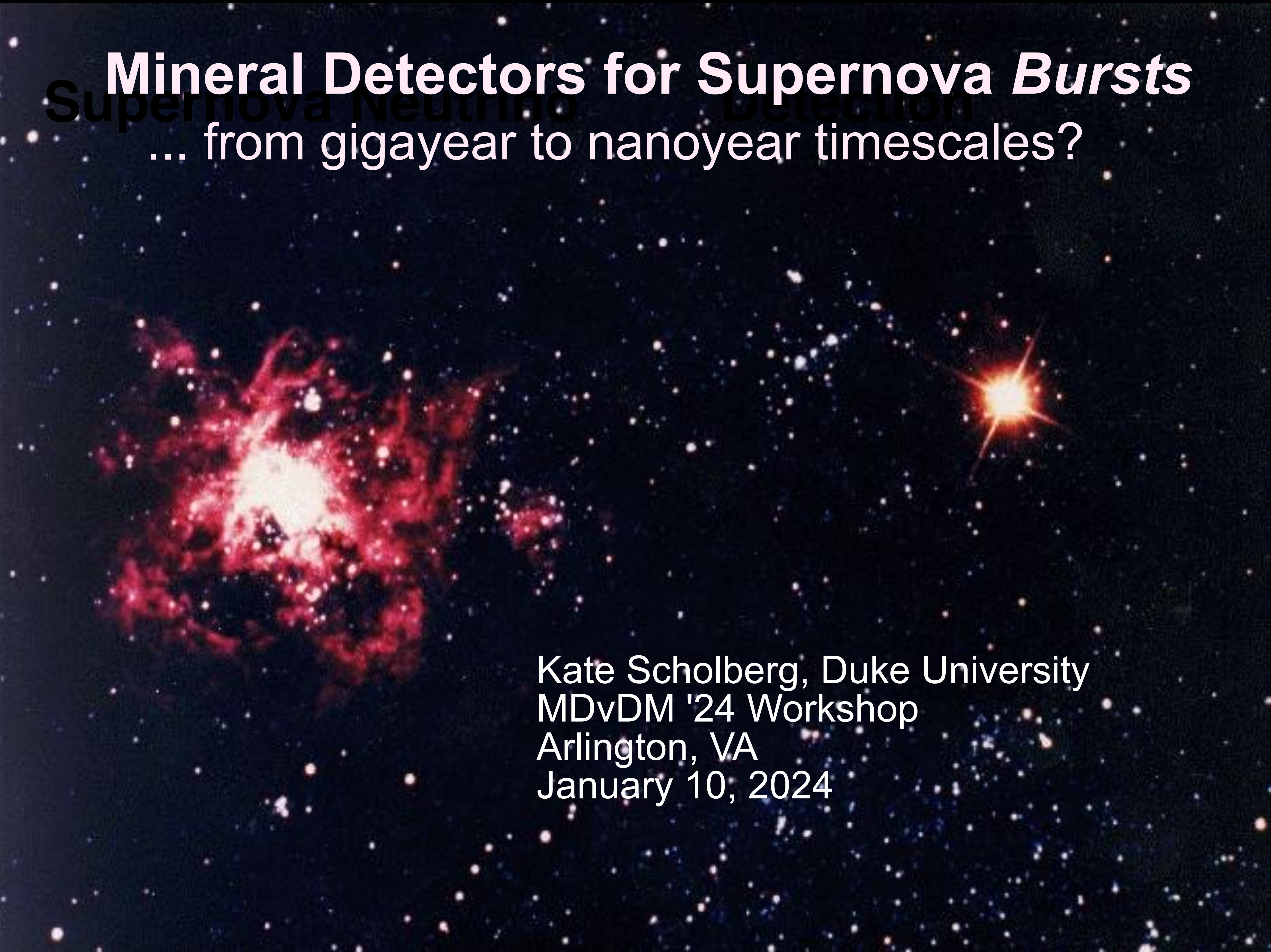


Mineral Detectors for Supernova *Bursts*

Supernova Neutrino Detection

... from gigayear to nanoyear timescales?

Kate Scholberg, Duke University
MDvDM '24 Workshop
Arlington, VA
January 10, 2024

Caveat

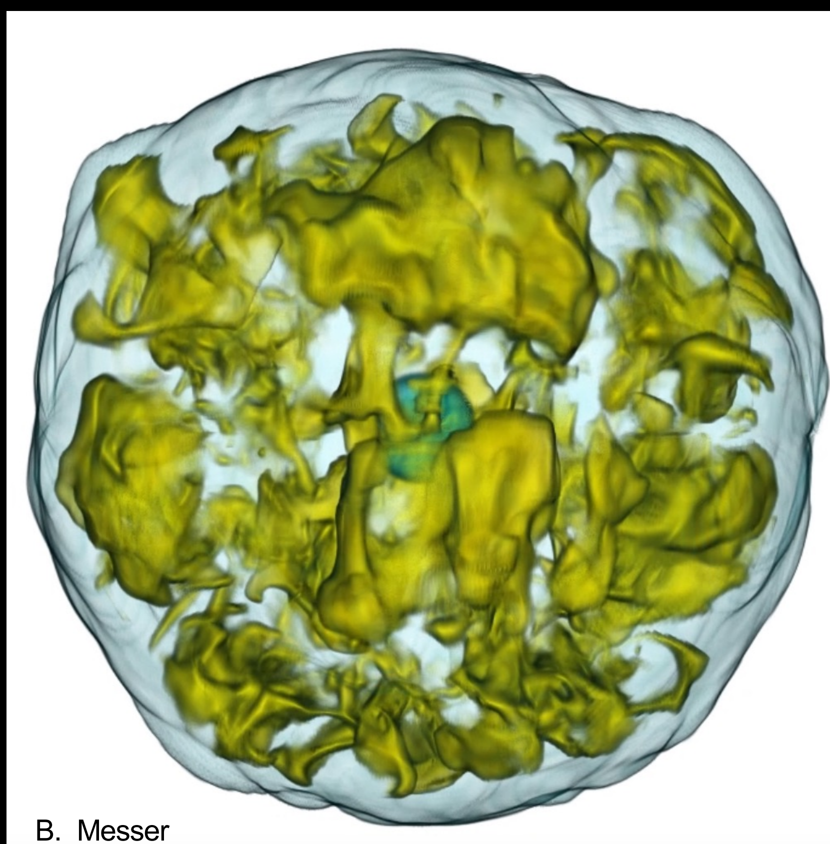
This is very conceptual and sanitized... I'm fully aware it might be insane...

Neutrinos from core-collapse supernovae

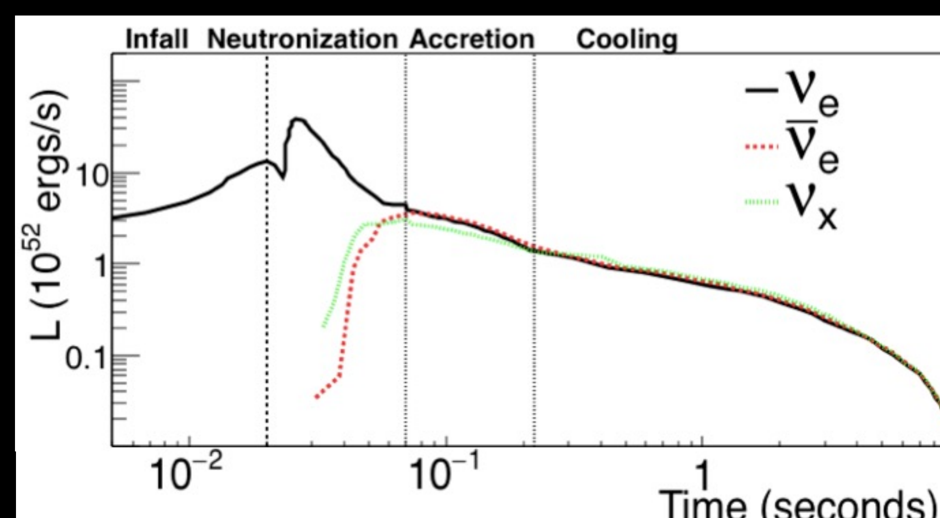
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-νbar pairs from proto-nstar cooling

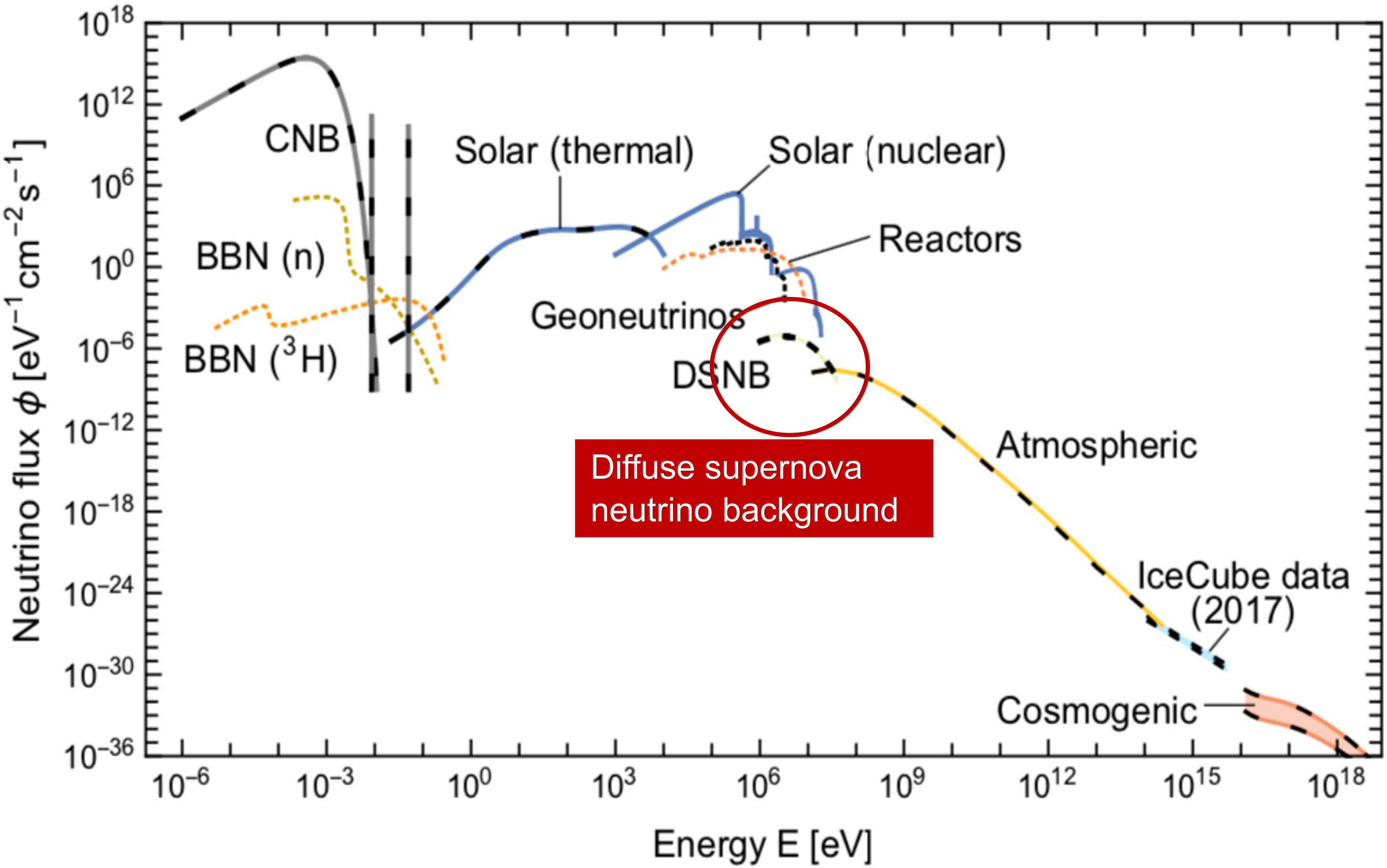


Timescale: *prompt* after core collapse, overall Δt~10's of seconds



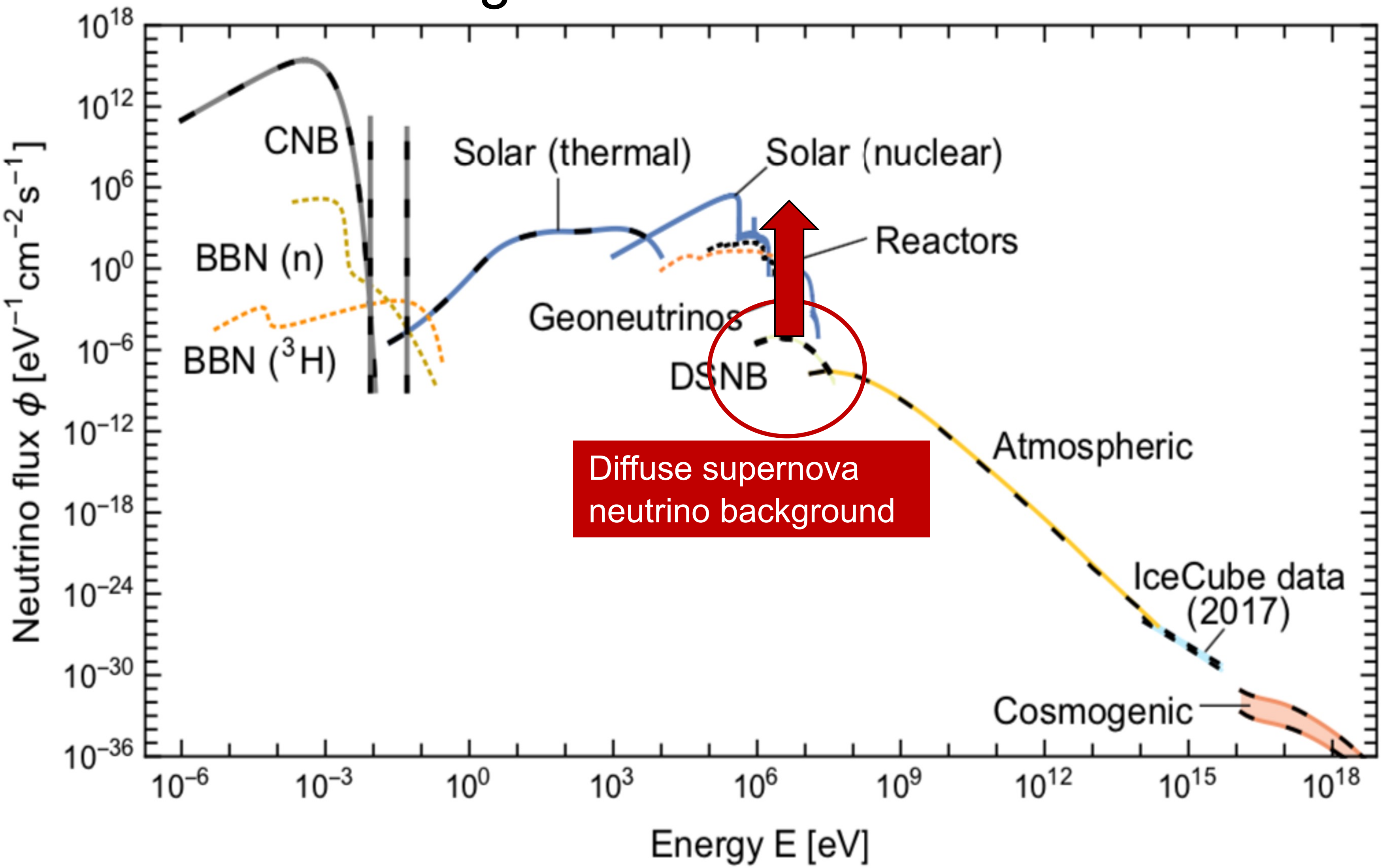
The Steady State Neutrino Spectrum @ Earth

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



During a ~10s Galactic burst, SN flux can increase 9-10 orders of magnitude

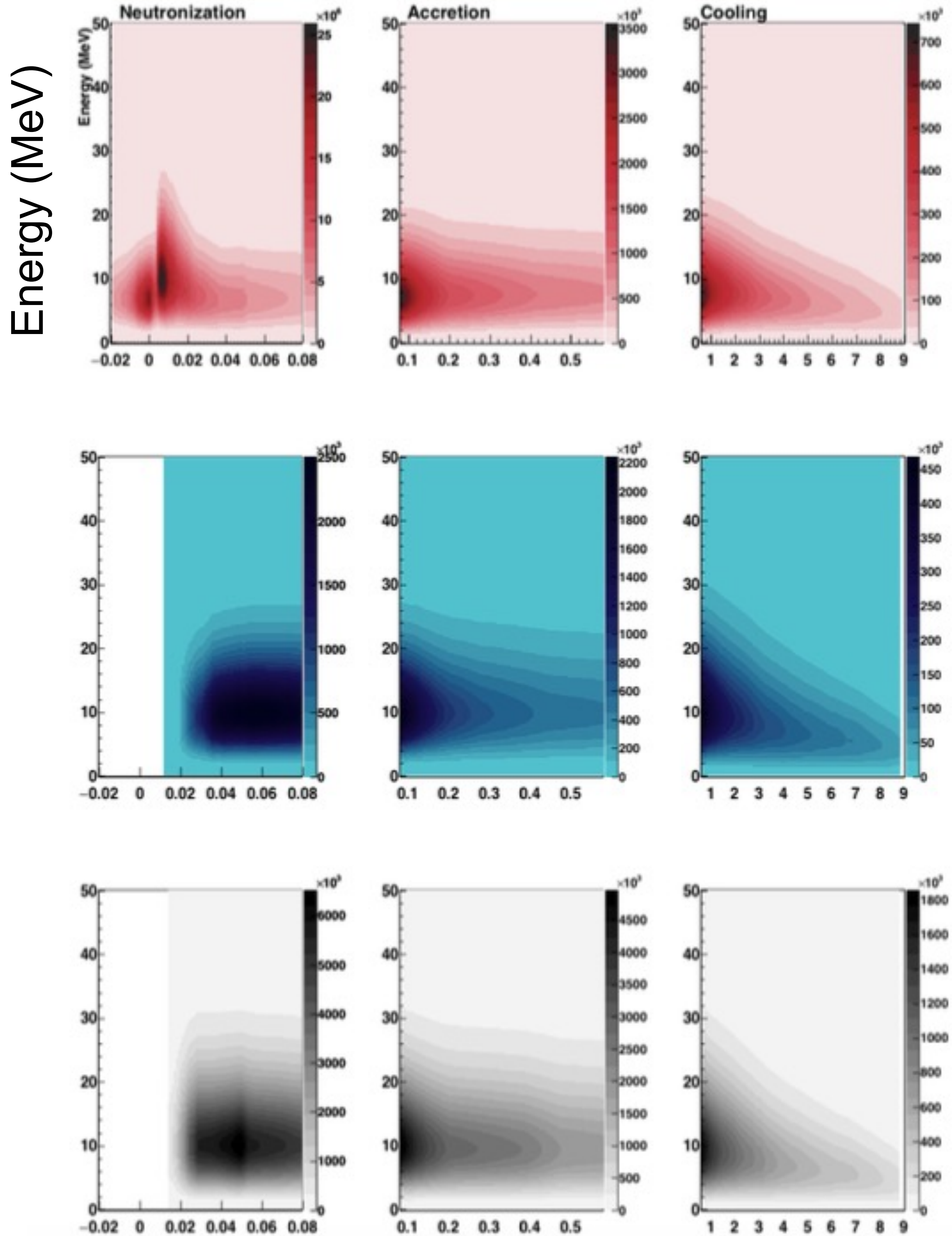
Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF



A few SNB per century lasting 10-100 secs

→ Galactic SNB dominates when integrated over very long time scales

Fluxes as a function of time and energy



ν_e

$\bar{\nu}_e$

ν_x

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

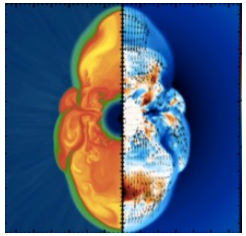
Neutrinos per cm^2 per bin (per ms per 0.5 MeV)

Huedepohl et al. model

Time (s)

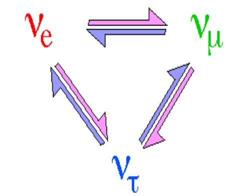
What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS



explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from neutrino experiments



from flavor, energy, time structure of burst

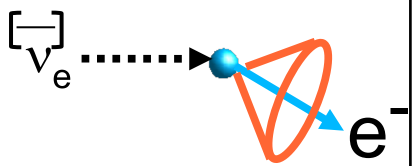
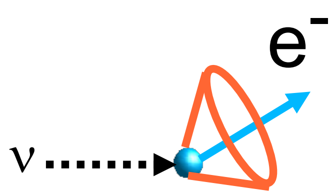
NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

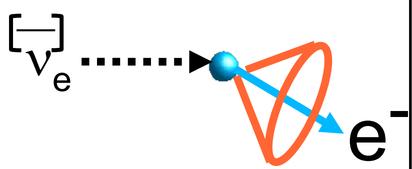
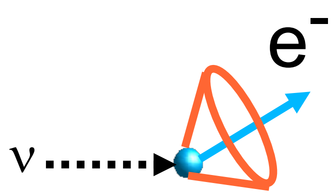
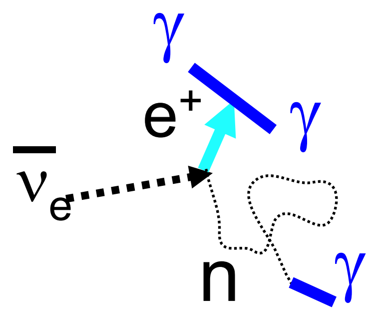
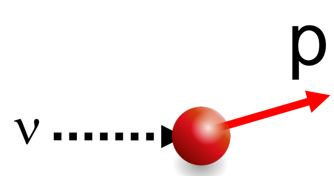
input from **multimessenger** observations

+ EARLY ALERT

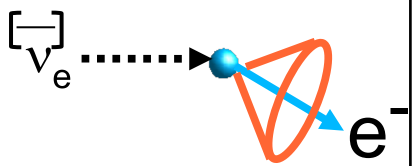
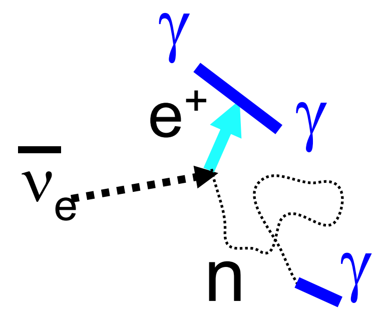
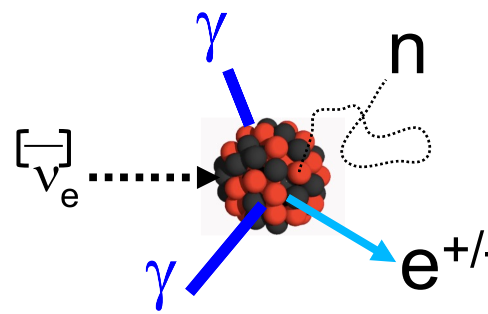
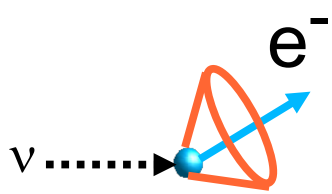
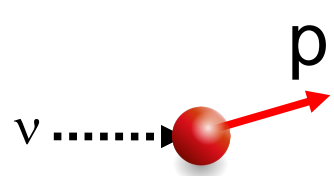
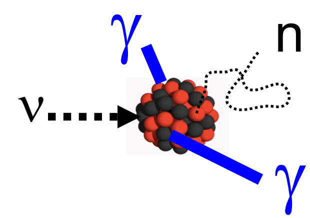
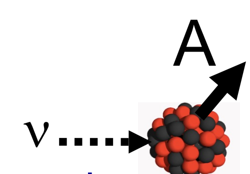
Neutrino interactions in the ~10 MeV range

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

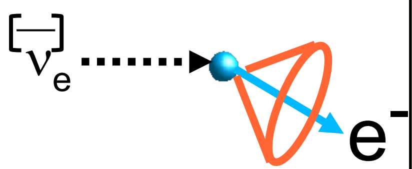
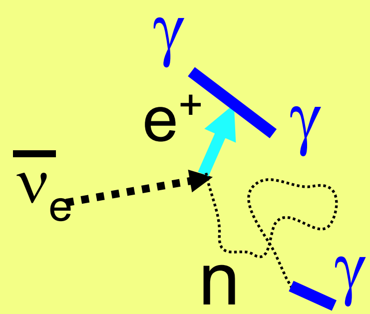
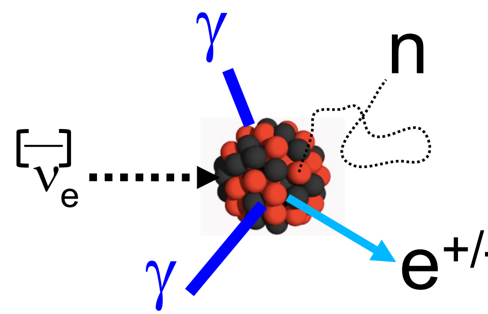
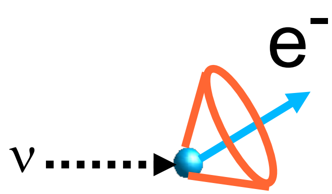
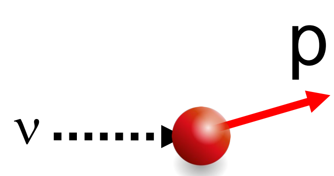
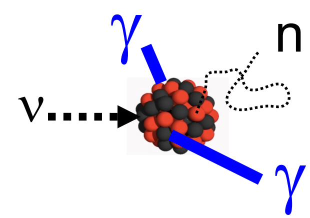
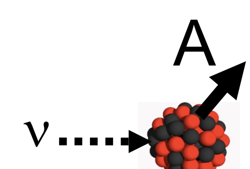
Neutrino interactions in the ~10 MeV range

<table>
<tr><th></th><th>Electrons</th><th>Protons</th><th></th></tr>
<tr><td>Charged current</td><td rowspan="2">Elastic scattering
$\nu + e^- \rightarrow \nu + e^-$


Useful for pointing</td><td>Inverse beta decay
$\bar{\nu}_e + p \rightarrow e^+ + n$
</td><td></td></tr>
<tr><td>Neutral current</td><td>Elastic scattering

very low energy recoils</td><td></td></tr>
</table>

Neutrino interactions in the ~10 MeV range

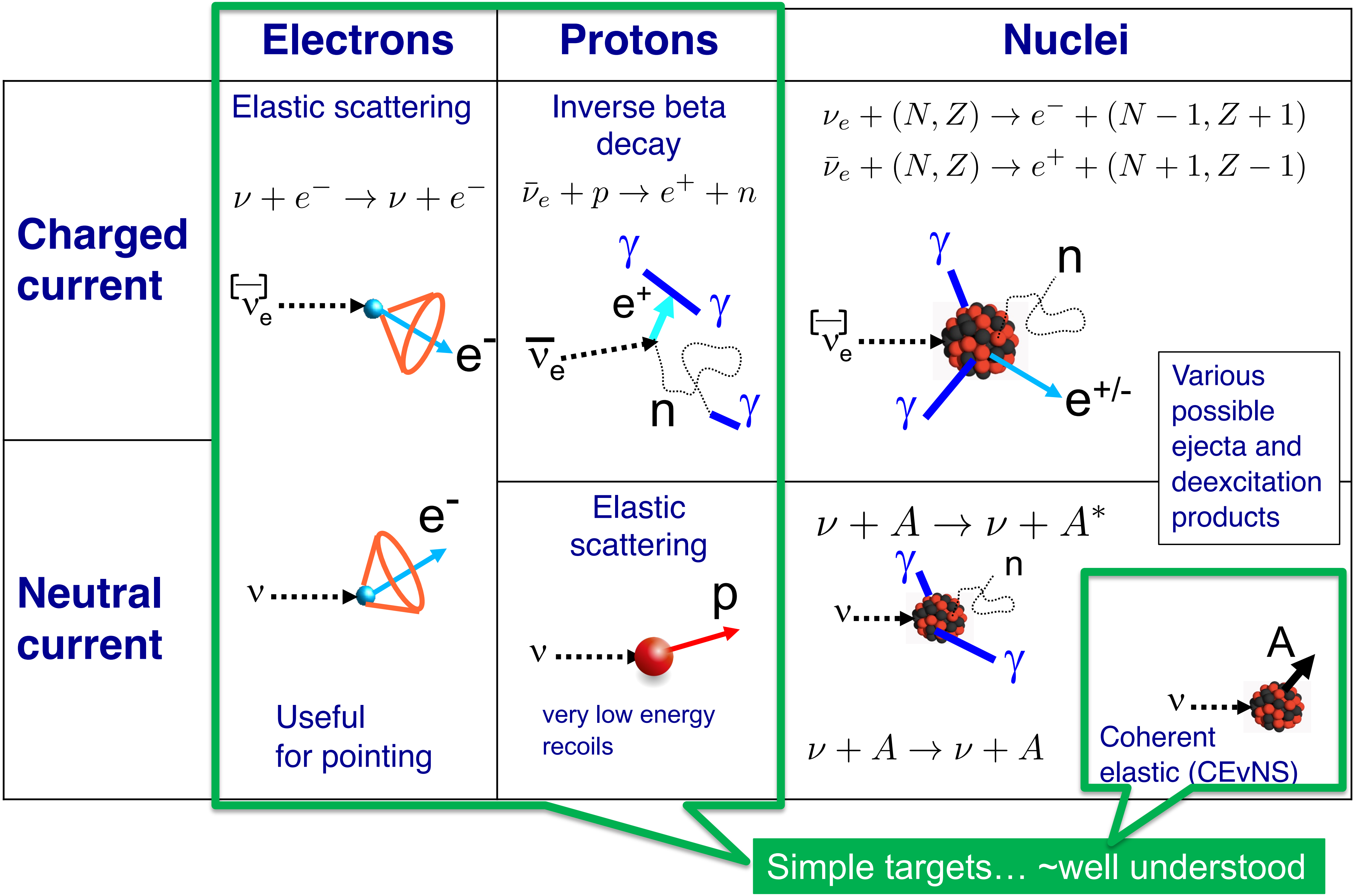
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \to \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \to e^+ + n$ 	$\nu_e + (N,Z) \to e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \to e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing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

Neutrino interactions in the ~10 MeV range

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

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

How well are the cross sections understood?



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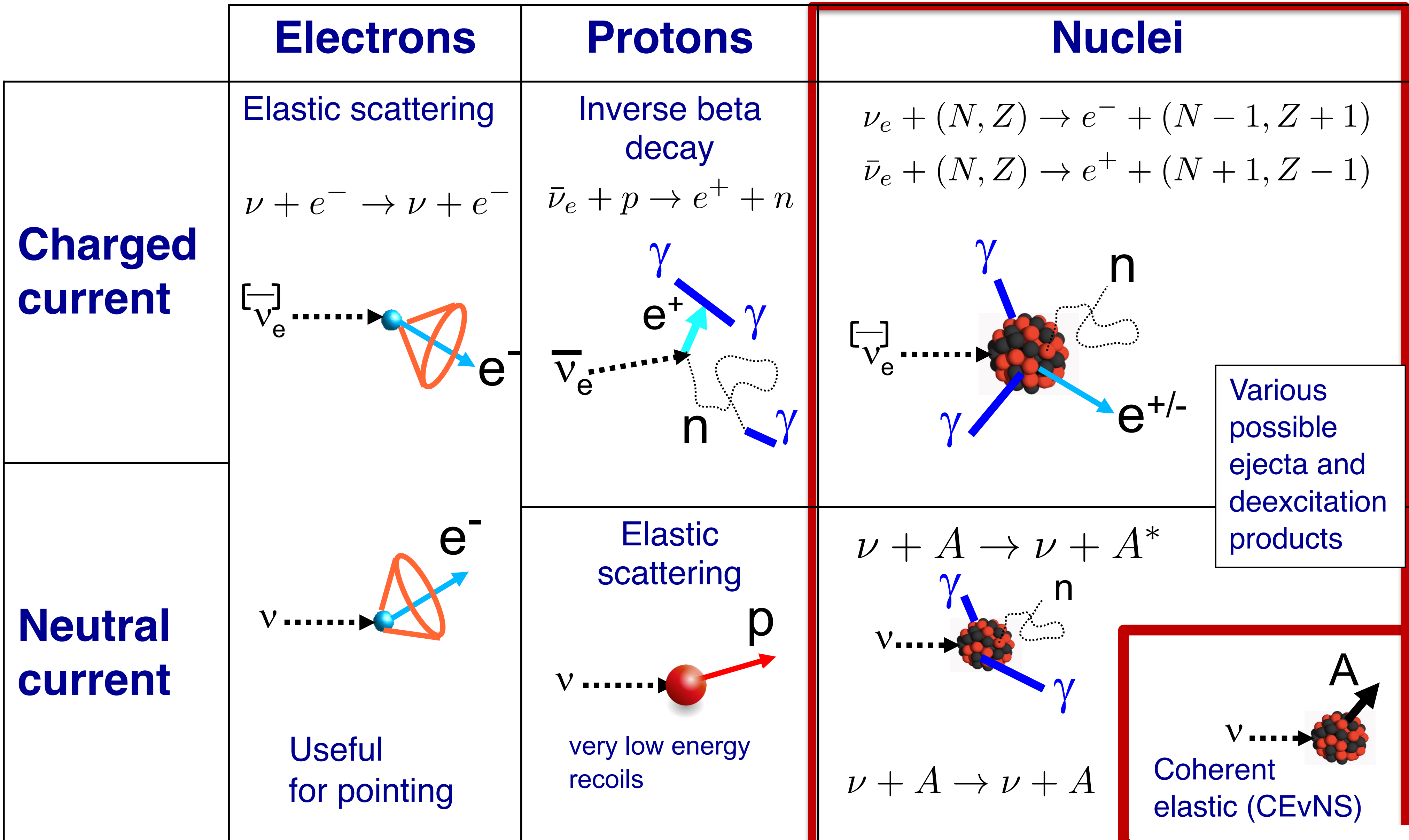
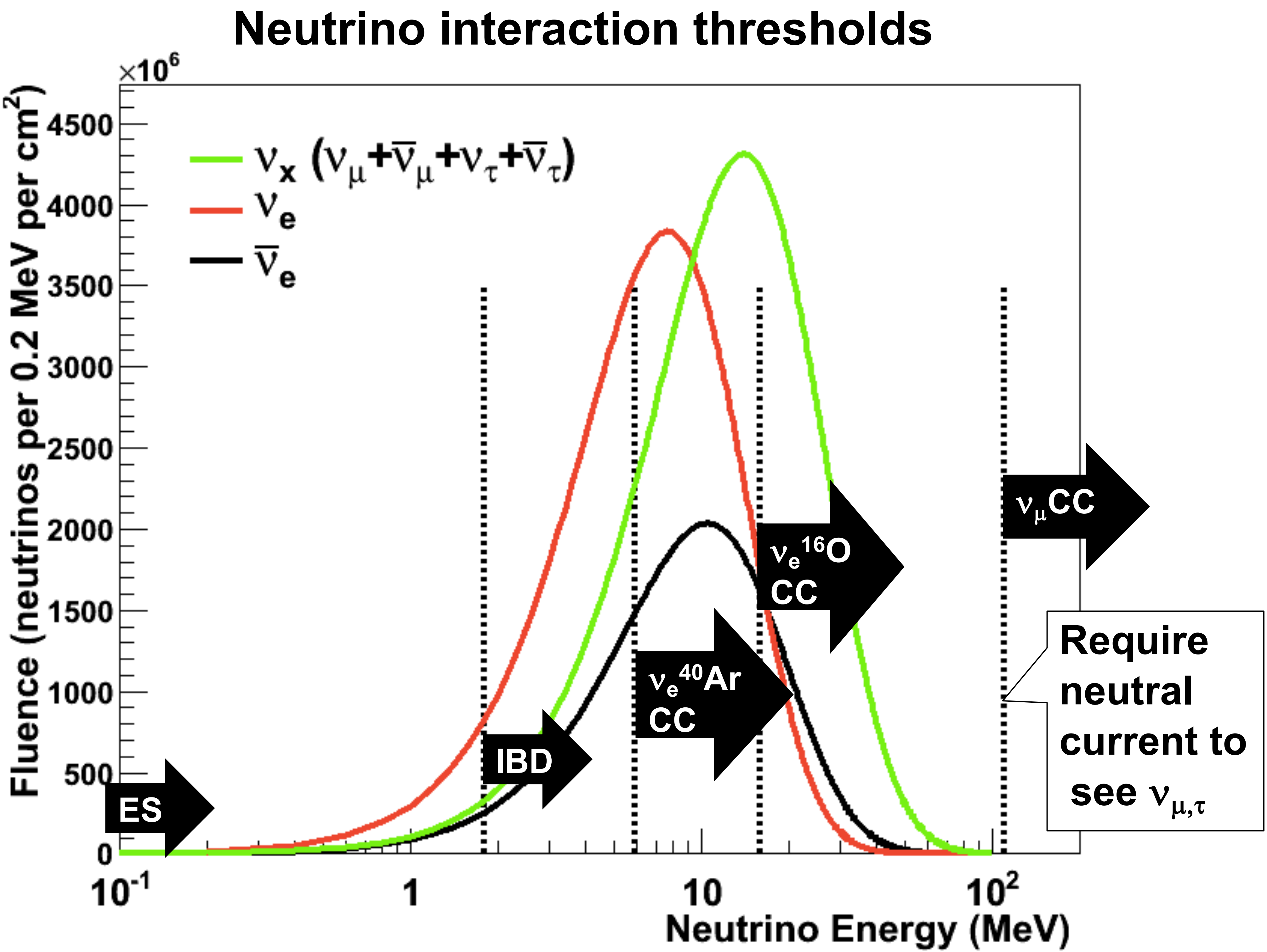
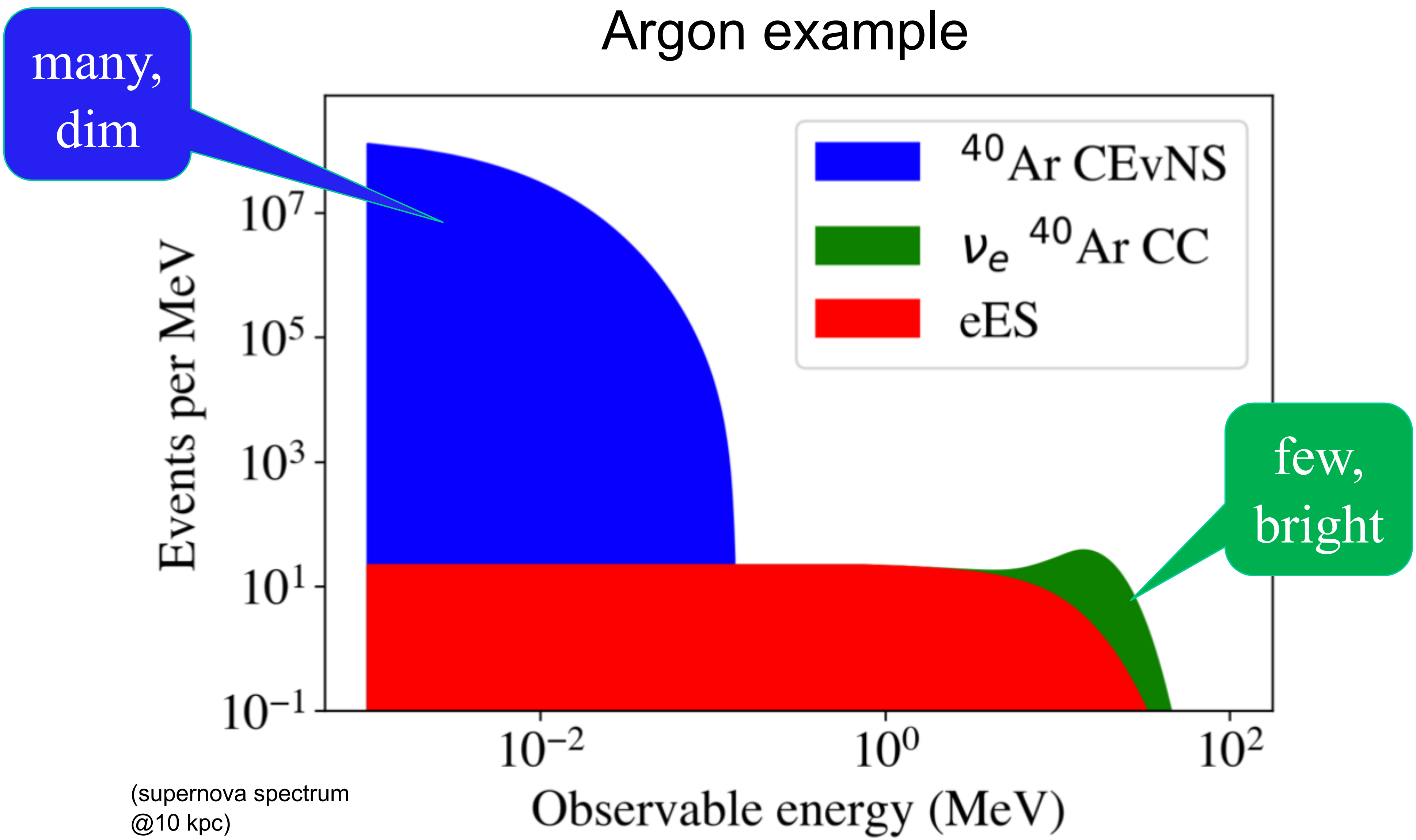


Generally poorly understood! Factors of ~few uncertainties



Neutrino interaction thresholds
$\times 10^6$
Fluence (neutrinos per 0.2 MeV per cm^2)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
ν_x ($\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$)
ν_e
$\bar{\nu}_e$
ES
IBD
ν_e ^{40}Ar CC
ν_e ^{16}O CC
ν_μCC
Require neutral current to see $\nu_{\mu,\tau}$
10^{-1}
1
10
10^2
Neutrino Energy (MeV)

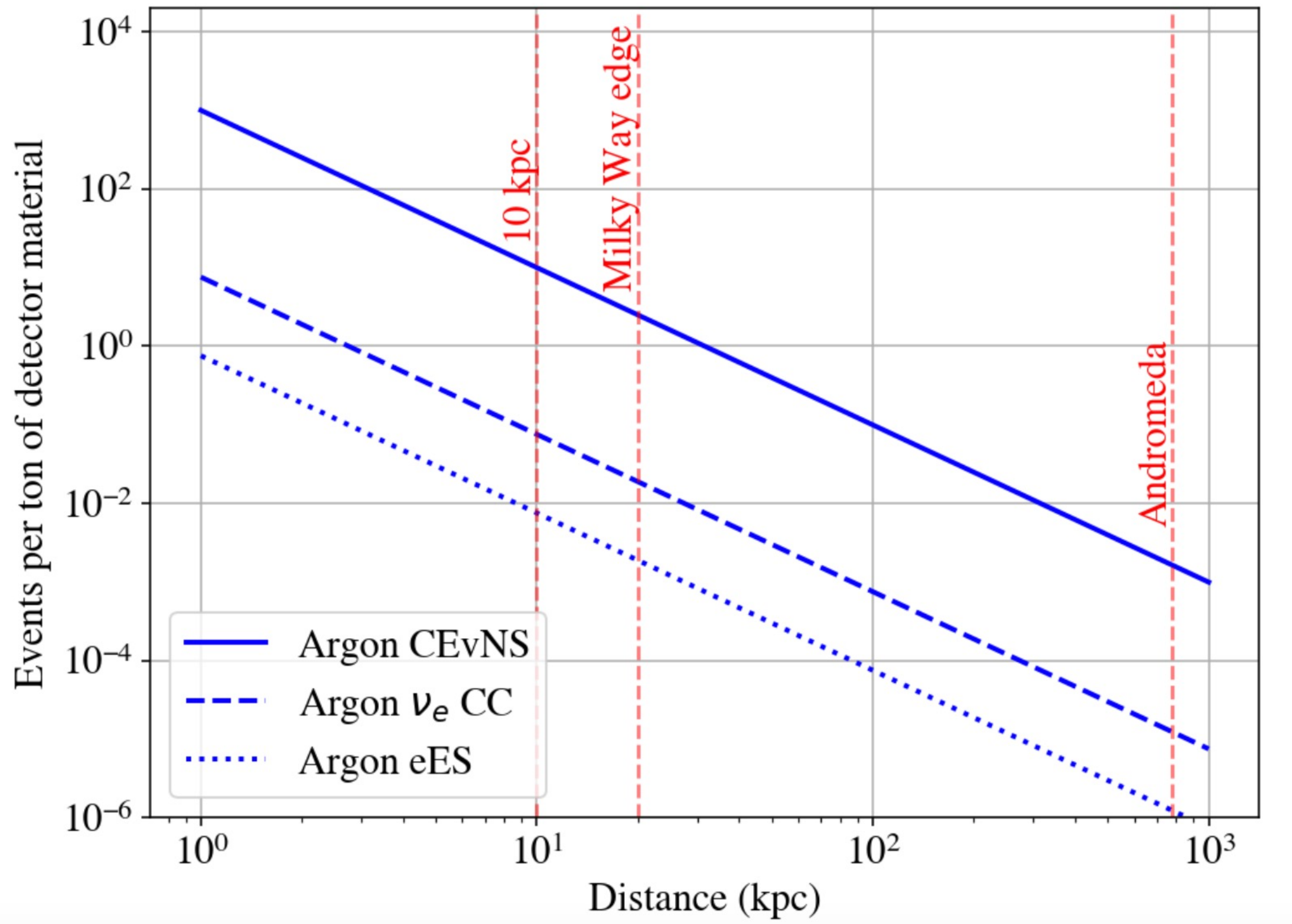
Relative rates & observable energies of these processes



(supernova spectrum @10 kpc)

CEvNS rate ~ N*6*CC rate

Overall interaction rates per mass for SN bursts



- scales as $1/d^2$
- factor of ~10 uncertainty in model flux

Variation with target type

- CEvNS/mass scales as $\sim(N^2/N)\sim N$; but recoil energies ~1/A
- CC/mass ~ flat vs target, but variation of factors of ~few (because nuclear physics..)
- eES/mass ~ flat vs target

zoom in here

First suggestion for **supernova detection via CEvNS**:

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany
(Received 21 November 1983)

First exploration in modern DM detector context:

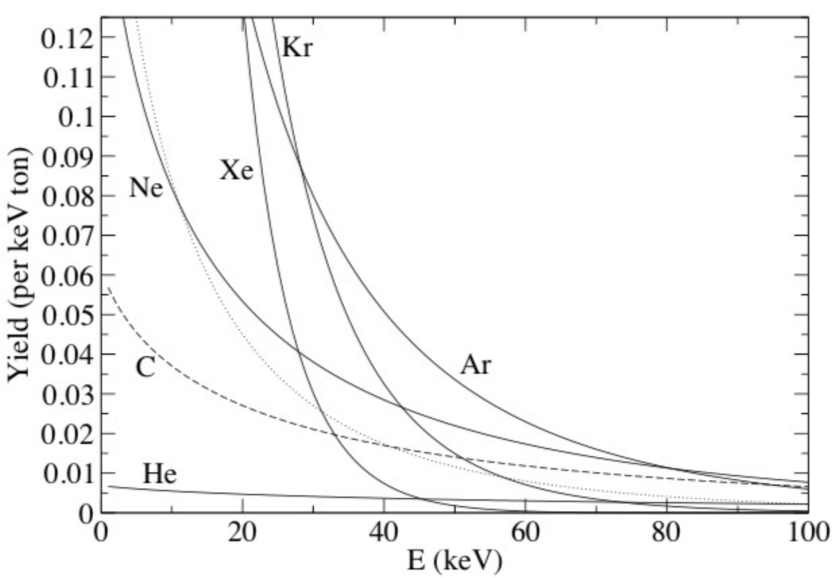
PHYSICAL REVIEW D **68**, 023005 (2003)

Supernova observation via neutrino-nucleus elastic scattering in the CLEAN detector

C. J. Horowitz*
Nuclear Theory Center and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA

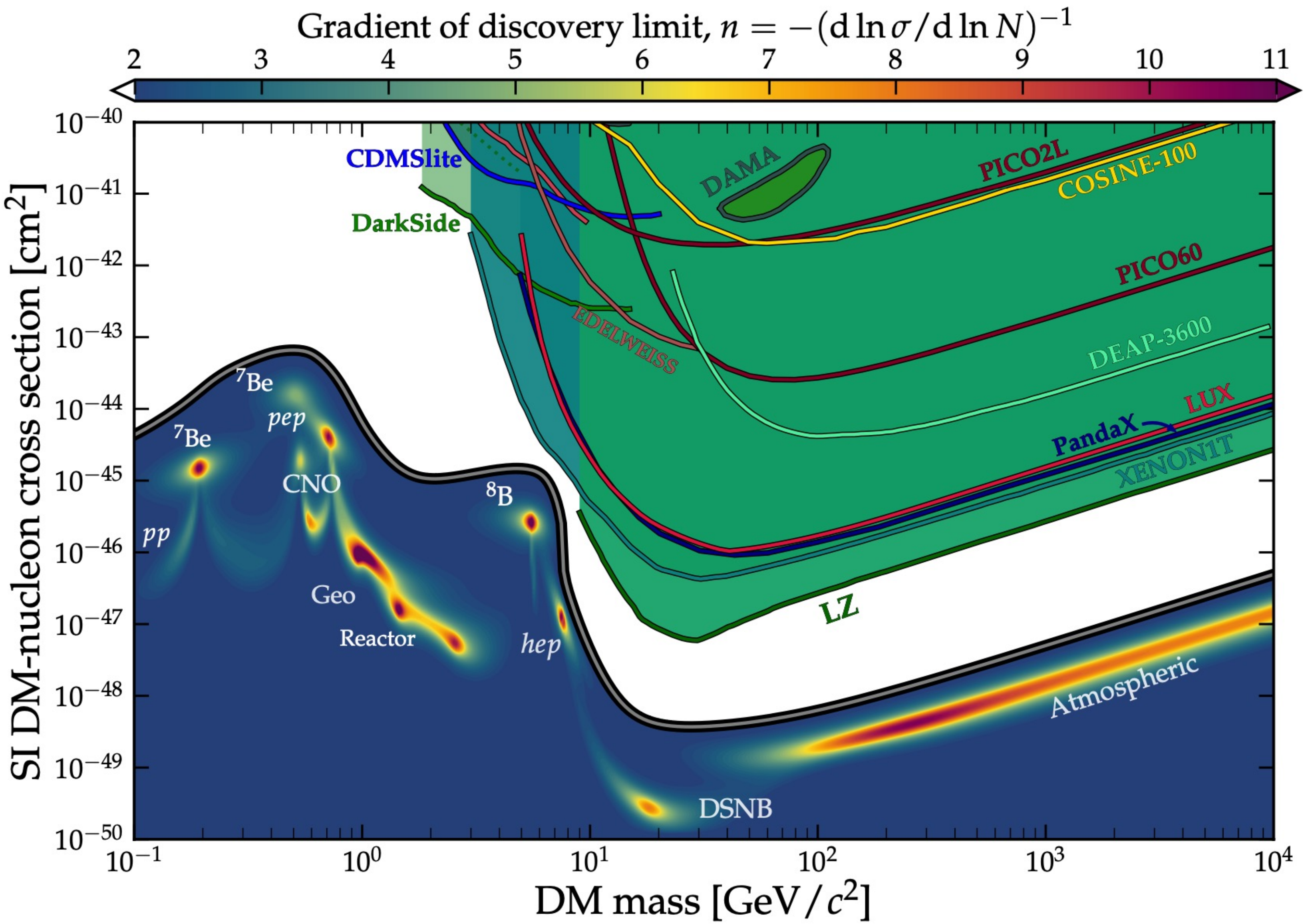
K. J. Coakley
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

D. N. McKinsey
Physics Department, Princeton University, Princeton, New Jersey 08544, USA
(Received 5 February 2003; published 28 July 2003)



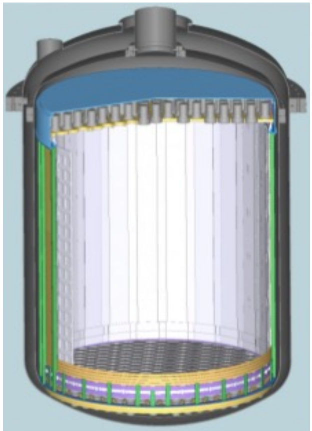
- WIMP DM detectors tend to be low background, low threshold (10's of keV or less)
- Scalability to large mass is desirable

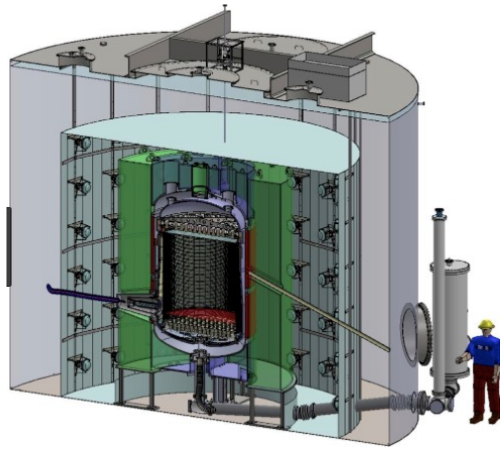
Interesting things may eventually emerge from the ~~fog~~ *glare*...

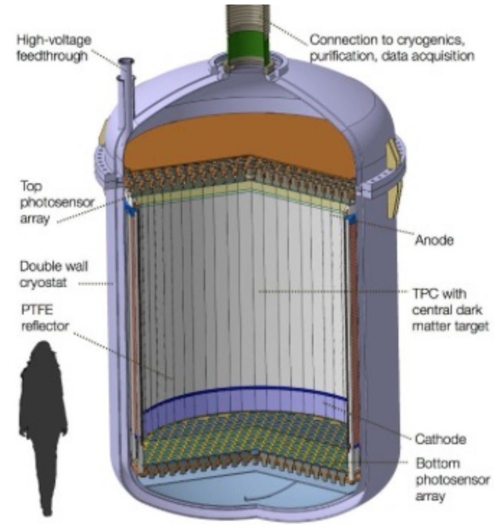


O'Hare [2109.03116]

Supernova **burst** detection in large DM detectors

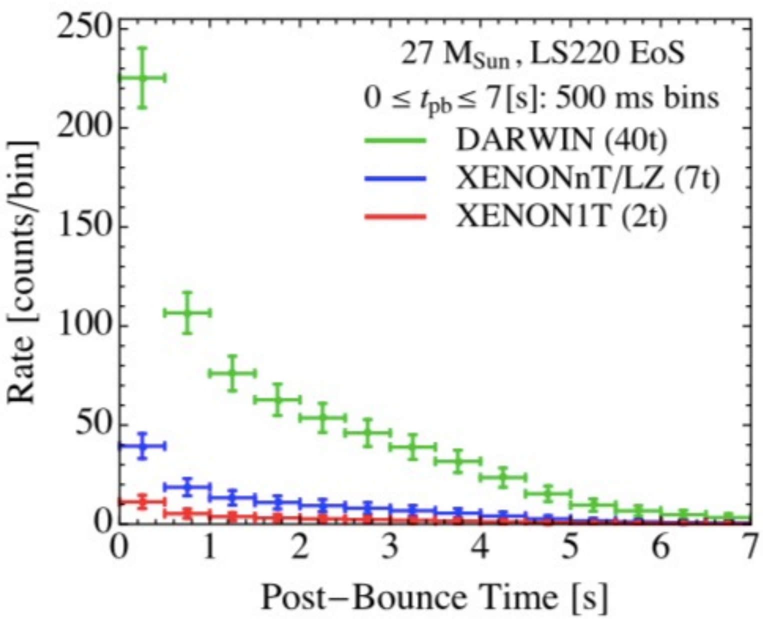


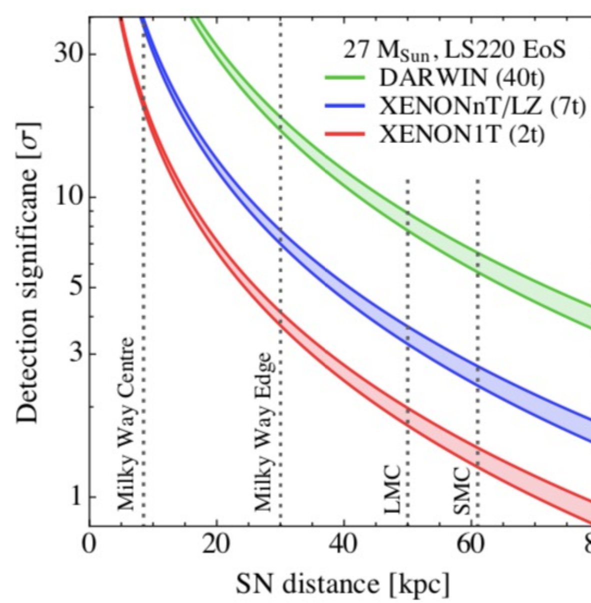


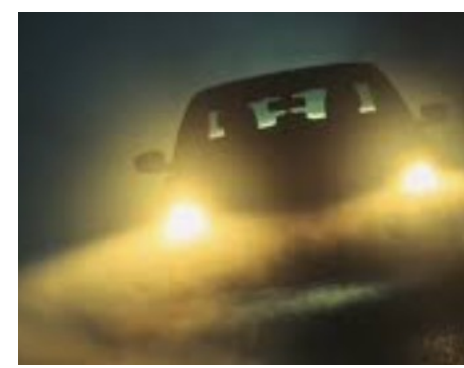


Example: dual-phase xenon time projection chambers

DARWIN



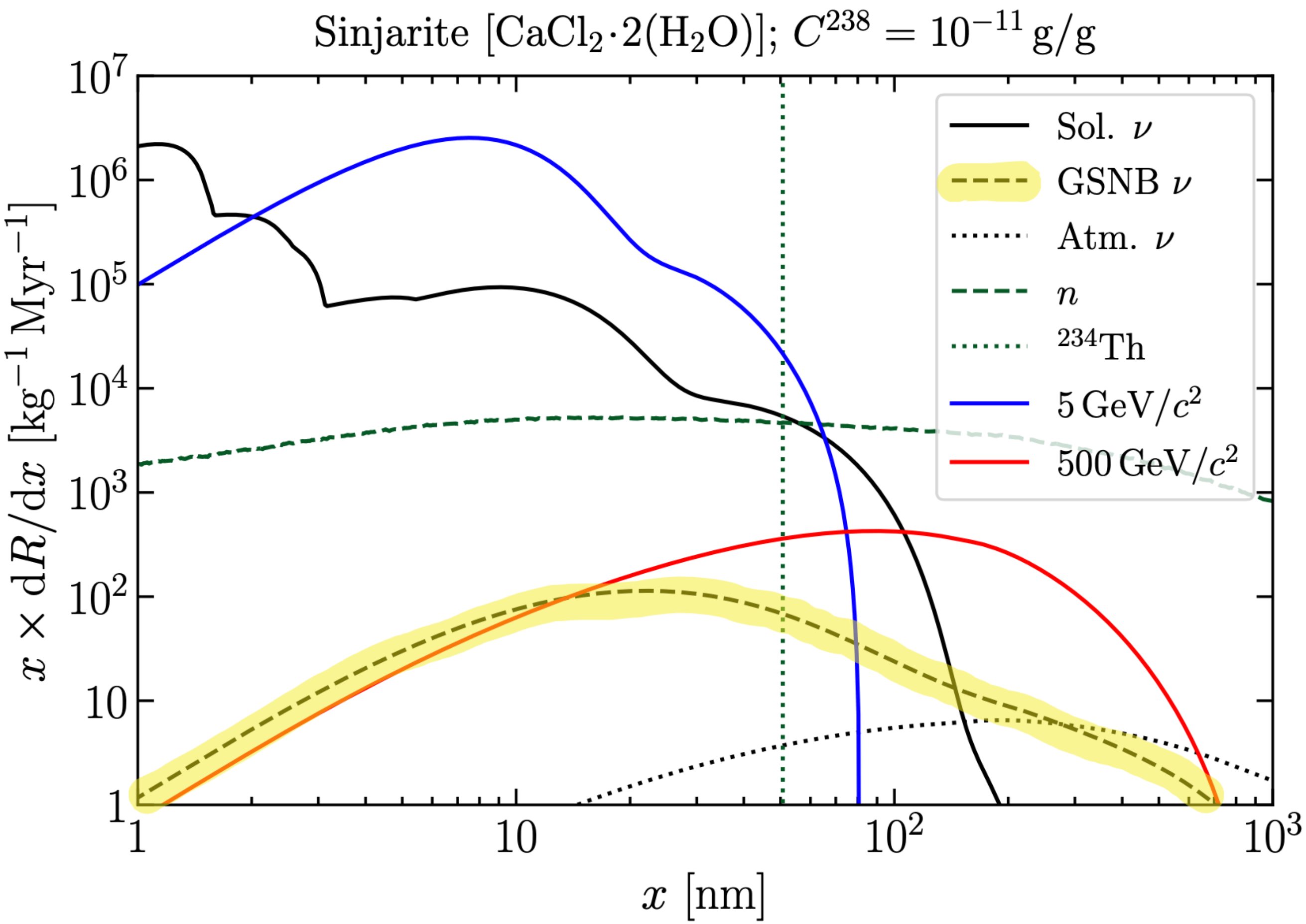




Lang et al.(2016). *Physical Review D*, *94*(10), 103009. http://doi.org/10.1103/PhysRevD.94.103009

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

What about mineral detection for *prompt* Galactic supernova *burst* detection?



For 10 kpc SN, get few-10s of fresh ns-μs tracks per ton in ~10s of seconds

2023 Mineral Detection white paper

Can we find them promptly?

What would it take to go after these?

- **ton scale** or more of target
- **~nm track resolution**
- ability to scan/monitor/interrogate entire target on short timescale
  (minutes best!... at least hours... days maybe OK)
  → **ton/hour**
- freshly annealed/blank target (integrated paleo SN signal is bg!)
- low ambient and cosmogenic background
  (probably, underground location)
- external prompt trigger (SNEWS) could be possible

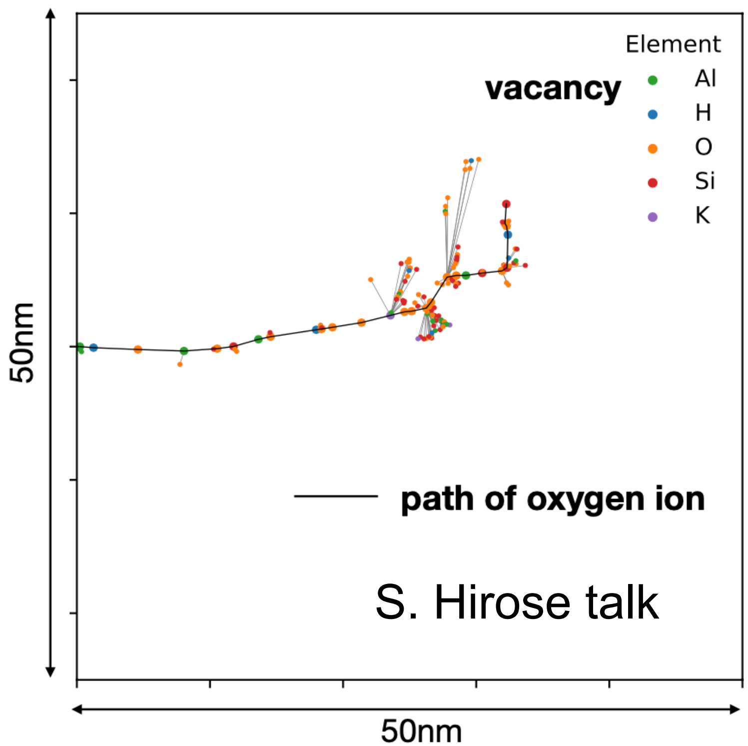
How to do this? Is this completely crazy?

- I don't know ... seems to need 10^6-10^9 scale up of some of the ideas from this workshop...
- Multi-modal/hybrid approach? i.e., zoom in on ROI to scan small volume (emulsion detector style)

And what would we learn anyway?

- CEvNS provides **spectral** information on the **full-flavor** SN flux
  (see Shunsaku's talk)
- But there will be a bunch of other detectors measuring this, in real time too... is it worth the effort?

Possible killer app: POTATOES
(Point Over There At That Old Exploding Star*)



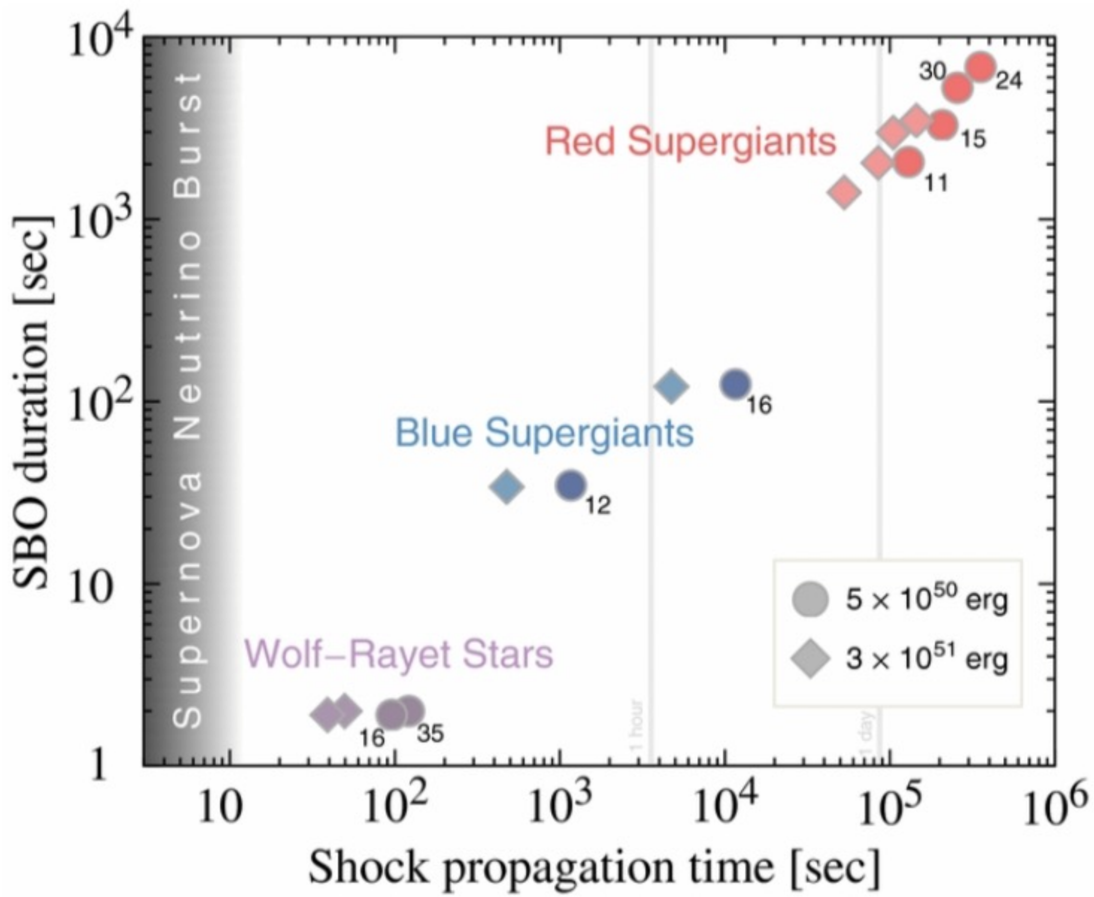
Exploit **high-precision recoil directionality**

*Acronym credit: Ed Kearns

Why point?

Find the supernova!*

Early light observations are valuable….



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.

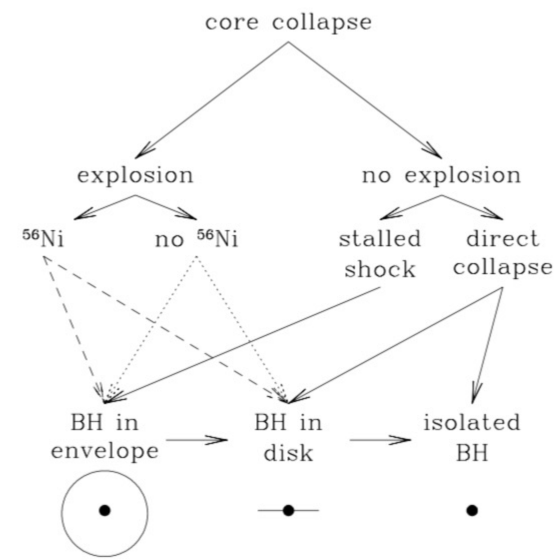
We're racing the shock!

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

Want to point with ***low latency***

*Also physics reasons, e.g. neutrino energy resolution

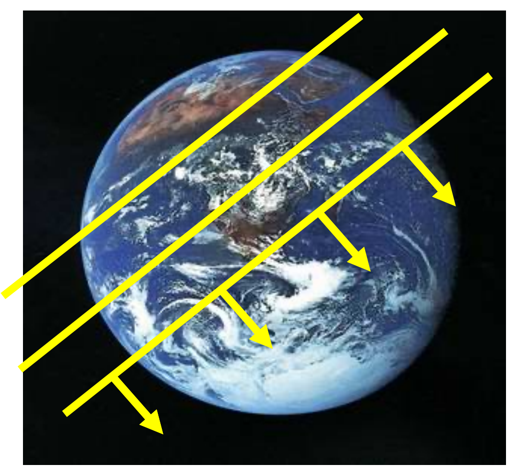
But even if it's not prompt, there are still motivations to use neutrinos to see the SN direction…



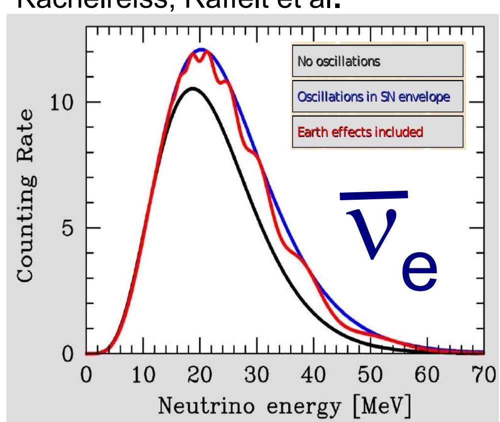
C. Kochanek et al., Ap.J.684:1336-1342,2008

There may be no bright supernova!

→ narrow down
the search for a progenitor,
or a "winked out" star



Kachelreiss, Raffelt et al.



And even if we never find an optical counterpart or progenitor, we need to know the trajectory through the Earth for matter oscillation evaluation

So refined direction information late is better than never…
(but still... better to be fast!)

Neutrino Pointing Methods

- **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it, using the burst neutrino signal
- **Triangulation**
  using inter-detector timing
- **Oscillation pattern pointing**
  in high-energy resolution detectors
- **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos
- **All of the above!**

Neutrino Pointing Methods

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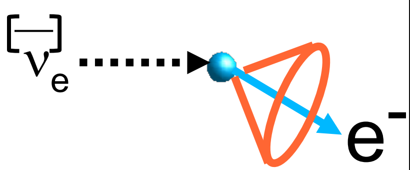
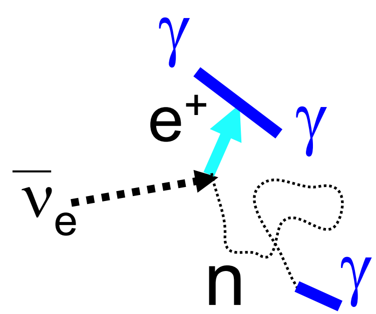
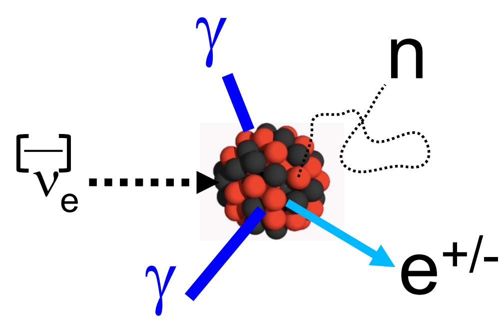
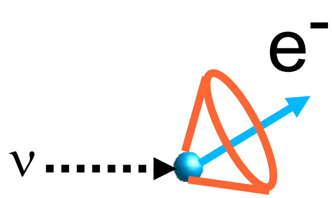
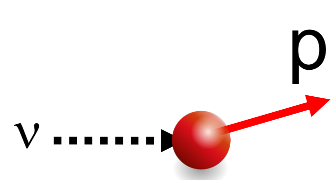
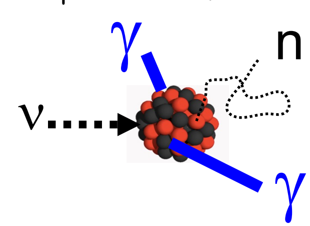
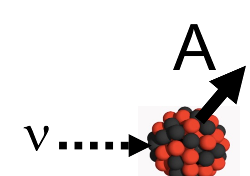
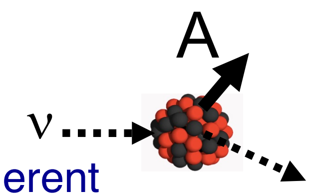
Revisit these with directionality in mind...

	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)

How do these interactions feel to the neutrino?

oops...



Coherent
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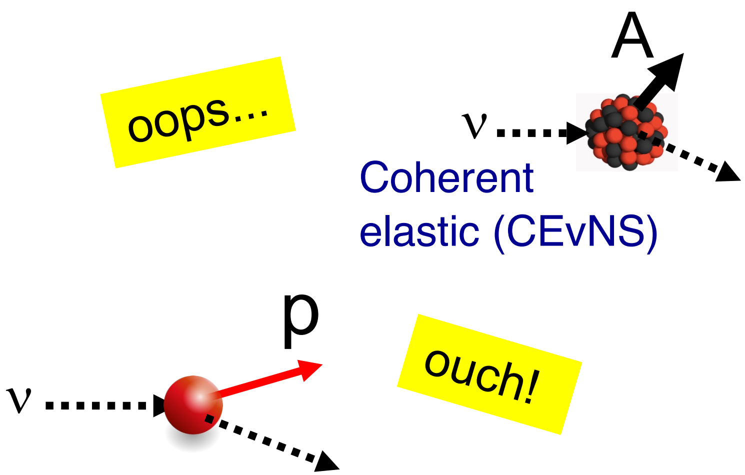

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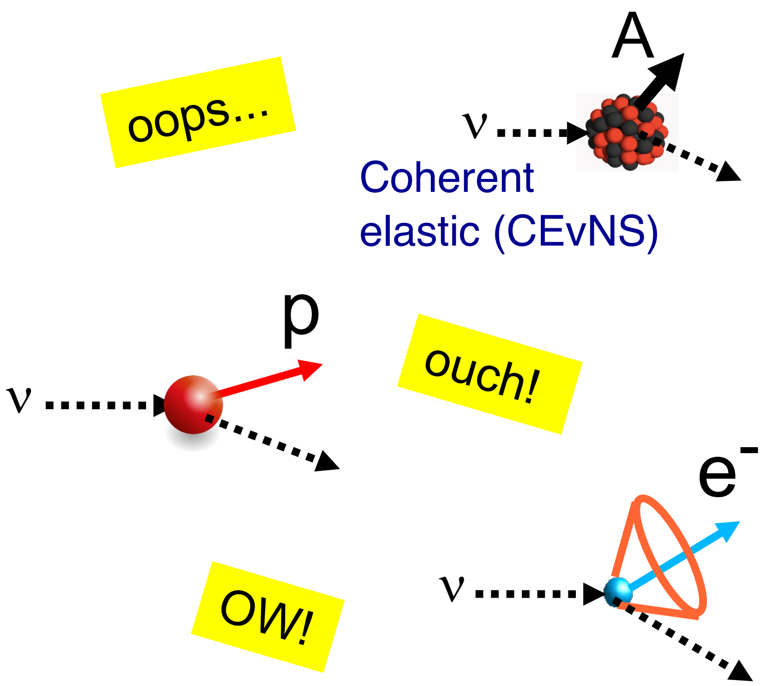

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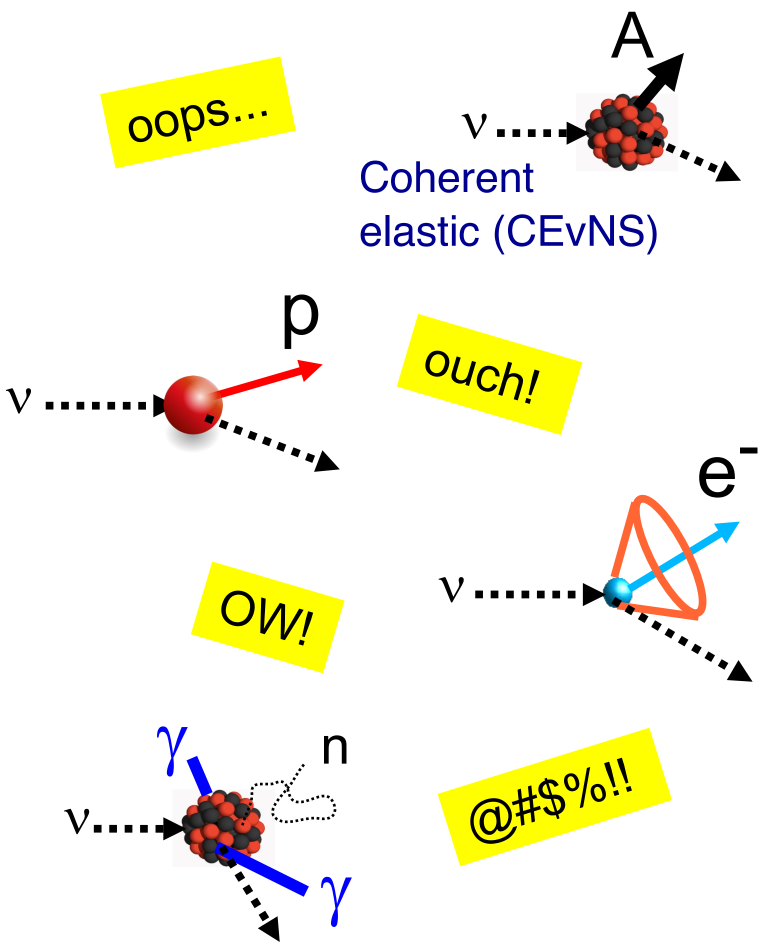

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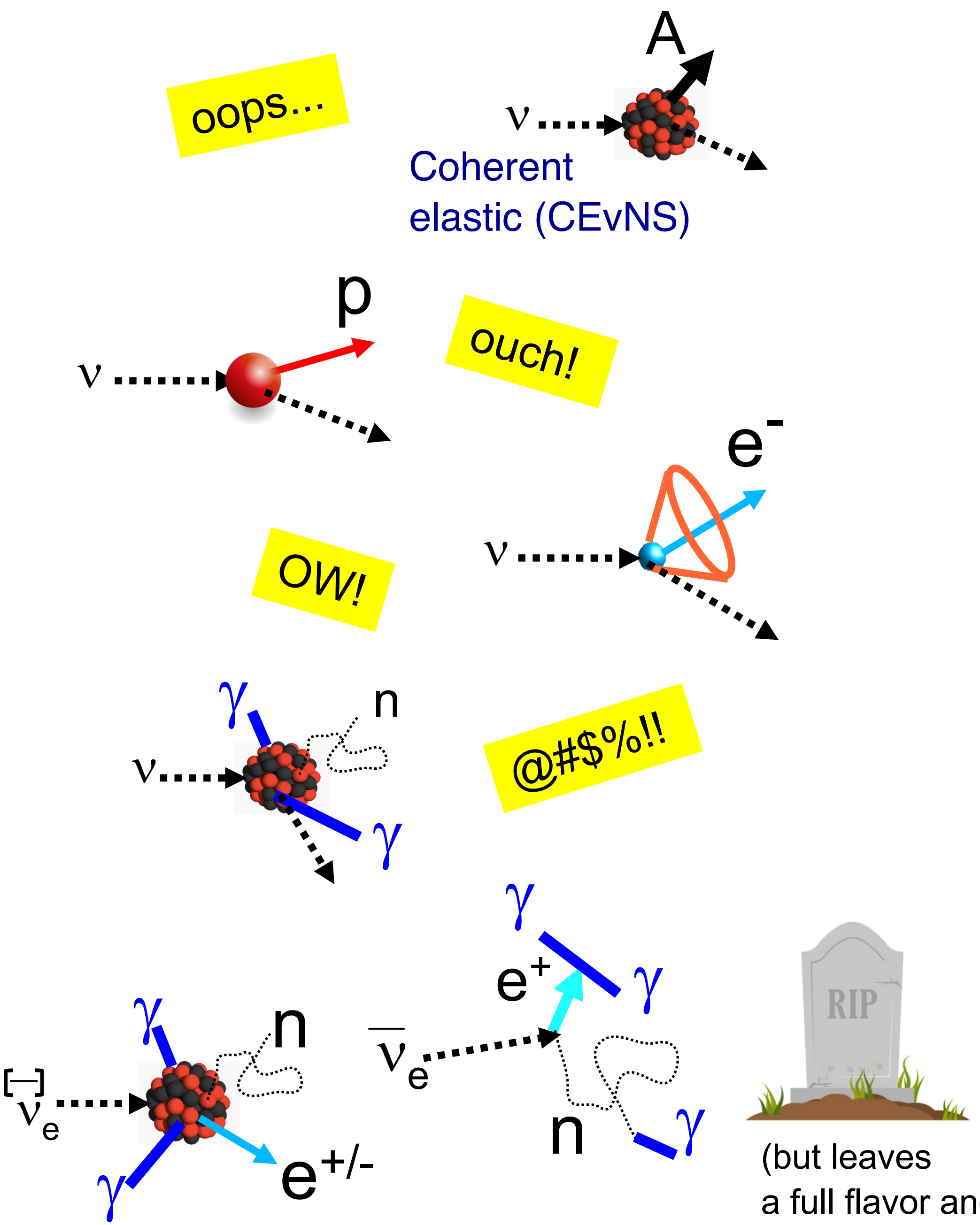
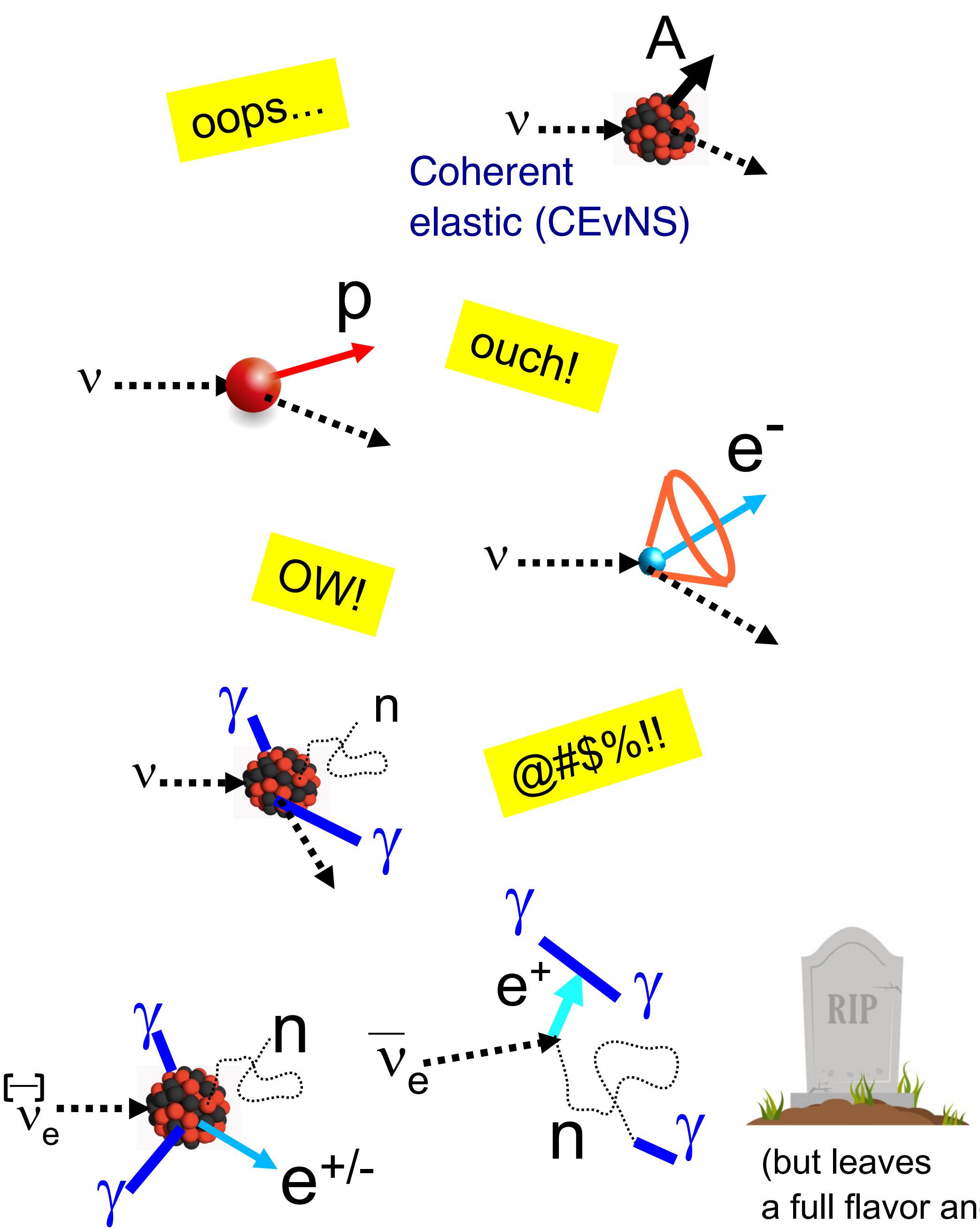


(but leaves
a full flavor and
four-mom legacy)

How do these interactions feel to the neutrino?



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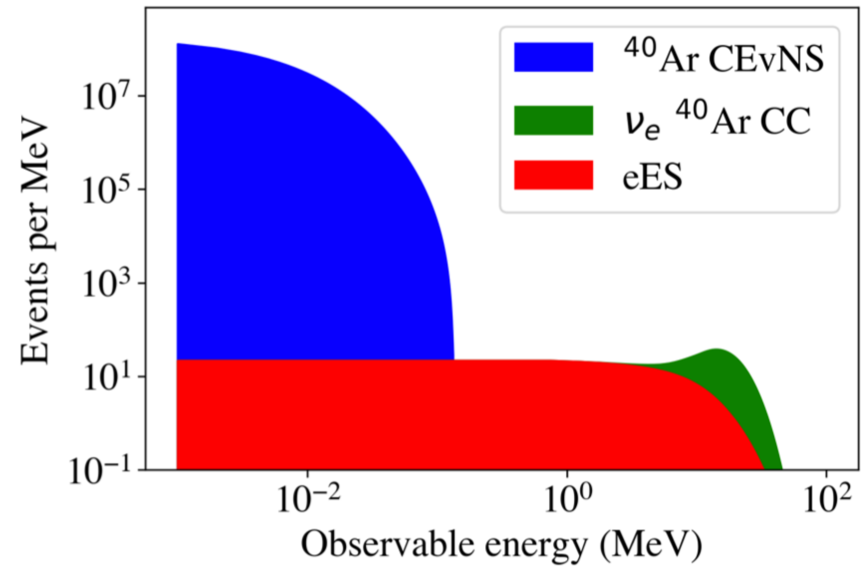

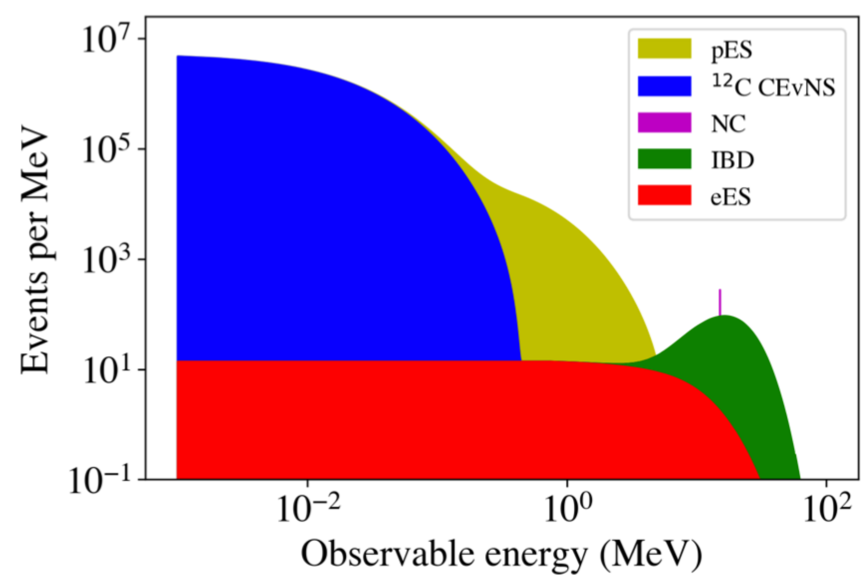

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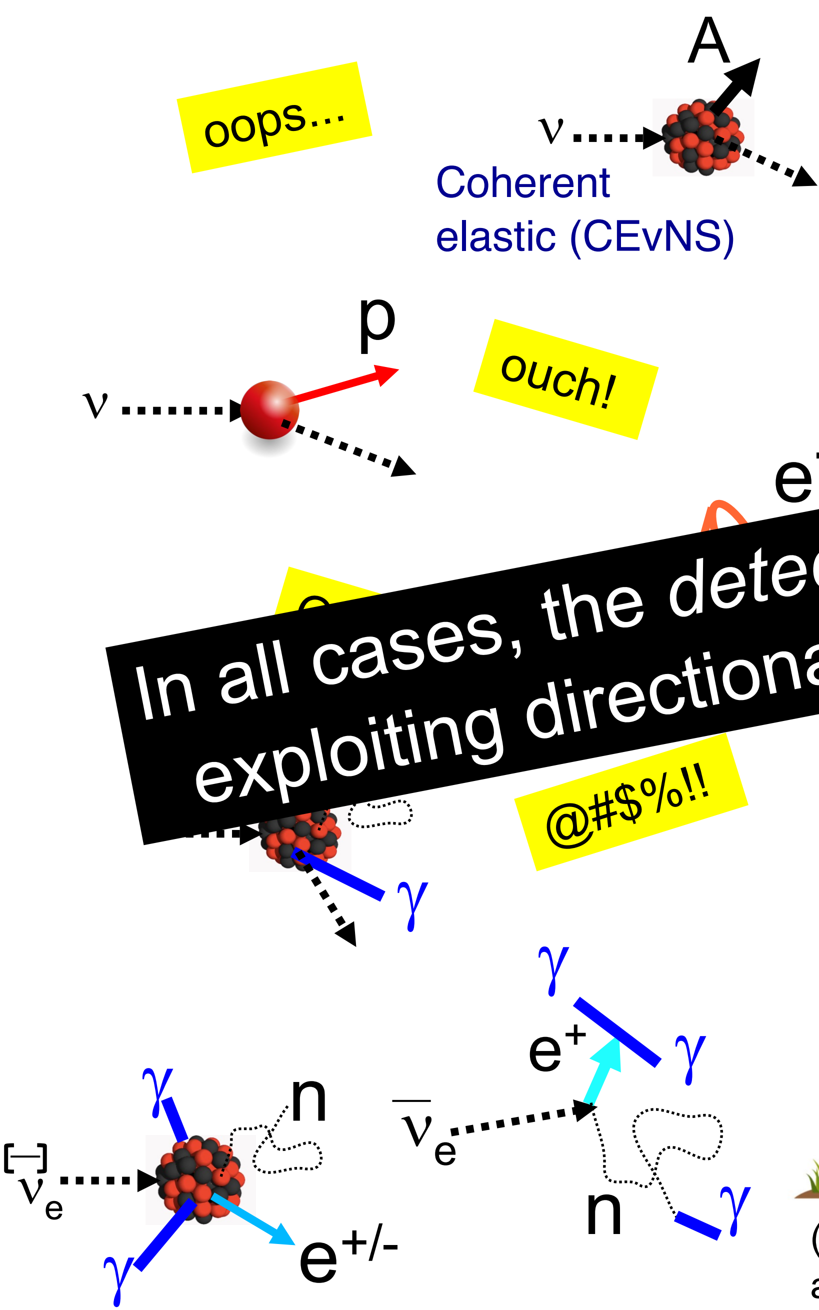
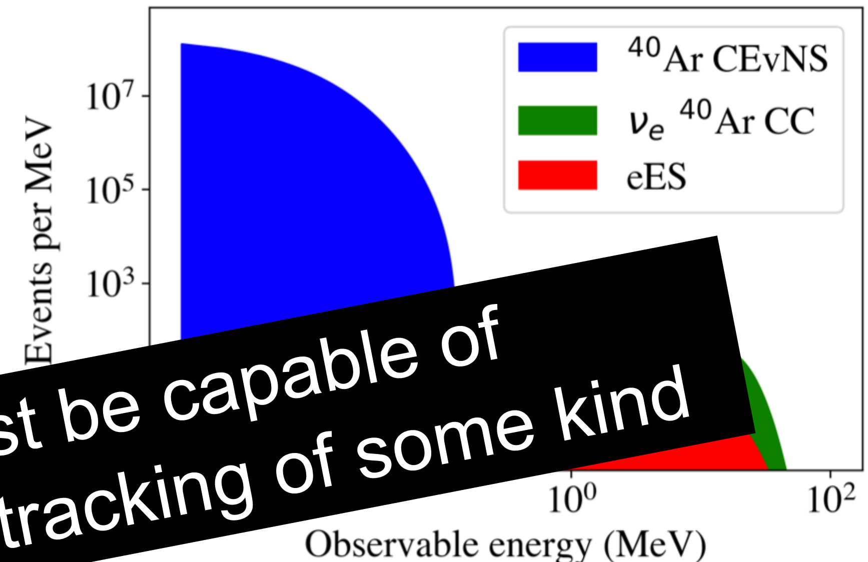
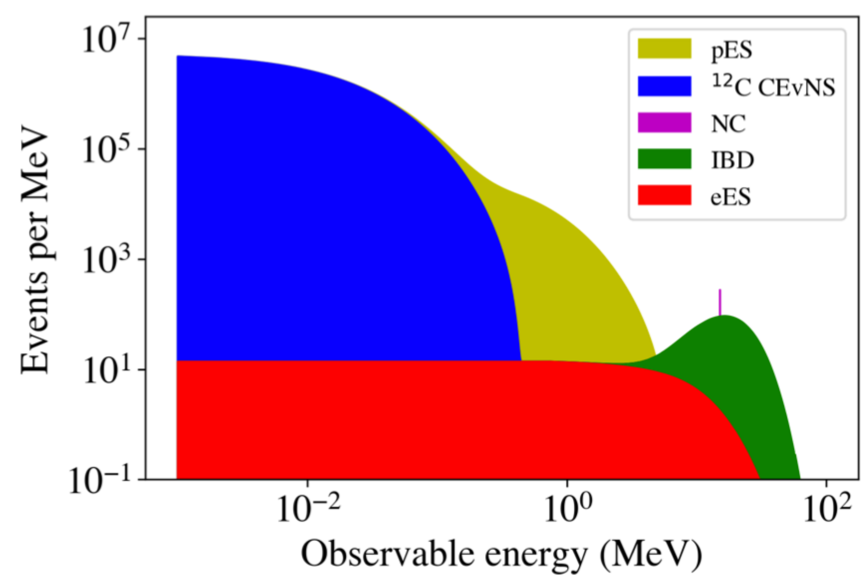


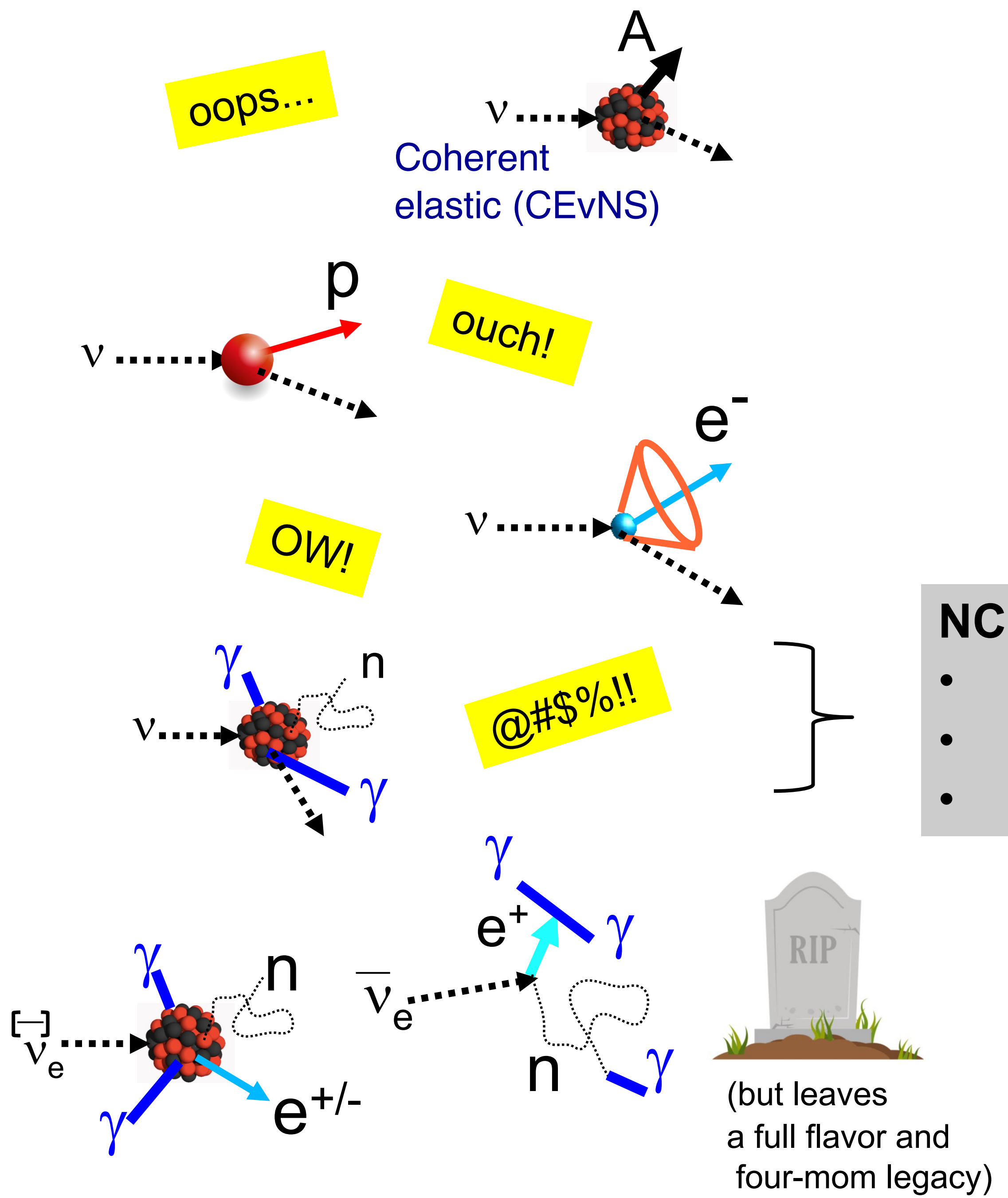
In all cases, the detector must be capable of exploiting directionality via tracking of some kind

(but leaves
a full flavor and
four-mom legacy)





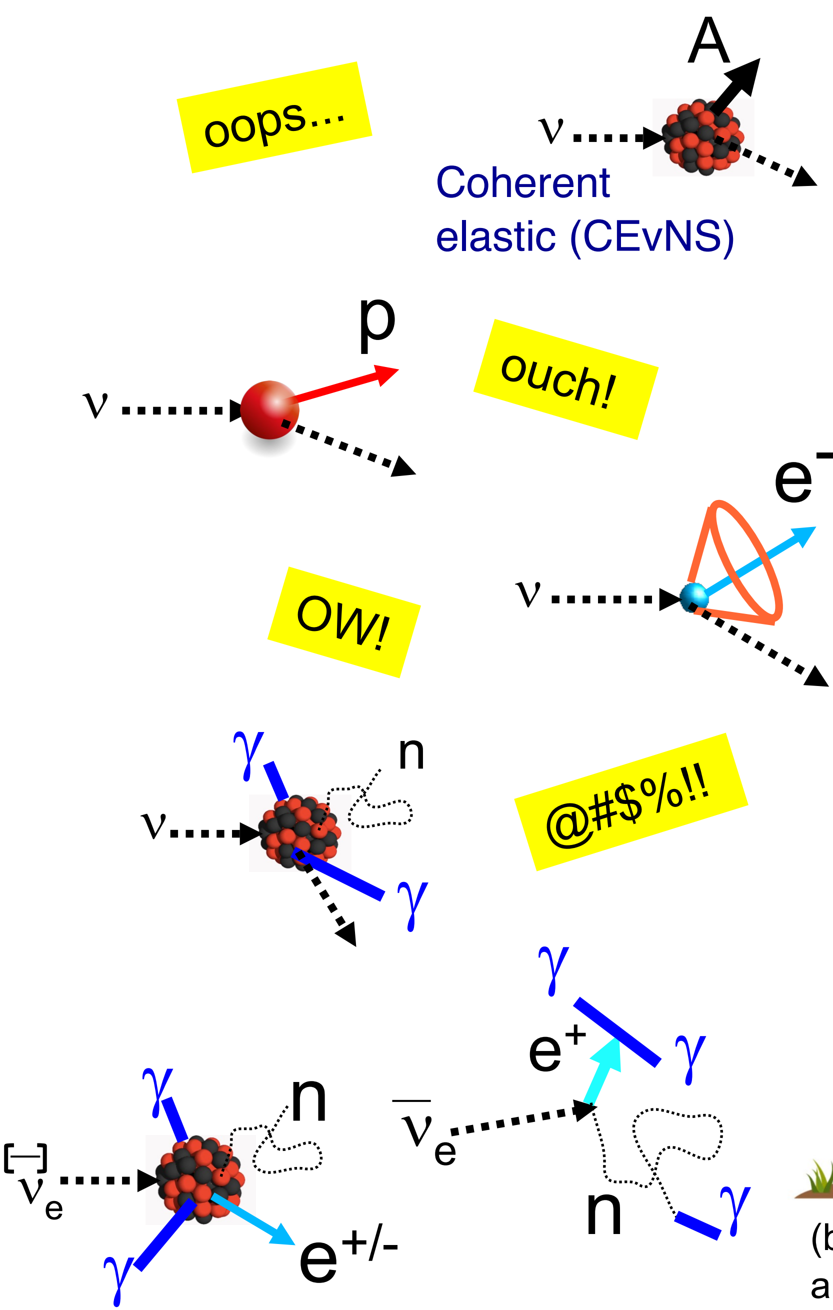
Current thinking about use in SN pointing



NC inelastic ν-nucleus

- Poorly understood
- Low cross section
- ~Isotropic observables

Current thinking about use in SN pointing

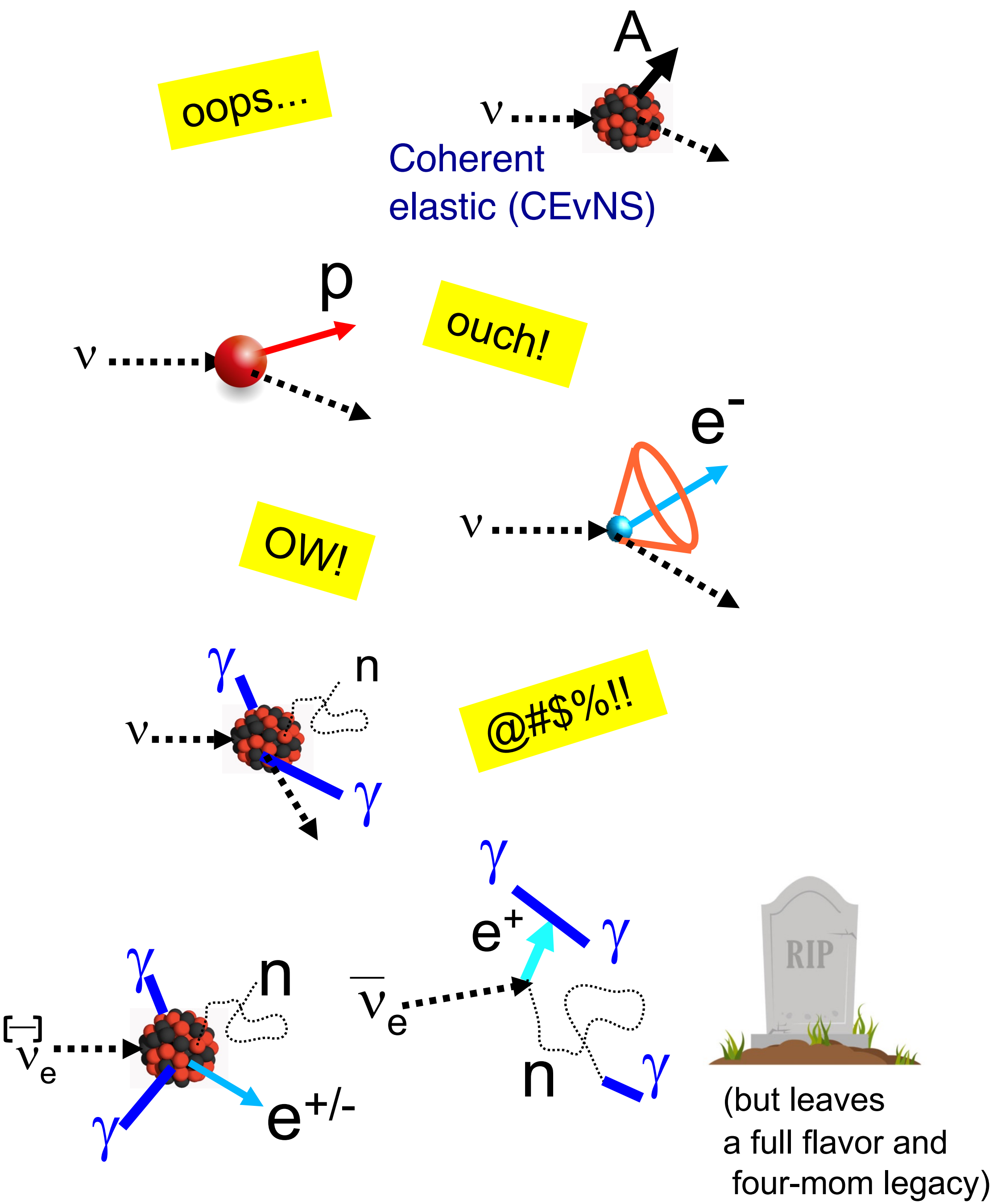


CEvNS and pES

- Well-defined anisotropy
- Large statistics per detector mass
- Experimentally hard…(tiny recoils, tracking hard w/ high stats)

(but leaves
a full flavor and
four-mom legacy)

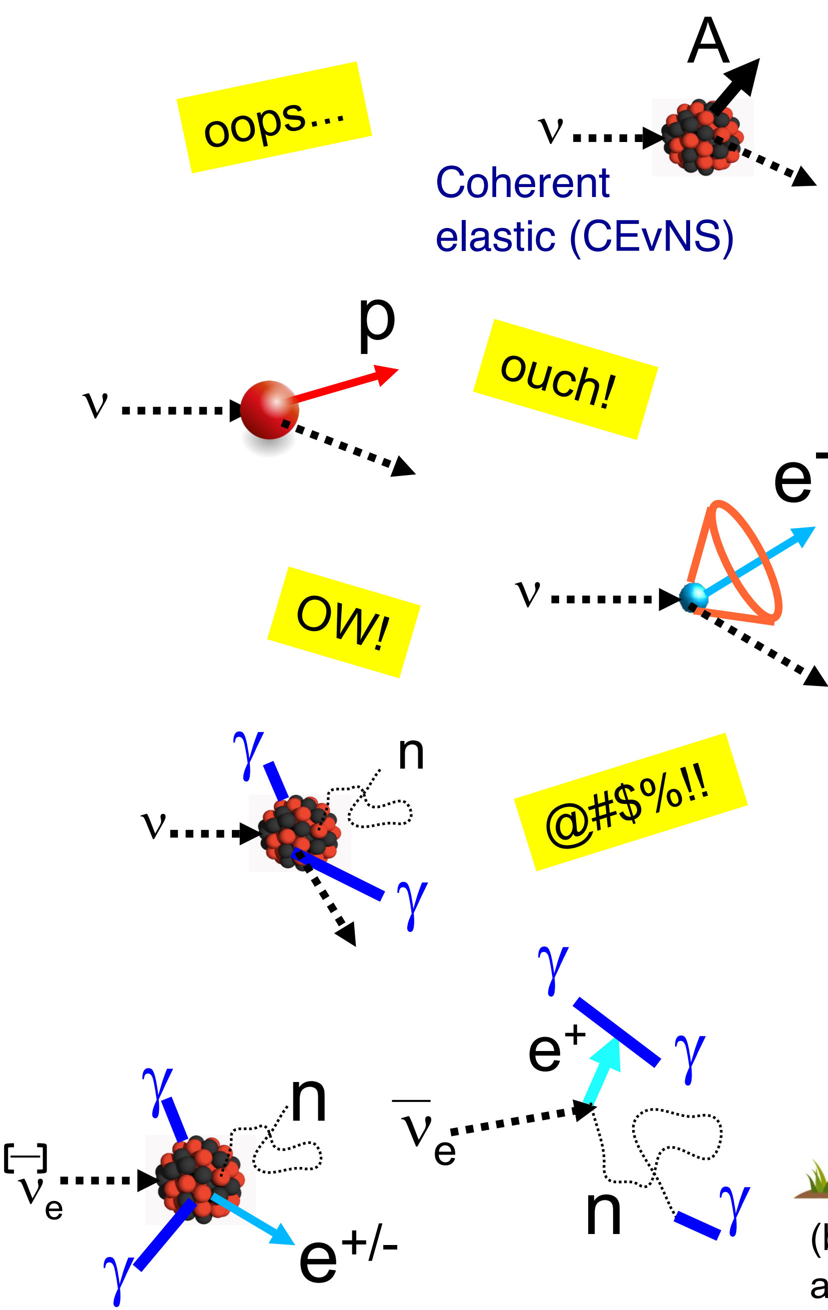
Current thinking about use in SN pointing



IBD & ν_eCC

- Can be high event rate (e.g. pIBD)
- Poorly understood xscns on nuclei
- Observable lepton anisotropy is weak

Current thinking about use in SN pointing



eES (neutrino-electon elastic scattering)

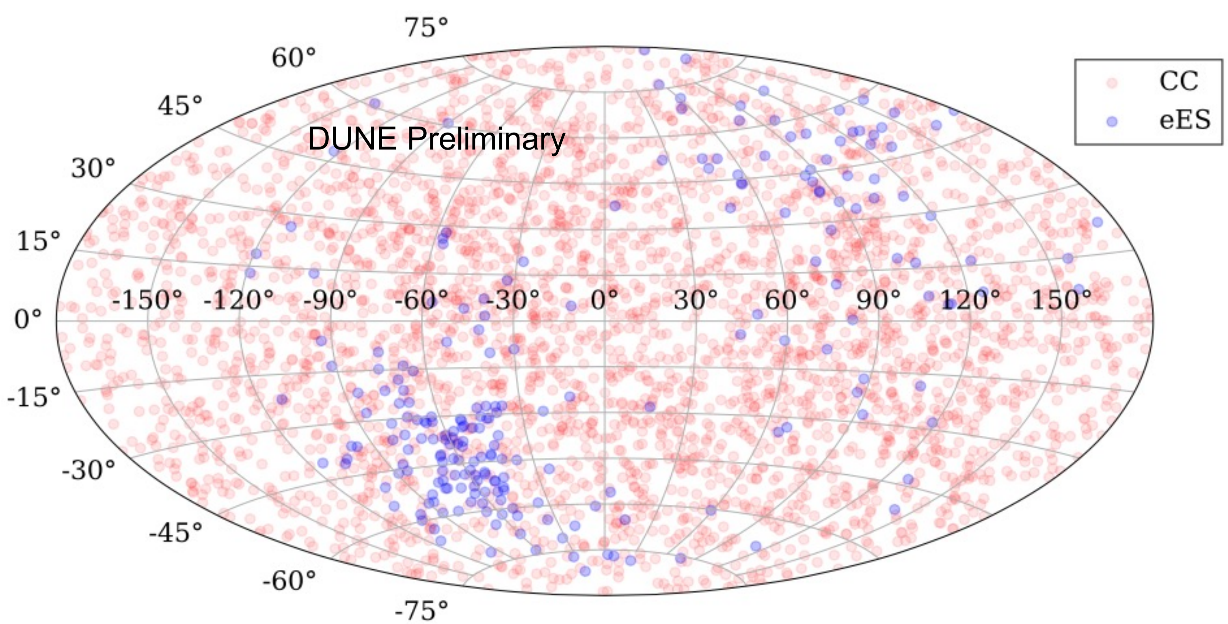
- Every detector has electrons
- Well-defined anisotropy
- Forward pointing
- But, low cross section

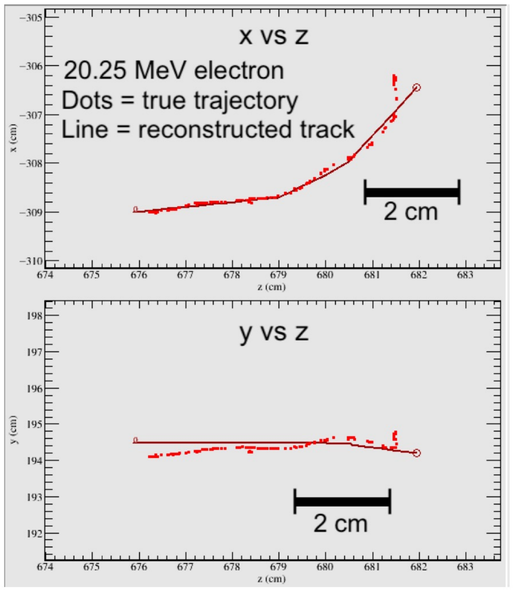
Works well in *large* (>10-kton scale) detectors
(Super-K/Hyper-K/DUNE)

(but leaves
a full flavor and
four-mom legacy)

The strategy for large detectors is to use eES for pointing

Example for DUNE

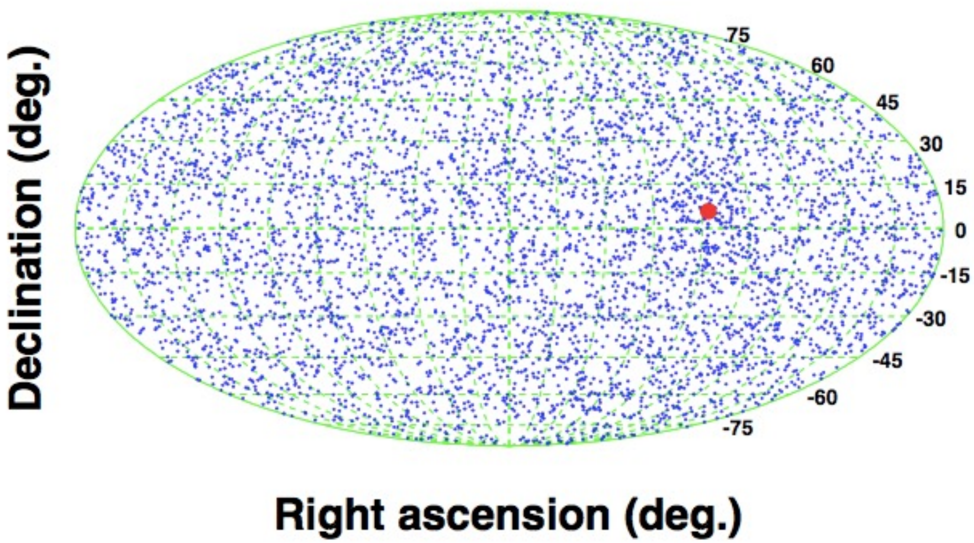


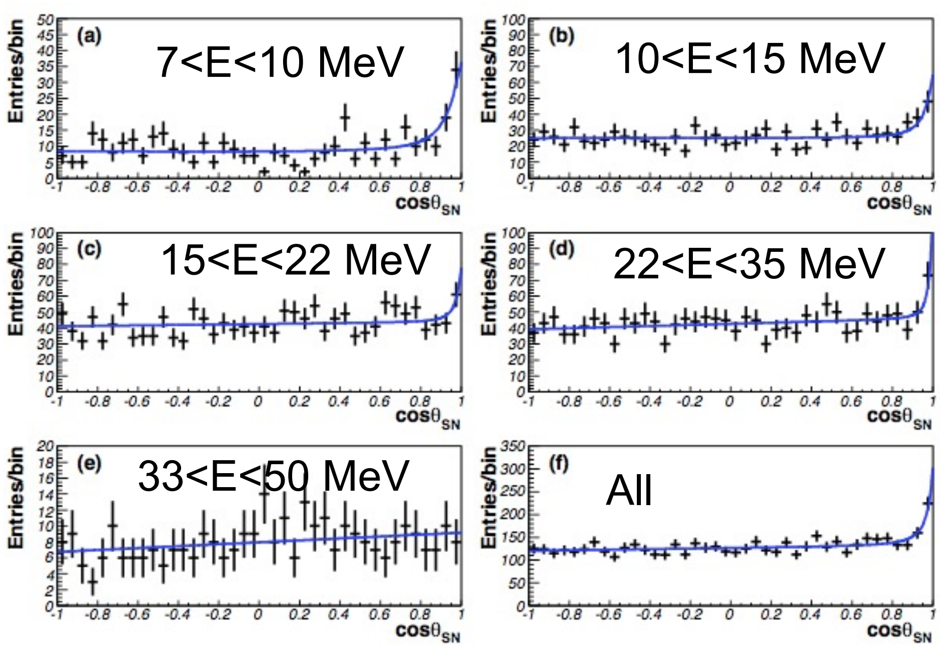


directional eES signal on an ~isotropic CC background

Resolution ~ $\frac{\Delta\theta}{\sqrt{N}}$, where Δθ is the intrinsic spread of kicked electron directions, N~ 50-80 eES /kton

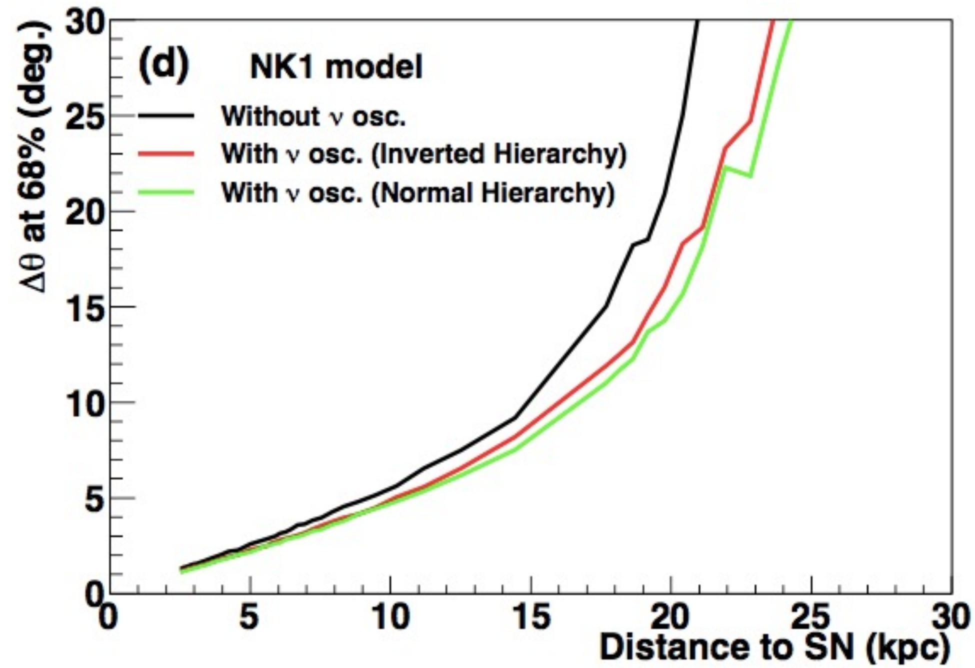
Example: pointing in Water Cherenkov (Super-K)





Fit to ES+ mildly anisotropic IBD (+^{16}O)

K. Abe et al., Astropart. Phys. 81 (2016) 39-48

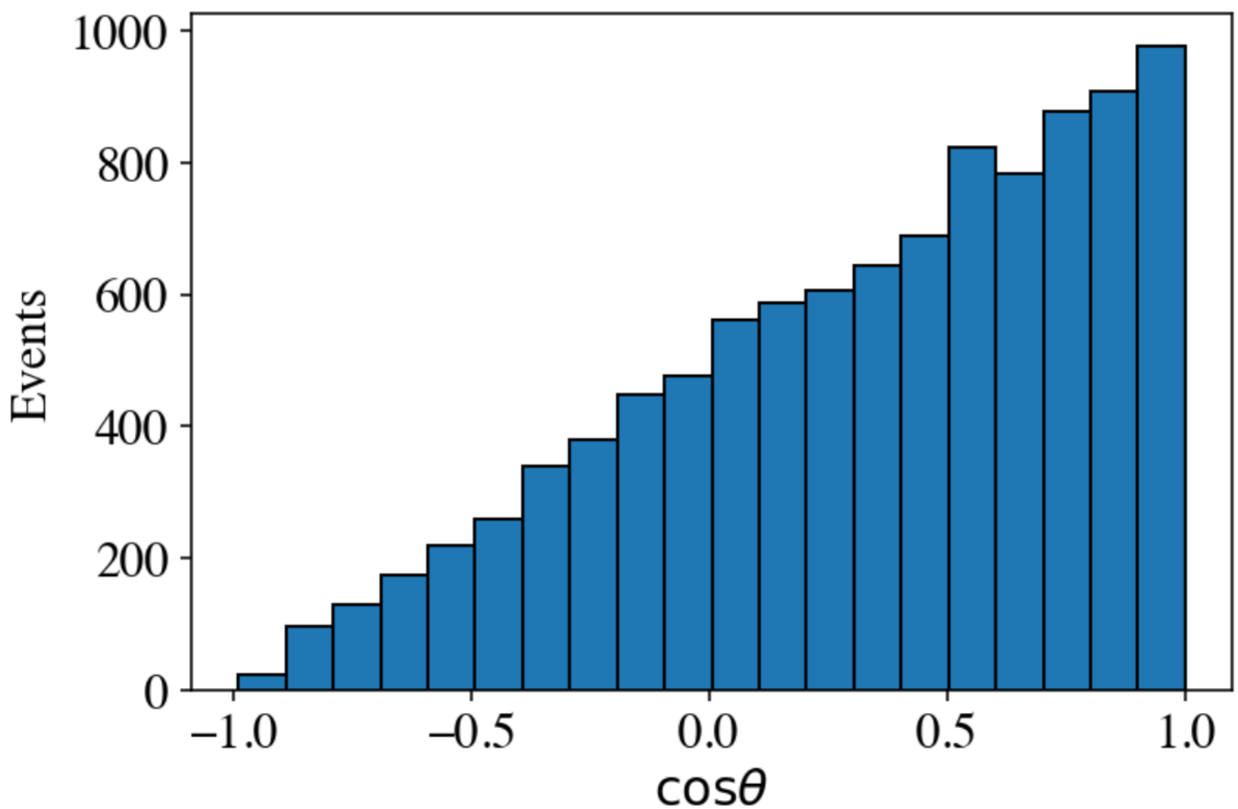


- Improves w/SK-Gd
- HK will get to ~few deg

How well can CEvNS do for pointing?

CEvNS events point forward on average

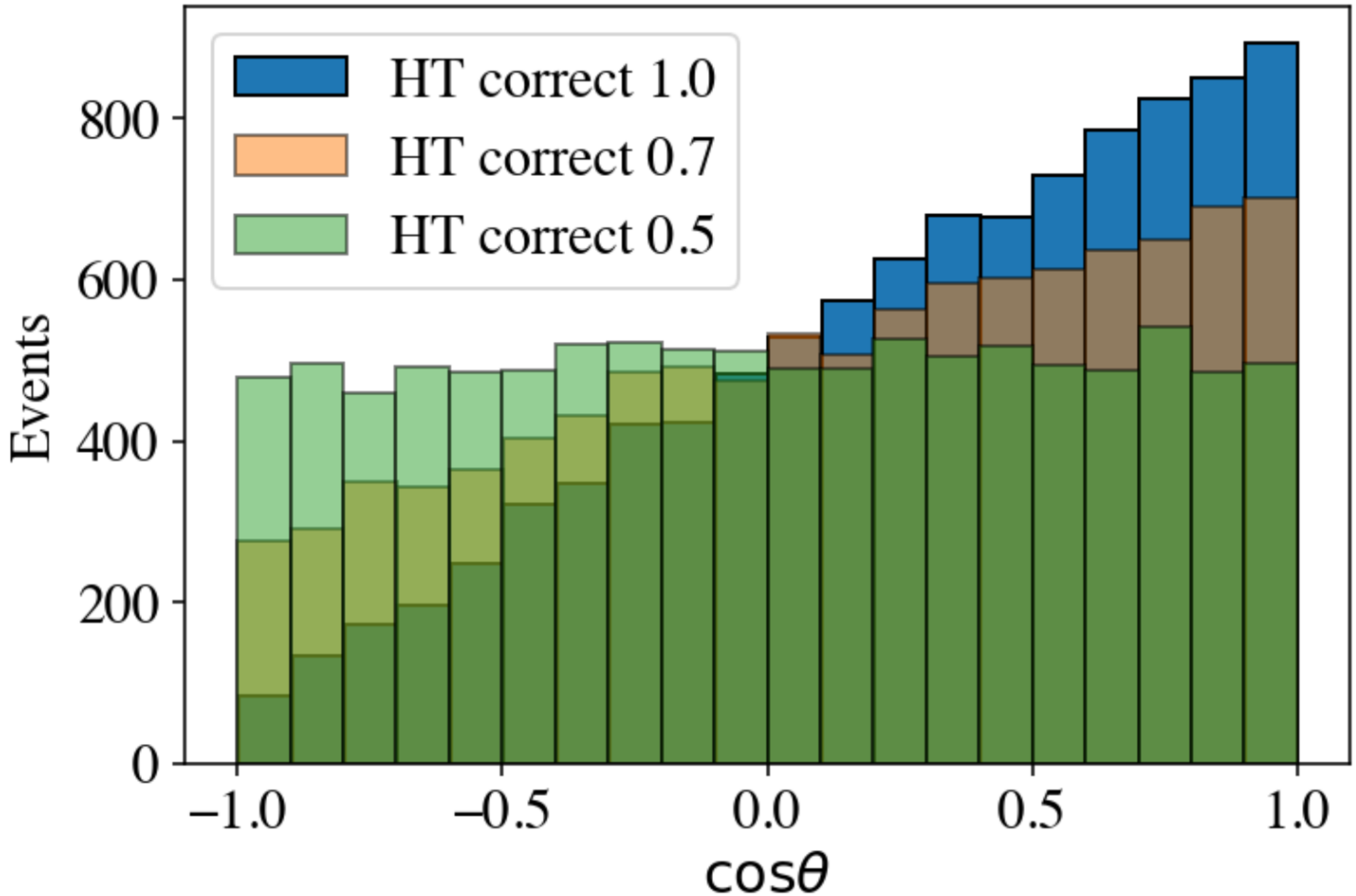
$$\frac{d\sigma}{d(\cos\theta)} = \frac{G_F^2}{8\pi}\left[Z(4\sin^2\theta_W - 1) + N\right]^2 E_\nu^2 (1+\cos\theta)$$



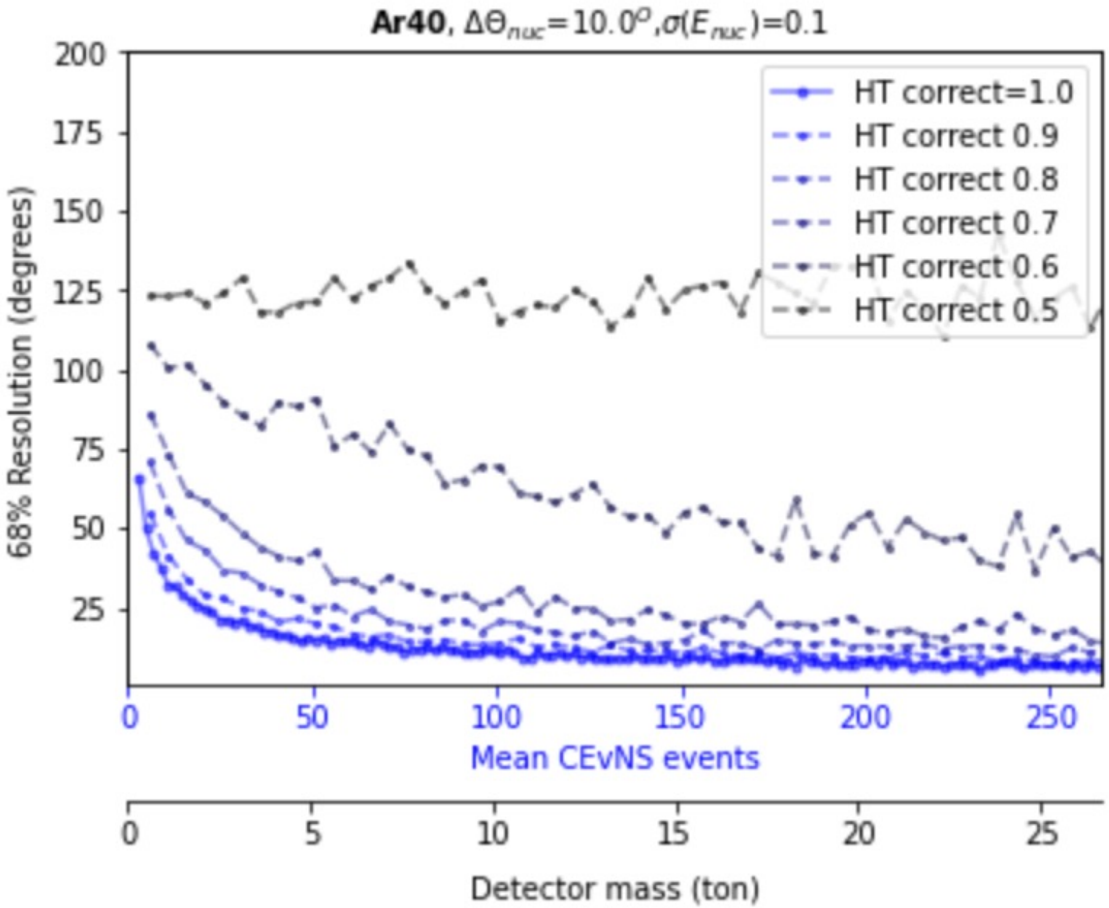
θ is angle wrt neutrino direction

How well can CEvNS do for pointing?

But... if you have a head-tail ambiguity, you lose directional information!



Some overall pointing quality for CEvNS...
poor head-tail disambiguation weakens it

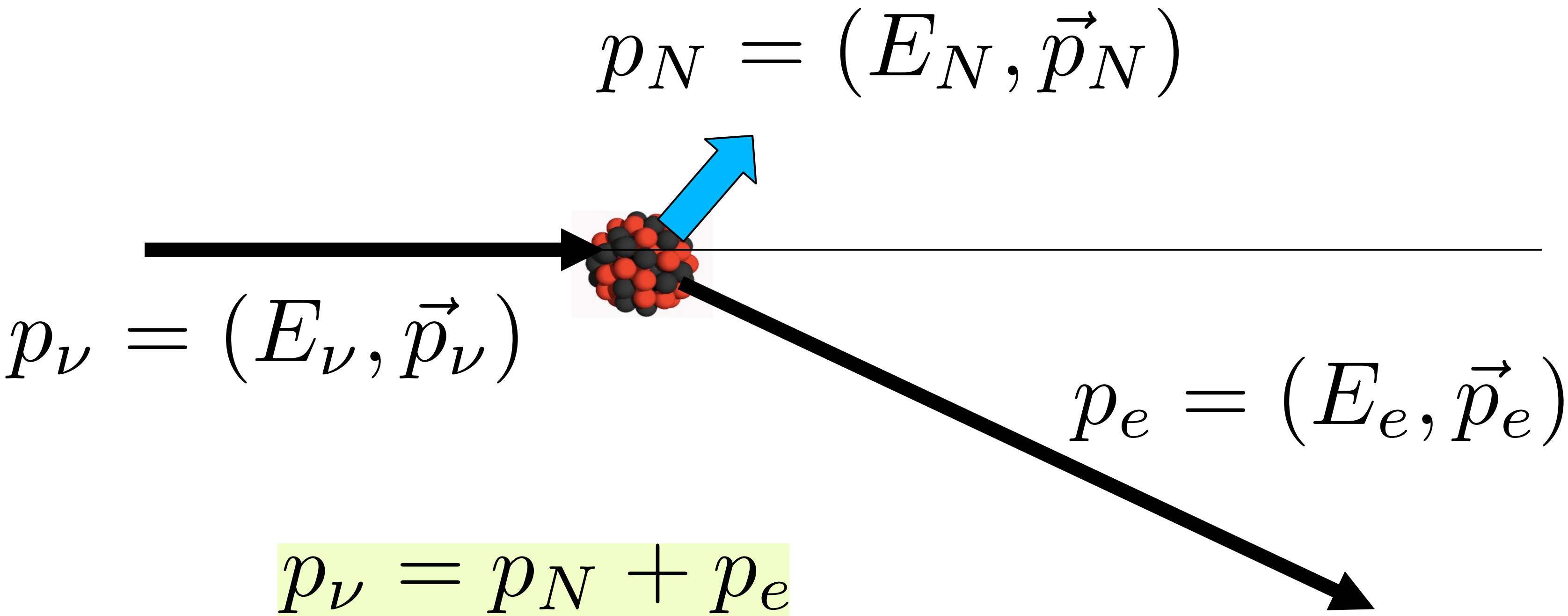


From a toy angular smearing MC [simple assumptions]

(This is argon; I know argon is not a mineral, but angular distribution is independent of target in this approximation)

More craziness: what about CC events?

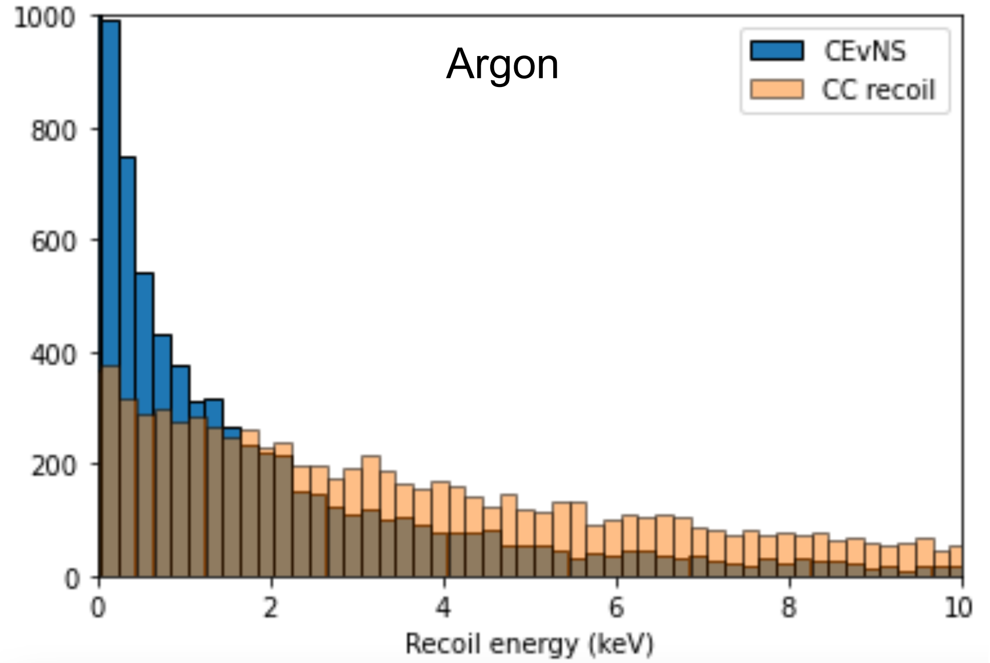
What if you can ***fully reconstruct the final state*** with fine resolution using the recoil?



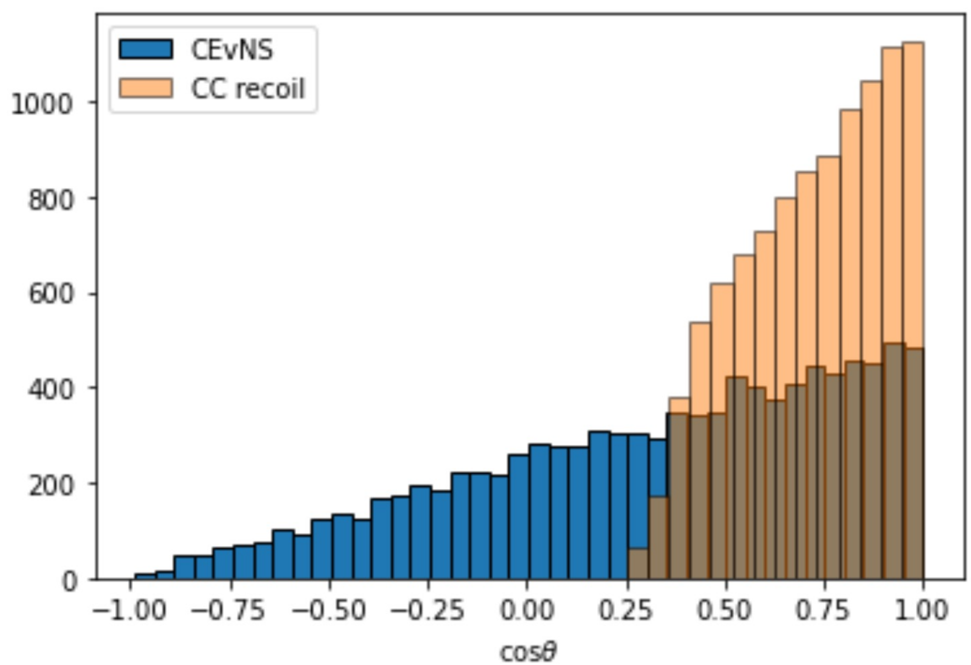
$$p_\nu = p_N + p_e$$

Need energy and angular resolution for both final-state products

Charged-current "quasi-elastic" events: **the nuclear recoil**

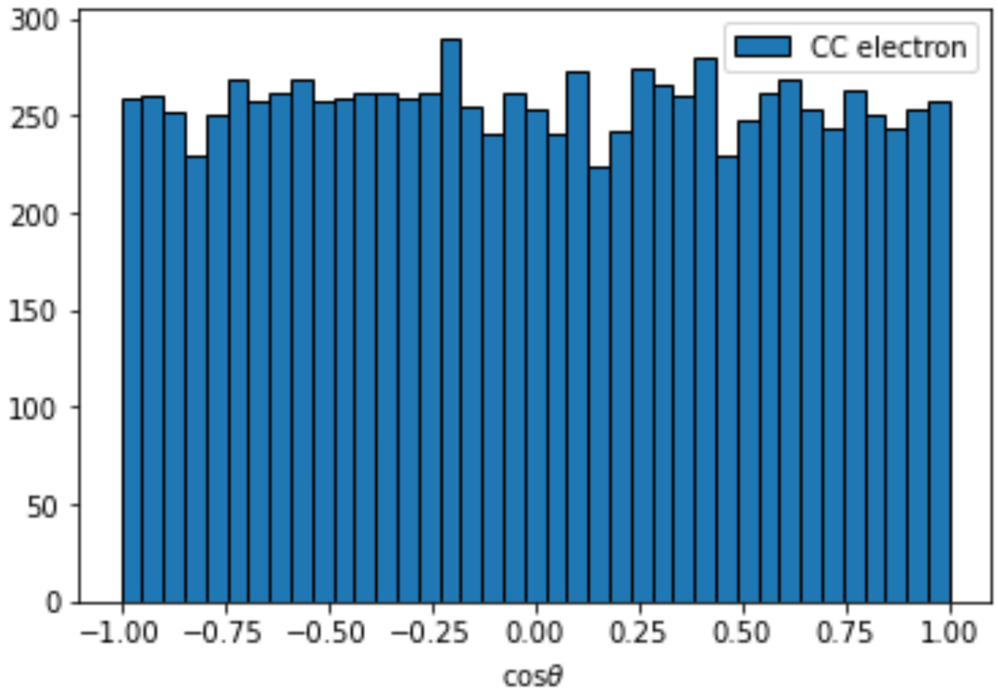


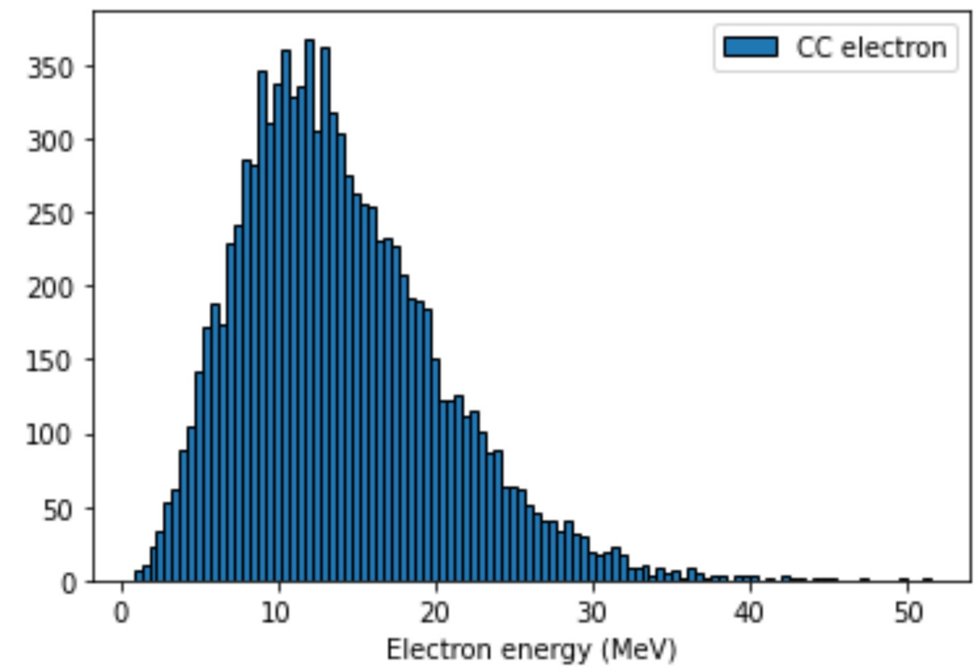
The CC nuclear recoil is somewhat more energetic than CEvNS

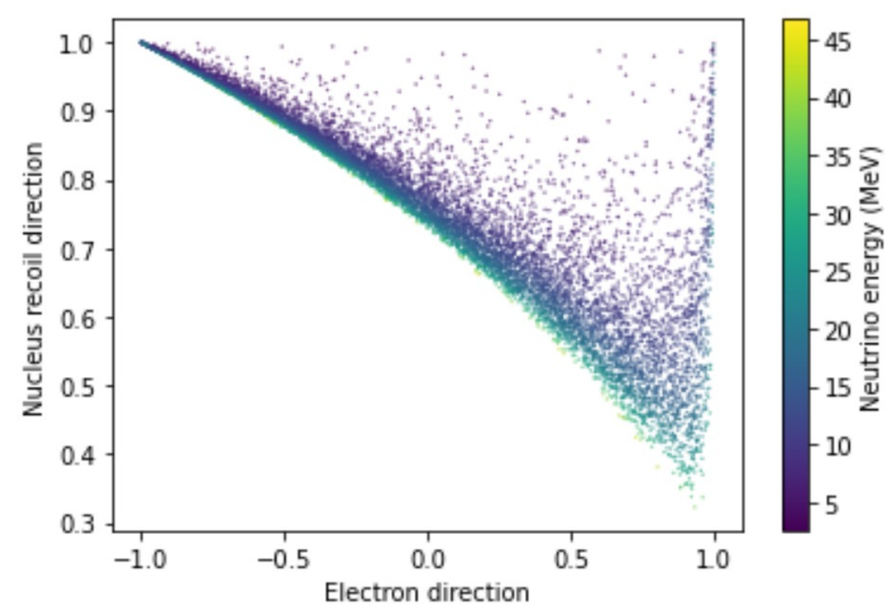


... and it's pointed more forward

Charged-current "quasi-elastic" events: **the lepton**



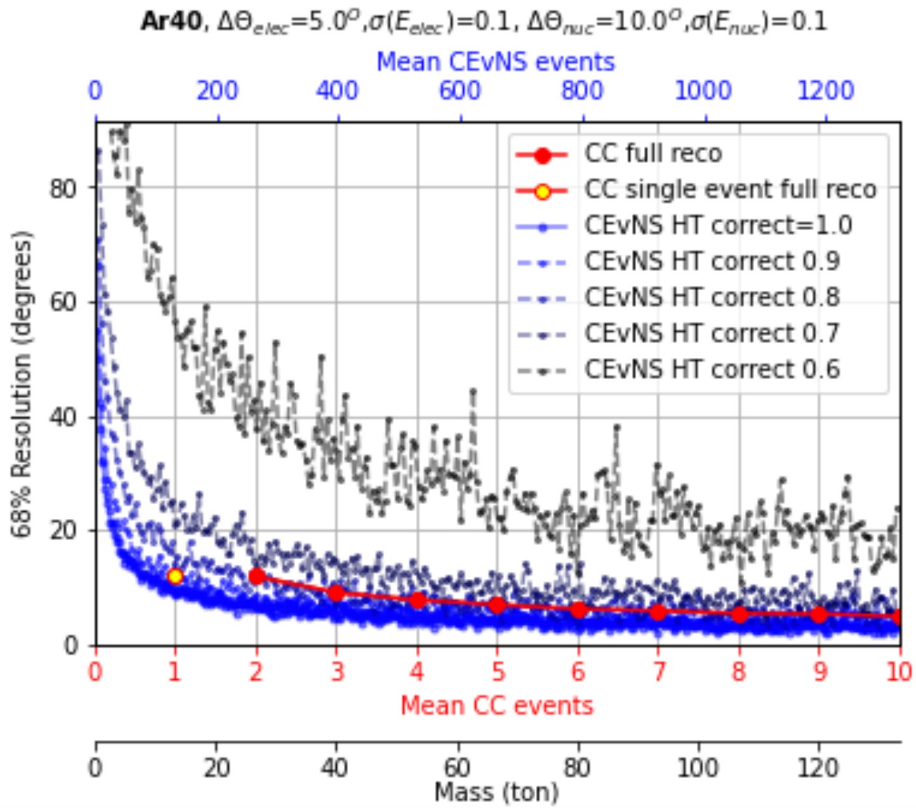


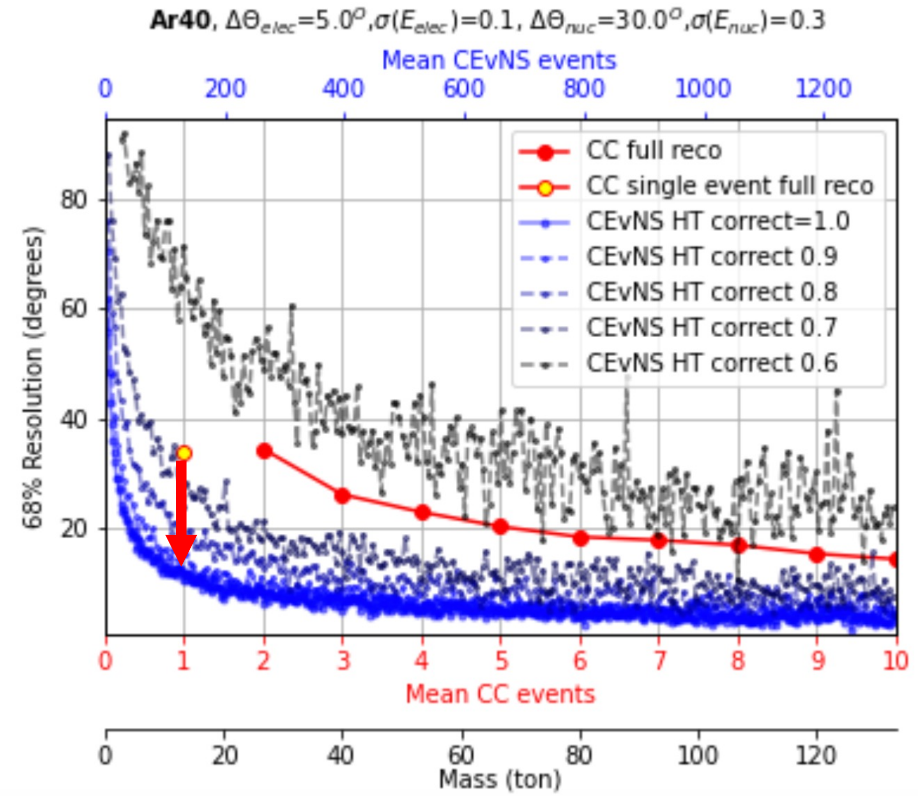


Lepton is ~nearly isotropic (typically $1+\alpha \cos\theta$ distribution, small α): when electron backscattered, nucleus is forward scattered

In "normal" neutrino detectors, it's reasonable to reconstruct the lepton to ~5^{o} and 10% energy resolution

Some toy-smearing MC results for full CC reco:





- good full reco achievable for good recoil pointing
- for poor recoil pointing, CC doesn't help that much
- but, still disambiguates head-tail for CEvNS!

Some comments:

- Same issues as for CEvNS wrt backgrounds etc.

- Need the electron as well with reasonable resolution ... cannot be a fully passive mineral detector

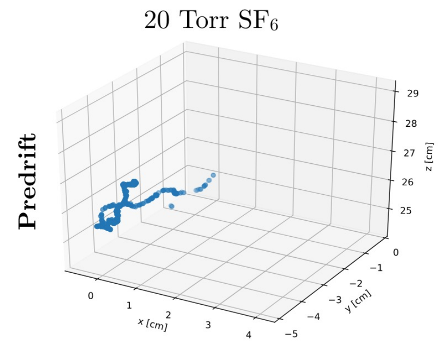
- Lepton & nuclear resolutions may be correlated event by event

- Final nuclear state may be excited and have characteristic decays and extra recoil energy (but... could help as a topological tag?)

- Even if poorly reconstructed, a single CC event **breaks the head-tail degeneracy**, and can improve the pointing from the higher-stats CEvNS

Mineral detection is a candidate, but may not be the best use case for this CC full reco concept...
other possibilities:

- Gas recoil detectors-- large footprint for given mass, but recoil has longer track
- IBD neutron tracking
  [already in statistical use for SNB directionality]
- Emulsions?



For reasonable probability of at least one CC event from a Galactic supernova (+ 6N times the CEvNS), need **~several ton scale**

Next steps:

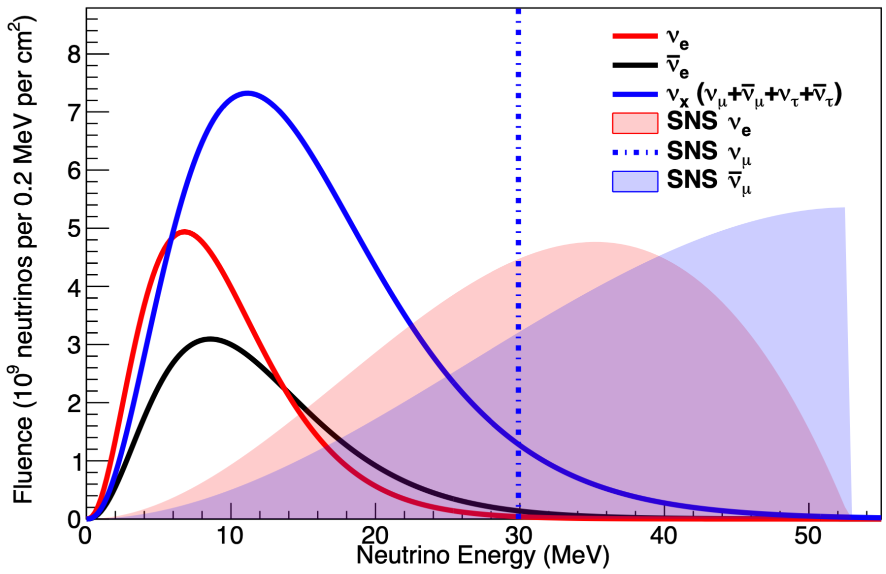
- survey materials and techniques
- go beyond toy sim (SRIM...?)

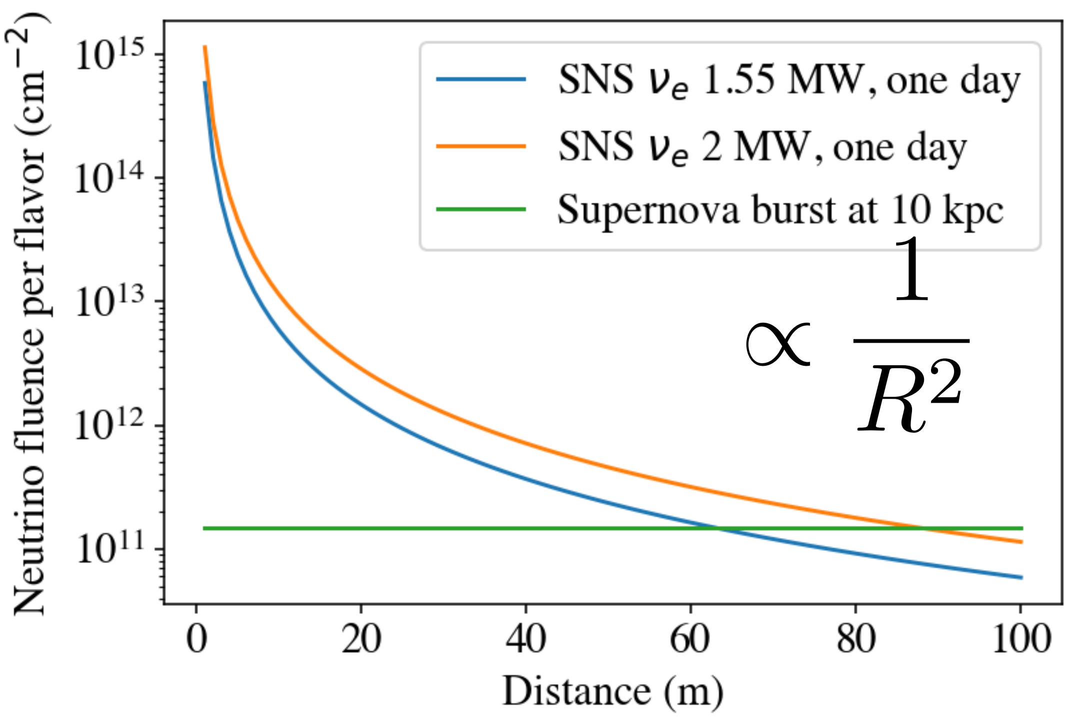
Other applications of precision CC full reco:

- IBD for reactors?
- neutrino communications??

Suggestions welcome...

Final note: we have an **artificial SN in Neutrino Alley**

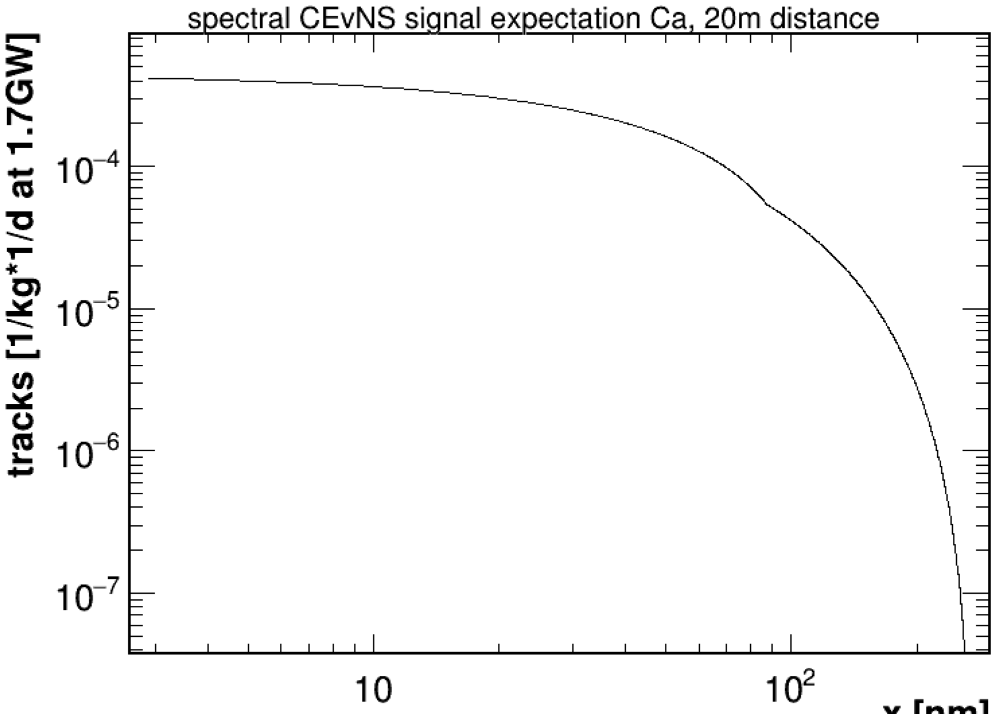


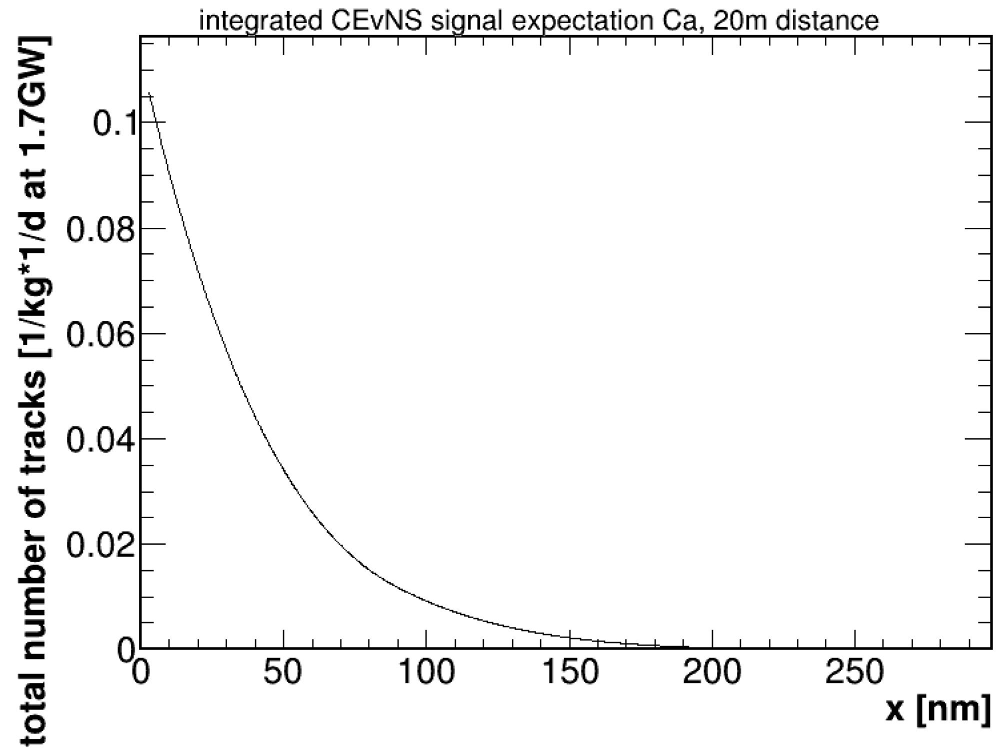


Neutrino flux at ~20-30 m from the SNS amounts to ~ 2 SNe per day! (and will be twice that soon)

Some example event rates for the SNS:

Plots by Janina Hakenmüller





- Event rates @ 20 m: tens per year
- Backgrounds will be challenging for CEvNS w/o timing
- Can exploit timing for real-time approaches (e.g., CC), but event rates are lower

Take-Away Messages

SNB directional information is valuable

- Need it fast!
- But late may be better than never

Pointing with neutrinos

- Anisotropic neutrino interactions work well
- Large detectors make use of eES
- With high-precision recoil pointing, can exploit directionality
- CEvNS .... head–tail ambuiguity is a problem
- **Full kinematic reco of CC events using recoils**: can rival SK in small detector, and lift head-tail degeneracy with even a single event

Mineral detection on nano-year timescales?

- might be crazy... need nm resolution for for several tons of material in ~hours...

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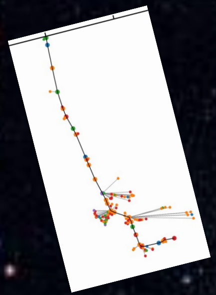

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