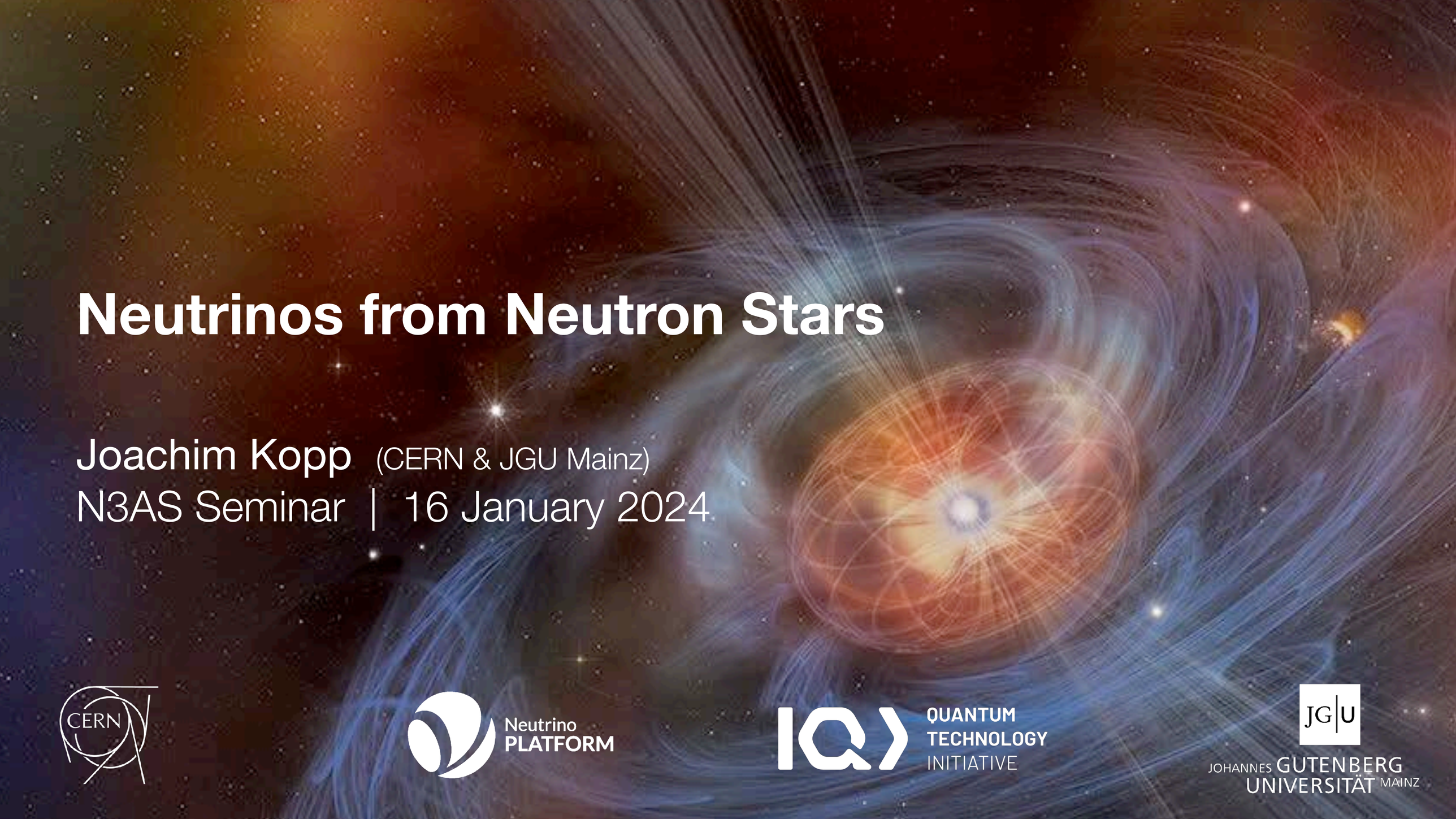


Neutrinos from Neutron Stars

Joachim Kopp (CERN & JGU Mainz)

N3AS Seminar | 16 January 2024

CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

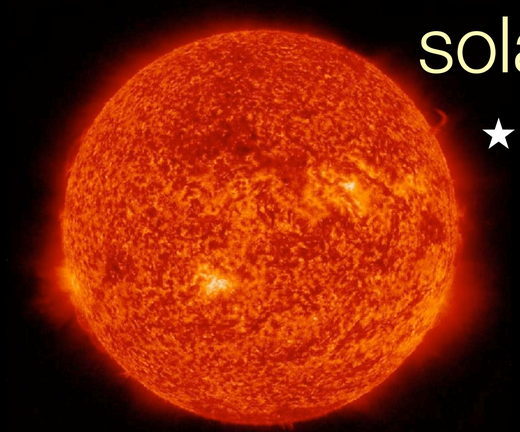
Neutrinos as Astrophysical Messengers

Neutrinos as Astrophysical Messengers

solar neutrinos

- ★ stellar evolution

Neutrinos as Astrophysical Messengers



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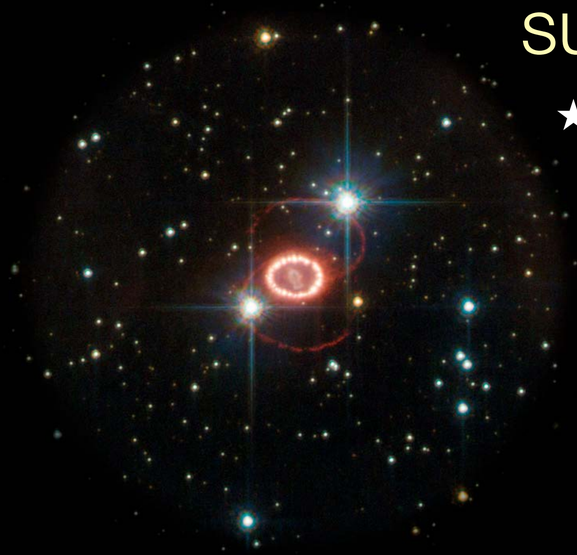

supernova neutrinos

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

Neutrinos as Astrophysical Messengers

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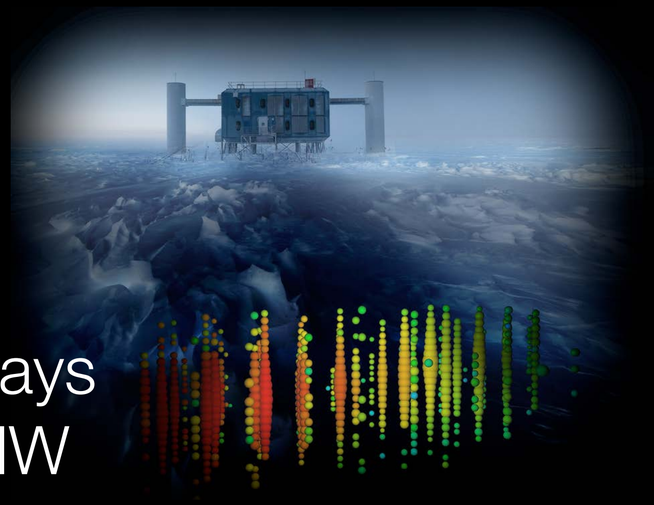
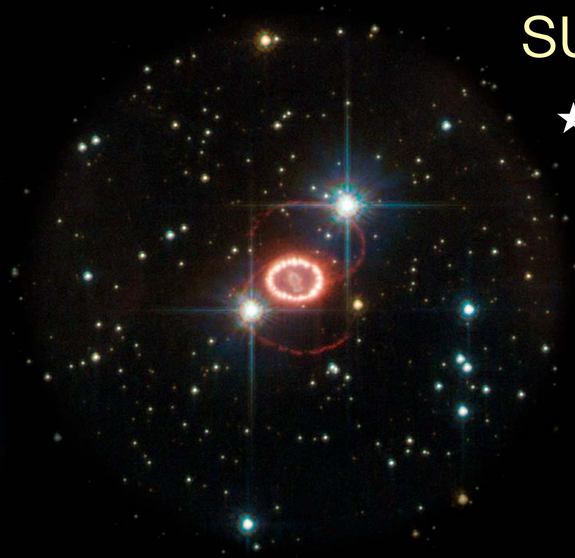


high-*E* neutrinos

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



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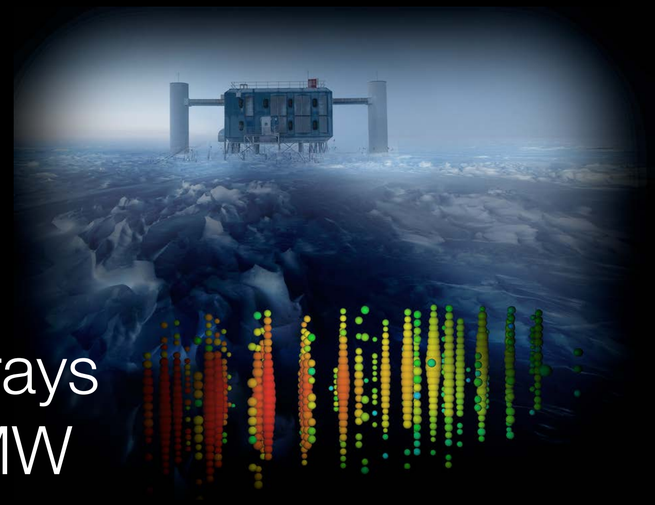

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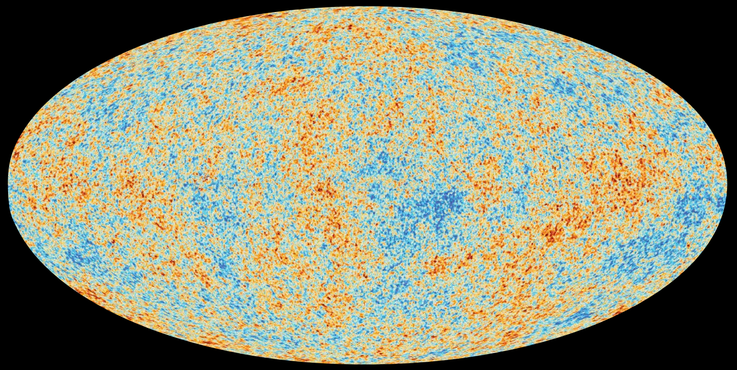
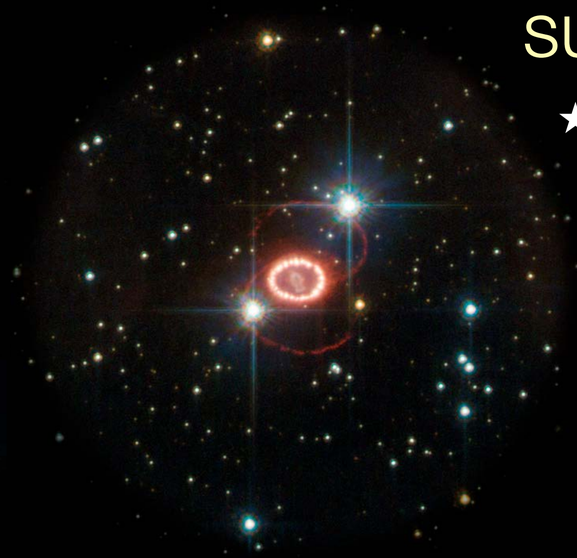


cosmology

- ★ early Universe



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Neutrinos as Astrophysical Messengers

solar neutrinos

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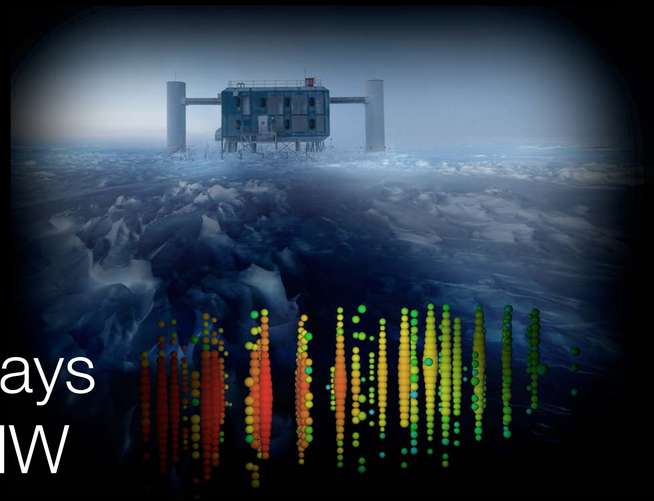

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★ origin of cosmic rays

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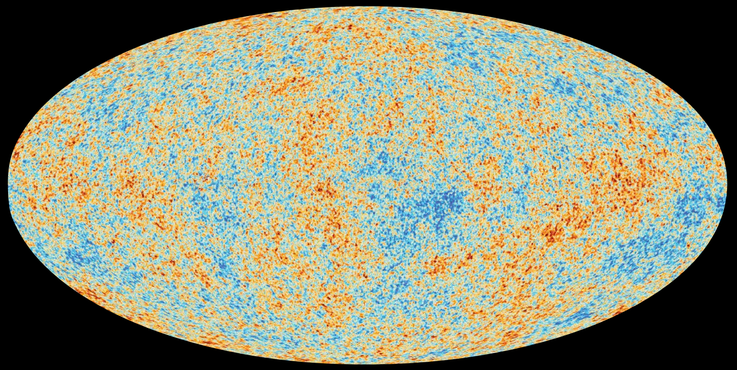

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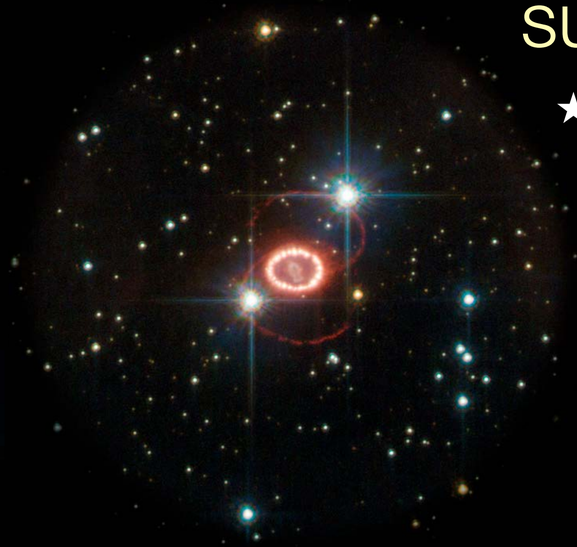


supernova neutrinos

★ death throes of massive stars

★ nucleosynthesis

★ matter under extreme conditions

neutron stars

★ Urca cooling

★ muon decays

★ common-envelope evolution

➠ THIS TALK

Neutron Stars

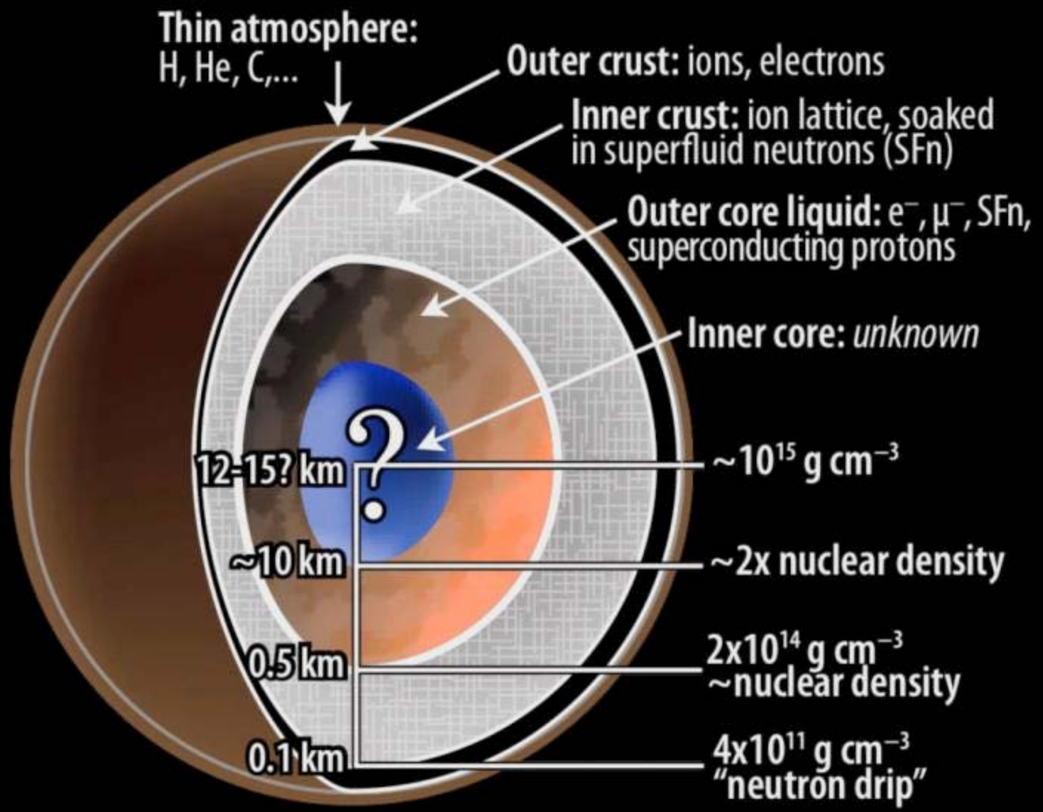
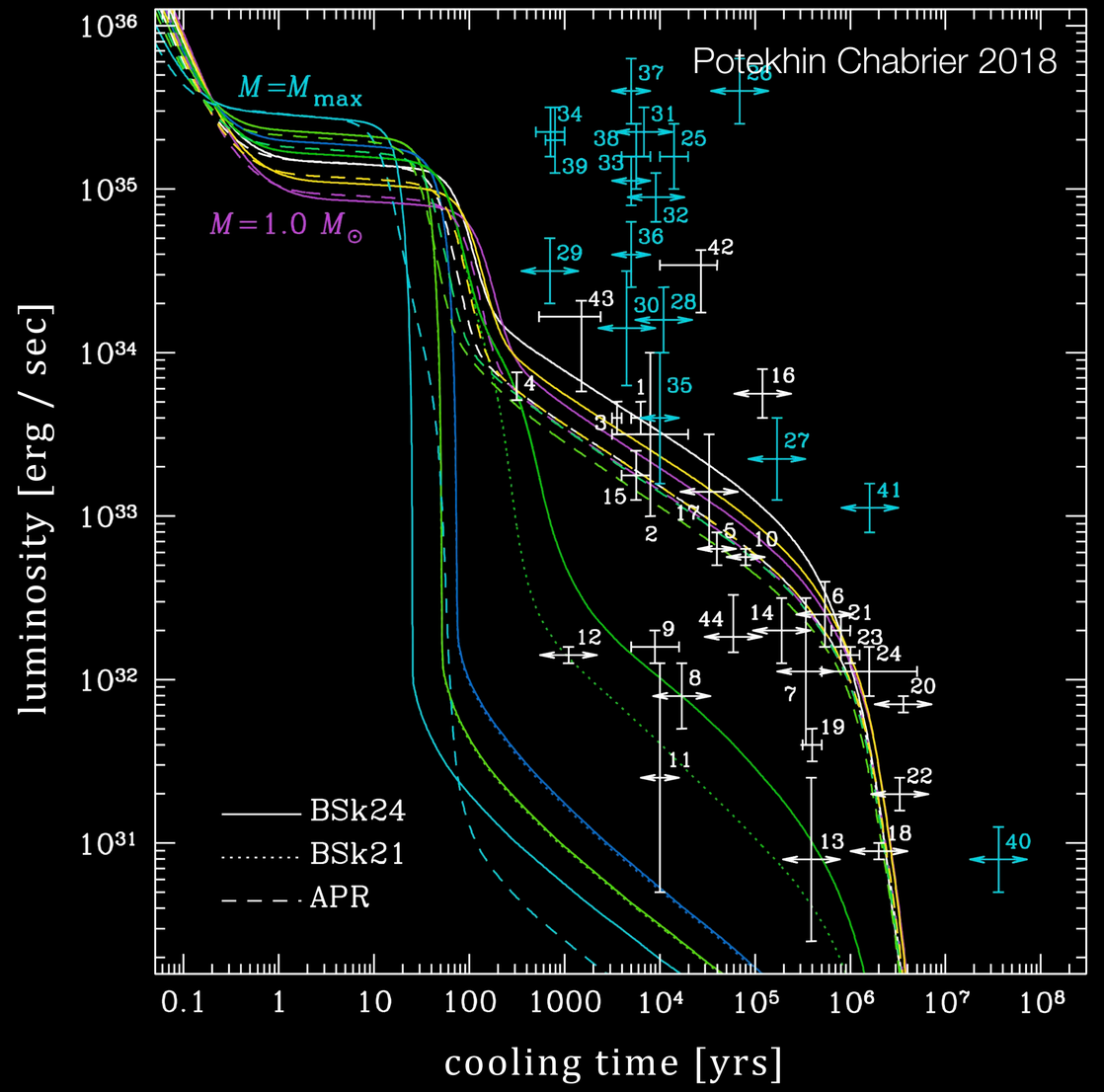
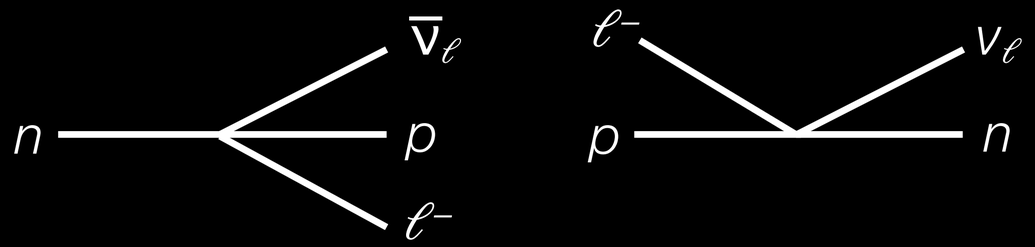


Image: Gendreau *et al.*

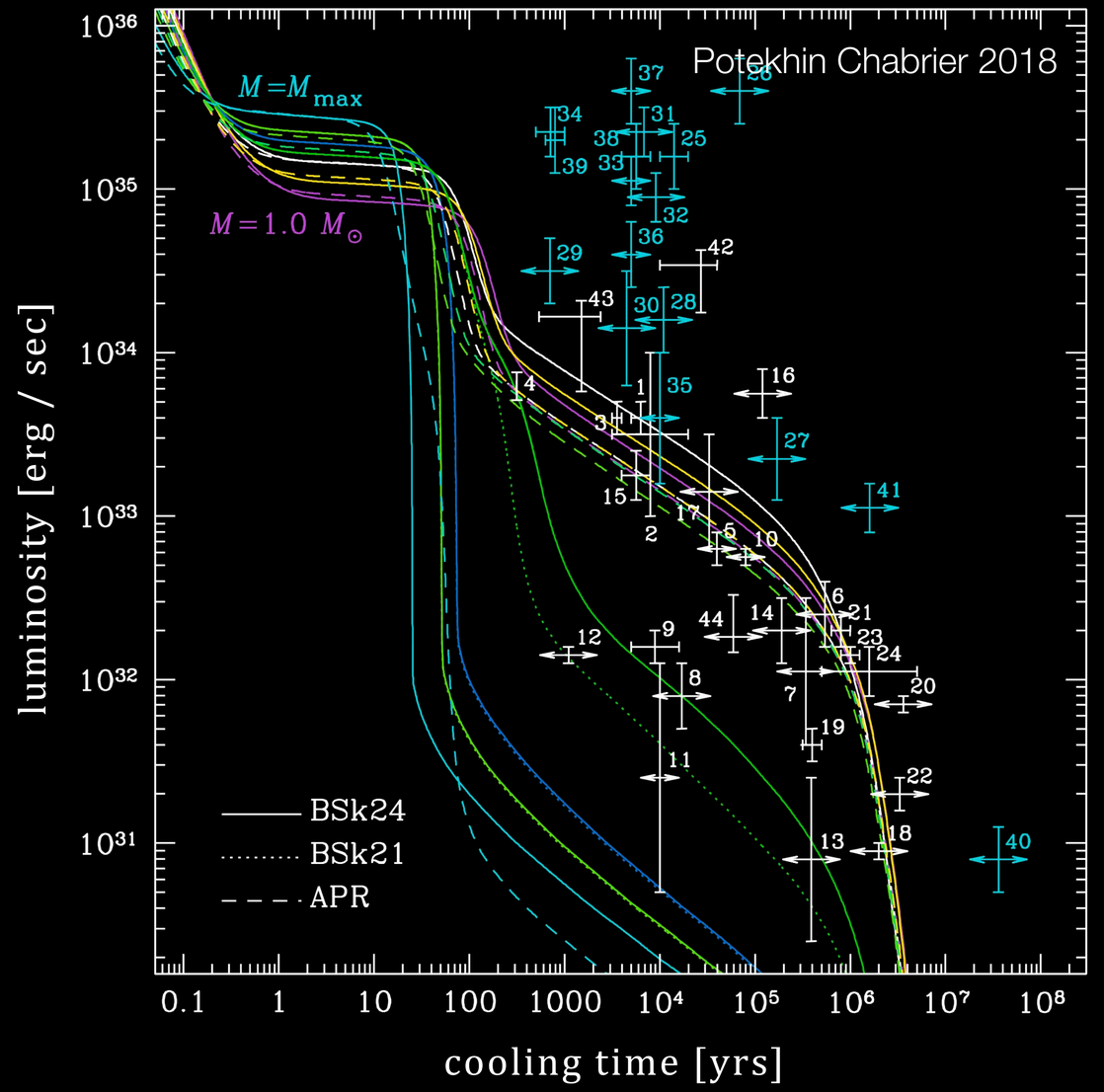


Neutrino Cooling

Direct Urca Processes



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



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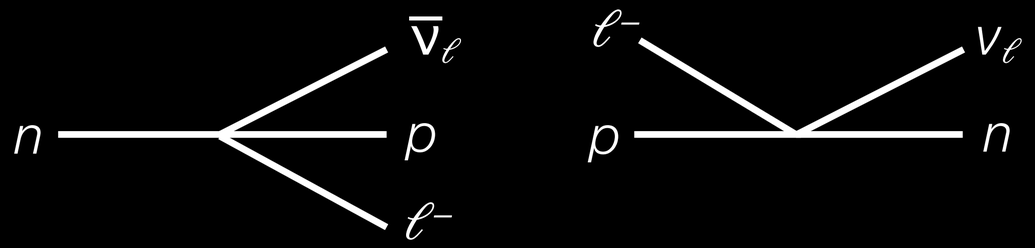

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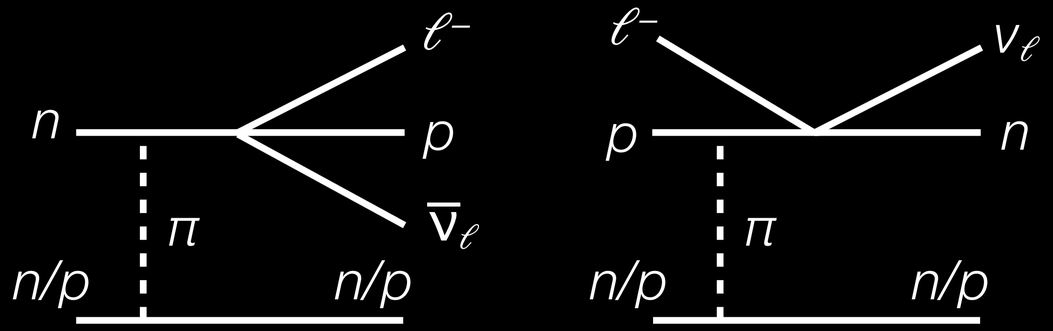
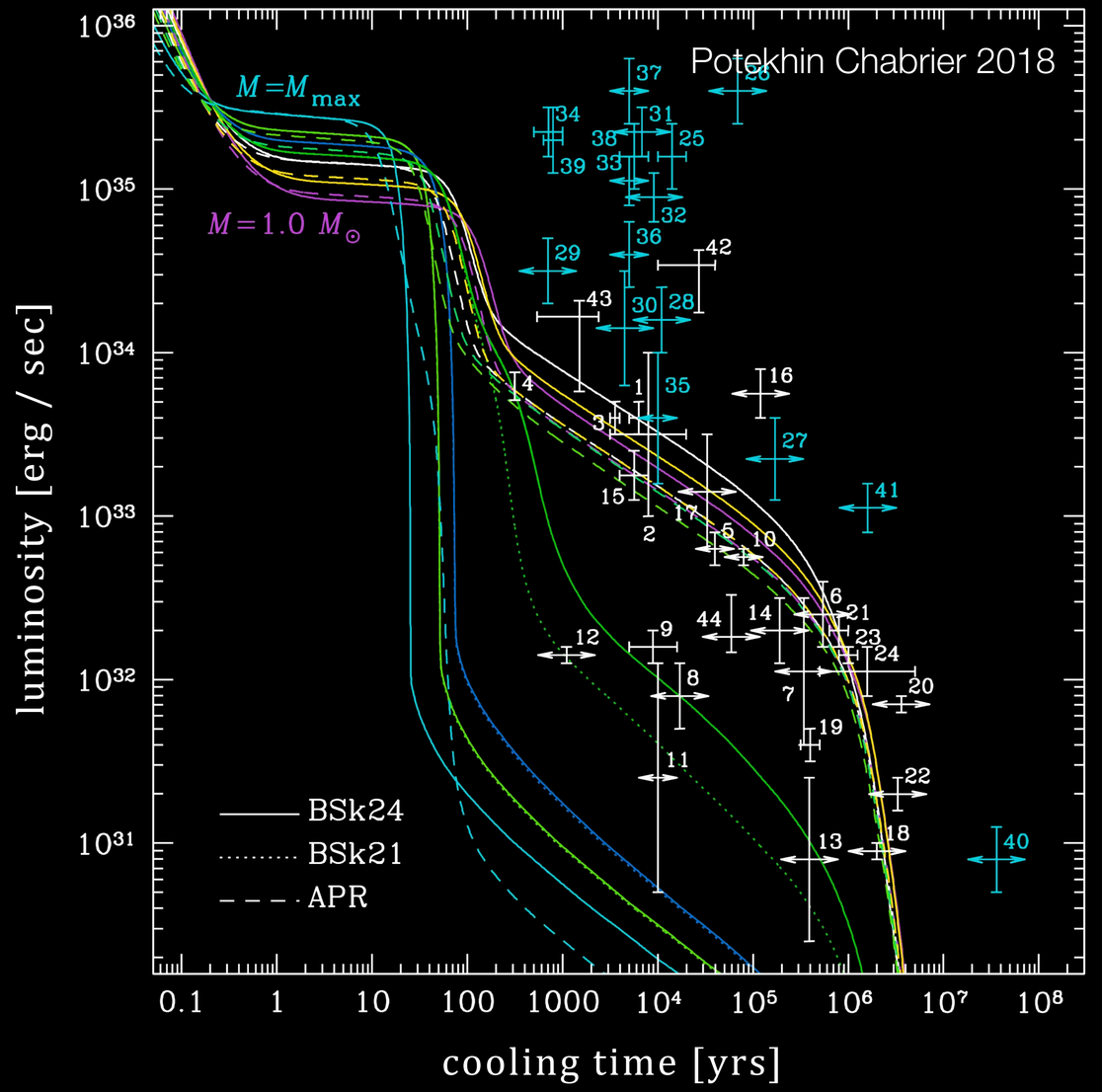


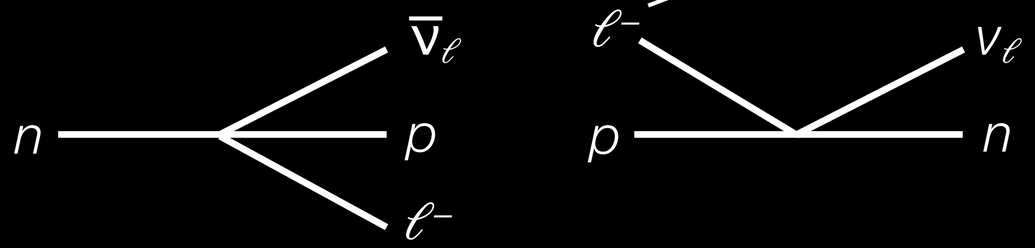
- allowed in all neutron stars



Neutrino Cooling

electron (e) or muon (μ)

Direct Urca Processes



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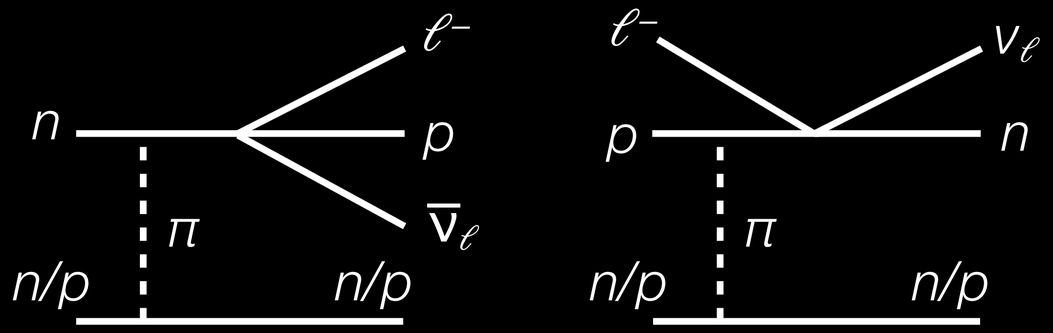

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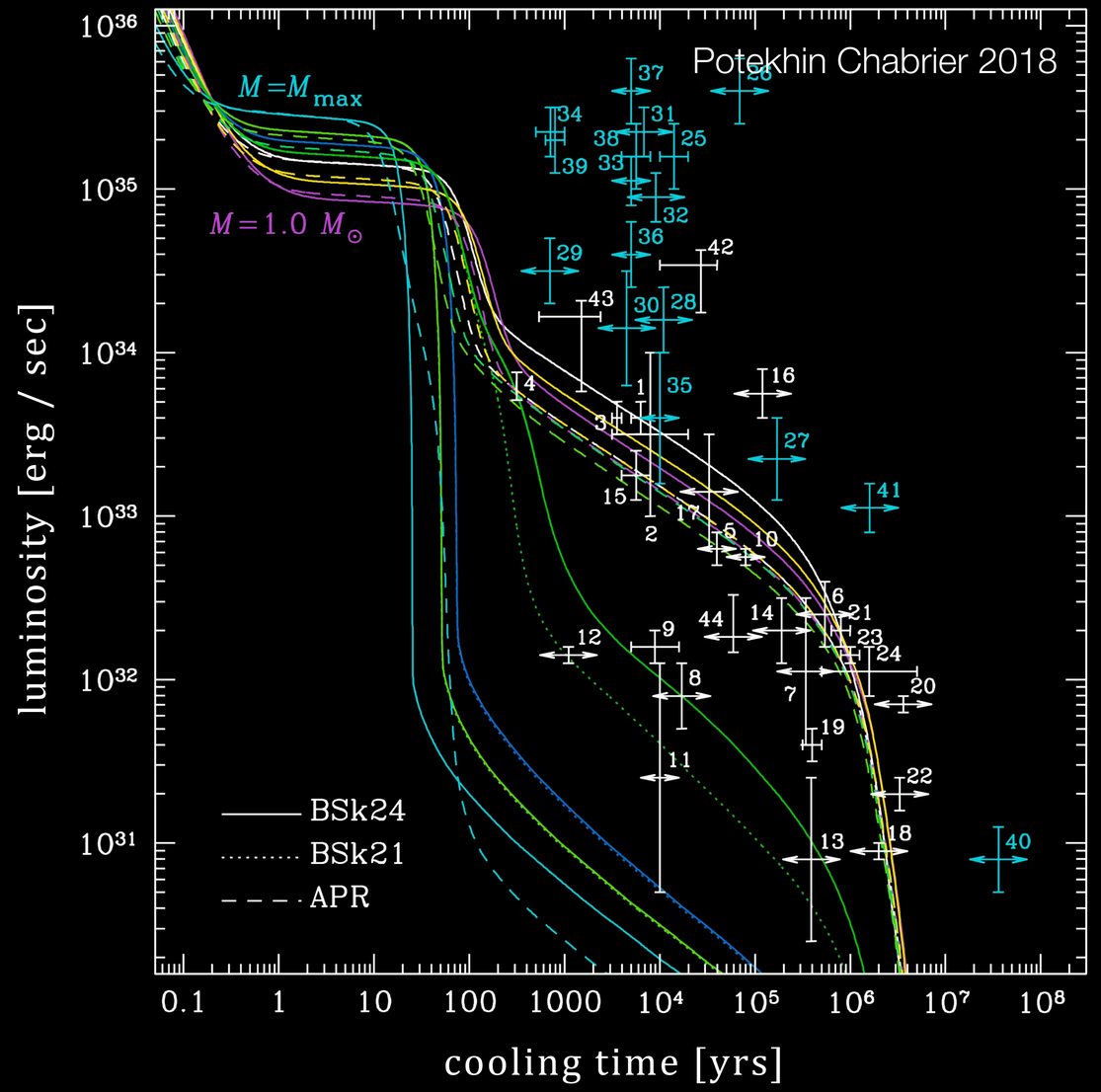
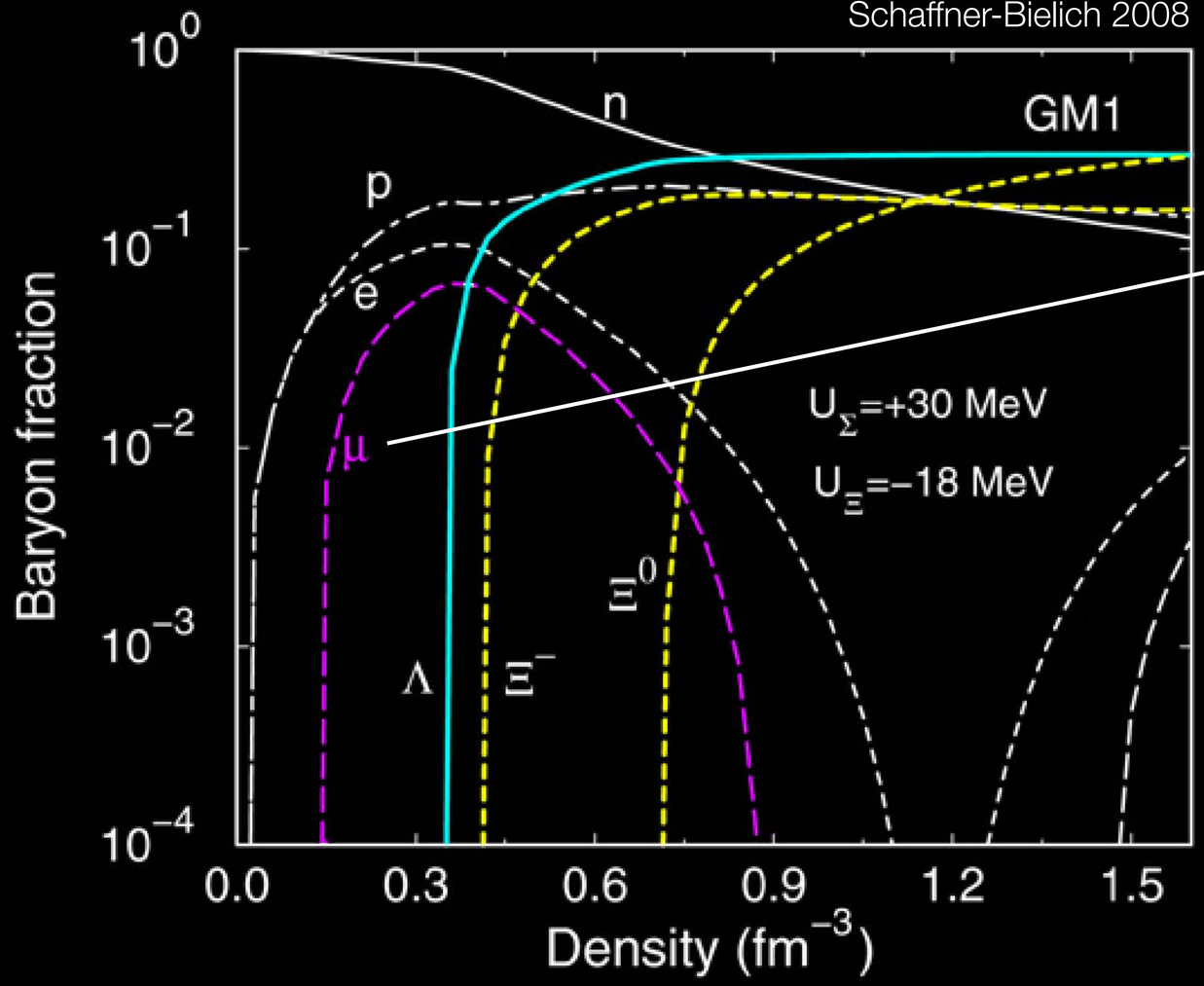


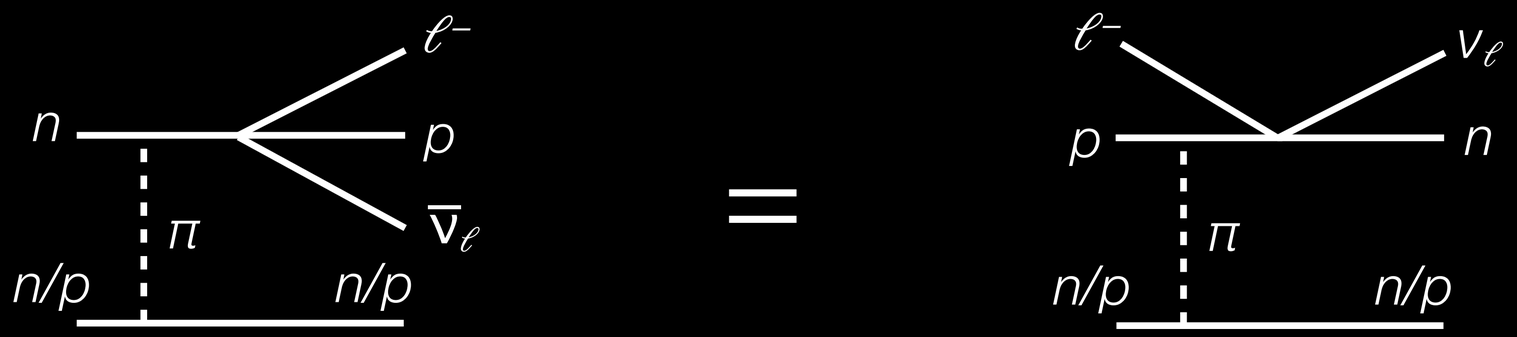
Muons in Neutron Stars

Schaffner-Bielich 2008



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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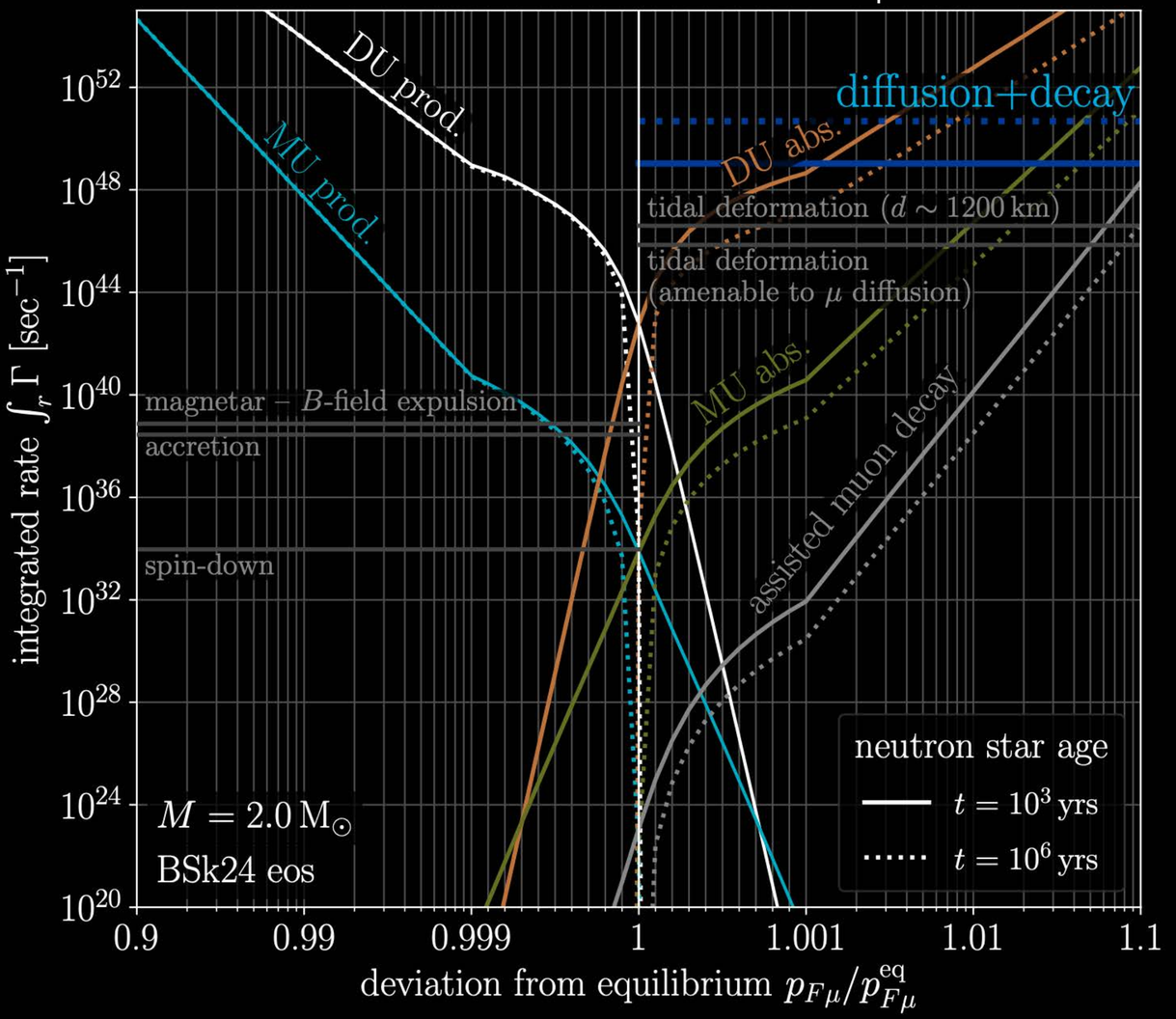

Departure from Equilibrium

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

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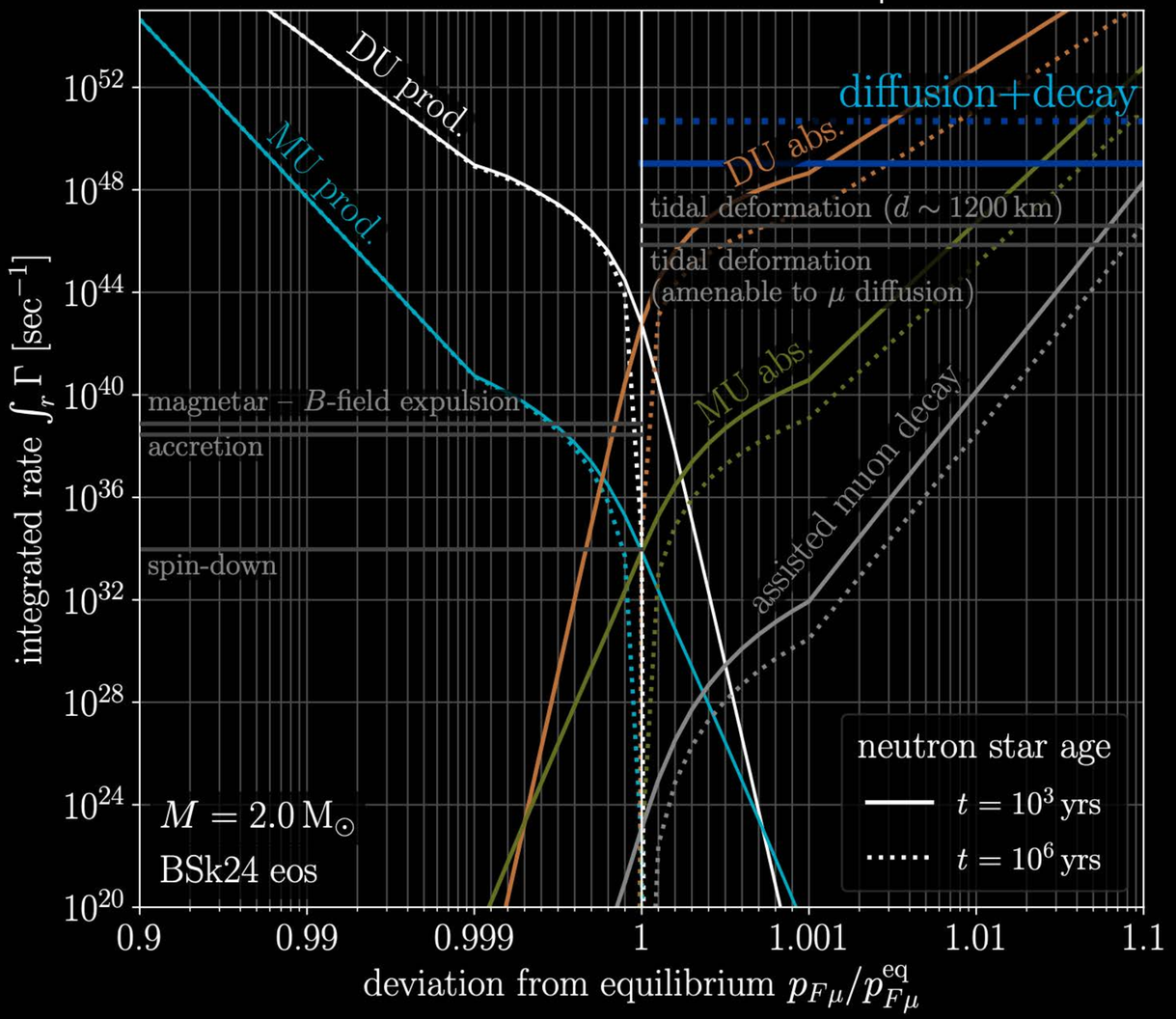

Departure from Equilibrium

Strategy for calculating rates

- apply Feynman rules + phase space integral + Pauli-blocking factors
- phenomenological parameterisation of nuclear matrix element
- neglect angular dependence of hadronic + leptonic matrix element
- treat nucleons as non-relativistic
- all momenta close to Fermi surfaces
- carry out angular integrals
- carry out energy integrals (multiple applications of residue theorem)

Friman Maxwell 1979
Yakovlev Levenfish 1995
Yakovlev Kaminker Gnedin Haensel 2000
Shapiro Teukolsky 1983

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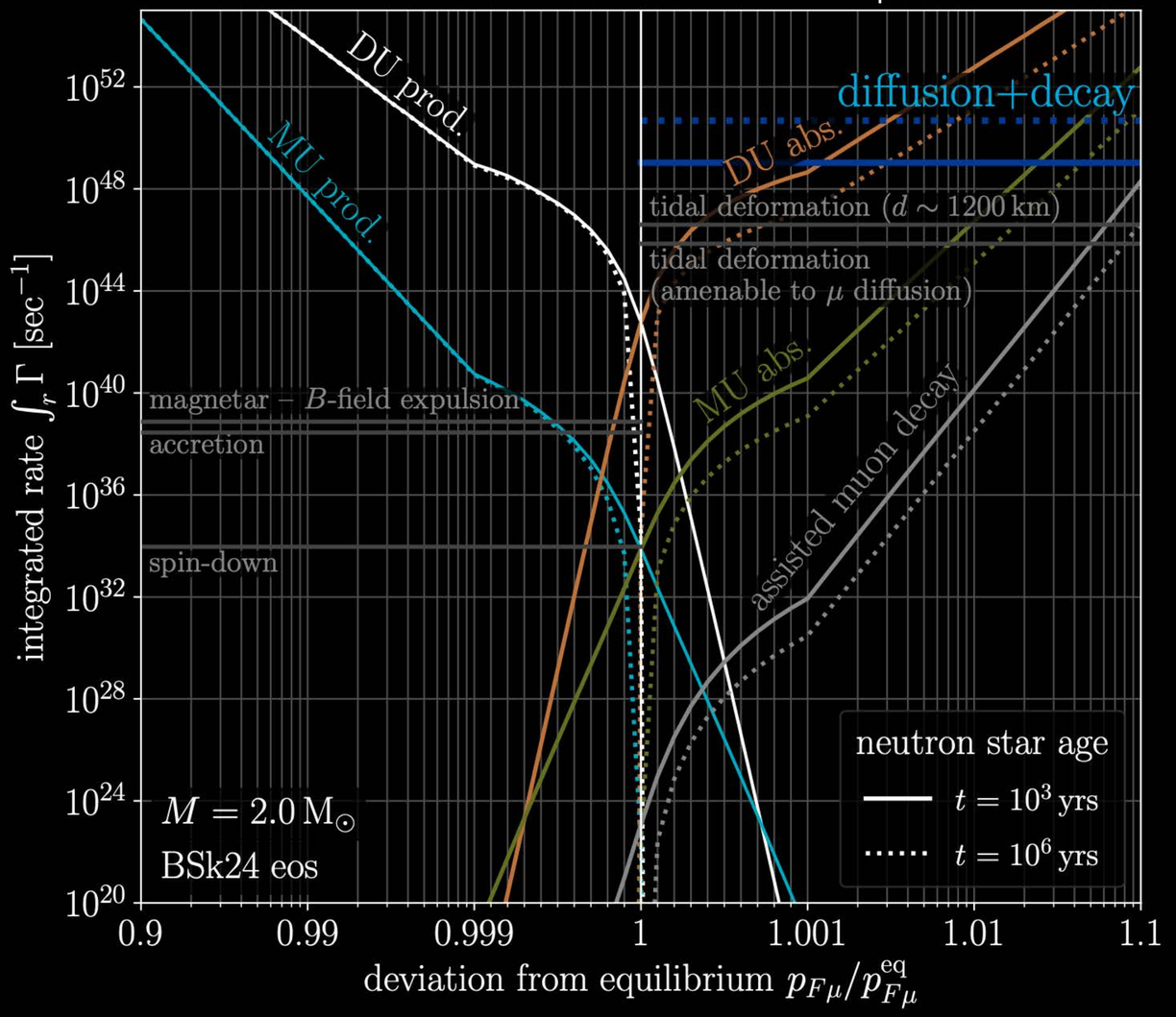

Neutrino Flux

Regular modified Urca (in equilibrium)

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

  Yakovlev Levenfish 1995

- E_ν ~ 10^9 K ~ 100 keV
- at 10 kpc: **38 cm^{-2} sec^{-1}**

➠ large flux, but low energy

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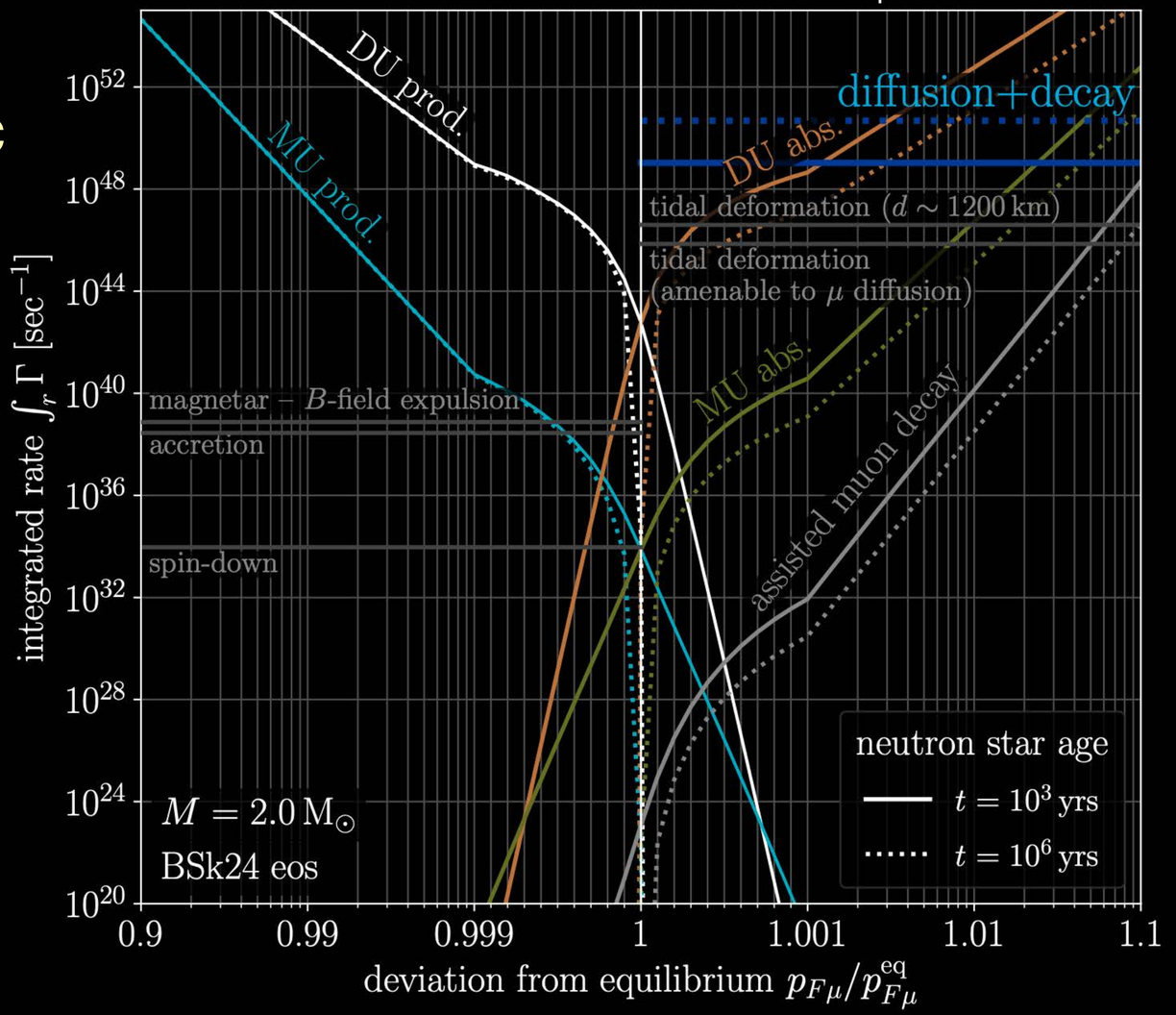

Neutrino Flux

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: ~ 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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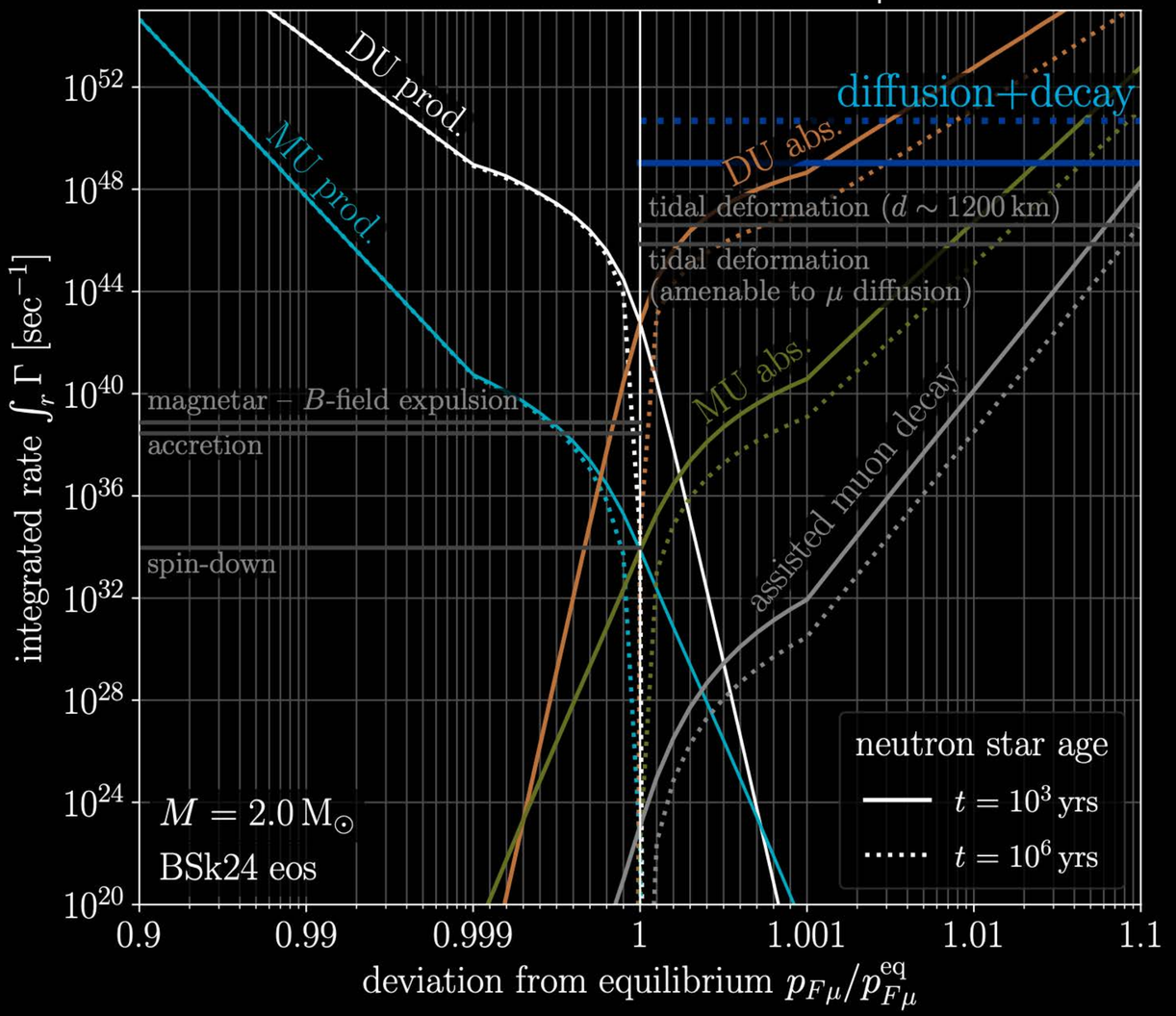
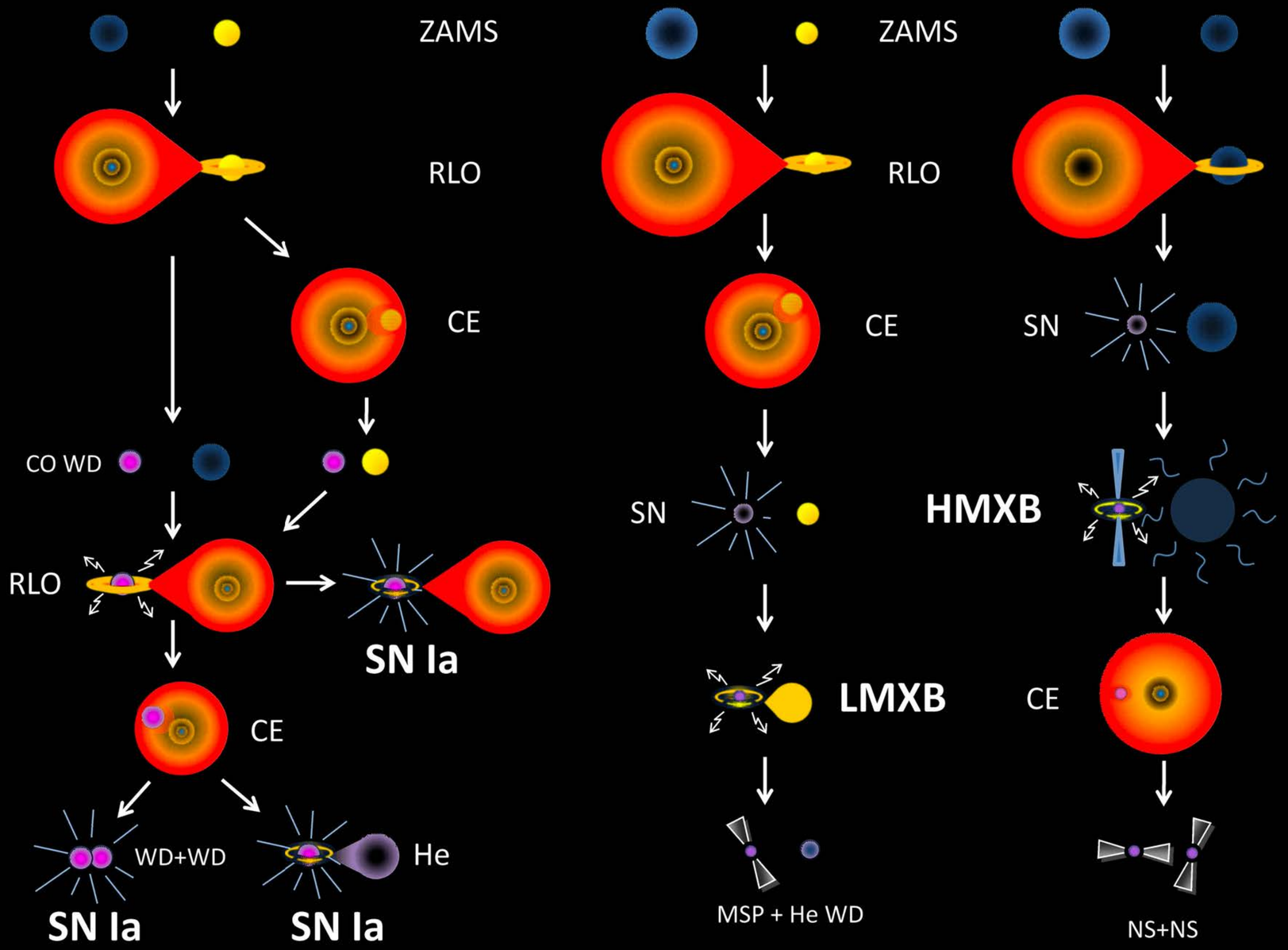


Common-Envelope Systems

Ivanova *et al.* 2012

Common-Envelope Evolution – Examples



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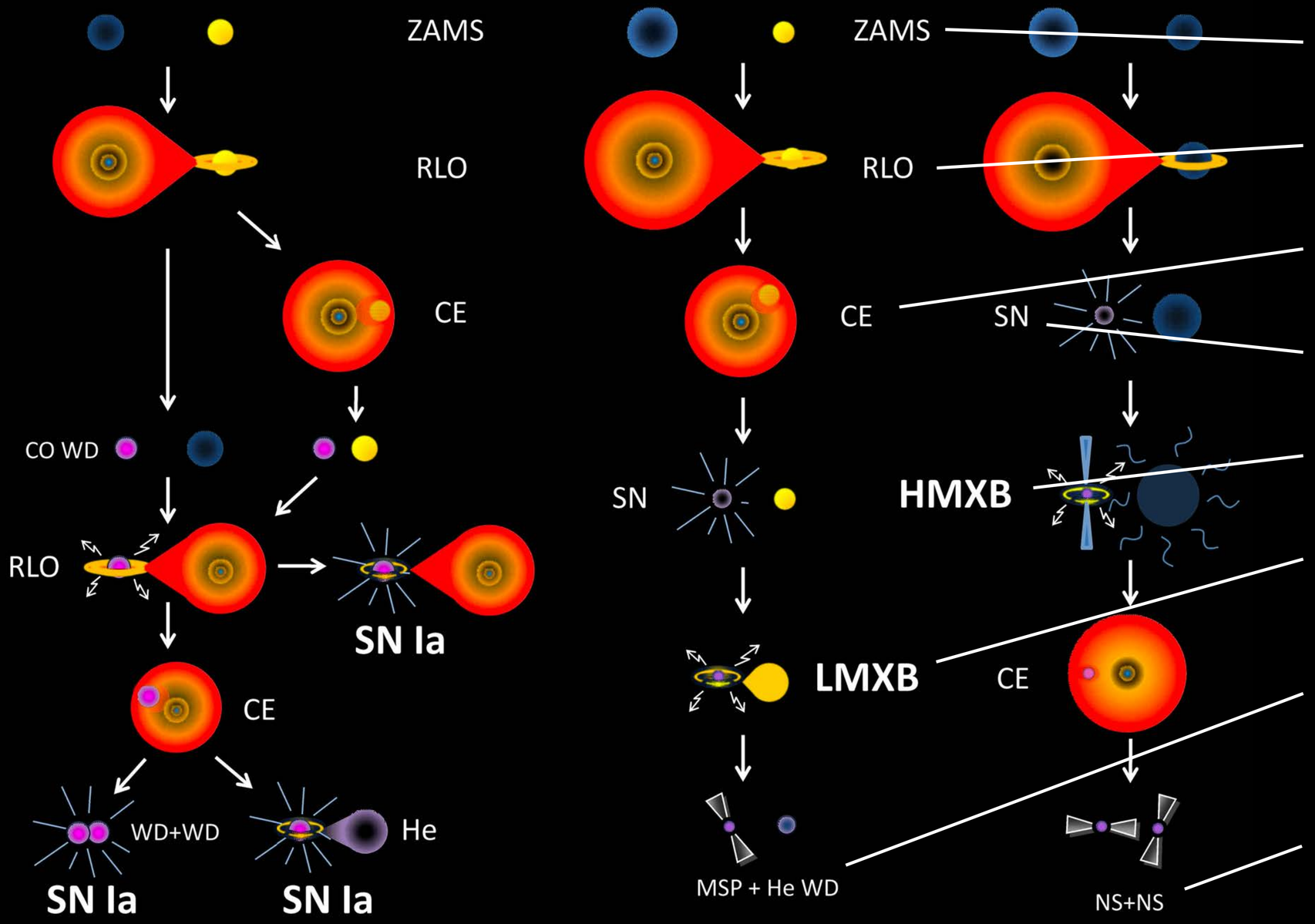


zero-age main sequence

Roche-lobe overflow

common-envelope evolution

supernova

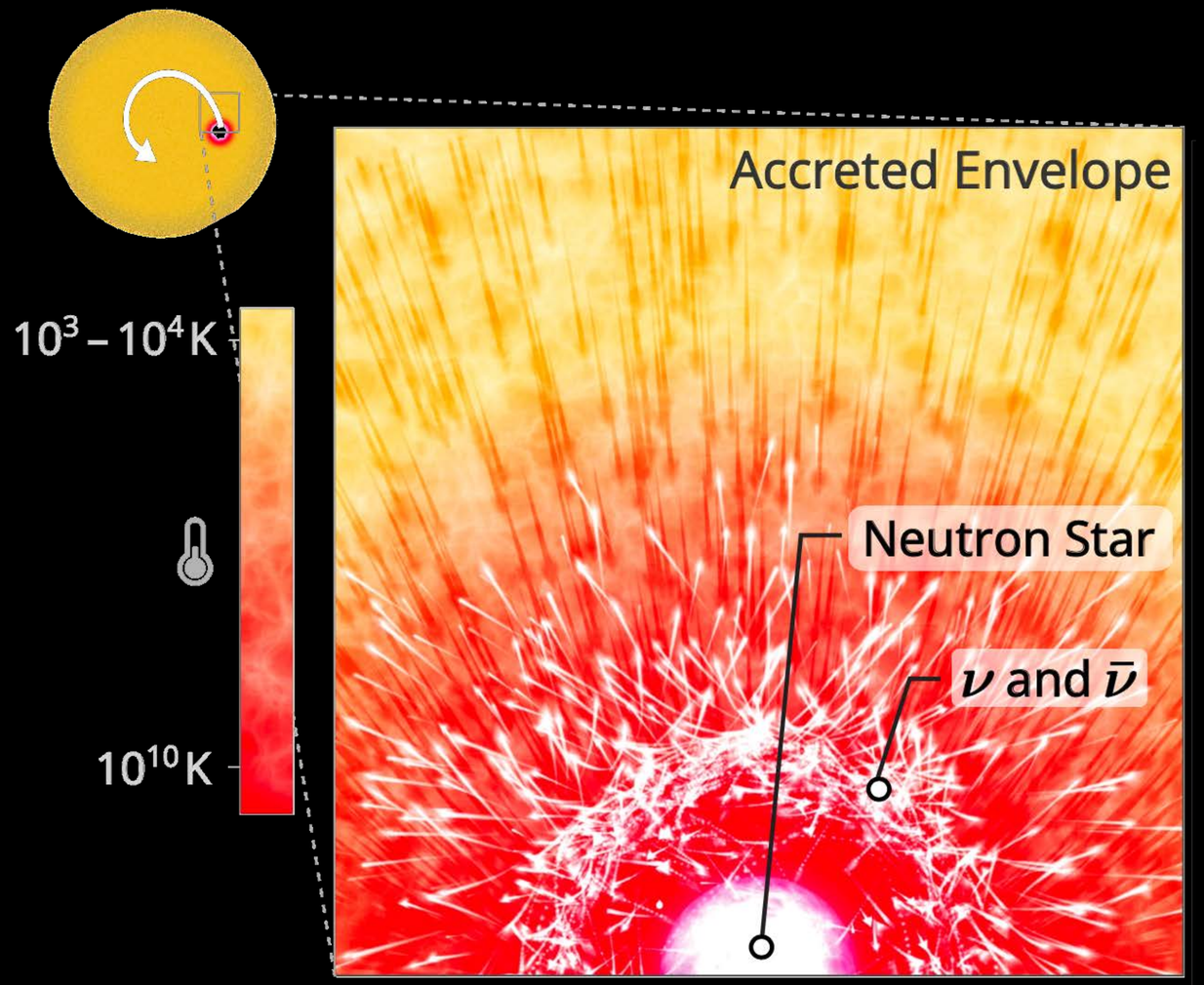
high-mass X-ray binary

low-mass X-ray binary

millisecond pulsar
+ He white dwarf

neutron star–neutron star
(or BH–BH) binary
potential GW source!

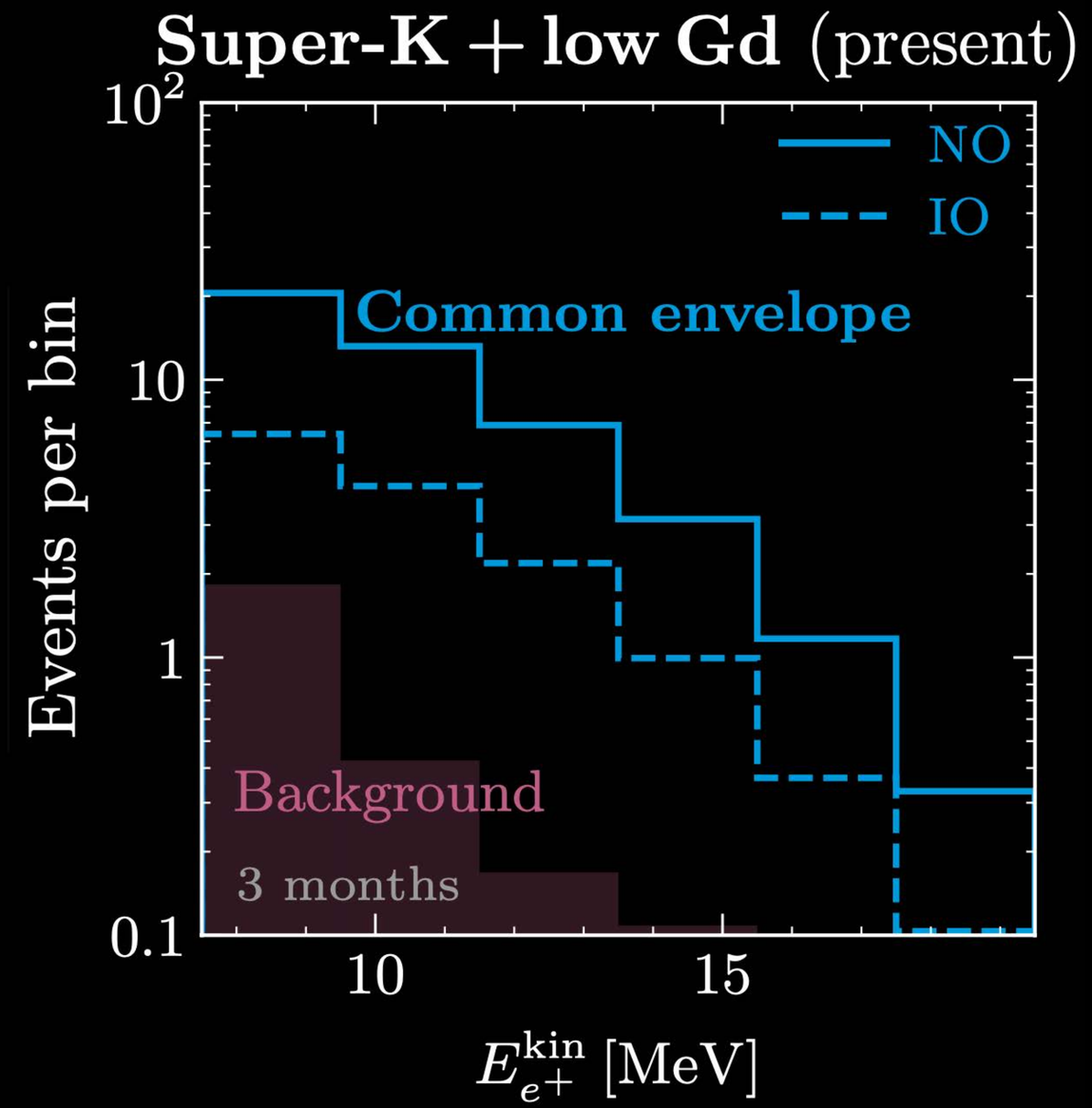
Common-Envelope Evolution – Neutrino Emission



- neutron star enters companion star
- gigantic accretion rates
  (up to 0.1 $M_\odot$/yr for several months)
- only cooling channel is via neutrinos
  ➠ new type of neutrino source
- in addition: de-protonization
- rate < core collapse SN rate

Esteban Beacom JK 2023

Common-Envelope Evolution – Neutrino Emission



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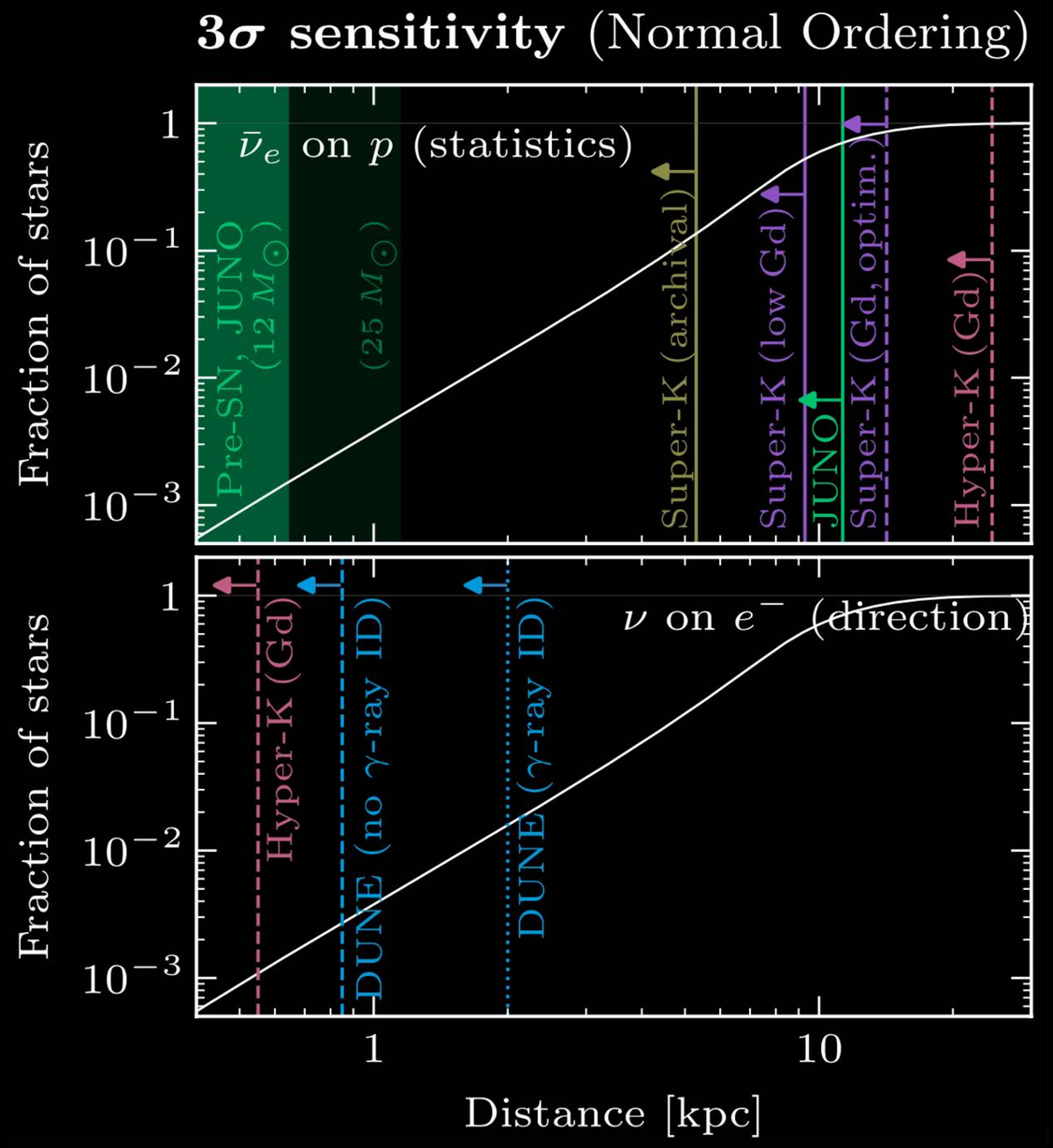

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Thank You!
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