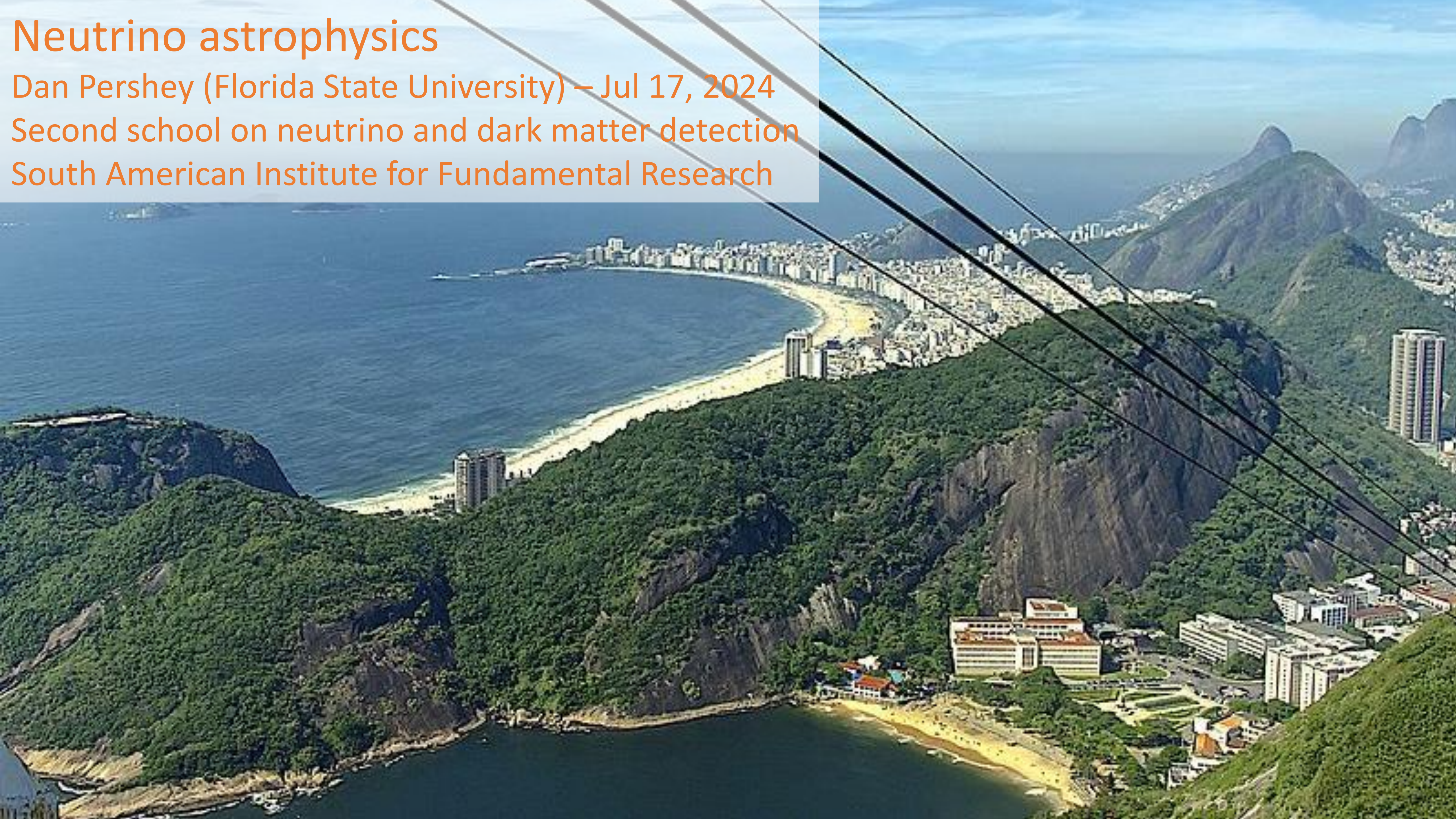
Neutrino astrophysics

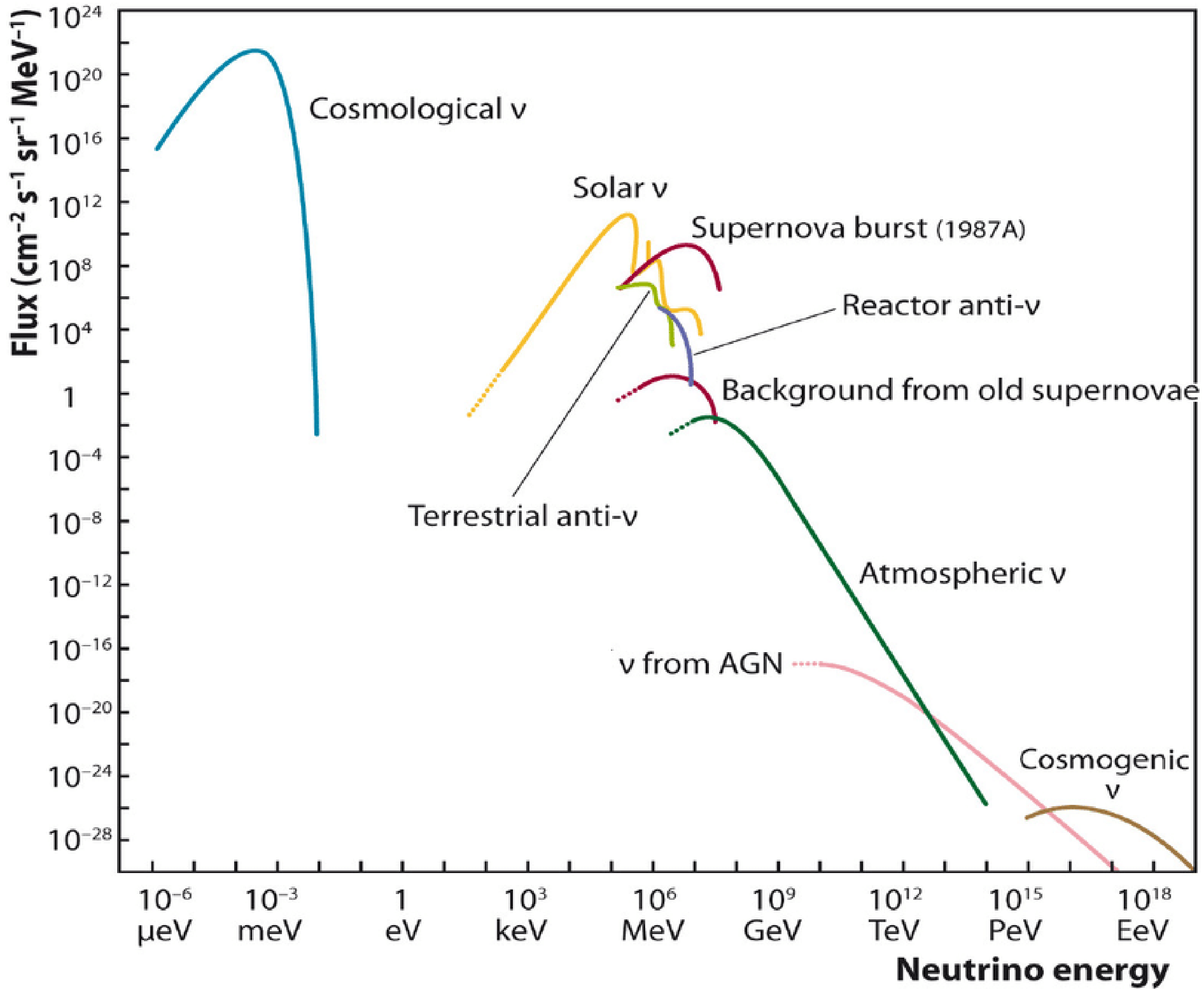
Dan Pershey (Florida State University) – Jul 17, 2024

Second school on neutrino and dark matter detection

South American Institute for Fundamental Research



Sources of astrophysical neutrinos



Solar and atmospheric neutrinos incredibly influential to particle physics

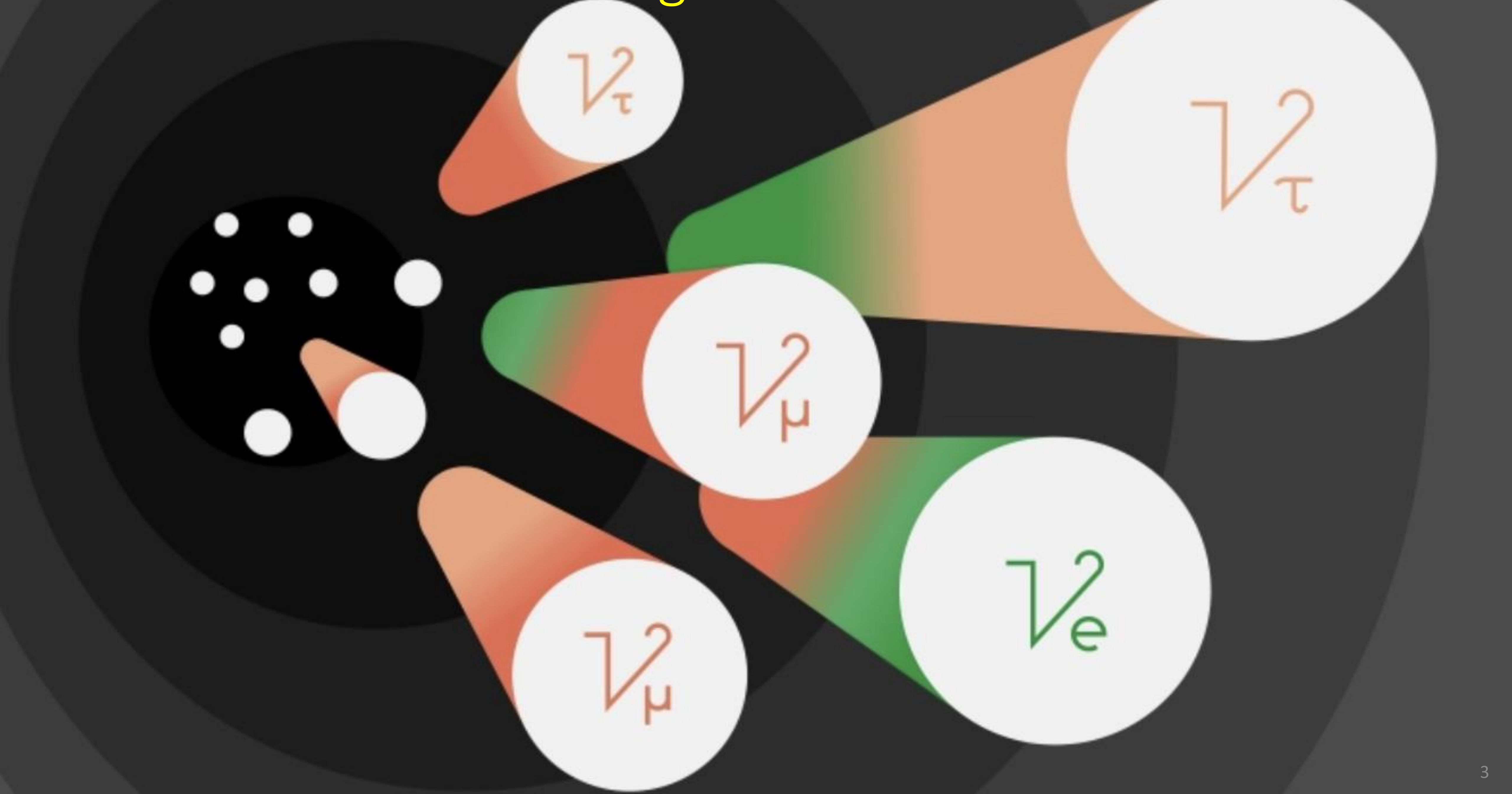
- Discovery of neutrino oscillations and mass

New field of neutrino astronomy

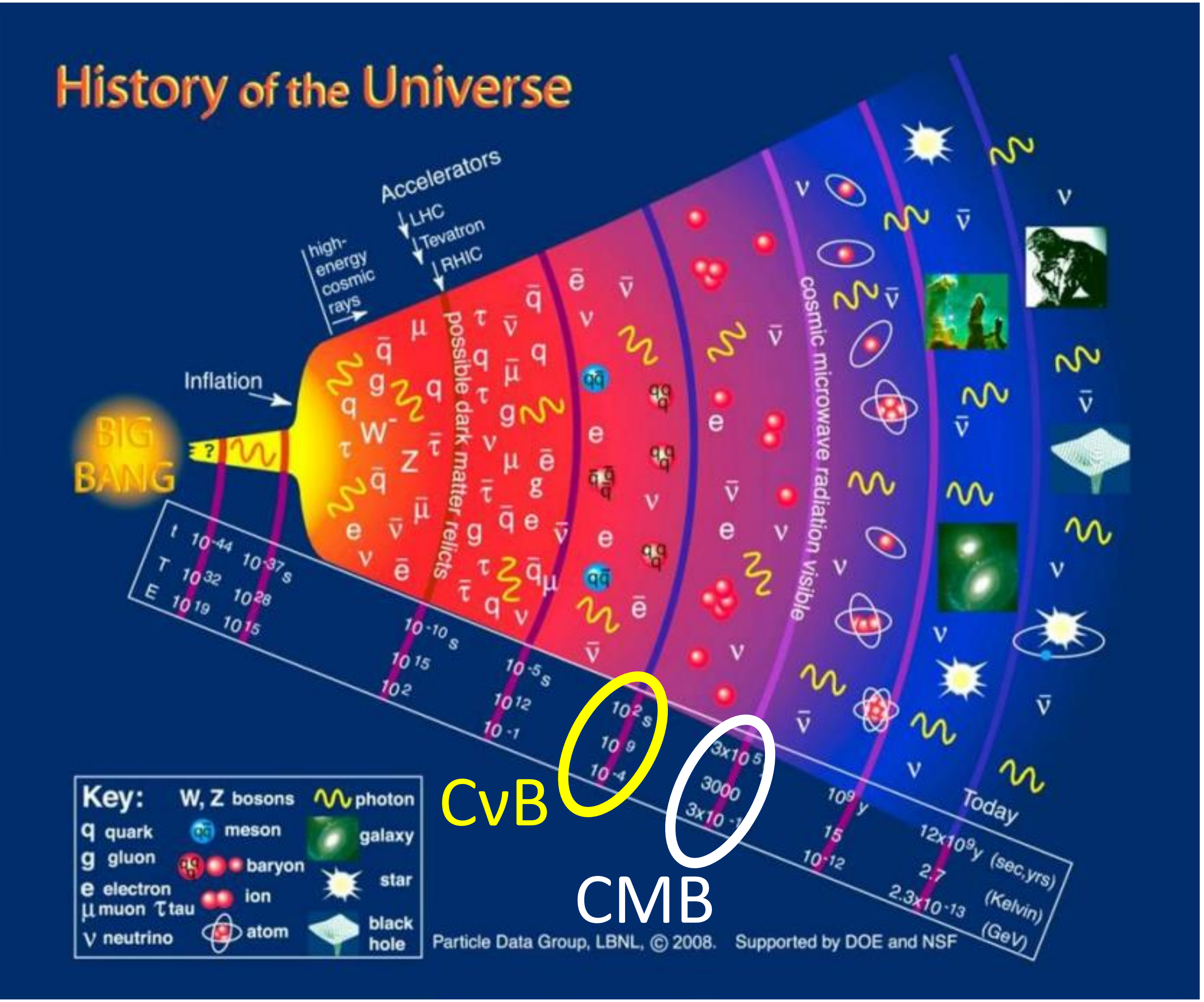
- Supernova and > TeV-scale neutrinos complement light and GW probes to understand the physical processes responsible for these phenomena

Solar and atmospheric neutrinos discovered oscillations – will cover tomorrow

The cosmic neutrino background



Detecting a non-relativistic neutrino



Big-bang neutrinos, initially in equilibrium, decoupled much sooner than CMB, 1 s after – cosmic neutrino background CνB

– Temp = 1.945 K from cosmology

– KE = 3/2(kT) = 0.5 meV << neutrino mass!

– density ≈ 56 / cm^3

Weinberg proposed detection by tritium absorption

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

$$KE_{e,max} = m_H - m_{He} - m_e - m_\nu$$

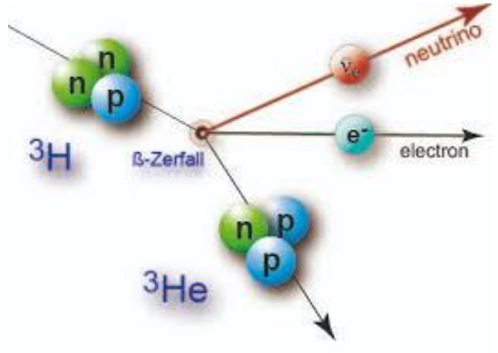
$$\nu_e + {}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-}$$

$$KE_{e,max} = m_H - m_{He} - m_e + m_\nu + T_\nu$$

Electron endpoint $2m_\nu + T_\nu \approx 2m_\nu$ for absorbed CνB neutrinos than for decays

Diagram of the PTOLEMY method

Step 0: Ultra-cold source



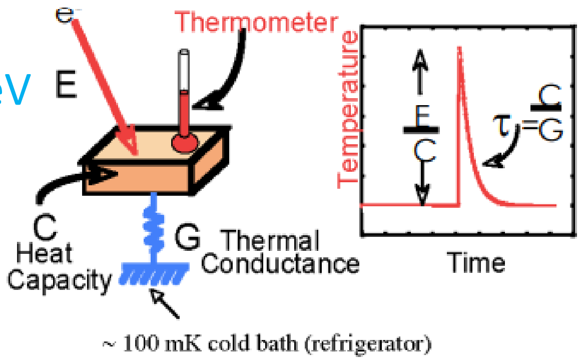
Step 1: EM filter

ΔV = 18591 eV

Tritium Q-value is 18592 eV

KE ≈ 1 eV

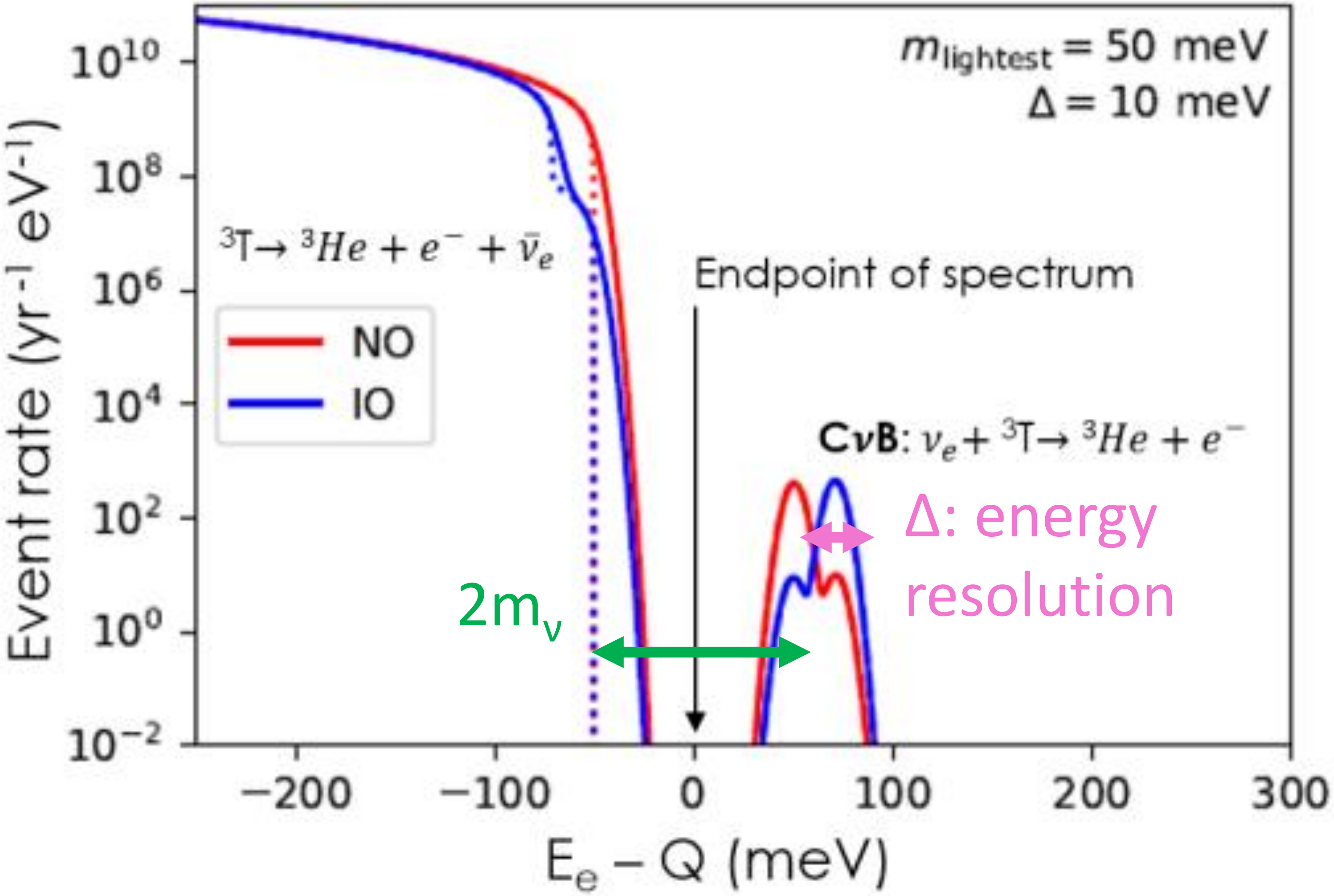
Step 2: Microcalorimeter



Chris Tully L'Aquila Seminar

Goal to achieve 50 meV final resolution for electrons. Currently prototyping both the EM filter spectrometer and the microcalorimeter detector

Potential Ptolemy spectrum (optimistic)

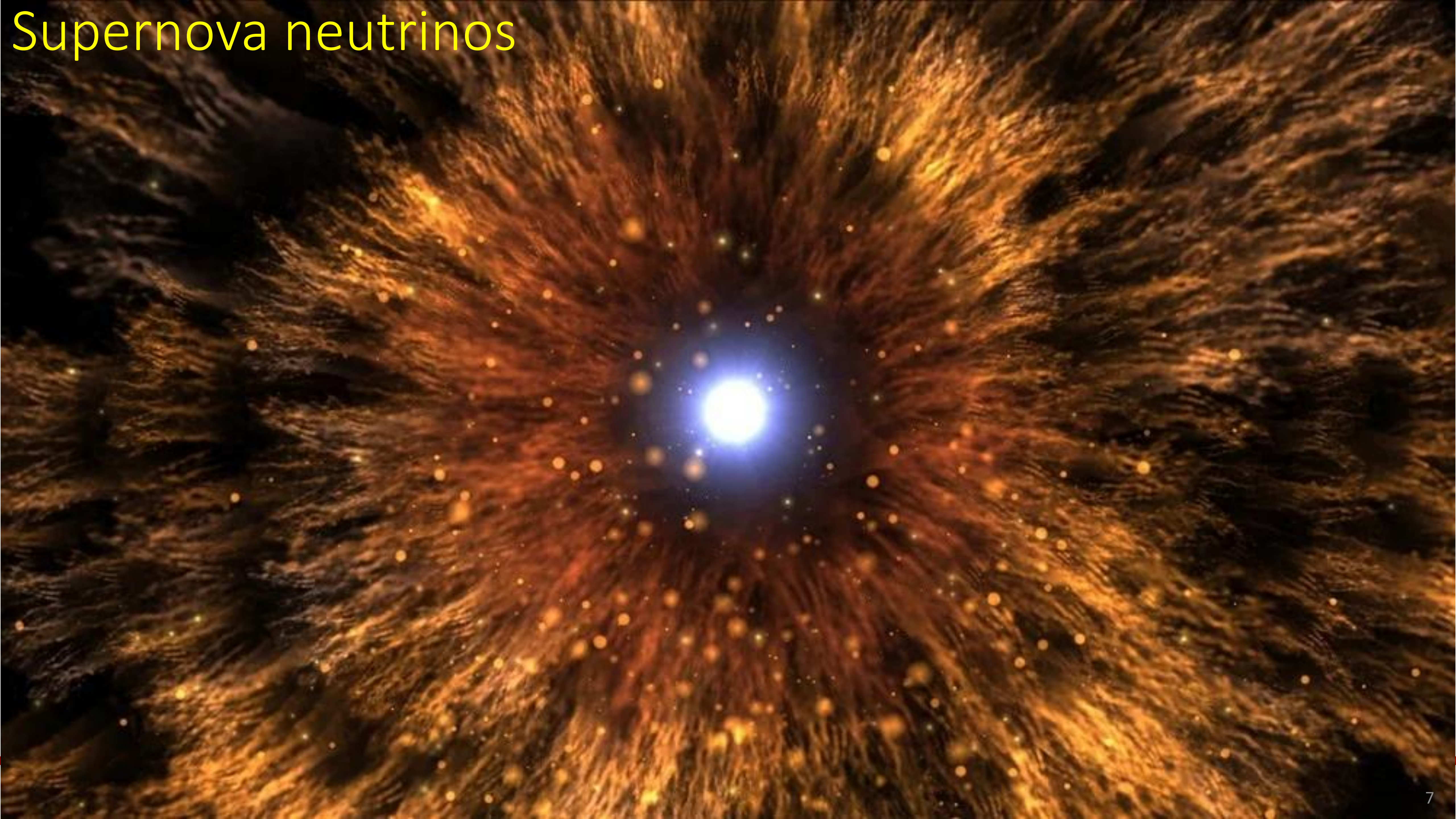


Ptolemy, *JCAP* **07** 047 (2019)

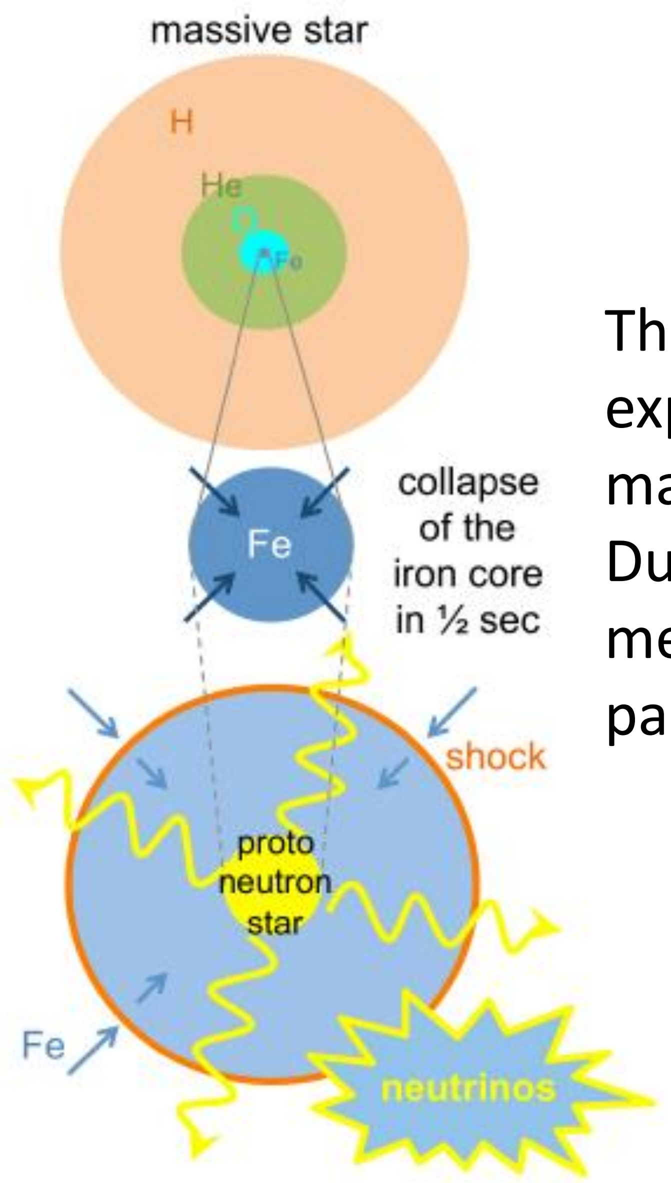
If resolution better than the neutrino mass is achieved, measurement is possible

Currently prototyping, efficacy of approach will be clearer by 2030

Supernova neutrinos



Core-collapse mechanism

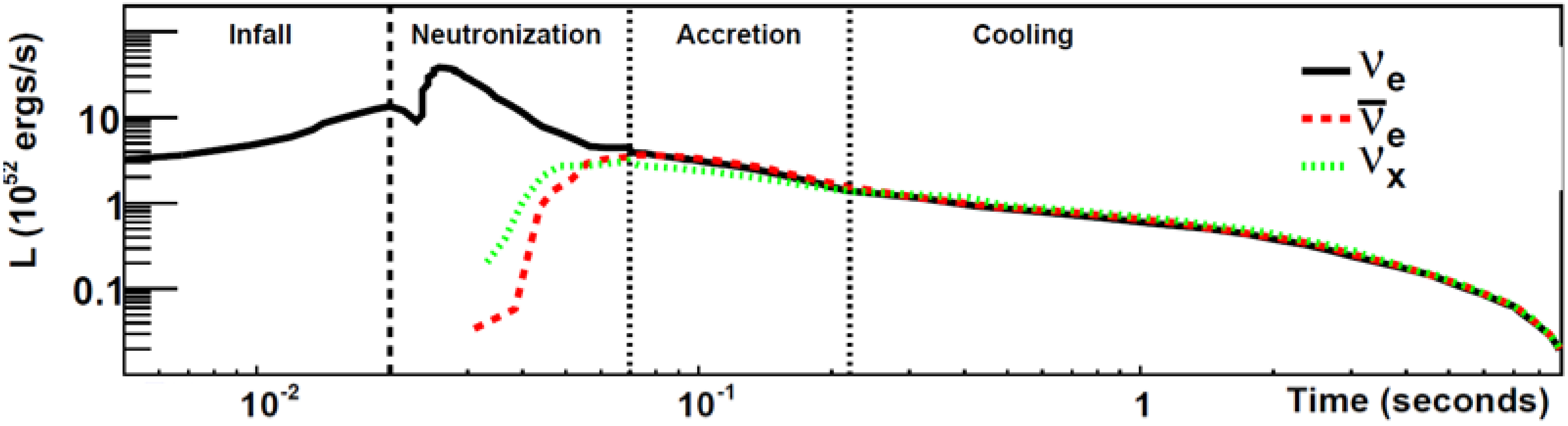


Though neutrinos interact very feebly, they drive some of the largest explosions in the universe – the core-collapse supernova of the most massive stars

During collapse, matter becomes incredibly hot but is trapped in a dense medium – will cool by releasing huge amount of the least-interacting particle produced in the explosion, our neutrinos

$\sim 10^{57}$ ν with <E> = 10 MeV in 10 s

Phases of a supernova explosion



1. Neutronization through $p + e \rightarrow n + \nu_e$ in the core gives a short-lived, intense flash of ν_e
2. Explosion! Shock wave forms, neutrino production dominated by matter accreting
3. Shock wave expands outward. Neutrino emission cools the proto-neutron star

Rapid cooling of proto-neutron star – Urca processes

A supernova has no choice but to cool itself through neutrino emission

Cooling happens on timescales smaller than shock propagation

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

Can lead to neutrino emissions: temp << 10 MeV, timescales >> 10 s

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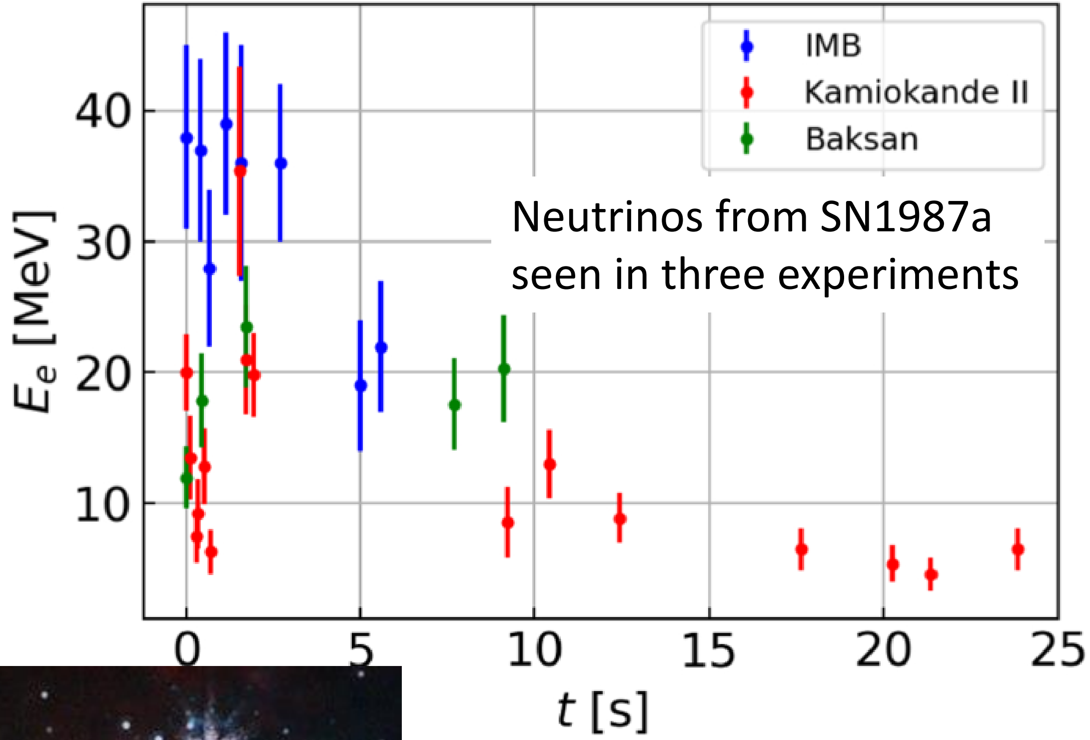
$$p + e^- \to n + \nu_e$$

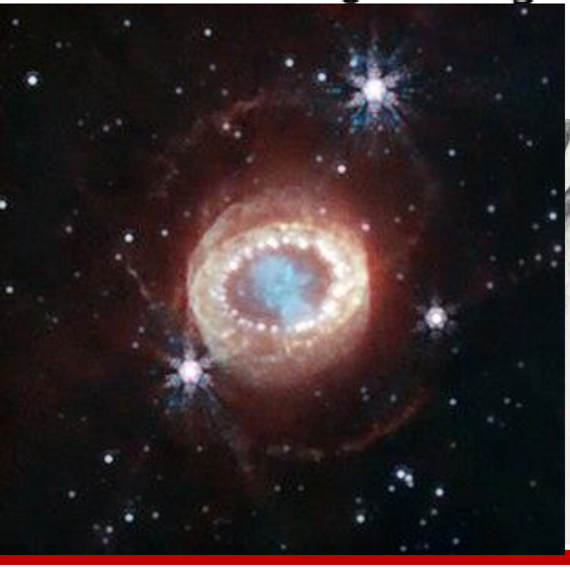
Can lead to neutrino emissions: temp << 10 MeV, timescales >> 10 s

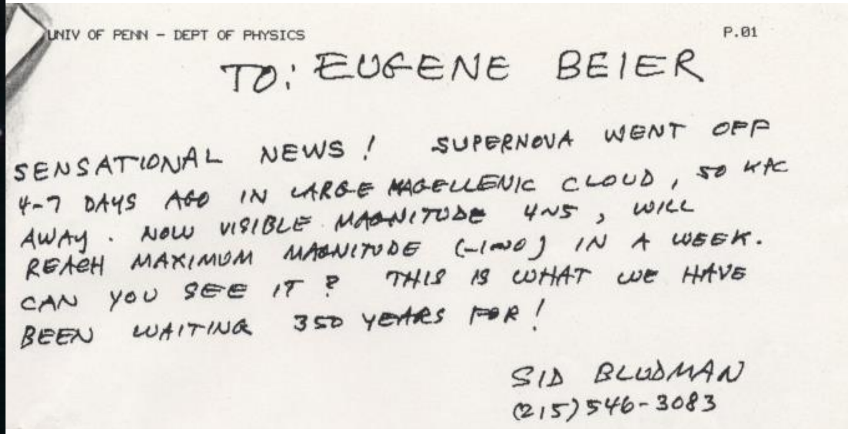
"because the Urca Process results in a rapid disappearance of thermal energy from the interior of a star, similar to the rapid disappearance of money from the pockets of the gamblers on the Casino de Urca" – George Gamow

Observation of Supernova 1987a



Water Cherenkov:
Kamiokande-II (Japan) 11-12 evts
Irvine-Michigan-Brookhaven (USA) 6 evts
Scintillator:
Baksan (Russia) 5 evts





UNIV OF PENN – DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4½, WILL REACH MAXIMUM MAGNITUDE (-1 to 0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

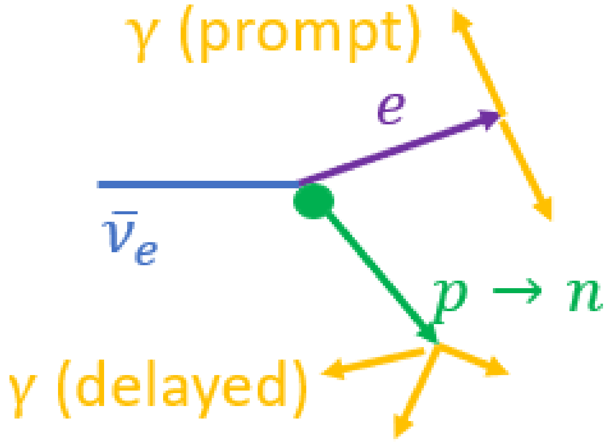
SID BLUDMAN
(215) 546-3083

Countless papers based on 22 events!
Nuclear physics, astro of collapse, DM, axions, ν magnetic moment,
ν-ν interactions, sterile ν, more

Dominant interaction channels

Water/Scintillator

Chemically, these are
H_2O, CH_2 – lots of free protons!
Inverse Beta Decay, IBD, ($\bar{\nu}$ CC)



Positron + neutron capture gives time-correlated activity for background rejection

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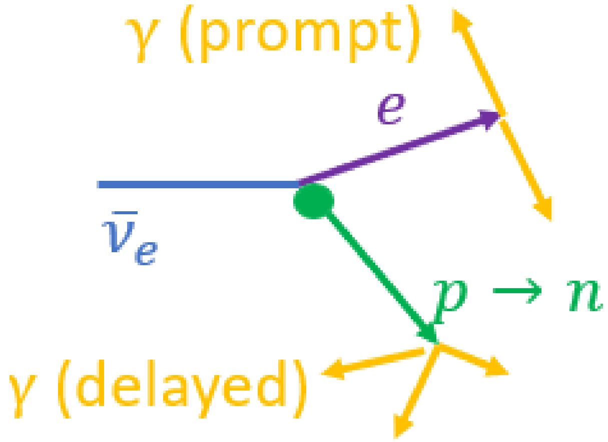
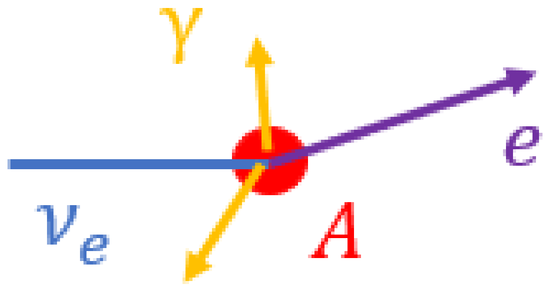
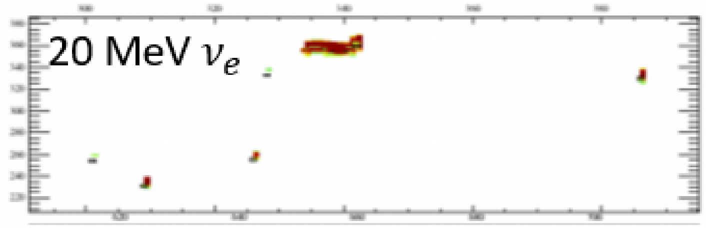


Positron + neutron capture gives time-correlated activity for background rejection

LArTPC's

Scattering material is argon,
large ν CC cross section





Distinctive event topology, leverage precision tracking

Dominant interaction channels

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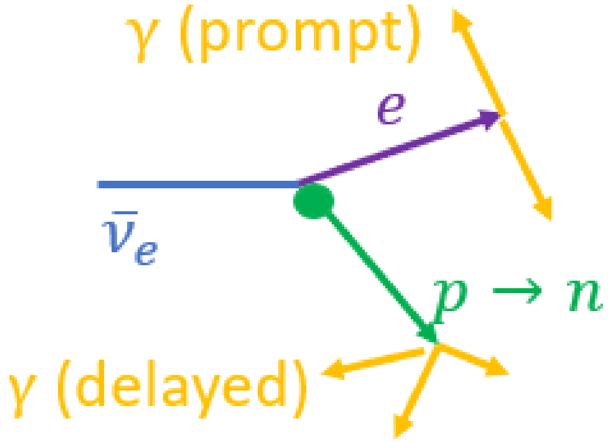

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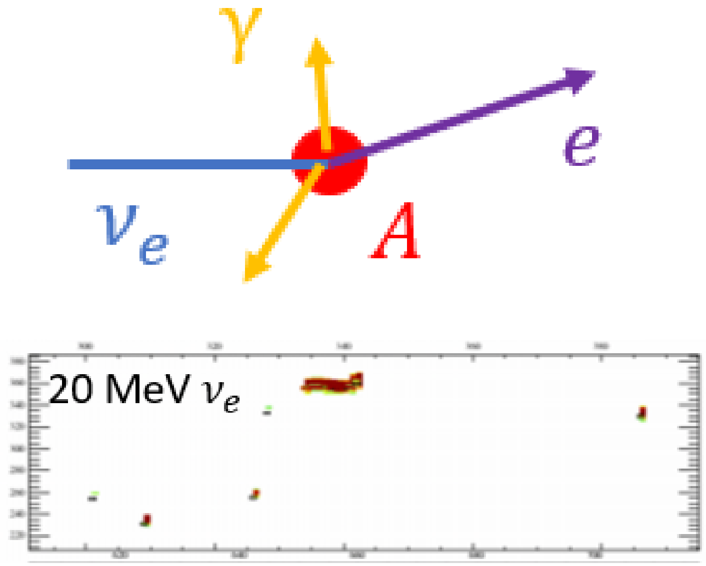
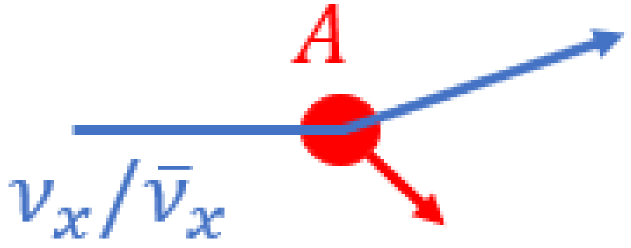


Distinctive event topology, leverage precision tracking

Dark matter detectors

Low threshold makes these sensitive to CEvNS, largest cross section in 10s of MeV



Sensitive to all the flavors! No uncertainties on oscillations, gives direct estimate of flux

Dominant interaction channels

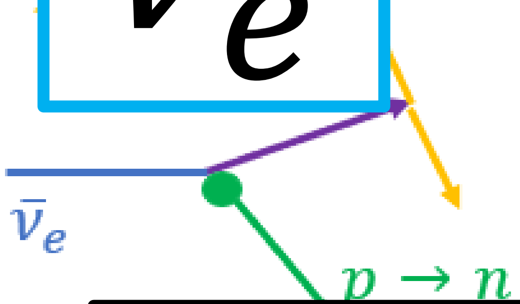
Water/Scintillator

Chemically, these are

H_2O, CH e protons!

Inverse BD, ($\bar{\nu}$ CC)

$$\bar{\nu}_e$$



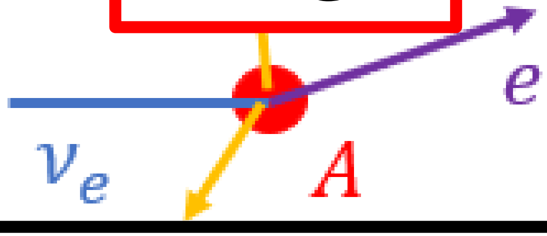
γ (dela

Positron
gives ti
activity for background
rejection

LArTPC's

Scattering material is argon,
large ν ion

$$\nu_e$$

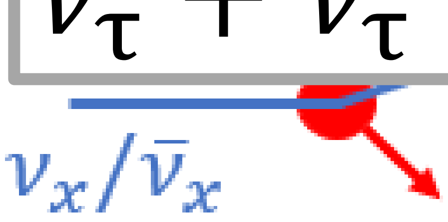


leverage precision tracking

Dark matter detectors

Low threshold makes these
sen
cros

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



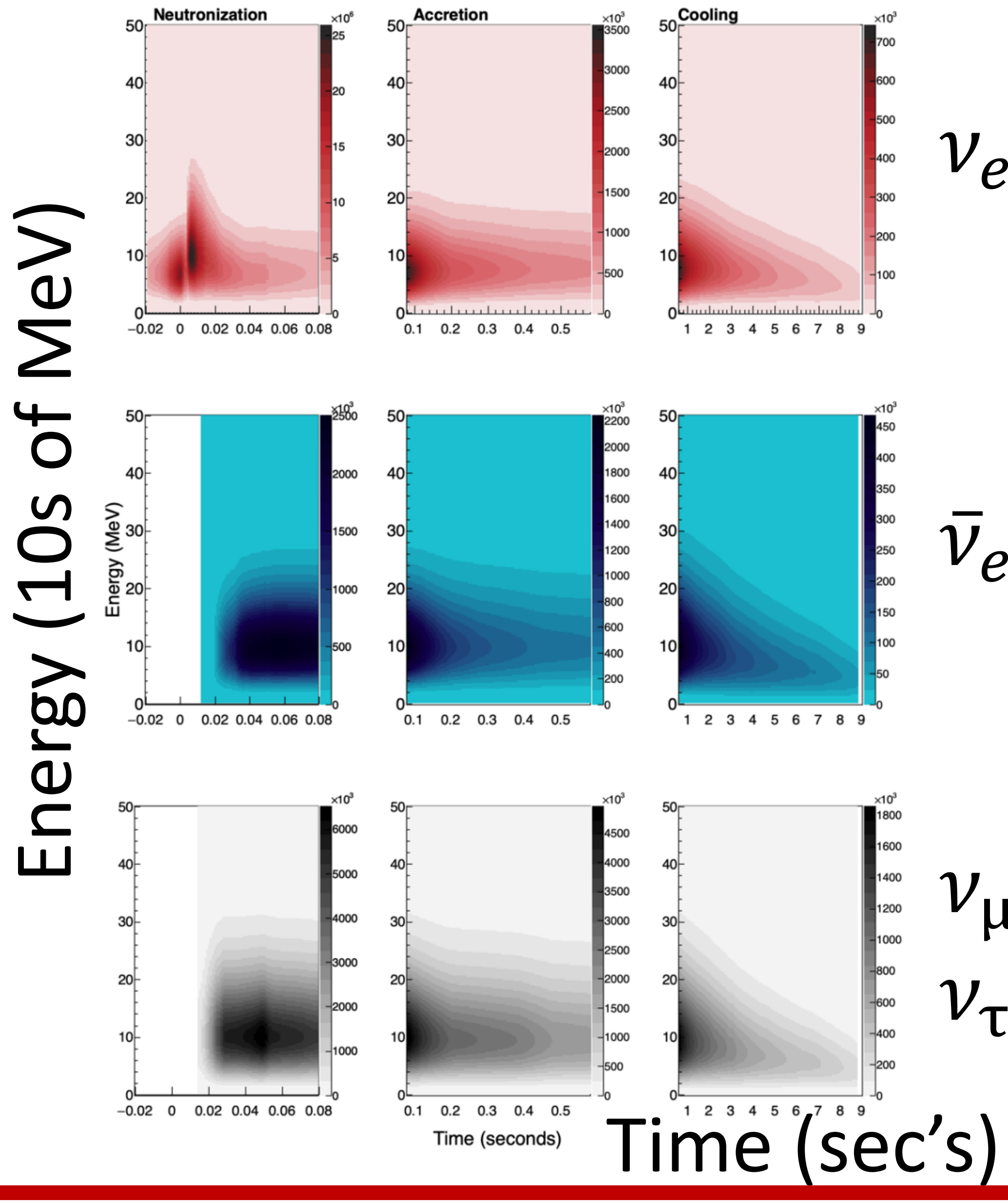
avors!

rect

estimate of flux

Fundamental differences in detectors.
Each technology complements others!

An experimentalist's goal for a supernova



ν_e

$\bar{\nu}_e$

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

Rare event with rich physics – design a diverse, global experimental program that provides detailed kinematic information from all channels

	ν_e	$\bar{\nu}_e$	ν_x
LArTPC[1]	89%	4%	7%
Dark Matter	0%	0%	100%
Water[2]	10%	87%	3%
Scintillator[3]	1%	72%	27%

[1]DUNE, *Eur. Phys. J. C* **81** 423 (2021)
[2]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[3]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

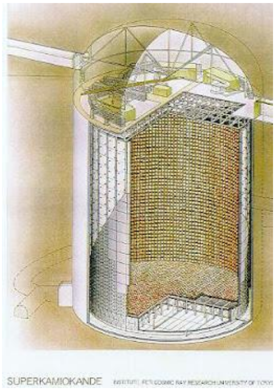
Upcoming supernova detectors

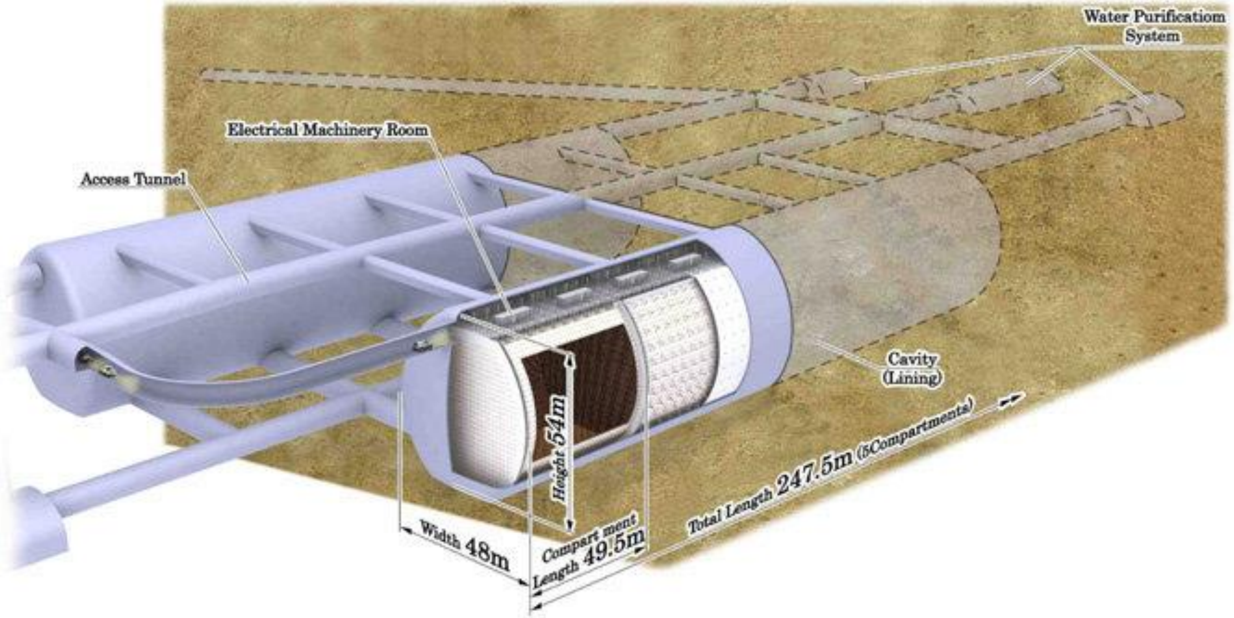
Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple





Old friends and the new kid on the block

SK: 22.5 kt running with gadolinium doping

HK: new 260 kt detector to be commissioned in 2027

50000 evts per typical collapse for HK

Upcoming supernova detectors

Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple

20 kt of organic liquid scintillator in acrylic ballon
78% photodetector coverage! 17612 20” and 25600 3” PMT’s
35 kt outer Cherenkov detector for veto
Construction progressing rapidly
1000s of events for typical collapse

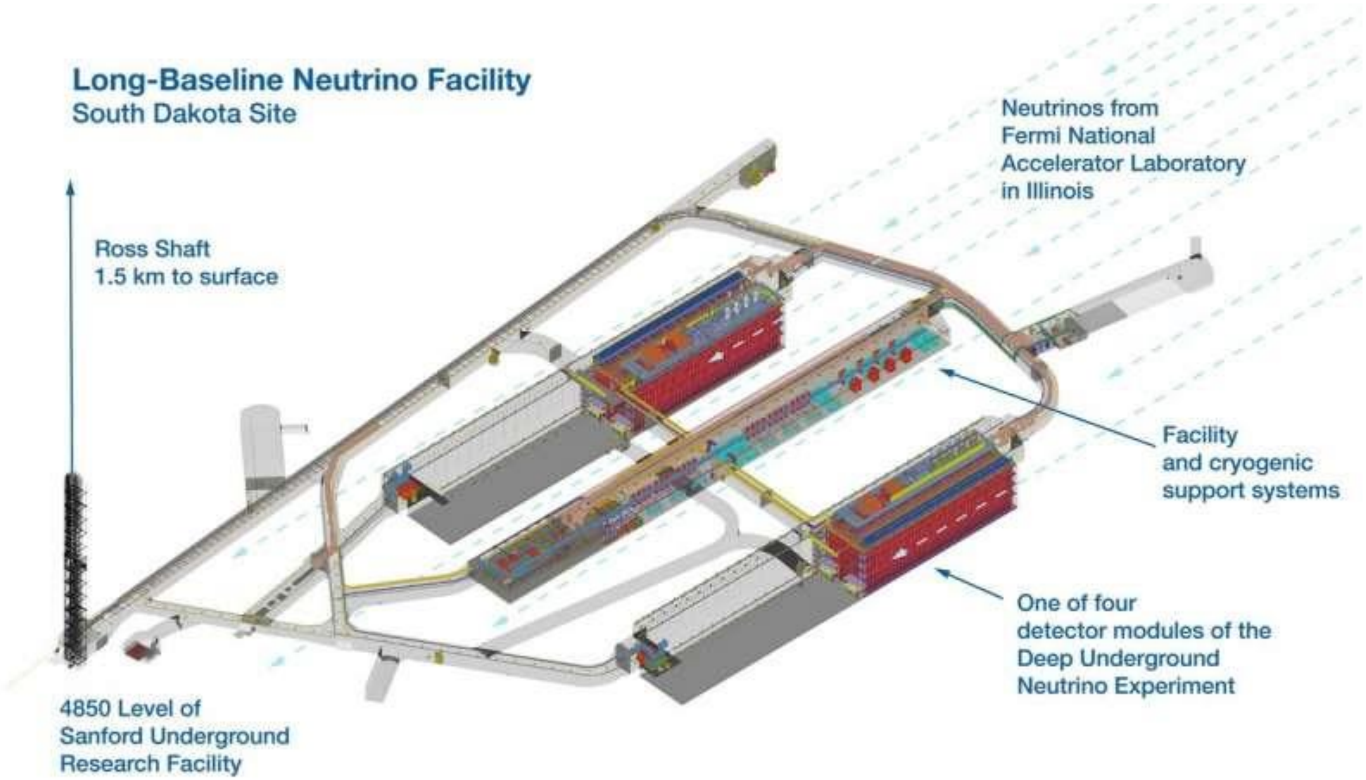
Upcoming supernova detectors

Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple



4 x 17 kt LArTPC modules with first expected by ≈ 2028
Sanford Underground Research Facility (SURF)
3300 meters-water-equivalent of overburden
1000s of events for typical collapse

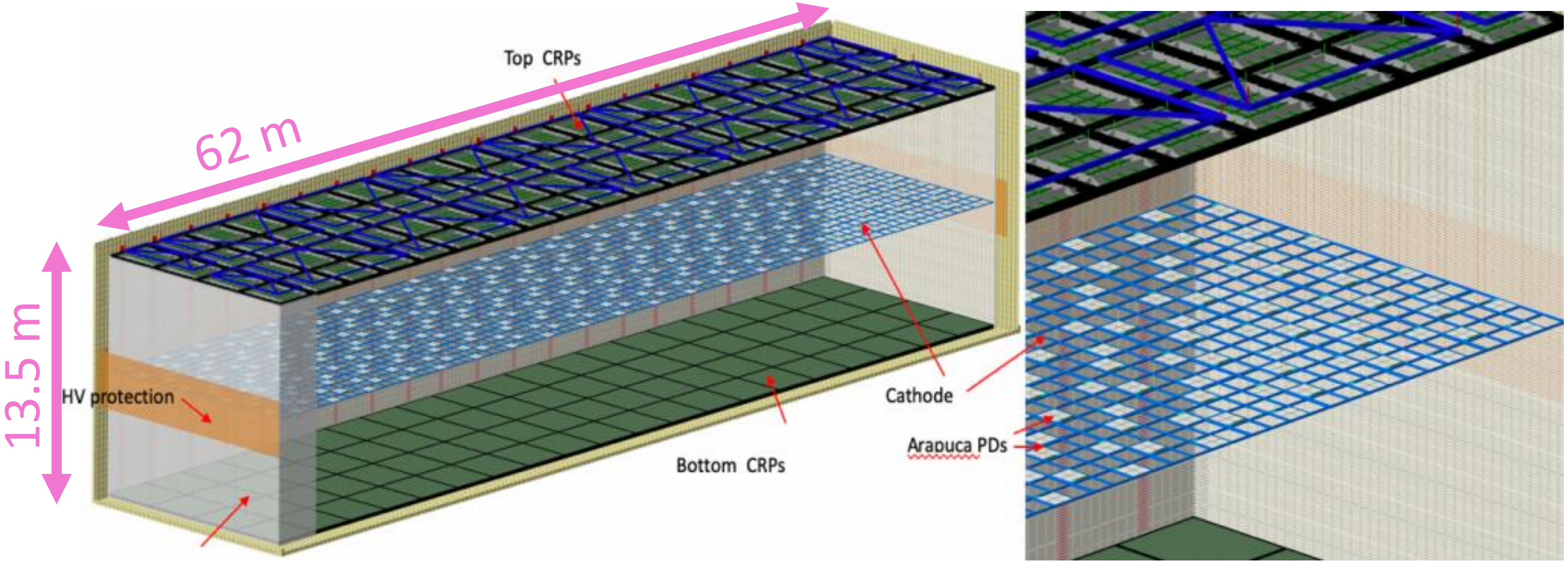
Upcoming supernova detectors

Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple



Each of 4 modules unique – technology set for first two

First module is the “vertical drift”

- Charge readout on top and bottom planes of detector
- Photodetectors on central plane and along detector walls

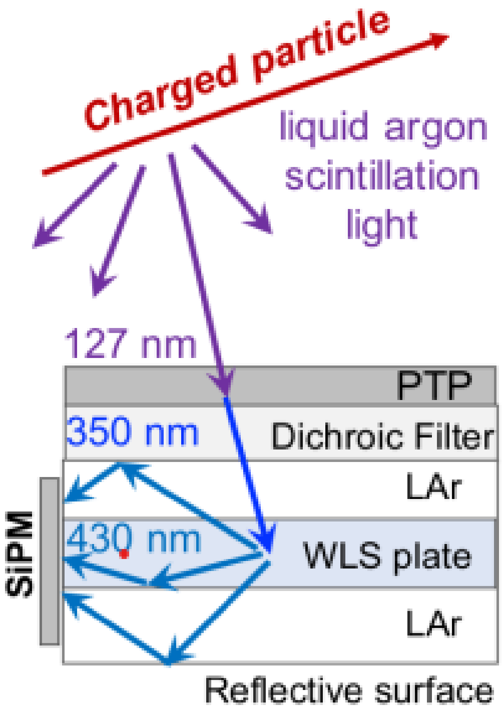
Upcoming supernova detectors

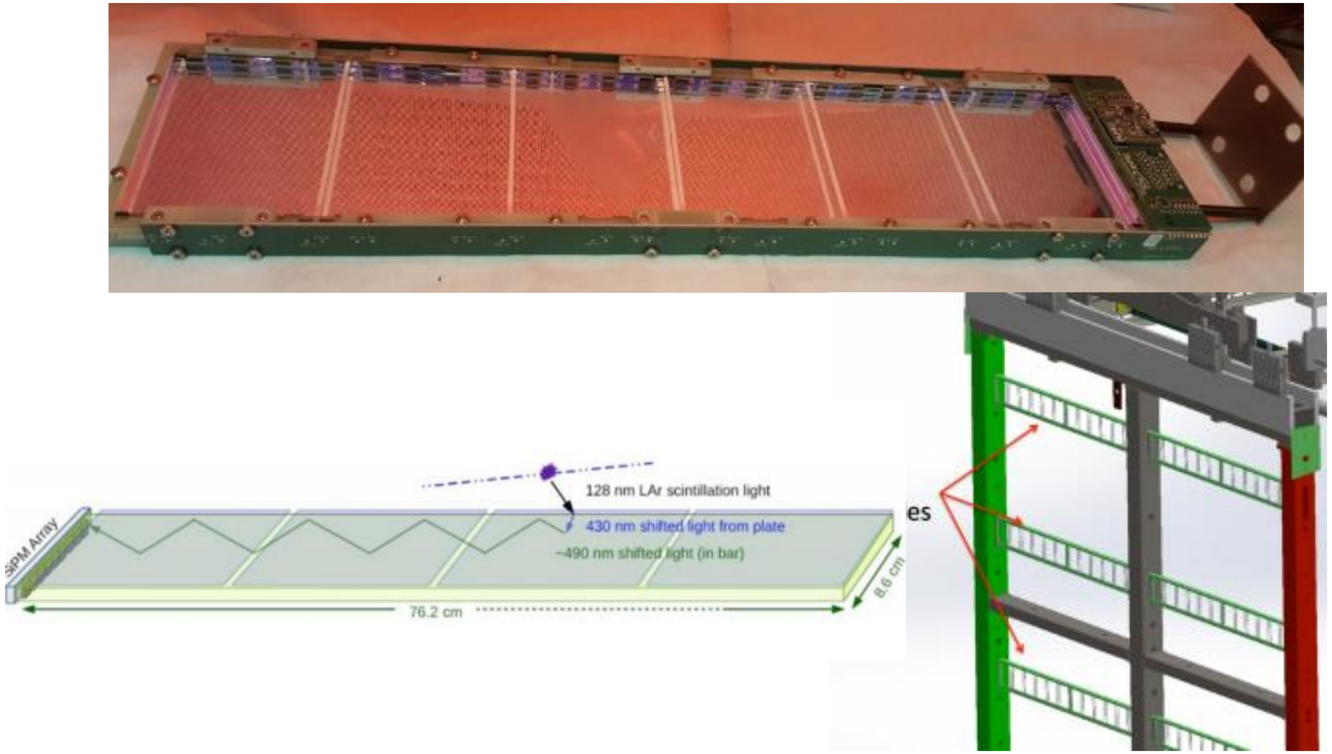
Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple





ARAPUCA collaboration, arXiv:2405.12014 (2024)

ARAPUCA: dichroic filter waveguides with SiPM readout
Long bars trap light and focus into specific light detectors
First tests at Brazilian Synchrotron Light Laboratory in 2016

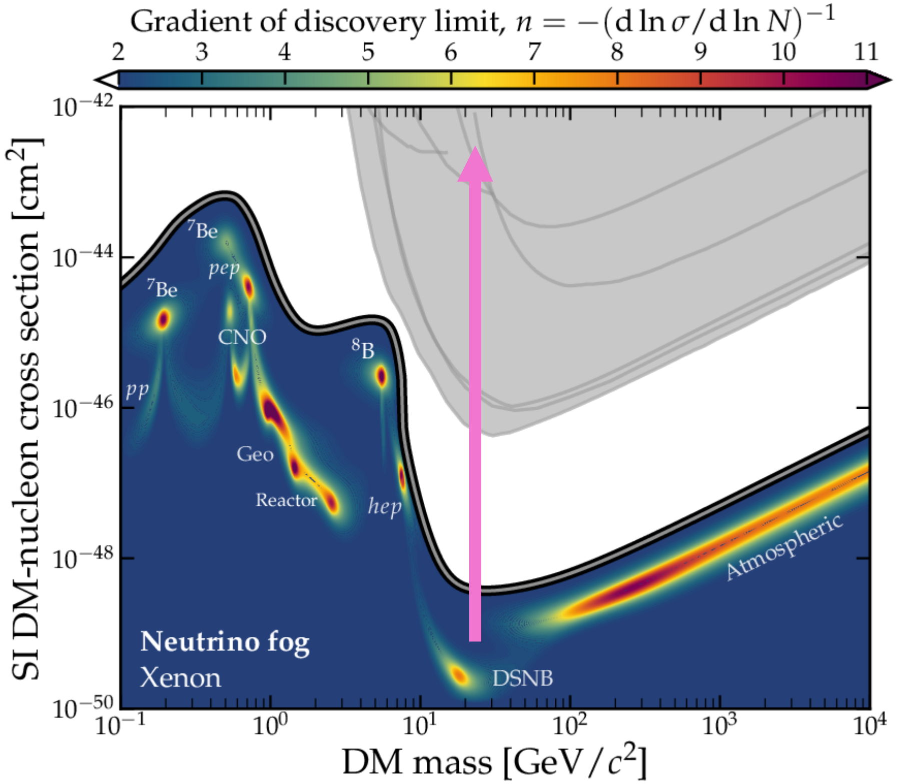
Upcoming supernova detectors

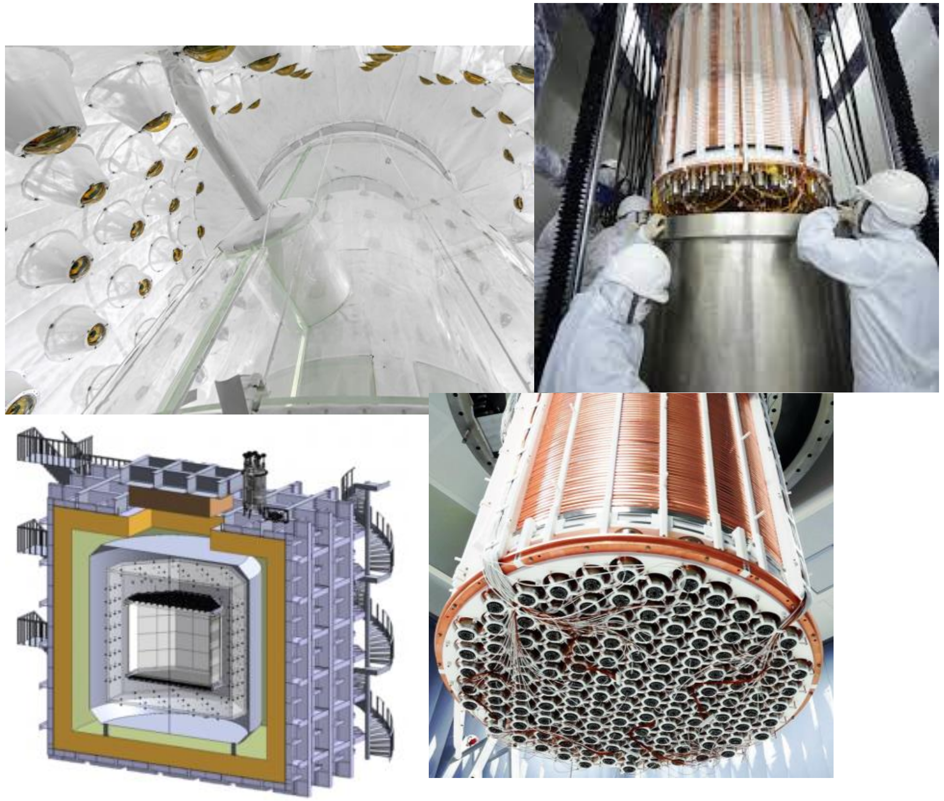
Water: SK/HK

Scintillator: JUNO

Argon: DUNE

DM: multiple





Large, ton-scale dark matter experiments will see CEvNS from SN

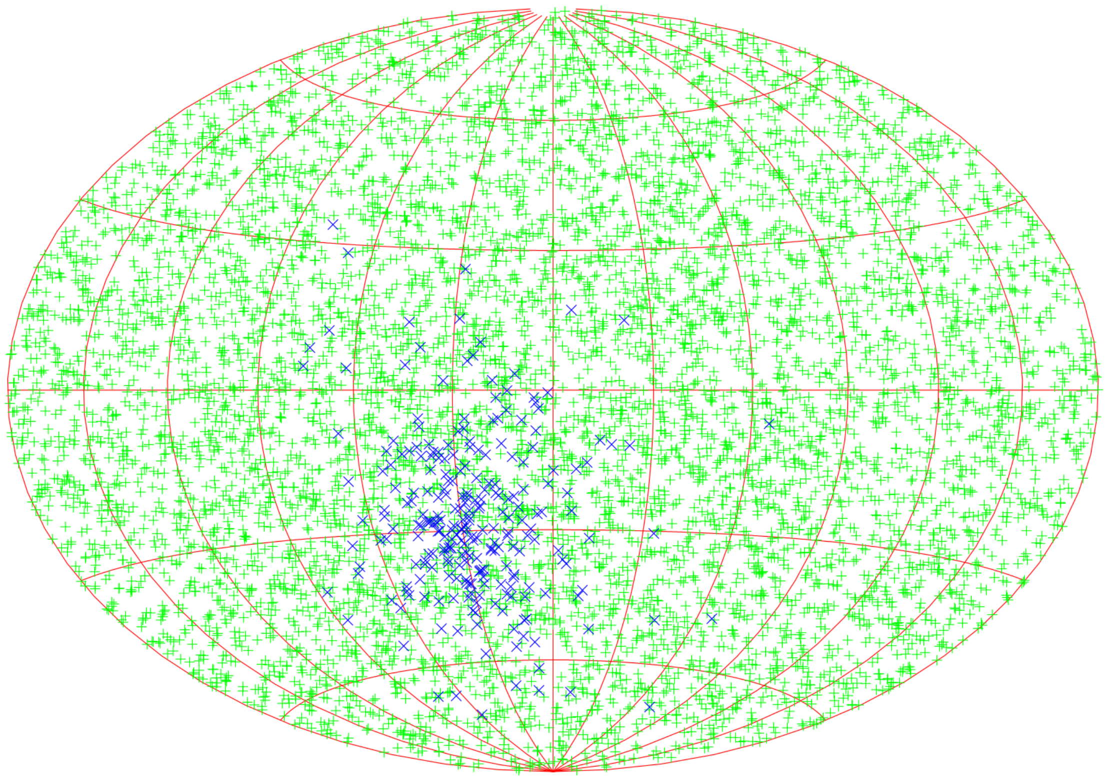
Liquid noble detectors most sensitive:

LZ, XENONnT, PandaX-4T, DarkSide-20k

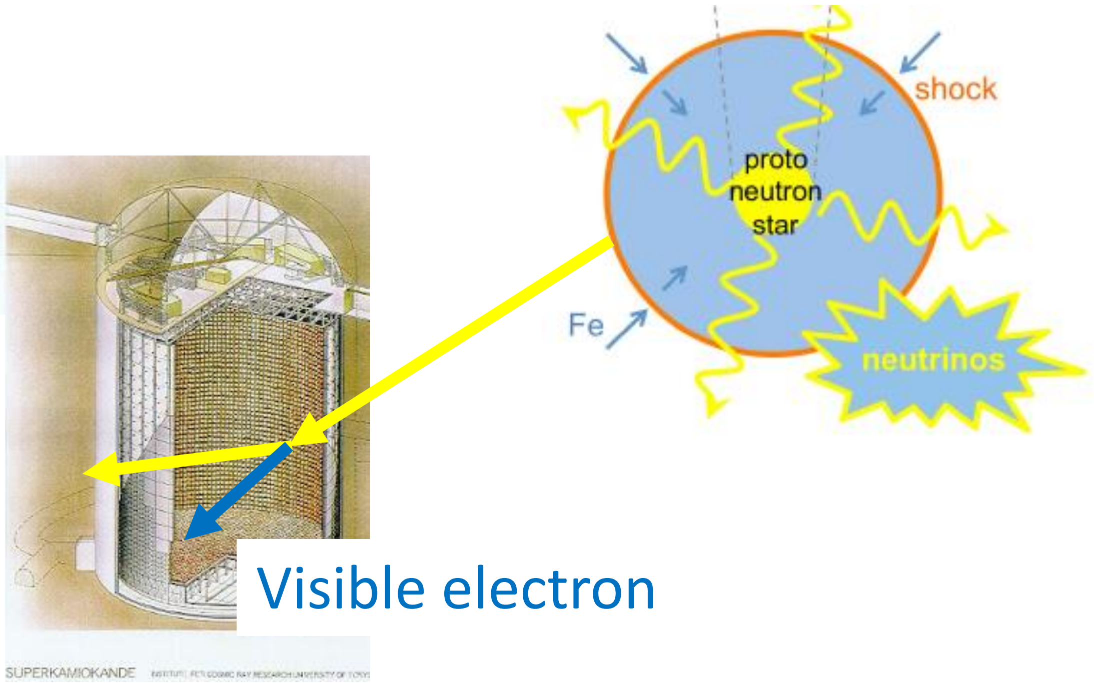
100s of events for typical collapse

Supernova pointing

Water Cherenkov (SK + HK) and argon tracking (DUNE) detectors can estimate the source of the supernova collapse in the sky



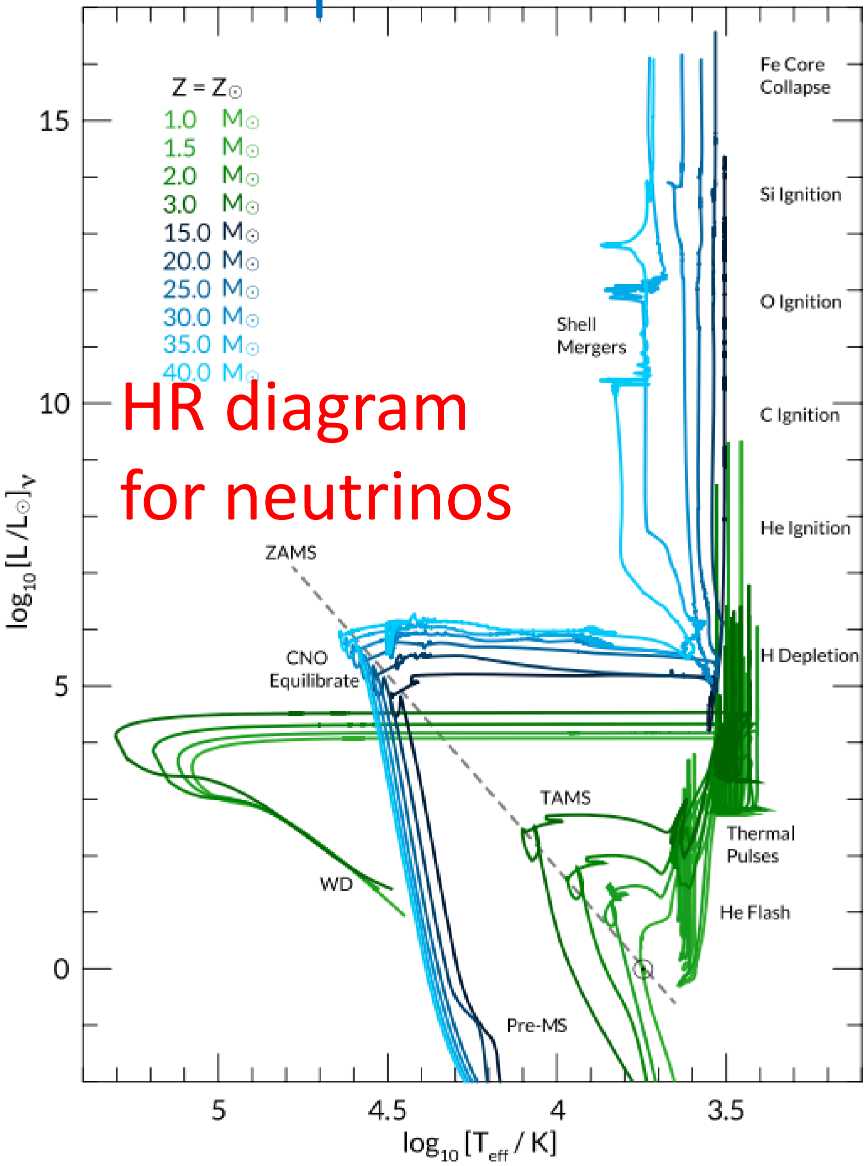
Example: SuperKamiokande



Dominant IBD channel is ≈ isotropic
Small fraction are ES – which point away from supernova collapse

Resolution of 1-5 deg depending on distance

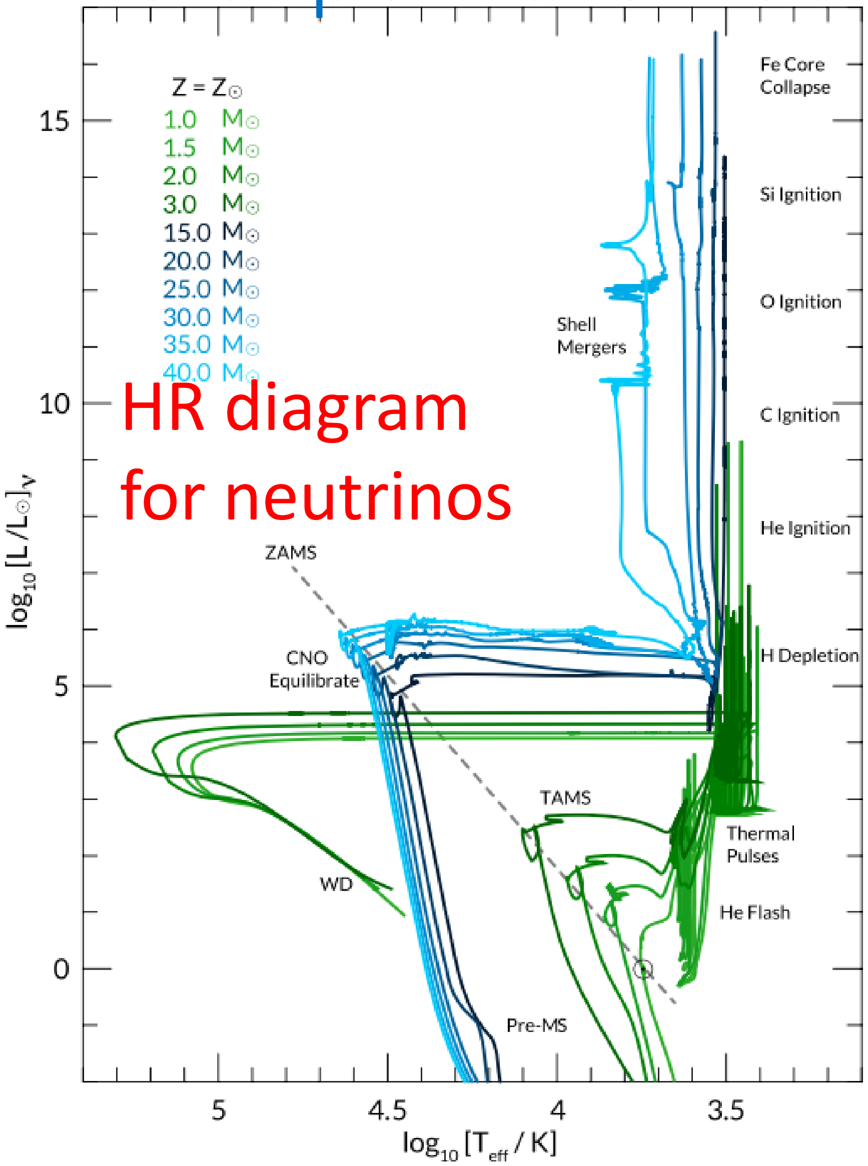
Pre-supernova neutrinos in JUNO



Farag et al., *APHYS J*, **893**, 133 (2020)

$\sim$ 1 day before collapse, stars begin fusing Si to Fe, releasing few MeV neutrinos that can be detected to kpc distance

Pre-supernova neutrinos in JUNO



Farag et al., *APHYS J*, **893**, 133 (2020)

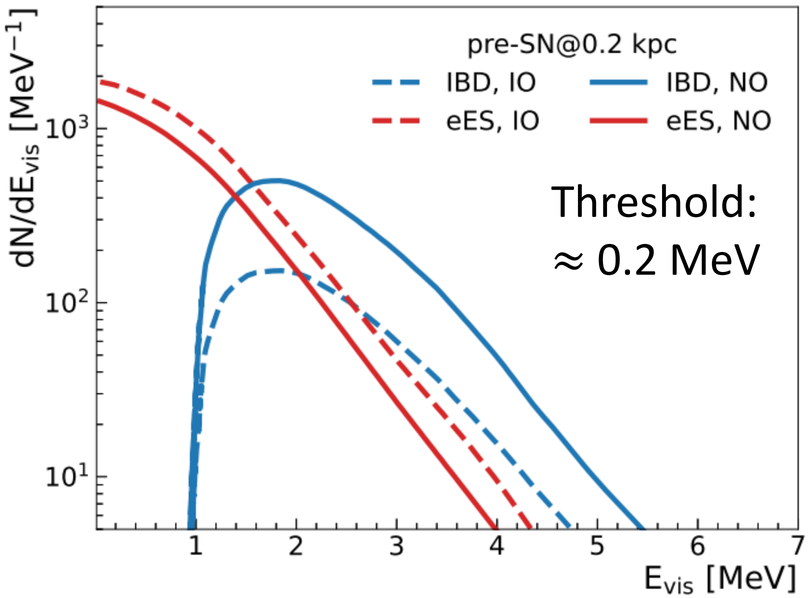
~ 1 day before collapse, stars begin fusing Si to Fe, releasing few MeV neutrinos that can be detected to kpc distance

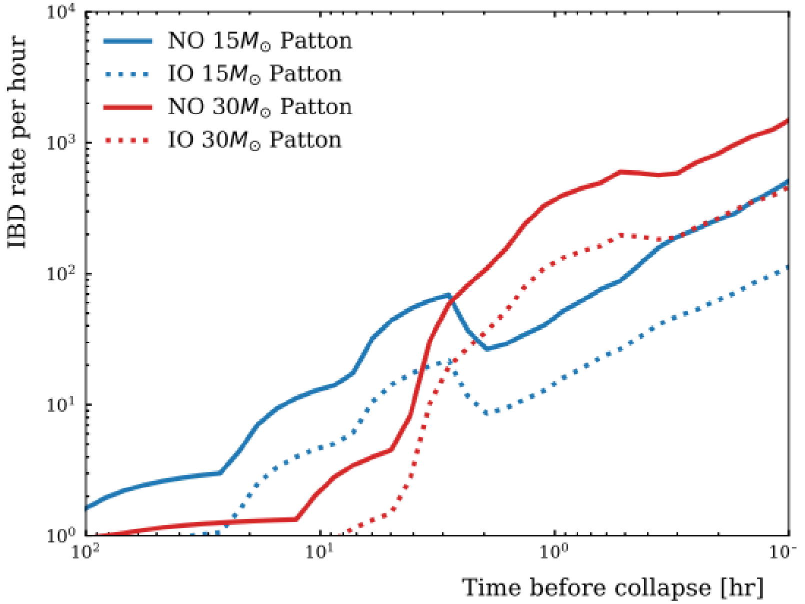
Scintillators have high light yield + low threshold + low backgrounds. JUNO excellent for this physics

Can detect neutrinos before collapse up to 1.6 kpc away

Early-warning to the early warning experiments

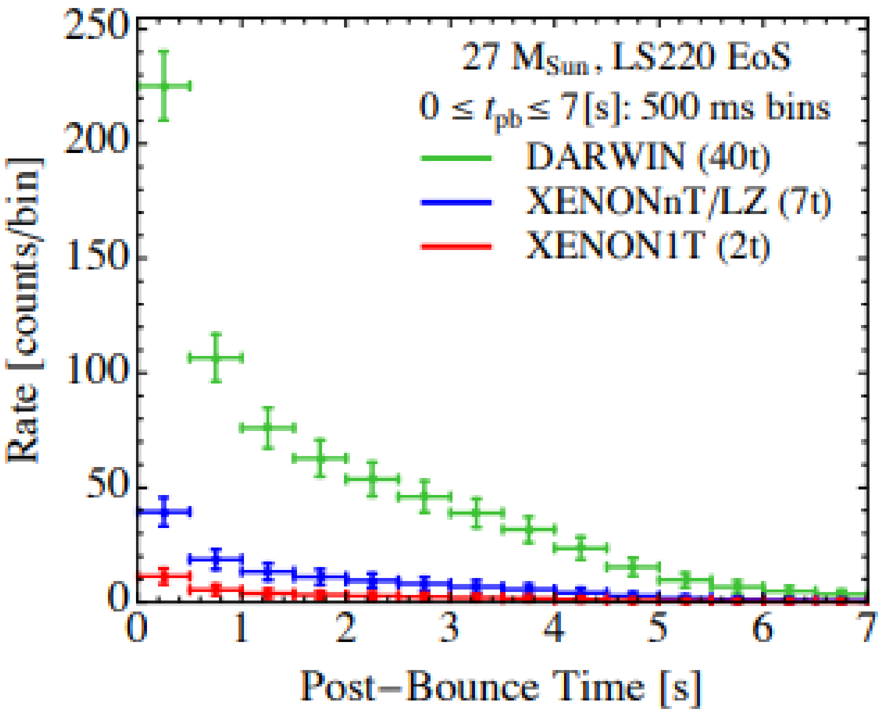
JUNO, *JCAP* **01** 057 (2024)



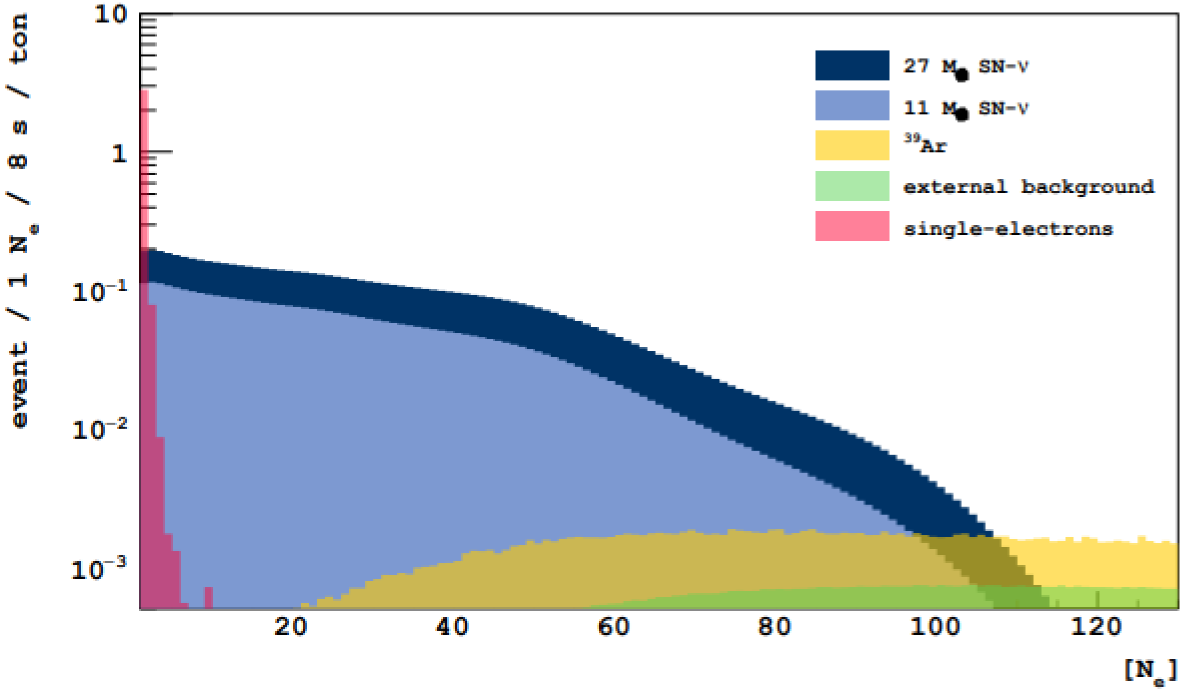


Simplest question – measuring rate with DM experiments

Lang, McCabe, Recihard, Selvi, Tamborra, PRD 94 103009 (2016)



DarkSide-20k JCAP 03 043 (2021)

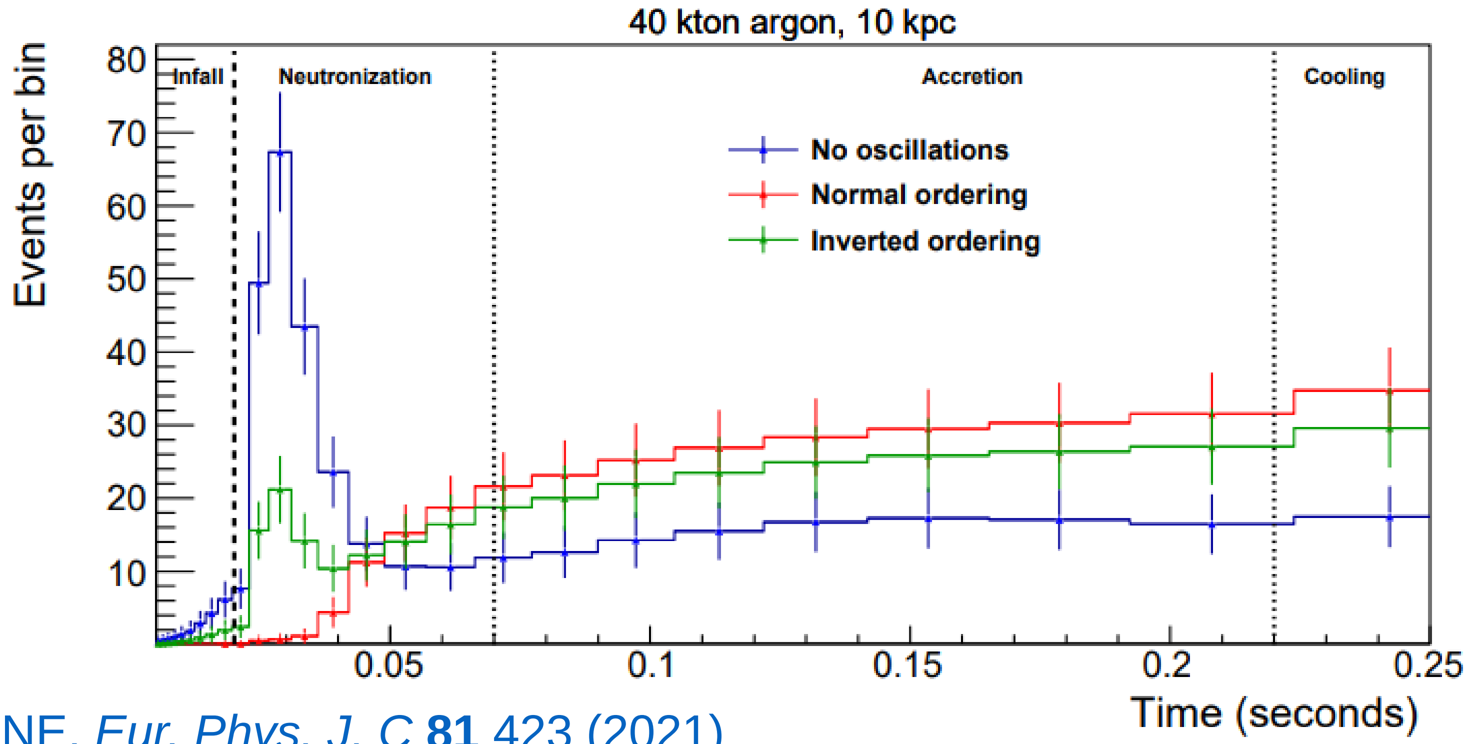


No uncertainty from neutrino oscillations, understood detector response and signal

Very low-energy! Opens to new physics searches

Each detector would only see 100s of events – pooling between multiple experimeints

Probing the neutronization burst with DUNE



[DUNE, *Eur. Phys. J. C* **81** 423 (2021)]

Argon detectors have strong sensitivity to the ν_e flux – gives unique sensitivity to characteristics of the neutronization burst

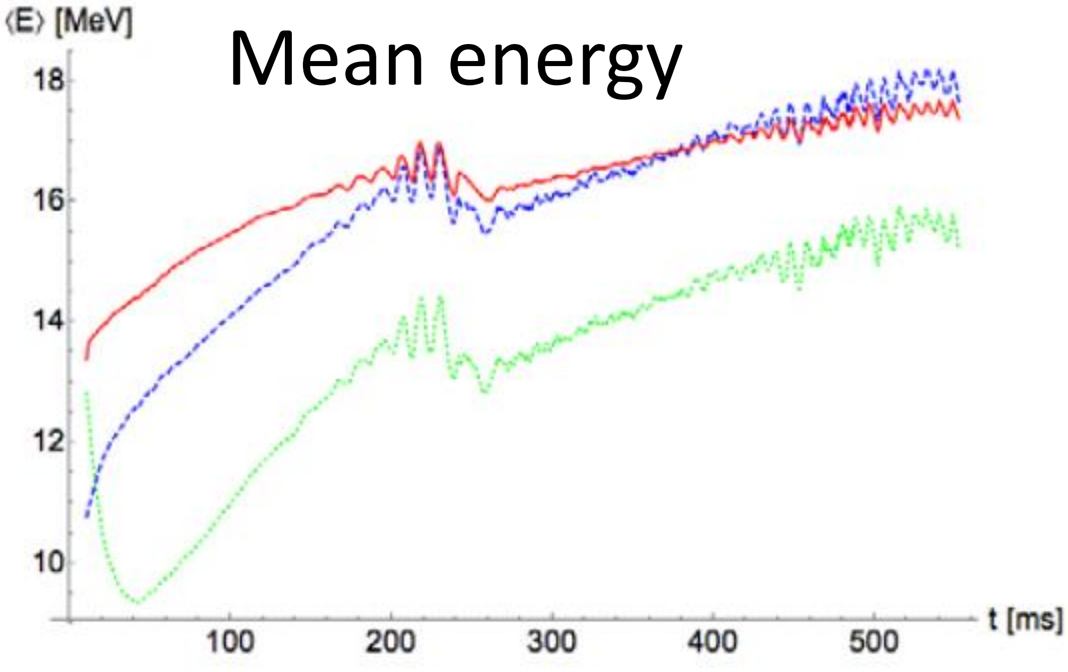
Neutronization burst often considered a “standard candle” – easy time window to study nuclear physics of proto neutron star, new neutrino properties, and the core-collapse mechanism

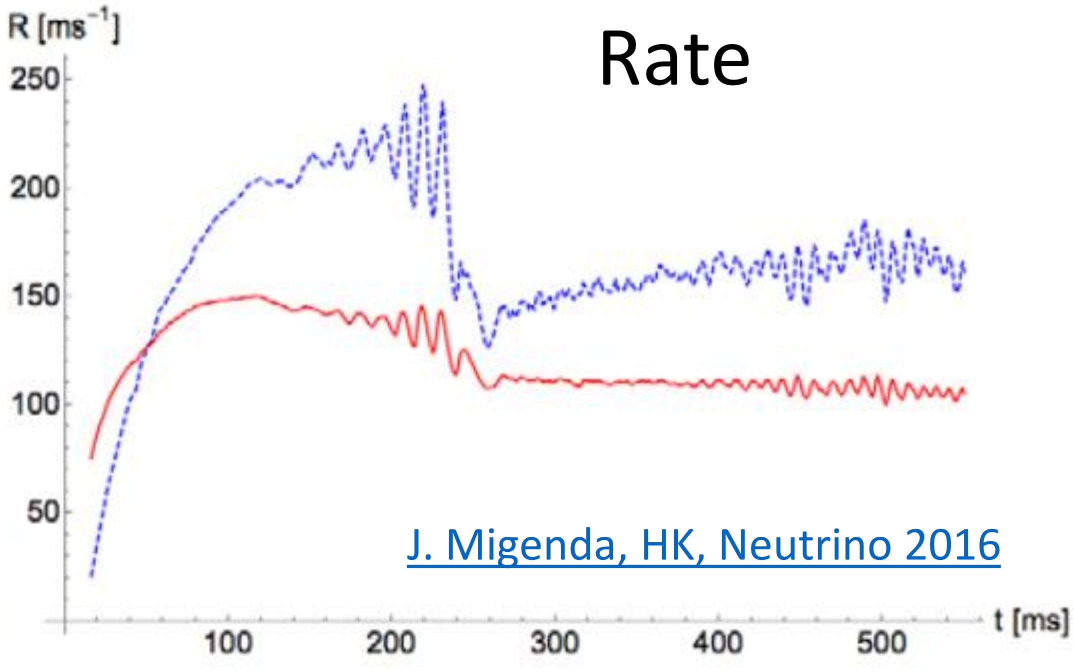
Searching for SASI oscillations in HK

Standing accretion shock instability (SASI) – as shock wave stalls, a modulating pattern in emission rate and energy is expected

Amplitude and frequency gives direct information about matter properties in collapse

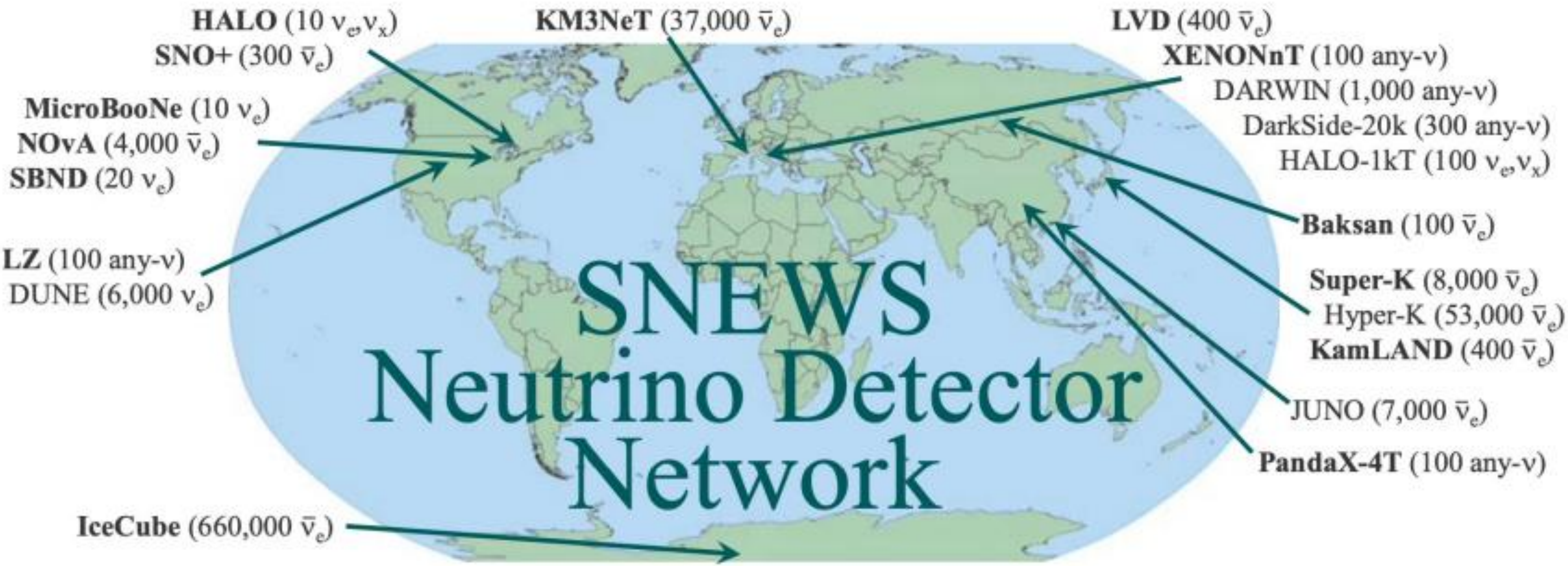
At 260 kt, HK's massive size makes it ideal for studying SASI





J. Migenda, HK, Neutrino 2016

A global picture



https://snews2.org/

Sign up for the email list or be left behind: https://snews.bnl.gov/mailinglists.html

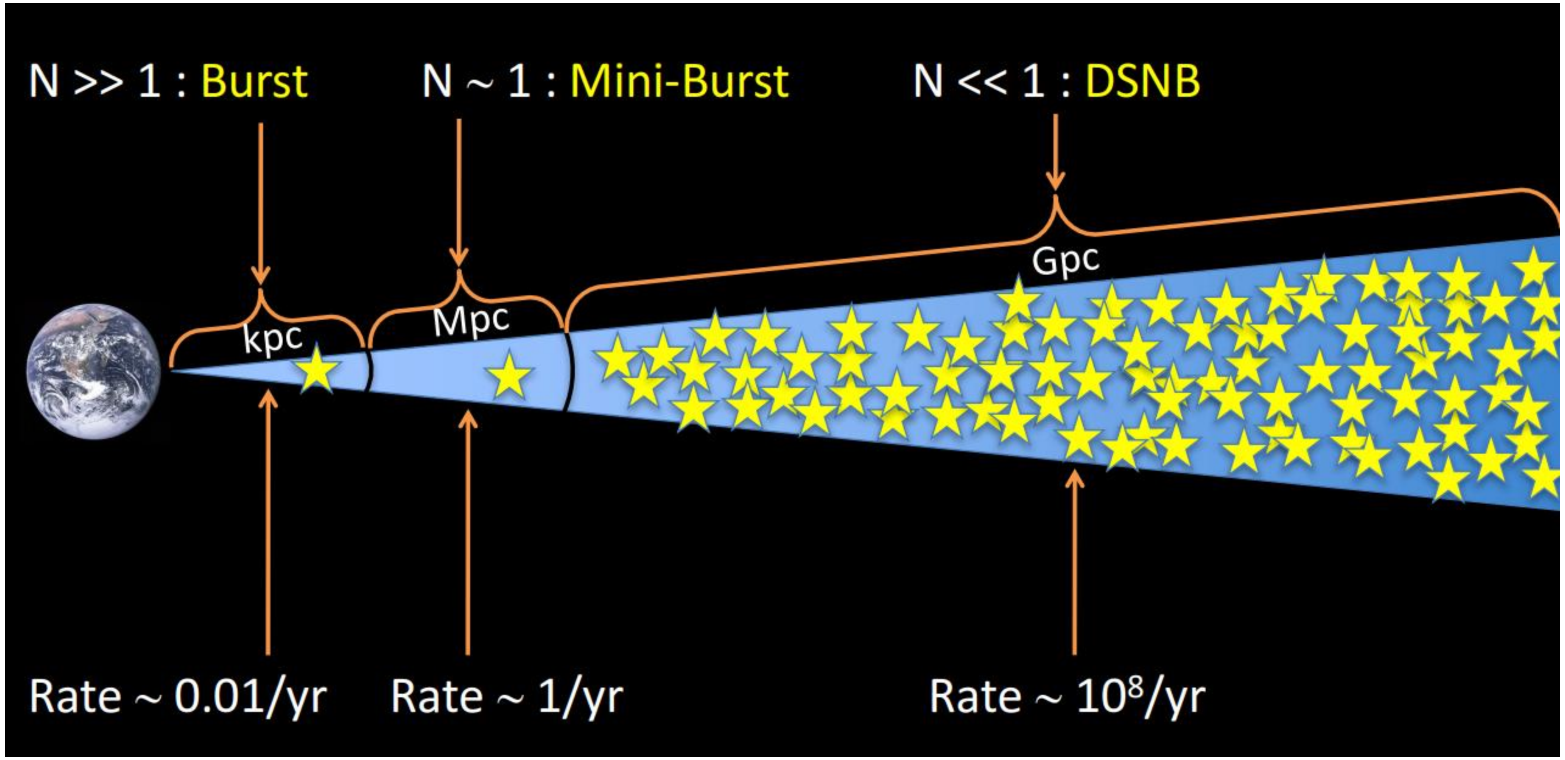
Extra-galactic supernova neutrinos

Neutrino flux per $\propto 1/r^2$
Rate of supernova $\propto r^2$

Two effects cancel out and the total flux of supernova events sums to a finite contribution

Guaranteed signal!

Diffuse supernova neutrino background (DSNB)



$$\frac{d\Phi}{dE} = \int_0^{z_{max}} R_{SN}(z) \times \frac{dN(E'_\upsilon)}{dE'_\upsilon}(1+z) \times \left| c\frac{dt}{dz} \right| dz$$

Density of supernova events (/Mpc^3/s)

Neutrino spectrum released by supernova (redshifted)

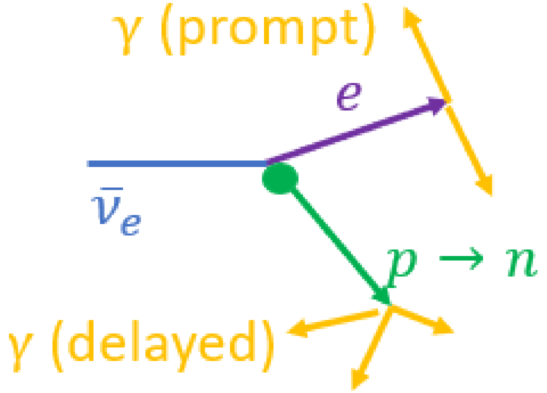
Inflation effects

Low flux, < 2.7 $\bar{\nu}$ / cm^2 / s

SK *PRD* **104** 122002 (2021)

DSNB measurements in SK

Water detector – IBD search

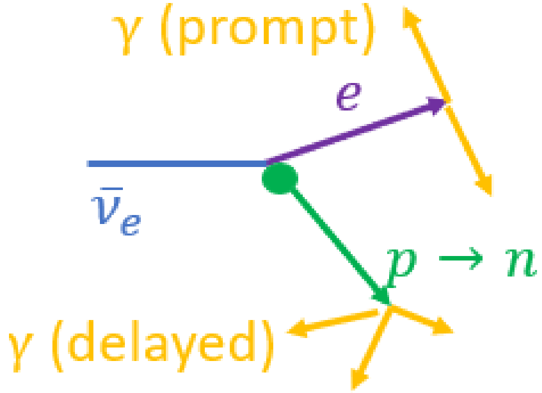


In water, neutron captures on ^{1}H giving 2.2-MeV gamma -> below SK threshold (3.5 MeV)

Isotope	Cross-section [mb]	Q-value [MeV]
^{1}H	332.6	2.2
^{12}C	3.53	4.9
^{16}O	0.190	4.1
^{157}Gd	2.54×10^{8}	7.9

DSNB measurements in SK

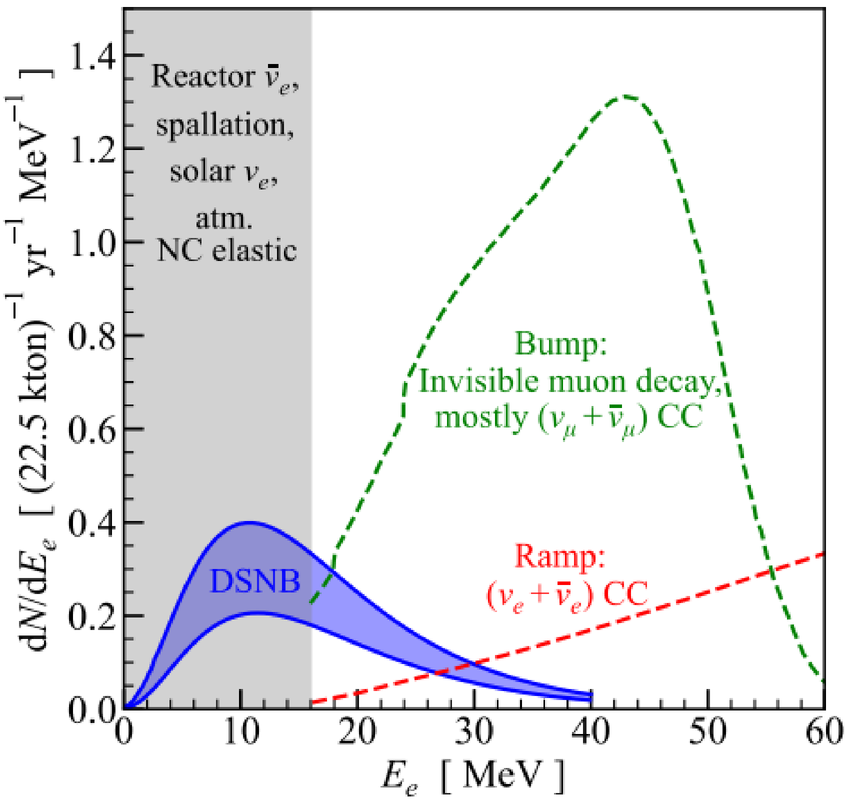
Water detector – IBD search



In water, neutron captures on ^{1}H giving 2.2-MeV gamma -> below SK threshold (3.5 MeV)

Isotope	Cross-section [mb]	Q-value [MeV]
^{1}H	332.6	2.2
^{12}C	3.53	4.9
^{16}O	0.190	4.1
^{157}Gd	2.54×10^8	7.9

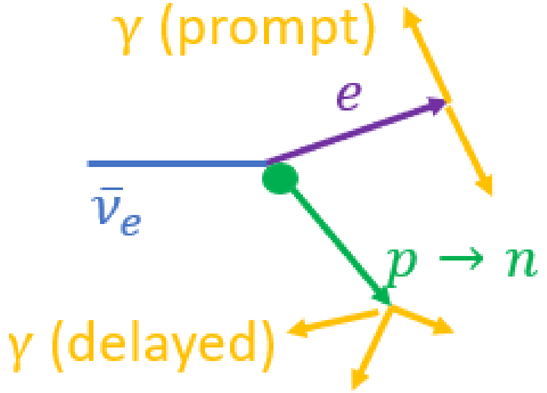
Gives giant bkg from muon decay



Zhou and Beacom, arXiv:2311.05675 (2023)

SK-Gd upgrade – for DSNB measurements

Water detector – IBD search



SK doped 0.03% Gd -> captures now visible releasing 7.9 MeV! Removes

Isotope	Cross-section [mb]	Q-value [MeV]
^{1}H	332.6	2.2
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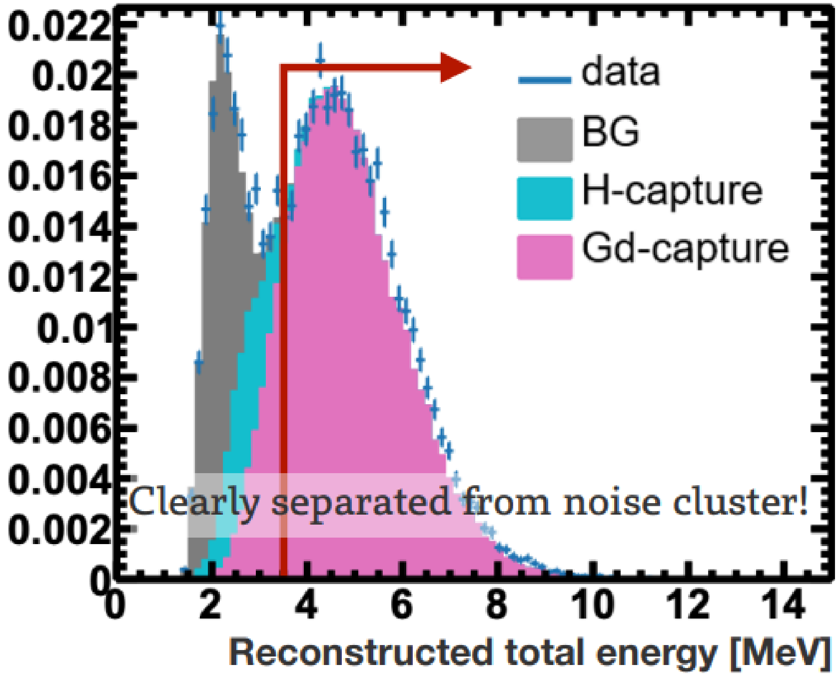
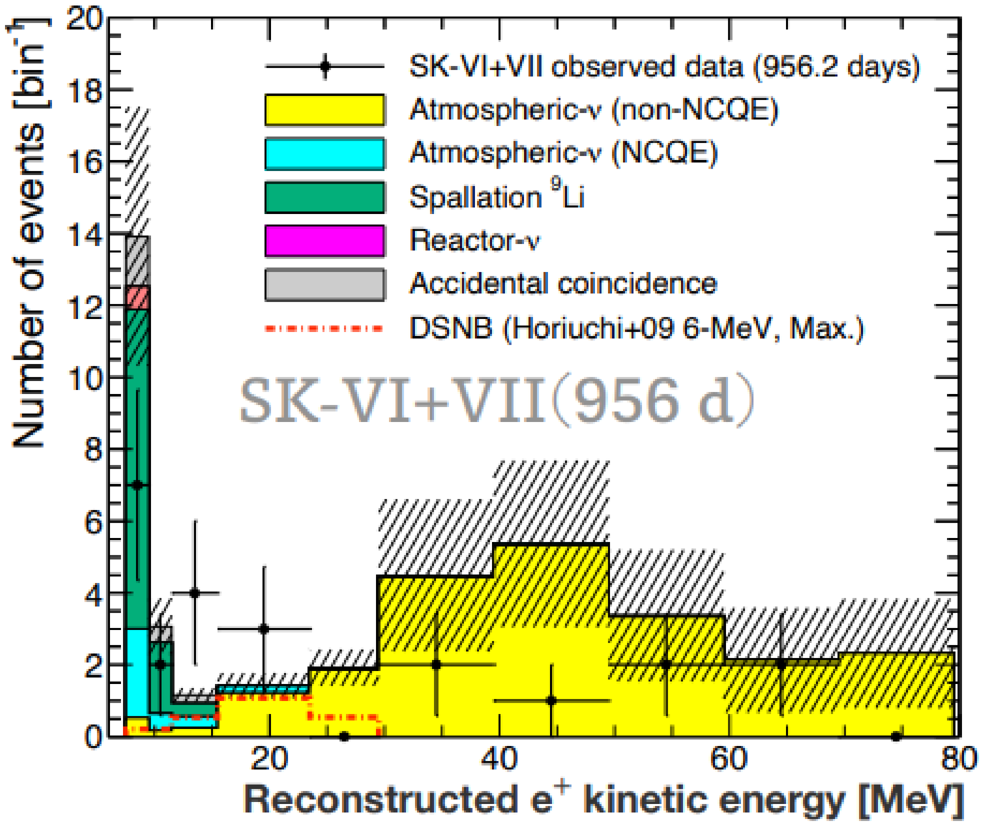
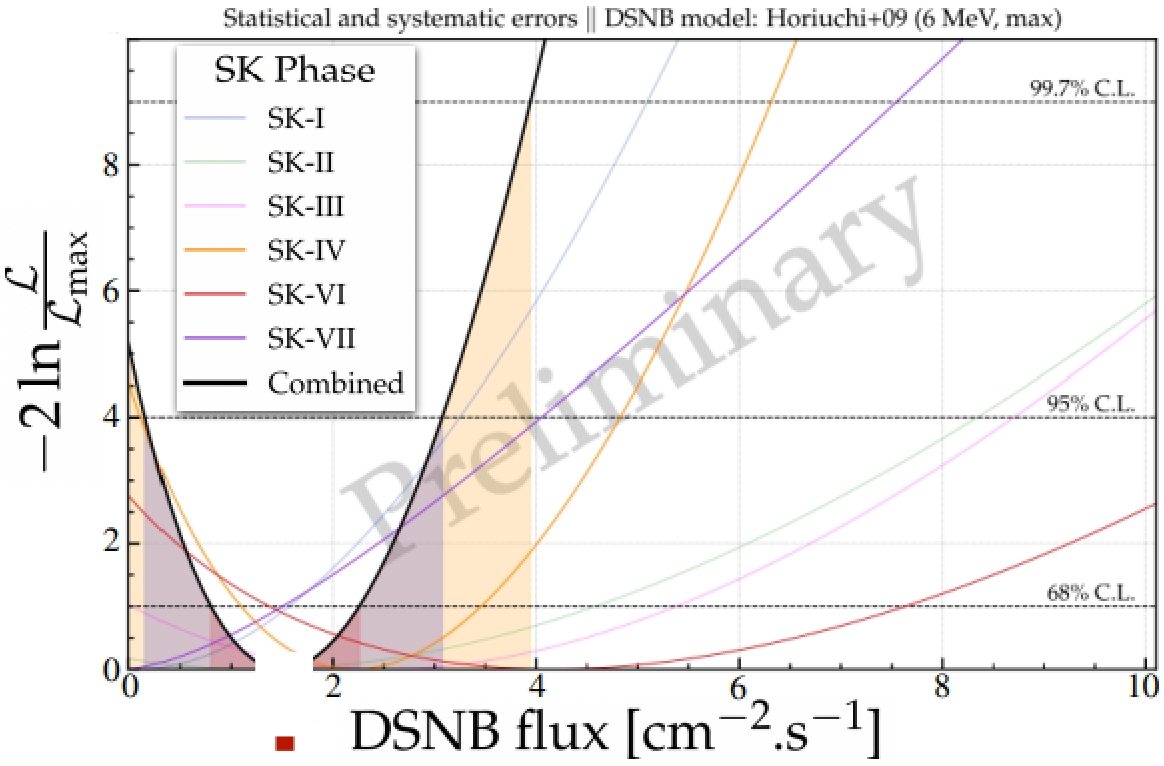


SK-Gd offers a hint of DSNB

956 days of SK-Gd gives similar sensitivity to 5823 days of SK

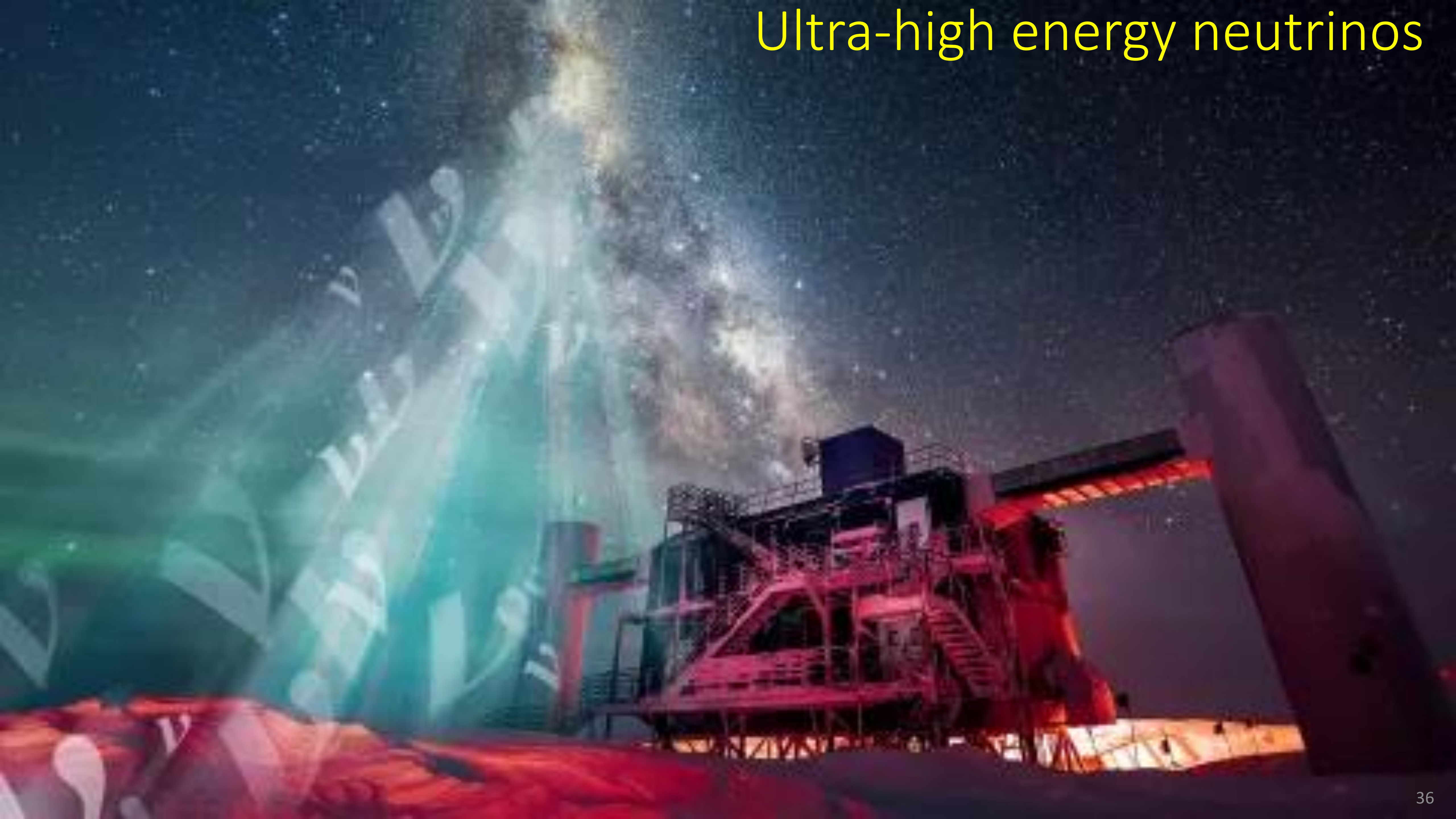
2.3 σ excess: preliminary data looks like a flux of 1-2 $\bar{\nu}$ / cm^2 / s





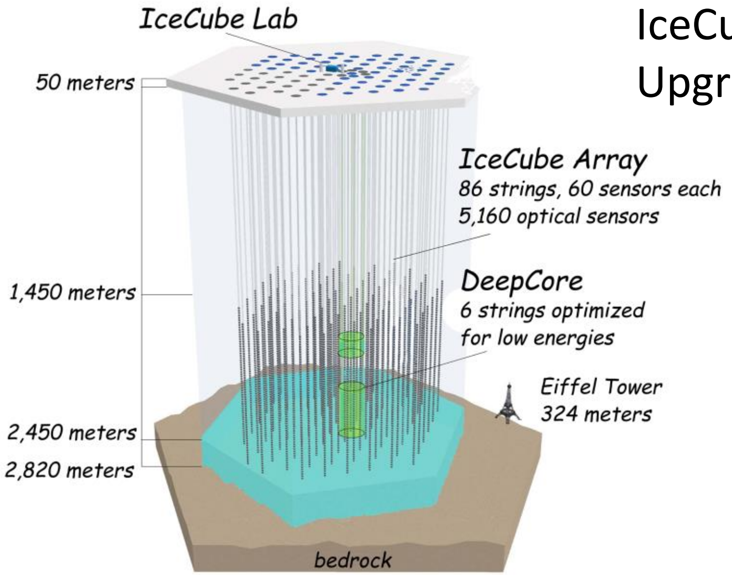
Masayuki Harada, Neutrino 2024

Ultra-high energy neutrinos



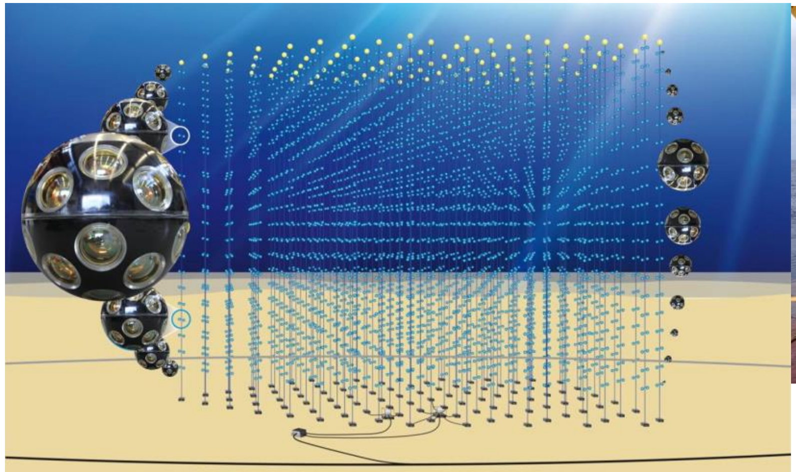
Cherenkov neutrino telescopes at the km^3 scale

Glacier



IceCube – results since 2013
Upgrade to gen2 in mix

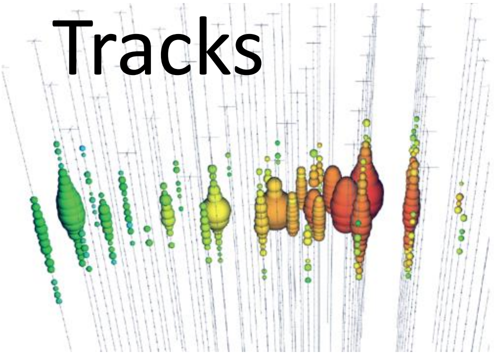
Ocean



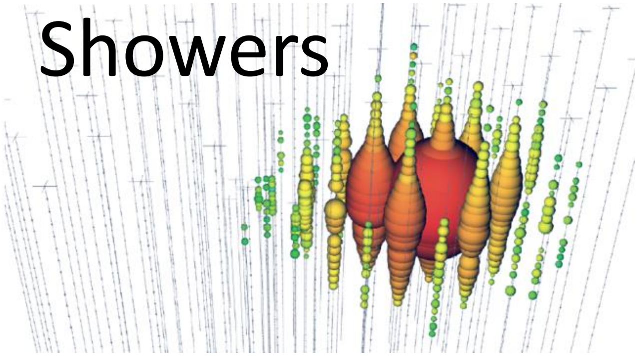
KM3NeT/ARCA
28/230 deployed

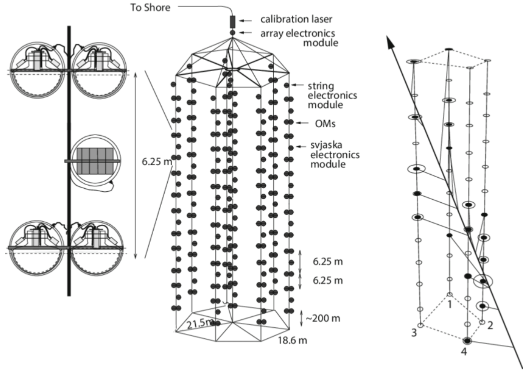
Baikal
110 strings deployed

Tracks



Showers





Advantage: less optical absorption = better light collection

Advantage: less optical scattering = better angular resolution

Is Earth transparent to neutrinos?

Scattering length: $L = 1/n\sigma$

Earth's diameter = 12700 km

Earth is transparent for $\sigma > 1/nL$

$\sigma >$ 1/[(6 g/cm^3 x 6e23/g) x (1e9 cm)]

$\sigma >$ 3e-34 cm^2

Is Earth transparent to neutrinos?

Scattering length: $L = 1/n\sigma$

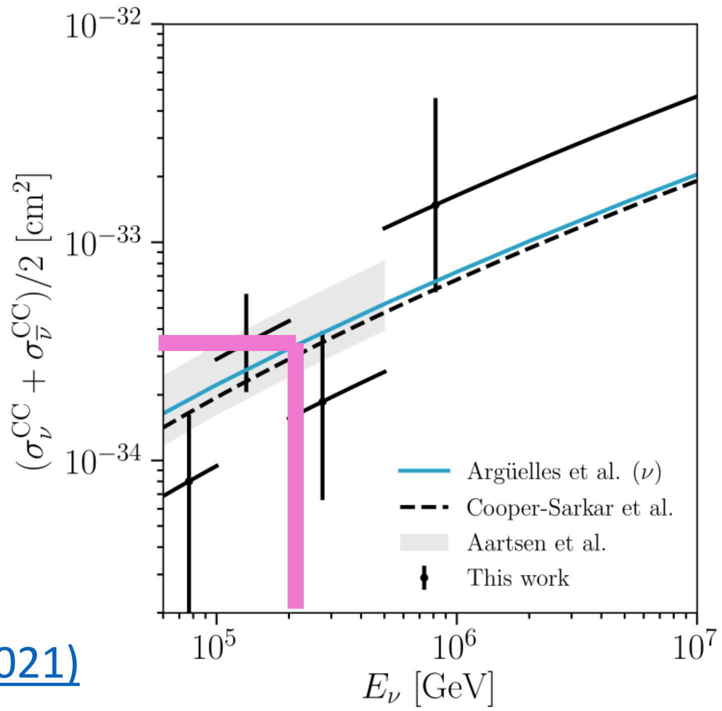
Earth's diameter = 13000 km

Earth is transparent for $\sigma > 1/nL$

$\sigma > 1/[(6\ \mathrm{g/cm^3} \times 6\mathrm{e}23/\mathrm{g}) \times (1.3\mathrm{e}9\ \mathrm{cm})]$

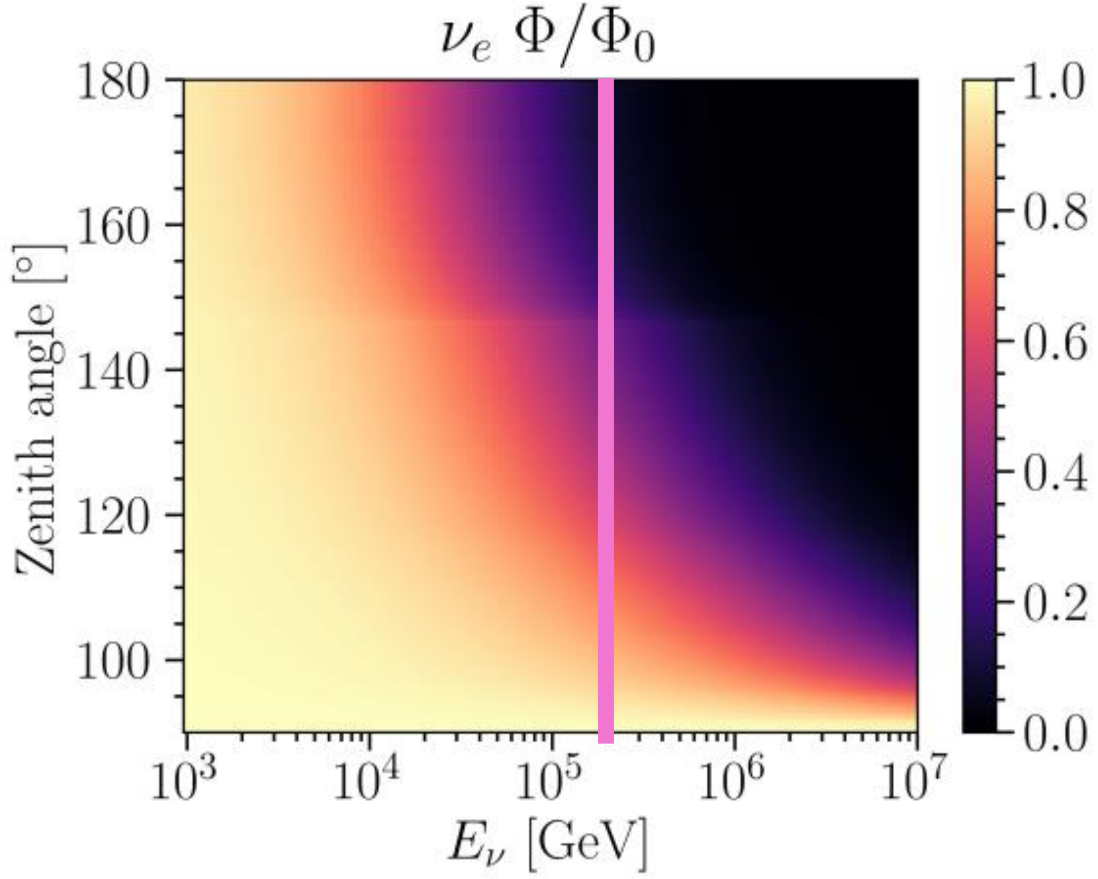
$\sigma > 3\mathrm{e}{-34}\ \mathrm{cm}^2$

Above 2e5 GeV worry about absorption in Earth

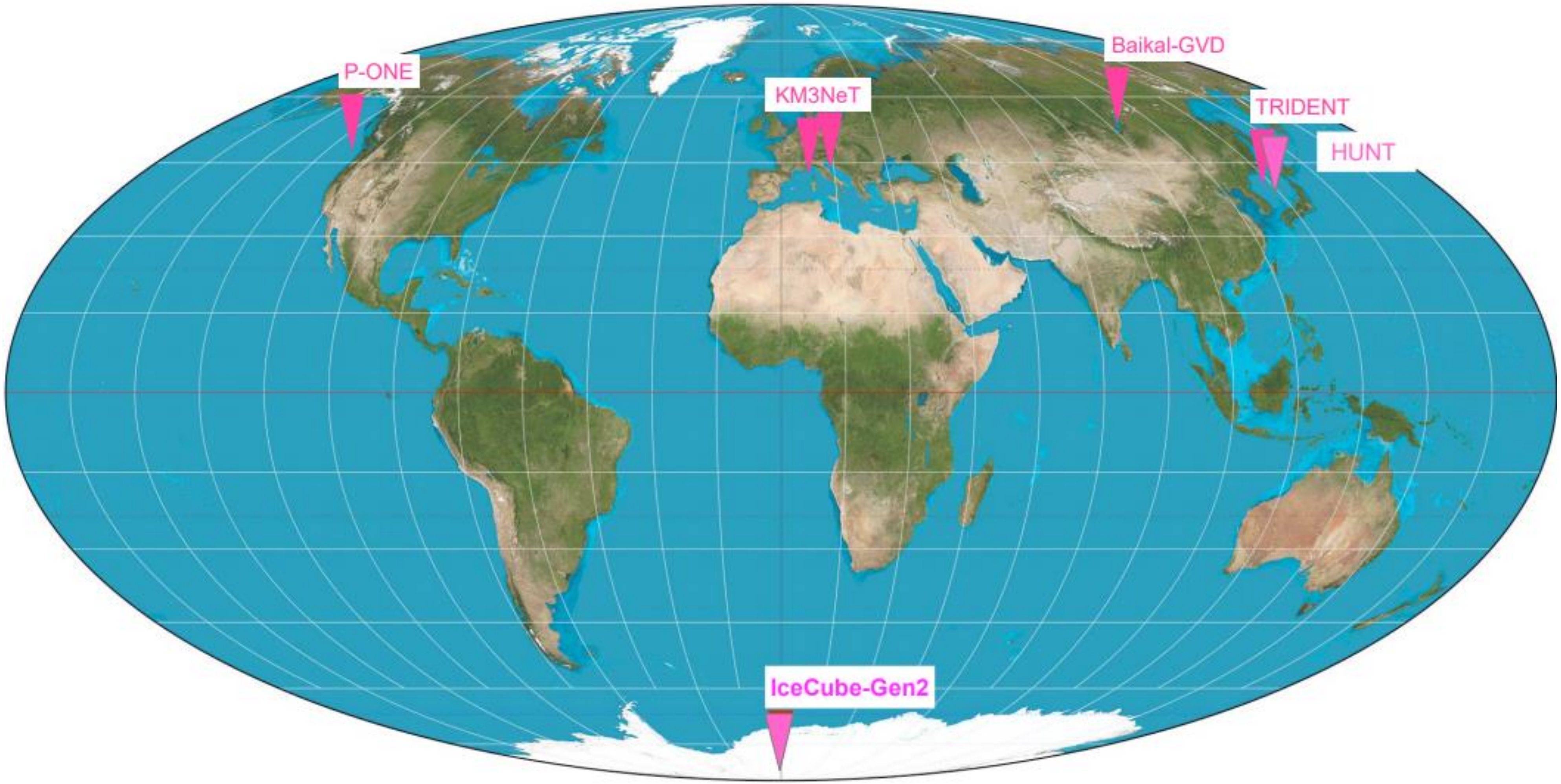


IceCube, *PRD* **104**, 022001 (2021)

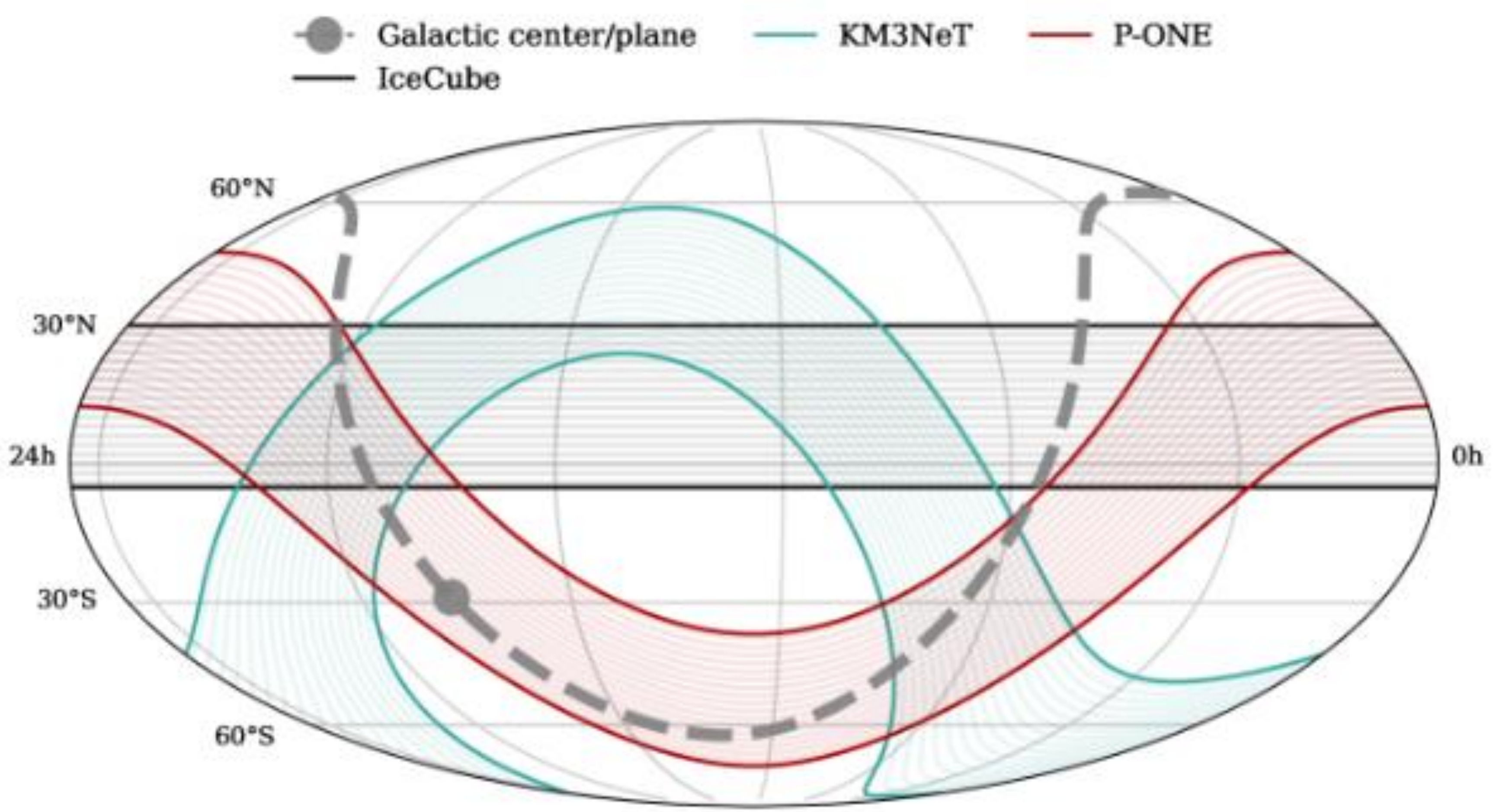
Only sensitive to sky just under horizontal at high energy



Solution: multiple telescopes across the globe

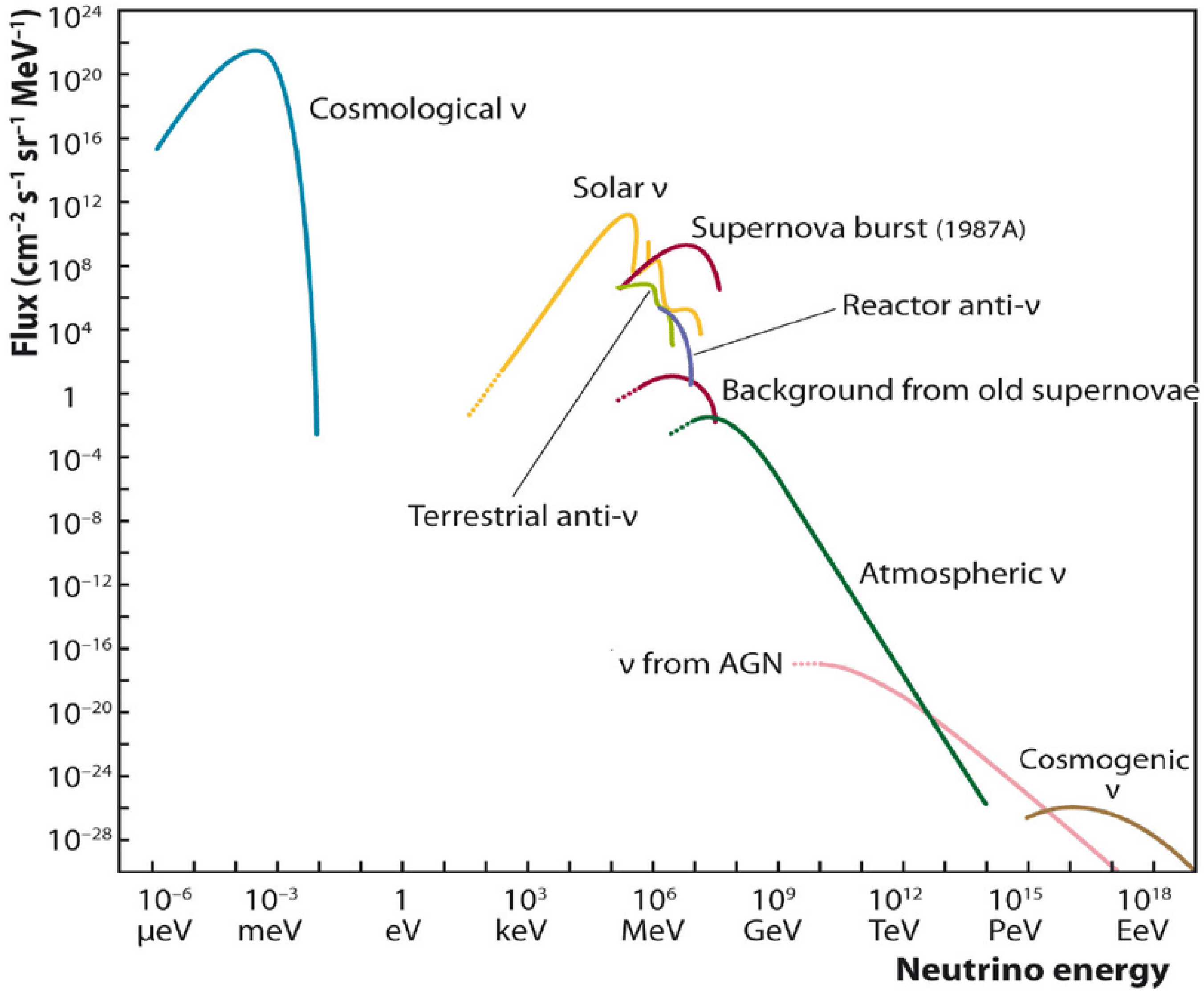


Complimentary sky sensitivity



[Arguelles, Hlazen, Kurahashi, arXiv:2405.17623](https://arxiv.org/abs/2405.17623)

Reaching beyond the solar system

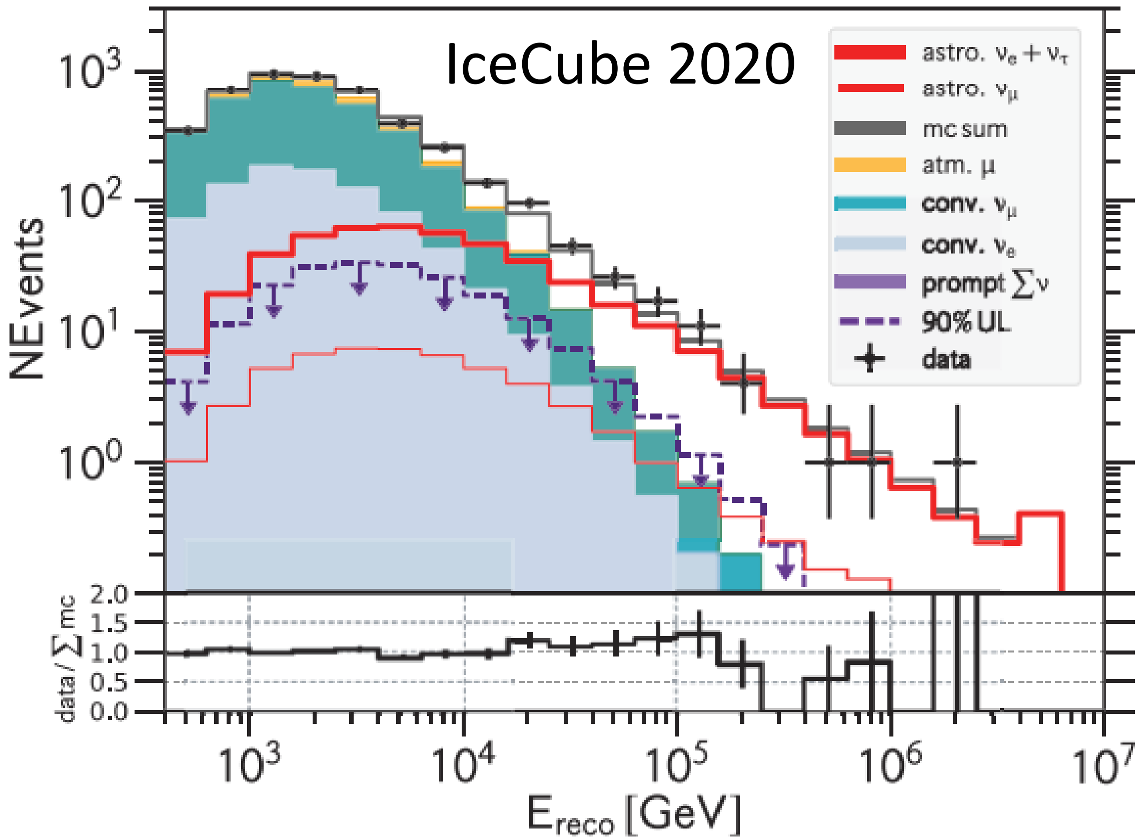


With light, cosmic rays, and gravitational waves, neutrinos are an important component of modern astronomy

Step 1:
Above several TeV, astrophysical and cosmogenic neutrinos dominate over atmospherics. First goal is to observe these neutrinos

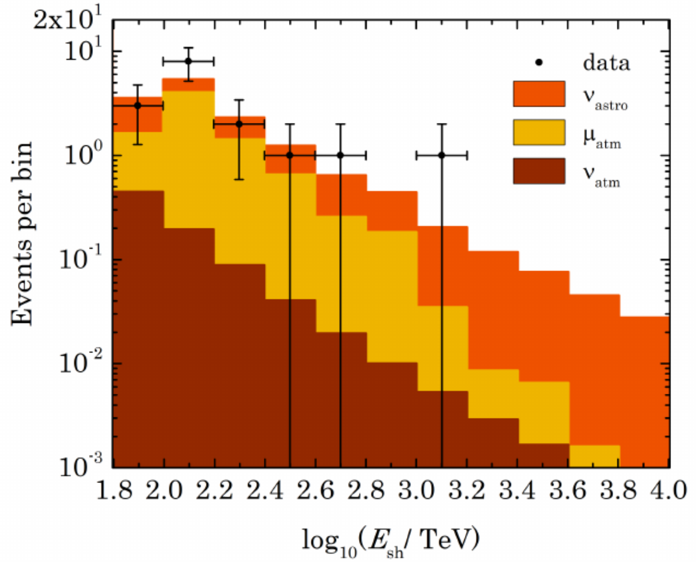
Step 2:
Classify the identified sources

Measuring astrophysical neutrinos: the PeV frontier

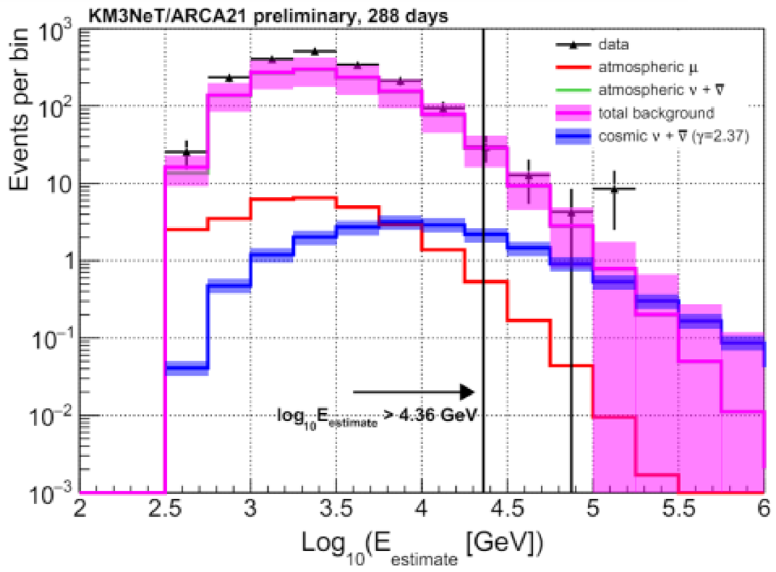


IceCube *PRL* **125** 121104 (2020)

In reach of partially-commissioned liquid telescopes

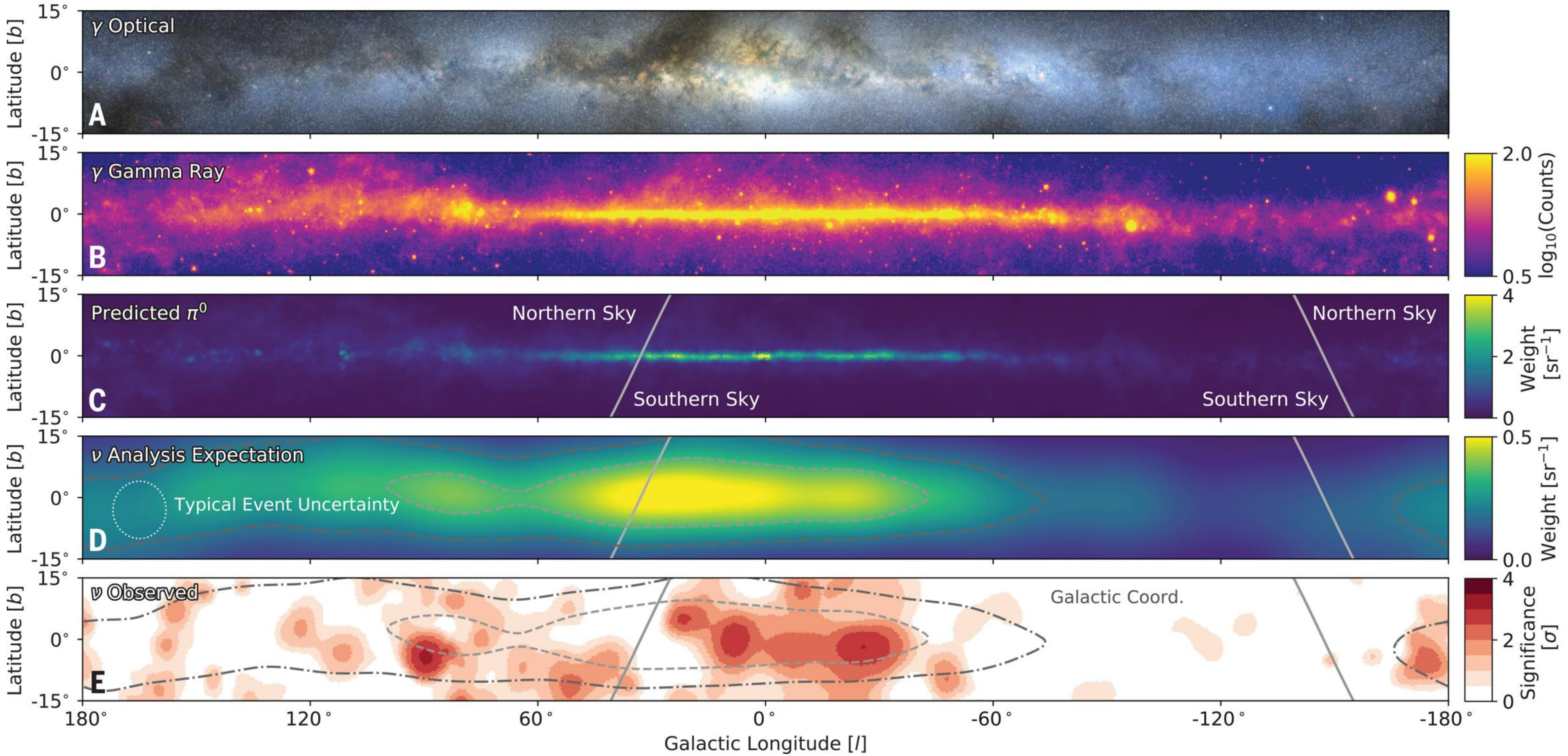


Baikal, *PRD* **107** 042005 (2023)

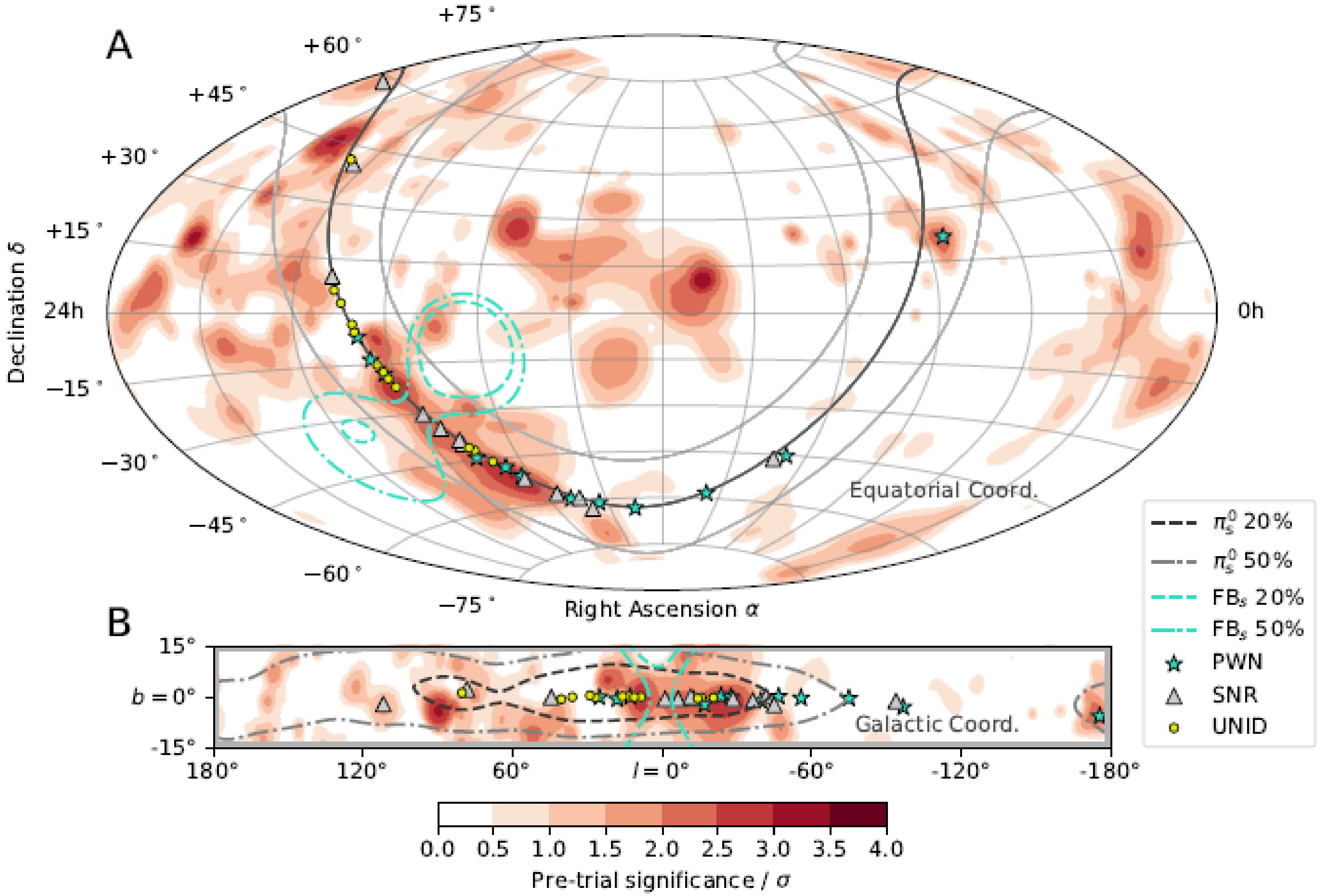


J. Coelho, Neutrino 2024

Neutrinos from the Milky Way



Resolving individual sources

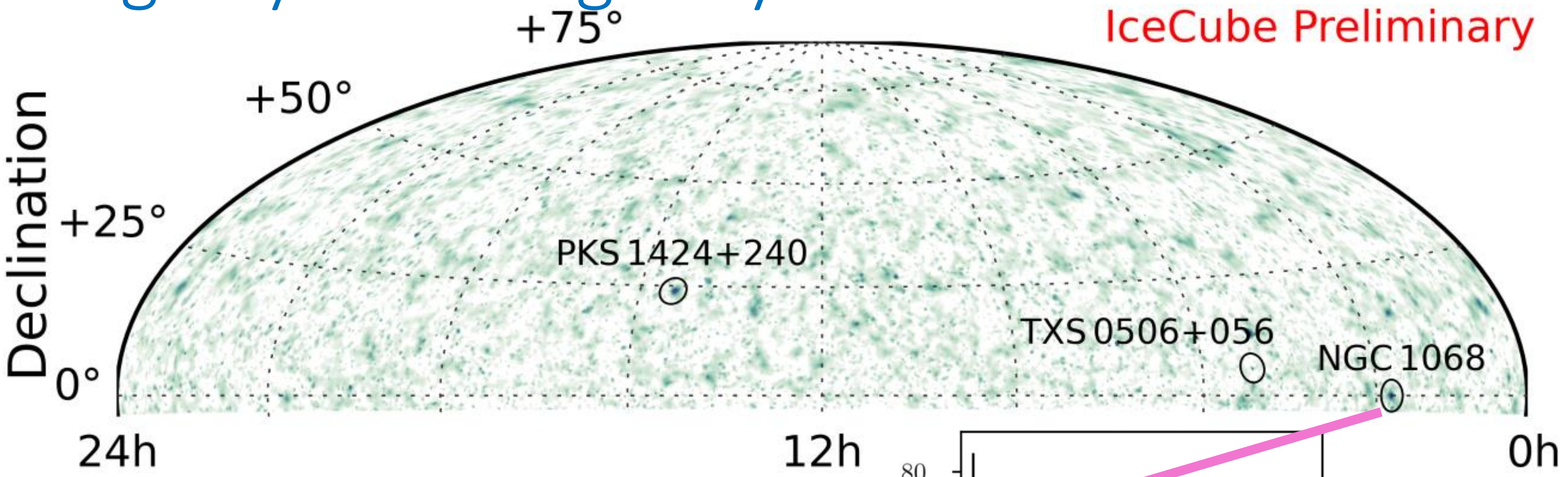


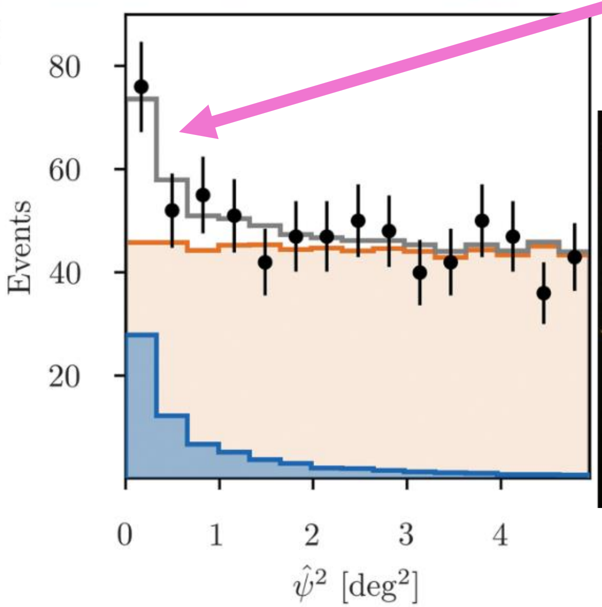
Do these neutrinos correlate to a specific source?

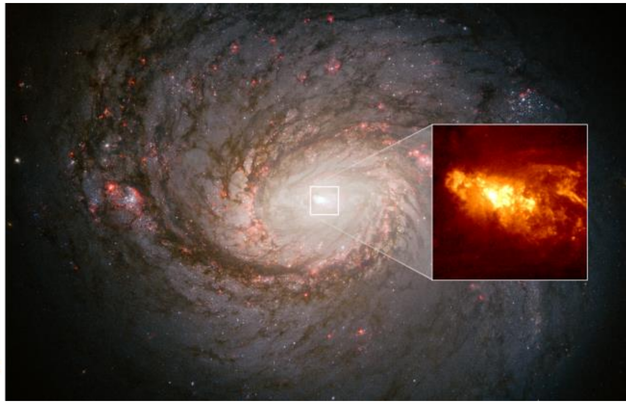
Some local densities that cluster around supernova remnants – more data needed!

Combination of IceCube gen2 and Baikal, KM3NeT, and p-ONE could make clear statement

Reaching beyond the galaxy



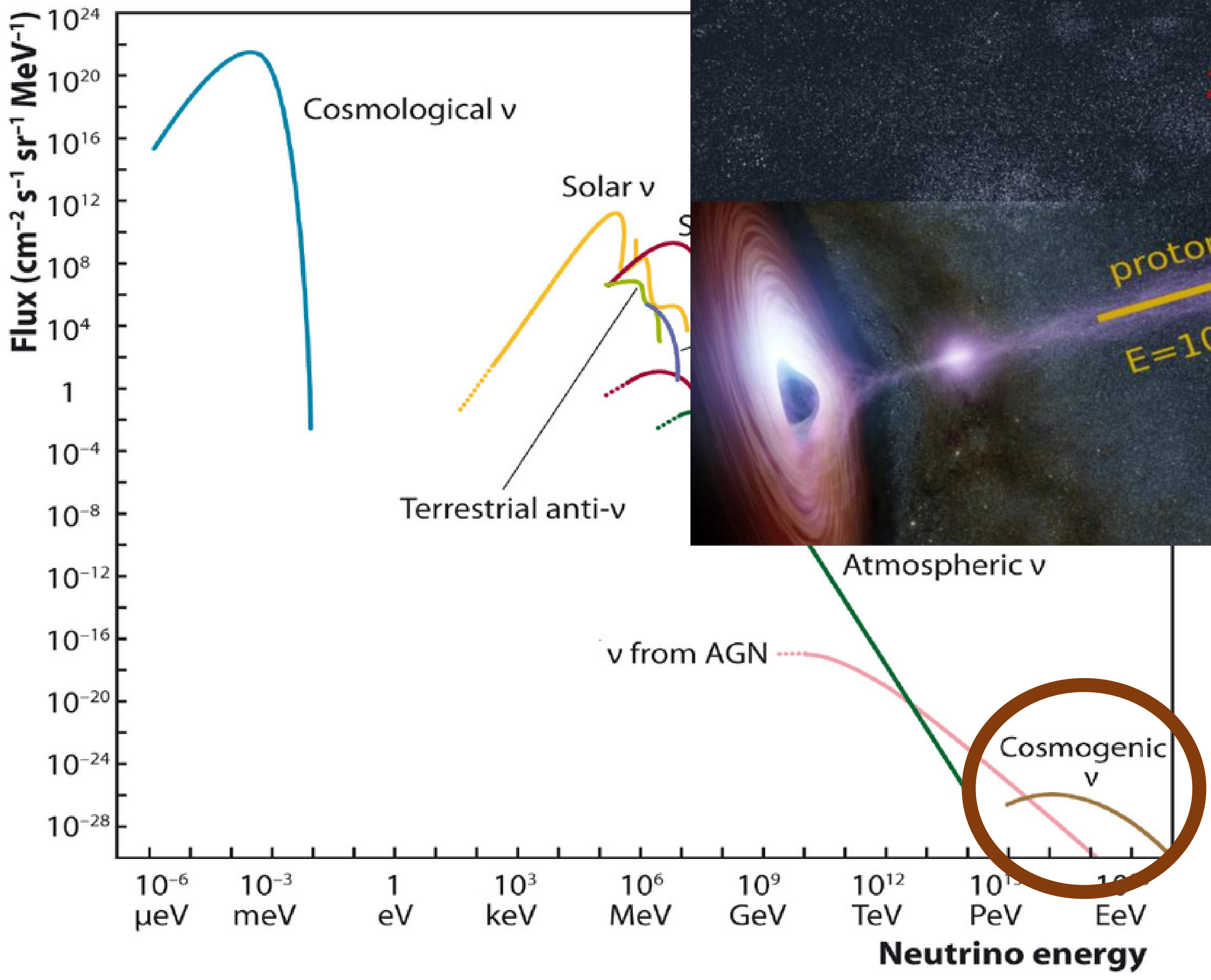


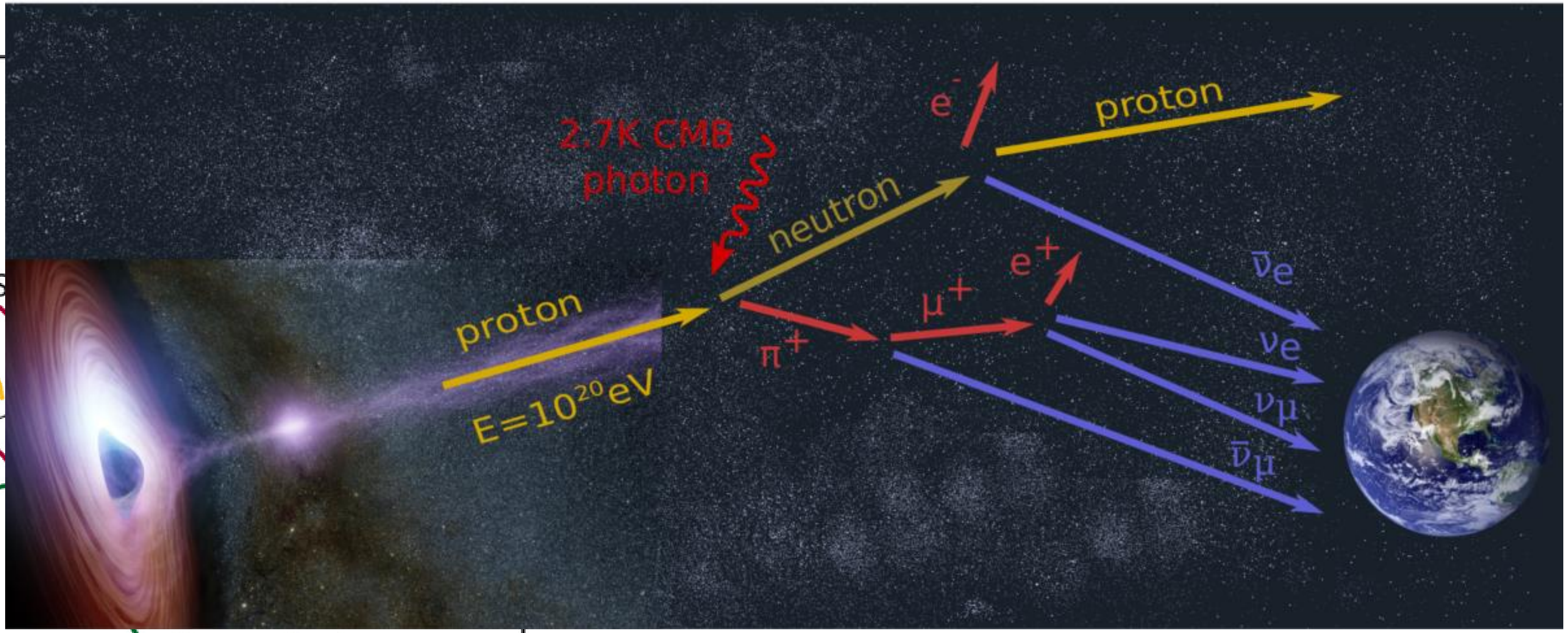


4.0 σ identification of multi-TeV neutrinos from galaxy NGC 1068

AGN with supermassive black hole emitting radiation, including neutrinos
Searching other Seyfert galaxies for similar neutrino spectra with 2-3 σ evidence

Cosmogenic neutrinos





10^{20} eV protons resonantly scatter off CMB photon making a Δ_{1232} whose decay produces PeV-EeV neutrinos: The GZK resonance neutrinos

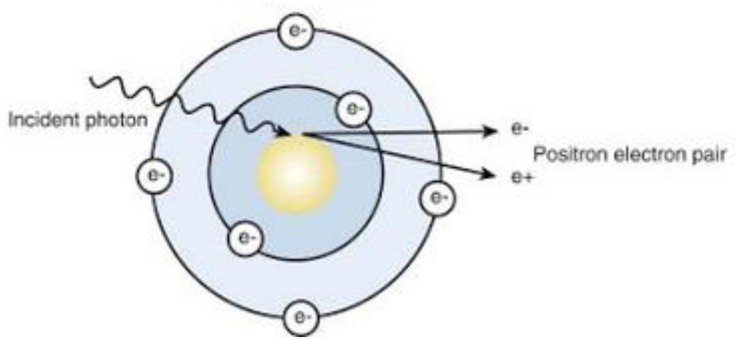
Very rare, very large interactions. Need more fiducial mass

Radio detection of neutrinos

Askaryan radiation:

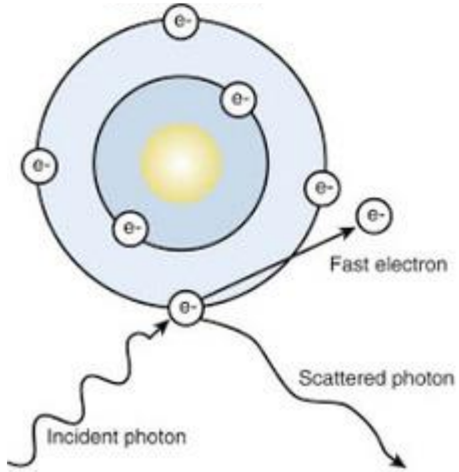
Electromagnetic showers drive a current of electrons and positrons – **but more electrons produced due to Compton scattering**

Pair production



e+ and e- current

Compton



e- current

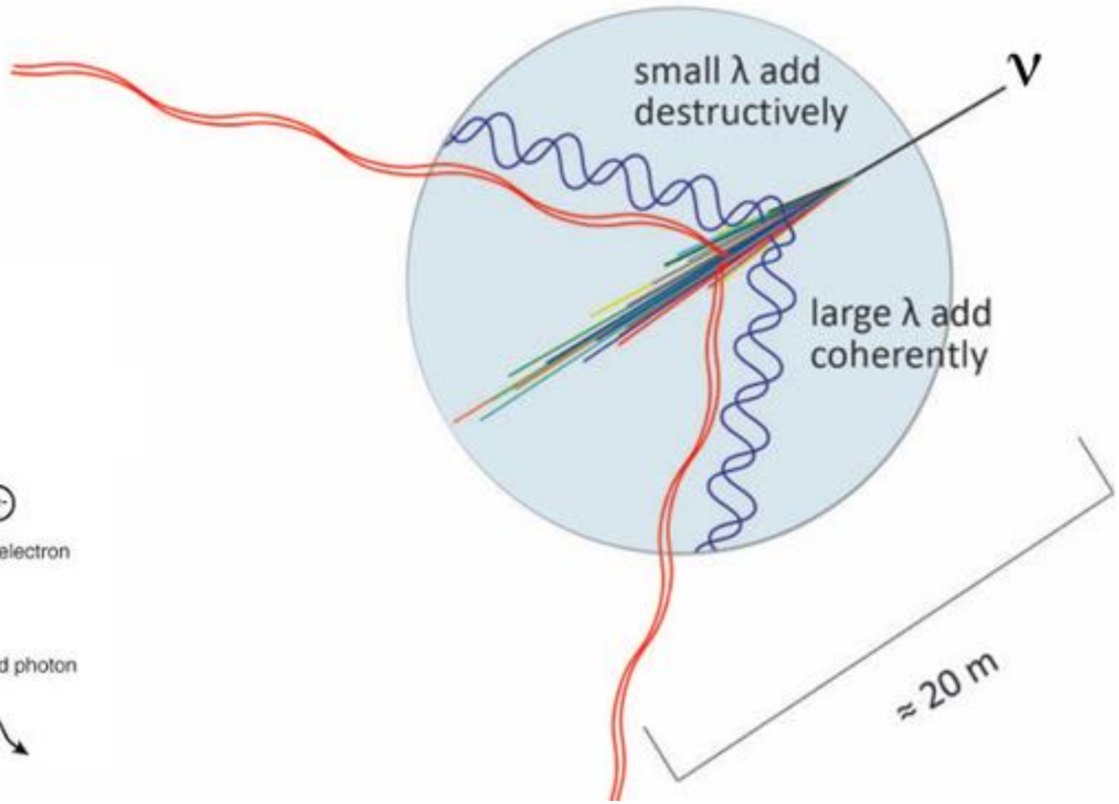
Radio detection of neutrinos

Askaryan radiation:

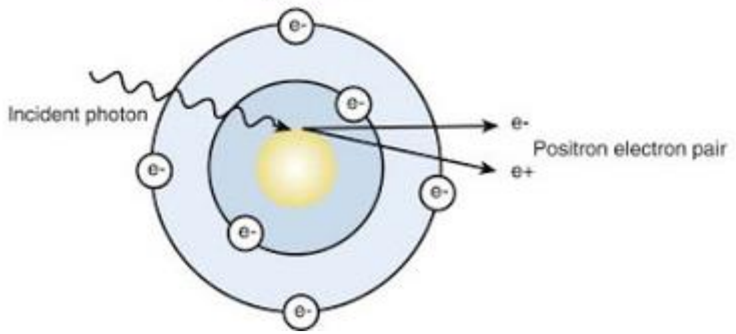
Electromagnetic showers drive a current of electrons and positrons – **but more electrons produced due to Compton scattering**

For constructive interference:
Need wavelength > shower size

Radio emission!!!

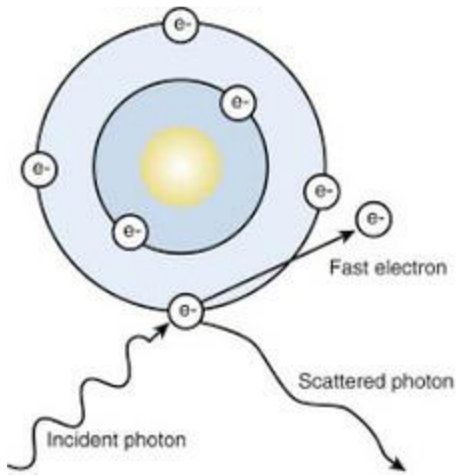


Pair production



e+ and e- current

Compton



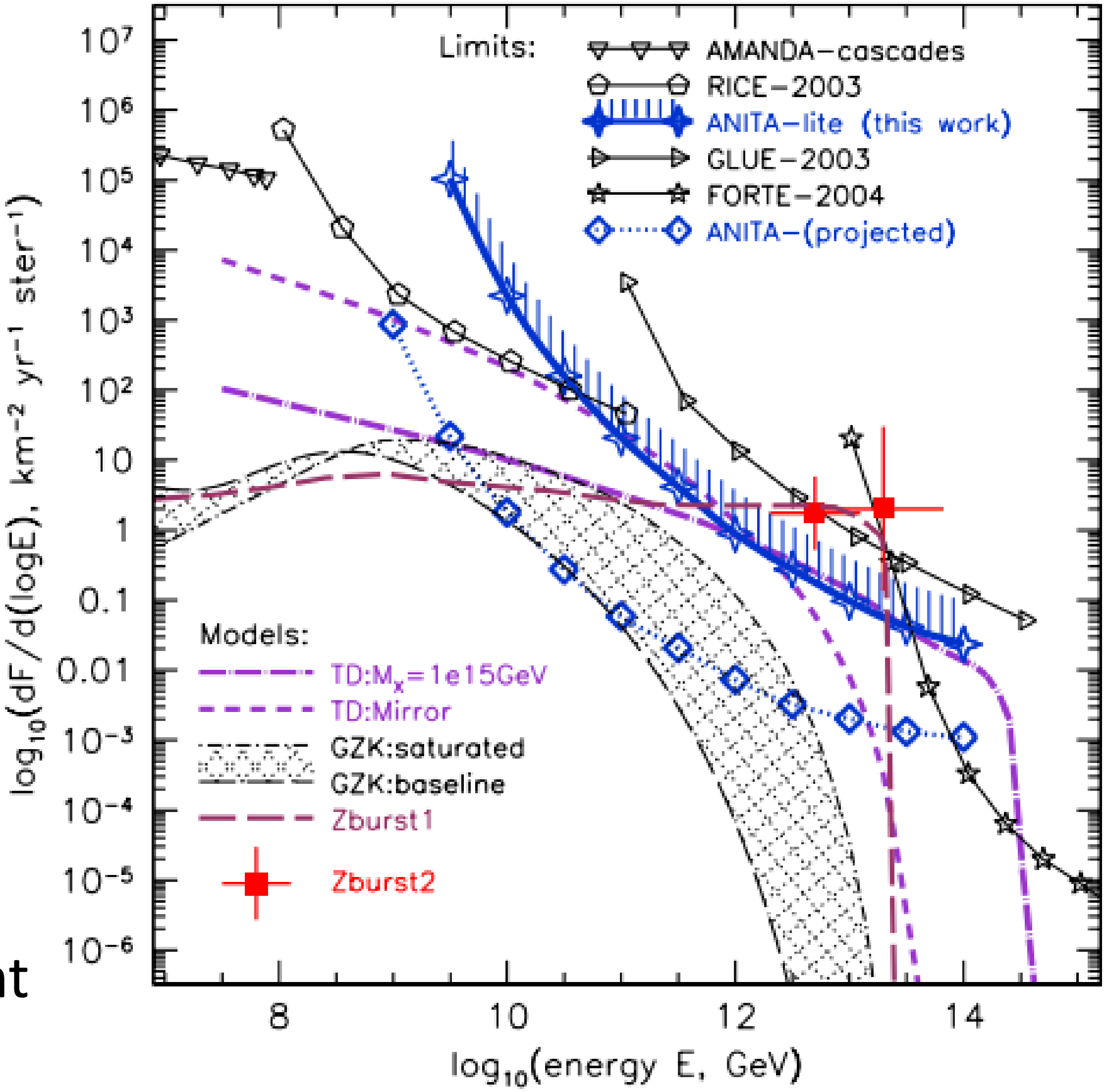
e- current

ANITA – a balloon-based experiment

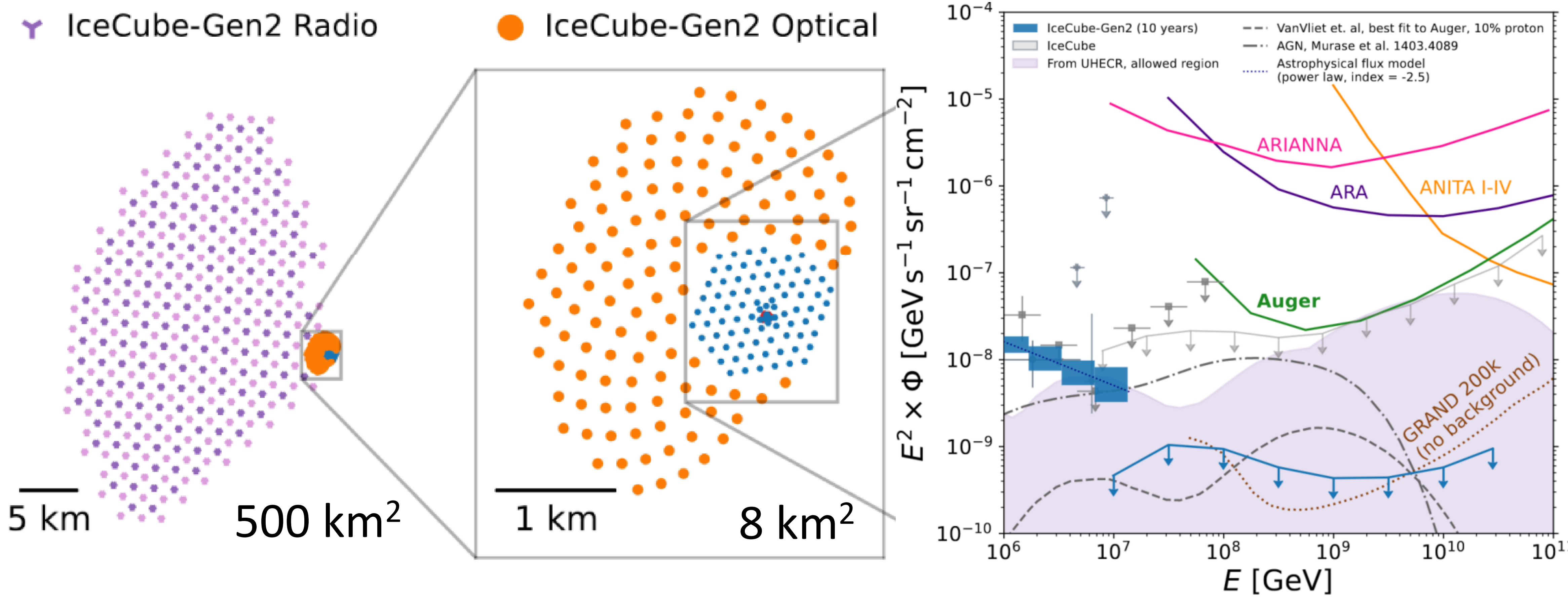
First attempts used balloons scanning areas of 10^4 km^2

Upcoming PUEO experiment may probe expected GZK

ANITA, *PRL* **96** 171101 (2006)



IceCube gen2 radio upgrade



Good news – attenuation length much longer for radio in ice. IceCube gen2 plans to deploy a sparse network of radio antennae with excellent coverage of GZK neutrino parameter space

Summary

– Neutrinos’ feeble interaction strength make them an important aspect of modern astronomy giving information about the most dense and exotic objects in the universe

– Neutrinos were first fermions to decouple in the universe – big bang evidence

– Core-collapse supernova are rare, but their neutrino bursts give an incredible amount of information about particle physics and astrophysics

– Dedicated km^3 or larger telescopes becoming critical to astronomy

– Most experiments also involved in neutrino oscillations – stay tuned for tomorrow!