Neutrinos: Here, There & Everywhere, Guest Lecture

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

MODELLING, DETECTION PROSPECTS, AND PHYSICS POTENTIAL

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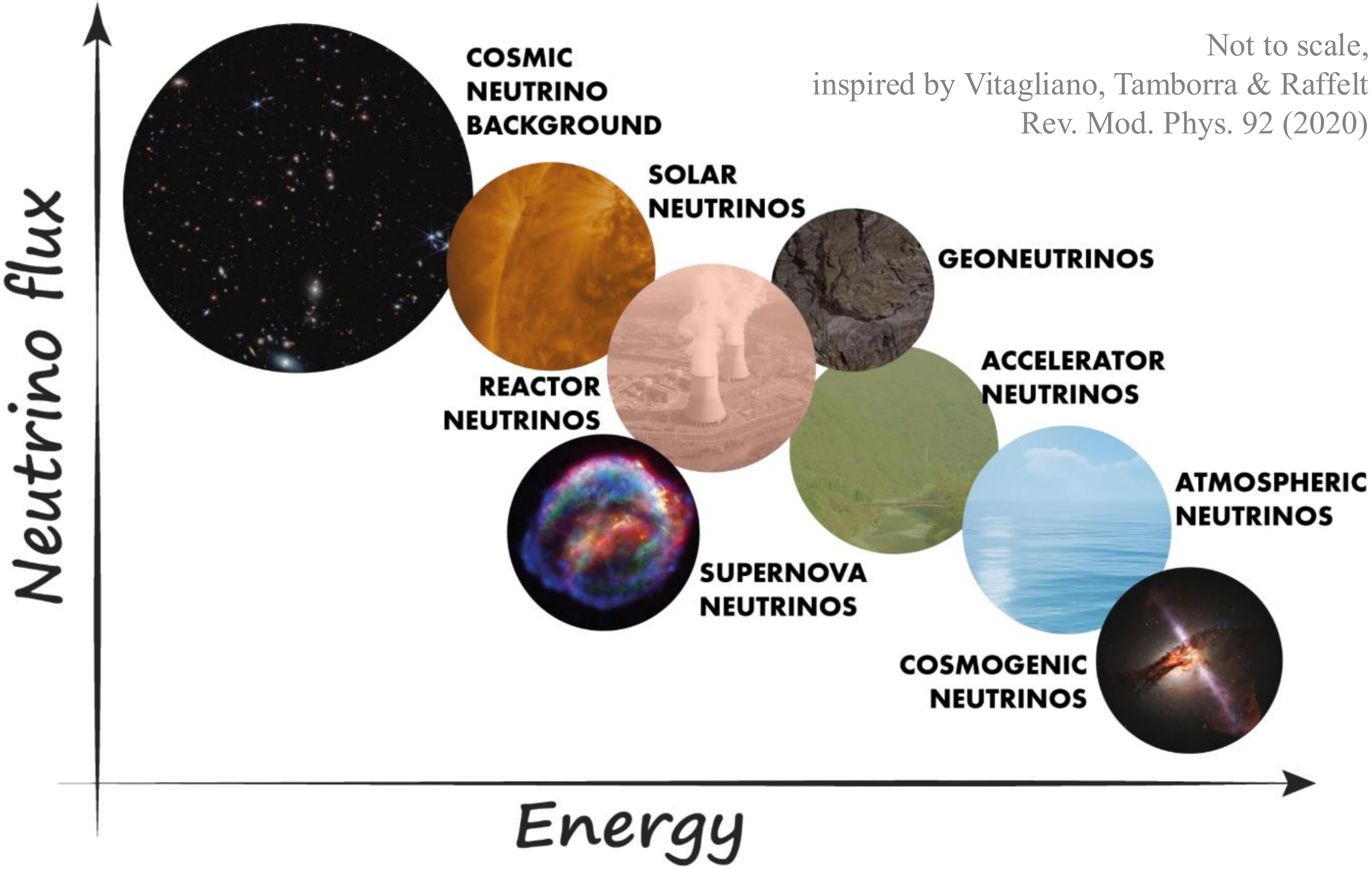
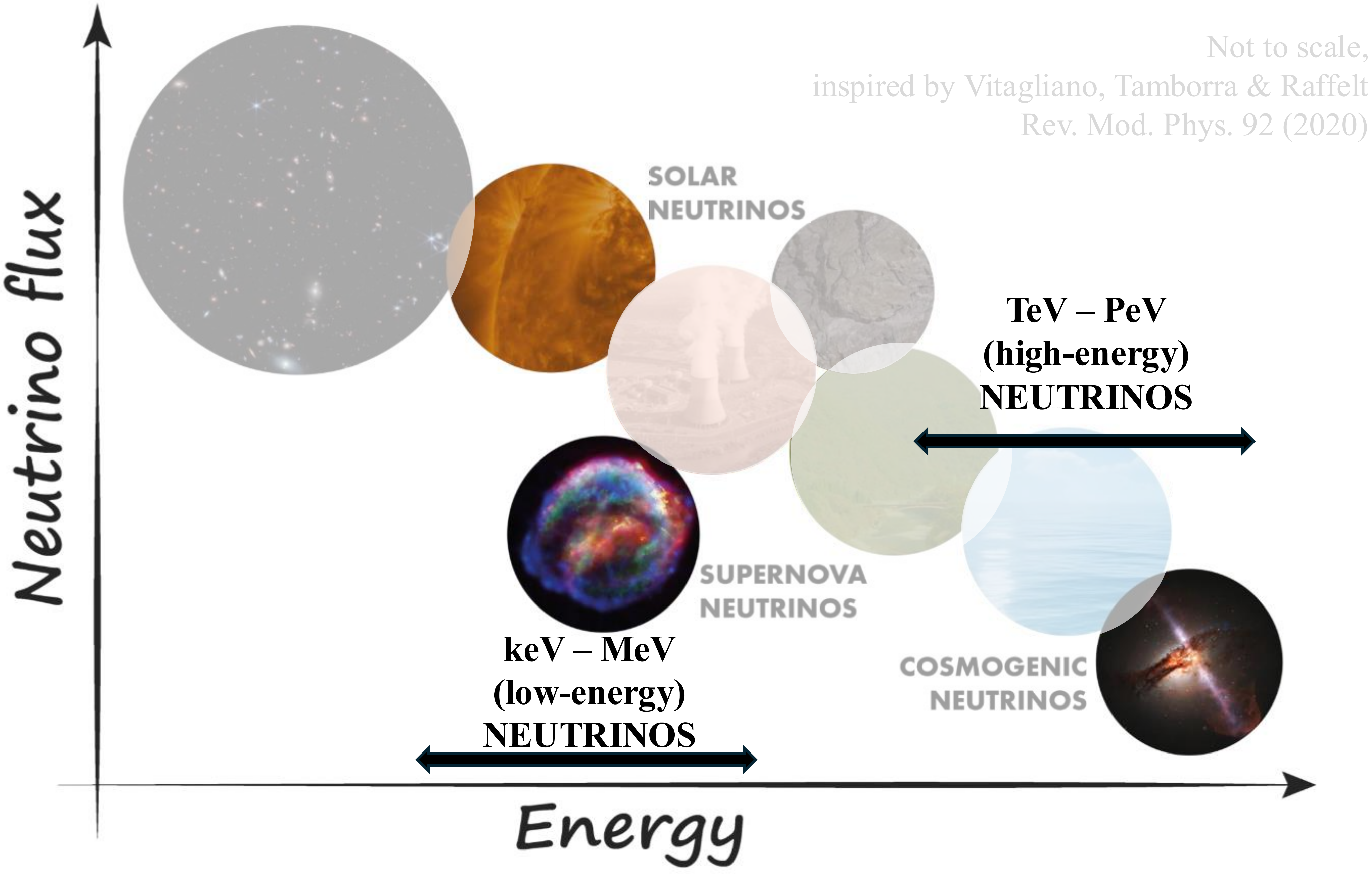
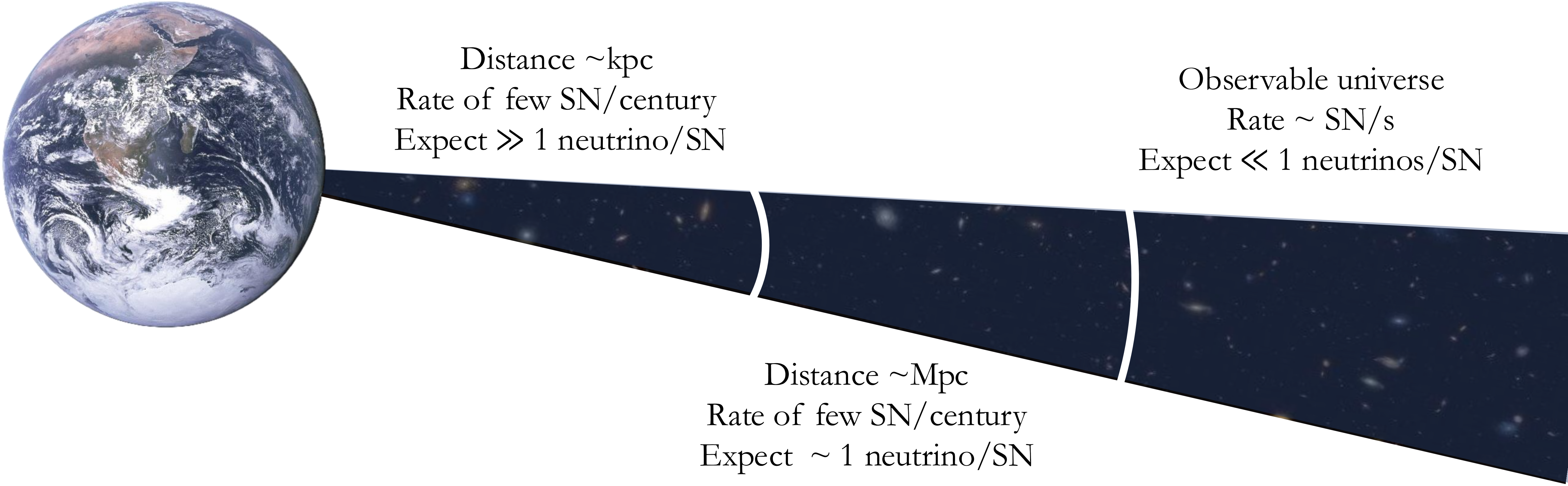


Not to scale,
inspired by Vitagliano, Tamborra & Raffelt
Rev. Mod. Phys. 92 (2020)


Not to scale,
inspired by Vitagliano, Tamborra & Raffelt
Rev. Mod. Phys. 92 (2020)
SOLAR
NEUTRINOS
TeV – PeV
(high-energy)
NEUTRINOS
SUPERNOVA
NEUTRINOS
COSMOGENIC
NEUTRINOS
keV – MeV
(low-energy)
NEUTRINOS
Neutrino flux
Energy


Distance ~kpc
Rate of few SN/century
Expect ≫ 1 neutrino/SN
Distance ~Mpc
Rate of few SN/century
Expect ~ 1 neutrino/SN
Observable universe
Rate ~ SN/s
Expect ≪ 1 neutrinos/SN

OUTLOOK

MODELLING
the diffuse supernova neutrino background

DETECTING
the diffuse supernova neutrino background

LEARNING FROM
the diffuse supernova neutrino background

MODELLING

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

Supernova population

$$\Phi_{\mathrm{DSNB}} = c \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} dM \int_{z=0}^{z_{\mathrm{max}}} dz \frac{\mathcal{R}(z, M)}{H(z)} F_\nu(M, (1+z)E)$$

Universe expansion

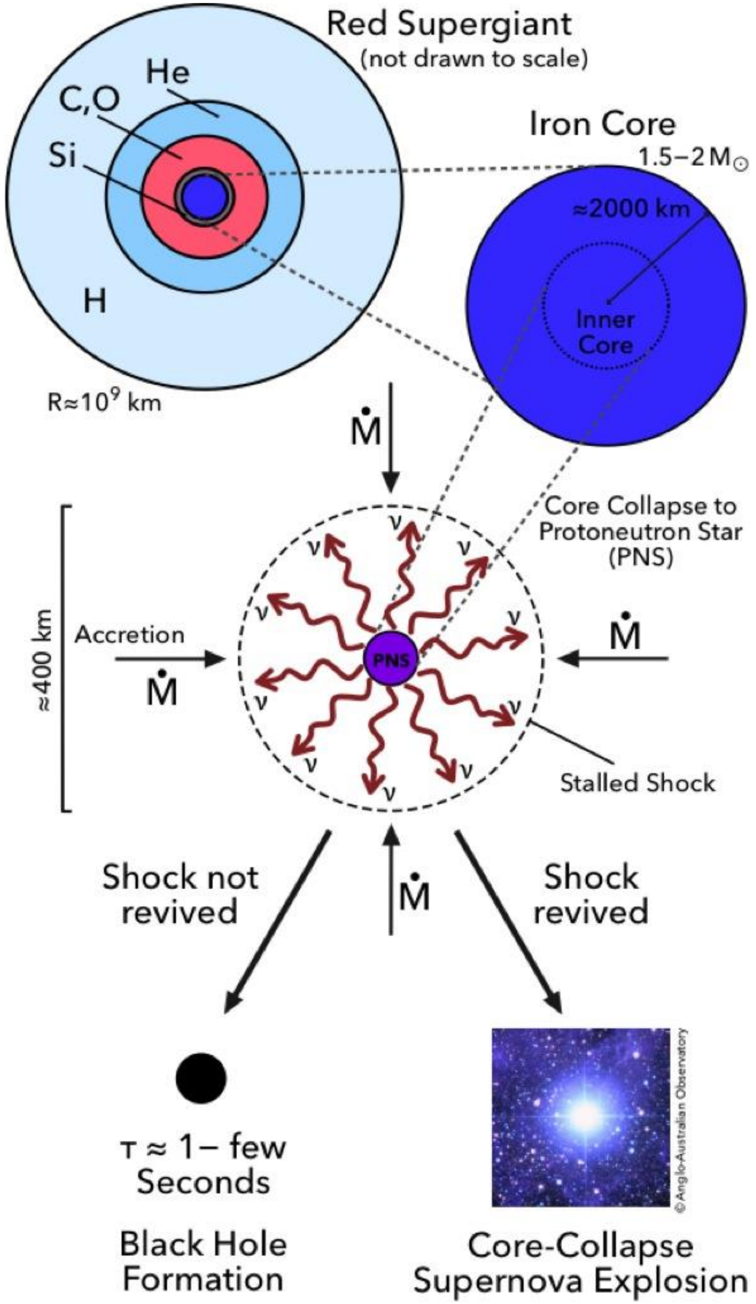
Supernova neutrino emission

Supernova population

$$\Phi_{\mathrm{DSNB}} = c \int_{M_{\min}}^{M_{\max}} dM \int_{z=0}^{z_{\max}} dz \frac{\mathcal{R}(z, M)}{H(z)} F_\nu(M, (1+z)E)$$

Universe expansion

Supernova neutrino emission


Red Supergiant
(not drawn to scale)
He
C,O
Si
H
R≈10^9 km
Iron Core
1.5–2 $M_\odot$
≈2000 km
Inner Core
$\dot{M}$
Core Collapse to Protoneutron Star (PNS)
PNS
ν
≈400 km
Accretion
$\dot{M}$
$\dot{M}$
Stalled Shock
Shock not revived
$\dot{M}$
Shock revived
τ ≈ 1– few Seconds
Black Hole Formation
©Anglo-Australian Observatory
Core-Collapse Supernova Explosion

Metallicity

Binary interactions

Shock-revival mechanism

Neutron star properties

Fraction of black hole-forming collapse

Flavour conversions

MODIFY THE CHARACTERISTICS OF SUPERNOVA NEUTRINO EMISSION

Supernova population

$$\Phi_{\mathrm{DSNB}} = c \int_{M_{\min}}^{M_{\max}} dM \int_{z=0}^{z_{\max}} dz \frac{\mathcal{R}(z, M)}{H(z)} F_\nu(M, (1+z)E)$$

Universe expansion

Supernova neutrino emission

The simplest analytical supernova rate:

INITIAL MASS FUNCTION

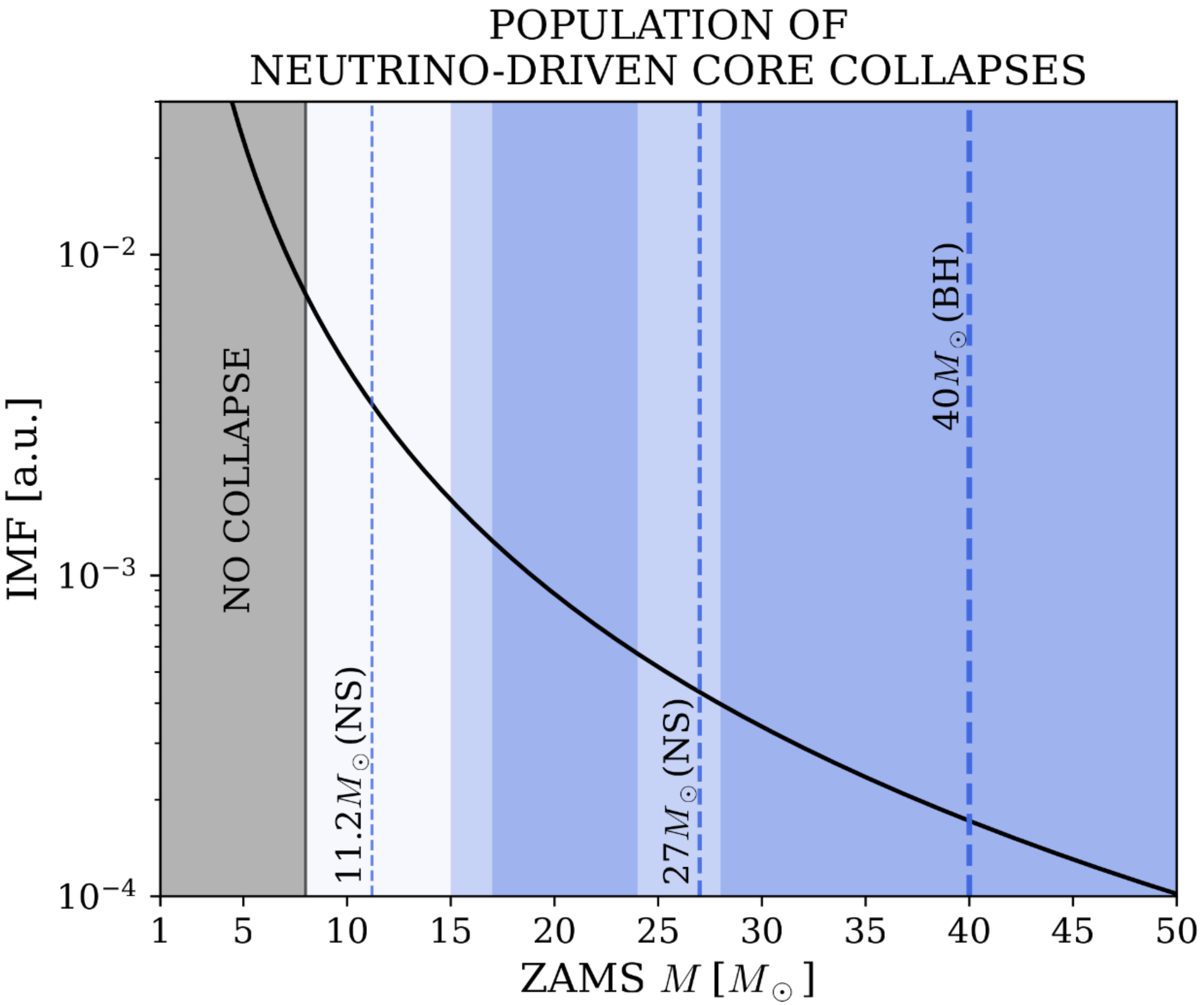
$$\mathcal{R}(z, M) = \frac{\boxed{\mathrm{IMF}(M)}}{\int_{M_{\min}}^{M_{\max}} dM\, M\, \mathrm{IMF}(M)} \boxed{\dot{\rho}_*(z)}$$

STAR FORMATION HISTORY

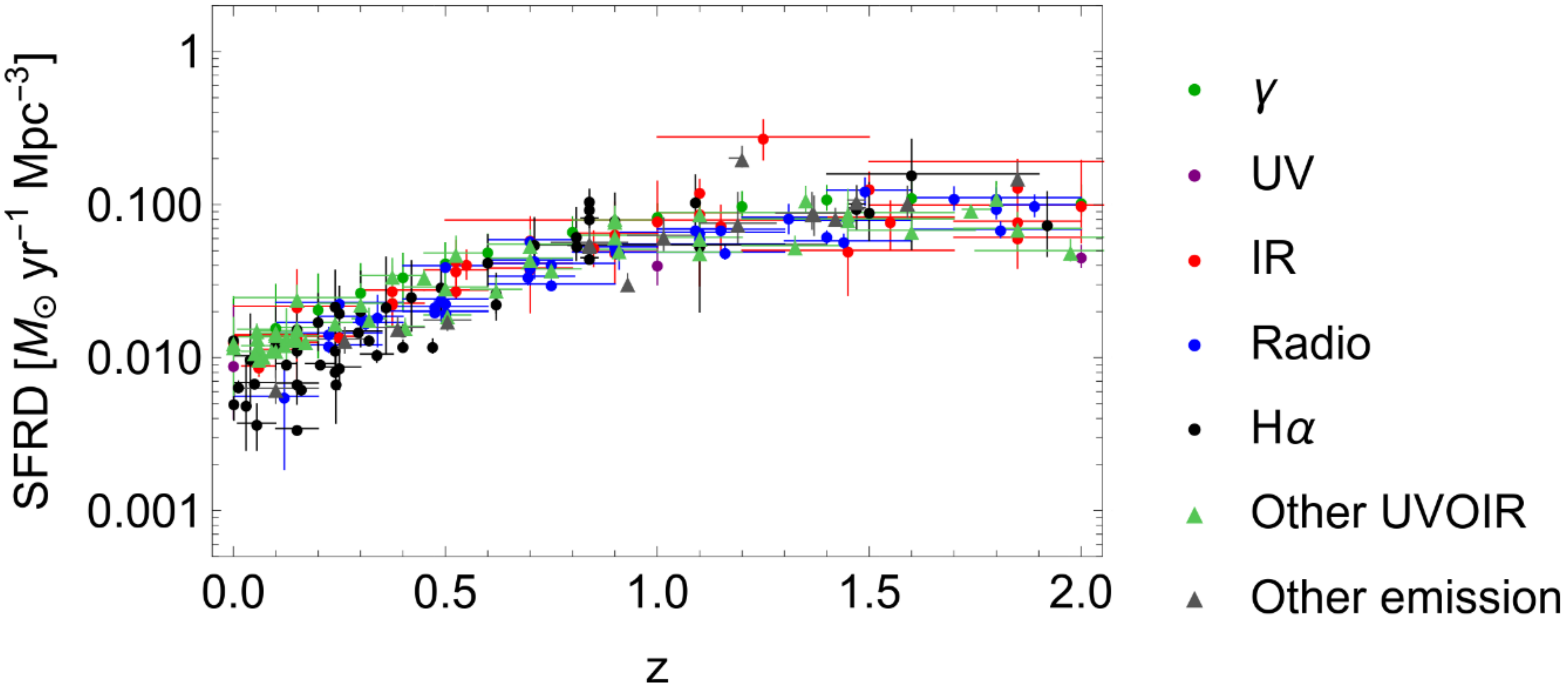
INITIAL MASS FUNCTION:
Distribution of zero age main sequence mass of the stellar population.

Steeply decreasing with mass.

The minimum mass needed for core collapse depends on the mechanism.

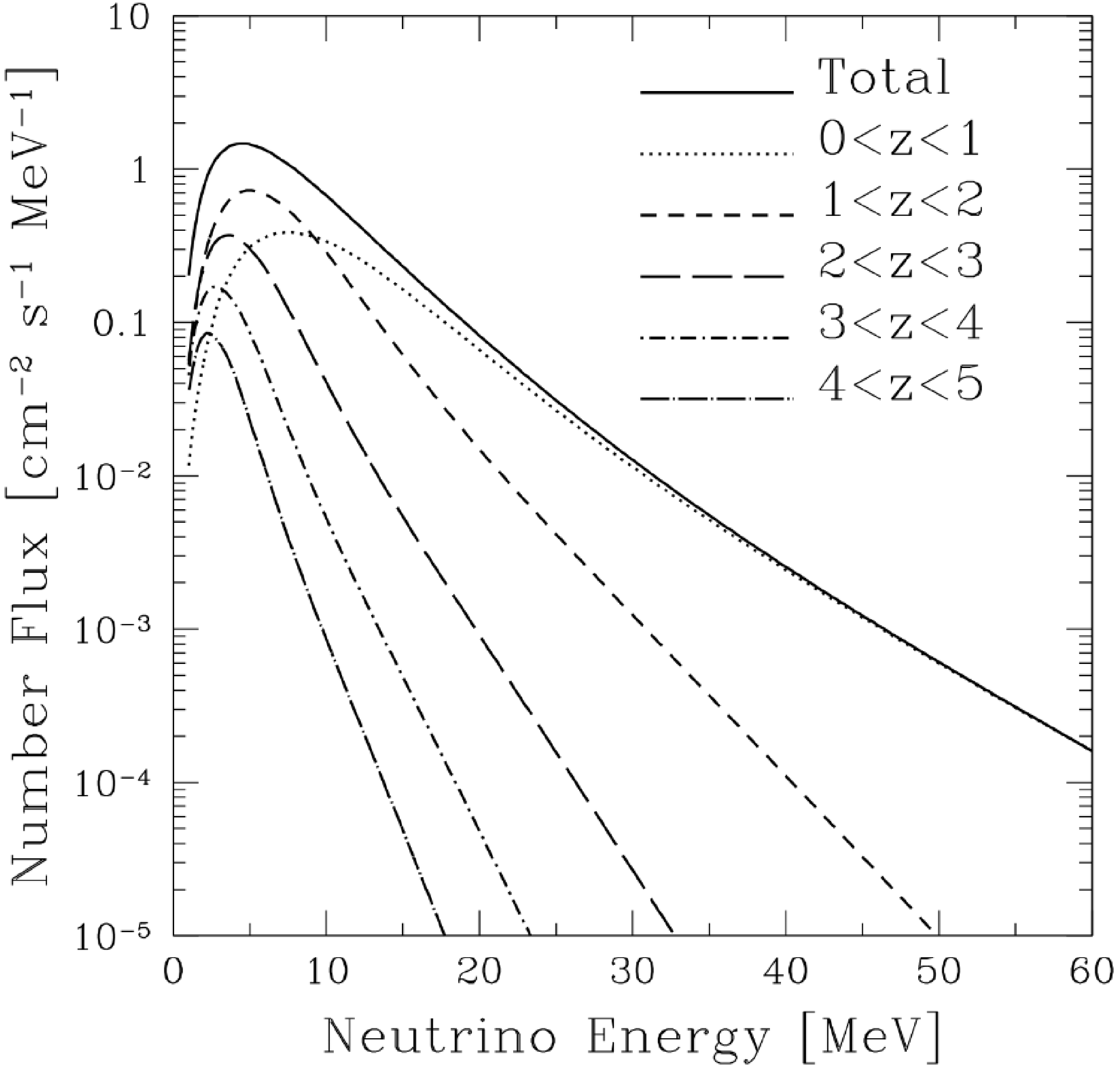


STAR FORMATION RATE from electromagnetic observations



N. Ekanger *et al.* PRD (2024)

Ando, Astrophys.J.(2004)



Contributions are relevant mainly up to redshift z ~ 5.

$$\Phi_{\rm DSNB} = c \int_{M_{\rm min}}^{M_{\rm max}} dM \int_{z=0}^{z_{\rm max}} dz \frac{\mathcal{R}(z,M)}{H(z)} F_\nu(M,(1+z)E)$$

Supernova population

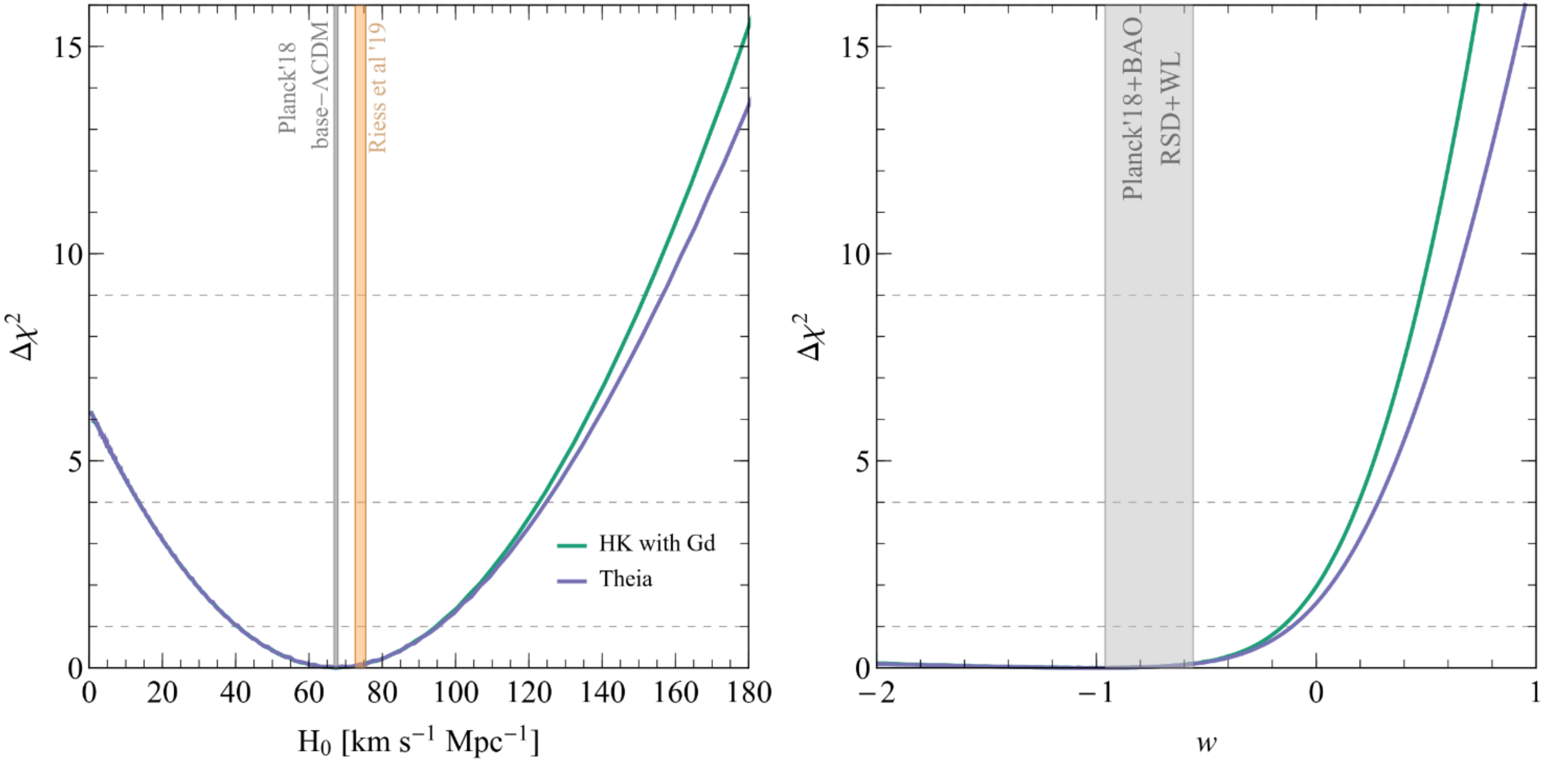
Universe expansion

Supernova neutrino emission

Very little impact since

- contributions from z>5 are negligible
- local supernova rate is uncertain

The DSNB predictions are very robust given current knowledge about H0 or the dark energy equation of state.



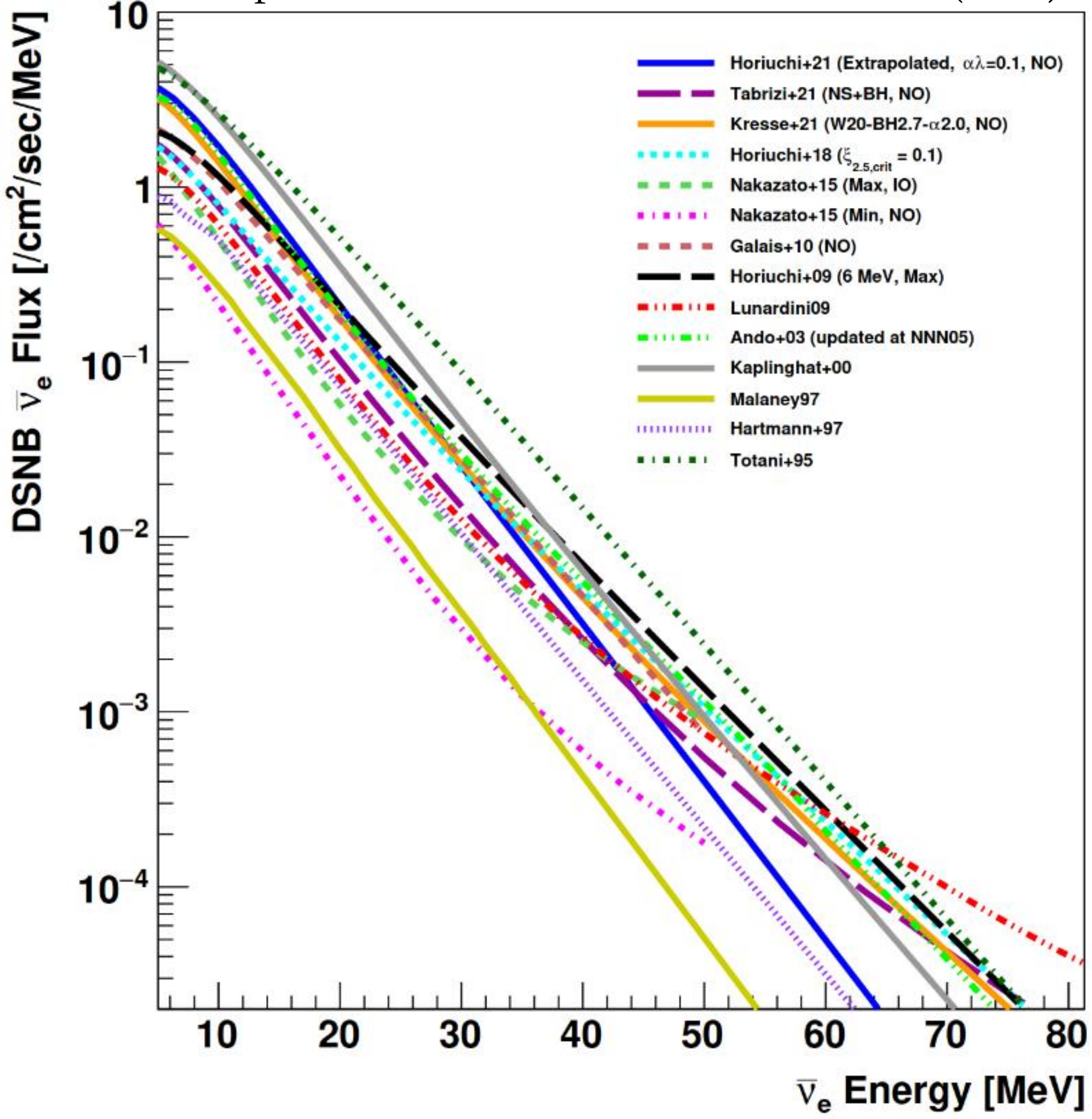
A. De Gouvêa *et al.* PRD (2020)

STATUS OF DSNB MODELS

STATUS OF DSNB MODELS

(INCOMPLETE)

Super-Kamiokande Collaboration, PRD (2021)

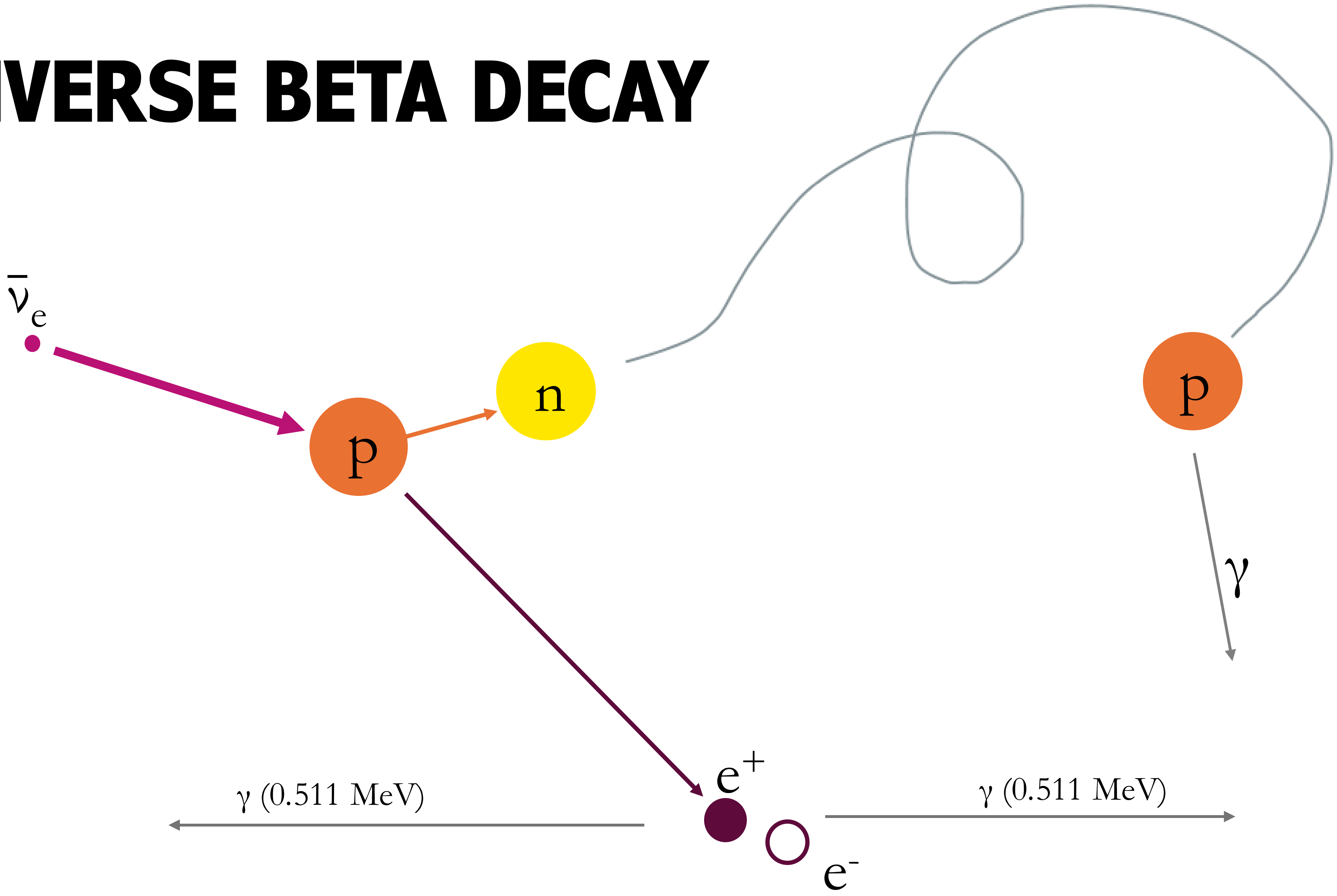


$$\Phi_{\mathrm{DSNB}} = c \int_{M_{\mathrm{min}}}^{M_{\mathrm{max}}} dM \int_{z=0}^{z_{\mathrm{max}}} dz \frac{\overset{\text{Supernova population}}{\boxed{\mathcal{R}(z, M)}}}{\underset{\text{Universe expansion}}{\boxed{H(z)}}} \underset{\text{Supernova neutrino emission}}{\boxed{F_\nu(M, (1+z)E)}}$$

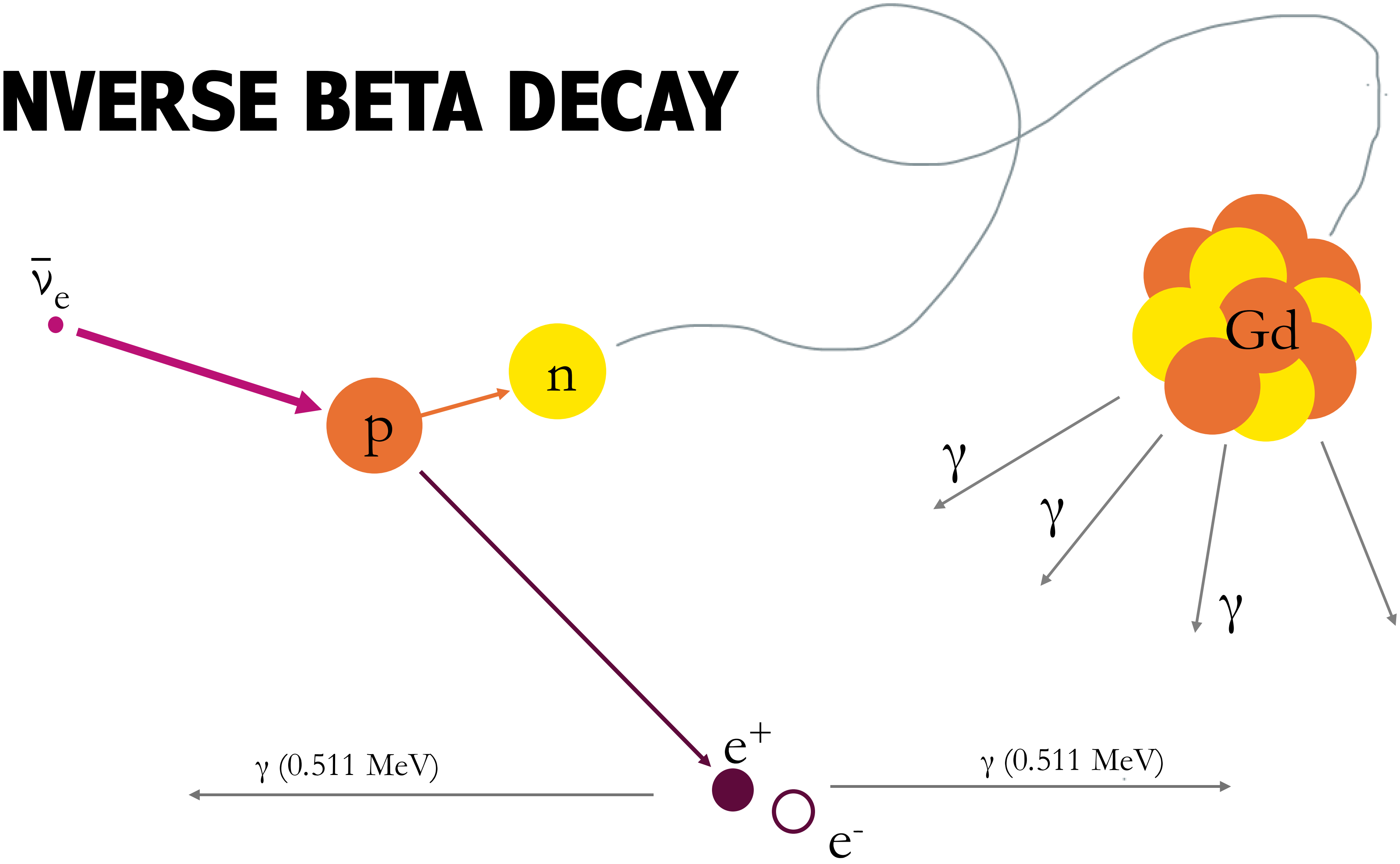
DETECTING

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

INVERSE BETA DECAY



INVERSE BETA DECAY



DSNB SEARCHES

Representative detectors

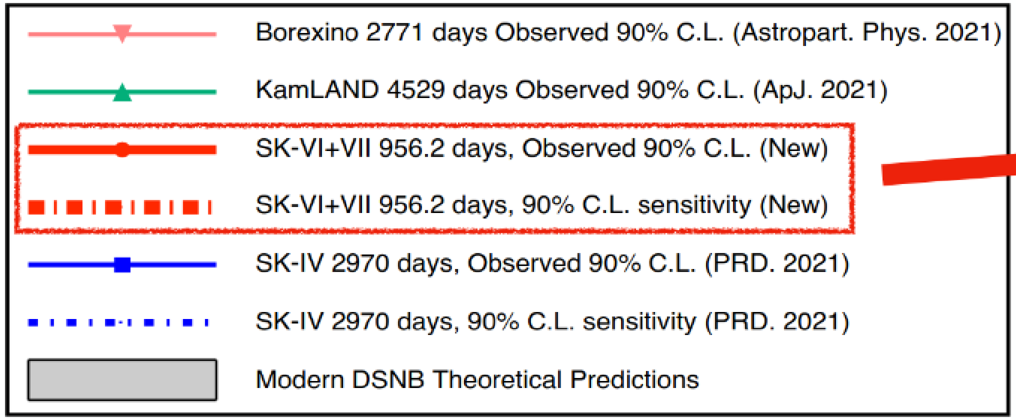
- **Liquid scintillator (LS):** KamLAND(1 kt), Borexino (O(100) t)
- **Water-Cherenkov (WC):** Super-Kamiokande(22.5 kt), SNO(0.7 kt)
- **Gd loaded WC detector:** SK-Gd

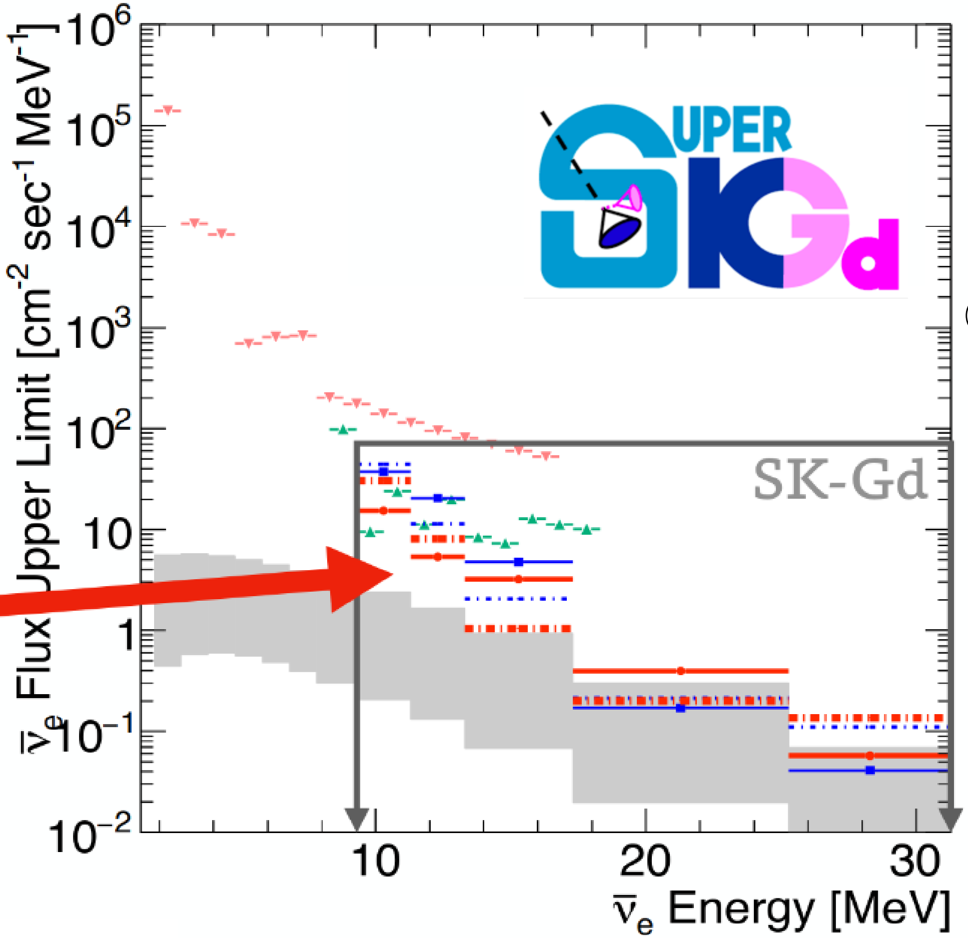
Next-generation experiments

- **Liquid scintillator (LS):** JUNO
- **Water-Cherenkov (WC):** Hyper-Kamiokande

STATUS: SUPER-KAMIOKANDE Gd

No excess so far, even after loading with Gadolinium

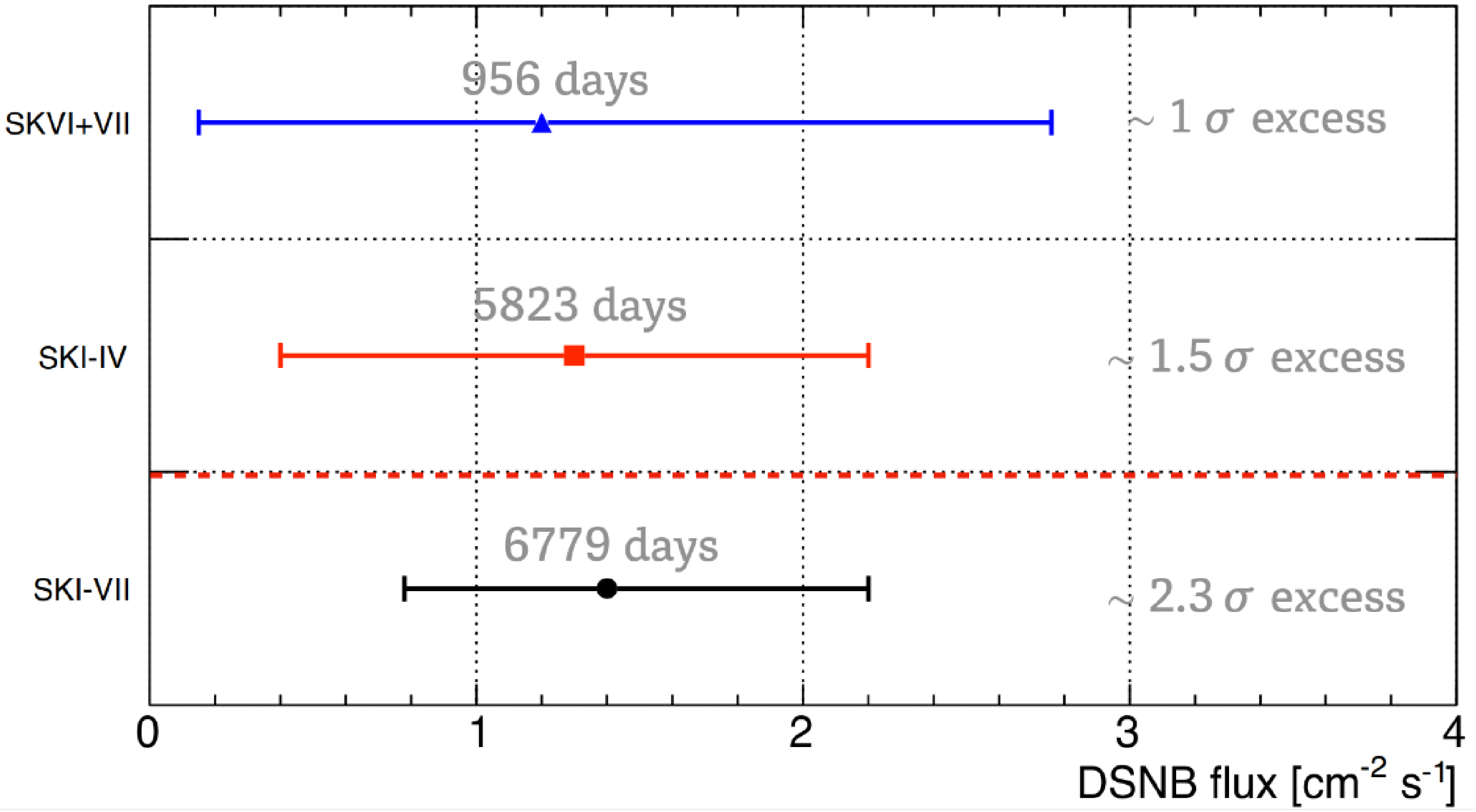




Harada @ Neutrino 2024

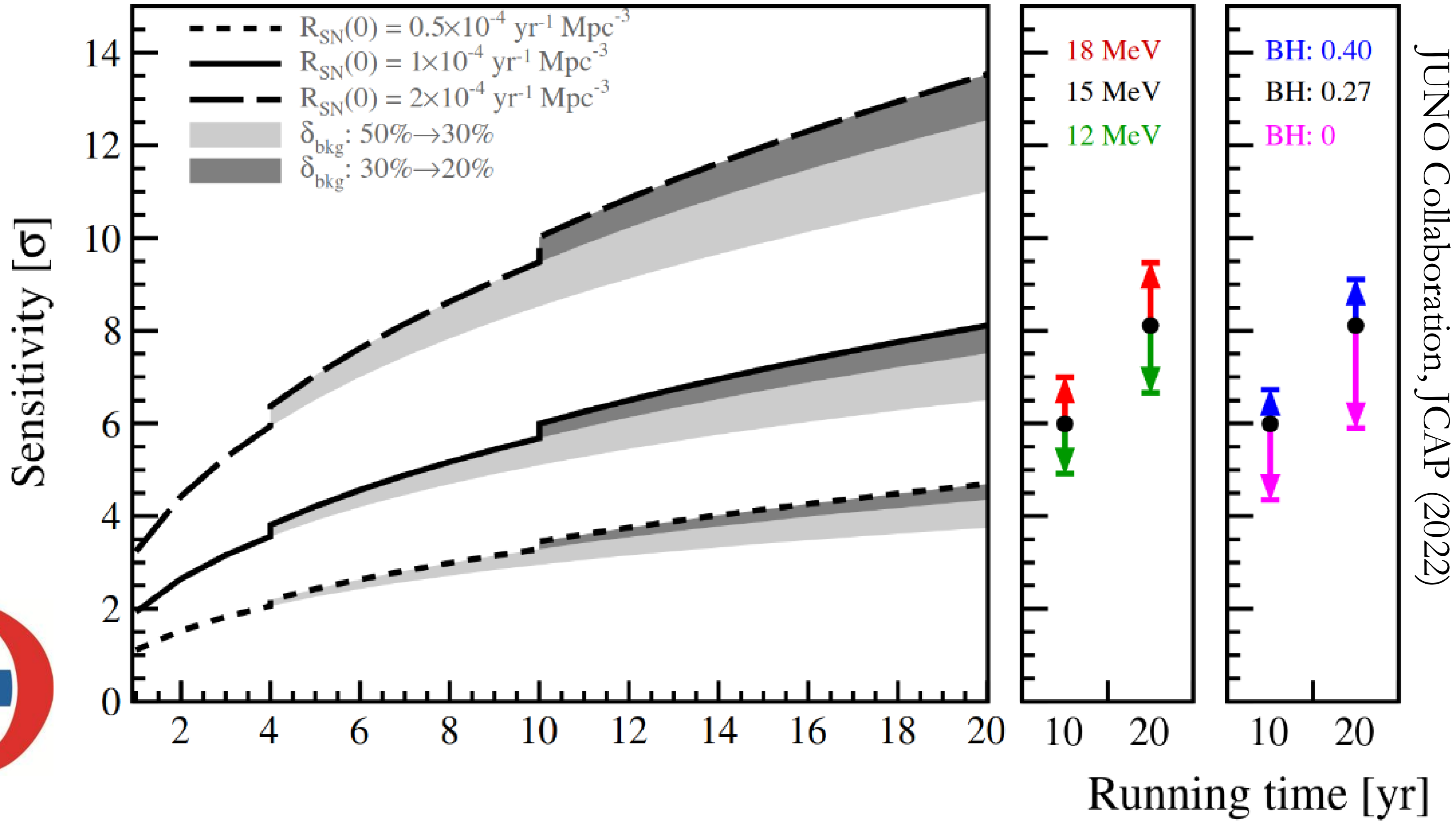
STATUS: SUPER-KAMIOKANDE Gd

Spectral analysis: non-zero best fit for $E_\nu > 17.3$ MeV *(Horiuchi +09 model)

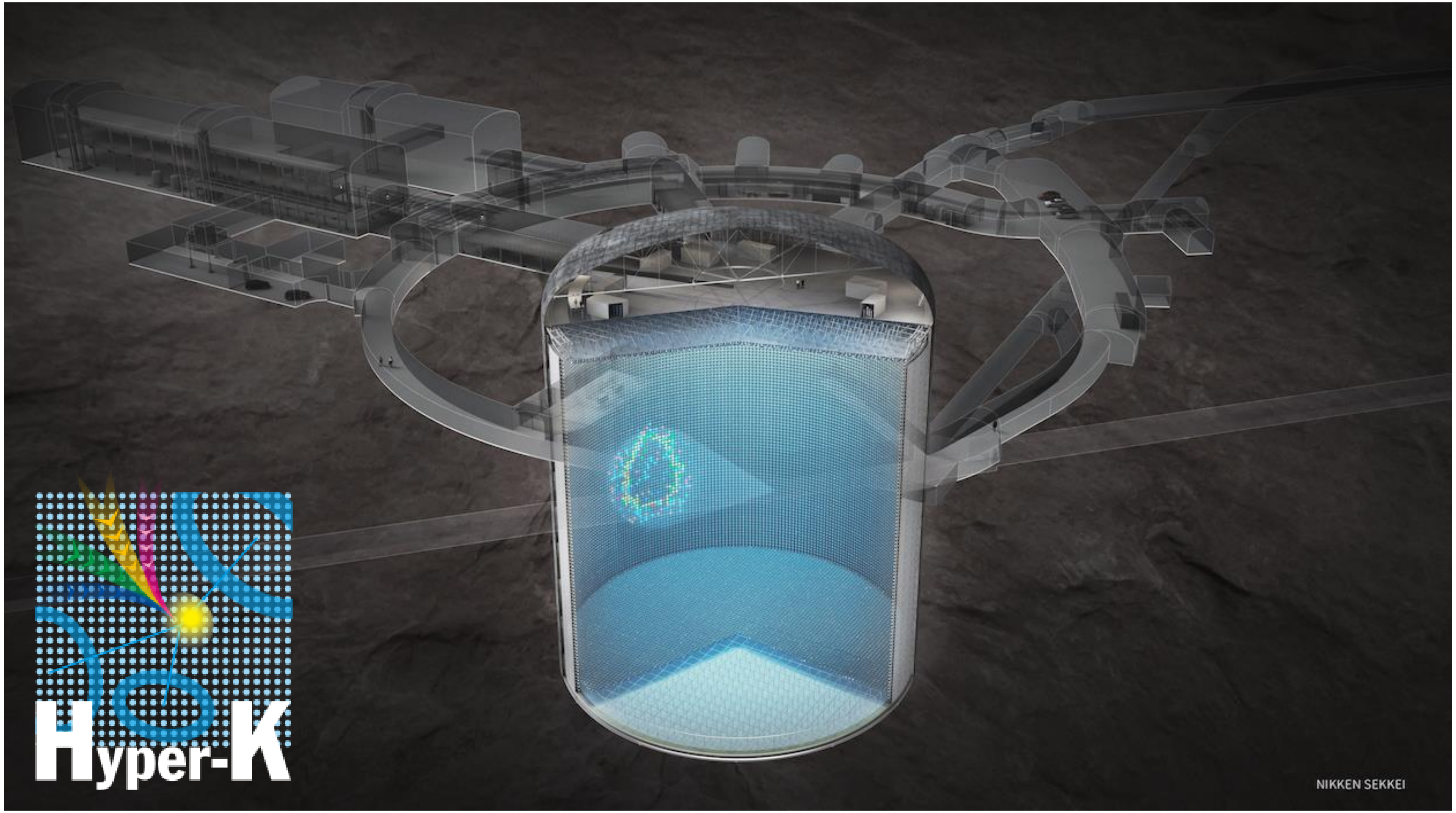


Harada @ Neutrino 2024

JUNO: NEAR FUTURE



FUTURE: HYPER-KAMIOKANDE



OTHER POTENTIAL DETECTION CHANNELS

DUNE

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

+ Sensitive to electron neutrinos

- Large backgrounds
- Low signal rate (small volume)

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) @ XLZD, RES-NOVA

$$\nu + A \rightarrow \nu + A$$

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

+ Sensitive to the total flux

- Large backgrounds
- Low signal rate (small volume)

LEARNING FROM

THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

NEUTRINO LIFETIME

Neutrinos are massive particles. As a direct implication of non-zero masses, one also finds that at least the two heaviest neutrino mass eigenstates may be unstable.

Neutrinos travelling over astrophysical and cosmic distances are ideal to probe neutrino lifetime.

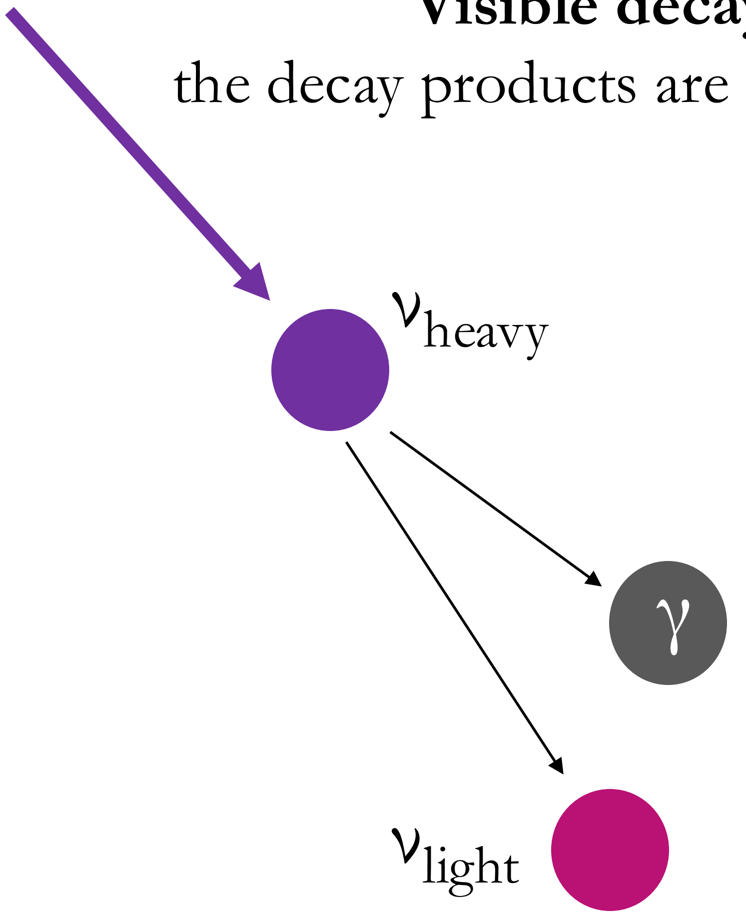
Experimentally, one tests the mass over lifetime ratio

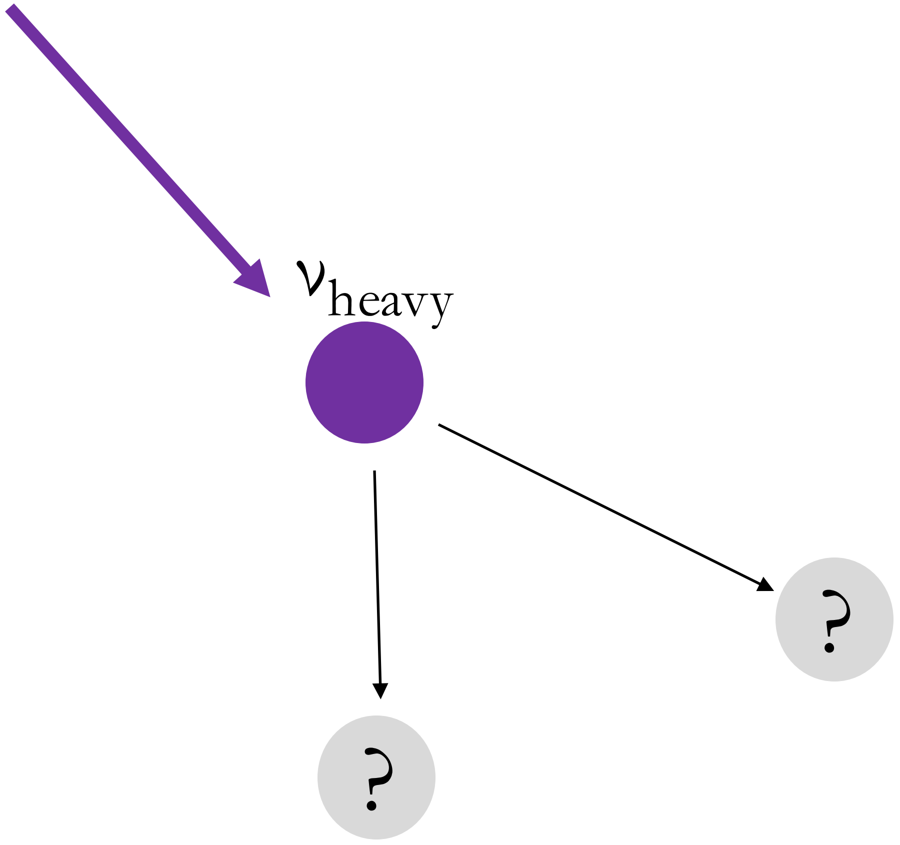
$$\alpha_i = \frac{m_i}{\tau_i}$$

NEUTRINO LIFETIME

Visible decay

the decay products are observable



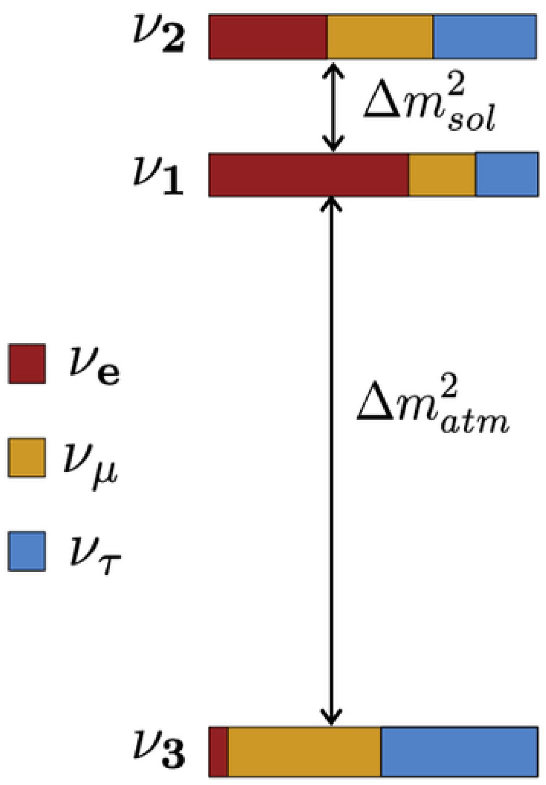


Invisible decay

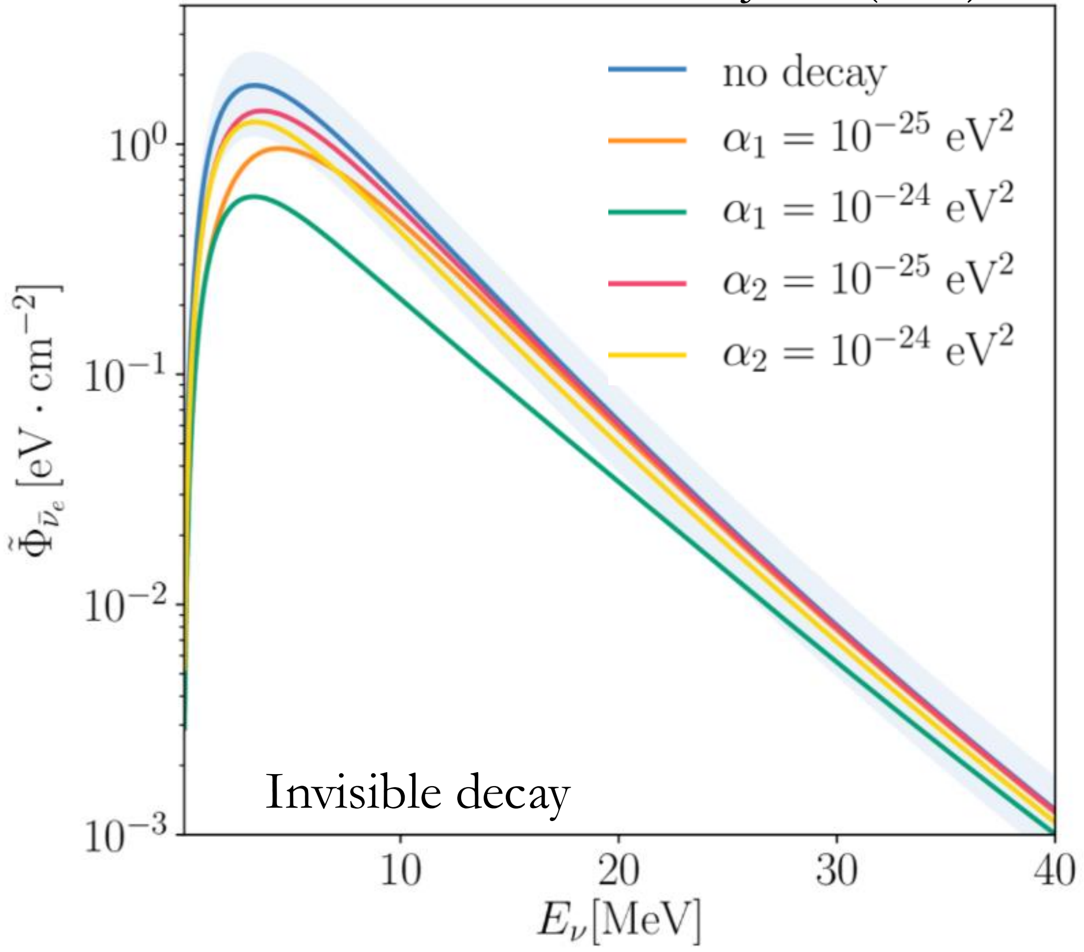
the decay products evade detection

NEUTRINO LIFETIME

Inverted hierarchy

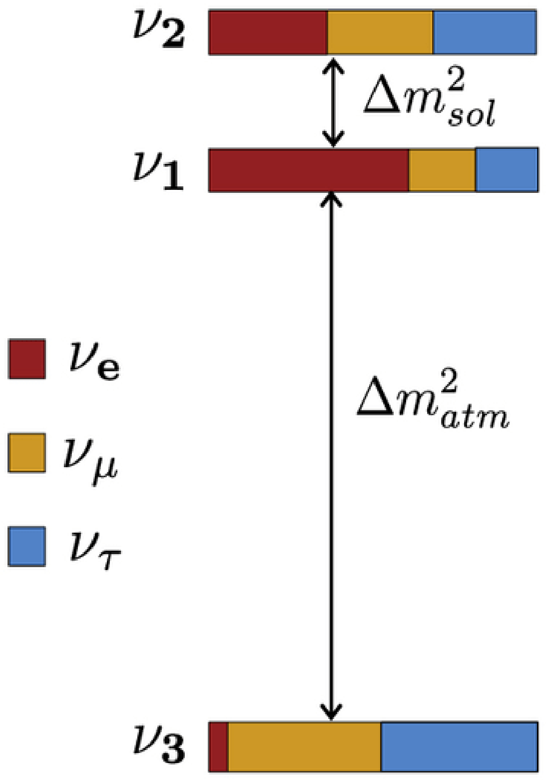


P. Martínez-Miravé *et al.*, JCAP (2025)

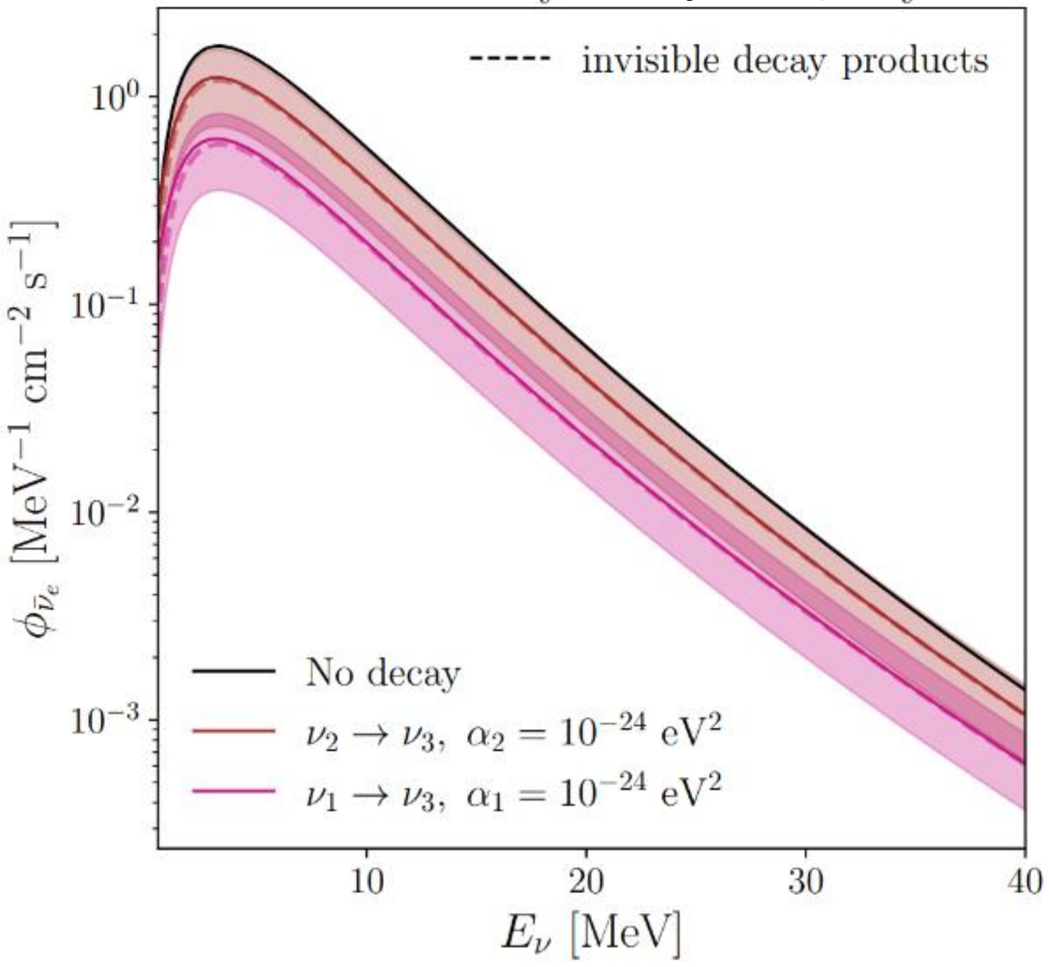


NEUTRINO LIFETIME

Inverted hierarchy



M. MacDonald *et al.* , JCAP (2025)



Signatures of BSM scenarios in the DSNB are

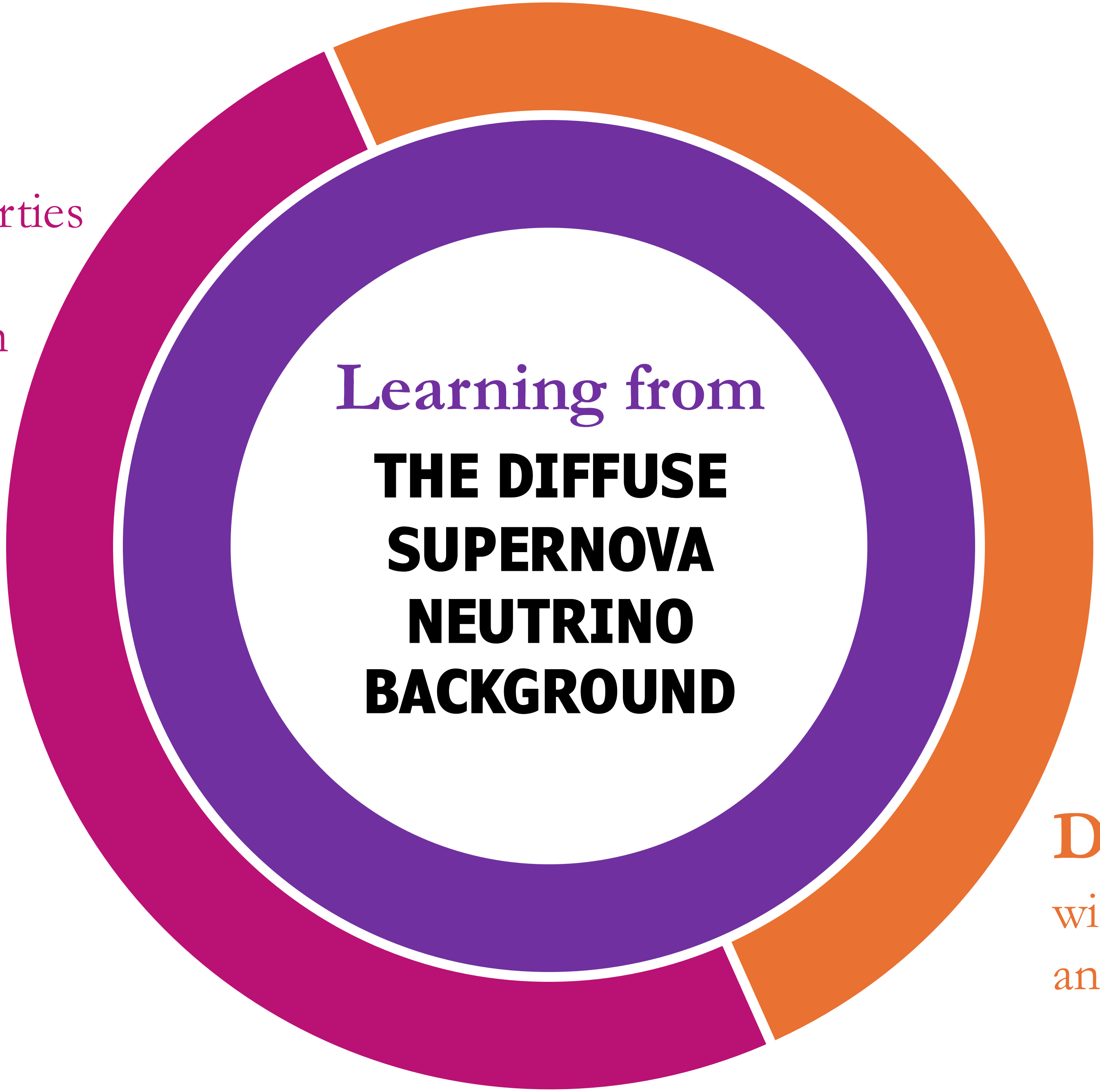
- highly degenerate between them in many cases → Use complementary constraints from neutrino experiments

- degenerate with astrophysical uncertainties in the modelling → Continue refining models with inputs from simulation and electromagnetic probes

- less prominent due to experimental limitations (e.g. backgorunds) → Identify and minimise relevant backgrounds

Modelling

population properties
and characteristic
neutrino emission



Detecting

with different techniques
and despite backgrounds