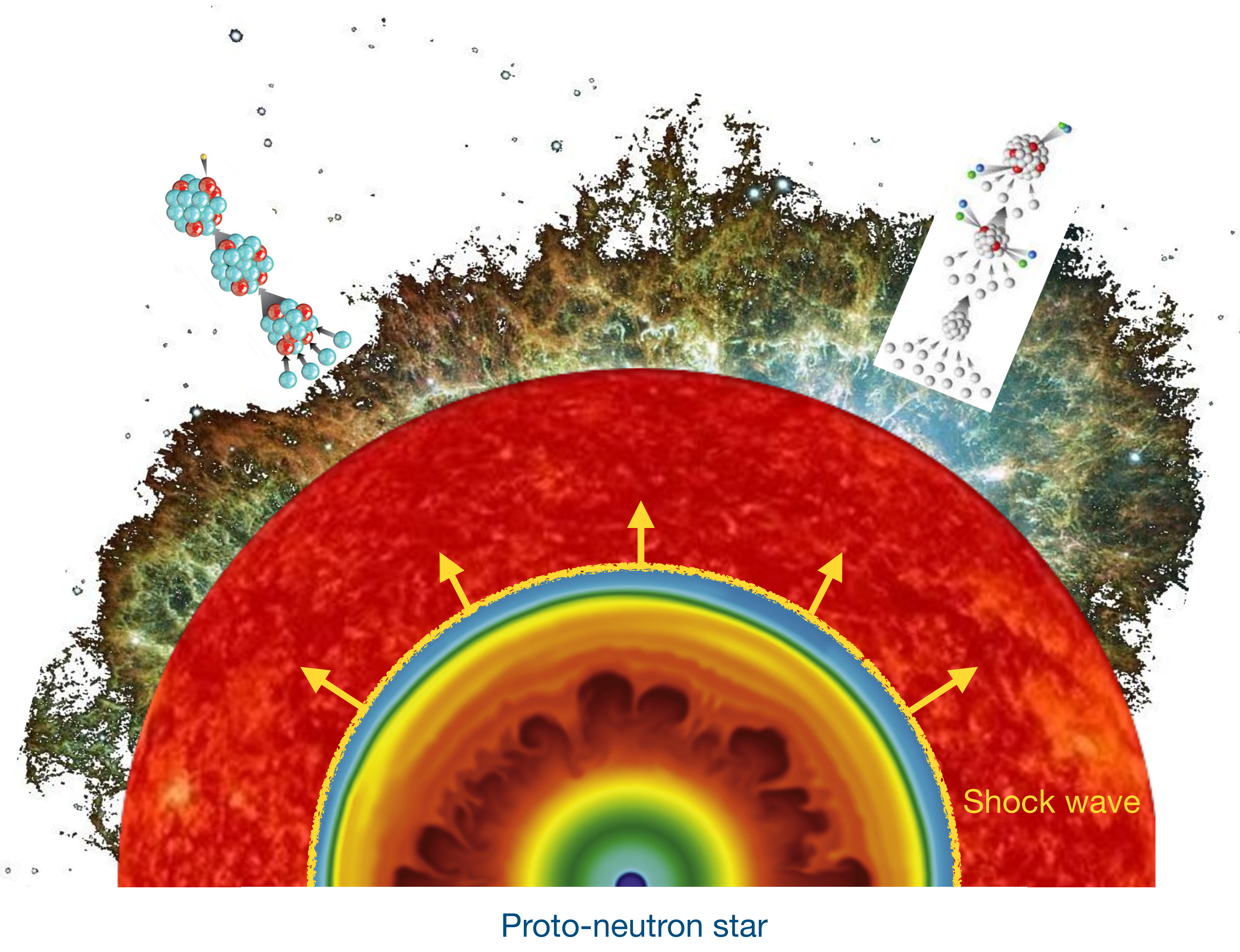
Teaming up for supernova discovery

Exploiting synergies between neutrino experiments for the next galactic core-collapse supernova

M. Bendahman, A.C. Buellet, M. Bugli, J. Coelho, A. Coleiro, J. Dawson, V. van Elewyck, S. El Hedri, T. Foglizzo, D. Franco, I. Goos, J. Guilet, A. Kouchner, J. Novak, M. Oertel, T. Patzak, S. Sacerdoti, A. Tonazzo, C. Volpe, G. de Wasseige (LEAK collaboration)

Core-collapse supernovae

Extreme, complex, and not-fully-understood phenomena



- End of life of a heavy star (> 8 solar masses)
- Collapse of the core of the star: explosion or black hole formation
- Nucleosynthesis of heavy elements, key role in star formation
- Conditions for explosion not fully understood

  ⇒ Need to observe the core of the star

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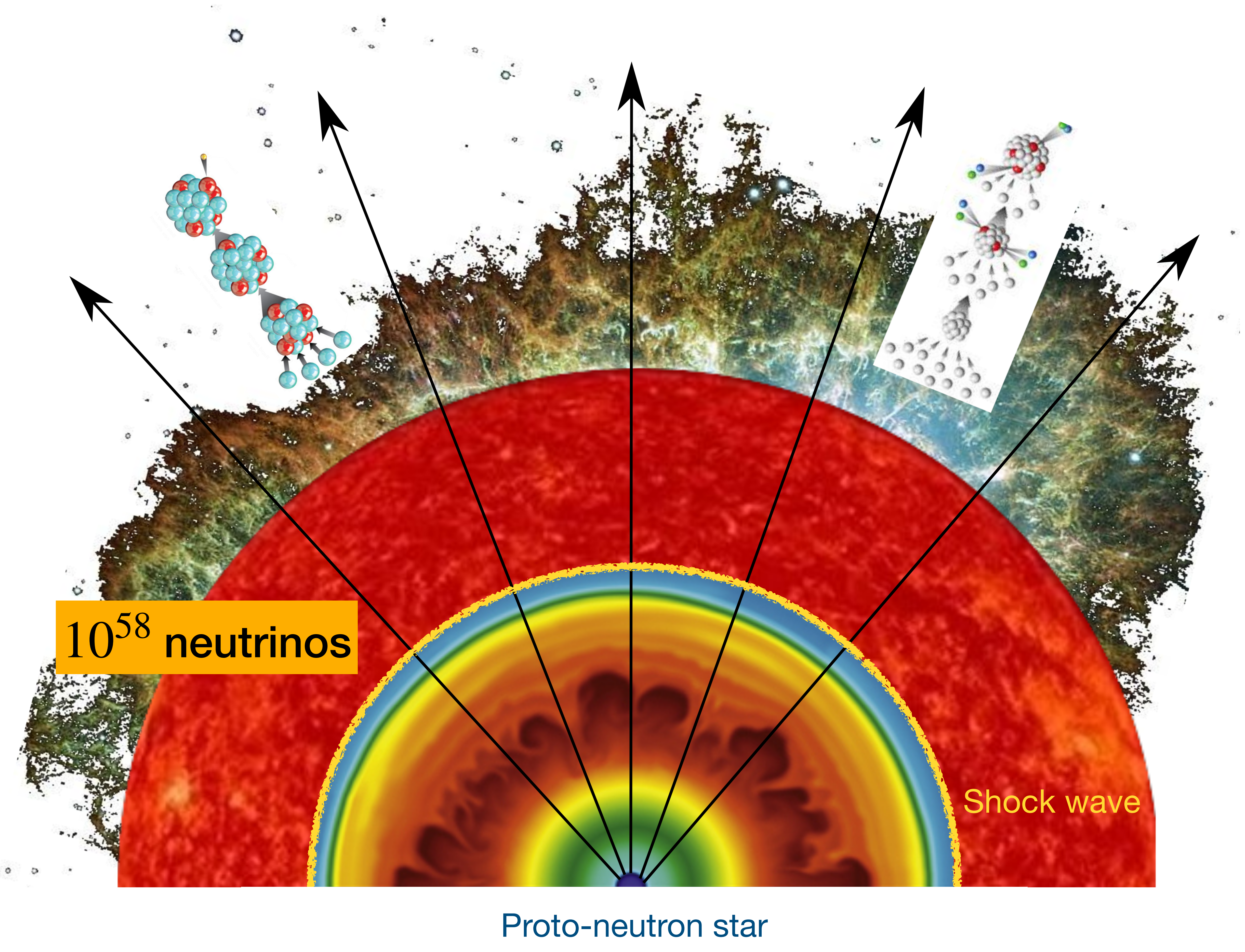

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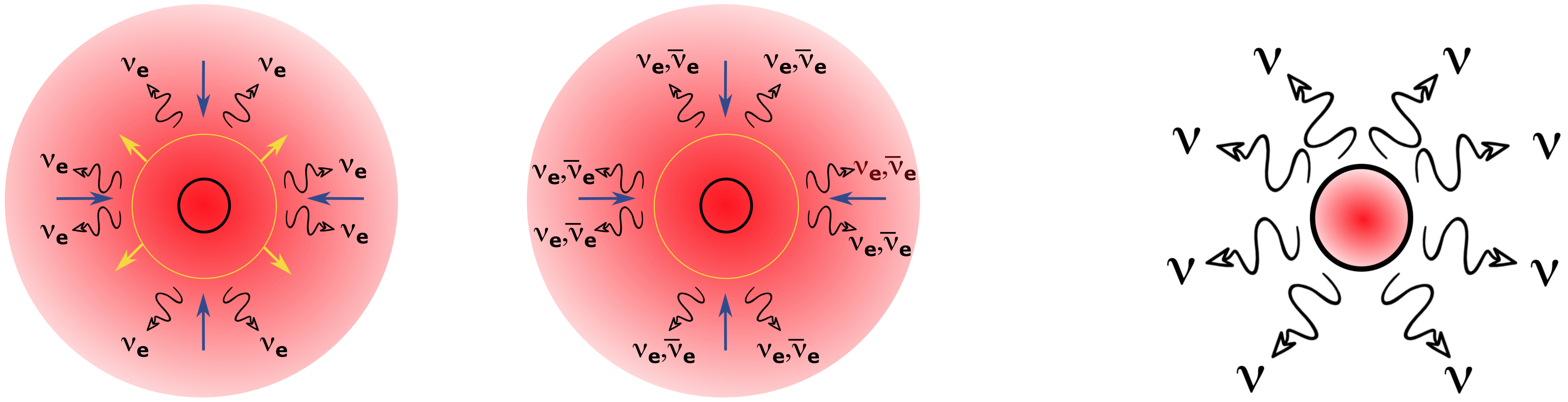
Supernova neutrinos

A first-hand account of the core-collapse process



H. T. Janka [arXiv:1702.08713]

- **Complementary** information from the different **flavors**
- **Advance warning** for telescopes + **analysis window** for gravitational wave detectors

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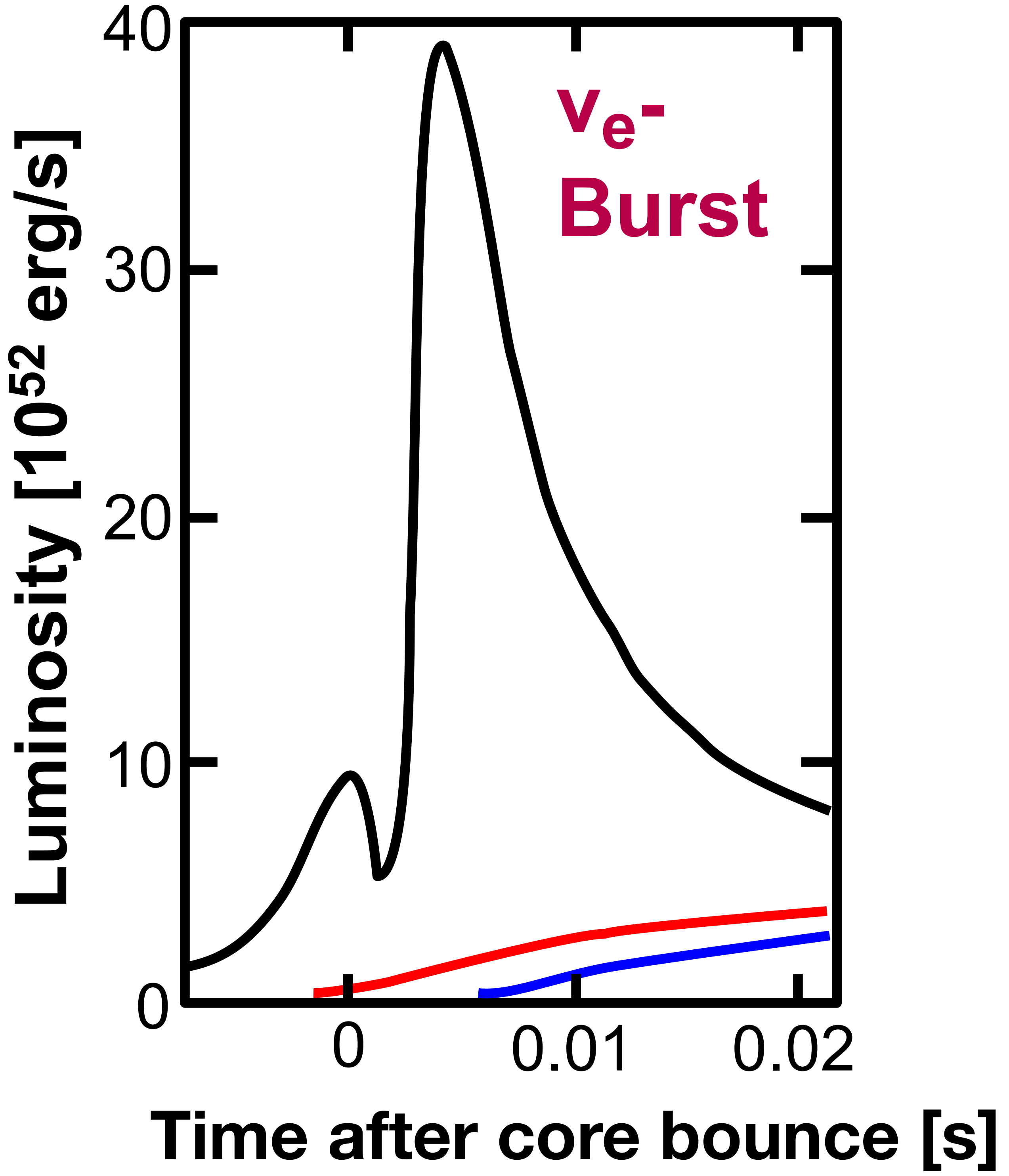

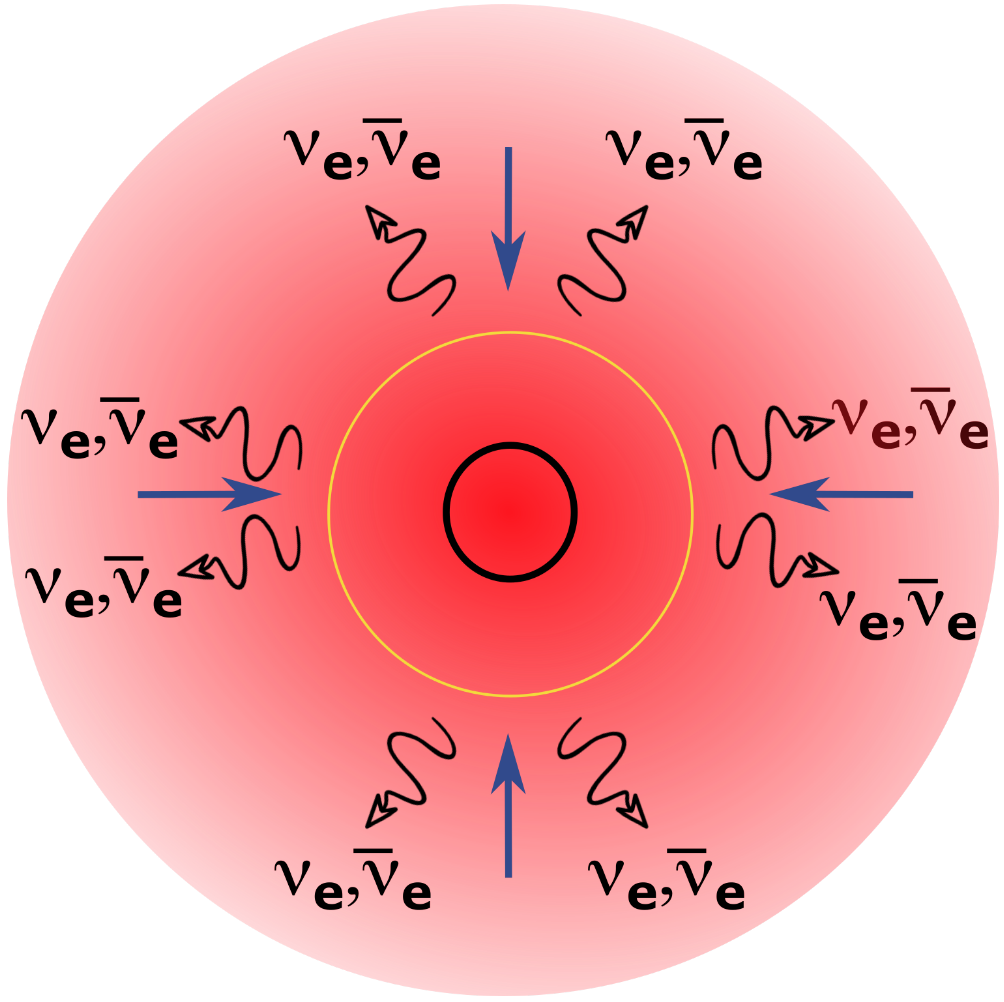

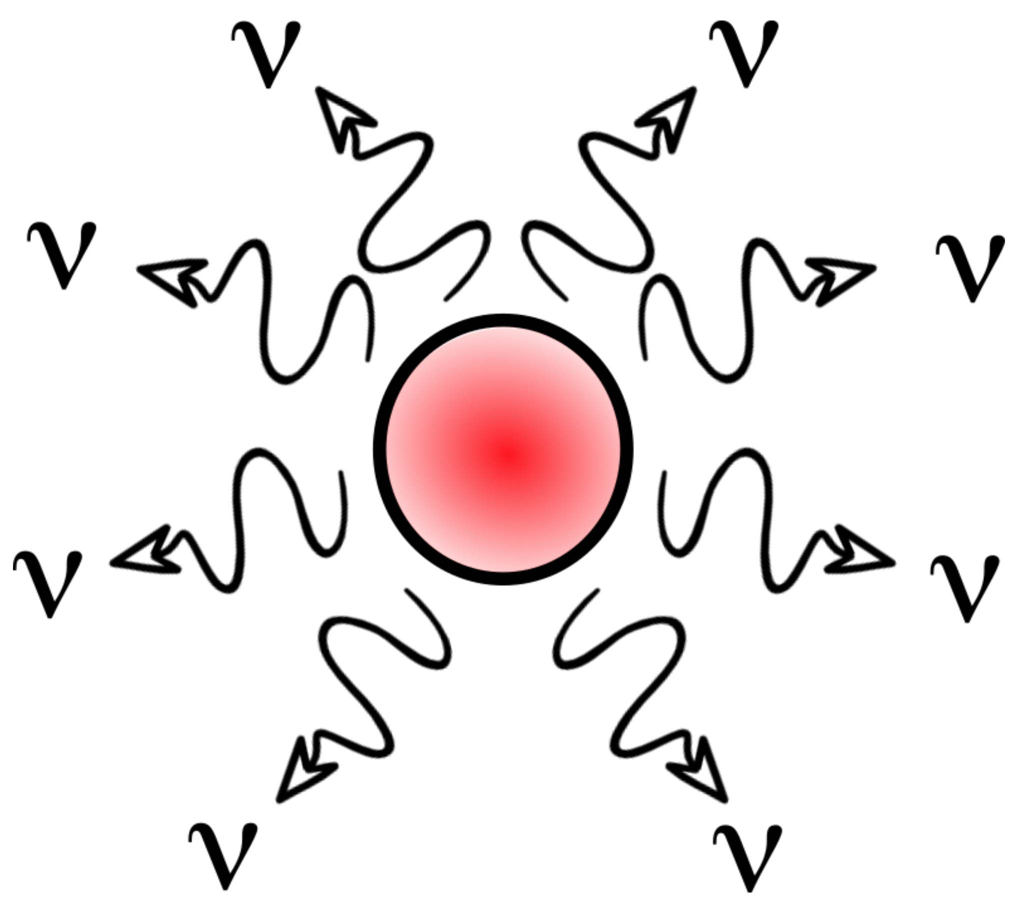

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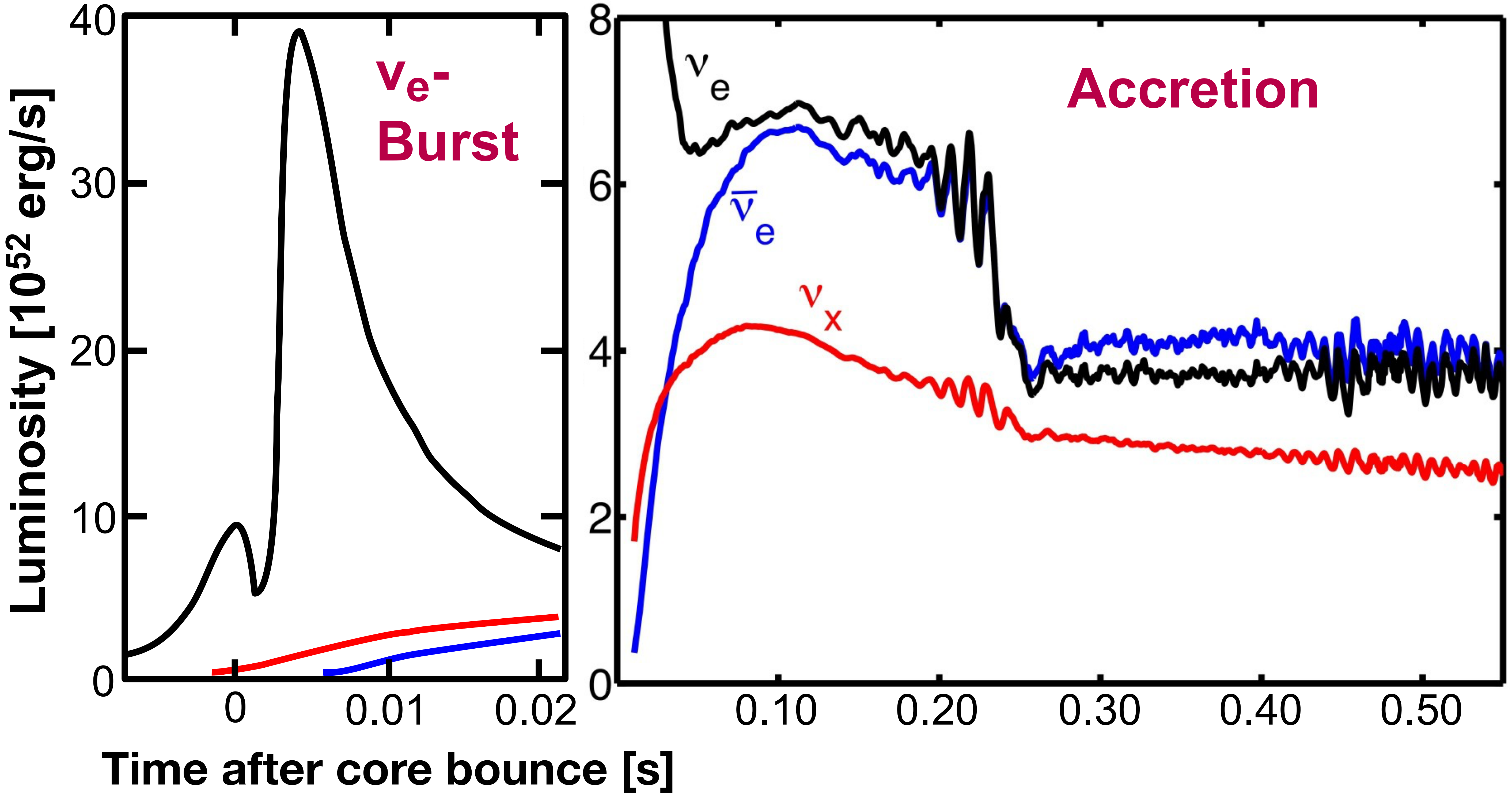

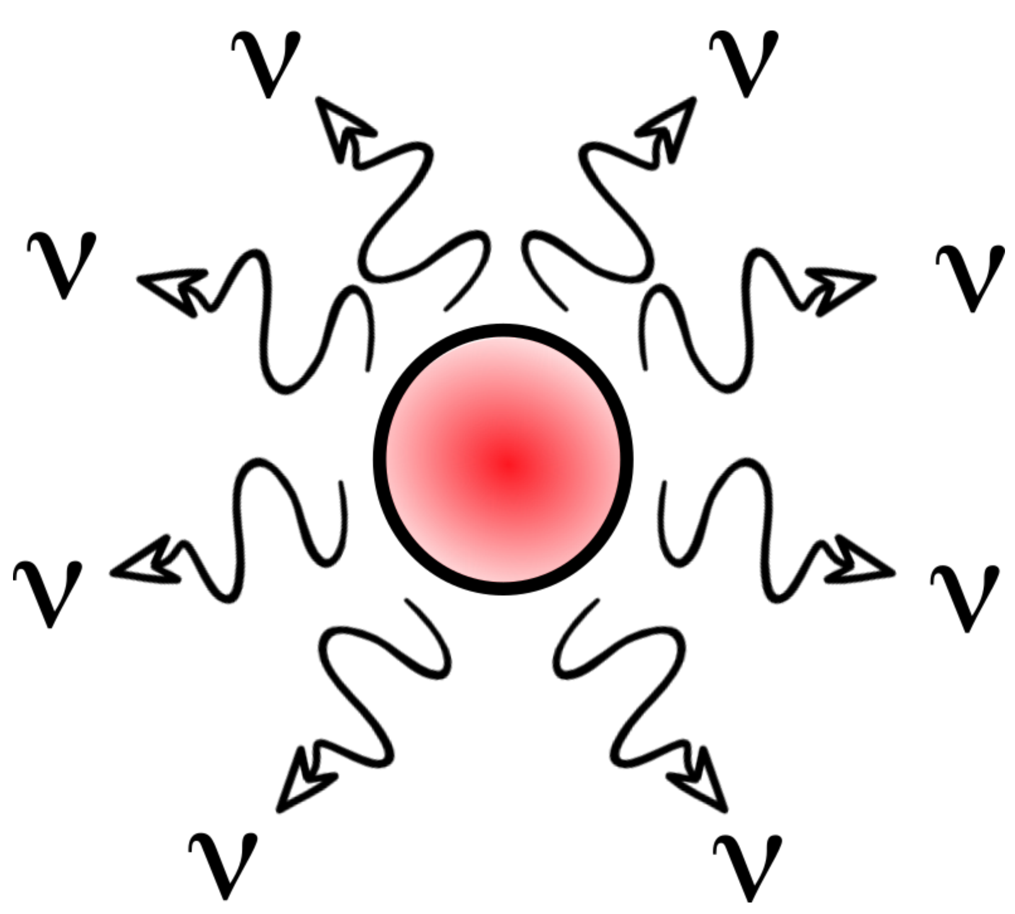

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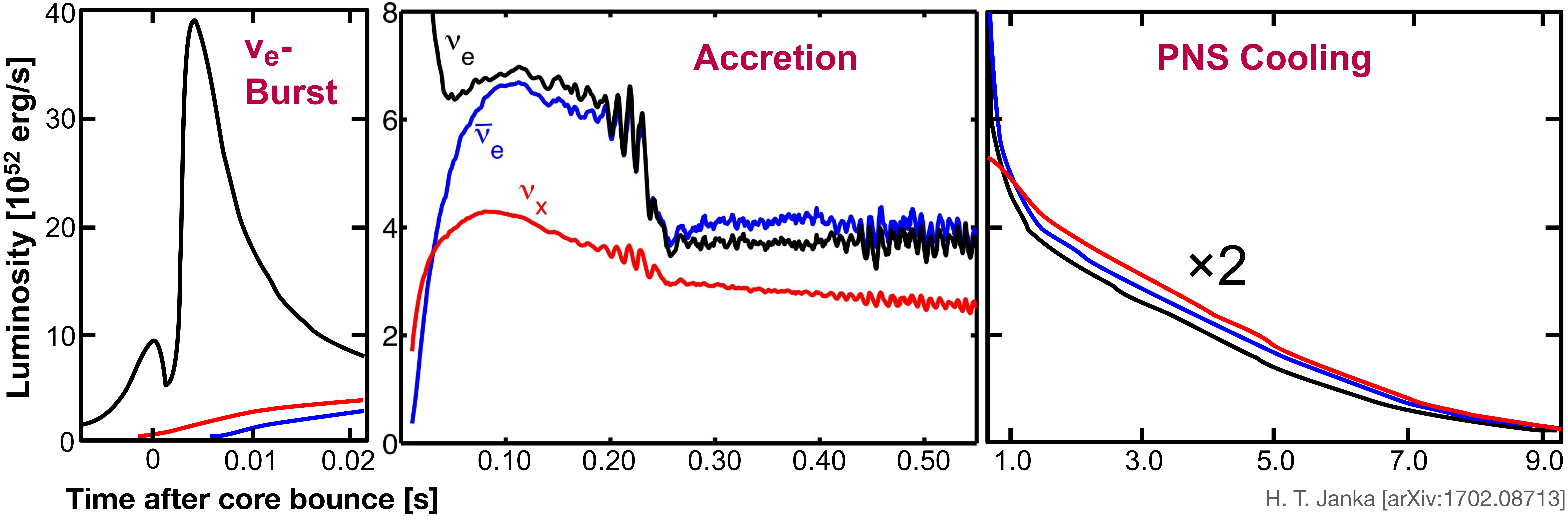

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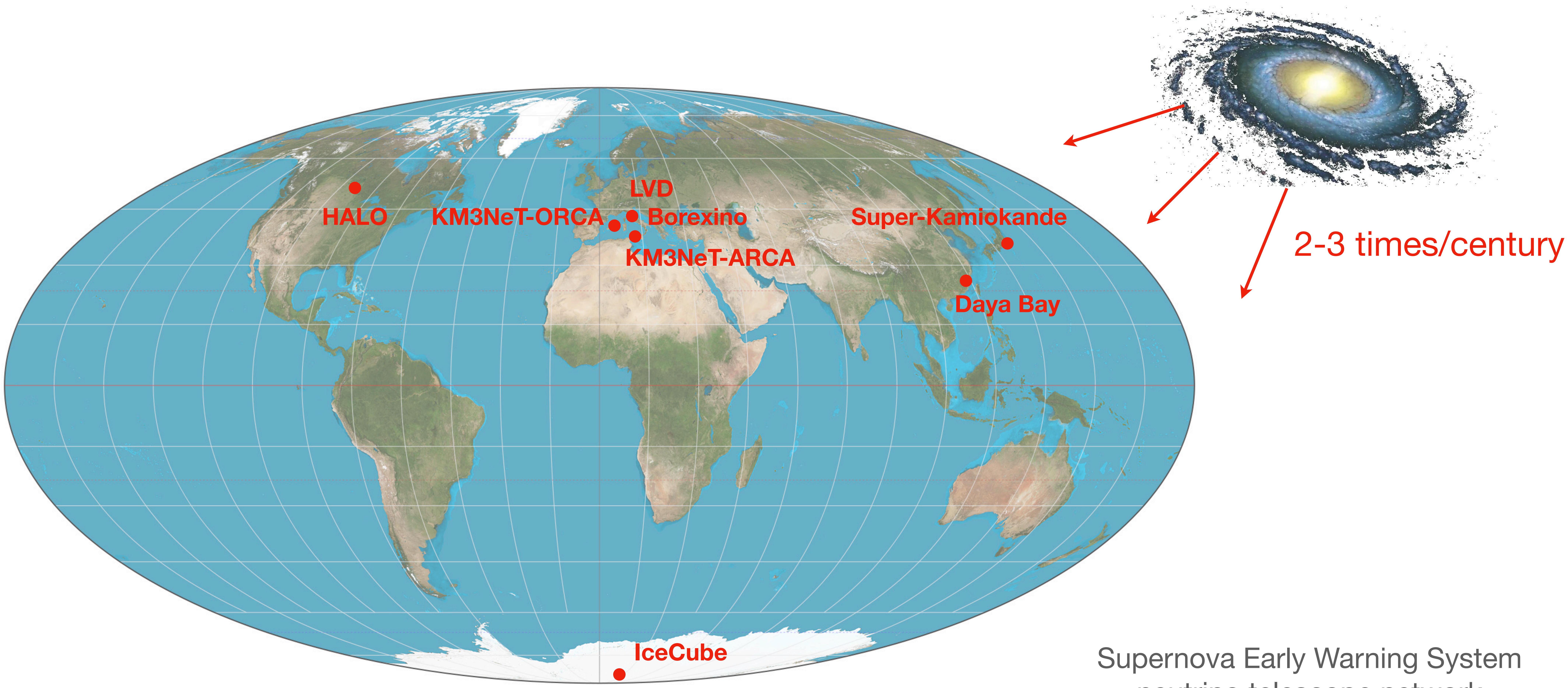
Neutrino telescope networks

Capturing an extremely rare and short event



Supernova Early Warning System
neutrino telescope network

The LEAK project

Combining neutrino experiments to characterize supernovae

- Joint project, gathering:
  Experimentalists from KM3NeT, DUNE, and DarkSide-20k (APC)
  Theorists working on CCSN simulations (AIM, CEA)
  proto-neutron-star dynamics (LUTh)
  neutrino flavor conversions (APC)

- Improve the sensitivity of large-scale water Cherenkov telescopes to core-collapse supernovae
  *Historically: **L**ow **E**nergy **A**nalyses at **K**M3NeT*

- Investigate the **impact of progenitor properties on neutrino spectra**

- Characterize supernova and neutrino properties by **combining complementary neutrino experiments**

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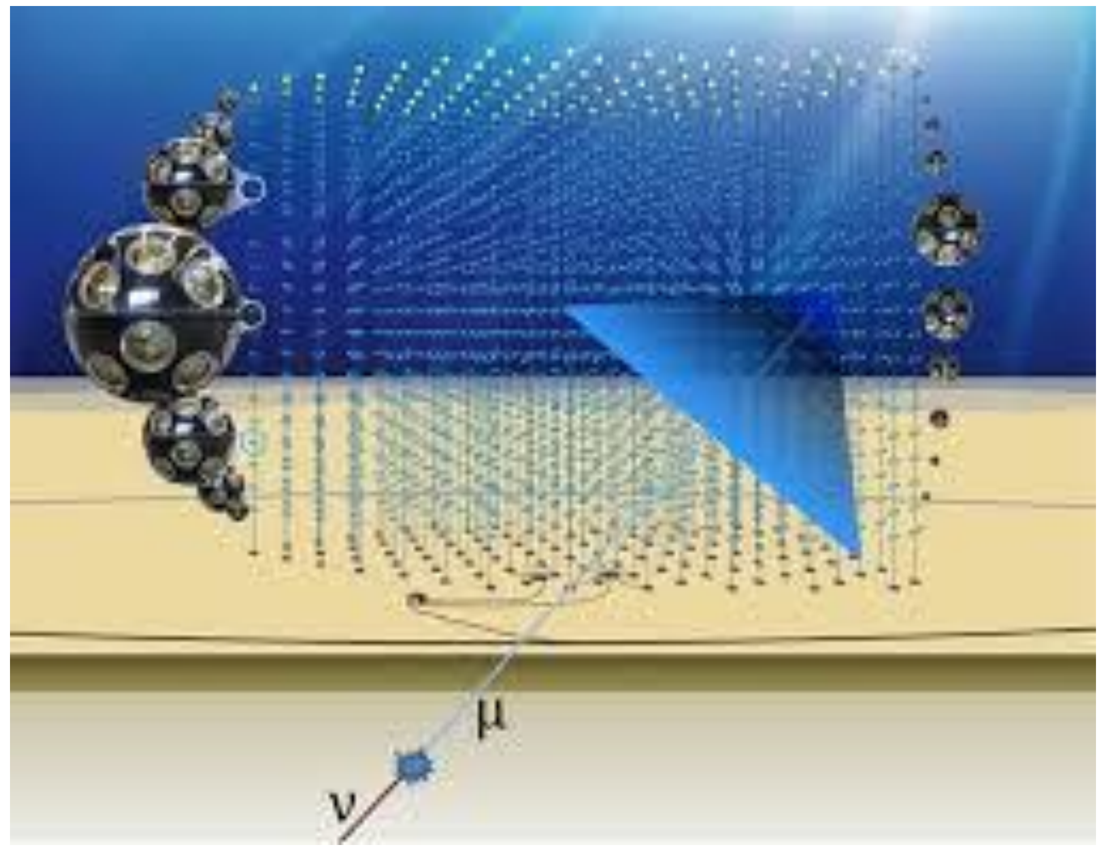
Featured neutrino experiments

KM3NeT, DUNE, and DarkSide-20k



Water Cherenkov detectors
(starring KM3NeT)

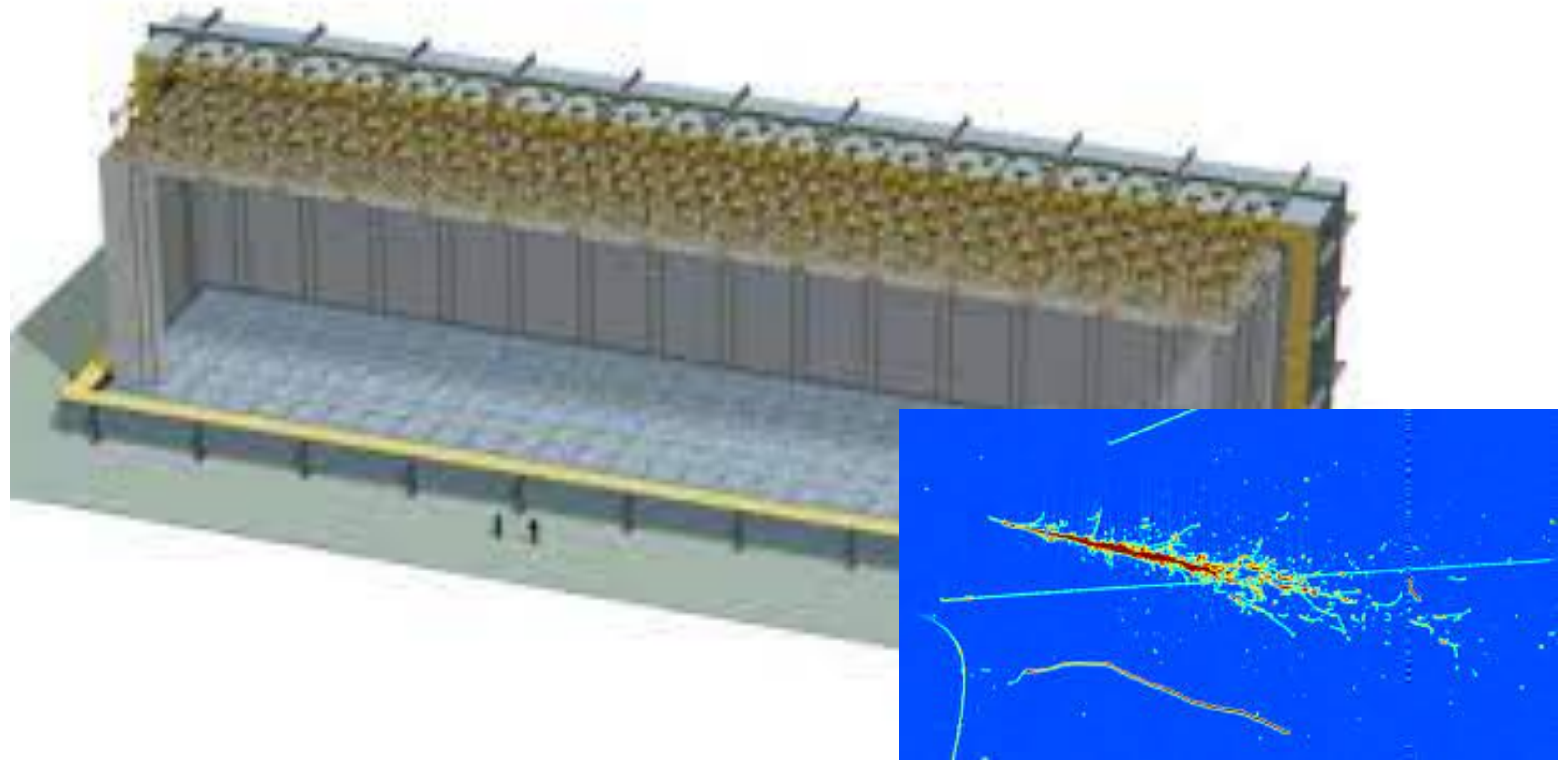
$\overline{\nu_e}$

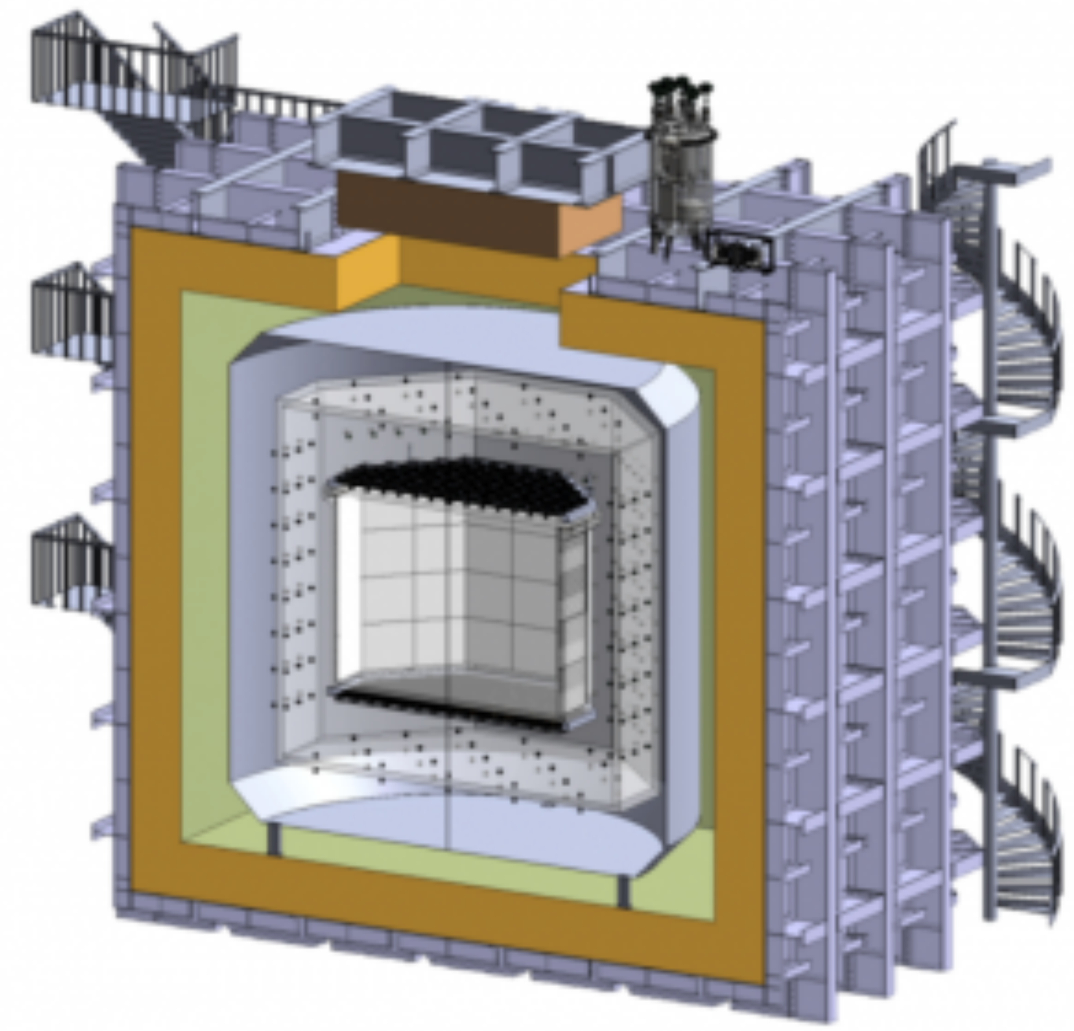
Effective mass: 100 ktons

DUNE
(liquid argon detector)

ν_e

Effective mass: 40 ktons





DarkSide-20k
(liquid argon detector)

all flavors

Effective mass: 50 tons

Coherent neutrino-nucleus scattering

LEAK activities

Characterizing core-collapse supernovae

- Locate supernovae using triangulation
  See previous talk by M. Bendahman [Core-collapse supernovae at KM3NeT]

- From neutrinos to supernovae: combine neutrino observations

- From supernovae to neutrinos: rotating progenitors with magnetic fields

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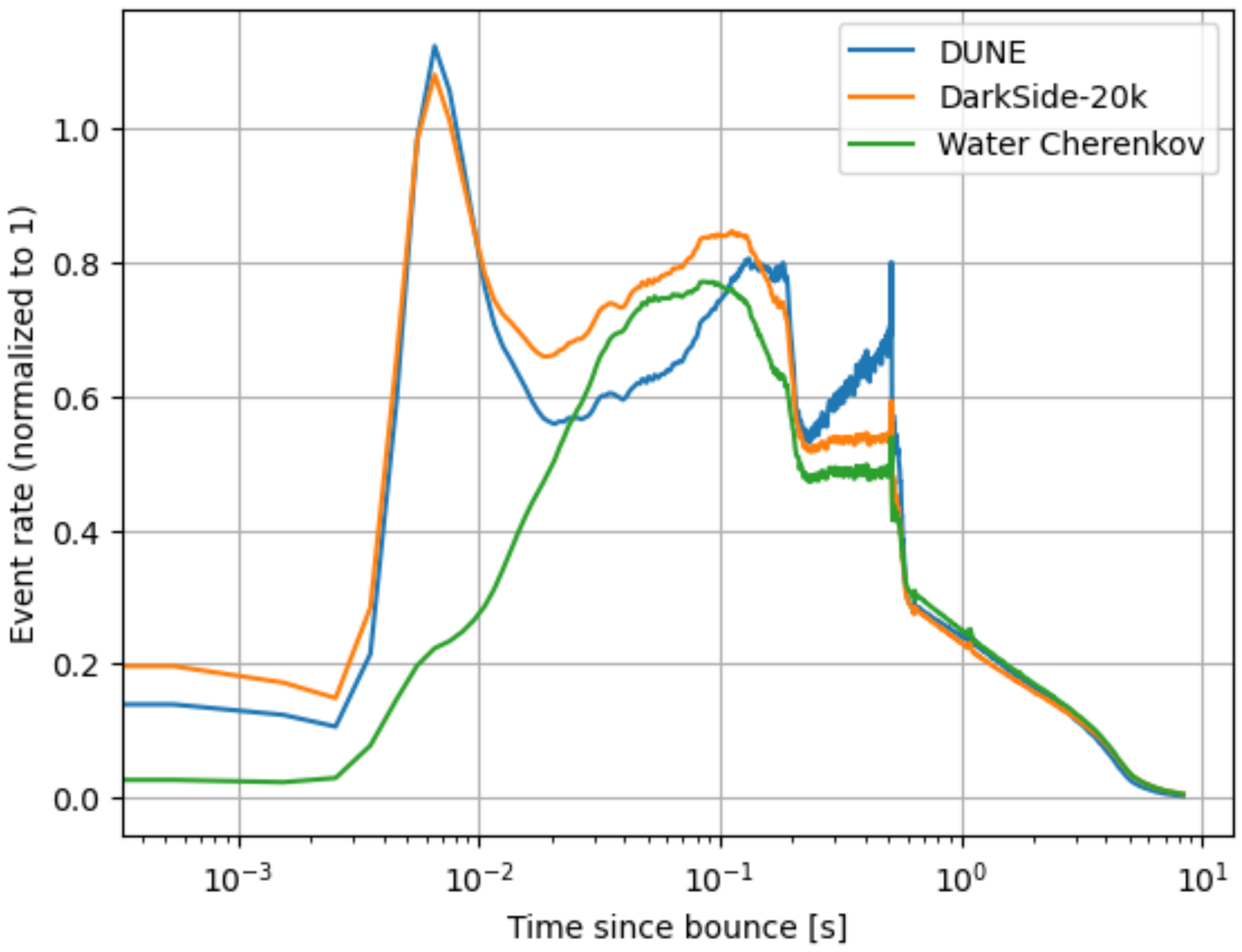
CCSN properties from neutrino rate variations

Each flavor has its own story to tell

- All neutrino experiments can record the **neutrino rate time variations** (aka light curves)
- Complementary flavor sensitivity
  ⇒ distinctive light curves for each experiment
- Predict light curve shapes using CCSN simulations
- Build observables to combine observations and infer CCSN parameters



27 solar mass progenitor with LS220 equation of state
Simulations from A. Mirizzi *et al* [Nuovo Cimento Rivista Serie,39,1]

Combining detector observations

Preliminary study with “perfect” detectors

- Optimistic scenario: **neglect background and resolution** effects
- Investigate all CCSN phases ⇒ predictions using **1D simulations**
  A. Mirizzi *et al* [Nuovo Cimento Rivista Serie,39,1]
- Flavor conversion: assume **MSW adiabatic transitions** for all phases
- Observables: relative contribution of electronic flavors

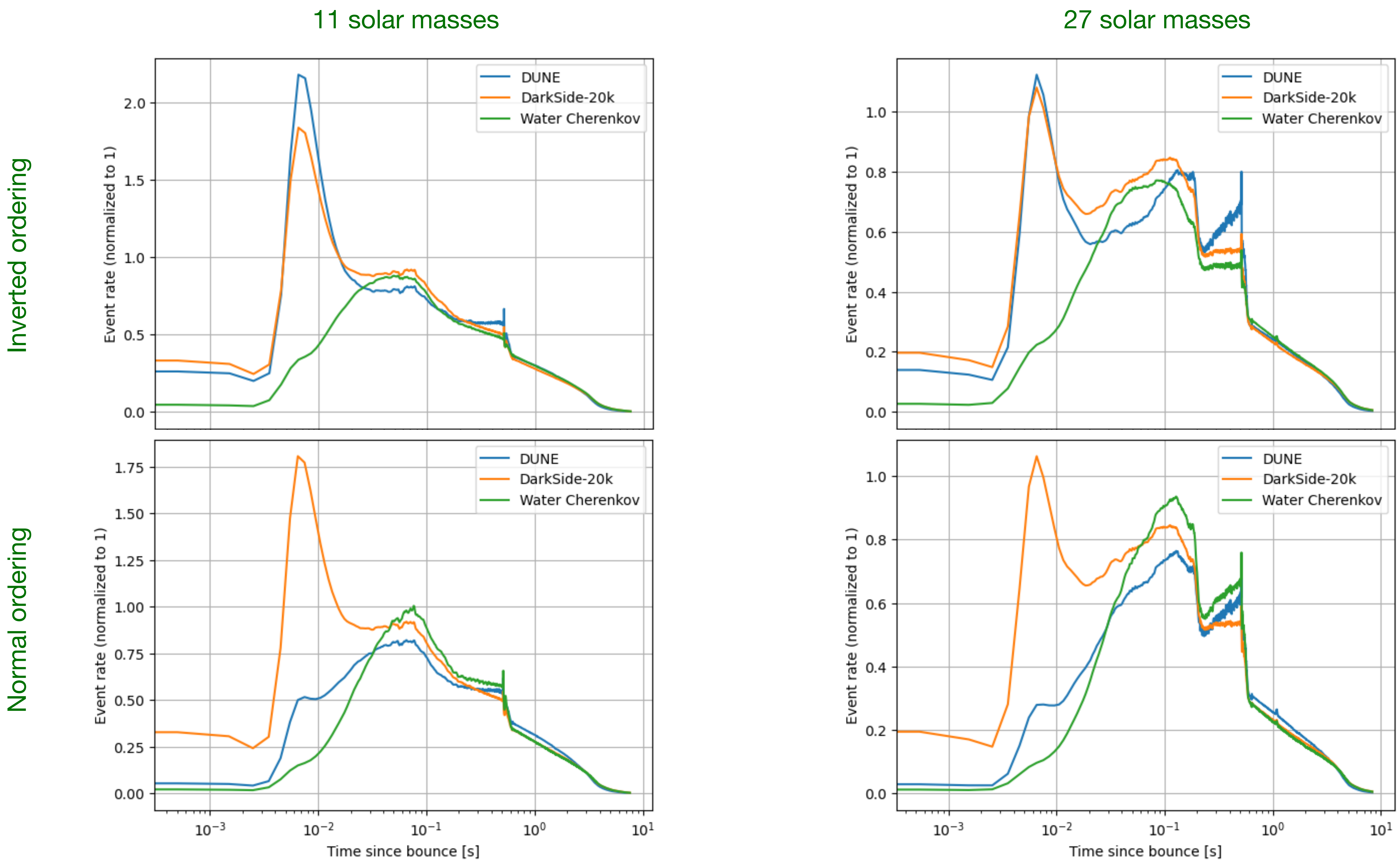
$$\text{Ratio} = \frac{\text{KM3NeT} + \text{DUNE}}{\text{DarkSide}}$$

$$\text{Asymmetry} = \frac{\text{KM3NeT} + \text{DUNE} - \text{DarkSide}}{\text{KM3NeT} + \text{DUNE} + \text{DarkSide}}$$

- Estimate observables over different **time windows**, evaluate discriminating power

From CCSN properties to neutrino rates

Varying the progenitor mass and the neutrino mass ordering



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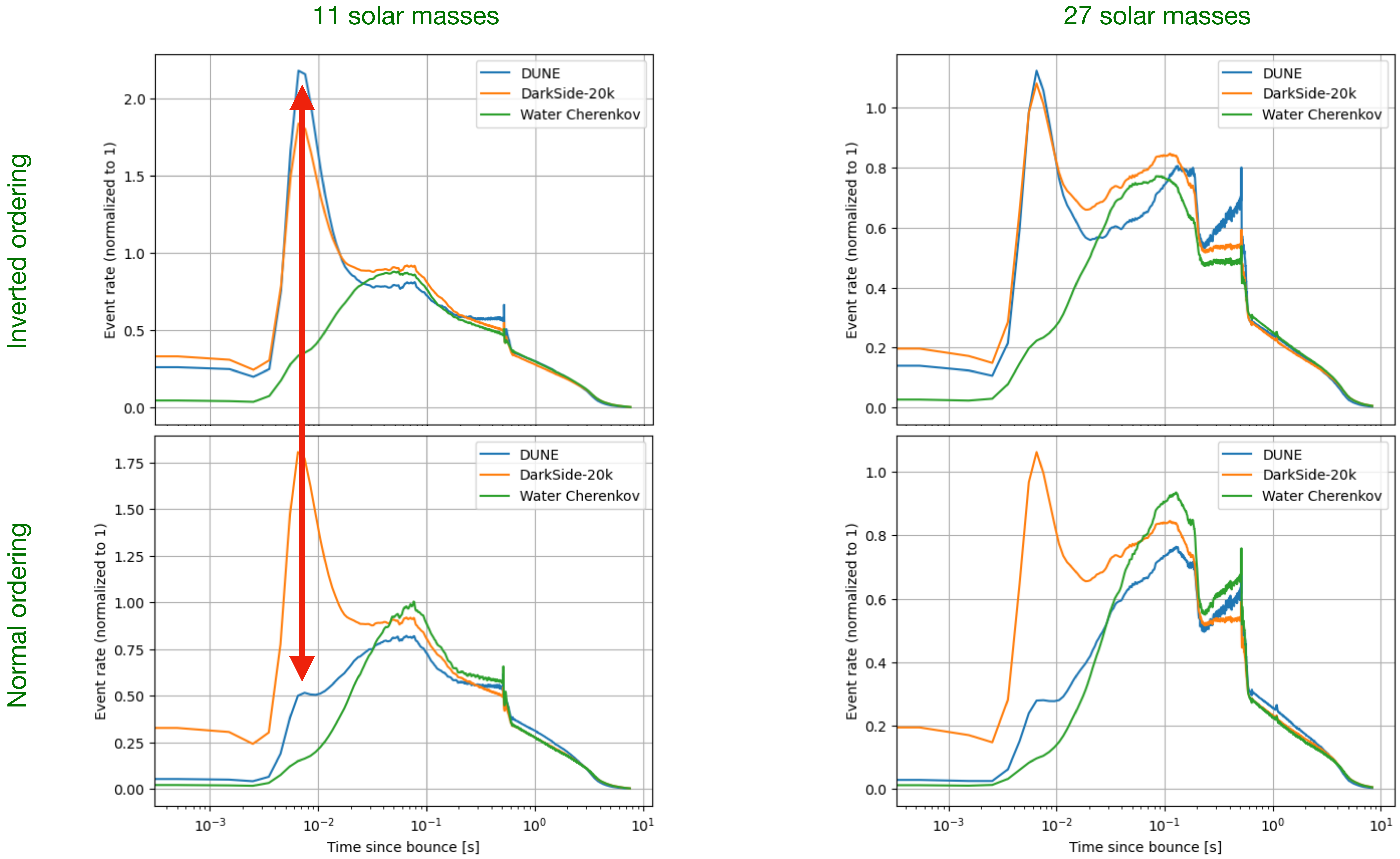

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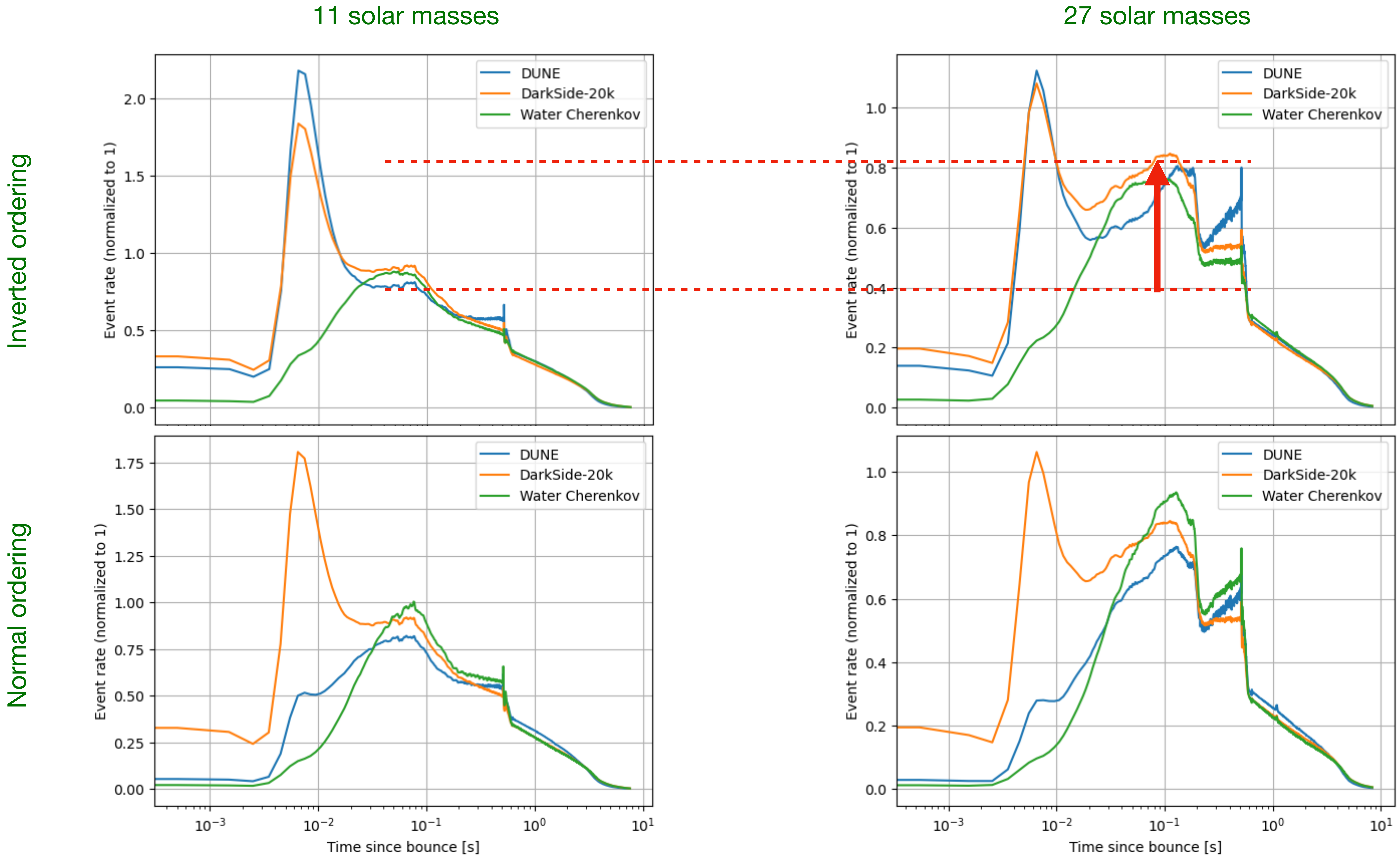

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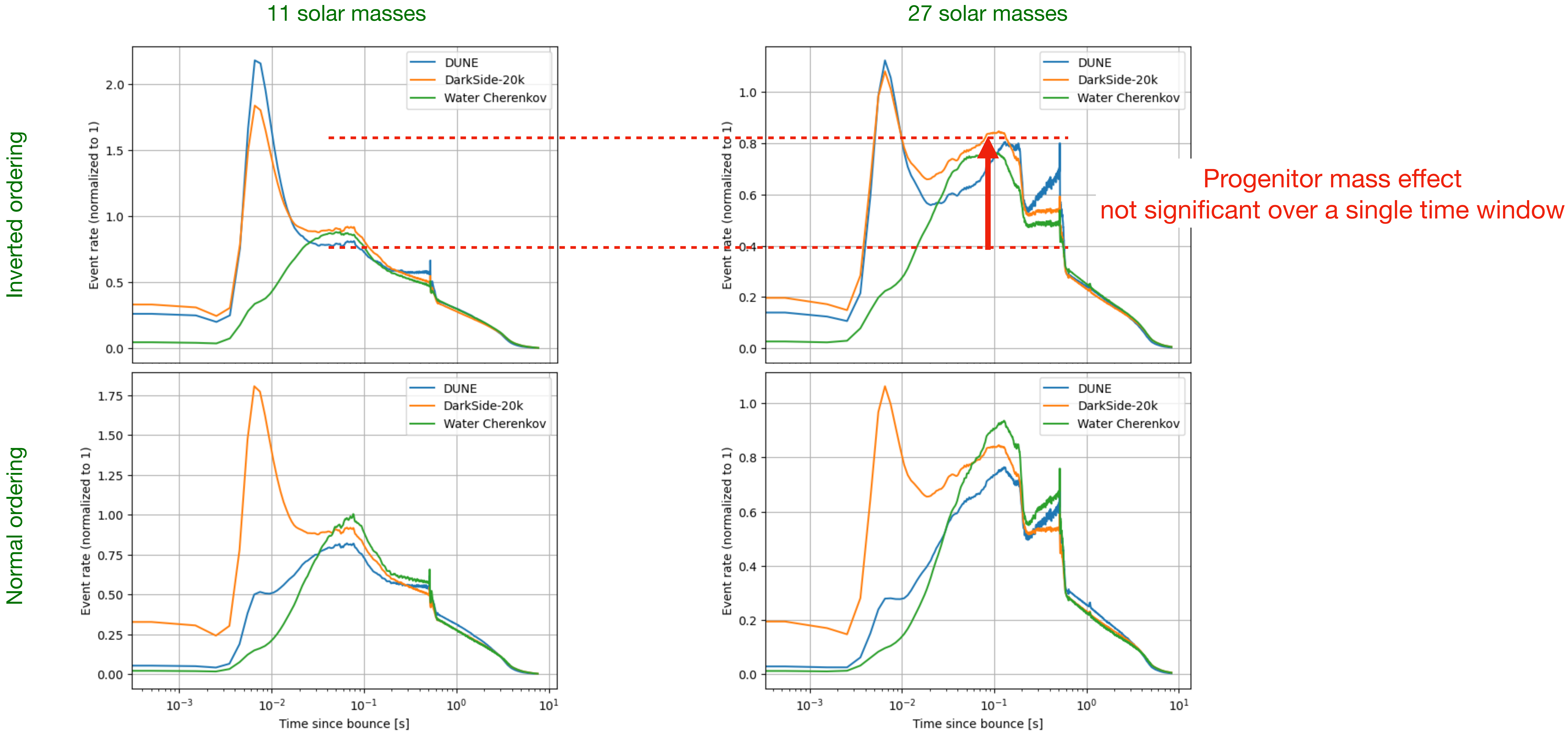
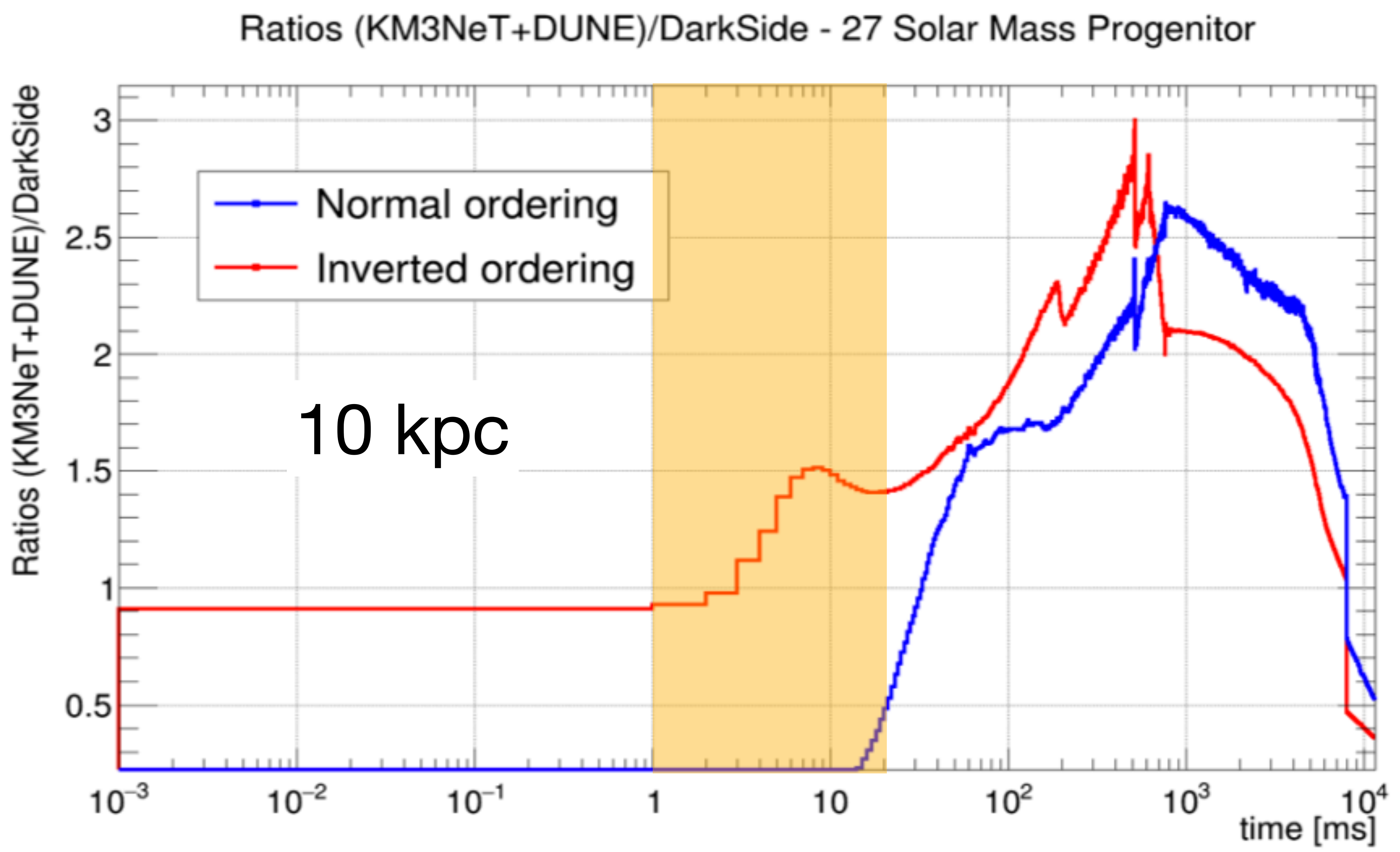
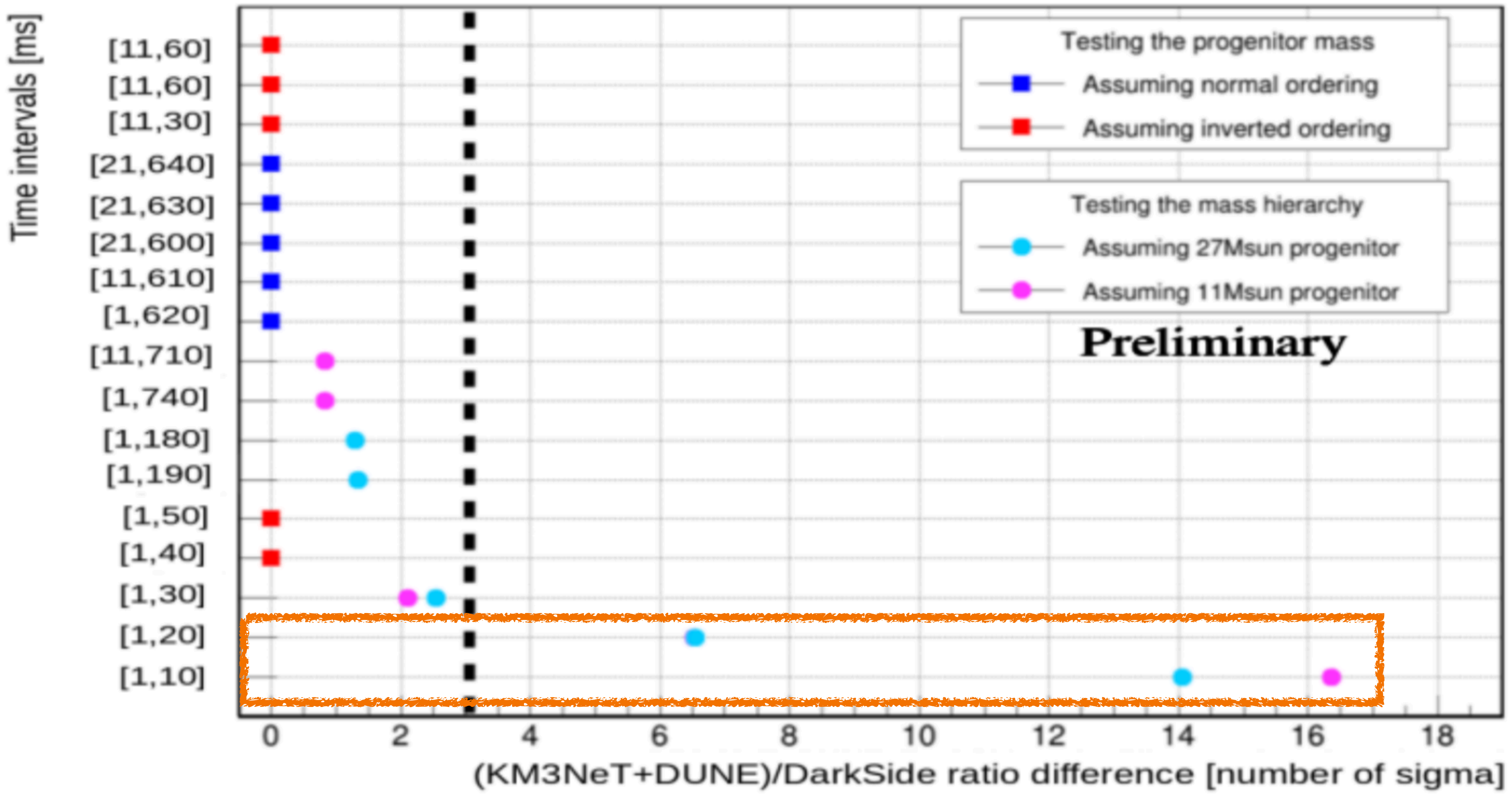


Identifying the neutrino mass ordering

Ratio of electronic neutrinos rates over all flavor contributions





- The **ratio** of electronic vs non-electronic flavors **strongly depends on the neutrino mass ordering**
- Effect expected to be robust, warrants a more in-depth study

From mass ordering to survival probabilities

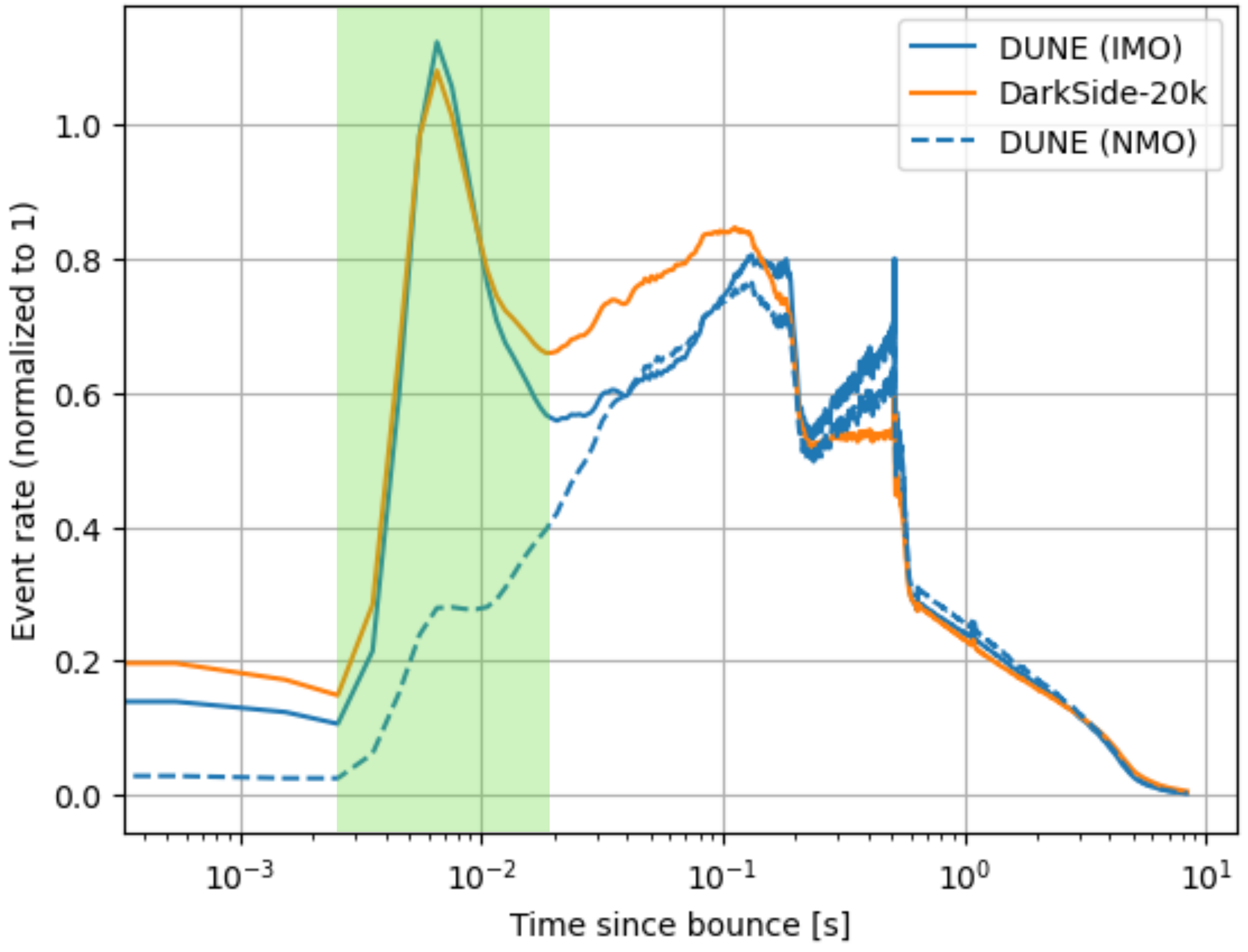
The wonders of the DUNE/DarkSide ratio

- The visibility of the neutronization peak in DUNE depends on p_{ee}

  Inverted ordering: p_{ee} ~ 0.3
  Normal ordering: p_{ee} ~ 0.02

- Traditional approaches: measure mass ordering with DUNE alone, compare trigger times between experiments, etc..
  V. Brdar *et al* [*JCAP* 08 (2022) 067]

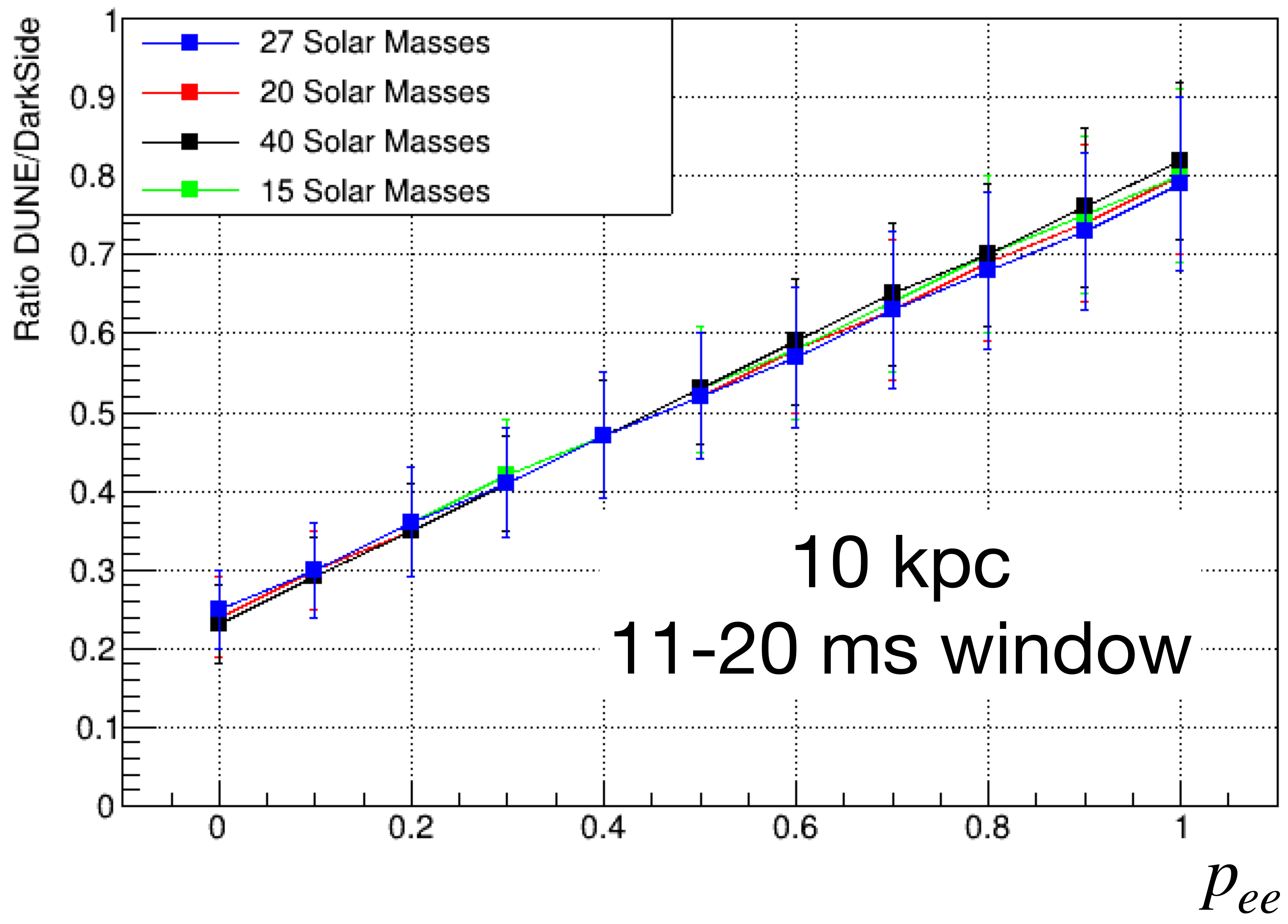
- Our approach: compare DUNE and DarkSide results to measure p_{ee}

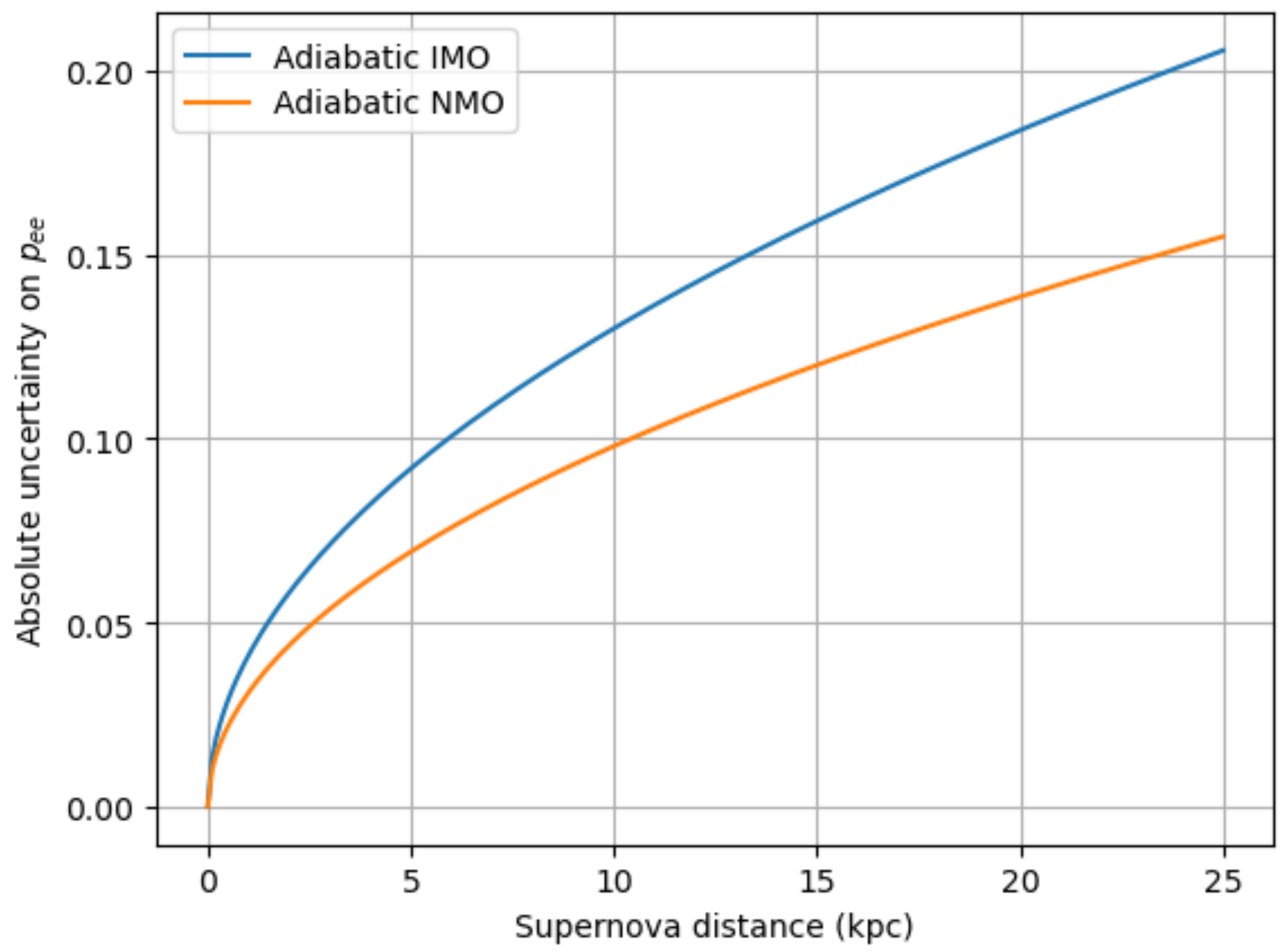


Estimate the ν_e survival probability

Capturing the neutronization peak

Simulations from I. Tamborra *et al* [Phys. Rev. D 90 (2014) 4, 045032]





- p_{ee} dependence of DUNE/DarkSide ratio for 3D simulations with different progenitor masses
  ⇒ similar dependence across models, only %-level variations

- Perspectives: extract neutronization peak to reduce model dependence, constrain new physics scenarios
  (e.g. neutrino decay, see A. de Gouvea *et al* [*Phys. Rev. D* 101 (2020) 4, 043013])

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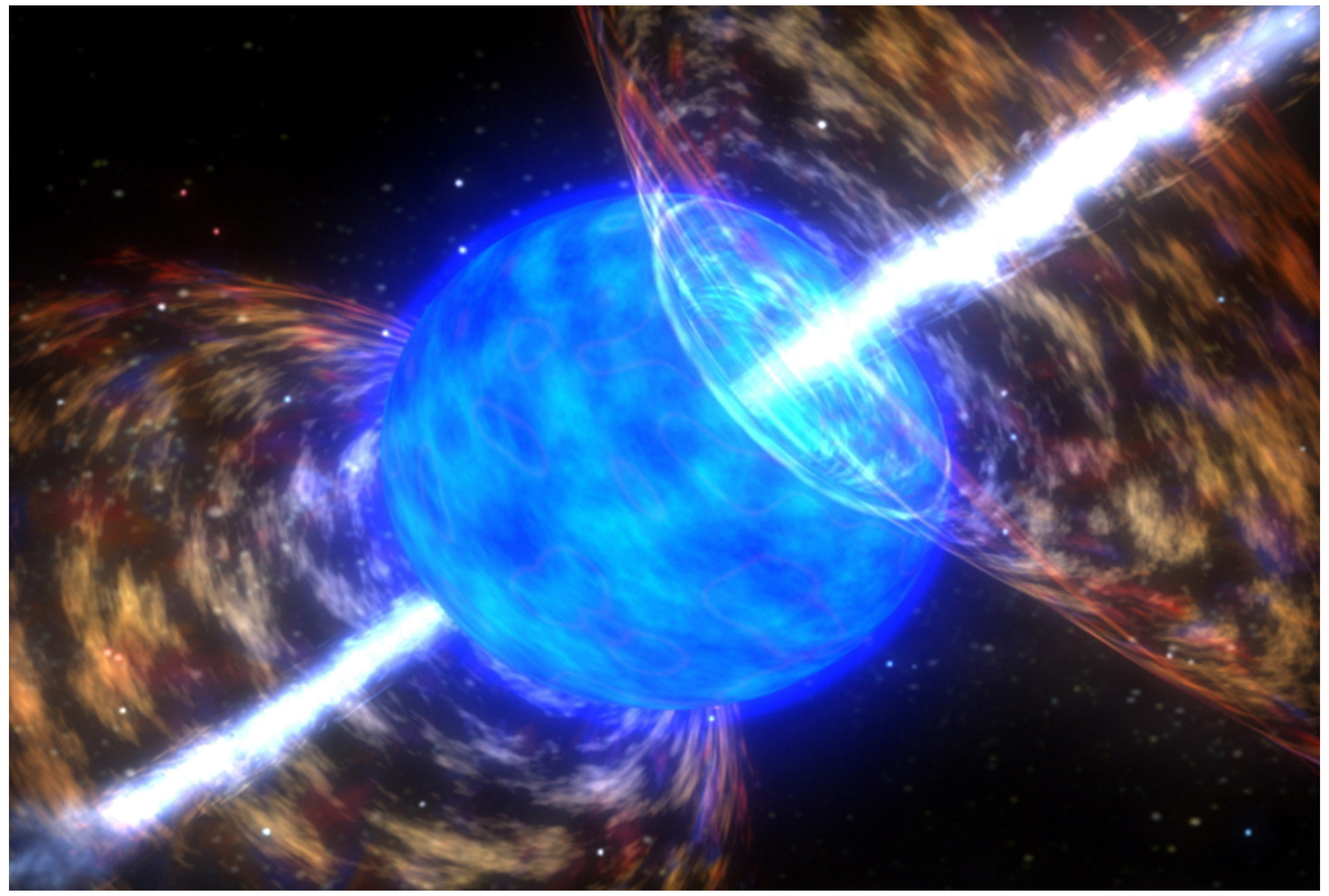
Atypical supernovae: rotation and magnetic fields

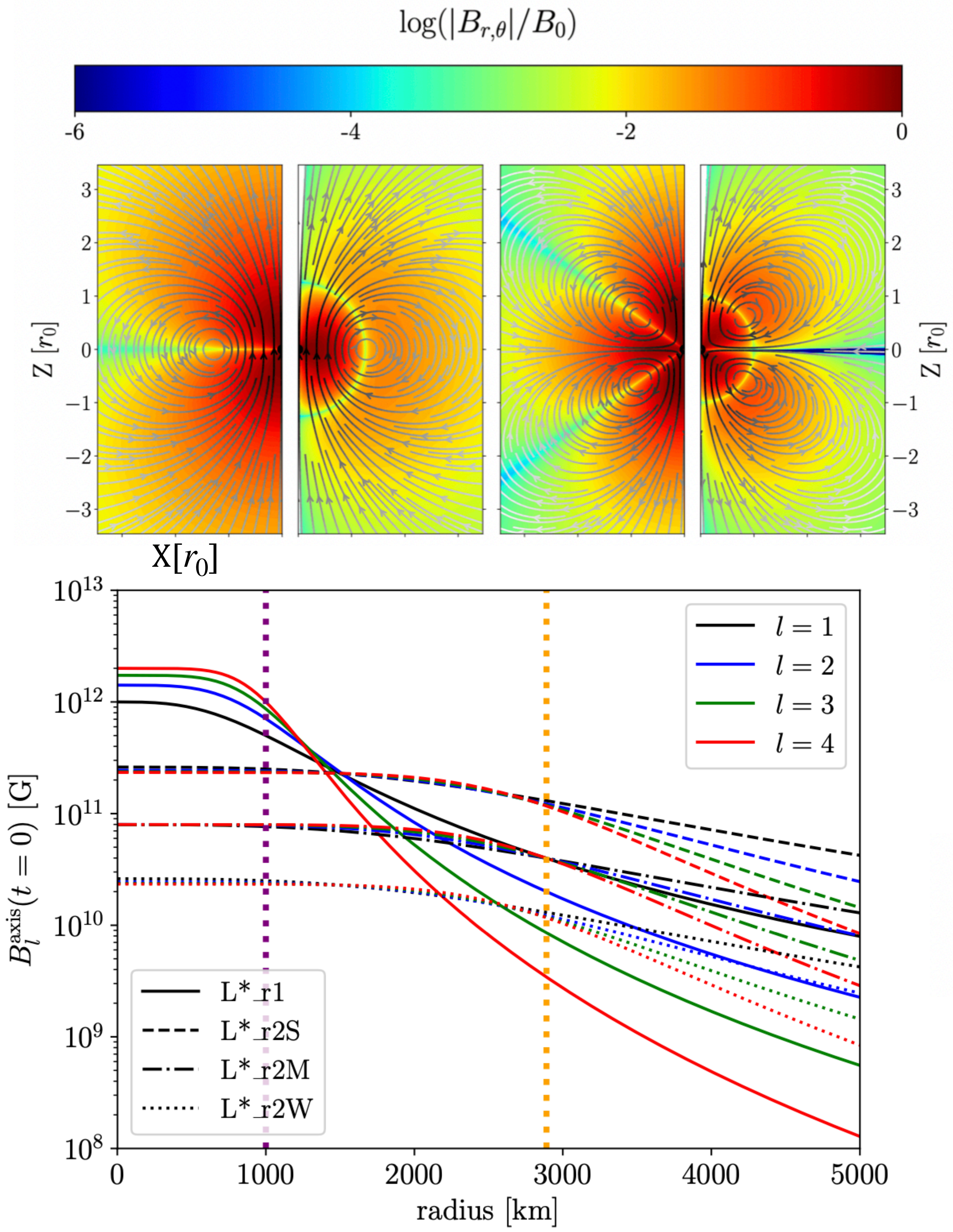
Unraveling the dynamics of gamma ray bursts with neutrinos



- Rotating progenitors + magnetic fields of $\sim 10^{15}$G can lead to **magnetars**
- Magnetic fields **modify the rotation profile** of the CCSN progenitor
- Impact of the magnetic field **magnitude and polarity** on the CCSN explosion?
- Investigate the imprints of magnetic fields on the CCSN neutrino spectra

Simulating magnetic fields

Impact on the magnetic field polarity on the accretion phase

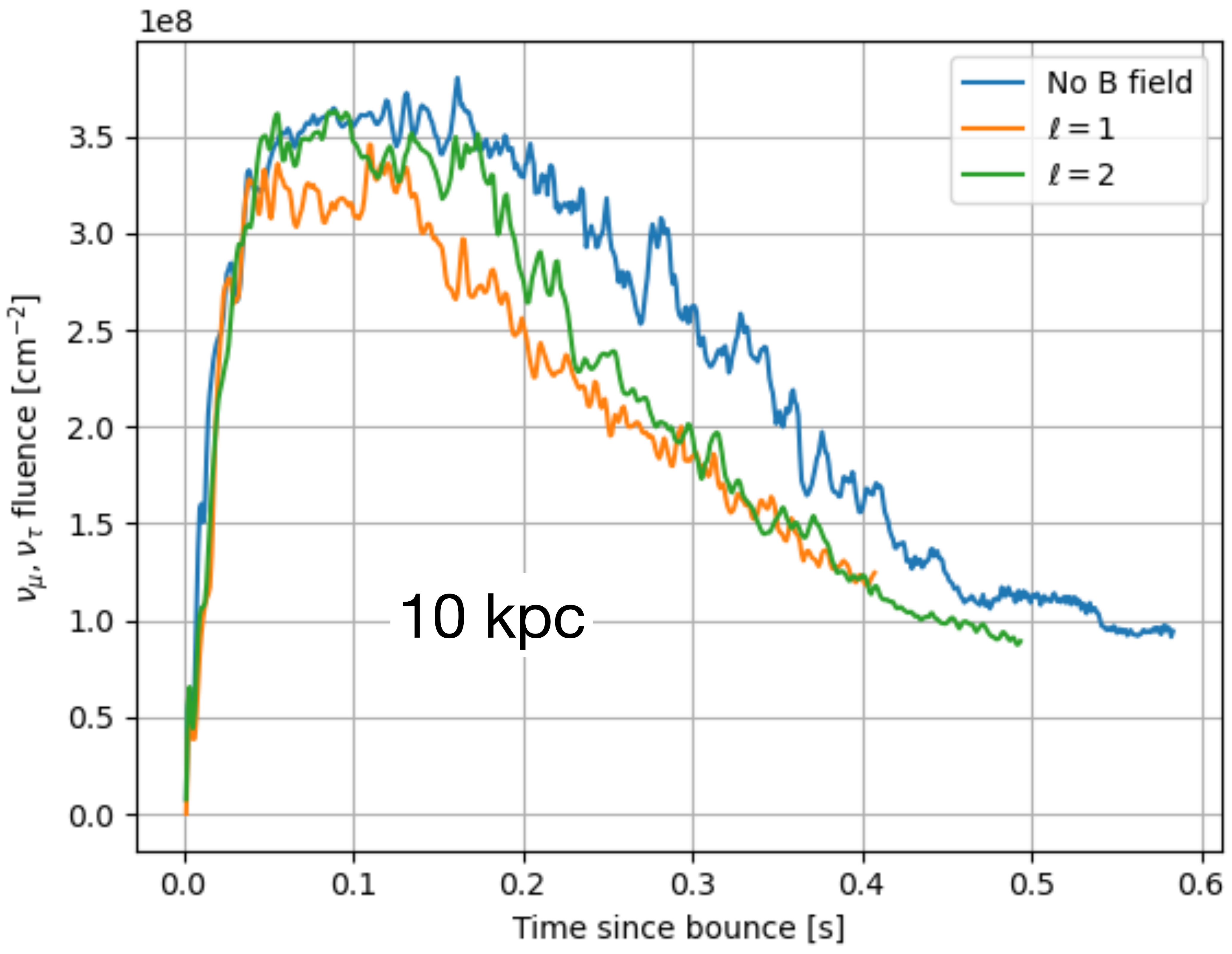


- Effects of **magnetic field alone:** 3D simulations, rotating $28M_{\odot}$ progenitor
- One "control" simulation with no magnetic field
- Add an initial 10^{12} G field, test different polarities
- Run simulations up to 400-600 ms

M. Bugli *et al, Mon.Not.Roy.Astron.Soc.* 507 (2021) 1, 443-454

Magnetic fields and neutrino fluxes

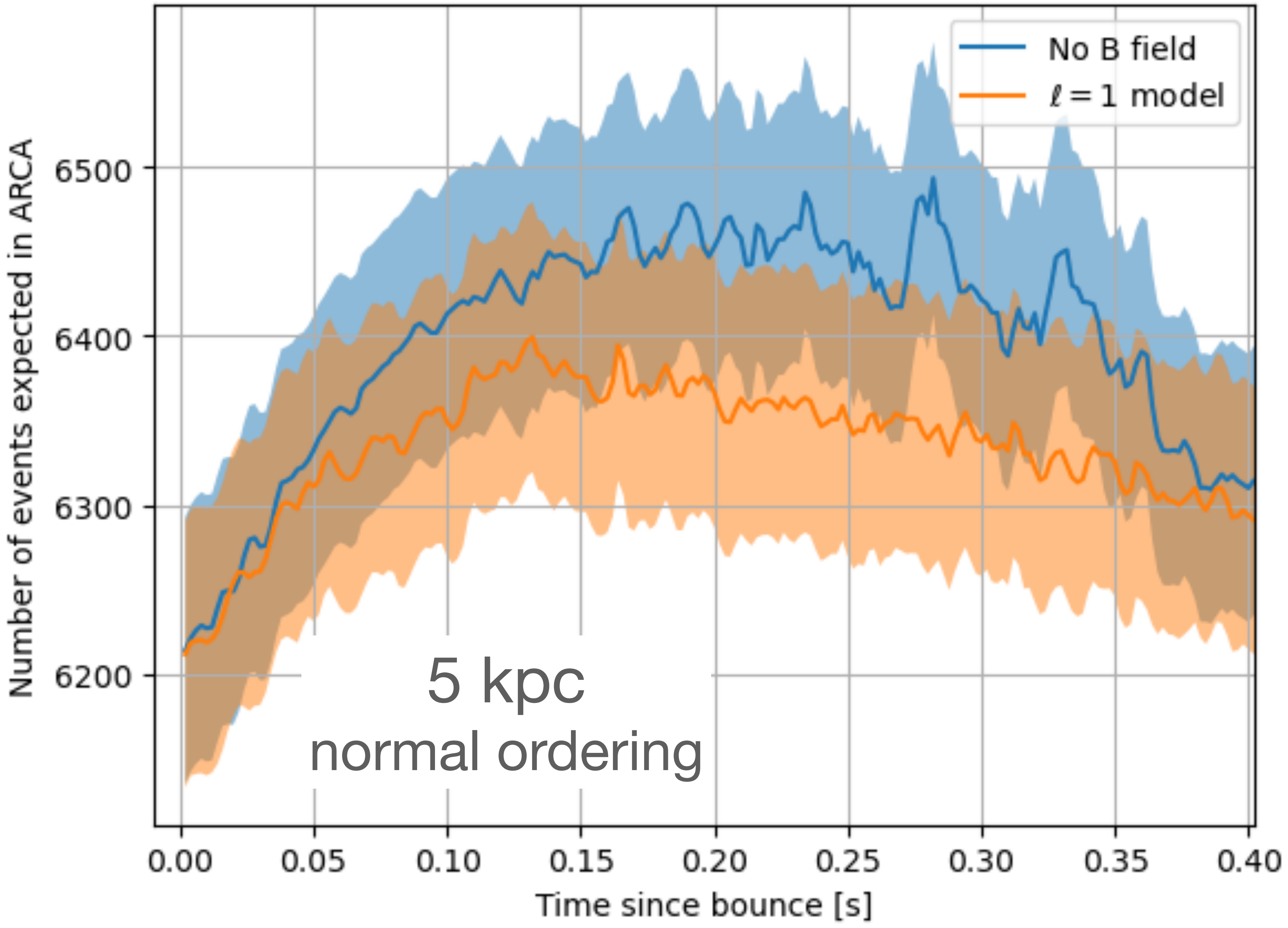
Impact of magnetic fields in the progenitor's equatorial plane

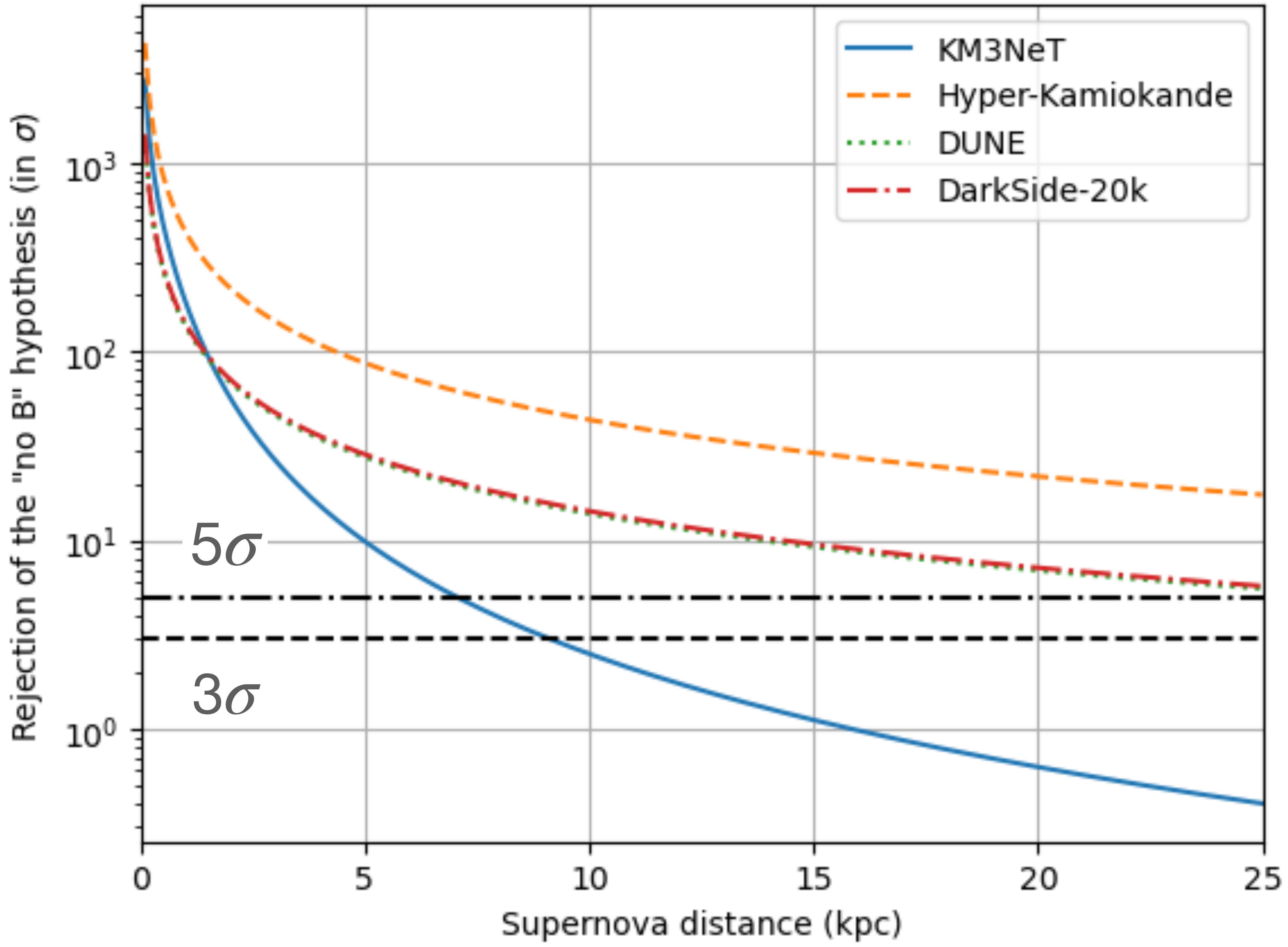


- Most robust predictions in the equatorial plane
- Magnetic fields reduce neutrino emission during the late accretion phase
- Reduction observed for all flavors, with varying strengths
- Is this reduction visible in all experiments?

Capturing the effect of magnetic fields

A noticeable impact in most neutrino experiments





- Proof of principle: compare the numbers of observed events in [200-400] ms
- All experiments can reject the “no B” hypothesis up to almost the galactic center

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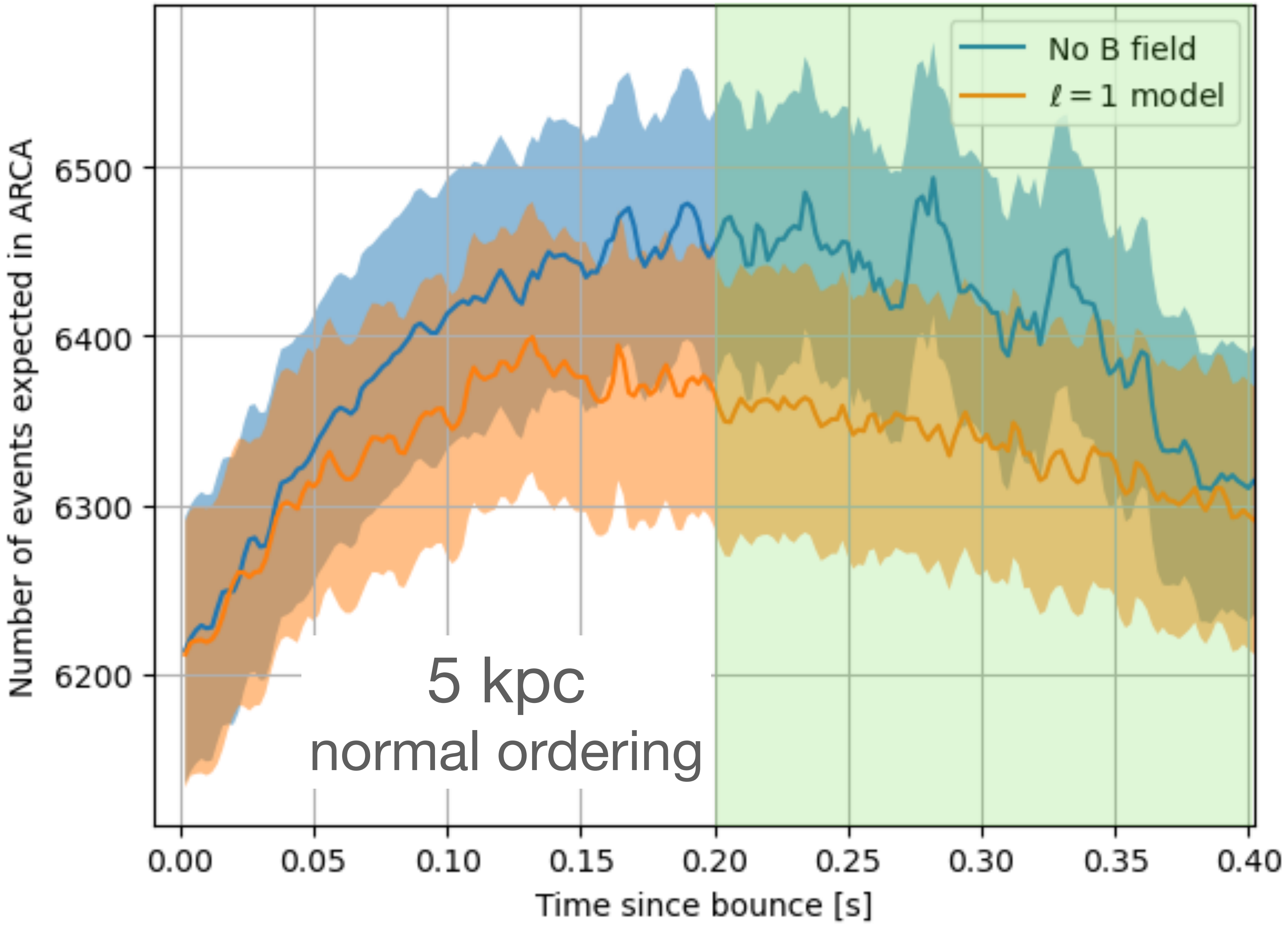

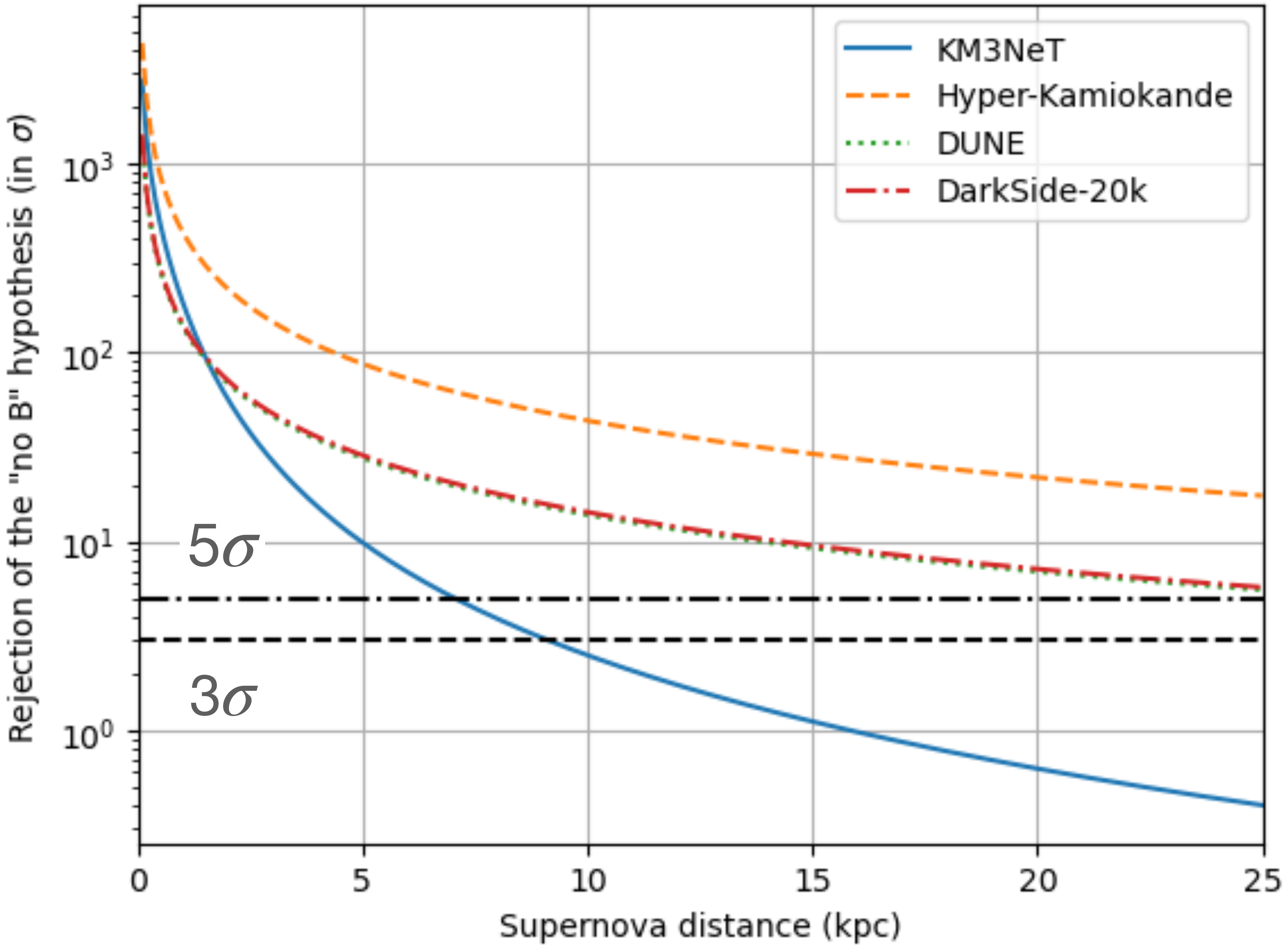

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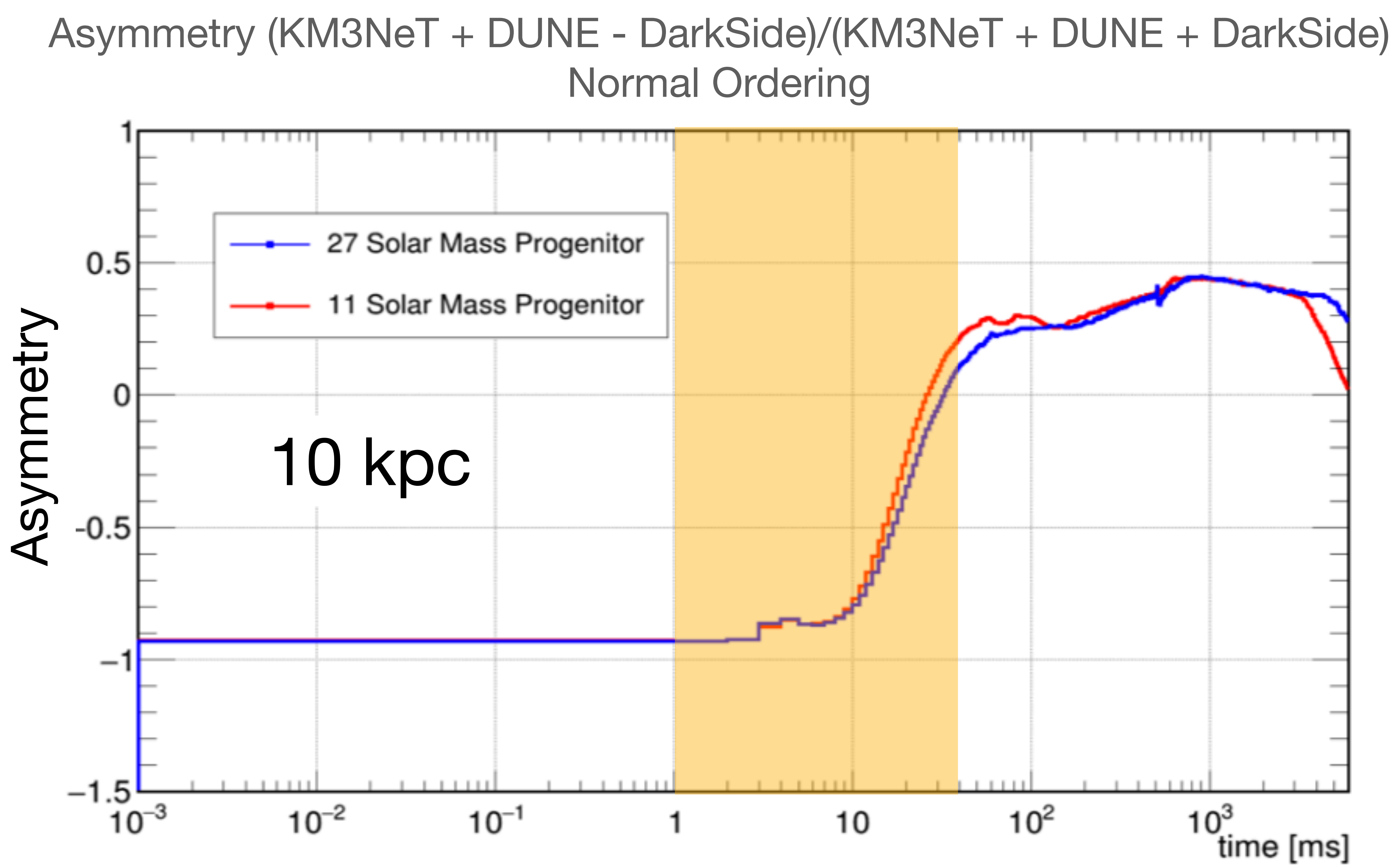
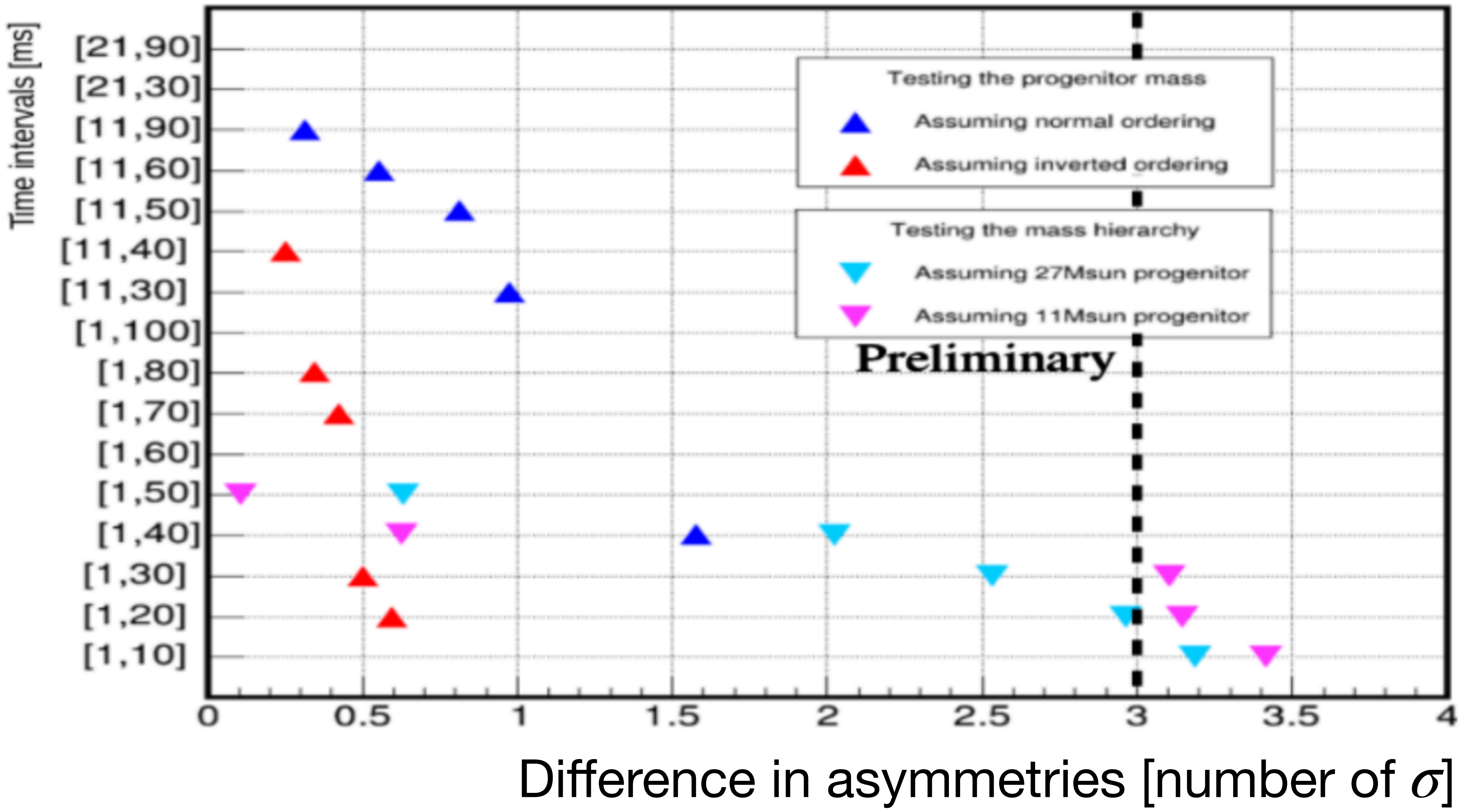
Conclusion

- Supernova studies go two ways: extracting supernova properties from neutrino experiments and enrich the landscape of possible neutrino signatures
- Combining neutrino experiments allows to evaluate flavor conversion parameters
  Key asset of coherent neutrino-nucleus scattering experiments
- Strong magnetic fields in supernova progenitors can lead to visible signatures in neutrino experiments (e.g. suppression of the neutrino flux)
- Future: build a catalogue of observables and CCSN simulations
  $\Rightarrow$ toolbox to characterize the next core-collapse supernova

Distinguishing progenitor masses

Asymmetry between electronic and non-electronic flavors





- Higher discriminating power for the asymmetry than for the ratio, **no significant discrepancy** at 10kpc
- Need more complex observables, test robustness w.r.t CCSN models carefully