

# NEUTRINOS IN ASTROPHYSICS - OVERVIEW

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# The theme

*Astrophysical neutrinos: particle physics opportunities  
in the near future (and beyond)\*, \*\*, \*\*\**

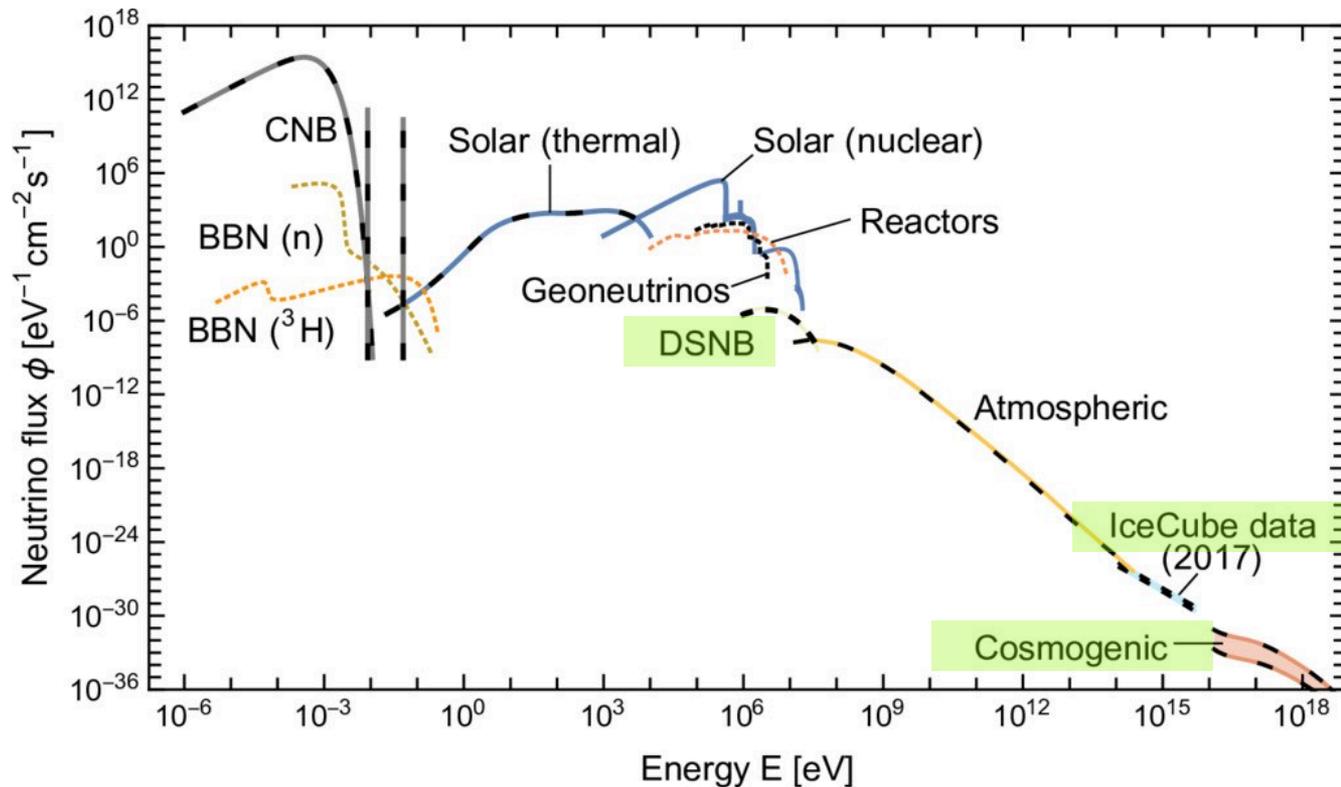
\* Apologies for incompleteness

\*\* Apologies for inaccuracies

\*\*\* Apologies for choice of minimal citations

# At a glance: *the Grand Unified neutrino spectrum*

- Focus on: diffuse supernova flux, HE extragalactic flux, cosmogenic
  - *The Earth's atmosphere is clearly an obstacle...*

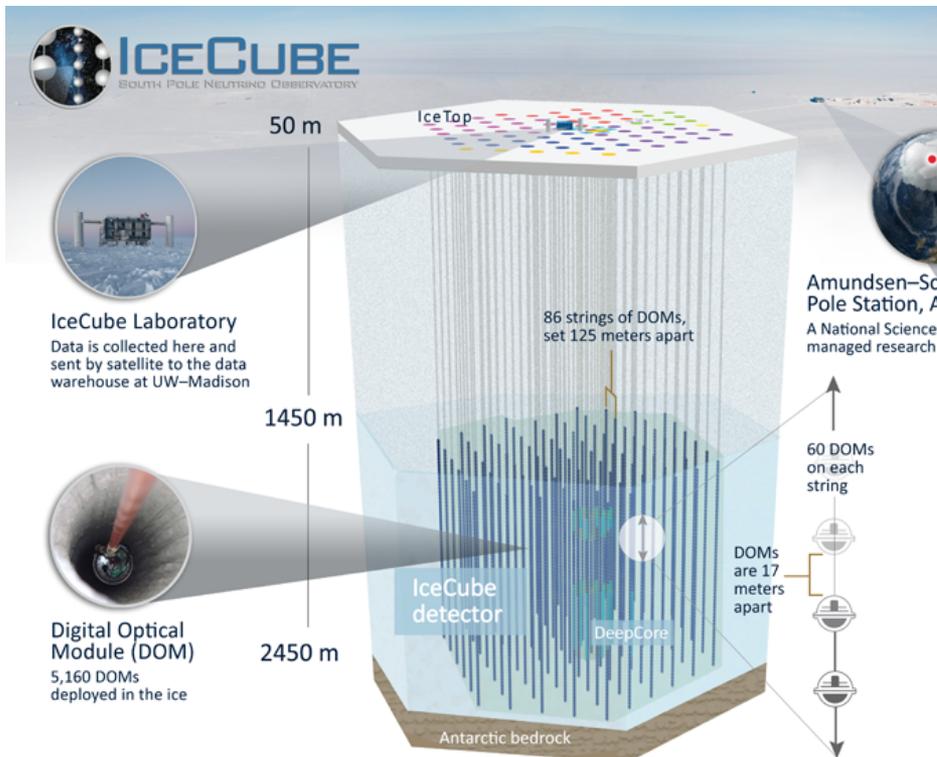


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Happening **now**: high energy extragalactic  
neutrinos

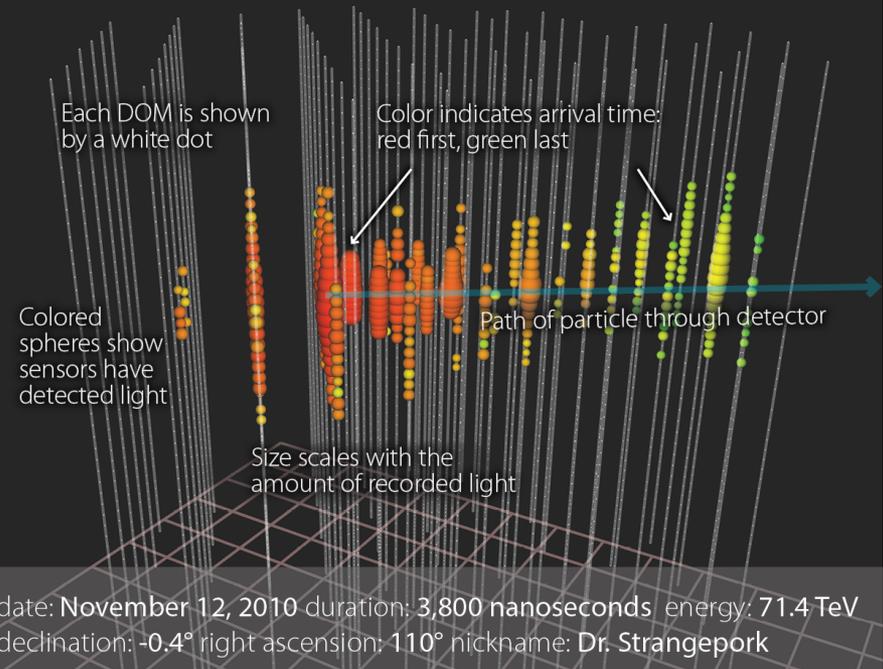
# Towards $\text{Km}^3$ arrays

- IceCube (10 years running!)
- ANTARES, Baikal



## How does IceCube work?

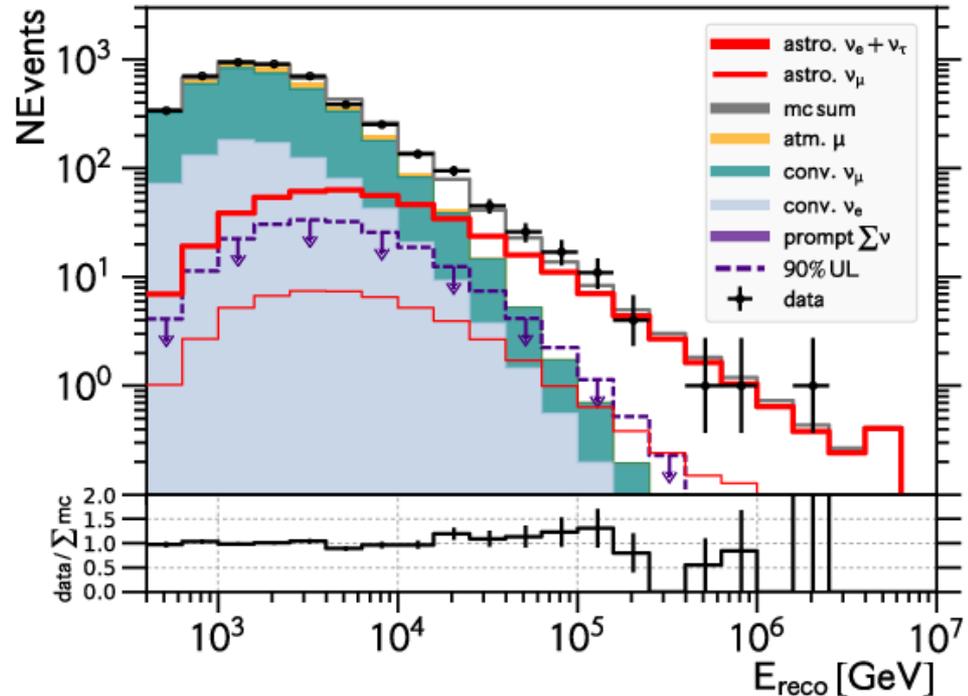
When a neutrino interacts with the Antarctic ice, it creates other particles. In this event graphic, a muon was created that traveled through the detector almost at the speed of light. The pattern and the amount of light recorded by the IceCube sensors indicate the particle's direction and energy.



- Near future:
  - Km3NET (mediterranean)
  - IceCube – Gen2

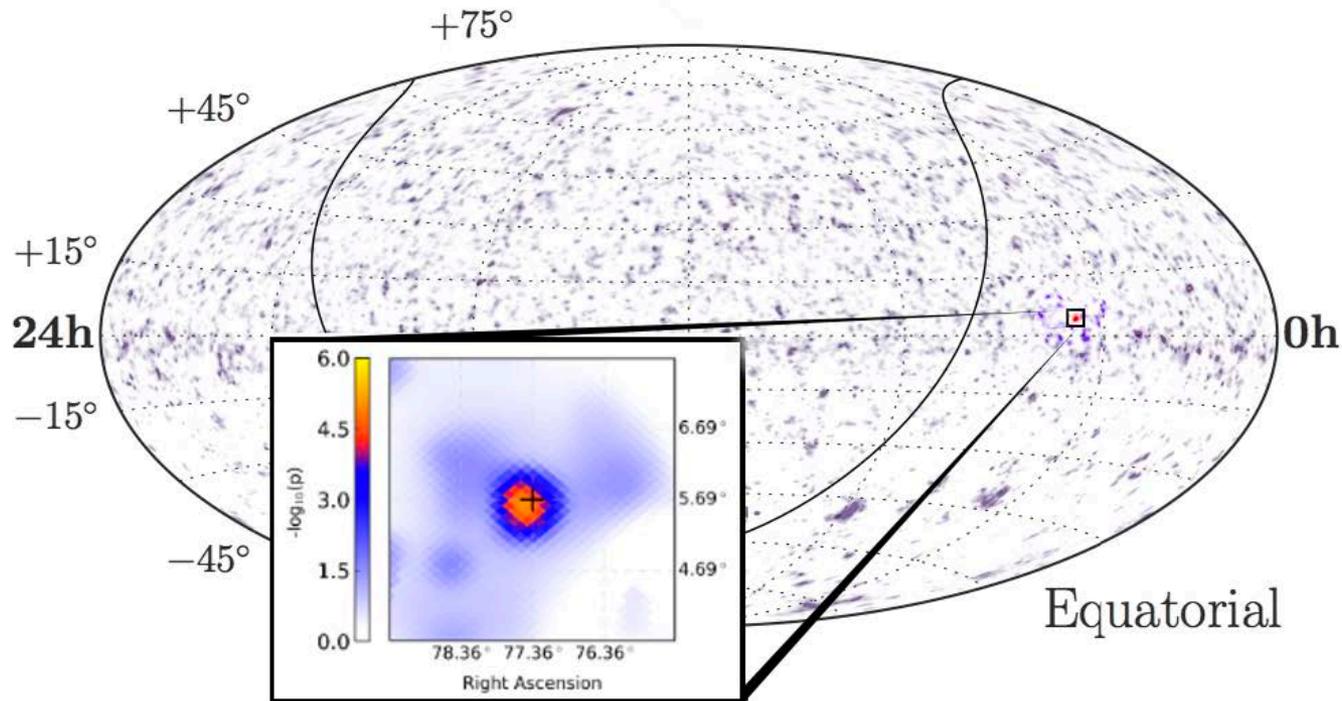
# IceCube: discovery of extragalactic HE neutrinos

- Evidence above/beyond atmospheric neutrinos
- multi- PeV events observed
- Mapping the sky
  - Track-like :  $\sim 1^\circ$  resolution
  - Shower-like :  $\sim 10\text{-}30^\circ$  resolution



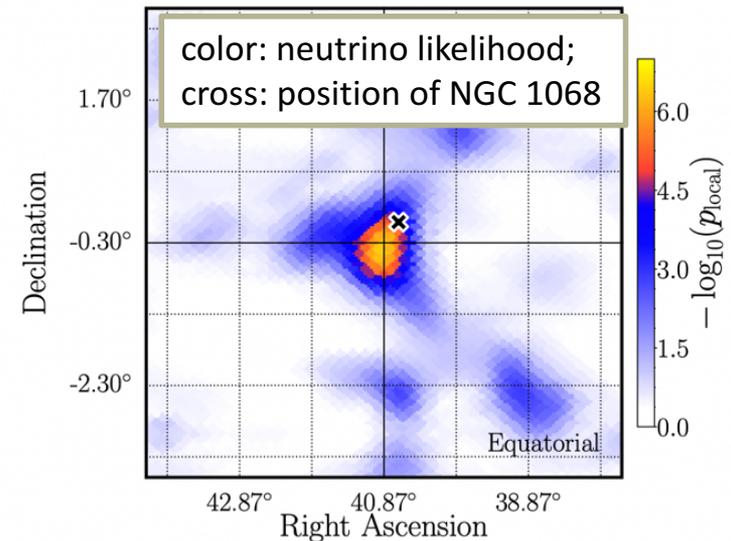
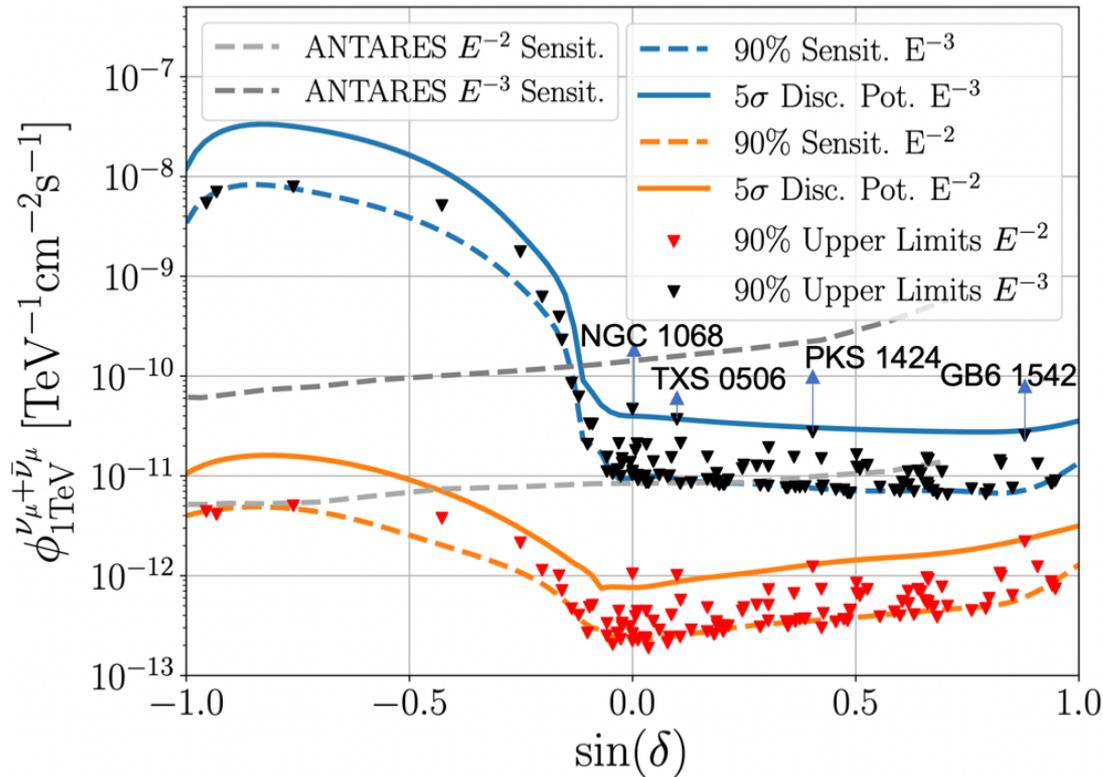
# New: evidence for non-uniform distribution

- Mostly from 4 extragalactic sources



no evidence for neutrinos associated with Galactic sources

- 4 active galaxies emerging from diffuse flux



# Flavor composition: testing for new physics

- Consistent with propagation in vacuum with PMNS mixing matrix (standard mixing)
- Initial exclusions of exotic flavor compositions
  - Improvements expected with Gen2

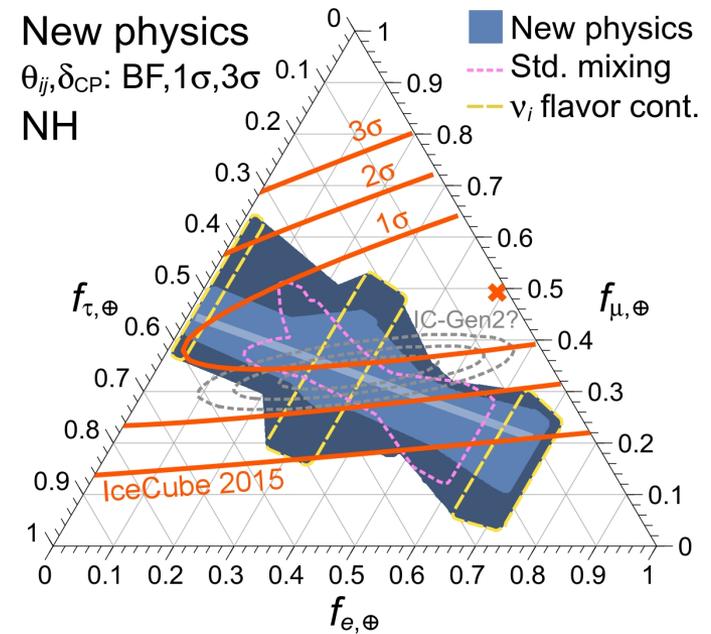
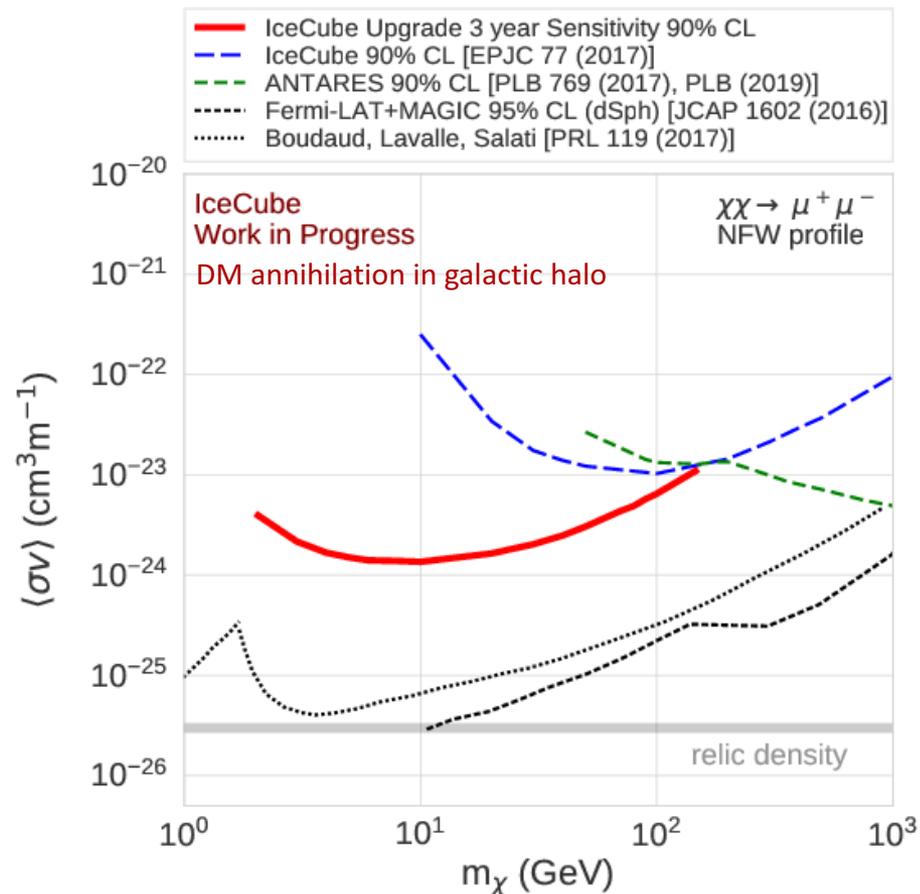


Fig. From Bustamante, Beacom & Winter, PRL 115, 161302 (2015)

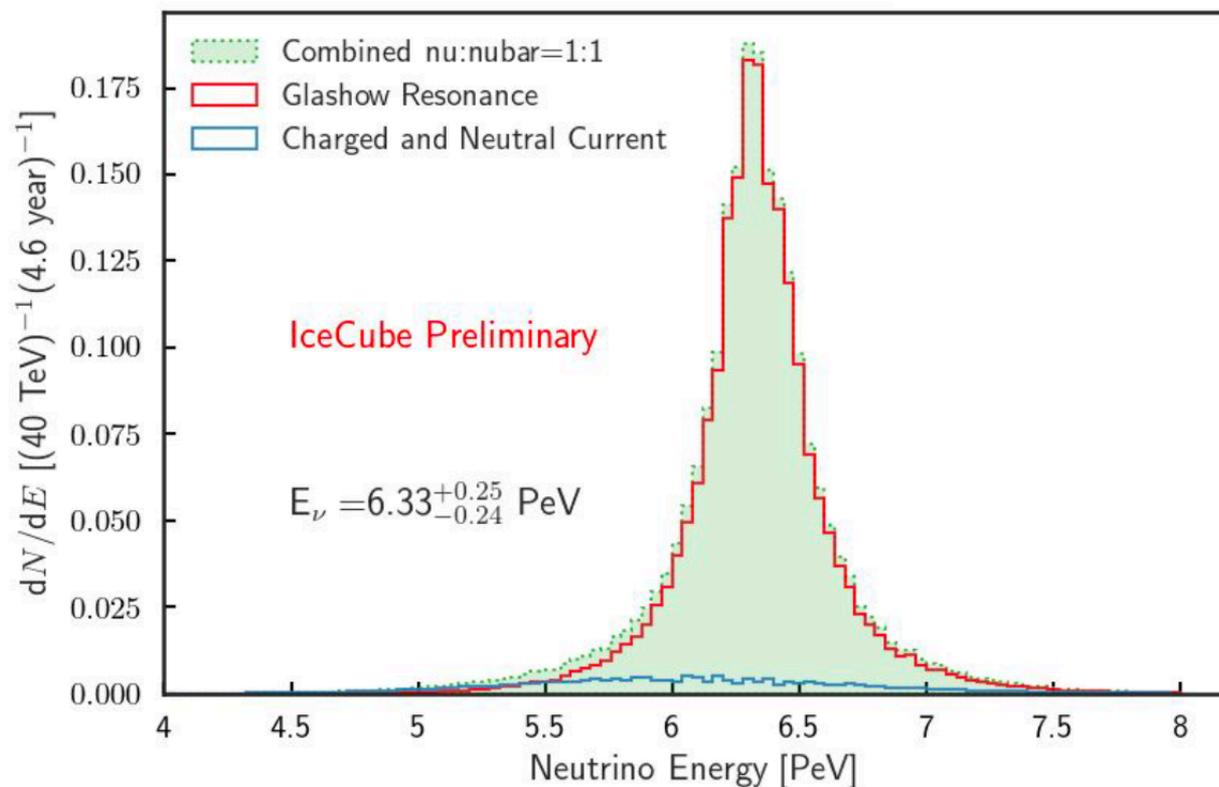
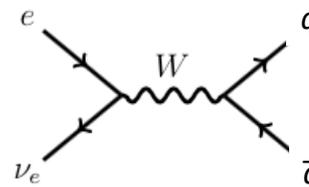
# Constraining Dark Matter annihilation/decay

- *Non-observation of of galactic flux*  $\rightarrow$  limits on neutrinos from DM annihilation/decay in galactic halo
  - Complementary to ANTARES
- Also searching for annihilation/decay inside the Sun and Earth



# New: indication of Glashow resonance!

- energy measurement understood
- identification of anti-electron neutrinos



- Implications of Glashow resonance observation
  - Tests a *precise* neutrino energy
  - Tests anti- $\nu_e$  flux: probes flavor composition, distinguish between different production/propagation models

*See, e.g., Barger et al., PRD 90 (2014) 121301*

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Coming up: diffuse supernova neutrinos

# Diffuse Supernova Neutrino Background (DSNB)

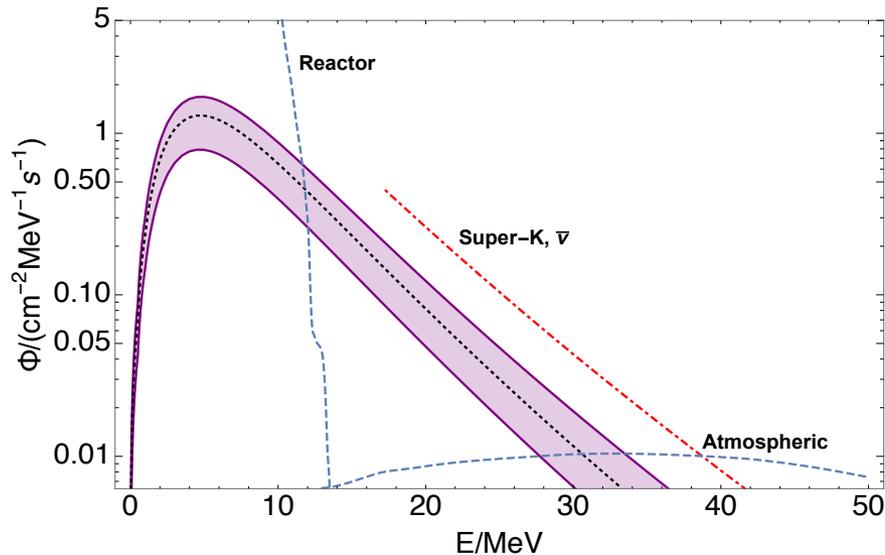
- Whole sky flux; constant in time

$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0} \int_{M_0}^{M_{\max}} dM \int_0^{z_{\max}} dz \frac{\dot{\rho}_{SN}(z, M) F_{\nu_\beta}(E', M)}{\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}}$$

Progenitor mass
SN rate
Propagated neutrino flux

$$M_0 \simeq 8M_{sun}$$

$$M_{max} \simeq 125M_{sun}$$



# Detectable within the next decade

- Main channel:  $\bar{\nu}_e + p \rightarrow n + e^+$ 
  - Sensitivity is *background-limited*
- Ongoing: **SuperK-Gd** (50 kt),  
Water + Gadolinium, for n-  
tagging
- Under construction: **JUNO**  
(Jiangmen Underground  
Neutrino Observatory ) (17 kt)
  - Liquid scintillator
- detection will change from  
exceptional to *routine!*

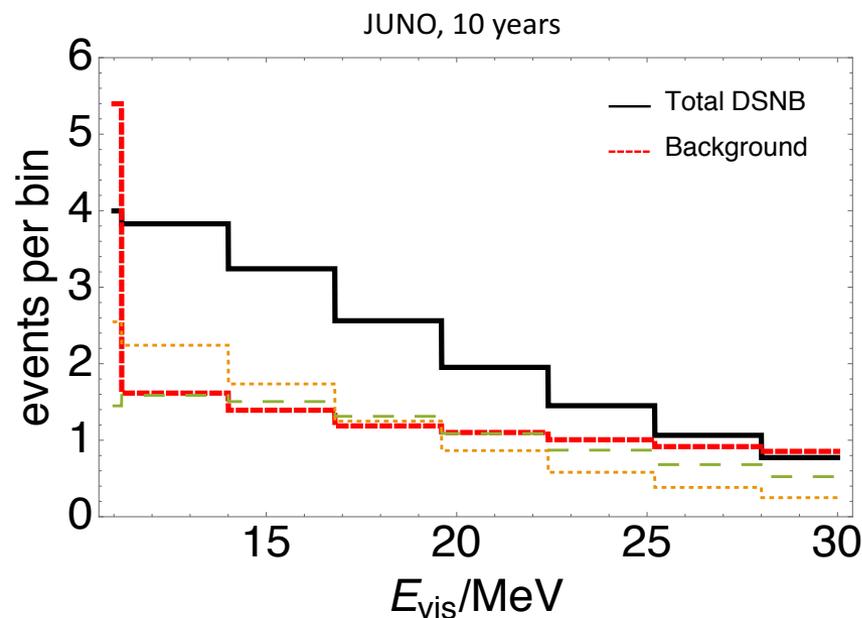


Figure: A. Priya and CL, JCAP 1711 (2017) no.11, 031

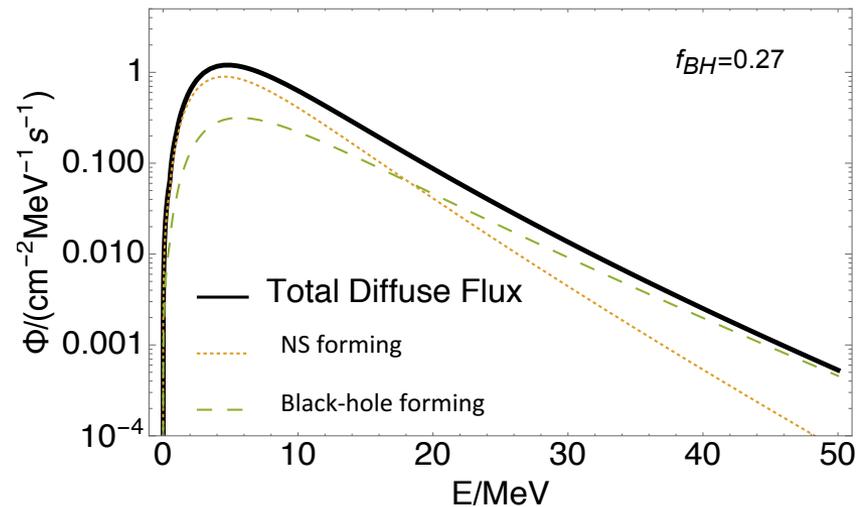
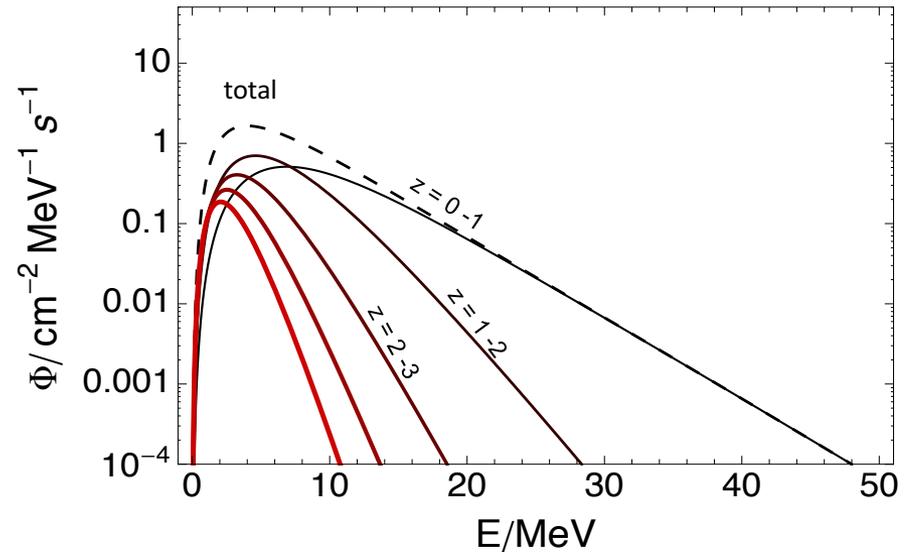
Beacom and Vagins, PRL93, 2004

Xu et al., J. Phys: Conf. Ser. 718 (2016)

An et al., J. Phys. G: Nucl.Part. Phys. 43 (2016) 030401.

# Astro-cosmo potential

- Strong *cosmological* component
  - Core collapse at high redshift?
  - evolution of SN rate (z-dependence)
- Gives image of the *entire* SN population
  - Diversity of core collapses (ONeMg cores, black hole formation, ...)



# Particle physics tests

- Neutrino decay

Ando, Phys.Lett.B 570 (2003)  
Fogli, Lisi, Mirizzi & Montanino, PRD70,2004

- Resonant absorption due to new physics

- New light mediators, exotic targets, ...

- Oscillations due to pseudo-Dirac neutrinos

de Gouvêa, Martinez-Soler, Perez-Gonzalez, Sen,  
arxiv:2007.13748

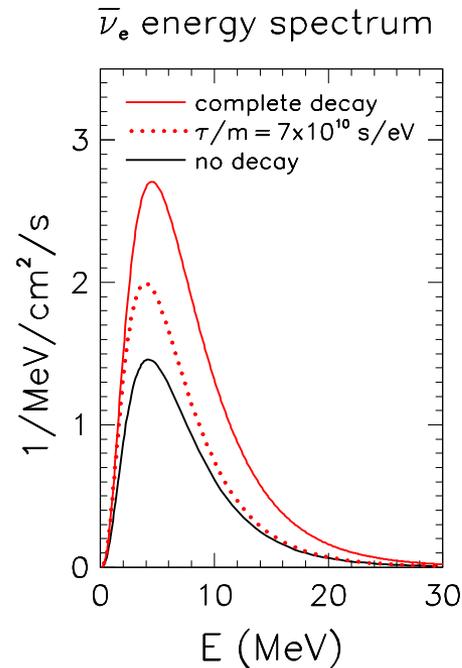


Figure from Fogli, Lisi, Mirizzi & Montanino, PRD70,2004

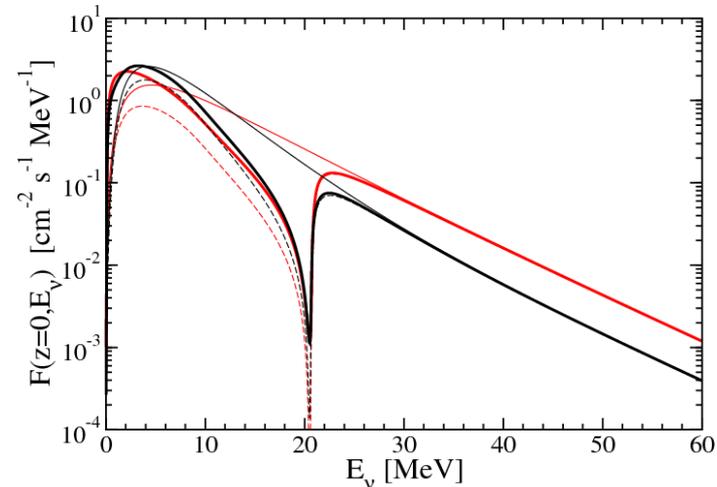


Figure from Farzan and Palomares-Ruiz, JCAP 06 (2014) 014

- Non-supernova neutrinos:  
MeV dark matter  
annihilation, etc.
- **Fun stuff** (what if a primordial black  
hole lives in the center of the Earth?)

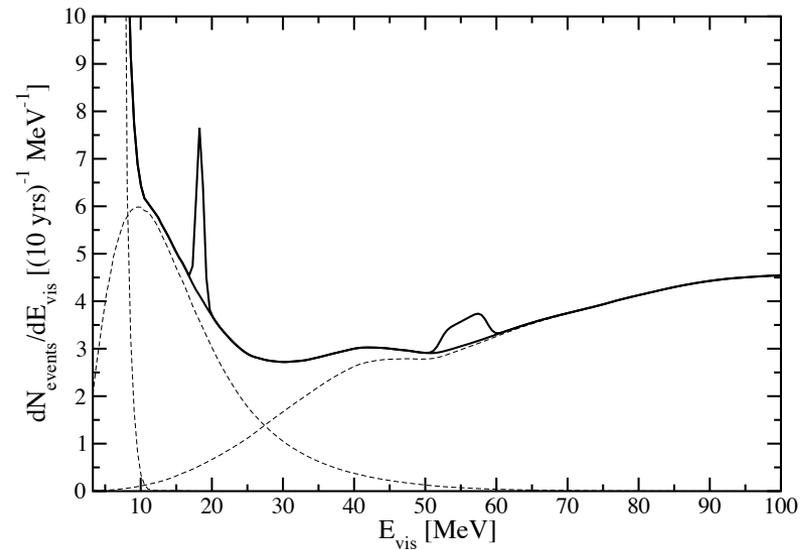


Figure from Palomares-Ruiz  
and Pascoli, PRD77,2008

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Things to look forward to

# The next galactic supernova

- Unique *thermal* neutrino emission,  $O(10)$  s burst,  $T \sim 3-7$  MeV
  - $O(10^4)$  neutrino events at SuperK
- Neutrino burst as precursor of core collapse
  - Supernova **E**arly **W**arning **S**ystem (**SNEWS**) 2.0. Network of neutrino detectors, stronger focus on multi-messenger astronomy



SN1987A - Credit: Anglo-Australian observatory



<https://snews.bnl.gov/>

# Testing neutrino physics in ultra-dense matter

- Exotic cooling channels (causing dimmer/shorter neutrino flux)
- Oscillations in matter and neutrino backgrounds
  - Resonant  $\theta_{13}$  effects, self-interaction effects
  - sterile neutrinos, non-standard interactions

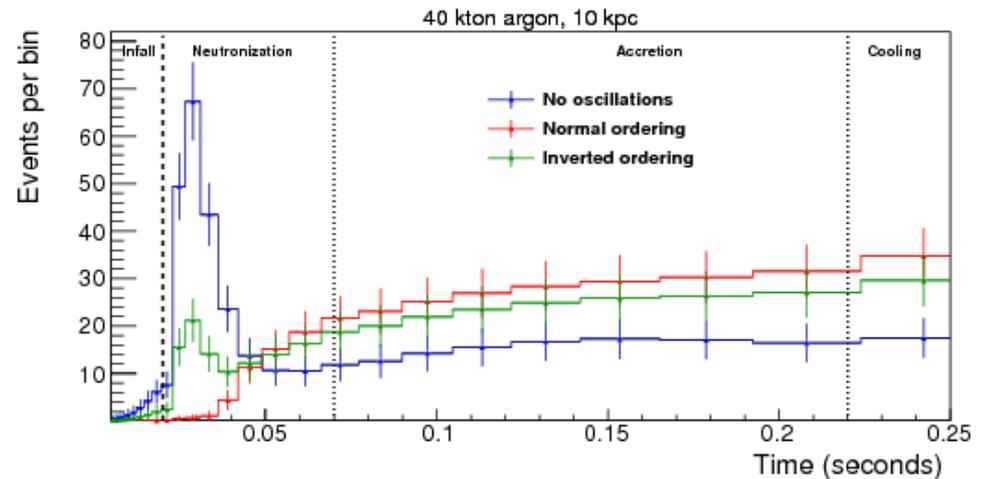


Figure from K. Scholberg, J.Phys. G45 (2018) no.1

# The ultra-high energy frontier: $E > 10$ PeV

- Searching for:
  - Air showers, Earth-skimming events
  - Coherent Cherenkov RF emission of from cascades (*Askaryan effect*)
- Main goal: cosmogenic neutrinos
  - Due to UHECR absorption on CMB

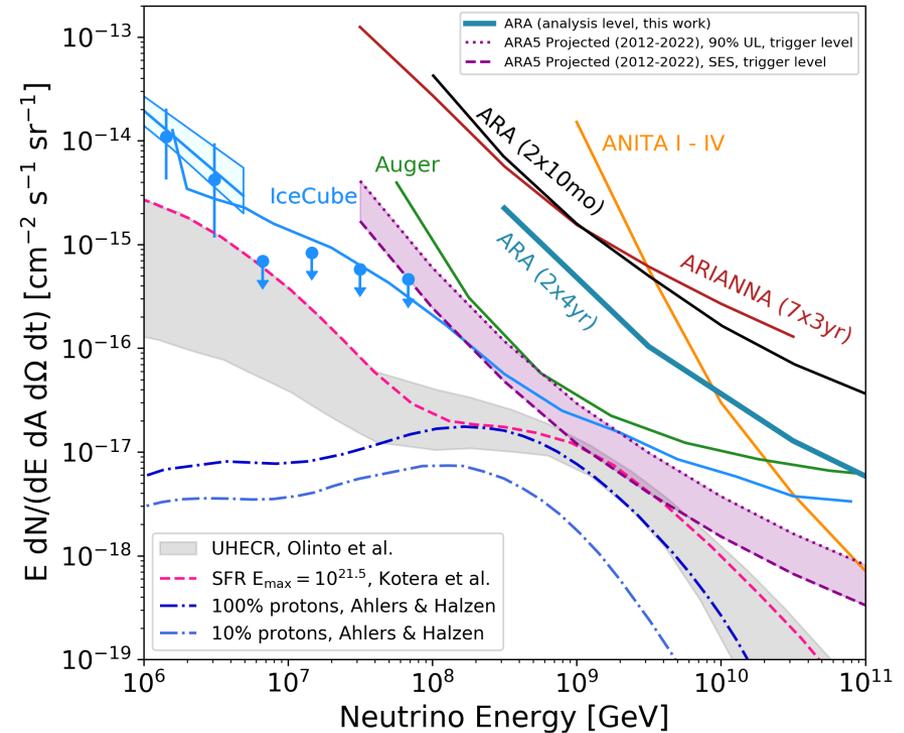
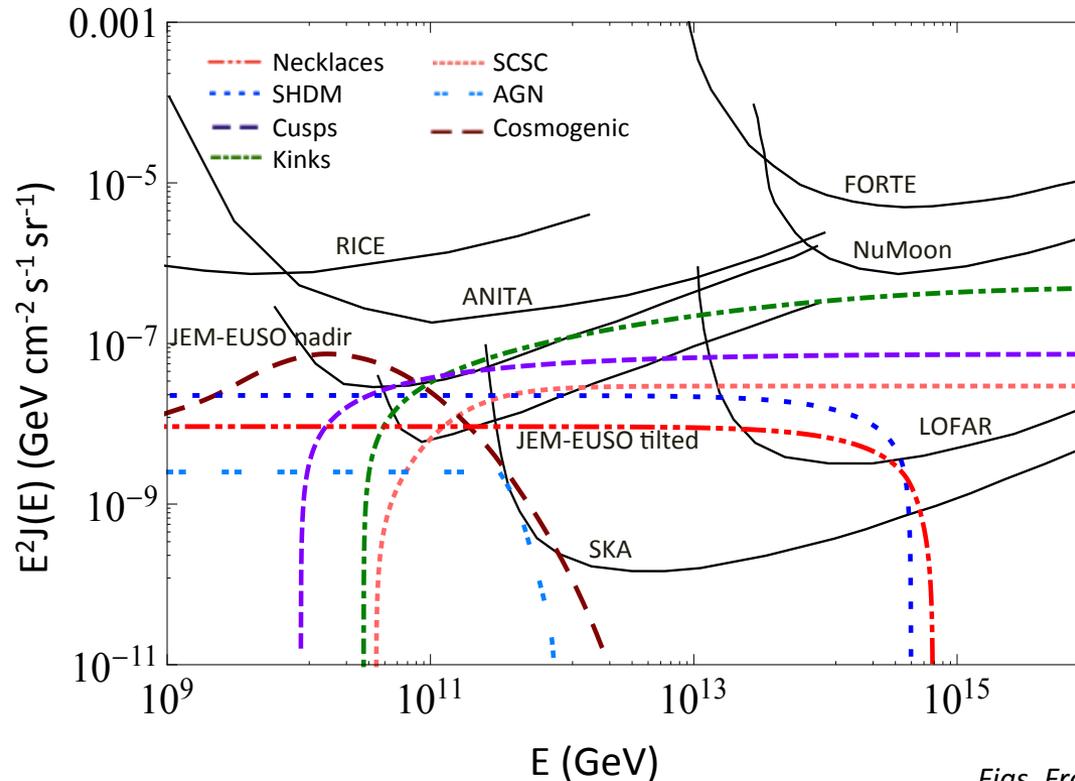


Fig. From Connolly, (ARA) coll., PoS(ICRC2019)1177

# Test for super-heavy exotic neutrino emitters

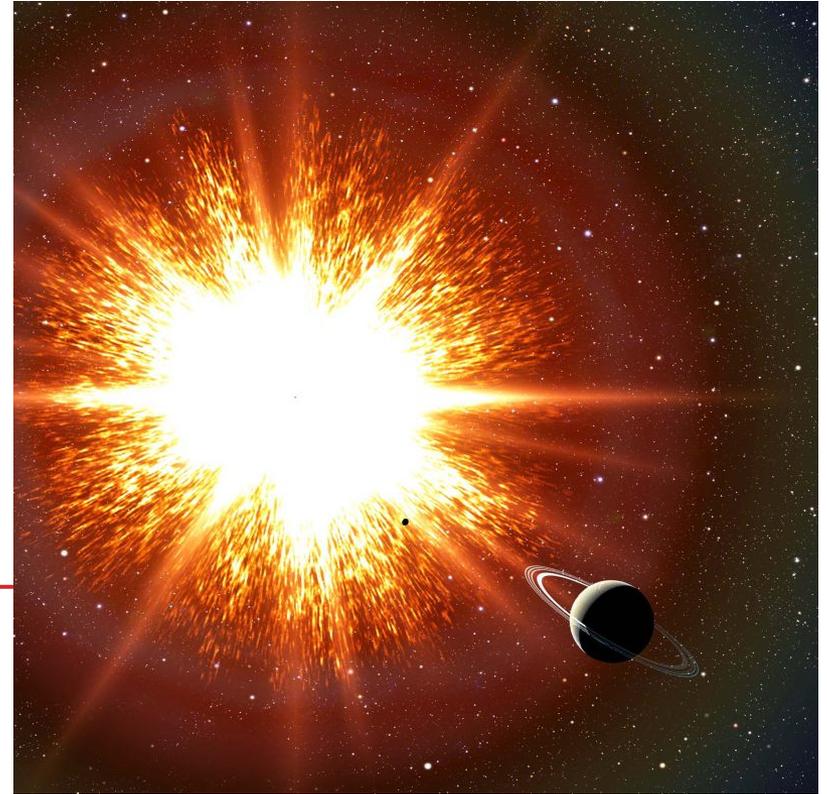
- “top-down” models:
  - cosmic strings, superheavy Dark Matter, etc.



*Figs. From Lunardini, Sabancilar and Yang, JCAP 08 (2013) 014*

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Final remarks



# Certainties and possibilities

- The solar neutrinos started from astronomy and ended up in particle physics....  
So.... You never know the turn things take...
- There are (almost) guaranteed *discoveries* ahead in neutrino astronomy
  - Multi-messenger astronomy (photon, cosmic rays, neutrinos, gravitational waves) is becoming a field of its own
- There are guaranteed *constraints* ahead on particle/nuclear physics from neutrino astronomy
  - And a very large number of *possibilities* for discovery

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*Thank you!*

BACKUP

# Robust oscillation signatures

- Distinguishable from stellar physics effects

Suppression of  $\nu_e$  neutronization peak  
due to  $\theta_{13}$ -driven MSW resonance,  
For Normal mass hierarchy

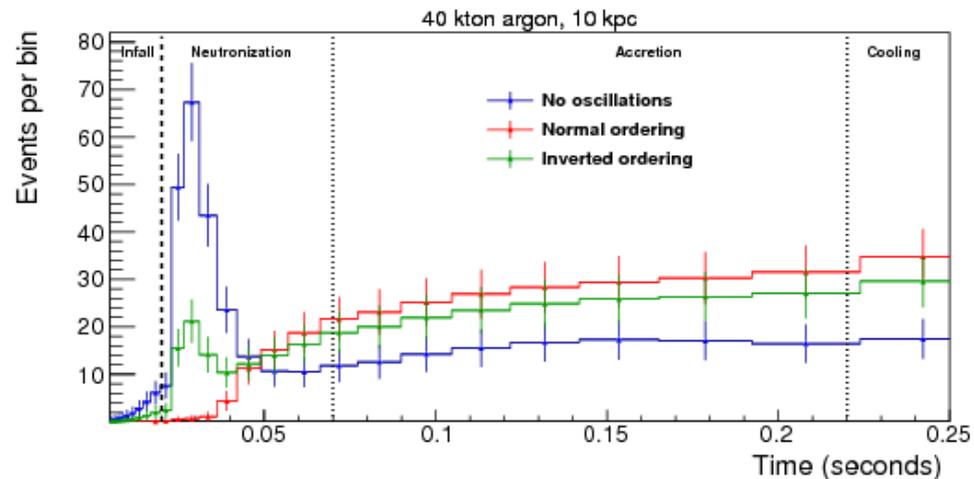
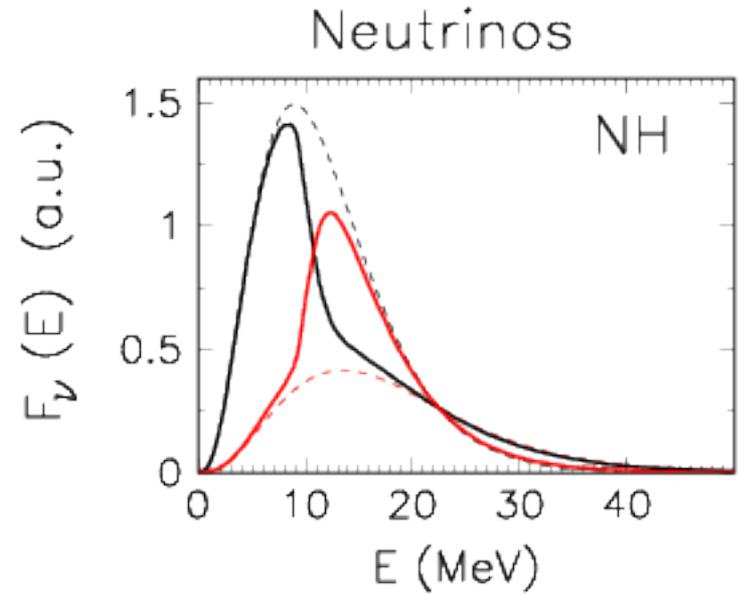


Figure from K. Scholberg, J.Phys. G45 (2018) no.1

## Spectral splits due to collective effects

Figure from Chakraborty and Mirizzi, PRD90 (2014) no.3, 033004



Electron flavor re-generation inside the Earth;  
sensitive to spectral difference of states  
in the  $\theta_{12}$ -driven MSW resonance

Figure from Borriello et al., PRD86 (2012) 083004

