# SuperNovae Neutrino Observatories

Luca Pattavina
INFN - Laboratori Nazionali del Gran Sasso

- Why neutrinos
- Which neutrinos
- How neutrinos
- What neutrinos
- Where neutrinos

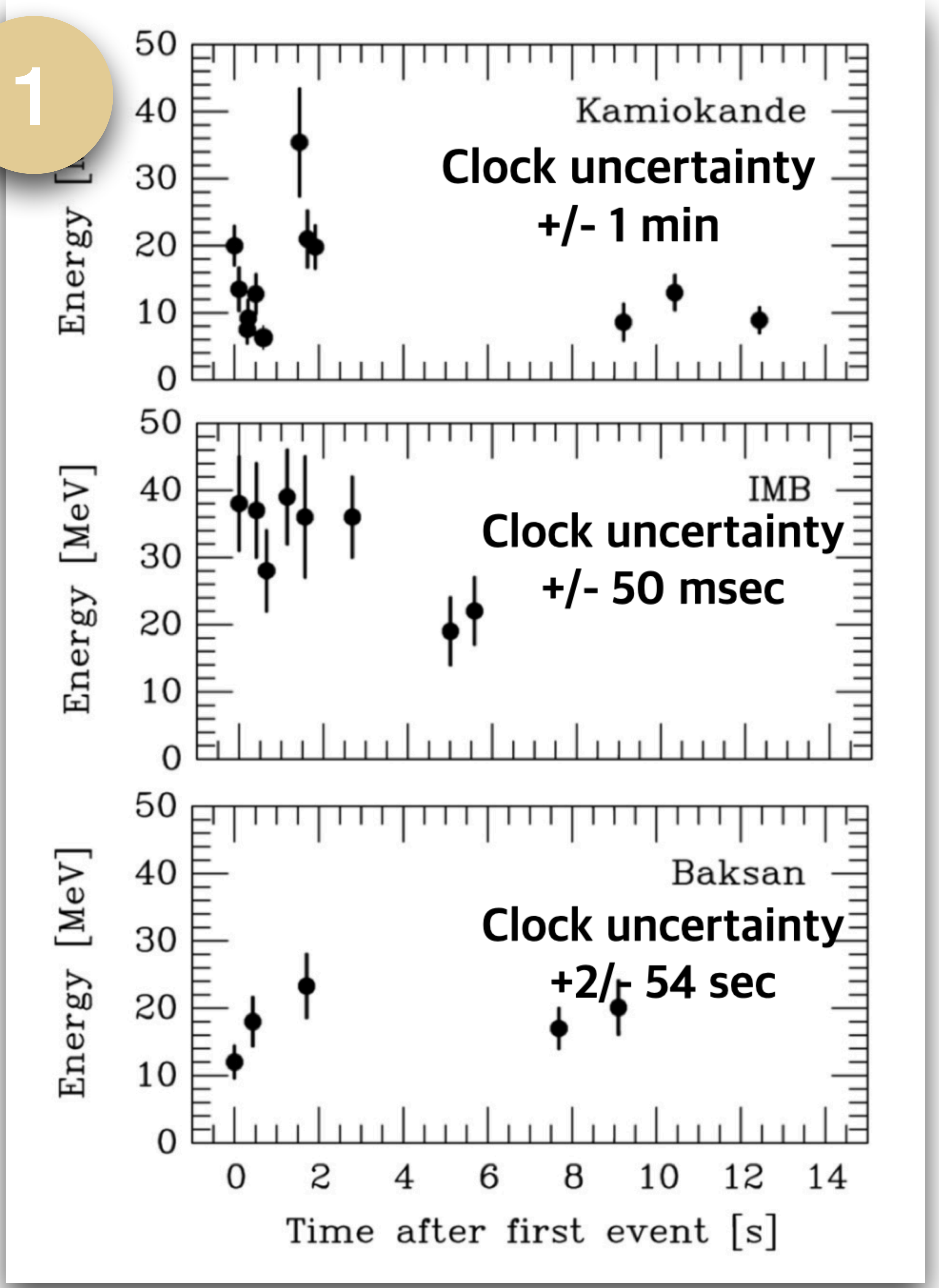
INFN LNGS

European Research Council
Established by the European Commission

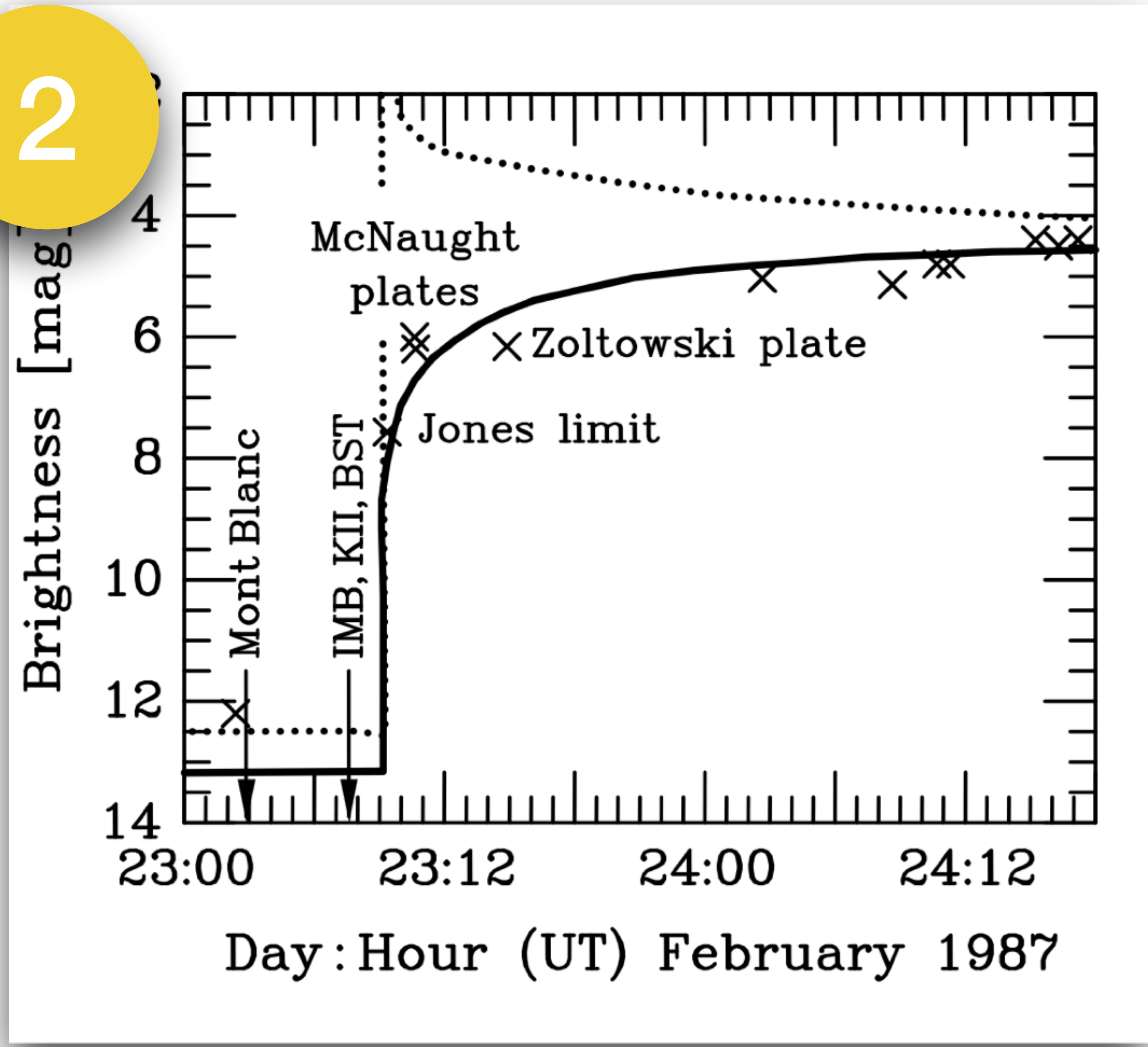
XX International Workshop on Neutrino Telescopes
Venice - 23-27 October 2023

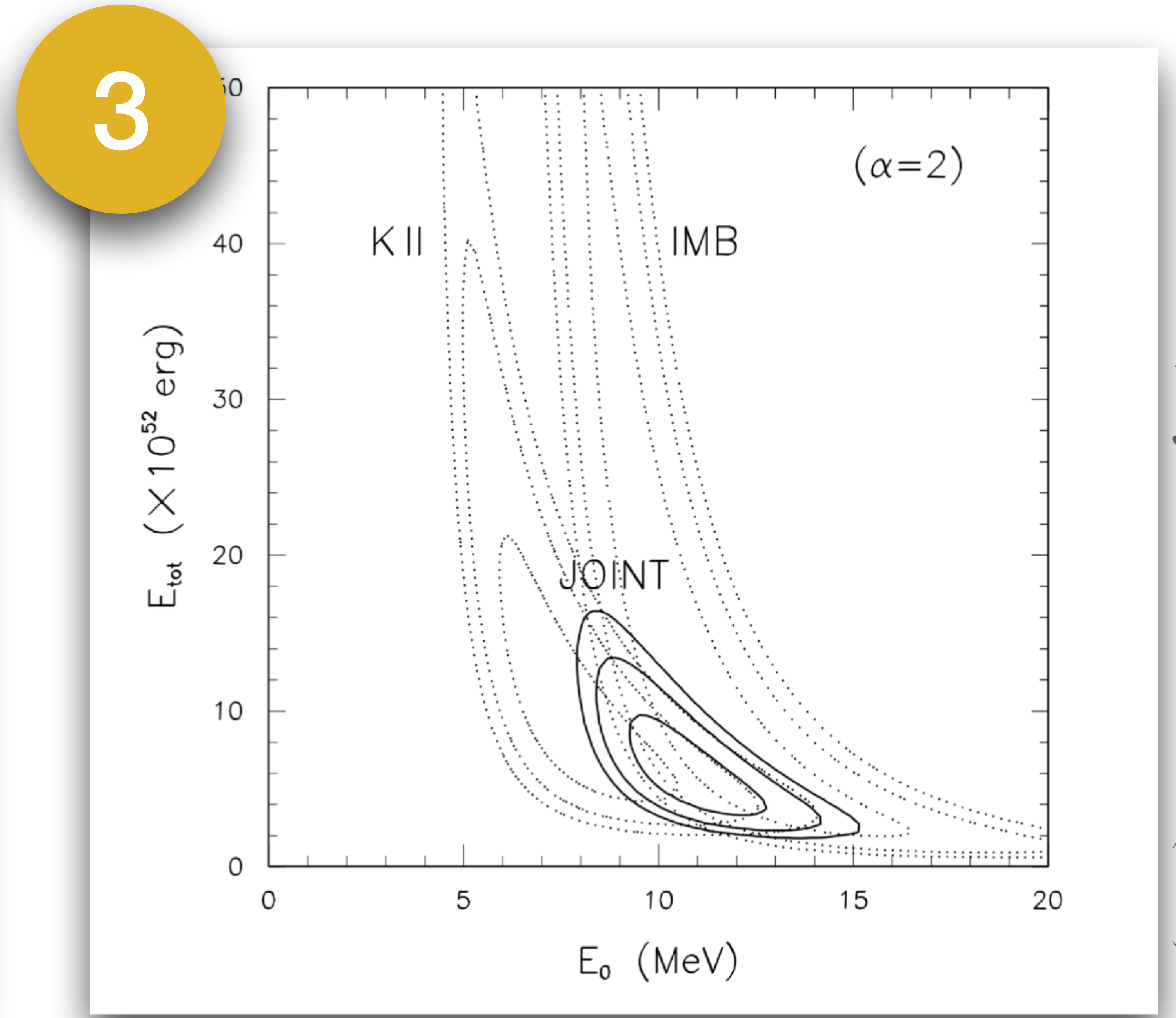
# How did we detect SN1987A

## we can do better than that




Stars as Laboratories for Fundamental Physics, G. Raffelt (1996)




A. Mirizzi et al, Phys.Rev. D 72:063001 (2005)

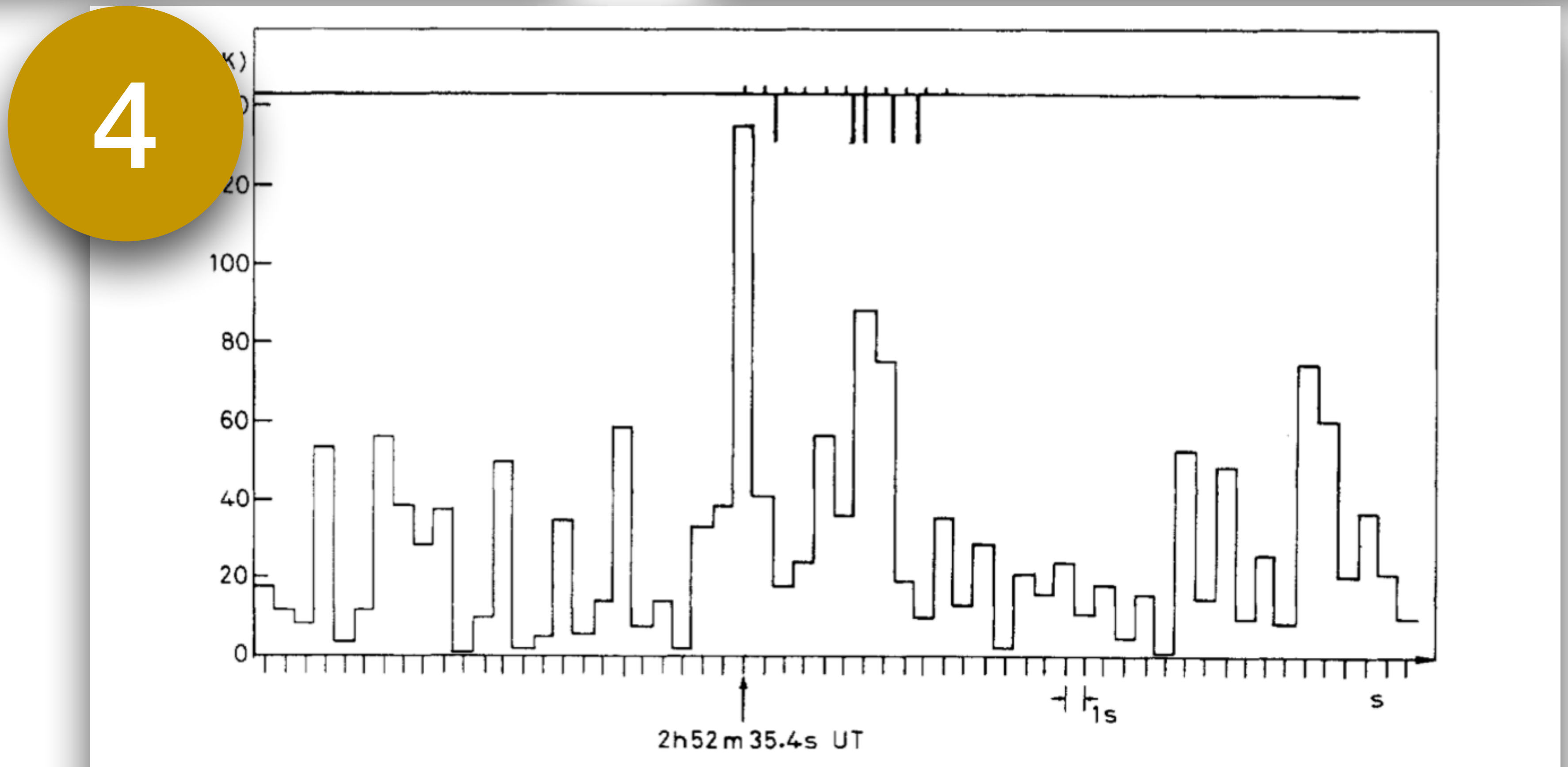
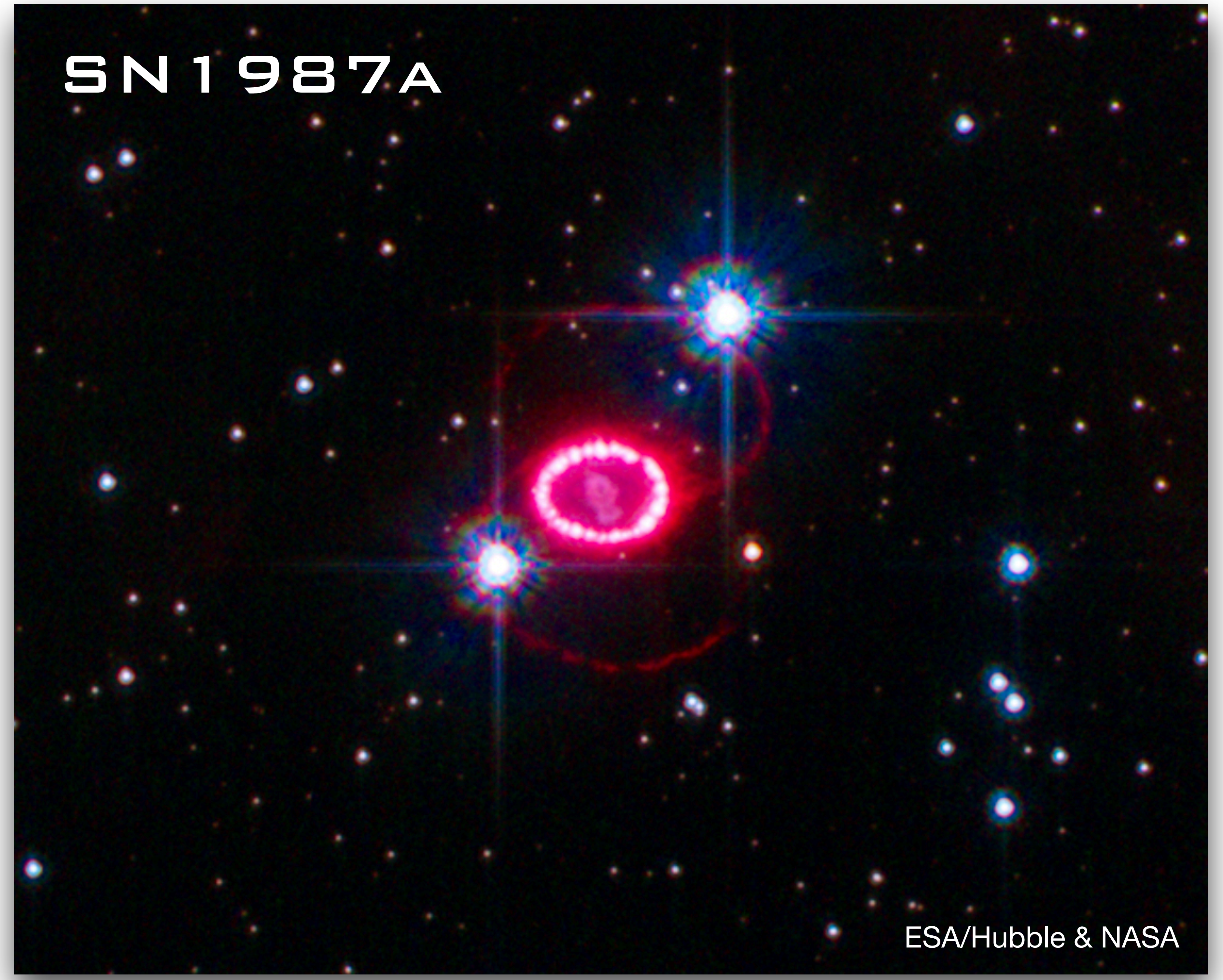



Fig. 2. – Plot of the WK filtered data *vs.* UT with the upper five segments indicating the neutrino event times measured by the LSD collaboration [3].

E. Amaldi et al., Europhys.Lett., 3, 1325 (1987).

# Supernovae: cosmic fireworks

## Setting the stage




High-energy **explosions of massive stars**

W Baade, F Zwicky PNAS (1931)

Star binding energy is converted into:

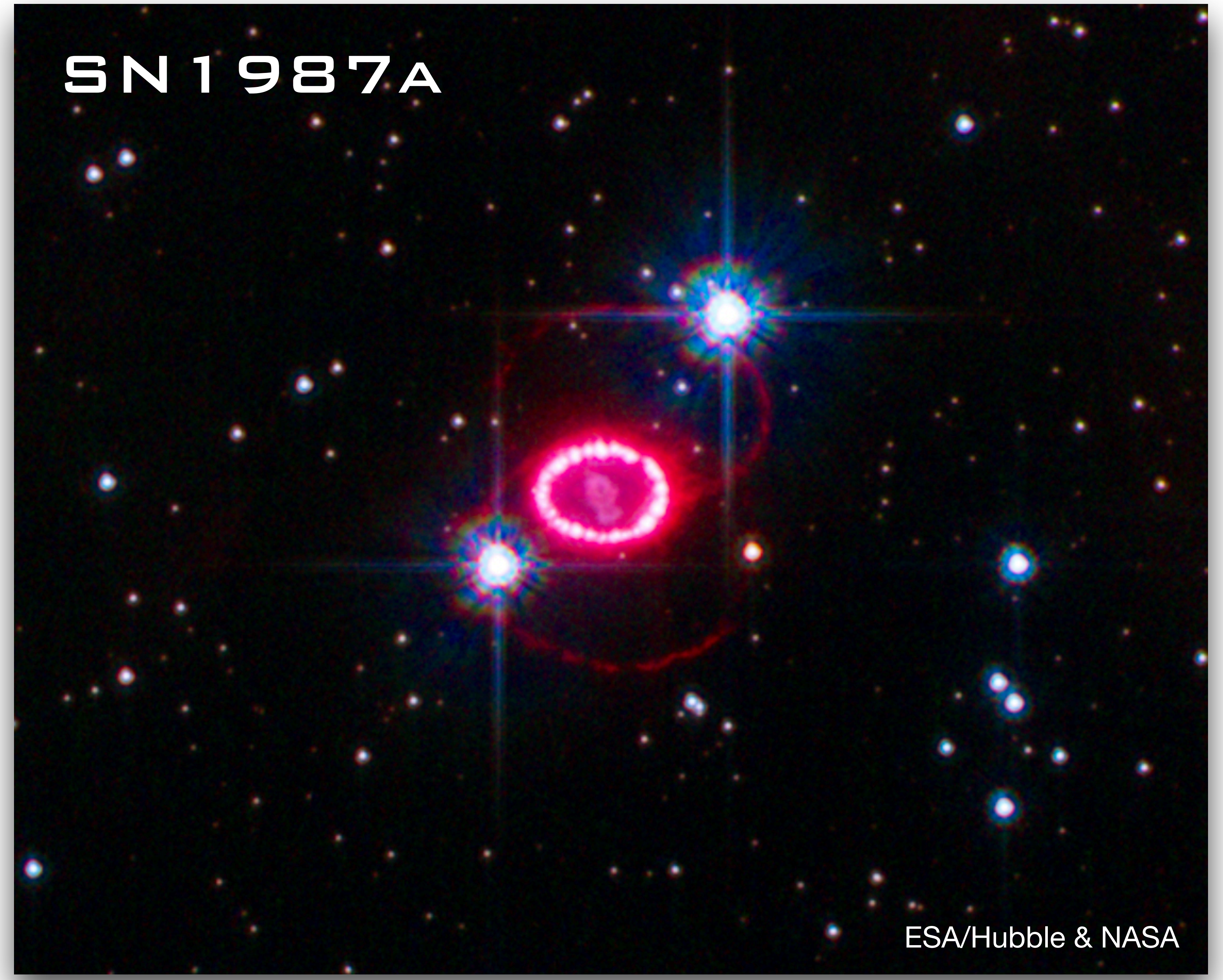
**all flavor-neutrinos, GW, EM radiation**

G. Gamow and M. Schoenberg, Phys. Rev. 59, 539 (1941)

Why neutrinos are interesting?

# Supernovae: cosmic fireworks

## Setting the stage

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Why neutrinos are interesting?

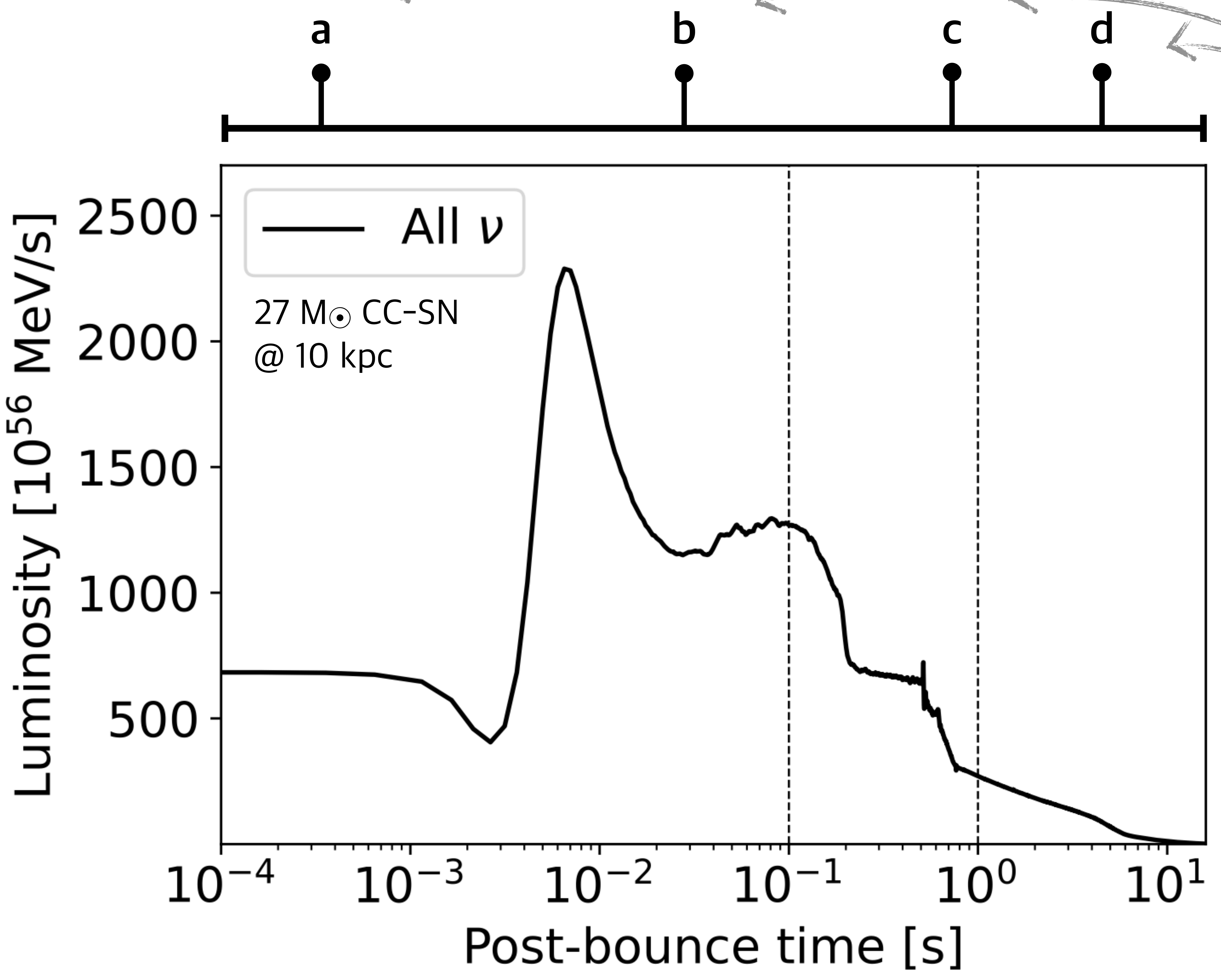
Highest luminosity

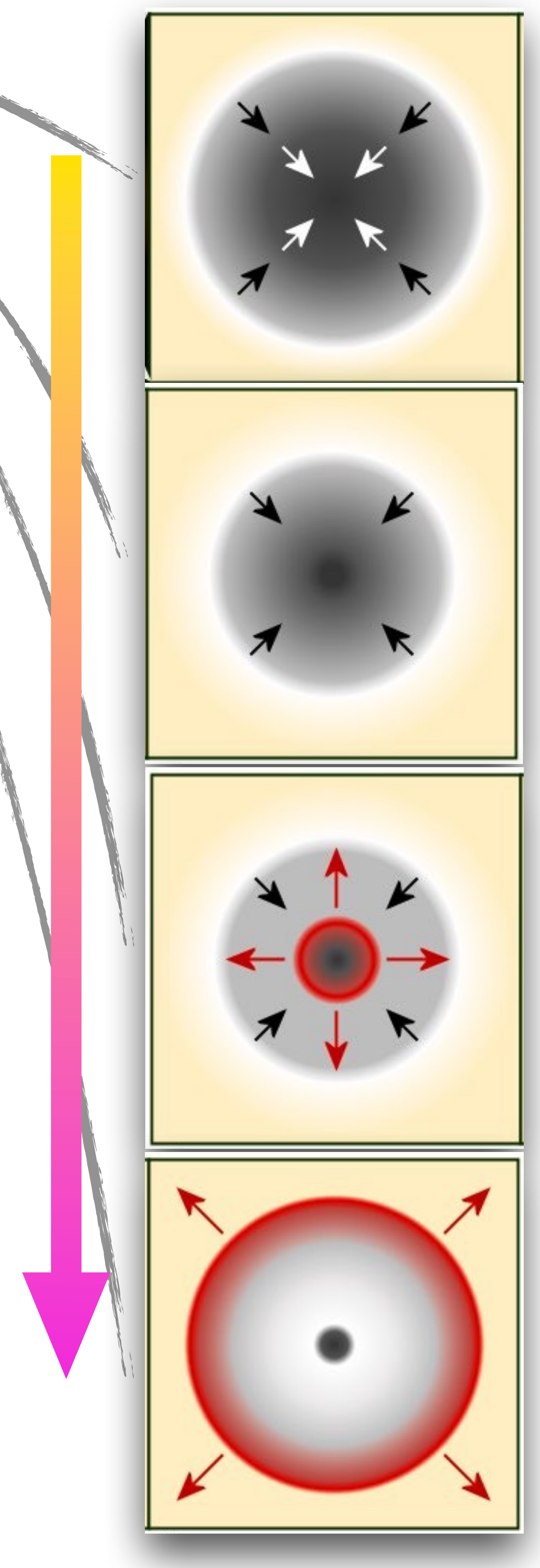
Direct **probes** and **messengers** of SN dynamics

Neutrinos provide **early alerts** of the explosion

# How does a star explode ?

## Neutrinos drive the firework



Wikipedia - Supernova

**Main SN phase**

Star's collapse

Neutronization

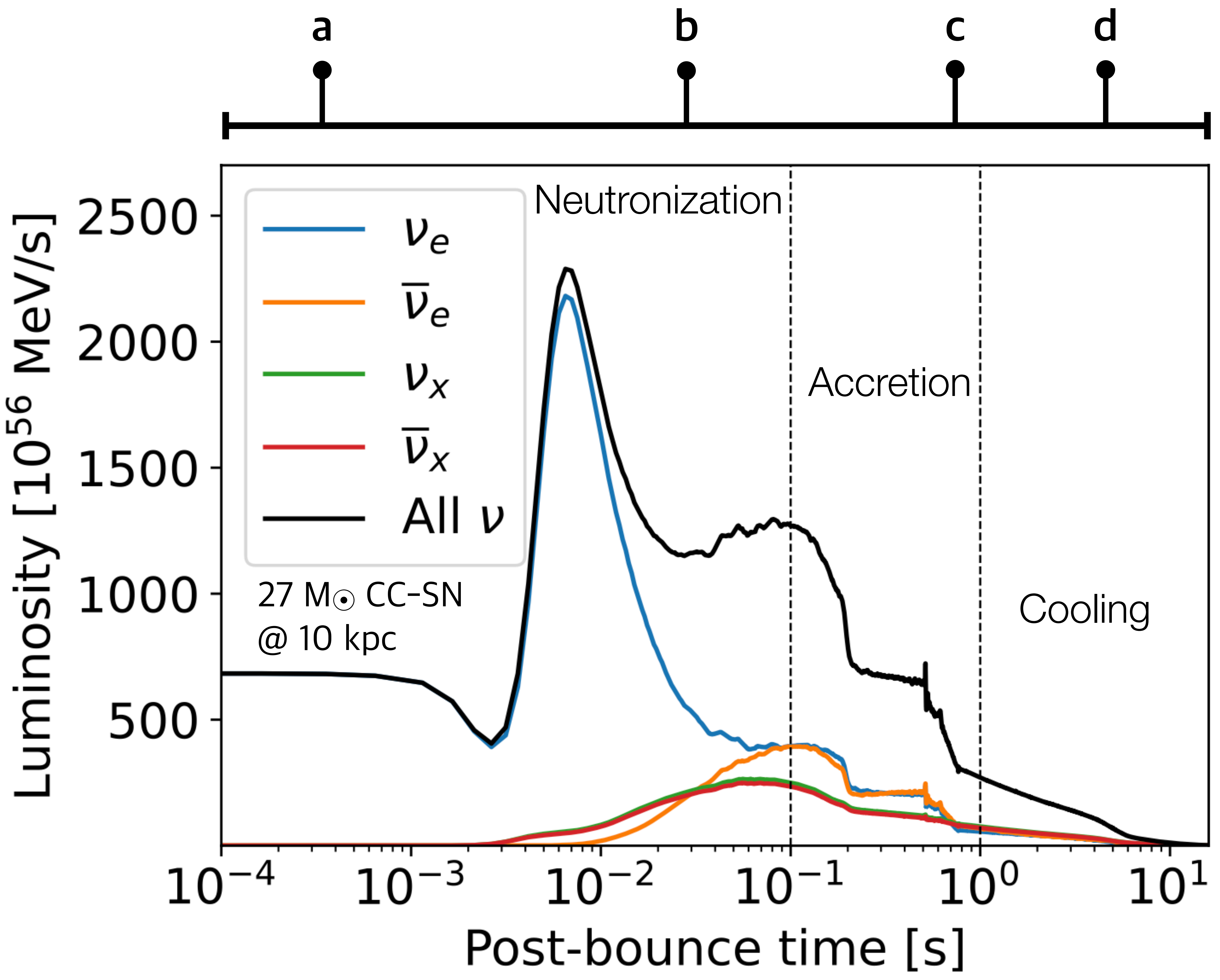
Accretion

Cooling

MPA Supernova Archive

# DETAILS OF A SN NEUTRINO SIGNAL

## ALL FLAVORS EMISSION




➜ Which flavor should we look at ?

MPA Supernova Archive

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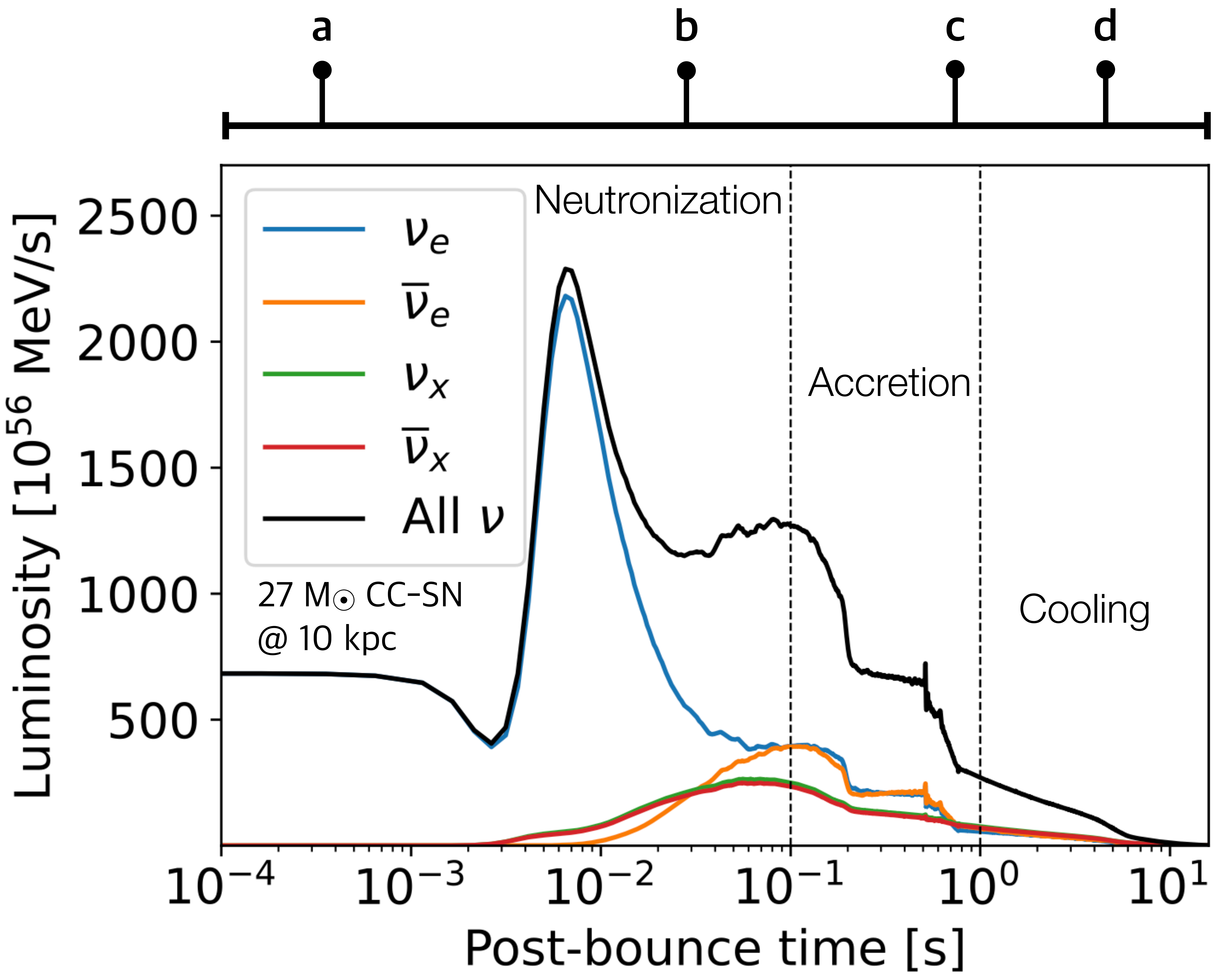
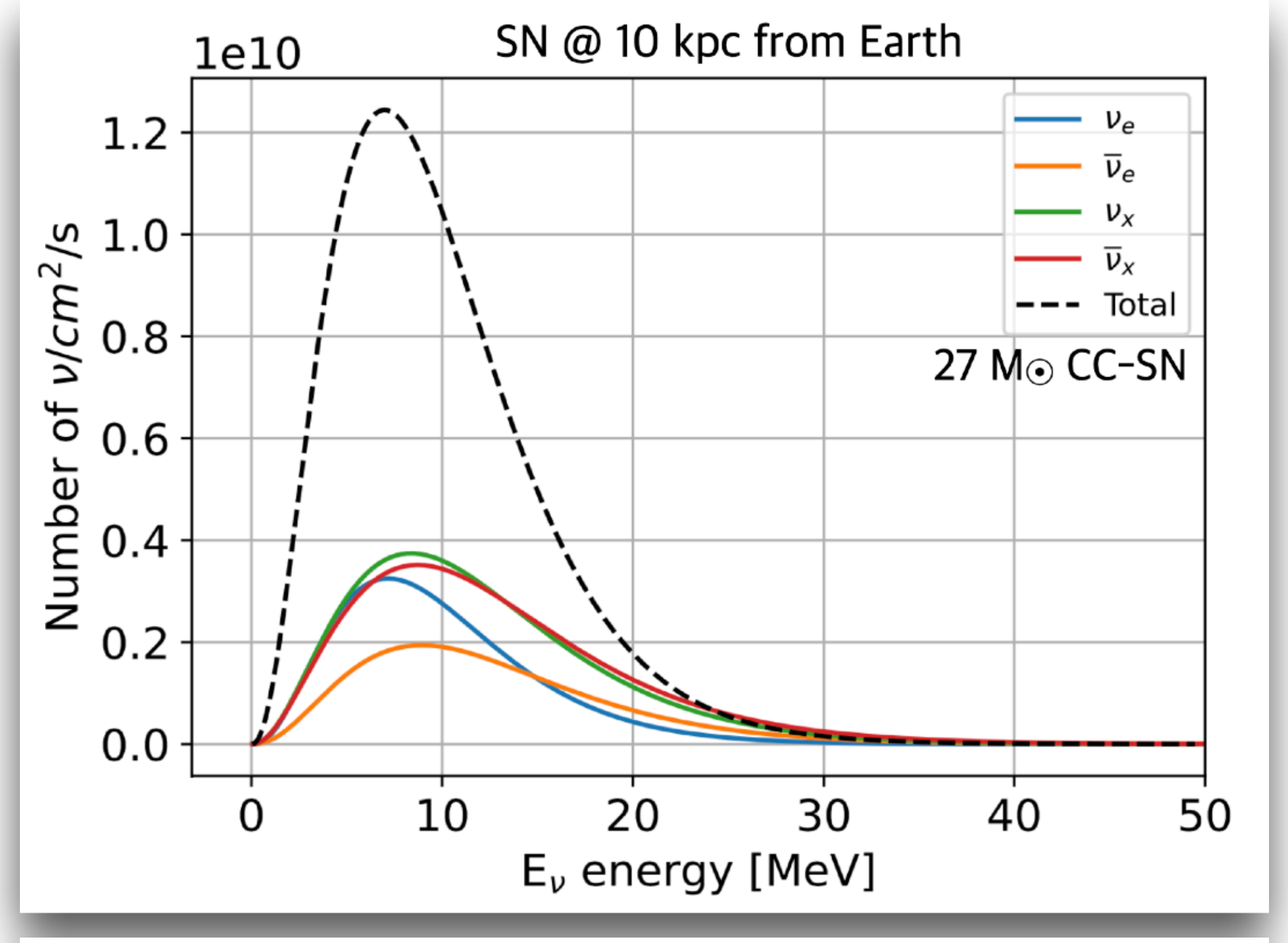
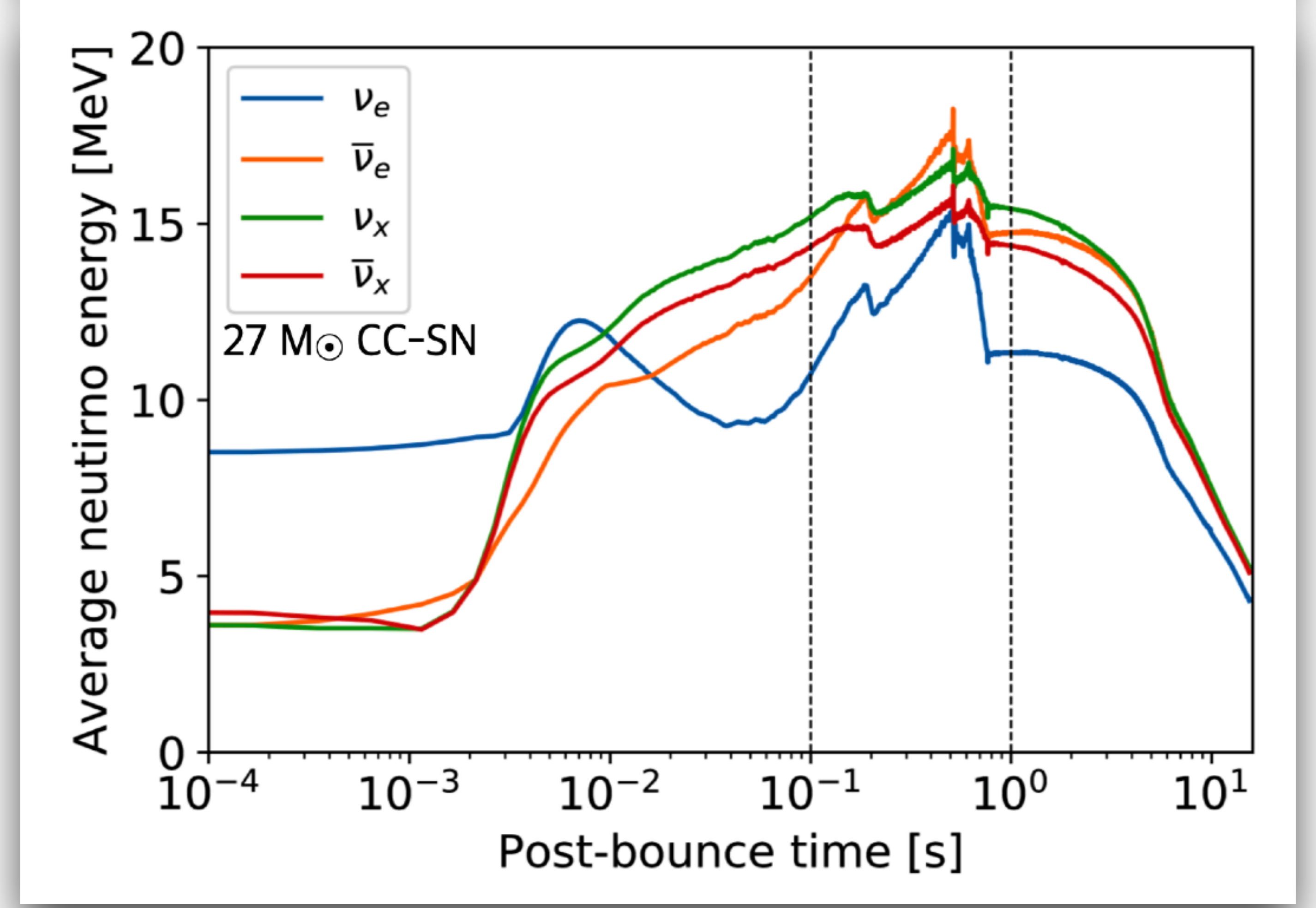



$\nu_x$ is the most **intense** flavor




$\nu_x$ is the most **energetic** flavor

**Sensitive detection channel for $\nu_x$ is needed**

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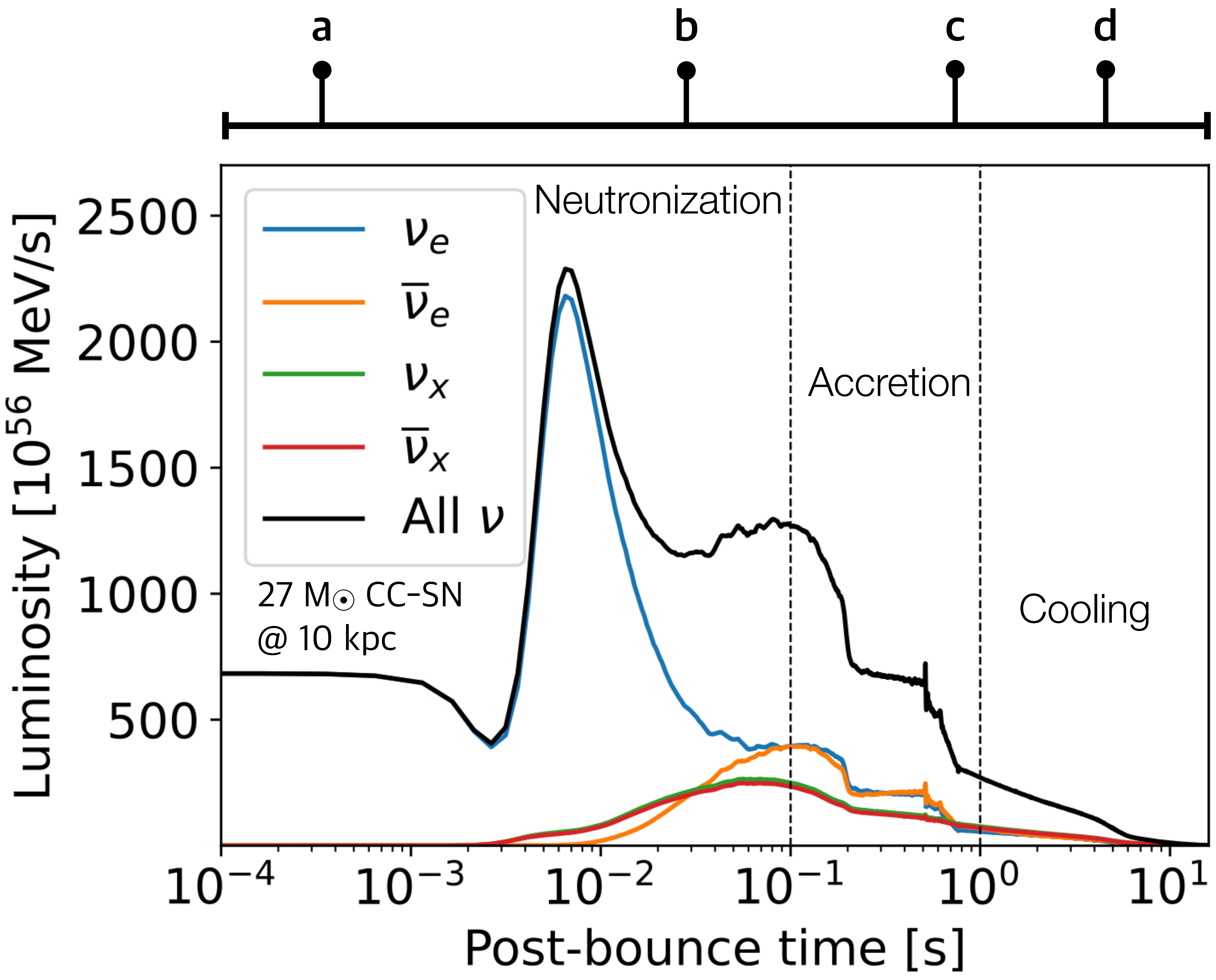
# DETAILS OF A SN NEUTRINO SIGNAL

## WE KNOW LITTLE ABOUT ν OSCILLATION INSIDE SNe

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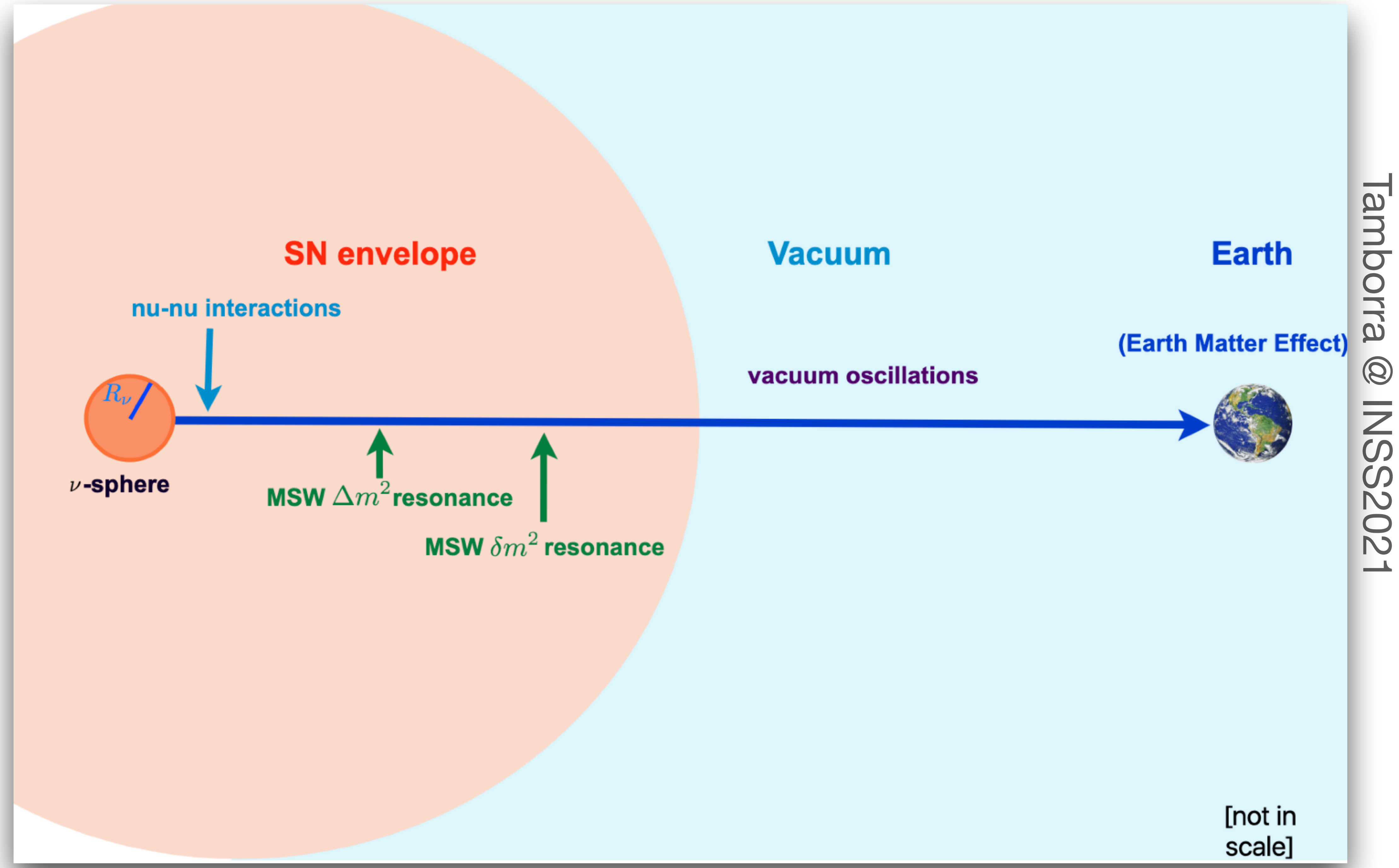
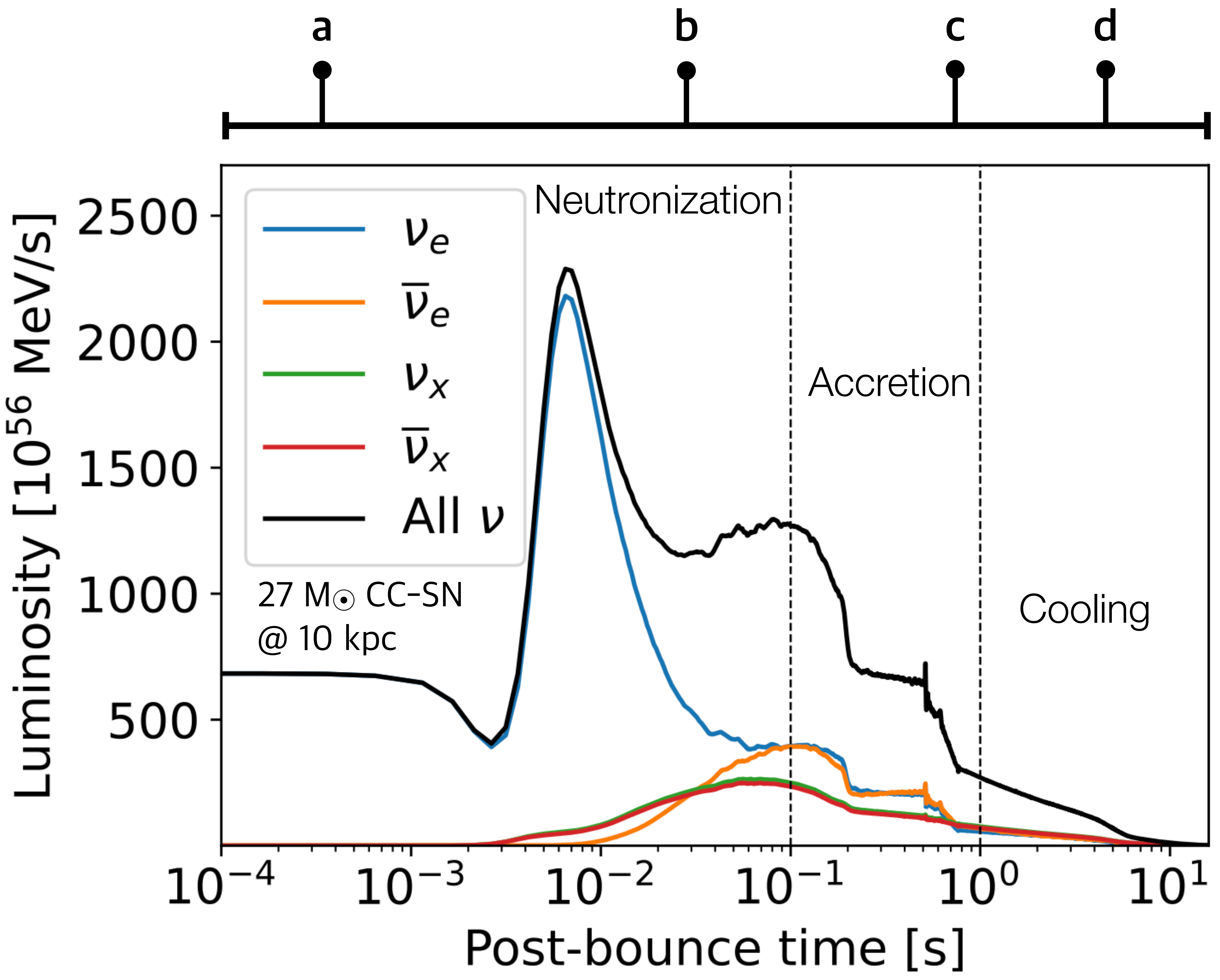
➜ Which flavor should we look at ?




Nota Bene: neutrino flavor oscillations in the stellar envelope are not included

# DETAILS OF A SN NEUTRINO SIGNAL

## WE KNOW LITTLE ABOUT ν OSCILLATION INSIDE SNe




MPA Supernova Archive

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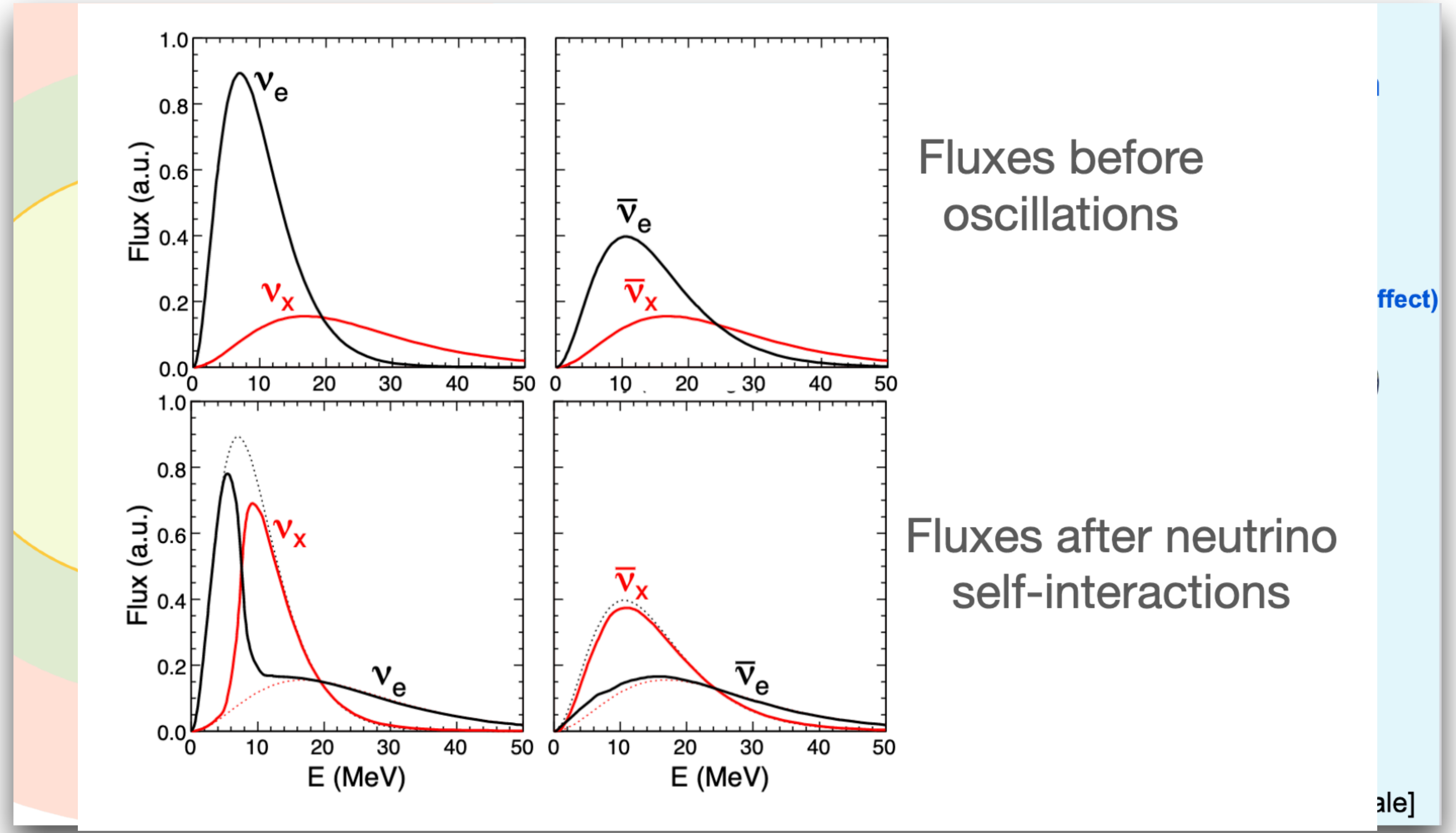
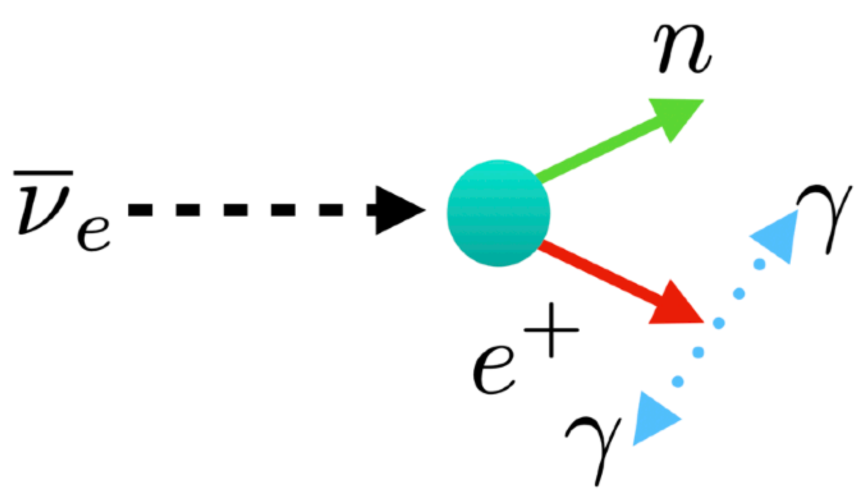
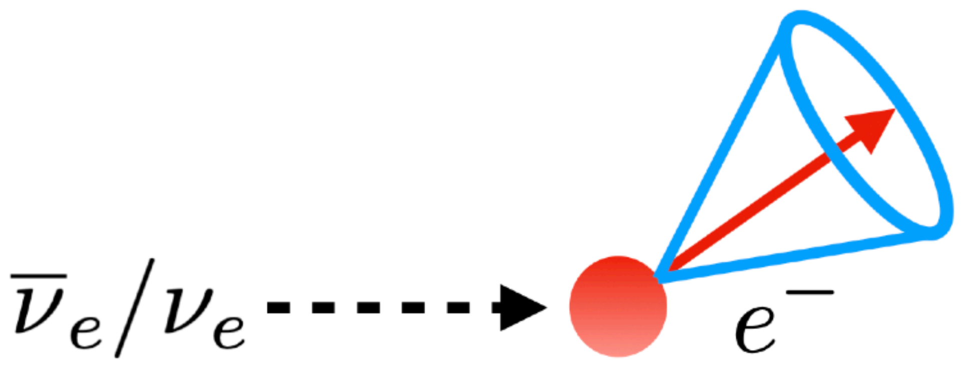
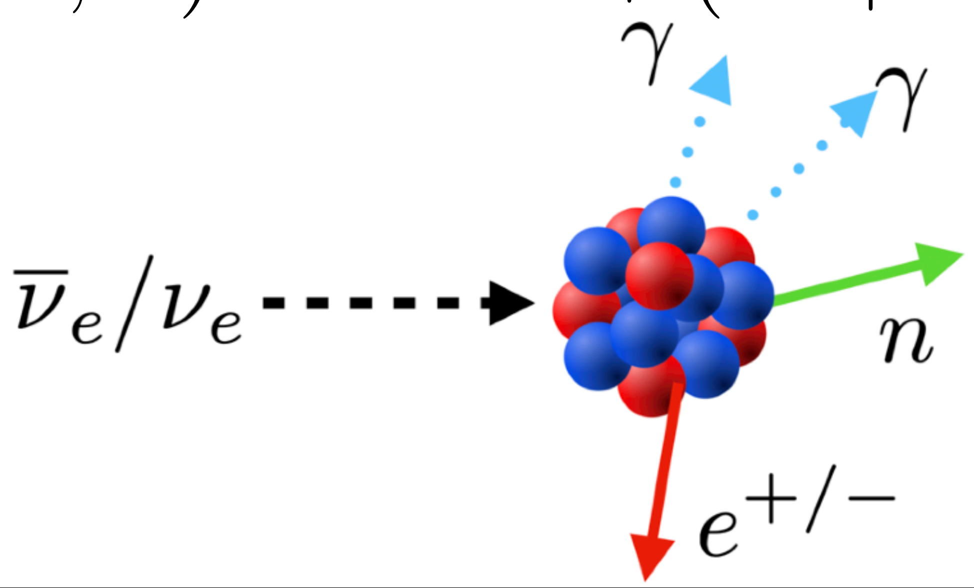
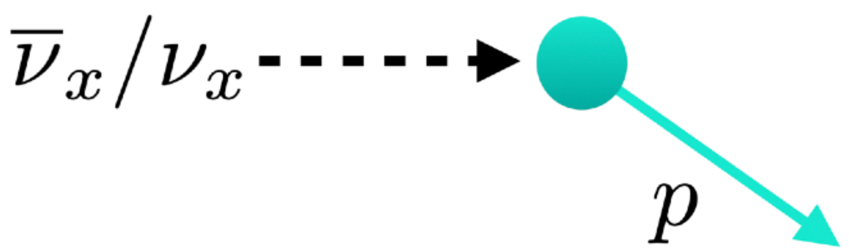
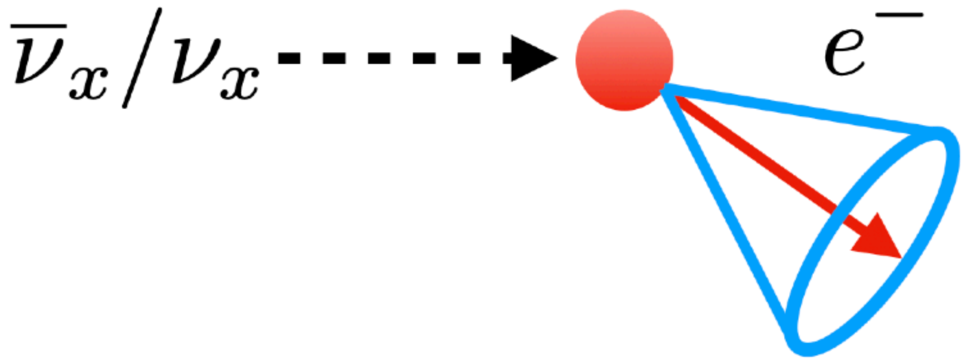
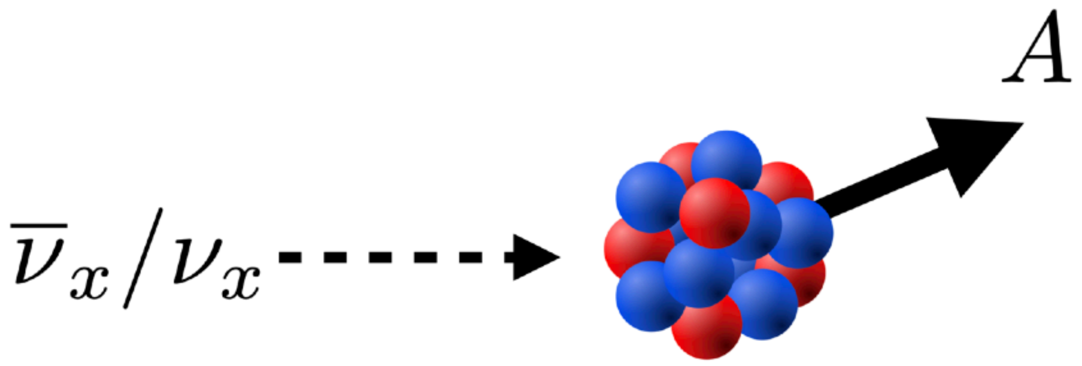



Spectral swap!

Tamborra @ INSS2021

# How do we detect SN neutrinos?

| | PROTONS | ELECTRONS | NUCLEI |
|---|---|---|---|
| **CHARGE CURRENT** | **Inverse beta decay**<br>$\overline{\nu}_e + p \rightarrow e^+ + n$<br> | **Elastic scattering**<br>$\nu + e^- \rightarrow \nu + e^-$<br> | **Inelastic scattering**<br>$\nu_e/\overline{\nu}_e + (N, Z) \rightarrow e^{-/+} + (N \mp 1, Z \pm 1)$<br> |
| **NEUTRAL CURRENT** | **Elastic scattering**<br>$\overline{\nu}_x/\nu_x + p \rightarrow \overline{\nu}_x/\nu_x + p$<br> |  | **Coherent Elastic neutrino-nucleus scattering (CEvNS)**<br>$\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$<br> |

# How do we detect SN neutrinos?

| | PROTONS | ELECTRONS | NUCLEI |
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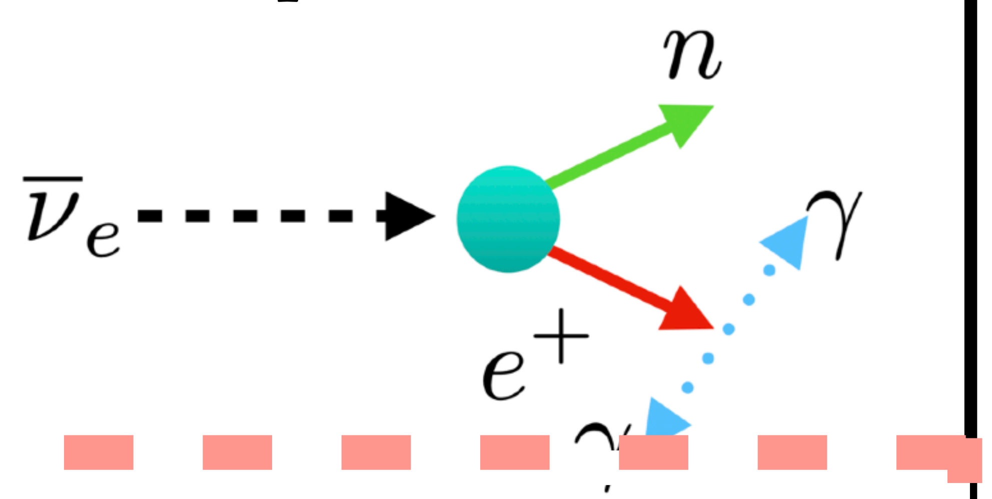
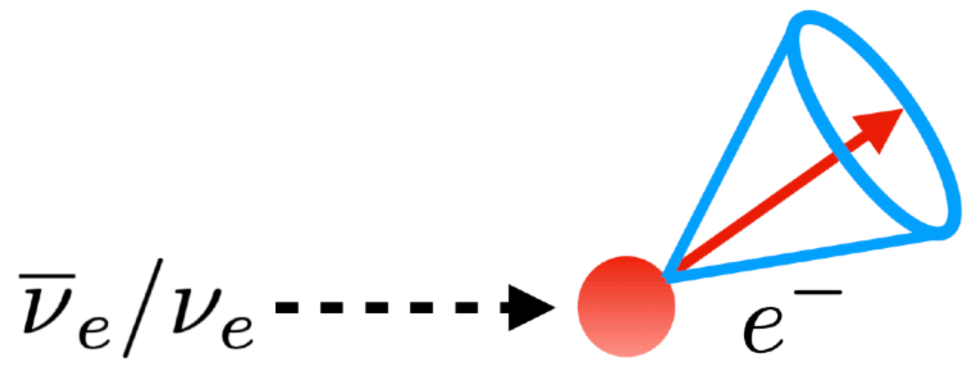
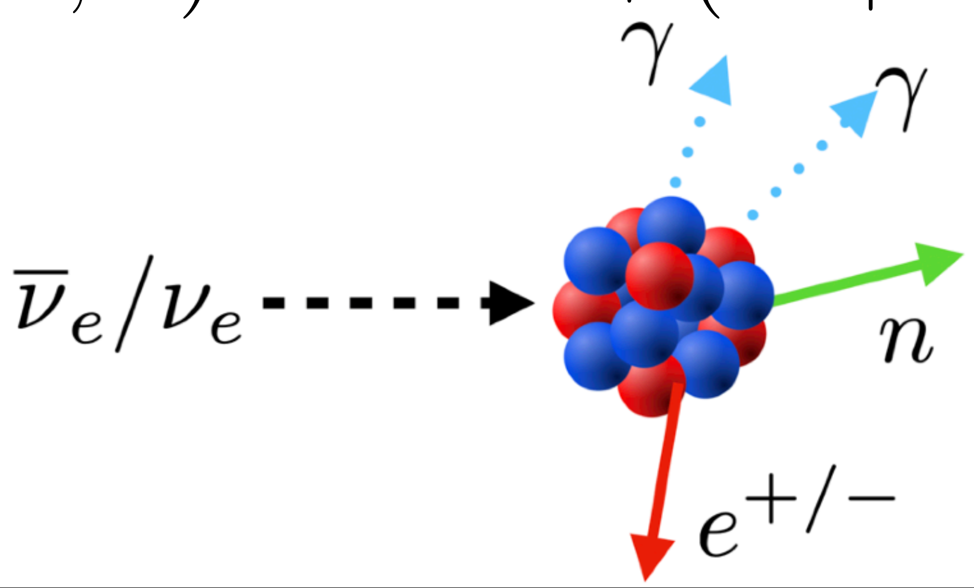
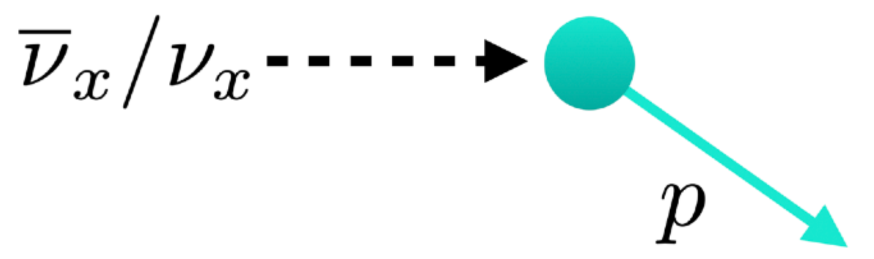
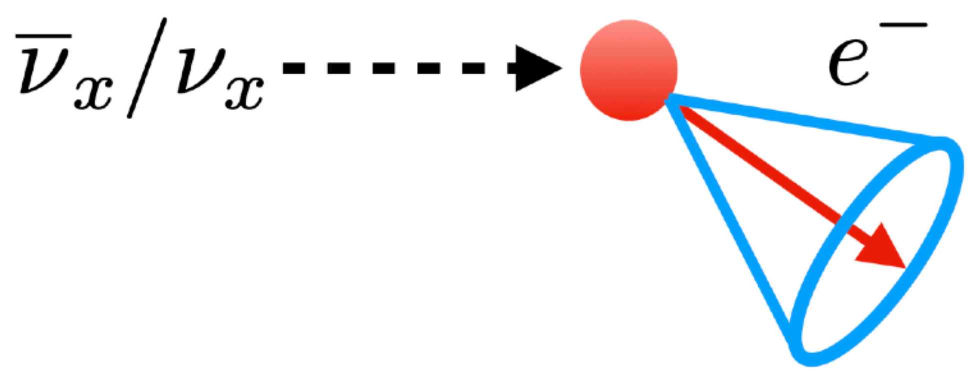
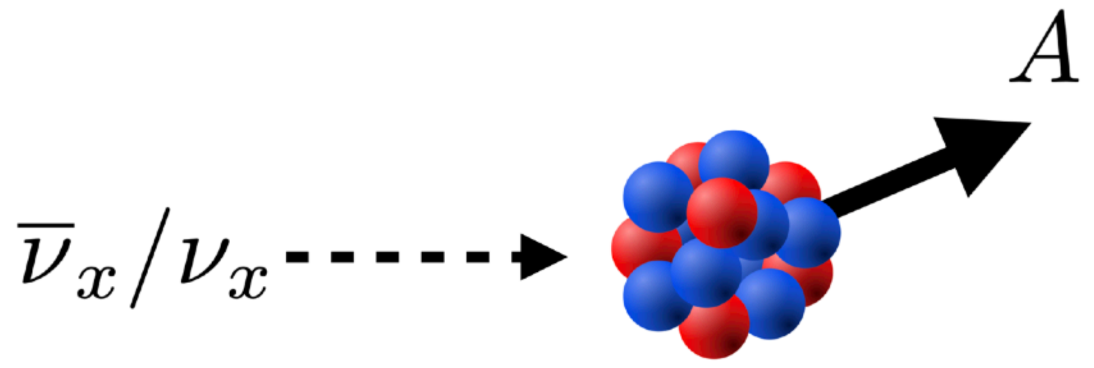
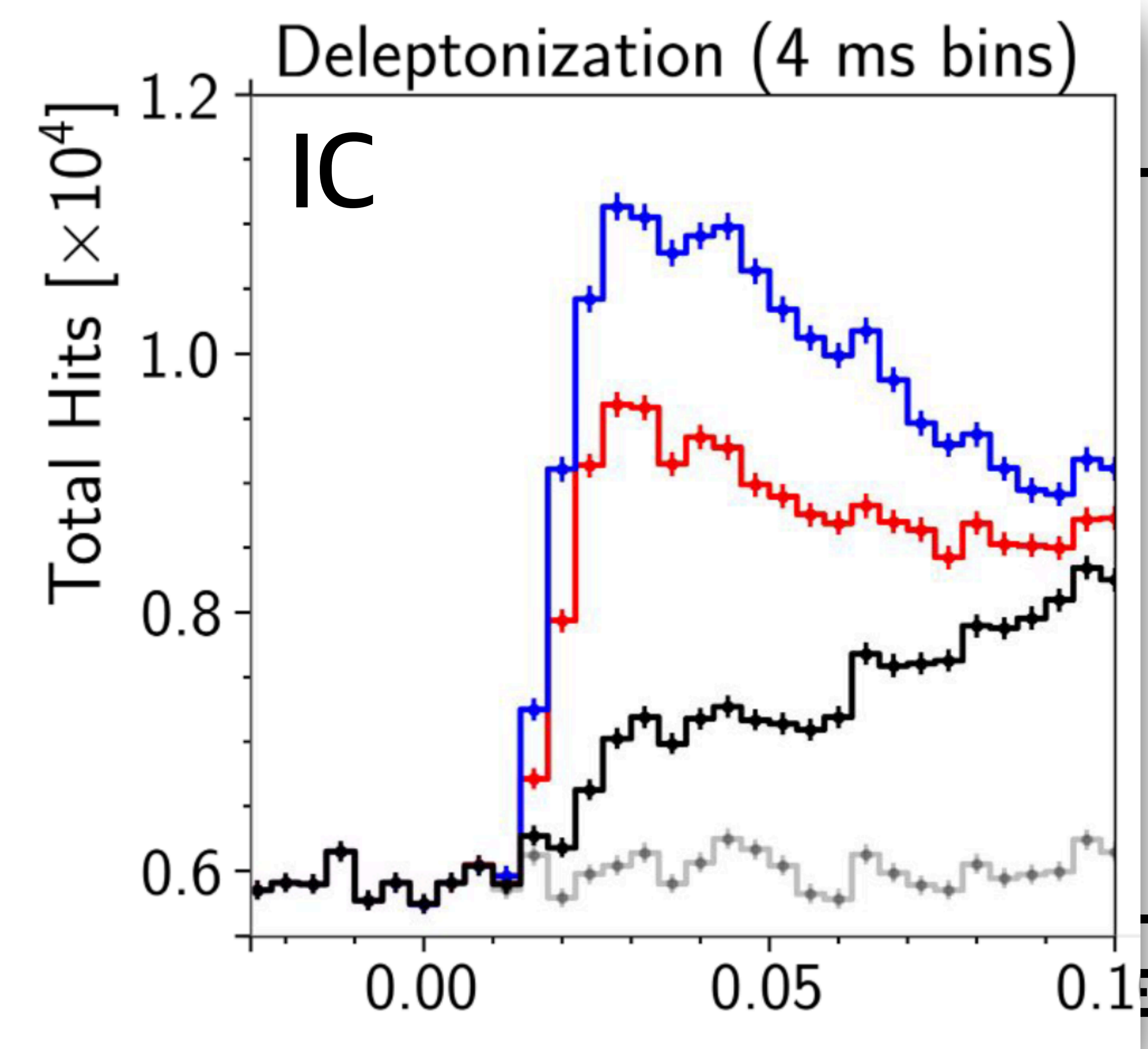
| **CHARGE CURRENT** | **Inverse beta decay** $\overline{\nu}_e + p \rightarrow e^+ + n$  | **Elastic scattering** $\nu + e^- \rightarrow \nu + e^-$  | **Inelastic scattering** $\nu_e/\overline{\nu}_e + (N,Z) \rightarrow e^{-/+} + (N \mp 1, Z \pm 1)$  |
| **NEUTRAL CURRENT** | **Elastic scattering** $\overline{\nu}_x/\nu_x + p \rightarrow \overline{\nu}_x/\nu_x + p$  |  | **Coherent Elastic neutrino-nucleus scattering (CEvNS)** $\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$  |

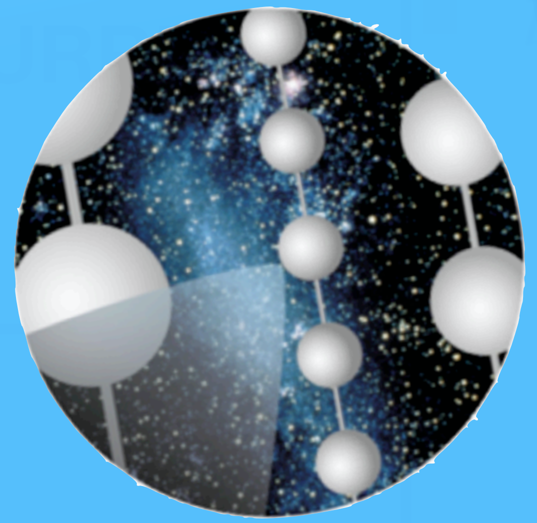
From 1987 to nowadays

# How … TEC … NEUTRINOS?

## KM3NeT
Chn: IBD
ν: anti-$\nu_e$
Mass: 1-7 Mton
SN Distance: <50 kpc
Bonus: Mass & timing

## SK-Gd
Chn: IBD
ν: anti-$\nu_e$
Mass: 22 kton
SN Distance: ≫60 kpc
Bonus: Mass & pointing




## IceCUBE

Chn: IBD
ν: anti-$\nu_e$
Mass: 1 Mton
SN Distance: <60 kpc
Bonus: Mass & timing

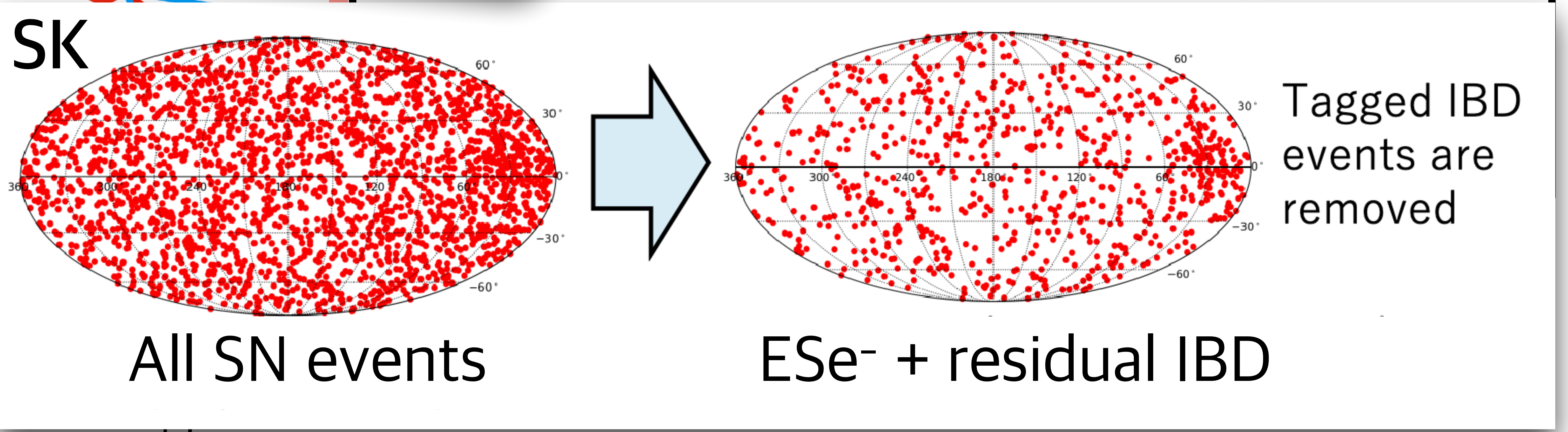
$\nu_x + p$ … $\overline{\nu}_x/\nu_x$ … $e$

…t Ela… …EvNS)

$$\overline{\nu}_x/\nu_x + A \to \overline{\nu}_x/\nu_x + A$$

$A$

…1987 to nowad…



# How do we det N neutrinos?

| | PROTONS | | NUCLEI |
|---|---|---|---|
| CHARGE CURRENT | **Inverse beta decay** $\overline{\nu}_e + p \rightarrow e^+ + n$ | | **Inelastic scattering** $\nu_e/\overline{\nu}_e + (N,Z) \rightarrow e^{-/+} + (N \mp 1, Z \pm 1)$ |
| NEUTRAL CURRENT | **Elastic scattering** $\overline{\nu}_x/\nu_x + p \rightarrow \overline{\nu}_x/\nu_x + p$ | $\overline{\nu}_x/\nu_x$ $e^-$ | |

JUNO

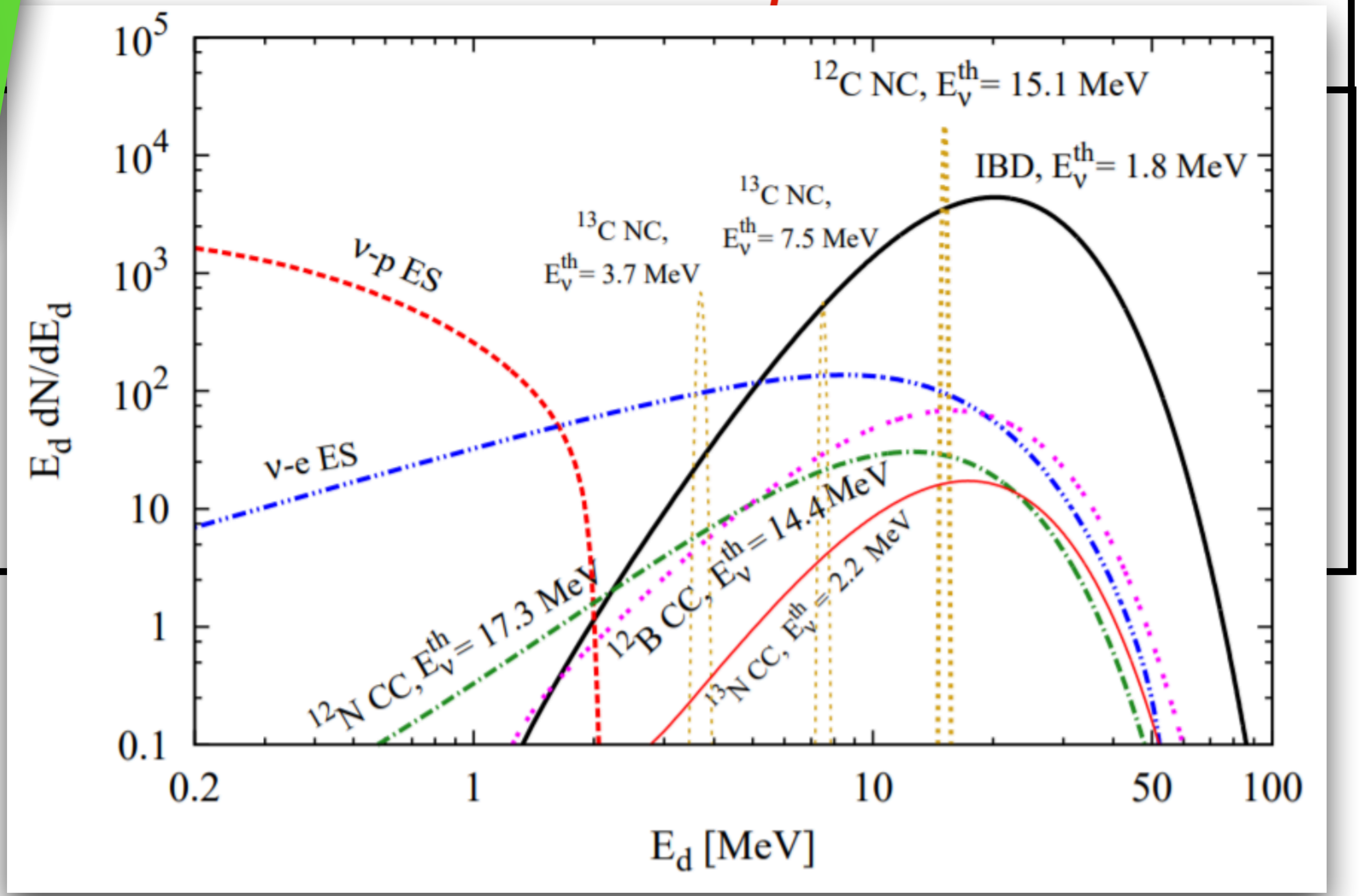
Chn: IBD + eES + pES

ν: all

Mass: 20 kton

SN Distance: ≫60 kpc

Bonus: Mass & Resolution




From 2024 on

# How do we detect SN neutrinos?

**PROTONS** | **ELECTRONS** | **NUCLEI**

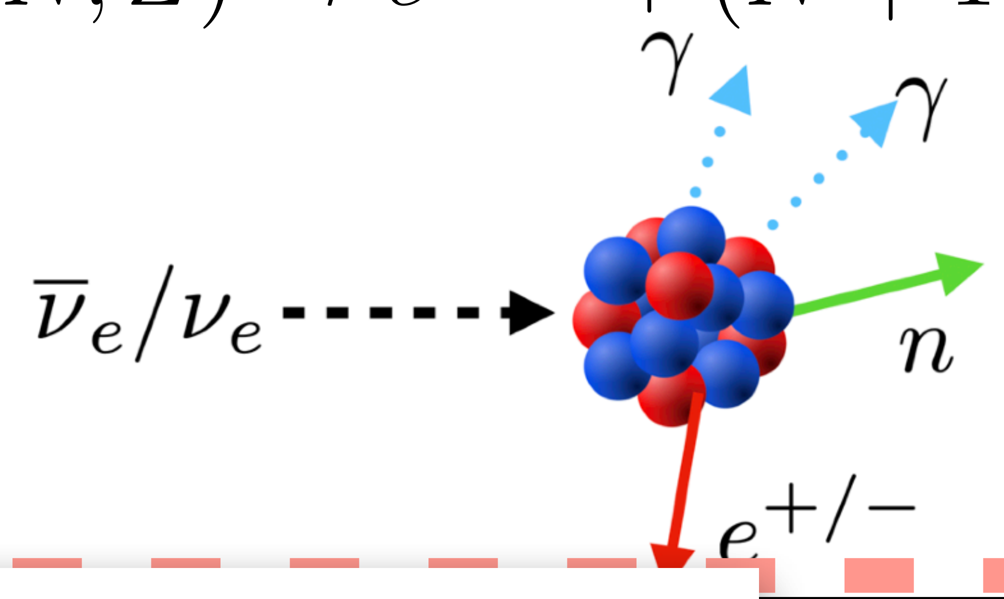
**eta decay**

**Elastic scattering**

$\bar{\nu}_e/\nu_e \; e^-$

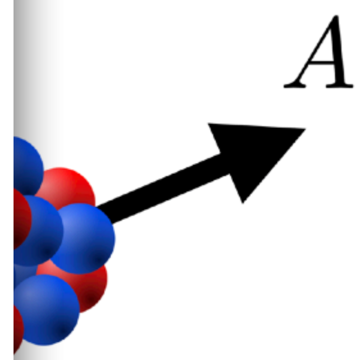
**Inelastic scattering**

$$\nu_e/\overline{\nu}_e + (N,Z) \to e^{-/+} + (N\mp 1, Z\pm 1)$$




**s scattering (CEvNS)**

$\nu_x + A$




NE

CU

$+\,p$

$p$

$$\nu_e + {}^{40}Ar \to {}^{40}K^* + e^-$$
$$\bar{\nu}_e + {}^{40}Ar \to {}^{40}Cl^* + e^+$$

DUNE

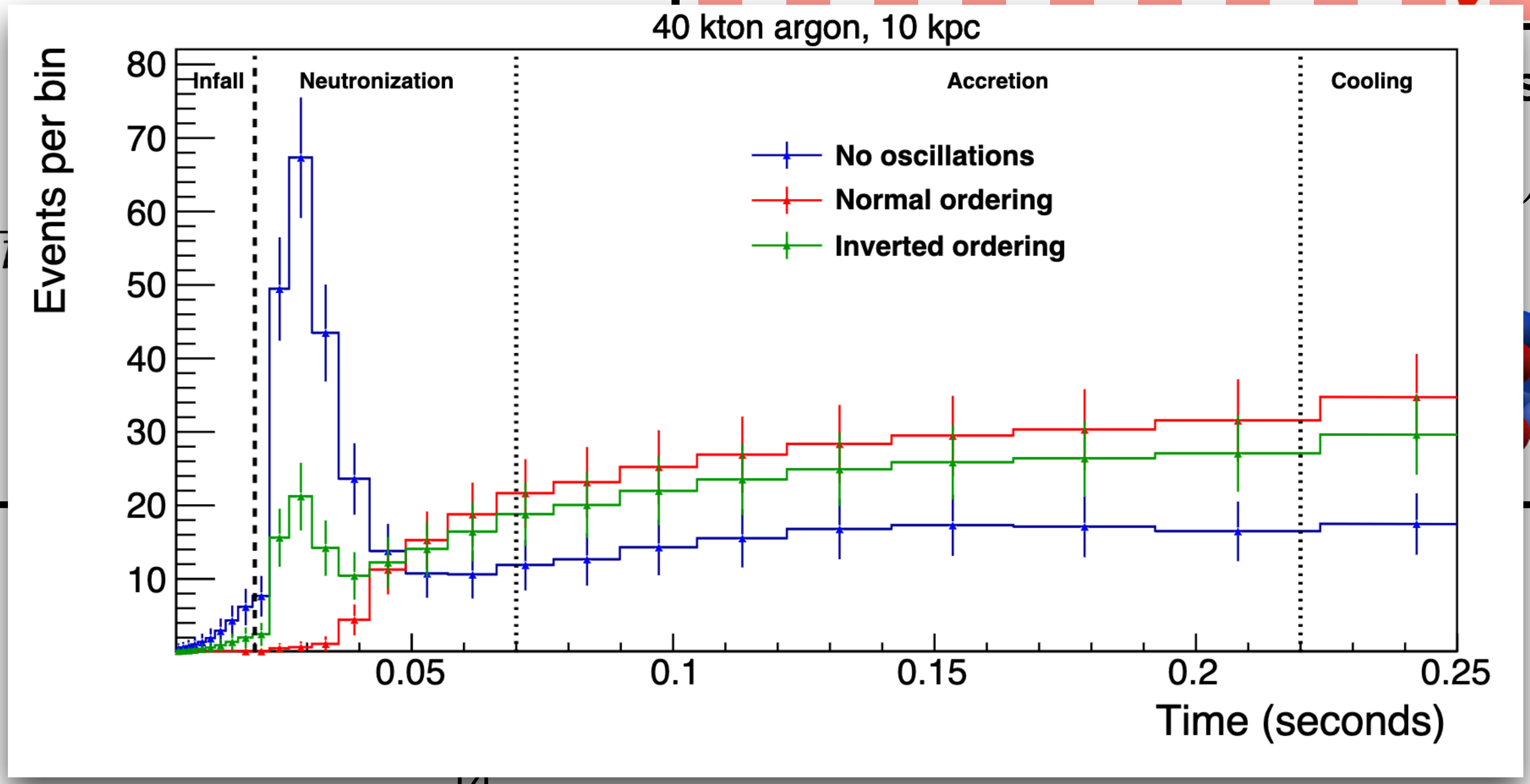
Chn: CC on $^{40}$Ar

ν: $\nu_e$ and anti-$\nu_e$

Mass: 10+10 kton

SN Distance: <60 kpc

Bonus: $\nu_e$ and anti-$\nu_e$



# How do we de… neutrinos?

PROTONS

CHARGE

Inve…

$\overline{\nu}_e +$

$\sigma_{CE\nu NS} \propto N^2$

cross-section

Neutron number

$e^{+/-}$

ResNova

Chn: CEvNS on Pb

ν : all

Mass: 1.8 ton

SN Distance: <40 kpc

Bonus: High-xs & Res & siz

Xenon-nT

Chn: CEvNS on Xe

ν : all

Mass: 5 ton

SN Distance: <40 kpc

Bonus: High-xs & size

DS-20k

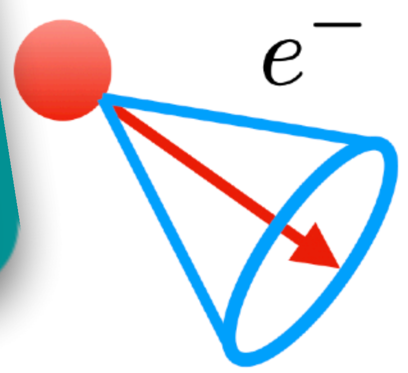
Chn: CEvNS on Ar

ν : all

Mass: 20 ton

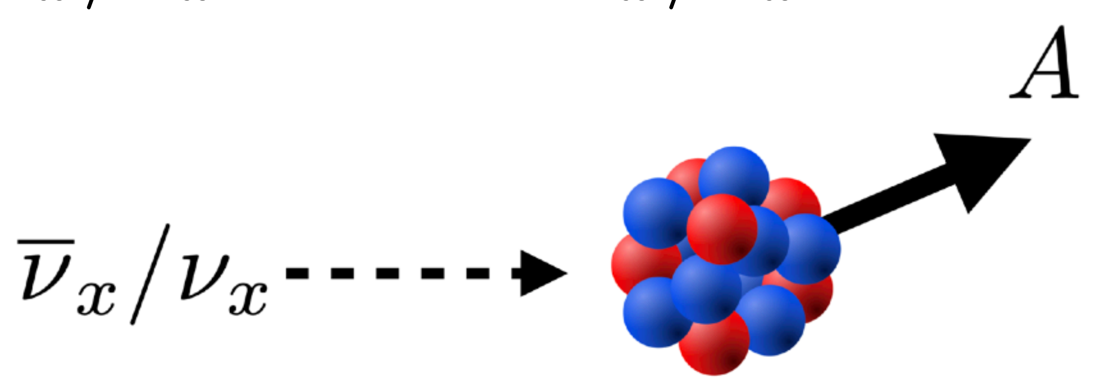
SN Distance: <20 kpc

Bonus: High-xs & size




**Coherent Elastic neutrino-nucleus scattering (CEvNS)**

$$\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$$




Since 2017

COHERENT Coll., *Science* 357 (2017) 6356, 1123

# HOW DO WE DE… NE…

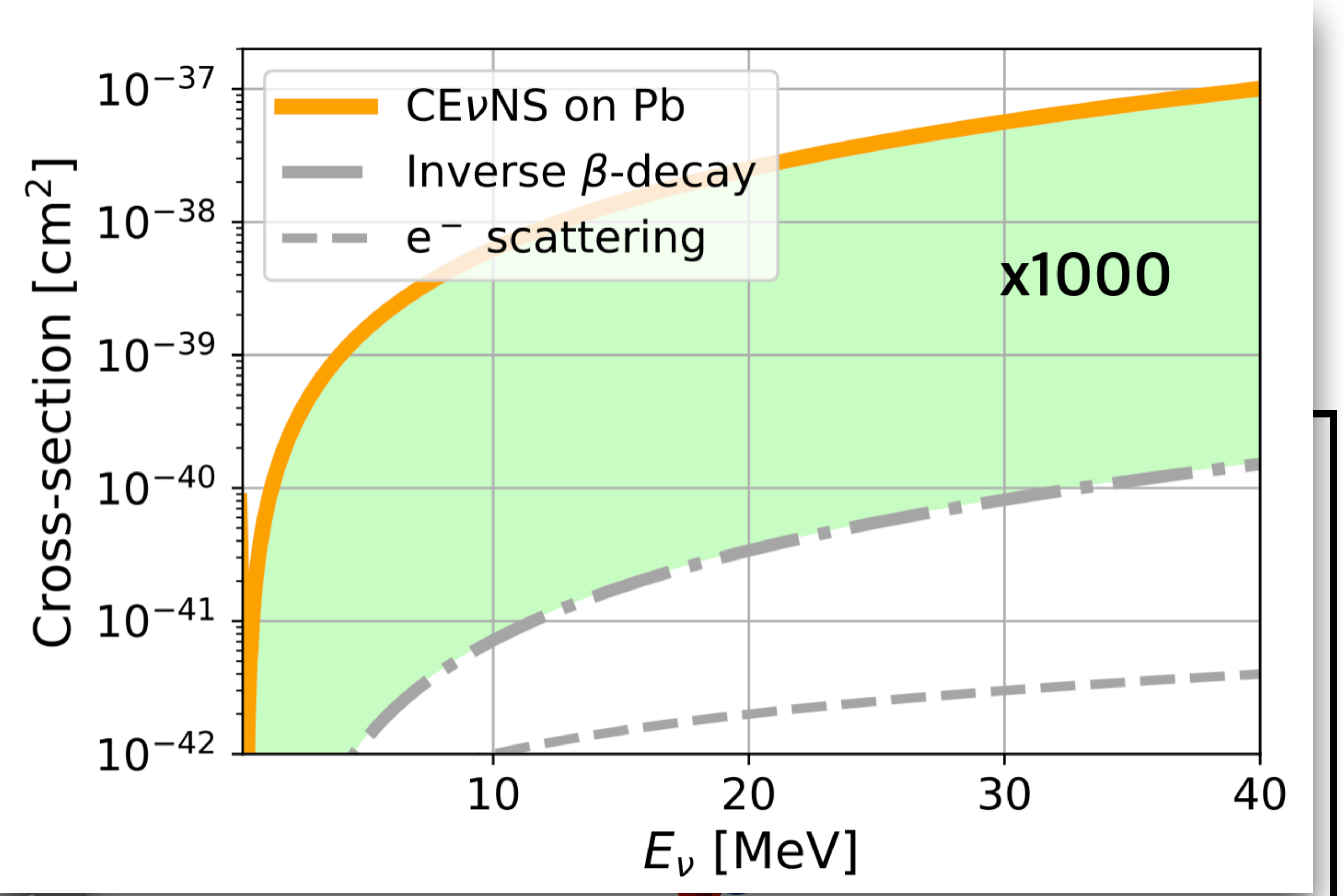
**PROTONS**

| | |
|---|---|
| **CHARGE CU…** | **Inve…** $\overline{\nu}_e +$ … |

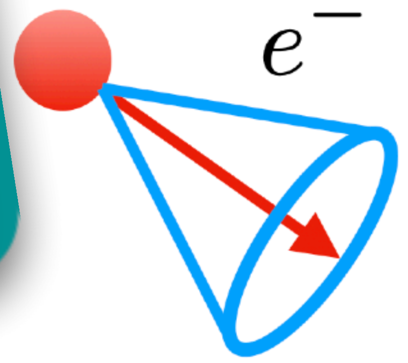
**ResNova**
Chn: CEνNS on Pb
ν : all
Mass: 1.8 ton
SN Distance: <40 kpc
Bonus: High-xs & Res & siz…

**Xenon-nT**
Chn: CEνNS on Xe
ν : all
Mass: 5 ton
SN Distance: <40 kpc
Bonus: High-xs & size

**DS-20k**
Chn: CEνNS on Ar
ν : all
Mass: 20 ton
SN Distance: <20 kpc
Bonus: High-xs & size




$e^{+/-}$

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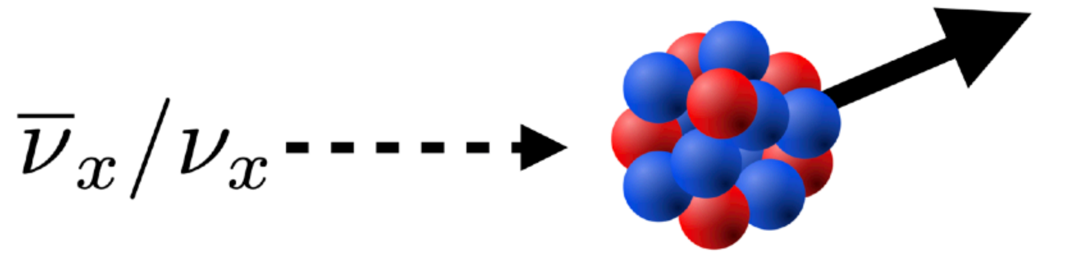
$$\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu_x + A$$

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# How do we de… …s …ne…

**PROTONS**

**CHARGE CU…**

**Inve…**

$\overline{\nu}_e +$

ResNova
Chn: CEνNS on Pb
ν : all
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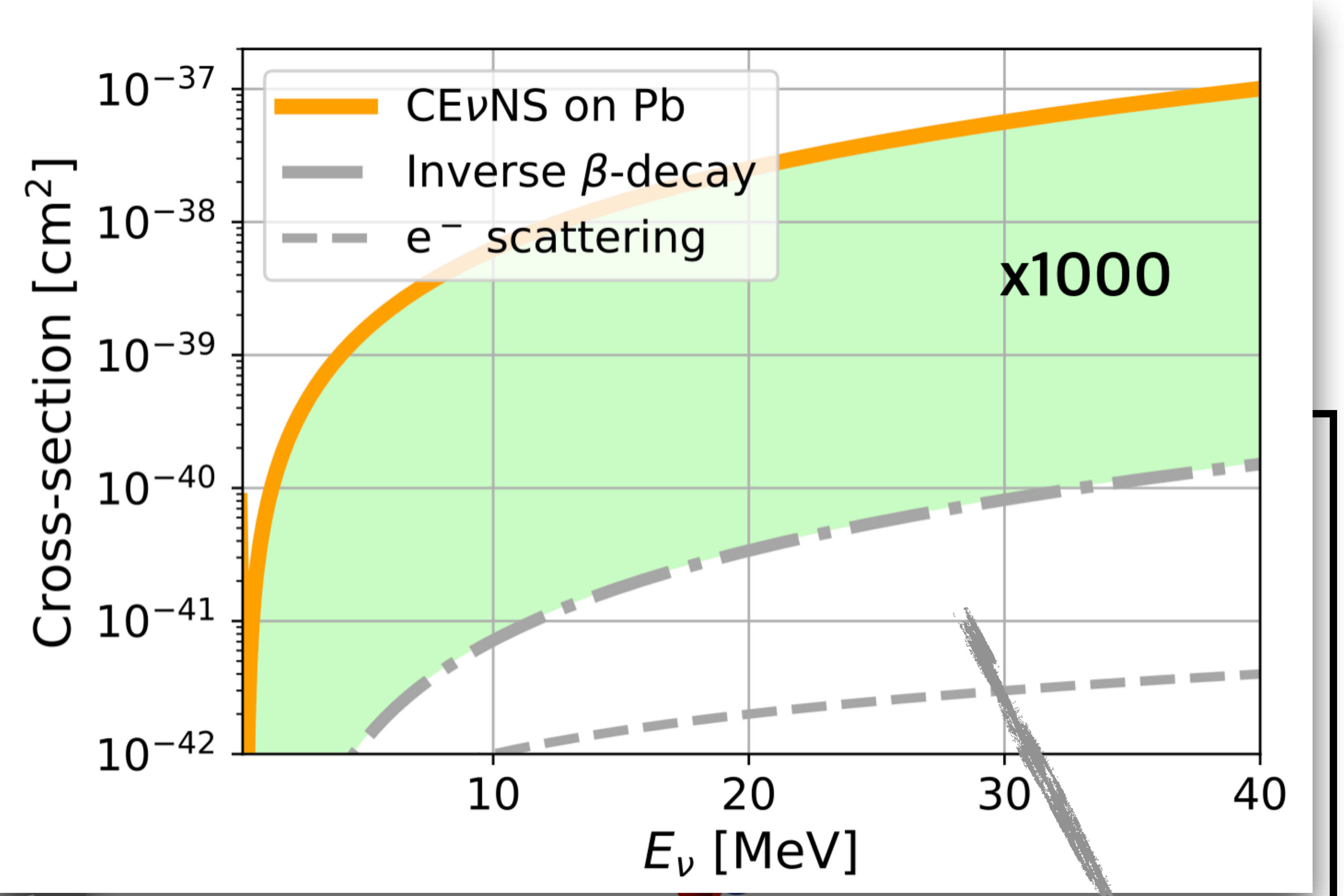
SN Distance: <20 kpc
Bonus: High-xs & size




$e^{+/-}$

$e^-$

**Coherent Elastic neutrino-nucleus …NS)**

$\overline{\nu}_x/\nu_x + A \rightarrow \overline{\nu}_x/\nu…$

$\overline{\nu}_x/\nu_x$

$\nu_{e,\mu,\tau} - p$

$\bar{\nu}_{e,\mu,\tau} - p$

CC $\nu_e - {}^{40}$Ar

CC $\bar{\nu}_e - {}^{40}$Ar

**Since 2017**

COHERENT Coll., *Science* 357 (2017) 6356, 1123

# SN as labs for Fundamental Physics

## extracting the most out of a SN

Using the $\nu$s: energy arrival time source location

| | |
|---|---|
| Location of the SN | $\nu$ Astronomy |
| Neutrino fundamental properties | $\nu$ in Particle Particles |
| SN remnants properties | $\nu$ in Nuclear Physics & Astrophysics |
| Physics of the CoreCollapse | $\nu$ in Nuclear Physics & Astrophysics |
| Multi-messenger observation | $\nu$ as connectors |
| * Stellar nucleosynthesis | $\nu$ in Nuclear Astrophysics |
| *Physics Beyond SM + Exotic Physics | $\nu$ for BSM Physics |

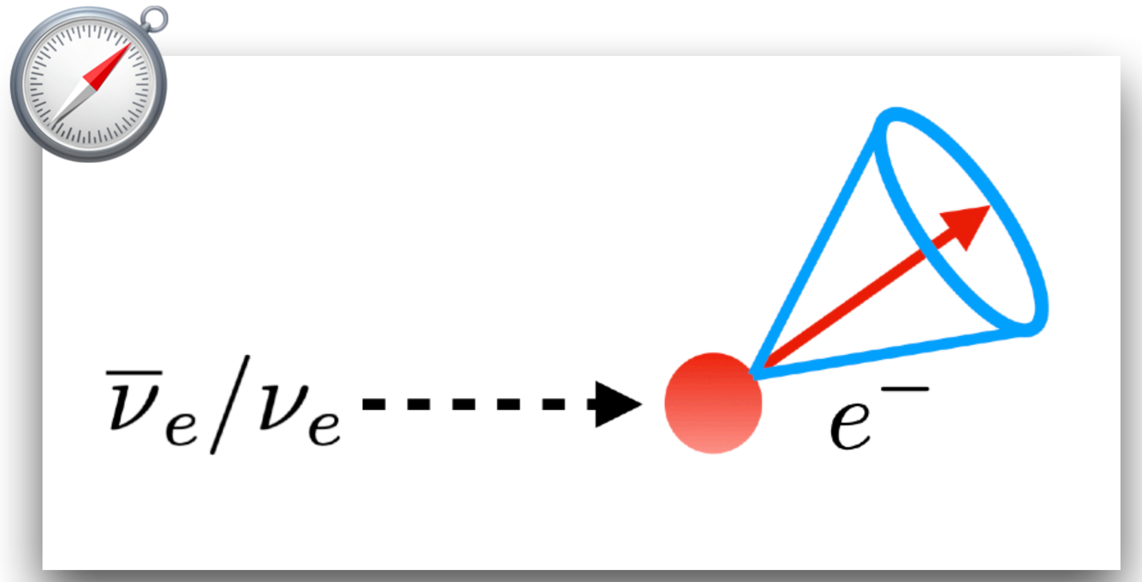


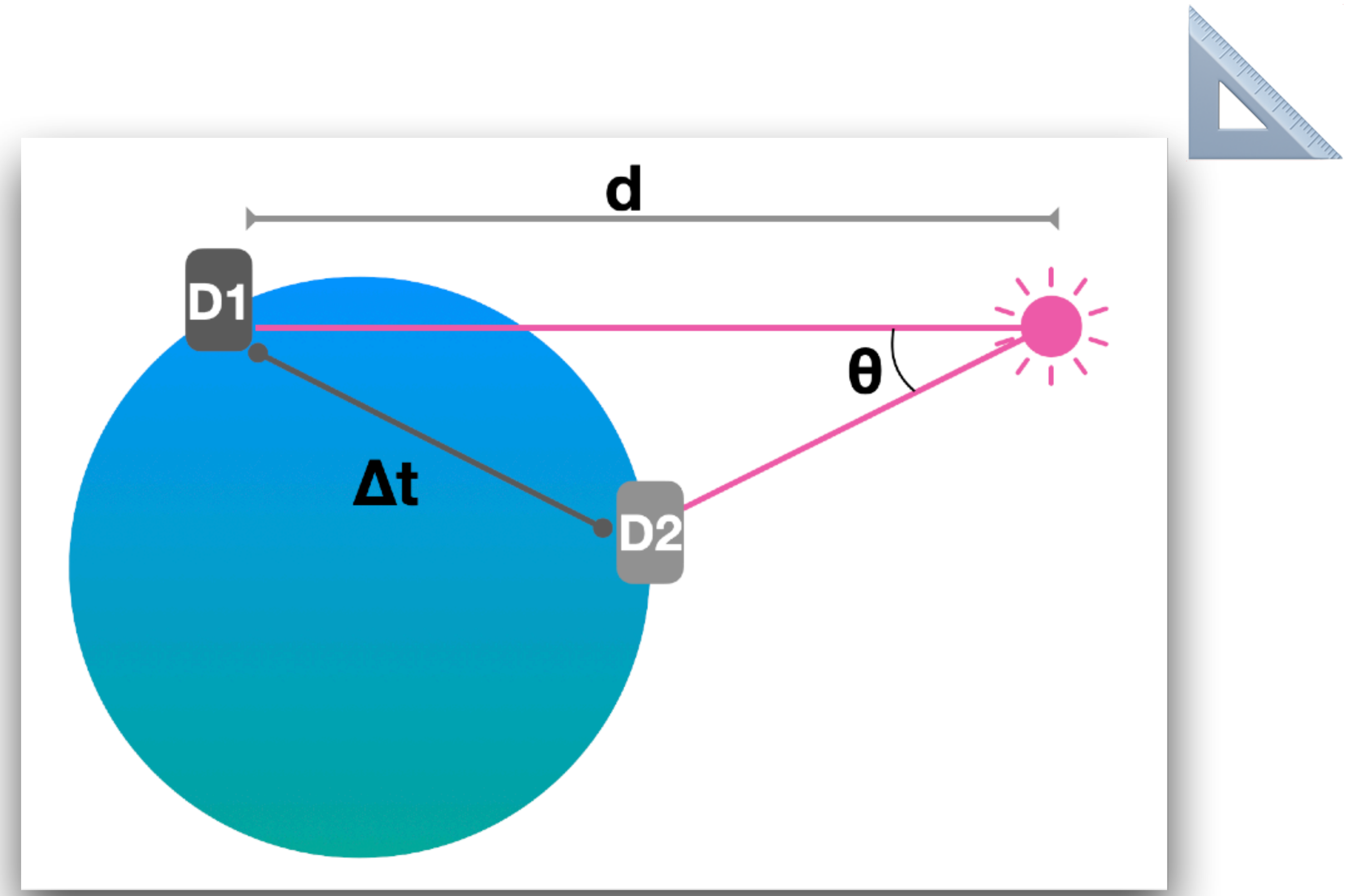
* not covered in this talk

# Locating the neutrino source

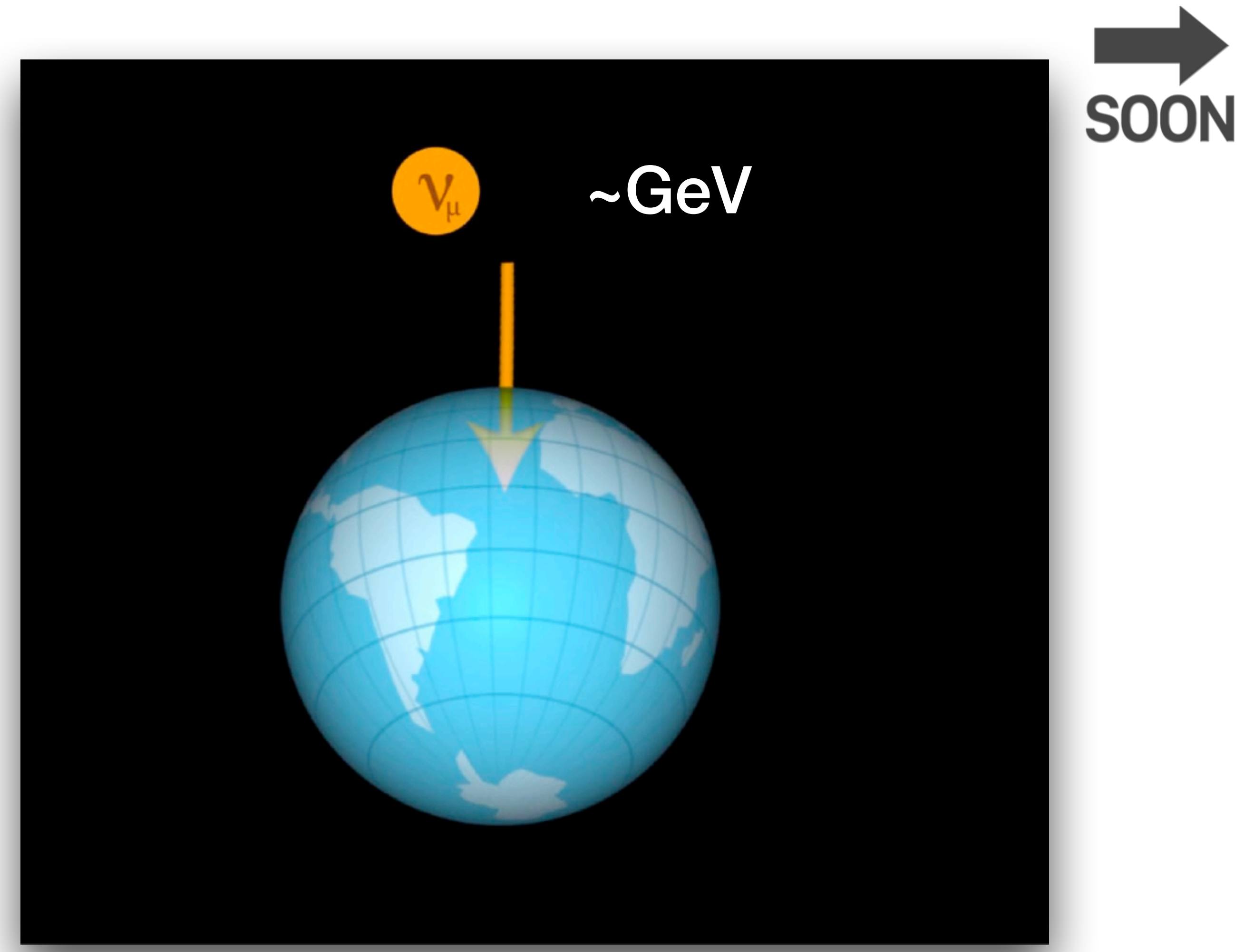
## where is the SN ? 🕵🏻‍♂️

| | Pointing | Triangulation | Directionality |
|---|---|---|---|
| **What:** | Anisotropic interactions | Time delay of neutrino arrival | High-Energy neutrino follow up (GeV) |
| **How:** | Detection channels | Large statistics & many detectors | Directional detector |
| | ➪ SK-Gd, Dune, SNO+ | ➪ Juno+SK, Juno+IC, … | ➪ IC, … |




JF. Beacom et al., Phys.Rev. D 60 (1999) 033007

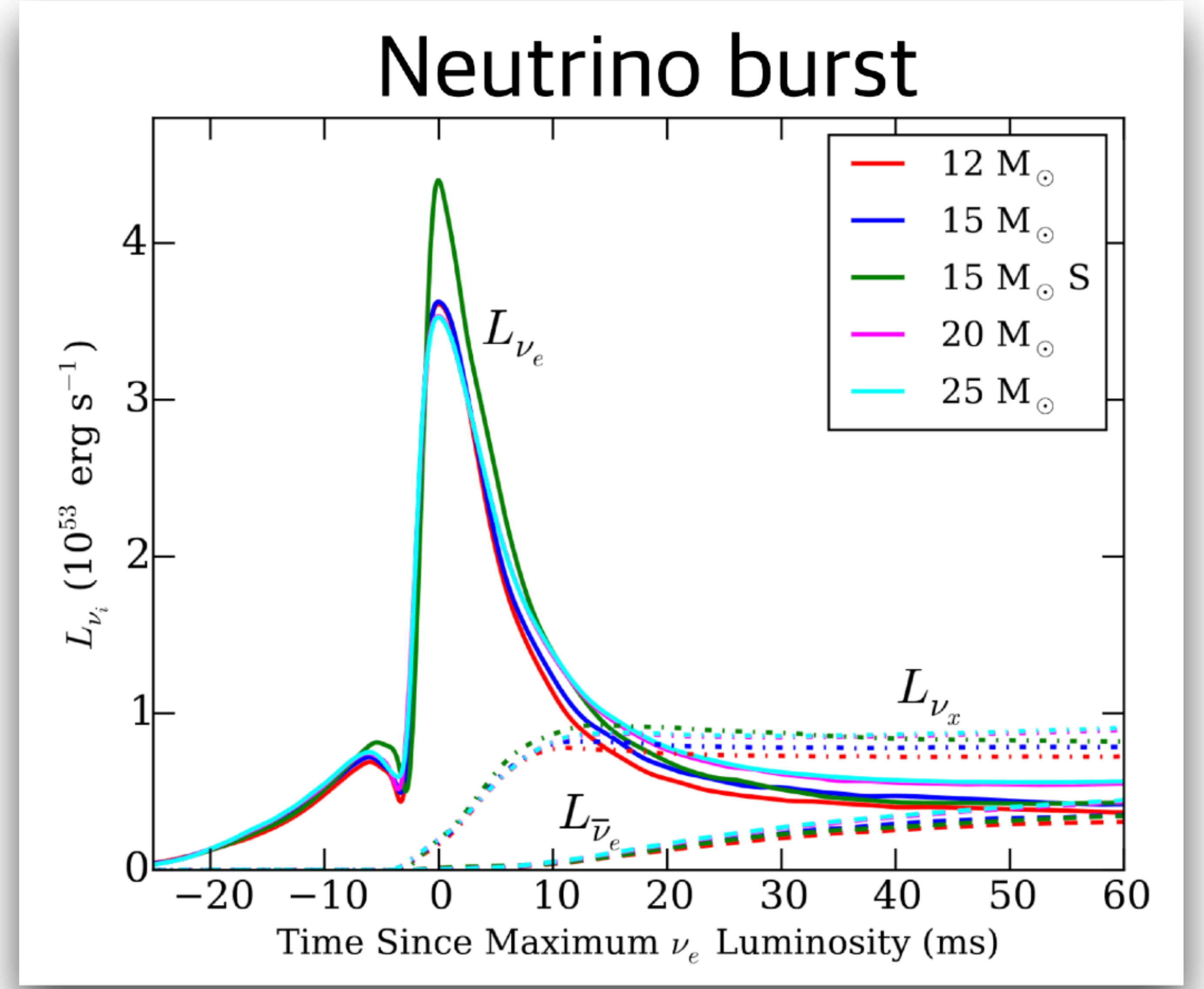



R. Tomas et al., Phys.Rev. D68 (2003) 093013

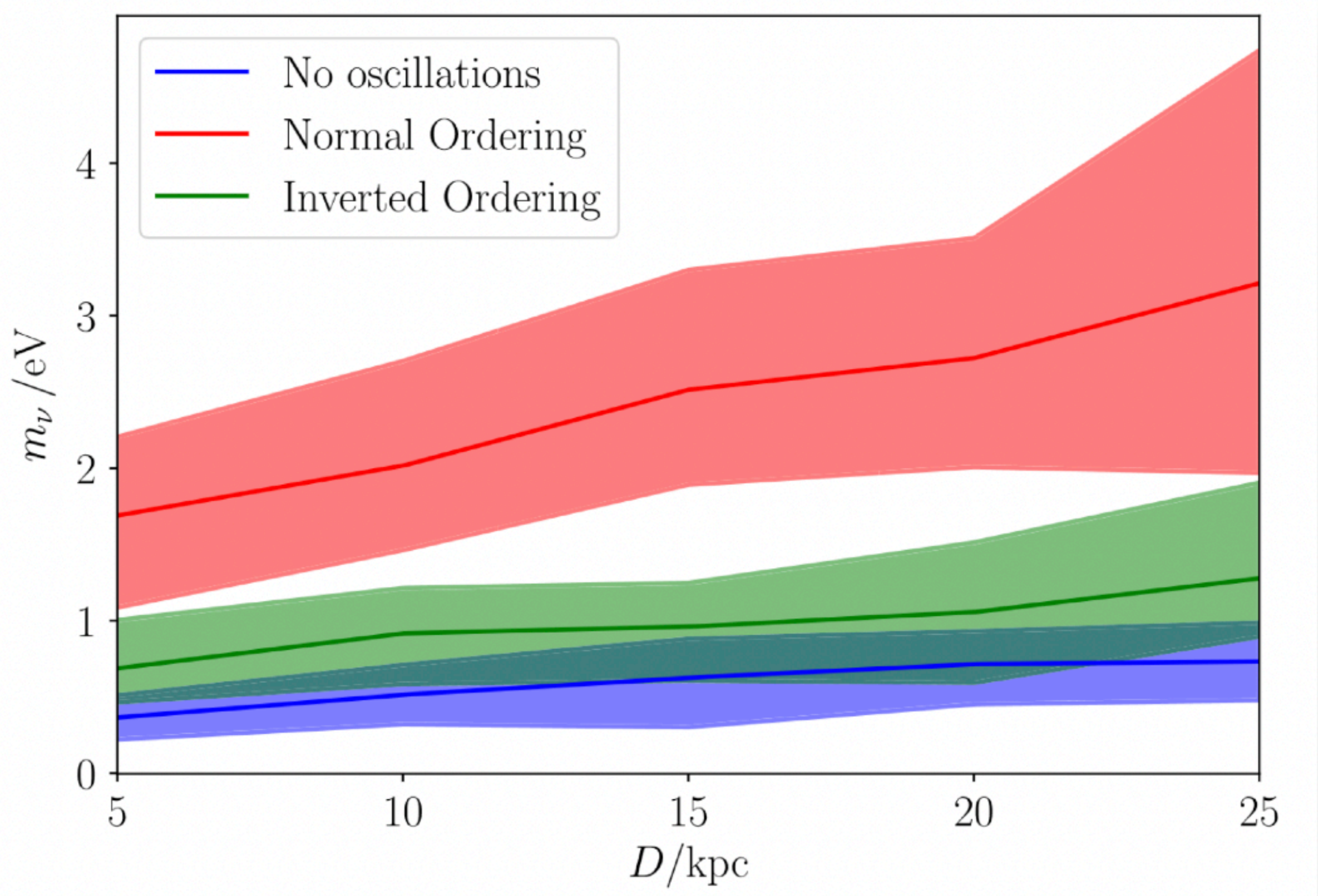
# Neutrino fundamental properties

## SNe, unique neutrino sources

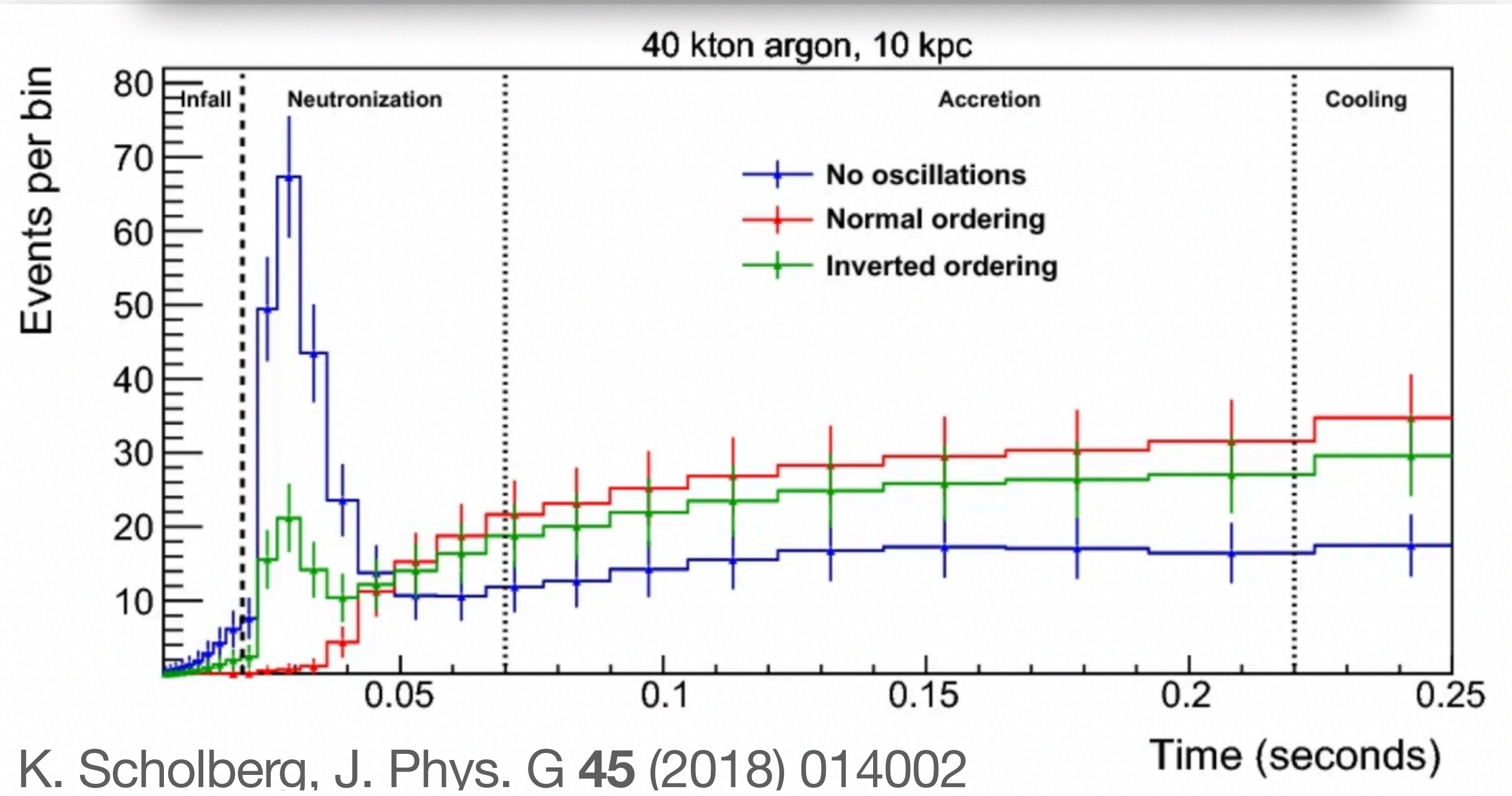
### $\nu_e$ Neutronization burst
### ➜ $\nu$ Mass Ordering
### ➜ $\nu$ absolute mass




➪ Progenitor independent measurement




F. Pompa et al., Phys. Rev. Lett. 129, 121802 (2022)




K. Scholberg, J. Phys. G **45** (2018) 014002

**Time of Flight measurement**

"Smearing" of $\nu_e$ burst

Statistics needed

➪ Katrin is already better

Nat. Phys. 18, 160–166 (2022)

**Suppression of $\nu_e$**

Sensitive to MSW effects

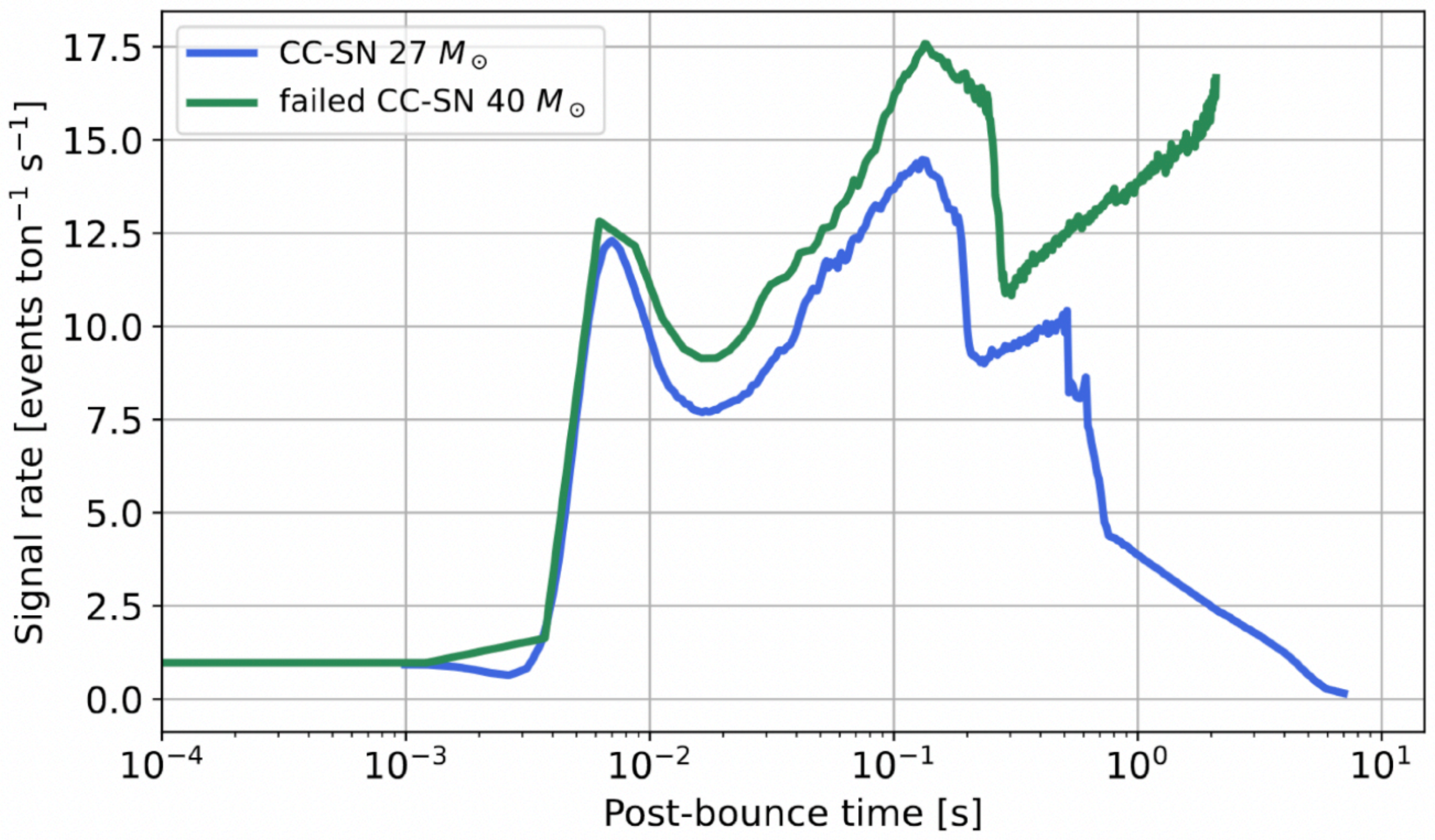
Statistics + Normalization

➪ IceCube, HK, Dune, Juno

# Neutrino signal time distribution

## Physics of core-collapse

ResNova time response to SN signals



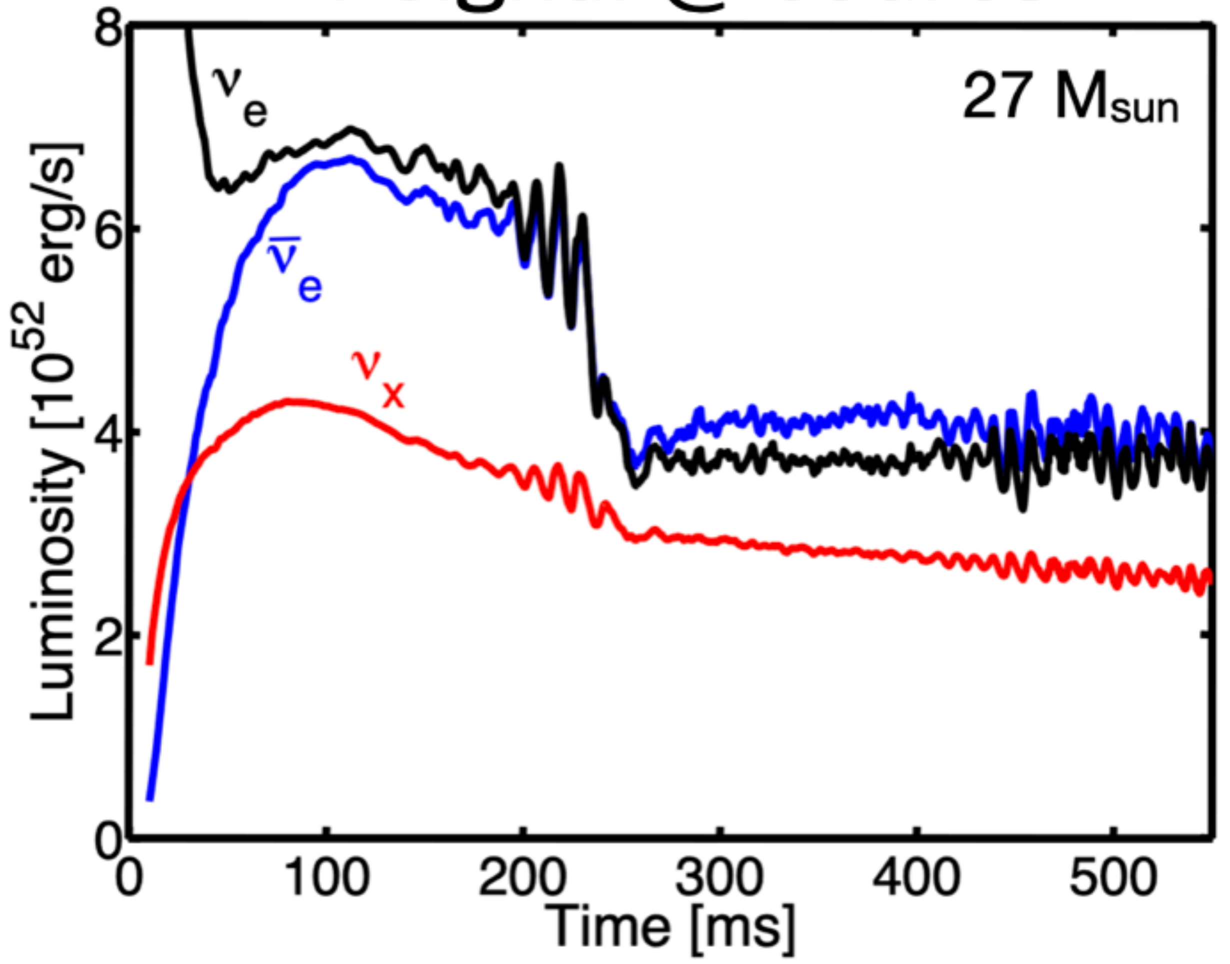

L. Pattavina et al., JCAP 10 (2021) 064

$\nu$ Signal duration

→ SN remnant

→ SN explosion mechanism

ν signal @ source




**Cooling phase rate**

BH vs NS requires time resolution of O($\ll$10 ms)

➪ Fast detectors: IC, ResNova, …

**Shock-wave instabilities (SASI)**

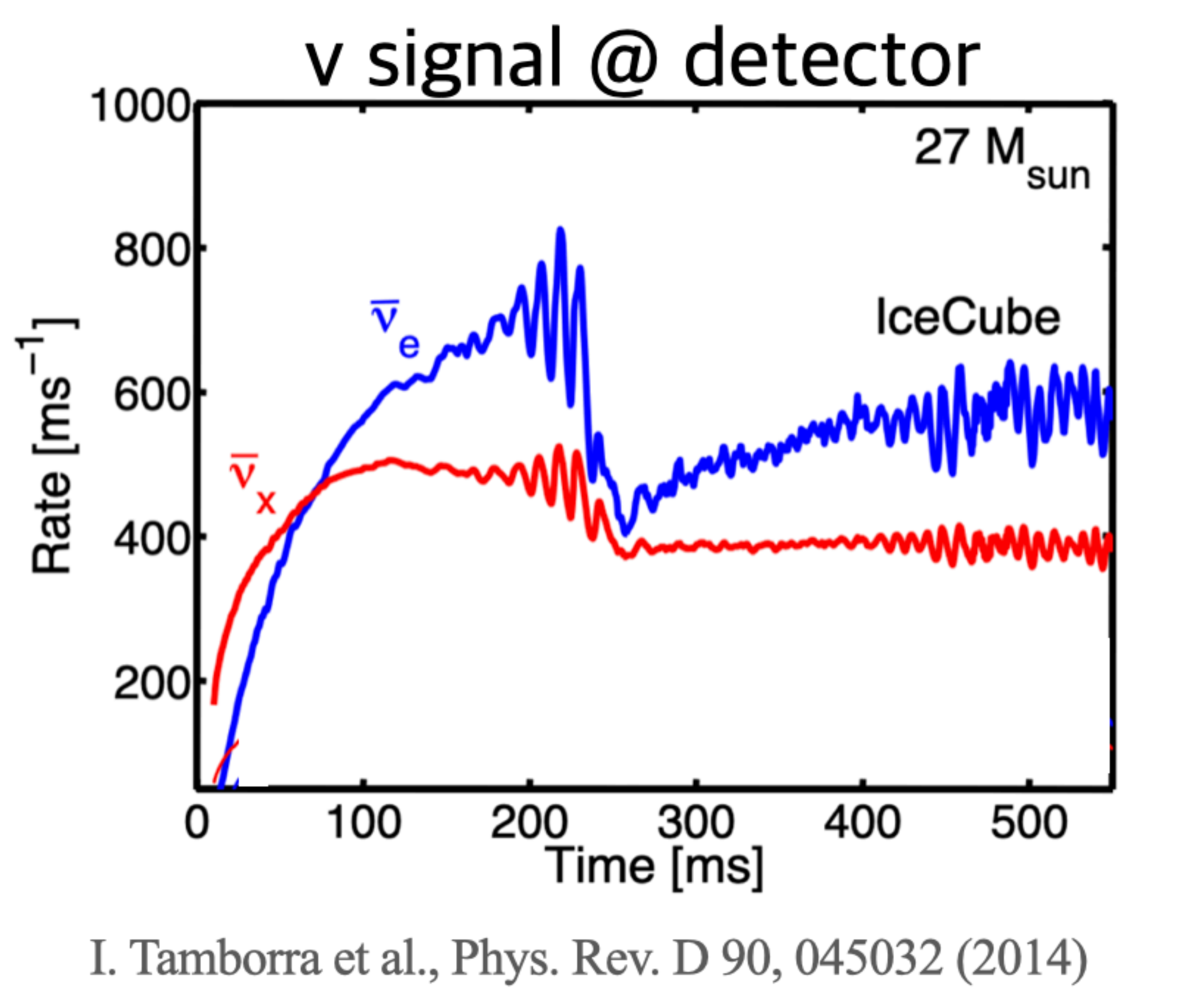
3D feature of SN models

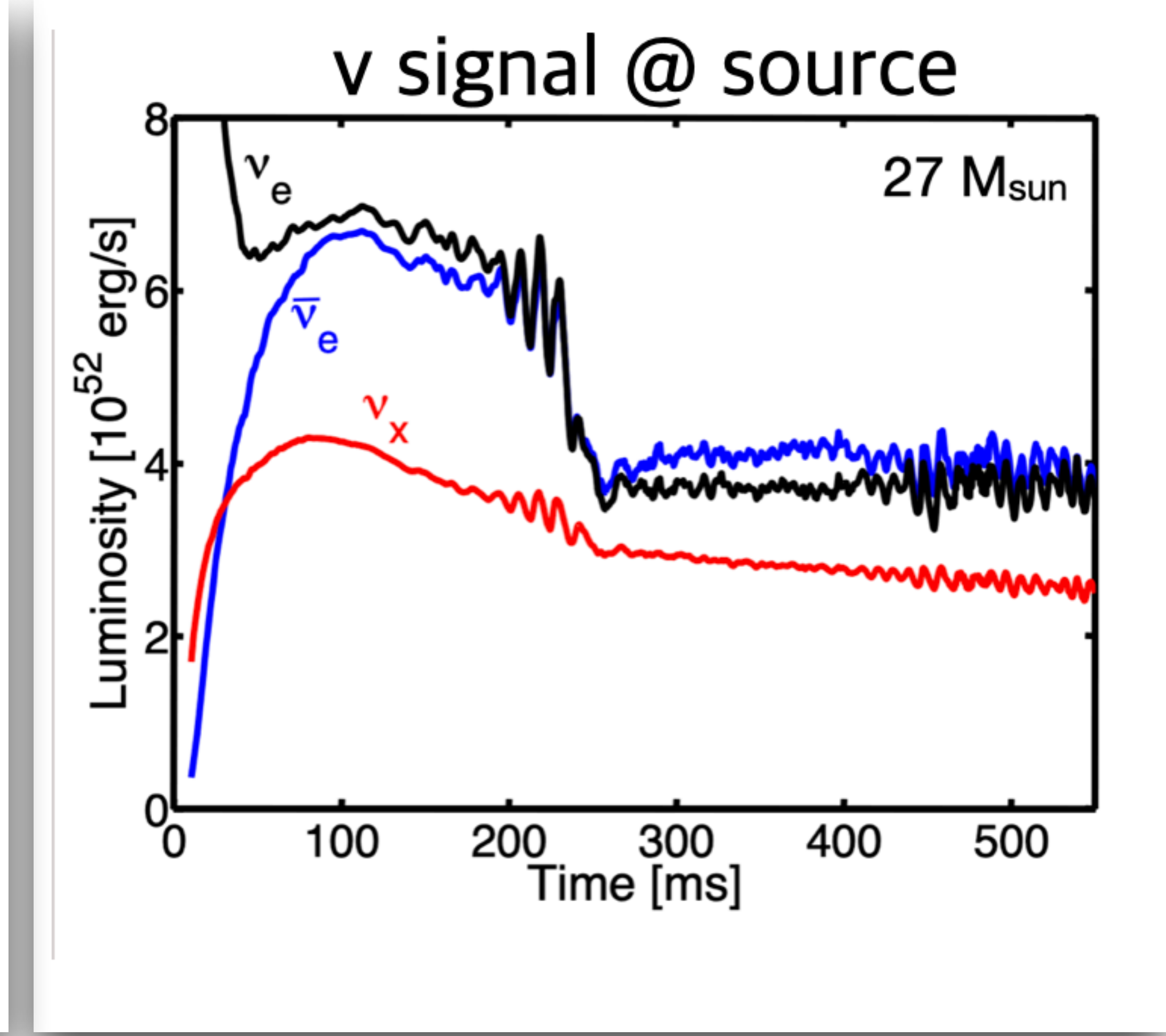
➪ Very large-stats: IC, HK, …

# Neutrino signal time distribution

## Physics of core-collapse




**Cooling phase rate**

BH vs NS requires time resolution of O(≪100 ms)

➪ Fast / modular detectors: KM3NeT, IC, …

**Shock-wave instabilities (SASI)**

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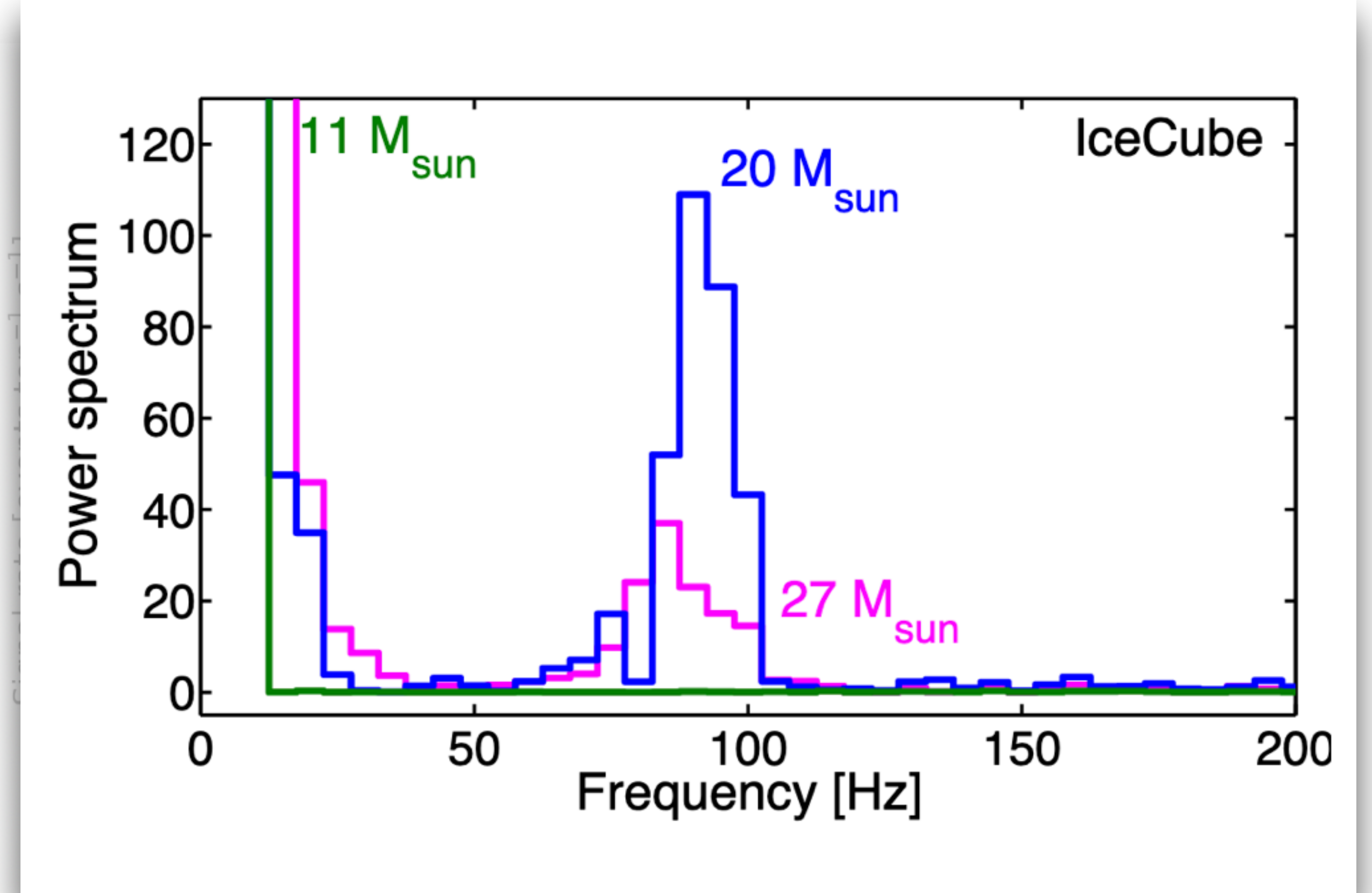
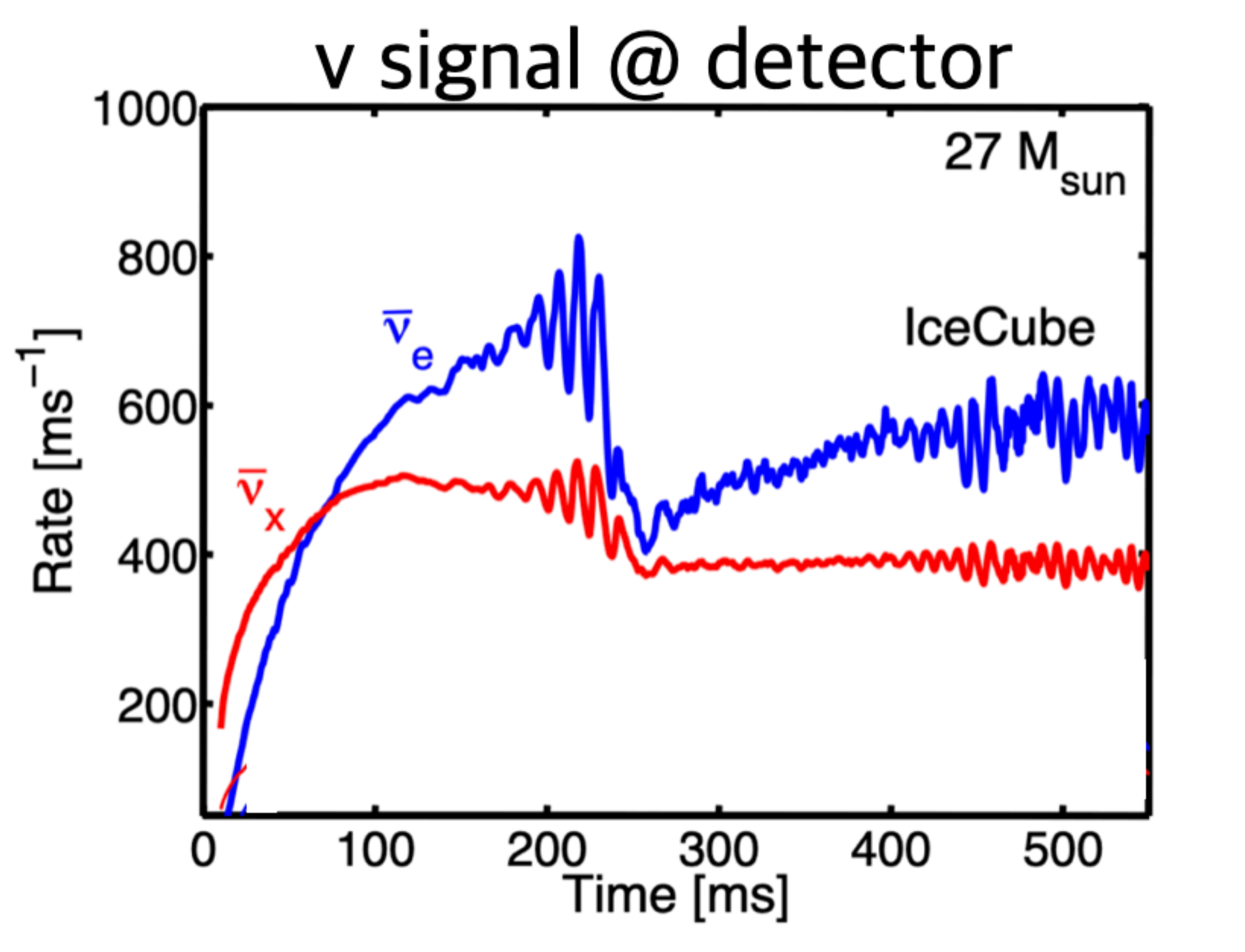
# Neutrino signal time distribution

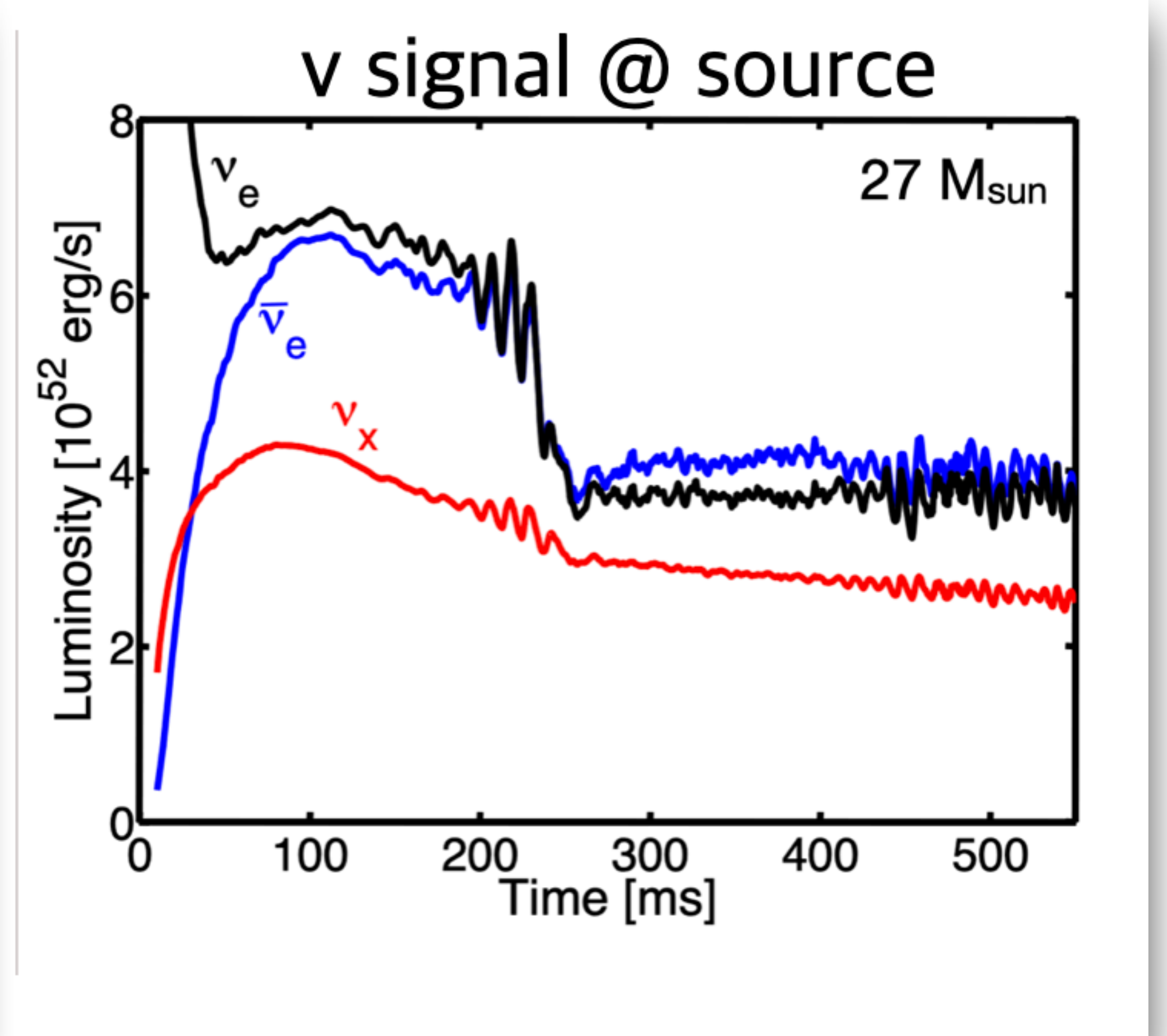
## Physics of core-collapse




L. Pattavina et al., JCAP 10 (2021) 064




I. Tamborra et al., Phys. Rev. D 90, 045032 (2014)

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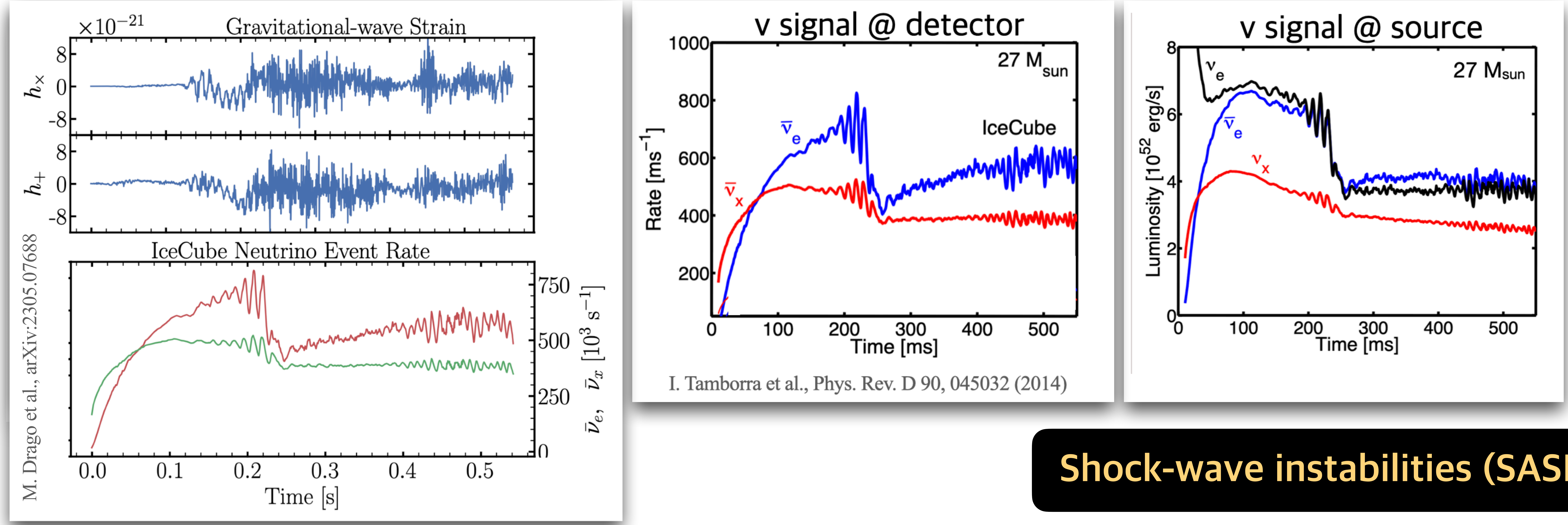


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Interplay νs and GWs

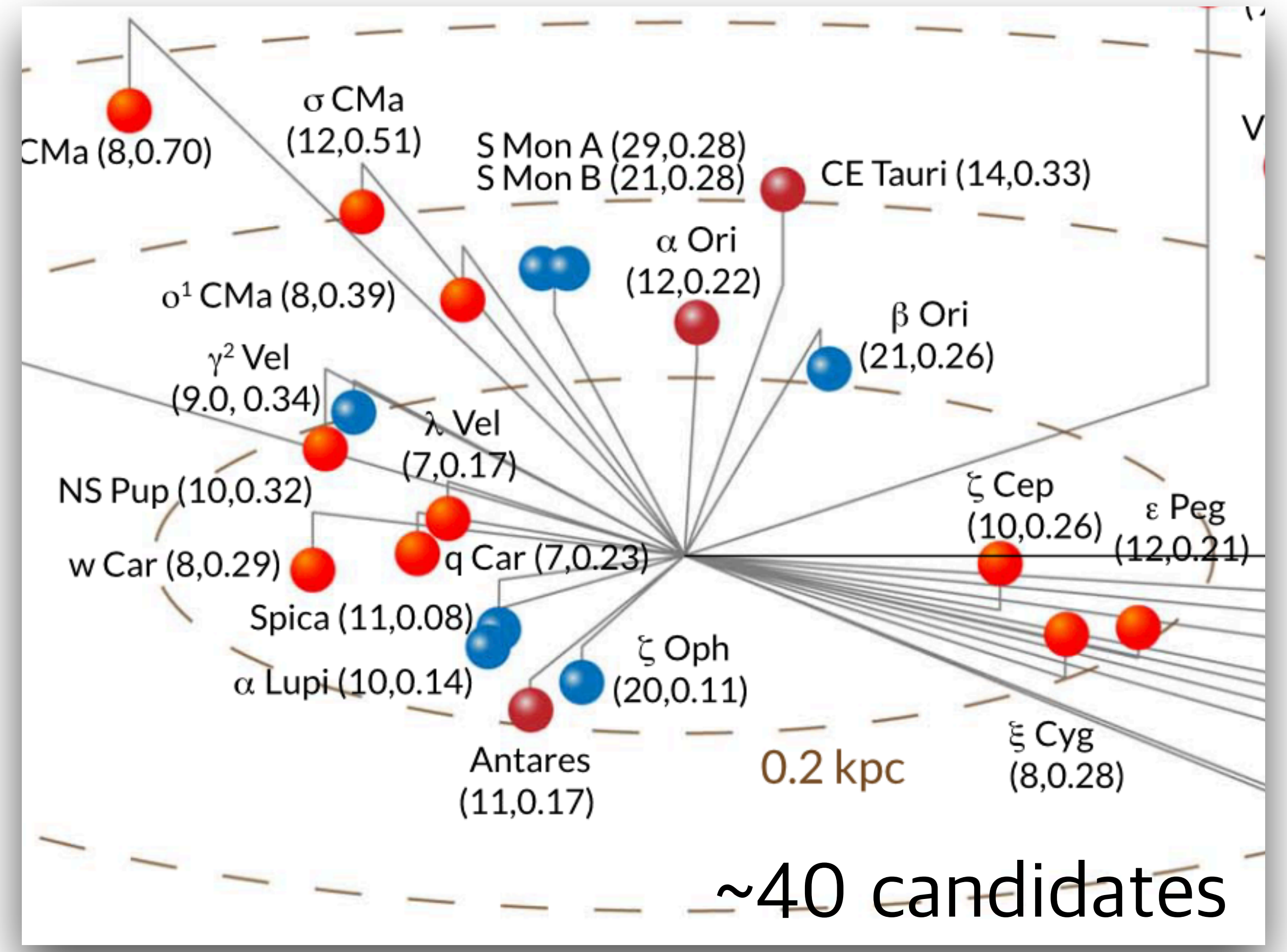
➪ Very large-stats: IC, HK, …

# Where should we look for SN?

## SN rate spatial distribution is not uniform

Galactic CCSN rate
- 1.63±0.46 SN/100y [R. Rozwadowska et la., New Astron. 83 (2021) 101498]
- 3.2(+7.3 -2.6) SN/100y [S. M. Adams et al., Astrophys. J., 778, 164 (2013)]

### Very Near (<500 pc)

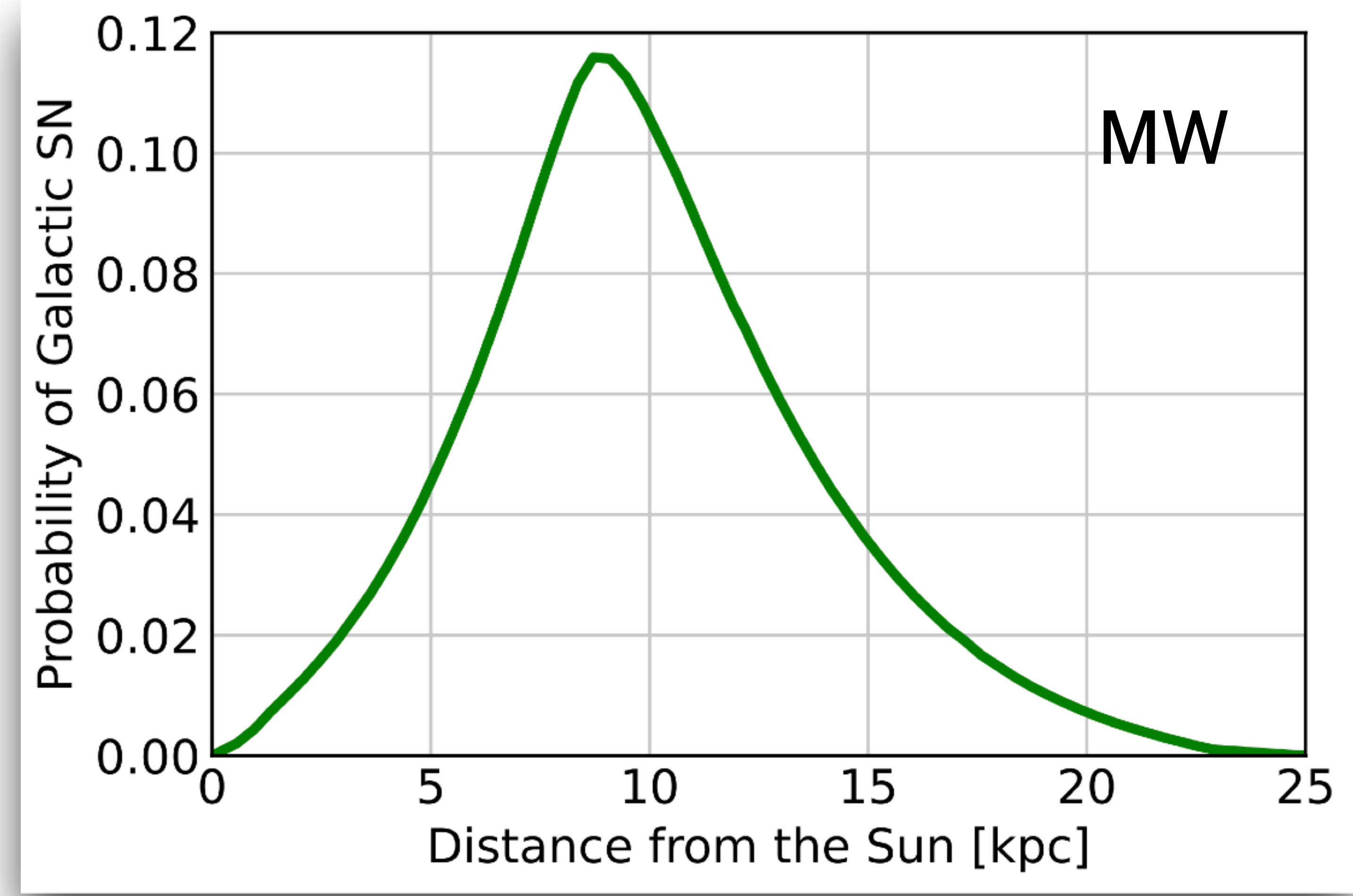



Mukhopadhyay, et al., 2020 Apj. 899 153

**High-intensity ν fluxes**

➪ Modular detectors: ResNova

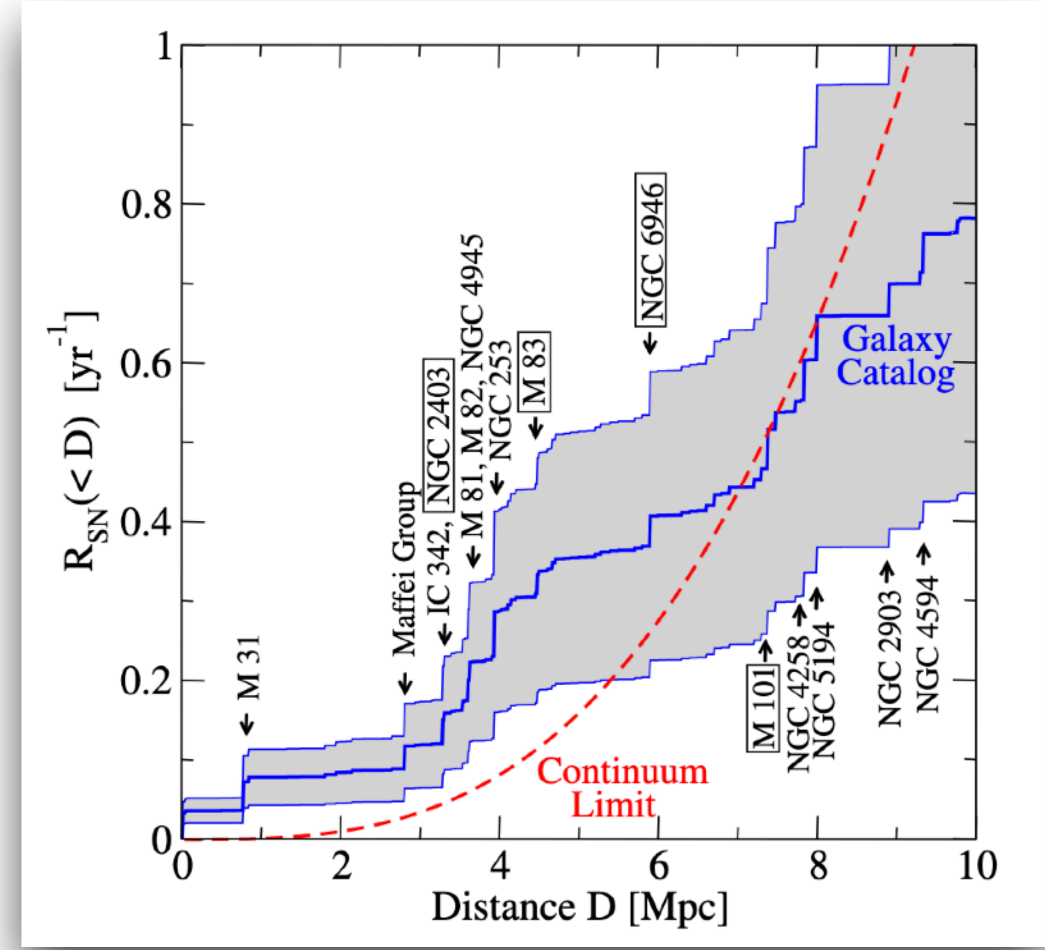
### Around us (<20 kpc)




**Fully covered**

➪ Current technology

### Very Far (3 Mpc)



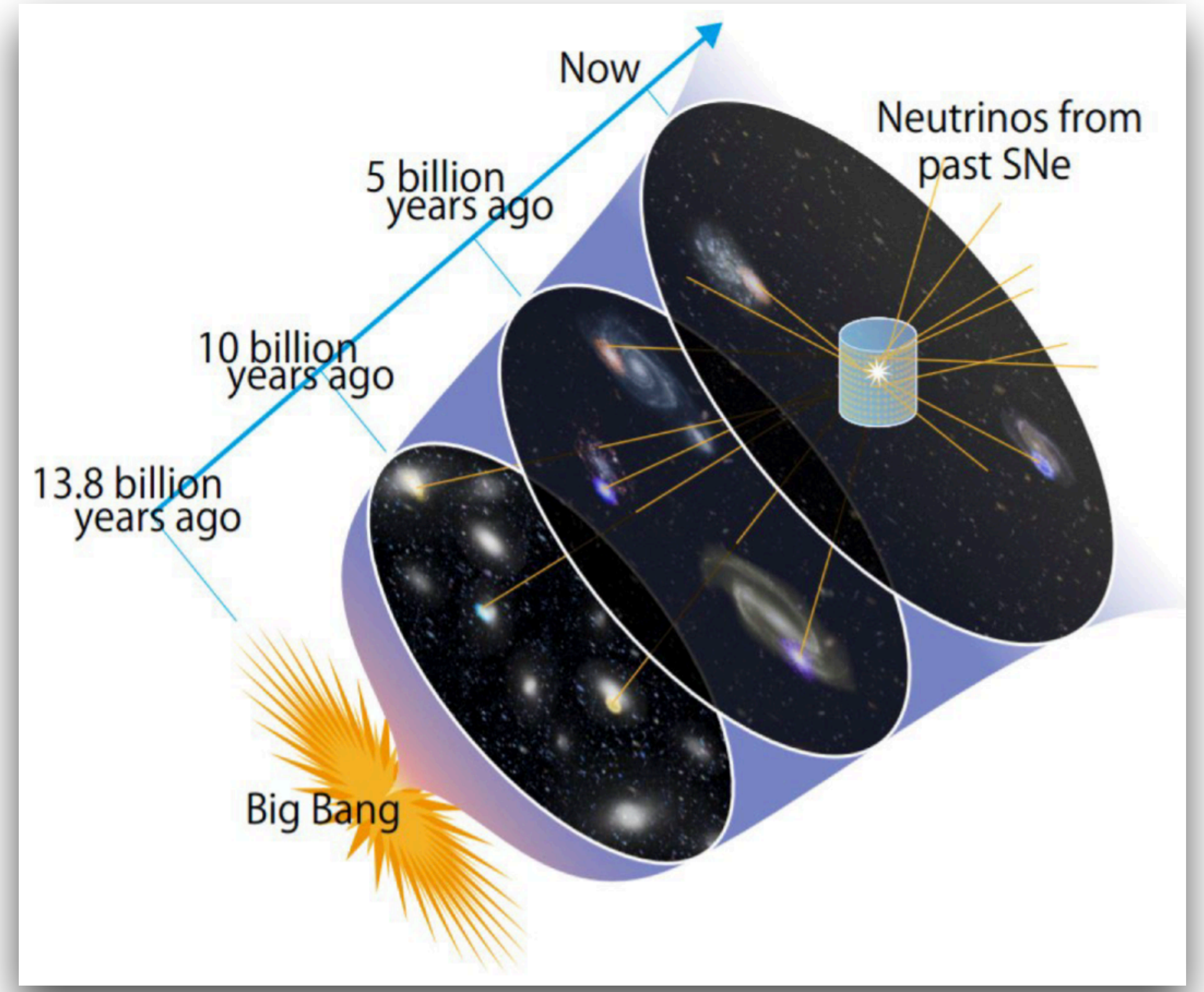

S. Ando et al., Phys.Rev.Lett. 95 (2005) 171101

**Weak ν fluxes**

➪ Mton-scale technology: HK

# Diffuse SN neutrino background

## not one SN, but all SNe!




SN rate at z

cosmology

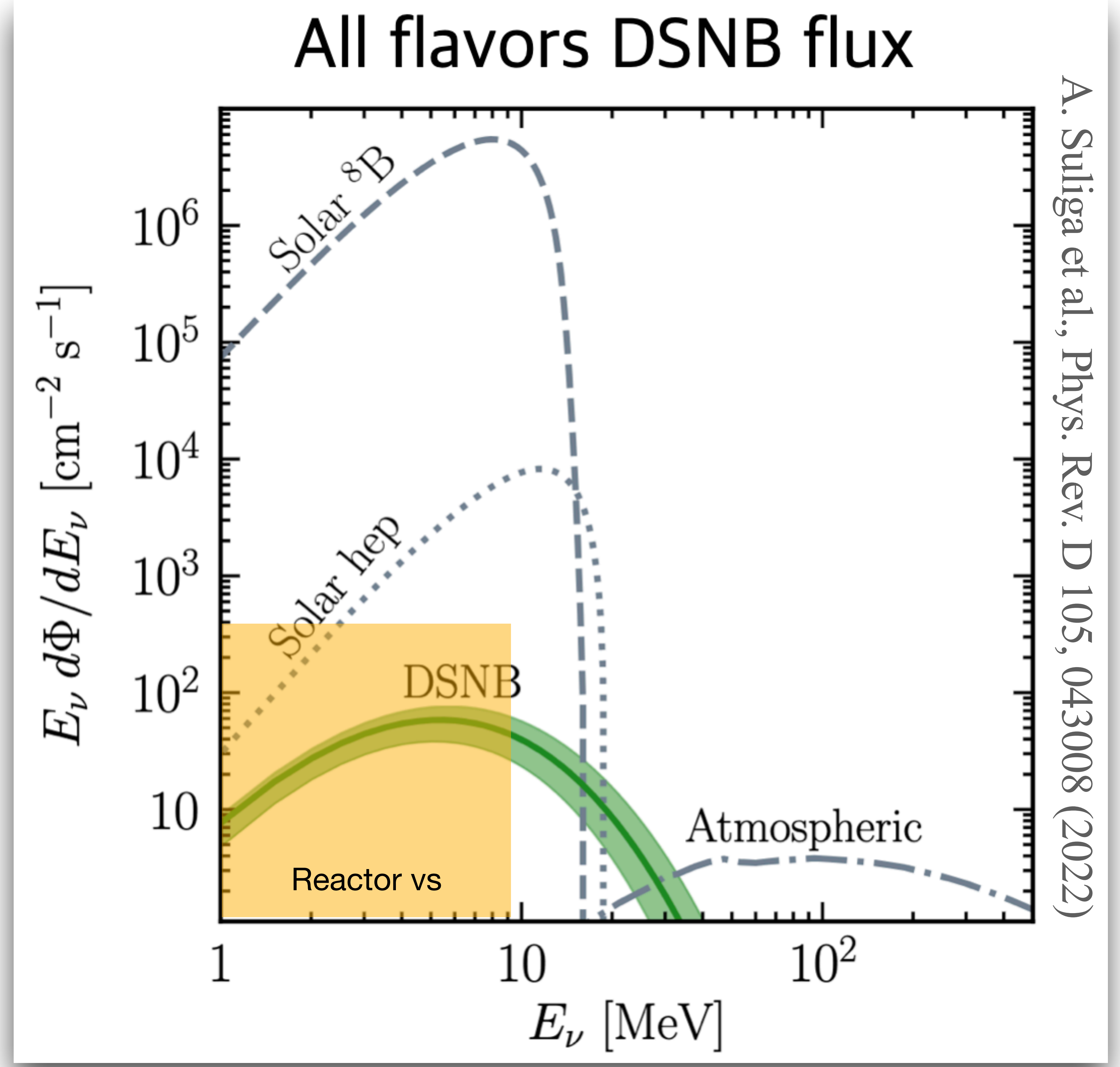
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{c}{H_0}\int_0^{z_{max}} R_{SN}(z)\,\frac{dN_\nu(E'_\nu)}{dE'_\nu}\,\frac{dz}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}$$

Averaged SN spectrum

The integral of:

- Failed- and CCSN
- SN explosion dynamics
- Star Metallicity
- Star formation rate
- Neutrino mass hierarchy

Strong model dependence



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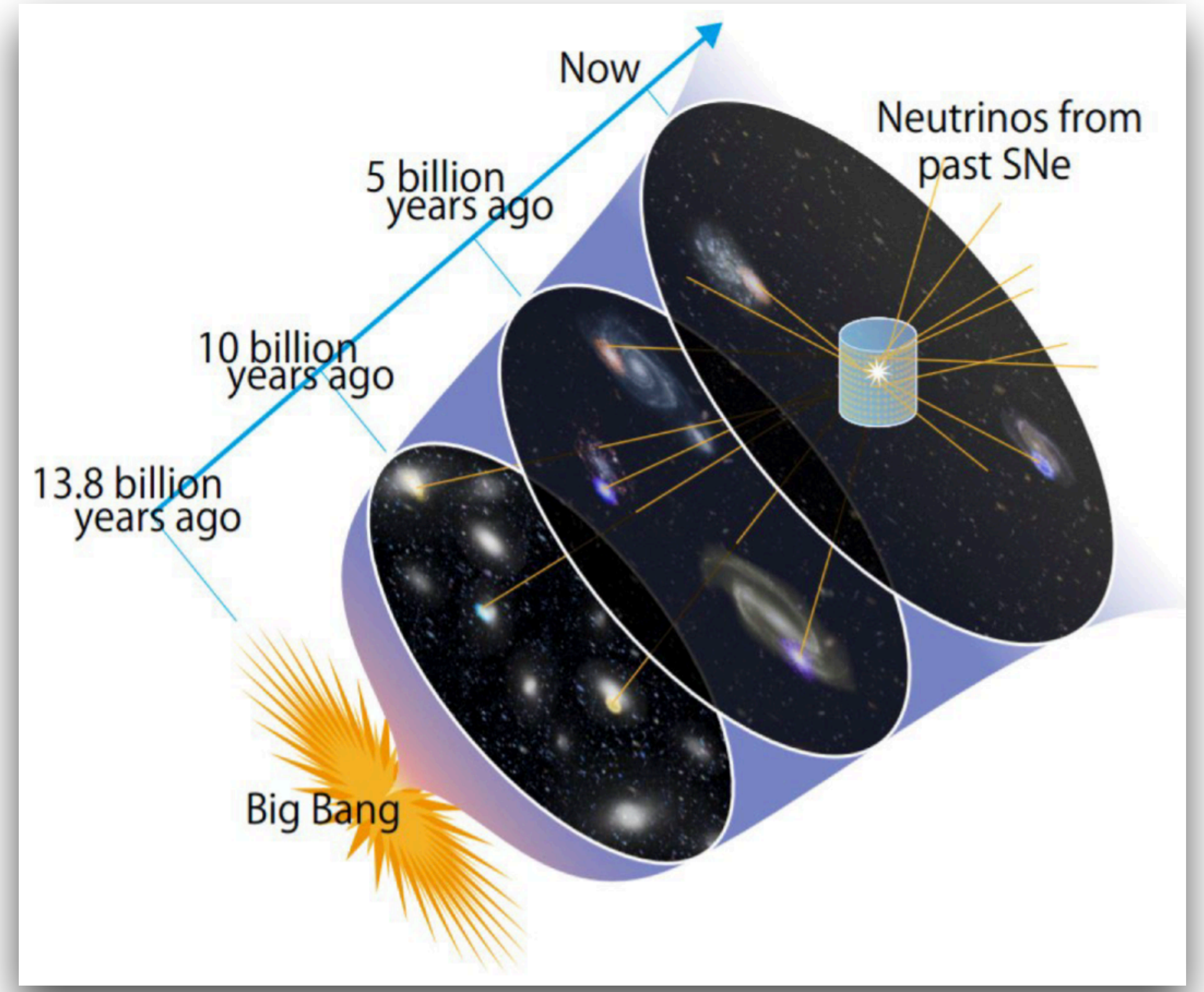


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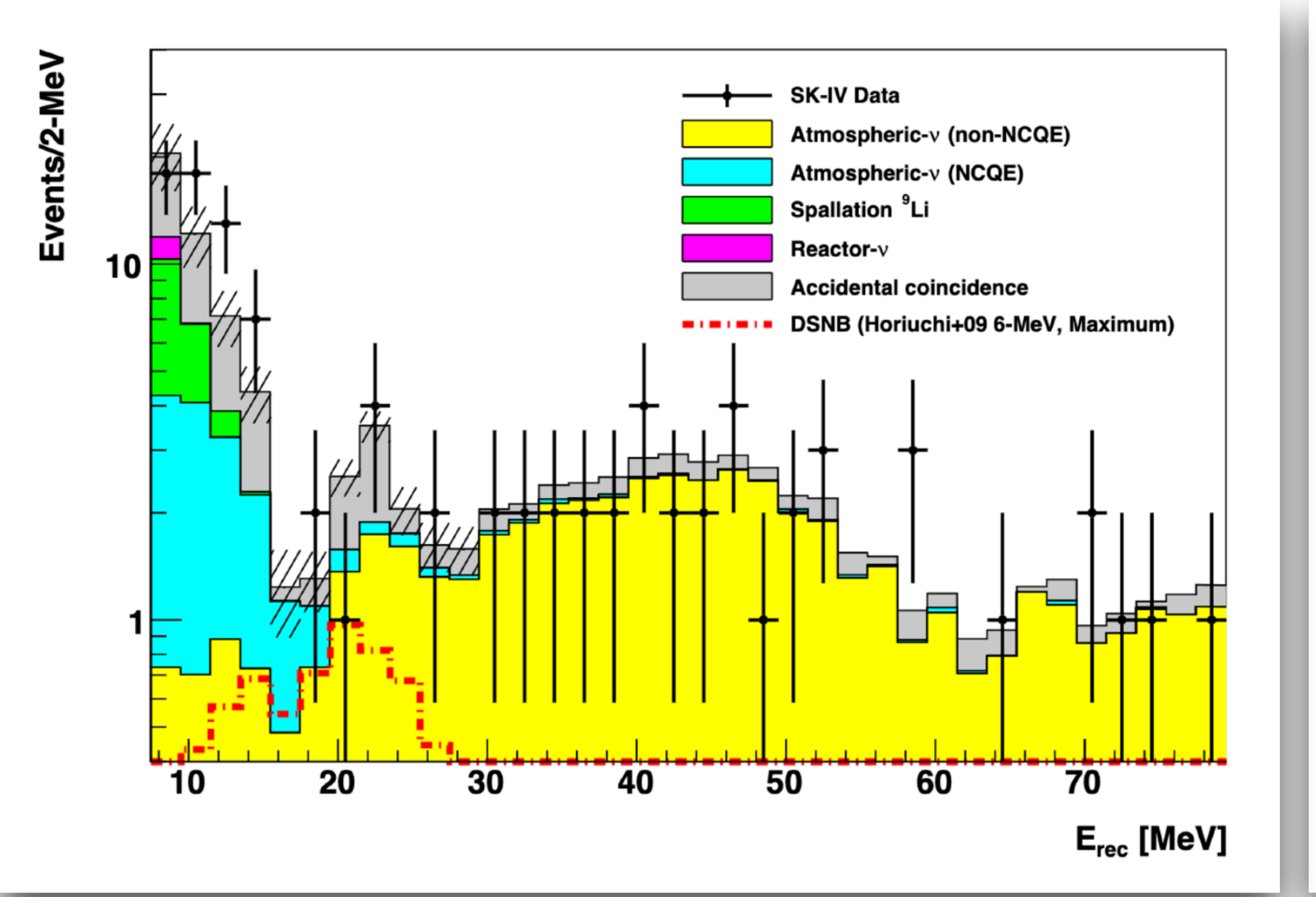
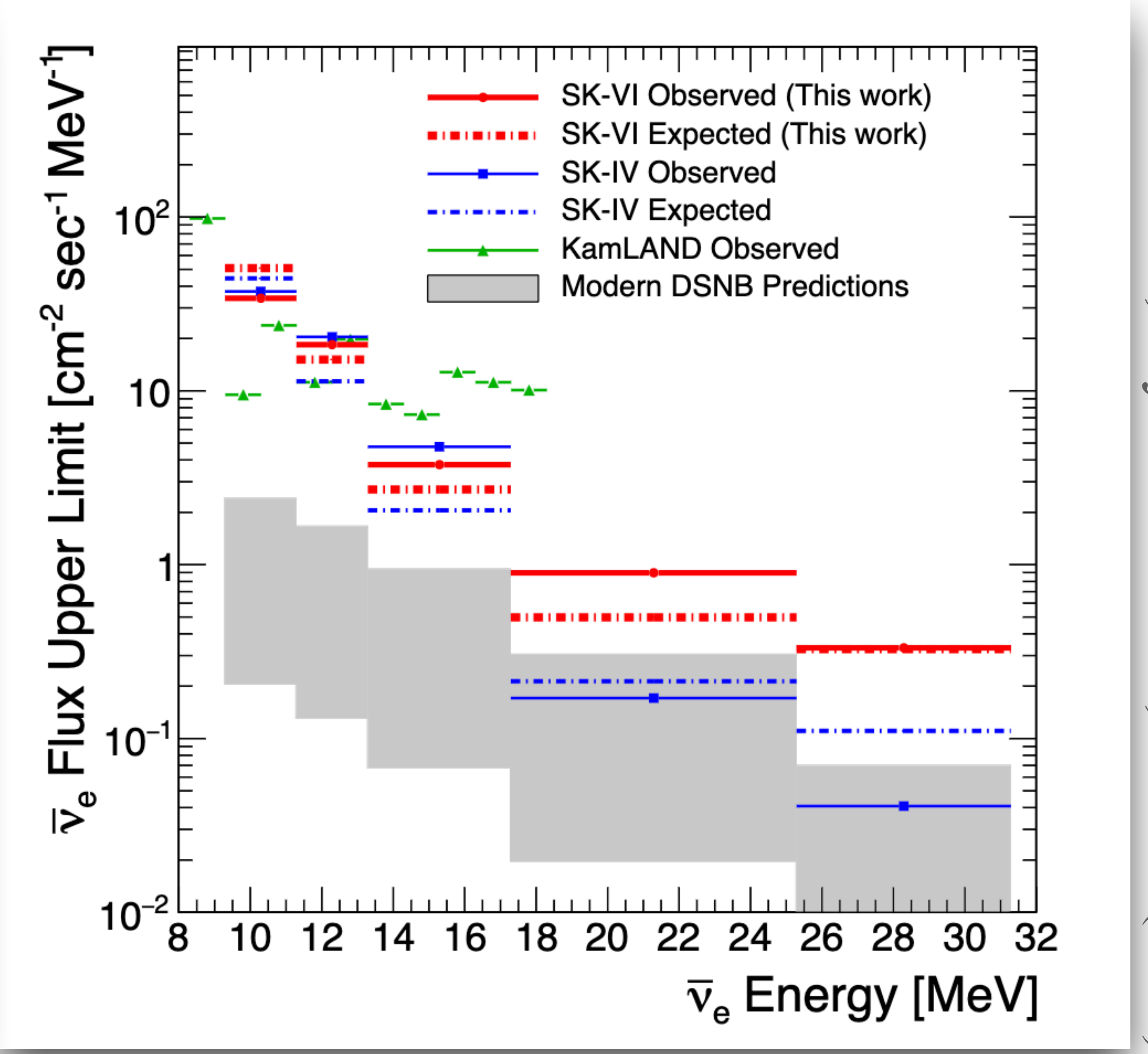
SK most stringent limits (anti-ve)




K. Abe et al., Phys. Rev. D 104, 122002 (2021)

DSNB in all flavors possible with CEvNS

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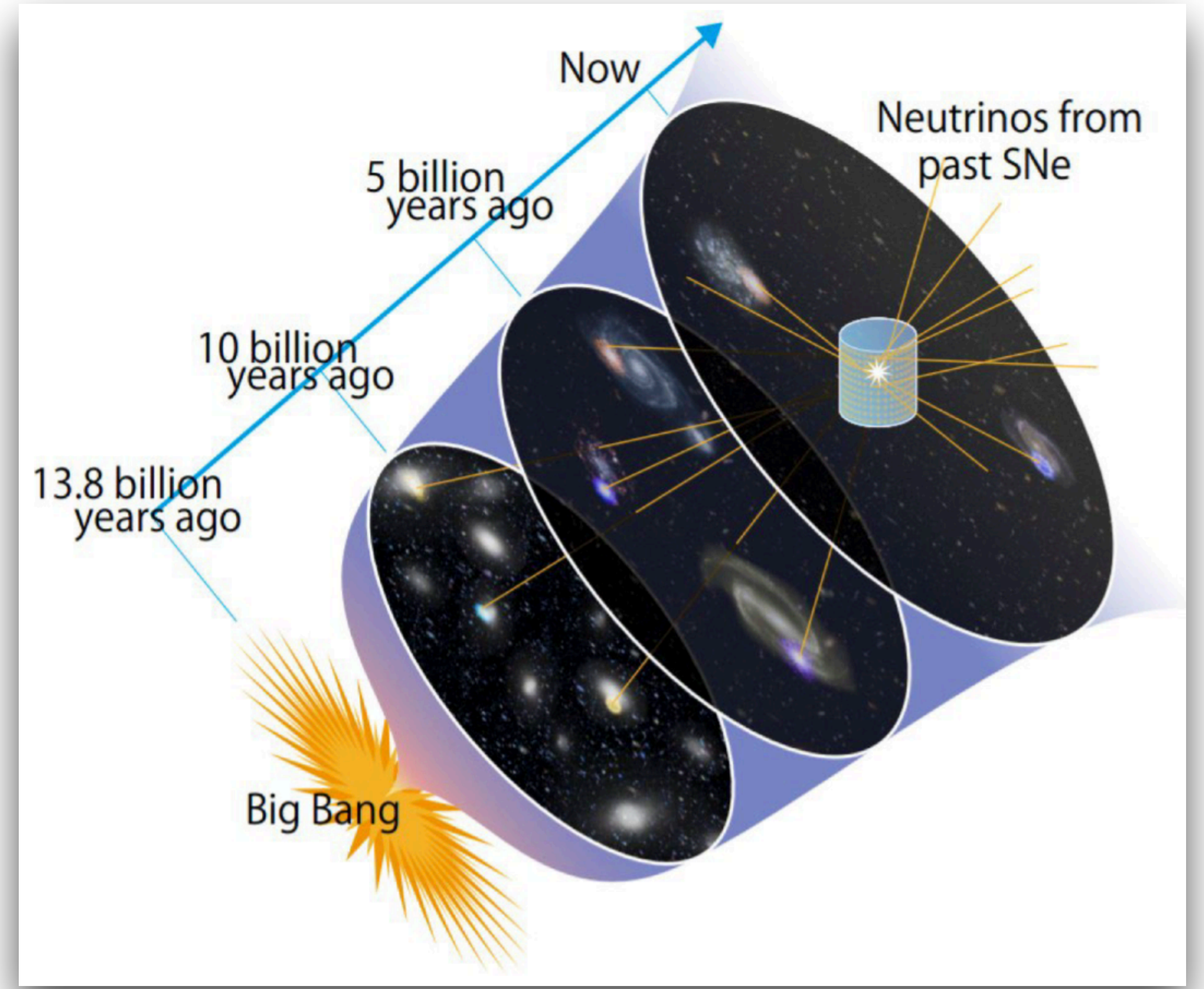


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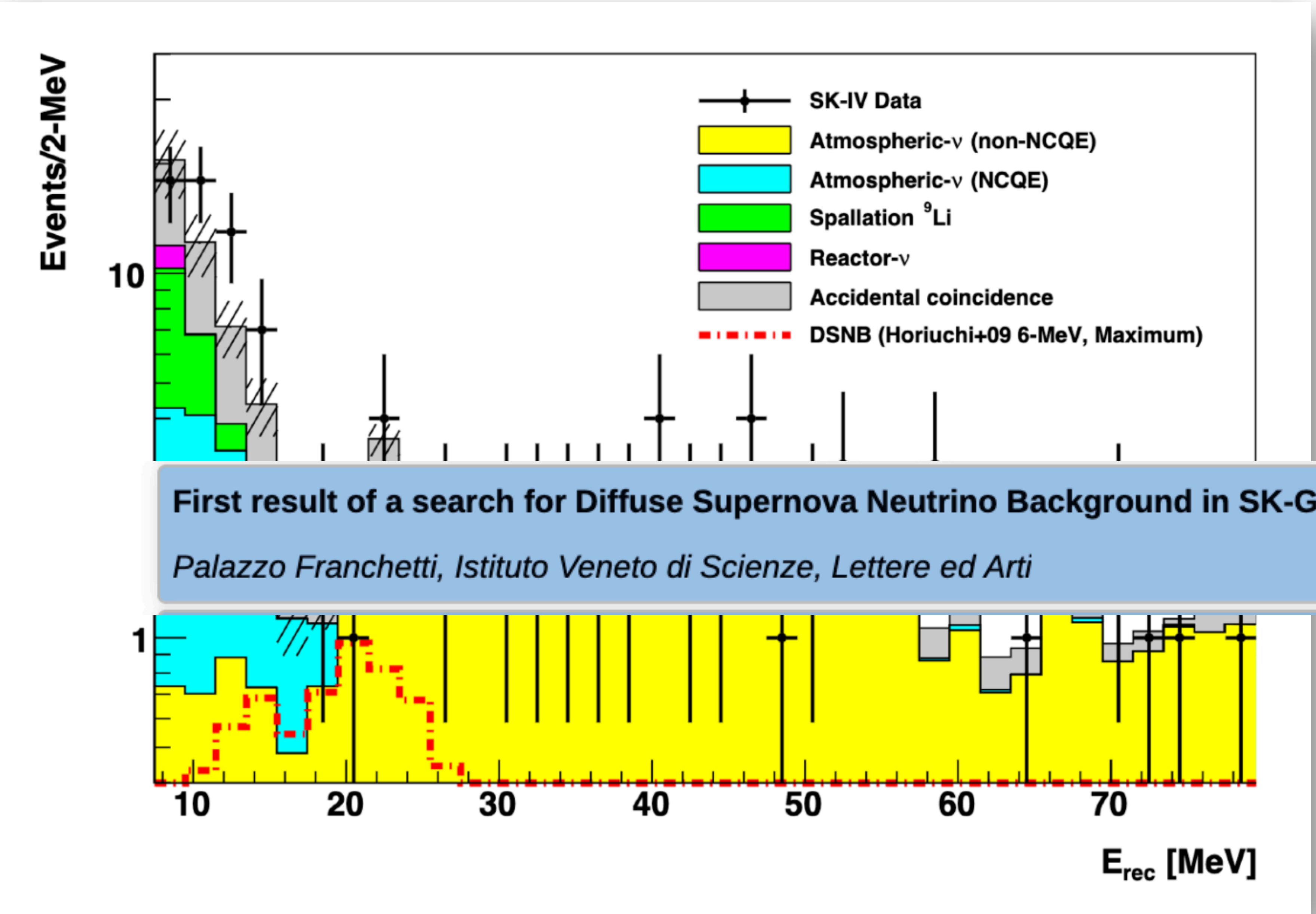


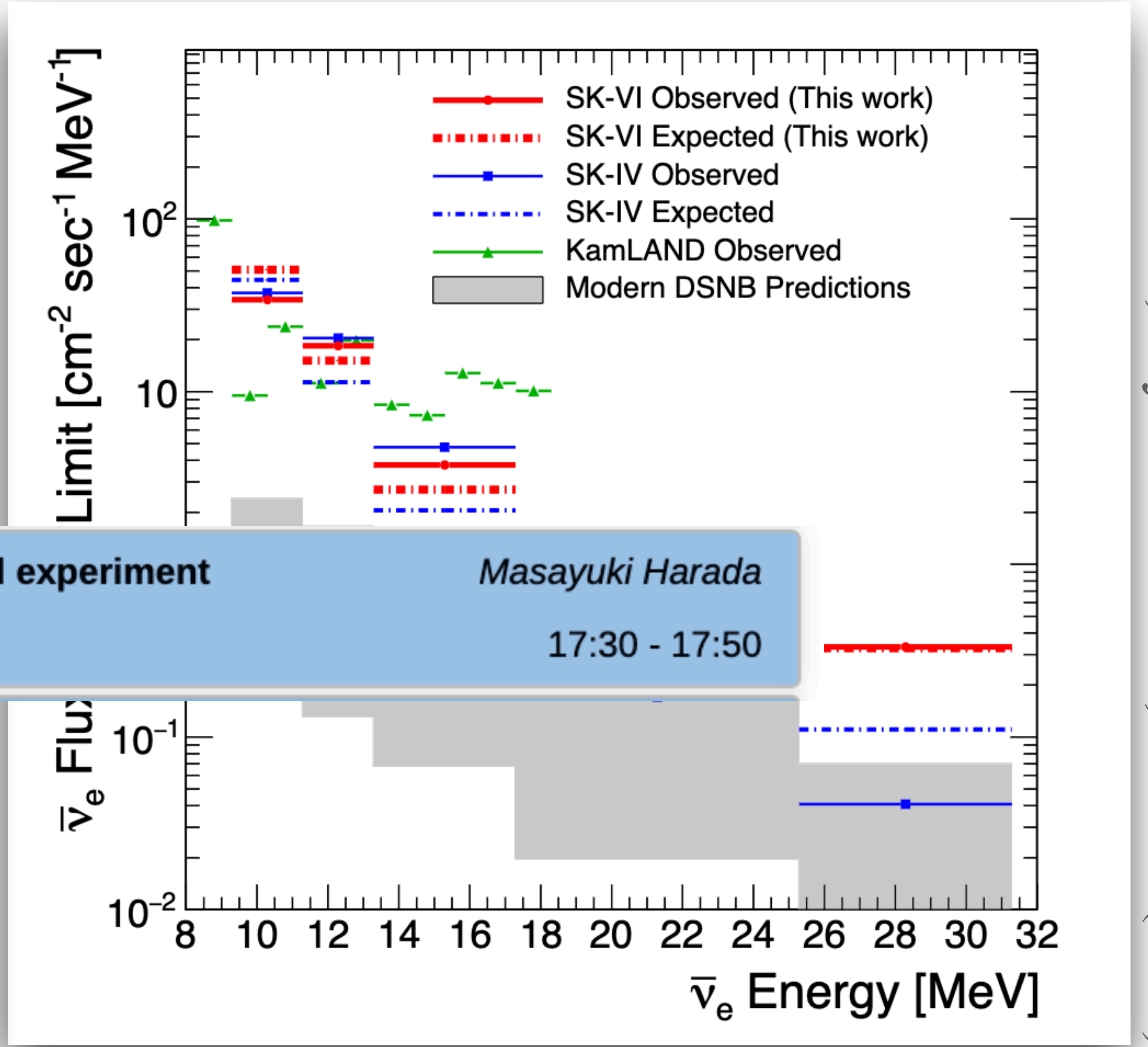


**First result of a search for Diffuse Supernova Neutrino Background in SK-Gd experiment** *Masayuki Harada*

*Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* 17:30 - 17:50

K. Abe et al., Phys. Rev. D 104, 122002 (2021)

DSNB in all flavors possible with CEvNS

# Summary

- ➜ SN1987A neutrinos took 160,000 y to reach our detectors
- ➜ Big technological leap since SN1987A
- ➜ High-sensitivity all flavors ν detection is coming to town
- ➜ SN202X will offer a wealth of opportunities and answer some big questions
    - ➜ SNEWS2.0 online network of ν-sensitive detectors
- ➜ Missing SN202X will be worse than no SN observation

# Beyond this talk

- Repurpose veto detectors for SN neutrinos
- Main Detectors for SN neutrinos

24/10

| | | |
|---|---|---|
| **Neutrinos in XENONnT dark matter experiment** | *Emanuele Angelino* | |
| *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* | | 17:10 - 17:30 |
| **First result of a search for Diffuse Supernova Neutrino Background in SK-Gd experiment** | *Masayuki Harada* | |
| *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* | | 17:30 - 17:50 |
| **Sensitivity to core-collapse supernovae neutrino signals in DarkSide-20k** | *Giuseppe Matteucci* | |
| *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* | | 17:50 - 18:10 |
| **Neutrino flux observation of the next galactic core-collapse supernova in the COSINUS dark matter detector** | *Matthew Stukel* | |

26/10

| | | |
|---|---|---|
| **Supernova detection and triggering with the DUNE Far Detector** | *Pablo Barham Alzás* | |
| *Palazzo Loredan,Sala delle Adunanze* | | 17:55 - 18:15 |
| **Core-Collapse Supernova Neutrino Observation in JUNO** | *Yibing Zhang* | |
| *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* | | 10:25 - 10:30 |
| **Neutrino flavor evolution in dense astrophysical sources** | *Marie Cornelius* | |
| *Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti* | | 11:00 - 11:05 |