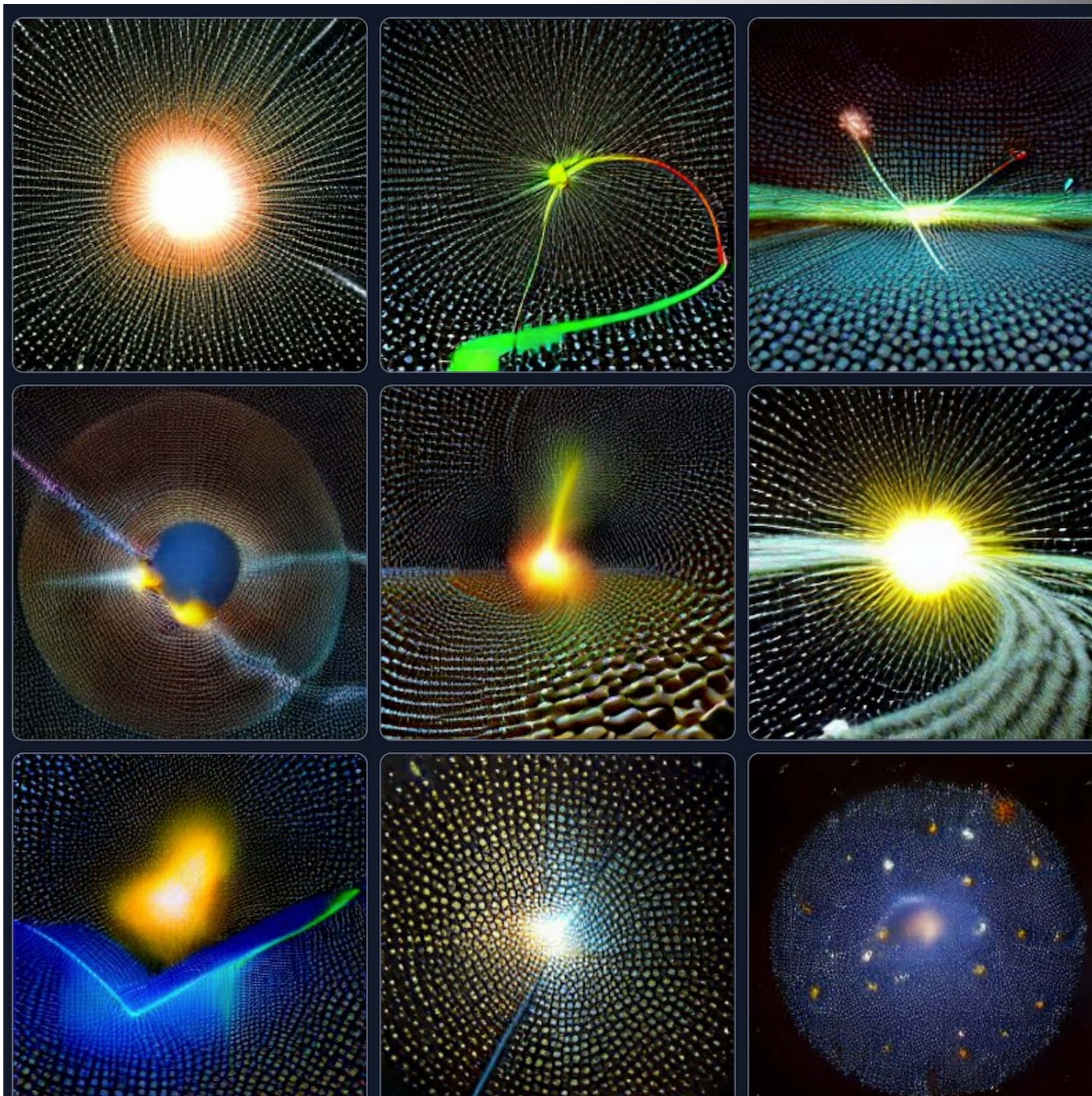
DALLE-Mini output



Neutrinos and* Particle Astrophysics: Experimental Overview

Kate Scholberg,
Duke University

COSMOS 22
August 24, 2022

*logical AND

What do we know about neutrinos?

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

neutral partners to the charged leptons

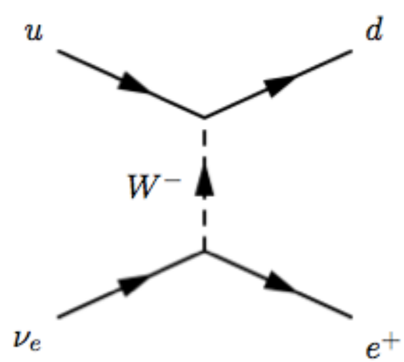
- **They have mass and mix!**

  3 flavors states, 3 mass states

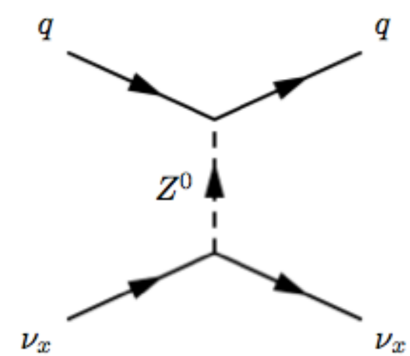
$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi} |\nu_i\rangle$$

- **The mass is tiny...** from lab experiments, $\Sigma m < 2.4$ eV

Interactions in the Standard Model:



charged-current (CC)
cares about ν flavor



neutral-current (NC)
flavor blind

*Some experimental anomalies...hints of new states or interactions in the data ...?

The three-flavor neutrino paradigm

$$|\nu_f\rangle = \sum_{i=1}^{N} U^*_{fi}|\nu_i\rangle$$

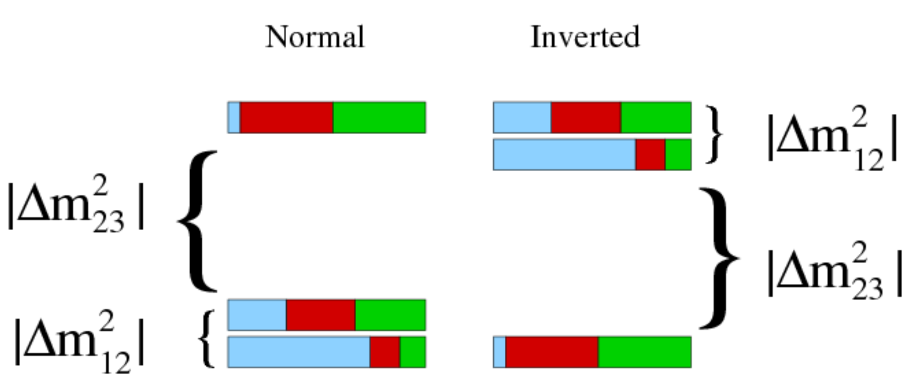
Parameterize mixing matrix U as

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\times \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij}$$

3 masses	m_1, m_2, m_3 (2 mass differences + absolute scale)
3 mixing angles	$\theta_{23}, \theta_{12}, \theta_{13}$
1 CP phase	δ
(2 Majorana phases)	α_1, α_2



signs of the mass differences matter

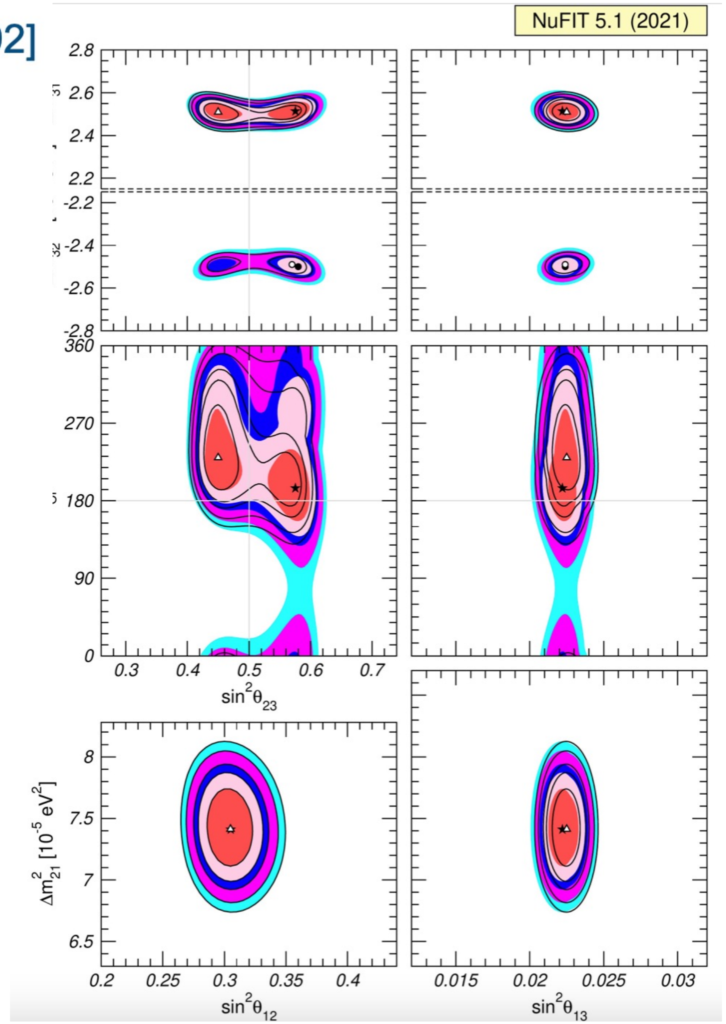
The three-flavor picture fits the data well

Global three-flavor fits to all data

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0 \text{ for NO and } \Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0 \text{ for IO.}$$



Esteban et al., arXiv:2007.14792, 10.1007/JHEP09(2020)178

What do we *not* know about the three-flavor paradigm?

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP'20 [2007.14792]

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{\mathrm{CP}}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

$\Delta m^2_{3\ell} \equiv \Delta m^2_{31} > 0$ for NO and $\Delta m^2_{3\ell} \equiv \Delta m^2_{32} < 0$ for IO.

Is θ_{23} non-negligibly greater or smaller than 45 deg?

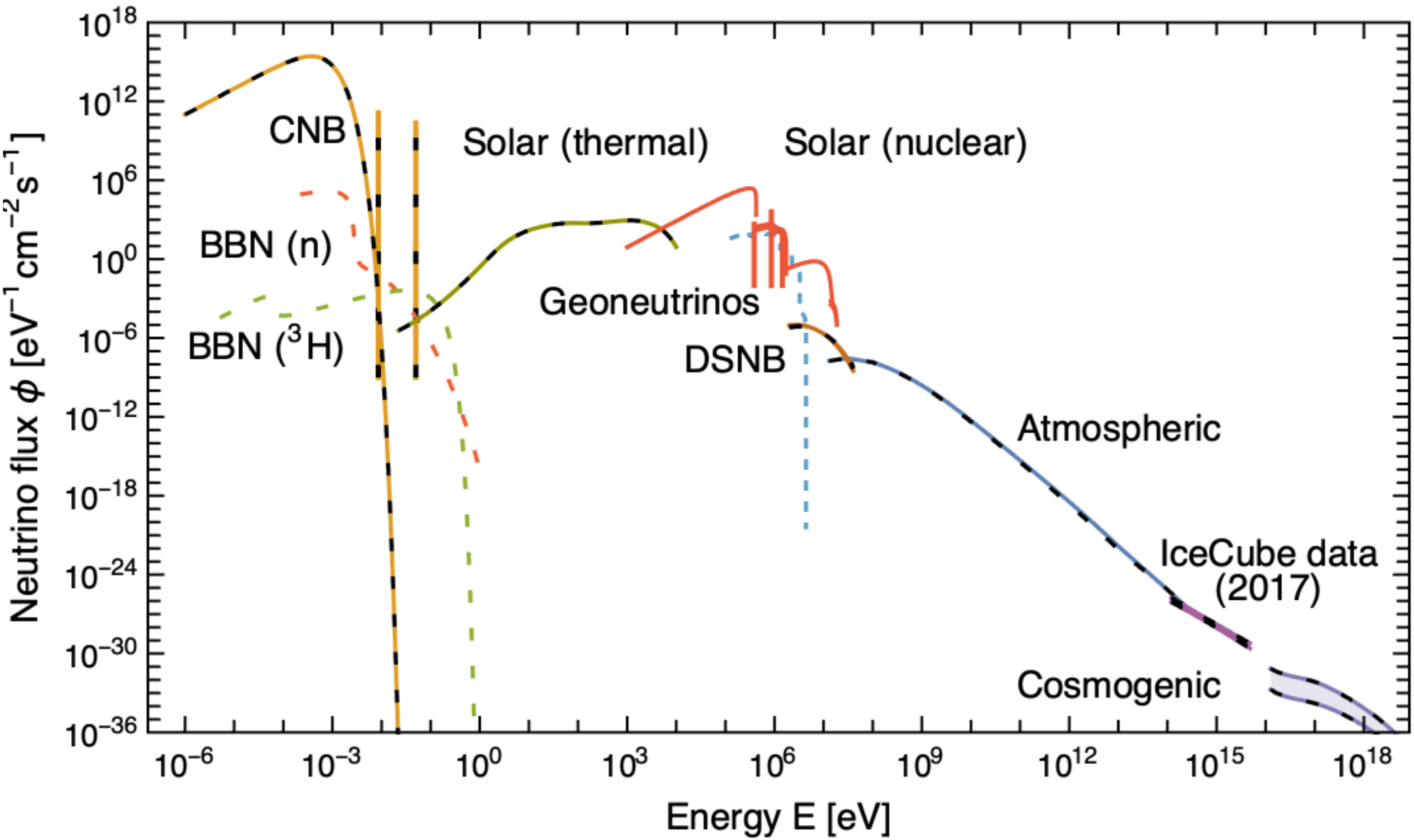
poor knowledge*

sign of Δm^2 unknown (ordering of masses)

**maybe* related to baryon asymmetry of the Universe?

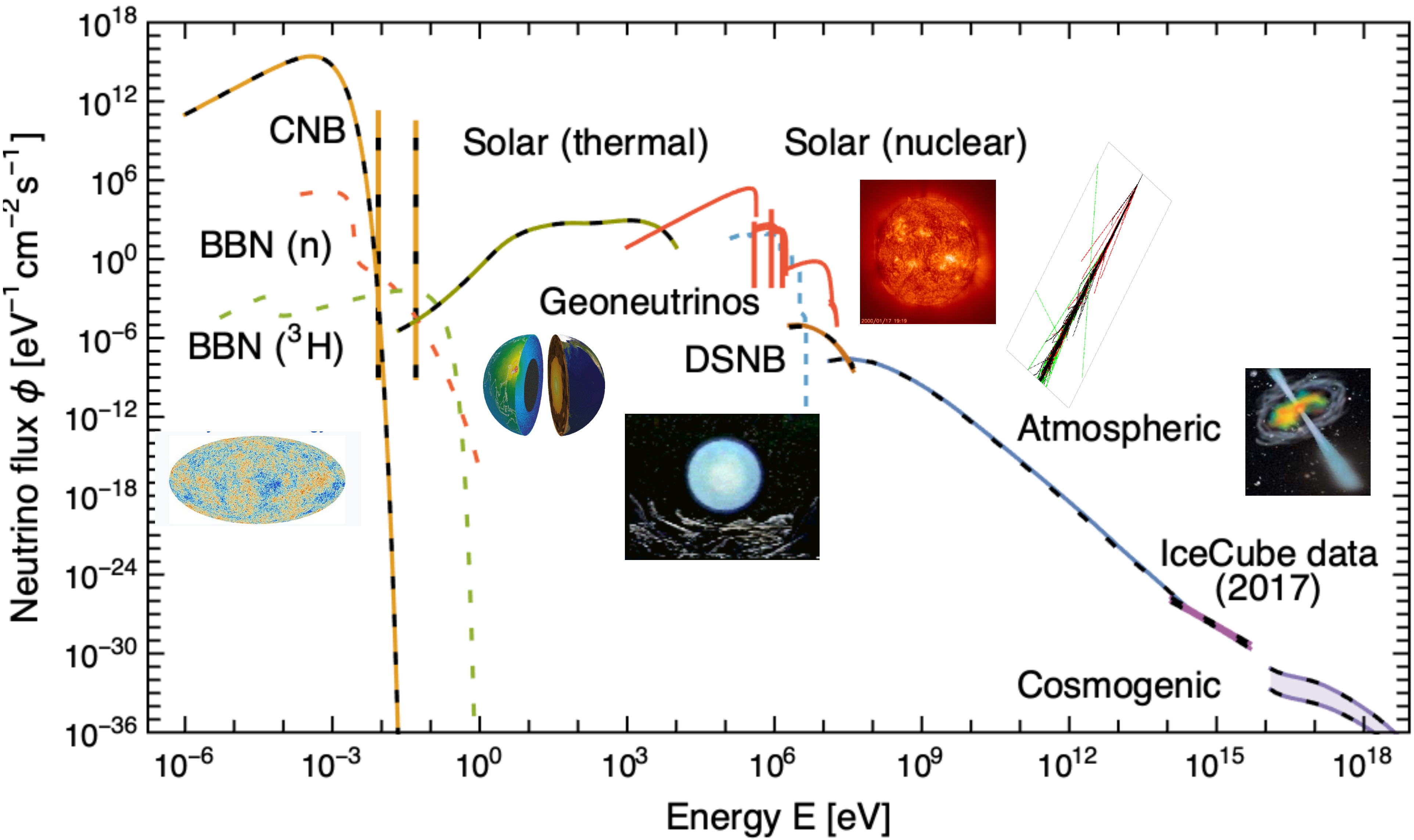
Natural neutrinos pervade the Universe....

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



Neutrinos bring unique information about the

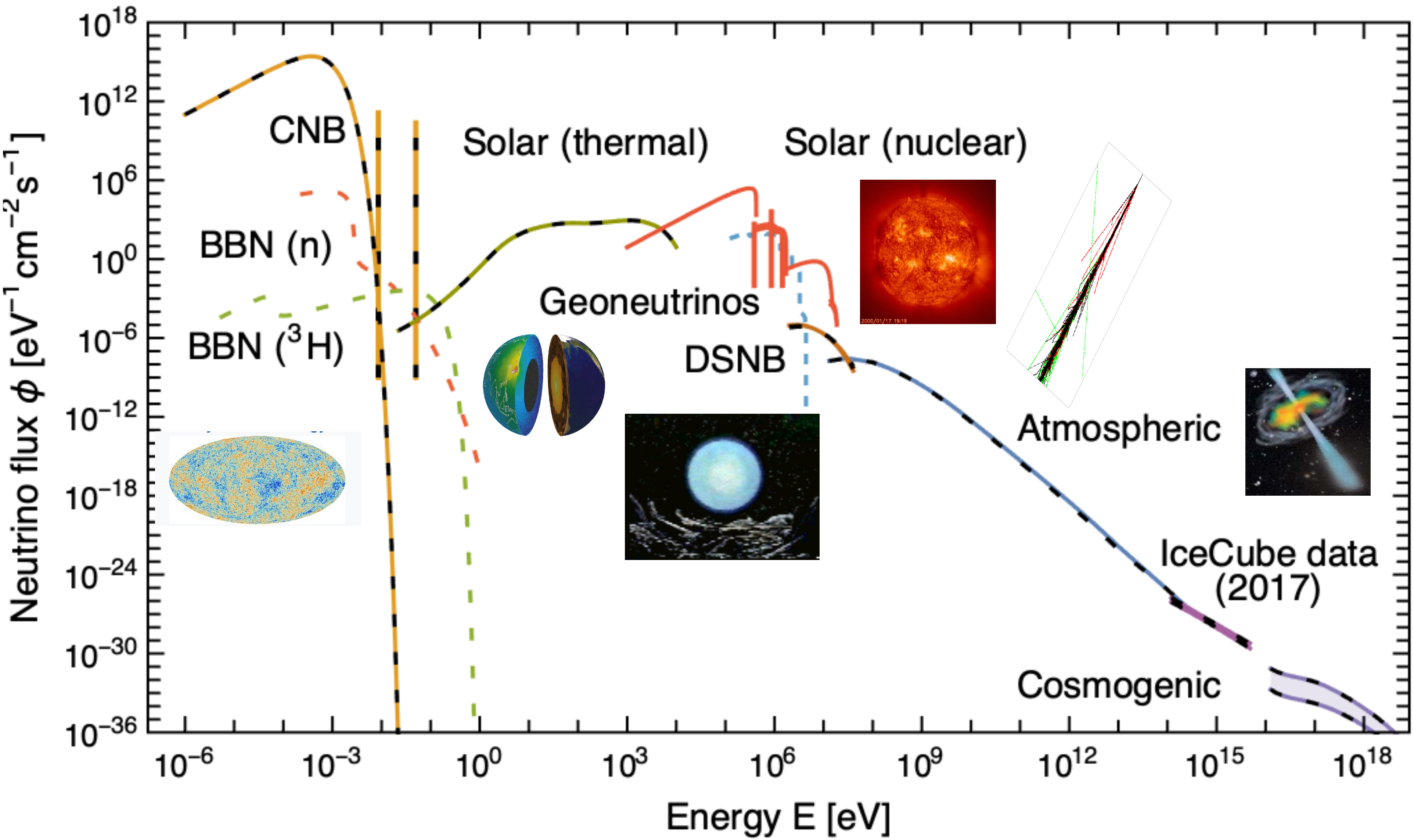
nature of natural sources



- Information from deep inside astronomical objects
- Messages ~unperturbed by matter & em fields

} thanks to the weakness of the interaction

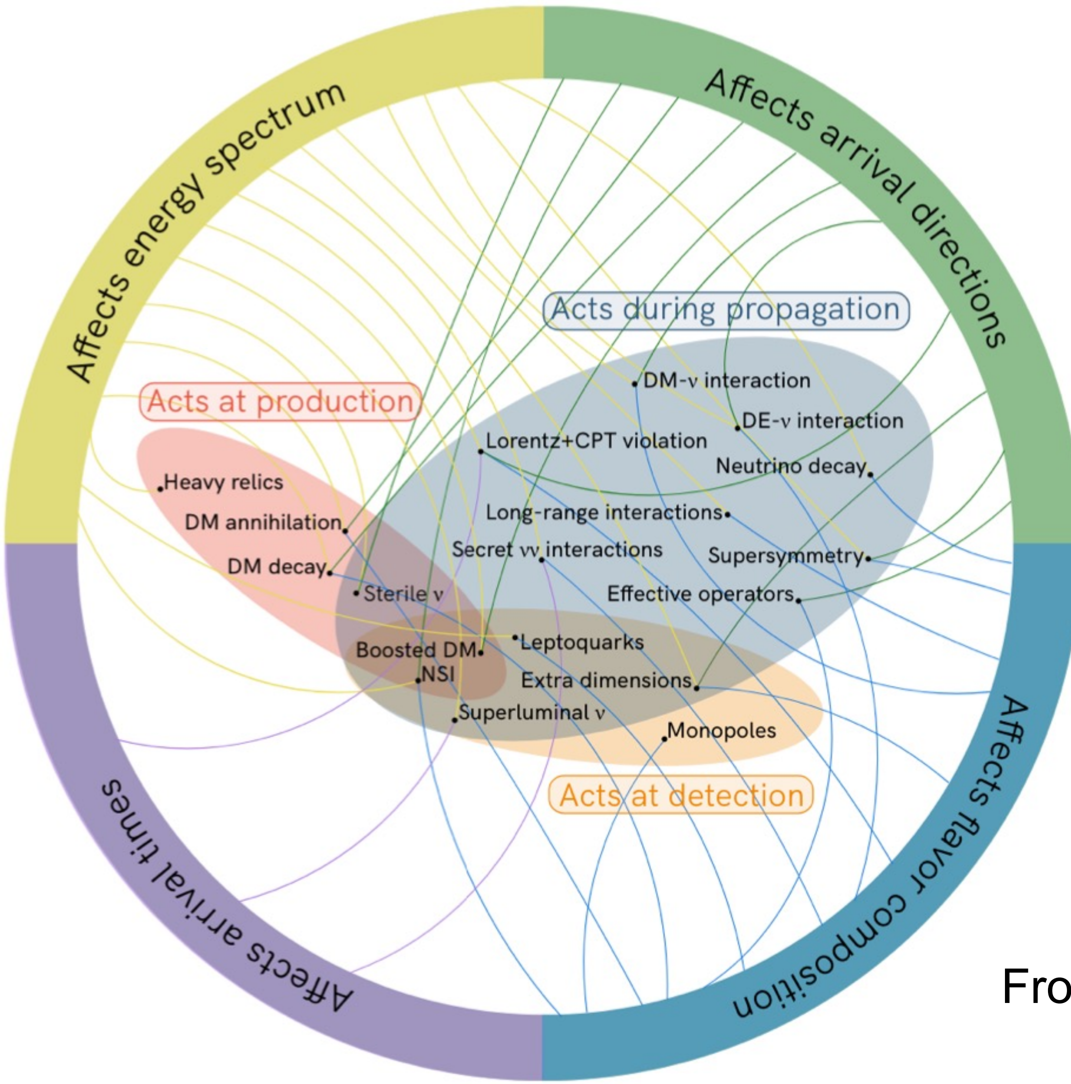
And astrophysical objects in turn give us sources for the study of **neutrino physics**...



... 3-flavor oscillations, anomalies, BSM searches...

Many opportunities to probe BSM physics

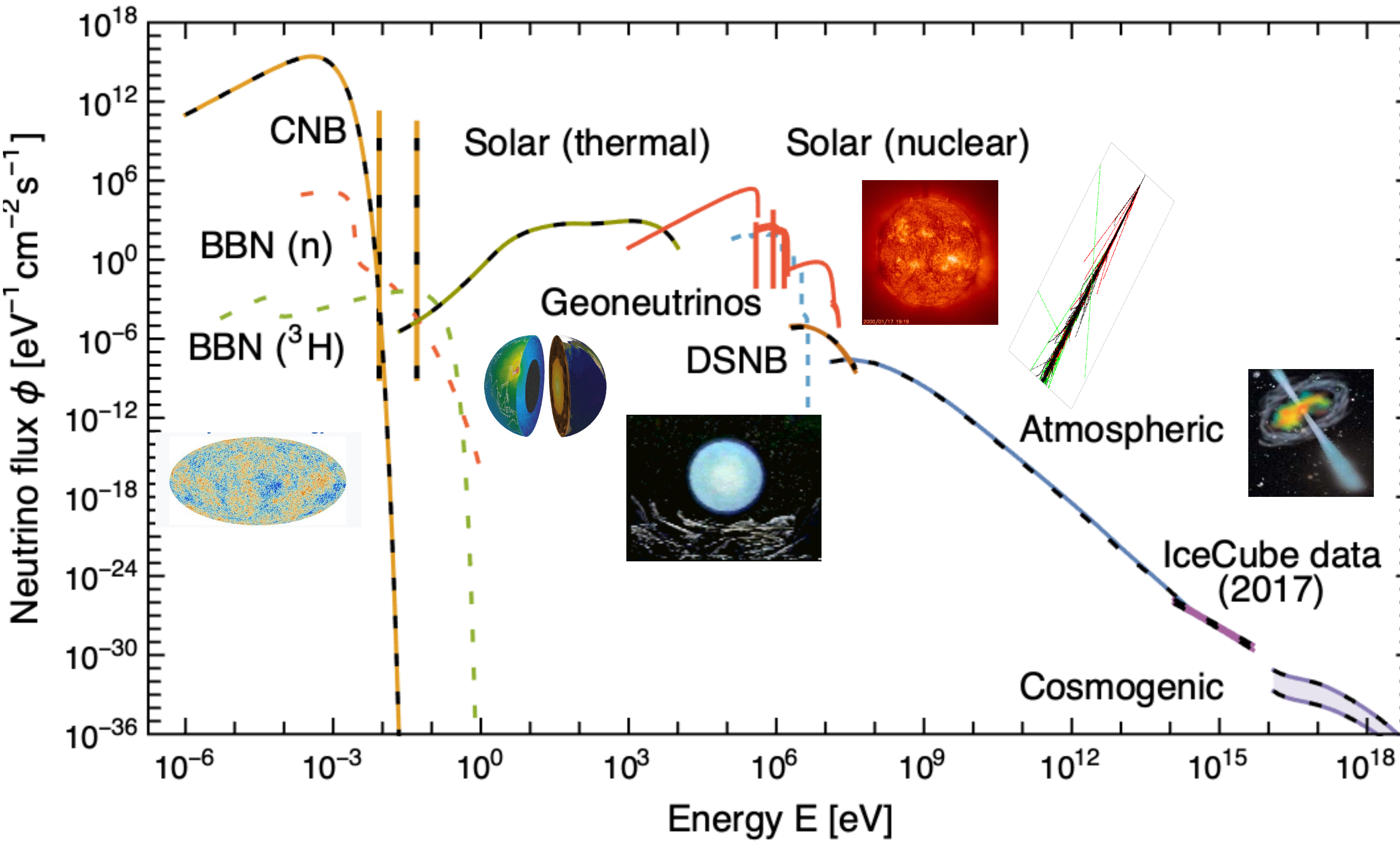
Neutrino observables*: energy, direction, time, flavor



From arXiv:2203.08096v2

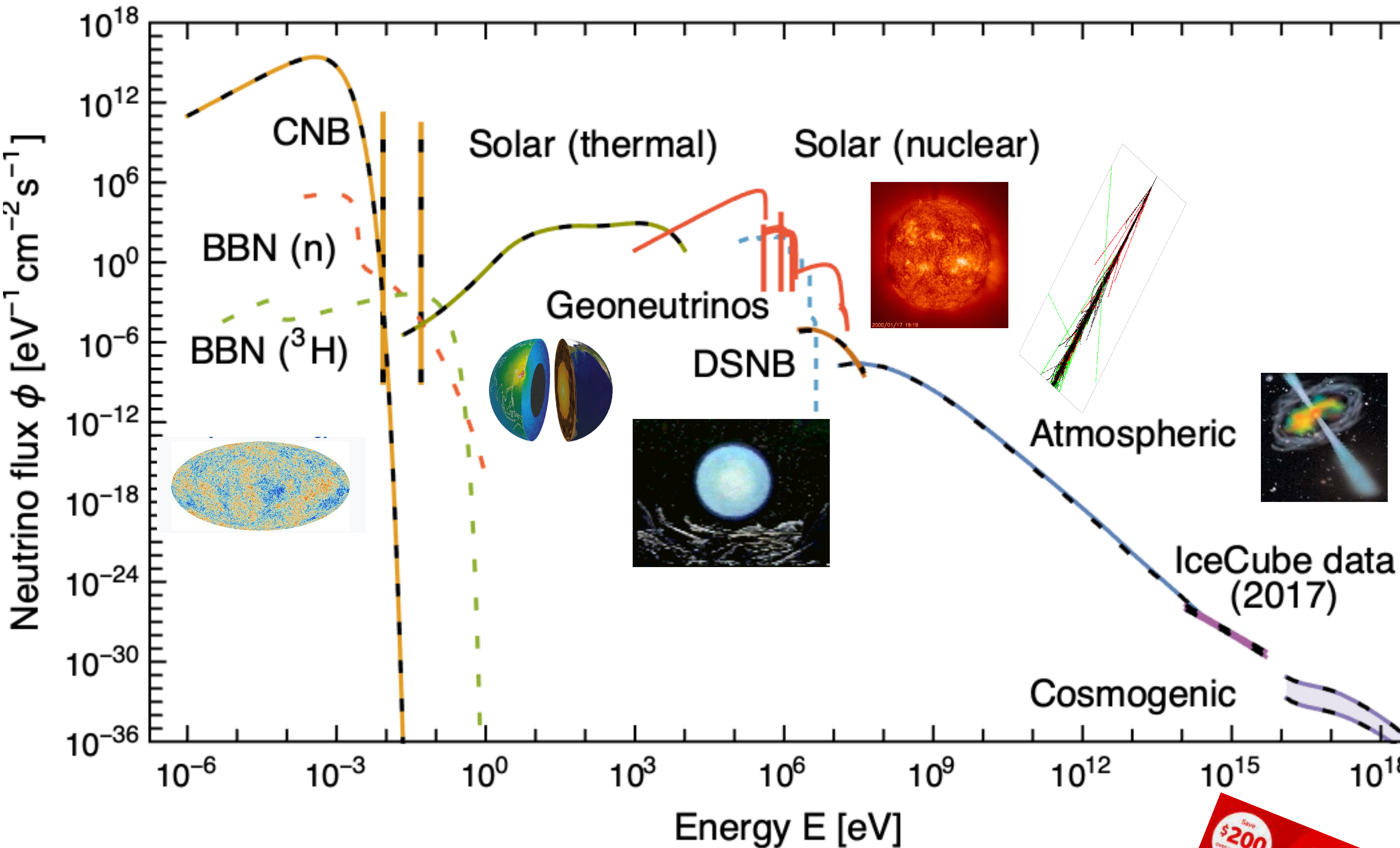
*also, non-neutrino-sector BSM signatures in neutrino detectors

And astrophysical objects in turn give us sources for the study of **neutrino physics**...



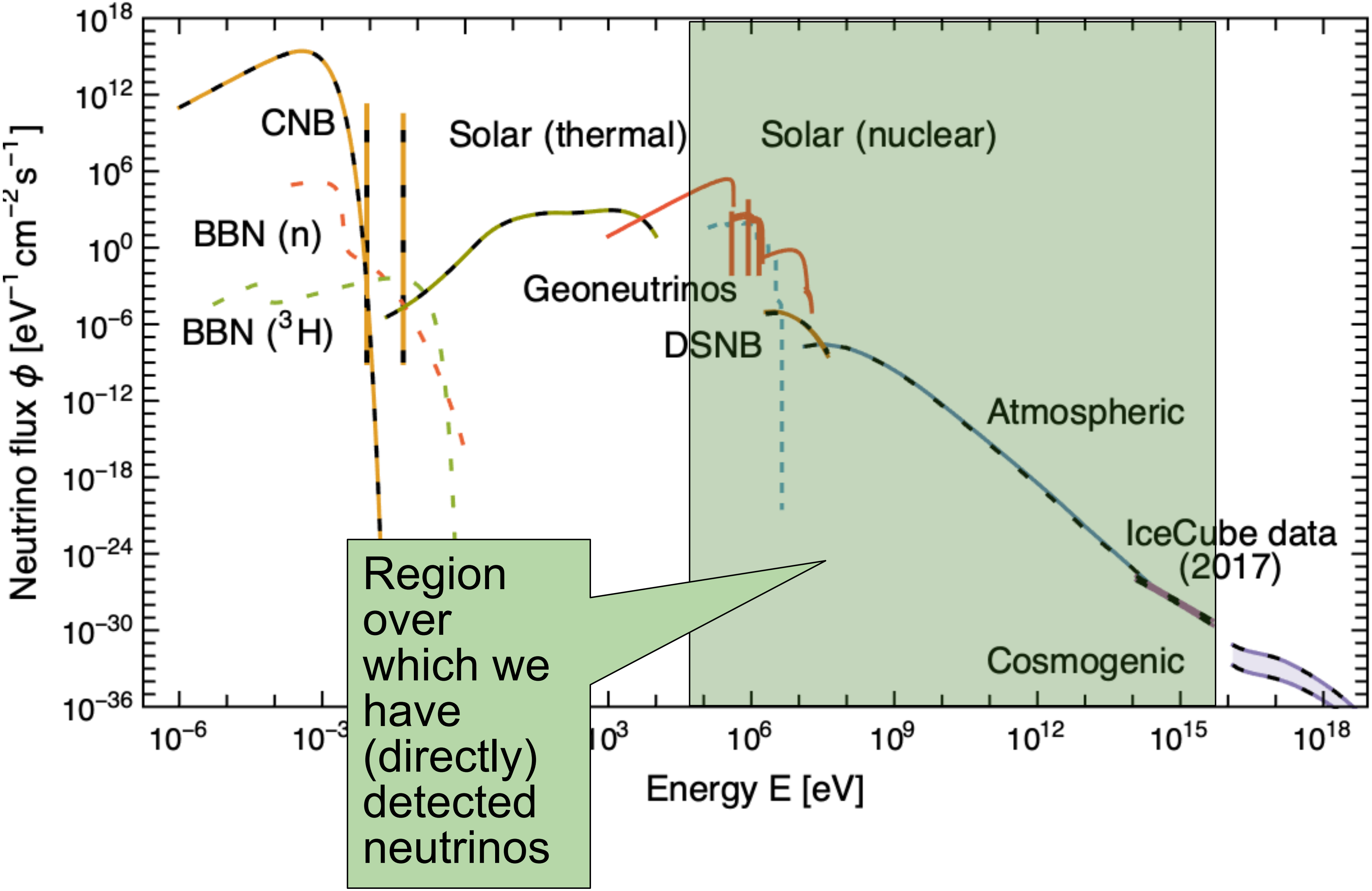
...for free! Just need to look up (and down!)

And astrophysical objects in turn give us sources for the study of **neutrino physics**...

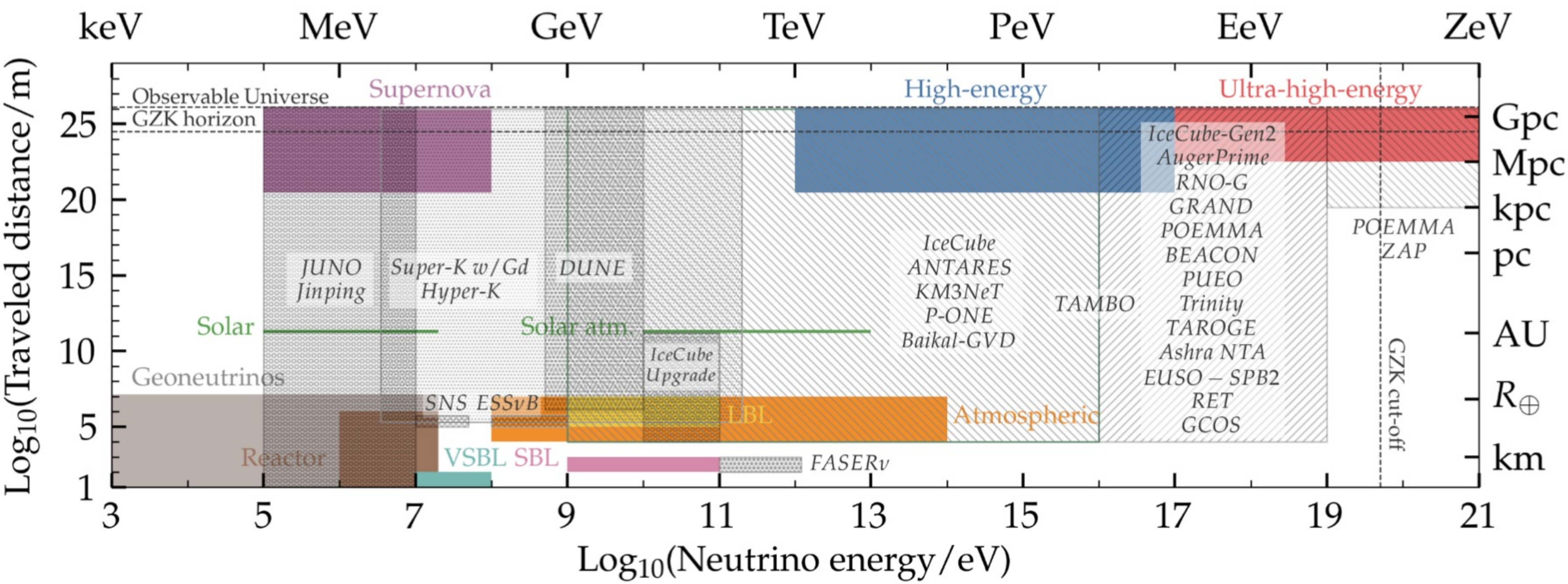


The catch: need some detectors!

There is information over ~25 orders of magnitude in energy



There is a vast array of detector technologies, and detector instances, existing and proposed



From arXiv:2203.08096v2

Multi-Messenger Astrophysics

Many, many detectors

ν

SuperK + gadolinium
JUNO
DUNE
Hyper-Kamiokande
KM3NeT
IceCube-Gen2
ARA, RNO-G

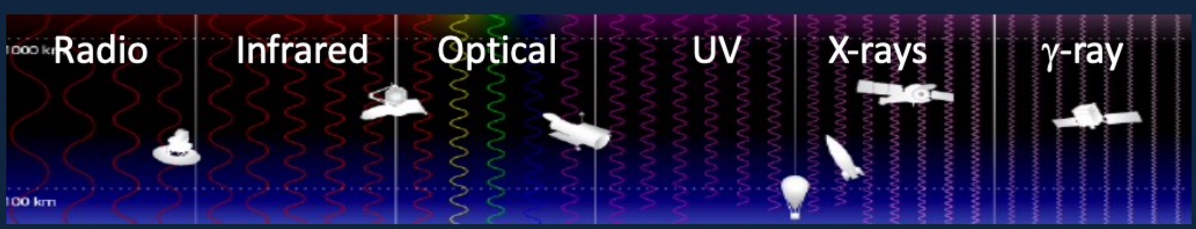
CR

LHAASO
PUEO
GRAND
TAMBO
POEMMA

GW

KAGRA
LIGO-India
LIGO Voyager
Cosmic Explorer
Einstein Telescope
LISA

γ



Radio	Infrared	Optical	UV	X-rays	γ-ray
LAST SKA	JWST	LSST TMT ELT		Athena	CTA SWGO

Shunsaku Horiuchi,
Snowmass Neutrino Colloquium

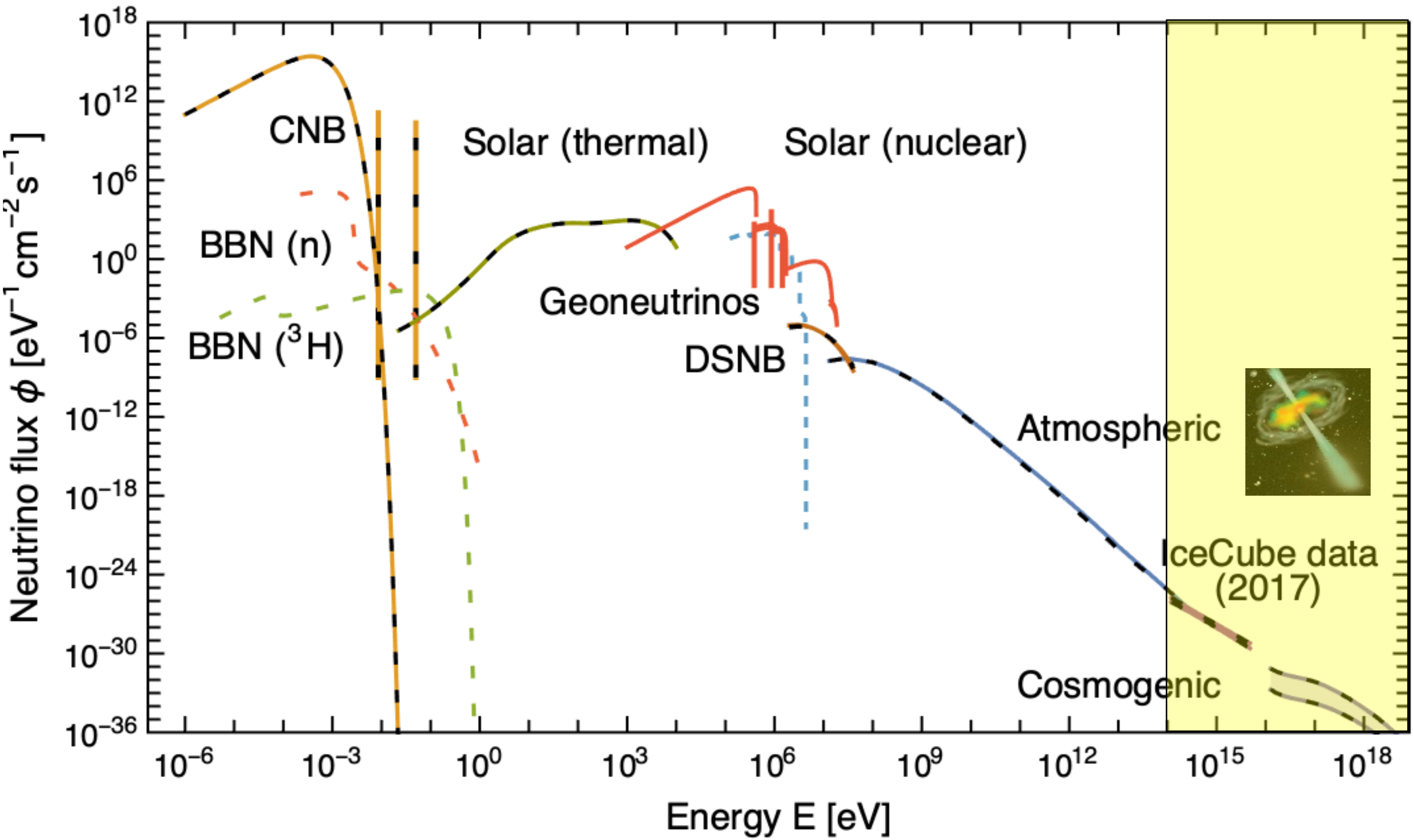
The standard disclaimer....

Multi-messenger astronomy

Neutrino astrophysics

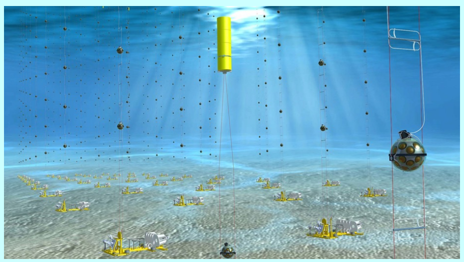
A "flight" of examples

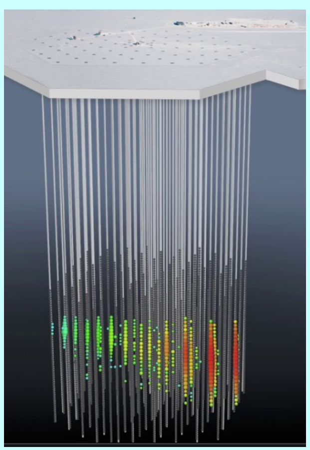
Start at the ultra-high-energy end



Detectors for ultra-high energy neutrinos (>TeV)

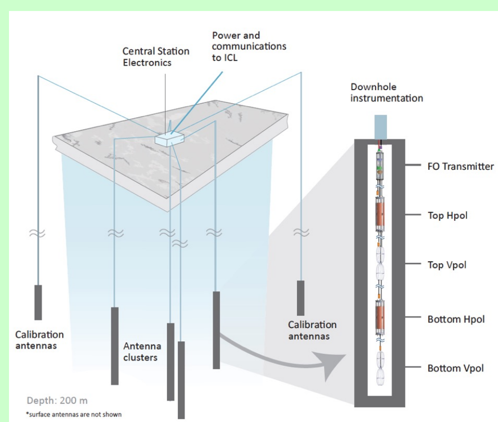
Long-string Water Cherenkov





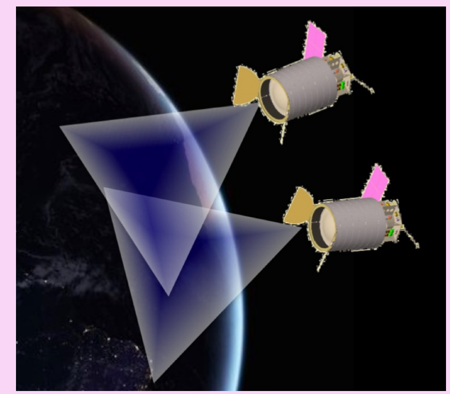
Water and ice

Antenna-based detectors



Balloon or in-ice

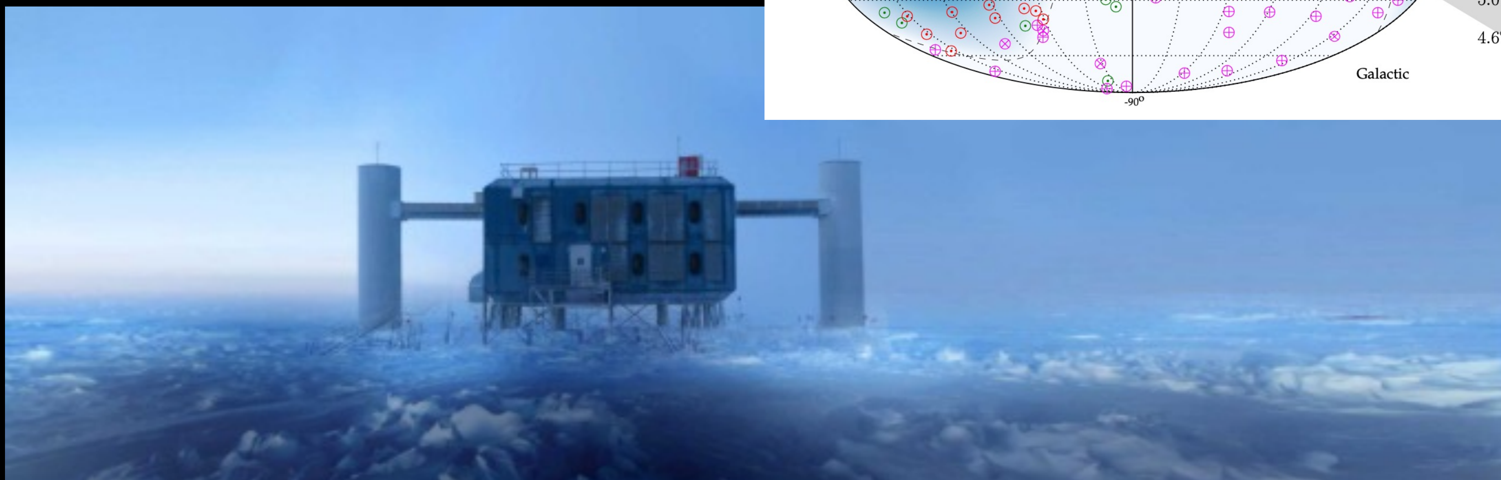
Cosmic-ray shower detectors

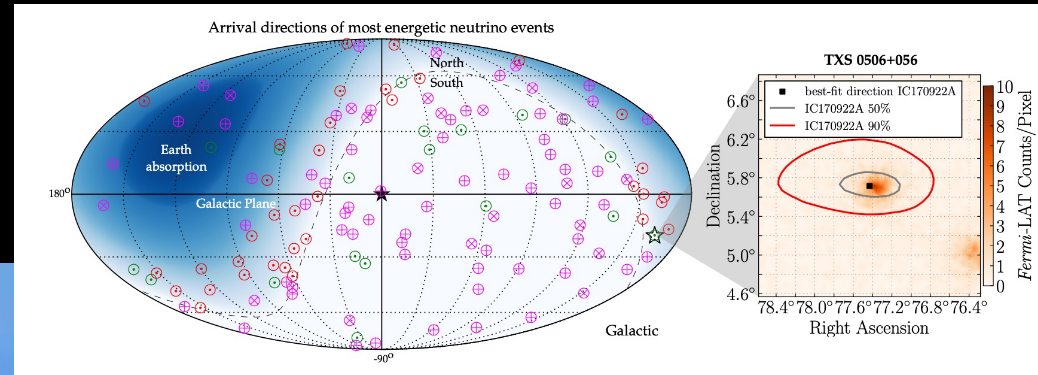


Ground-based or space-based

IceCube

@South Pole

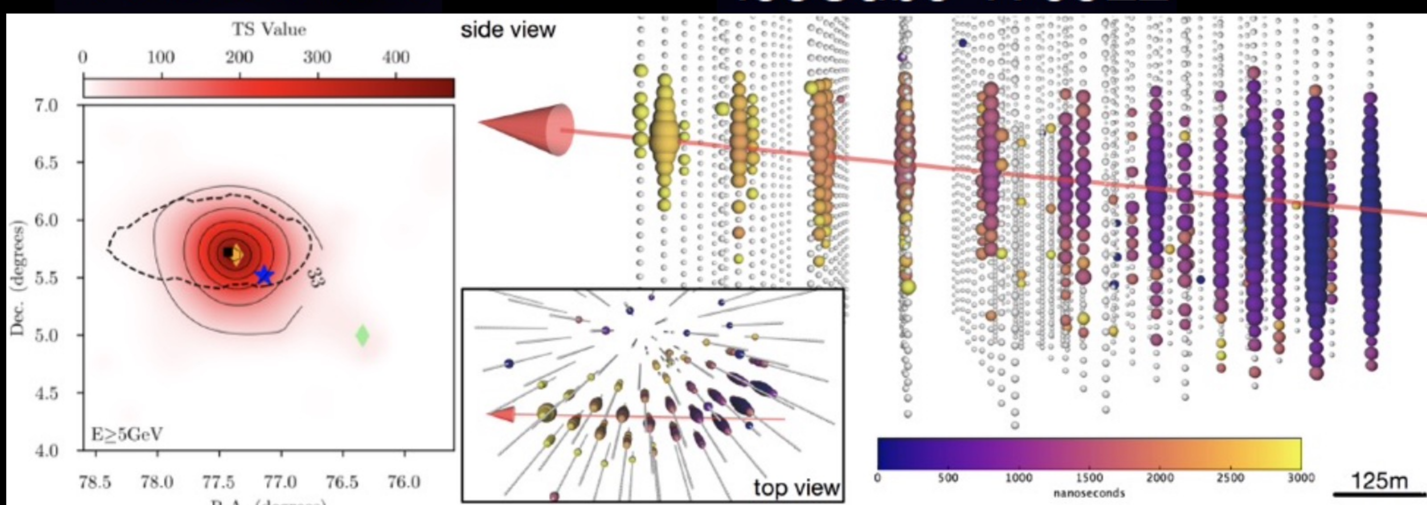




possible "jetted AGN"

TXS0506+056

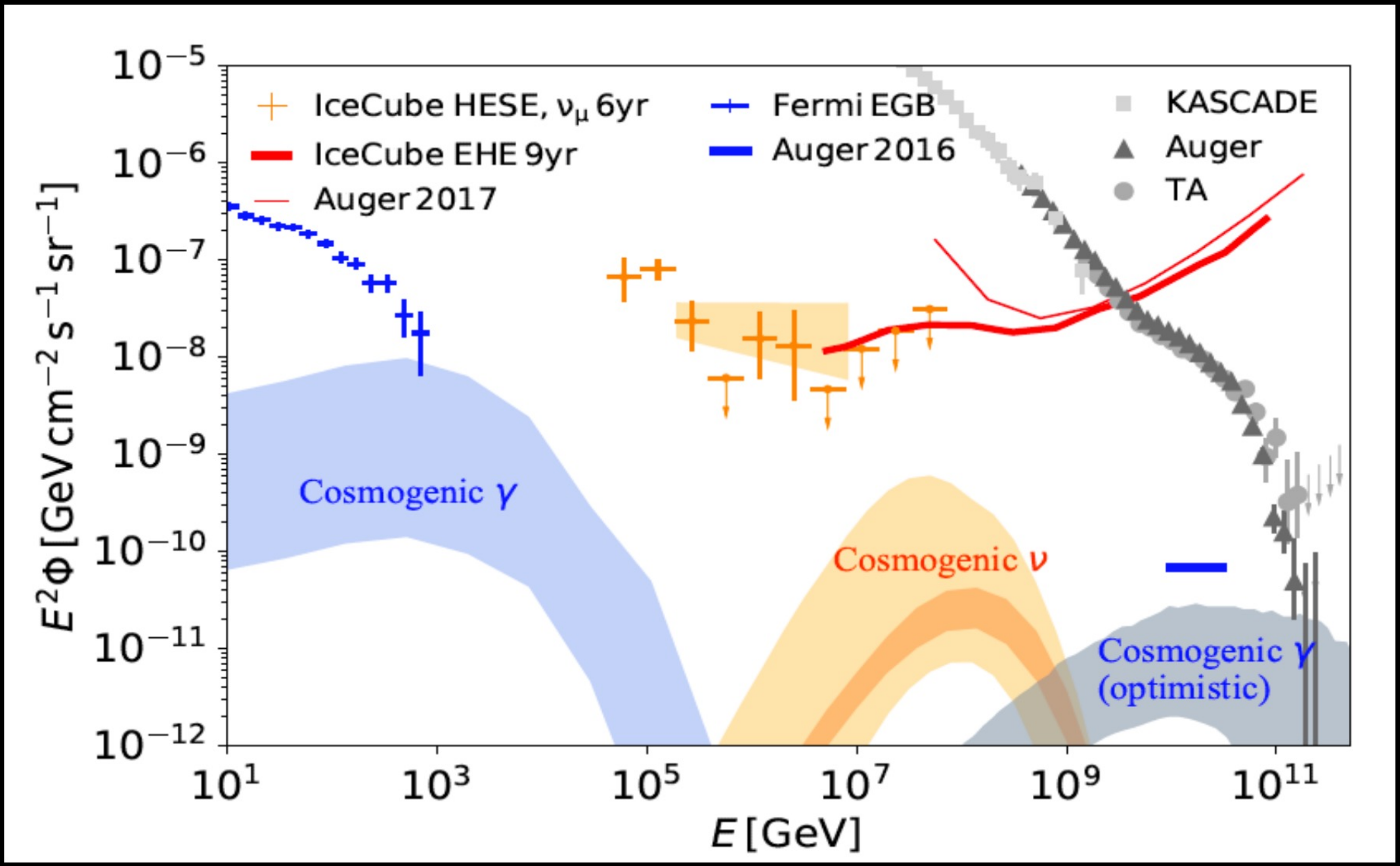
IceCube-170922



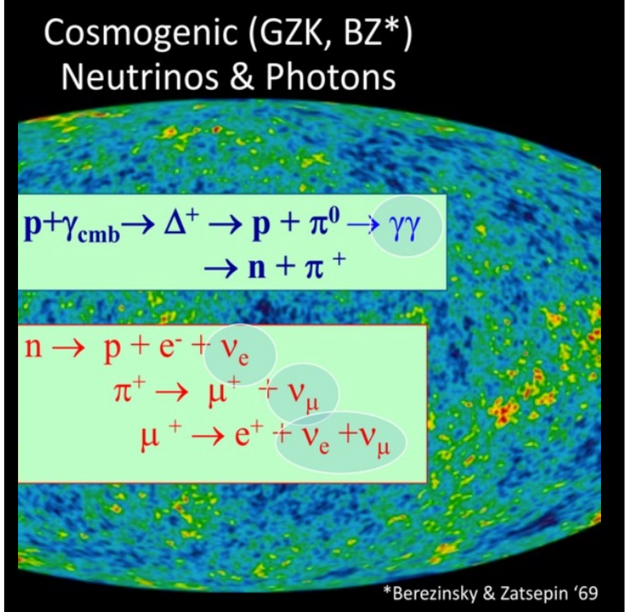
"Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A", The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, 2018

A. Olinto @ Snowmass"Blue Sky" session

Cosmogenic Neutrinos



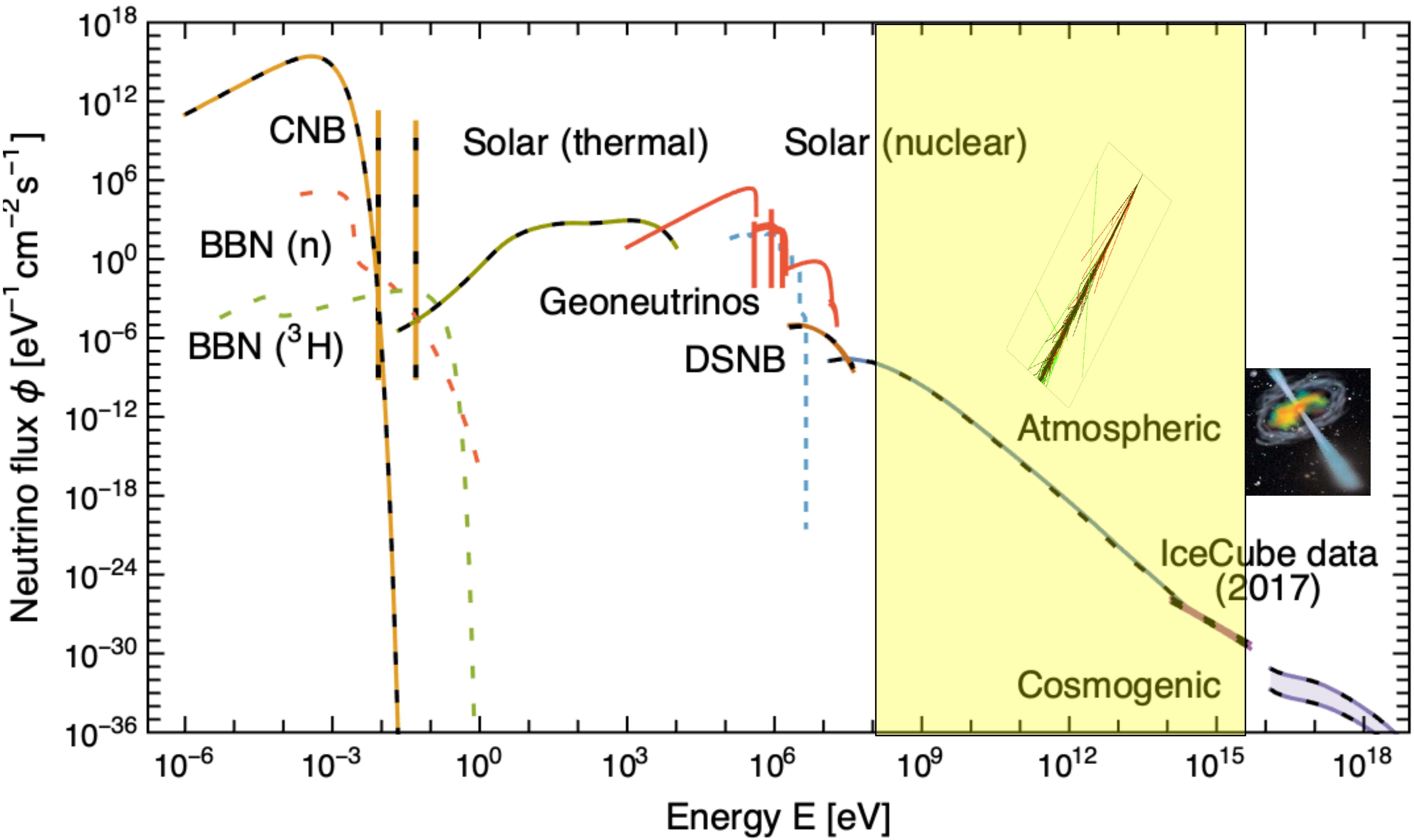
Batista et al, arXiv:1903.06714.pdf



Multiple programs going after these

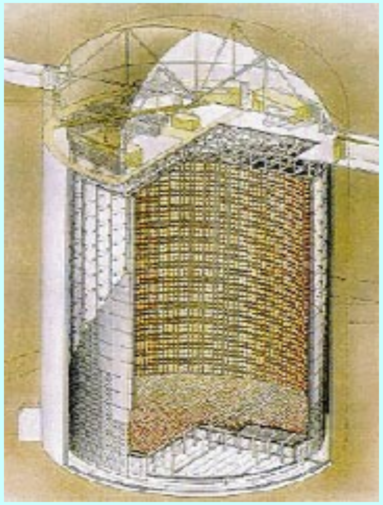
A. Olinto @ "Blue Sky" session

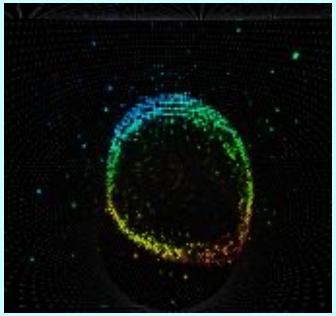
GeV-TeV scale: inhabited by atmospheric neutrinos



Large (multi-kton) detector technologies for ~GeV scale

Water Cherenkov

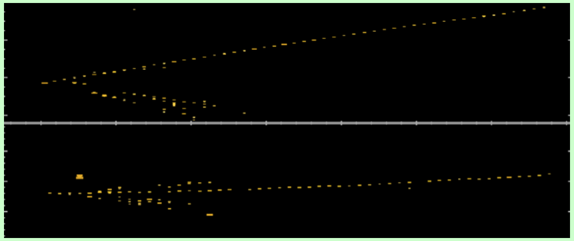




Cheap material, proven at very large scale

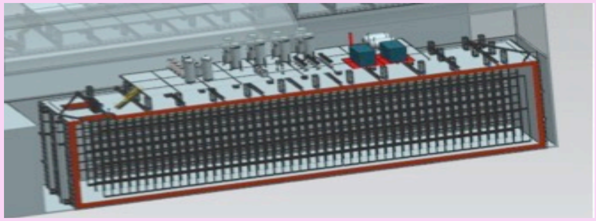
Trackers

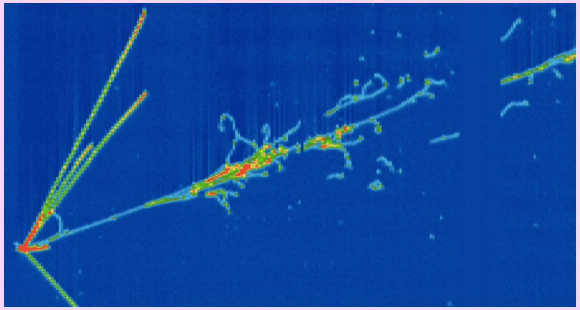
(a diverse category)



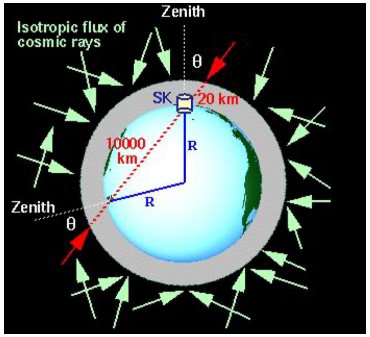
Good particle reconstruction

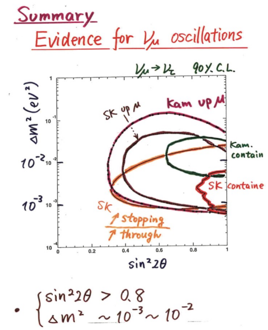
Liquid Argon Time Projection Chamber





Excellent particle reconstruction

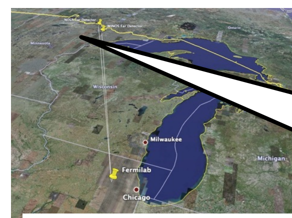




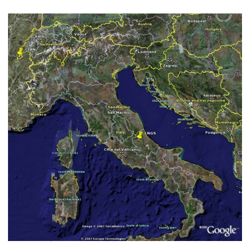
Water & tracking detectors made the original atmospheric neutrino oscillation measurements, and are now combined w/beams...

K2K
KEK to Kamioka

MINOS (+)
FNAL to Soudan

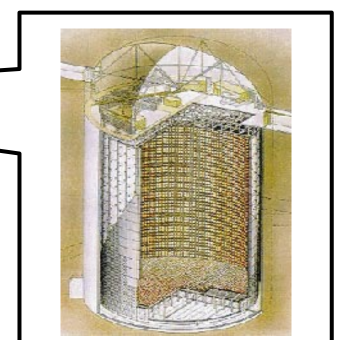


NOνA
FNAL to Ash River



CNGS
CERN to LNGS

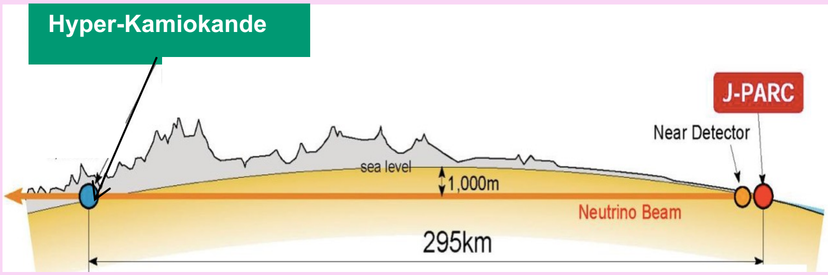
T2K
J-PARC to Kamioka



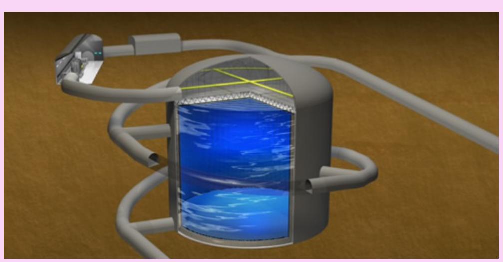
...they make good neutrino telescopes too!

Next-generation long-baseline beam experiments

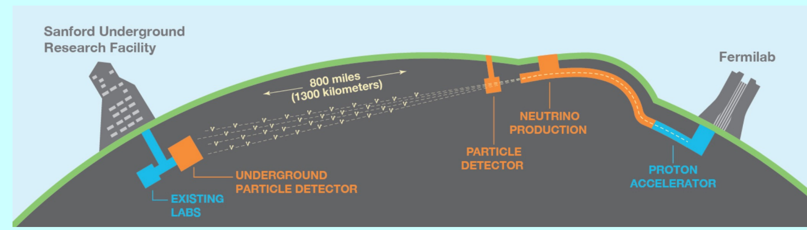
Hyper-Kamiokande



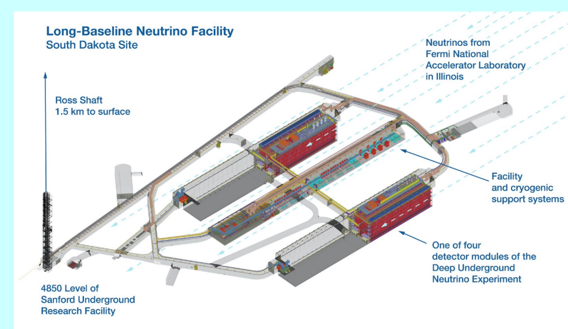
- 295-km baseline
- 260k (188k) ton mass water Cherenkov detector
- First data in 2027



DUNE/LBNF

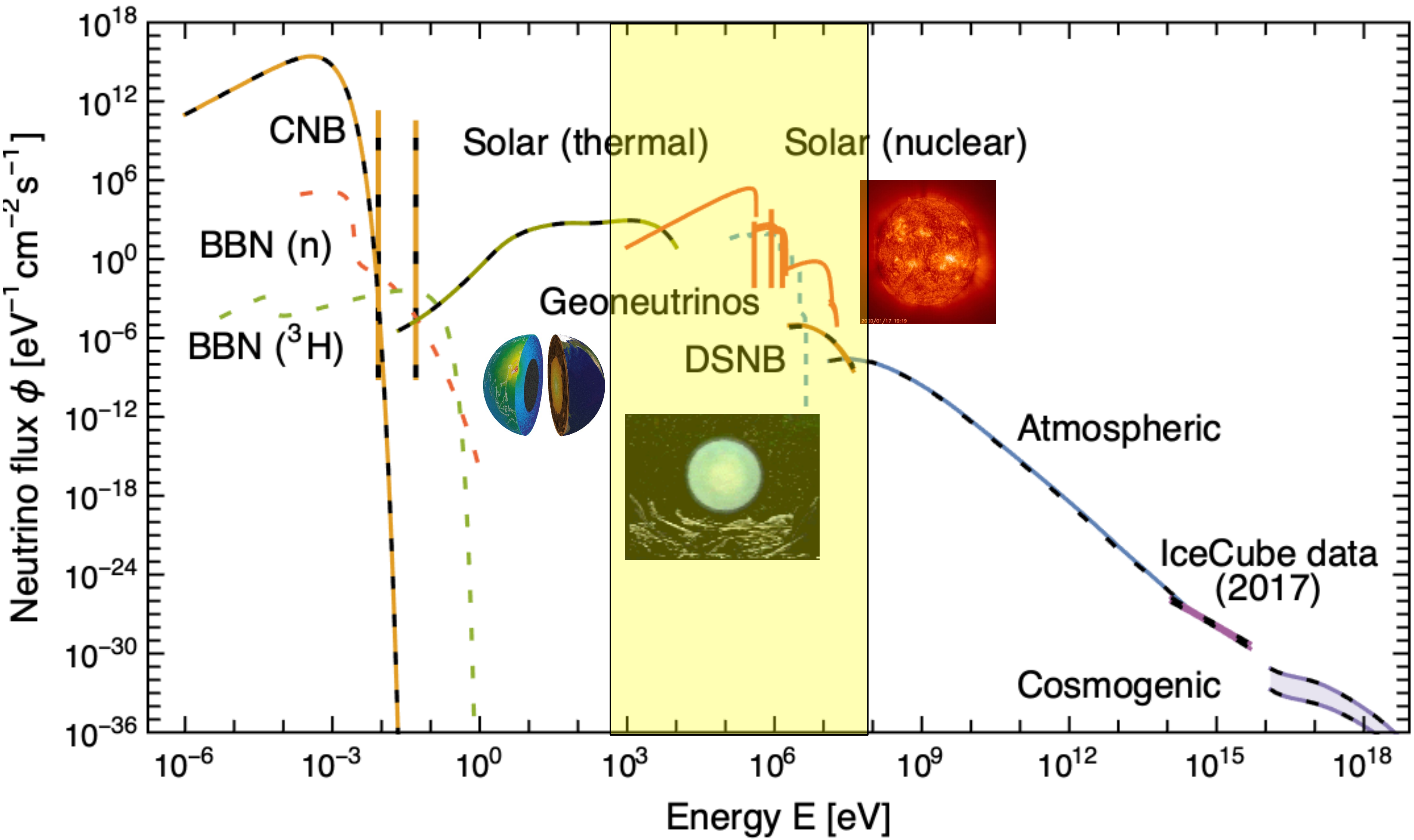


- 1300-km baseline
- 4 10-kton LArTPC modules
- 4850-ft depth
- Phase 2 "Module of Opportunity" for 3&4



Multi-purpose detectors, broad physics programs in both cases, including astrophysical neutrinos (over a range of energies)

Now moving down in energy to the few-100 MeV scale



The standard disclaimer...

Multi-messenger astronomy

Neutrino astrophysics

A "flight" of examples

The standard disclaimer...

Multi-messenger astronomy

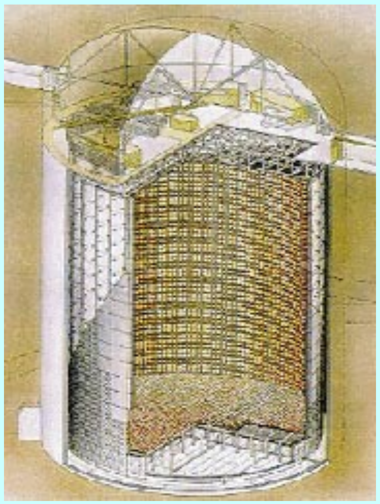
Neutrino astrophysics

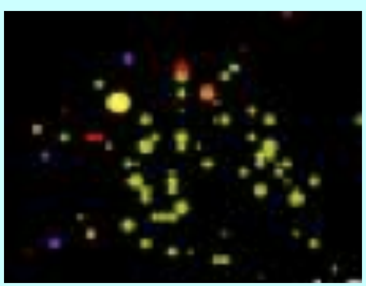
Having a bit more of my favorite...

A "f

Large detector technologies for low energies

Water Cherenkov

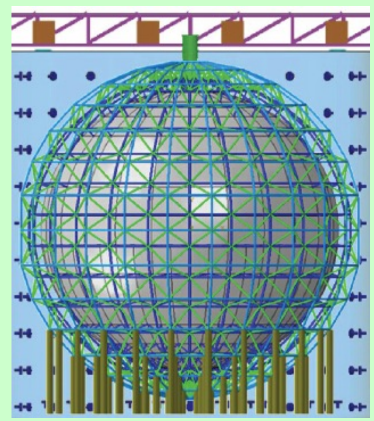


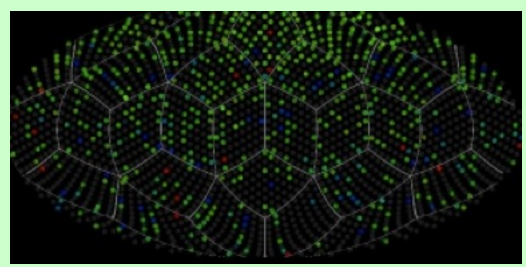


- Cheap, large
- Good directionality
- Low light yield

Liquid scintillator

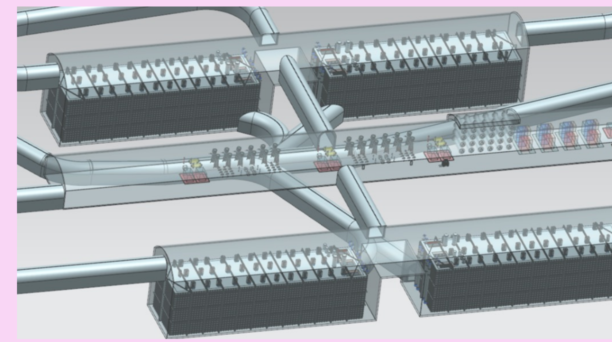
(and water-based LS, hybrid Ch/scintillation)





- High light yield → low threshold, good energy resolution
- Poor directionality

Liquid Argon Time Projection Chamber



- Ionization + scintillation
- Good directionality

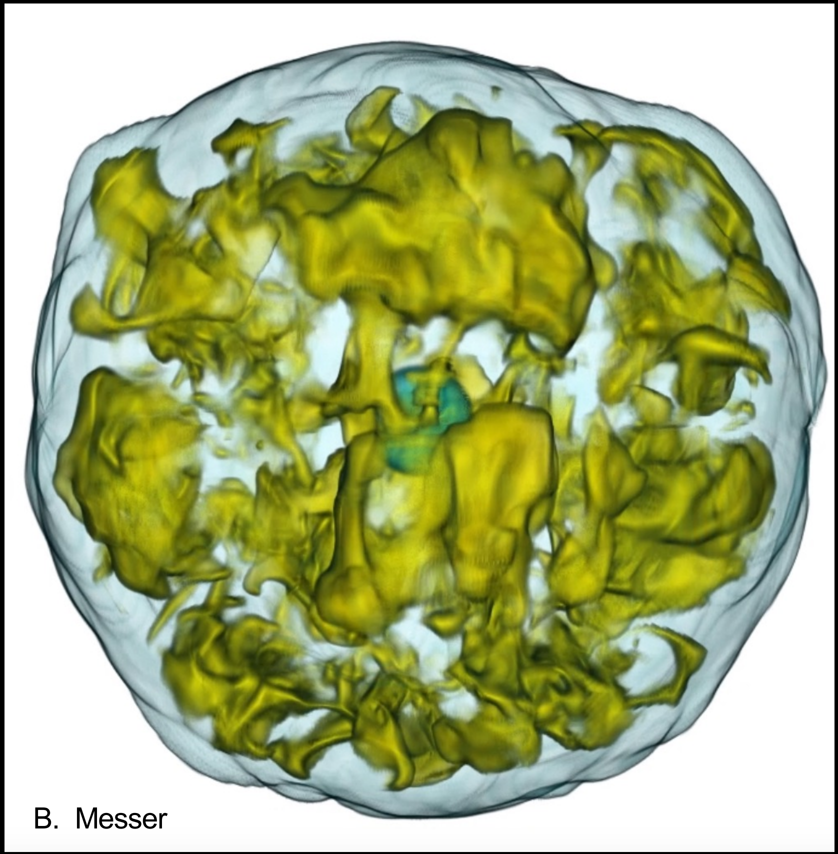
Generally limited by efficiency & background at ~MeV scale

Neutrinos from core-collapse supernovae

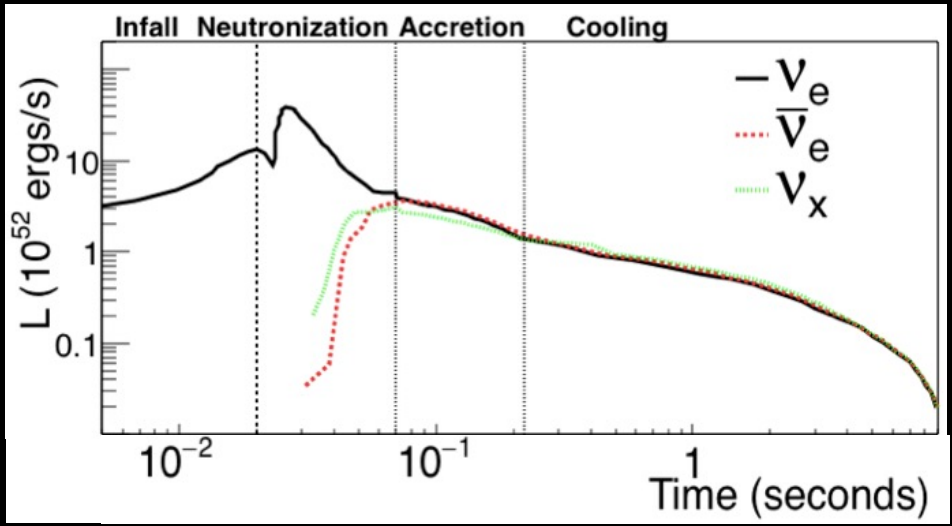
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

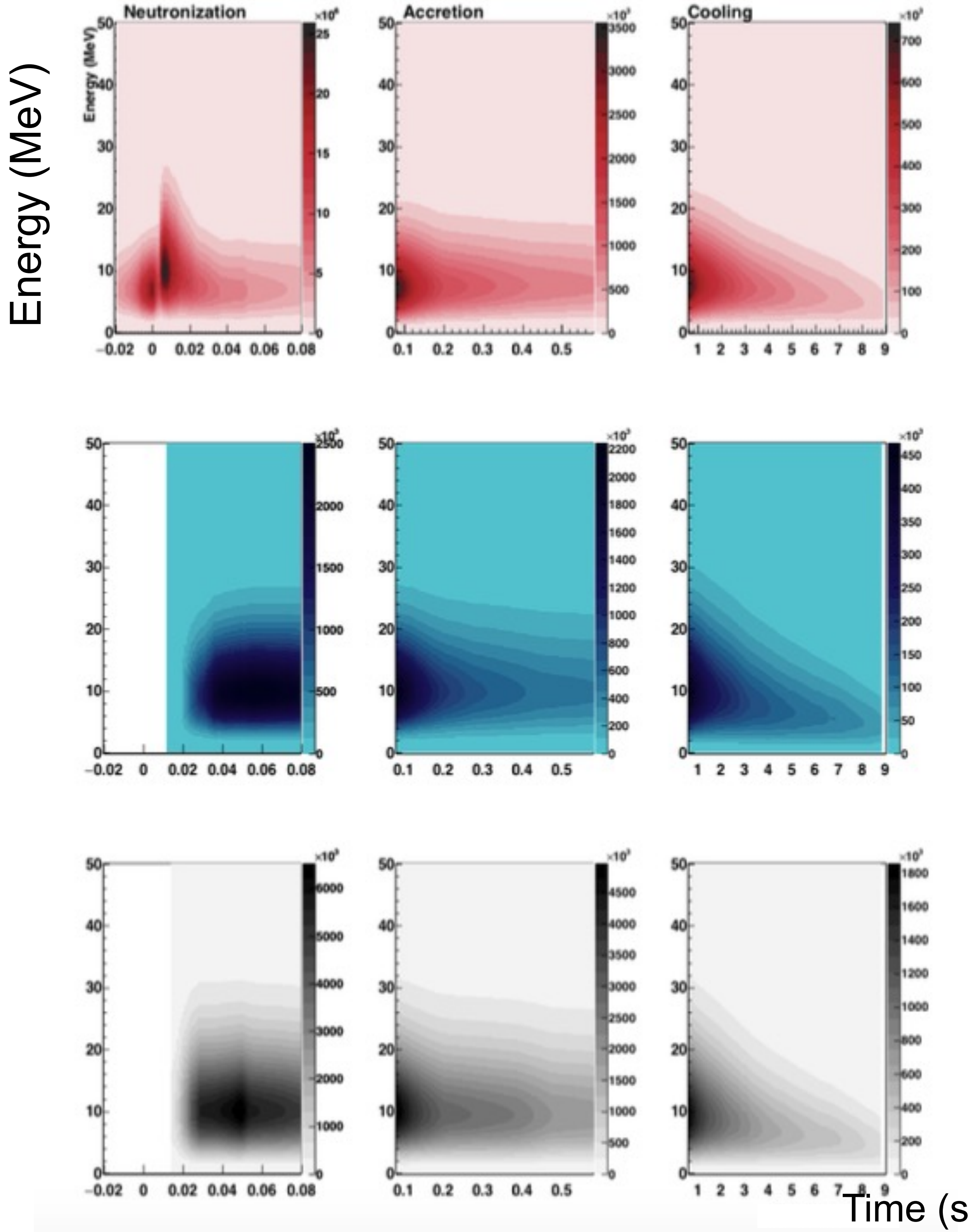
Mostly ν-νbar pairs from proto-nstar cooling



Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Fluxes as a function of time and energy



ν_e

$\bar{\nu}_e$

ν_x

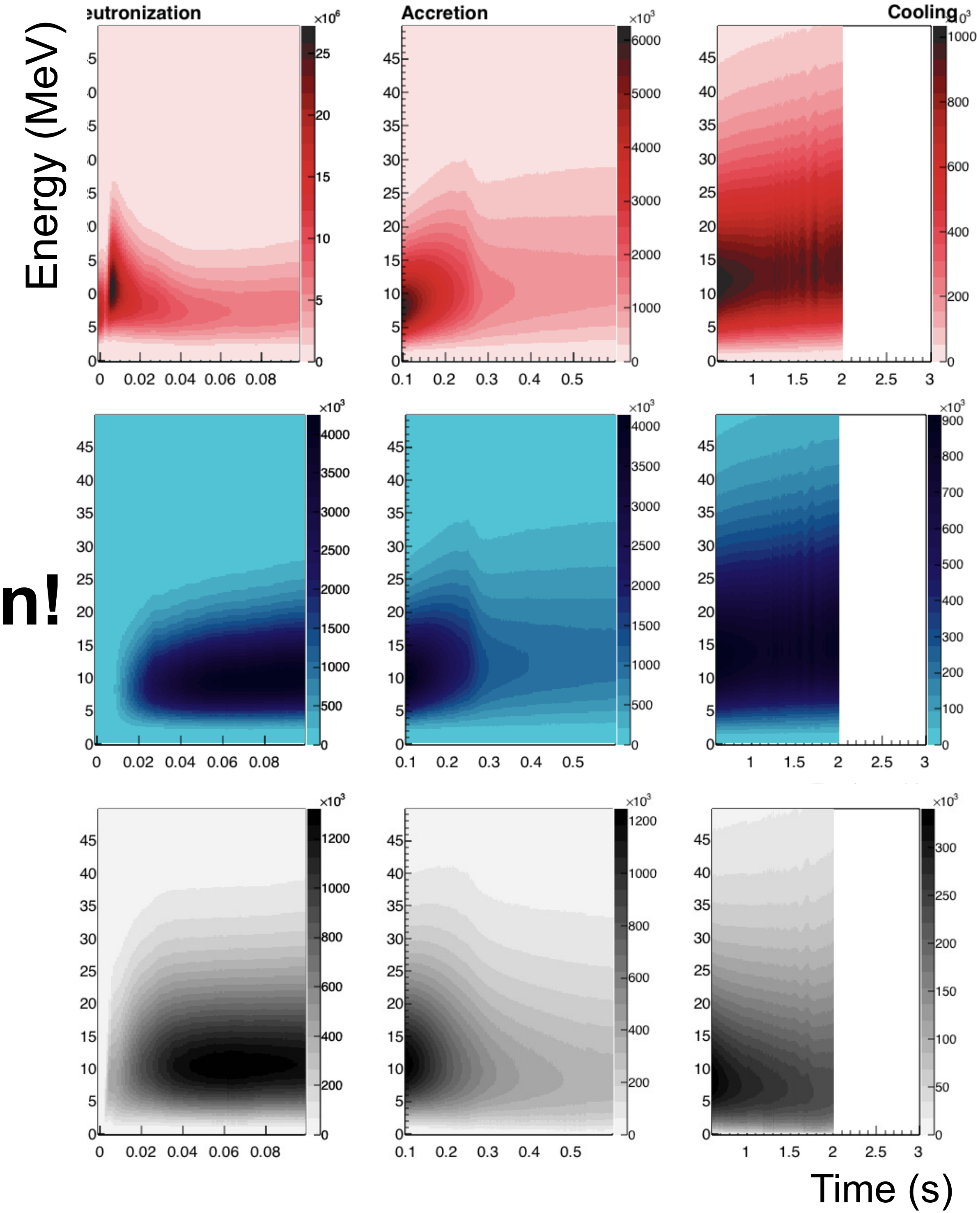
$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$

Neutrinos per cm^2 per bin (per ms per 0.5 MeV)

Another example of a model

…

black hole formation!



$$\nu_e$$

$$\bar{\nu}_e$$

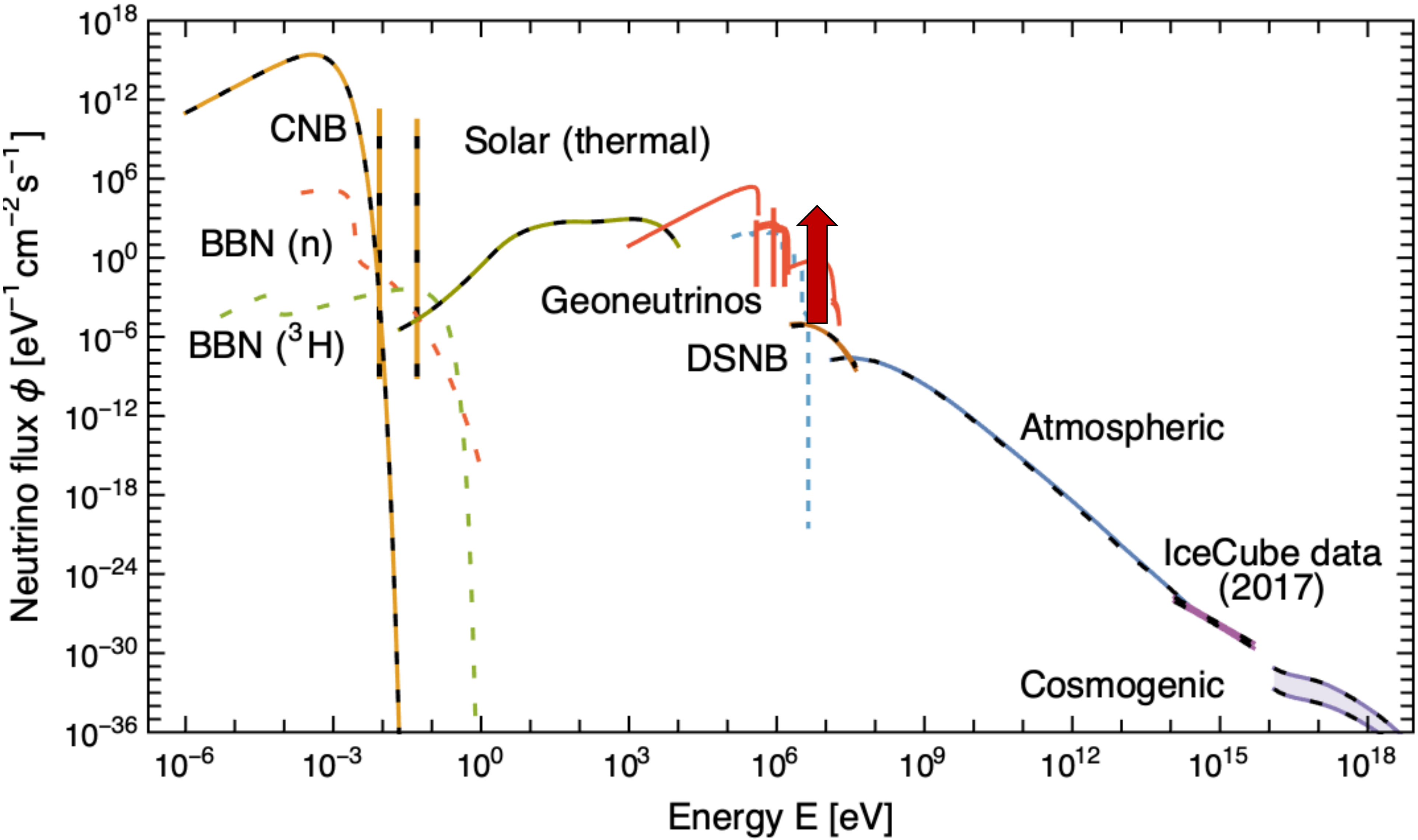
$$\nu_x$$

$$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$$

Model by L. Huedepohl

On this flux plot, for ~10 seconds,

diffuse supernova neutrino background x 10^{9} - 10^{10} !



Supernova neutrino detector types

Water

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

Water, long-string

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

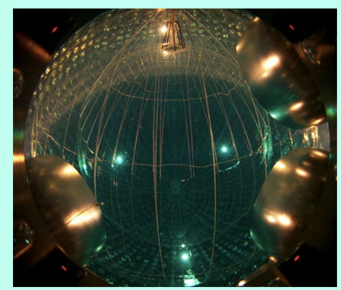
$\bar{\nu}_e$

Argon

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

ν_e

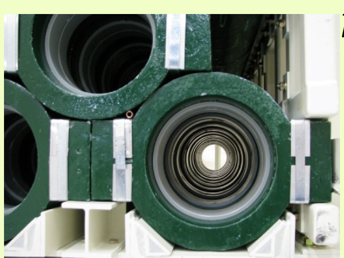
Scintillator



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$\bar{\nu}_e$

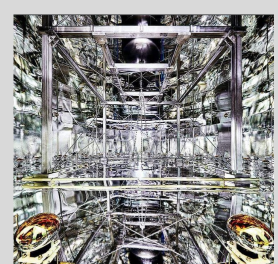
Lead



$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

ν_e

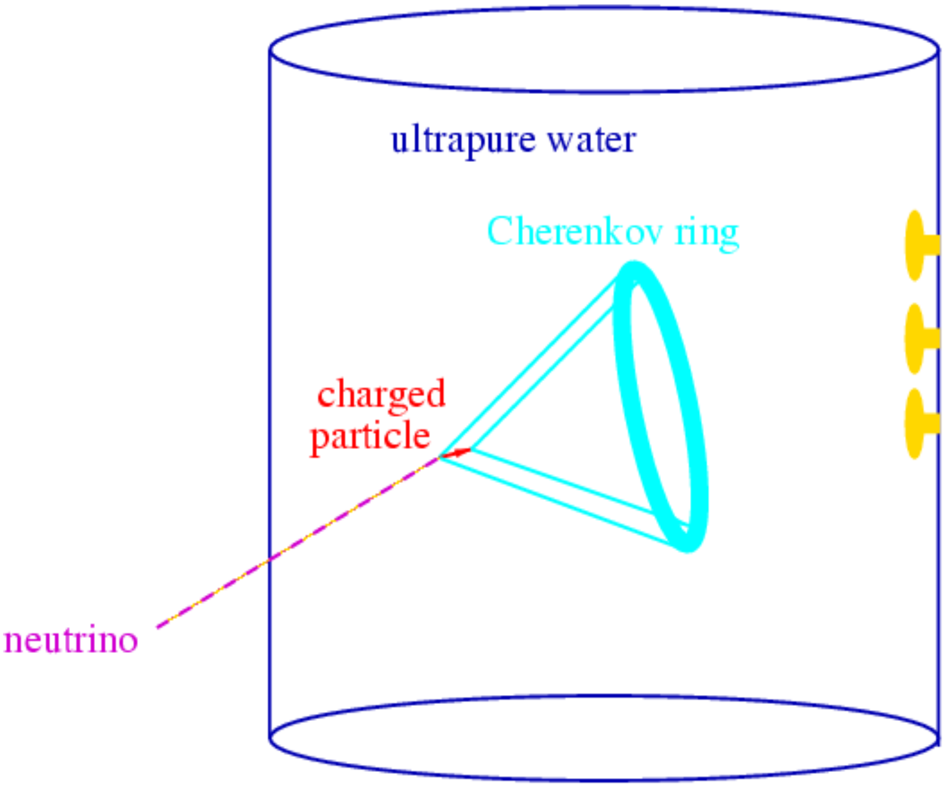
DM (Noble liquid)



$$\nu_x + \mathrm{A} \rightarrow \nu_x + \mathrm{A}$$

ν_x

Water Cherenkov detectors

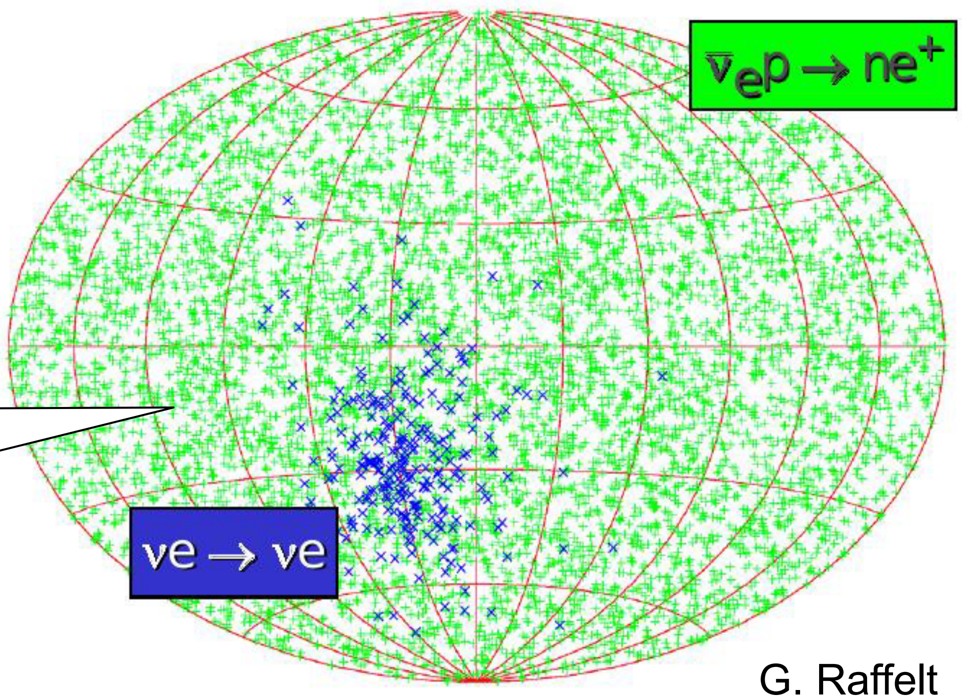


Inverse Beta Decay (CC)

$\bar{\nu}_e + p \rightarrow e^+ + n$ **dominates**

E_{thr}=1.8 MeV

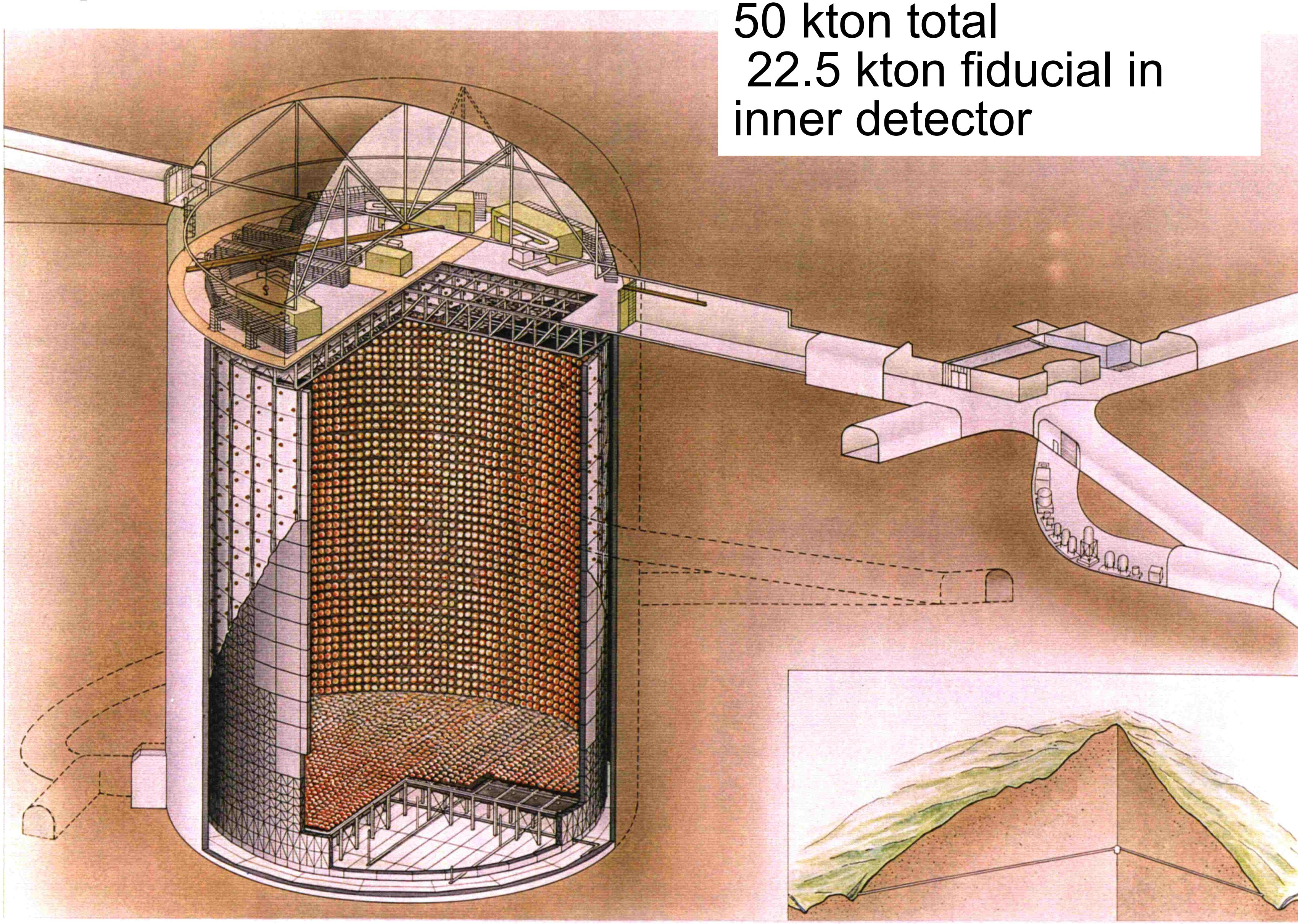
Pointing from neutrino-electron elastic scattering



G. Raffelt

Super-Kamiokande

50 kton total
22.5 kton fiducial in
inner detector



SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO

NIKKEN SEKKEI
planners | architects | engineers

Neutron tagging in water Cherenkov detectors

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

detection of neutron tags event as *electron antineutrino*

- especially useful for diffuse SN signal (which has low signal/bg)
- also useful for disentangling flavor content of a burst

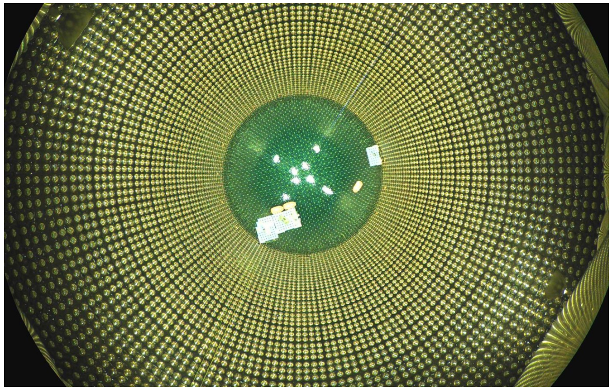
  (improves pointing, and physics extraction)

use gadolinium to capture neutrons **(like for scintillator)**

J. Beacom & M. Vagins, PRL 93 (2004) 171101

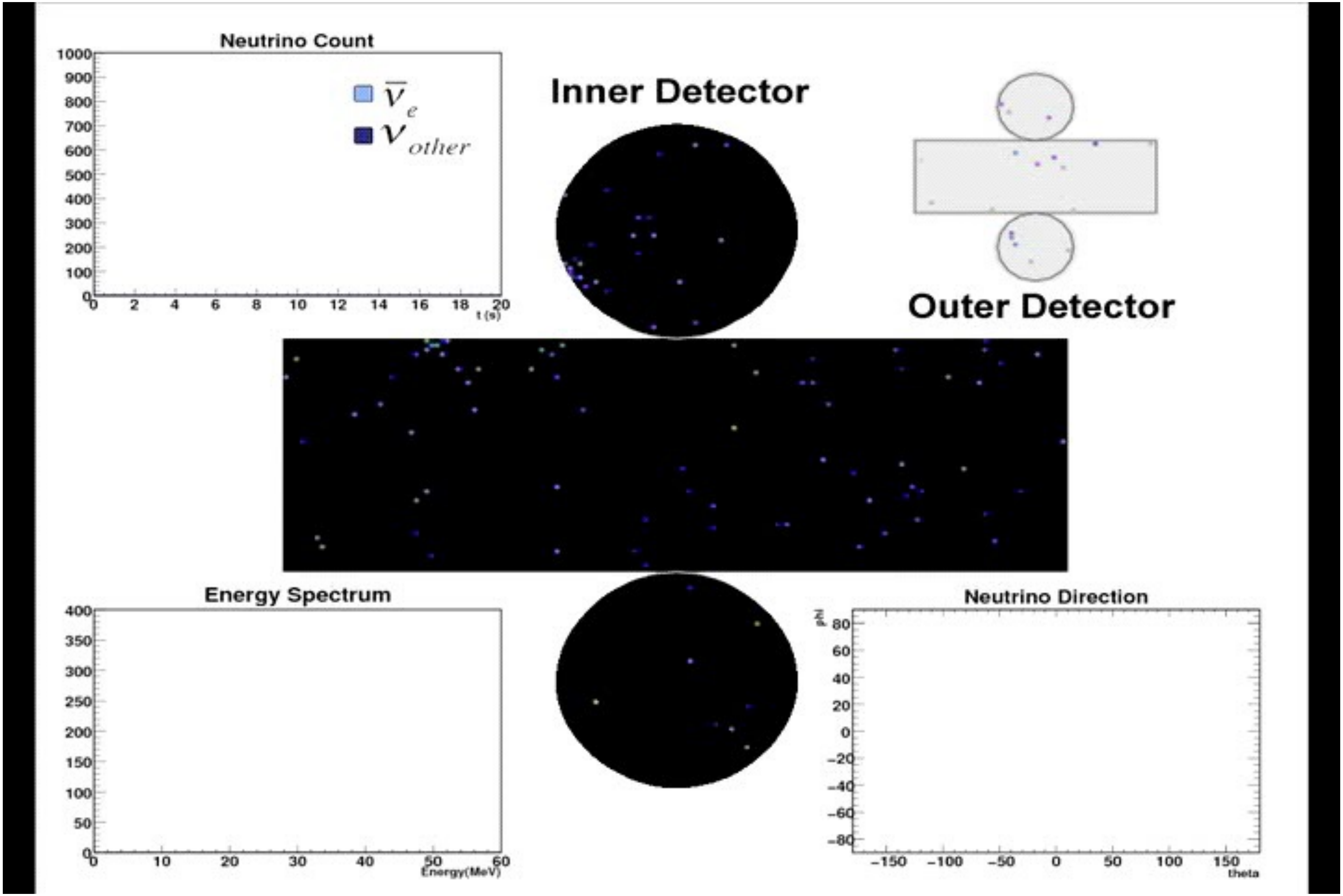
Gd has a huge n capture cross-section:
49,000 barns, vs 0.3 b for free protons

$$n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma \qquad \sum E_\gamma = 8\,MeV$$



SK-Gd is running with 0.01% Gd

(13.2 tons of $Gd_2(SO_4)_3{*}8H_2O$)



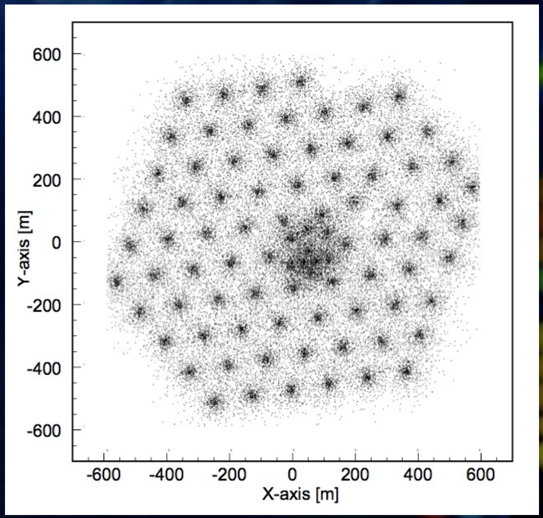
http://snews.bnl.gov/snmovie.html

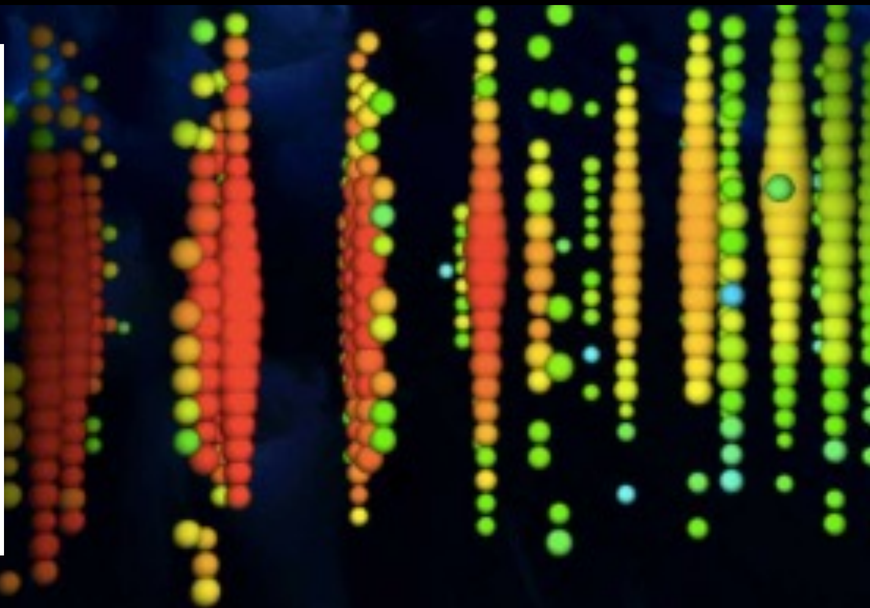
Long string water Cherenkov detectors

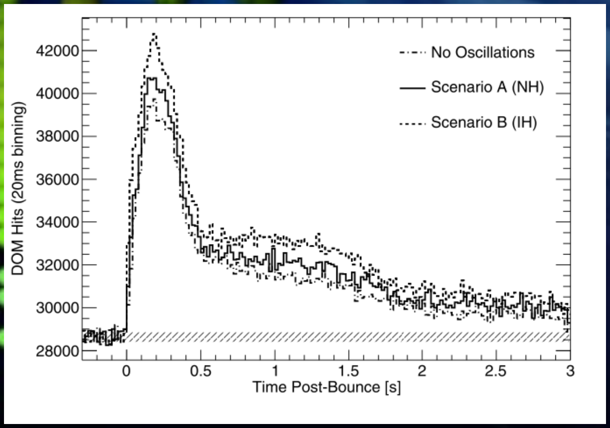
~kilometer long
strings of PMTs
in very clear water
or ice (IceCube, KM3NeT)

Nominally multi-GeV energy threshold...
but, may see burst of low energy (anti-) ν_e's as
coincident increase in single PMT count rate

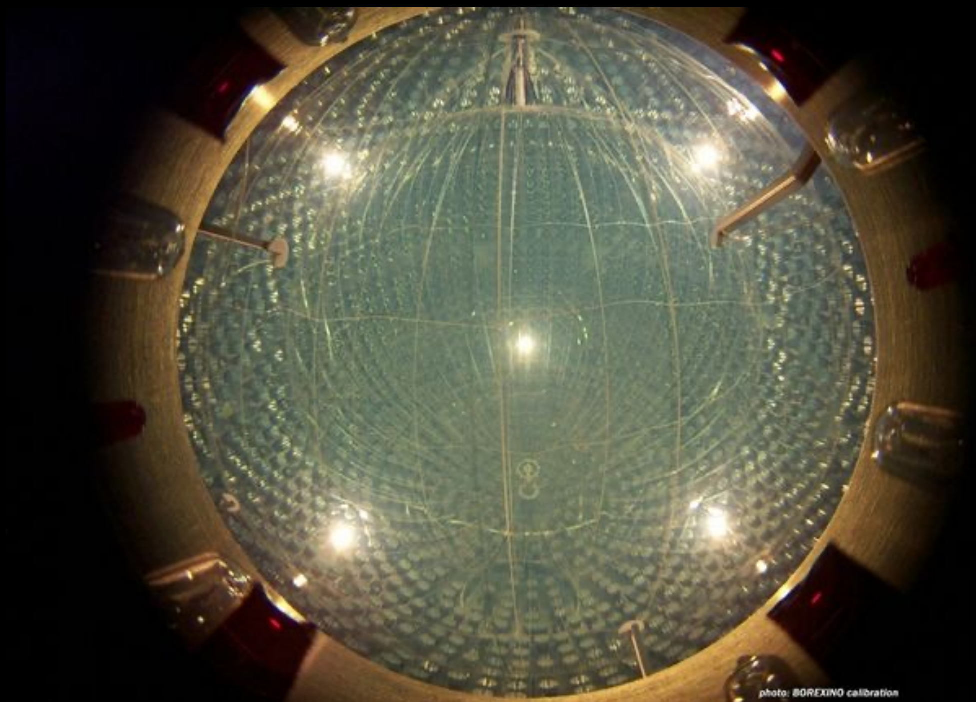
Map overall time structure of burst by tracking the single-PMT hit glow







Scintillation detectors

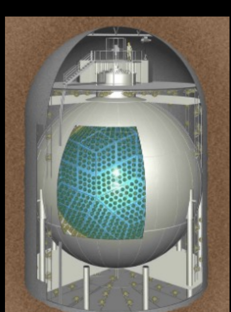


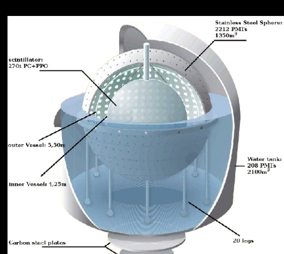
Liquid hydrocarbon (C_nH_{2n}) that emits (lots of) photons when charged particles lose energy in it

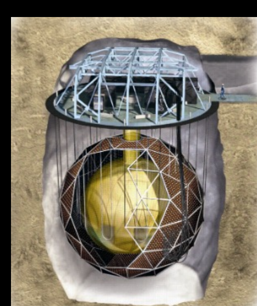
Will see supernova **electron antineutrinos**, with good energy resolution

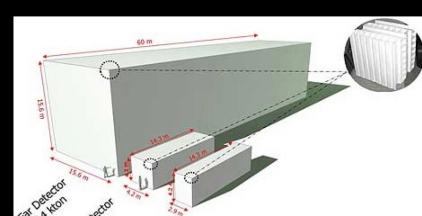
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Many examples worldwide of current and future detectors

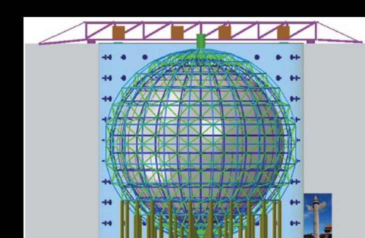




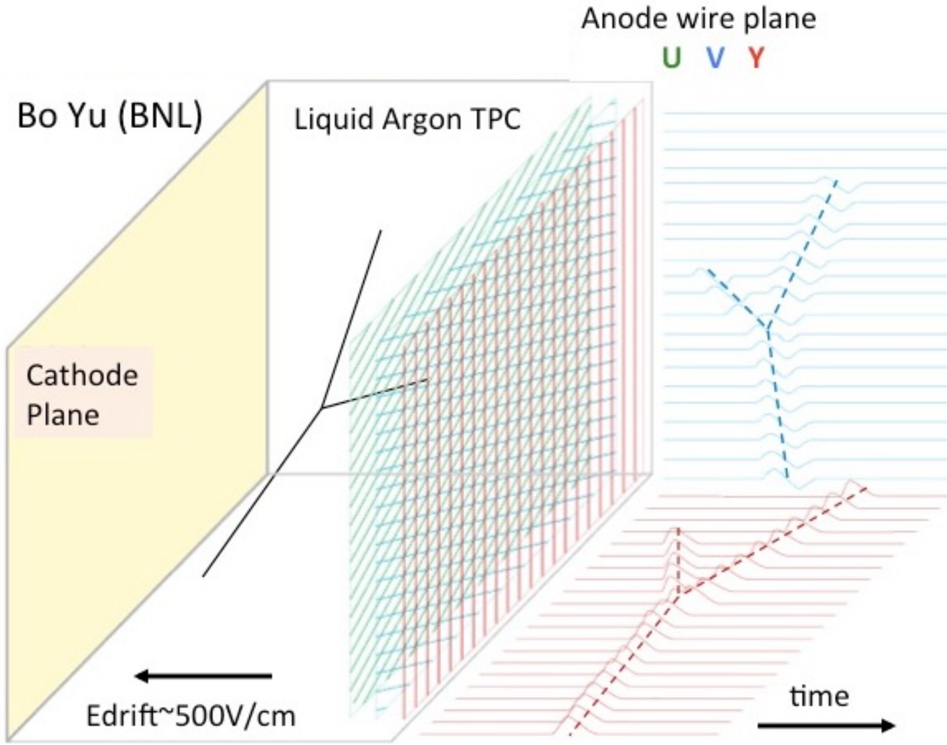




JUNO, 20 kt



Liquid argon time projection chambers



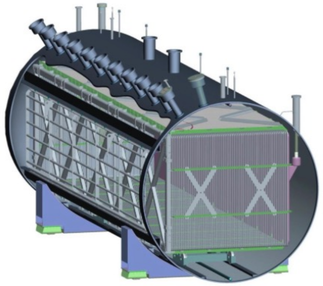
fine-grained trackers
ionization + scintillation photons

sensitive to **electron neutrinos**
(as opposed to antineutrinos)

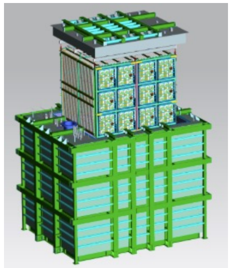
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

ICARUS
(Italy➔USA)
0.6 kton

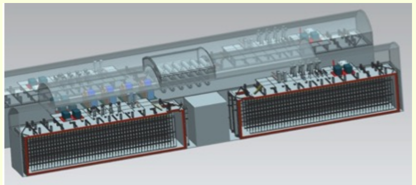
MicroBooNE
(USA)
0.2 kton



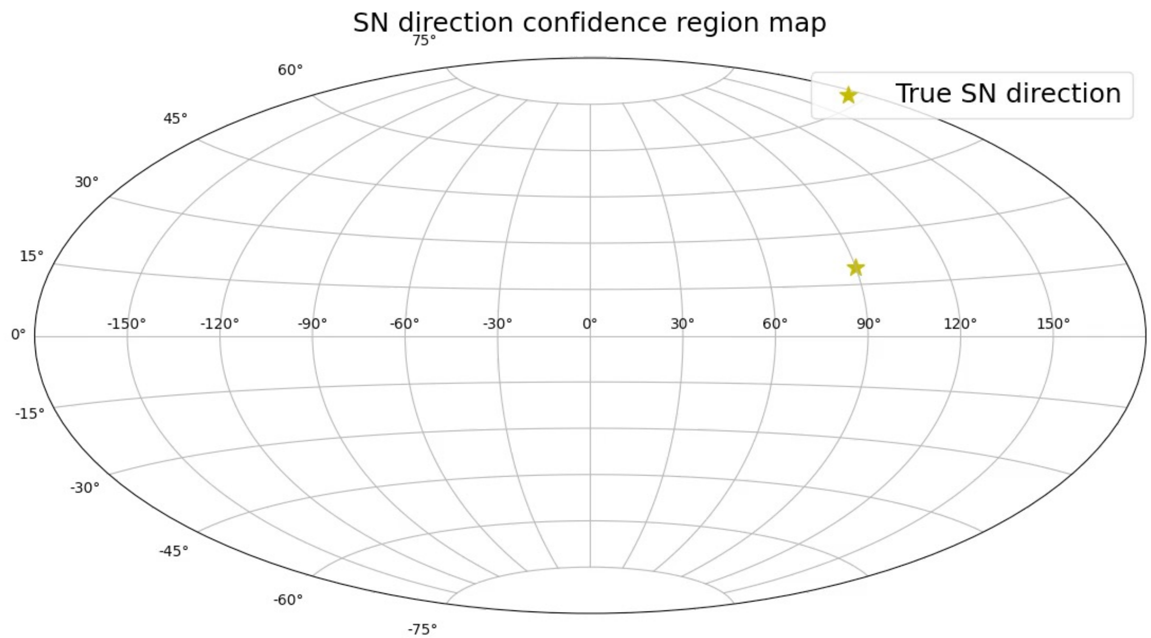
SBND
(USA)
0.112 kton

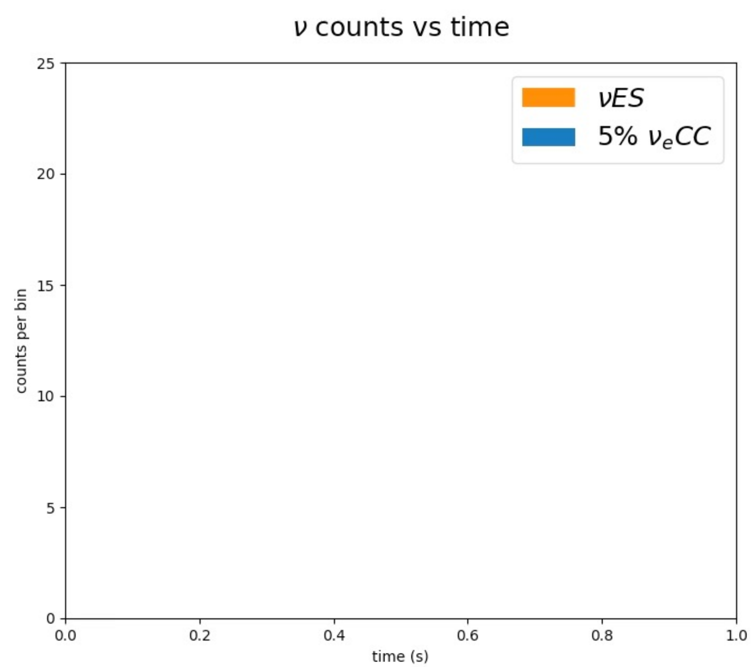


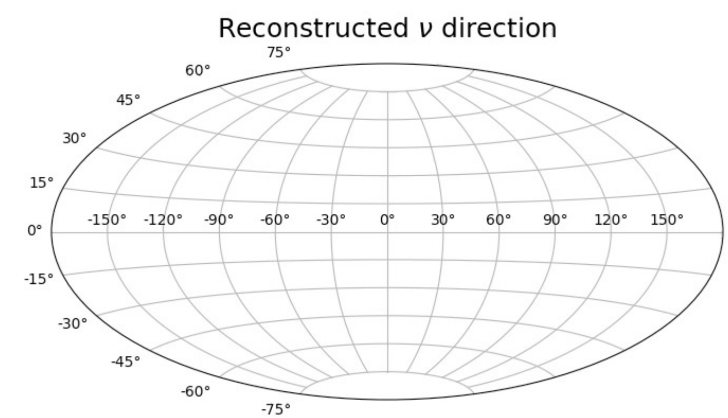
DUNE
(USA)
40 kton



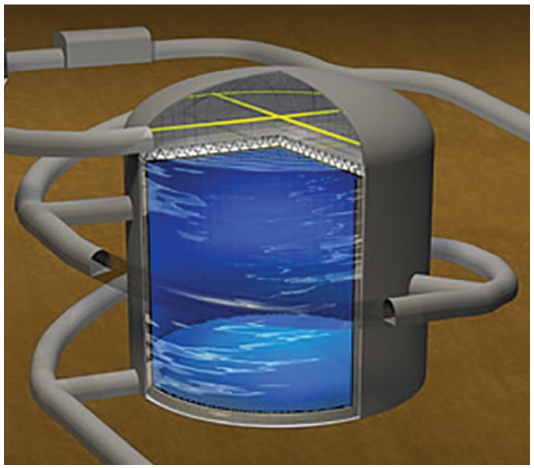
By Joshua Queen



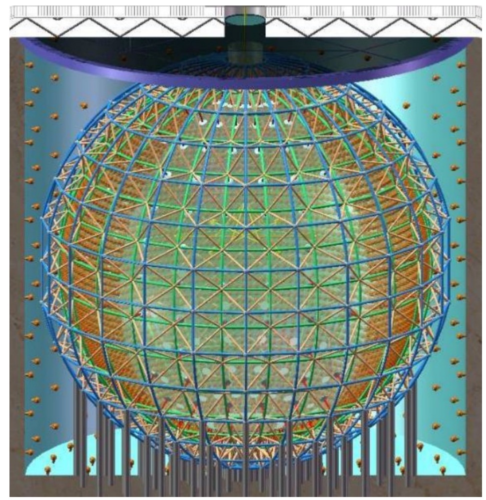




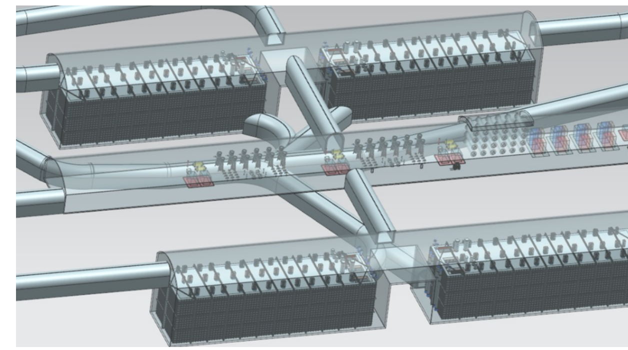
Future Large Supernova-Burst-Sensitive Neutrino Detectors



Hyper-Kamiokande
260 kton water
Japan



JUNO
20 kton scintillator (hydrocarbon)
China



DUNE
40 kton argon
USA

- Hyper-K /JUNO are primarily sensitive to **nuebar**

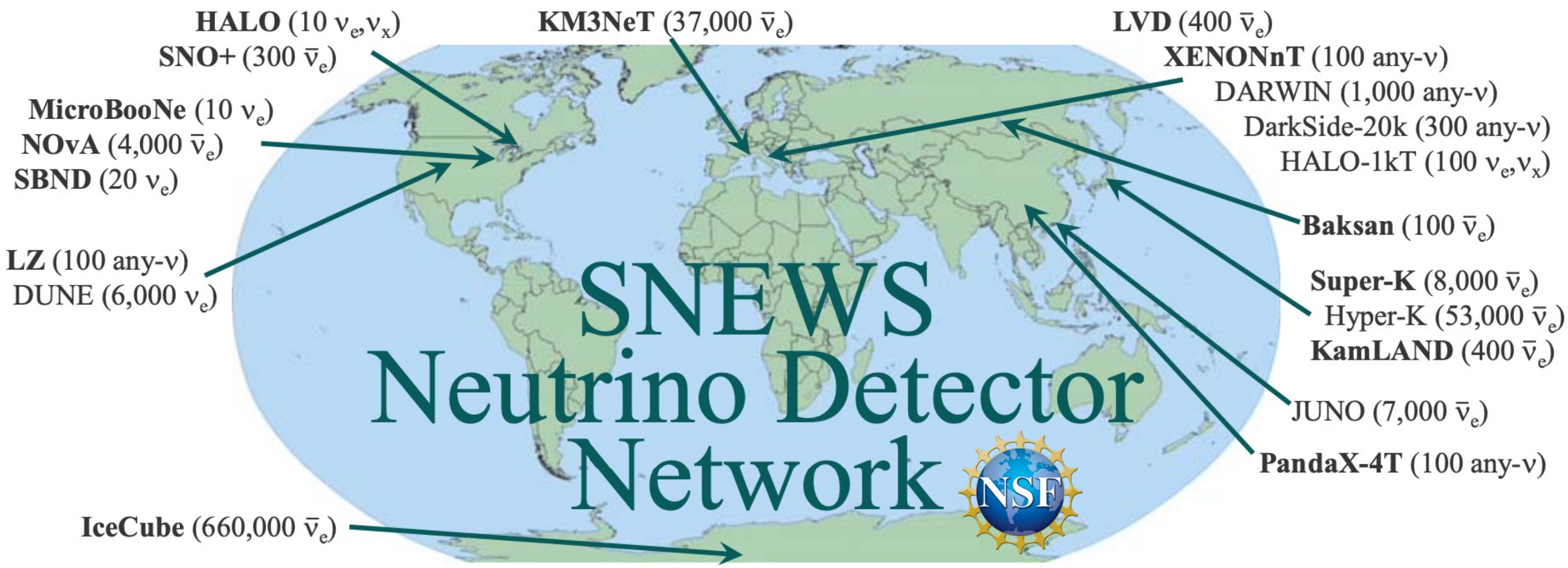
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- DUNE is primarily sensitive to **nue**

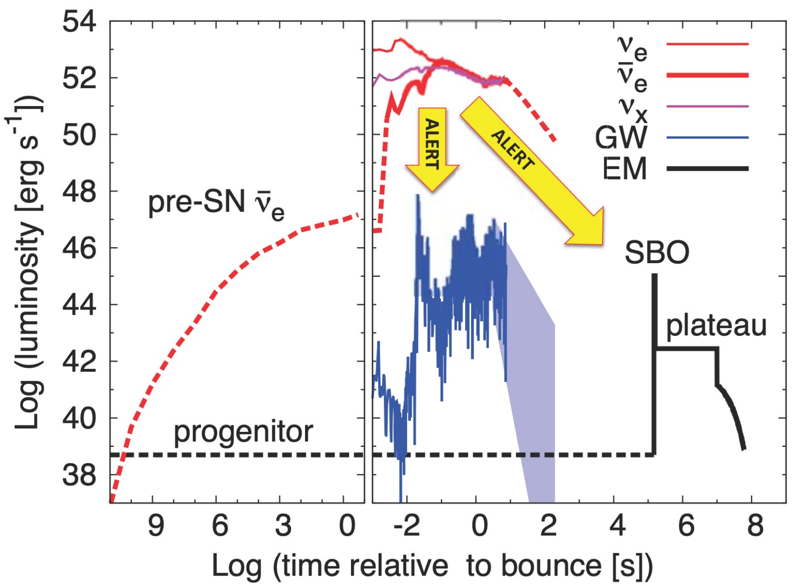
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

extreme *complementarity*

In general, the whole is more than the sum of the parts for multi-messenger astronomy

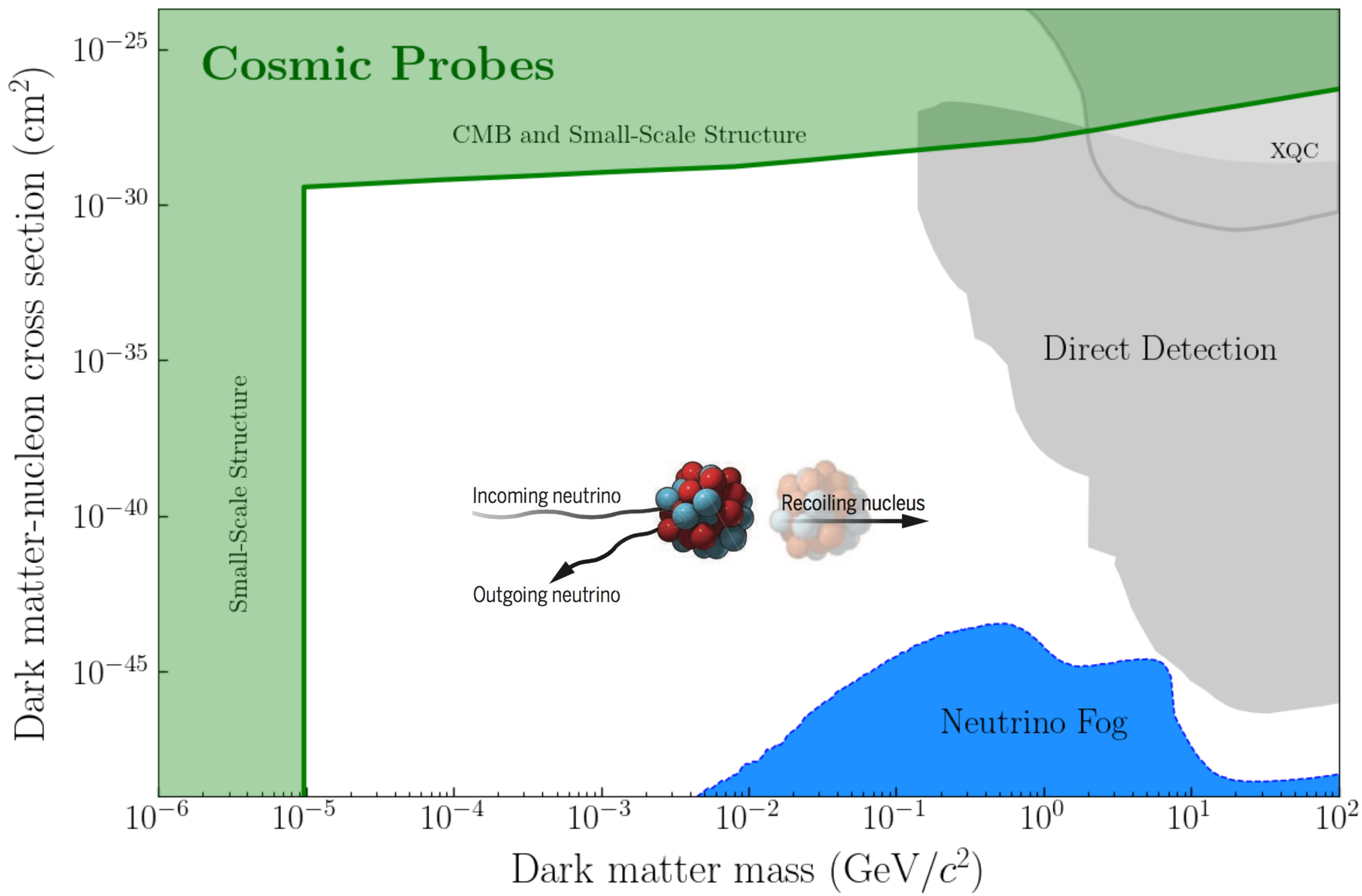


K. Nakamura et al., MNRAS 2016



Neutrinos arrive earlier than the first light from a supernova... combine signals for a high-confidence prompt alert, enabling more physics & astrophysics

Dark matter detectors as **neutrino observatories**

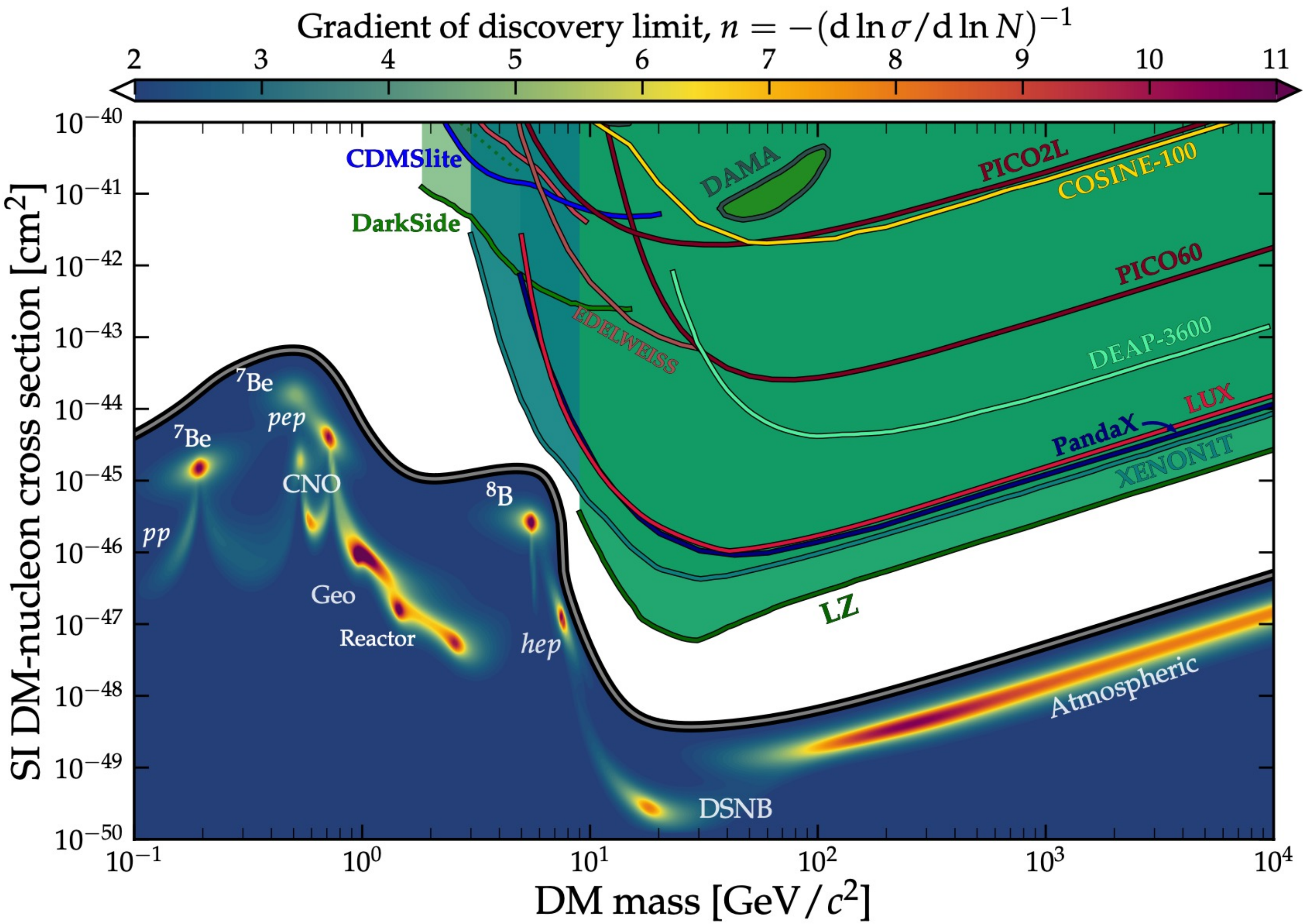


Plot from Snowmass CF01

Image: J. Link *Science* Perspectives

Once nuclear recoil detectors get sensitive enough, they are blinded by natural neutrinos

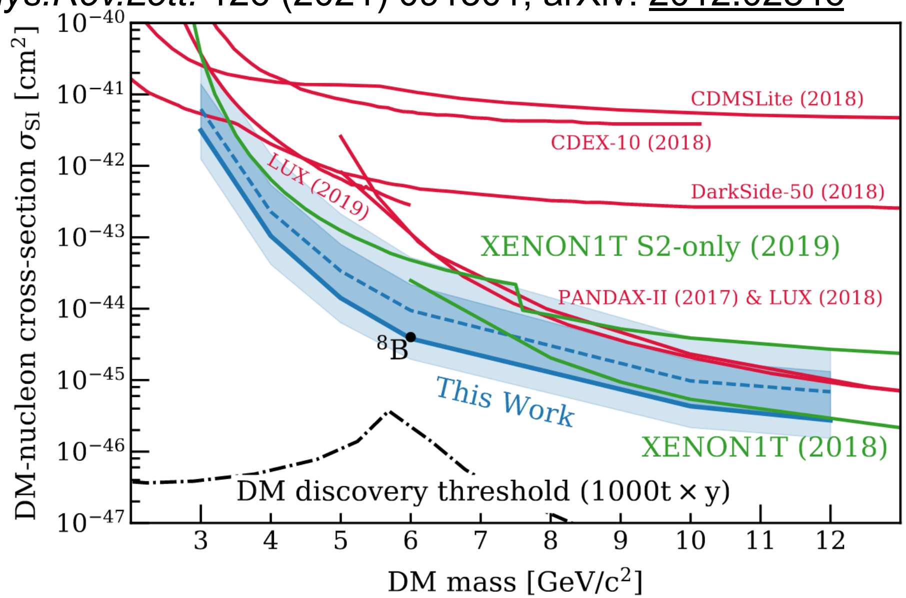
Interesting things may eventually emerge from the fog...

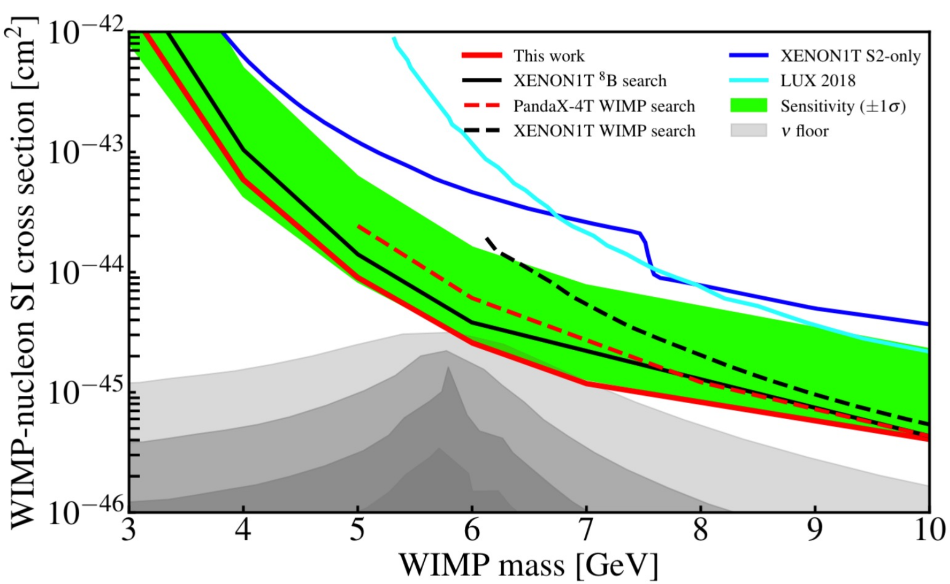


O'Hare [2109.03116]

Search for CEvNS from **solar neutrinos** with the XENON-1T experiment

Phys.Rev.Lett. 126 (2021) 091301, arXiv: 2012.02846

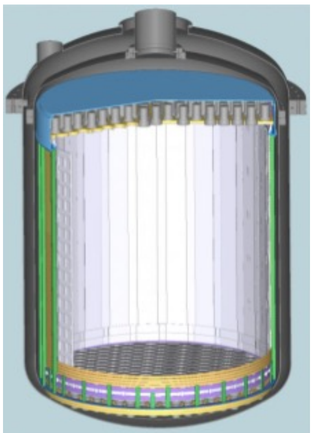


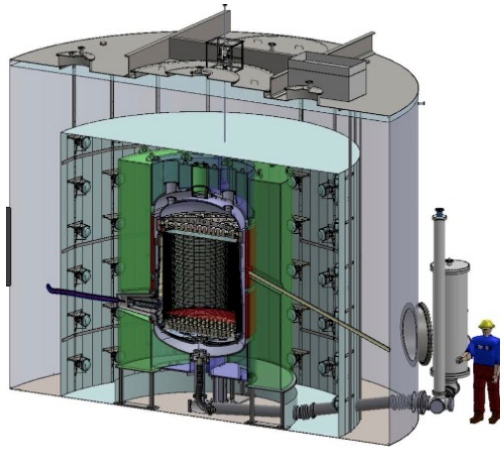


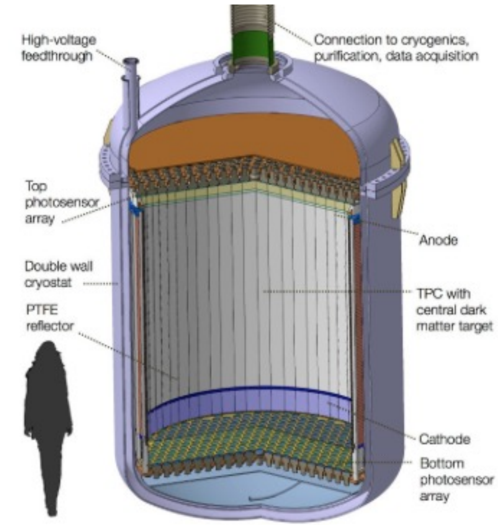
PANDA-X arXiv:2207.04883

Limits only so far
... but eventually we'll
see the glare

Supernova **burst** detection in large DM detectors

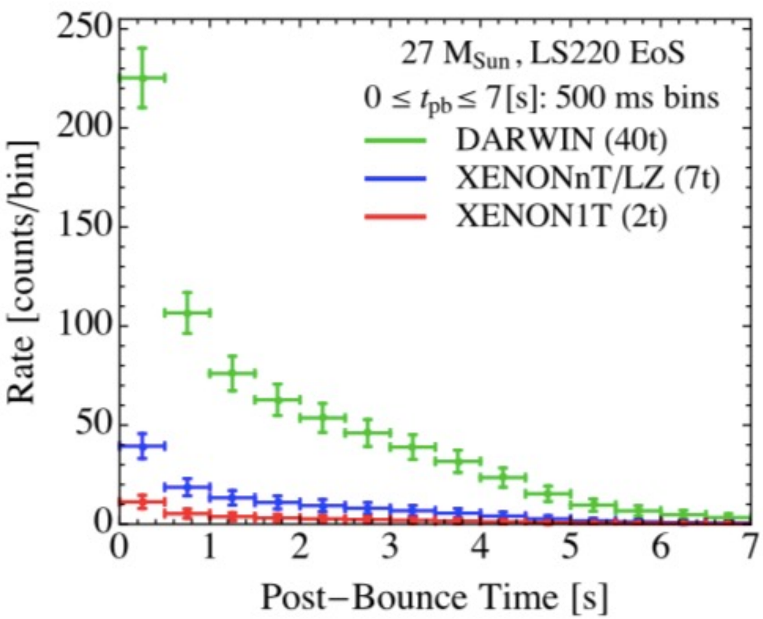


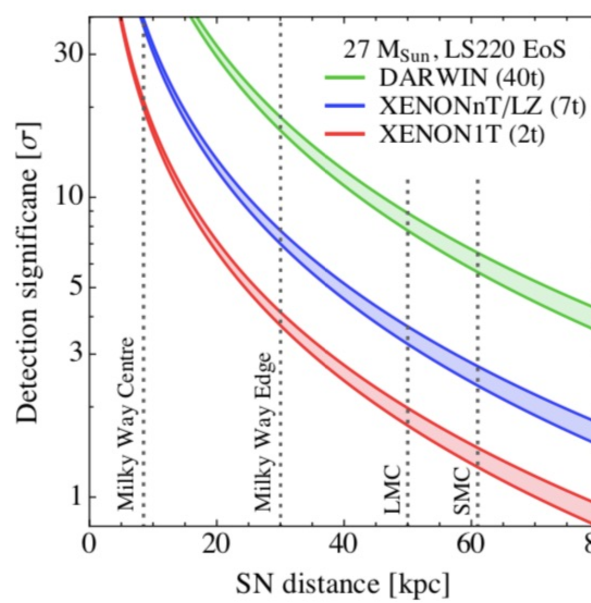


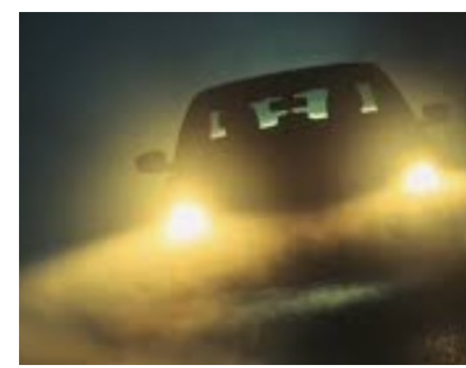


Example: dual-phase xenon time projection chambers

DARWIN





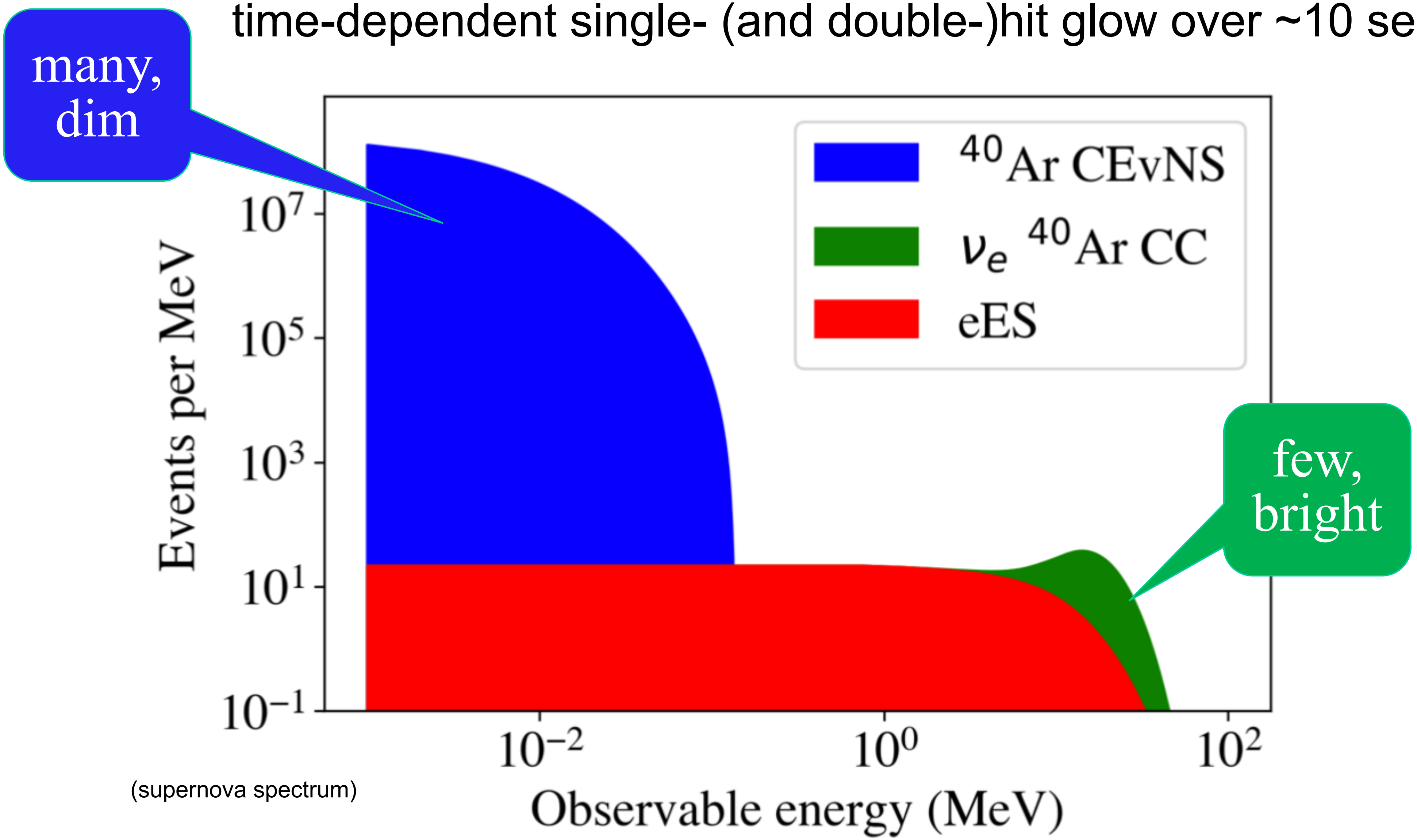


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

Also: DarkSide-20K, ARGO, RES-NOvA,...

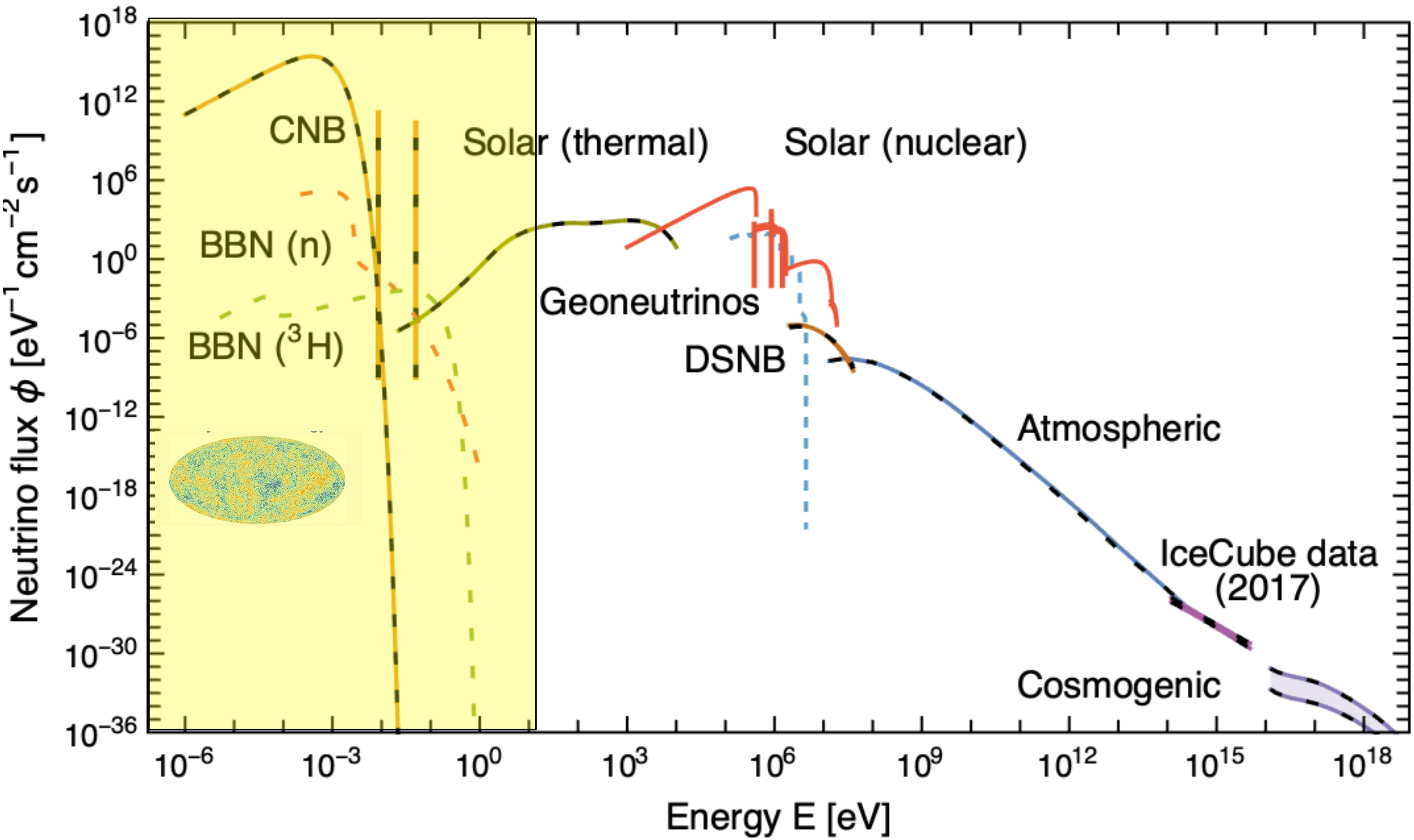
"CEvNS Glow" in large, high-threshold neutrino detectors

"IceCube-style" supernova detection:
Cherenkov photons in ice observed as
time-dependent single- (and double-)hit glow over ~10 sec



(supernova spectrum)

And now, down at the lowest energy end....



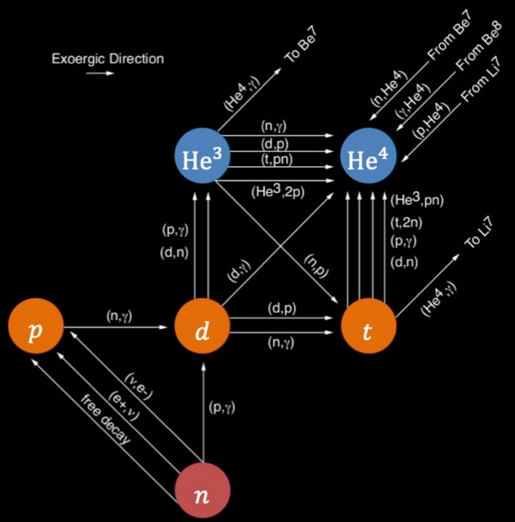
Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Cosmological observables…

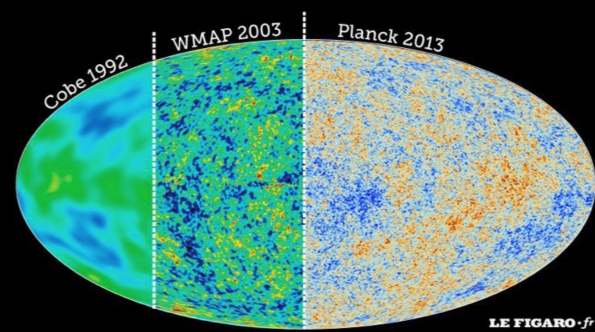
+ Supernova Ia, local H_0, etc.
(No direct neutrino effects)

Light element abundances from primordial nucleosynthesis



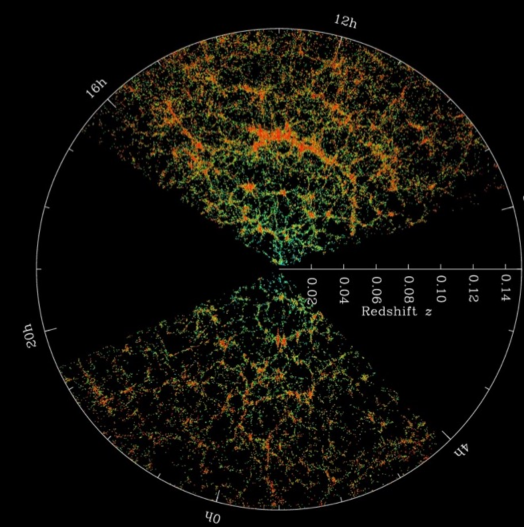
N_{eff} (expansion rate)

Cosmic microwave background anisotropies



N_{eff} (expansion rate)
Interactions (free-streaming)
Lifetime (free-streaming)

Large-scale matter distribution



$\sum m_\nu$ (perturbation growth)

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$$N_{eff} = 2.99 \pm 0.34 \text{ (95\% CL)}$$

Aghanim et al. [Planck] 2021

→ Remarkably consistent with Standard Model prediction $N_{eff} \approx 3$

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$$\sum m_\nu < 0.12 \text{ eV (95\% CL)}$$

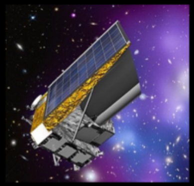
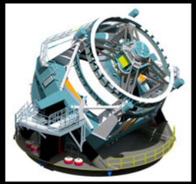
Aghanim et al. [Planck] 2021

At face value a factor of 30 tighter than current lab bound from KATRIN, $\sum m$ <2.4 eV (90% C.L.)
Aker et al. [KATRIN] 2022

Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Future cosmological probes…

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to N_{eff}
	**ESA Euclid**	2024	$0.011 - 0.02$ eV	0.05
	**LSST**	2024	0.015 eV	0.05
	**CMB-S4**	2027	0.015 eV	$0.02 - 0.04$

Minimum $\sum m_\nu = 0.06$ eV
From neutrino oscillations
(assuming normal mass ordering)

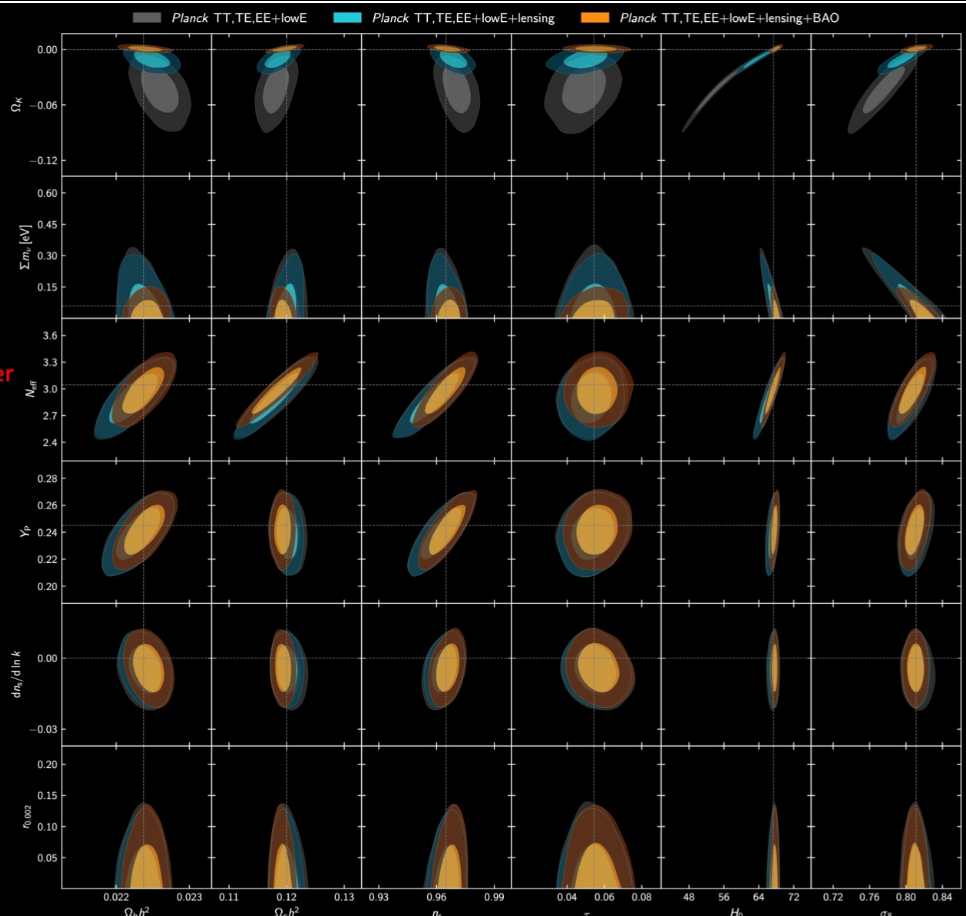
→ Detection of the absolute neutrino mass may be possible!

Neutrinos and Cosmology: indirect CNB

Yvonne Wong, Snowmass Neutrino colloquium

Neutrino mass

Effective number of neutrinos



Aghanim et al. [Planck] 2021

Dark matter density

Spectral index

Hubble parameter

Fluctuation amplitude

A direct neutrino mass measurement or even a confirmation of the inverted mass ordering (minimum $\sum m_\nu =$ 0.11 eV) by oscillation experiments would help to shrink these ellipses.

Establishing the existence (or not) of light sterile neutrino states through oscillation experiments would shrink the uncertainty in $N_{\rm eff}$ from the neutrino sector.

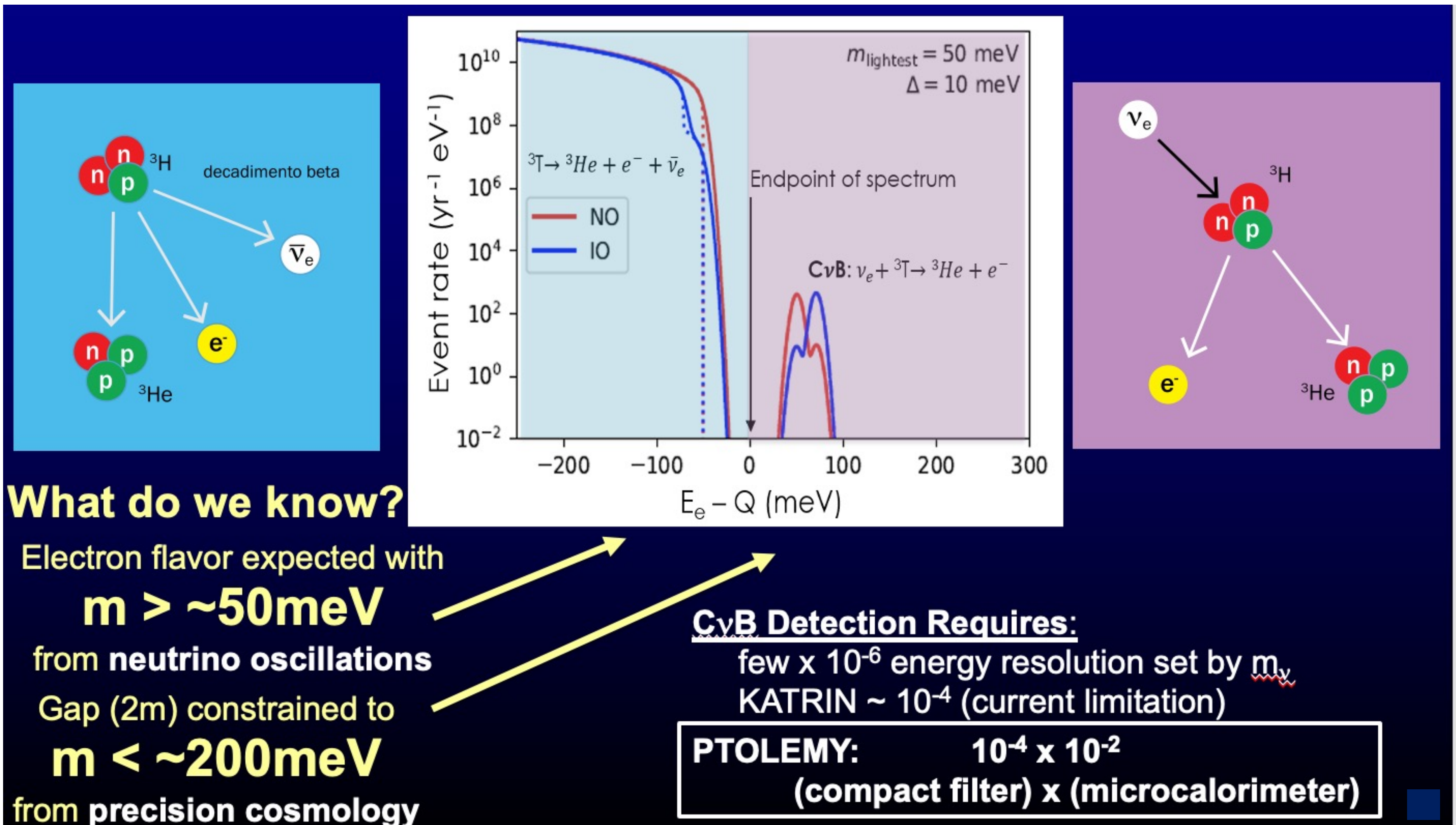
More accurate estimates of parameters inaccessible in the lab.

- Cosmological measurements tell us about ν properties
- **Lab experiments help to constrain cosmological fits**

Direct detection of Cosmic Neutrino Background

Very, very hard... lots of ideas but few promising...
Best possibility: "zero-threshold reactions"

C.Tully, Snowmass white paper workshop talk



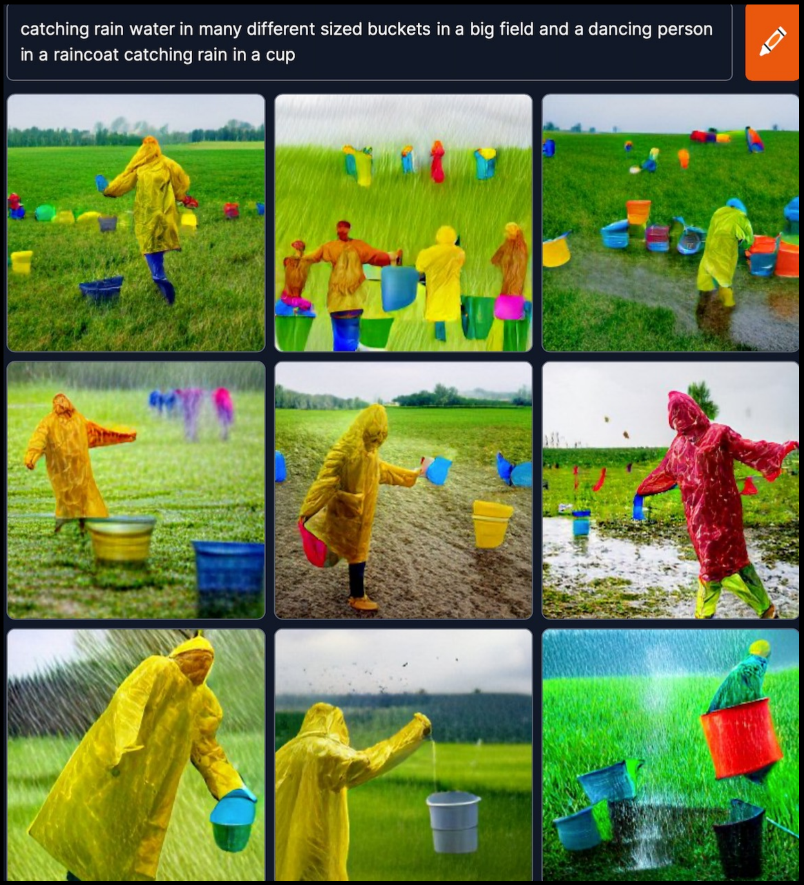
Take-Away Messages

Neutrinos are messengers of astrophysics and cosmology

- They tell us what's happening deep inside objects, and point from far away

Natural neutrinos are messengers of *physics*

- Astrophysical sources are free! Just need to build the detector...
- Enable 3-flavor osc and huge range of BSM searches



Not a competition! We want to catch them all!