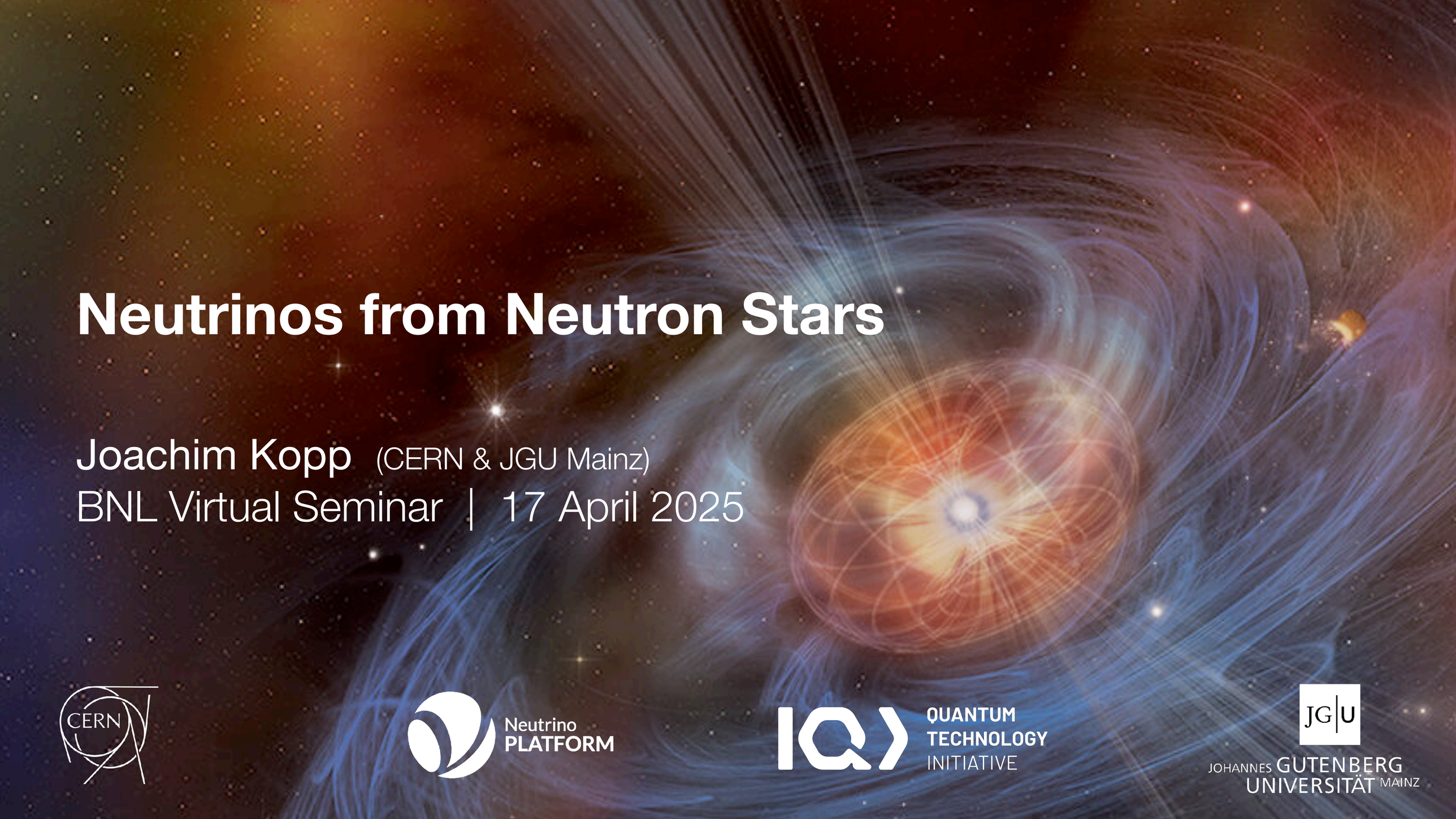

# Neutrinos from Neutron Stars

Joachim Kopp (CERN & JGU Mainz)

BNL Virtual Seminar | 17 April 2025

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

# Neutrinos as Astrophysical Messengers

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solar neutrinos

- ★ stellar evolution

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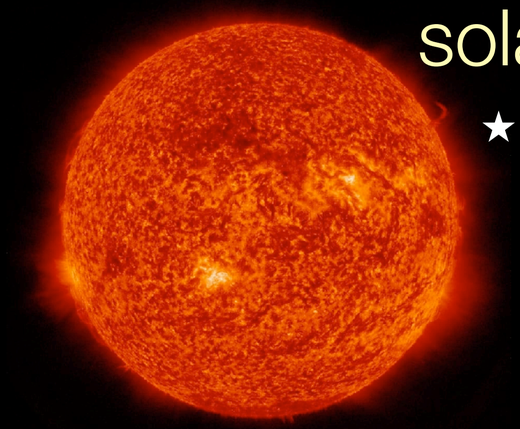

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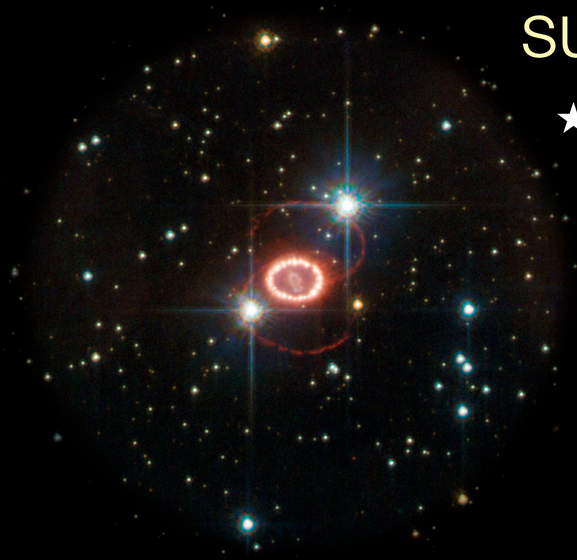

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- ★ death throes of massive stars
- ★ nucleosynthesis
- ★ matter under extreme conditions

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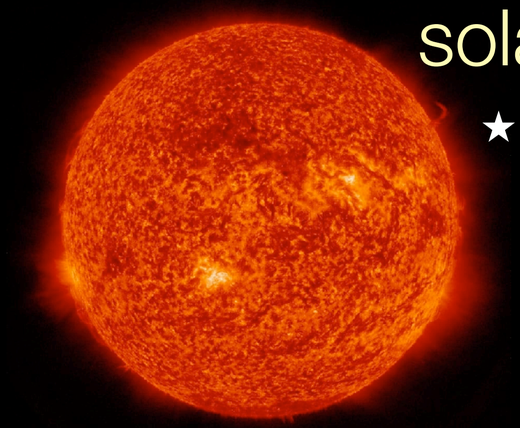

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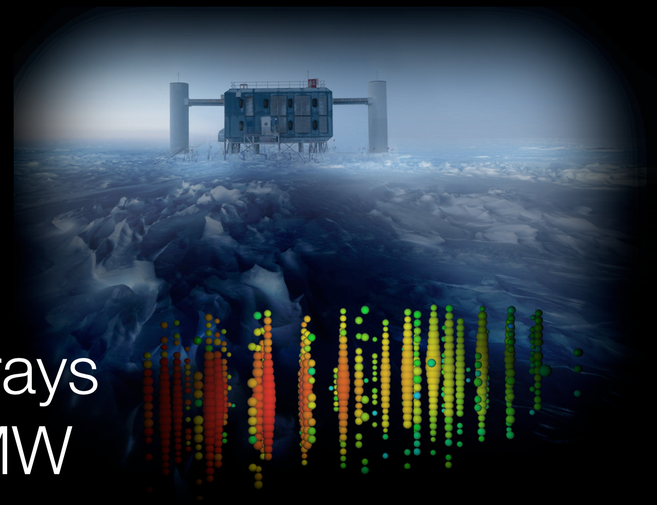
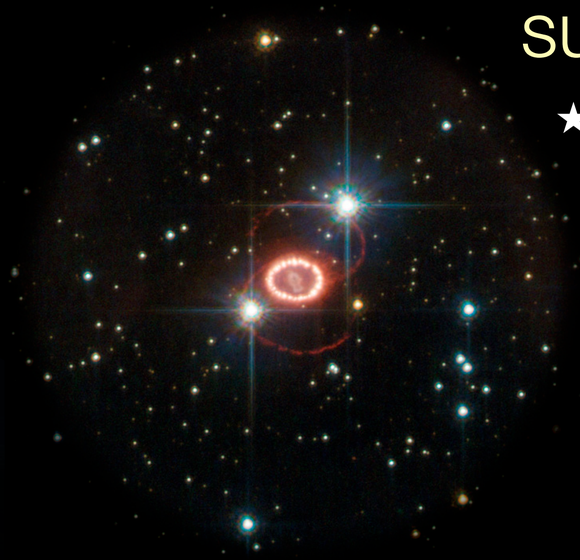


## high-*E* neutrinos

- ★ origin of cosmic rays
- ★ AGNs, blazars, MW



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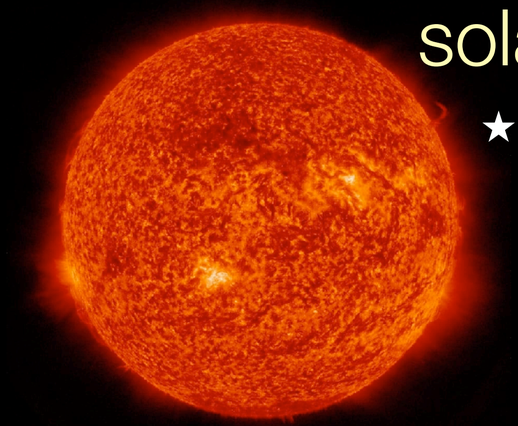

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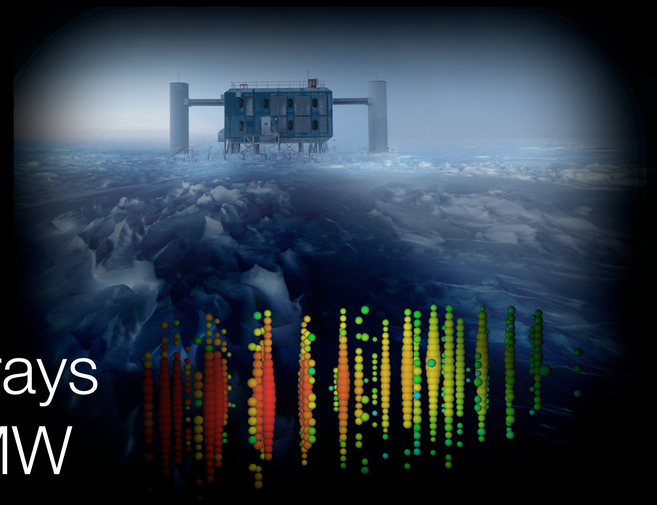

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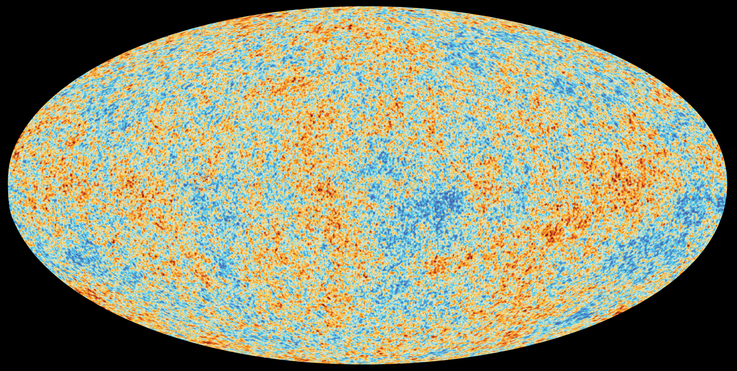
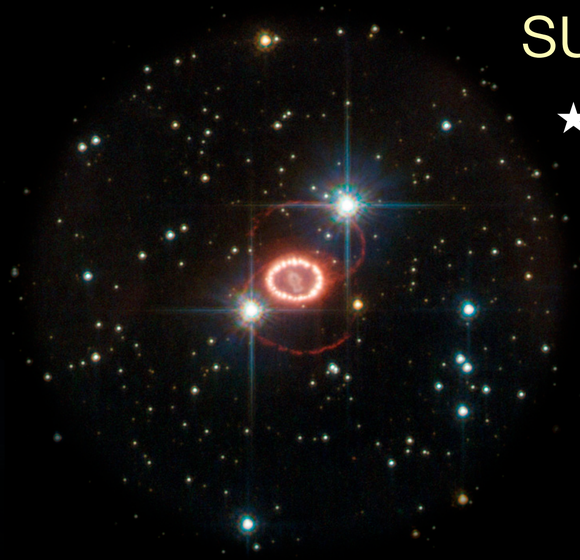


## cosmology

- ★ early Universe



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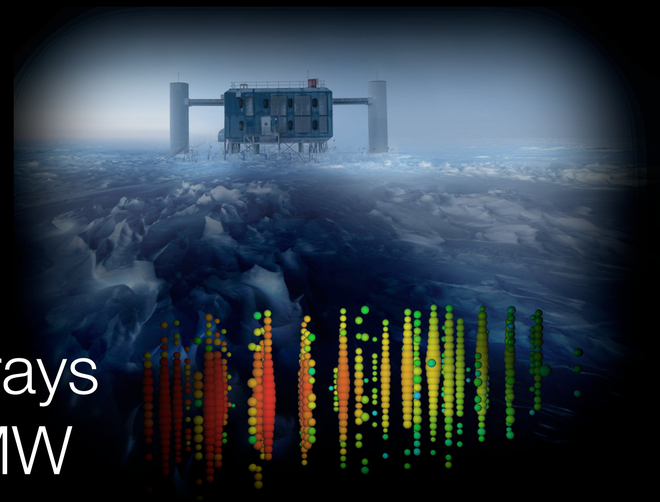

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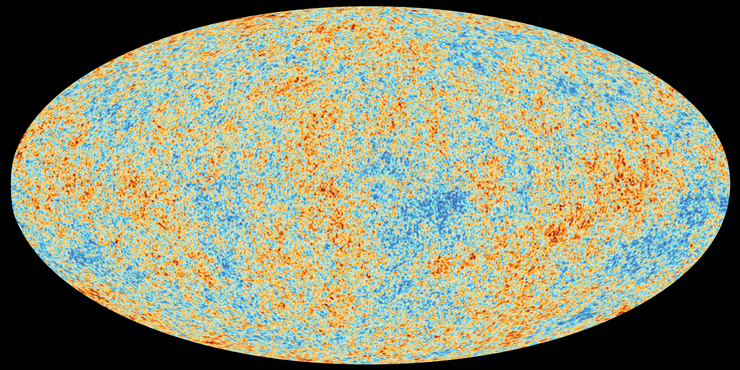

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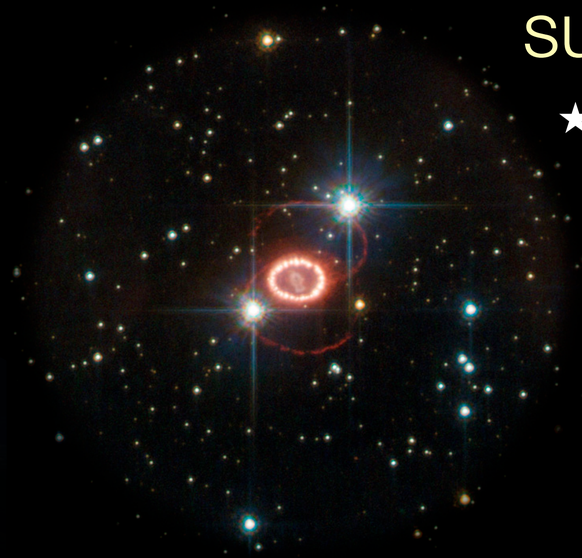

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## neutron stars

- ★ Urca cooling
- ★ muon decays
- ★ common-envelope evolution

➠ THIS TALK

# Neutron Stars

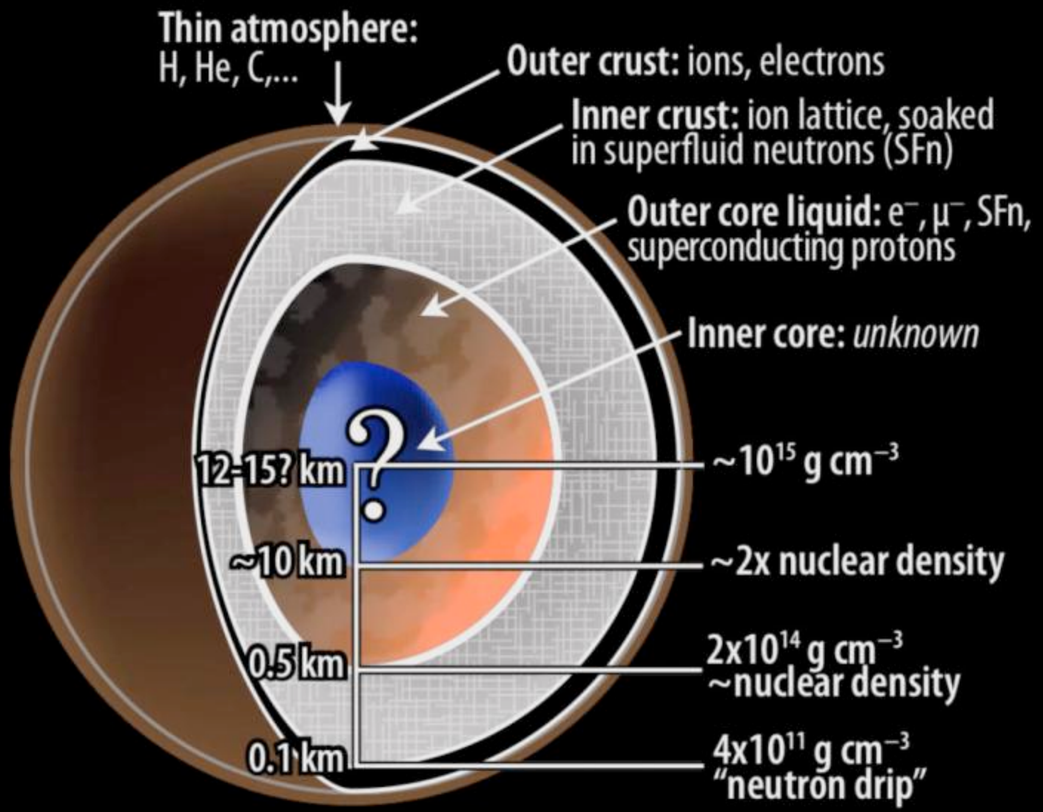
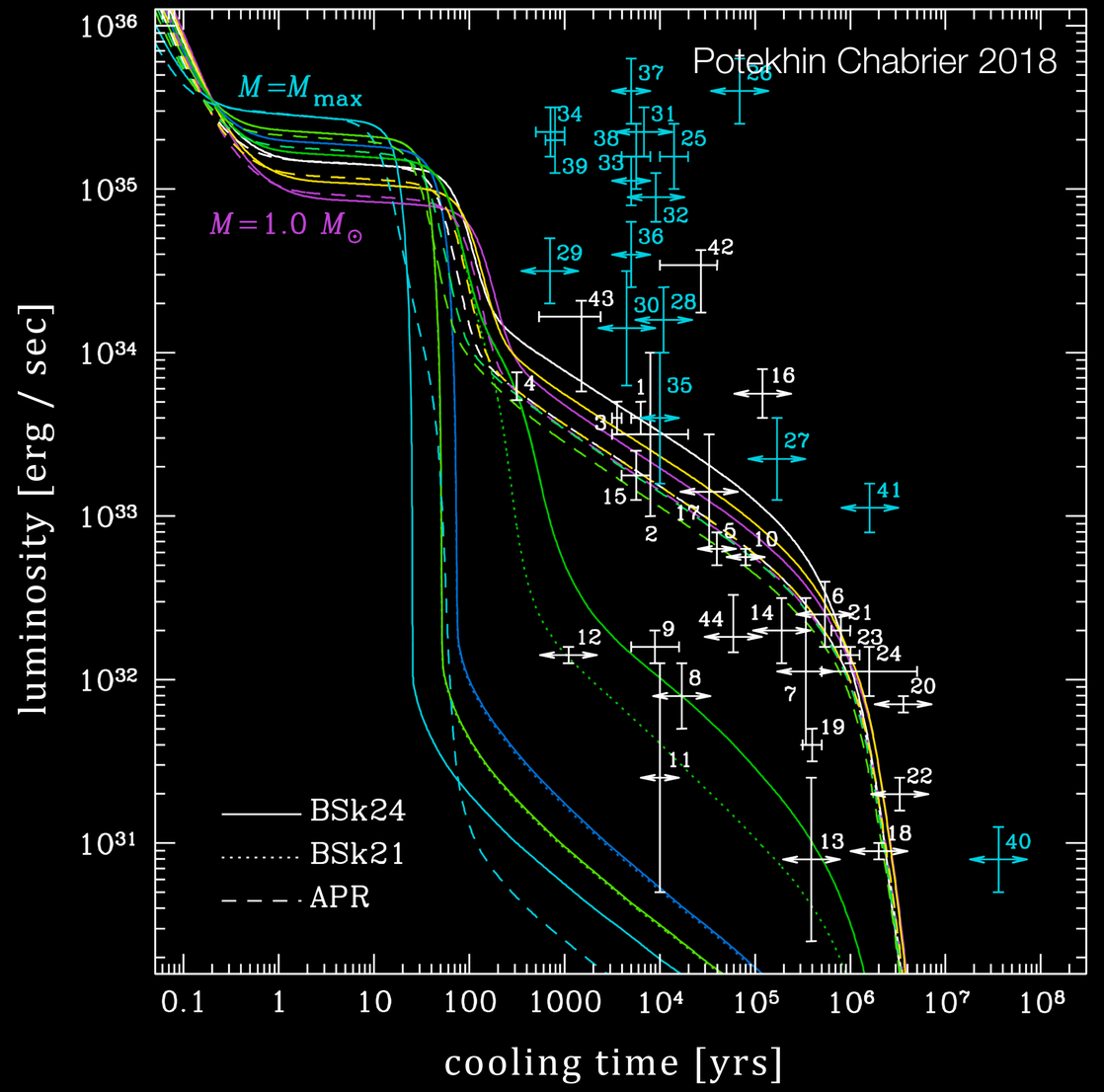
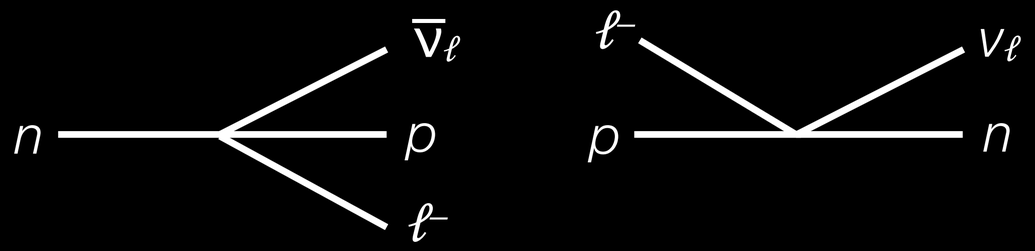



Image: Gendreau *et al.*

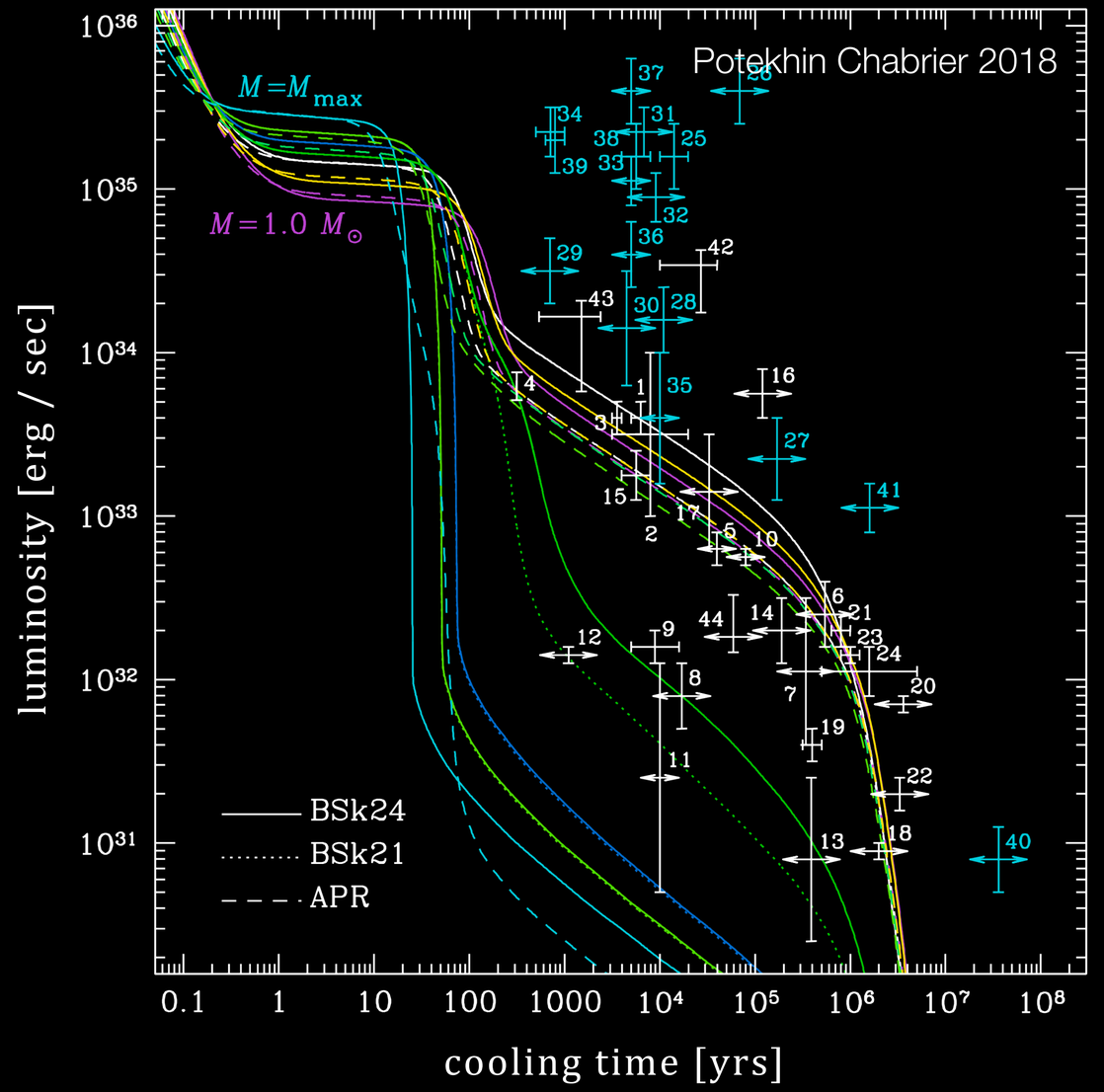


# Neutrino Cooling

## Direct Urca Processes




- kinematically forbidden except in the heaviest stars
- condition $p_{Fn} < p_{Fp} + p_{F\ell}$



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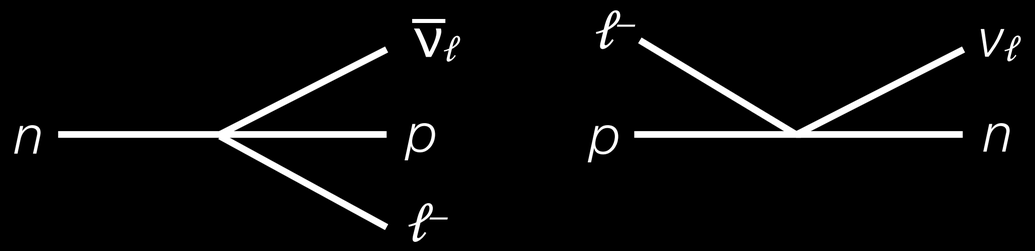


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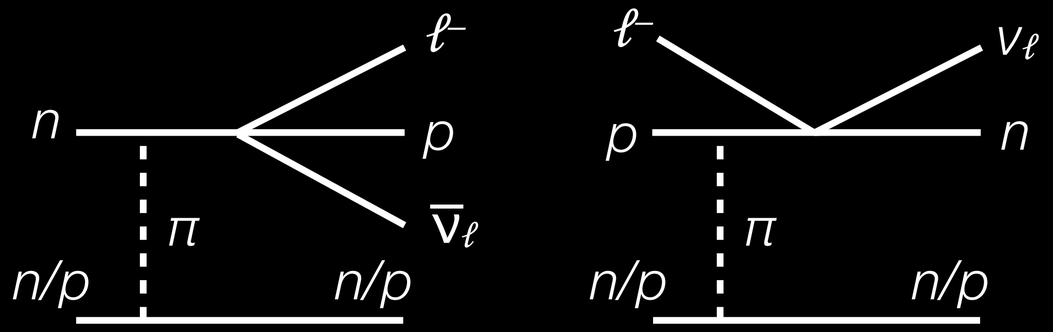
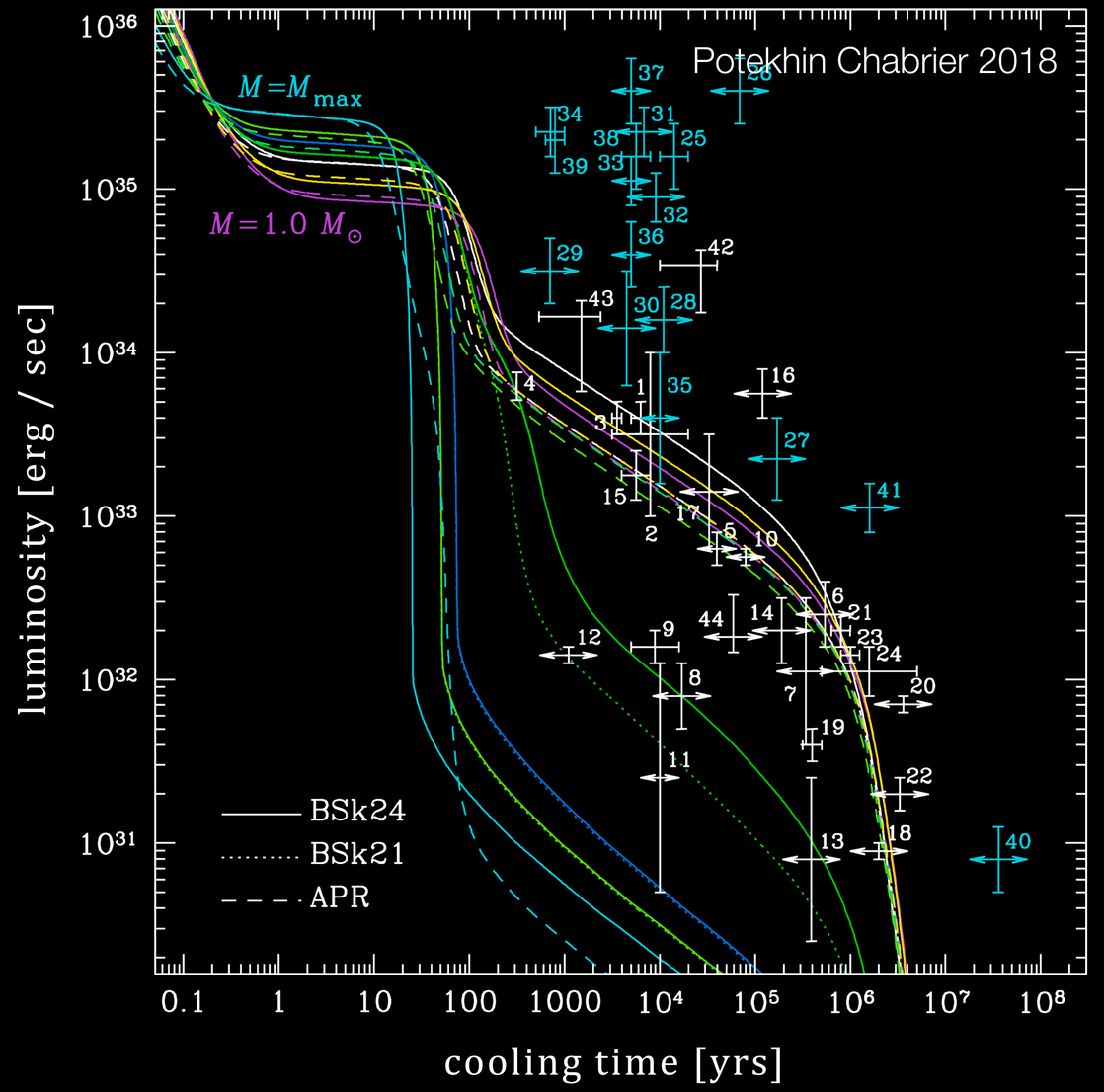



- allowed in all neutron stars



# Neutrino Cooling

electron ($e$) or muon ($\mu$)

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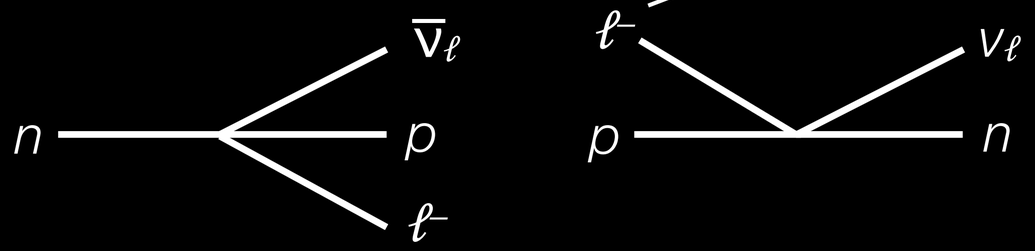


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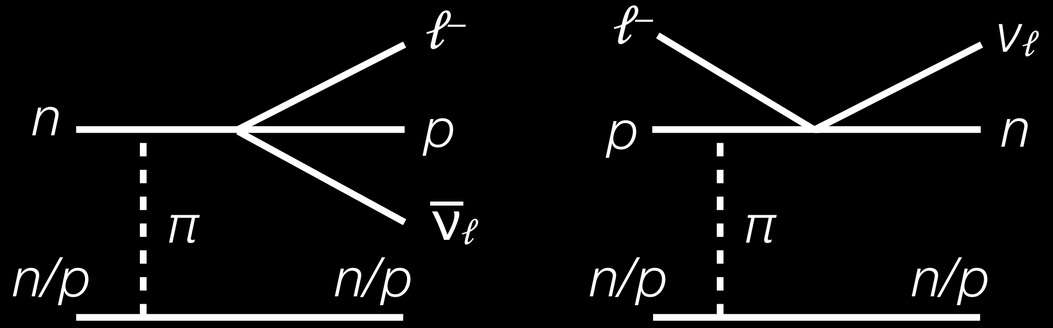


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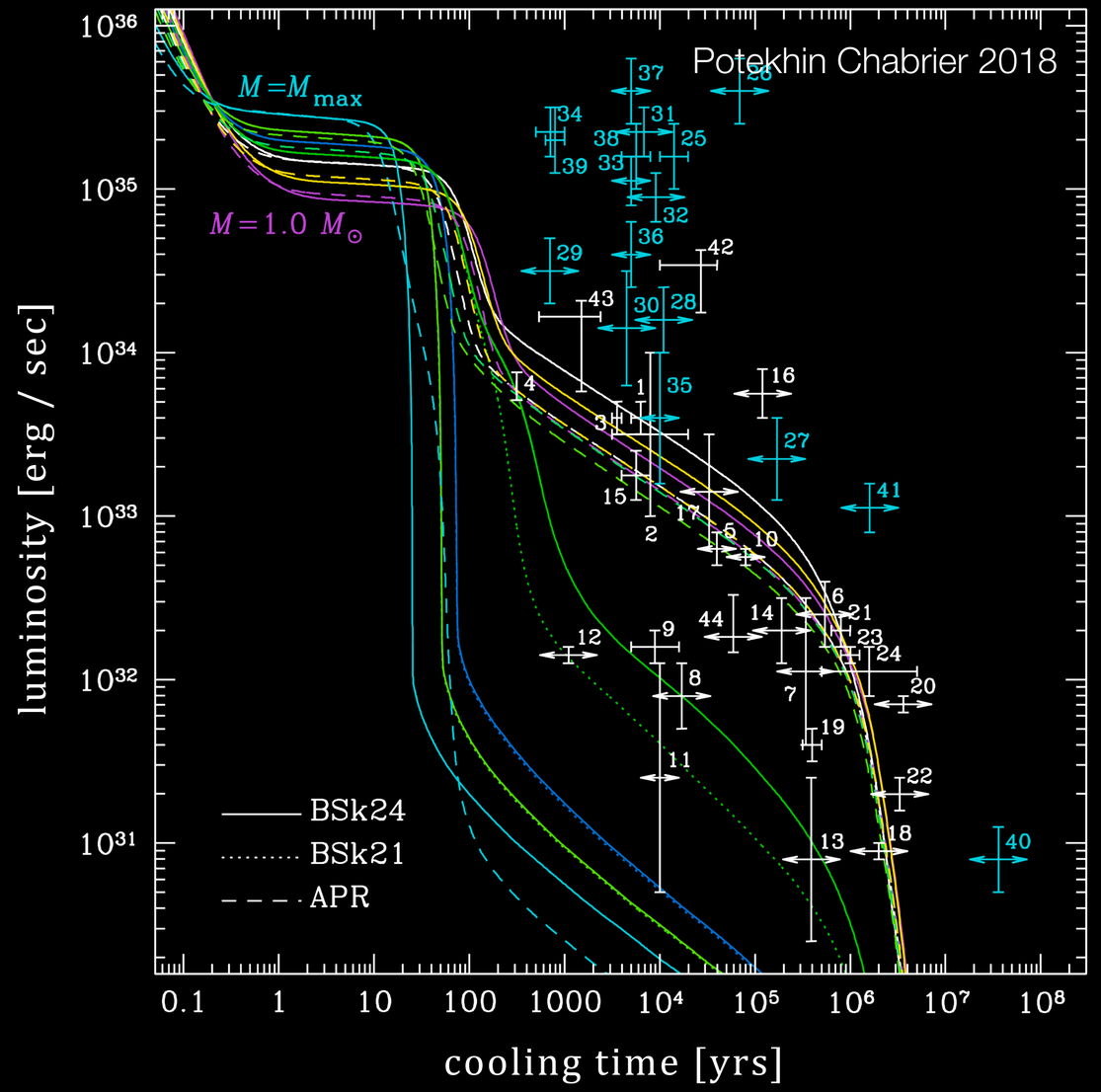
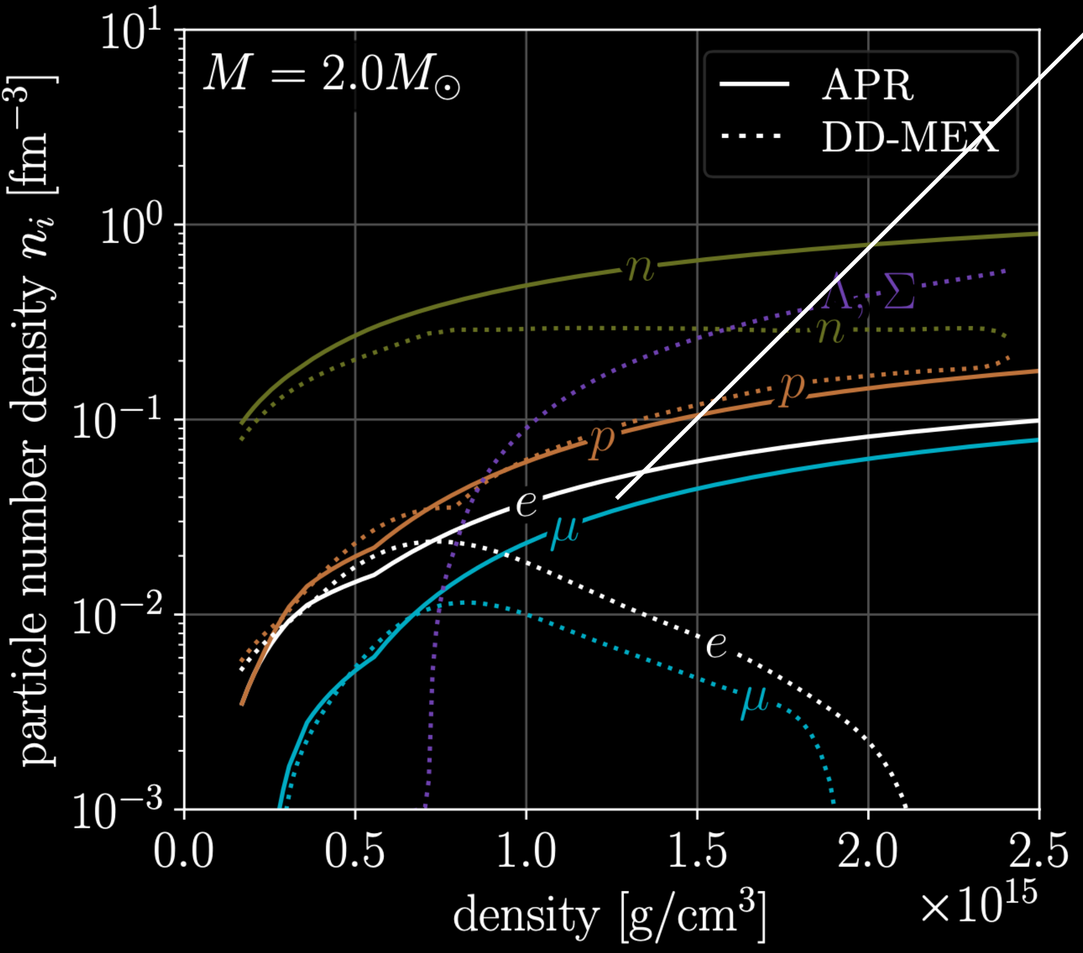
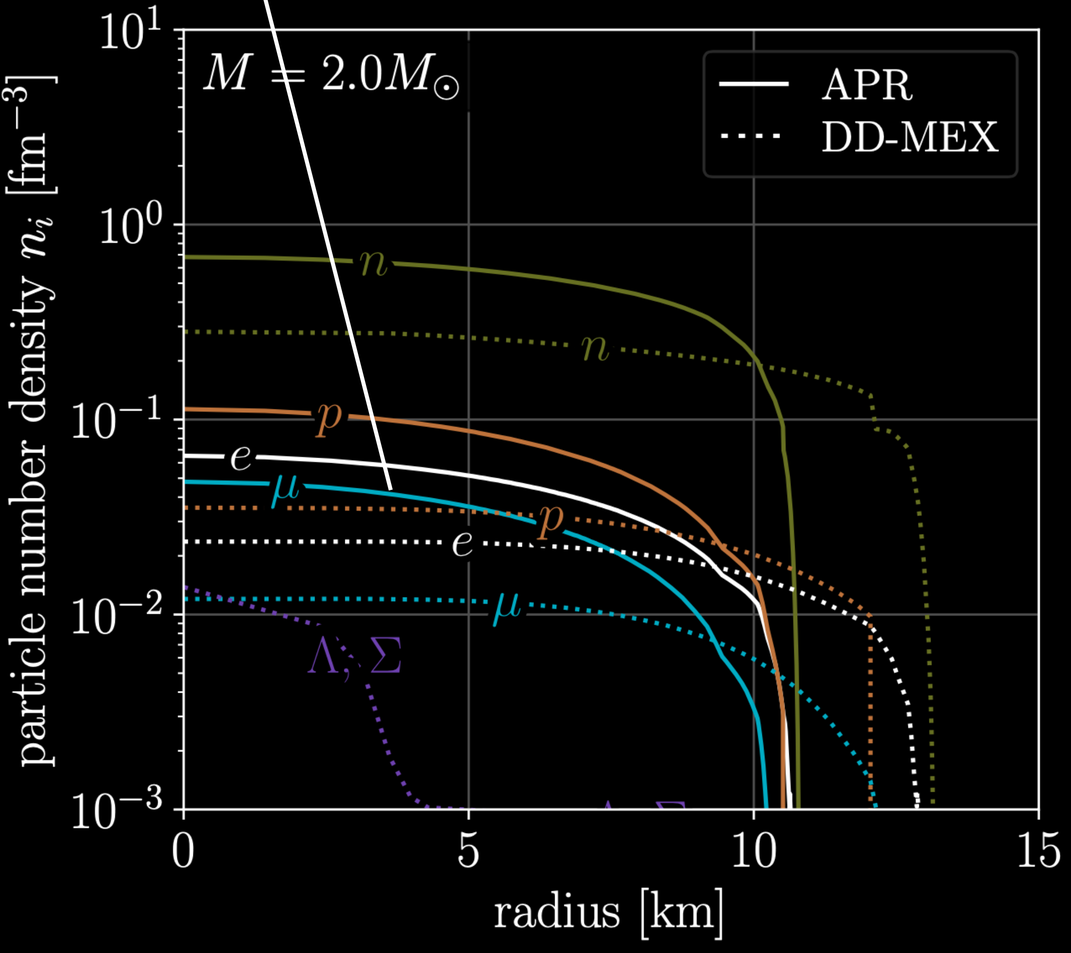


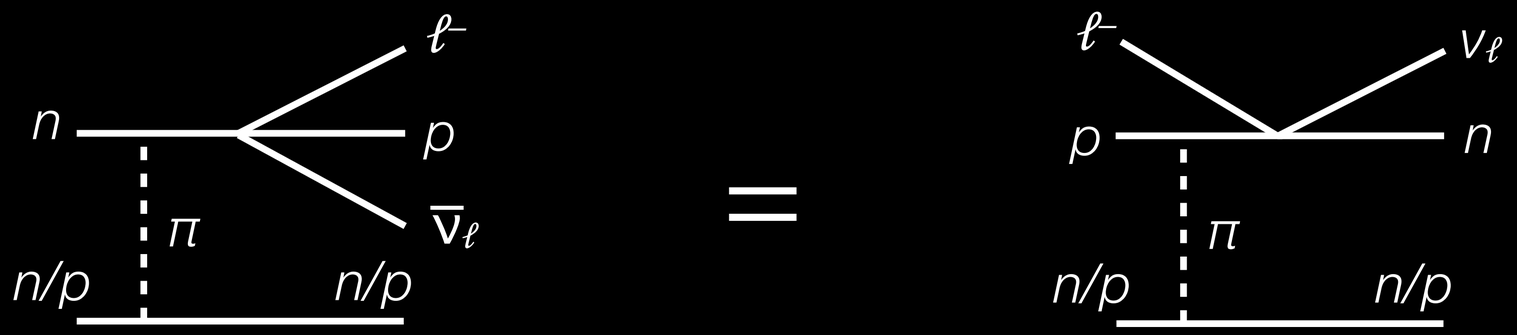
# Muons in Neutron Stars

neutron stars harbor
abundant quantities of muons



# Neutron Stars in Chemical Equilibrium



# Neutron Stars Away from Equilibrium

# Departure from Equilibrium

JK Opferkuch 2023

Neutron Stars are not always static

- spin-down (electromagnetic energy loss)
- accretion
- *B* field expulsion
- tidal deformation
  (tight binaries, random encounters)
- …?

➠ equilibrium abundances of particle species changes

➠ star needs to react via out-of-equilbrium Urca processes

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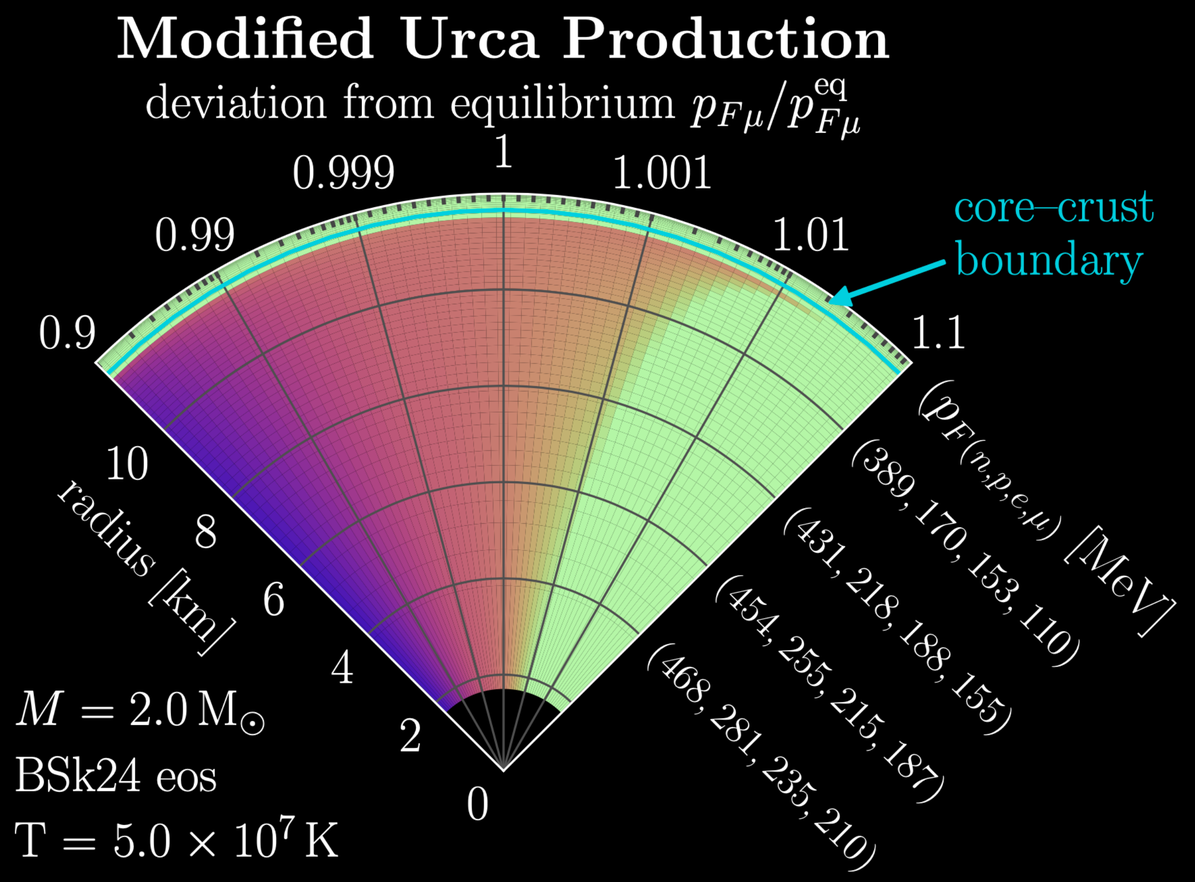

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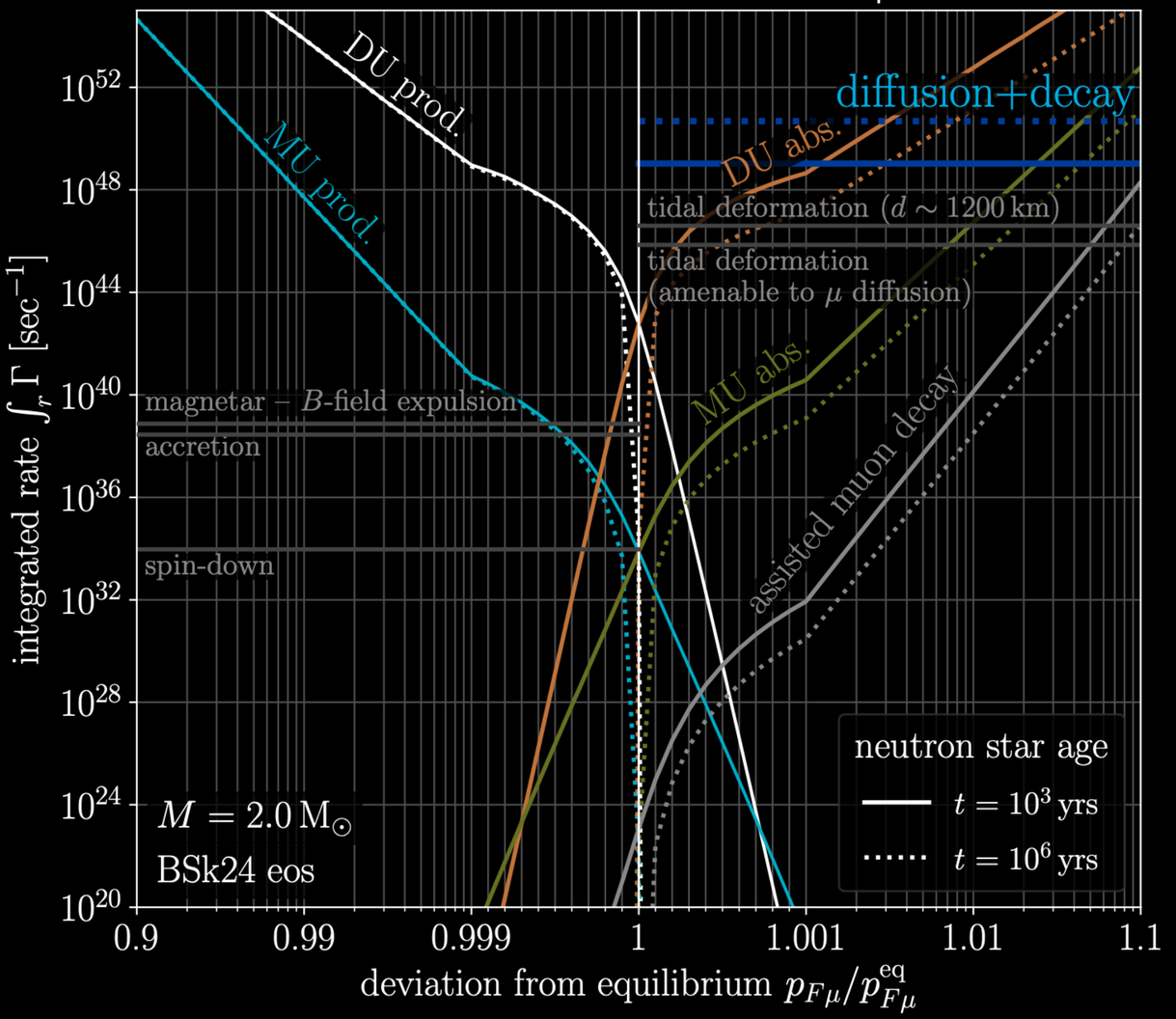
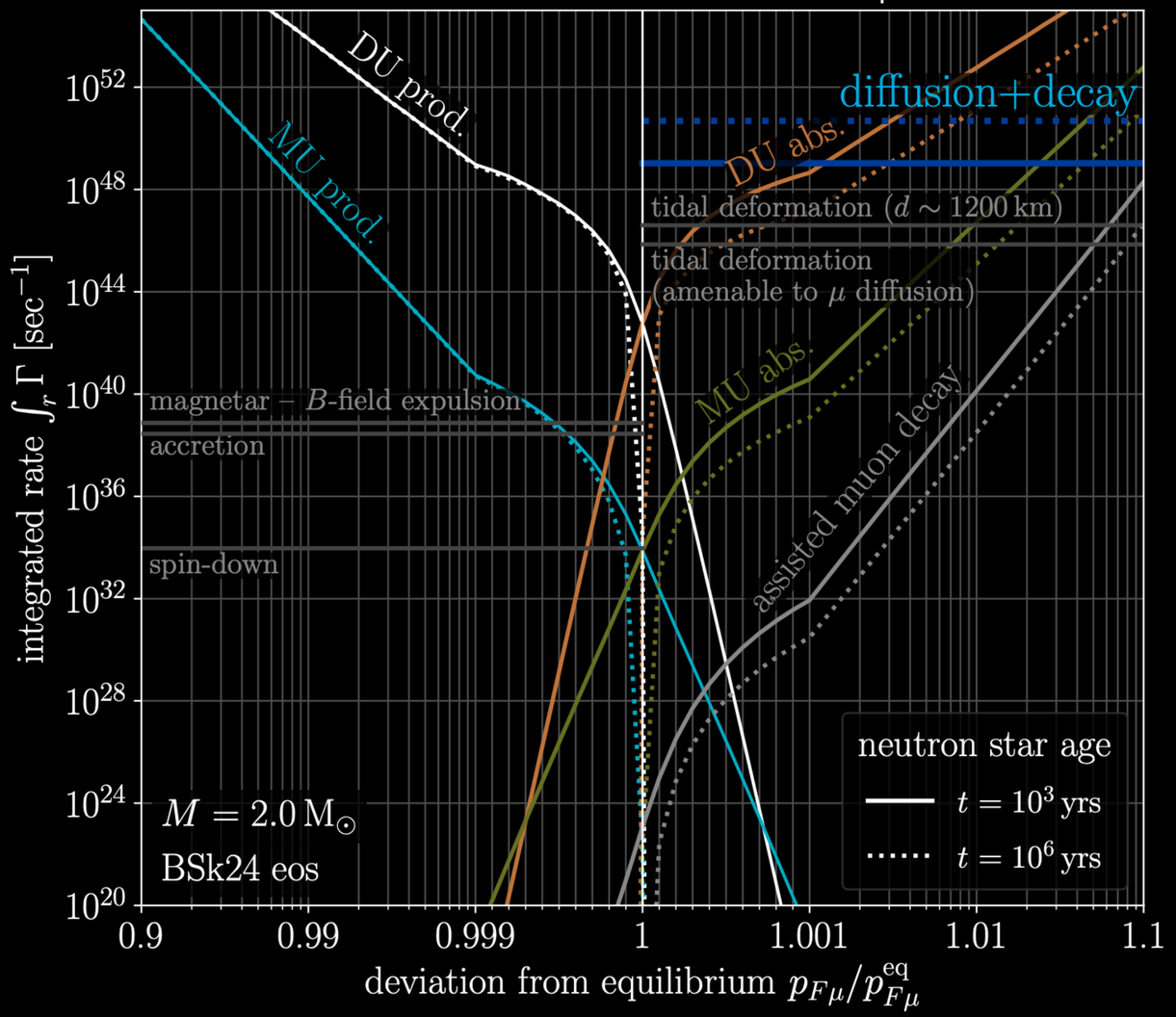


# Departure from Equilibrium

- very strong dependence on $p_F/p_F^{eq}$
- and on $T$
- For muons:
  diffusion (over $\mathcal{O}$(yr) time scales) + decay

JK Opferkuch 2023



# Departure from Equilibrium – The Technical Slide

JK Opferkuch 2023

Strategy for calculating rates

- parameterize hadronic matrix elements
  neglect angular dependence
- need to evaluate phase space integral

$$\Gamma_{\mathrm{MU}}^{\mathrm{prod}} = \int \left[ \prod_{j=1}^{5} \frac{\mathrm{d}^3 p_j}{(2\pi)^3} \right] \frac{\mathrm{d}^3 p_\nu}{2E_\nu (2\pi)^3} \frac{(2\pi)^4}{2E_\mu s} \delta^{(4)}(p_f - p_i) \mathscr{L}_{\mathrm{blocking}} \sum_{\mathrm{spins}} |\mathcal{M}_{\mathrm{MU}}|^2$$

Friman Maxwell 1979
Yakovlev Levenfish 1995
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hadronic matrix element

nucleon momenta

$$n(p_1) + n(p_2) \to n(p_3) + p(p_4) + \mu(p_5 \text{ or } p_\mu) + \overline{\nu}_\mu(p_\nu)$$

phase space density / Pauli blocking

$$\mathscr{L}_{\text{blocking}} = f_1 f_2 (1 - f_3)(1 - f_4)(1 - f_5)$$

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- angular integrals factorize ➠ evaluate separately
- Use $p_{Fn} \gg p_{Fp}, p_{Fe}, p_{F\mu} \gg T, p_\nu$ ➠ replace $|p| \to p_F$ wherever possible
- Treat nucleons as non-relativistic
- Define $x = \pm (E - \mu) / T$ for incoming / outgoing particles
- use residue theorem for remaining integrals

Friman Maxwell 1979
Yakovlev Levenfish 1995
Yakovlev Kaminker Gnedin Haensel 2000
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# Neutrino Flux

Regular modified Urca (in equilibrium)

- ~$10^{22}$ erg/cm$^3$/sec ➠ ~$10^{41}$ erg/sec

  Yakovlev Levenfish 1995

- $E_\nu$ ~ $10^9$ K ~ 100 keV
- at 10 kpc: **38 cm$^{-2}$ sec$^{-1}$**

➠ sizeable flux, but low energy

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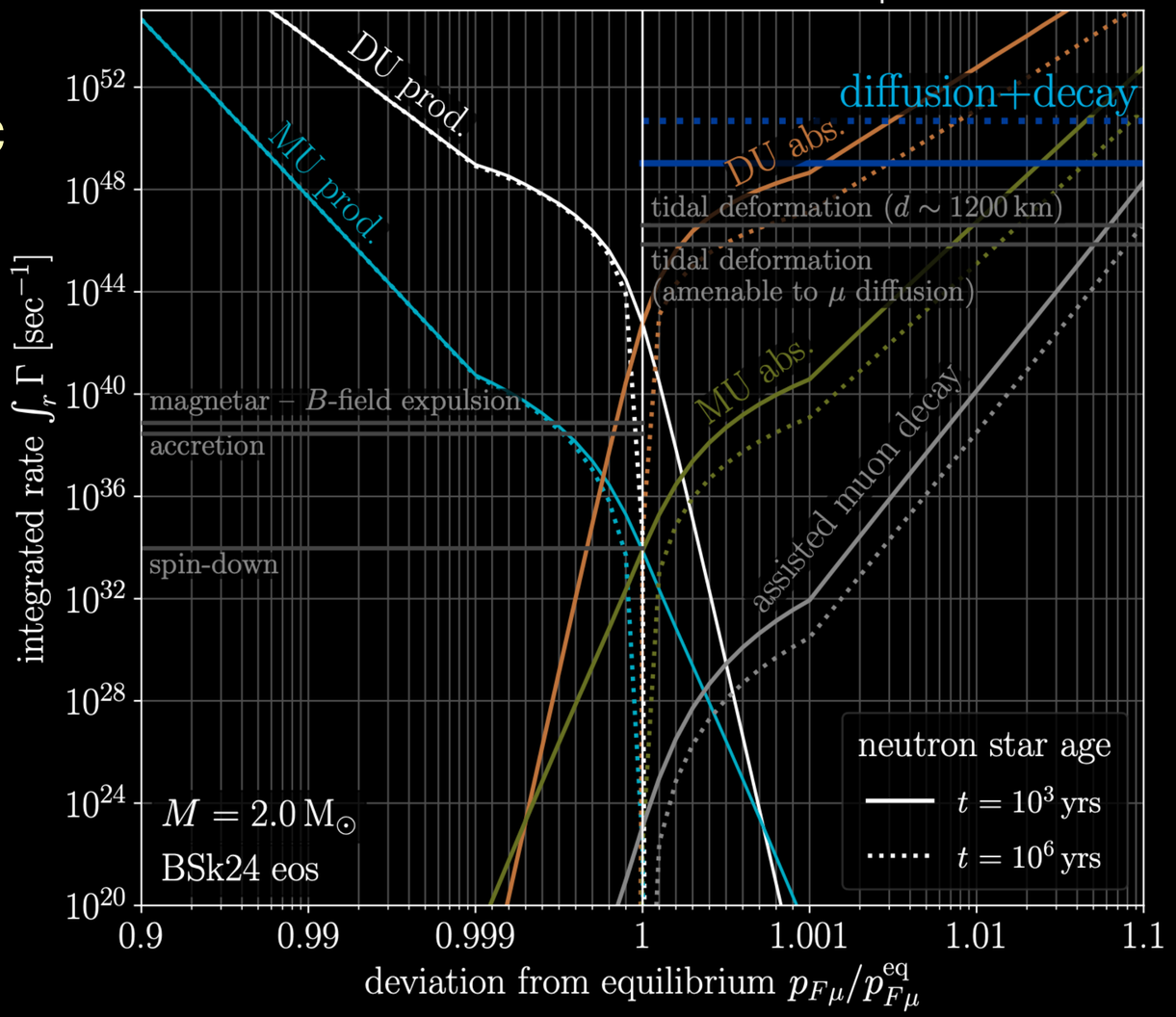

# Neutrino Flux

Muon diffusion + decay

- $E_\nu \sim 10$ MeV
- star contains $\mathcal{O}(10^{56})$ muons
- assume $10^{53}$ are lost over 1 Gyr
- flux at Earth **$\sim 10^{-10}$ cm$^{-2}$ sec$^{-1}$**
- current limit: $\sim 1$ cm$^{-2}$ sec$^{-1}$

What if all neutron stars in the Milky Way were to lose muons?

➠ no known mechanism

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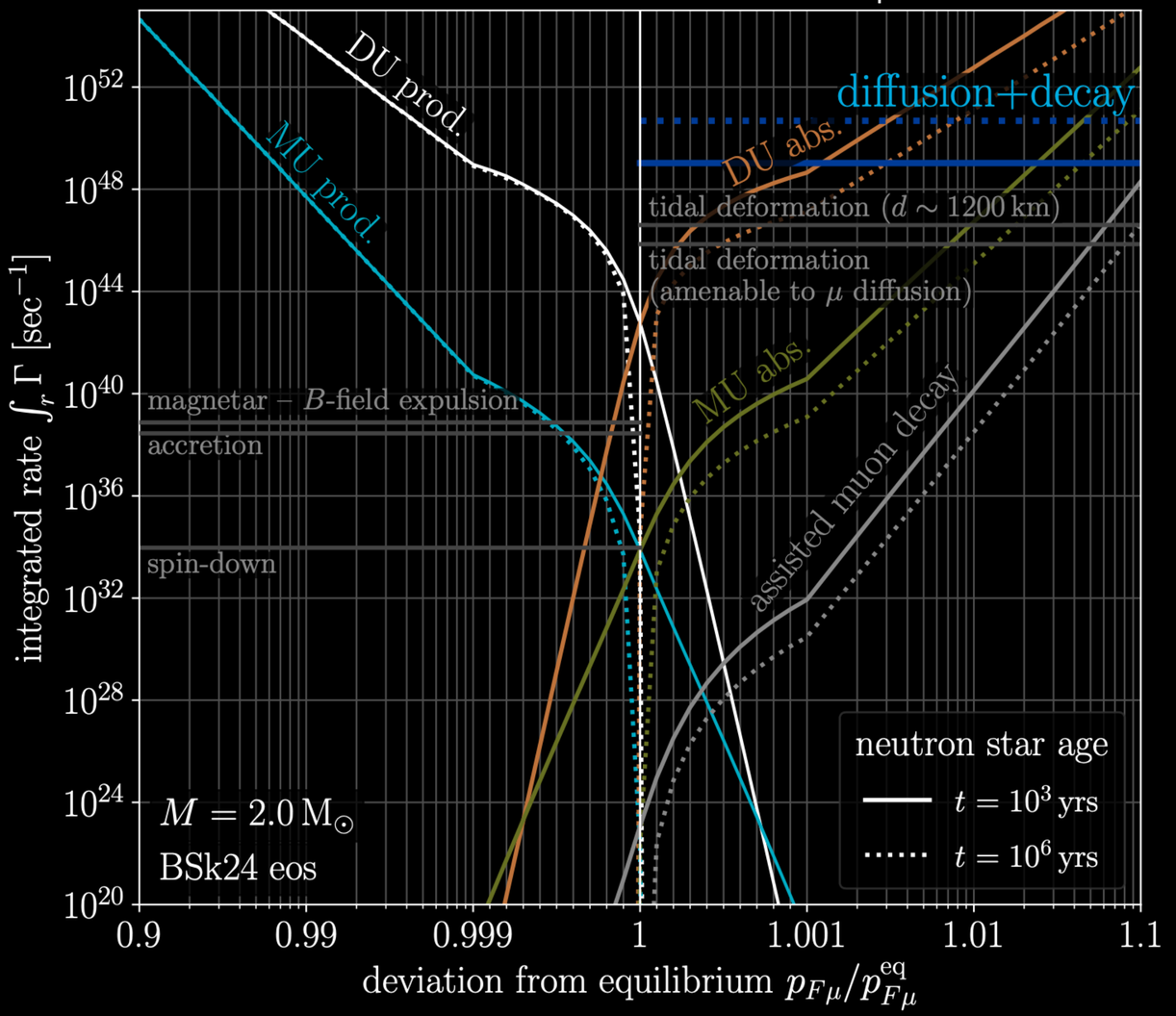

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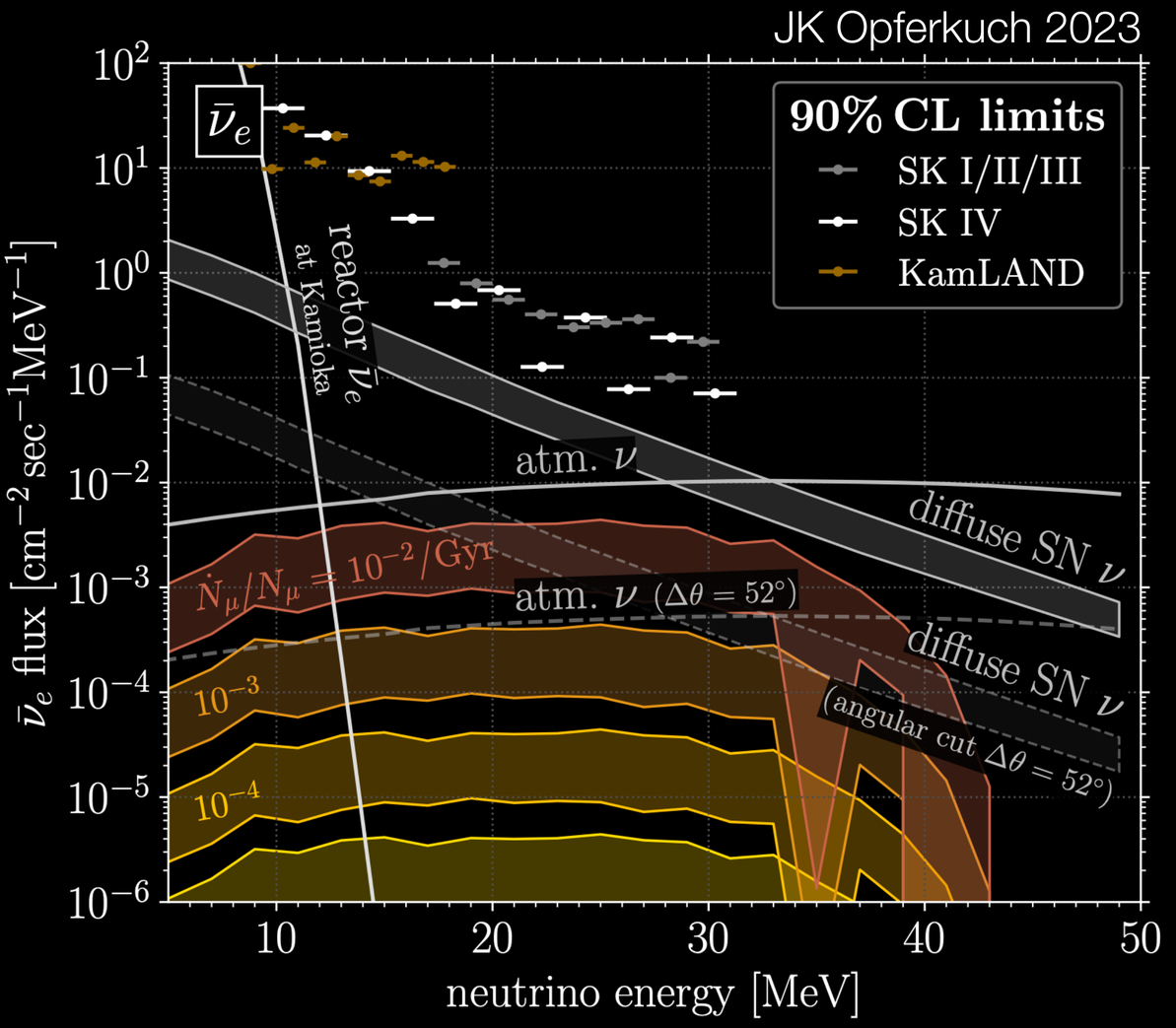

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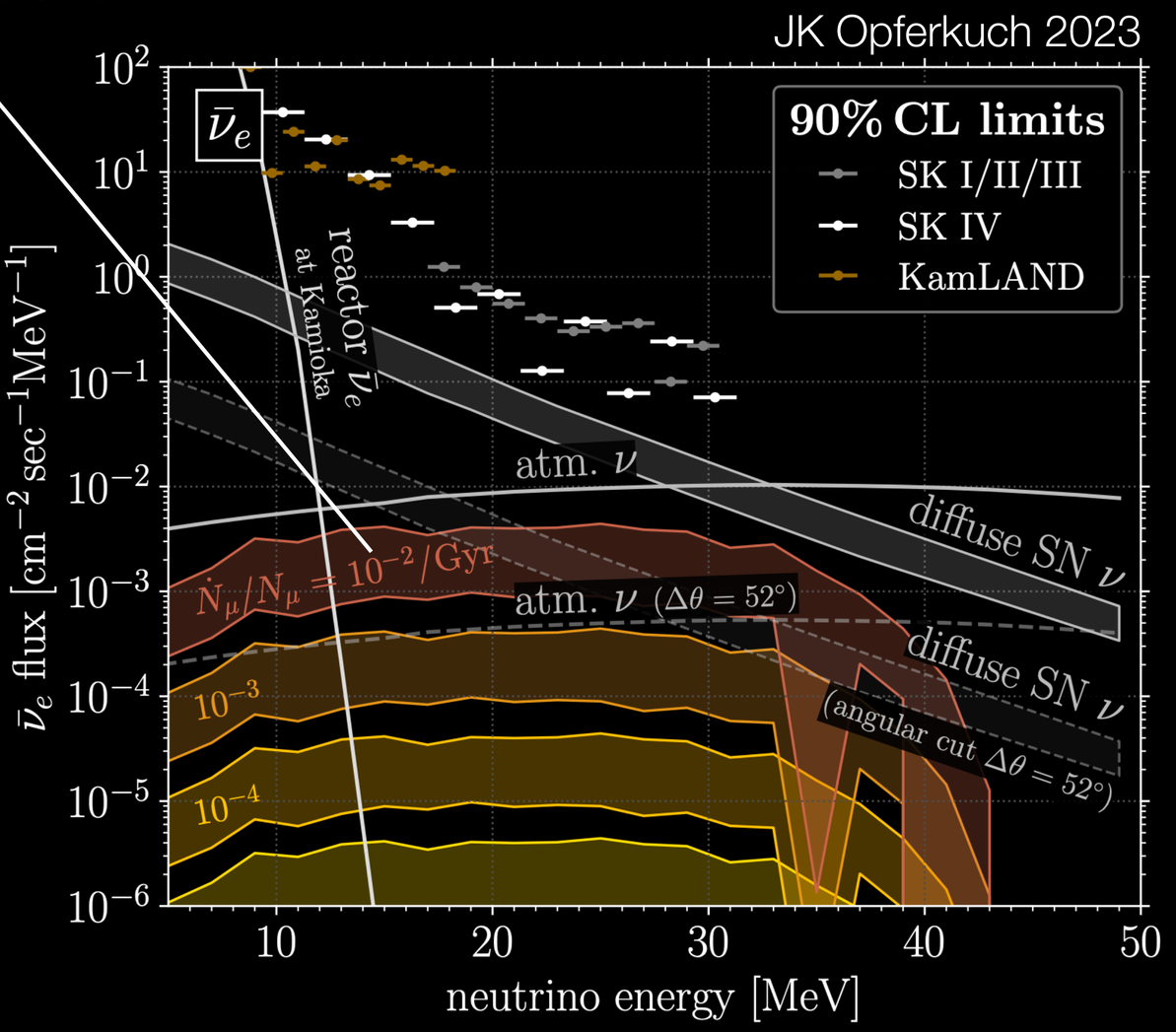
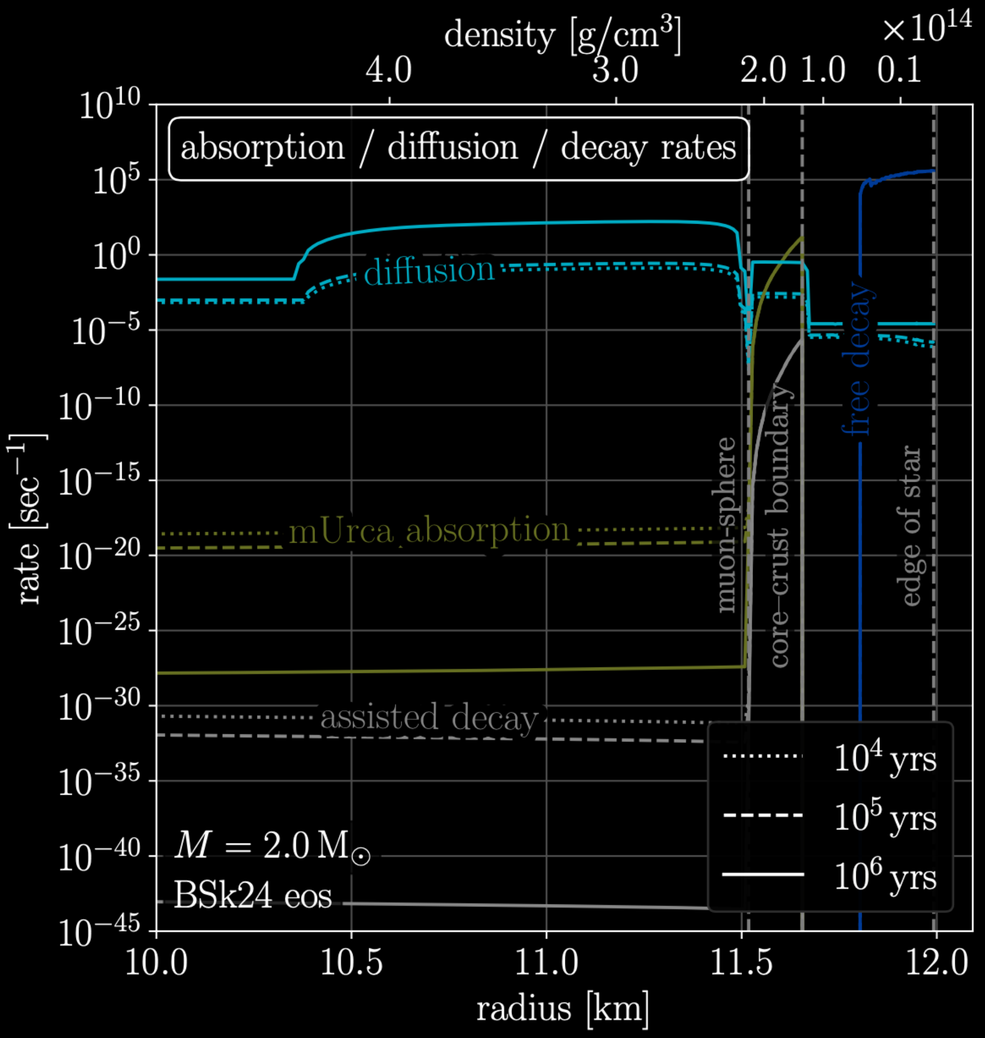
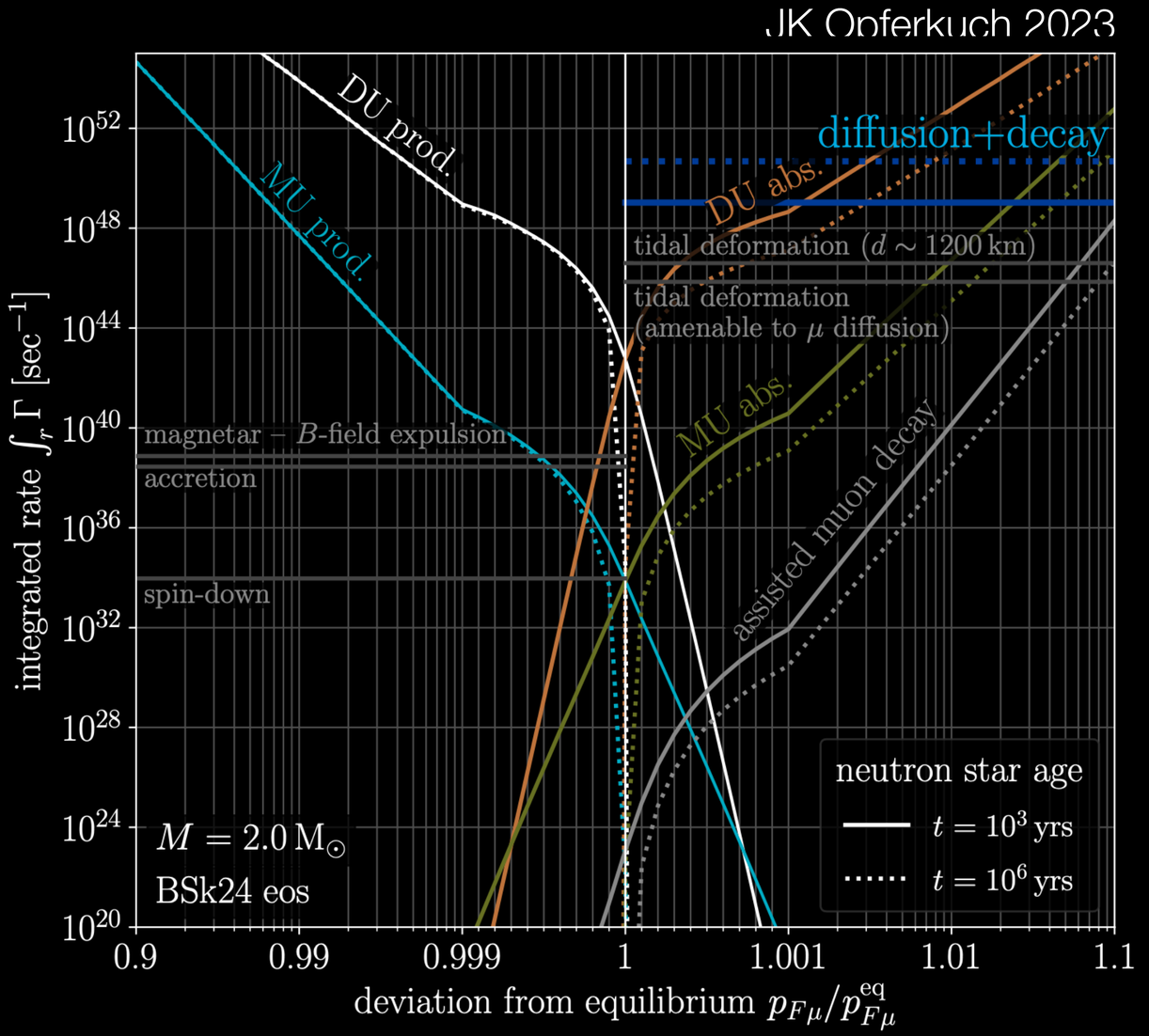
no mechanism known to us that does this



# Dynamics at the Core–Crust Boundary



# Common-Envelope Systems

# Common-Envelope Evolution

- compact star (neutron star, black hole, white dwarf, …) enters companion star
- significant friction
- gigantic accretion rates (up to 0.1 $M_\odot$/yr for several months)
- outcome: Thorne–Żytkov object or explosion
- crucial for the formation of gravitational wave sources
- rare (0.01 / century – 1 / century in our galaxy)
- **never observed**

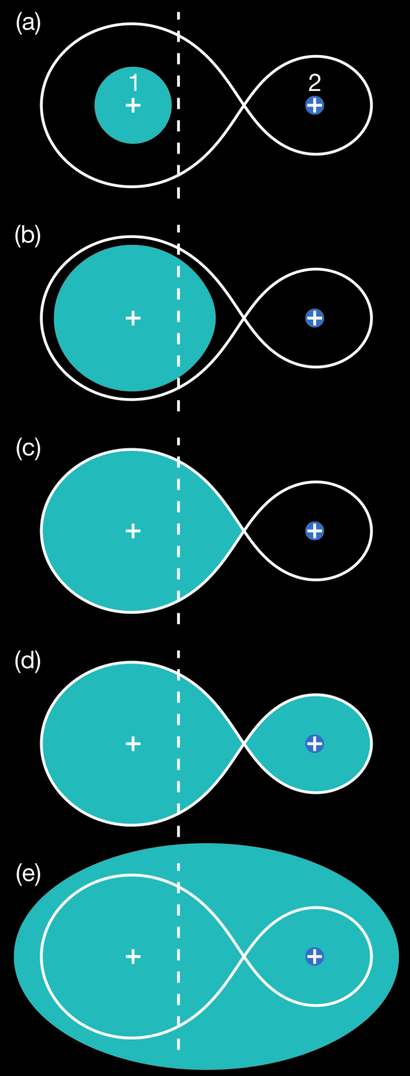
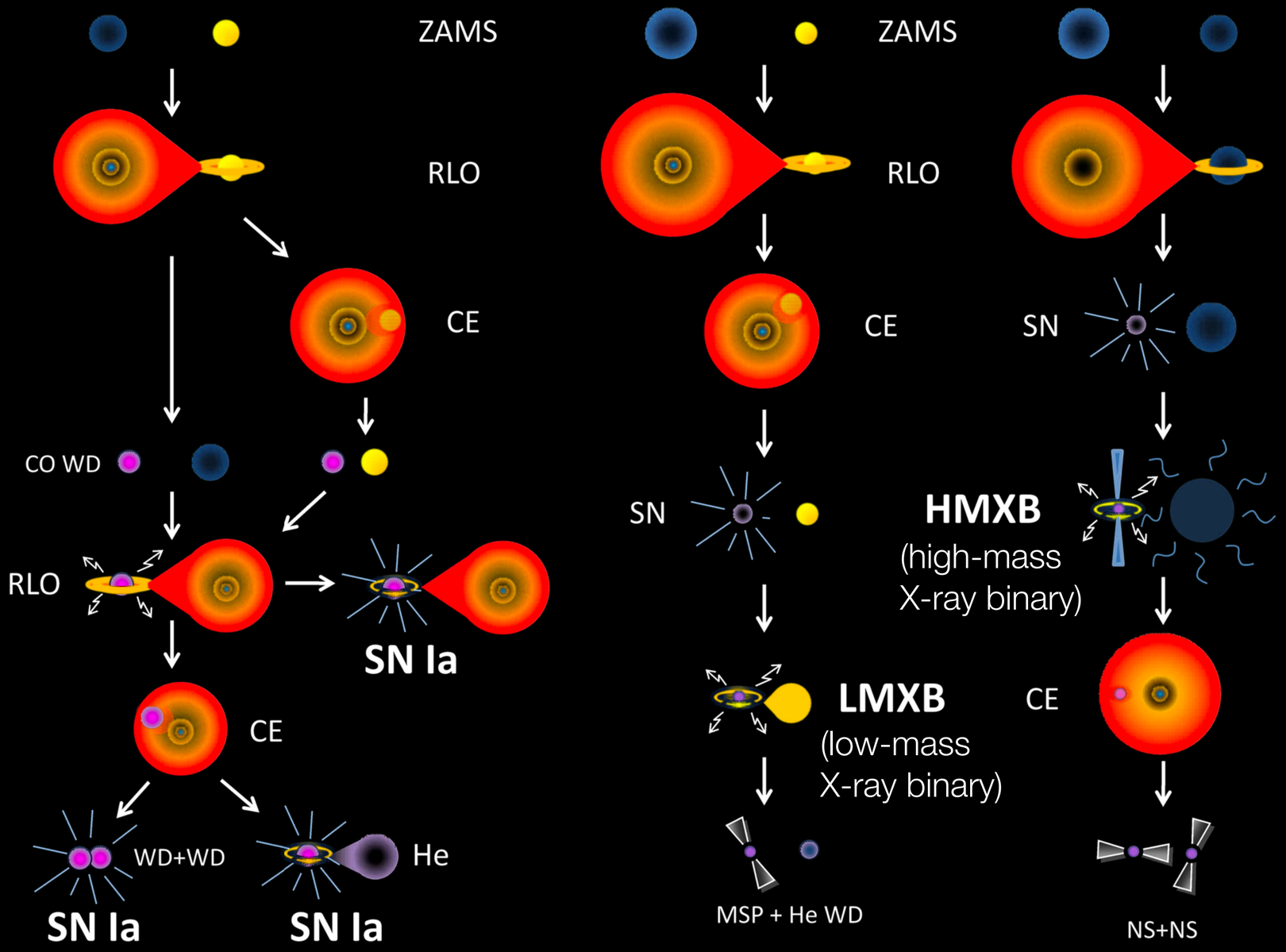



Image: Wikimedia Commons

# Common-Envelope Evolution – Examples

Ivanova *et al.* 2012



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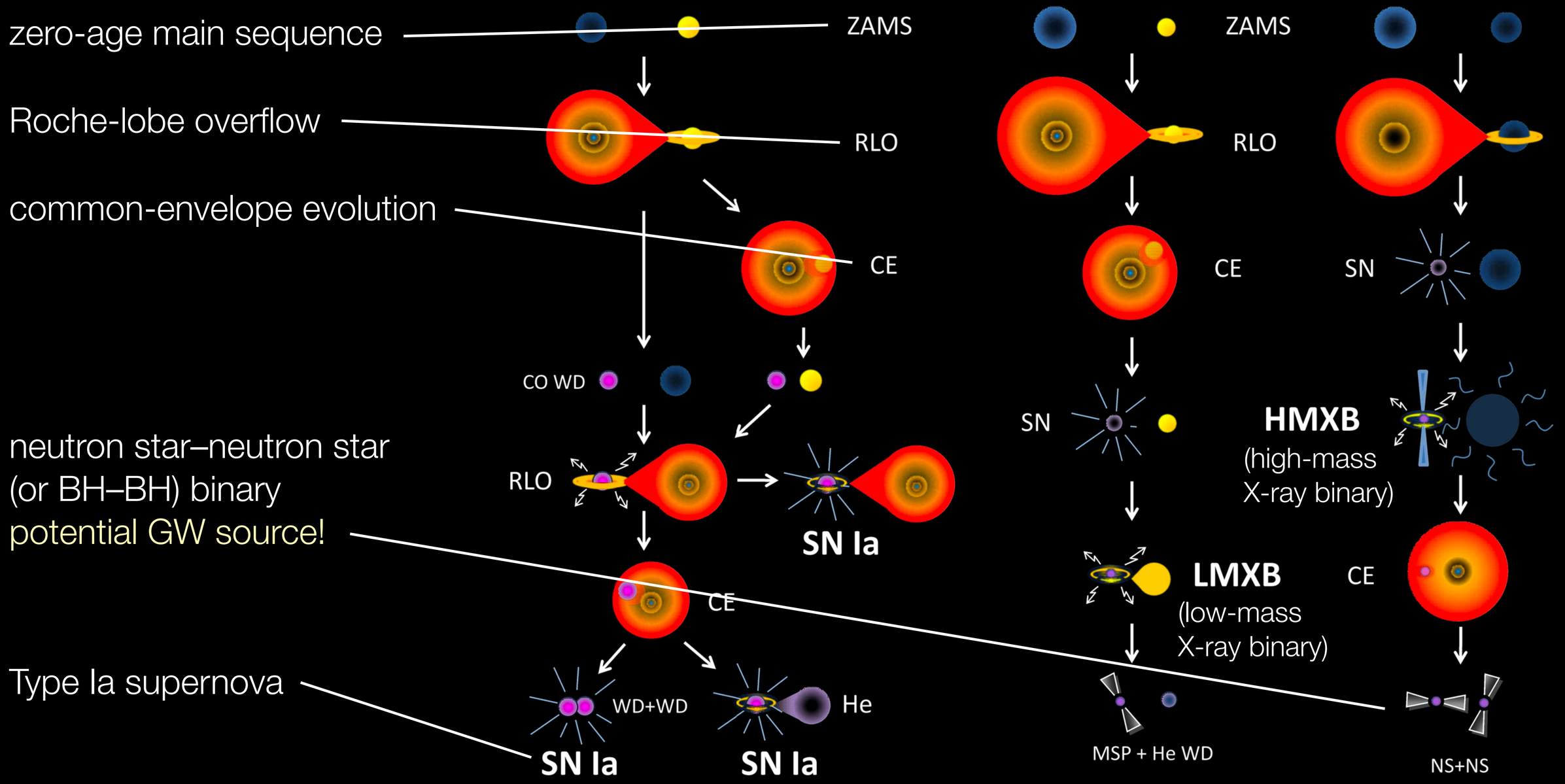
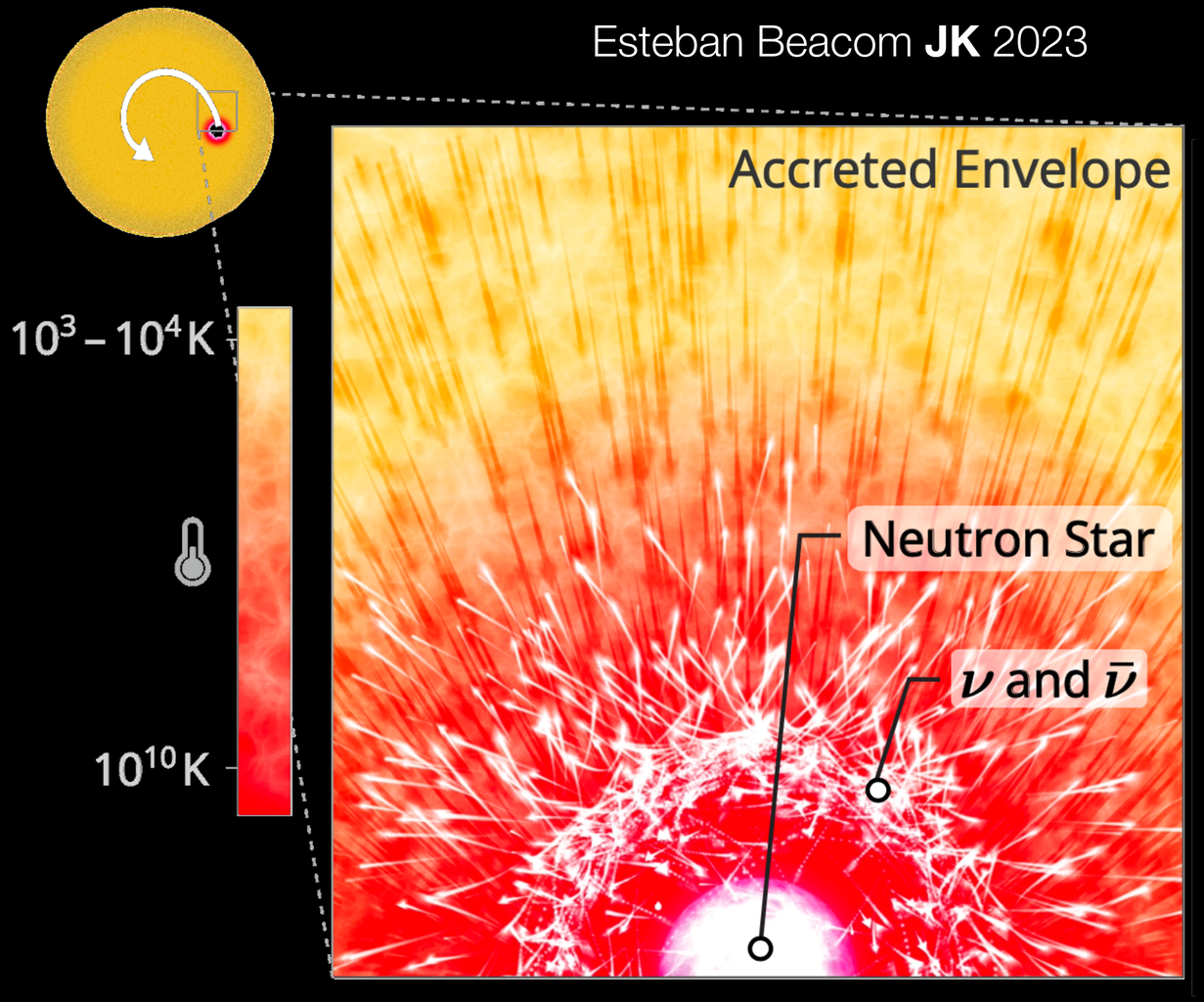


# Common-Envelope Evolution – Neutrino Emission




- gigantic accretion rates
- only cooling channel is via neutrinos

# Common-Envelope Evolution – Neutrino Emission

temperature / density profile

- solve hydrodynamic equations with appropriate boundary conditions (accretion shock discontinuity)

$$\frac{1}{r^2}\frac{\mathrm{d}(r^2\rho v)}{\mathrm{d}r} = 0\,,$$

$$\frac{\mathrm{d}(\rho c^2 + e)}{\mathrm{d}r} - \frac{w}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}r} = \frac{\varepsilon_{\mathrm{nuc}} - \mathcal{L}_\nu}{v}\,,$$

$$v\frac{\mathrm{d}v}{\mathrm{d}r} + \frac{GM_{\mathrm{NS}}}{r^2} + \frac{1}{w}\frac{\mathrm{d}P}{\mathrm{d}r}\left(v^2 + c^2 - \frac{2GM_{\mathrm{NS}}}{r}\right) = 0\,,$$

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# Common-Envelope Evolution – Neutrino Emission

temperature / density profile

- solve hydrodynamic equations with appropriate boundary conditions (accretion shock discontinuity)

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continuity equation

energy conservation

Euler equation (in Schwarzschild background)

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# Common-Envelope Evolution – Neutrino Emission

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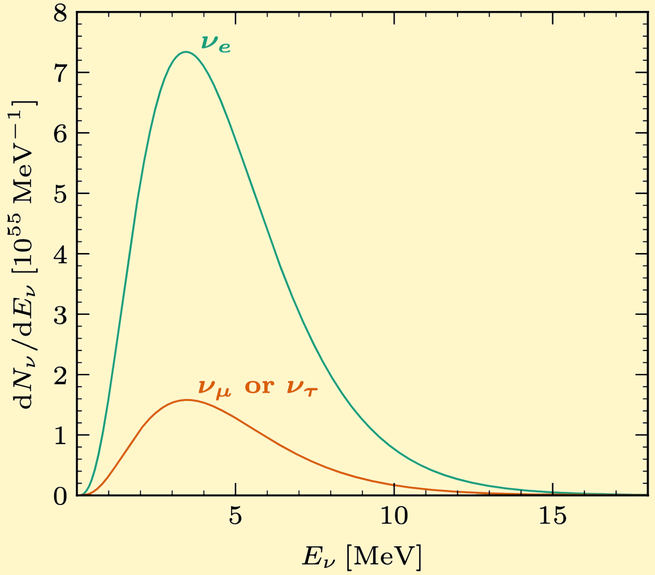
## neutrino emission

- $e^+e^-$ annihilation (dominant)
- plasmon decay (subdominant)




- neutrino oscillations

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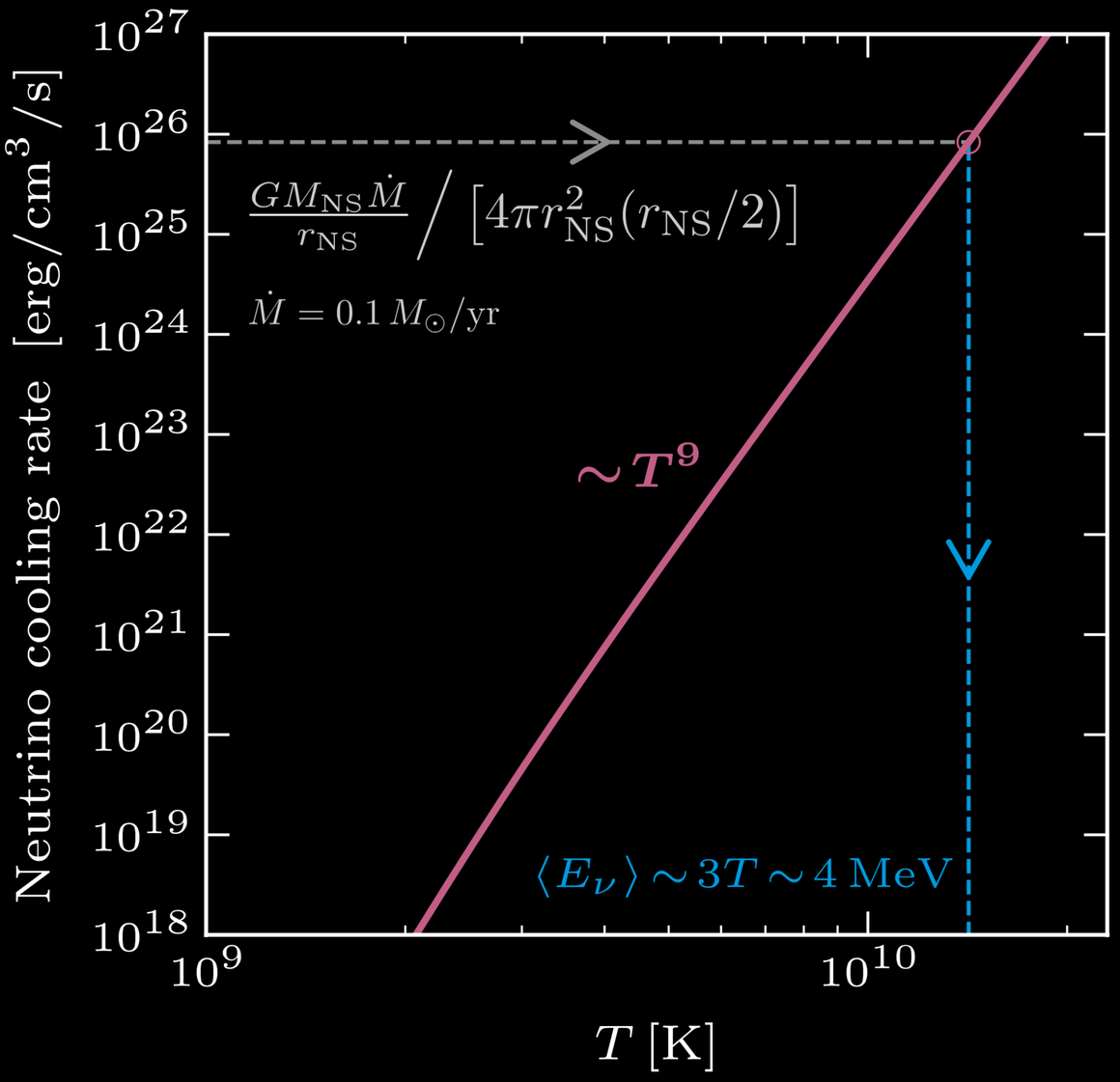
# Neutrino Temperature




- Neutrino temperature: obtained by equating cooling rate = accretion rate

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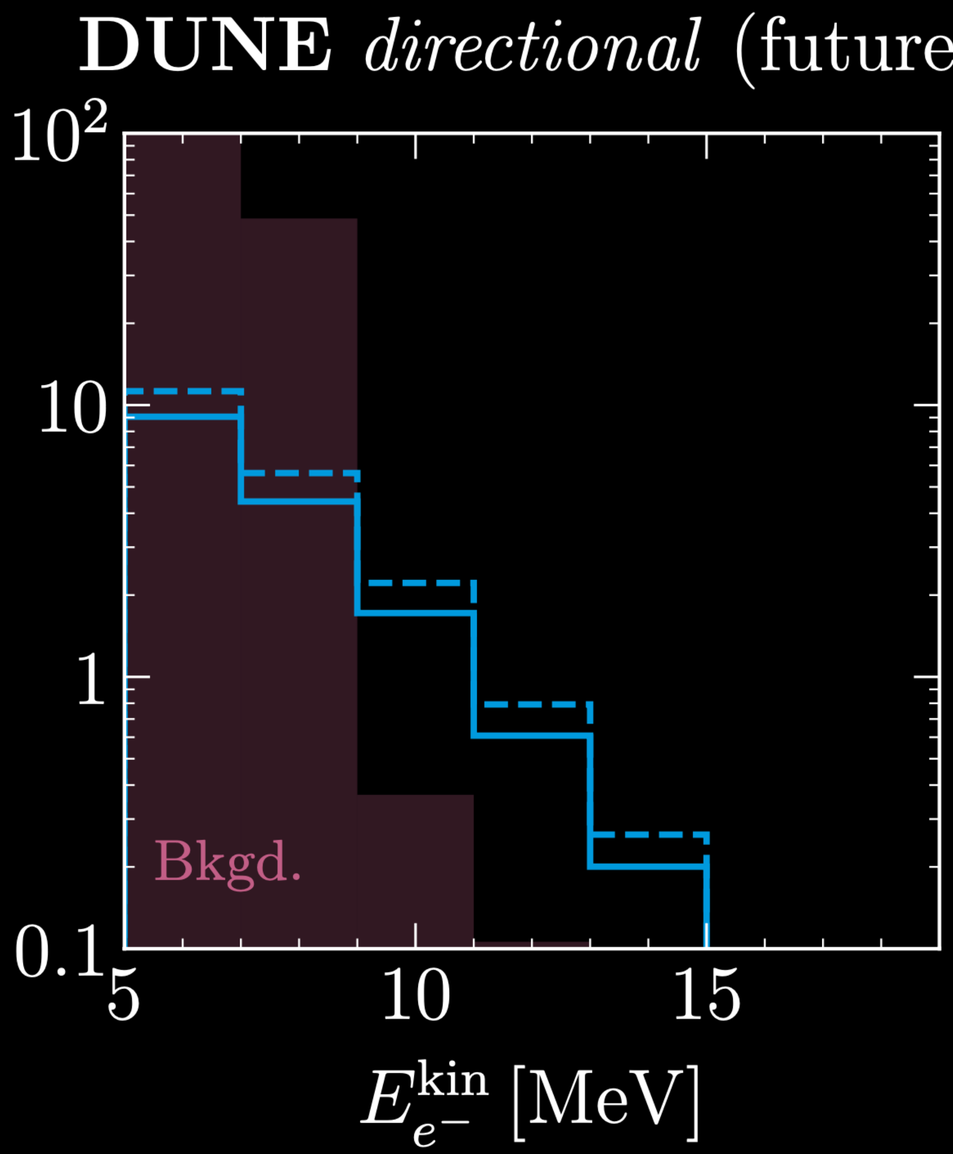
# Backgrounds: Liquid Argon




Main detection channel is ν–e scattering

- neutrons from the surrounding rock
- we assume CC interactions of solar ν on $^{40}$Ar are rejected by identifying de-excitation γ rays.
- directional sensitivity!

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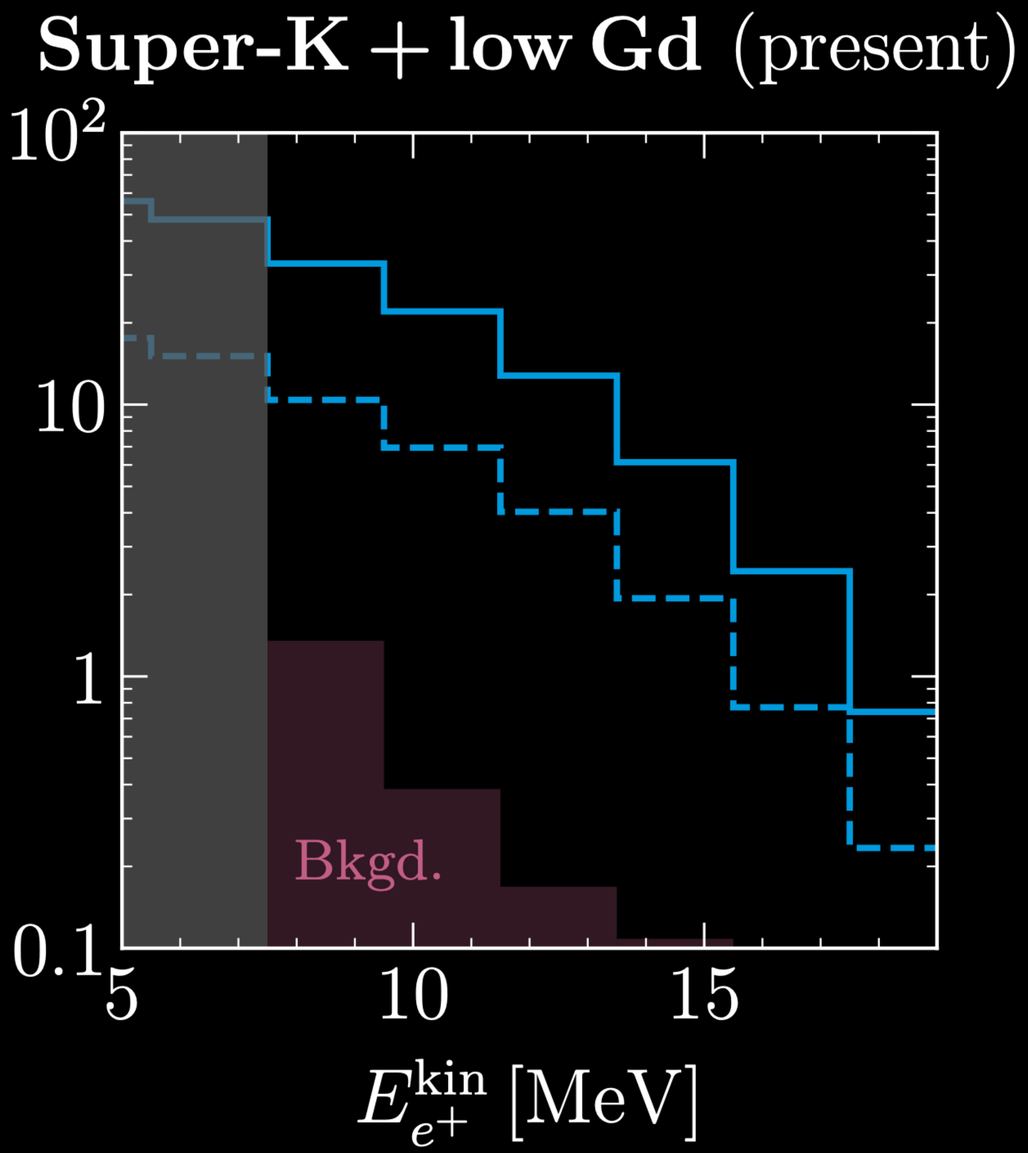
# Backgrounds: Water Čerenkov




Main detection channel is IBD.

**No** directionality

Backgrounds:

- Accidental coincidences
- Li-9 from spallation
- NC interactions of atmospheric ν
- reactor ν, CC atmospheric

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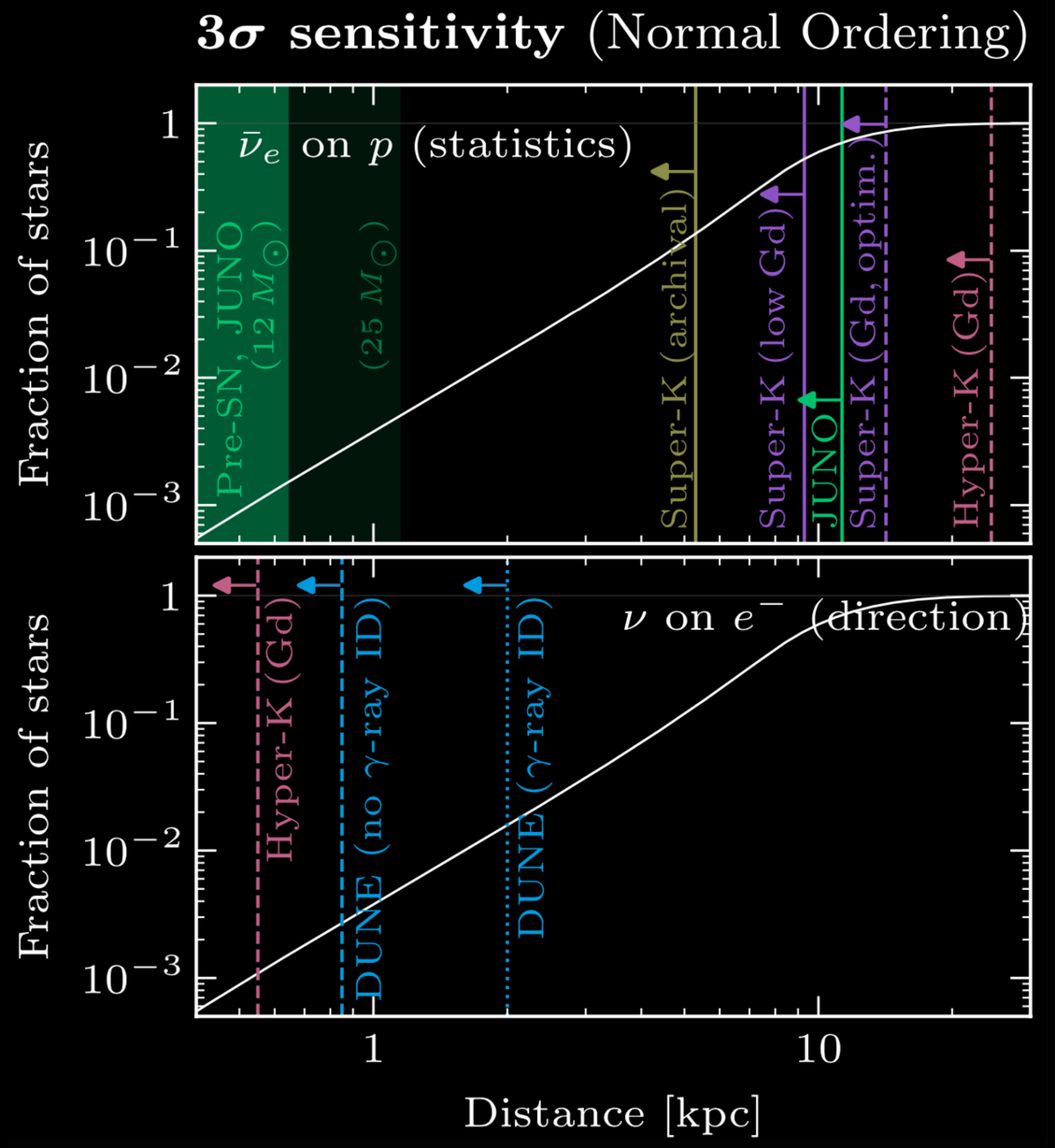
# Common-Envelope Evolution – Discovery Reach




- IBD generally offers better reach
  sensitive to events anywhere in the Milky Way
- but ν–e scattering in LAr provides directional information
- in addition: de-protonization
  (but signals expected to be about a factor ~100 smaller)
- Major caveat:
  CEE rate < core collapse SN rate

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# Common-Envelope Evolution – Discovery Reach

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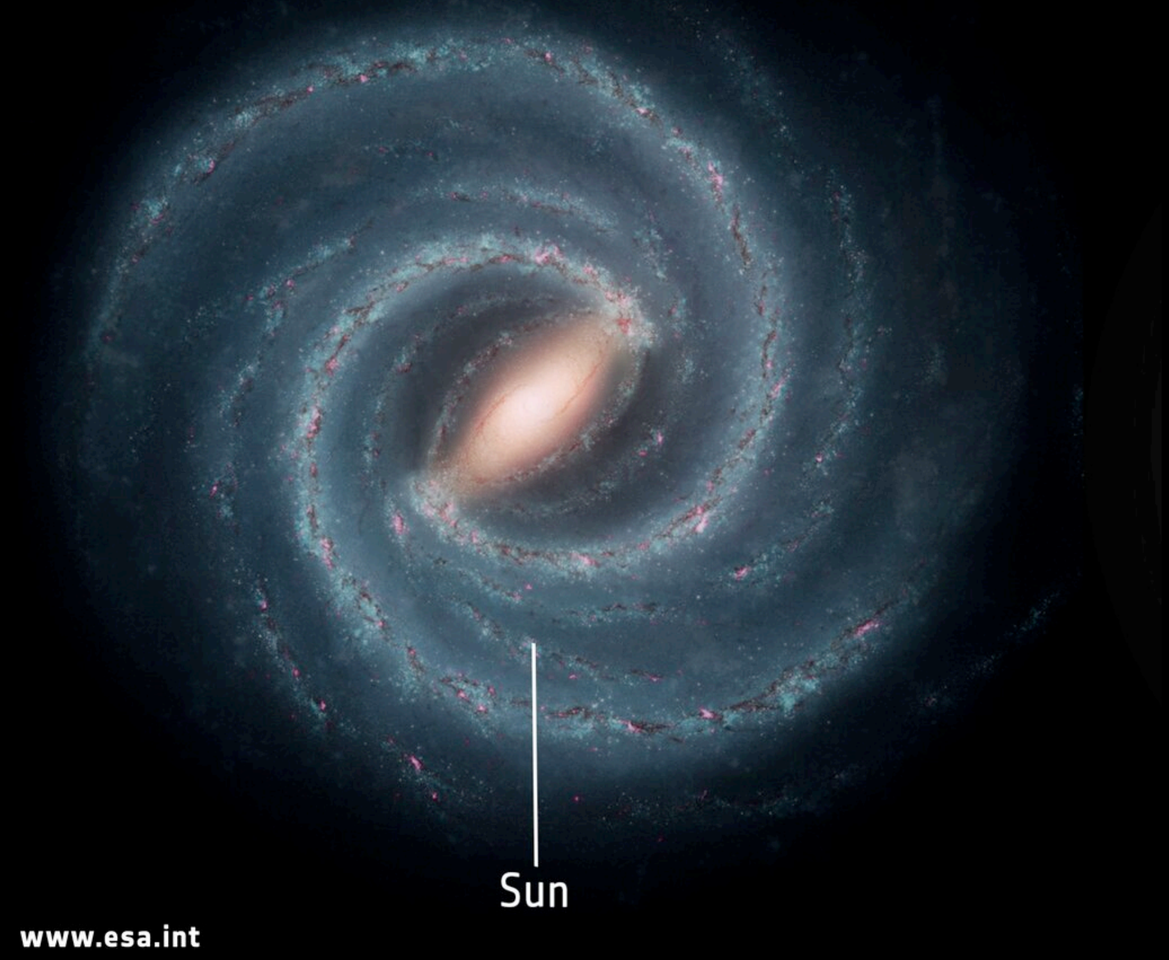

# Common-Envelope Evolution – Discovery Reach

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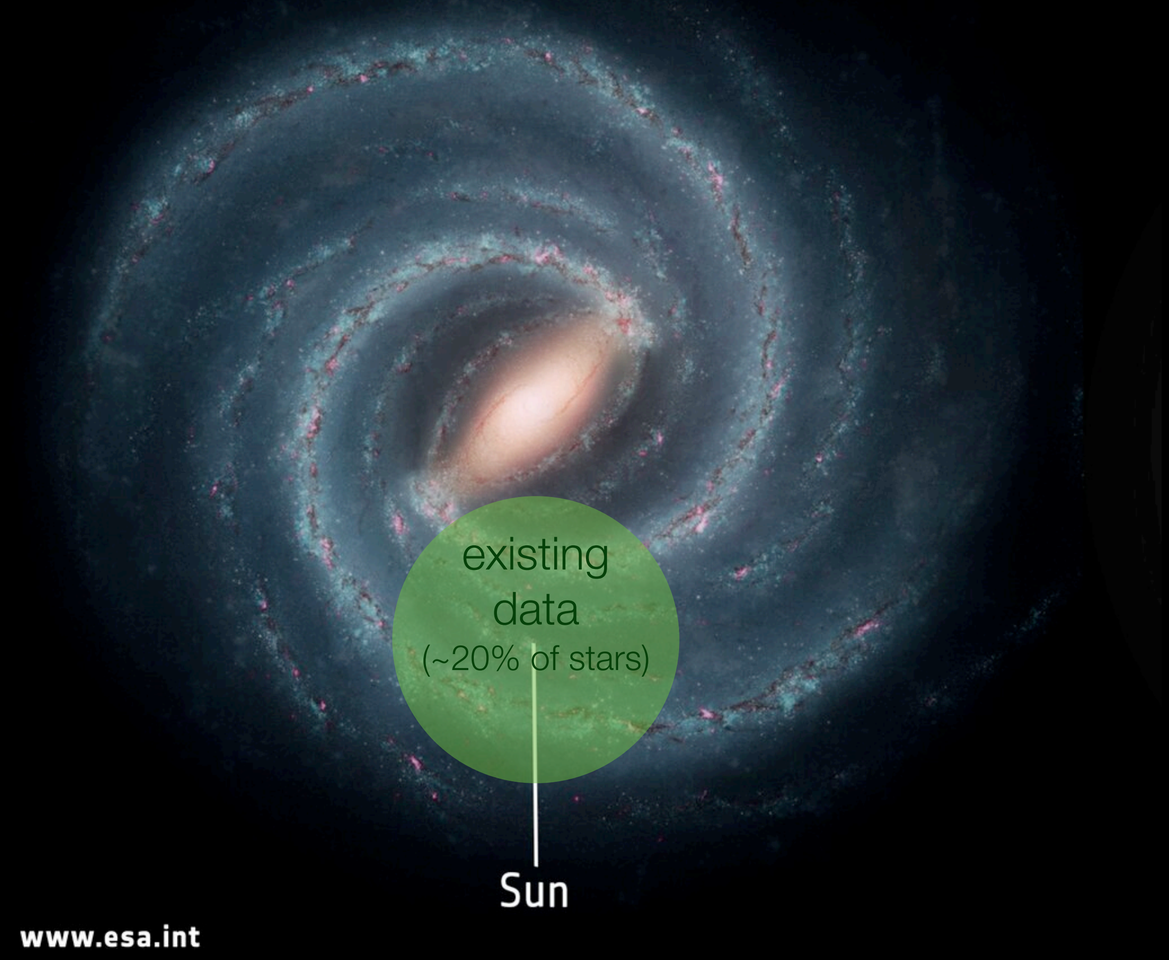

# Common-Envelope Evolution – Discovery Reach

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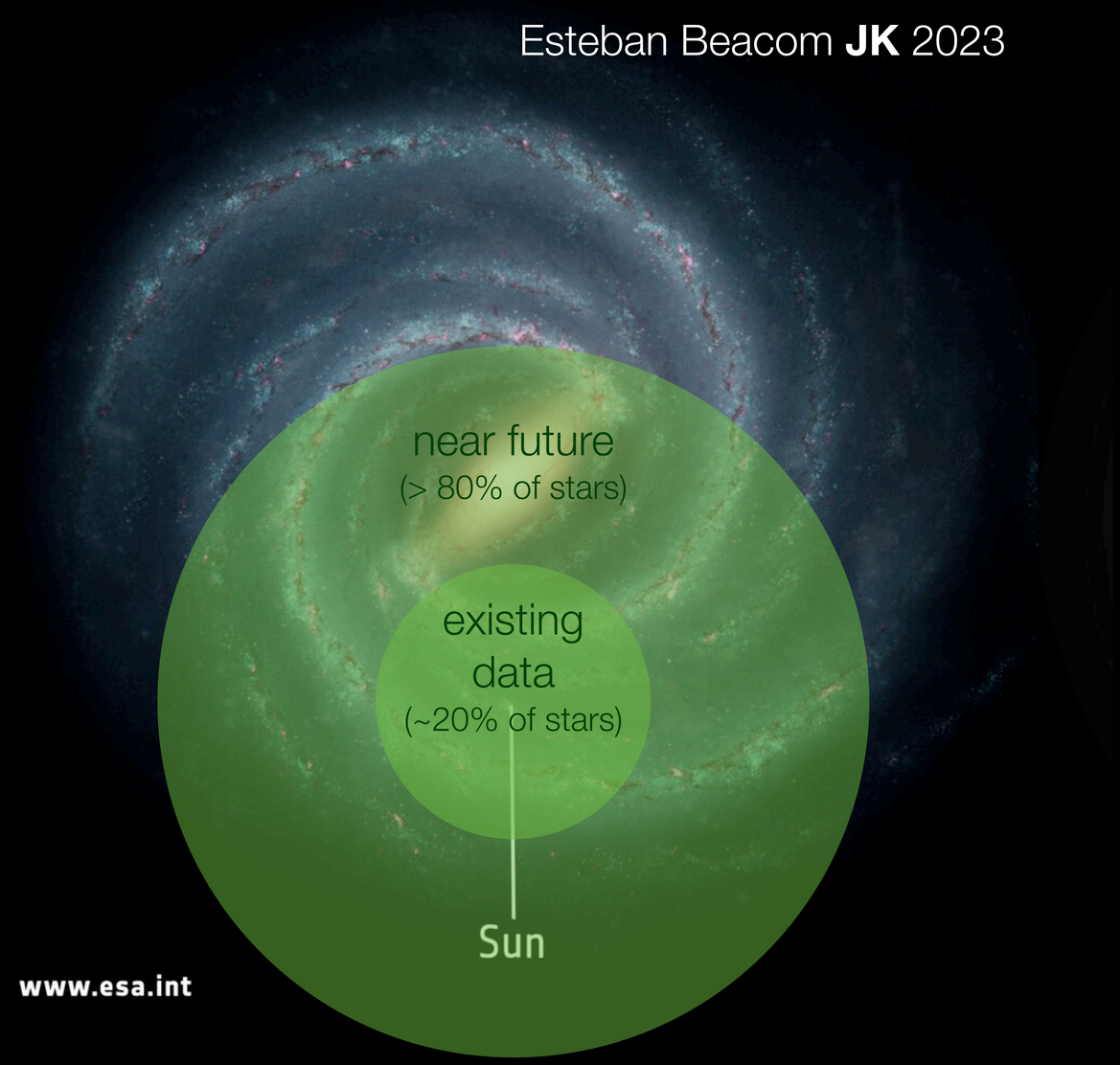

# Common-Envelope Evolution – Discovery Reach

- CEE detectable almost anywhere in our galaxy
- novel astrophysical neutrino source
- opportunity for discovery

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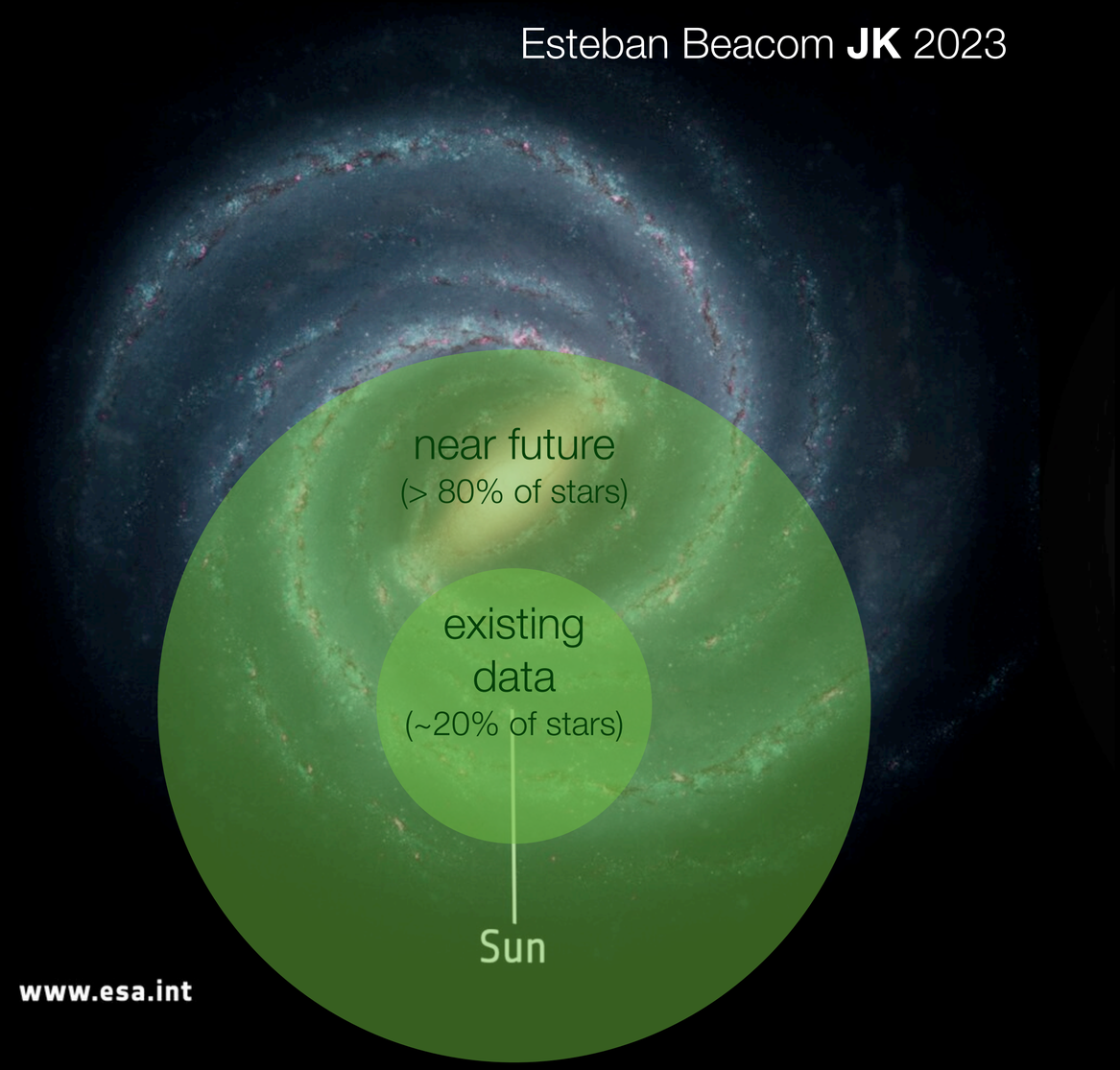

# Common-Envelope Evolution – Discovery Reach

- CEE detectable almost anywhere in our galaxy
- novel astrophysical neutrino source
- opportunity for discovery

**Future plans**

- deprotonization signal
- CEE with white dwarfs
- CEE with primordial black holes

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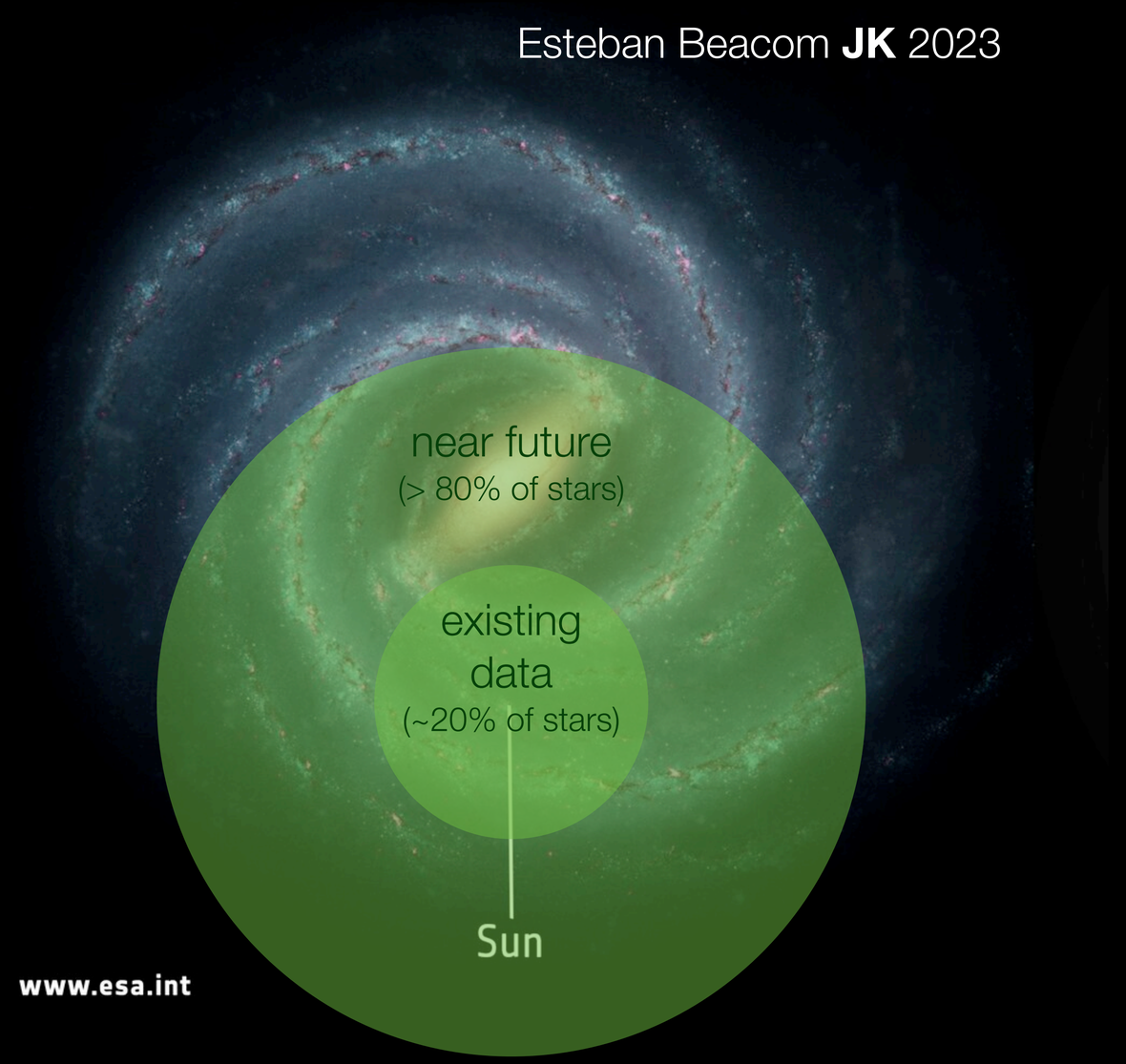


Thank You!
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