Overview and perspectives: Equation of state and nucleosynthesis programs

SFB 1245

SFB Workshop (4-7, Oct. 2022)

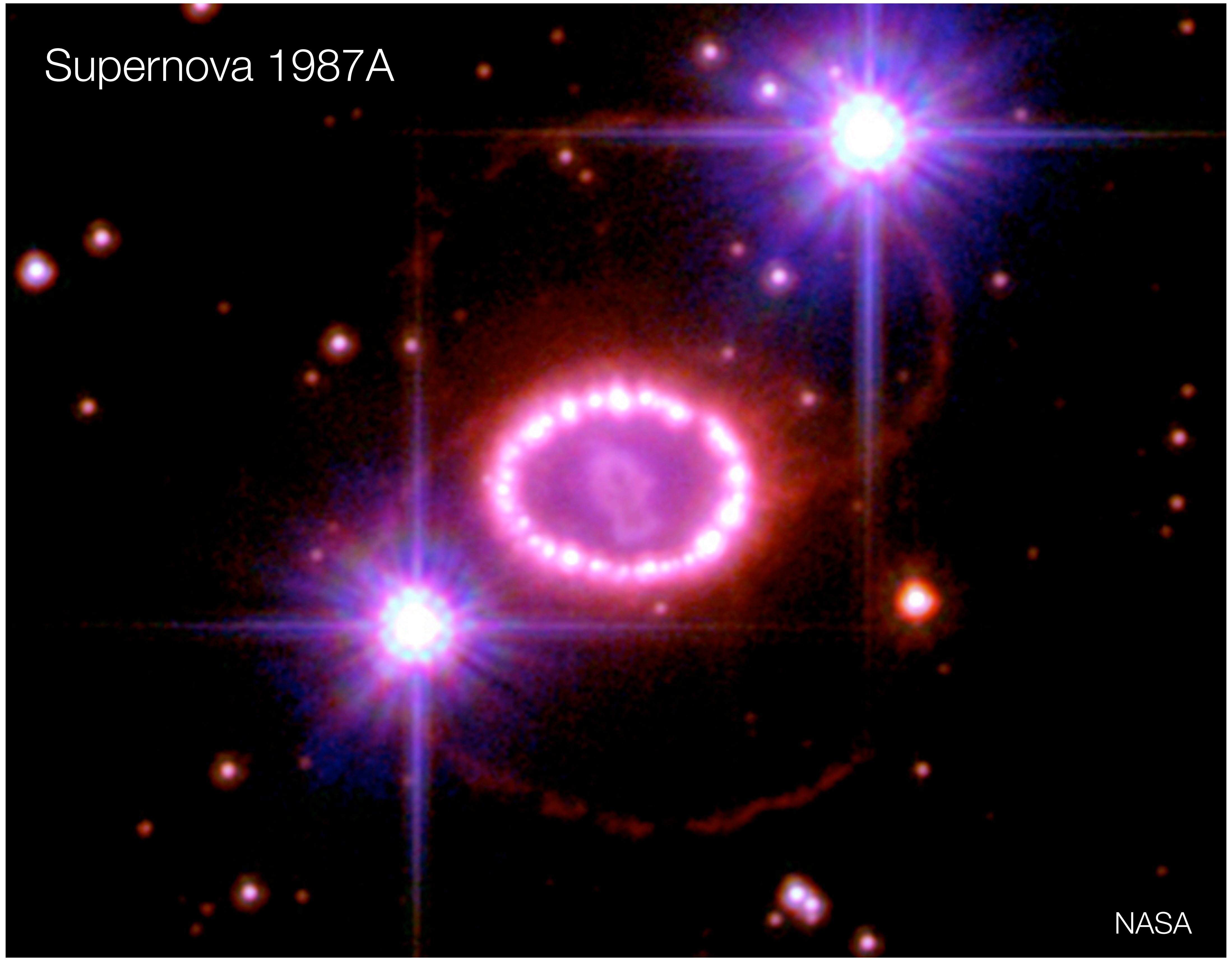
Nuclear astrophysics @ SFB 1245

B01 Weak interactions

B05 Neutron stars and equation of state

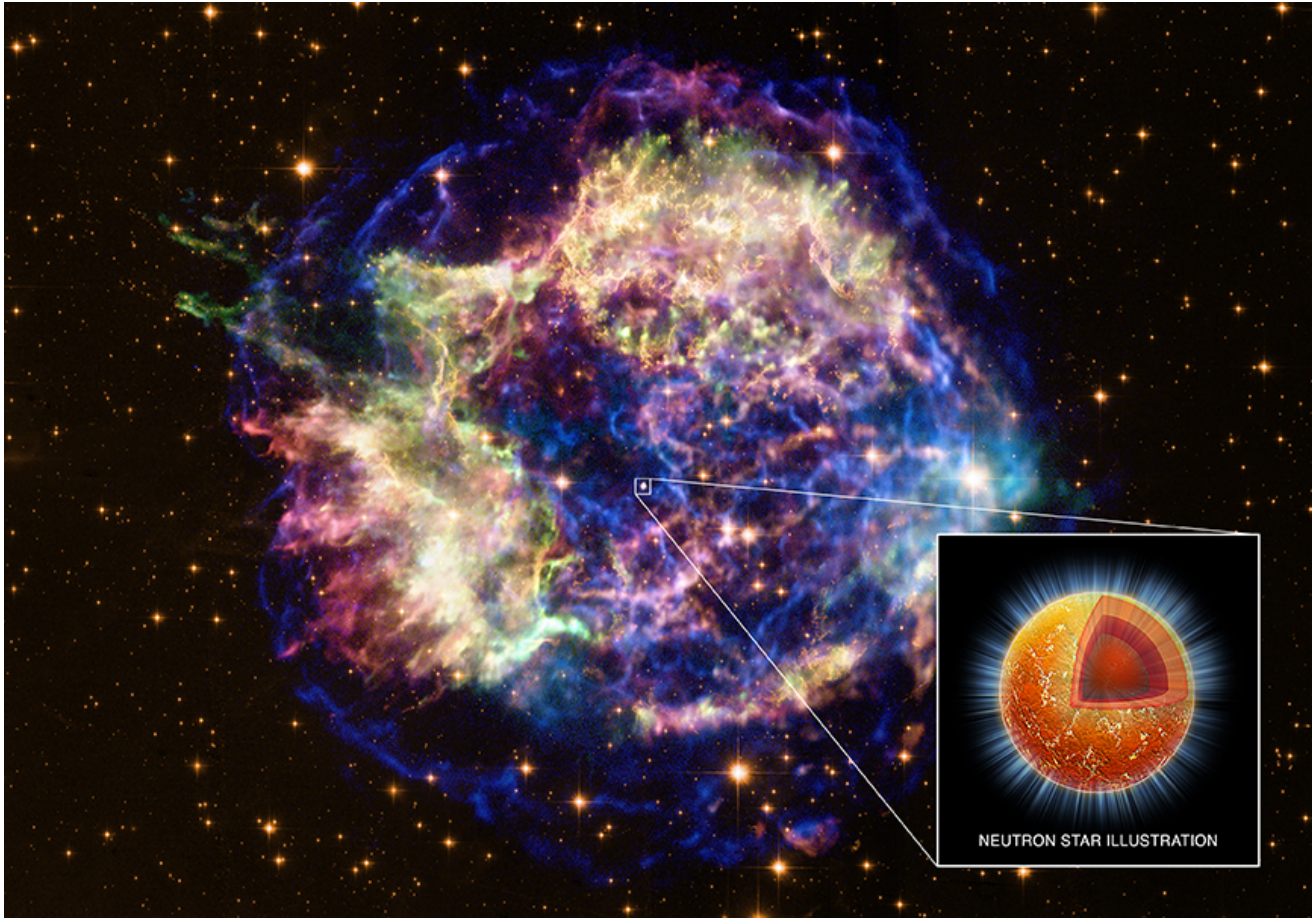
B06 Core-collapse supernovae

B07 Neutron star mergers

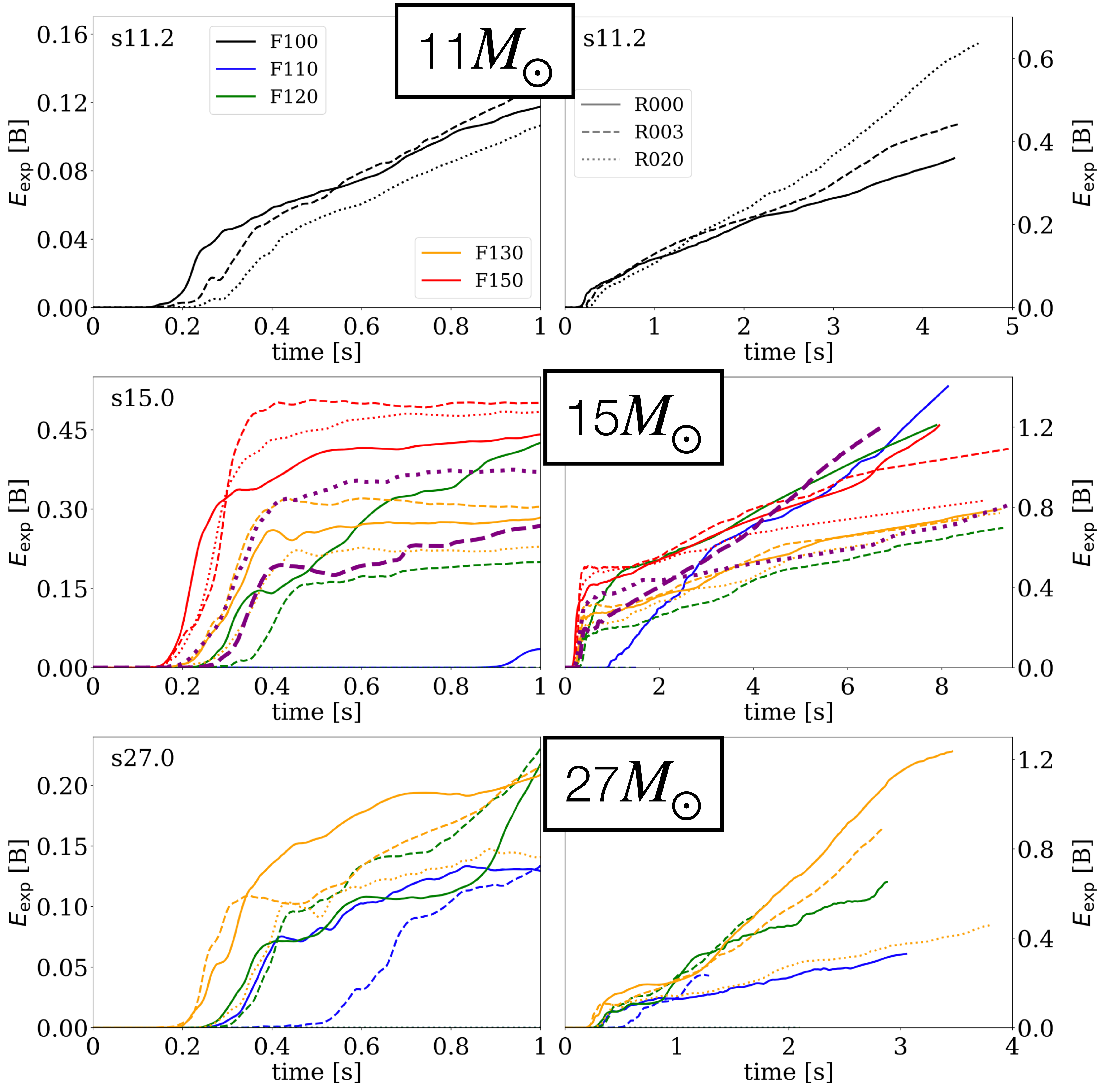


PIs:
Almudena Arcones, Andreas Bauswein, Jens Braun, Kai Hebeler, Gabriel Martinez-Pinedo, Achim Schwenk

Core-collapse supernovae (B06)



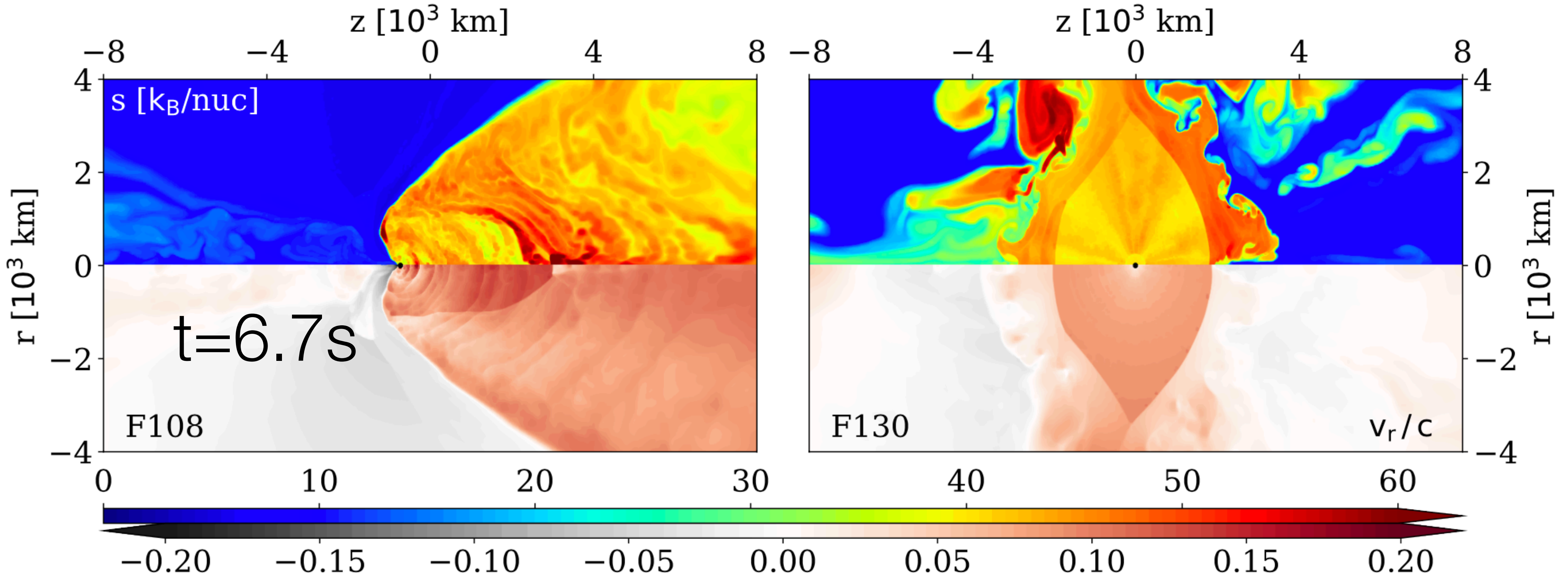
Post-explosion evolution of core-collapse supernovae



Witt et al. 2021

59 simulations (2D): 32 exploding models -> variation of explosion energy, rotation, progenitor

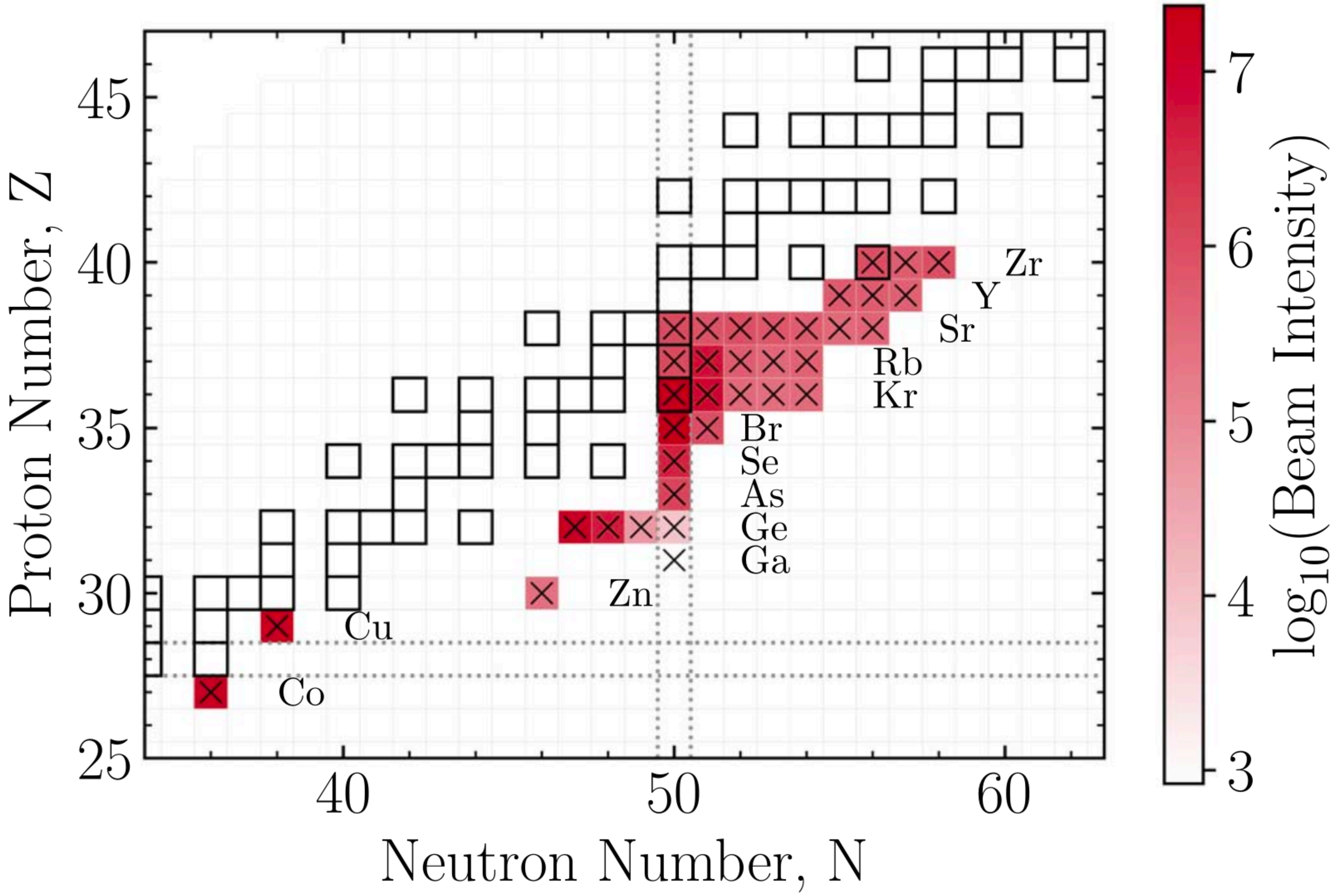
- Accretion lasts for seconds
- Explosion energy increases for seconds
- Neutrino-driven wind: rare
  -> long-time simulations in 3D

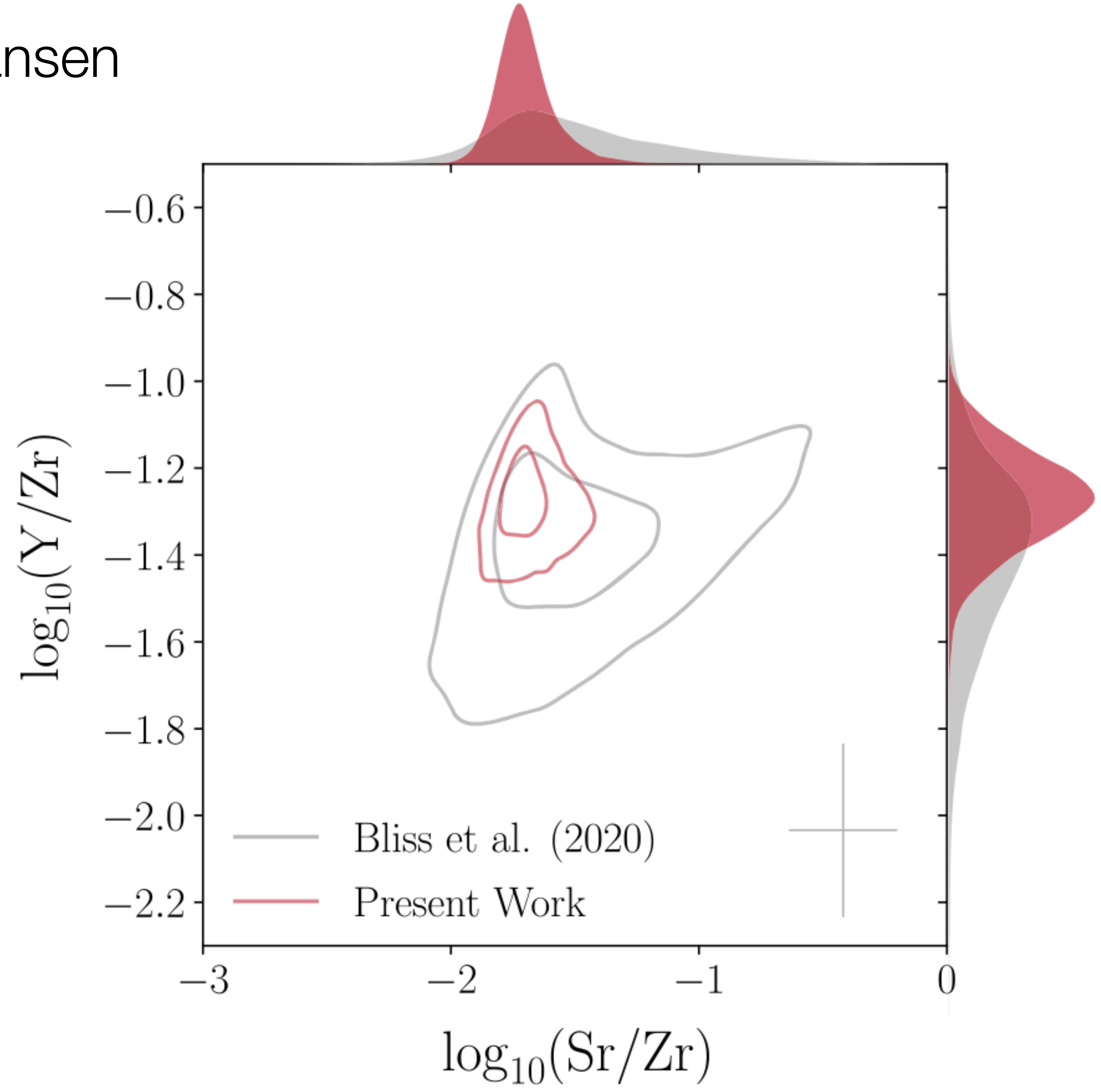


Talk: Gerard Navo

Weak r-process: (α, n) reactions

Key (α,n) reactions in supernova neutron-rich ejecta -> possible in current and future RIB facilities
Reduction of theoretical uncertainties
Comparison to observations -> with new PI Camilla J. Hansen





Bliss et al. 2020, Psaltis et al. 2022

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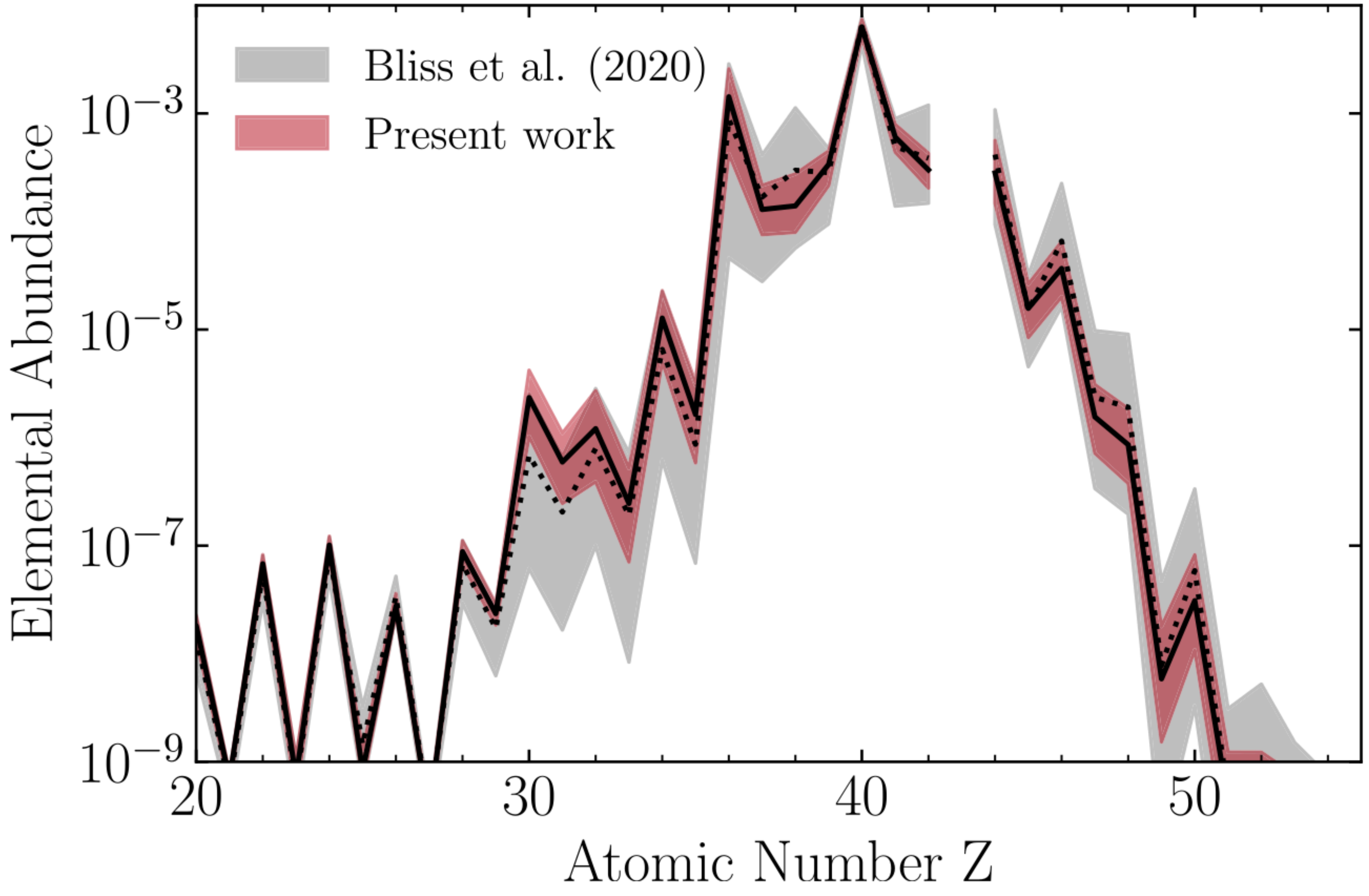

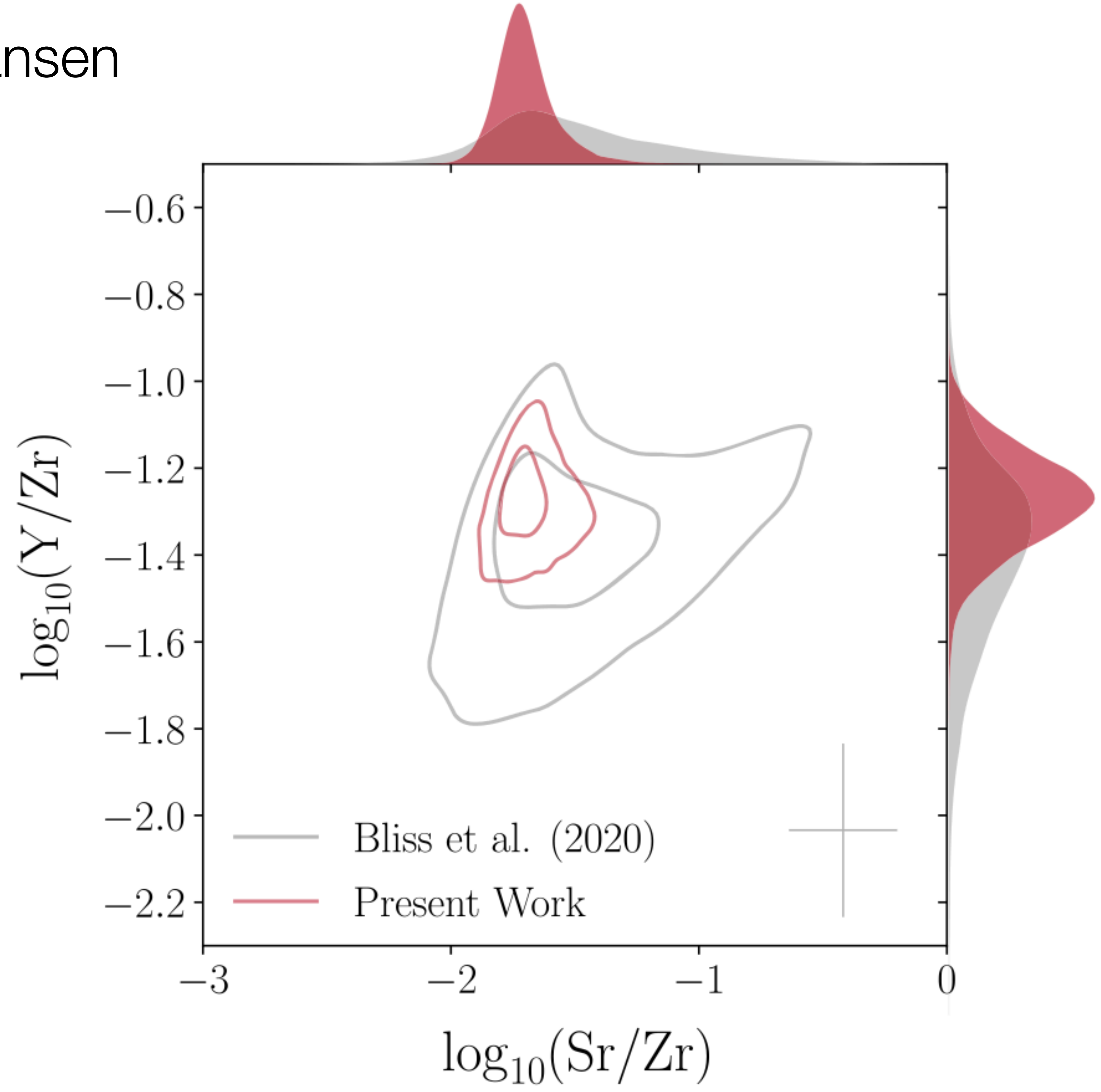

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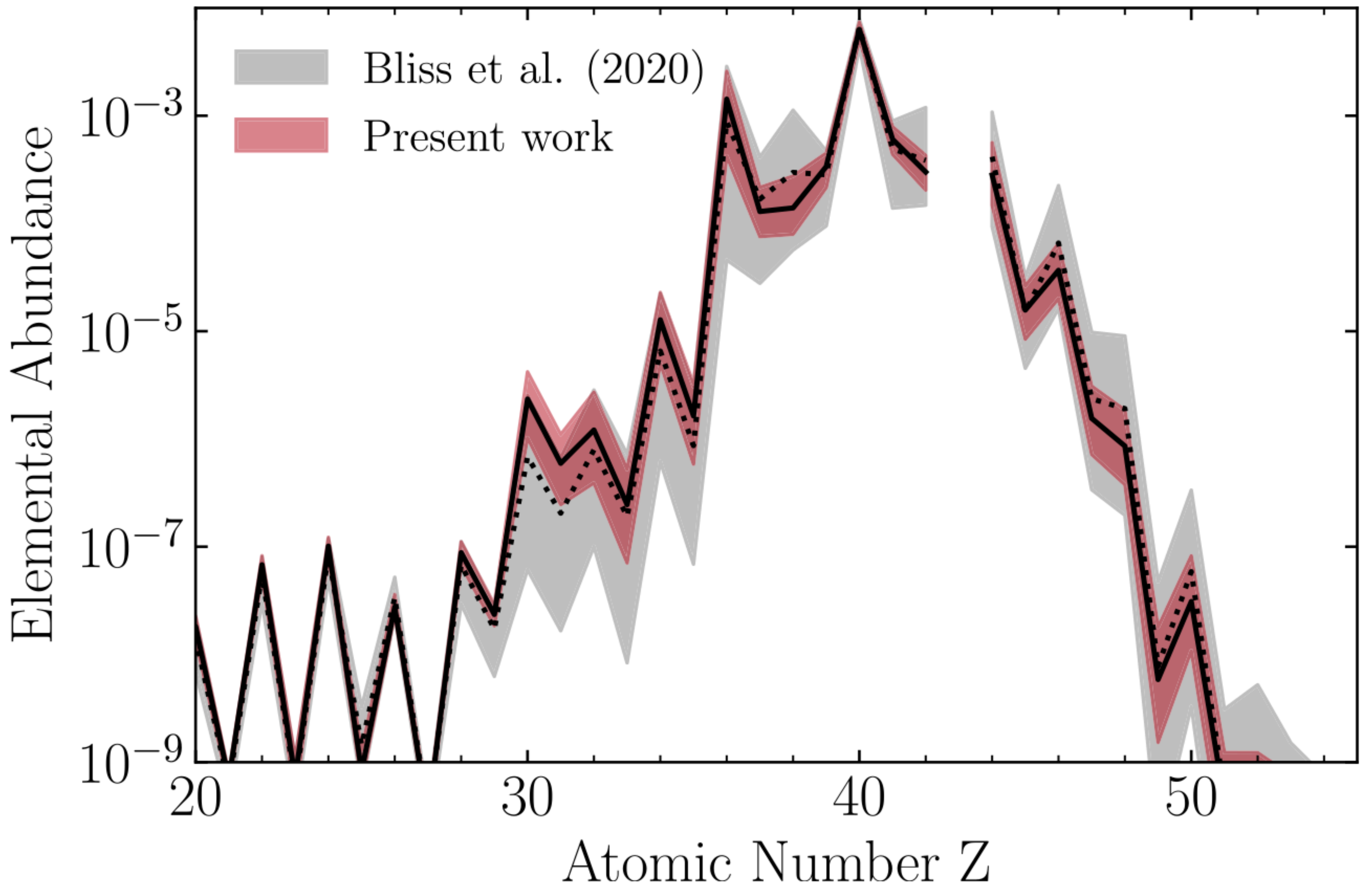
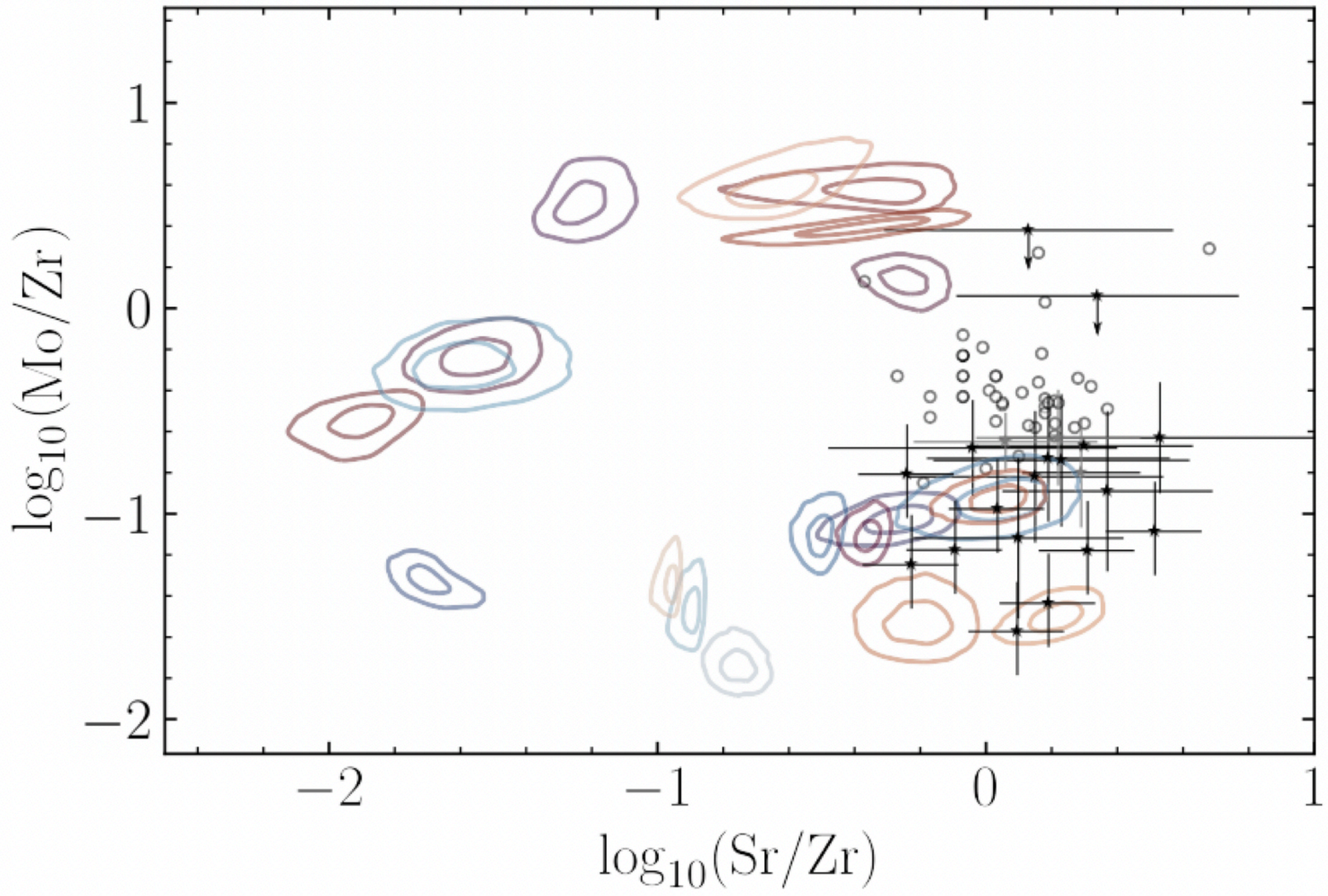
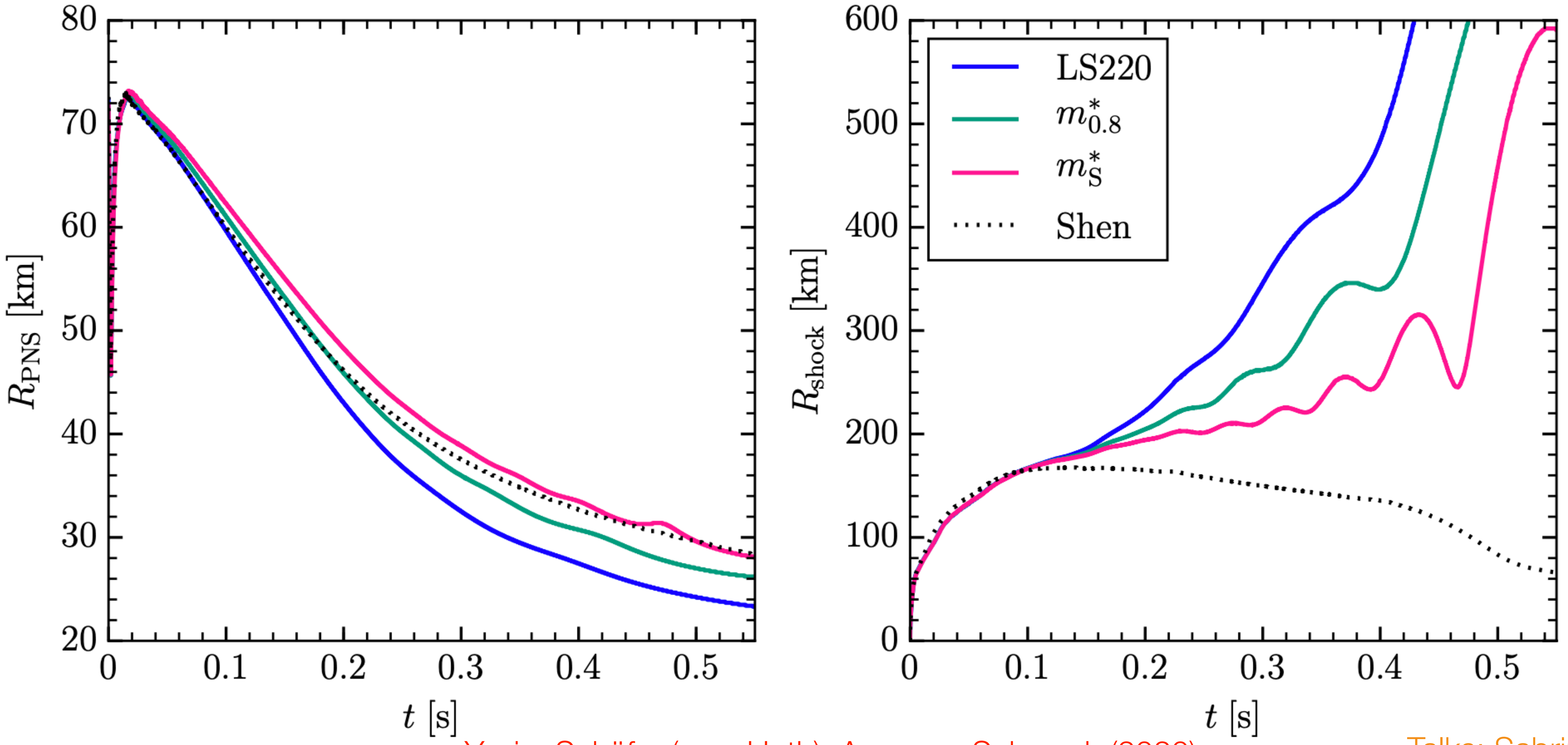




Bliss et al. 2020, Psaltis et al. 2022

Equation of state

First systematic study of nuclear matter properties
1D simulations, FLASH + M1 + increased neutrino heating



Effective mass:
PNS contraction

Yasin, Schäfer (now Huth), Arcones, Schwenk (2020)

Talks: Sabrina Huth, Maximilian Jacobi

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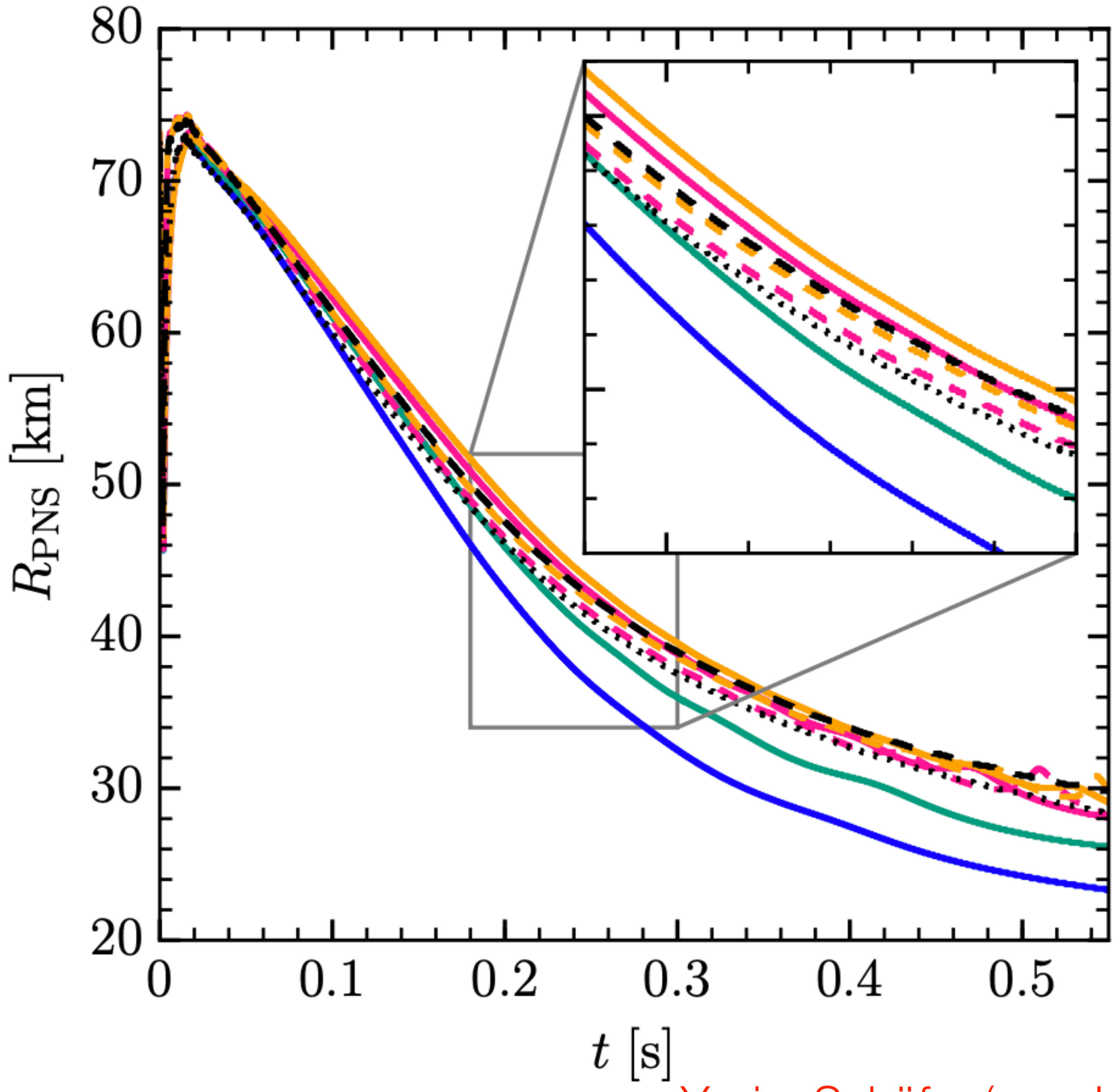

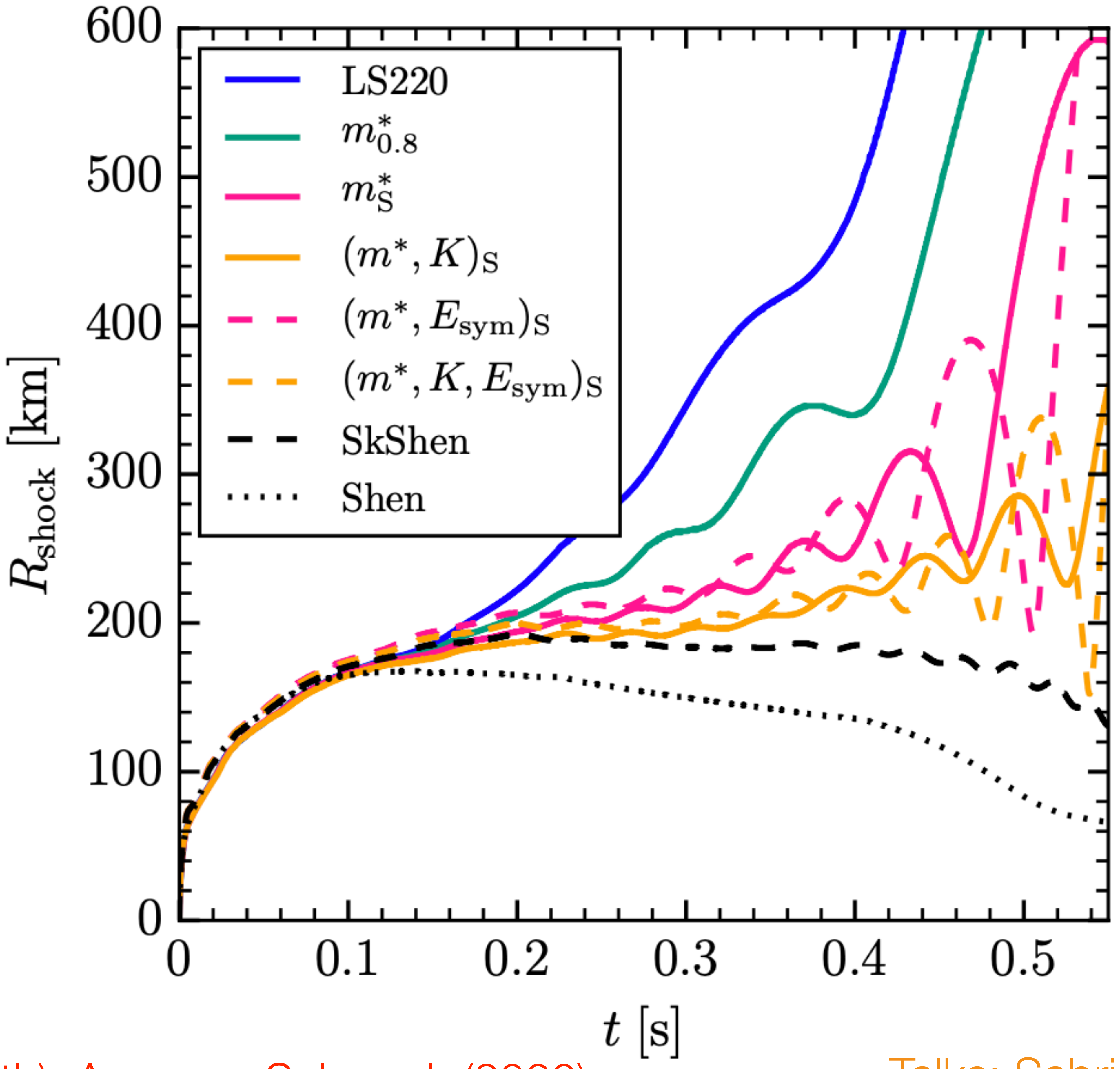

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Neutrino oscillations

- Equation for neutrino flavor evolution:

coherent forward scatterings

$$\frac{\mathrm{d}\varrho}{\mathrm{d}t} = -i[\mathbf{H}(\varrho), \varrho] + \mathbf{C}(\varrho) \quad \text{with neutrino flavor density matrix: } \varrho \sim \begin{pmatrix} n_{\nu_e} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & n_{\nu_\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & n_{\nu_\tau} \end{pmatrix}$$

incoherent collisions

- Neutrino oscillations:
  - Vacuum mixing
  - Mikheyev–Smirnov-Wolfenstein (MSW) effect
  - Collective neutrino oscillations and flavor instability
    (associated with special flavor modes enhancing the small flavor mixing resulted from neutrino propagation)
    1. Slow oscillations: lead to splitting of energy spectrum
    2. Fast oscillations: triggered by angular spectral crossing
    3. **Collisional oscillations: asymmetric collisional rates of emission and absorption**

Xiong, Martinez-Pinedo, et al. (to be submitted)

Collisional neutrino oscillations

- Evolve flavor evolution equation with background matter profiles provided from CCSN simulations

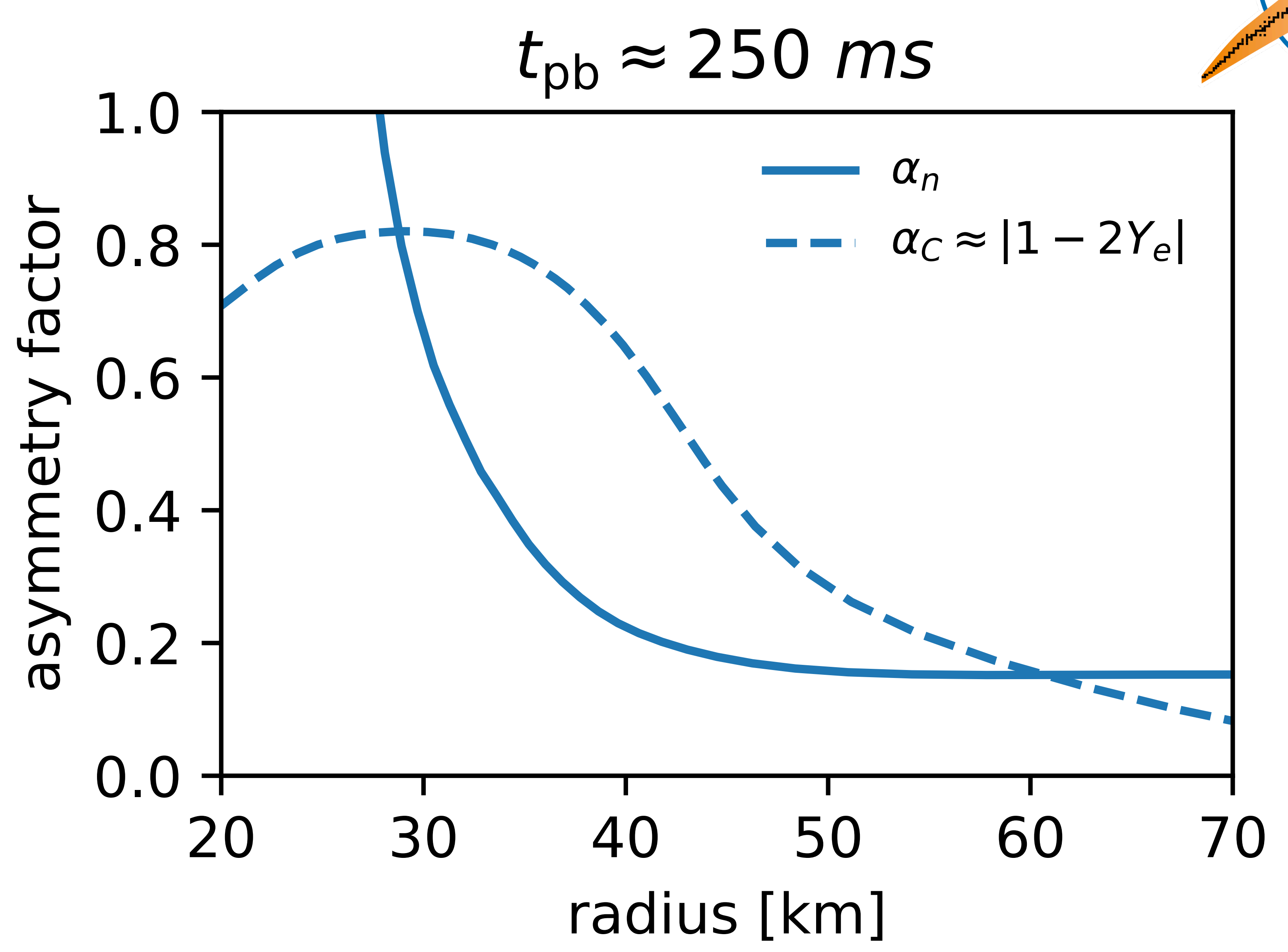
- Collisional flavor instability develops when [Johns, 2021]

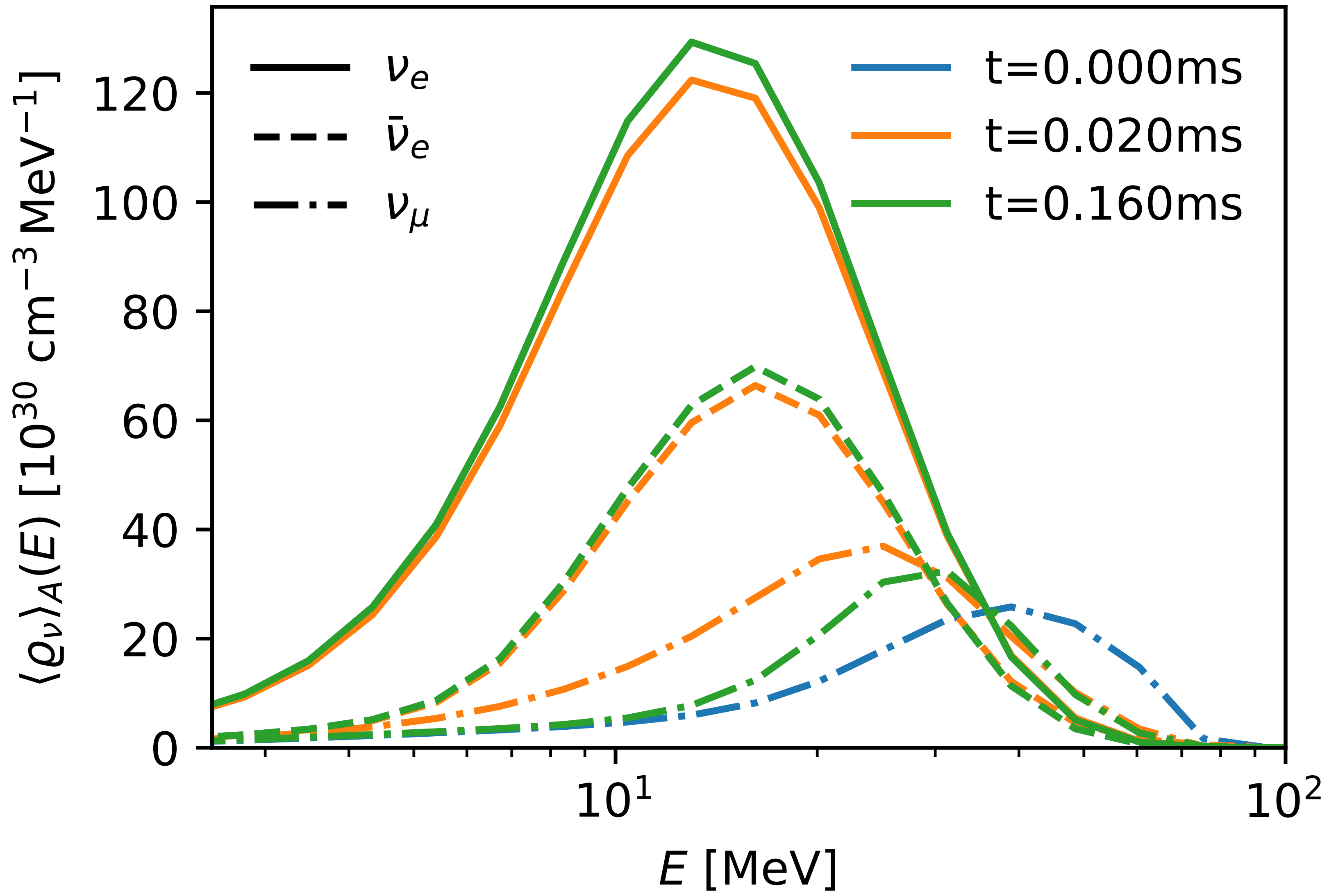
$$\alpha_n \lesssim \alpha_C,$$

with asymmetry factors

$$\alpha_n \sim \left| \frac{n_\nu - n_{\bar\nu}}{n_\nu + n_{\bar\nu}} \right| \text{ and } \alpha_C \sim \left| \frac{C - \bar C}{C + \bar C} \right|.$$

- Results:
  - Collisional flavor instability can occur near the neutrino sphere
  - ν_e and $\bar\nu_e$ convert to ν_μ and $\bar\nu_\mu$ when flavor instability occurs
  - Spectra of ν_e and $\bar\nu_e$ are quickly restored by the emissions

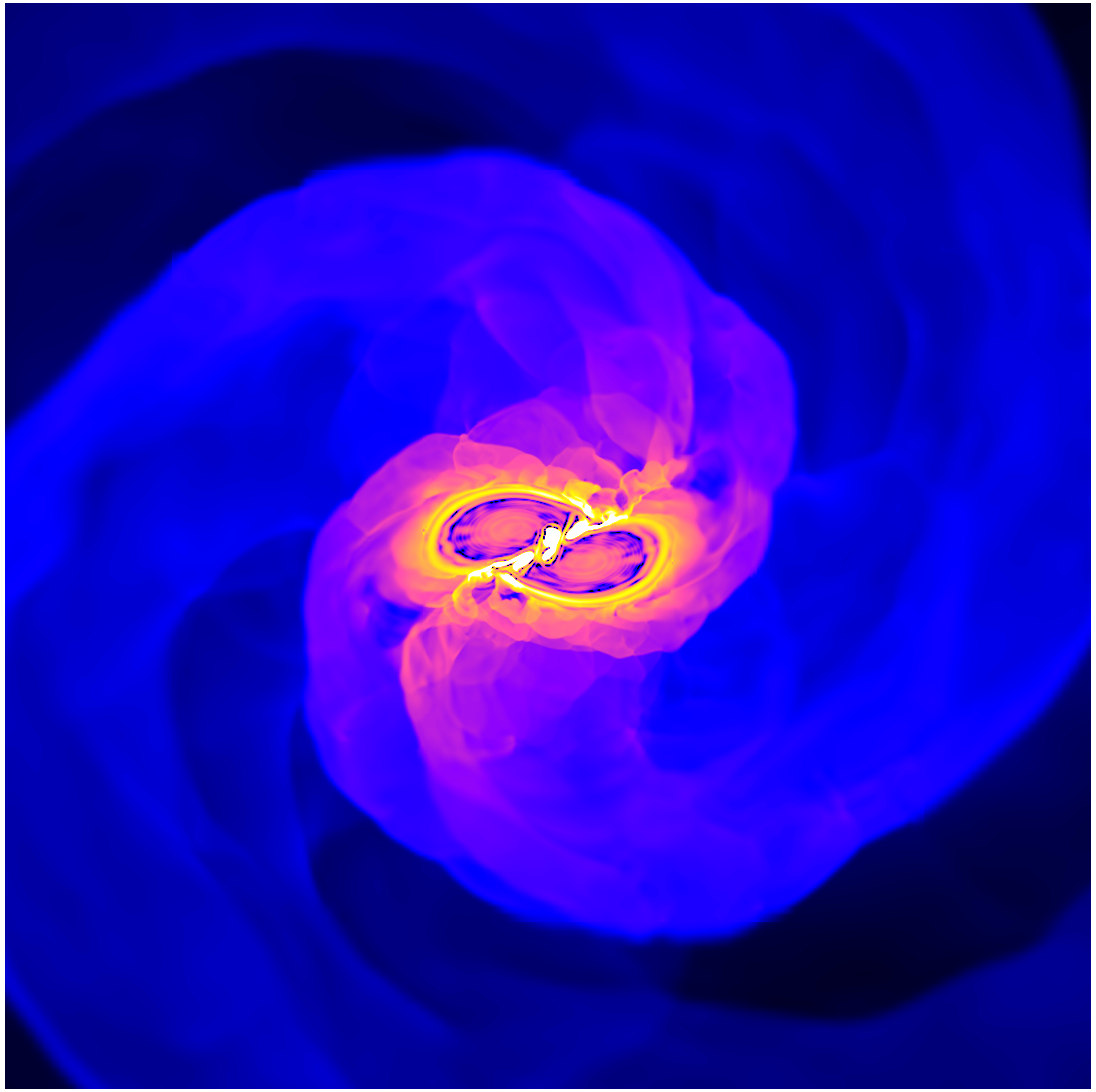




Xiong, Martinez-Pinedo, et al. (to be submitted)

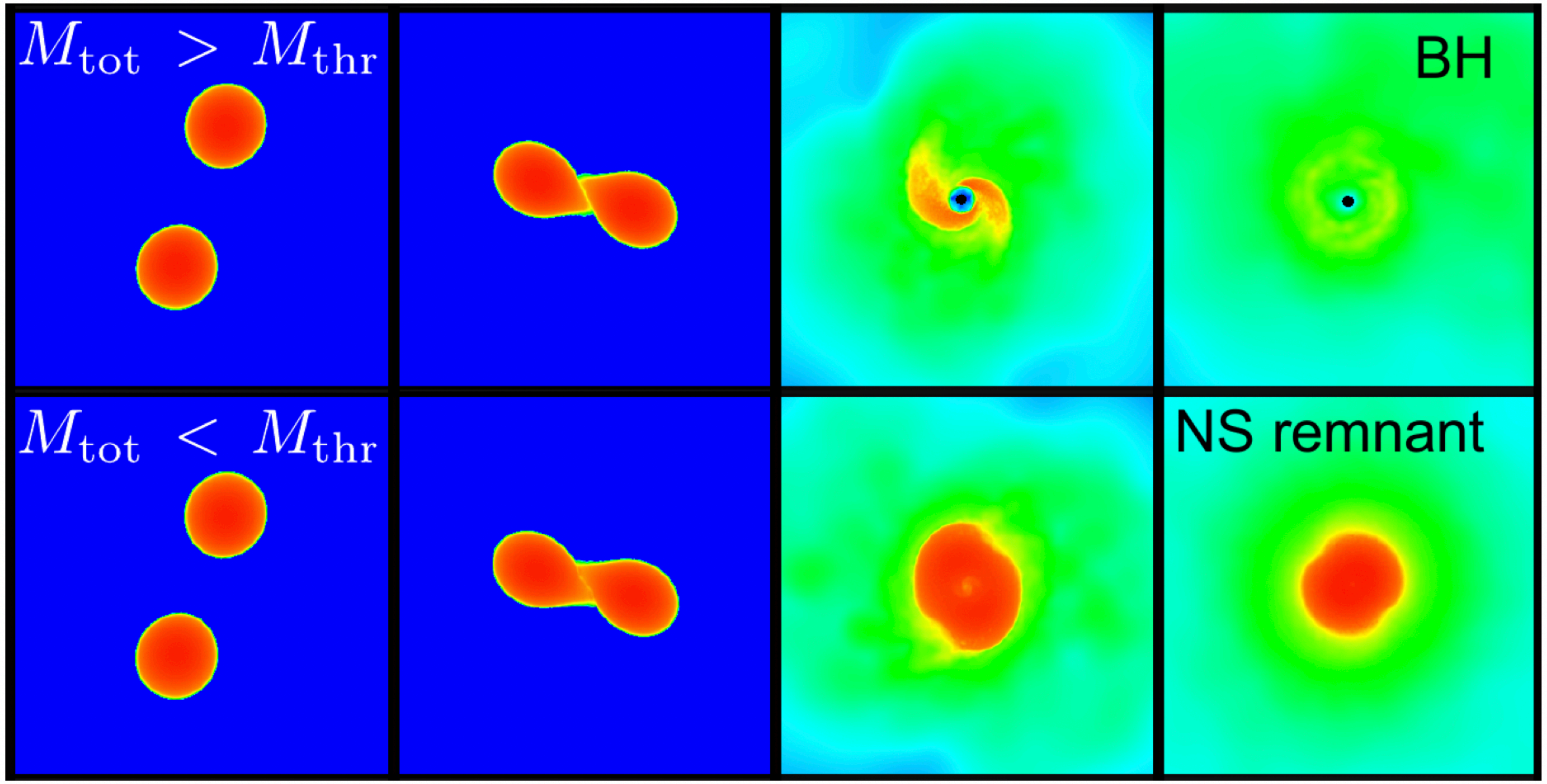
Talk: Ignacio Lopez de Arbina

Neutron star mergers (B07)



Collapse behaviour

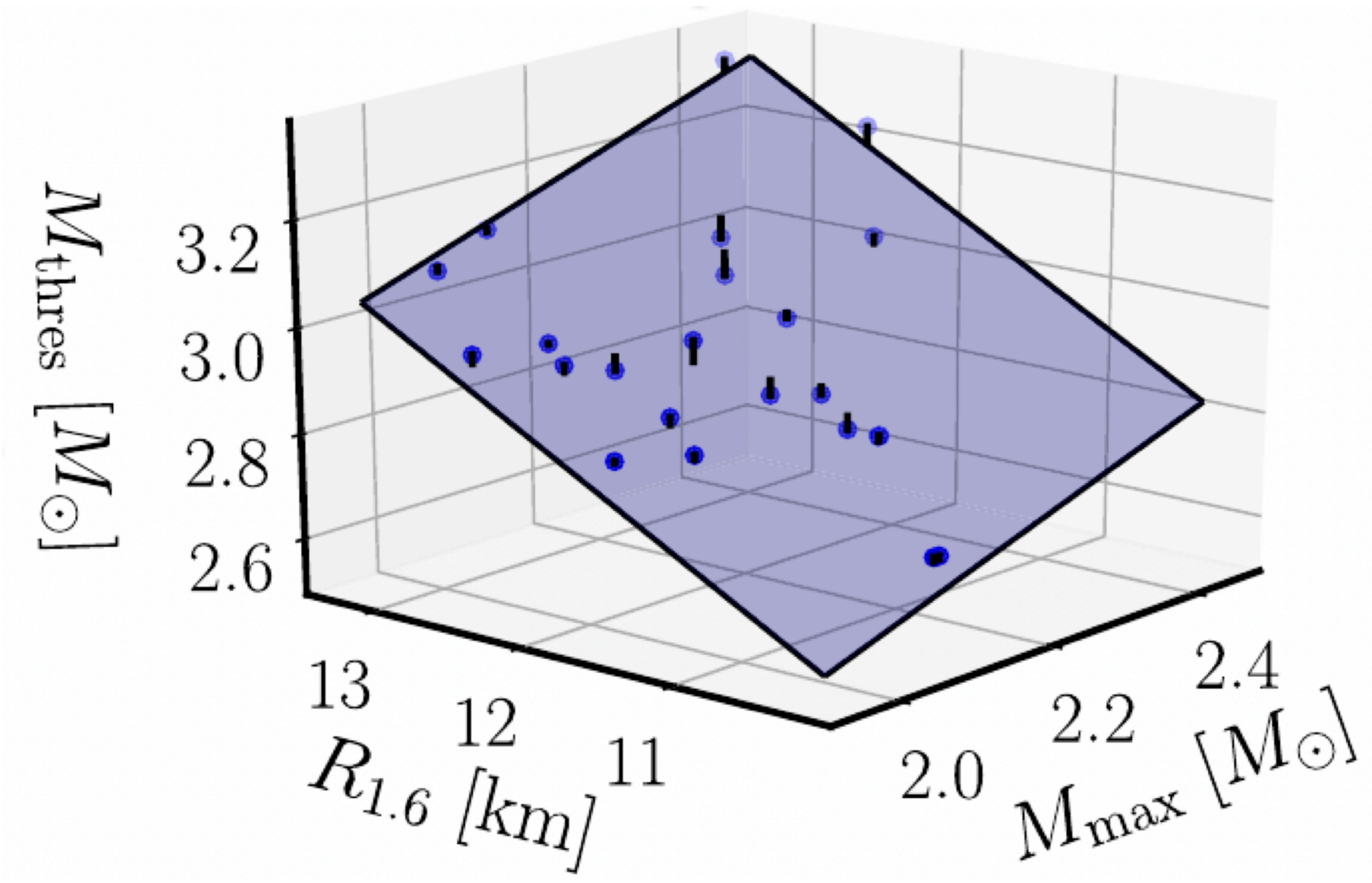
- Immediate outcome of a NSM: black hole or NS remnant (may collapse later)
- Characterised by M_{thres}
- All observables affected by collapse -> M_{thres} measurable (M_{tot} from GW inspired)
- Determine EOS dependence of M_{thres}

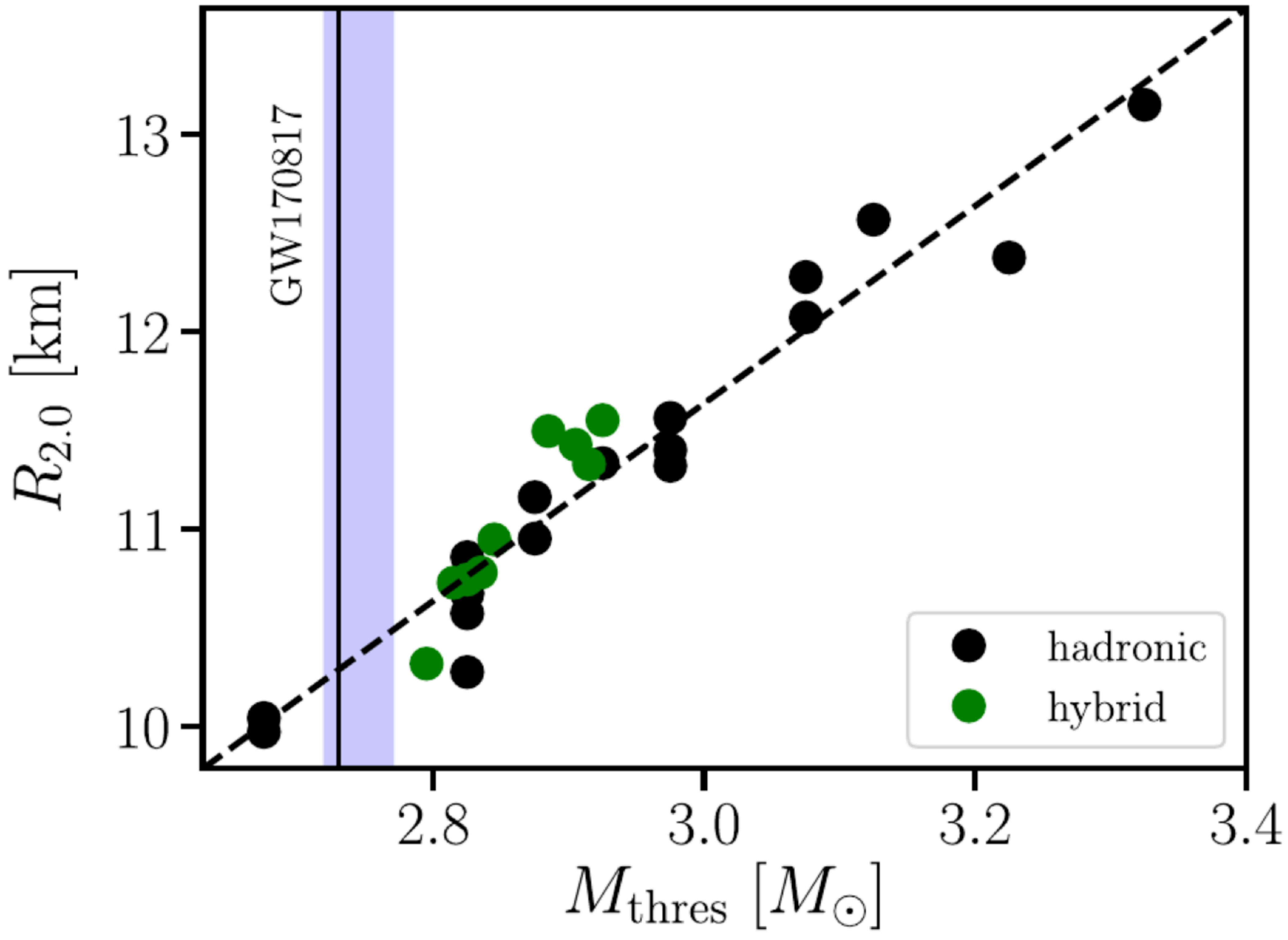


$M_{tot} > M_{thres}$	Prompt collapse
$M_{tot} < M_{thres}$	No immediate collapse

Collapse behaviour

- EOS dependence -> EOS constraints
- For M_{tot} of GW170817 (likely no prompt collapse) -> lower limit on NS radius





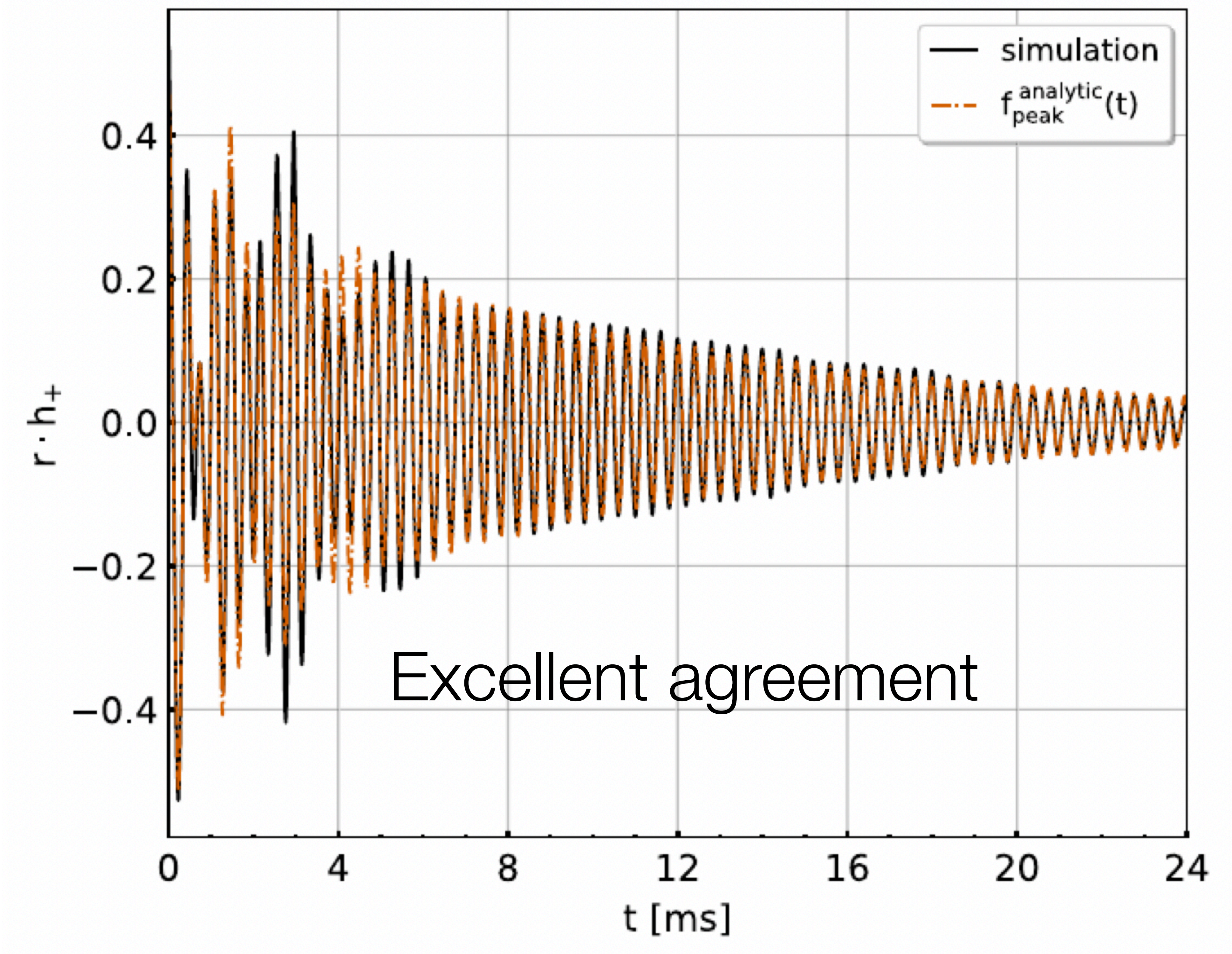
Phys. Rev. Lett. 125, 141103 (2020), Phys. Rev. D 103, 123004 (2021)

Talk: Sebastian Blacker

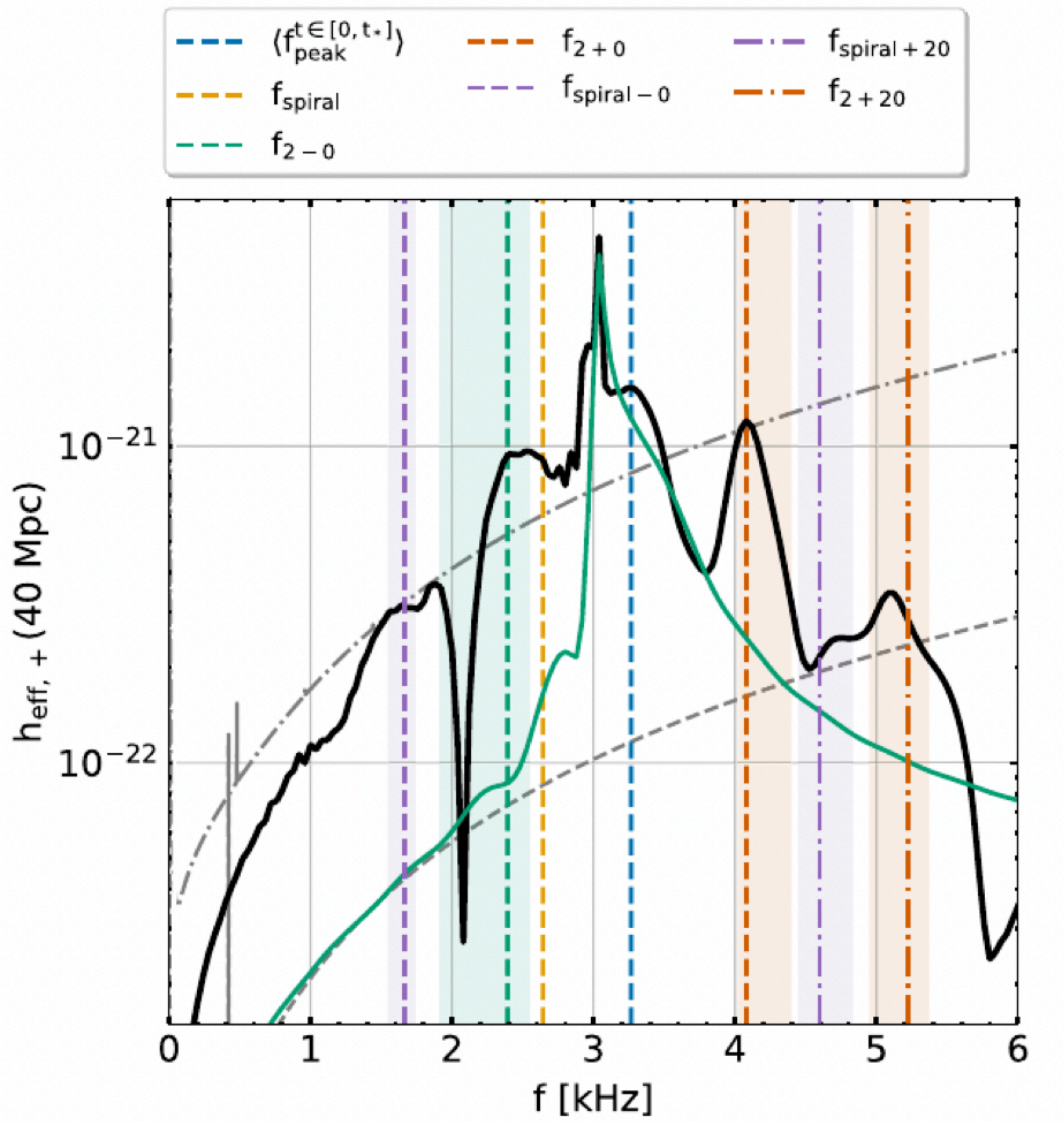
Gravitational wave spectra and templates

Analytic models of post merger GW signal indispensable:

- For GW data analysis, i.e. detection and parameter estimation
- For understanding merger dynamics



Phys. Rev. D 105, 043020 (2022)

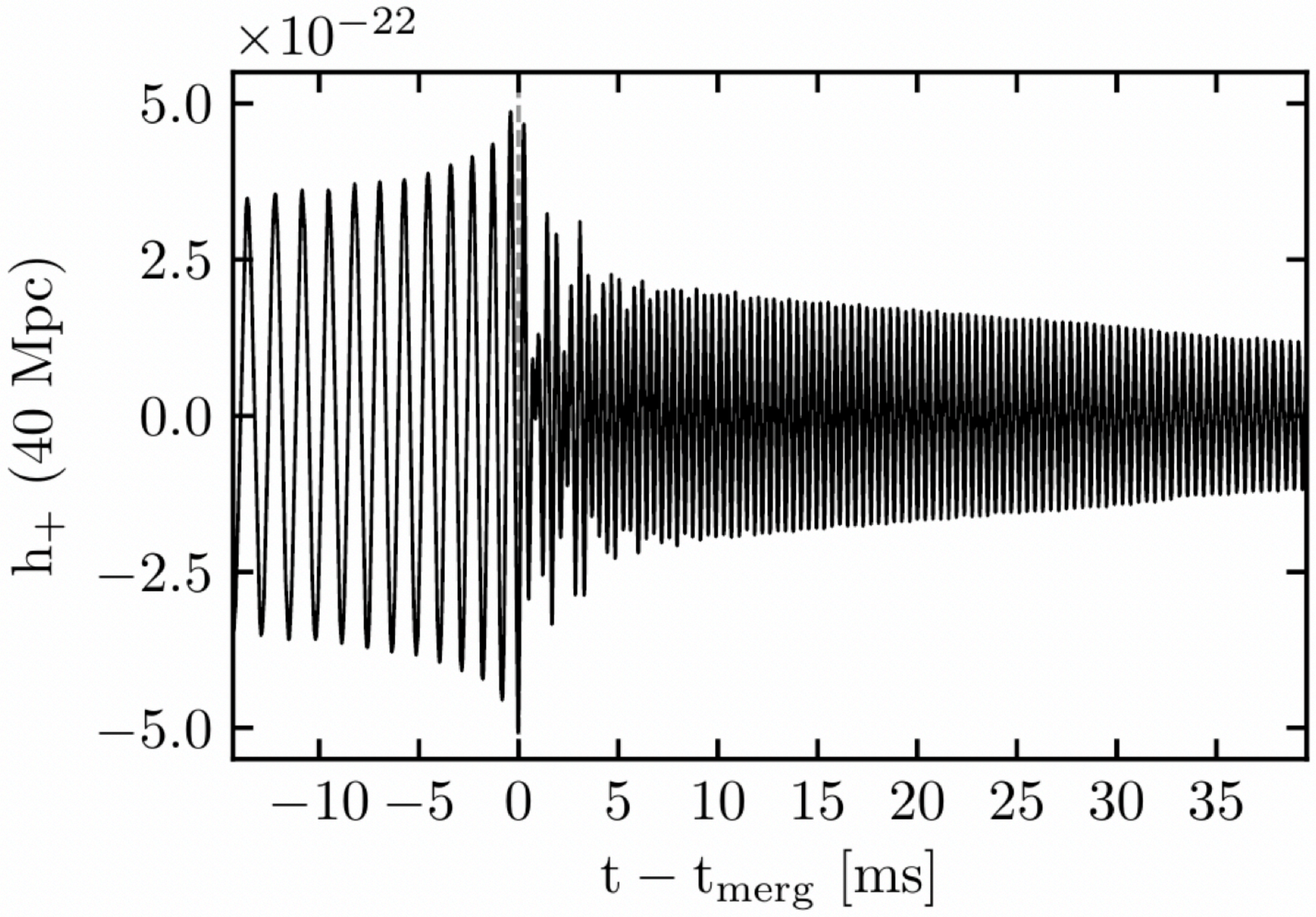


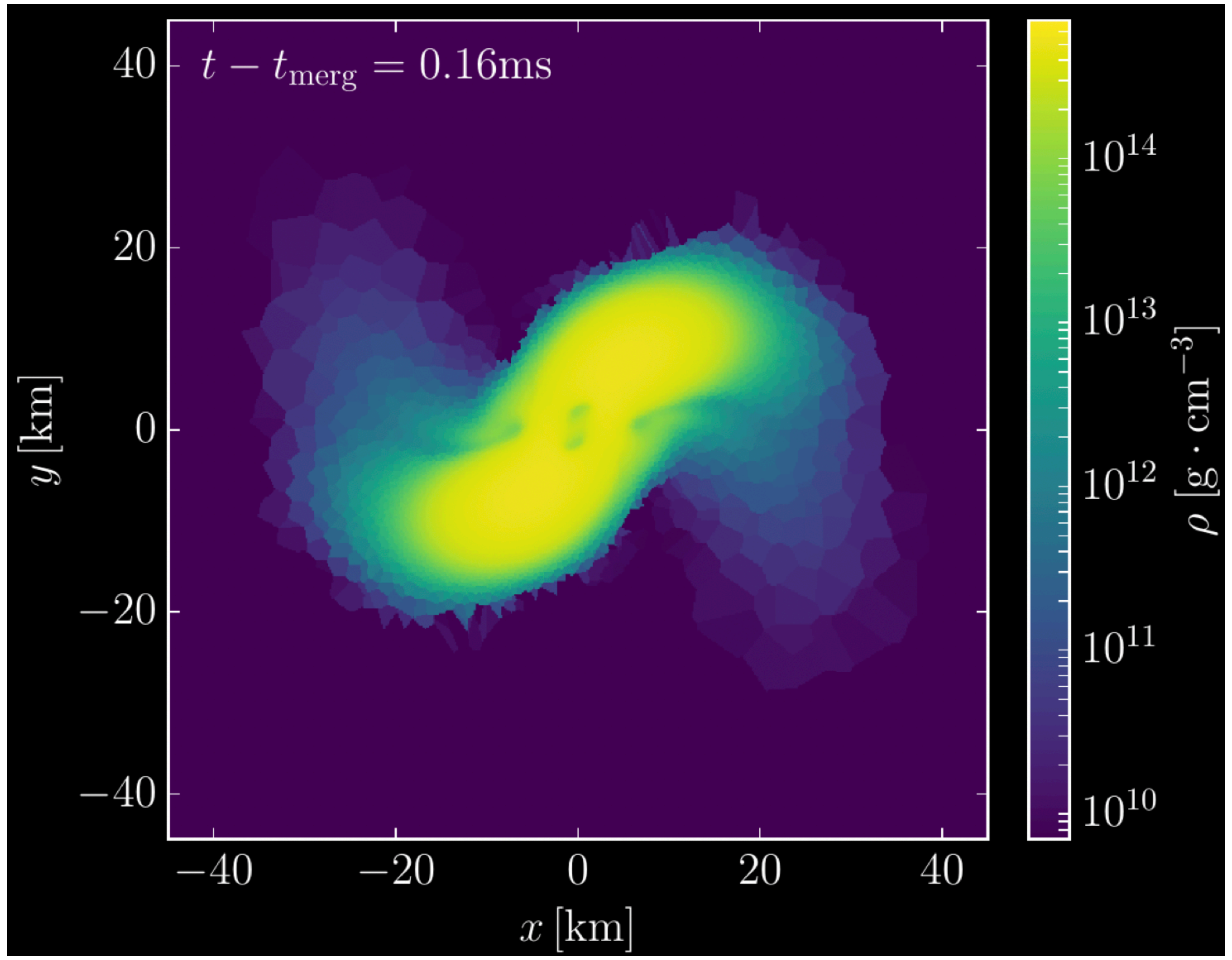
Identification of new spectral features

Essentially all features of GW spectrum explained

Mergers simulations: new tool

- 3D mergers simulations challenging even with today supercomputer capabilities
- First relativistic moving-mesh hydrodynamics simulations of NS merger
  - moving mesh minimises advection errors
  - significantly less numerical damping
  - less damping of physical features: GW signal, fluid oscillations, angular momentum, ….



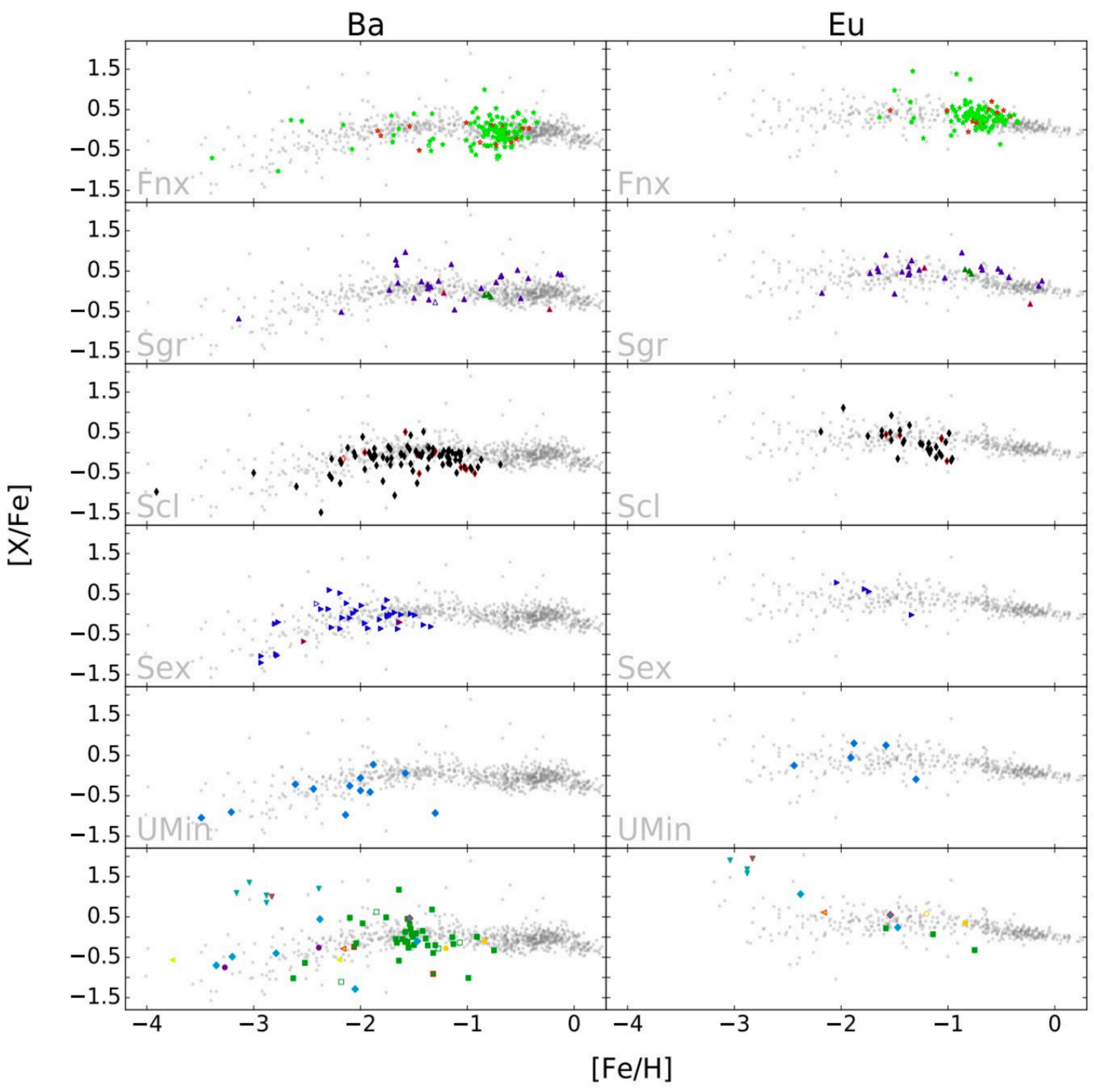


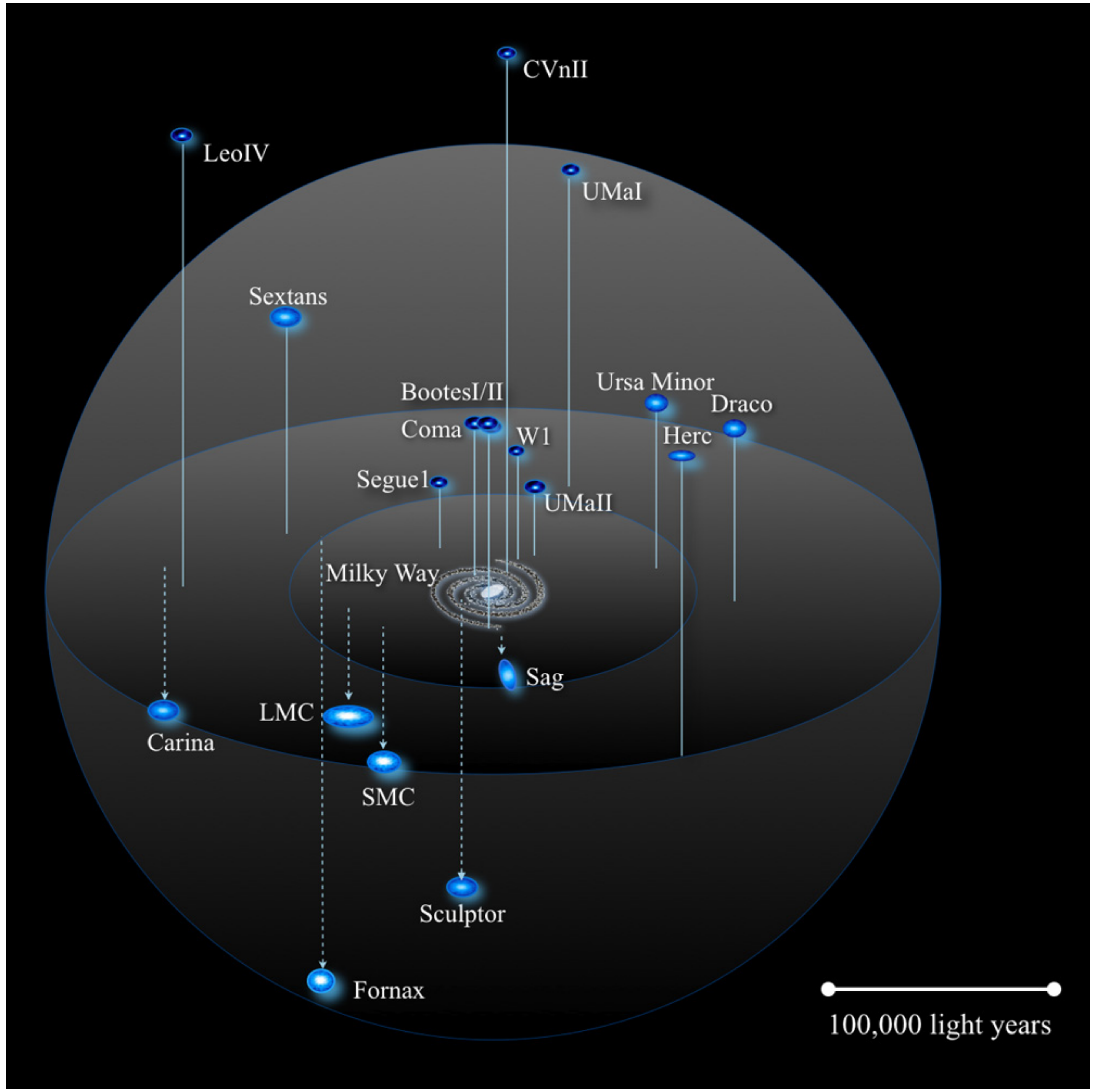
Submitted to MNRAS, arXiv:2208.04267 (2022)

R-process: observations and galactic chemical evolution

Largest set of homogenised abundances in dwarf galaxies: R-process sites?

Reichert et al. 2020, Molero et al. 2021





With new PI Camilla J. Hansen

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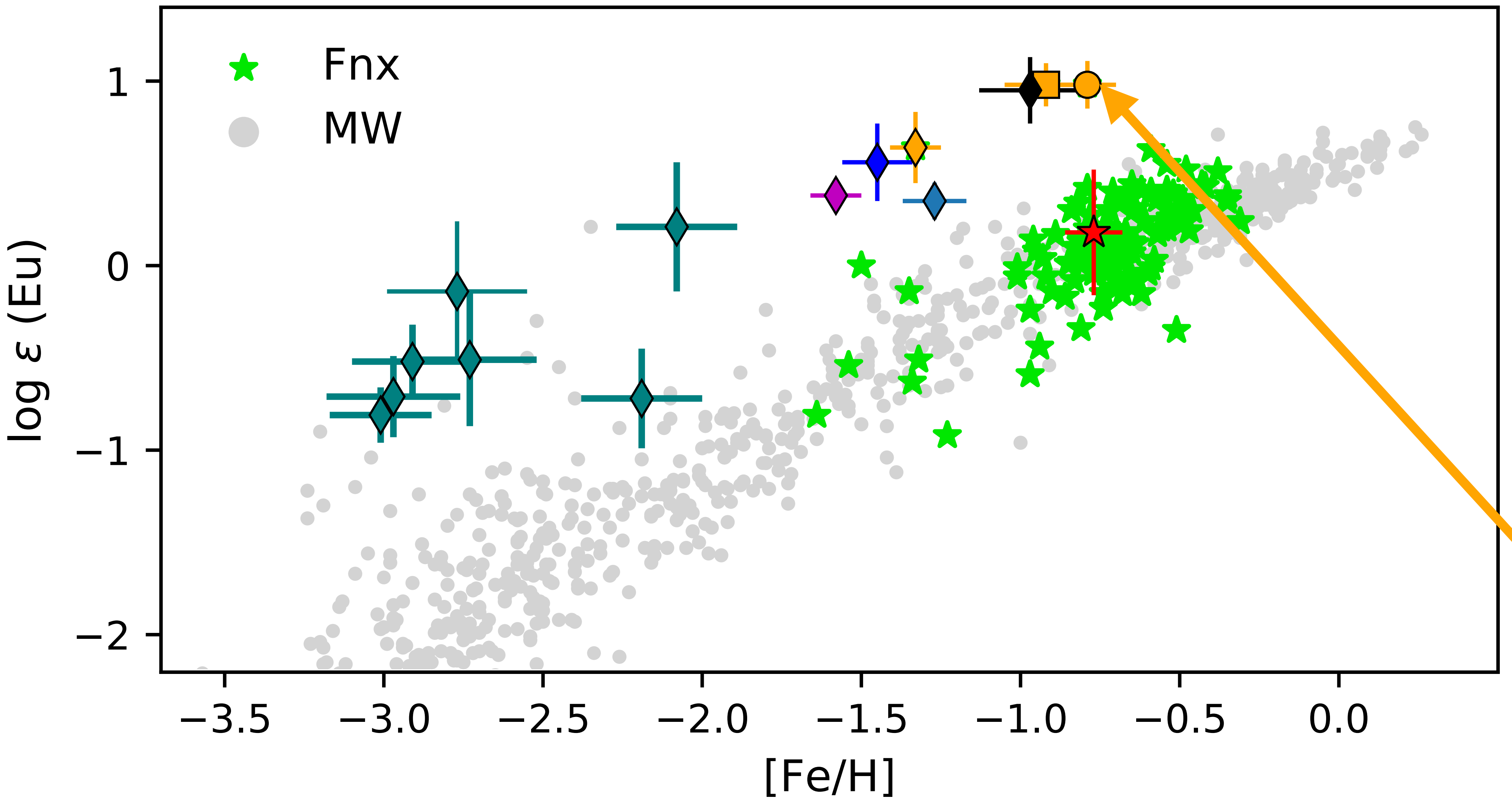
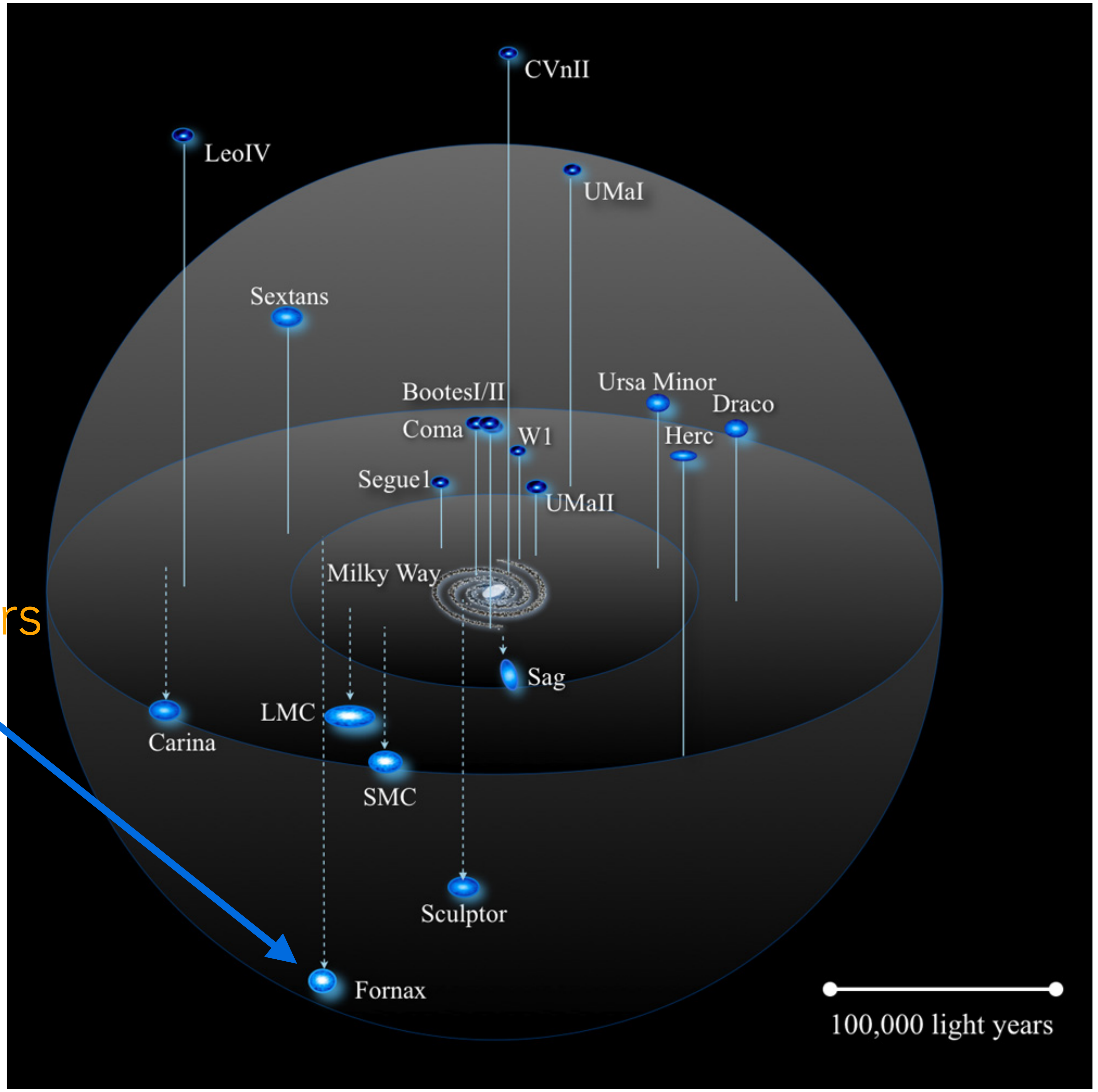


Reichert, Hansen, Arcones (2021)

Discovery

Europium stars

in Fornax



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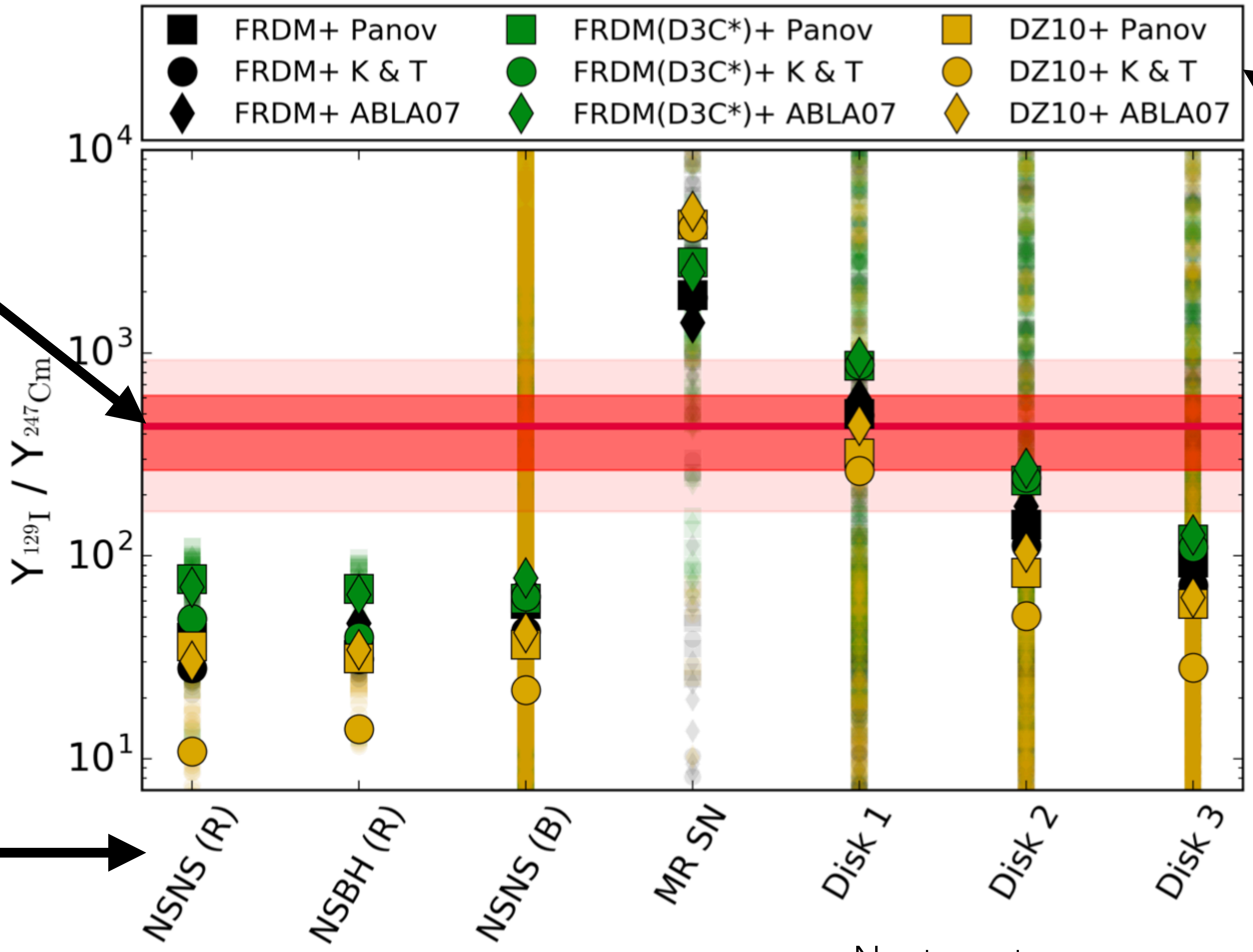


Observation
Meteorite

Nuclear physics

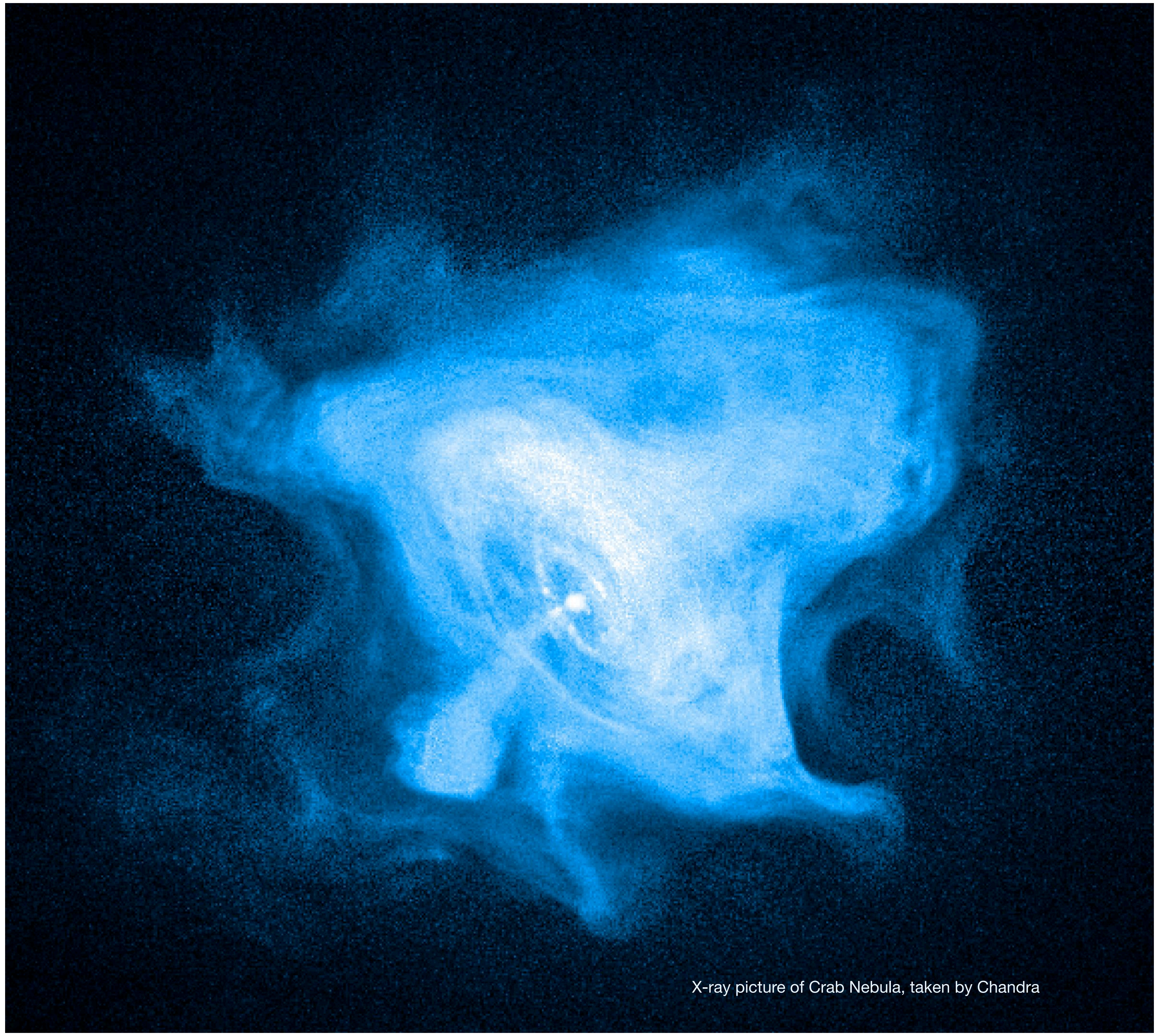
Astrophysics scenarios

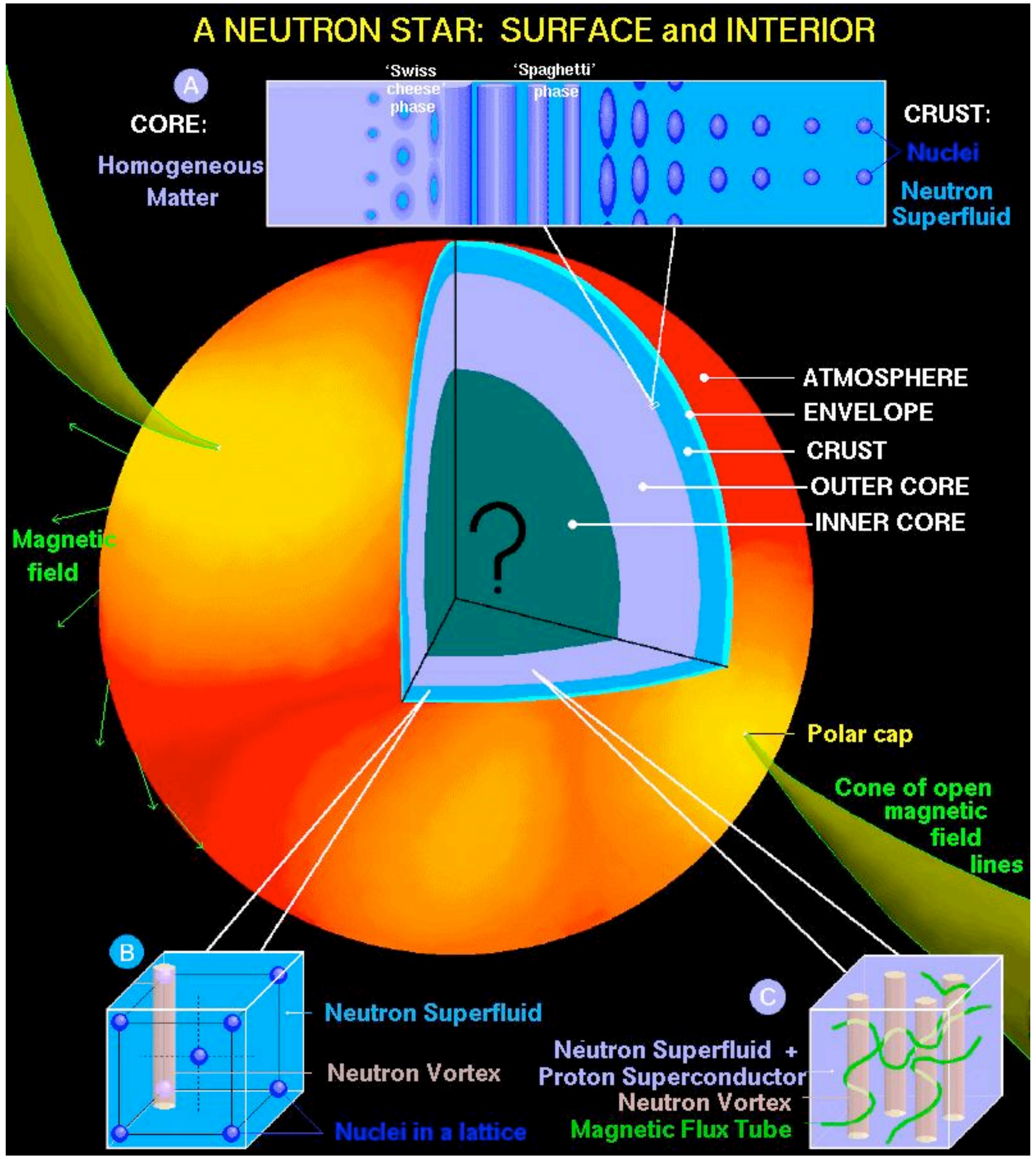
Neutron star mergers
Dynamical ejecta

Neutron star mergers
Disk ejecta

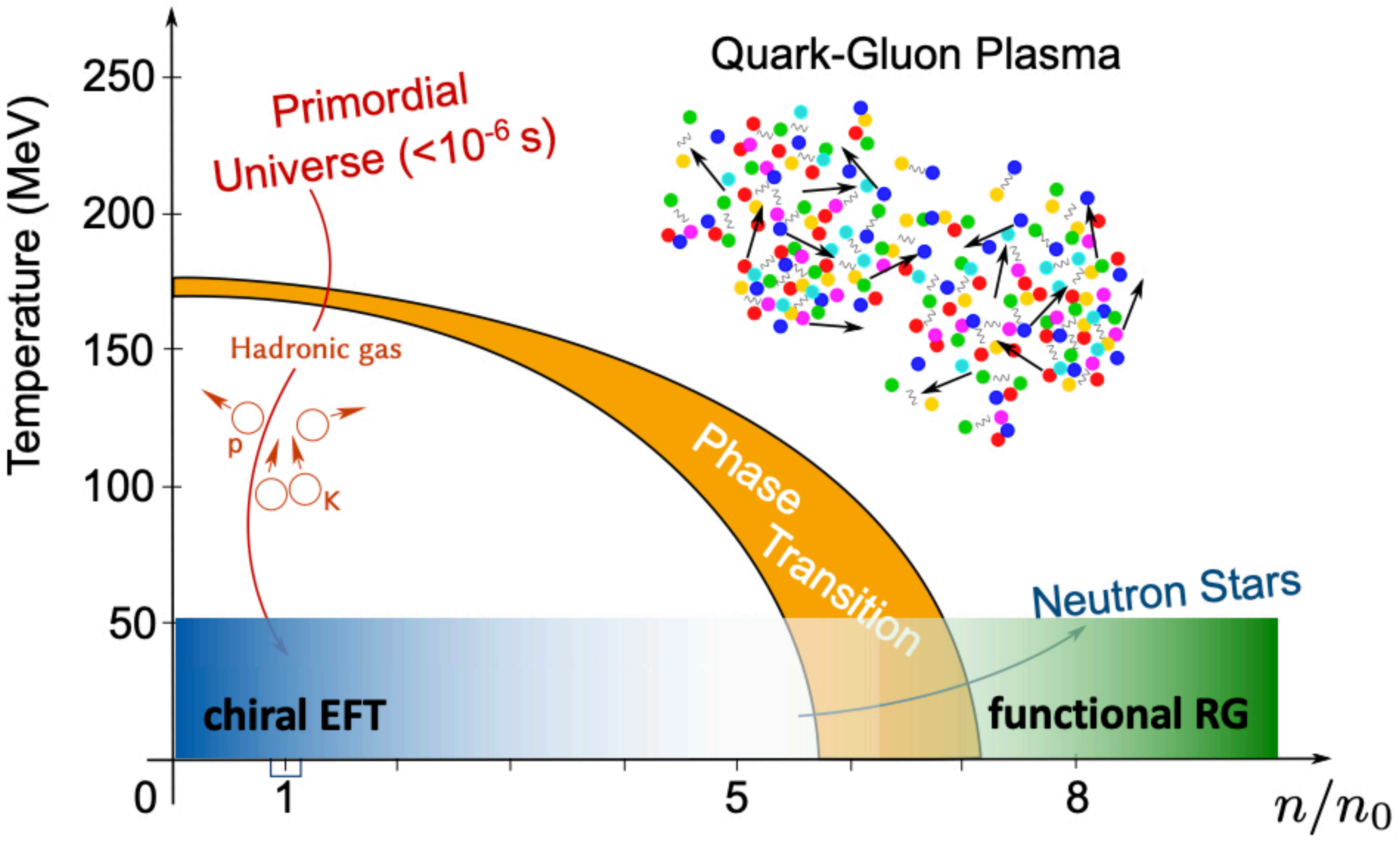
Côté et al. 2021
Science

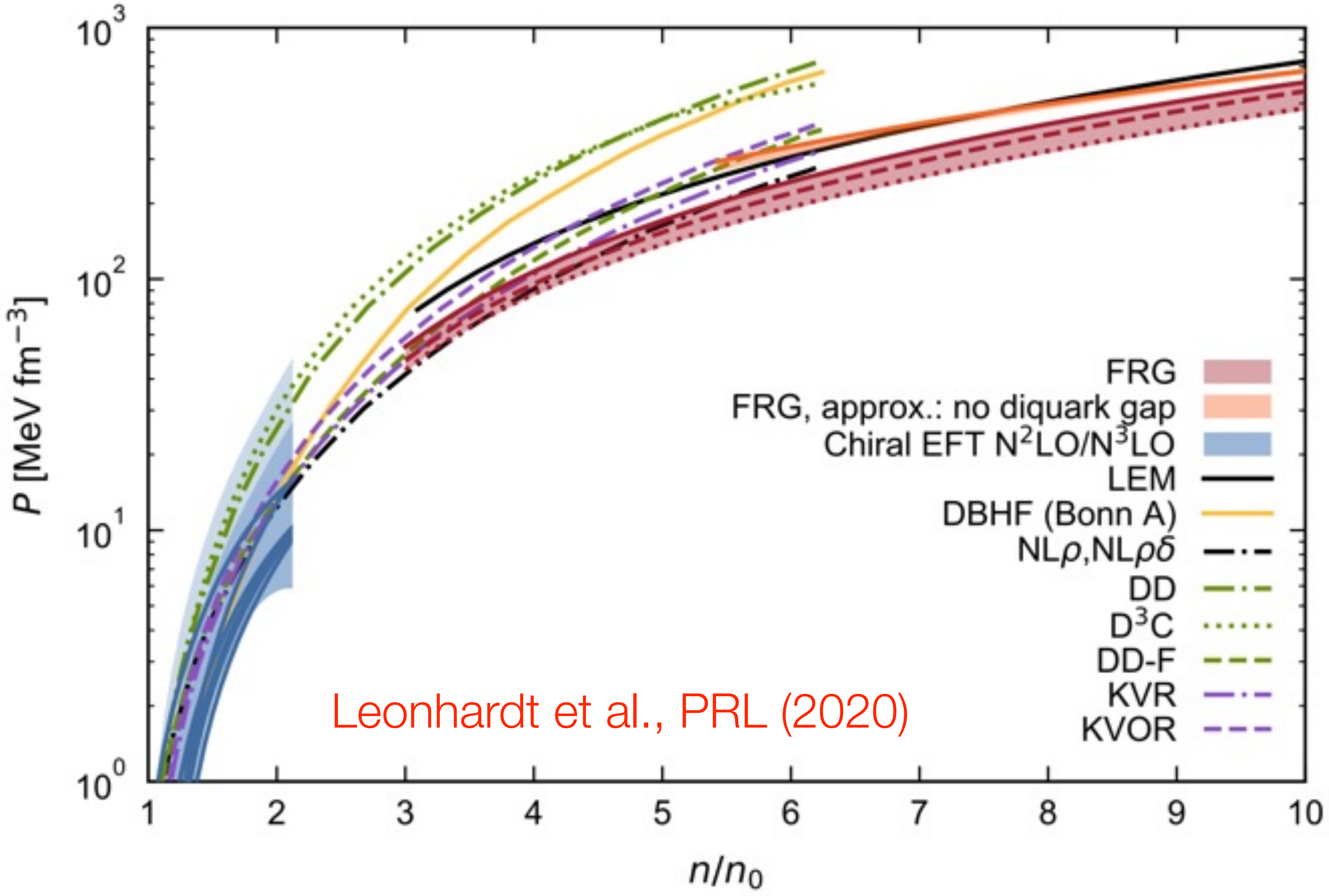
Neutron star equation of state (B05)


X-ray picture of Crab Nebula, taken by Chandra



Equation of state for astrophysical applications

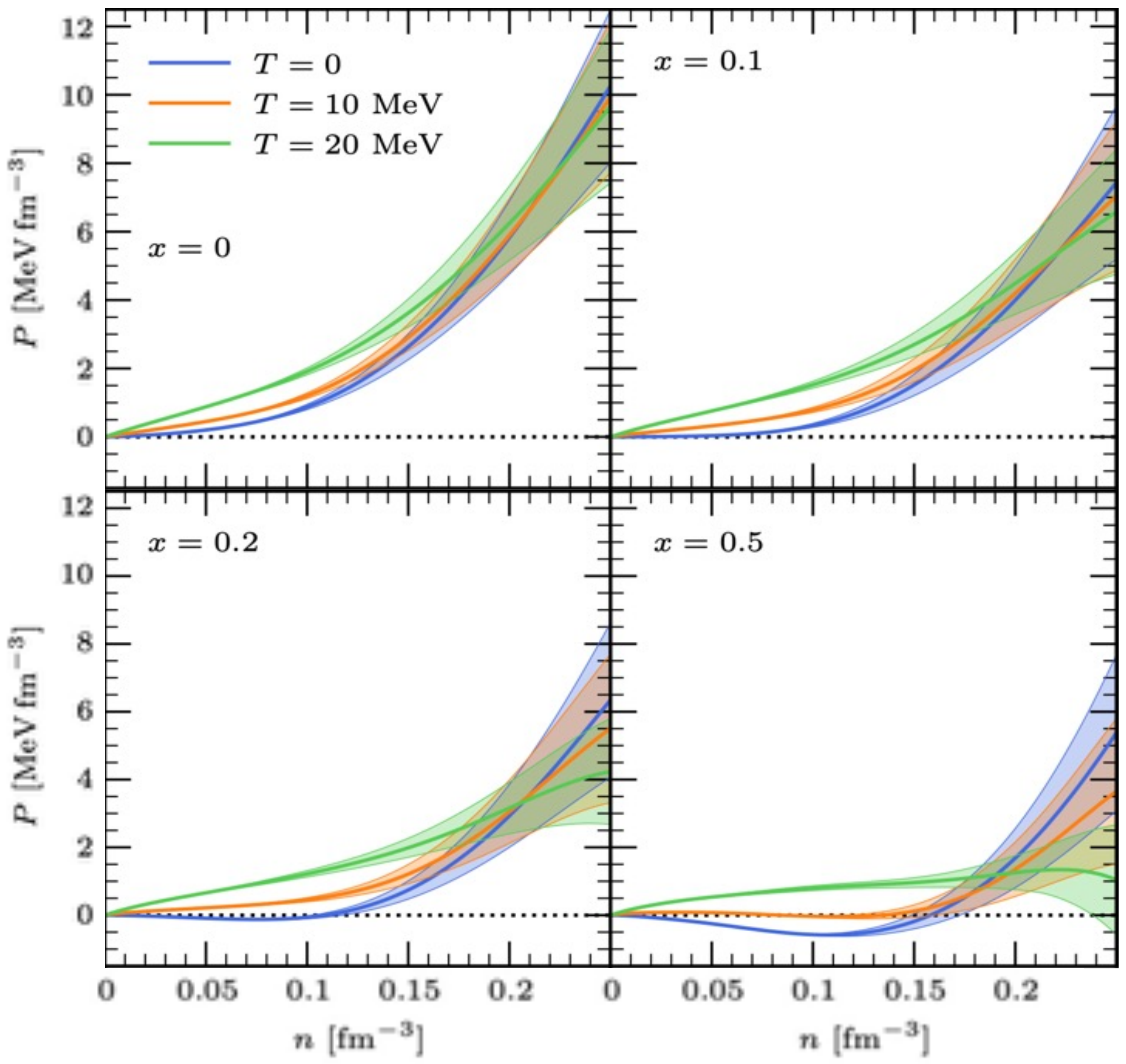




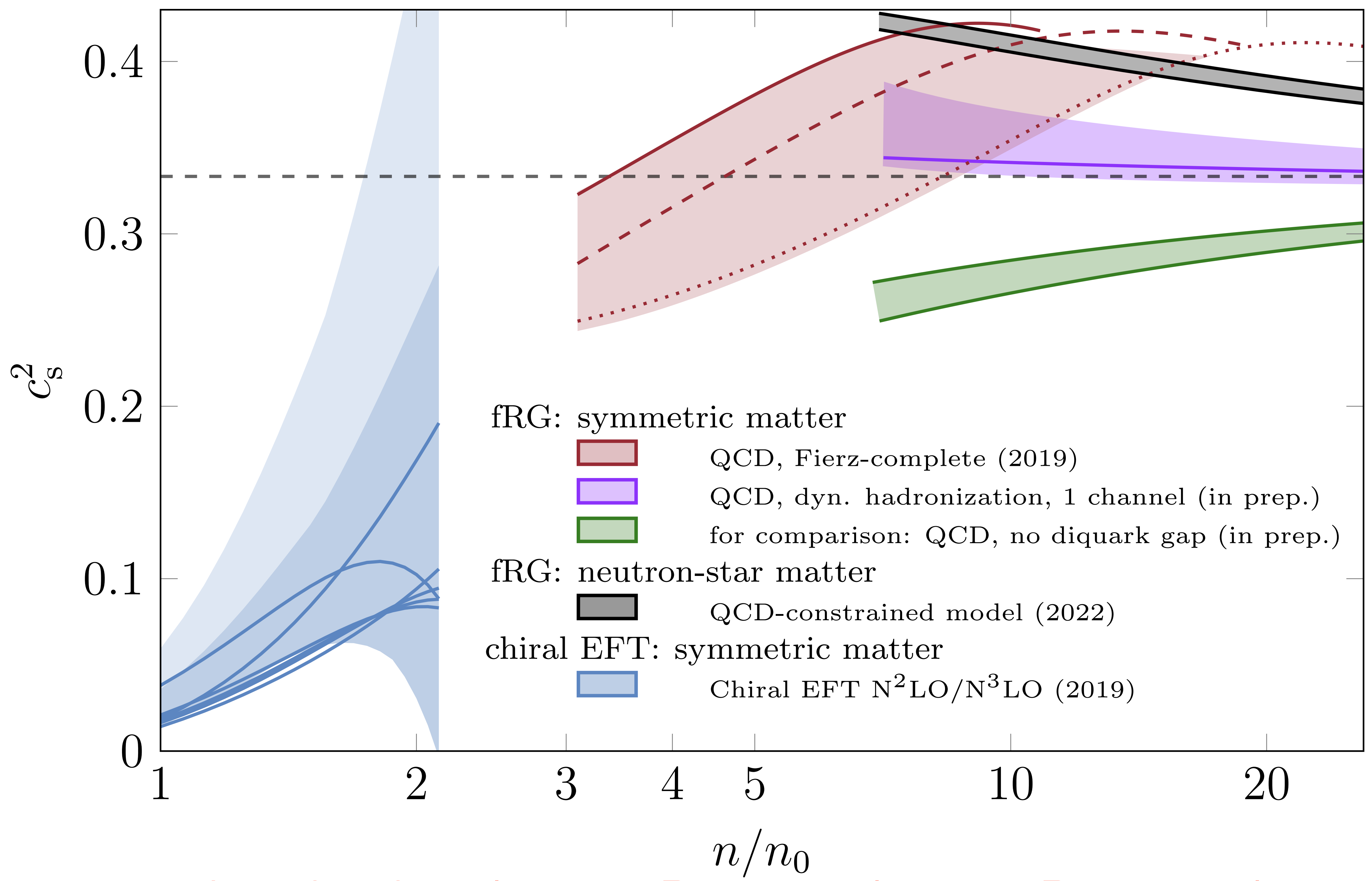
- chiral EFT: systematic theoretical uncertainties at nuclear densities
- fRG: ab initio calculations of EOS at high densities based on QCD
- combine and cross-benchmark EOS results from chiral EFT and fRG
- provide EOS with theoretical error bars for astrophysical applications

Equation of state for astrophysical applications

- generalization of chiral EFT calc. to finite temperature and general proton fractions
- implementation of Gaussian process emulator for efficient evaluations of EOS data
- implementation of dynamical hadronization techniques in fRG calculations
- inclusion of additional operators in fRG needed to extend results to lower densities



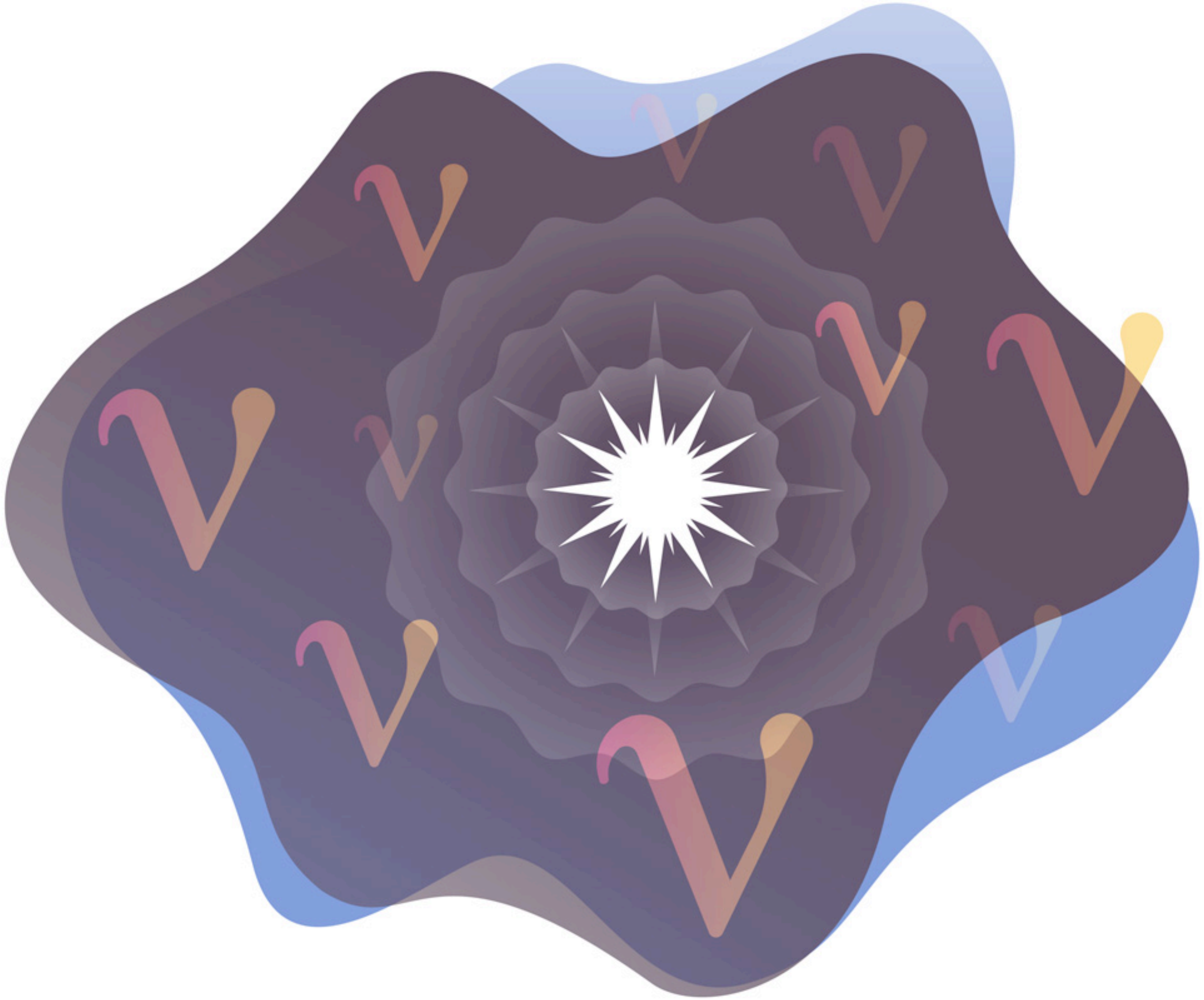
Keller et al. 2021, Keller et al. 2022



Leonhard et al. 2019, Braun et al. 2021, Braun et al. 2022

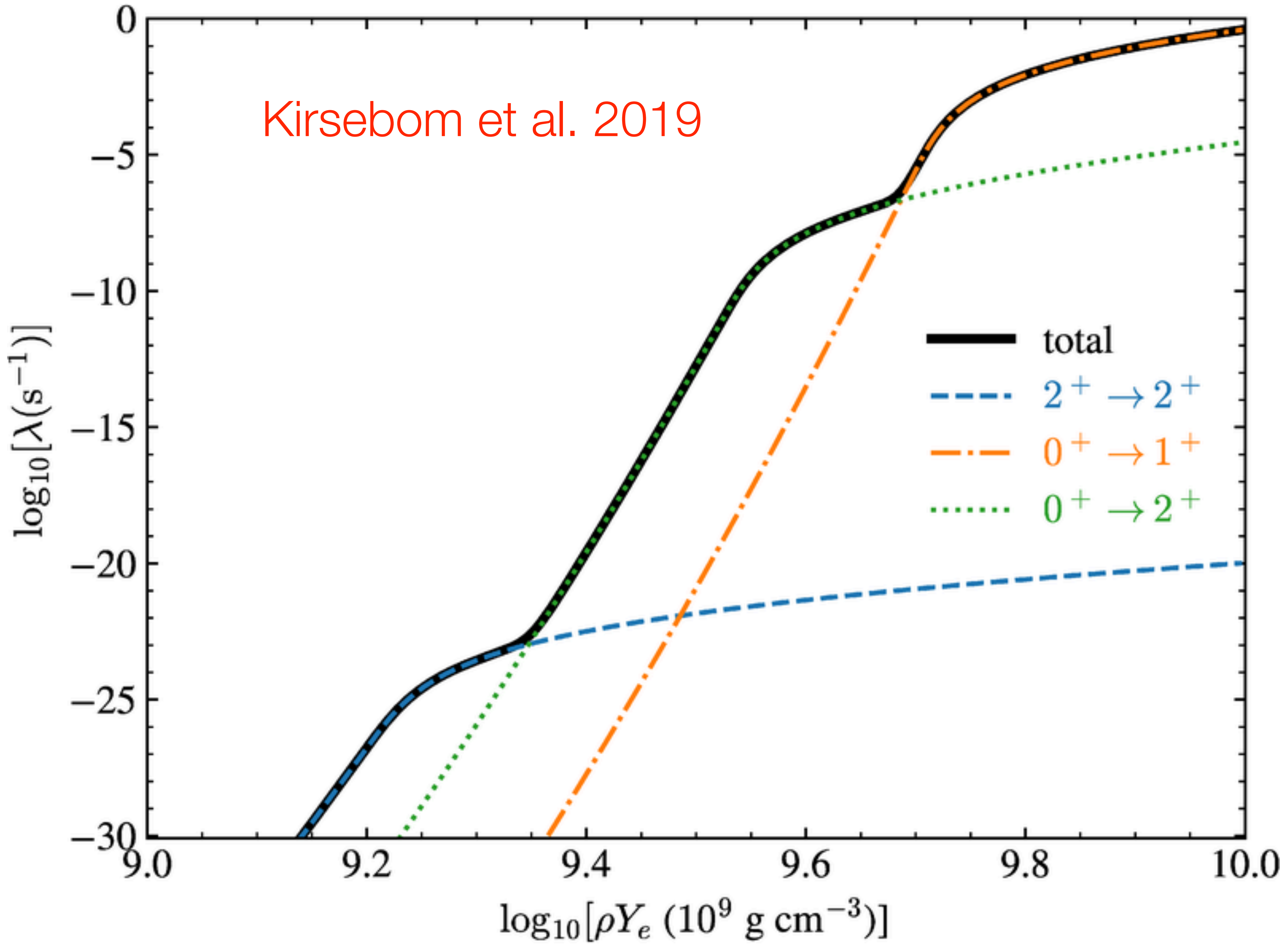
Talks:
Jonas Keller
Andreas Geissel

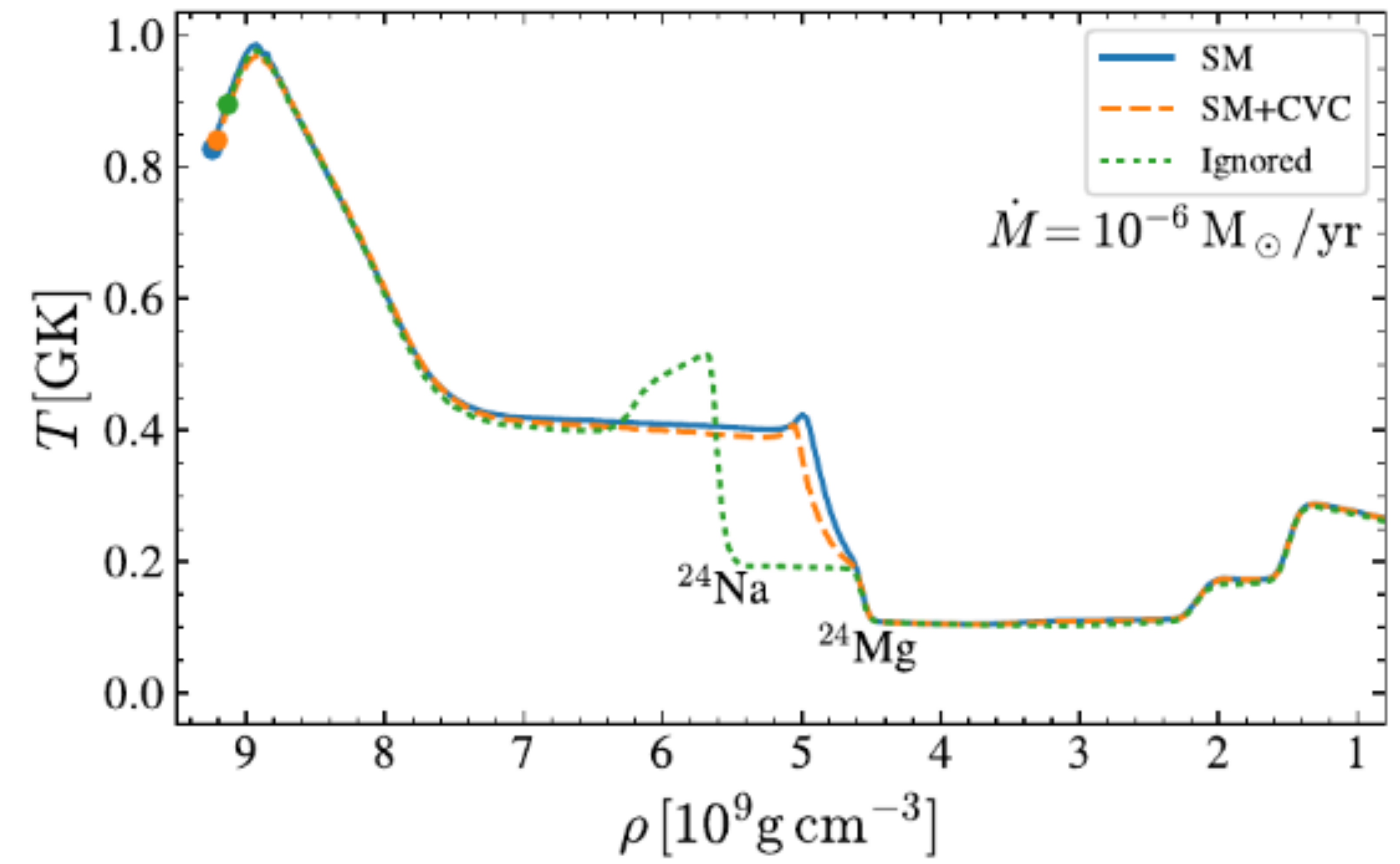
Weak interactions in astrophysics (B01)

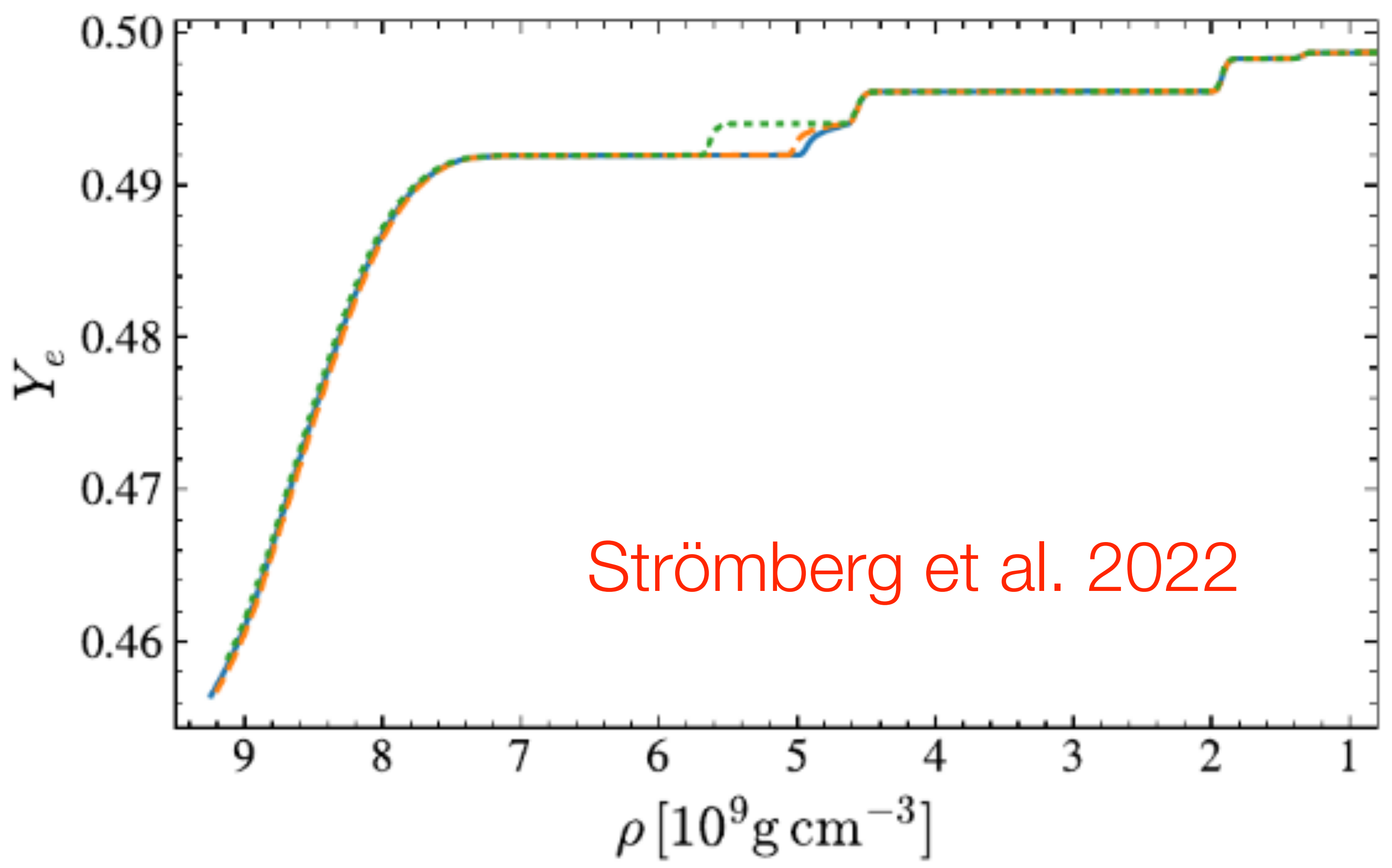


Evolution intermediate mass stars: Forbidden transitions ^{20}Ne and ^{24}Na

- Second forbidden transitions on ^{20}Ne and ^{24}Na determine evolution intermediate mass stars
- Experimental data increases ^{20}Ne electron capture rate by 8 orders of magnitude. Thermonuclear explosion favored over collapse as final fate of star.

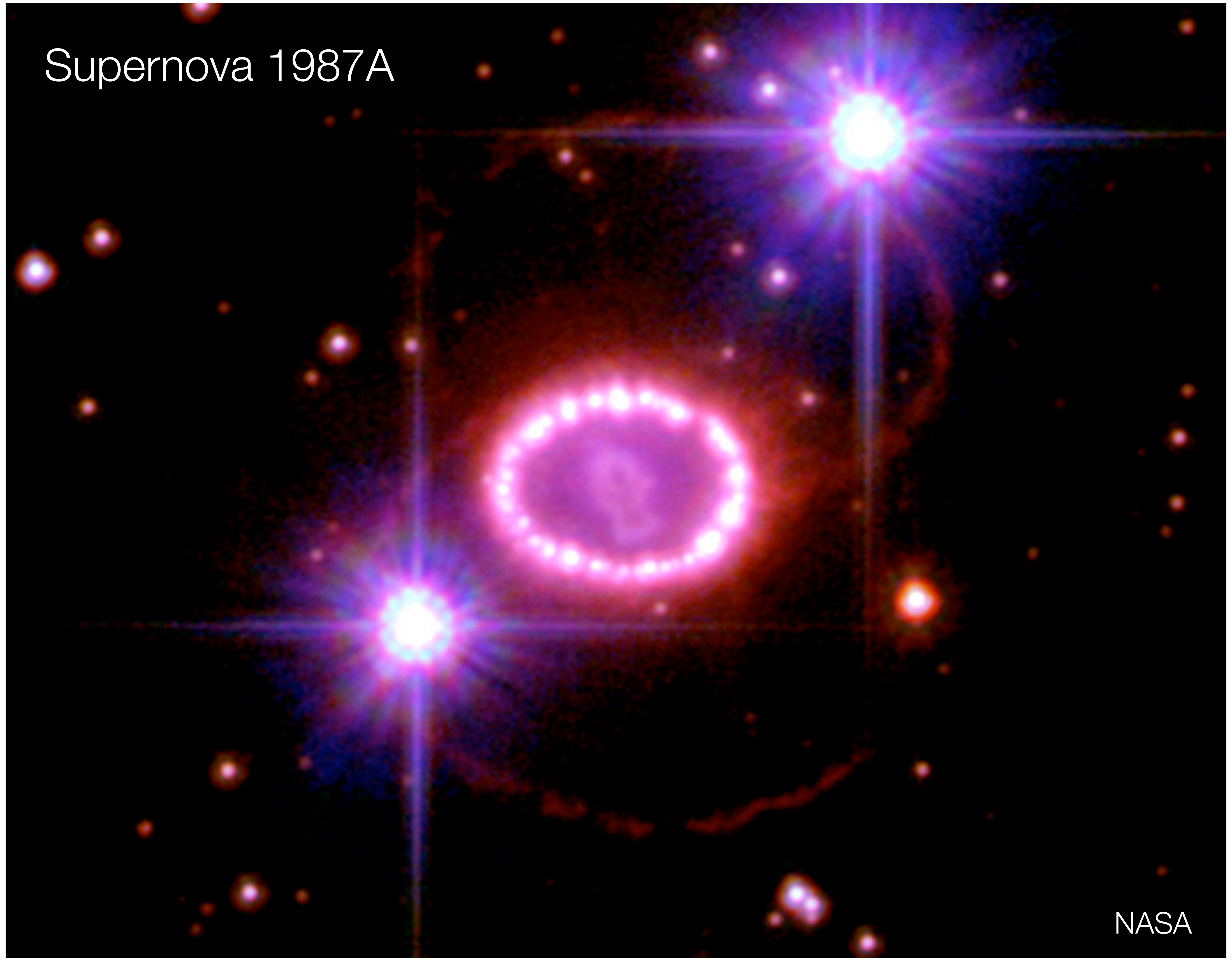






Forbidden electron capture on ^{24}Na impacts temperature profile and triggers convective instabilities

Nuclear astrophysics @ SFB 1245



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