Supernova neutrinos: from ν physics to new physics

APC — AstroCeNT annual meeting 2023

Sonia El Hedri — APC Laboratory — 24/11/2023

Labex UnivEarthS
Université Paris Cité
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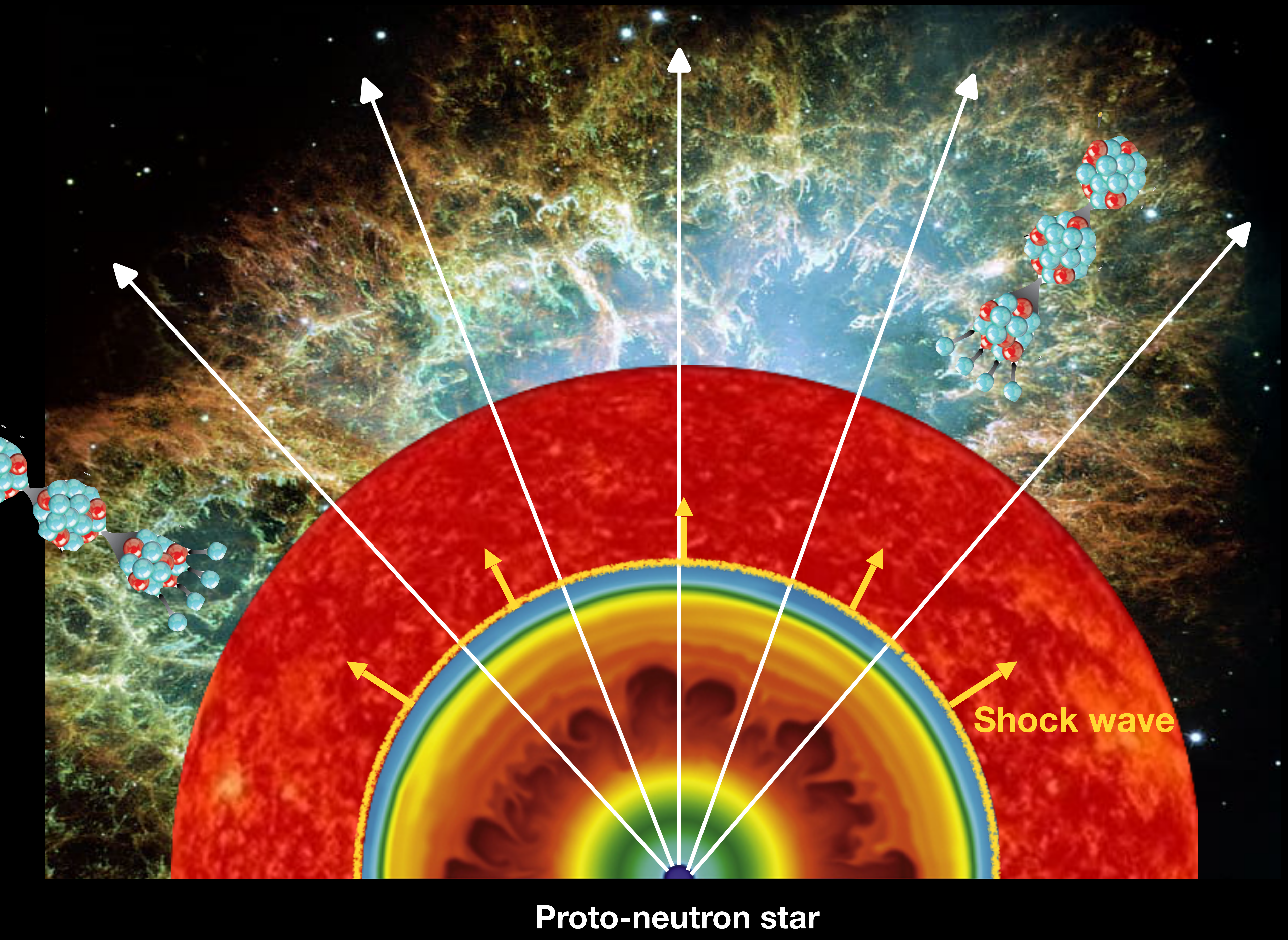
Core-collapse supernovae

Extreme, complex, and not-fully-understood phenomena



- End of life of a heavy star (> 8 $M_\odot$)
- Collapse of the core of the star: explosion or black hole formation
- Nucleosynthesis of heavy elements key role in star formation
- Explosion conditions not fully understood
  $\Rightarrow$ Need to observe the core of the star

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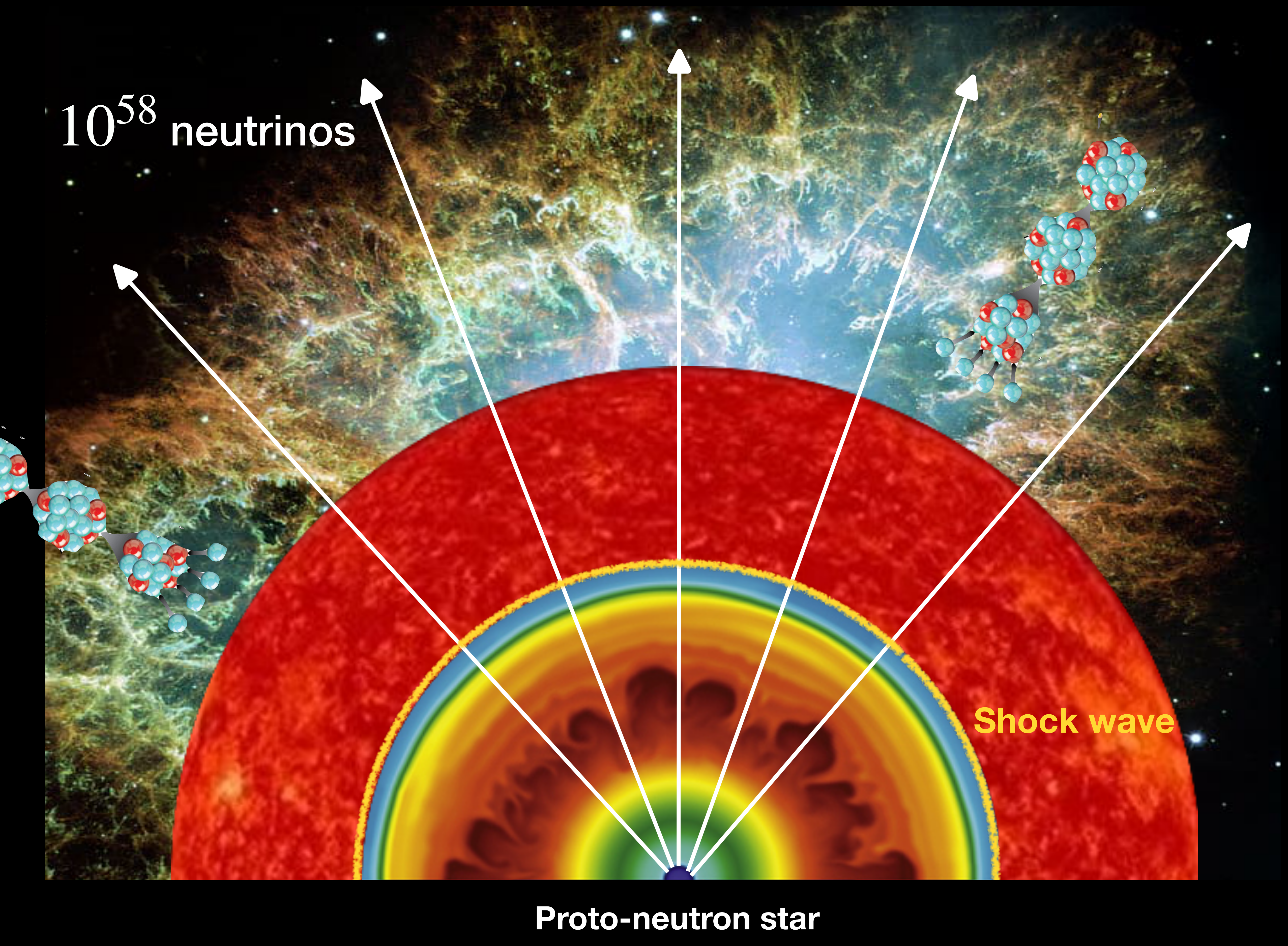

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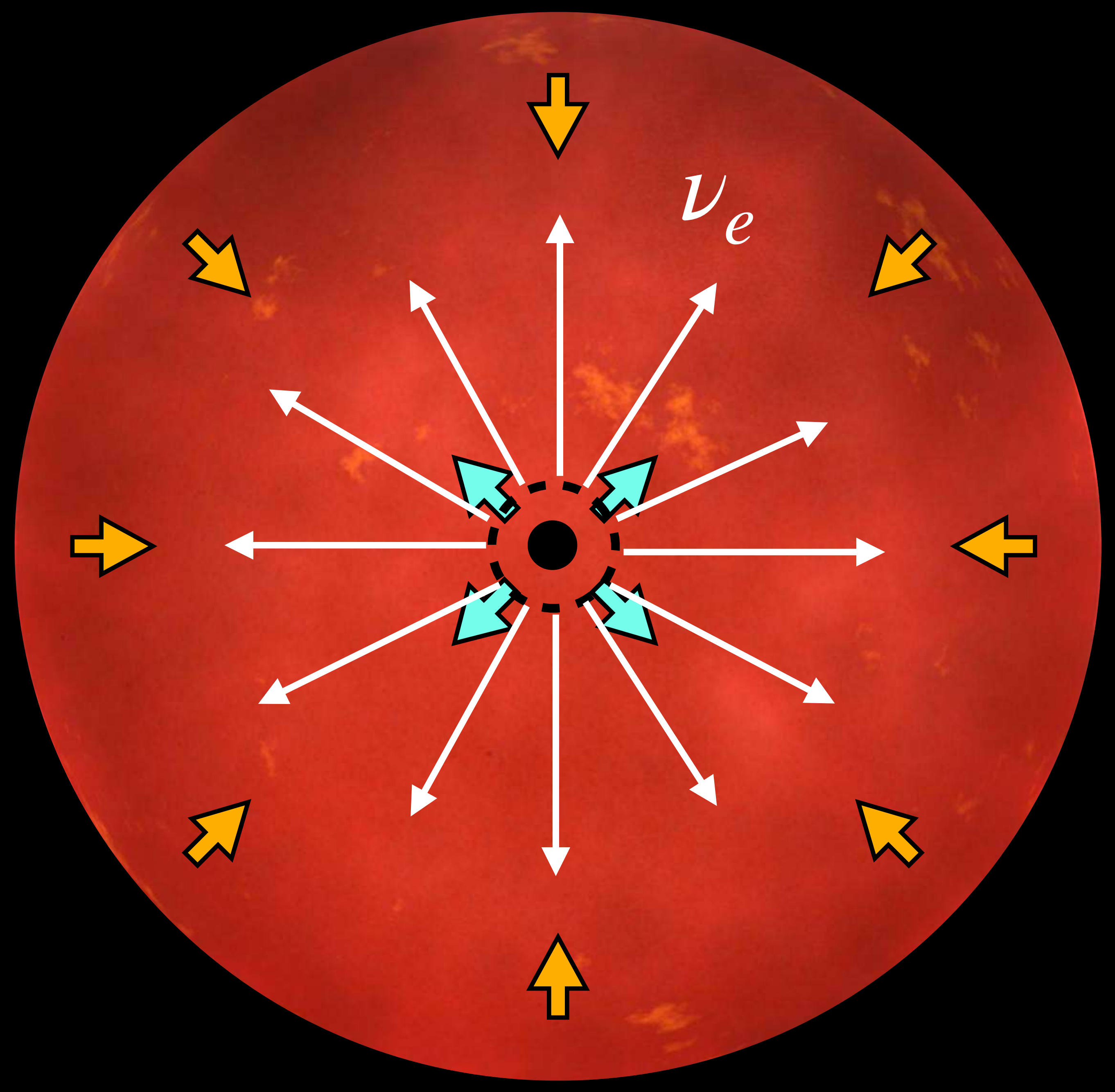
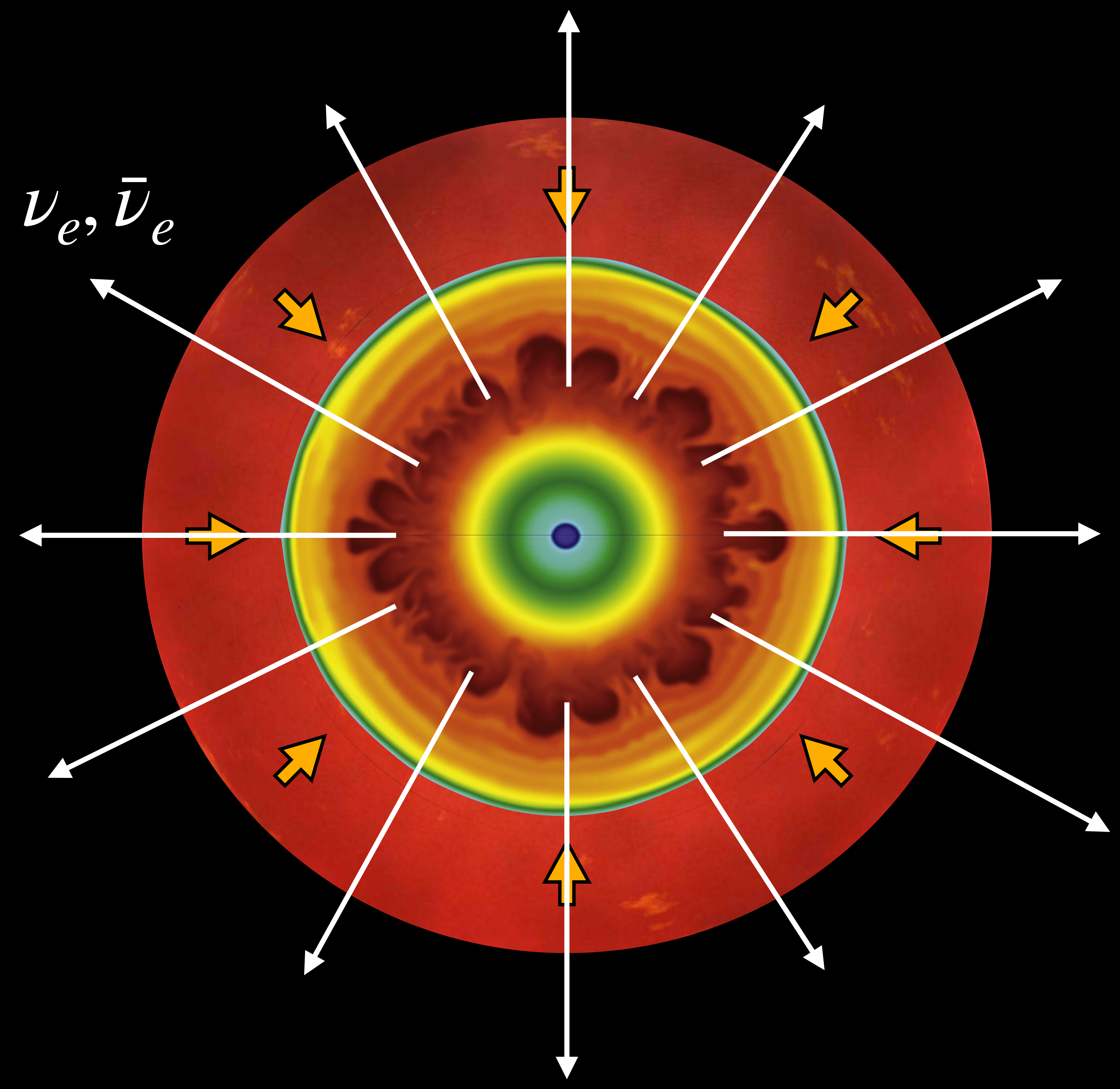
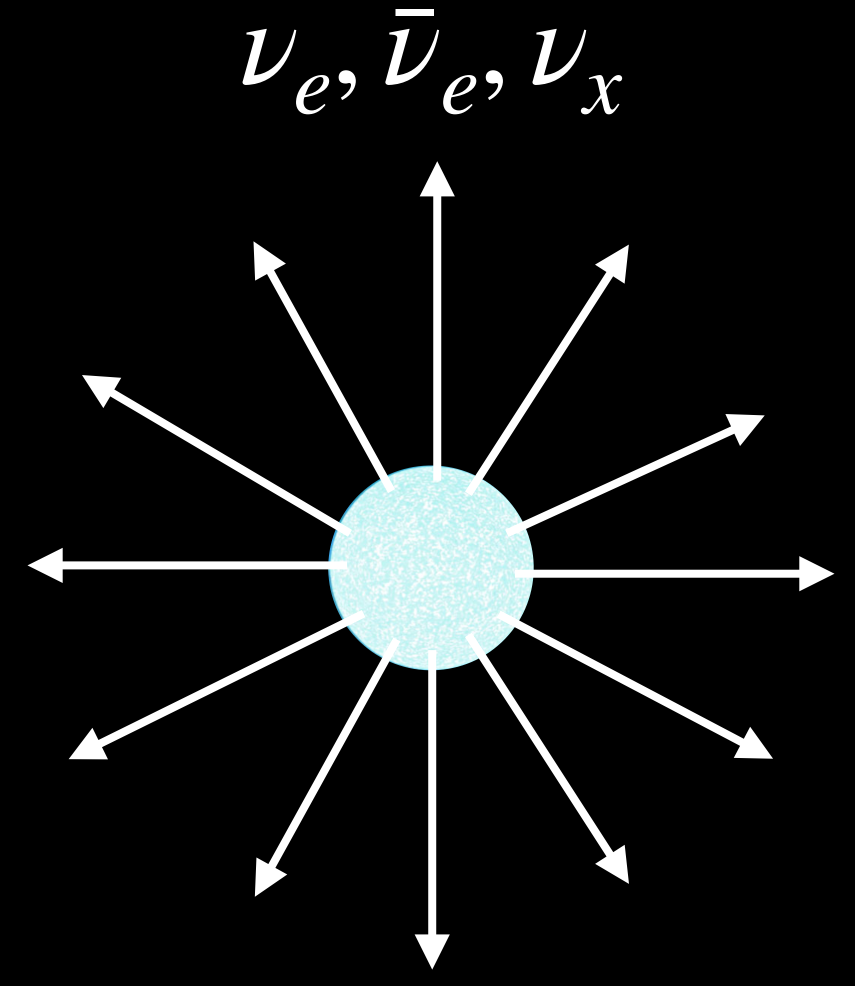
Counting supernova neutrinos

A first-hand account of the core-collapse process

H.T. Janka, [arXiv:1702.08713]







Neutronization burst

Nuclear dissociation

$p + e^- \rightarrow \nu_e + n$

Accretion

Photon conversion

$e^\pm$ capture on nucleons

Cooling

Neutral current interactions

$n \rightarrow \nu\bar{\nu} + n$

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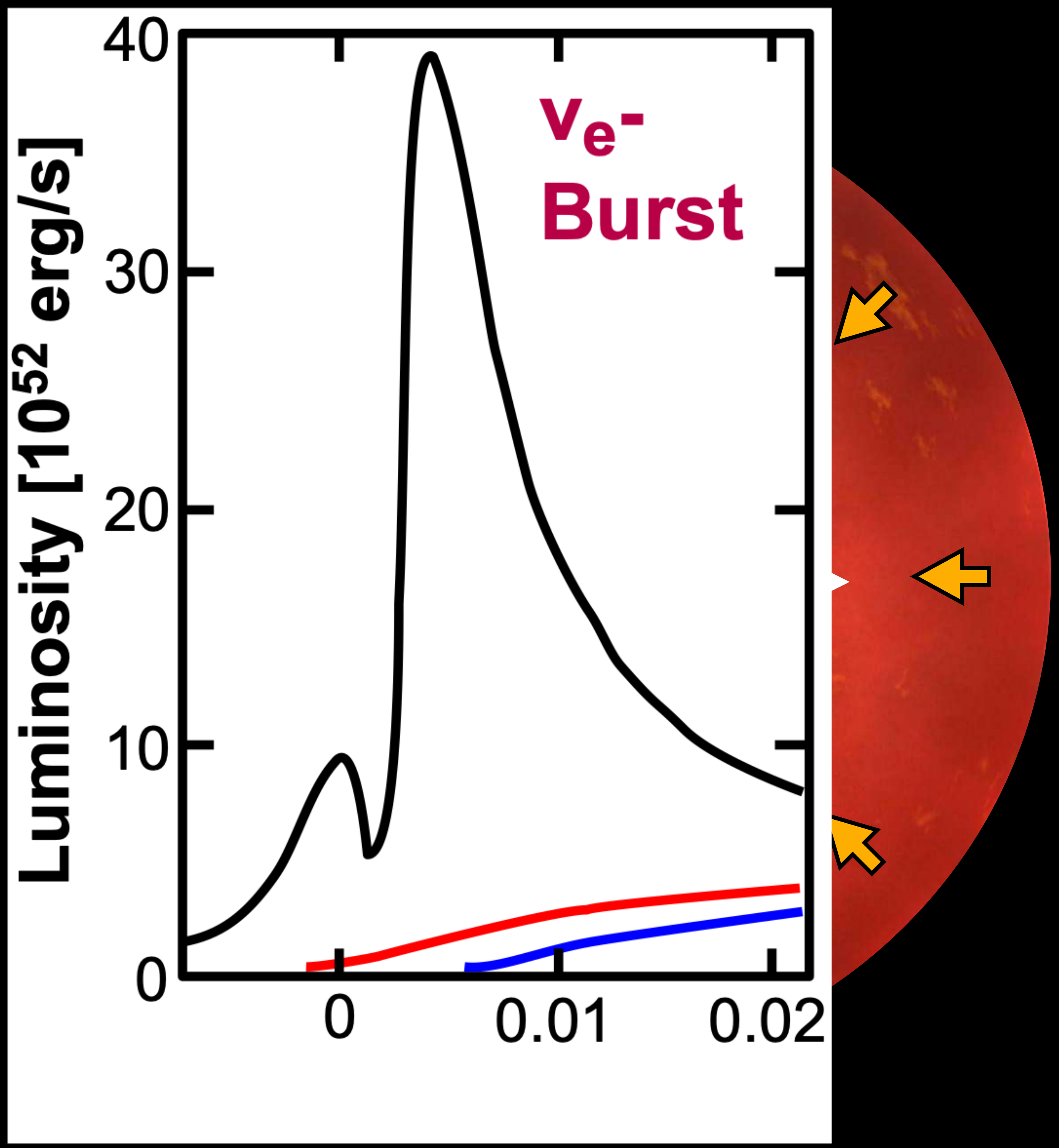

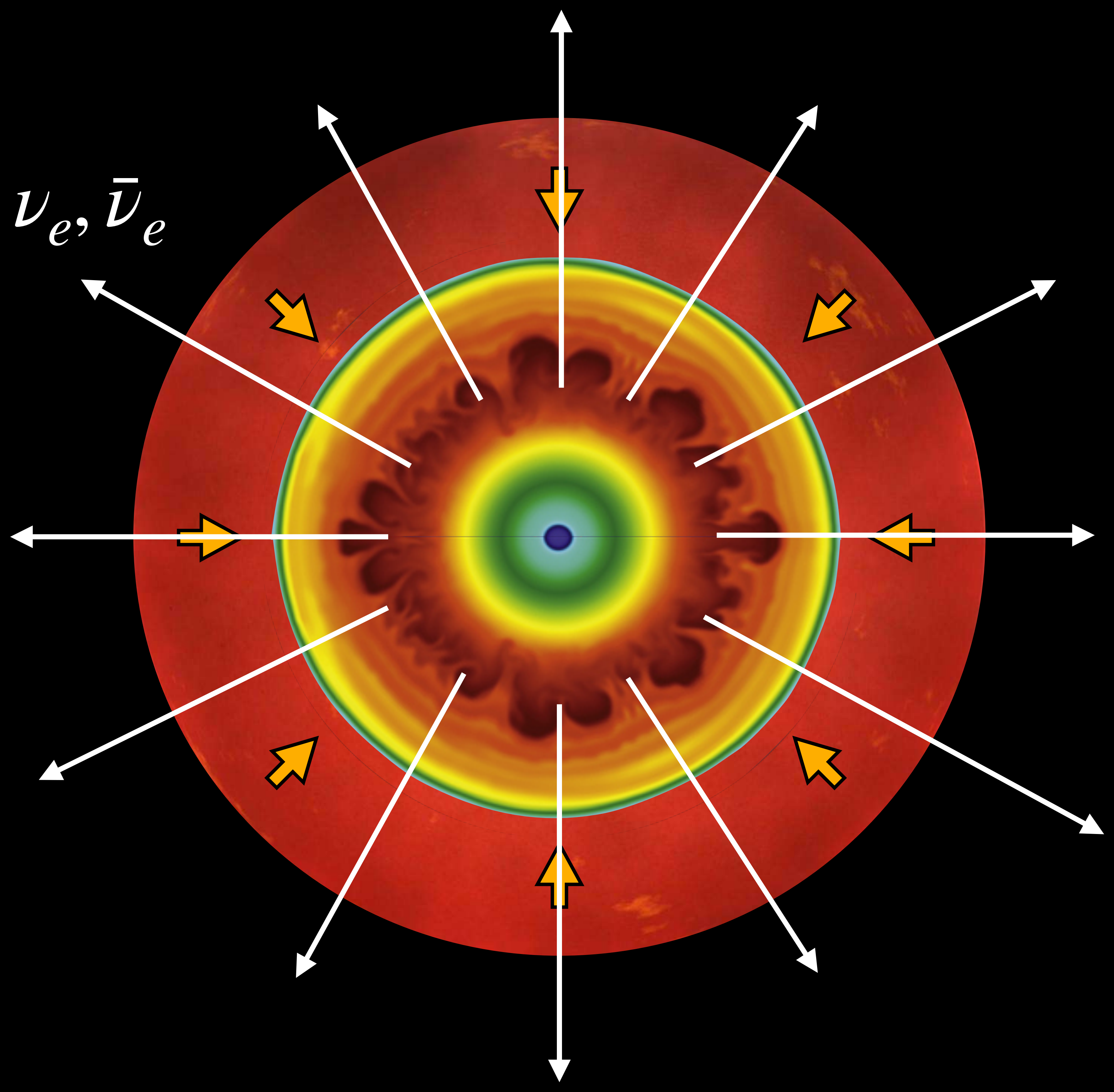

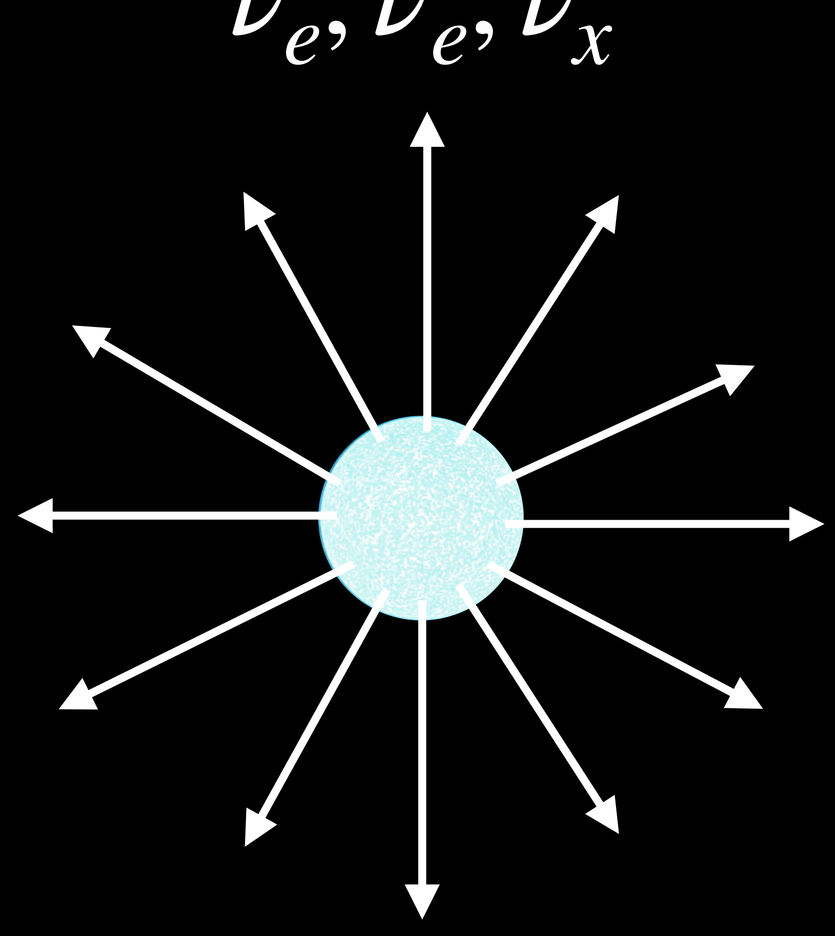

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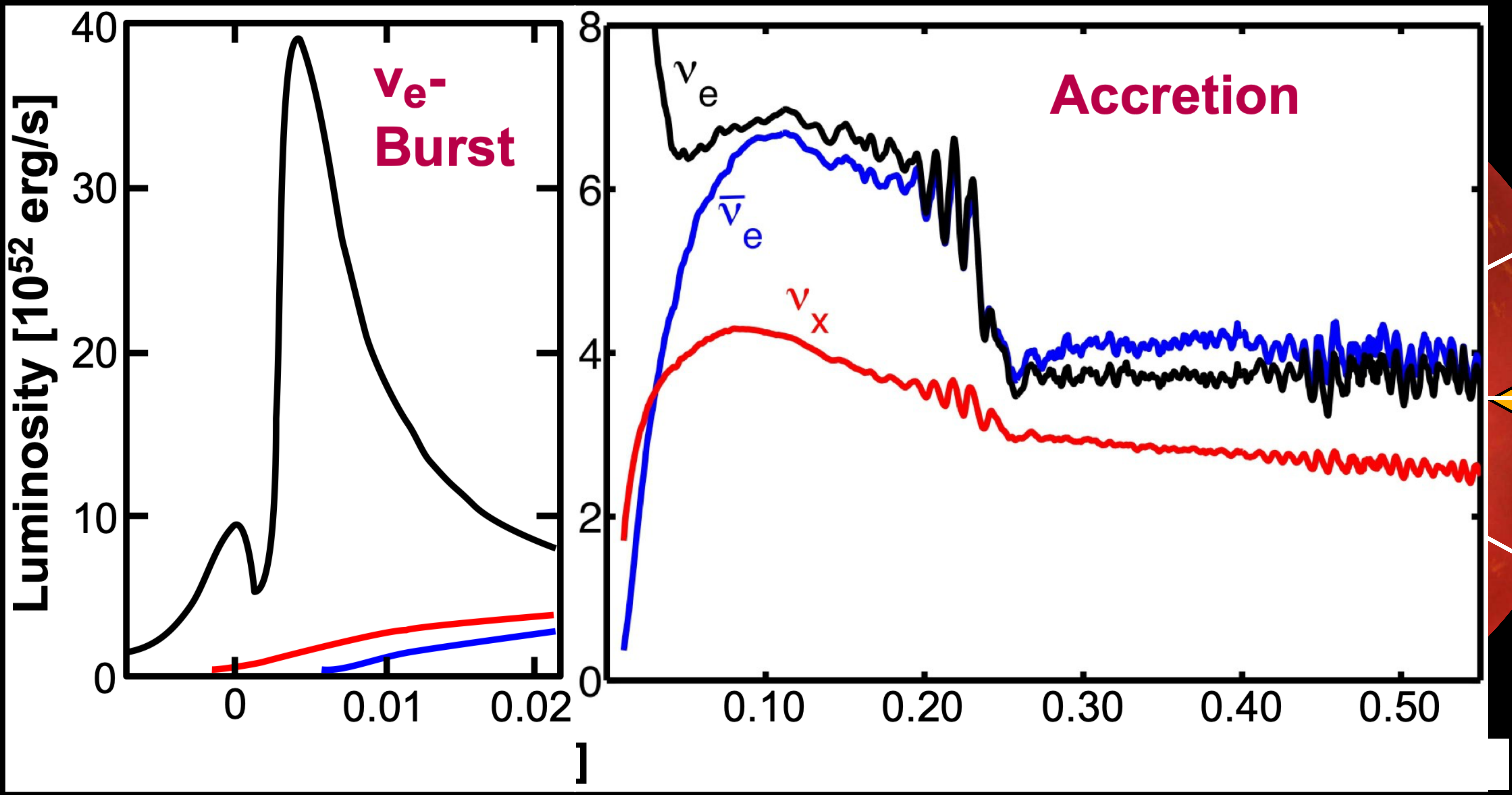

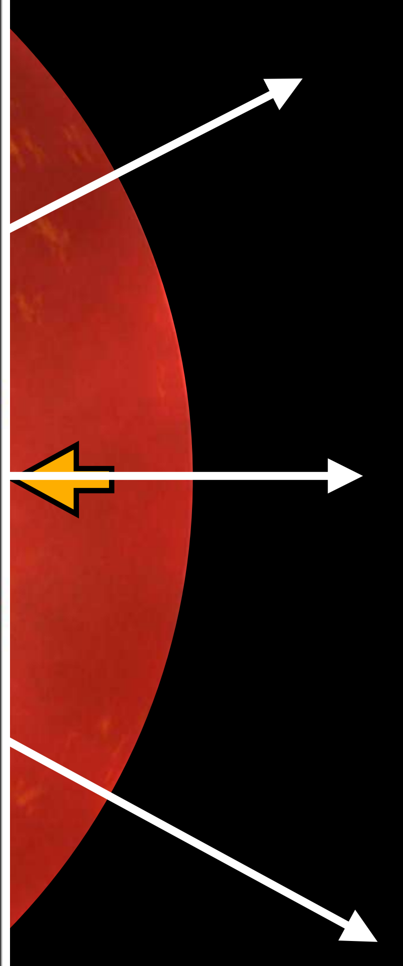

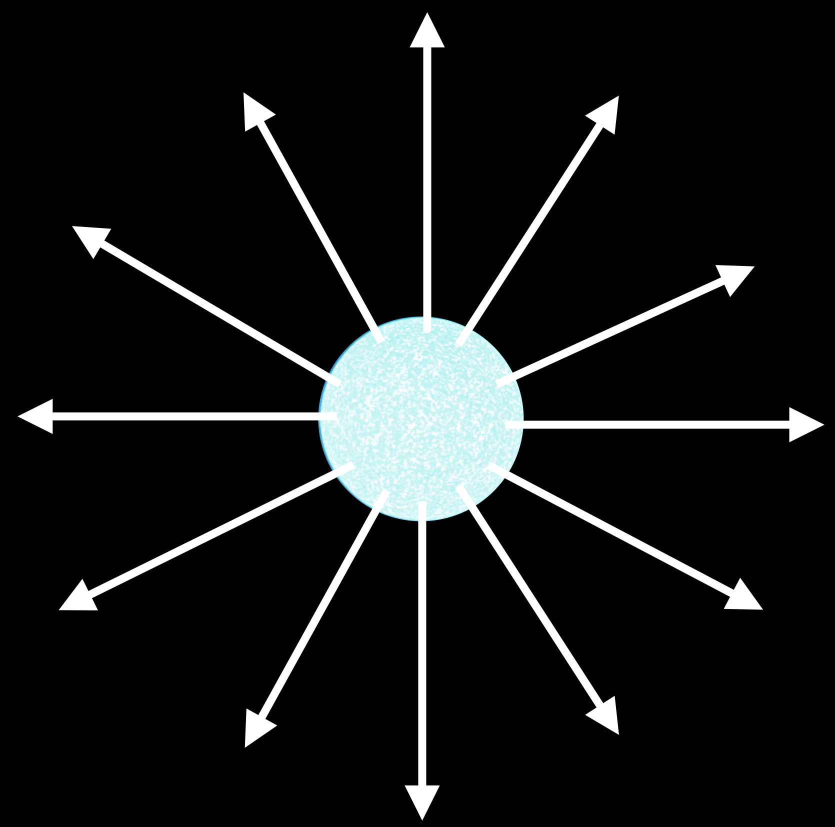

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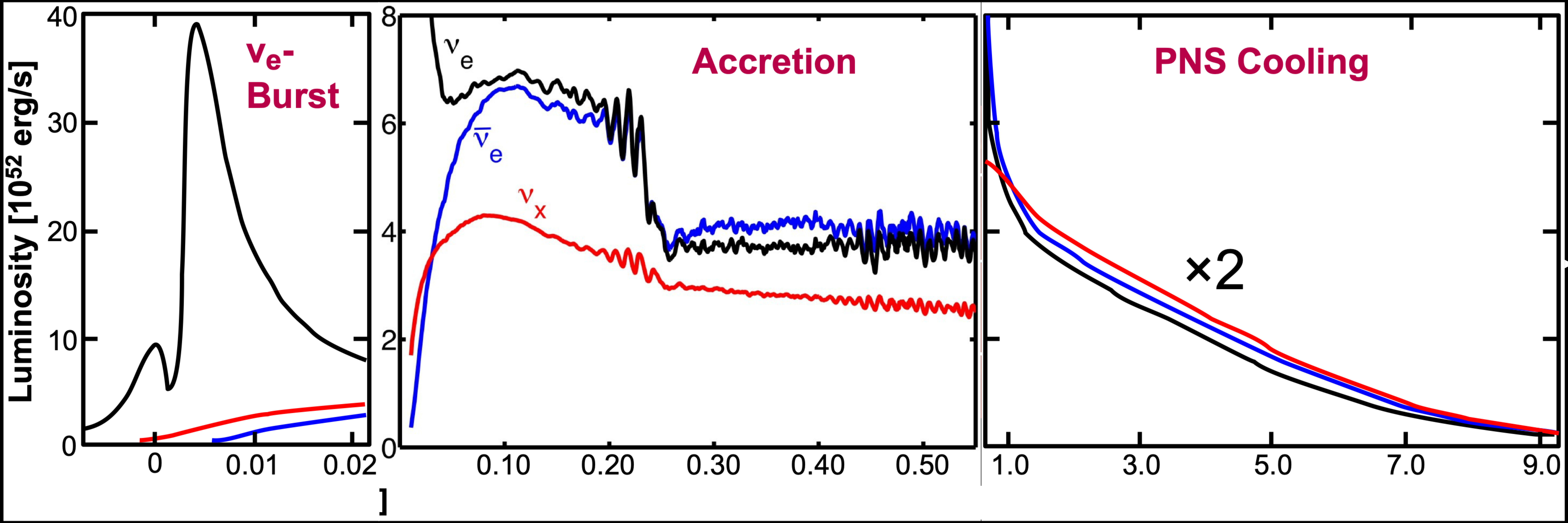

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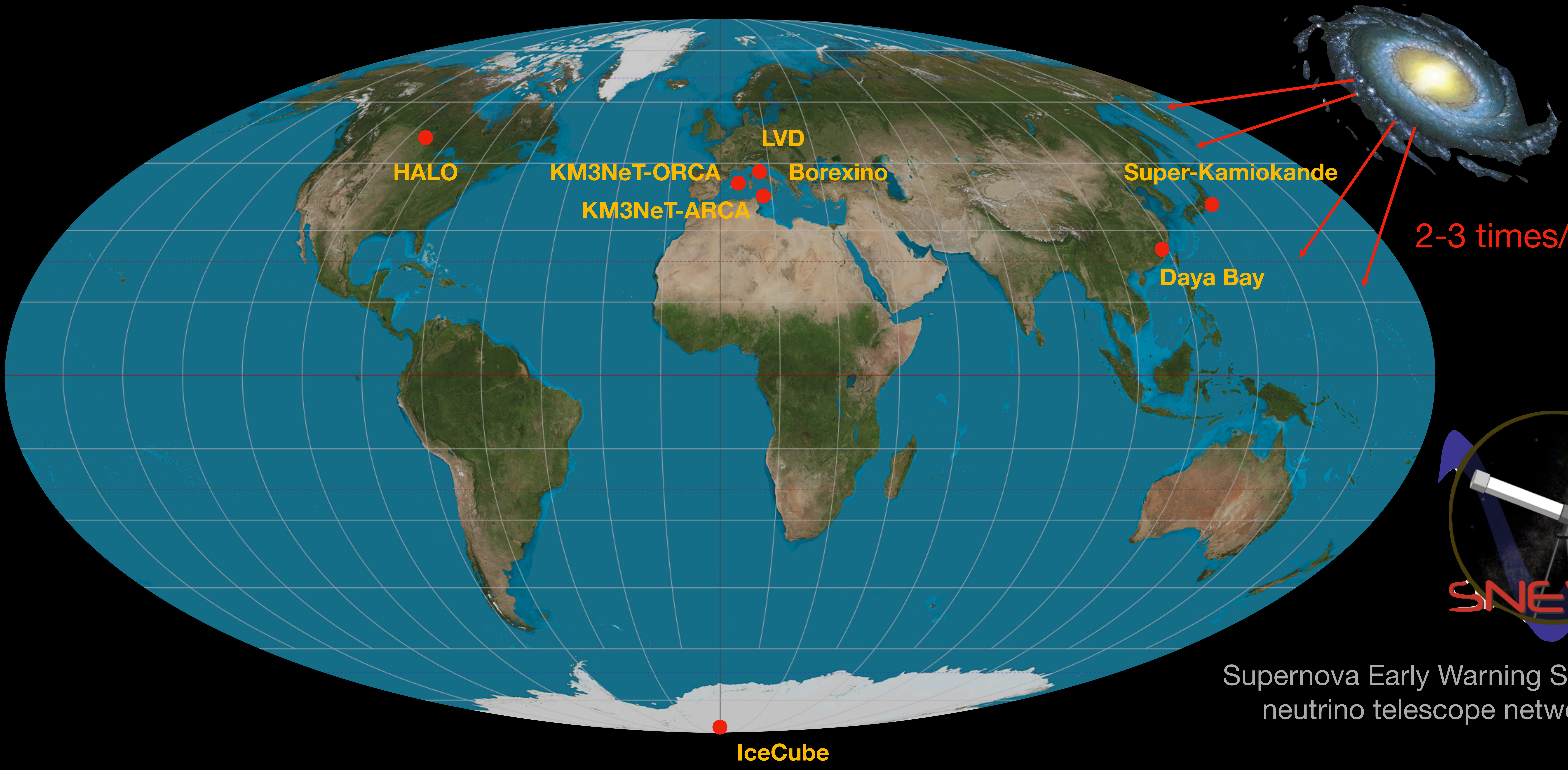
Neutrino telescope networks

Capturing an extremely rare and short event

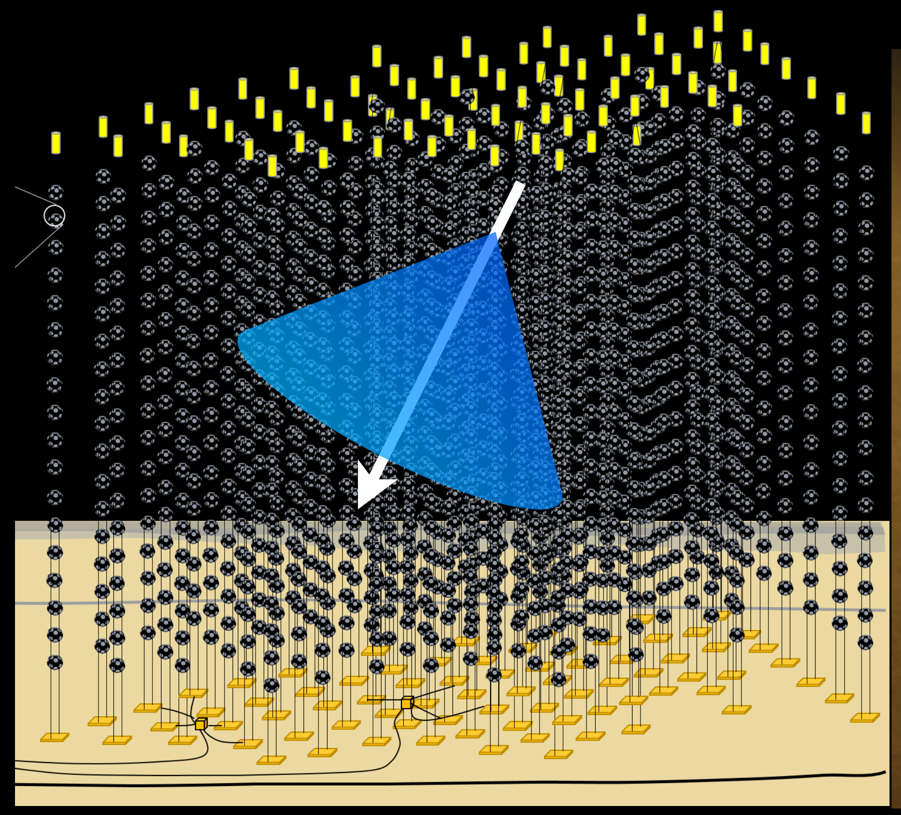


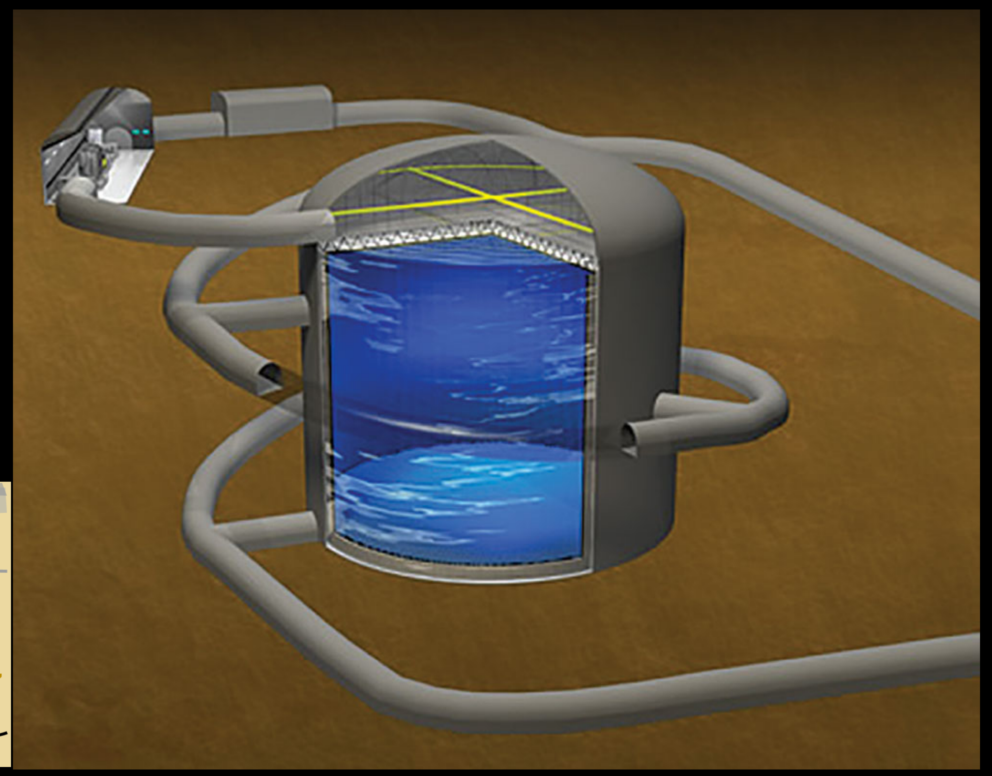
Supernova Early Warning System
neutrino telescope network

Next-generation experiments: 3-flavor sensitivity

Water Cherenkov detectors

Sensitivity to $\bar{\nu}_e$





KM3NeT, IceCube, Hyper-Kamiokande

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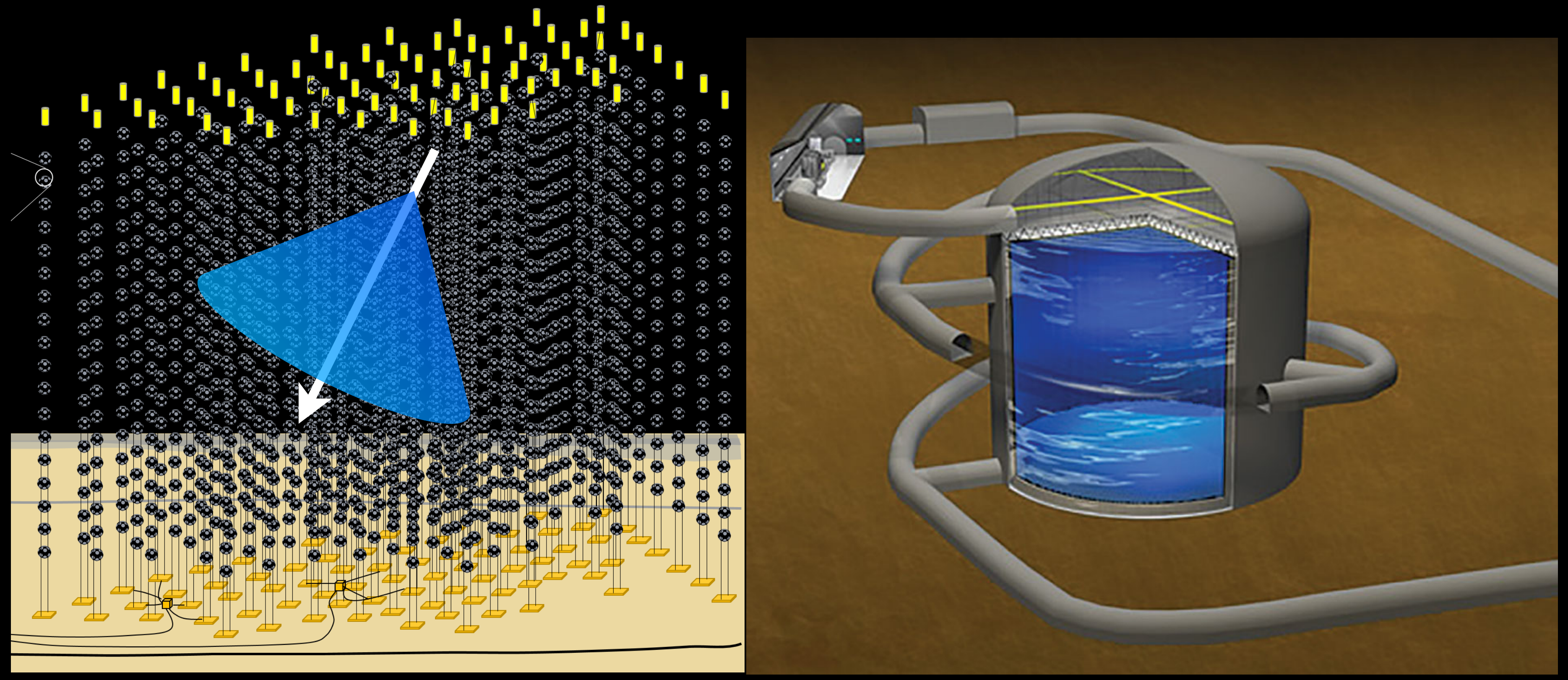
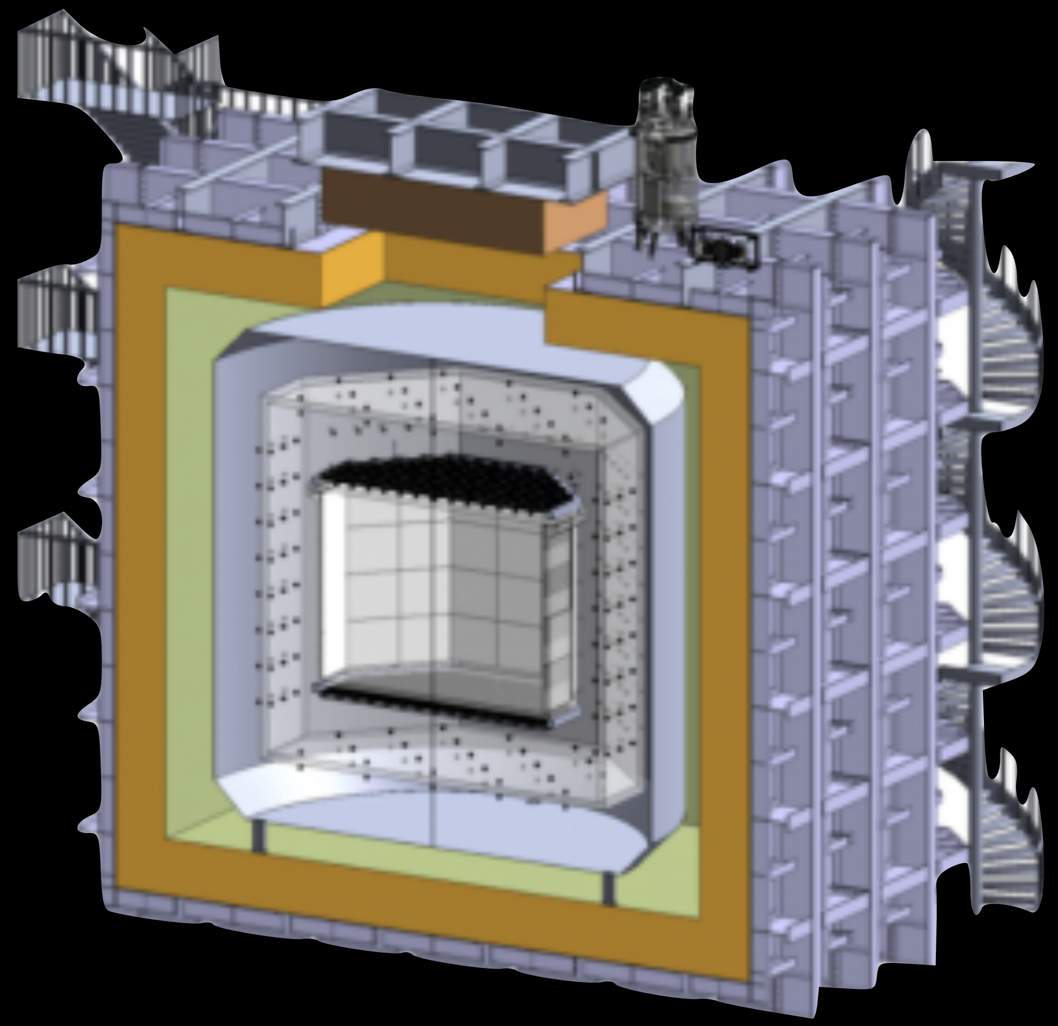
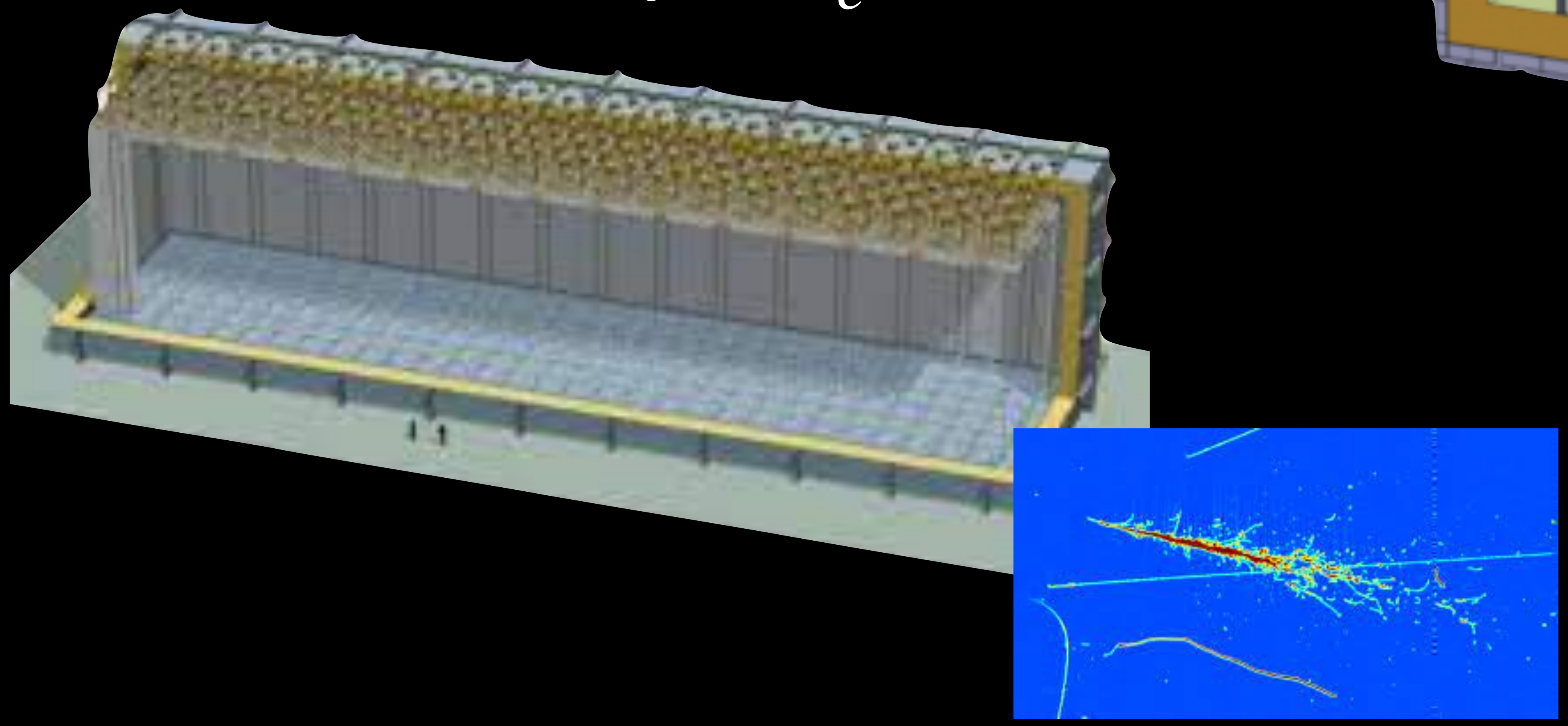


KM3NeT, IceCube, Hyper-Kamiokande

DarkSide-20k, ARGO
Sensitivity to all ν

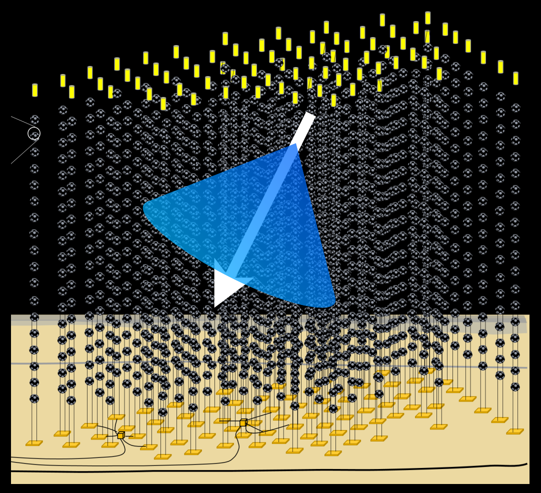


DUNE
Sensitivity to ν_e



The LEAK project

KM3NeT



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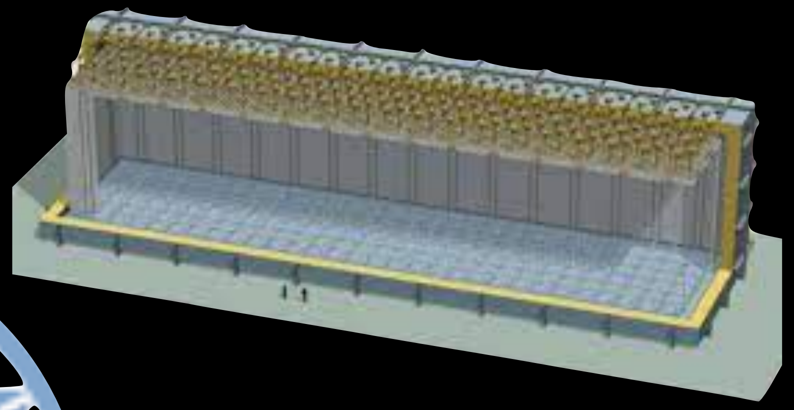
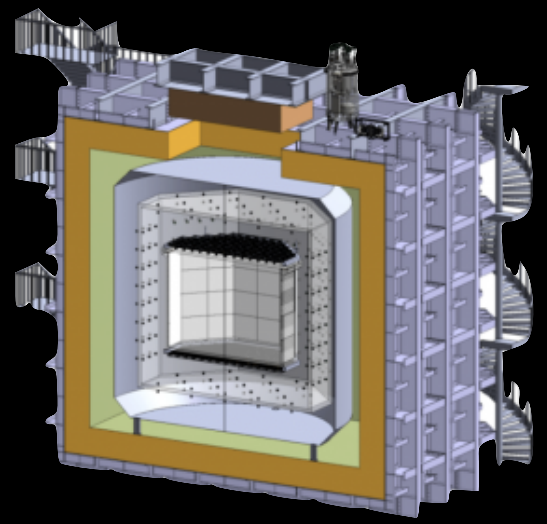
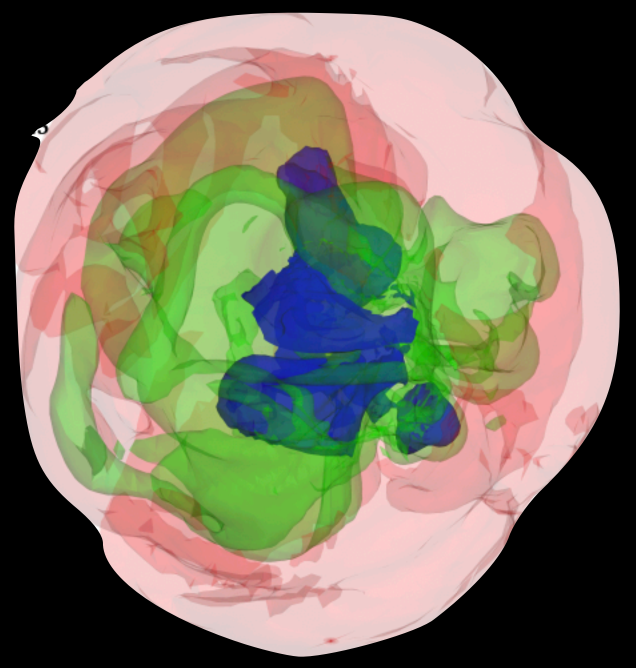




DarkSide-20k

CCSN simulations

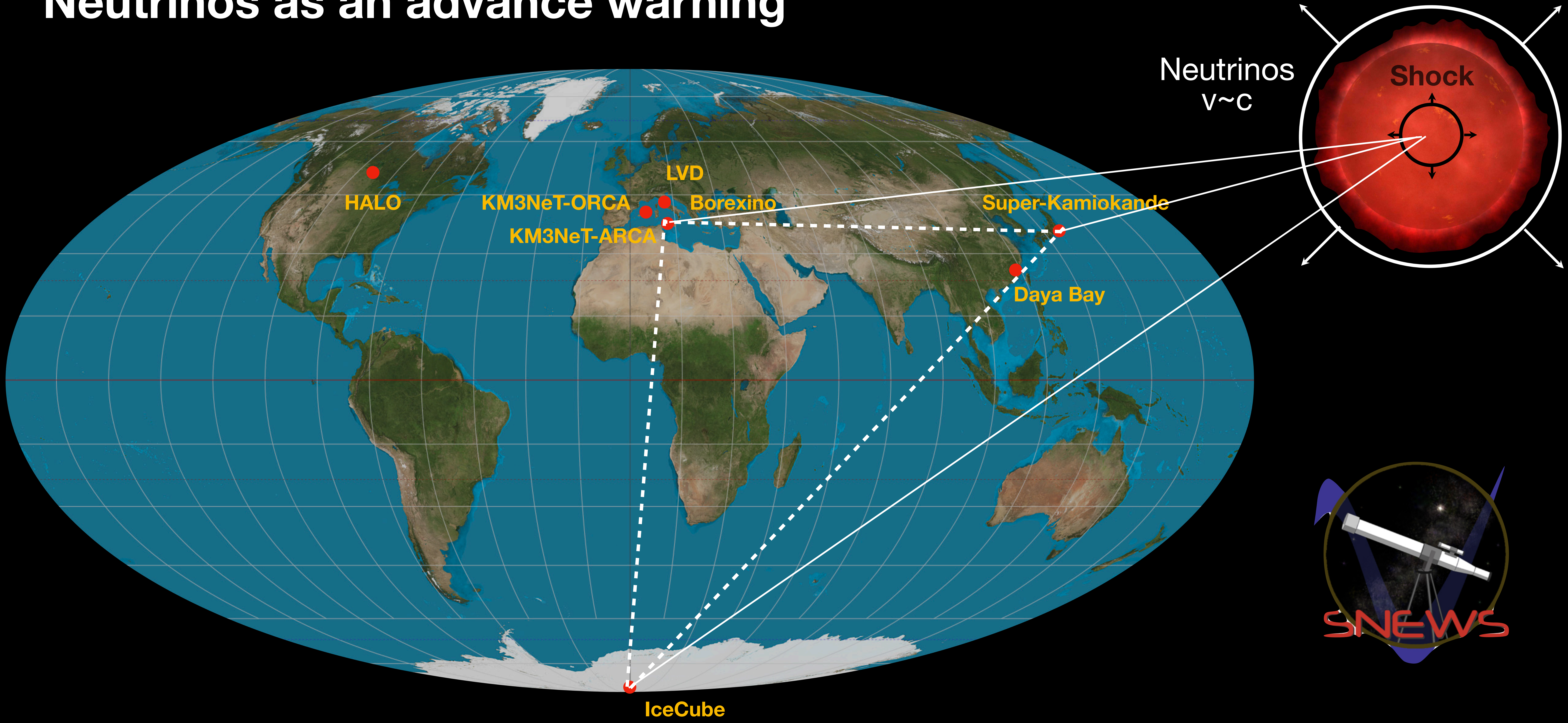


M. Bugli et al
Mon. Not. Roy. Astron. Soc. 507 (2021) 1

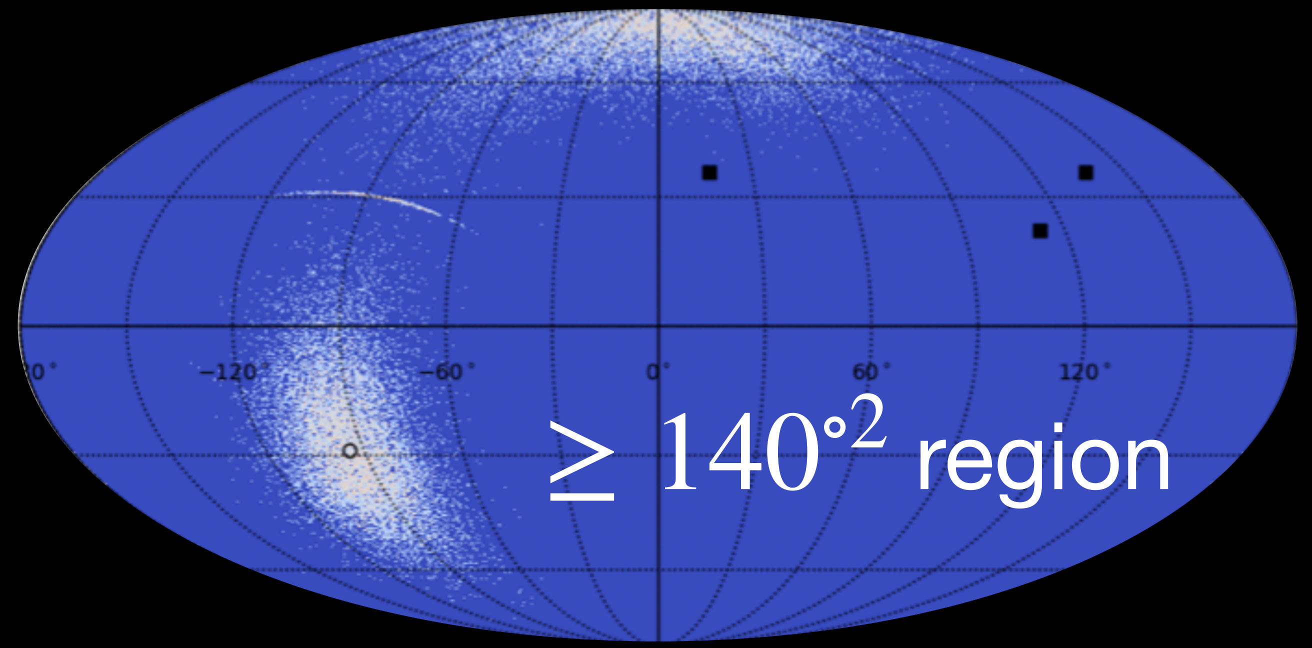
CCSN modelling

Locating a supernova

Neutrinos as an advance warning

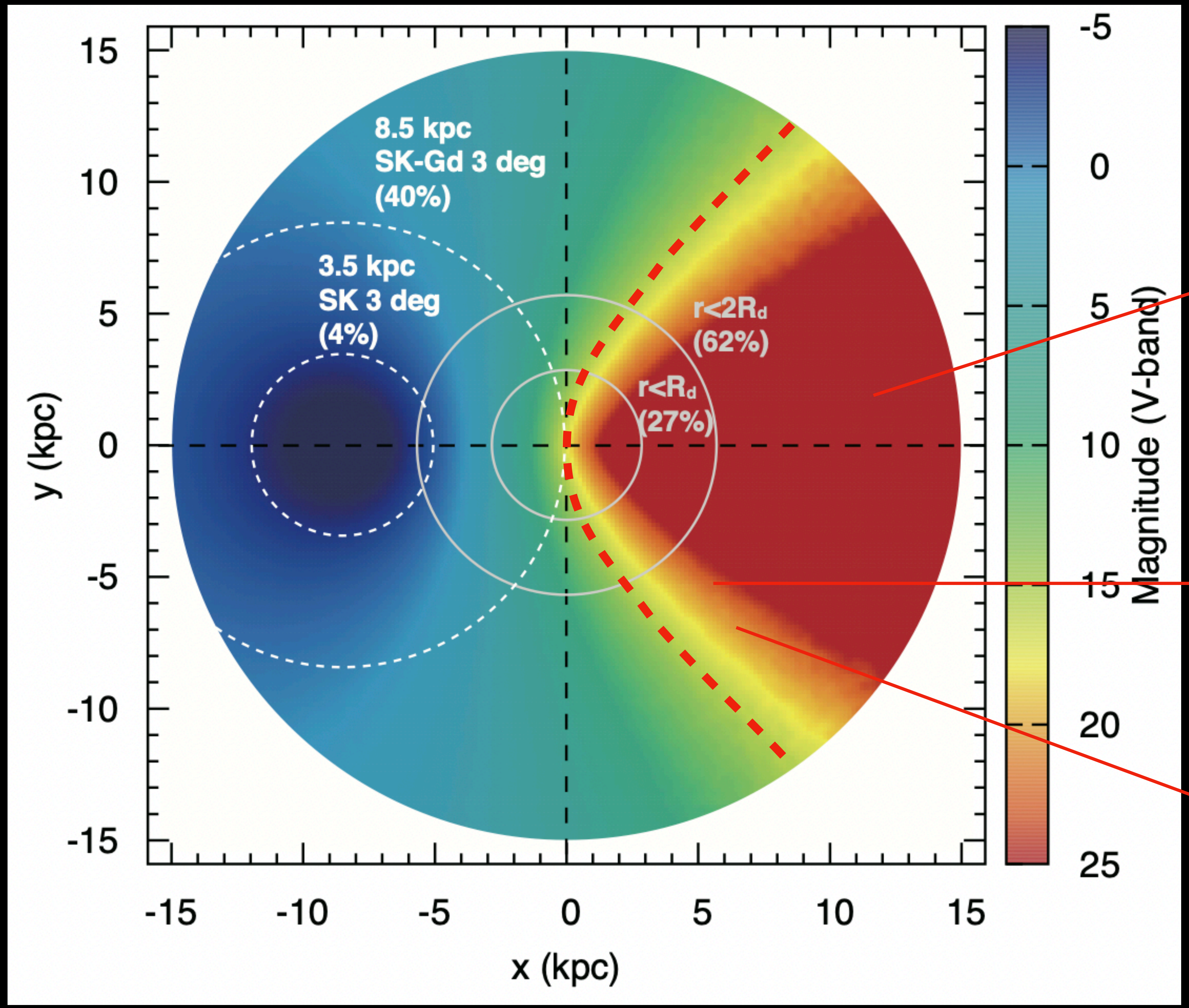


Evaluating the CCSN's visibility



A. Coleiro et al, Eur. Phys. J. C 80 (2020) 9

Evryscope
Field of view 100°
Mag $\lesssim 15$



IR telescopes
Non-prompt emission

LSST, CFHT
Field of view $1-2^{\circ}$
Mag $\lesssim 24-25$

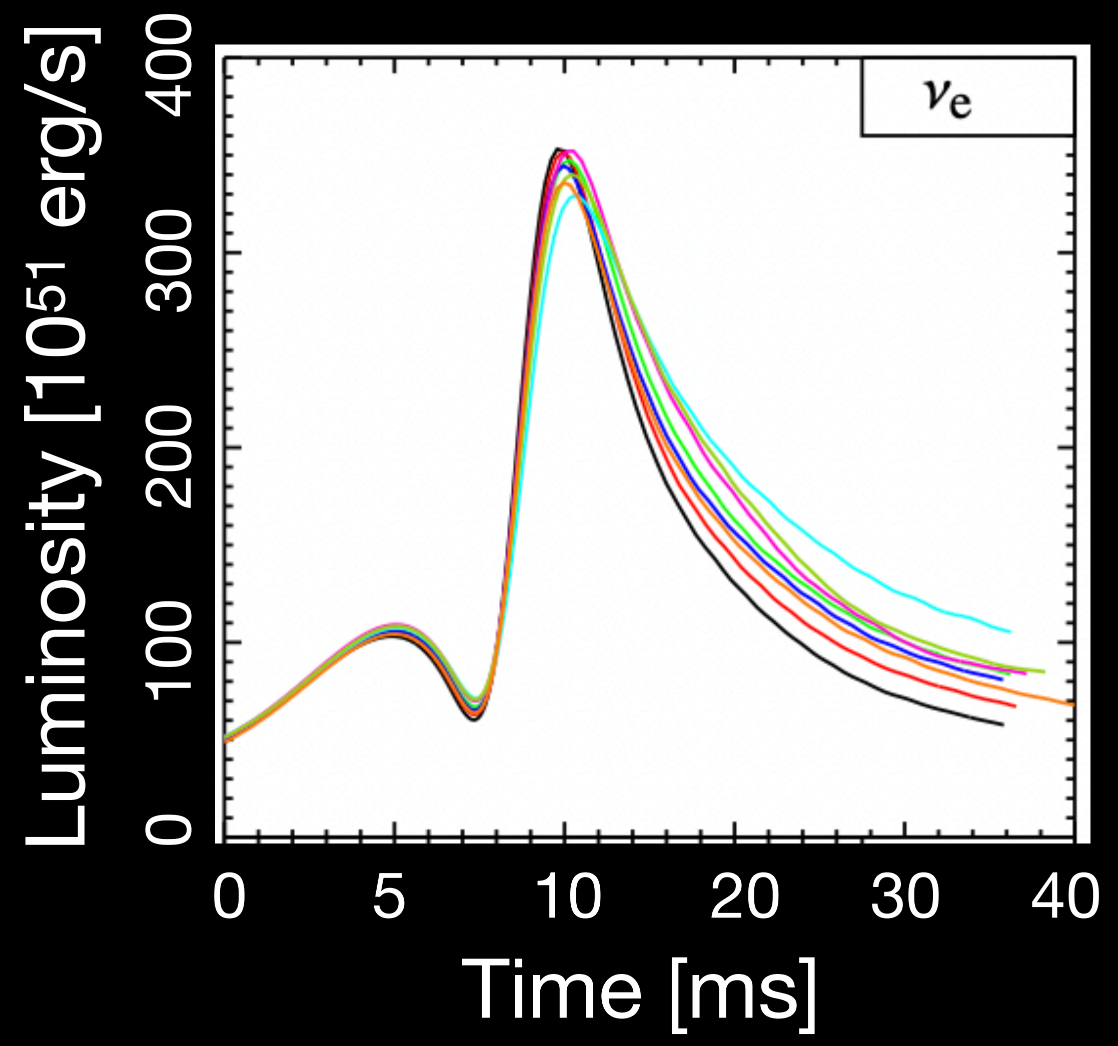
ZTF
Field of view 6°
Mag $\lesssim 21$

K. Nakamura et al, Mon. Not. Roy. Astron. Soc. 461 (2016) 3

Standard candles for CCSN distance estimates

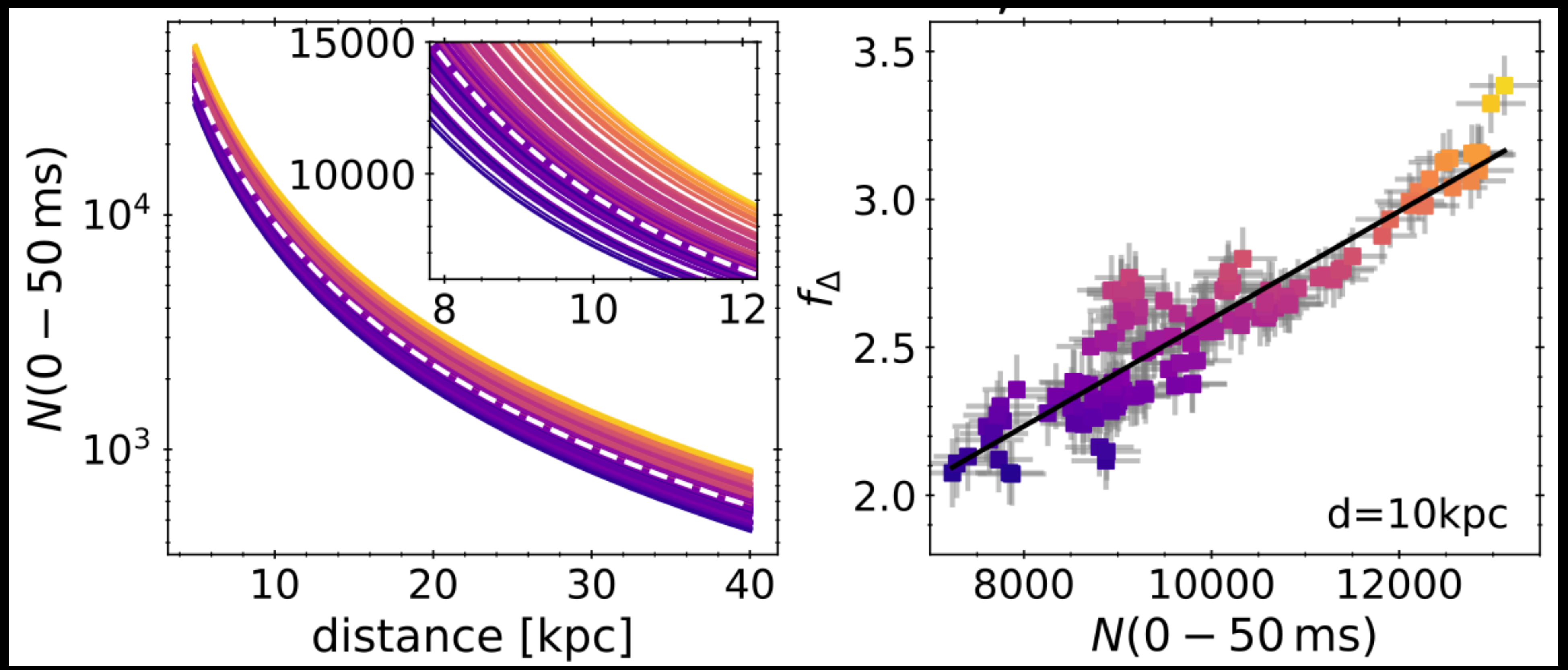
Neutrino rates in the neutronization phase

M. Kachelriess et al
Phys. Rev. D 71 (2005) 063003



- Neutrino rates in the first 10s of ms after CCSN onset : weak dependence in CCSN model
- Trade off between statistical uncertainties and model-related uncertainties

- Current window at SNEWS: 0-50 ms
- Add 100-150 ms window to reduce residual CCSN model dependence



M. Segerlund et al [arXiv:2101.10624]

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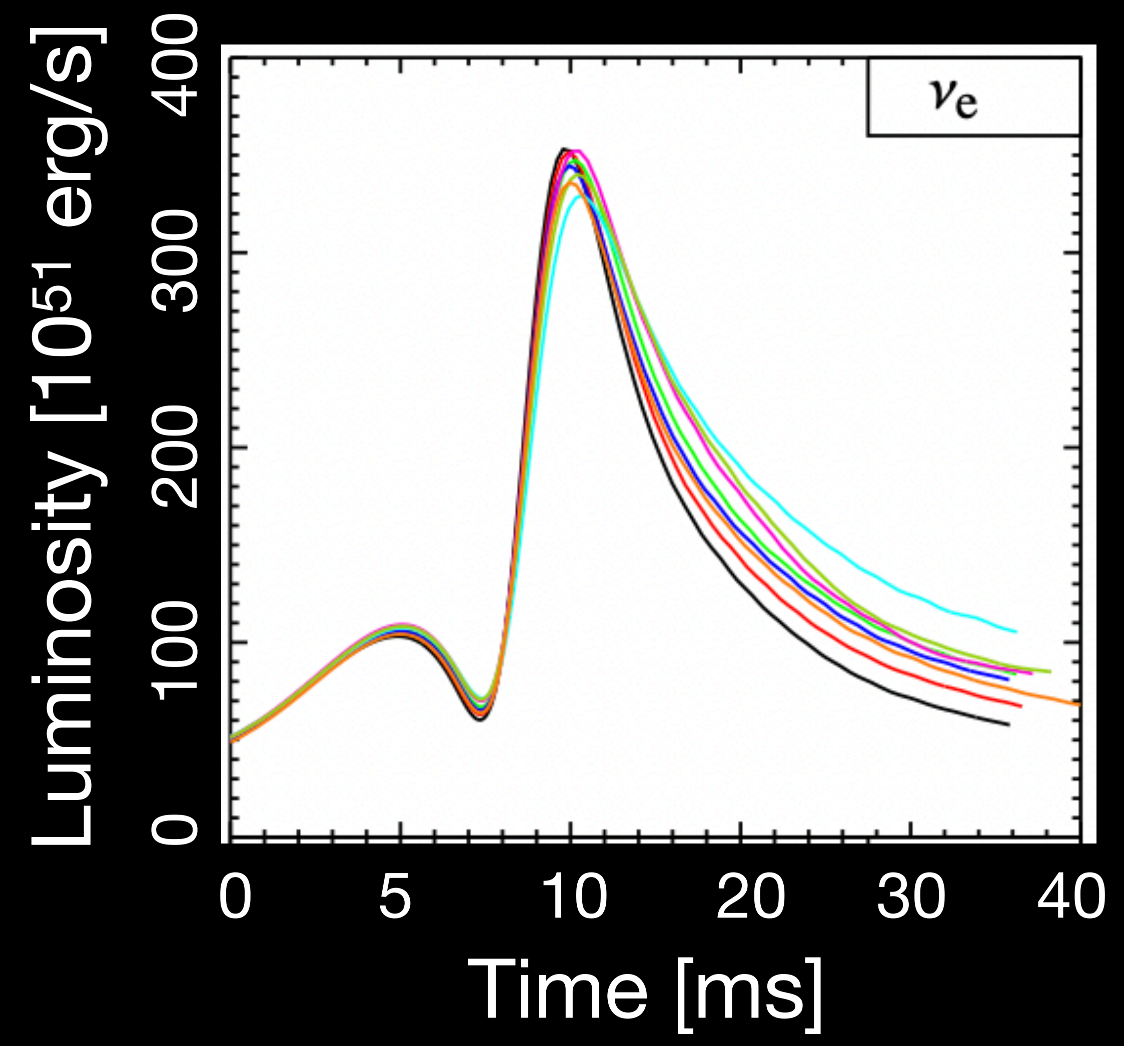

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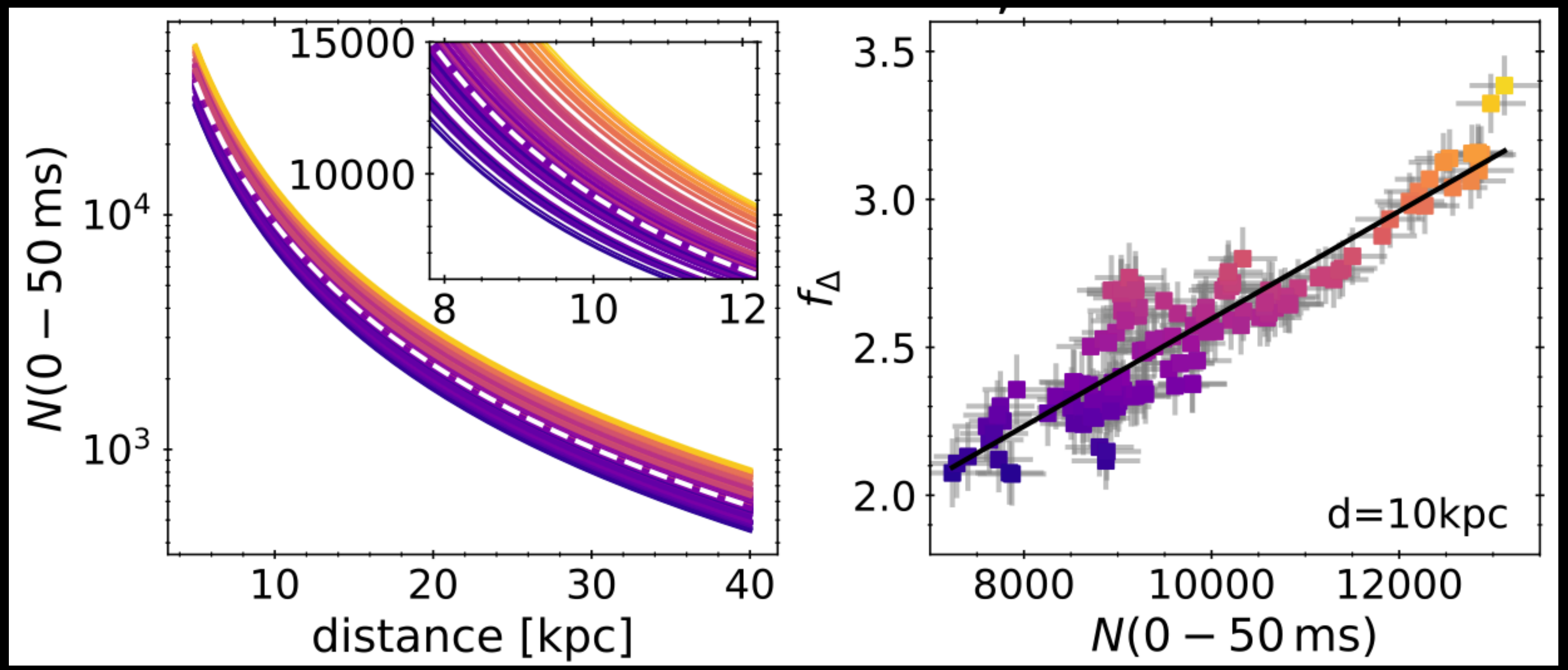

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“Not-so-standard” candles

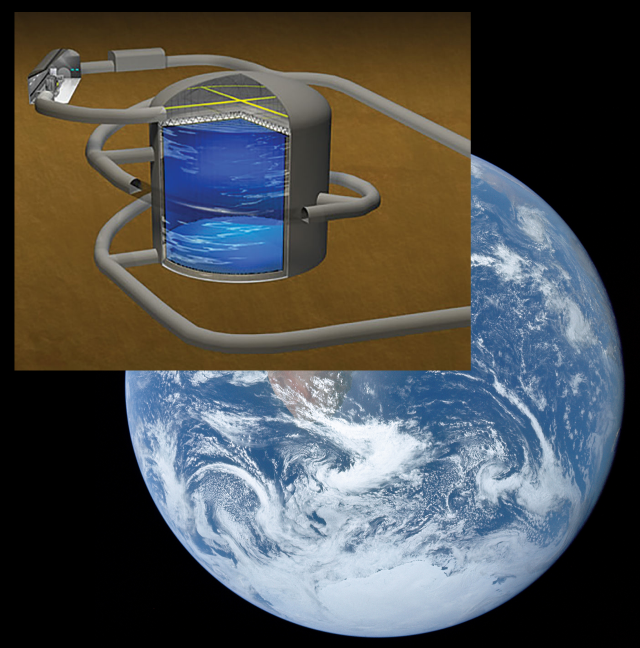
Distance estimates could be biased in the presence of new physics

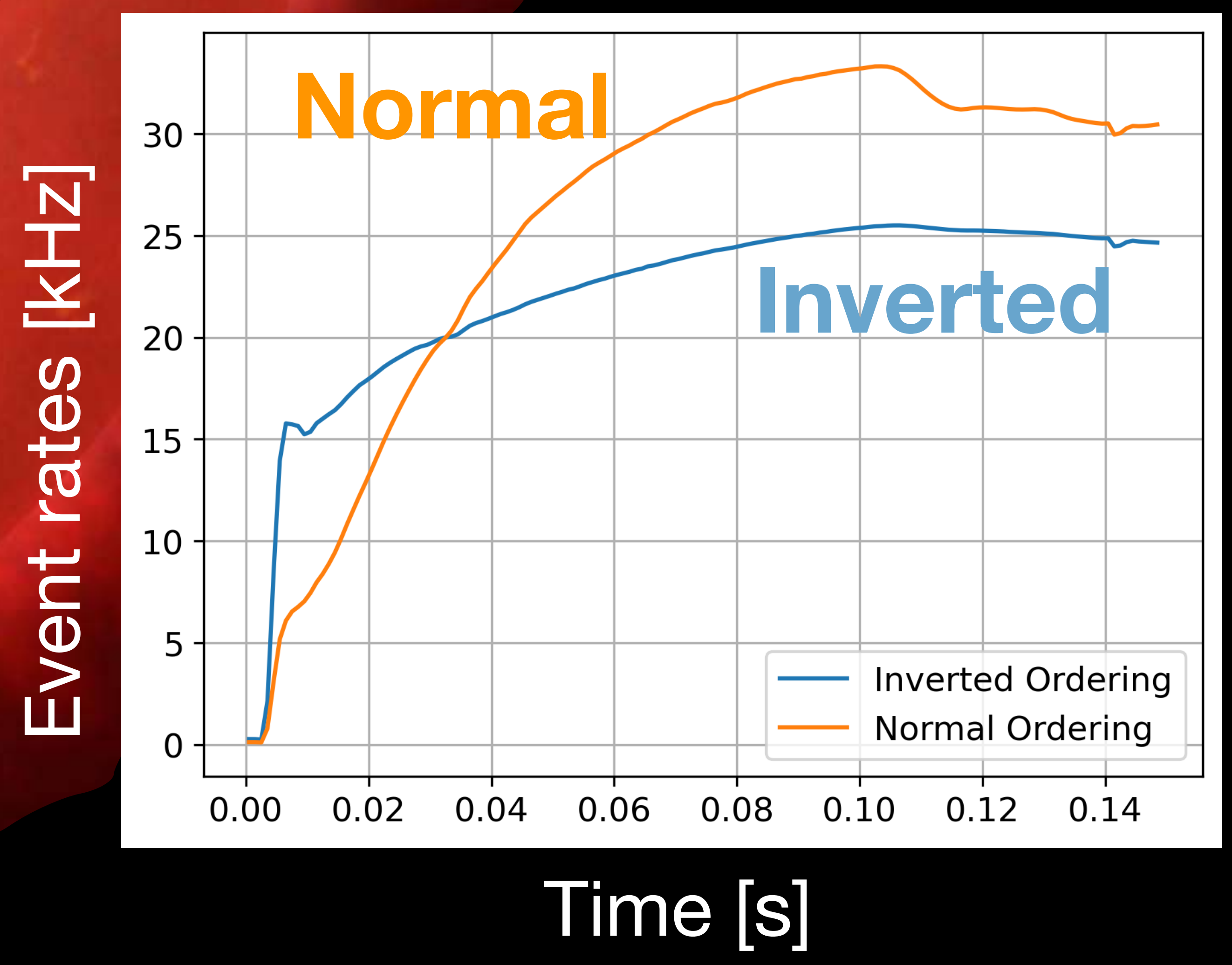
Mykheev-Smirnov-Wolfenstein “MSW” resonance(s)

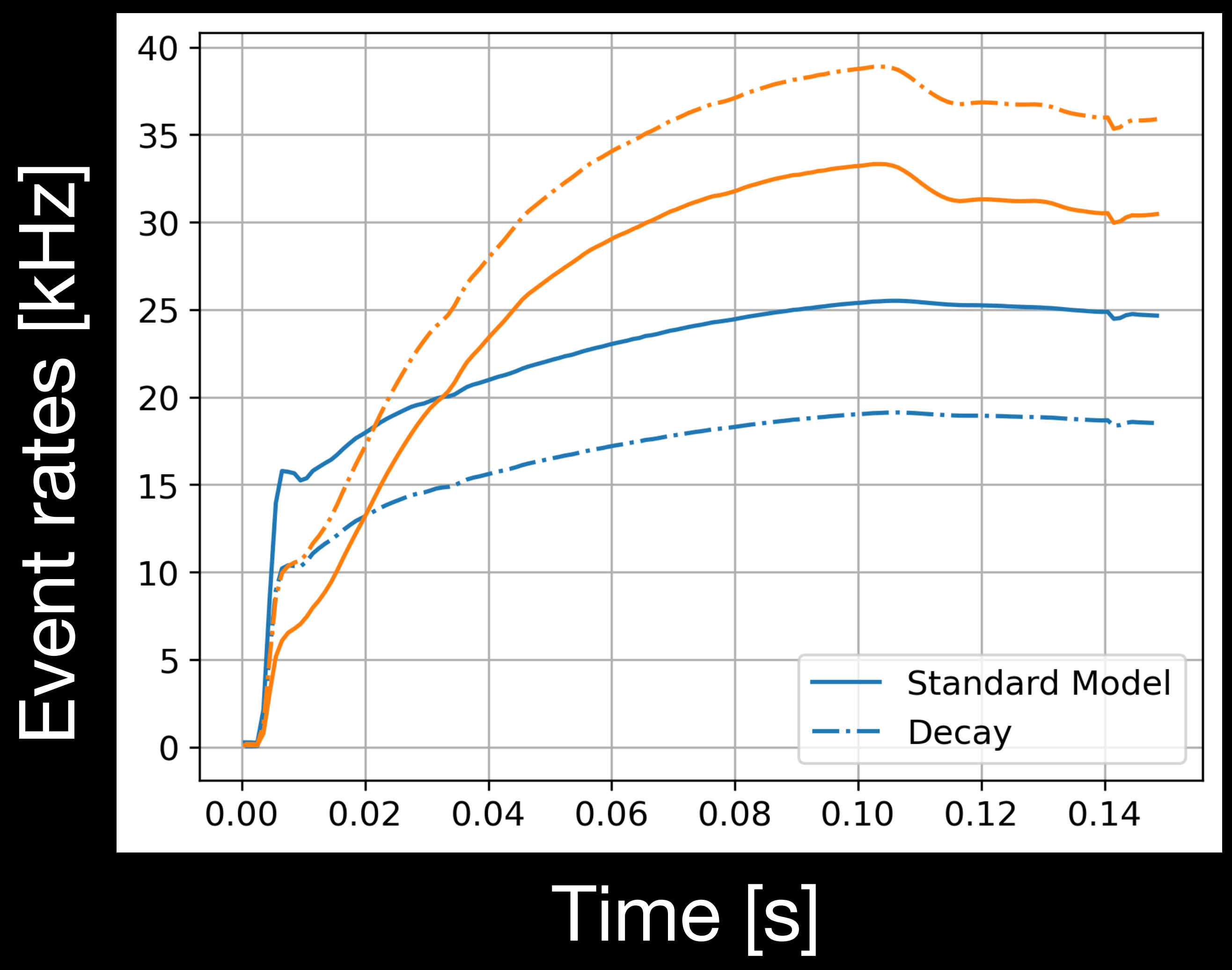
Neutrino two-body decays

$$\nu_h \to \nu_\ell + \phi$$

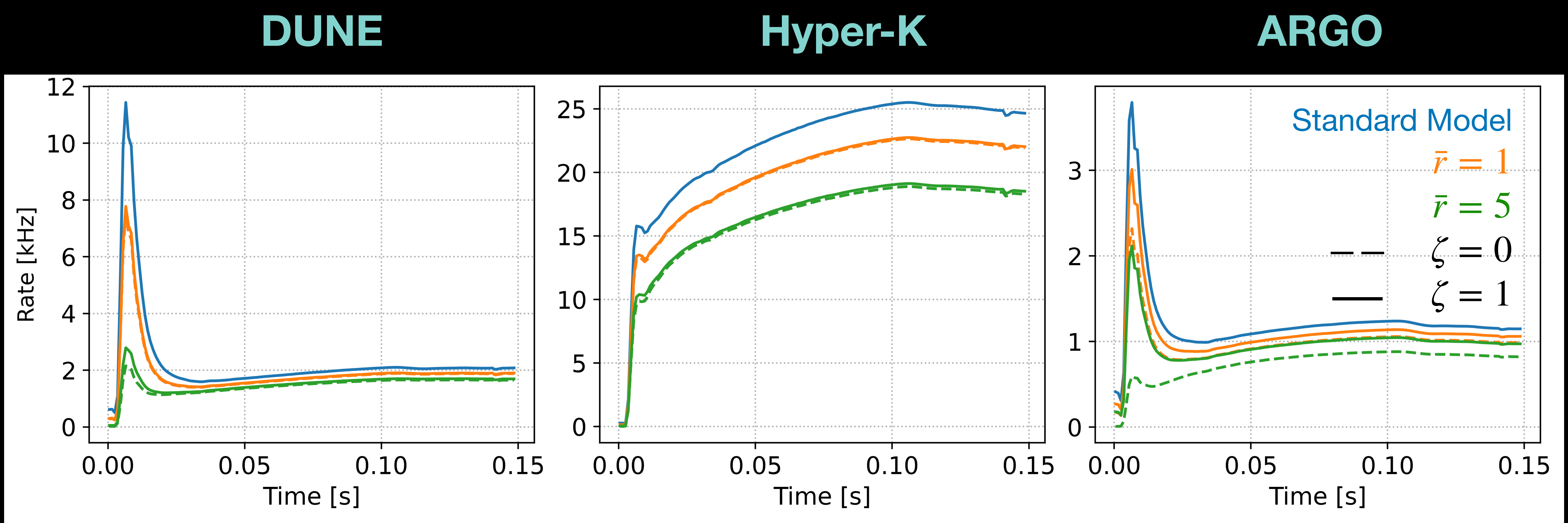
Hyper-K







Catch new physics by combining detectors



$\bar{r} = \frac{\text{distance}}{r_{\text{decay}}}$

ζ = branching to active νs

- Water Cherenkov: neutrino decays indistinguishable from distance change
- DUNE, ARGO: less statistics but significant shape distorsions
- DUNE + ARGO + HK: measure the CCSN distance AND identify new physics

Fitting early neutrino rates @ multiple detectors

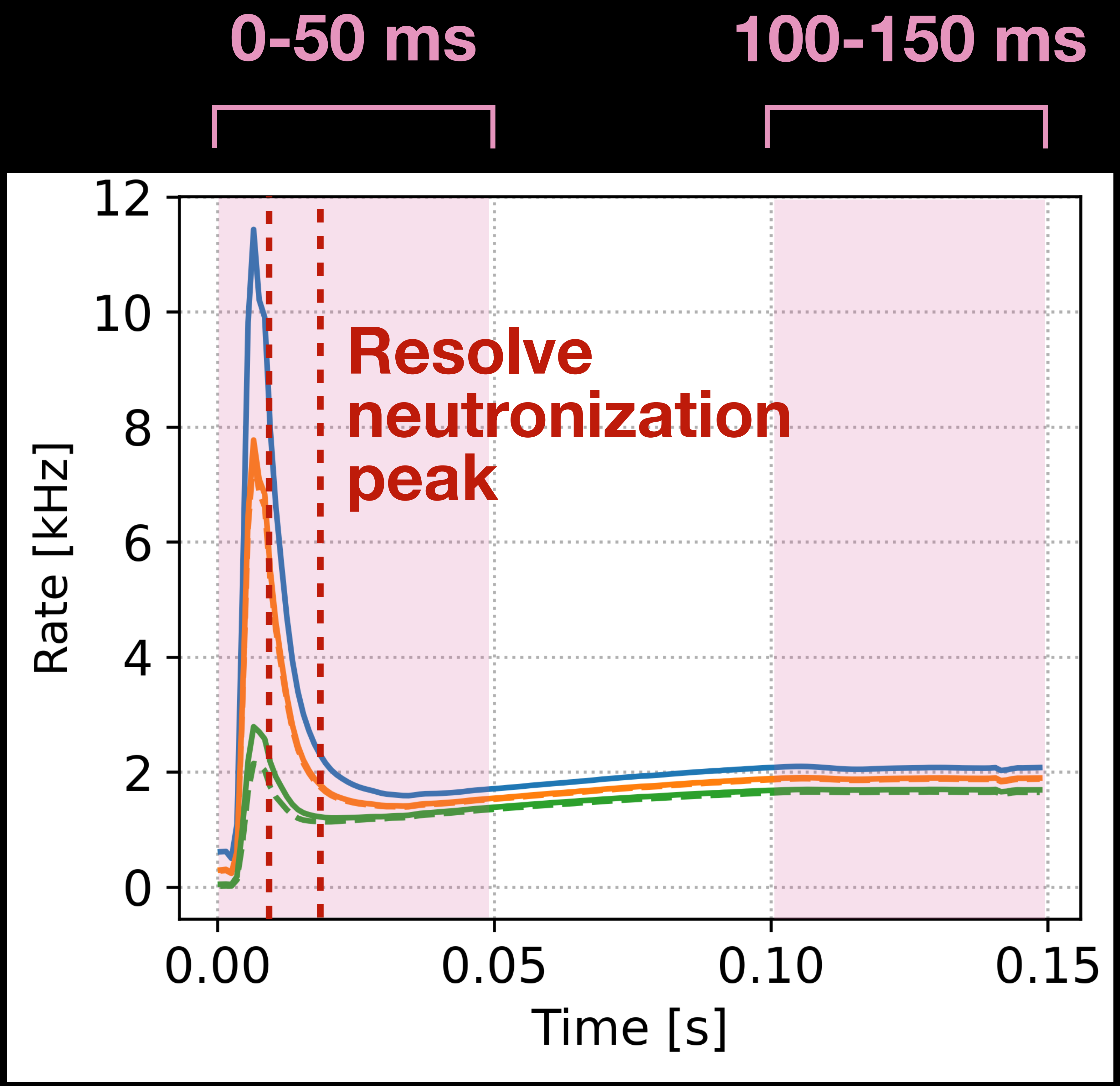
Simultaneously estimate the CCSN distance & neutrino properties

- **CCSN models:** 149 models, 9 to 120 $M_\odot$
  M. Segerlund et al, arXiv:2101.10624

- **Detection rates:** SNEWPY & SnowGLoBES

- **Time windows:** [0,10], [10,20], [20,50] ms
  + [100,150] ms to constrain CCSN model

- **Likelihood function:** rates for all time windows and detectors



Neutrino properties: mass ordering

- Evaluate **rejection probability** of the NMO (IMO) if the IMO (NMO) is true

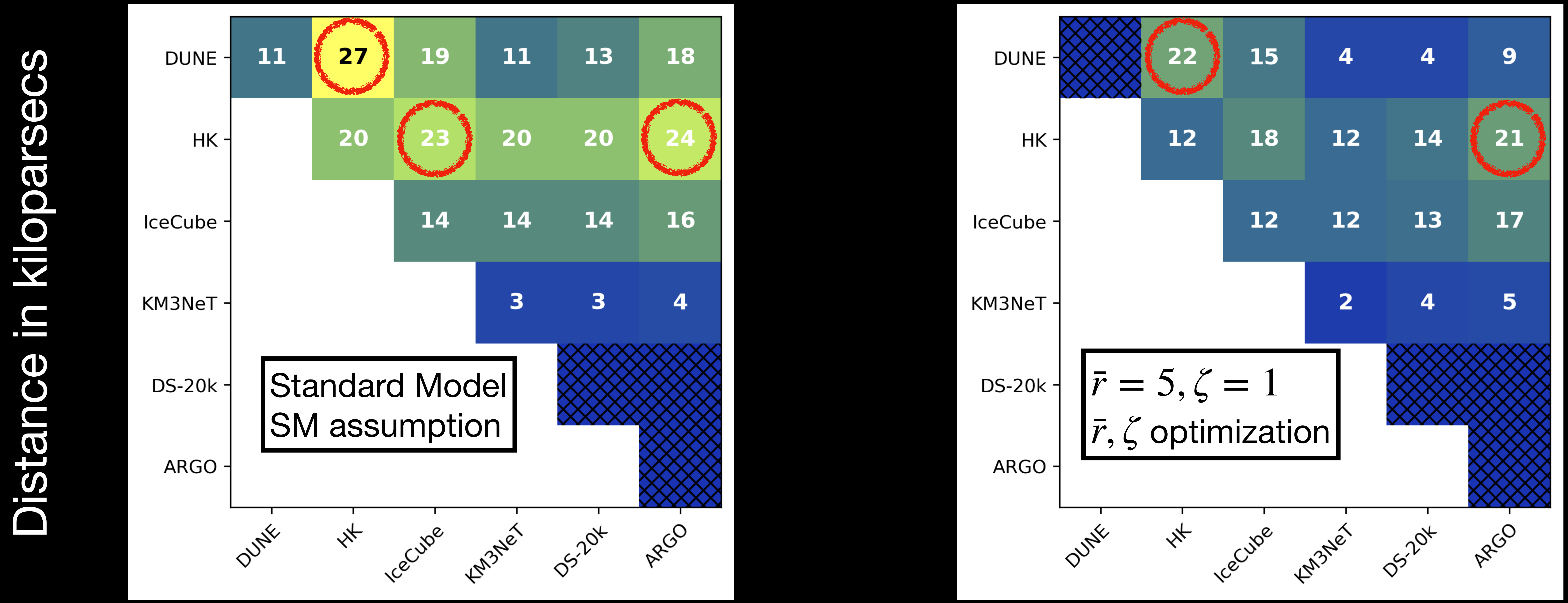
Test statistic $$t = \frac{\max_{d,M,\bar{r},\zeta} \mathscr{L}(\mathcal{O}_{\text{obs}} \,|\, d, M, \bar{r}, \zeta, \text{NMO})}{\max_{d,M,\bar{r},\zeta} \mathscr{L}(\mathcal{O}_{\text{obs}} \,|\, d, M, \bar{r}, \zeta, \text{NMO})}$$

d: CCSN distance
M: CCSN model
$\bar{r}, \zeta$: Decay parameters (fixed if Standard Model assumed)

- **t probability distribution:** quick estimate using hybrid Bayesian-Frequentist method (sample over prior on measurements)

Maximal distance for 3σ IMO rejection

Combine HK with DUNE or ARGO ⇒ sensitivity to >99% of CCSNe

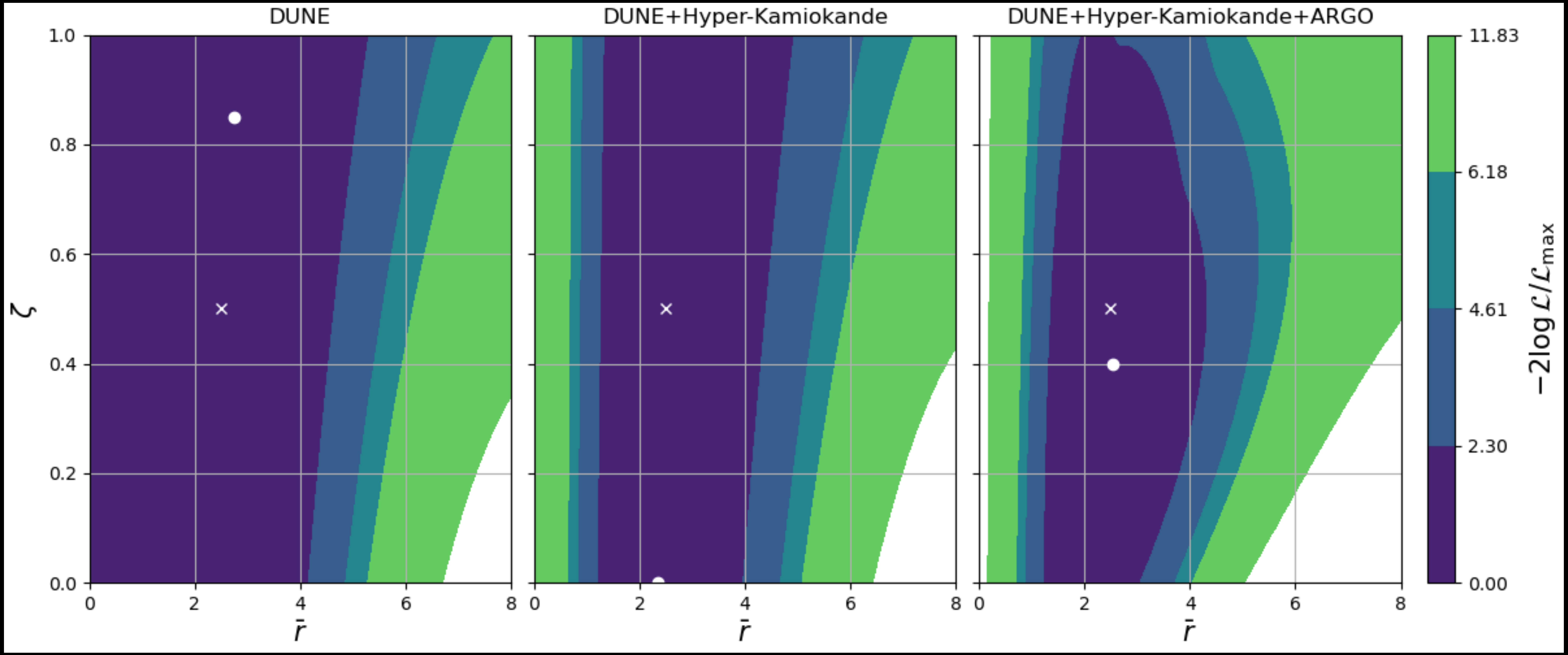


M. Bendahman, I. Goos et al [arXiv:2311.06216]

Constrain neutrino decay parameters

DUNE+HK+ARGO: 3σ exclusion of the SM for $\bar{r} \geq 2.5$ — CCSN @ 10kpc

Inverted mass ordering



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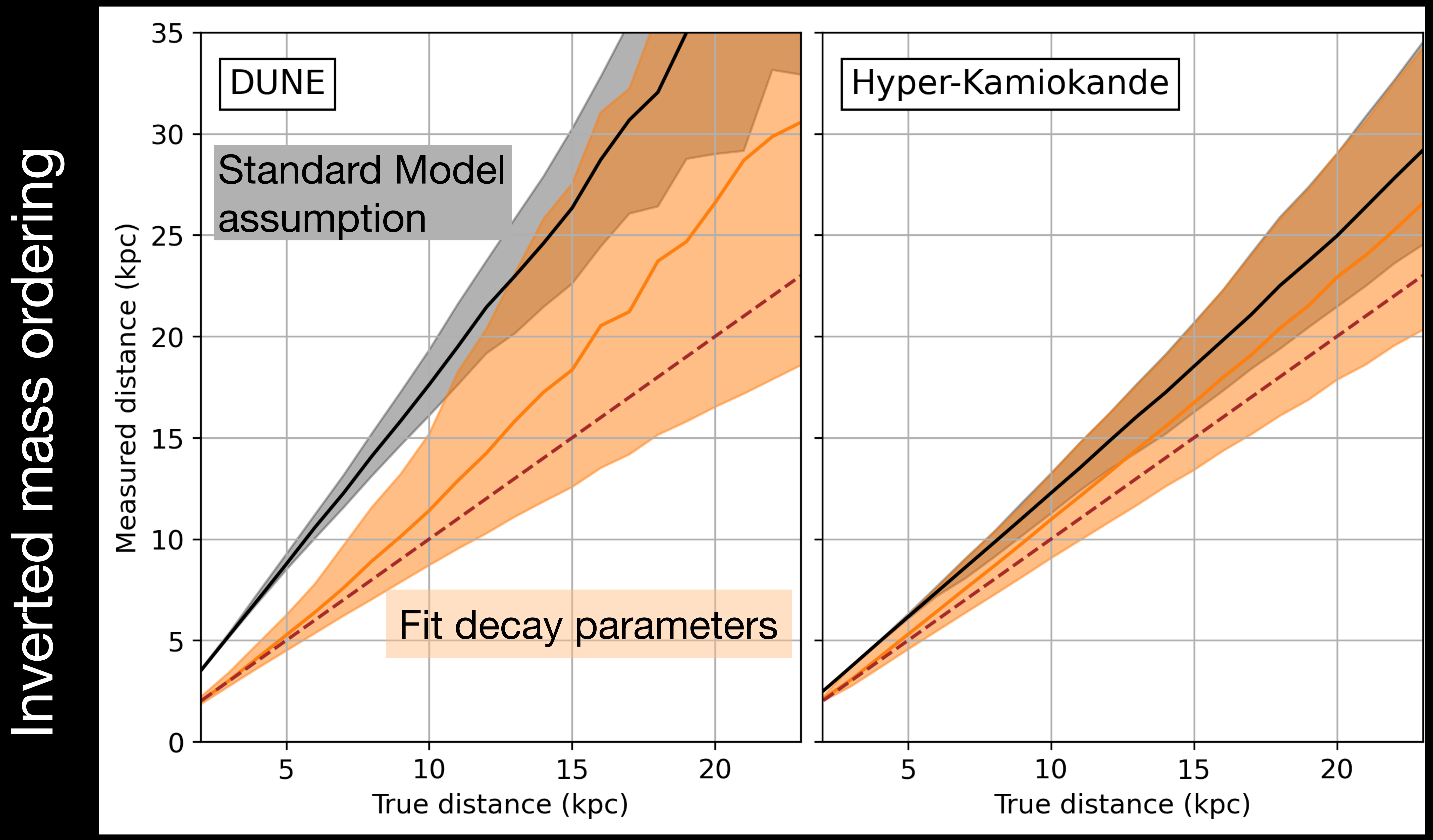
Measuring CCSN distance

Simulate observation with $\bar{r} = 5, \zeta = 1$



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Combine two flavor-complementary experiments $\Rightarrow$precision and accuracy!

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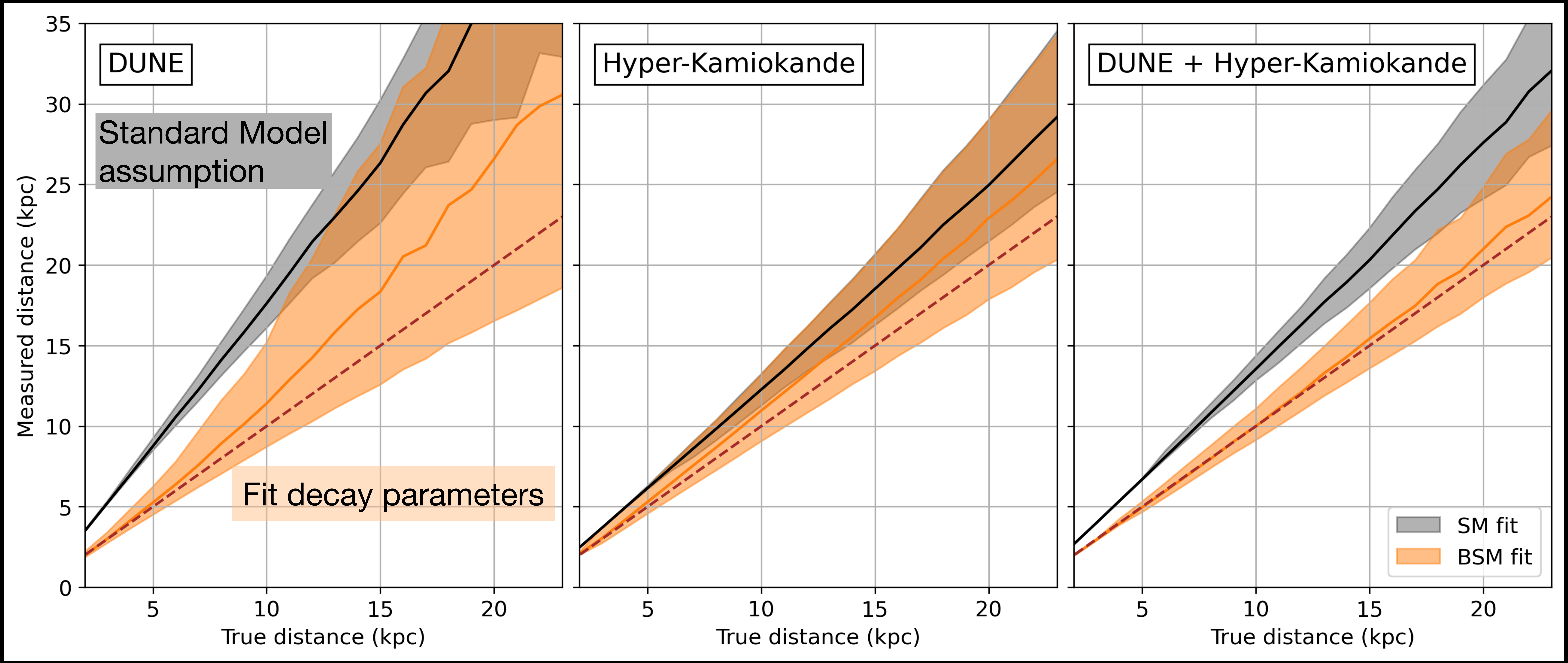

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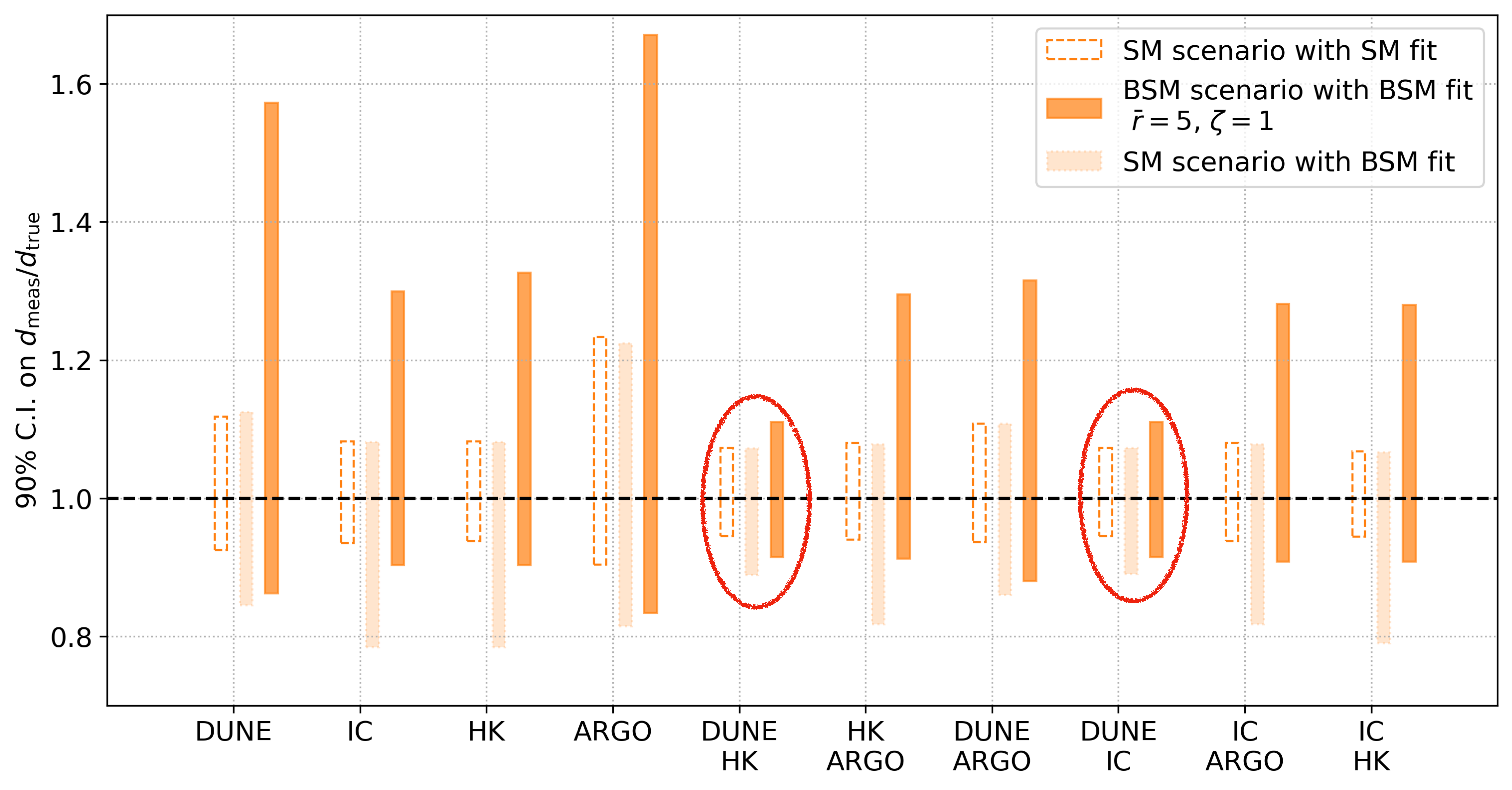
Combine two flavor-complementary experiments ⇒precision and accuracy!

CCSN distance estimates: pairing detectors

Inverted mass ordering — CCSN @ 10 kpc



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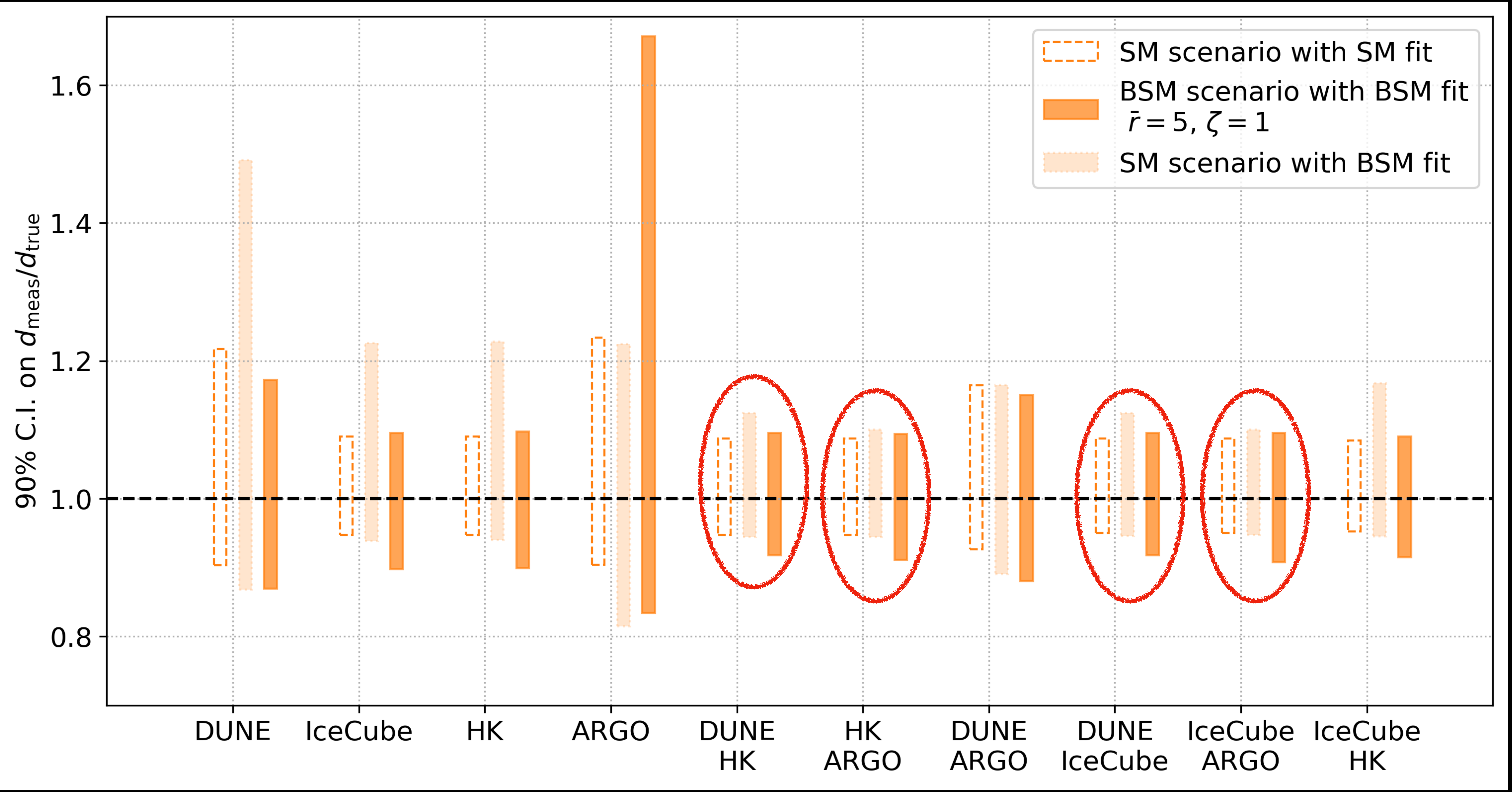
CCSN distance estimates: pairing detectors

Normal mass ordering — CCSN @ 10 kpc



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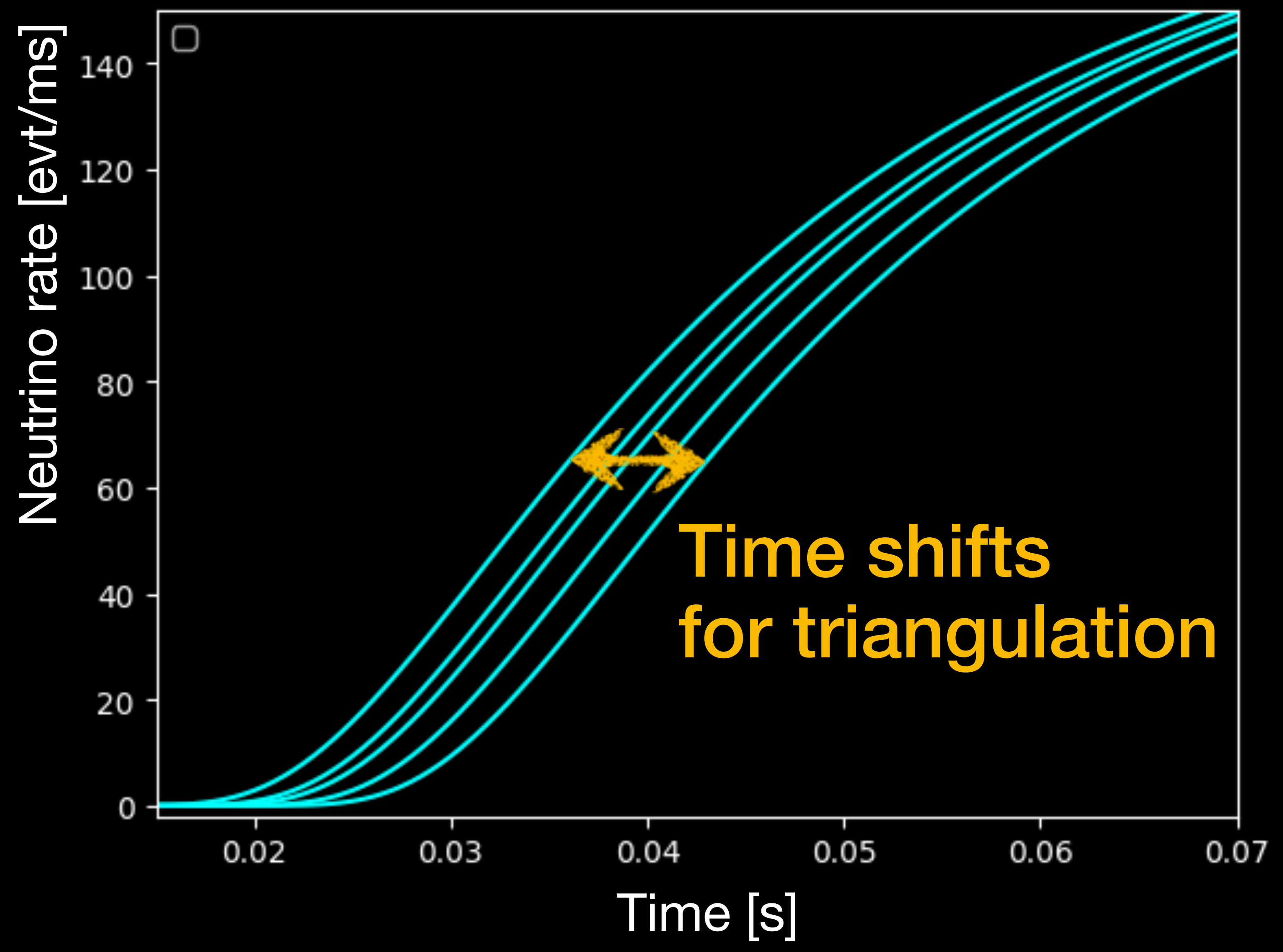
Conclusion

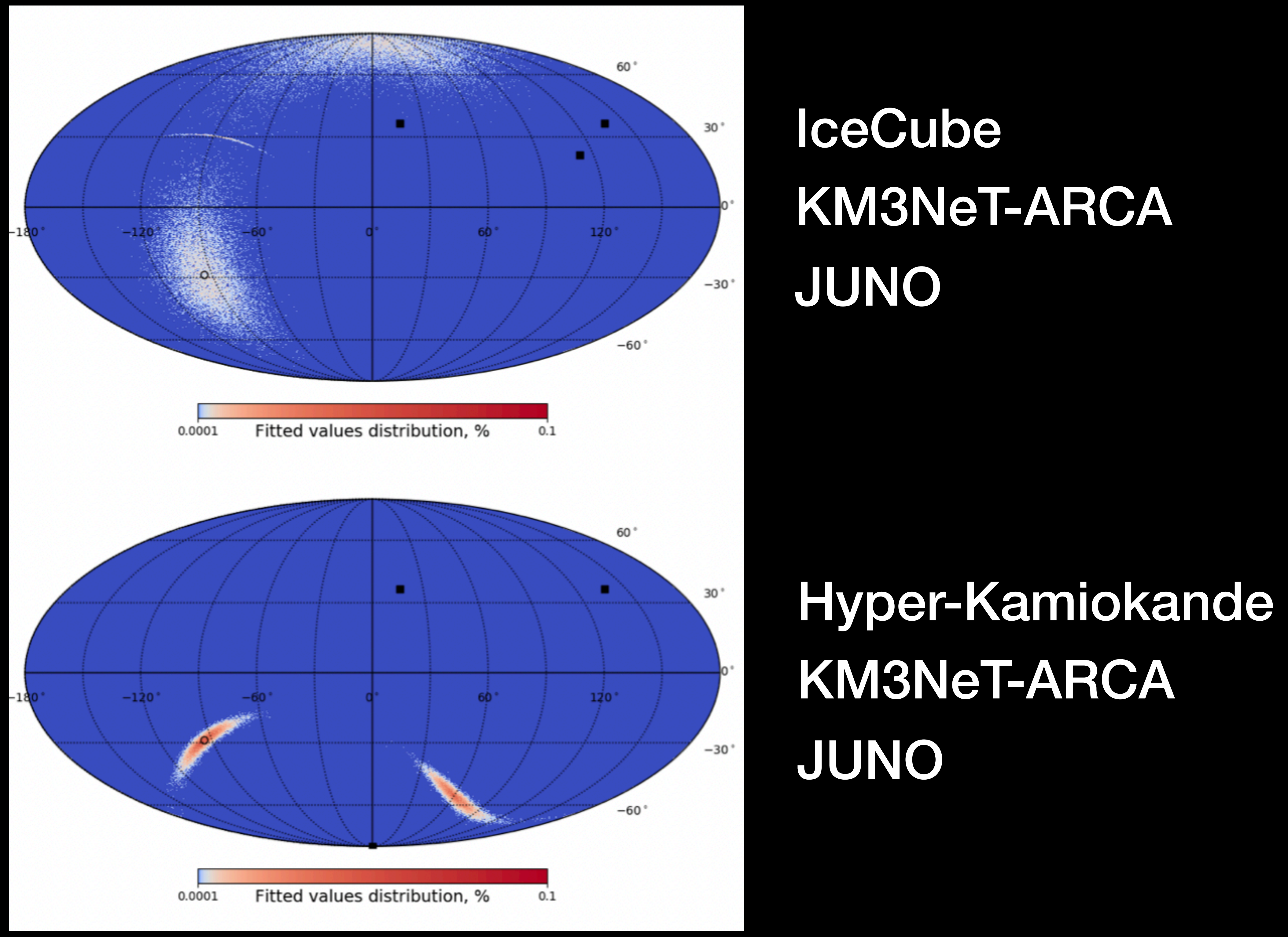
- Locating a CCSN and estimating its visibility using neutrinos will be crucial to prepare an observational strategy of the electromagnetic signal
- Measuring the distance to a CCSN requires assumptions about neutrino properties $\Rightarrow$ Standard Model assumed by alert systems
- Combining next-generation experiments will allow constraining neutrino properties in real time using only neutrino event counts
- Proposal for a new observation strategy tested on neutrino decay models
  $\Rightarrow$ Expand this strategy using an effective description of new ν interactions?

Thank you for your attention

More on supernova localization

Match supernova rate increases for multiple detectors





A. Coleiro *et al*, Eur. Phys. J. C 80 (2020)

Constraint down to a 140 squared degree region within minutes after detection

Wolf-Rayet stars: light can arrive 40 seconds after the neutrinos