_{\mathrm{by}}}{Rc^2}\right)$$

MM and MWL Astrophysics involving Compact Stellar Remnants

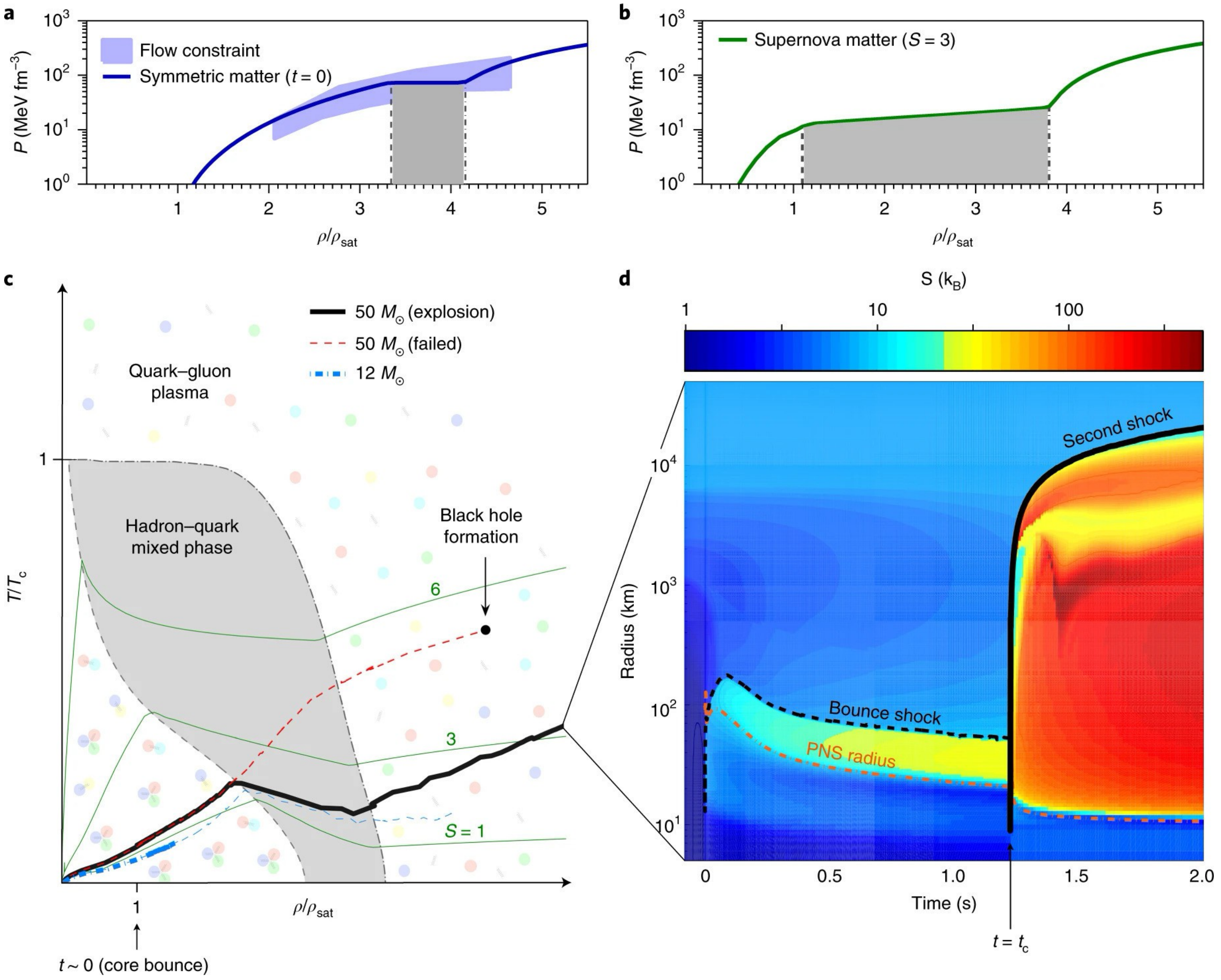
- NSs and BHs are MM and MWL sources by their nature.

- No single information sufficient to answer pivotal questions! MM information is essential for advancing theory.

- Upcoming surveys and planned facilities (e.g., ZTF, Ultrasat, Vera Rubin, SKA, Einstein Telescope, Cosmic Explorer, etc.) will yield gigantic plethora of transient events.

- From astro/nuclear/particle theorists' perspective, we also need comprehensive and detailed data from individual events to discriminate theoretical possibilities.

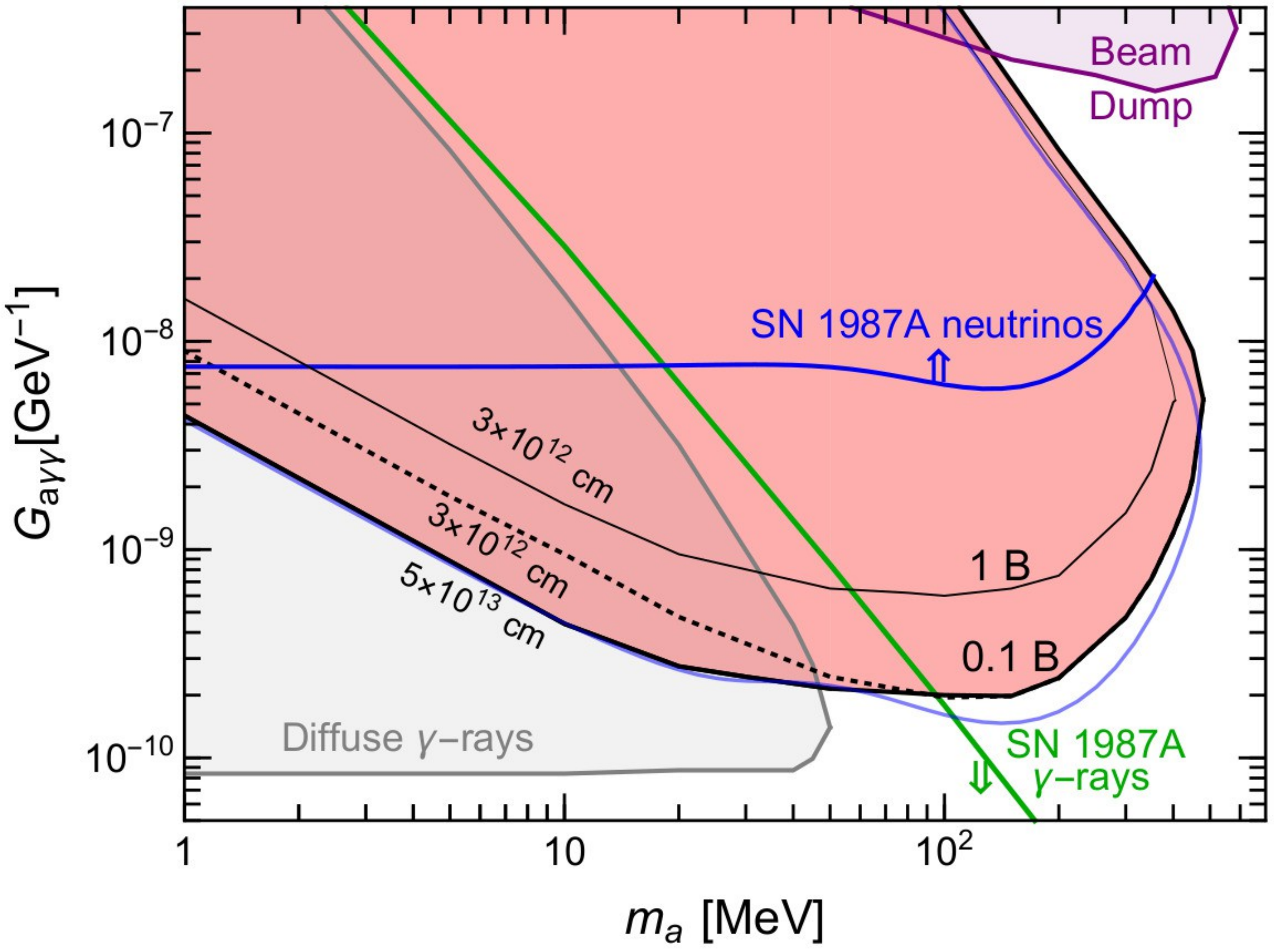
Does a Hadron-Quark Phase Transition Occur?



Fischer et al., Nature Astronomy 2 (2018) 980

Low-energy Supernovae Constrain Radiative Particle Decays

Energy deposition by radiative decays of axion-like particles (ALPs) must not over-power low-energy, low-luminosity SNe



Caputo, THJ, et al., PRL 128 (2022) 221103

General overview of new physics and SN ν's: Manibrata Sen's talk of 05/29!