Detecting Supernova Neutrinos

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CIPANP 2022
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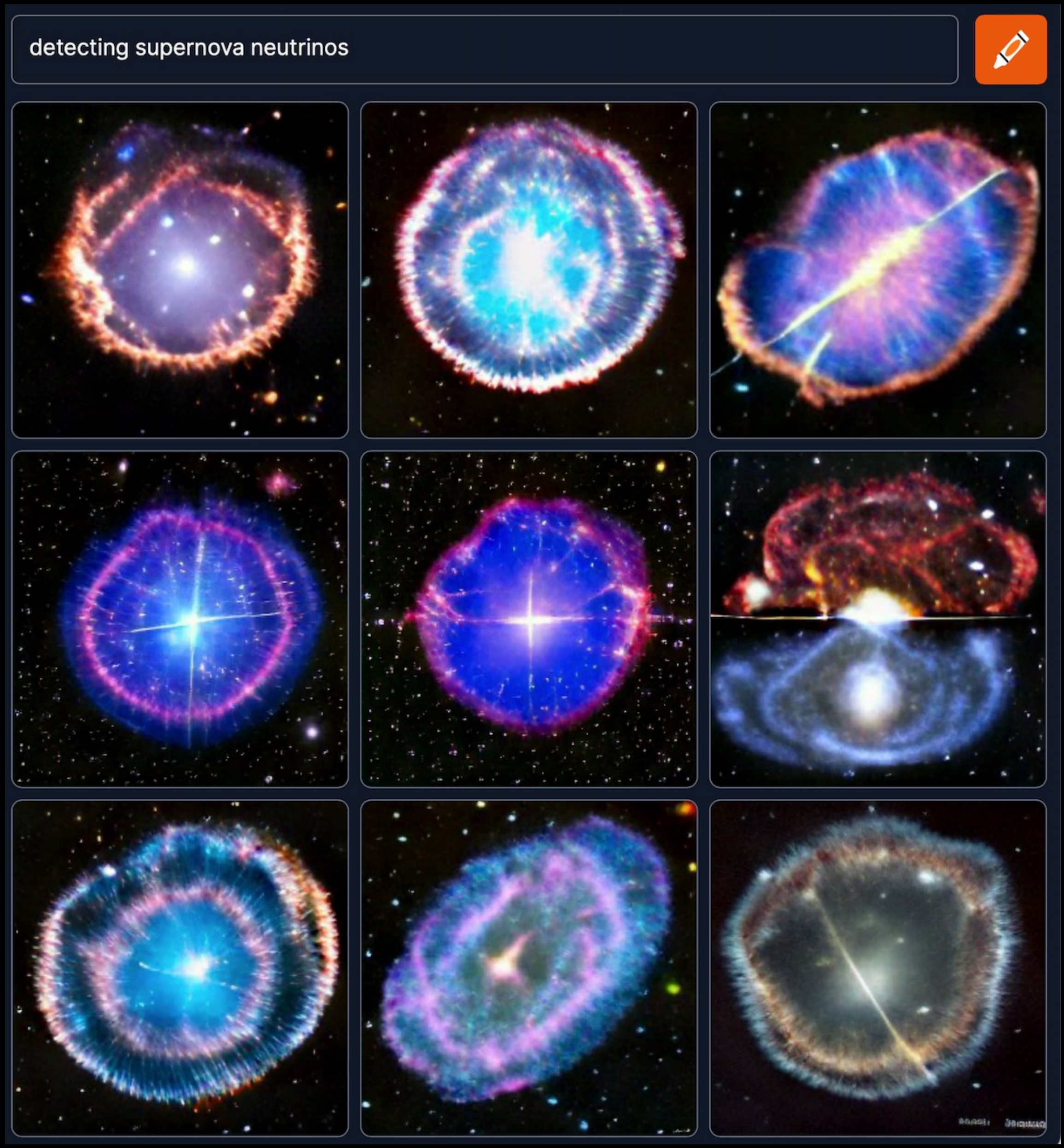
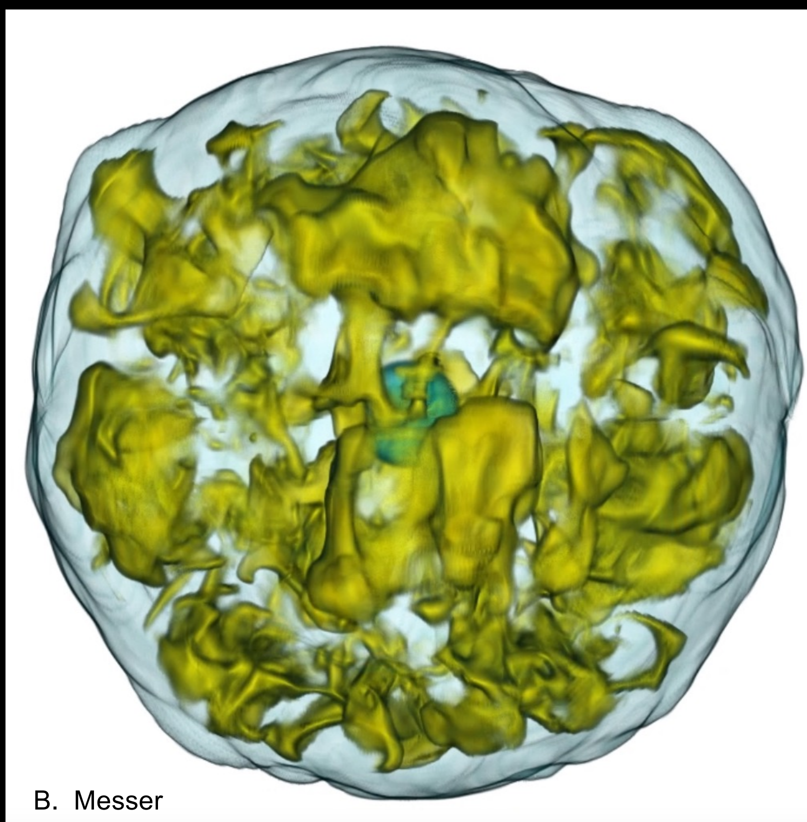


Neutrinos from core-collapse supernovae

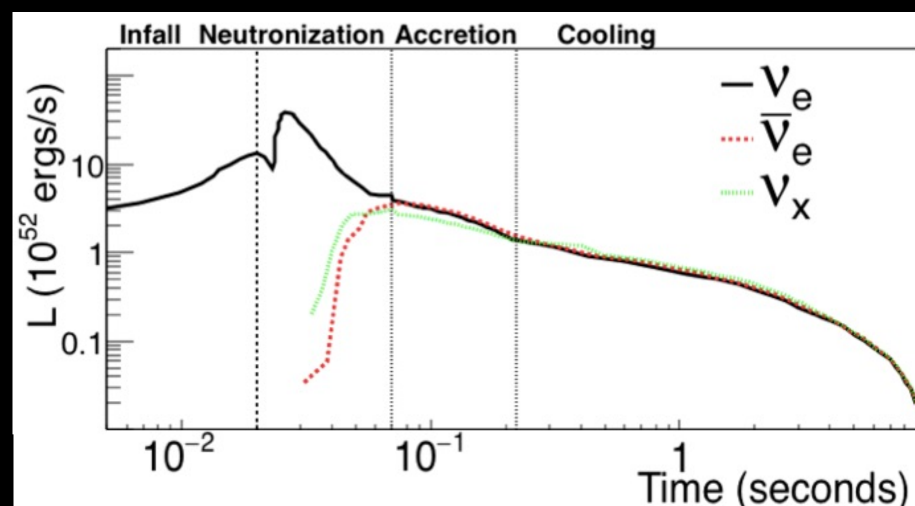
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

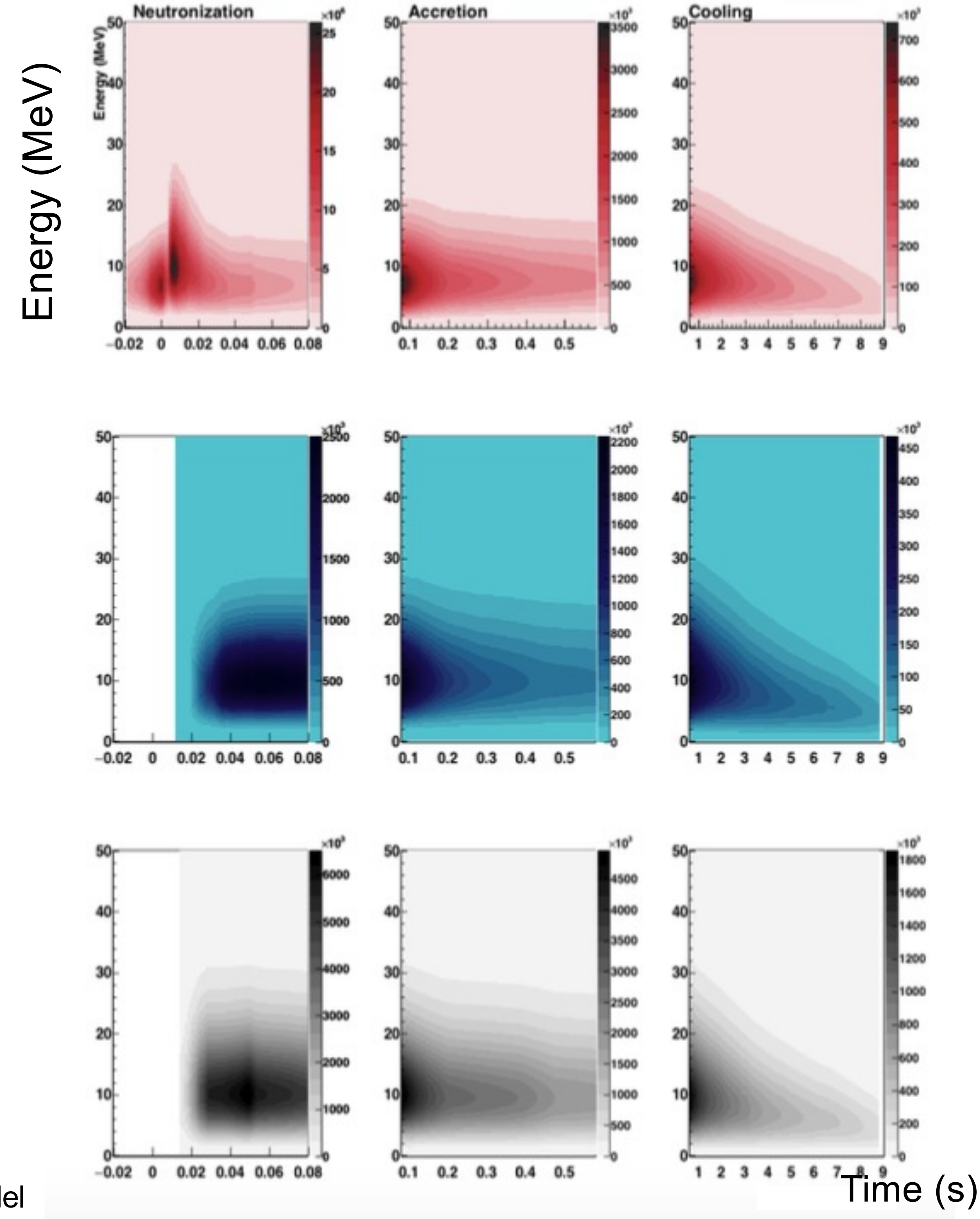
Mostly ν-νbar pairs from proto-nstar cooling



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

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

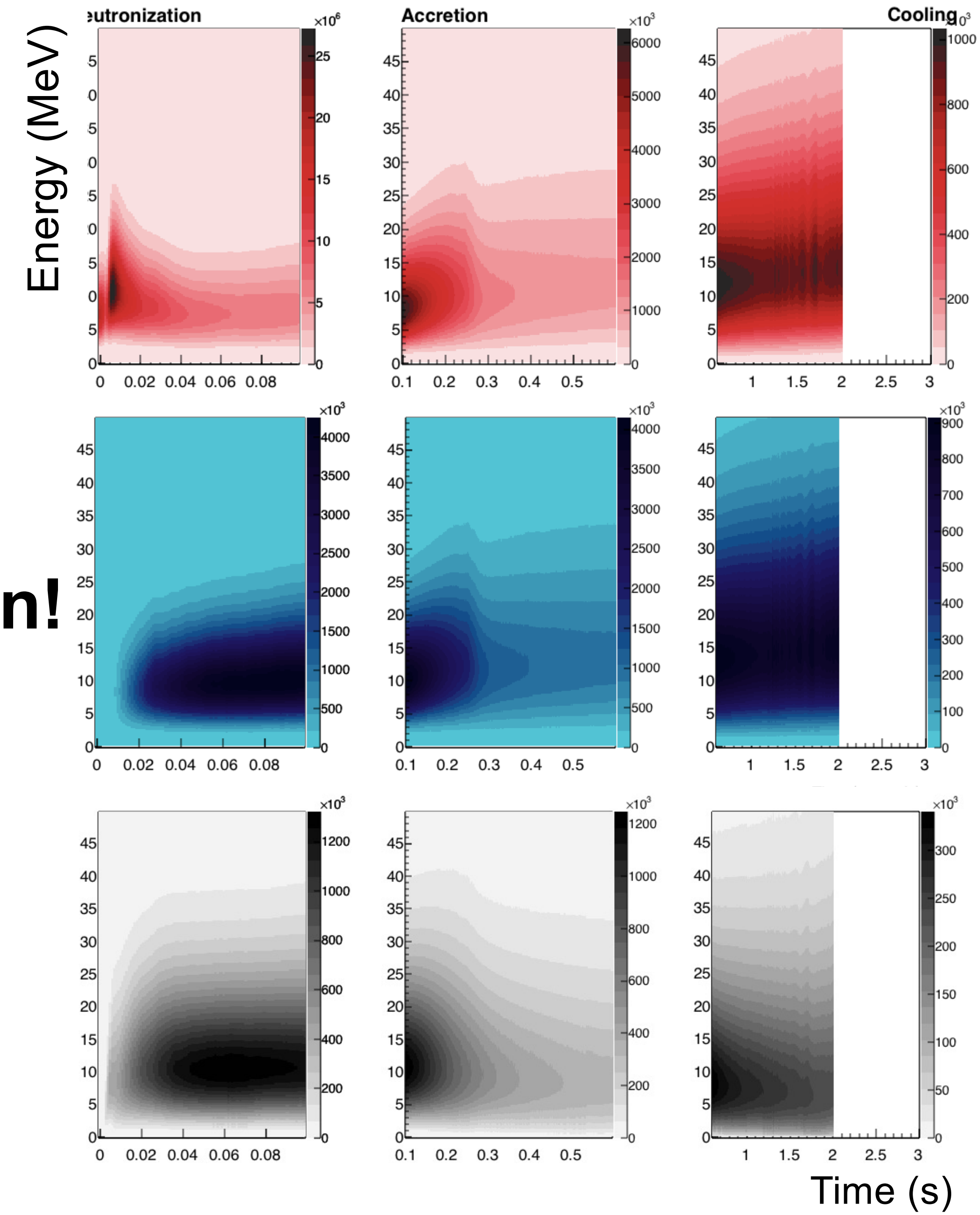
Neutrinos per cm^2 per bin (per ms per 0.5 MeV)

Huedepohl et al. model

Another example of a model

…

black hole formation!



$$\nu_e$$

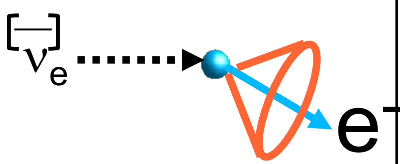
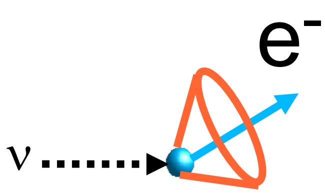
$$\bar{\nu}_e$$

$$\nu_x$$

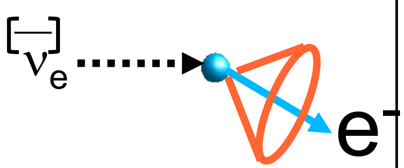
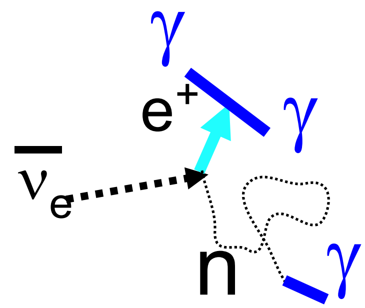
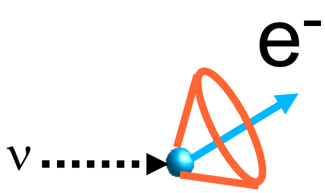
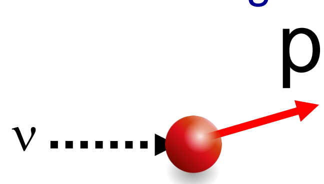
$$= \nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$$

Model by L. Huedepohl

Neutrino interactions in the ~10 MeV range

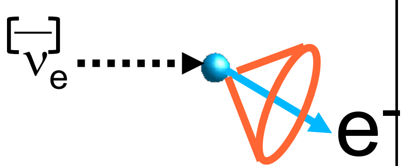
	Electrons		
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 		
Neutral current	 Useful for pointing		

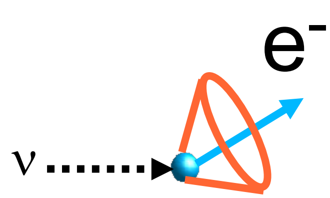
Neutrino interactions in the ~10 MeV range

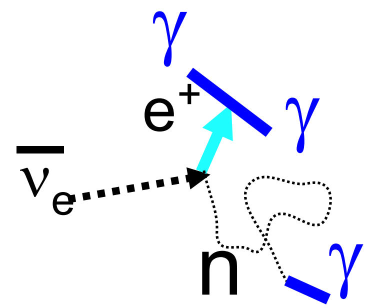
	Electrons	Protons	
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	

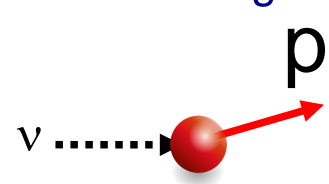
Neutrino interactions in the ~10 MeV range

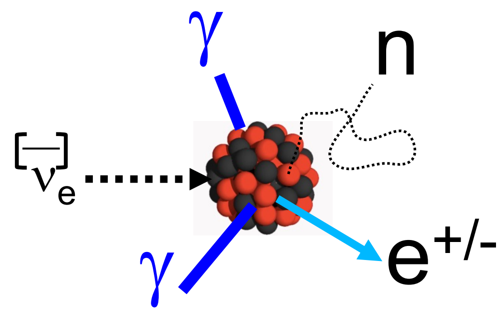
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$	$\nu_e + (N,Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \to e^+ + (N+1, Z-1)$
Neutral current	Useful for pointing	Elastic scattering very low energy recoils	$\nu + A \to \nu + A^*$ $\nu + A \to \nu + A$ Coherent elastic (CEvNS)



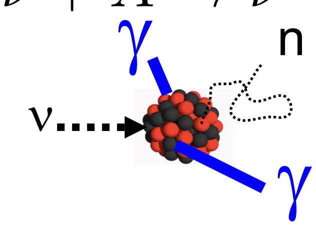


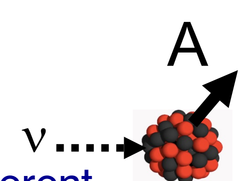




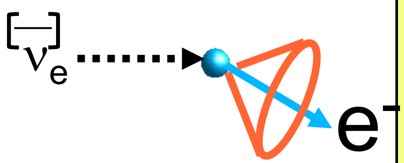
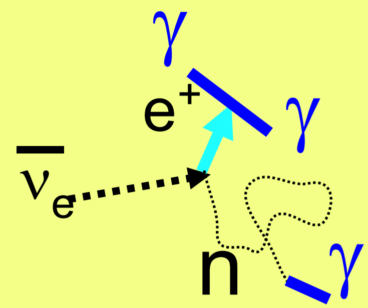
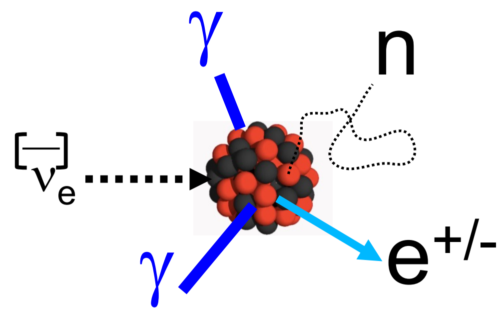
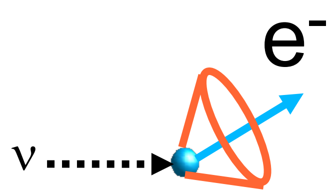
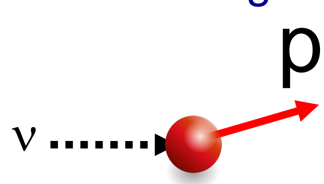
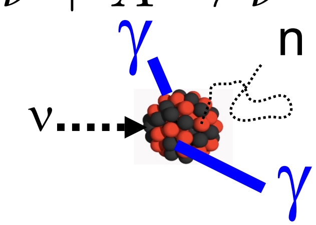
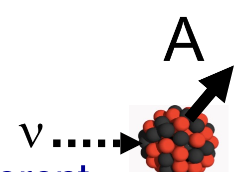


Various possible ejecta and deexcitation products





Neutrino interactions in the ~10 MeV range

	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N, Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \to \nu + A^*$  $\nu + A \to \nu + A$  Coherent elastic (CEvNS)

IBD (electron *anti*neutrinos) dominates for current detectors

Supernova neutrino detector types

Water

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

$\bar{\nu}_\mathrm{e}$

Water, long-string

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

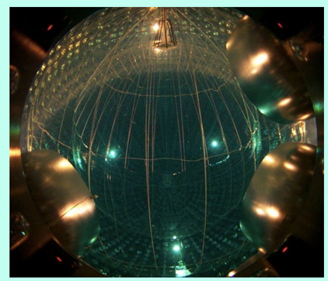
$\bar{\nu}_\mathrm{e}$

Argon

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

ν_e

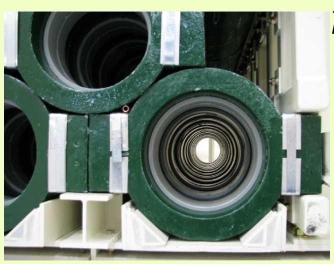
Scintillator



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

$\bar{\nu}_\mathrm{e}$

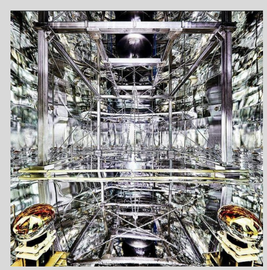
Lead



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

ν_e

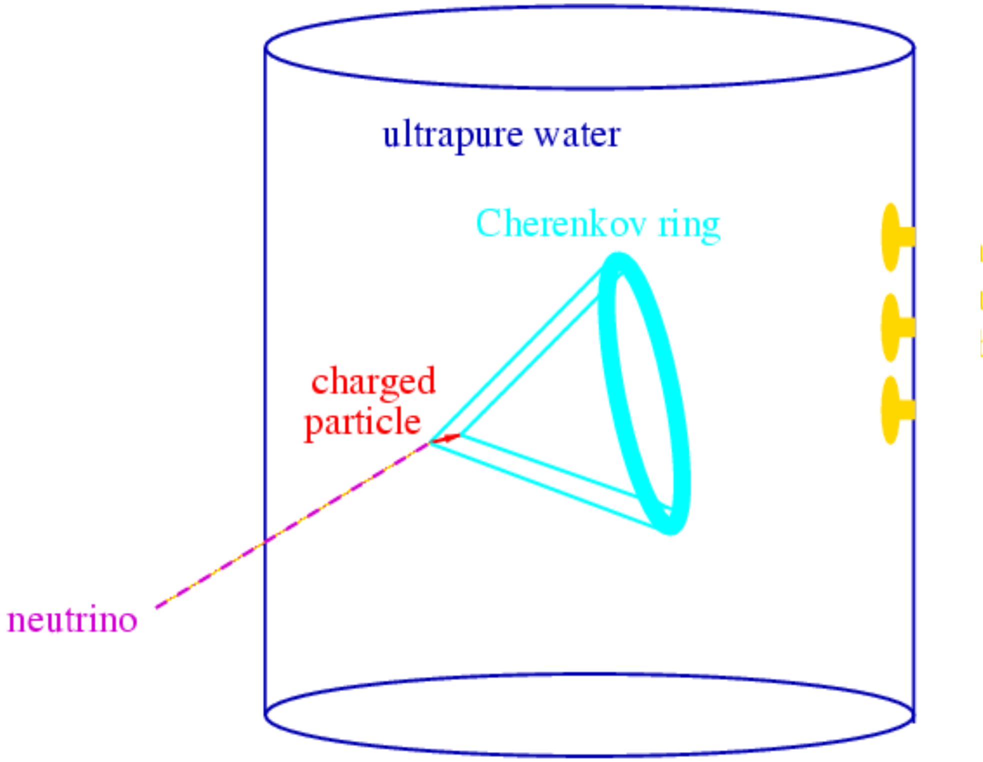
DM (Noble liquid)



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

ν_x

Water Cherenkov detectors

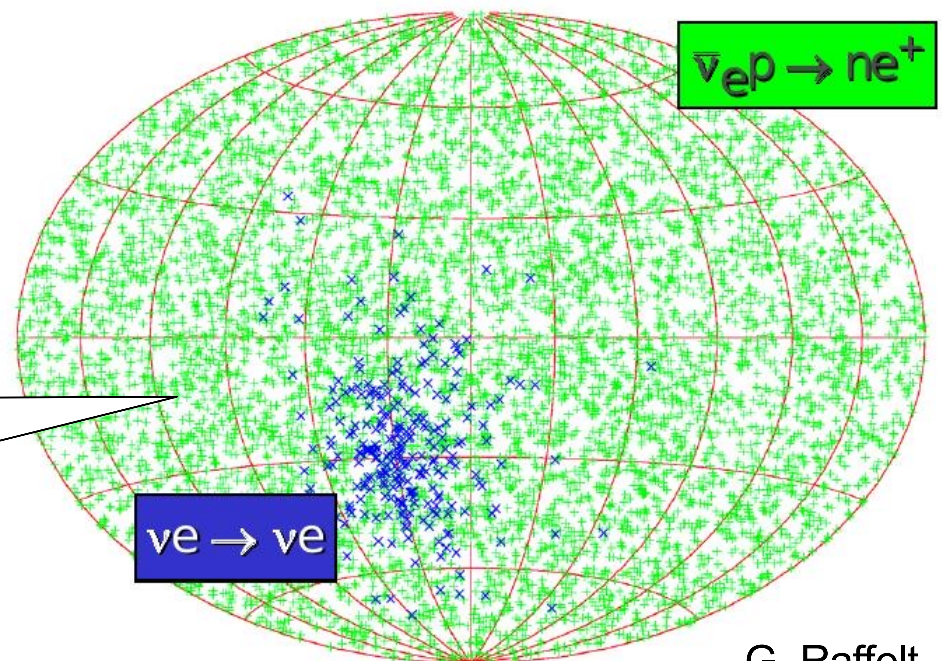


Inverse Beta Decay (CC)

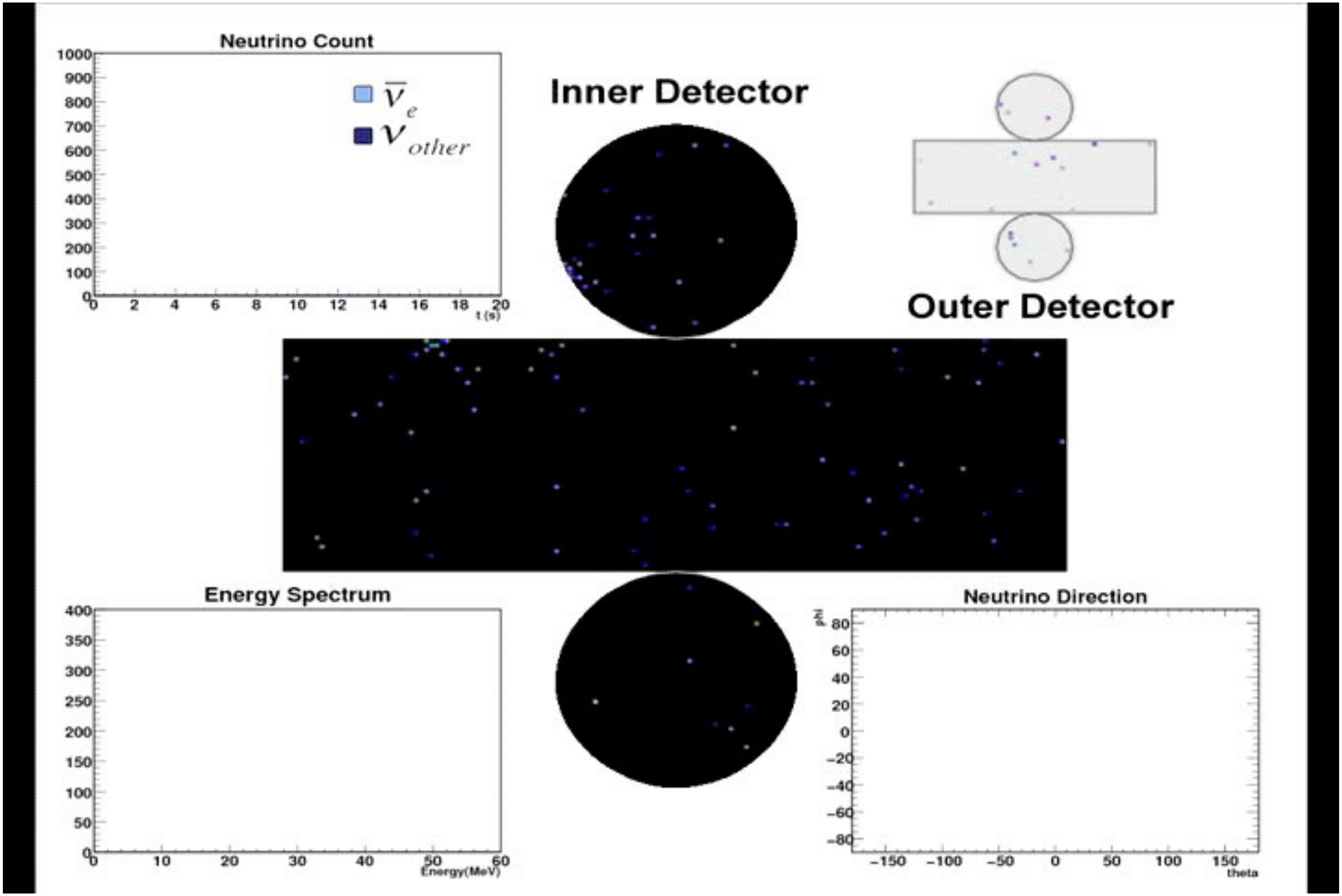
$\bar{\nu}_e + p \rightarrow e^+ + n$ **dominates**

E_{thr}=1.8 MeV

Pointing from neutrino-electron elastic scattering



G. Raffelt



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

Neutron tagging in water Cherenkov detectors

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

detection of neutron tags event as *electron antineutrino*

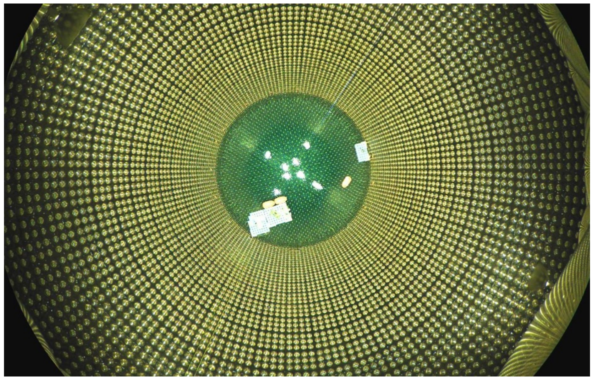
- especially useful for diffuse SN signal (which has low signal/bg)
- also useful for disentangling flavor content of a burst

  (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 0.03% Gd

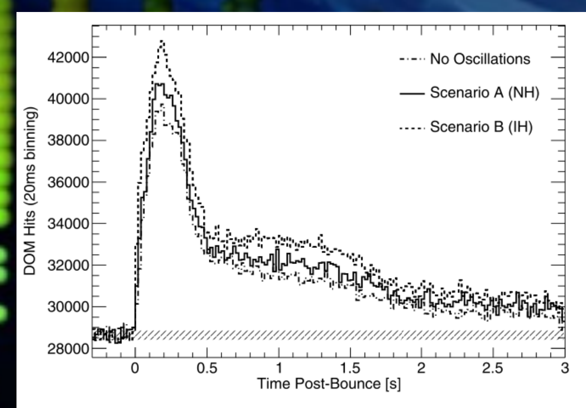
(13.2 tons of $Gd_2(SO_4)_3{*}8H_2O$)

Long string water Cherenkov detectors

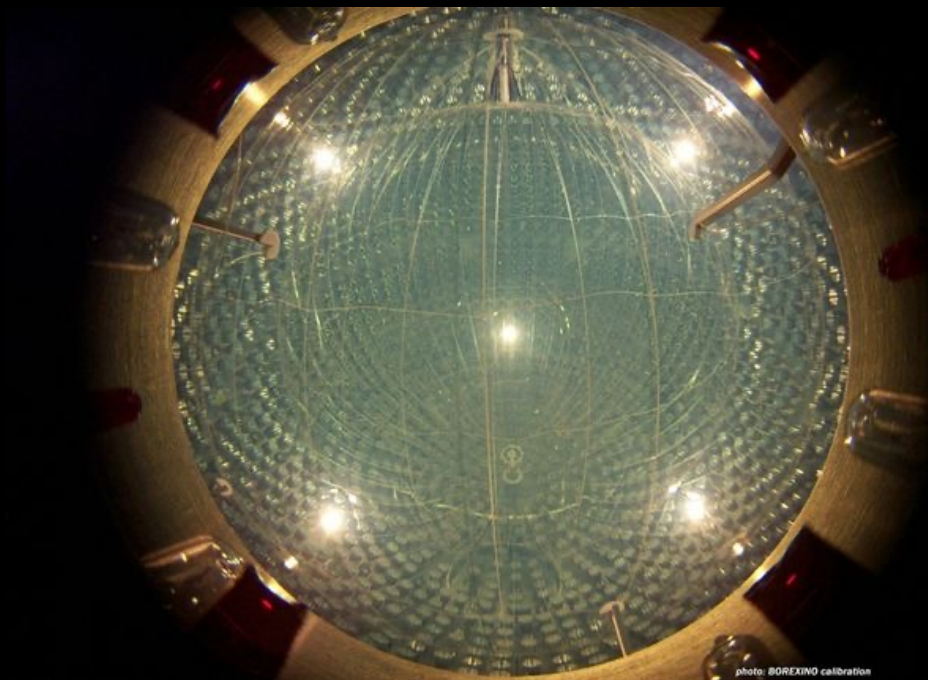
~kilometer long
strings of PMTs
in very clear water
or ice (IceCube, KM3NeT)

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

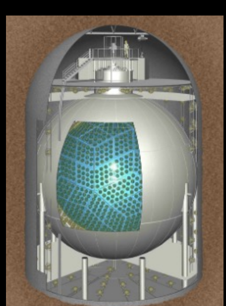


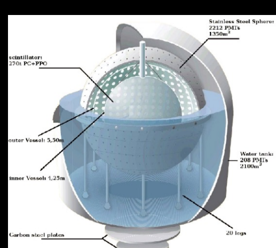
Liquid hydrocarbon (C_nH_{2n}) that emits (lots of) photons when charged particles lose energy in it

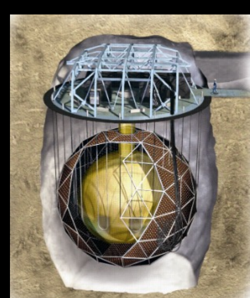
Will see supernova **electron antineutrinos**, with good energy resolution

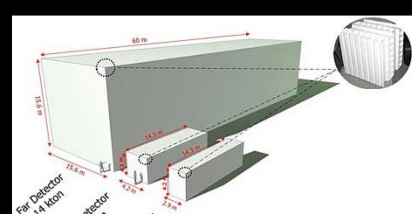
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Many examples worldwide of current and future detectors

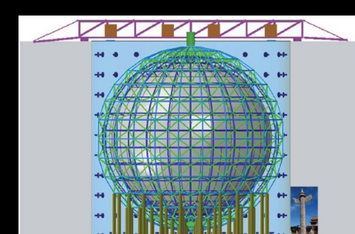




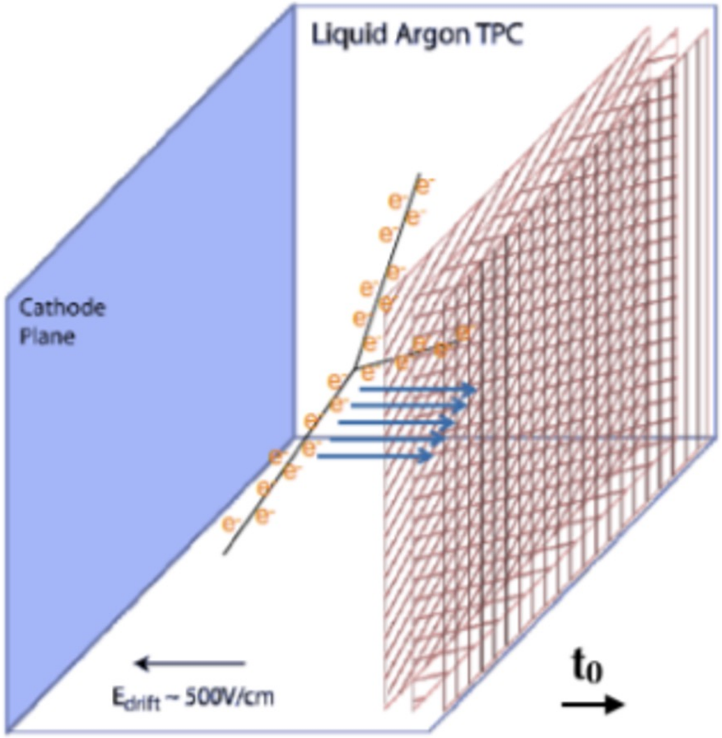




JUNO, 20 kt



Liquid argon time projection chambers



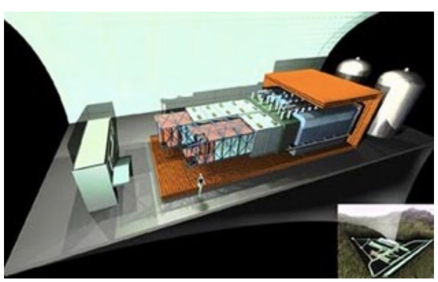
+photon detectors

fine-grained trackers
ionization + scintillation photons

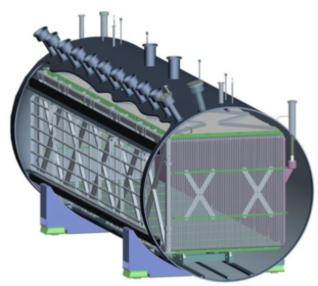
sensitive to **electron neutrinos**
(as opposed to antineutrinos)

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

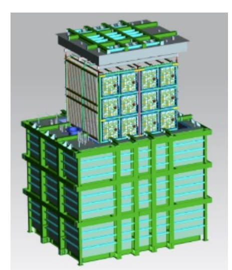
ICARUS
(Italy➔USA)
0.6 kton



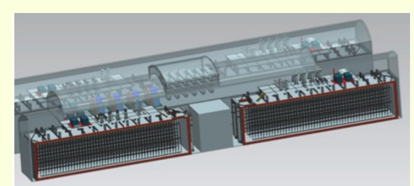
MicroBooNE
(USA)
0.2 kton



SBND
(USA)
0.112 kton

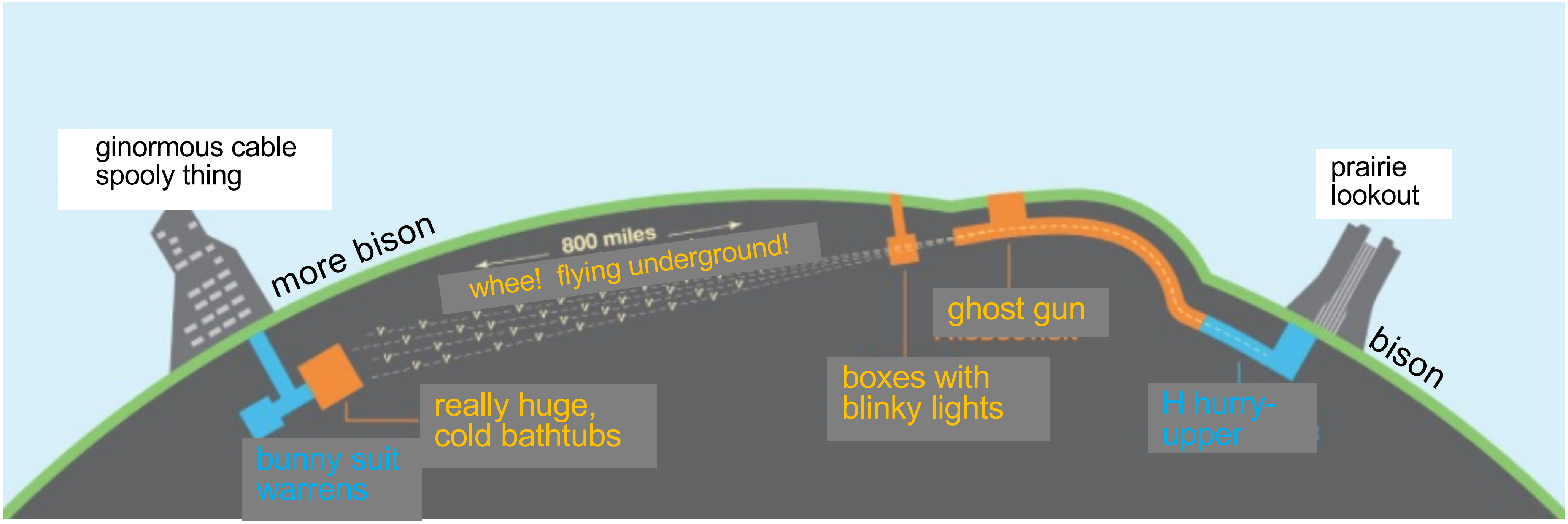


DUNE
(USA)
40 kton



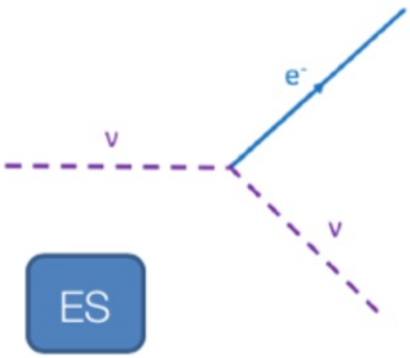
Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility

next big US-based international particle physics project



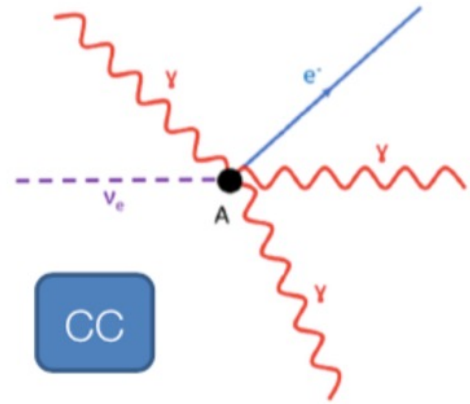
- new 1.2 MW beam, Fermilab to SD
- 40-kton fiducial
  liquid argon TPC far detector
- Also proton decay,
  supernova, atmospheric neutrino
  physics ...

SNB event topologies in argon TPC



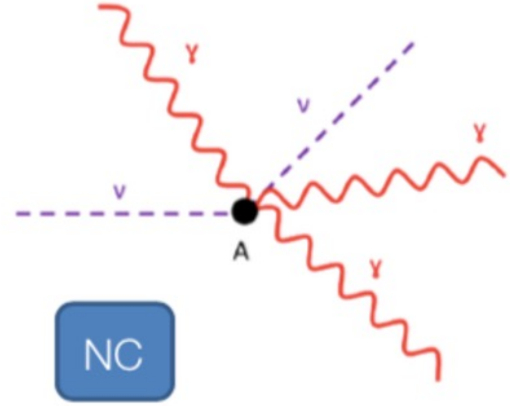
$$\nu + e^- \rightarrow \nu + e^-$$

stub



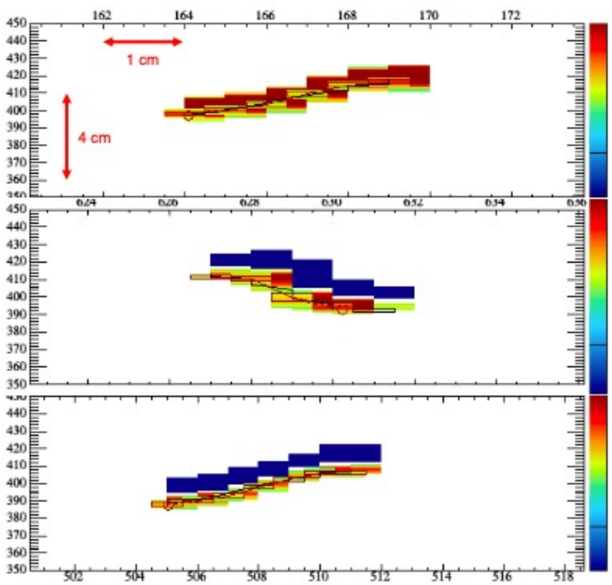
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

stub+sparkles



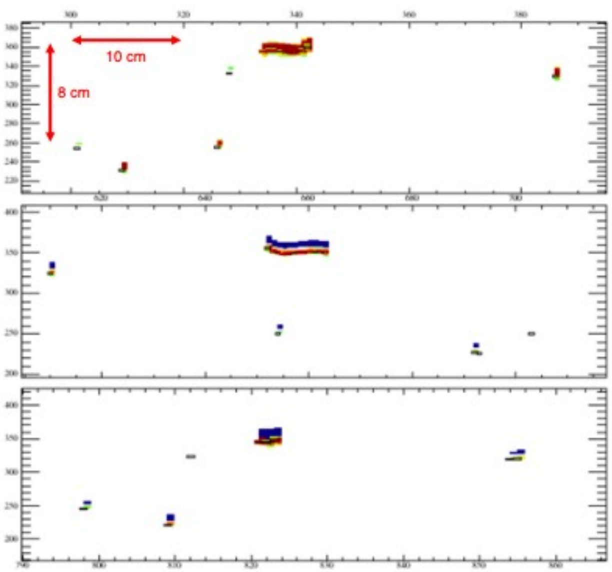
$$\nu + {}^{40}\mathrm{Ar} \rightarrow \nu + {}^{40}\mathrm{Ar}^*$$

cloud of sparkles



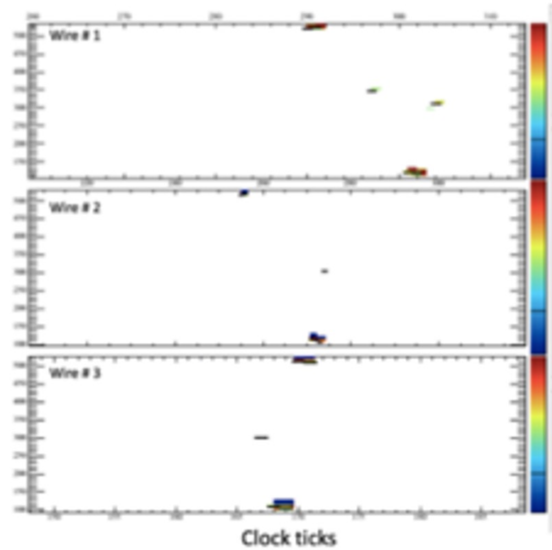
10.25 MeV electron (eES)

"clean" track



20.25 MeV neutrino (ν_eCC)

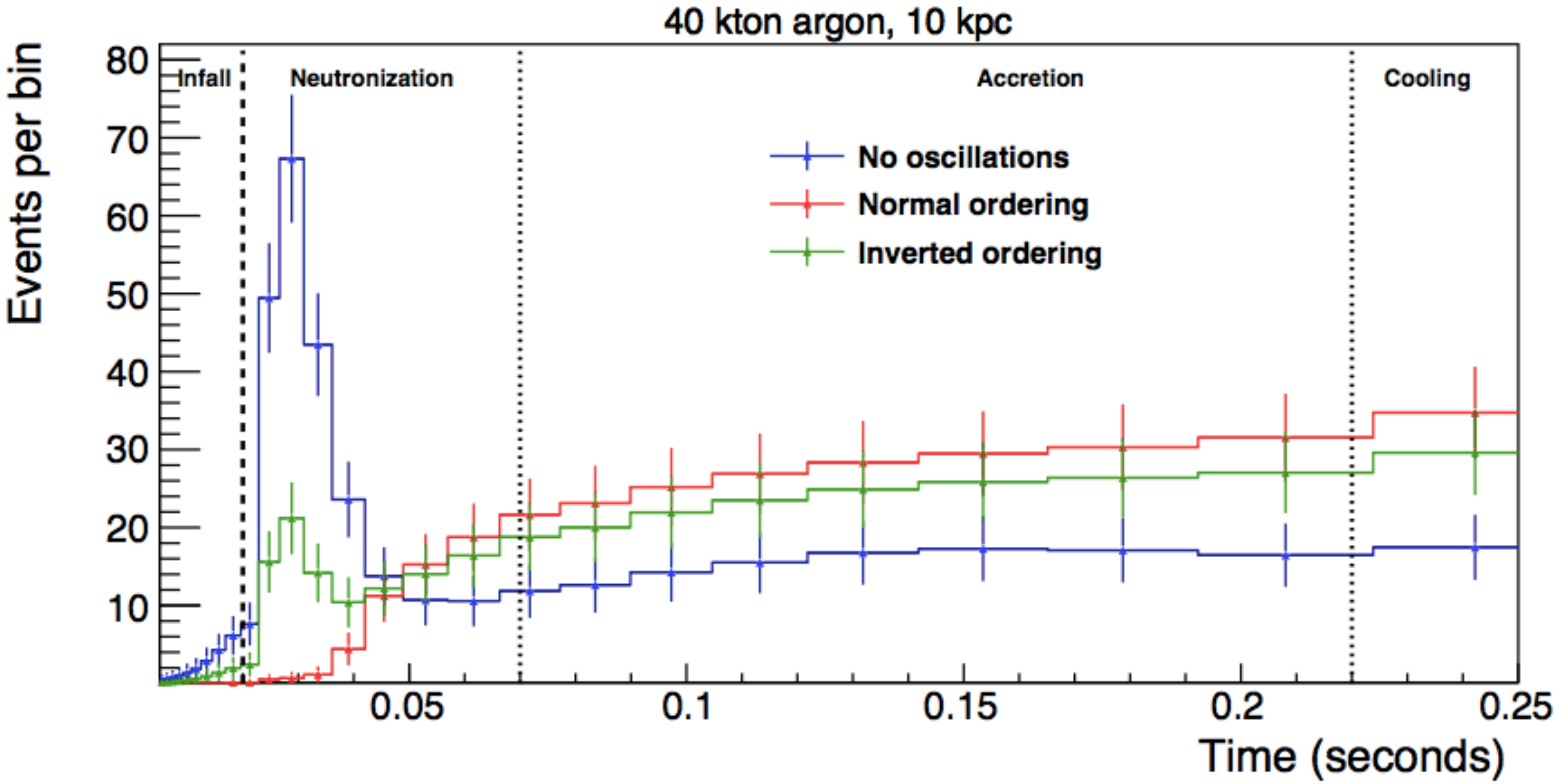
track + deex γ blips
+ brem γ blips



NC deexcitation

cloud of γ blips

In LAr **neutronization burst gets substantially suppressed** with flavor transitions



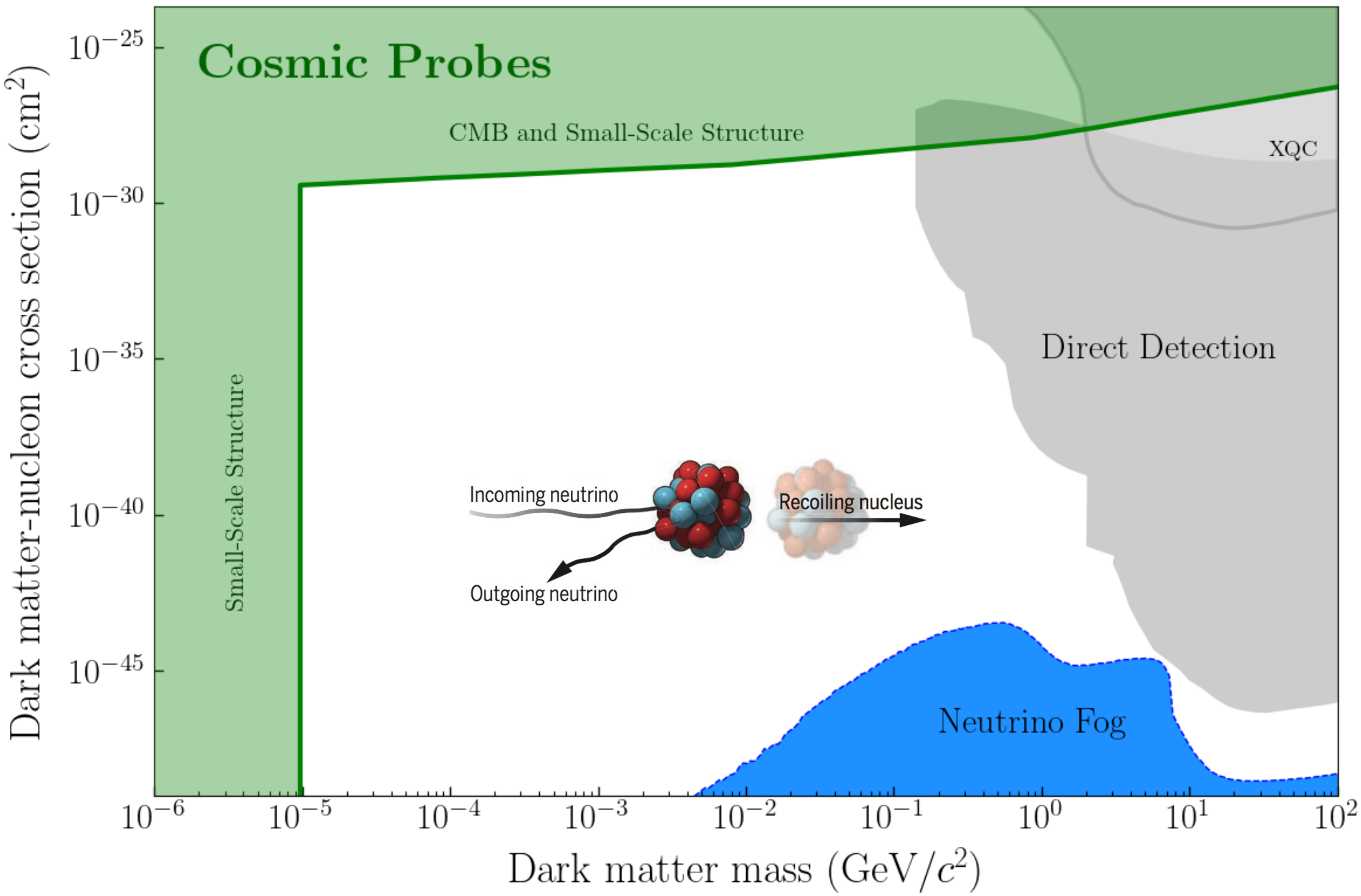
Simple MSW assumption (assume OK at early times)

NMO: $F_{\nu_e} = F^0_{\nu_x}$

IMO: $F_{\nu_e} = \sin^2\theta_{12} F^0_{\nu_e} + \cos^2\theta_{12} F^0_{\nu_x}$

(a mass ordering signature!)

Dark matter detectors as **neutrino observatories**

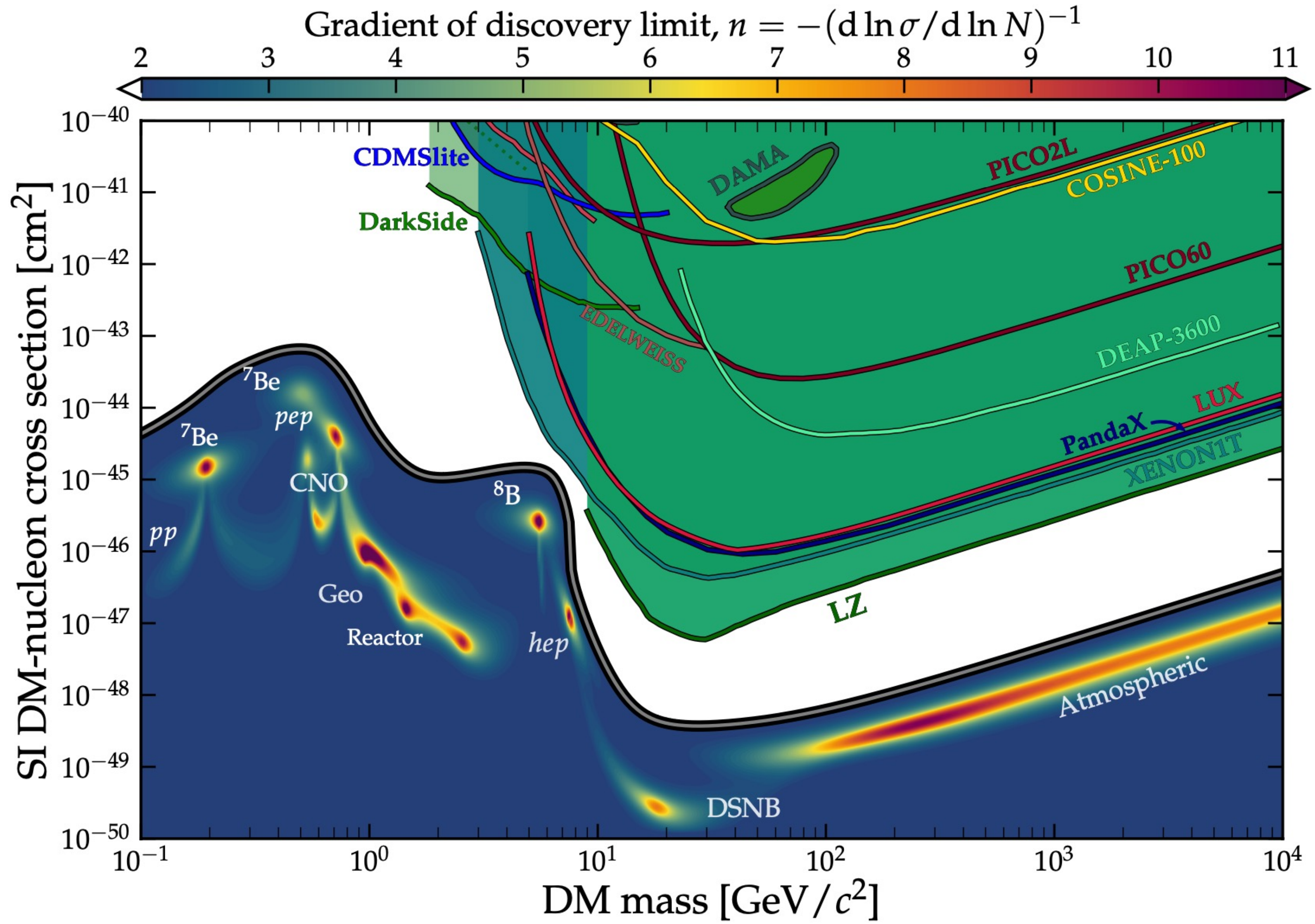


Plot from Snowmass CF01

Image: J. Link *Science* Perspectives

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

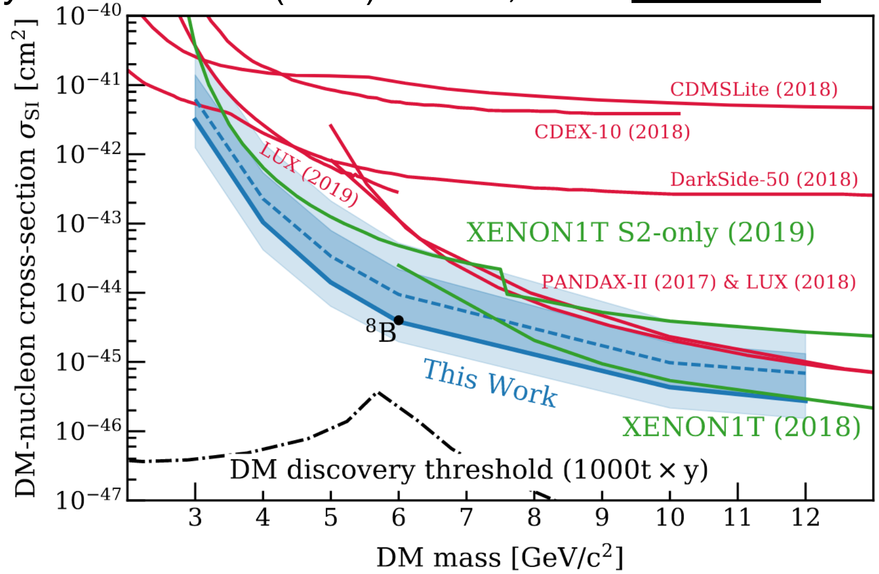
Interesting things may eventually emerge from the fog...

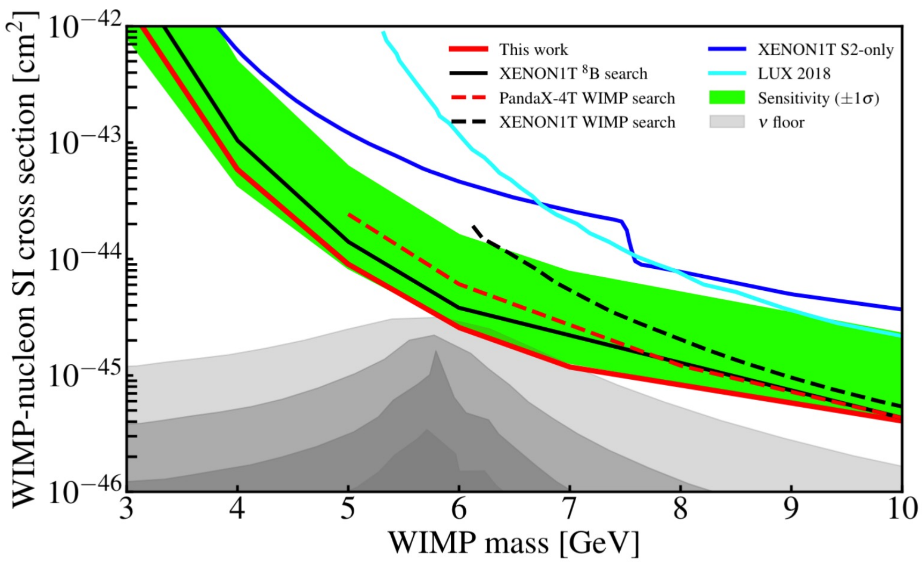


O'Hare [2109.03116]

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

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

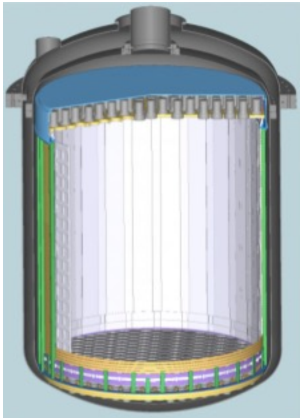


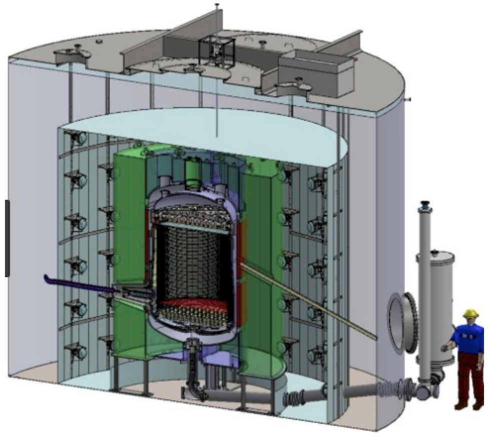


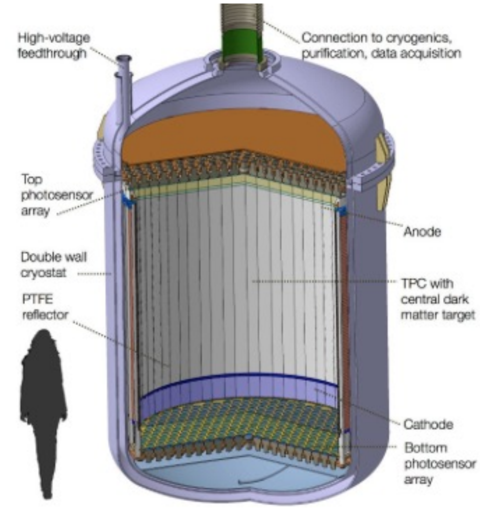
PANDA-X arXiv:2207.04883

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

Supernova **burst** detection in large DM detectors

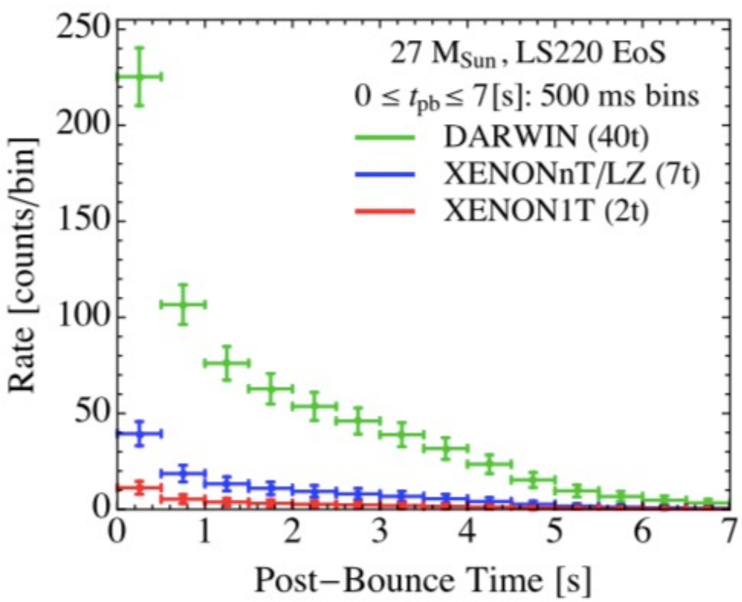


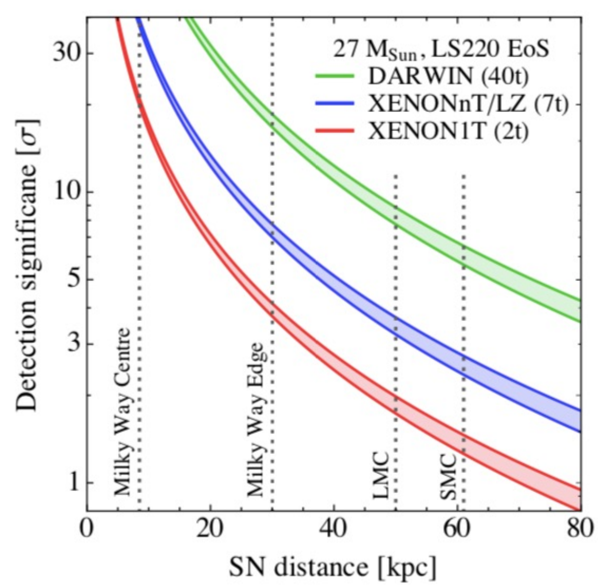




Example: dual-phase xenon time projection chambers

DARWIN



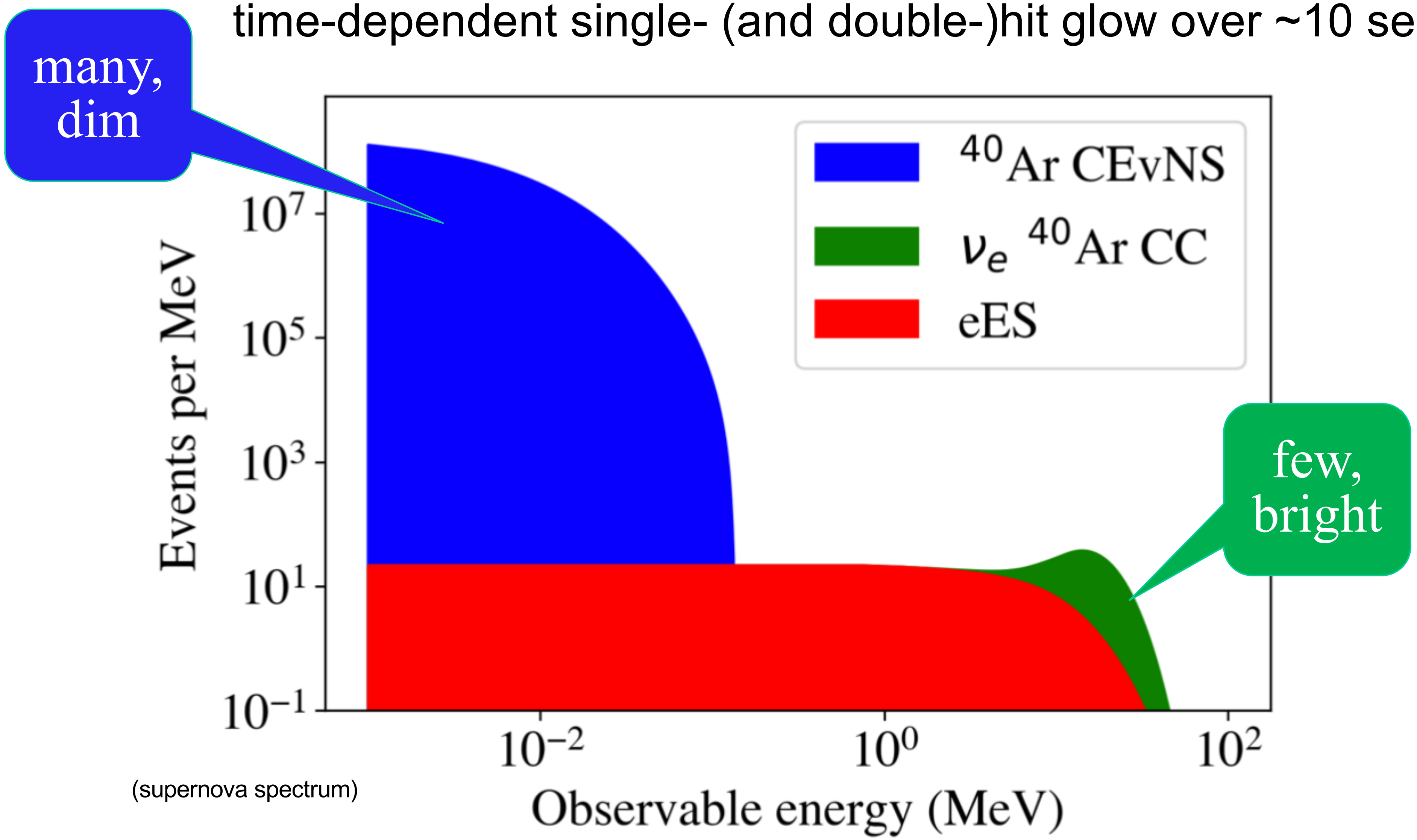


Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

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



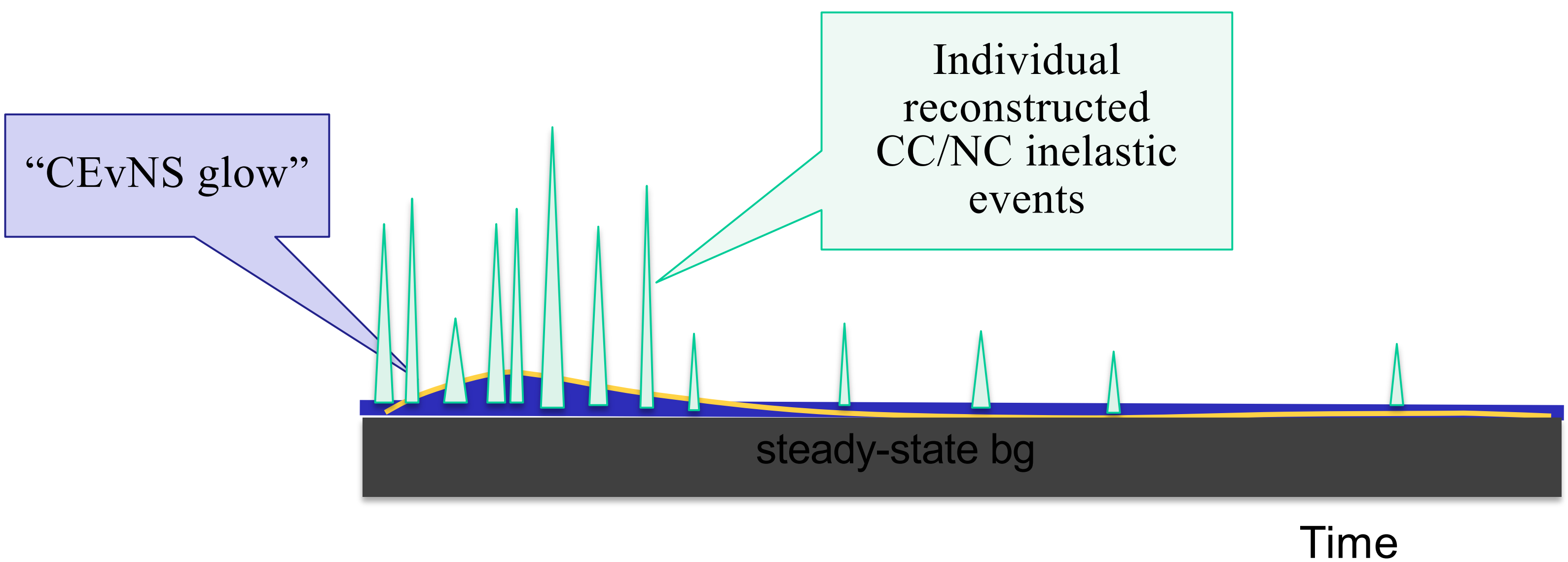
(supernova spectrum)

Back-of-the-envelope:
CEvNS signal vs Inelastic (CC/NC) signal:

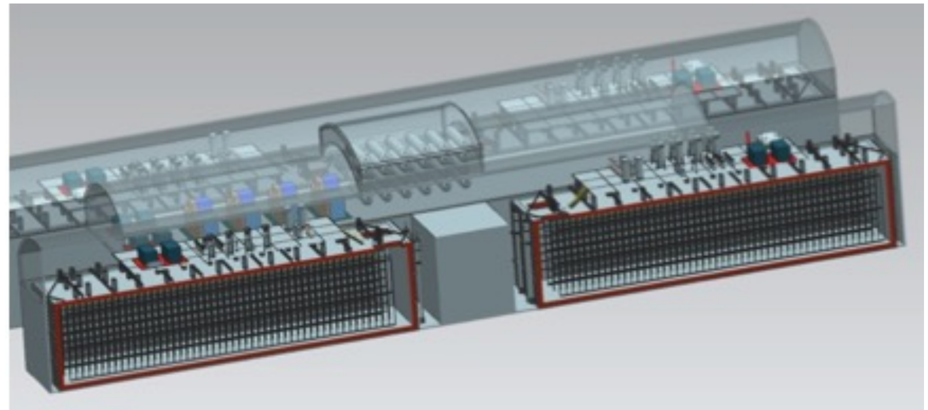
e.g., $\nu_x + A \rightarrow \nu_x + A$ vs $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$ in argon, or IBD in scint

~10^2 more CEvNS events per target wrt CC
~10^{-3} less energy deposited per event for CEvNS wrt CC
~ 6 due to sensitivity to all flavors
~0.001-0.2 quenching factor (photons wrt e/γ energy deposit) for nuclear recoil wrt CC

➔Total CEvNS photons are **~few-10% of CC-generated photons**, but, **diffused over the burst** rather than in individual event spikes
Issue is whether they exceed Sqrt[background]
(and triggering may be challengin!)

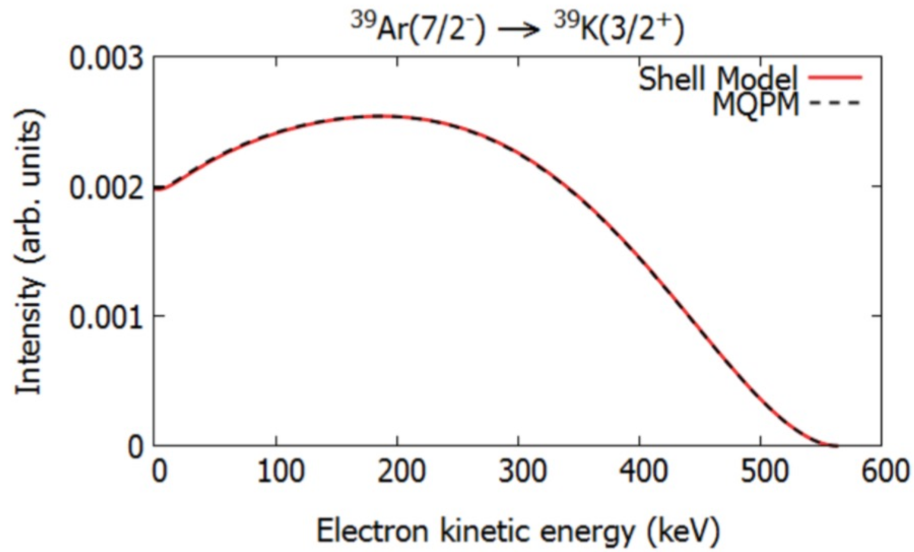


For **DUNE**: 40 kt LAr,
~24,000 photons/MeV
TPC + photon detectors



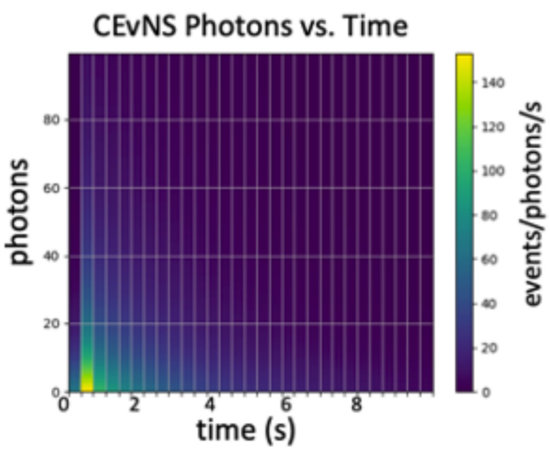
Most pernicious
issue for CEvNS glow:
^{39}Ar β decays
(dominant radiological)

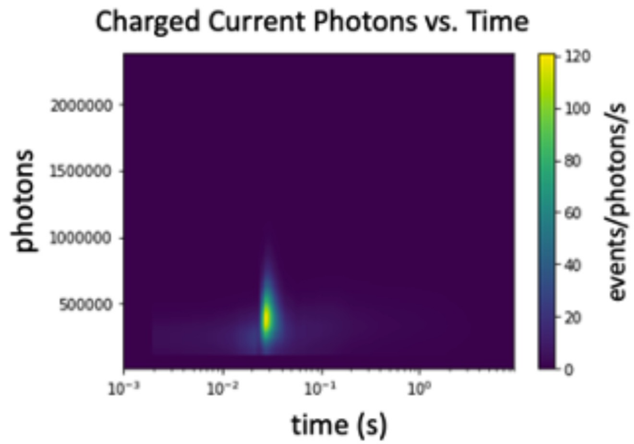
- 1 Bq/kg
- 260-yr half-life
- in principle can be mitigated w/underground argon (but 40 kton of it a challenge...)

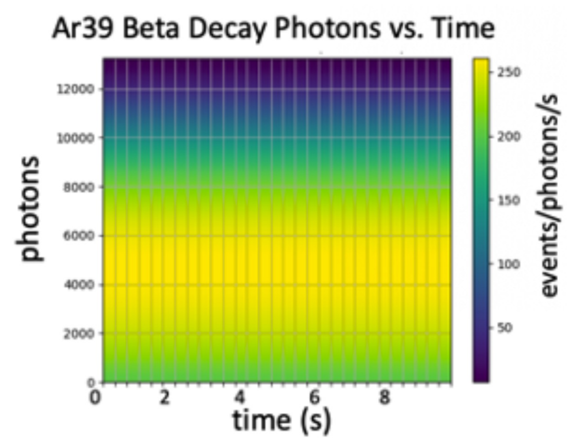


J. Kostensalo et al. (2017) arXiv:1705.05726

CEvNS Glow Photons in LAr: calculation by A. Major, Duke

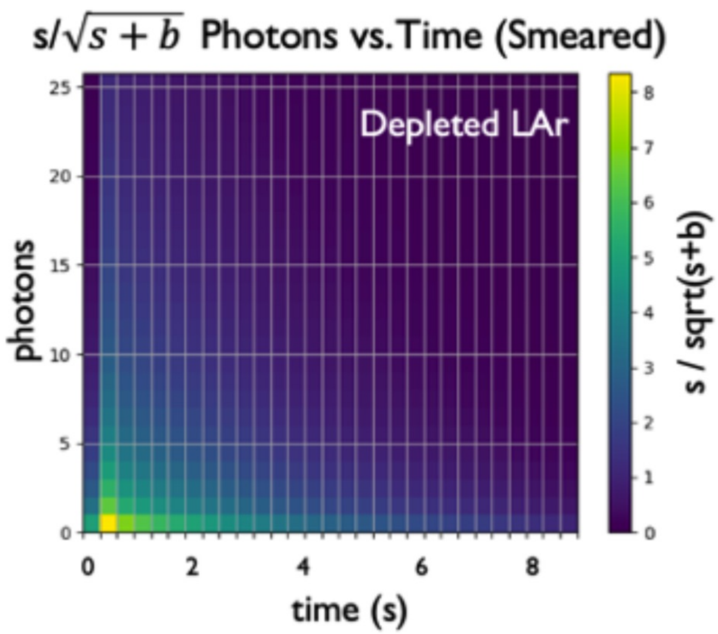






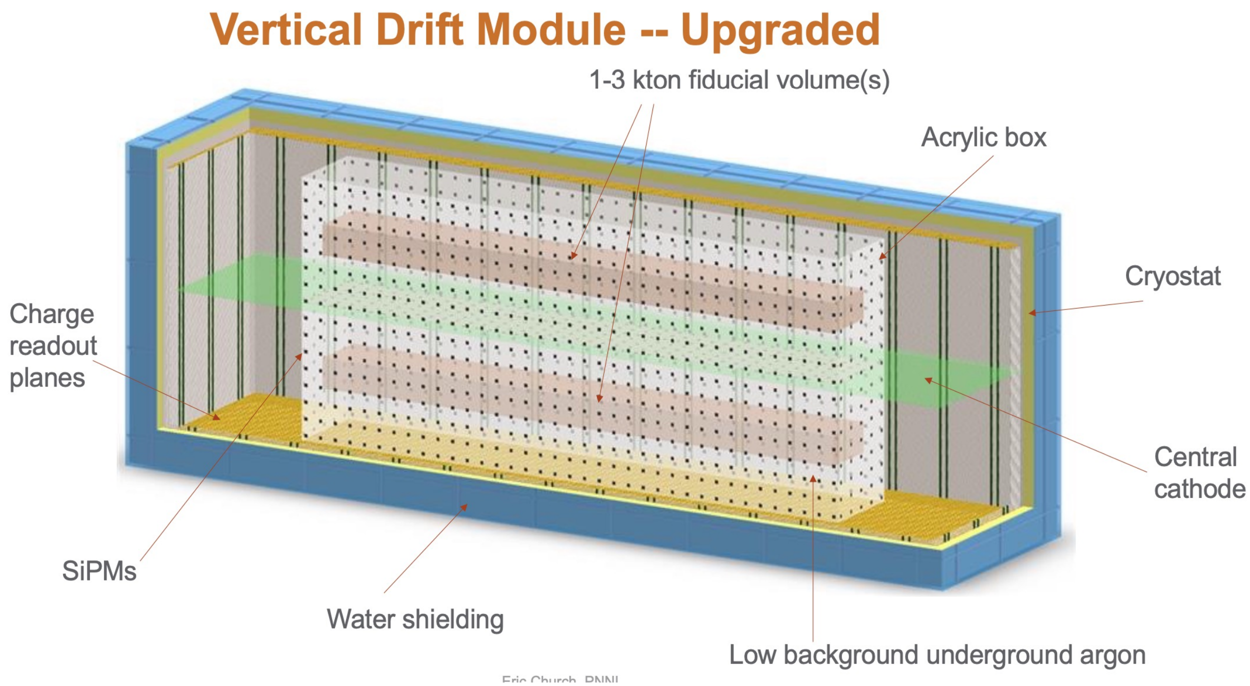
"Garching" supernova model, 10 kt, 10 kpc

Detected photons in simplified detector with ^{39}Ar x 0.001



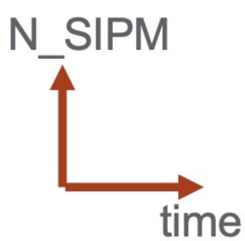
information
in time,
detected photon
multiplicity
spectrum

Approximate features matched by G4 sim of DUNE low-bg module



E. Church
LIDINE 2021

SLoMO
SURF
LOw
background
Module



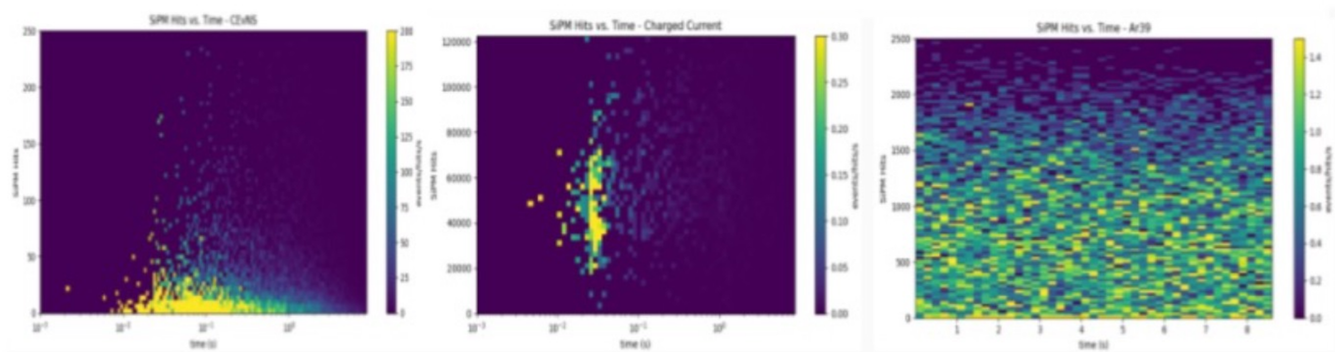


Figure 6: Figures from Carmelo Ortiz, DUNE low energy physics working group meeting,https://indico.fnal.gov/event/50302/

Carmelo Ortiz, Duke

Summary of supernova neutrino detectors

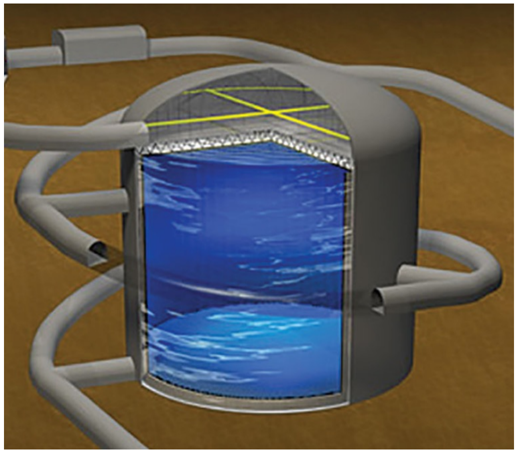
Galactic sensitivity

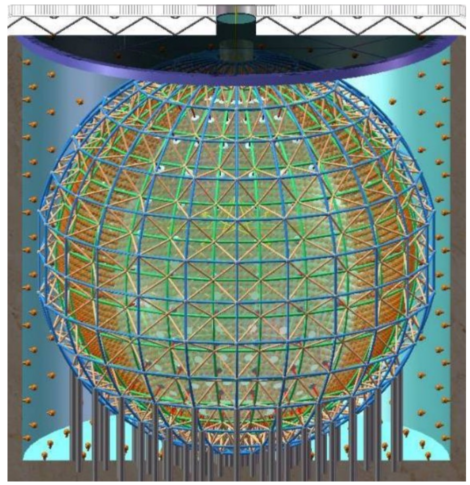
Extragalactic

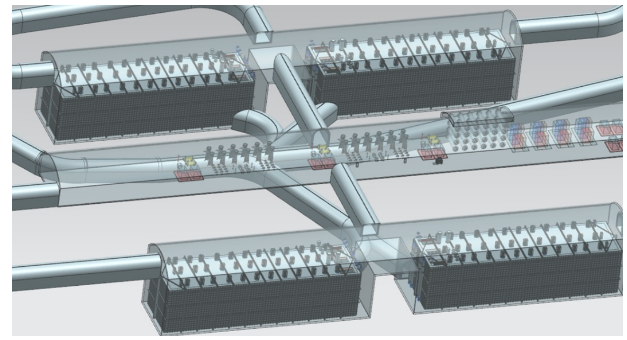
Detector	Type	Location	Mass (kton)	Events @ 10 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	(600)	(10^6)	Running
Baksan	Scintillator	Russia	0.33	50	Running
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	266	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole			
KM3Net	Long string	Mediterranean			

plus reactor experiments, DM experiments...

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**

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

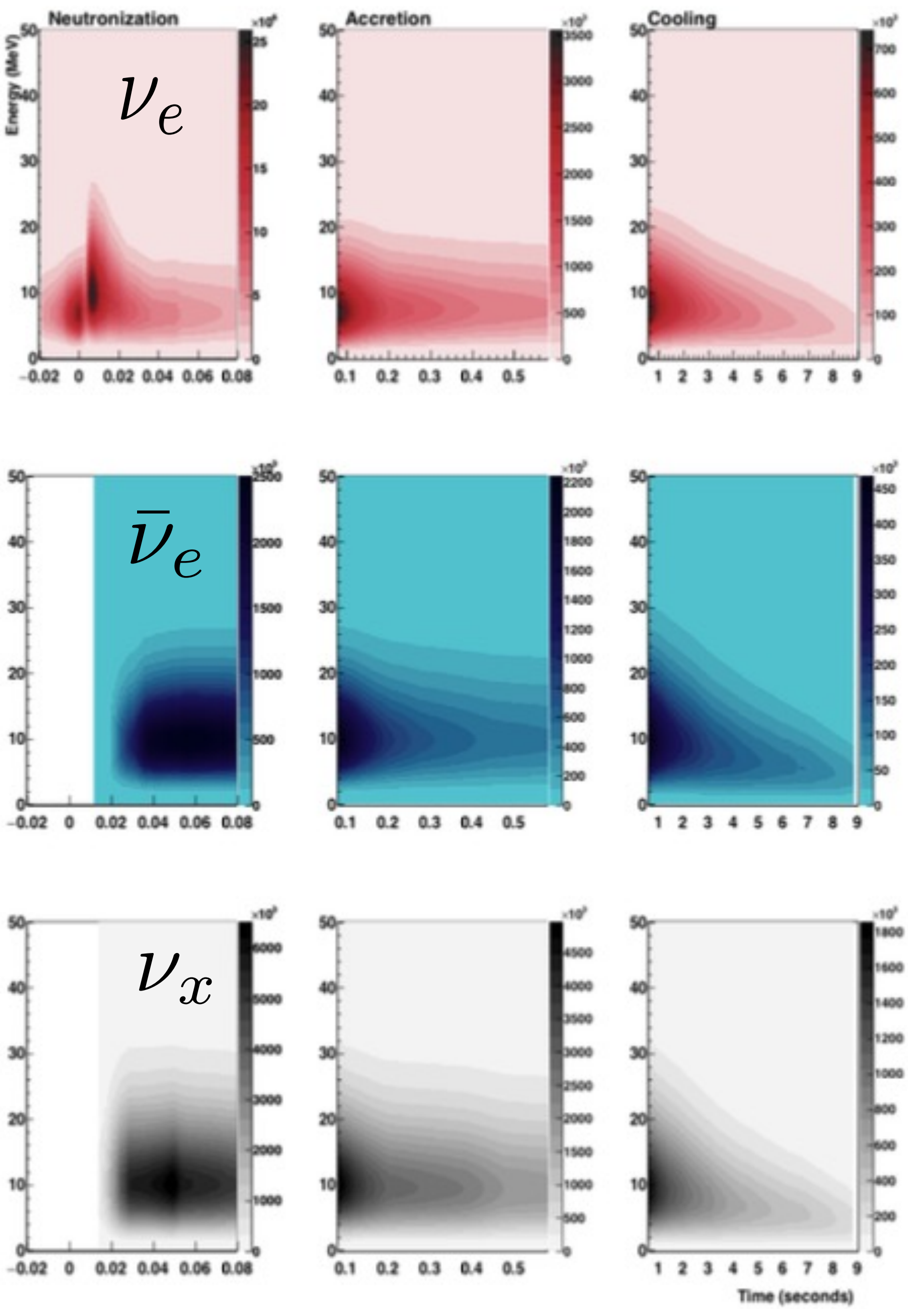
- DUNE is primarily sensitive to **nue**

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

extreme complementarity

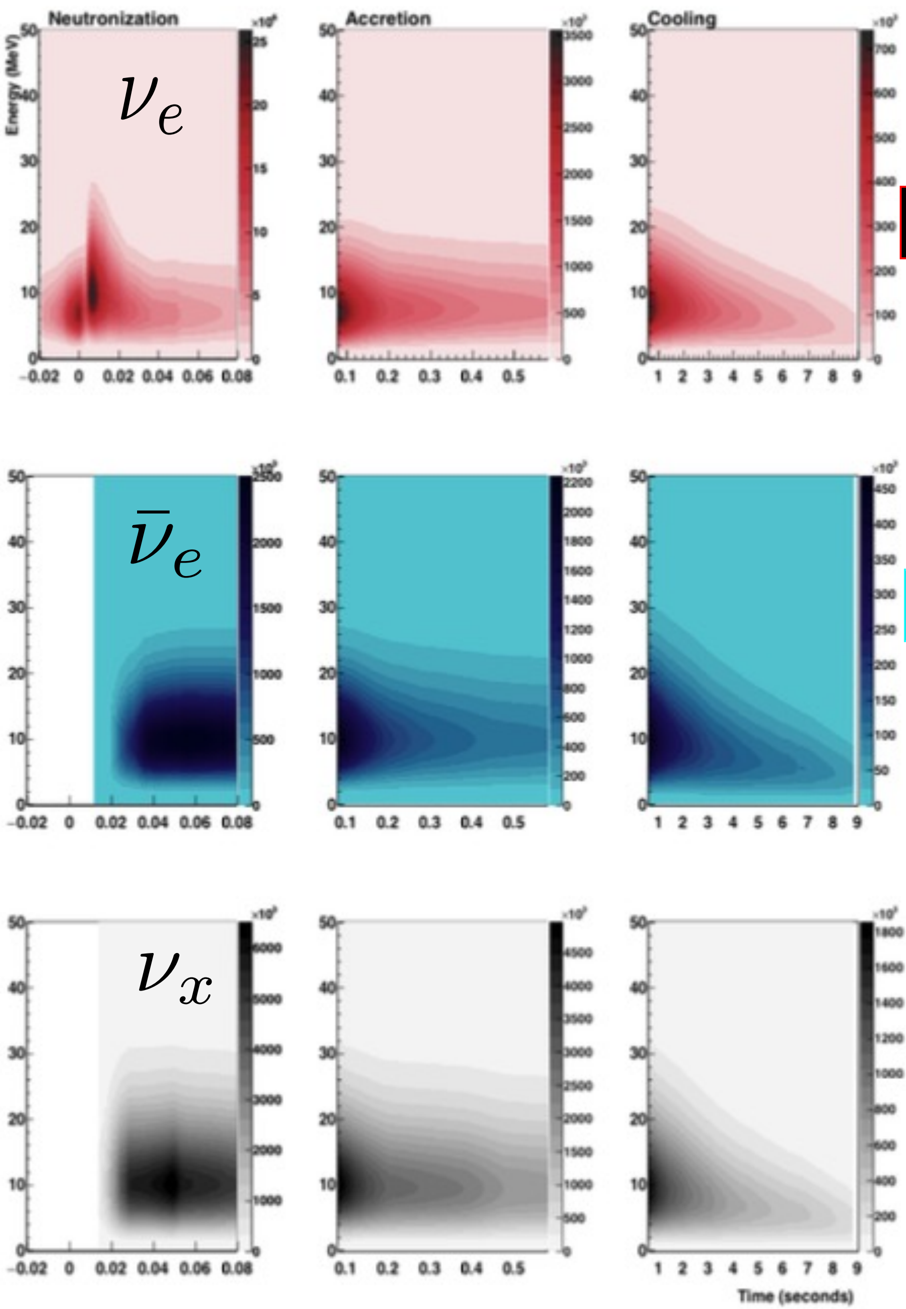
What we *want* to measure

Neutrino fluxes vs E, t



What we *want* to measure

Neutrino fluxes vs E, t



What we *can* measure

Event rates in different interaction channels vs E, t (with imperfect tagging & resolution)

$\nu_e \mathrm{CC}$

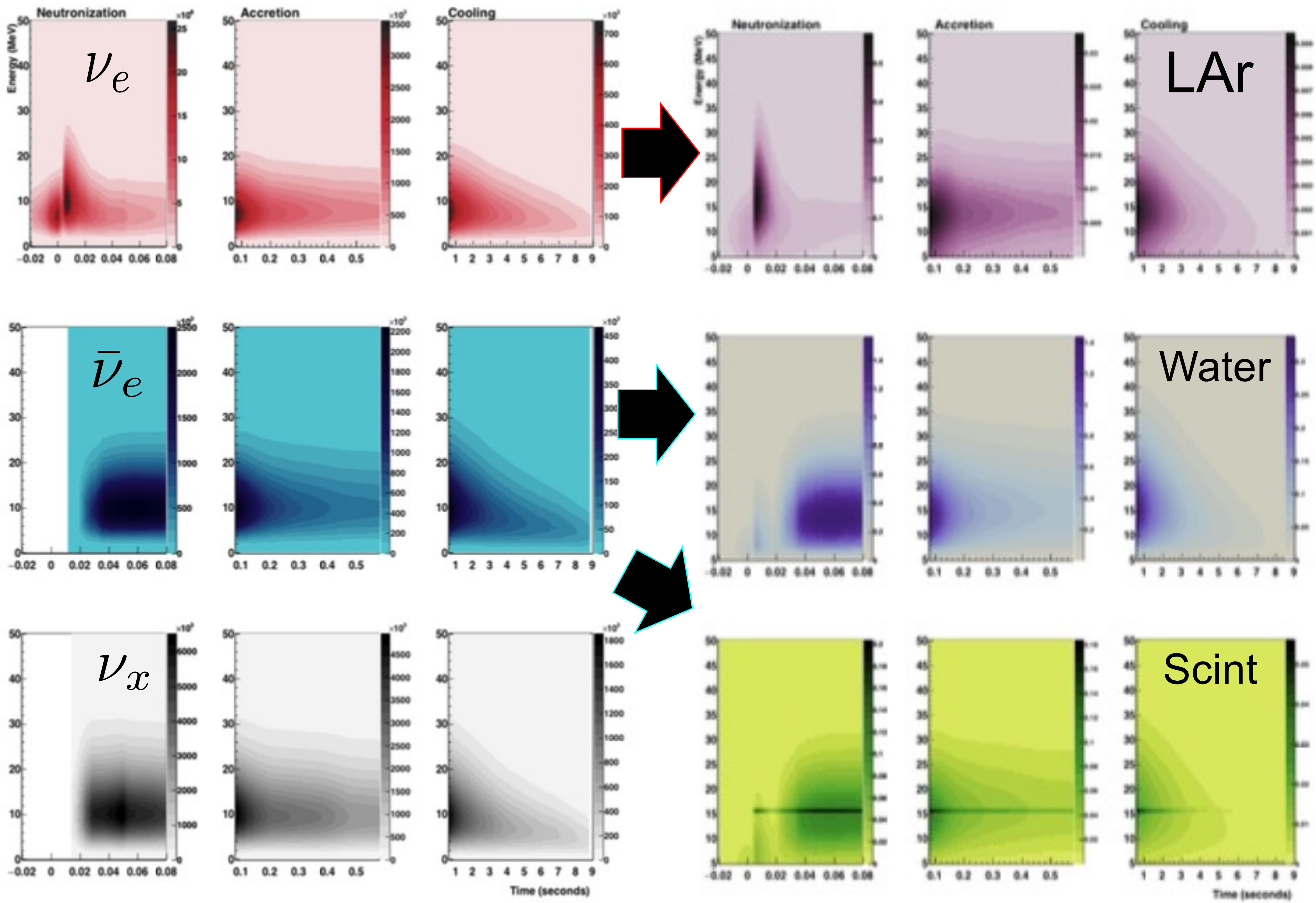
$\bar{\nu}_e \mathrm{CC}$

NC

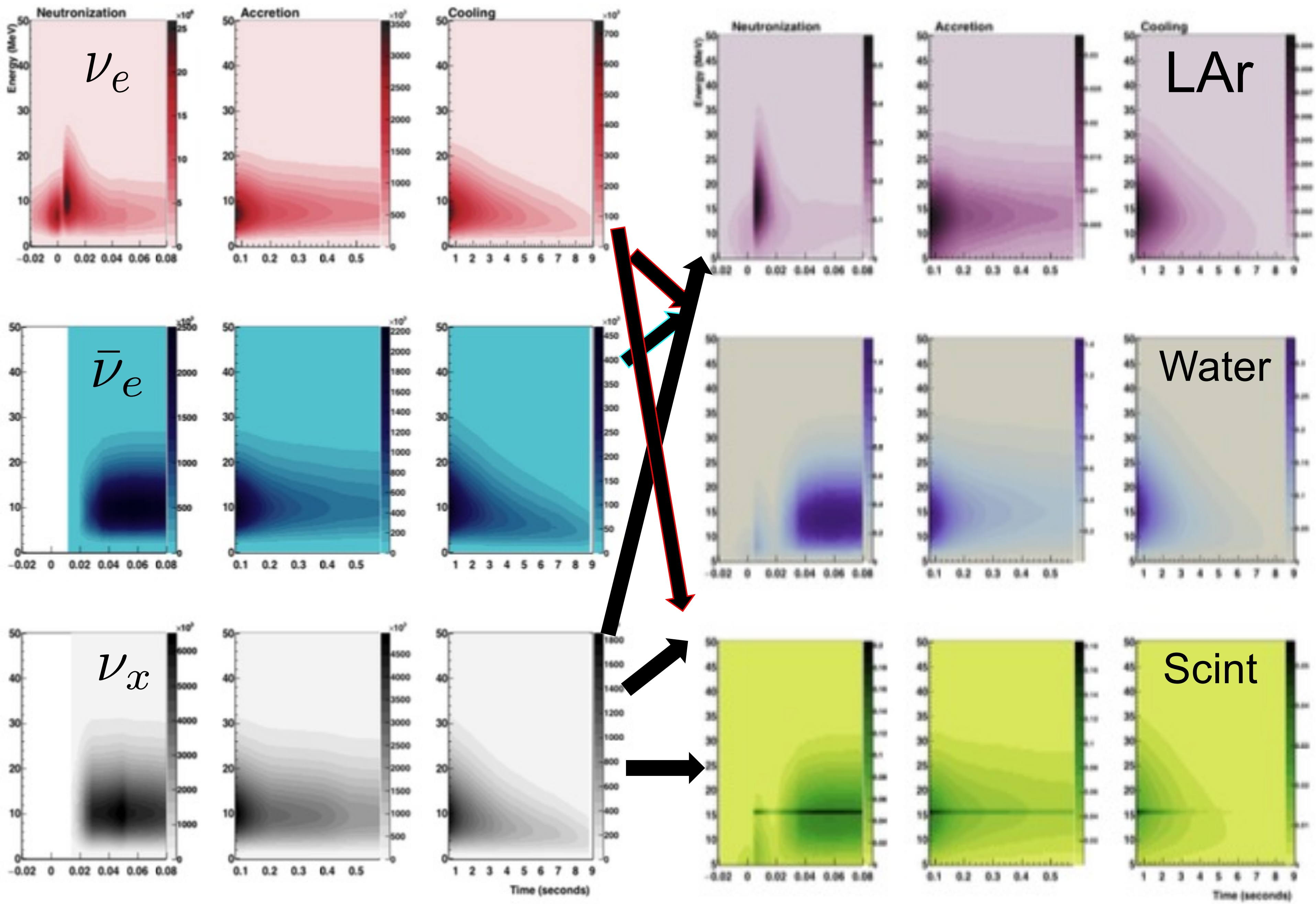
Neutrino fluxes vs E, t

Dominant channels

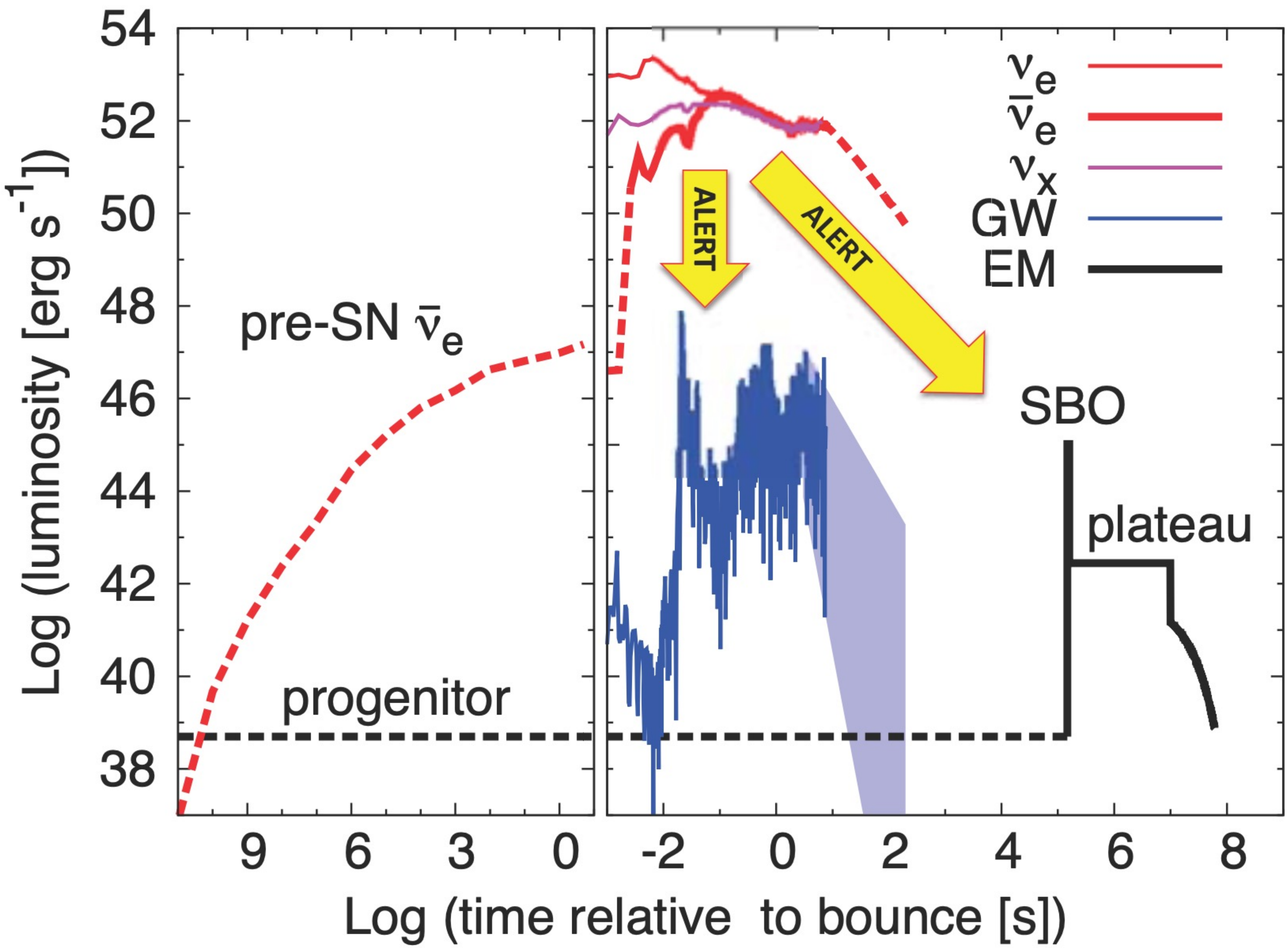
Event rates vs E, t



Subdominant channels are in the mix too,
and not always easily taggable... may be hard to disentangle!

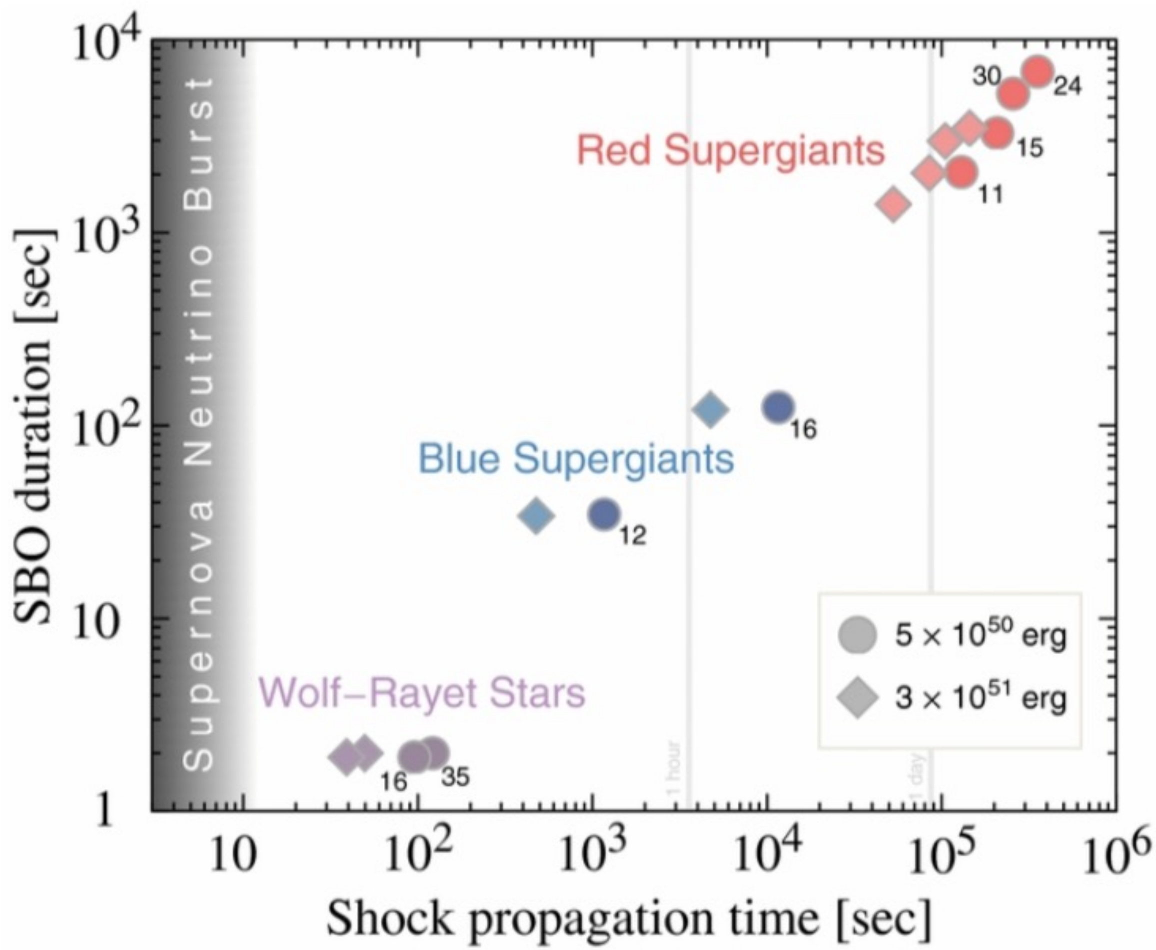


Multimessenger signals from core collapse



K. Nakamura et al., MNRAS 2016

If we see a neutrino burst... where's the supernova??

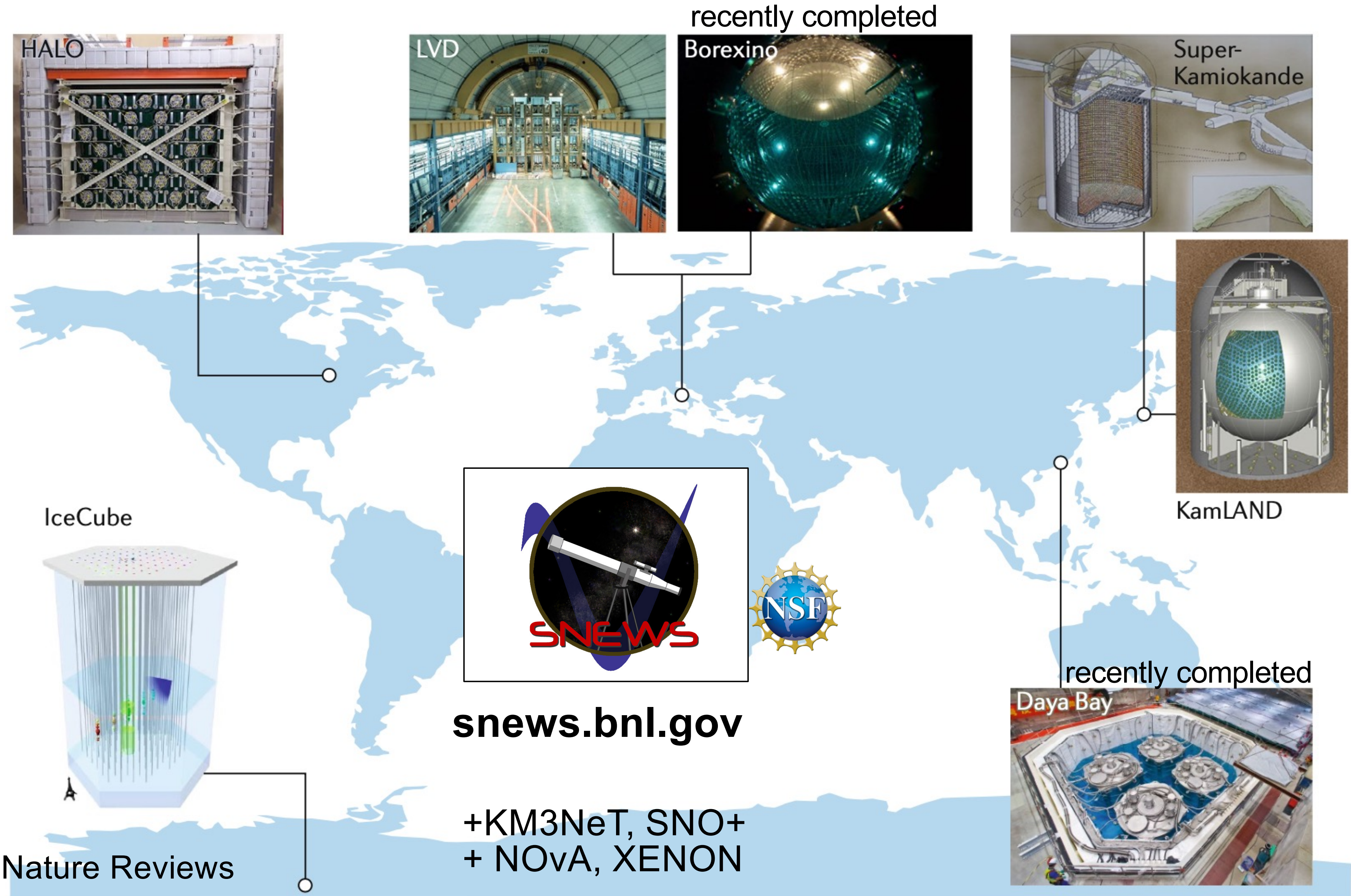


We're racing the shock!

May have less than a half hour, or even just minutes

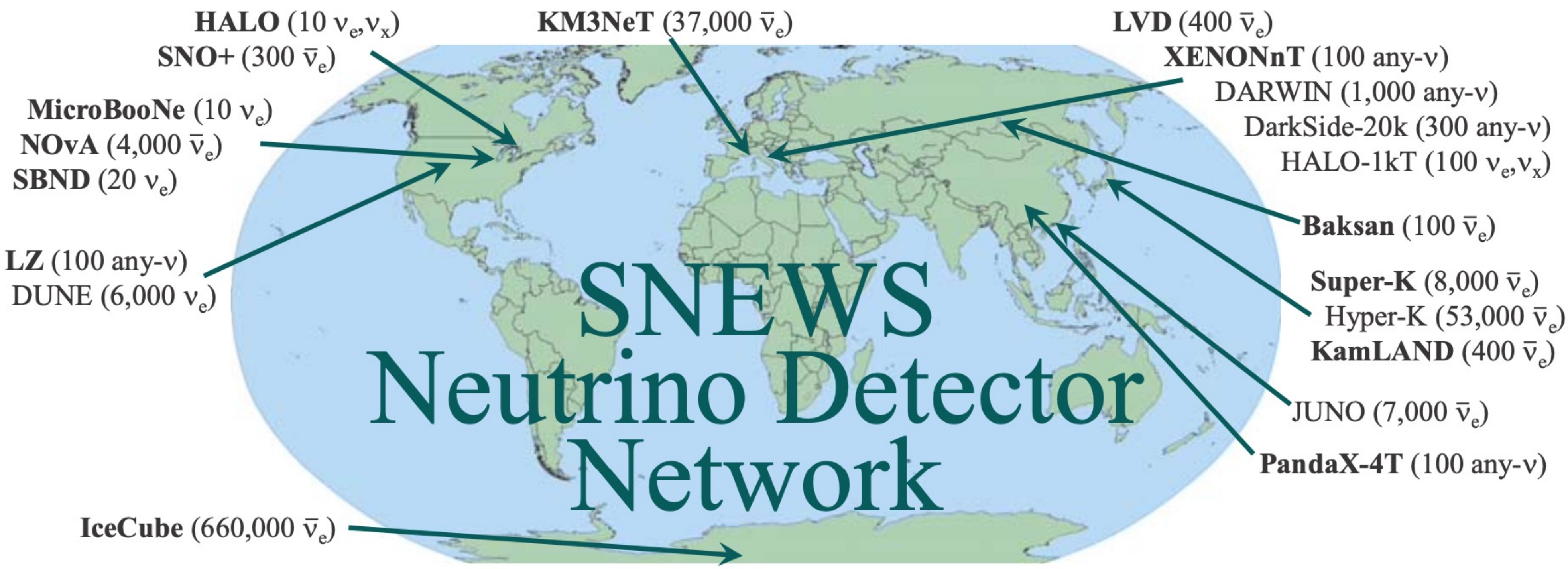
Matthew D. Kistler, W. C. Haxton, and Hasan Yüksel. Tomography of Massive Stars from Core Collapse to Supernova Shock Breakout. ApJ, 778:81, 2013, arXiv:1211.6770.

The Supernova Early Warning System 1.0



Simple 10-sec coincidence → email alert + socket connection +GCN
Running in automated mode since 2005 (no nearby CCSNe...)

Current effort: upgrade to **SNEWS 2.0**

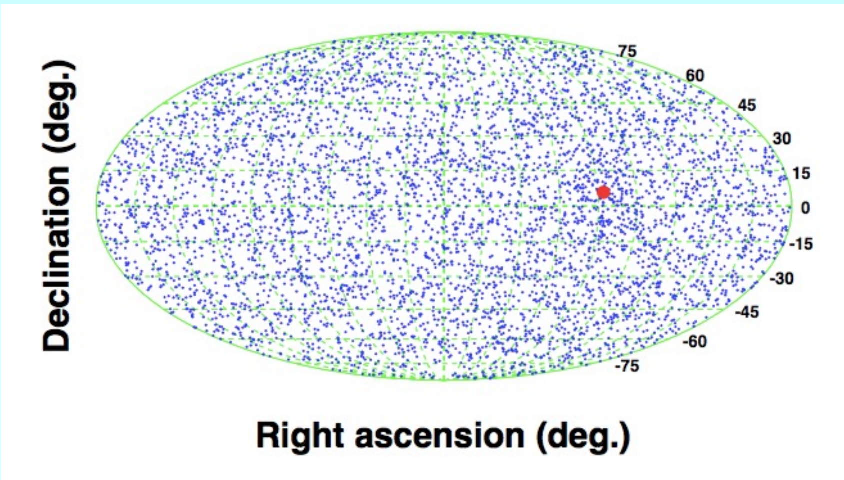


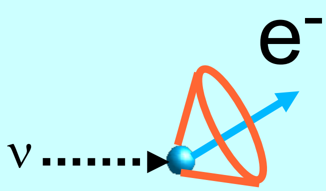
- improved latency
- neutrino-based pointing,
  including triangulation
- "fire drills"
- presupernova

snews2.org

Neutrino Pointing Approaches

Anisotropic interactions

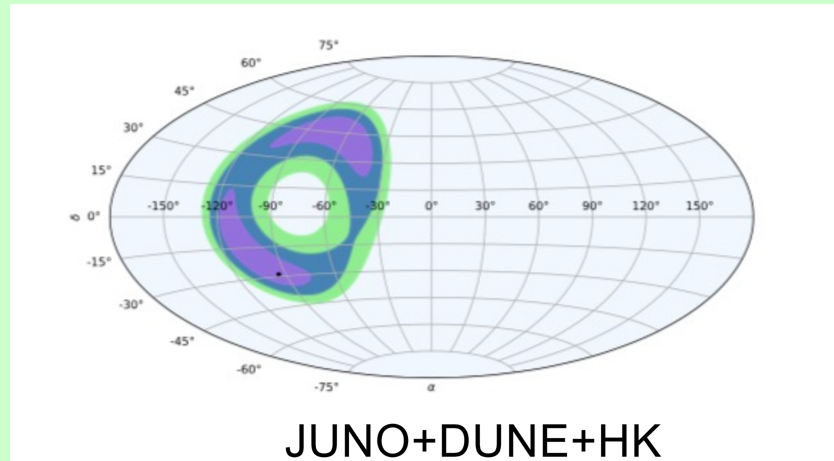




$$\sim \frac{25^\circ}{\sqrt{N}}$$

Likely best using
some detectors (currently, SK)

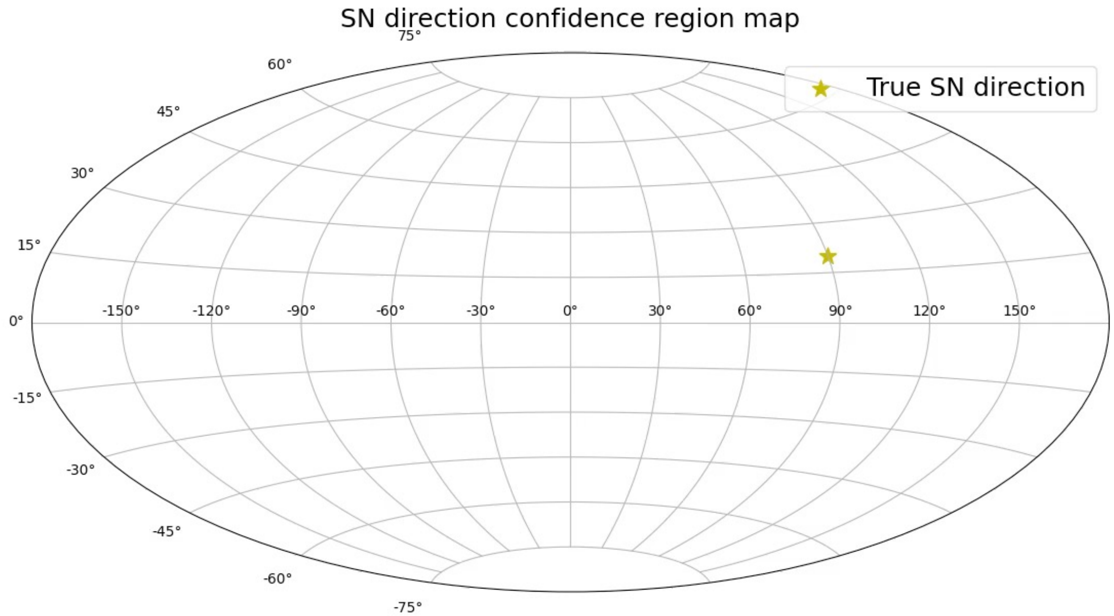
Triangulation from timing

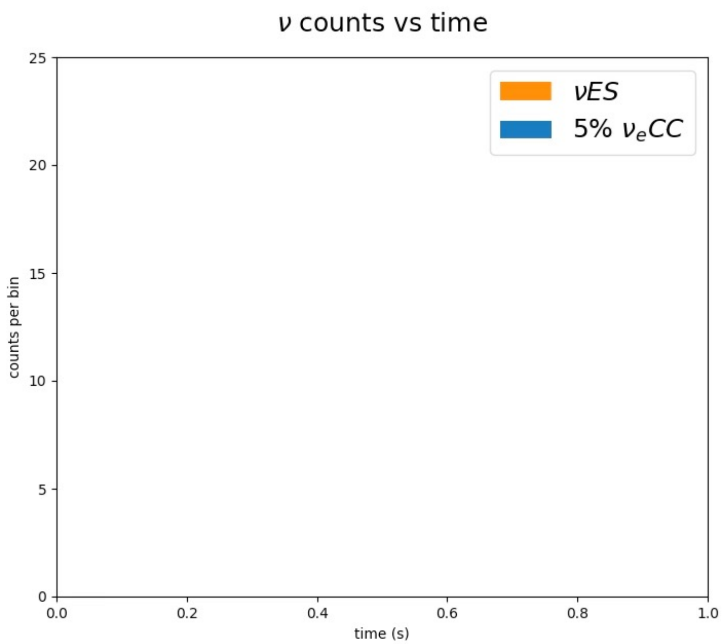


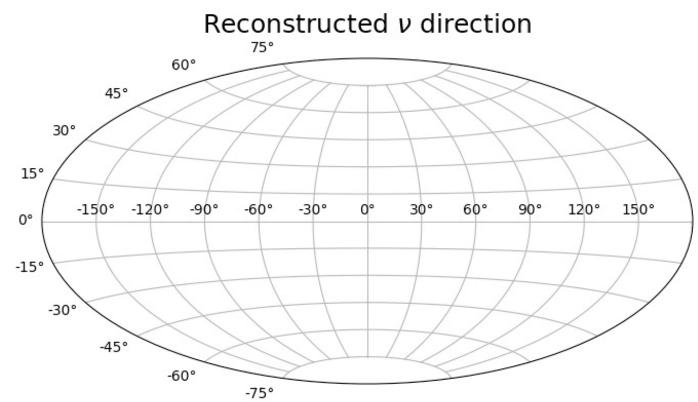
N. Linzer, KS: arXiv:1909/03151

Lower quality, but can
probably get very low latency,
with subsequent improvements

By Joshua Queen







Take-Away Messages

Core-collapse neutrinos

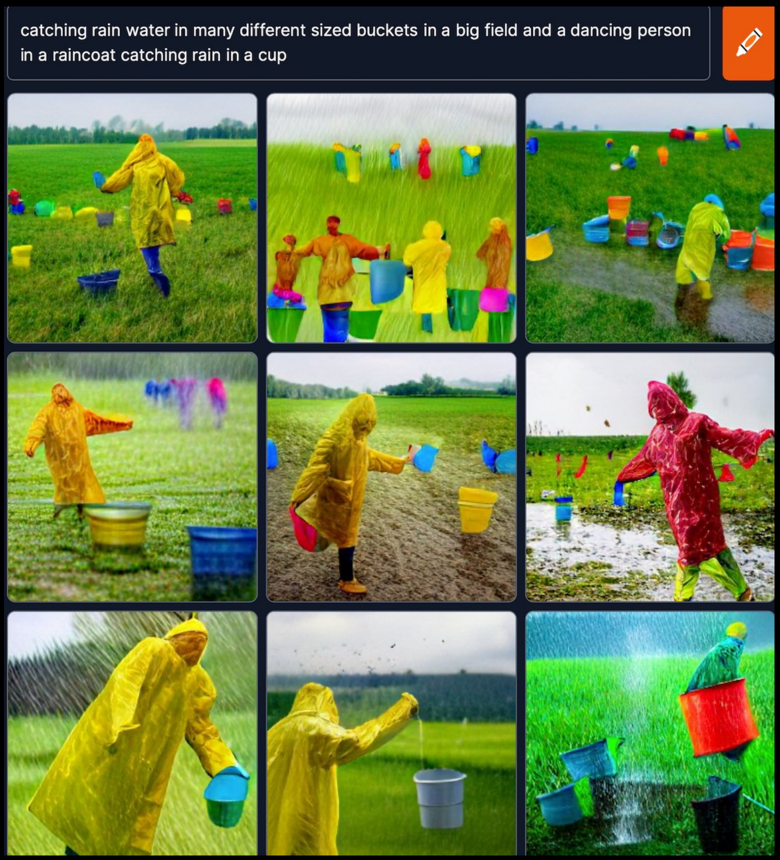
- ~10 second prompt burst of all flavors, few tens of MeV

Current & near future detectors

- ~Galactic sensitivity (SK reaches barely to Andromeda)
- can get some pointing from neutrinos
- SNEWS 1.0 network is waiting, **SNEWS 2.0 in near future**

Long term future

- huge statistics: extragalactic reach
- richer flavor sensitivity (e.g. ν_e in LAr!)
- multimessenger prospects



We want to catch them all!