Modern SN neutrino detection

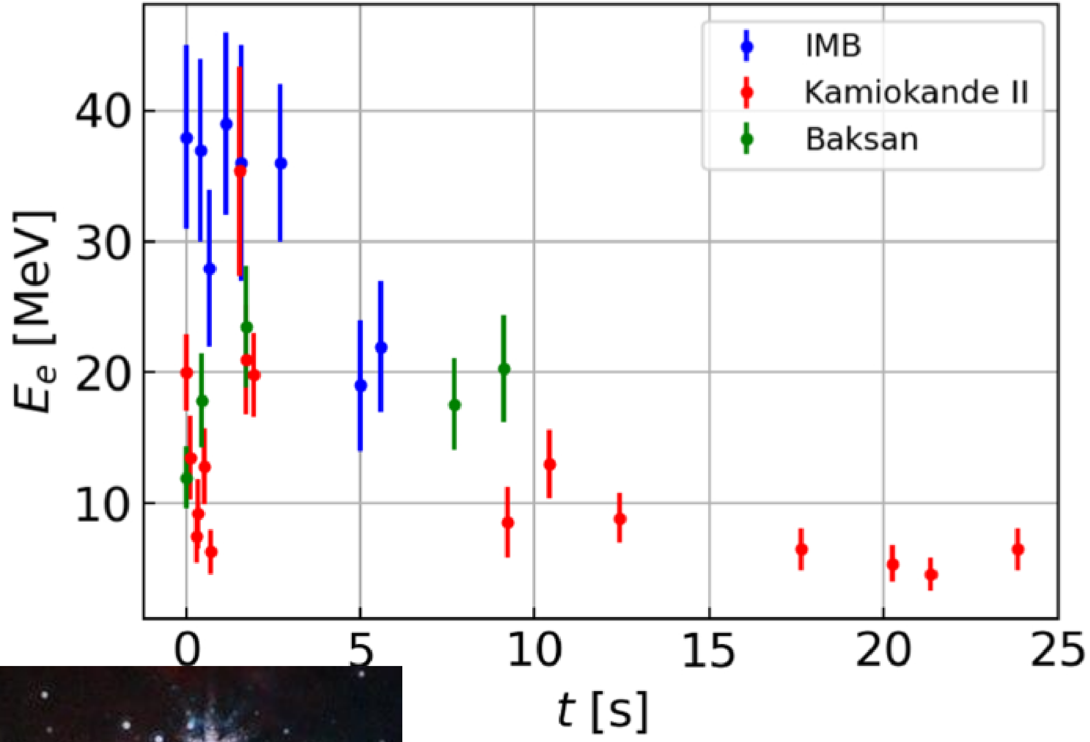
Dan Pershey – Florida State University

Workshop on ghost particle hunting

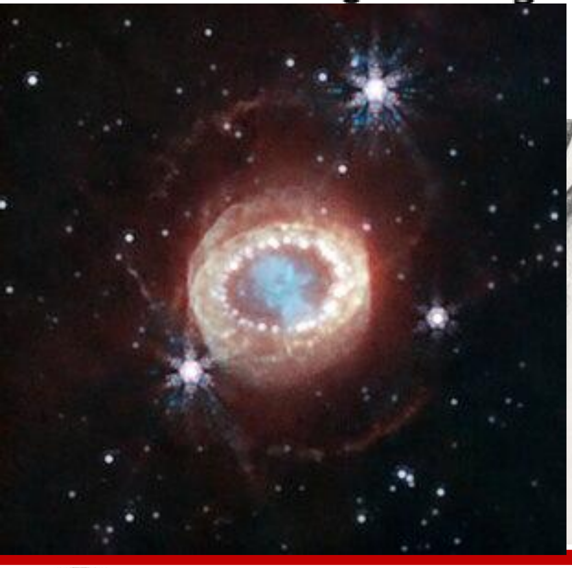
U Hawaii Manoa // Apr 29, 2025

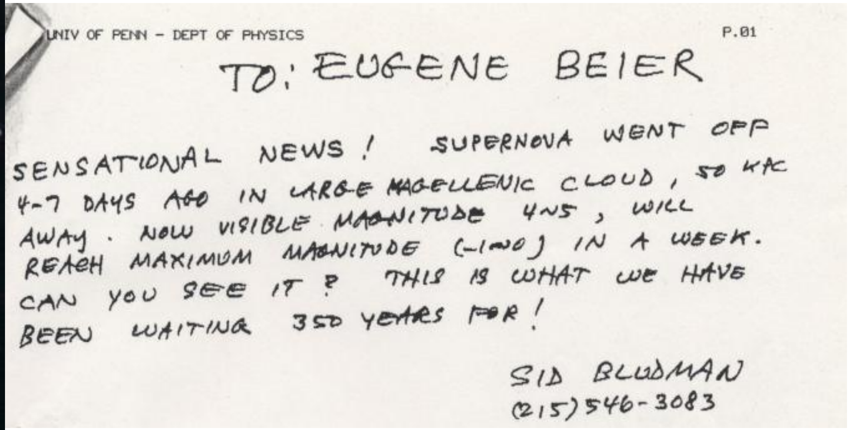
[[Not that kind of astronomy]]

Global SN neutrino data: 1987-current



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

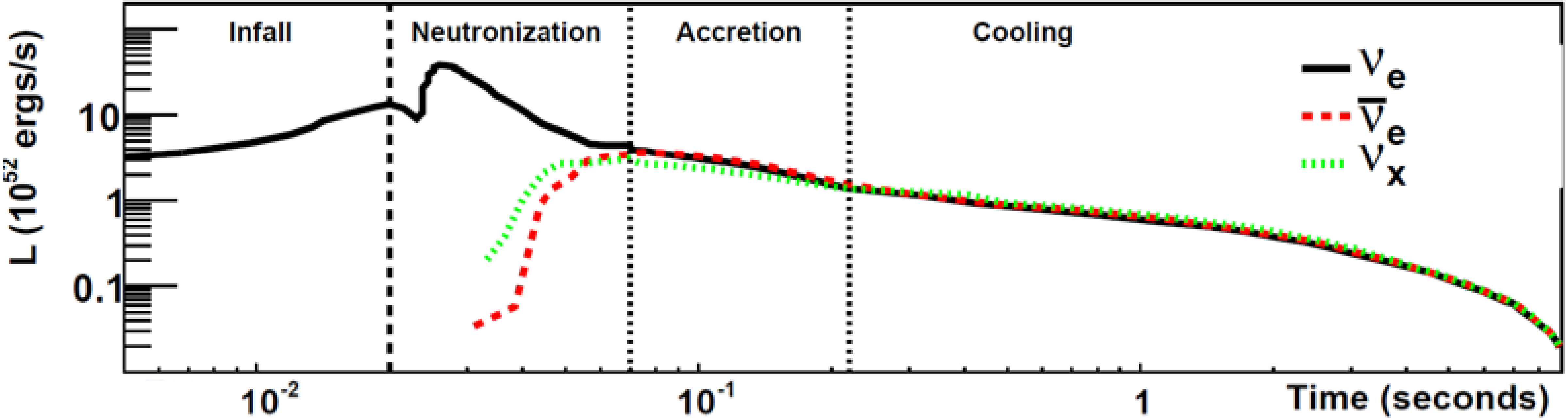
TO: EUGENE BEIER

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

SID BLUDMAN
(215) 546-3083

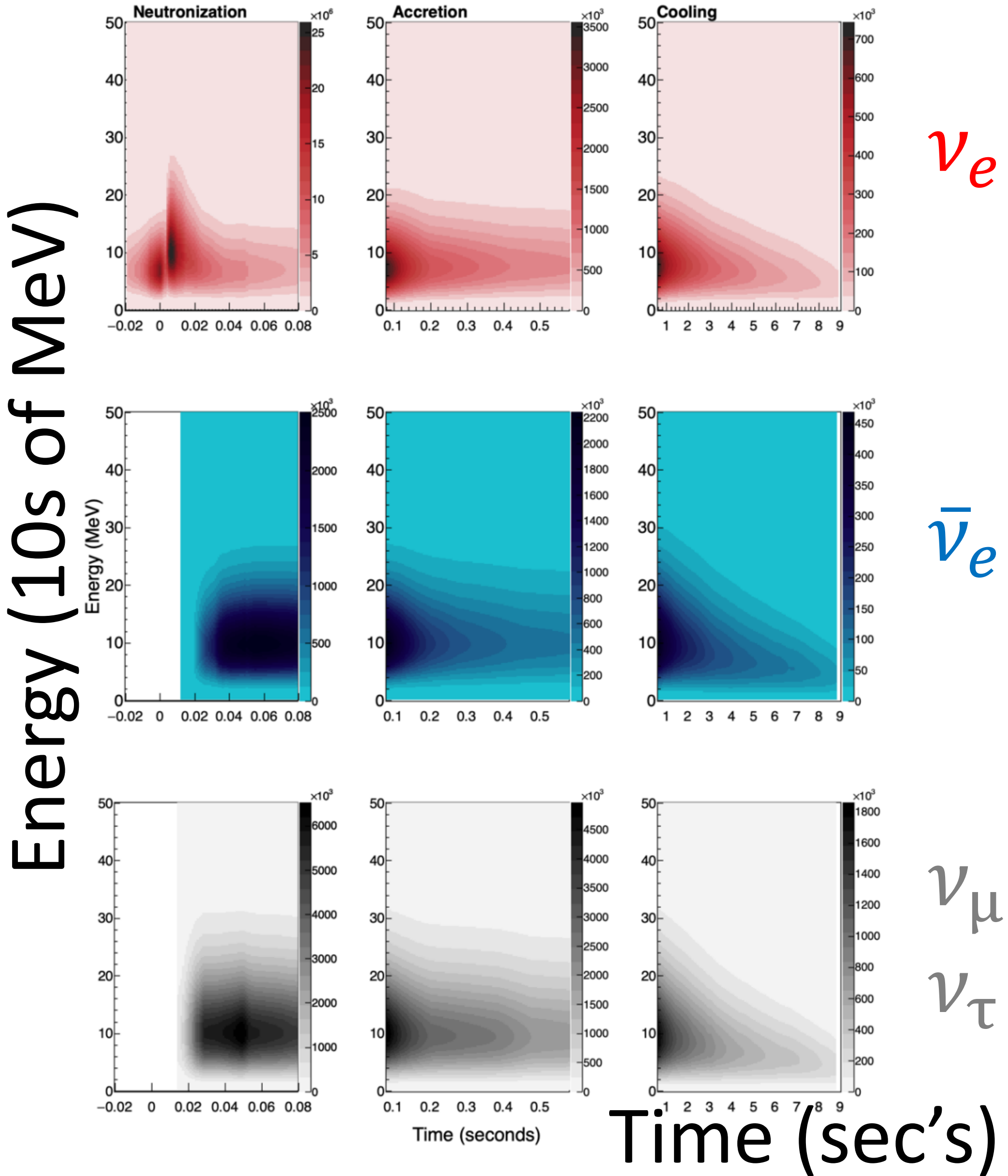
Countless papers based on 22 events!
Nuclear physics, astro of collapse, DM, axions, ν magnetic moment, ν-ν interactions, sterile ν, more

Phases of neutrino emission during collapse



1. Neutronization through $p + e \rightarrow n + \nu_e$ in the core gives a short-lived, intense flash of ν_e
2. Matter density in PNS high enough for neutrinos to thermally couple, neutrino production dominated by matter accreting
3. Shock wave expands outward. Neutrino emission cools the proto-neutron star

Neutrino observables from core collapse



ν_e

$\bar{\nu}_e$

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

Strategy: multiple detectors with complementary flavor sensitivity, each with unique advantages and cornering different physics

- ν_e – observe neutronization
- $\nu_e + \bar{\nu}_e$ CC – good for calorimetry
- ν_x NC – no oscillation ambiguity

	ν_e	$\bar{\nu}_e$	ν_x
DUNE[1]	89%	4%	7%
SK[2]	10%	87%	3%
JUNO[3]	1%	72%	27%
DM	0%	0%	100%

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

[2]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

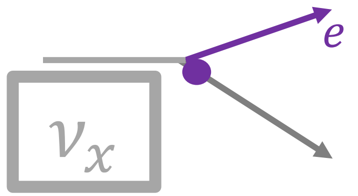
[3]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

SN interaction channels

Detector technologies

$\nu - e$ interactions

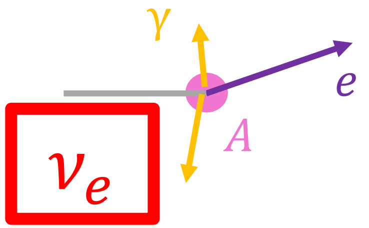
- **Electron scattering (ES)**
  - $\nu_x + e \rightarrow \nu_x + e$
  - Directional



All

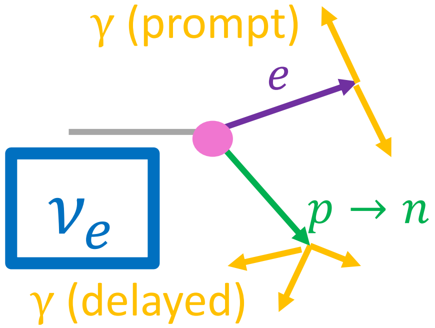
$\nu - A$ interactions

- **Charged current on nuclei (CC)**
  - $\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$
  - Good calorimetry



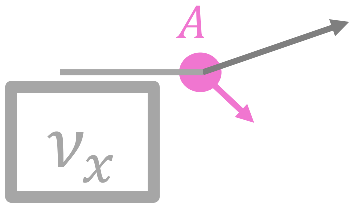
Argon: SBN, DUNE
lead: HALO,
xenon: nEXO

- **Inverse beta decay (IBD)**
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Low threshold, correlated n



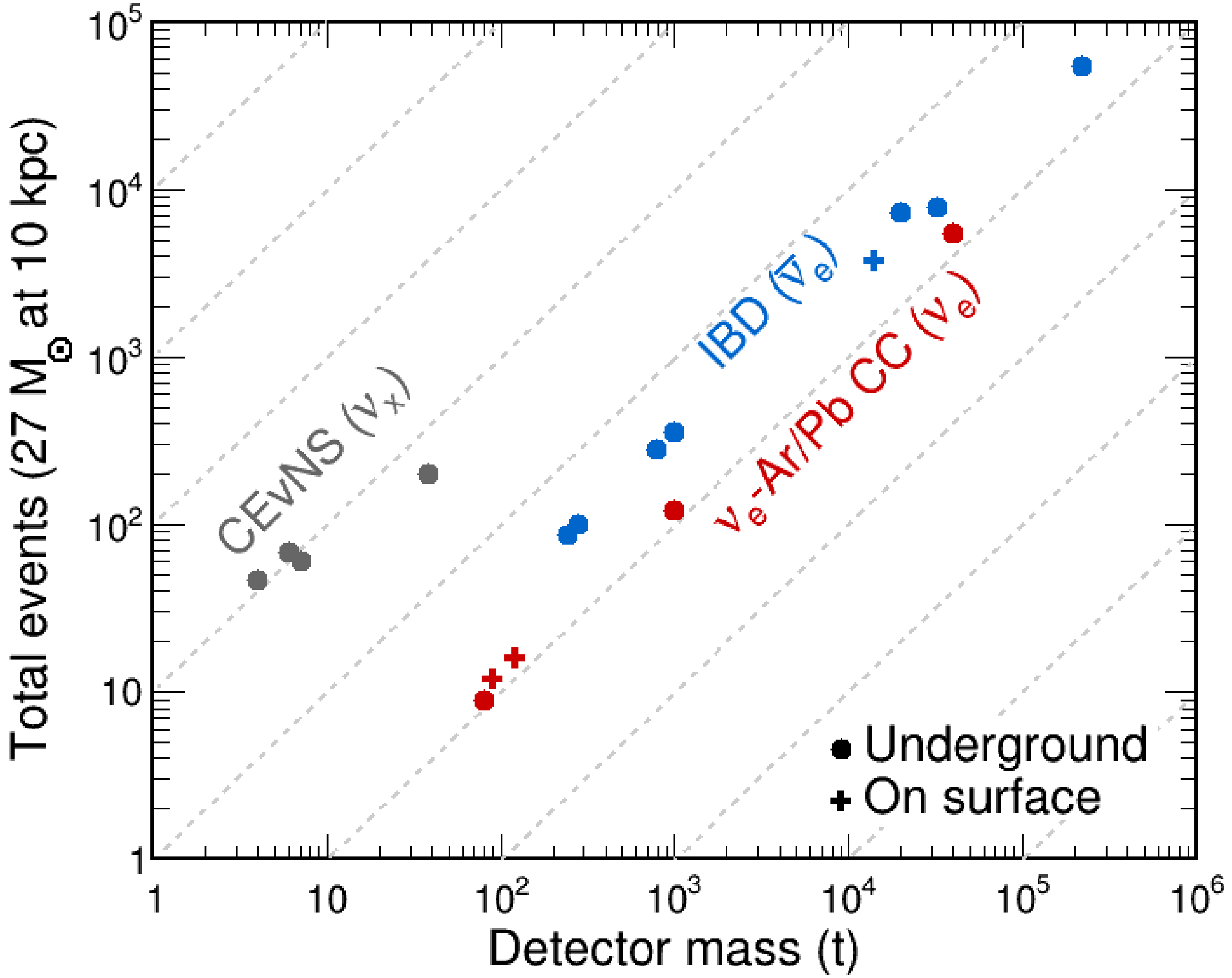
H_2O: SK, HK, IceCube, KM3NeT
CH_2: JUNO, NOvA, SNO+
KamLAND, LVD, Baksan

- **CEvNS**
  - $\nu_x + A \rightarrow \nu_x + A$
  - Uniform flavor sensitivity

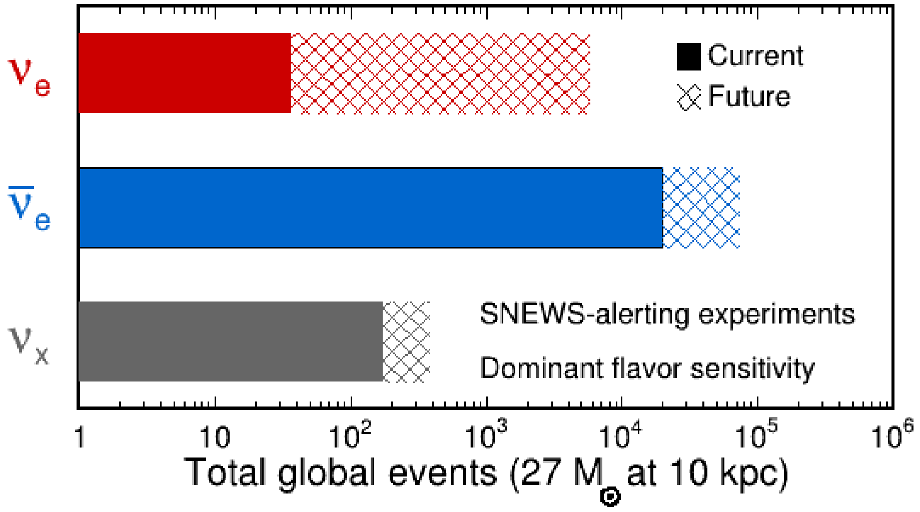


DM: LZ, PandaX-4T, XENONnT, DarkSide-20k

Supernova neutrino detection dashboard



Expect O(10^5) events with next collapse due to coordinated, global network of experiments

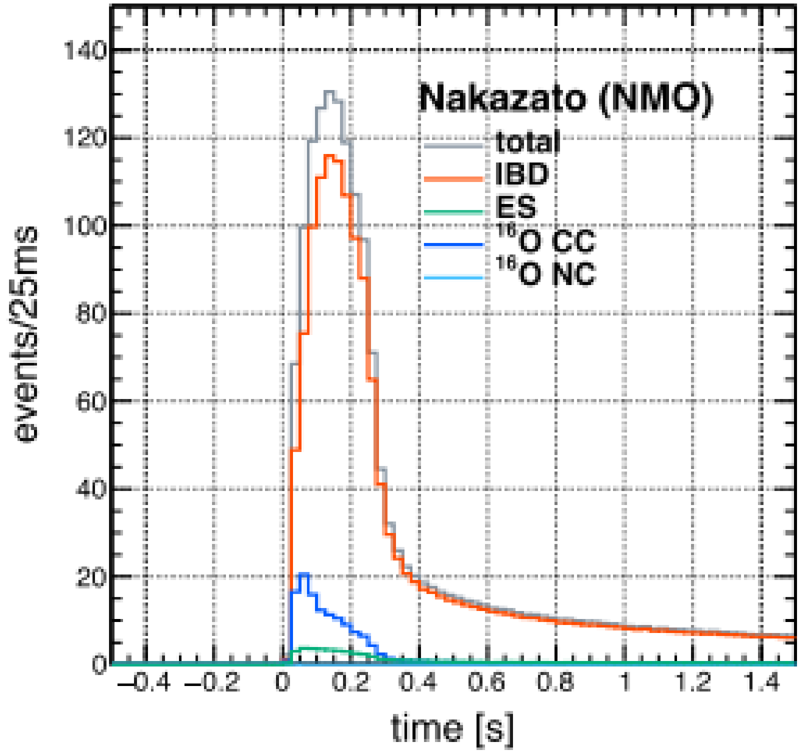


	1987a	2025	Future
$\bar{\nu}_e$-dominant	~ 23	19886	73886
ν_e-dominant	0	37	5657
ν_x-dominant	0	176	376

*Data from https://snews2.org/about/

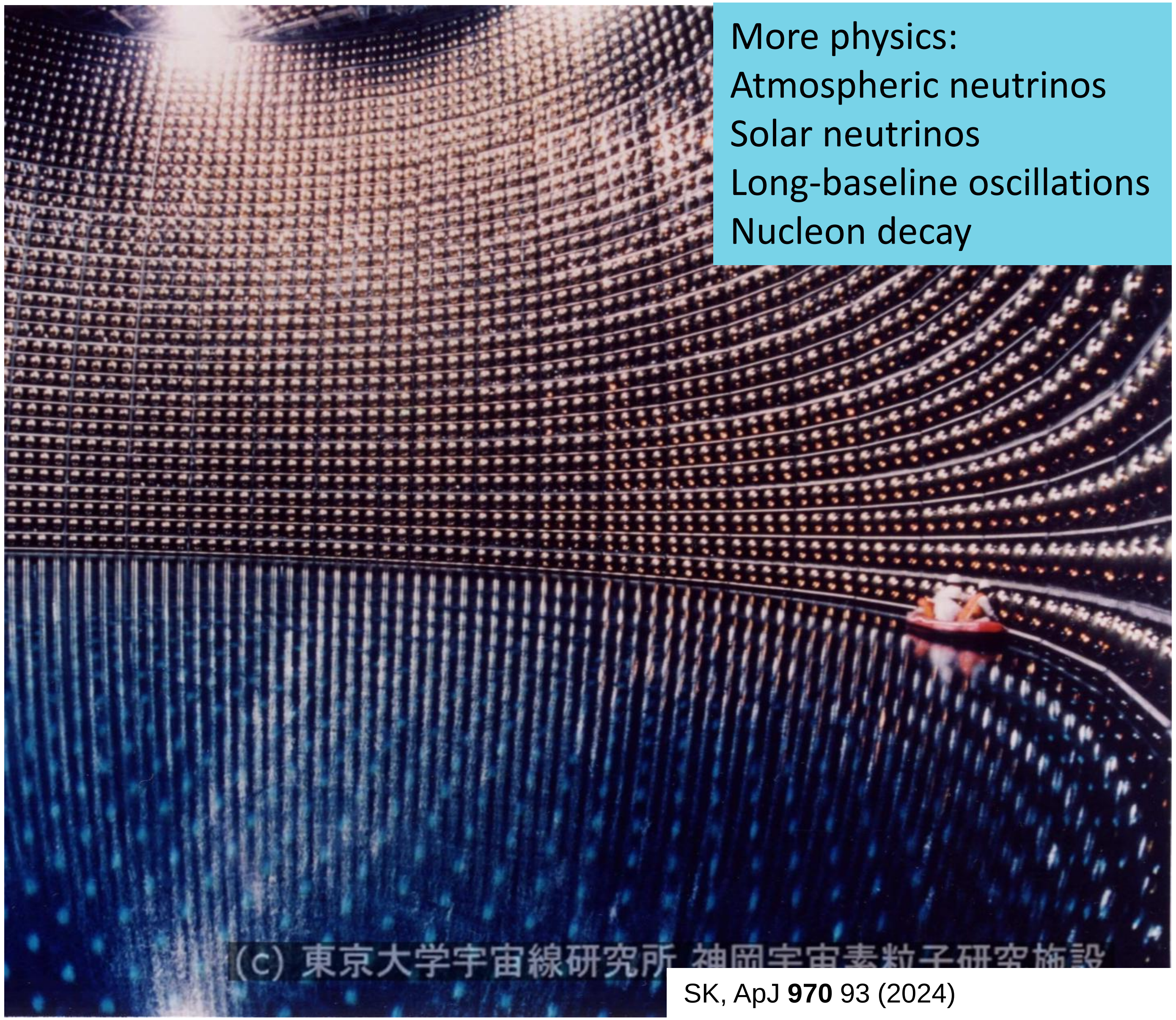
Water Cherenkov – SuperKamiokande

Proven technology – 1987a measurement
22.5-kt FV with outer water veto
Gifu, Japan
Solar ν: Demonstrated 3.49 MeV threshold
Now Gd-loaded – visible 8 MeV n capture



+ HK (future)

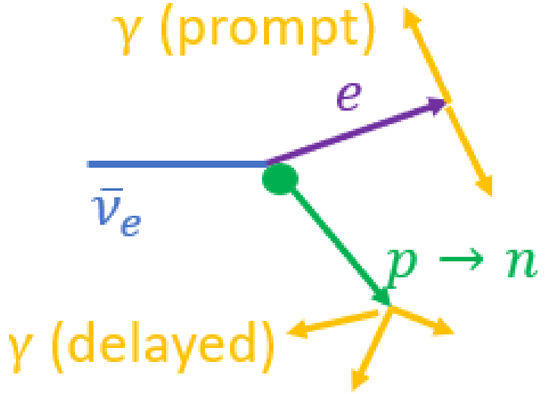
More physics:
Atmospheric neutrinos
Solar neutrinos
Long-baseline oscillations
Nucleon decay



SK, ApJ **970** 93 (2024)

DSNB measurements in SK

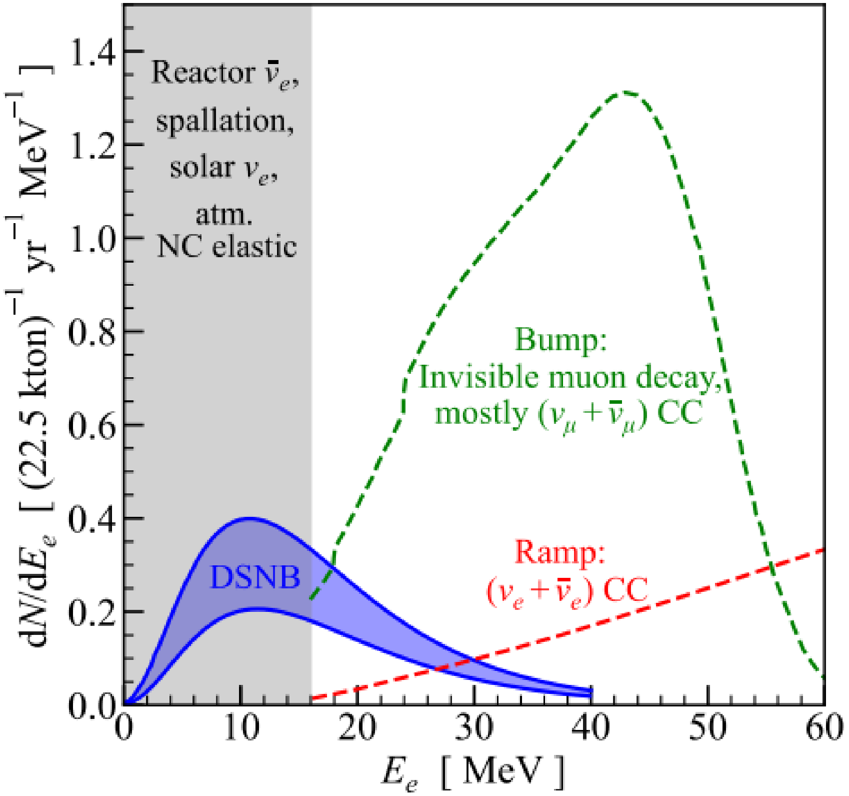
Water detector – IBD search



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

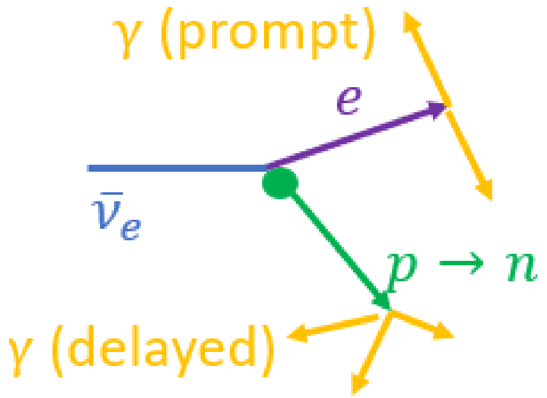
Gives giant bkg from muon decay



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]
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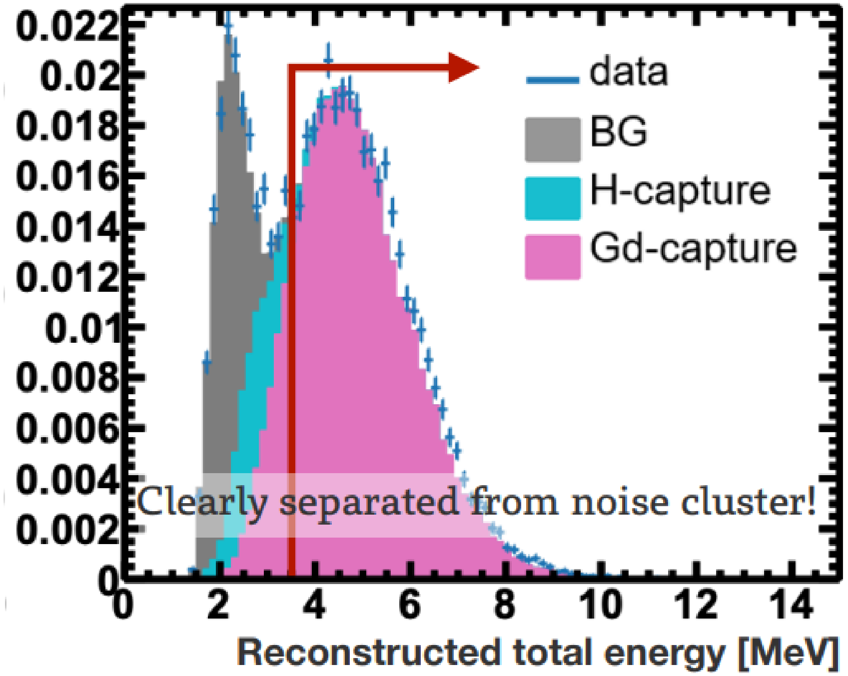
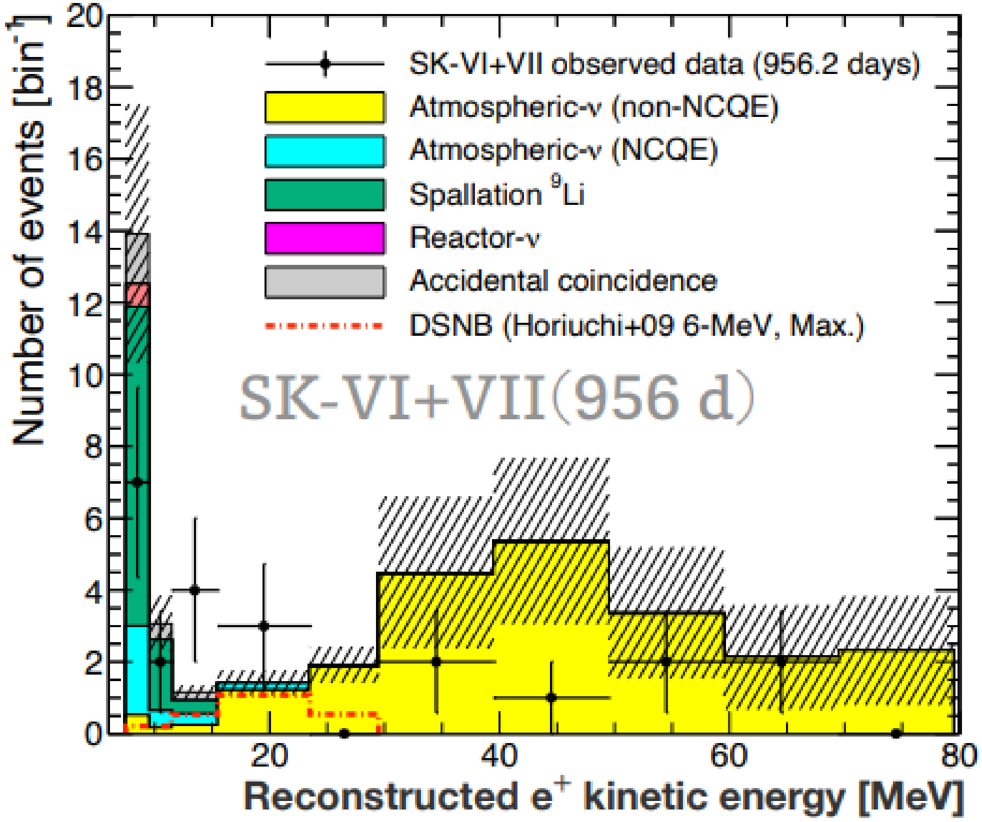
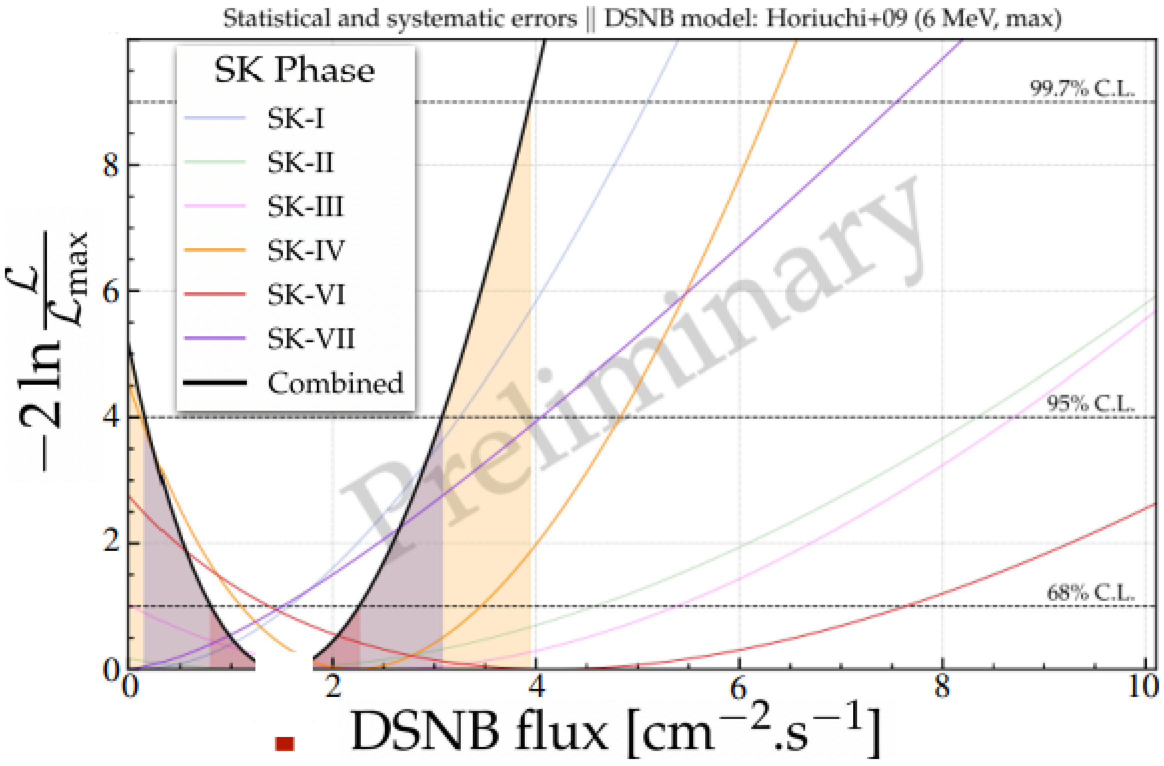


SK-Gd offers a hint of DSNB

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



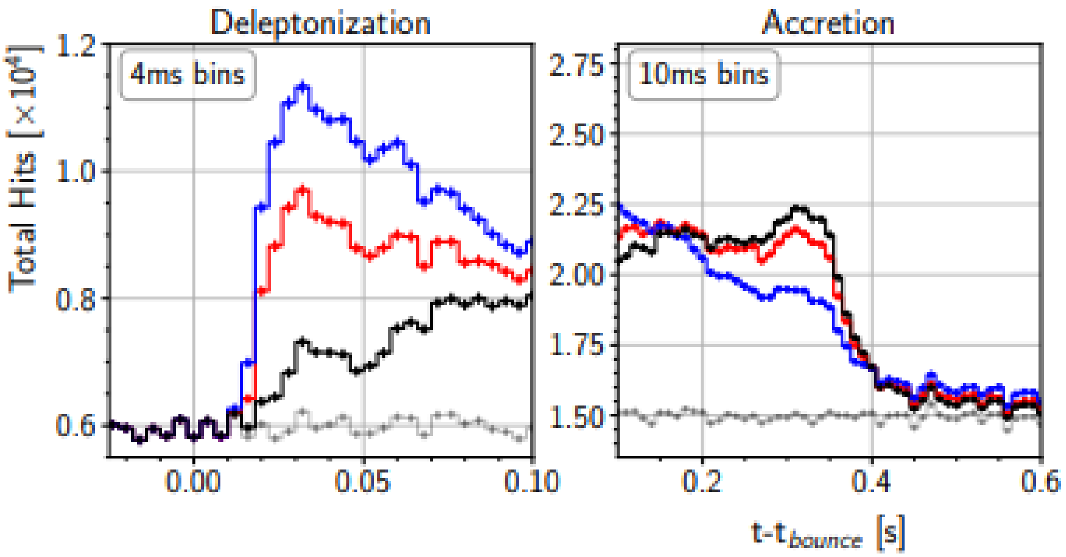


Masayuki Harada, Neutrino 2024

+ Mark Vagins's talk today

Water Cherenkov II (long-string experiments) – IceCube

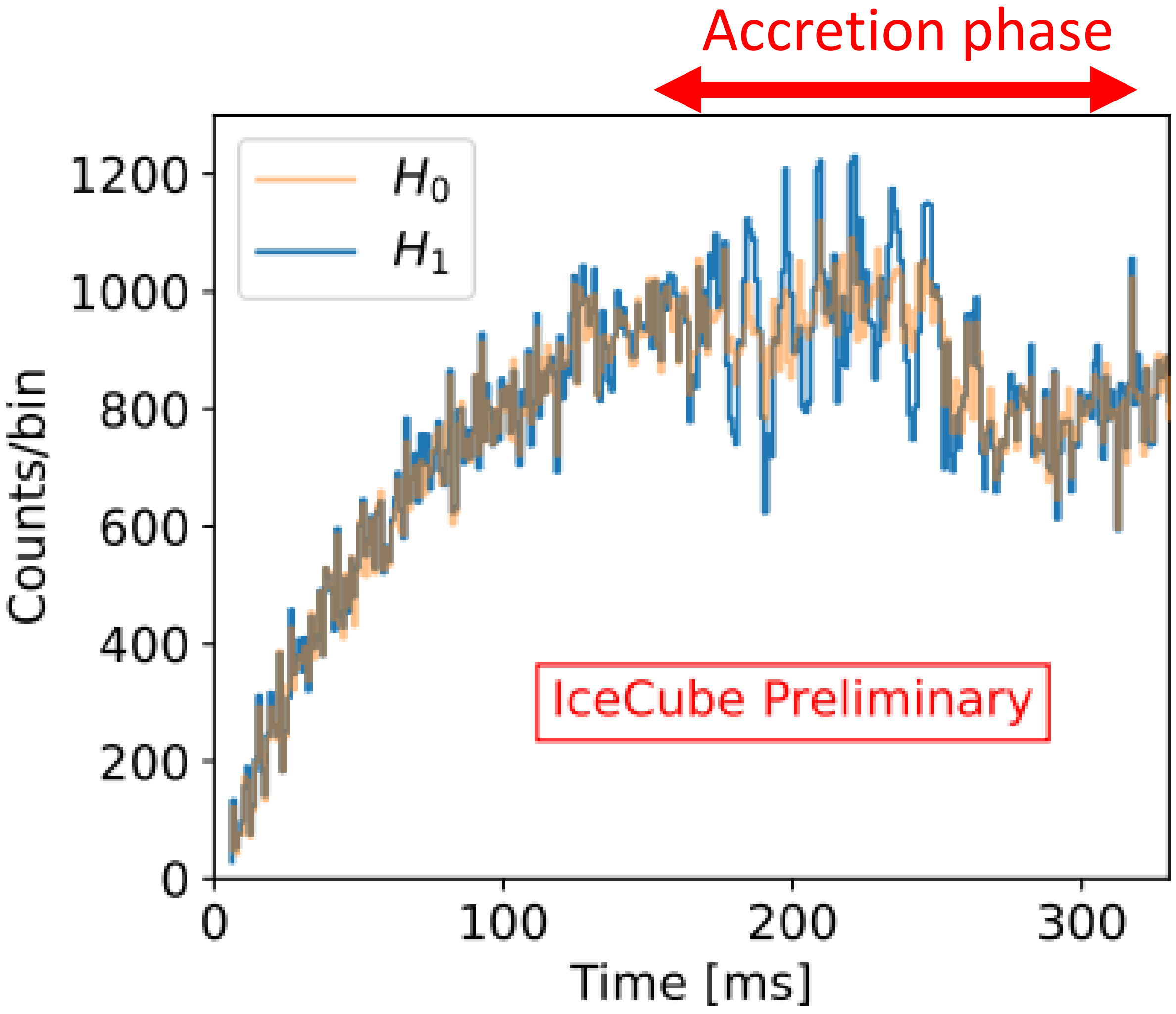
Instrument Antarctic ice with PD's
Massive O(Mt) mass
10^5-10^6 events / supernova burst
Individual events aren't observed
  See a glow: increase in PD hit activity



+ KM3NeT

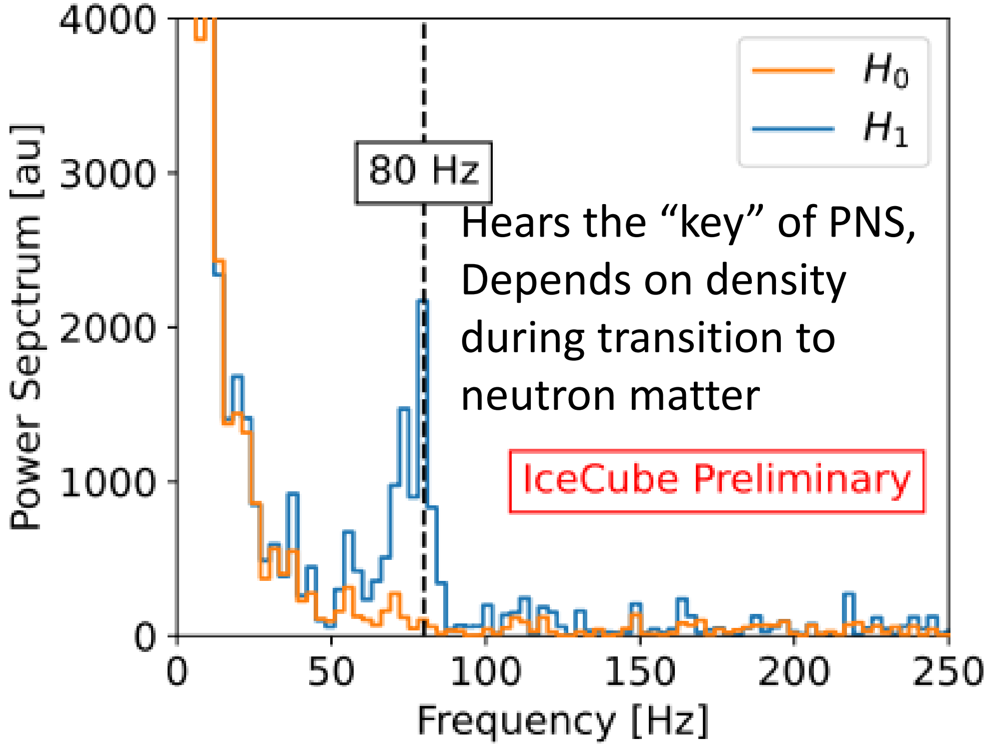
More physics:
High-energy astrophysics
GKZ neutrinos
Atmospheric neutrinos
Long-baseline oscillations

Example physics: SASI oscillations



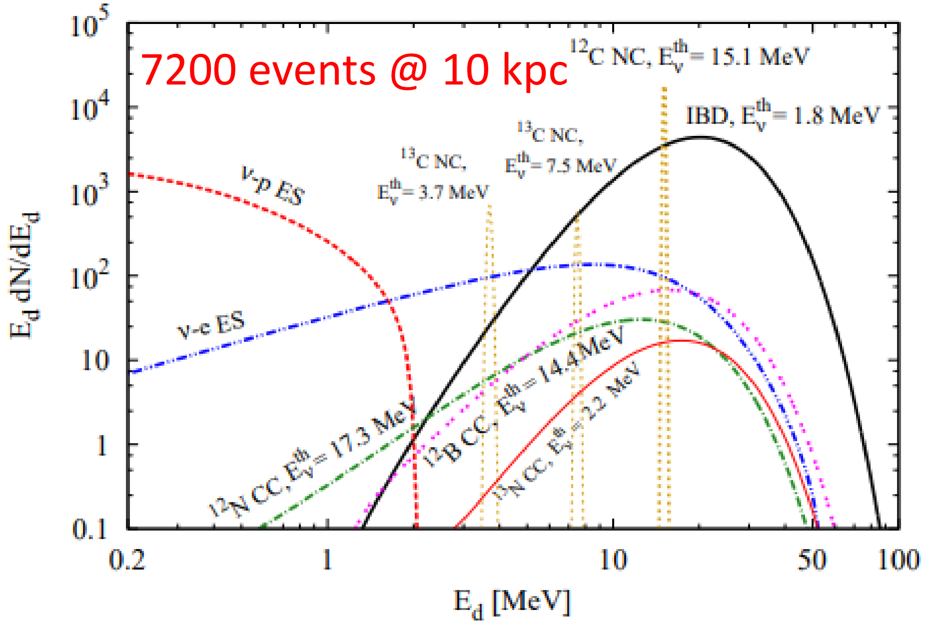
Beise, arXiv:2311.08898

Core collapse excites standing waves in PNS matter density which modulates neutrino emission rate and temperature

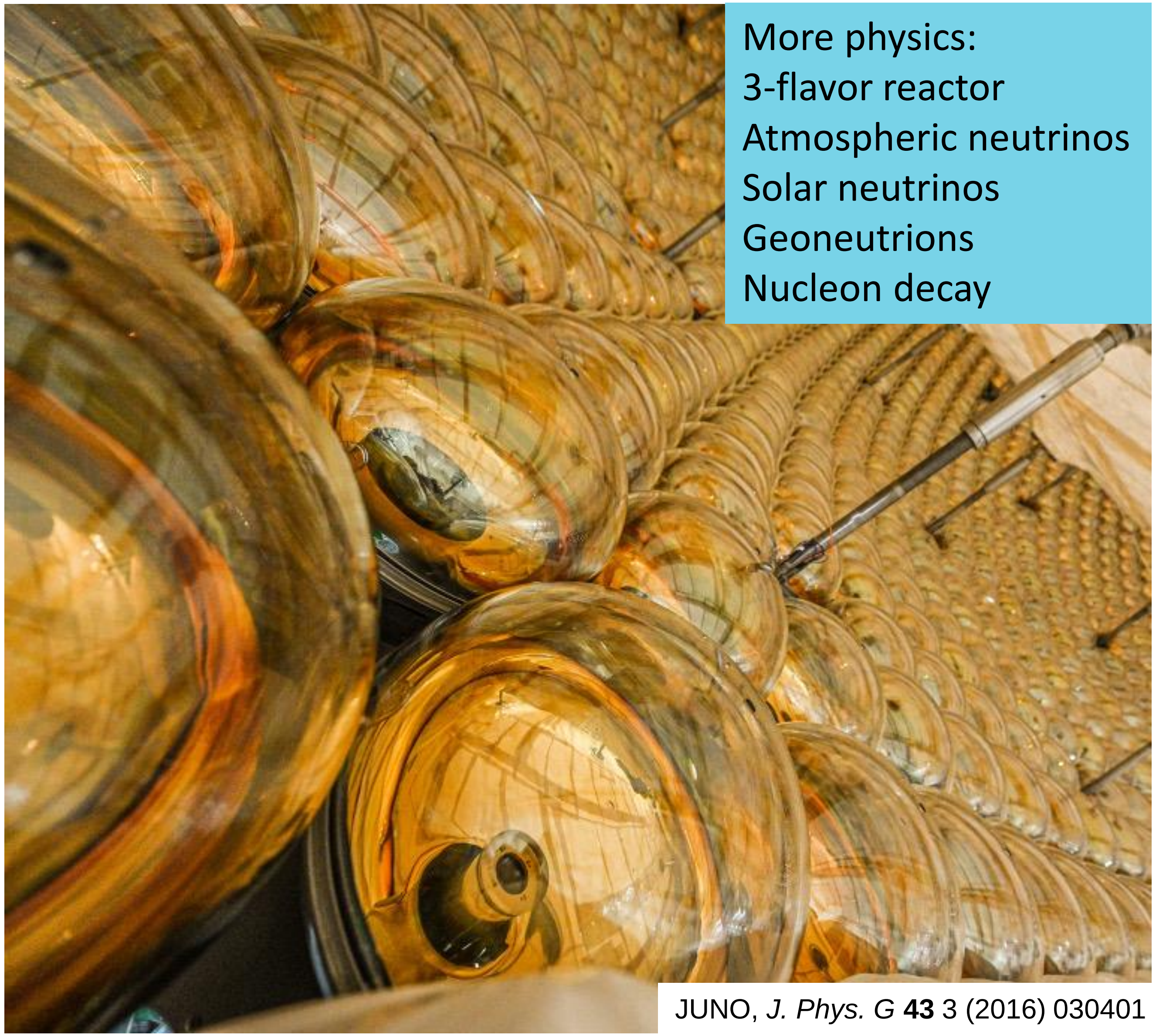


Scintillator experiments: e.g. JUNO

20-kt LS with 35-kt water veto
  LAB + 2.5g/L PPO + 3 mg/L bis-MSB
Operations begin this year
Guangdong, China
78% PD coverage, 1665 PE/MeV, 2.95% @ 1 MeV
Channel tagging: IBD (2.2-MeV capture gamma) and NC (excellent energy resolution)



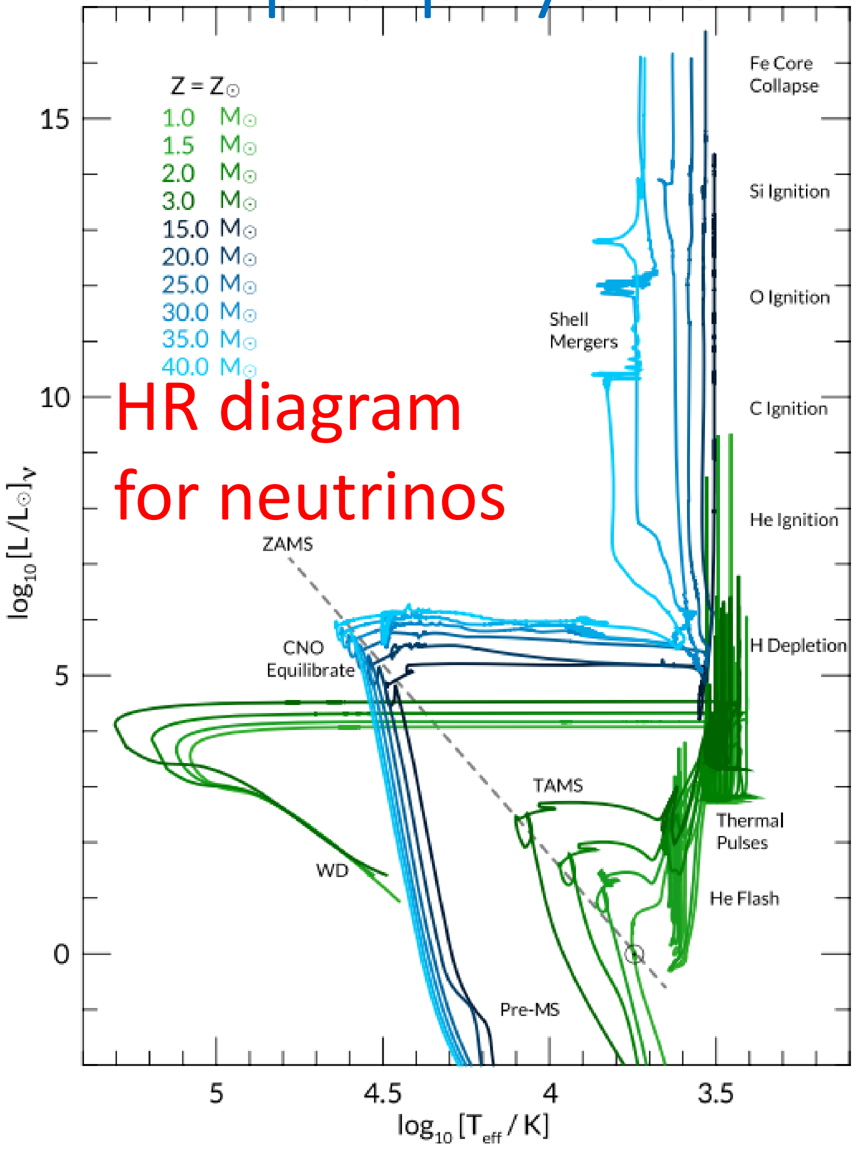
+ LVD, KamLAND, JUNO, SNO+, NOvA, Baksan



More physics:
3-flavor reactor
Atmospheric neutrinos
Solar neutrinos
Geoneutrinos
Nucleon decay

JUNO, *J. Phys. G* **43** 3 (2016) 030401

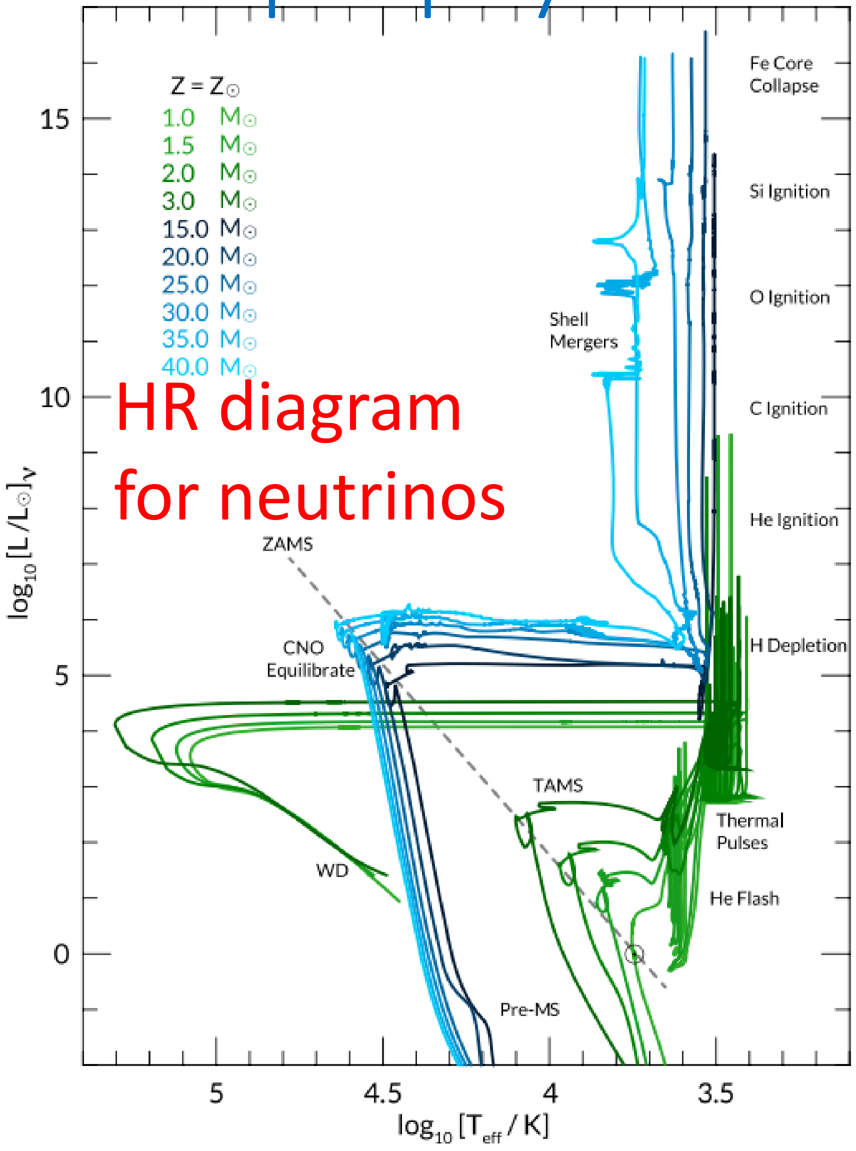
Example physics: Pre-SN neutrinos in JUNO



Fara, Timmes, Taylor, Patton, Farmer,
APHYS J, **893**, 133 (2020)

Before collapse, increasing rate of MeV neutrinos from Si fusion

Example physics: Pre-SN neutrinos in JUNO

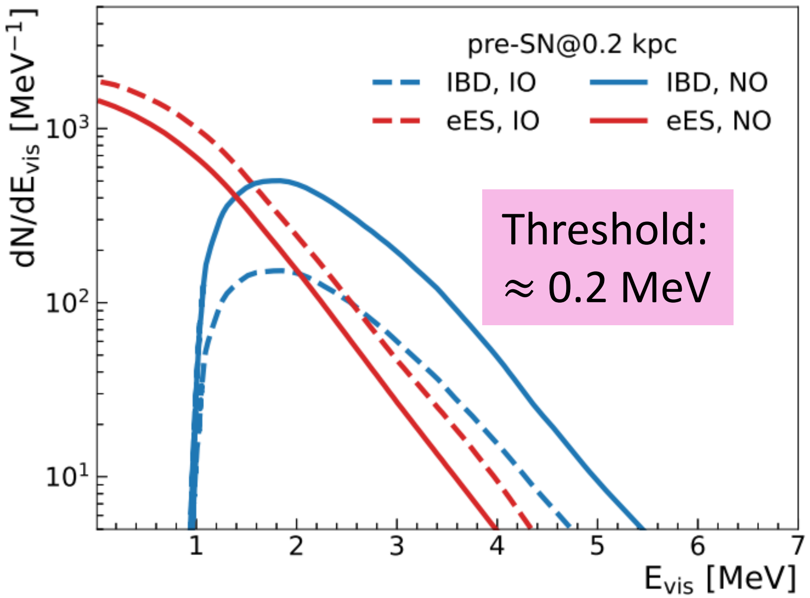


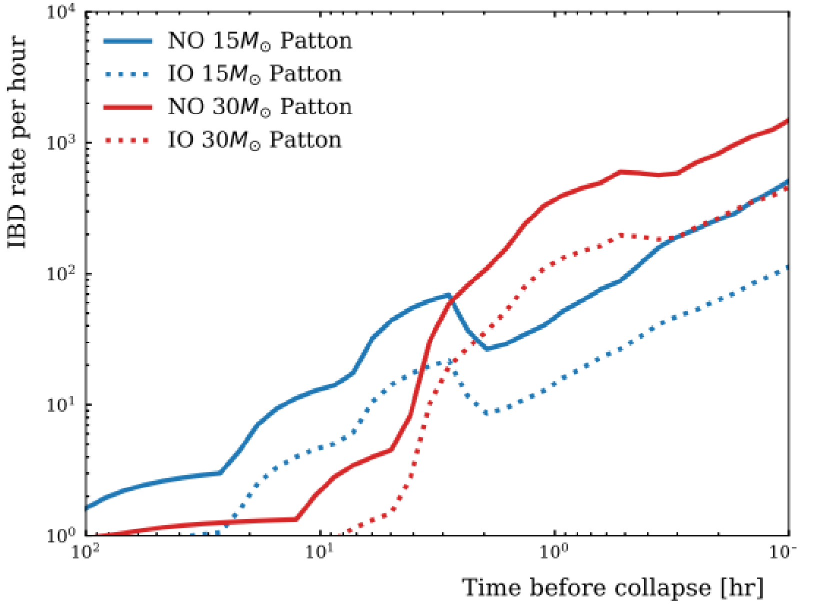
Fara, Timmes, Taylor, Patton, Farmer, *APHYS J*, **893** 133 (2020)

Before collapse, increasing rate of MeV neutrinos from Si fusion

JUNO: high light yield + low threshold + low backgrounds – excellent for pre-SN neutrinos with sensitivity up to 1.6 kpc away

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





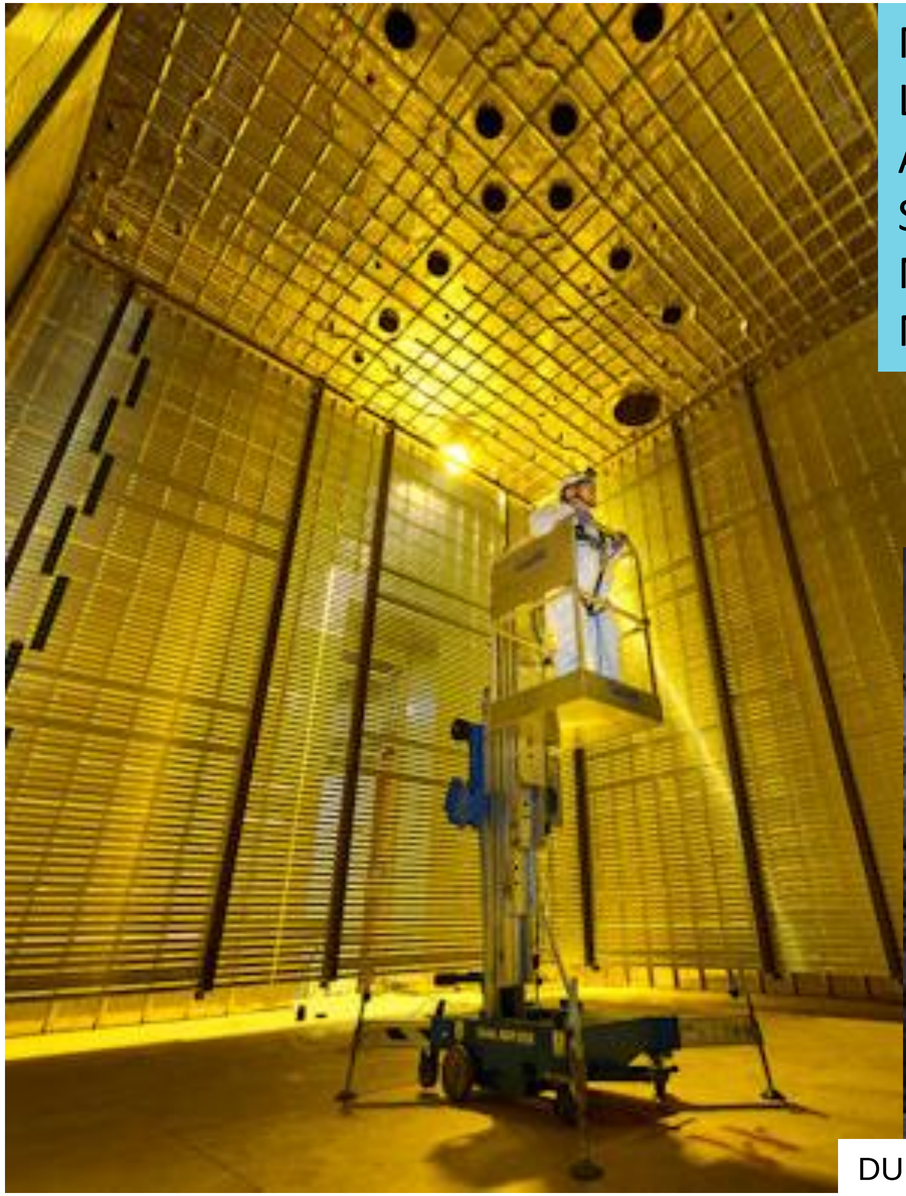
Liquid argon – DUNE

4 10-kt LArTPC modules (fiducial)
Operations of module 1 in 2029
Sensitive to ν_e
5 MeV electron threshold
Excellent reconstruction and channel tagging

Channel	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	260
Total	3770

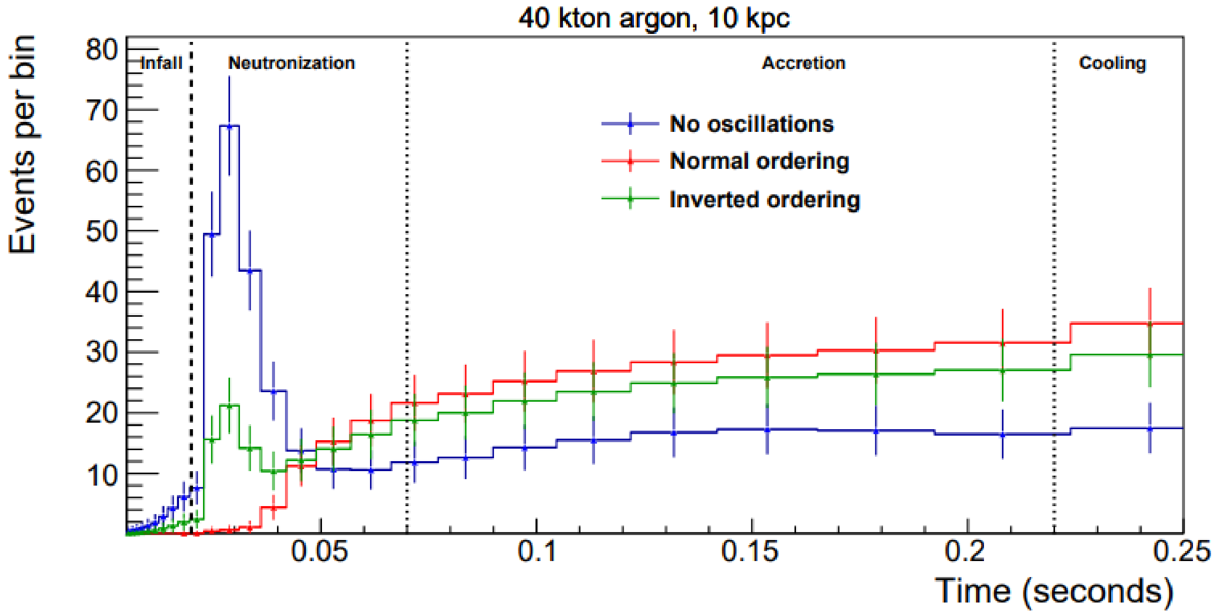
+ SBN detectors

More physics:
Long-baseline oscillations
Atmospheric neutrinos
Solar neutrinos
Near-detector BSM
Nucleon decay



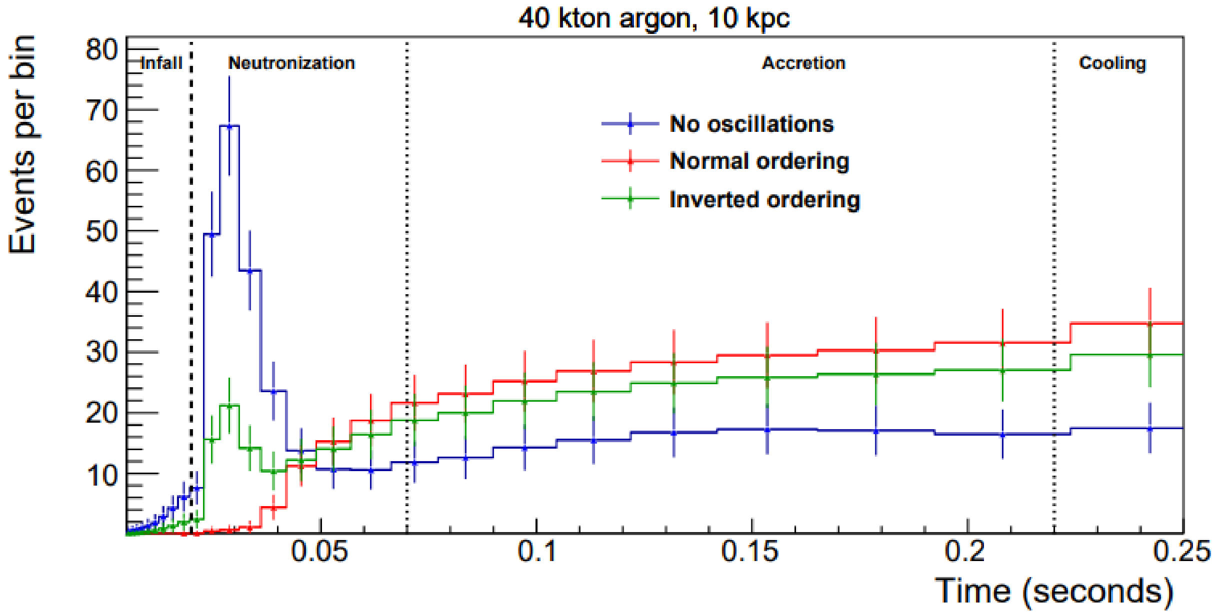
DUNE, *Eur. Phys. J. C* **81** 5 423 (2021)

Example physics: observing neutronization



DUNE sensitivity to the ν_e flux makes it ideal for neutronization – a standard candle for studying unique astro and particle physics e.g. collective oscillations

Example physics: observing neutronization



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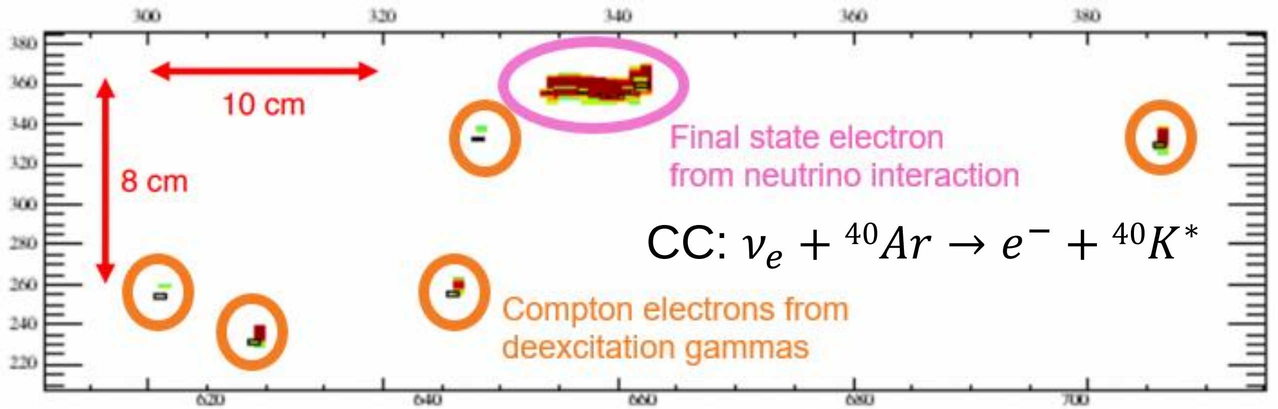
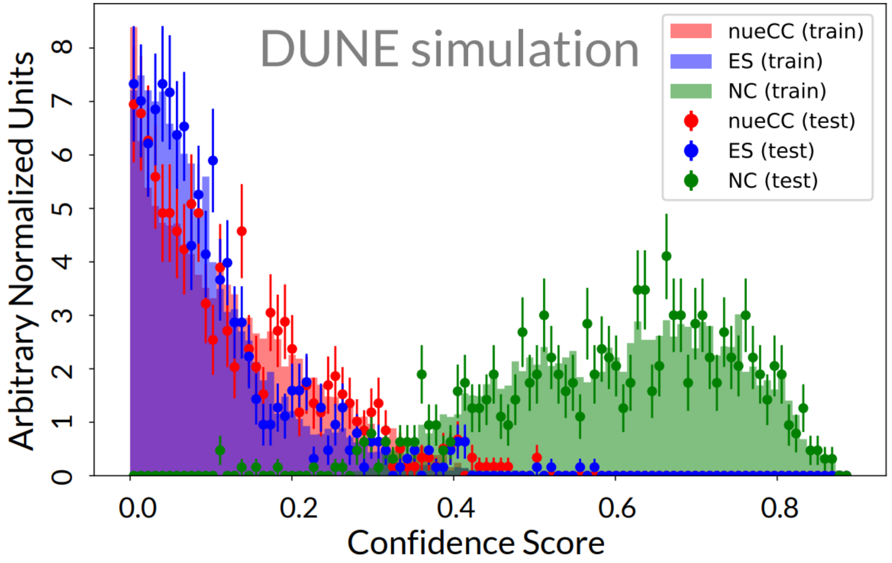


CC: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



+ will bring new level of reconstruction and channel tagging performance for SN neutrinos

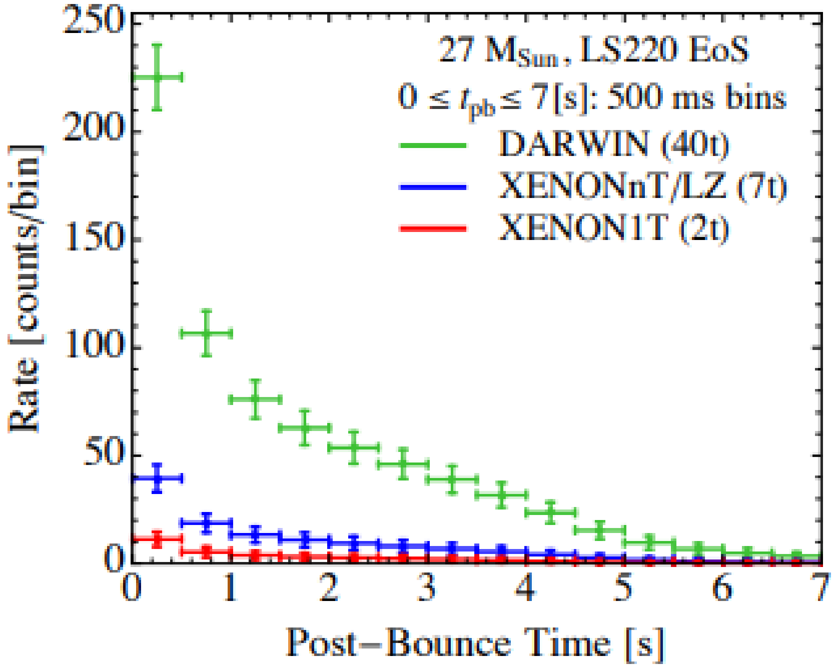
Dark matter detectors – LZ

Smaller ton-scale detectors with low-threshold
- LZ/XENONnT/PandaX-4t operating
- SURF/Italy/China

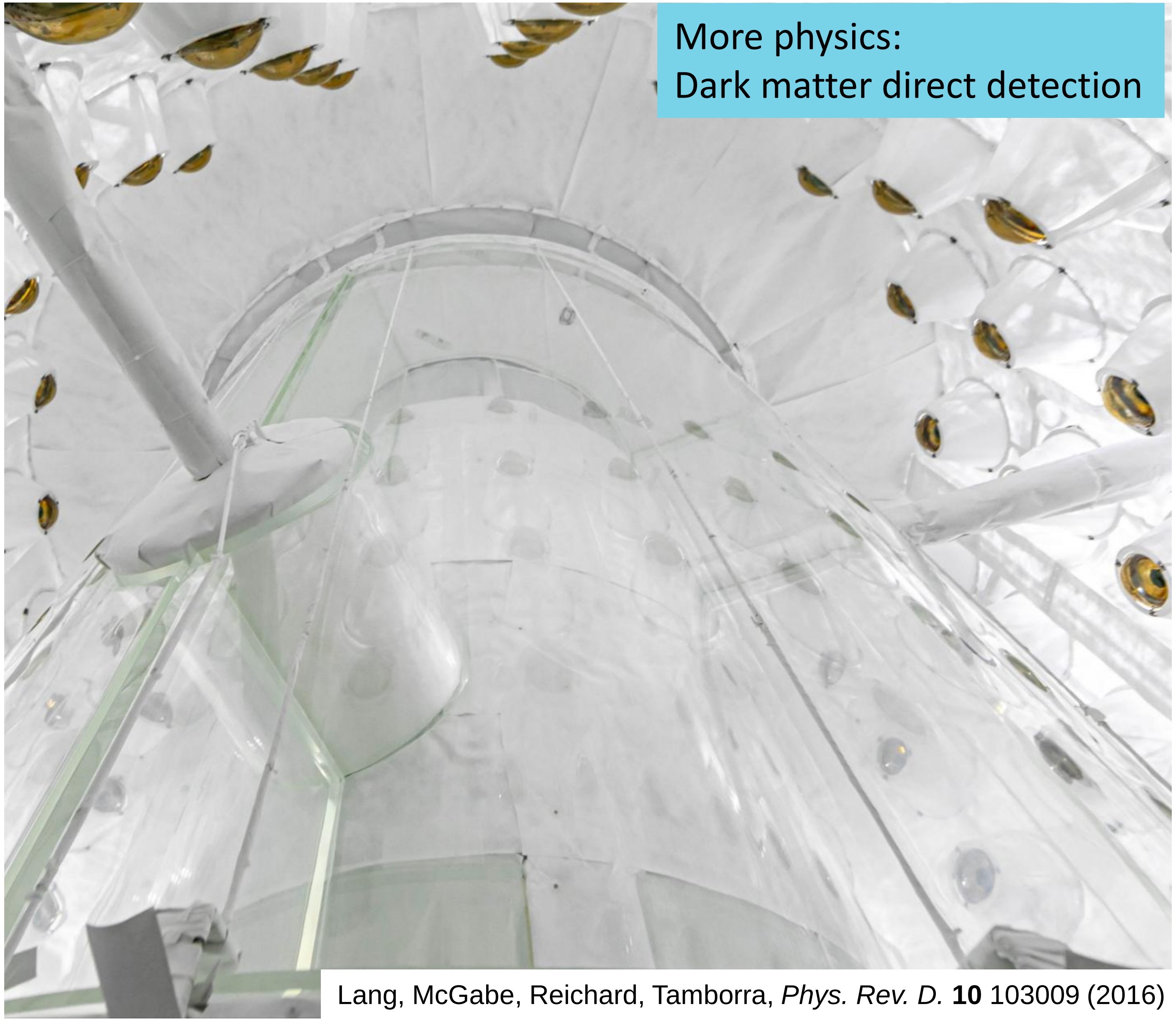
Sensitive to CEvnS – NC process

Very low background

Different energy regime, complementary BSM



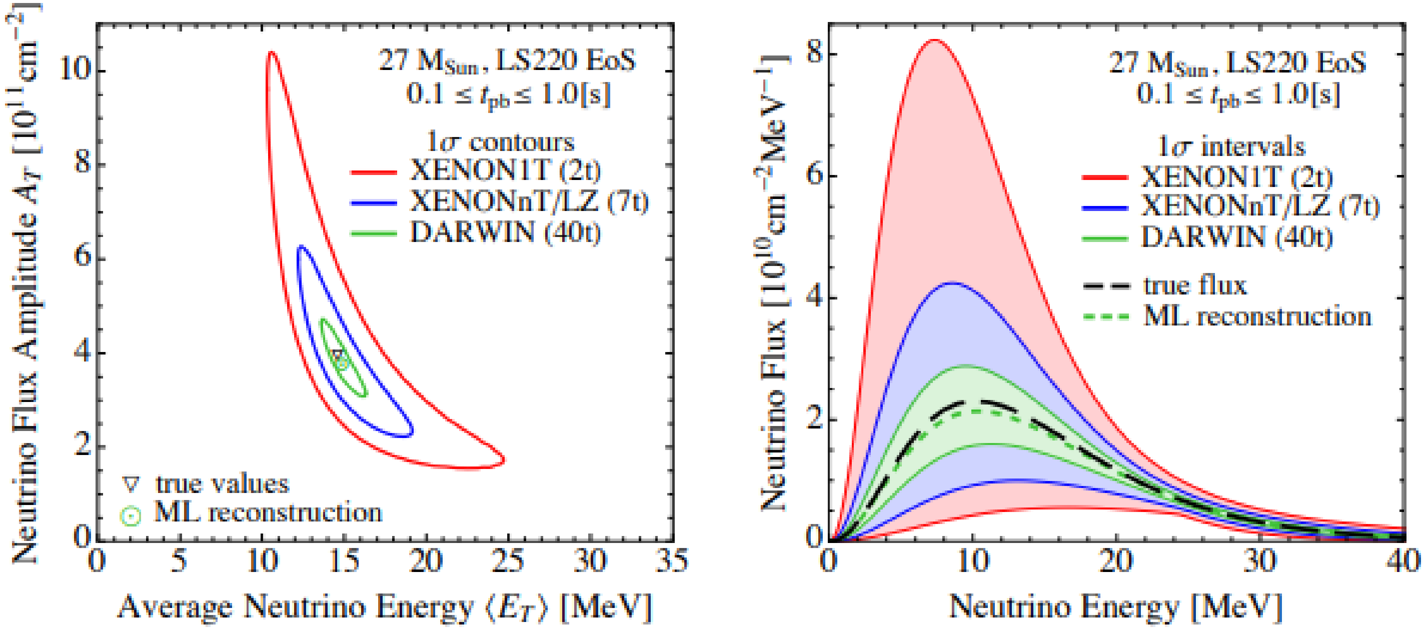
+ XENONnT, PandaX-4t, DarkSide-20k, others



More physics:
Dark matter direct detection

Lang, McGabe, Reichard, Tamborra, *Phys. Rev. D.* **10** 103009 (2016)

Physics example: measuring the total neutrino flux



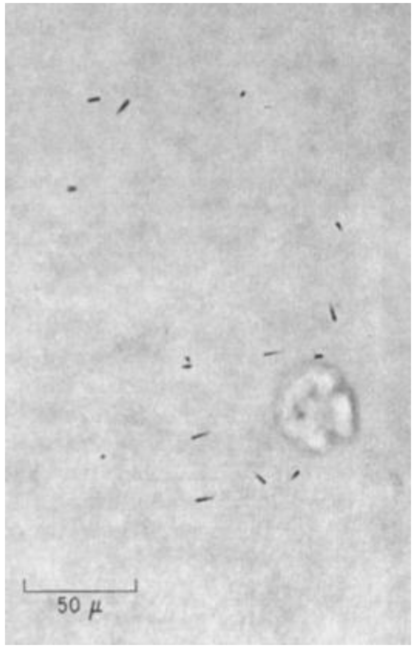
Dark matter detectors are sensitive to all flavors equally – they measure the total neutrino flux without bias

Critical for understanding any oscillation effects

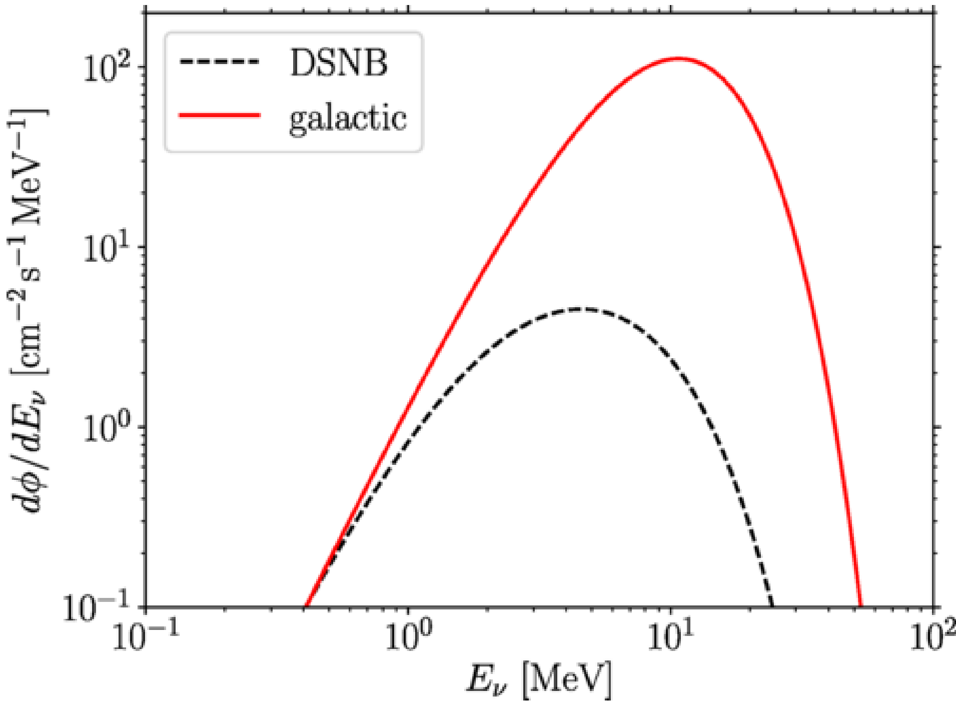
Fixes neutrino luminosity so other experiments can determine shape

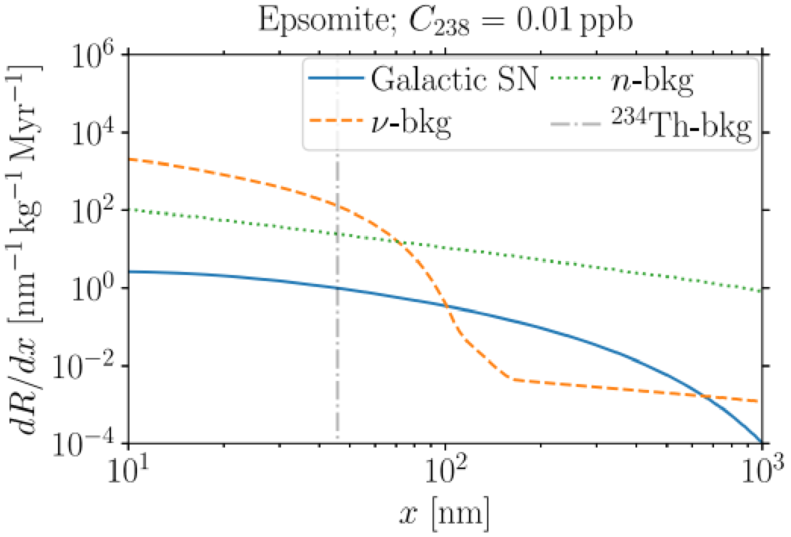
More new ideas to explore: paleo detectors

SN neutrinos burn tracks into rock – can we identify evidence of ancient collapse with old, deeply buried, radiopure rock? R&D – imaging large rocks and background characterizations



Galactic supernova relic





Probes new physics questions – average SN flux from Milky Way. Testing multiple samples can detect differences in rate, populations

Baum, Edwards, Kavanaugh, Stengel, Drukier, Freese, Gorski, Weniger, *Phys. Rev. D.* **101** 103017 (2020)

Multi-messenger SN signals

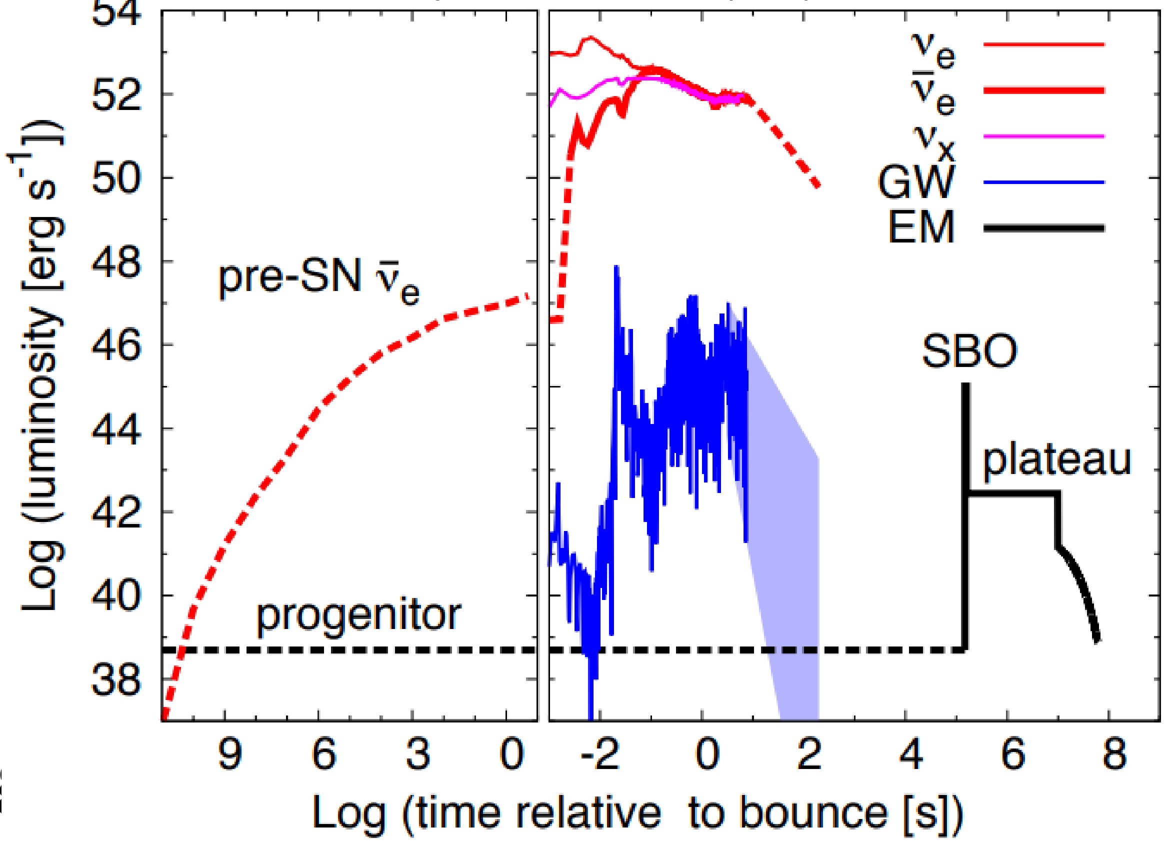
Understanding the mechanics of a stellar explosion is complicated, luckily, we're given multiple probes to understand the dynamics

– Pre-supernova fusion neutrinos

– Prompt emission of gravitational waves and neutrinos

– Delayed optical signal from shock break out and thermal cooling

Nakamura, Horiuchi, Tanaka, Hayama, Takiwaki, Kotake, *Mon. Not. Roy. Astron. Soc.* **46** 3 (2016) 3296-3313



Fundamental requirement for neutrino experiments – identify supernova source location to assist optical follow-ups

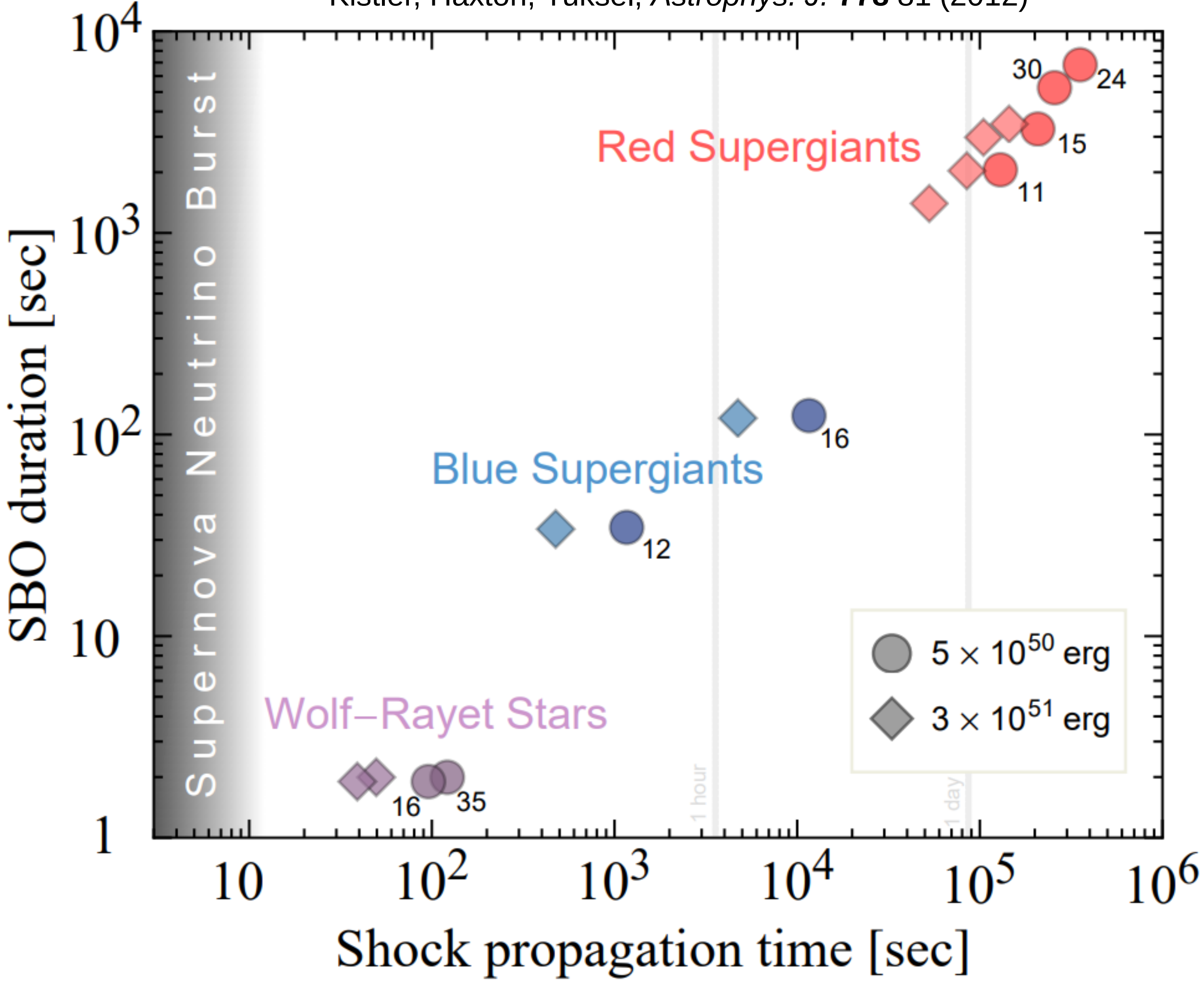
The first three minutes: reconstructing source quickly

First optical signal – and most interesting – is the shock break out (SBO)

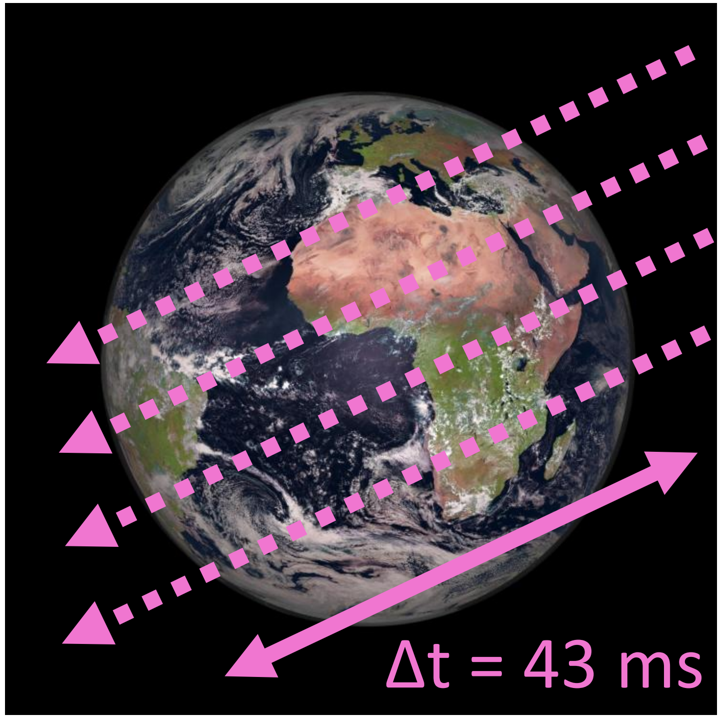
Time delay can vary from a minute to a day depending on the star's density and radius

Neutrino experiments must identify the expected location within a few minutes of the burst

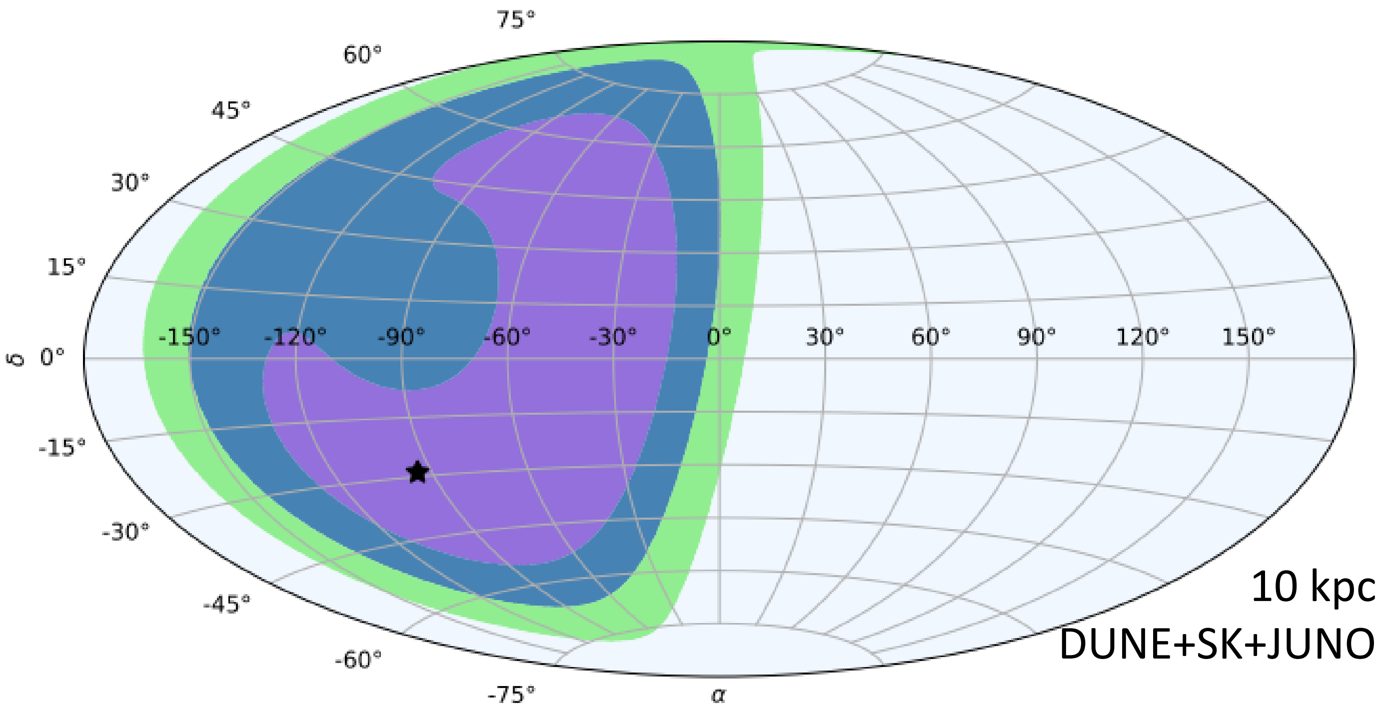
Kistler, Haxton, Yuksel, *Astrophys. J.* **778** 81 (2012)



Early supernova pinpointing



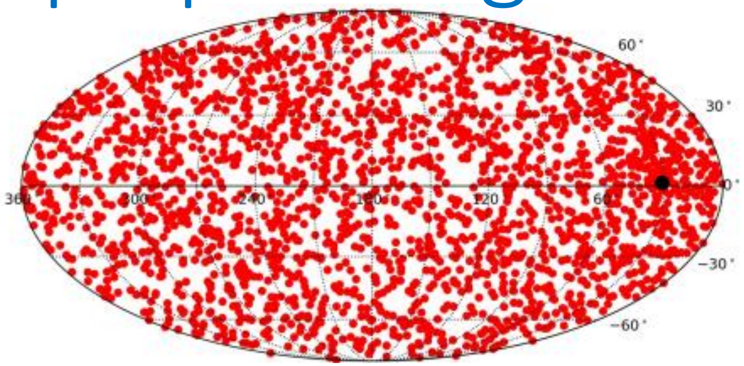
Linzer, Scholberg, *Phys. Rev. D* **100** 10 (2019) 103005



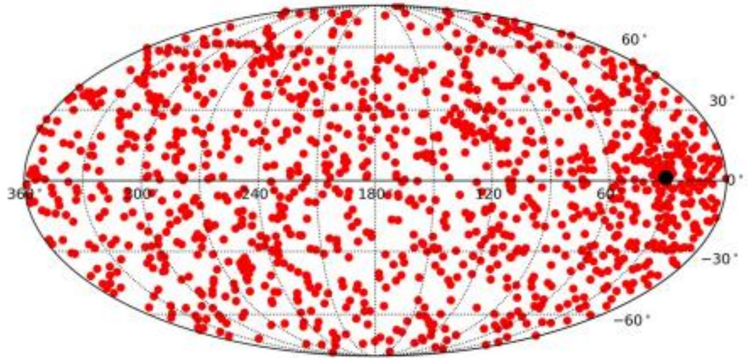
- Two methods based on early and later available information
- Triangulation: within seconds, each experiment identifies t0 – global comparison will constrain
- Want many detectors across the globe – NA, Asia, Europe, Antarctica, expansion into SA, Africa, South Asia, Australia would be excellent

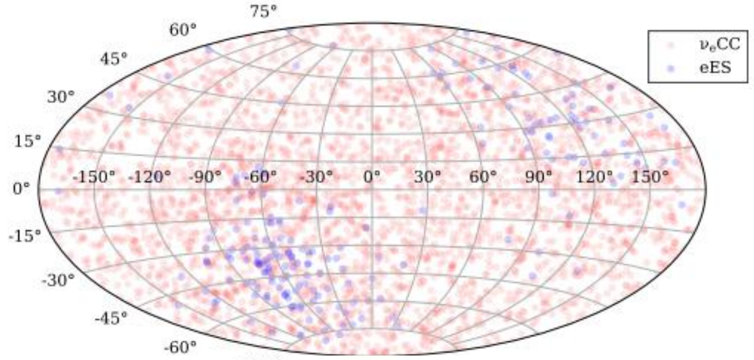
Precise pinpointing

SK

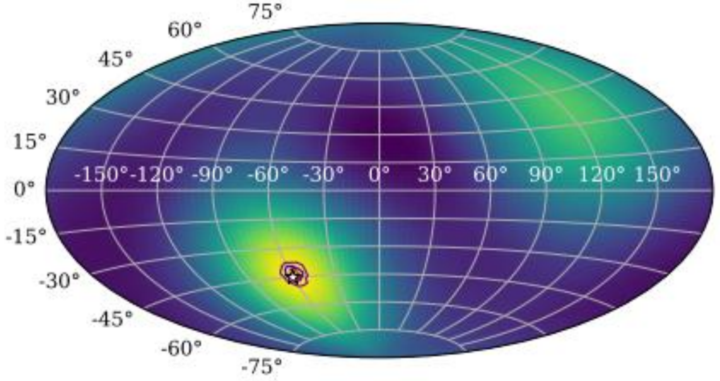


SKGd





DUNE



4.3 deg resolution

- Large tracking detectors – DUNE and SK (HK) – reconstruct particle direction on an event-by-event basis
- Rely on subdominant $\nu - e$ scattering, veto $\nu - A$ interactions
  - SKGd – Gd-doping significantly reduces the IBD rate
  - DUNE – PID from CC nuclear deexcitation

Summary

- Measuring neutrinos from a core collapse supernova is an active field, still at the fore-front of research after 40 years
- Multiple detector technologies have matured and are being scaled with complementary flavor sensitivity – humanity will be ready for the next galactic collapse
- These experiments bring a rich physics program beyond SN neutrinos