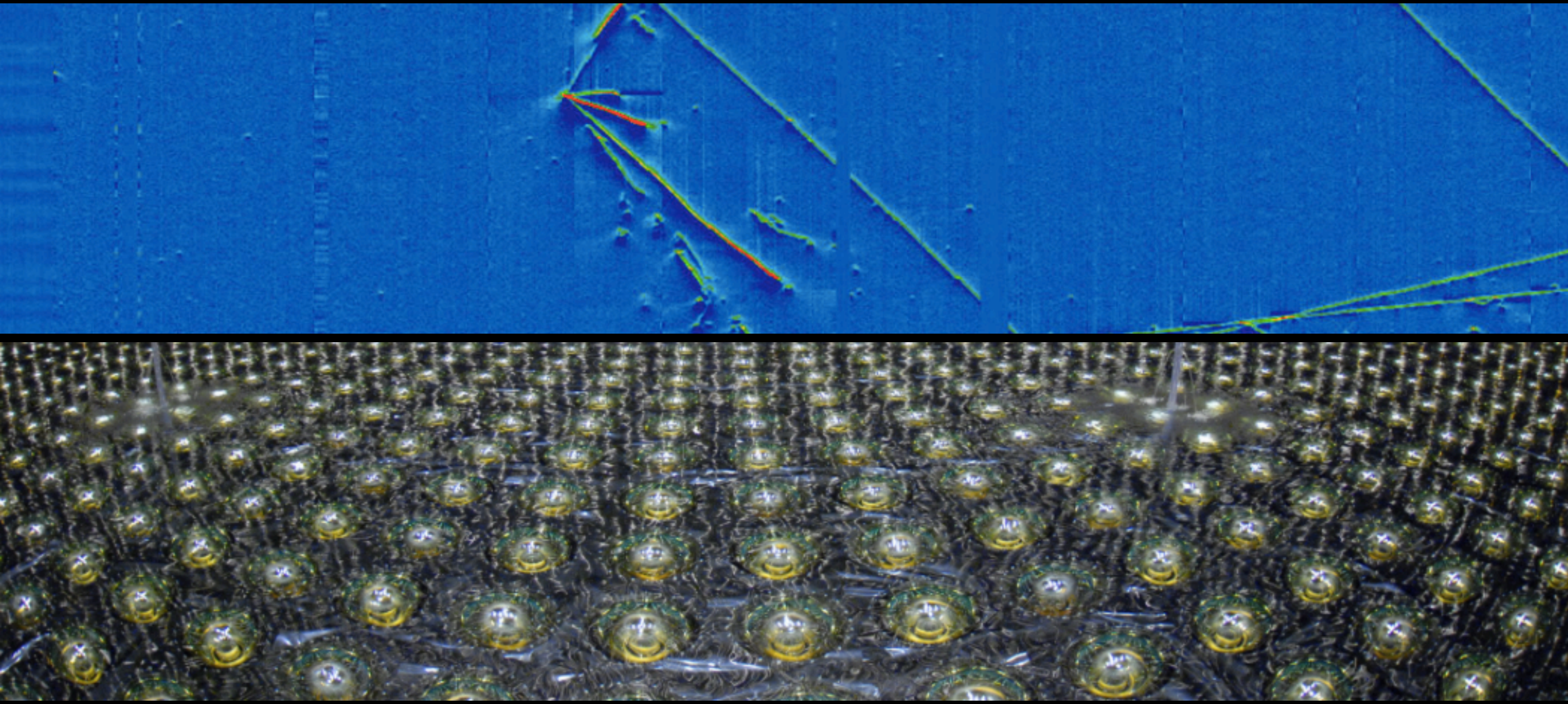
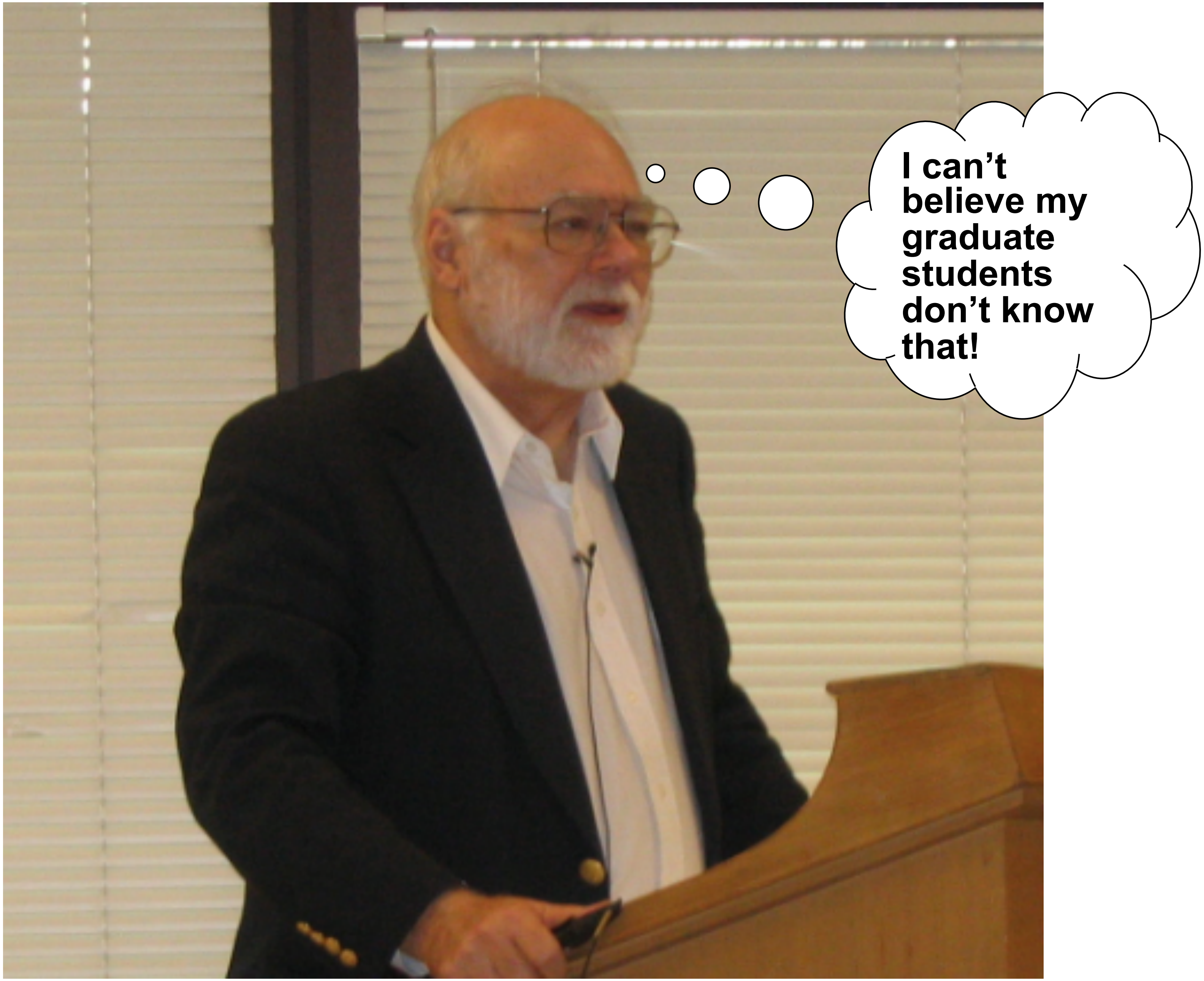
The Physics Associated with Neutrino Mass



Kate Scholberg, Duke University

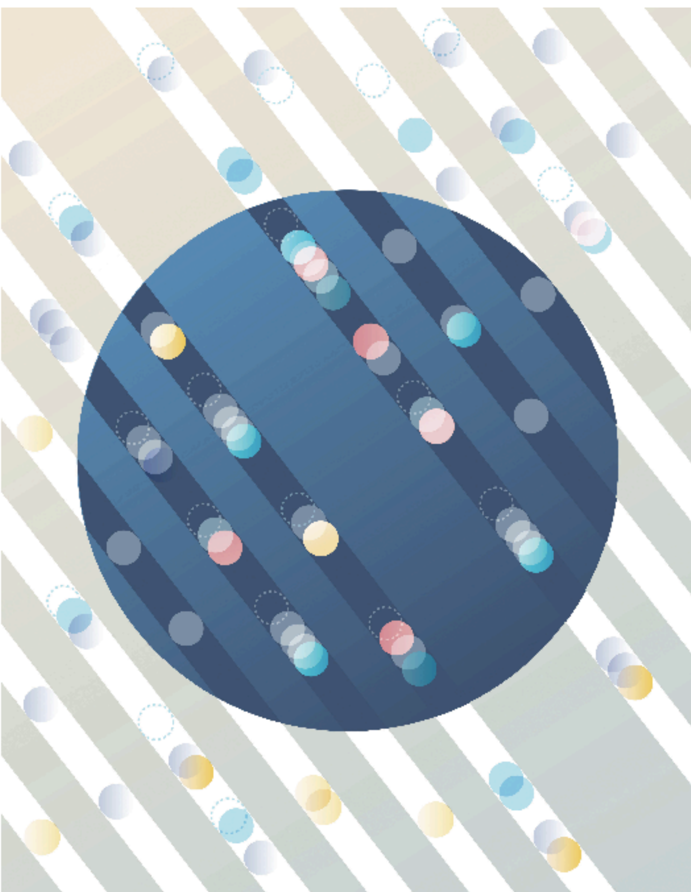
CPAD 2016, Caltech, October 2016

This talk is dedicated to my PhD advisor **Charlie Peck**



P5 Neutrino Questions

What is the origin of neutrino mass?
How are the neutrino masses ordered?
What are the neutrino masses?
Do neutrinos and antineutrinos oscillate differently?
Are there additional neutrino types and interactions?
Are neutrinos their own antiparticles?

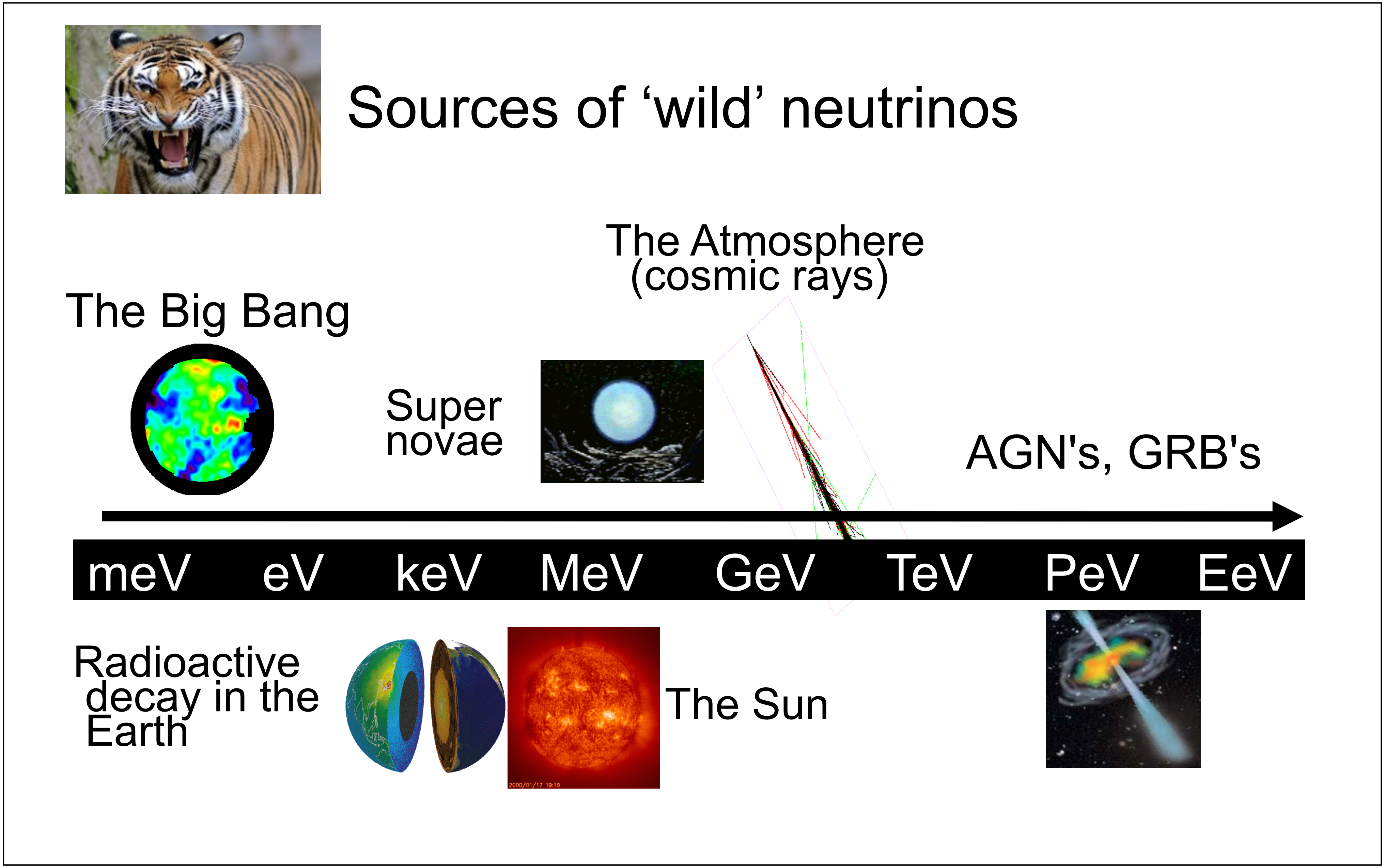


Diversity and balance in the neutrino program

The U.S. neutrino program envisioned in this report encompasses both small and large experiments in the near- and far-term to address fundamental questions in particle physics. Development of software and hardware for different experiments complement and enhance one another. Data from near-term experiments produce physics results while construction for next-generation experiments is underway. This provides a diversity and balance essential for the field.

Many diverse experiments addressing these questions...

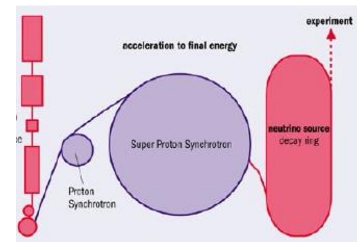
The relevant neutrinos **span a very wide energy range...**
➔very diverse instrumentation needs



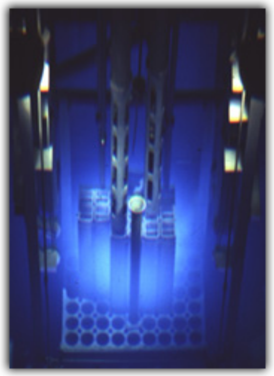
Sources of ‘tame’ neutrinos

Proton accelerators (muon DIF)

Beta beams

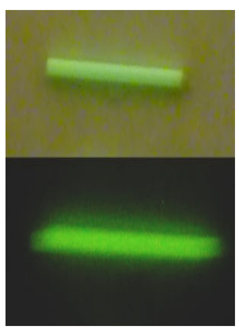


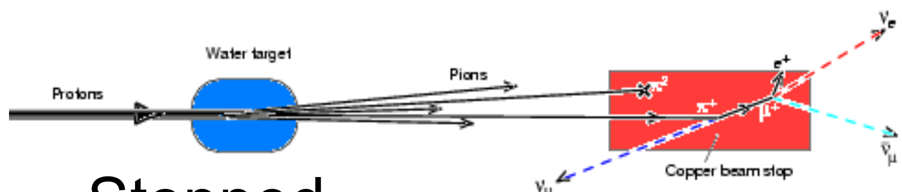
Nuclear reactors



eV keV MeV GeV TeV

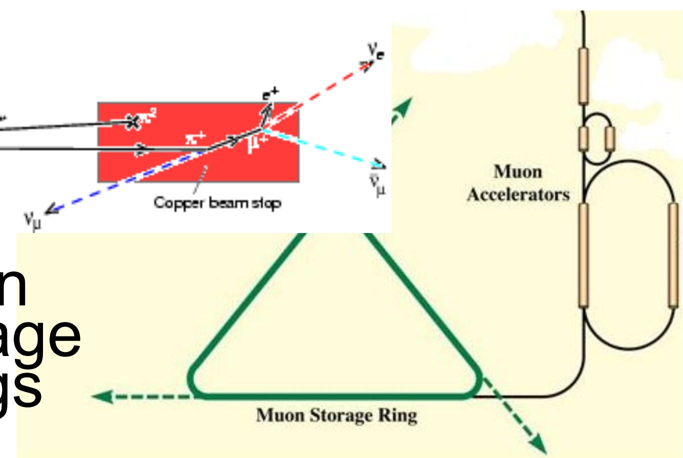
Artificial radioactive sources





Stopped pion sources

Muon storage rings



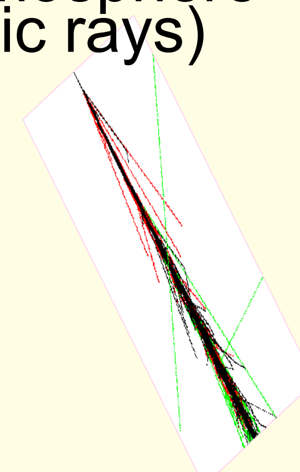
I will highlight some specific areas...
there are many interesting topics I will not cover!

Zoom in to the ~ GeV energy range

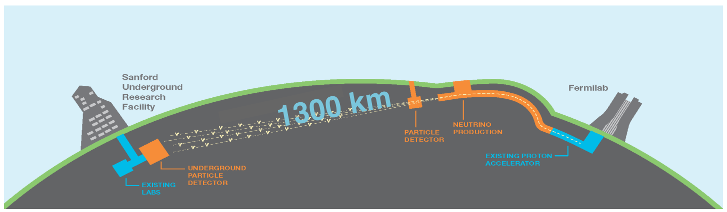
Proton accelerators

eV keV MeV GeV TeV

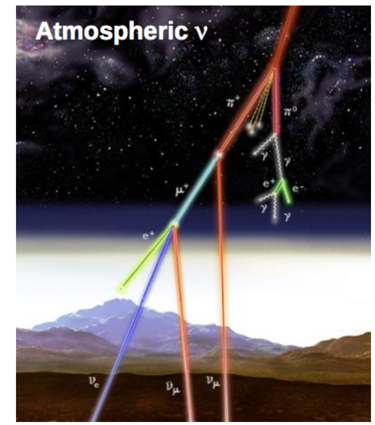
The Atmosphere (cosmic rays)



Physics questions of interest in this energy range:

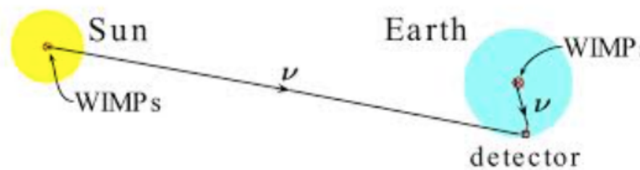


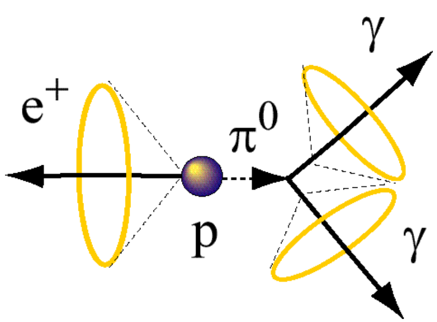
Neutrino oscillations with beam and atmospheric neutrinos



Astrophysical neutrinos/cosmic rays

WIMP dark matter





(Also: nucleon decay... original motivation for large underground detectors!)

Neutrino Oscillations

Current status of 3-flavor oscillations

Flavor states related to mass states by a unitary mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{U}^*_{\mathrm{e}1} & \mathrm{U}^*_{\mathrm{e}2} & \mathrm{U}^*_{\mathrm{e}3} \\ \mathrm{U}^*_{\mu 1} & \mathrm{U}^*_{\mu 2} & \mathrm{U}^*_{\mu 3} \\ \mathrm{U}^*_{\tau 1} & \mathrm{U}^*_{\tau 2} & \mathrm{U}^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

participate in weak interactions

unitary mixing matrix

eigenstates of free Hamiltonian

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

If mixing matrix is not diagonal, get *flavor oscillations* as neutrinos propagate (essentially, interference between mass states)

The three-flavor paradigm

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

Parameterize mixing matrix U as

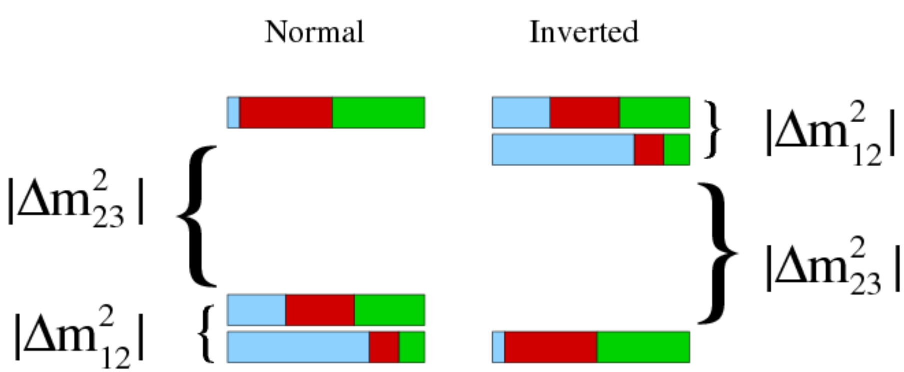
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

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

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

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

signs of the mass differences matter



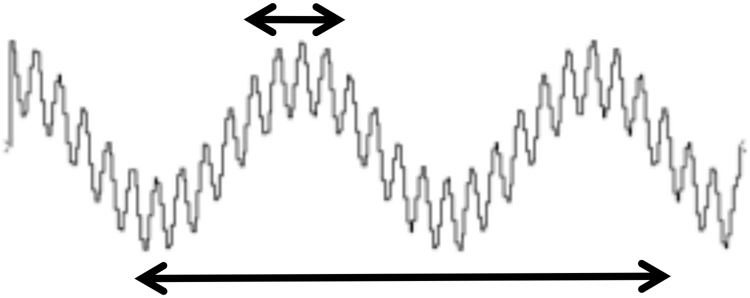
Oscillation probabilities in a 3-flavor context

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

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j \qquad \text{(L in km, E in GeV, m in eV)}$$

$$P(\nu_f \to \nu_g) = \delta_{fg} - 4\sum_{i>j}\Re(U^*_{fi}U_{gi}U_{fj}U^*_{gj})\sin^2(1.27\Delta m^2_{ij}L/E)$$
$$\pm 2\sum_{i>j}\Im(U^*_{fi}U_{gi}U_{fj}U^*_{gj})\sin(2.54\Delta m^2_{ij}L/E)$$

oscillatory behavior in L and E



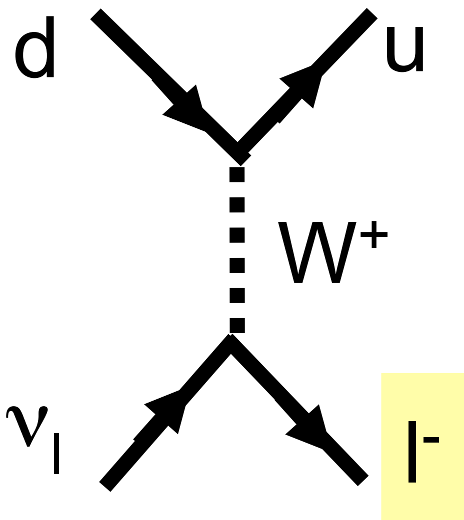
$$|\Delta m^2_{23}| >> |\Delta m^2_{12}|$$ ➔ two frequency scales

For appropriate L/E (and U_{ij}), oscillations “decouple”, and probability can be described by the 2-flavor expression

$$P(\nu_f \to \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

Look for ***flavor change*** and ***spectral distortion*** vs distance

Cleanest channel:
charged-current quasi-elastic



$\nu_l + N \rightarrow l^{\pm} + N'$

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

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

$\nu_\mu + n \rightarrow \mu^- + p$

$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$

Require $E_\nu \sim 110$ MeV

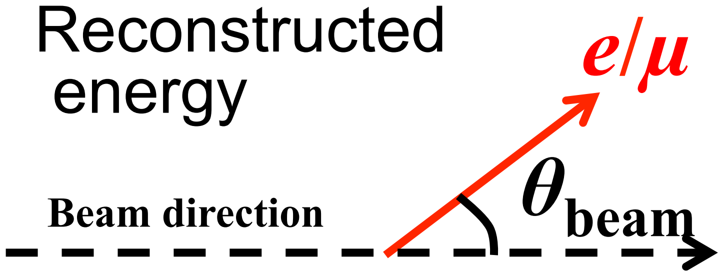
$\nu_\tau + n \rightarrow \tau^- + p$

$\bar{\nu}_\tau + p \rightarrow \tau^+ + n$

Require $E_\nu \sim 3.5$ GeV

Tag neutrino flavor by flavor of outgoing lepton

Reconstructed energy

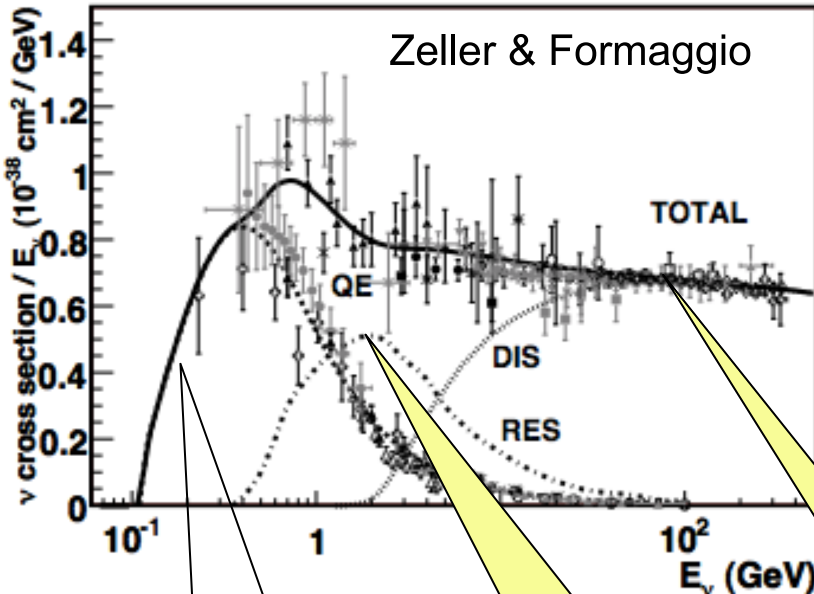


$$E_\nu = \frac{m_p^2 - m_{n'}^2 - m_\ell^2 + 2m_{n'}^2 E_\ell}{2(m_{n'} - E_\ell + p_\ell \cos\theta_{\text{beam}})}$$

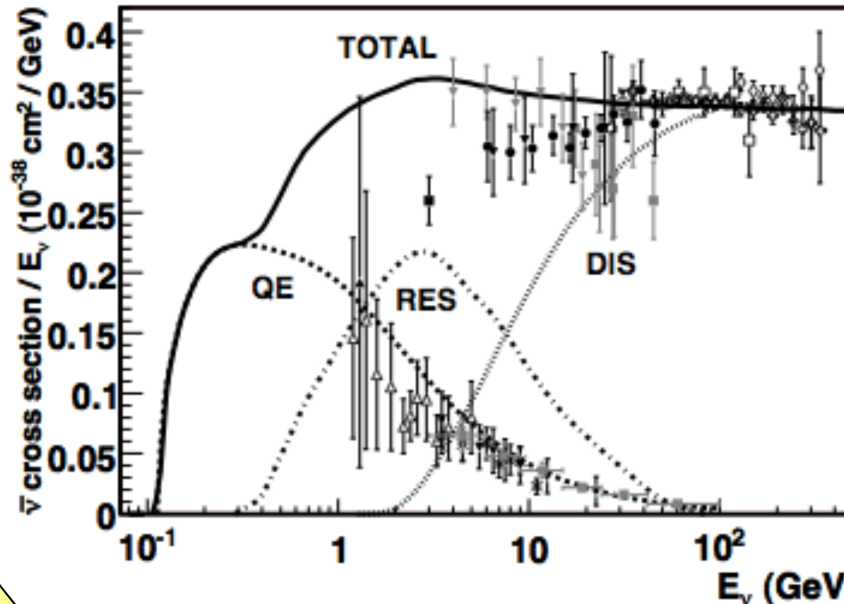
$\ell = e^\pm, \mu^\pm \qquad m_{n'} = m_n - E_b$

But there can be more complicated final states....

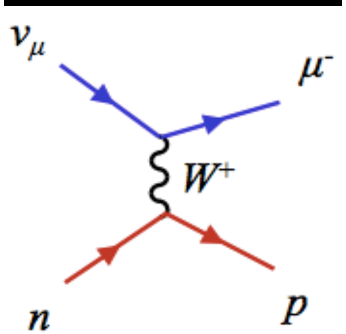
Neutrinos



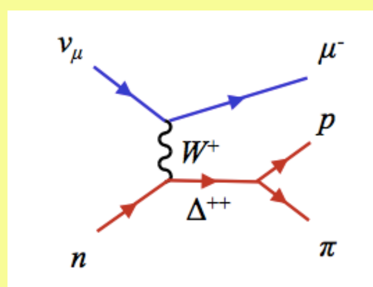
Antineutrinos



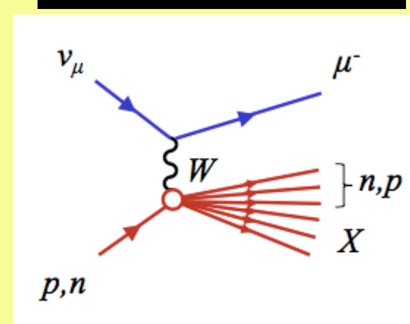
quasi-elastic



resonant



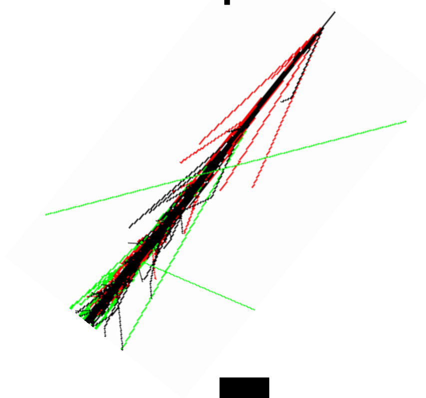
deep inelastic scattering



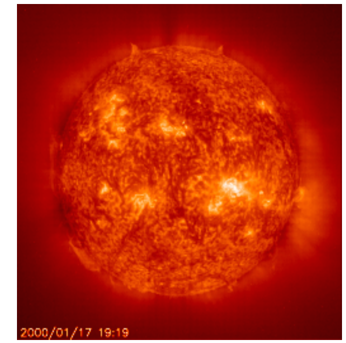
pions, ejected nucleons, ...

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



solar



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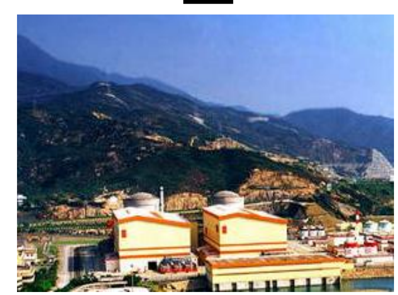
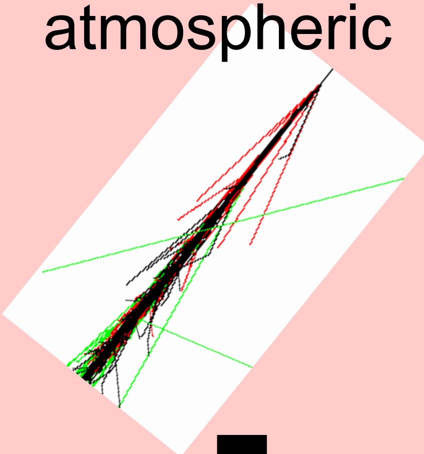
beams



reactor

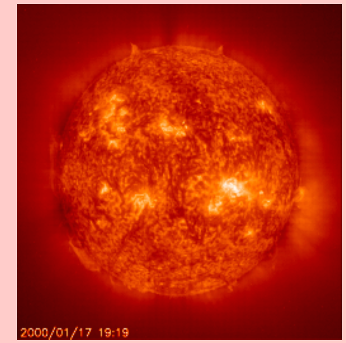
We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



signal with
“wild” neutrinos...

solar



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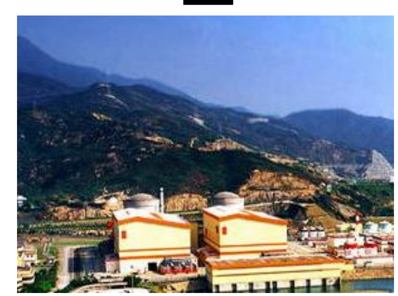
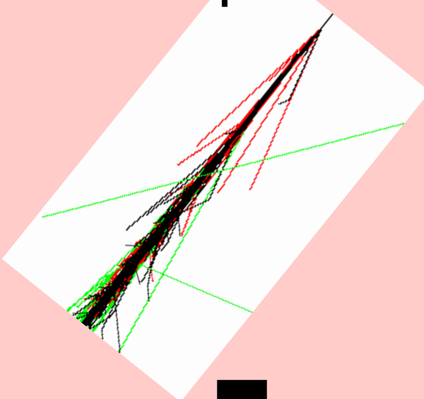
beams



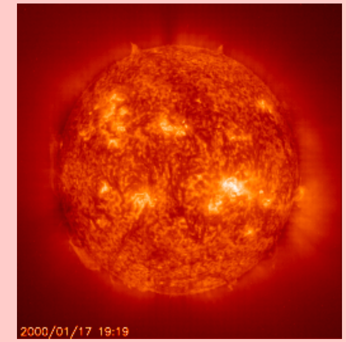
reactor

We now have clean flavor-transition signals in two 2-flavor sectors

atmospheric



solar



signal with
“wild” neutrinos...

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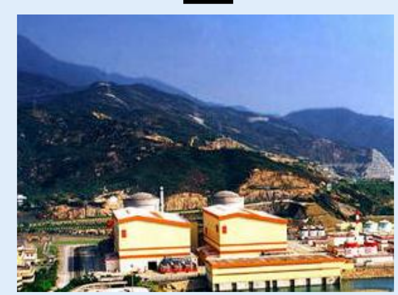
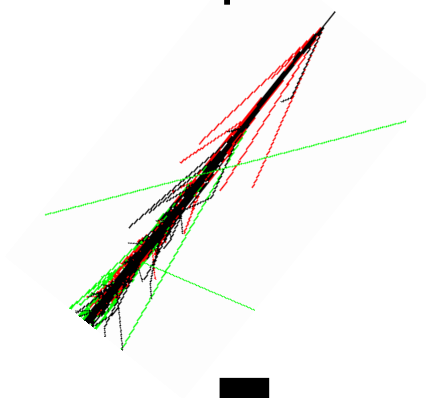
confirmed with
“tame” ones...

beams



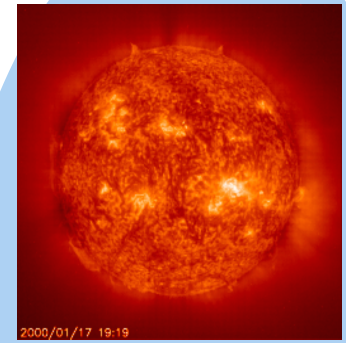
reactor

atmospheric



solar

SK, SNO,
Ga, Cl,
Borexino



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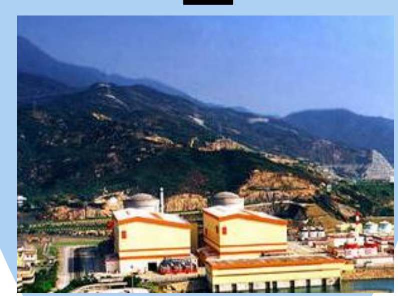
$$

beams

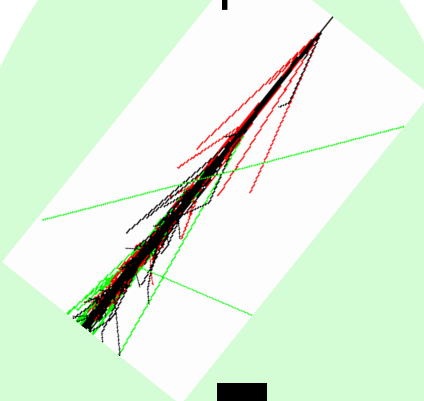
"Solar" sector: solar ν oscillations confirmed with reactors

KamLAND



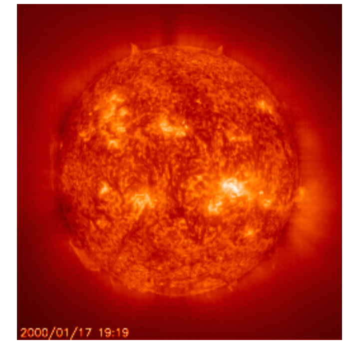
reactor

atmospheric



SK, Soudan,
MACRO,MINOS

solar



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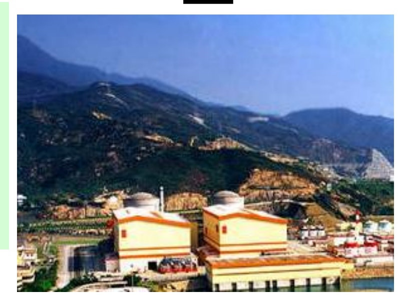
beams

K2K, MINOS,
T2K, MINOS+,
OPERA,NOvA

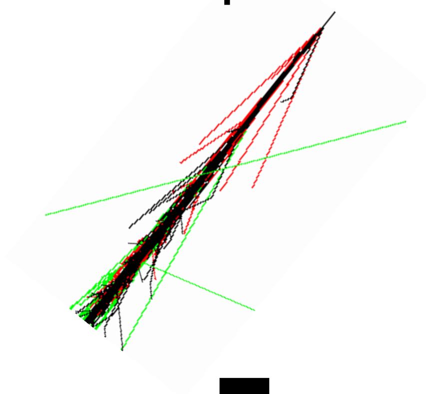
"Atmospheric" sector:
atmnu osc confirmed
with beams



reactor

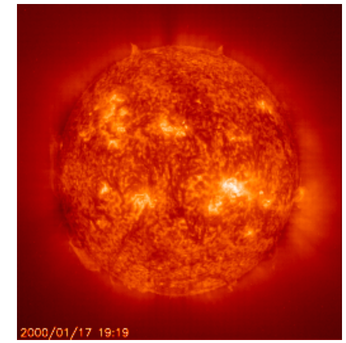
The mixing angle θ_{13}: new information from beams and burns!

atmospheric



θ_{13}, the "twist in the middle"

solar



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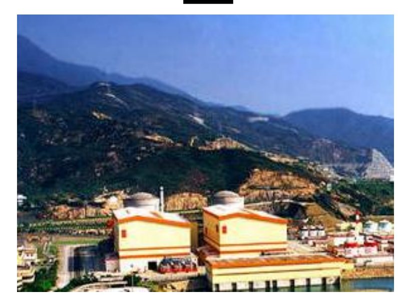
Before 2011, known to be small

beams

T2K, NOvA

Double CHOOZ, RENO, Daya Bay



reactor

The three-flavor picture fits the data well

Global three-flavor fits to all data

	3σ range	3σ knowledge
$\sin^2\theta_{12}$	$0.273 \to 0.349$	
$\theta_{12}/^\circ$	$31.52 \to 36.18$	~14%
$\sin^2\theta_{23}$	$0.390 \to 0.639$	
$\theta_{23}/^\circ$	$38.6 \to 53.1$	~33%
$\sin^2\theta_{13}$	$0.0187 \to 0.0250$	
$\theta_{13}/^\circ$	$7.86 \to 9.11$	~15%
$\delta_{CP}/^\circ$	$0 \to 360$	~no info
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.02 \to 8.08$	~14%
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$\begin{bmatrix} +2.351 \to +2.618 \\ -2.588 \to -2.348 \end{bmatrix}$	~12%

NuFIT 2.1 (2016); JHEP 11 (2014) 052

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

	3σ range
$\sin^2\theta_{12}$	$0.273 \to 0.349$
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Is θ_{23} non-negligibly greater or smaller than 45 deg?

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

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

sign of Δm^2 unknown (ordering of masses)

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

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$\delta_{CP}/^\circ$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.02 \to 8.08$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$\begin{bmatrix} +2.351 \to +2.618 \\ -2.588 \to -2.348 \end{bmatrix}$

$\sin^2\theta_{23}$ → Is θ_{23} non-negligibly greater or smaller than 45 deg?

δ_{CP} → almost unknown

$\Delta m^2_{3\ell}$ → sign of Δm^2 unknown (ordering of masses)

Going after remaining 3-flavor parameters...

There are a number of promising methods for mass ordering, but one is ***guaranteed*** with sufficient exposure at long baseline; also good for CP, octant

Long-baseline beams

Long-baseline approach for going after MO and CP

Measure transition probabilities for

$\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$

through matter

$$P_{\nu_e\nu_\mu(\bar{\nu}_e\bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_\mp}\right)^2 \sin^2\left(\frac{\tilde{B}_\mp L}{2}\right)$$
$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{A L}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{A}\,\frac{\Delta_{13}}{\tilde{B}_\mp}\,\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_\mp L}{2}\right)\cos\left(\pm\delta - \frac{\Delta_{13} L}{2}\right)$$

Change of sign for antineutrinos

A. Cervera et al., Nucl. Phys. B 579 (2000)

$$\tilde{J} \equiv c_{13}\,\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}$$

$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_\nu},\ \tilde{B}_\mp \equiv |A \mp \Delta_{13}|,\ A = \sqrt{2}G_F N_e$$

$\theta_{13}, \Delta_{12}L, \Delta_{12}/\Delta_{13}$ are small

Different probabilities as a function of L& E for neutrinos and antineutrinos, depending on:

- CP δ
- matter density (Earth has electrons, not positrons)

What do you want in a detector for a ~GeV neutrino oscillation experiment?

✔ **neutrino flavor ID...** usually "leading lepton"

(can be tricky for non-CCQE... want all the final state particles)

✔ **resolution on L/E**

$$P(\nu_f \rightarrow \nu_g) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

For beam ν's, you know L, so you need **energy resolution** ✔

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

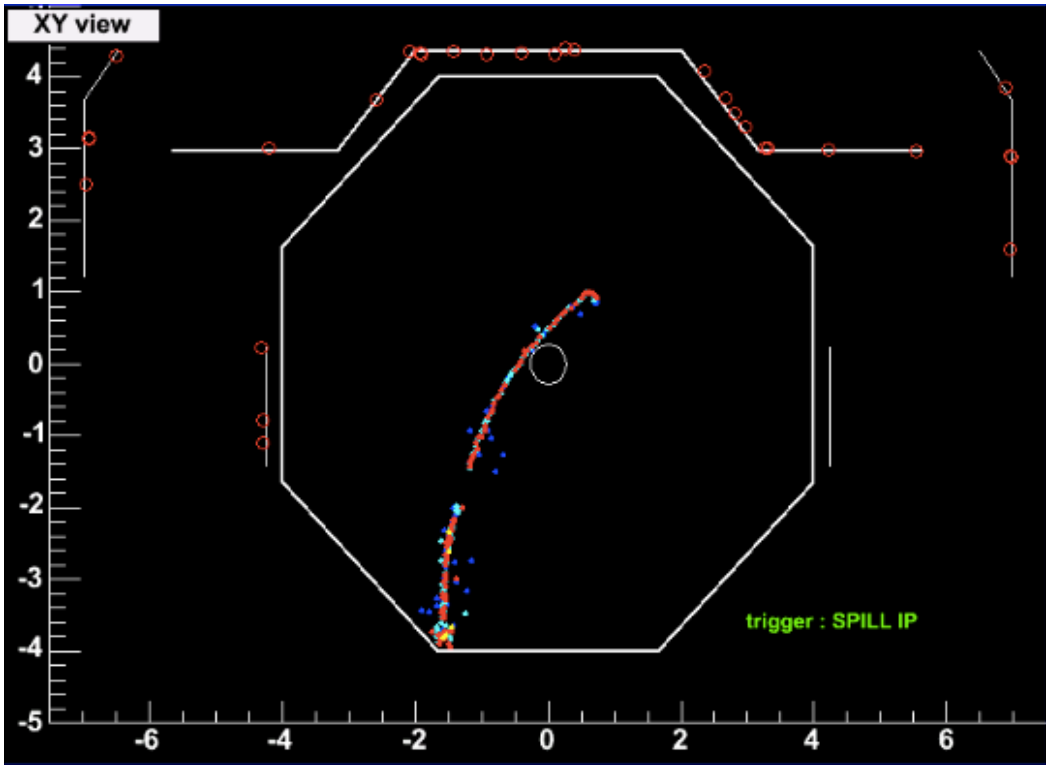
For atmν's, L must be inferred from direction

for CCQE, can improve with angular information in beam case (trickier if there's more debris)

} **angular resolution** ✔

✔ and of course, lots of events and low bg

✔ **Magnetic field** is nice for lepton sign selection, to tag **neutrino vs antineutrino**



$$\nu_\mu + n \rightarrow \mu^- + p$$

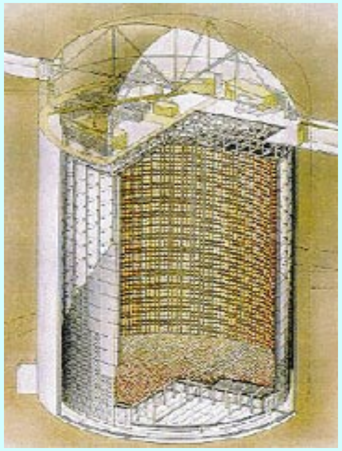
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$

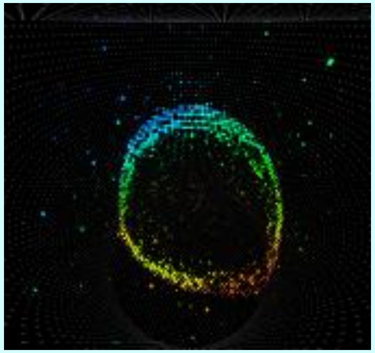
High volume magnetic fields hard, though... expensive, interfere with sensors, ...

Good final state reconstruction can also help tag nu vs nubar (protons or neutrons? muons from hadron decays?)

Large (multi-kton) detector technologies

Water Cherenkov

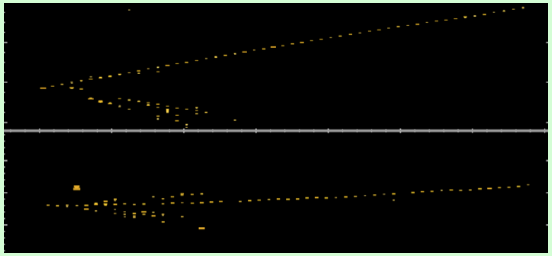




Cheap material, proven at very large scale

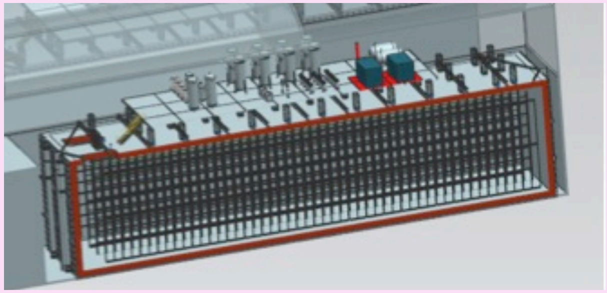
Trackers

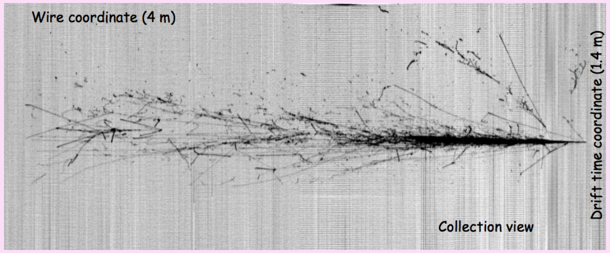
(a diverse category)



Good particle reconstruction

Liquid Argon

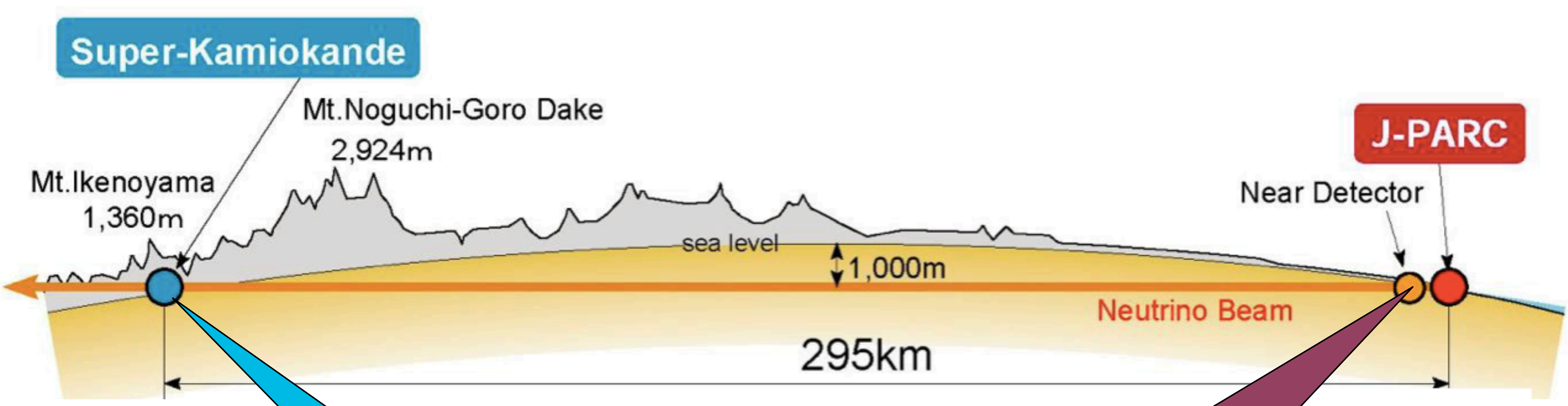




Excellent particle reconstruction

Comment on neutrino oscillation experiments:

Since you're looking for flavor *change*,
usually have **near and far** detectors*...



to evaluate whether neutrinos have oscillated here

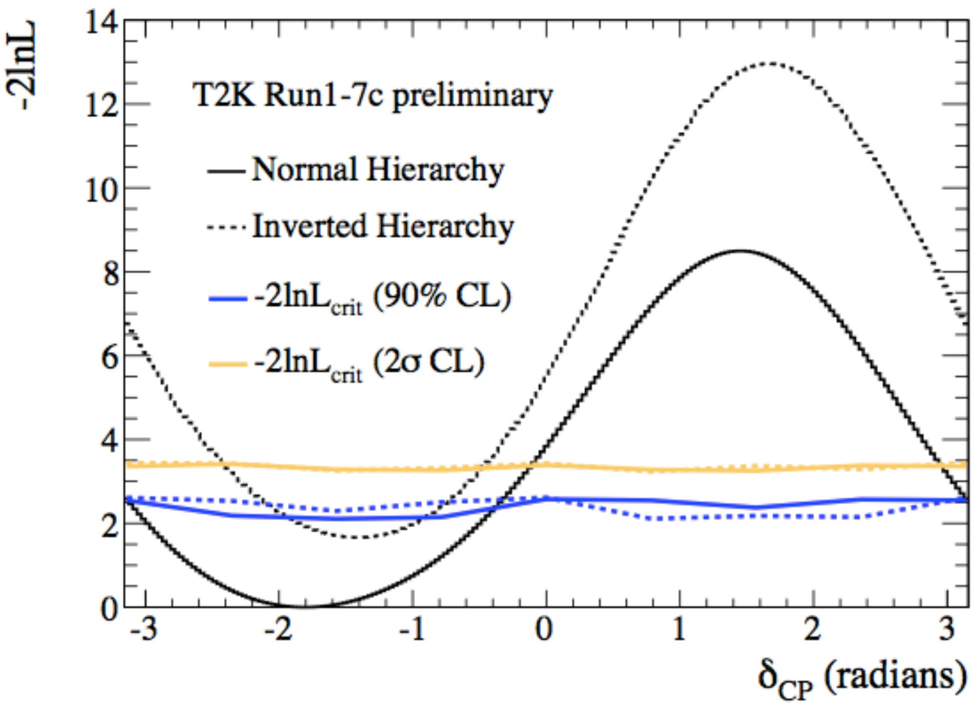
measure spectrum and flavor content here

Cancel systematics:
- flux (although note: spectra may be different)
- xscn and detector effects (for similar detectors)

*Atmospheric ν detectors are their own near and far detectors!

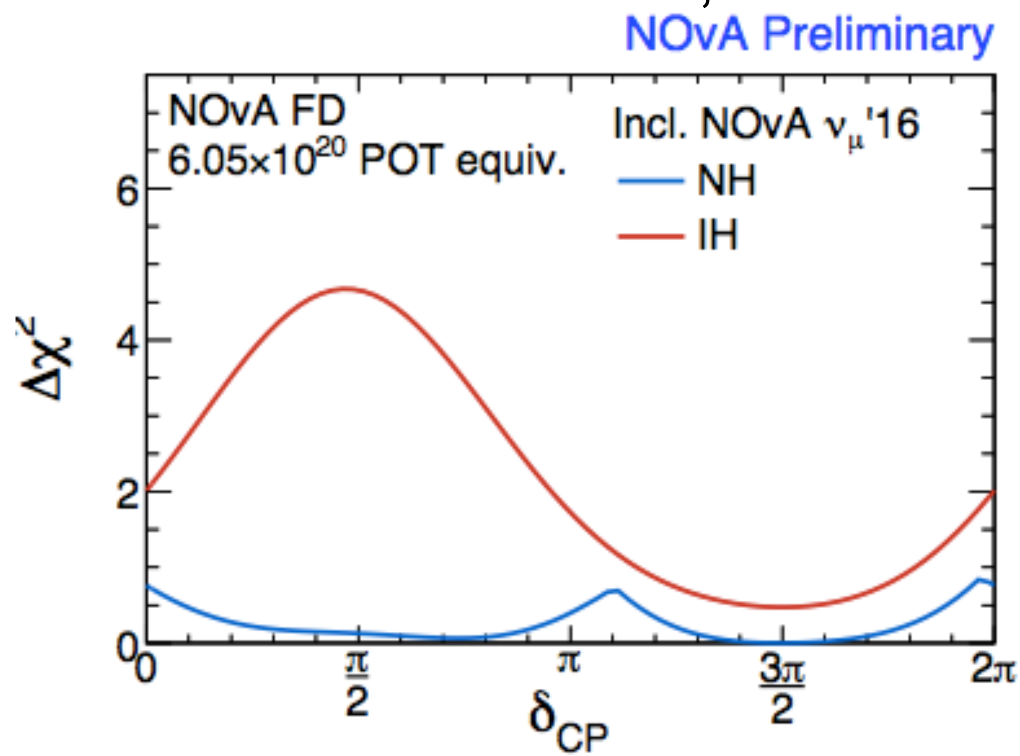
CP & MO hints already from beam experiments (+ atmnus)

T2K
J-PARC to SK, 295 km



joint fit to nue appearance,
numu disappearance,
neutrinos and antineutrinos+ reactor

NOvA
FNAL to Ash River, 810 km



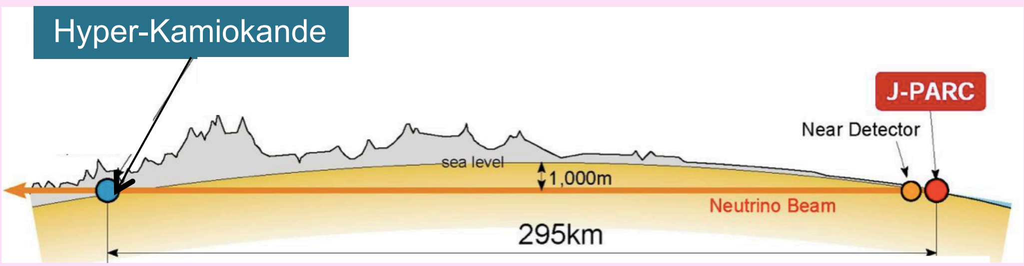
P. Vahle, Neutrino 2016

Some regions of δ_{CP} **weakly** (~90%) disfavored,
δ_{CP} **~** $-\pi/2$ and normal ordering **weakly** favored

Will need new experiments for MO/CP/octant,
precision measurements of all the parameters (and more...)

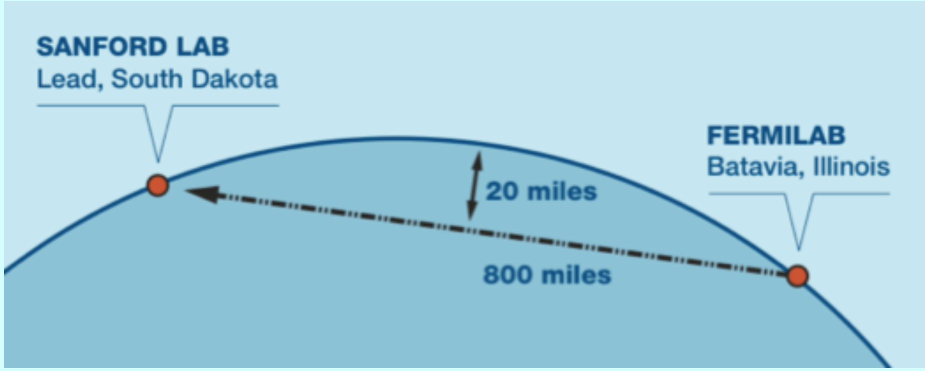
The Next Generation Long-Baseline Experiments

Hyper-Kamiokande



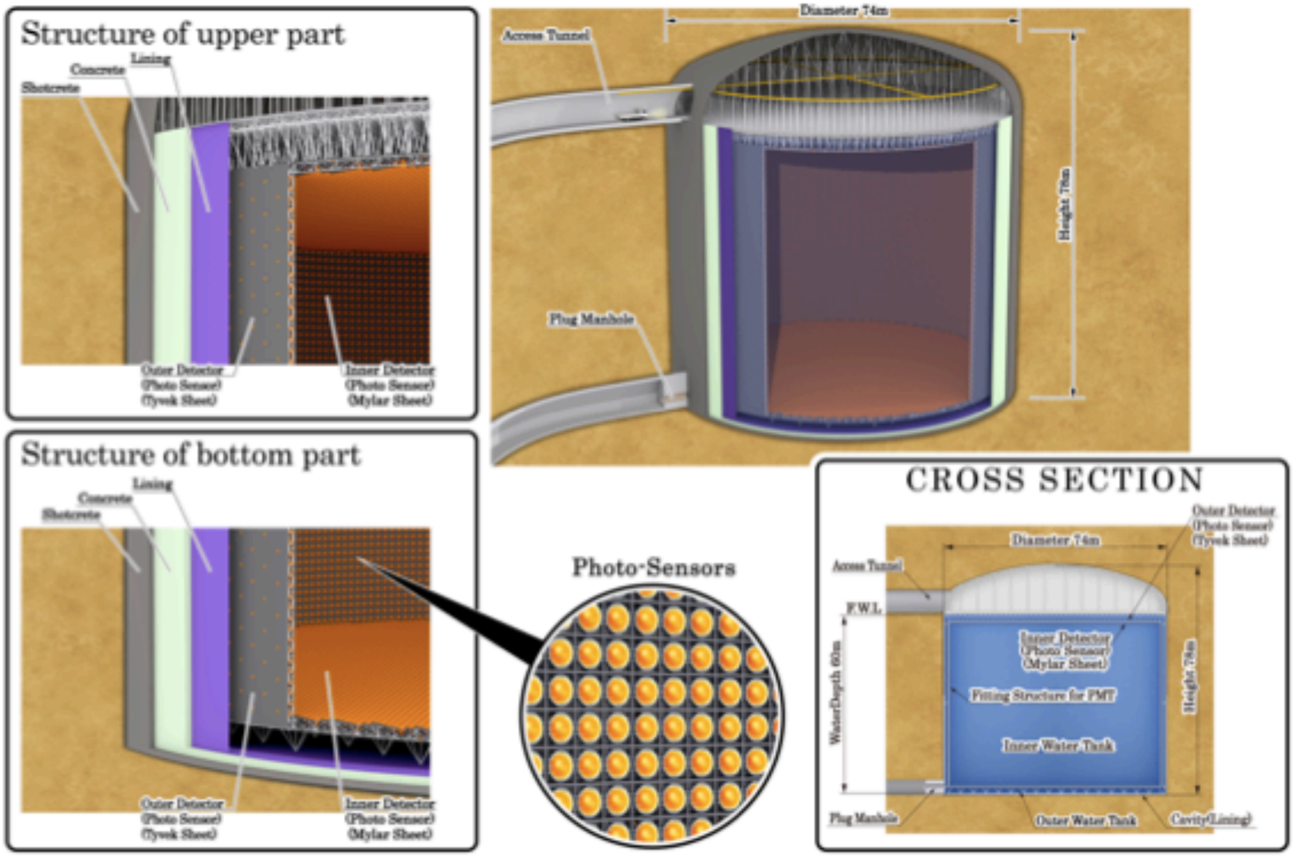
- 295-km baseline
- staged 2-module, 374-kton fid. **water Cherenkov detectors**
- upgraded J-PARC beam to 750 kW ➔1.4 MeV
- First module: 40% PMT coverage w/double efficiency

LBNF/DUNE



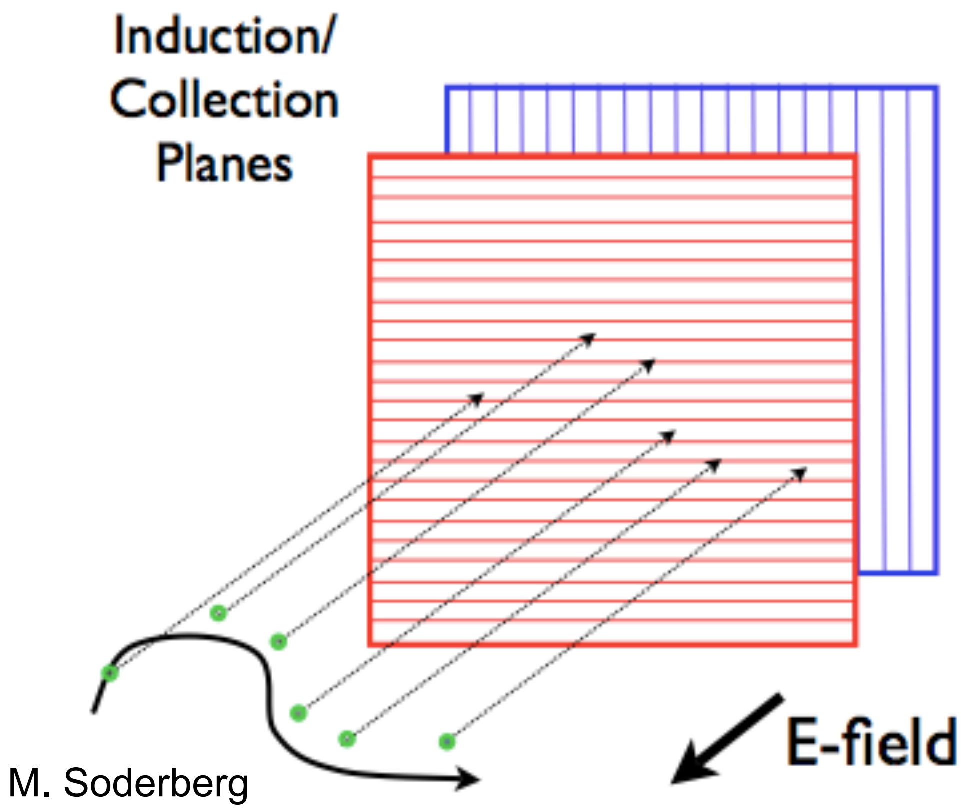
- 1300-km baseline
- 4 10-kton **LArTPC** modules
- 4850-ft depth
- New 1.2 MW beam (upgradeable to 2.3 MW)

Hyper-Kamiokande in Japan



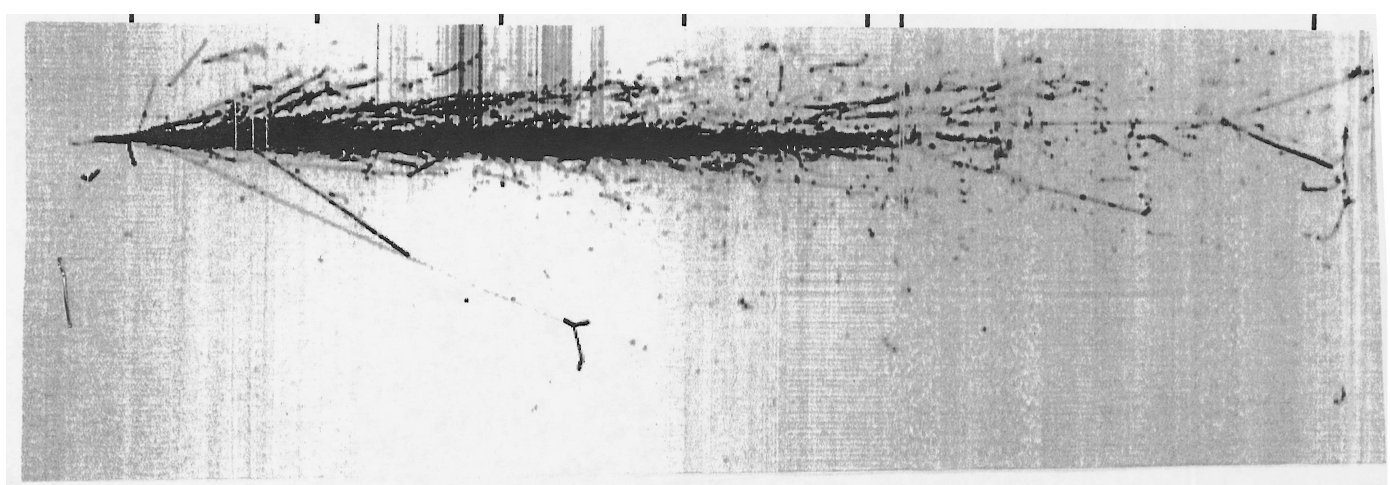
- Generally **well-understood** technology
  (lots of experience from SK)
- New: **Gd-loading** for neutron tagging for SK
  (option for HK)
- Photosensors: new **HQE PMTs**, other R&D underway

Liquid argon time projection chambers

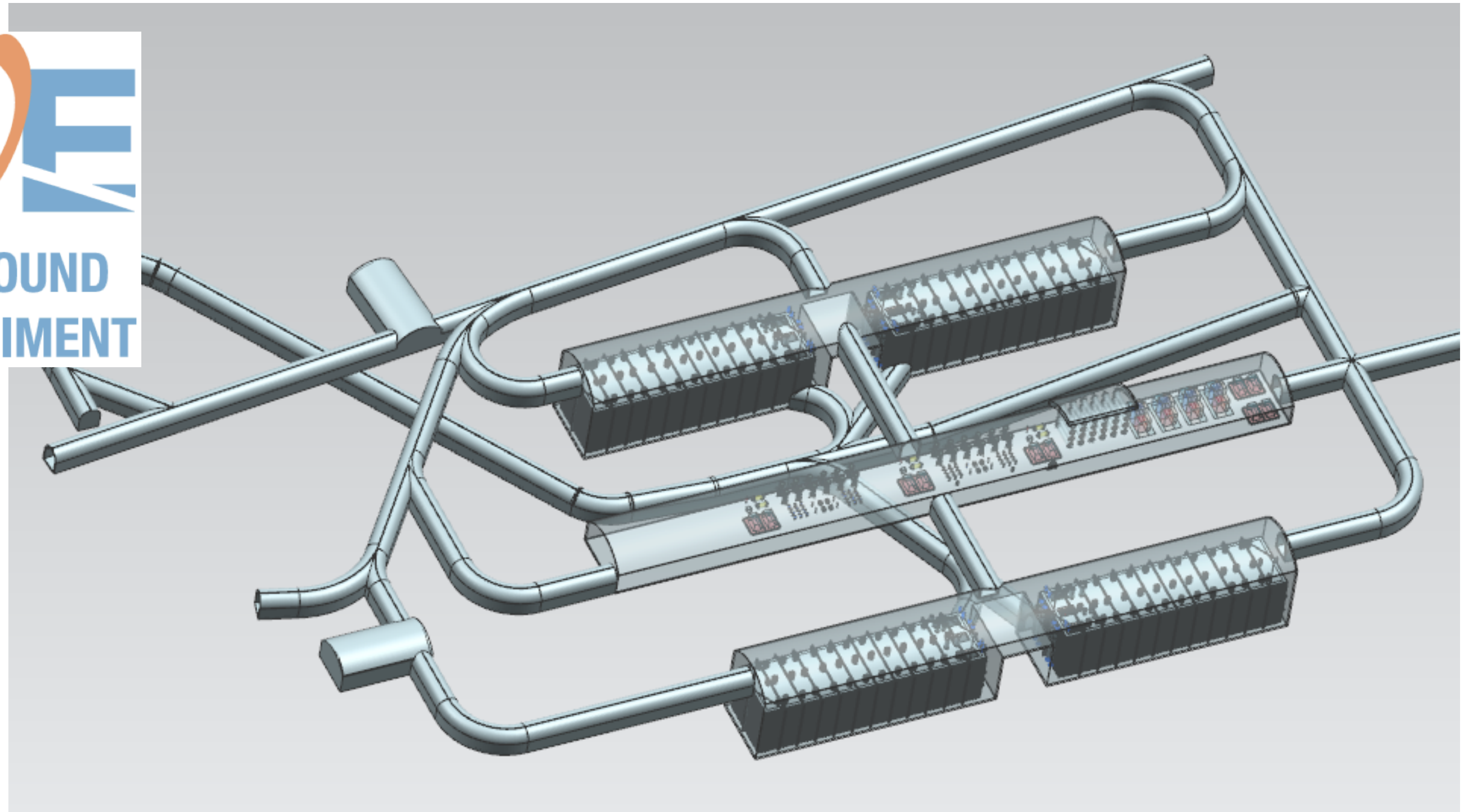


Ionization charge
drifted and collected;
3D track using time info

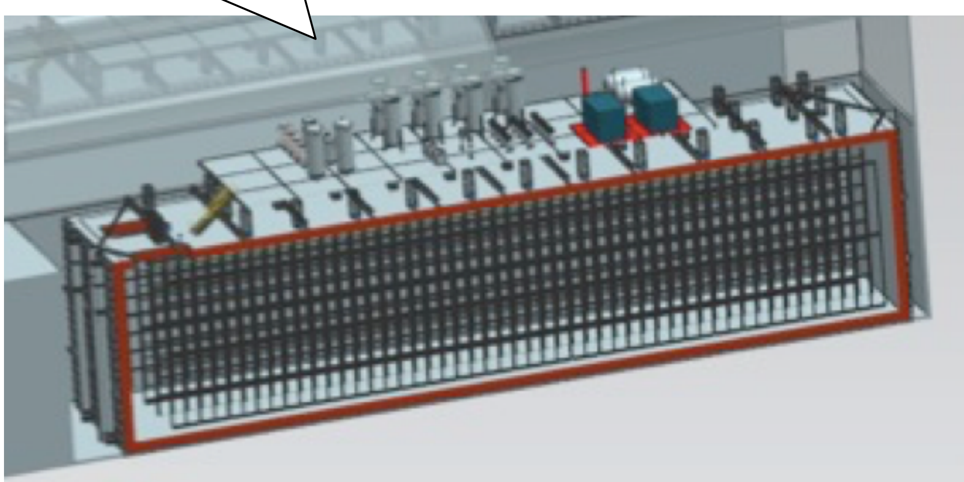
- **very high quality particle reconstruction** possible
- scintillation light (photosensors) for absolute time
- require very high purity, cryogenic liquid



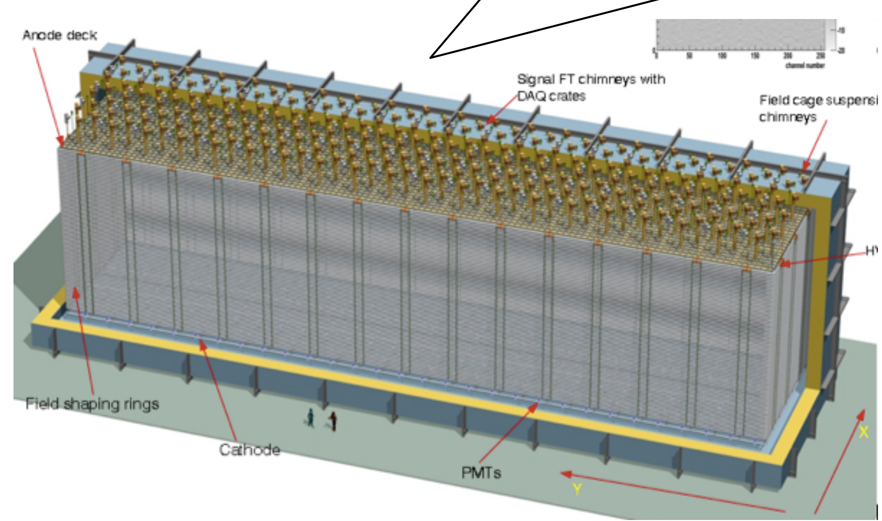
DEEP UNDERGROUND NEUTRINO EXPERIMENT



First module will be based on **single-phase** modular drift cell design



Dual phase design w/ single volume vertical drift, gas phase amplification, is candidate for subsequent modules

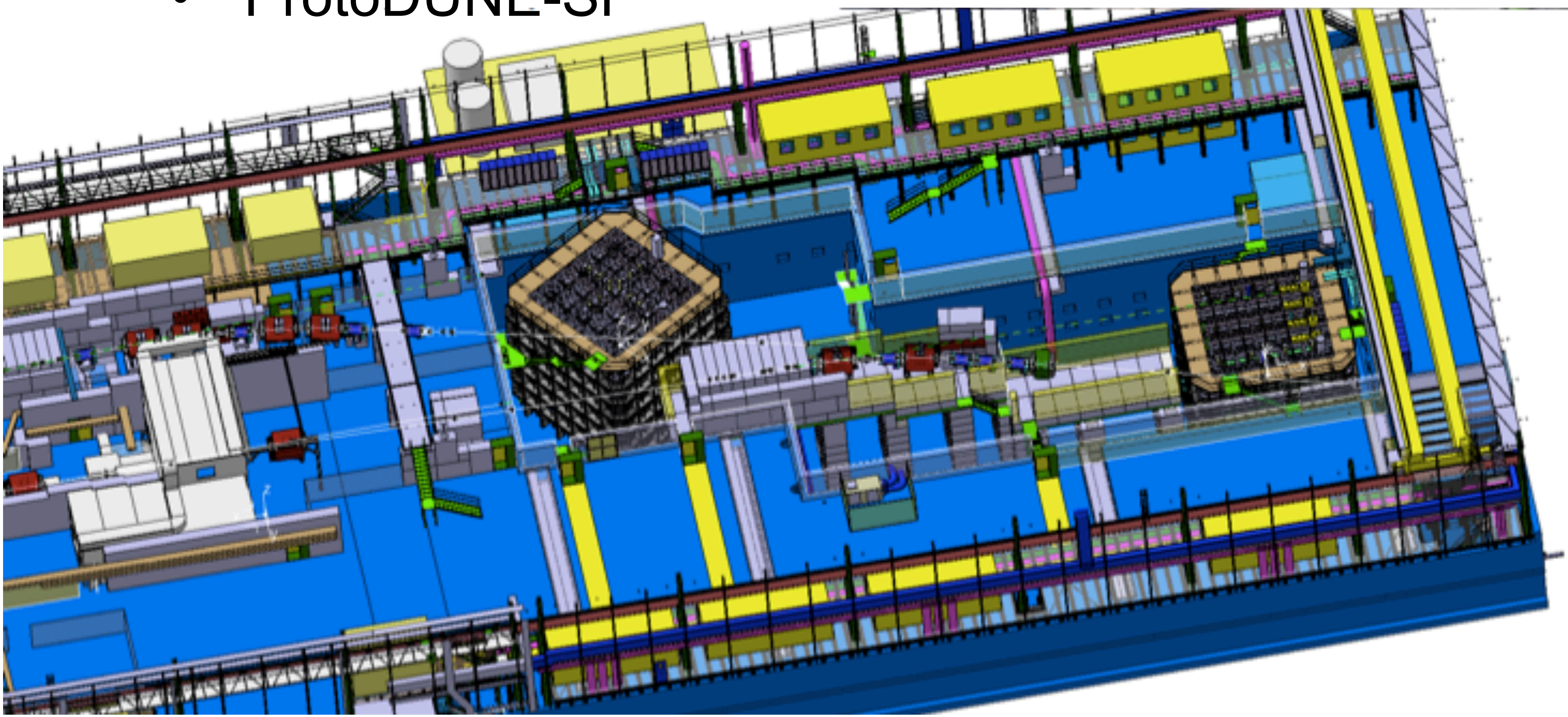


Many (interesting) R&D challenges...

HV, purity, photons, electronics, DAQ, backgrounds, reco, ...

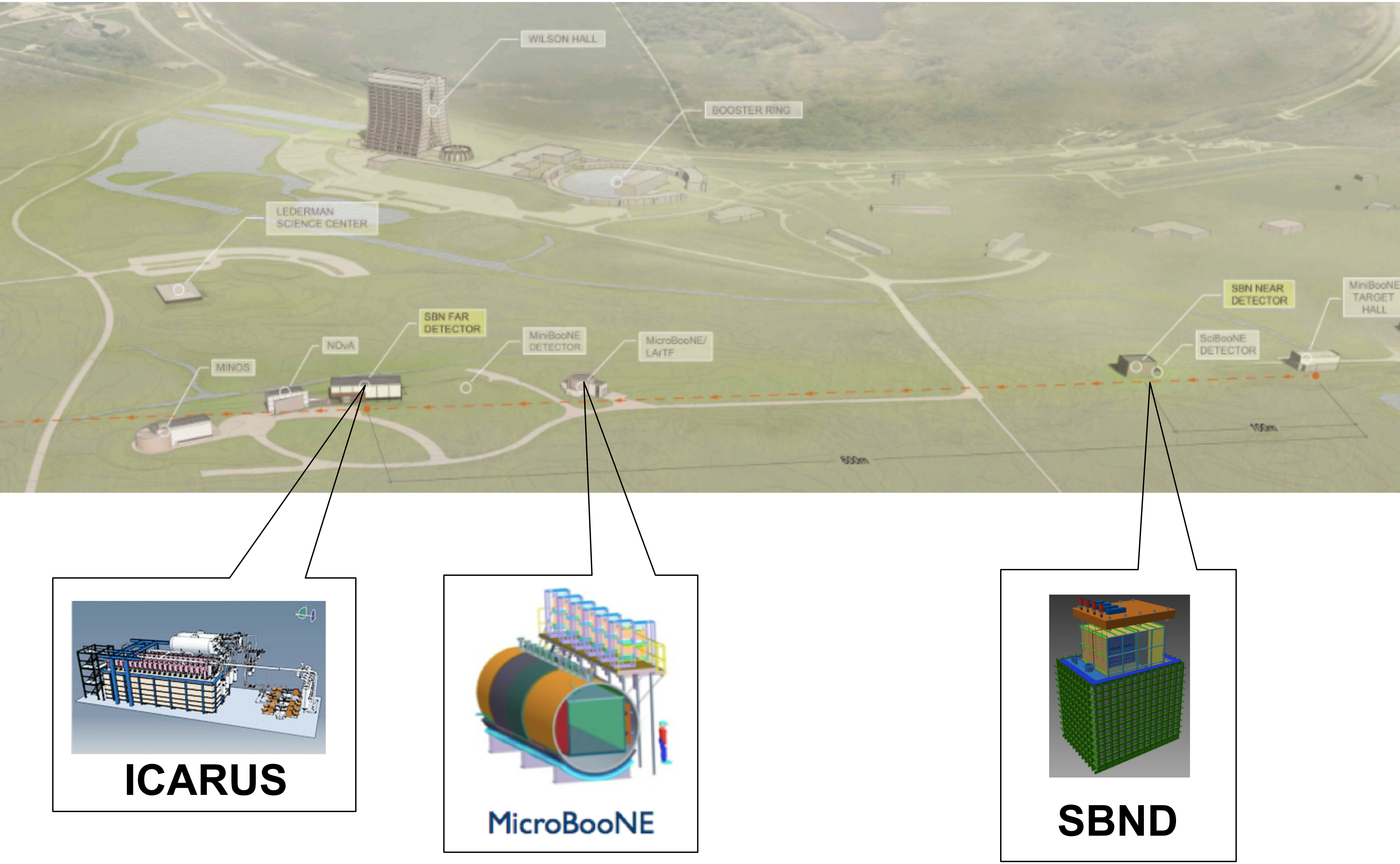
ProtoDUNEs at CERN

- 0.5-5 GeV/c charged-particle test beams
- WA105 ProtoDUNE-DP
- ProtoDUNE-SP

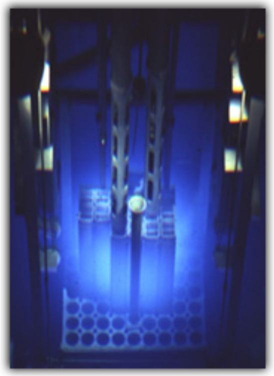


FNAL Short Baseline Neutrino program

- sterile neutrino oscillation searches, ν cross sections
- providing more LArTPC experience

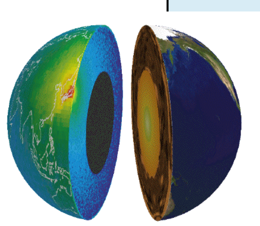


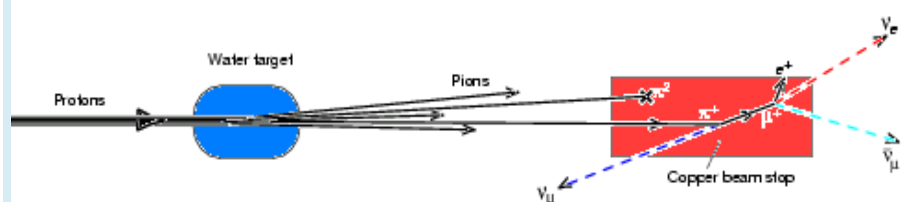
The ~1-100 MeV energy range

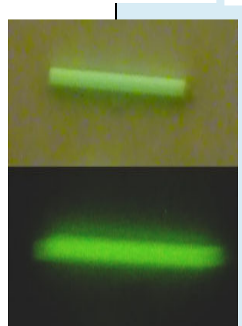


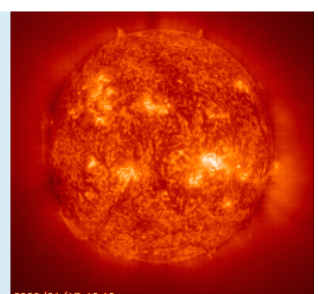
A lot of physics and astrophysics here... (solar, burst and diffuse supernova, reactor, low-energy accelerator ν's, neutrinoless ββdk,...)

eV keV MeV GeV TeV



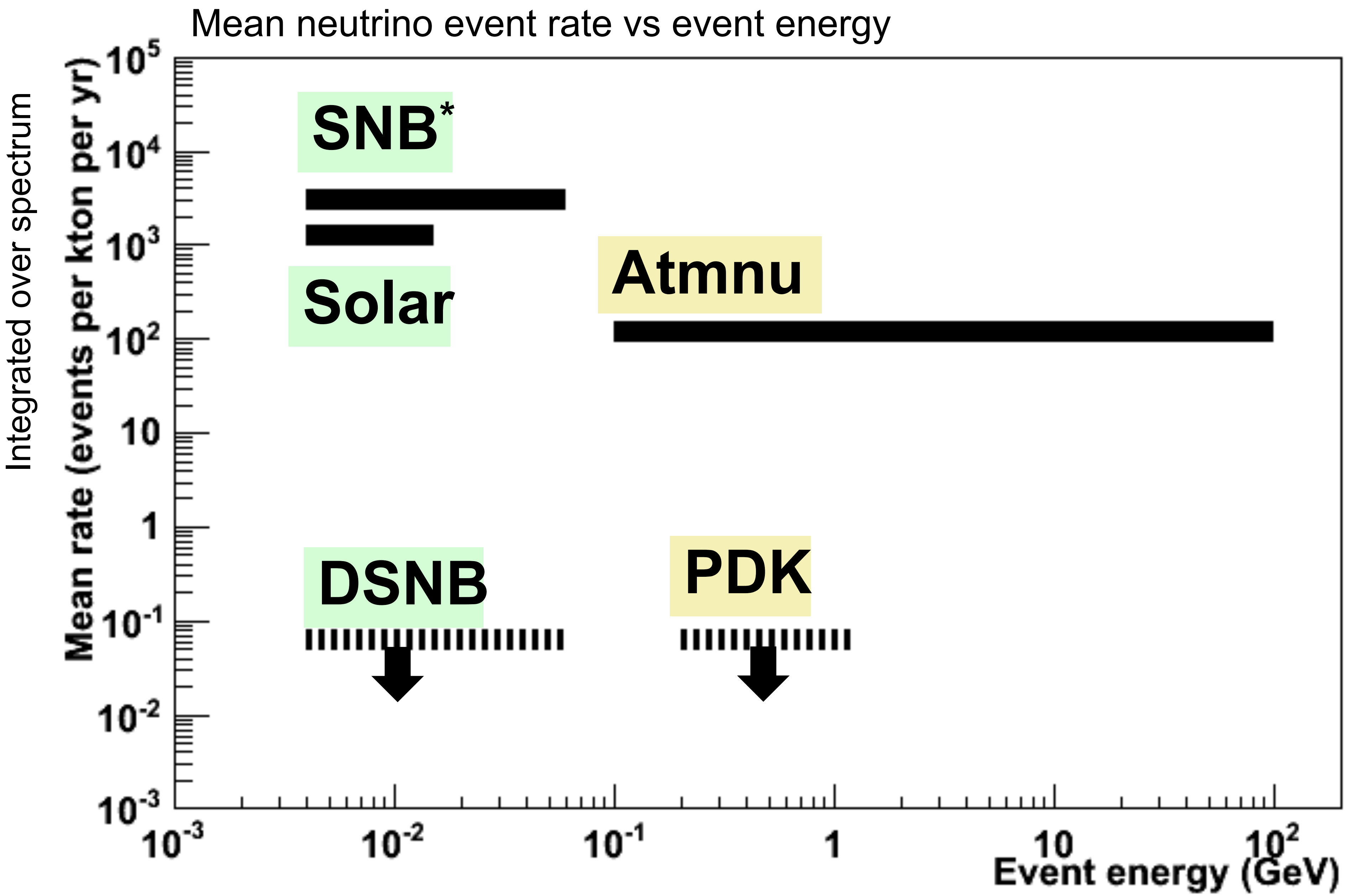






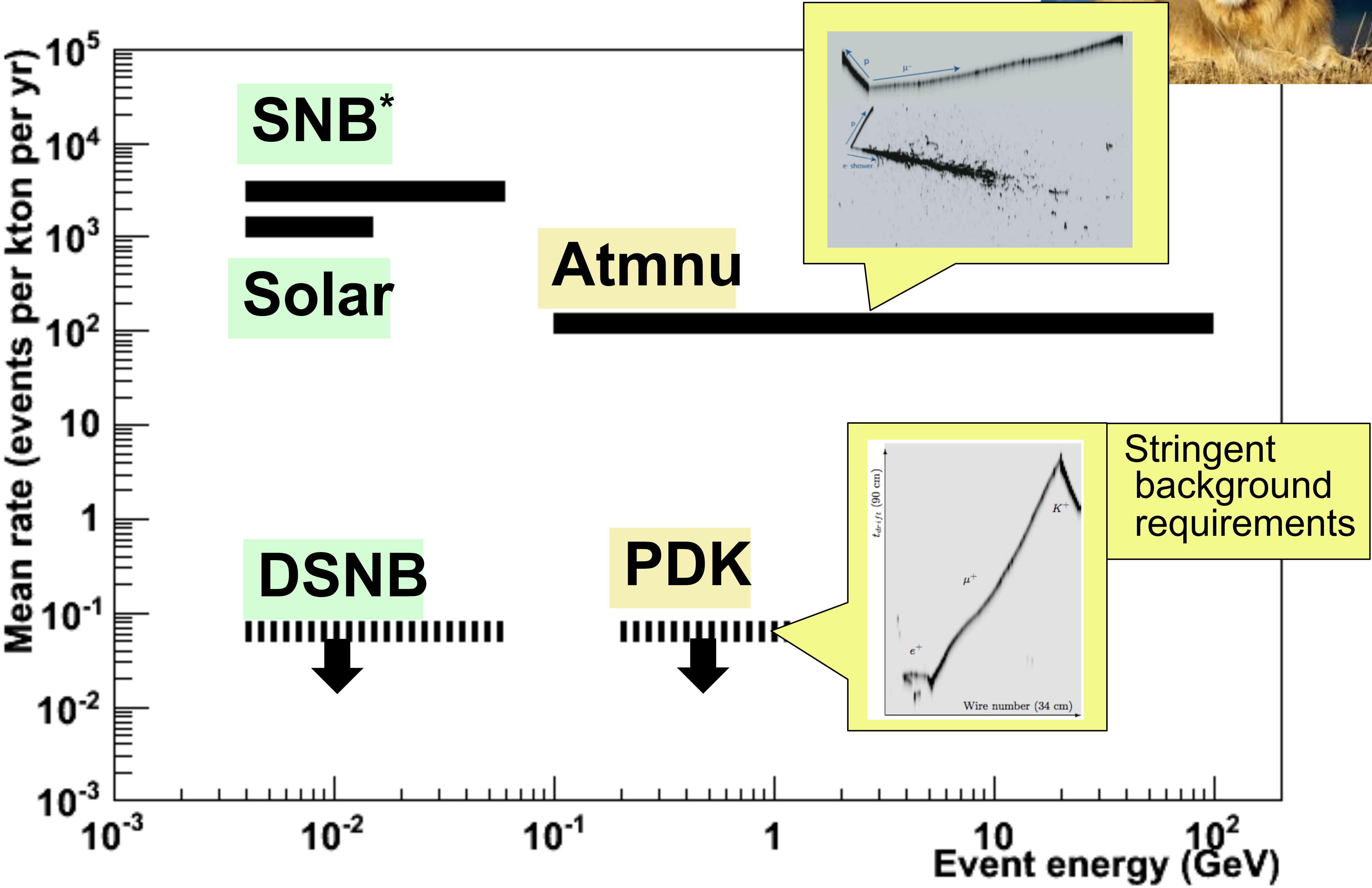
...detection issues are somewhat different...

“Wild” Neutrinos



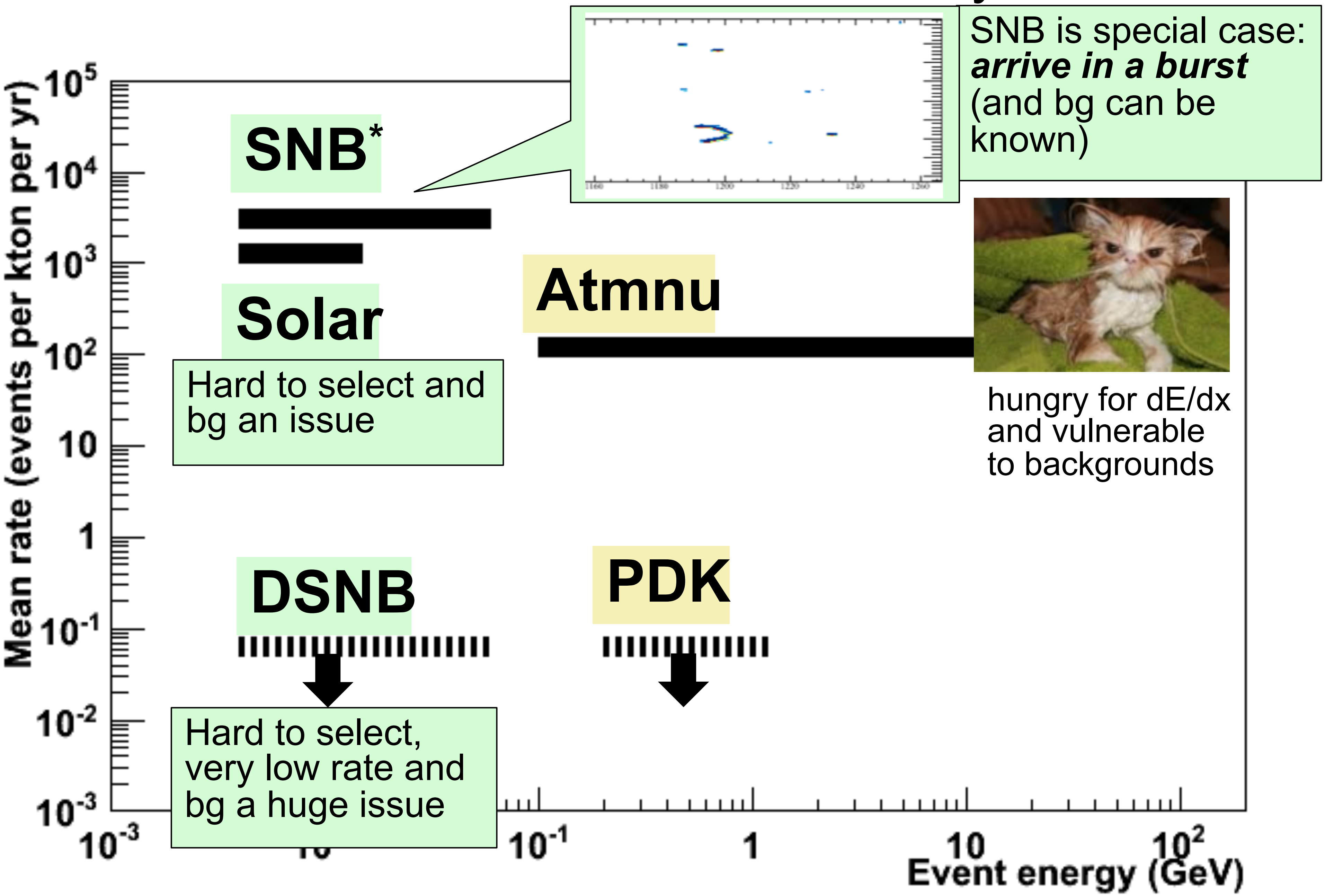
* @1 kpc, 30 s (not steady-state rate)

GeV-scale events: handsome and distinctive



* @1 kpc, 30 s

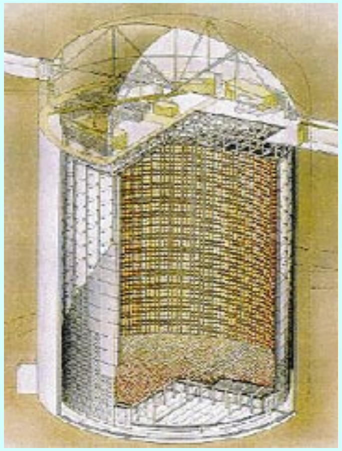
Few tens of MeV-scale events: crummy little stubs

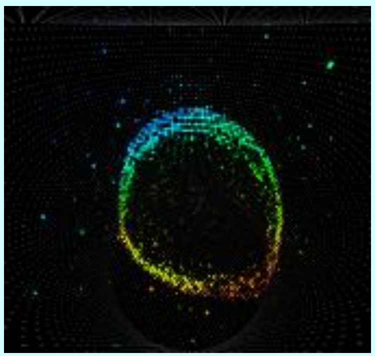


* @1 kpc, 30 s

Large (multi-kton) detector for low energy neutrinos?

Water Cherenkov

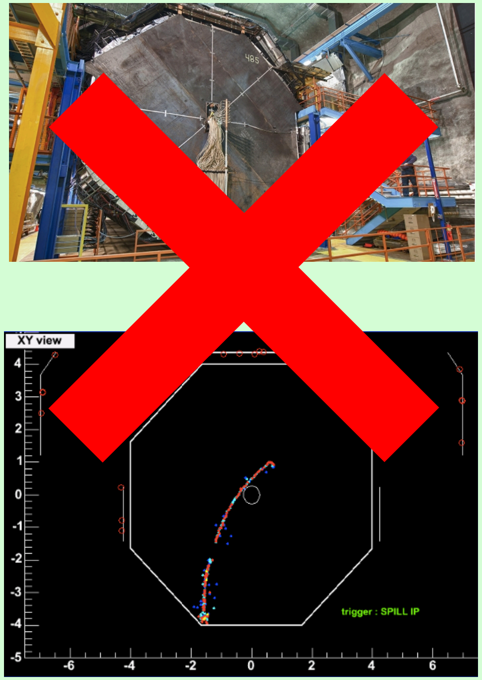




Cheap material, proven at very large scale

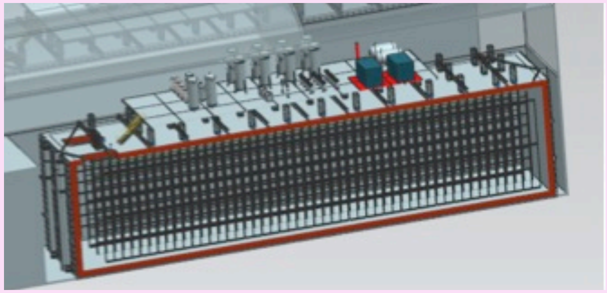
Trackers

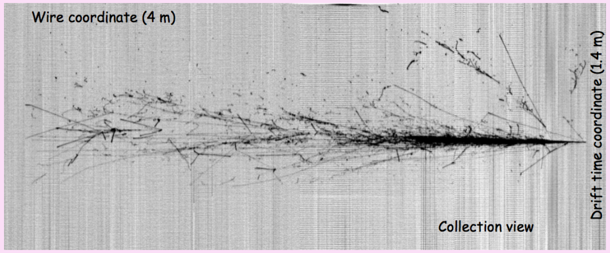
(a diverse category)



Not good for low energies (with some exceptions)

Liquid Argon

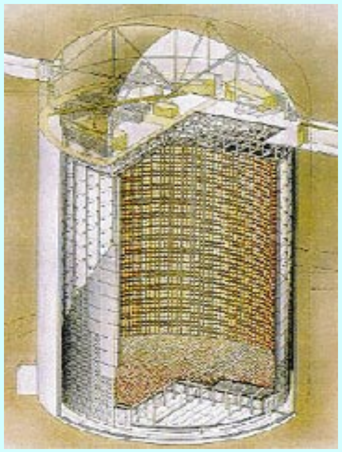


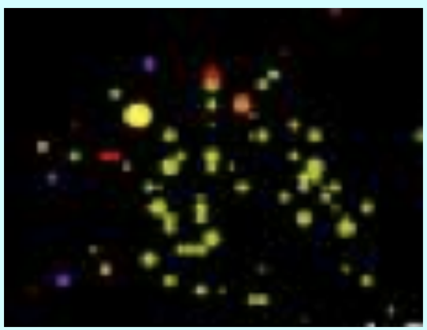


Excellent particle reconstruction

Large (multi-kton) detector technologies for low energies

Water Cherenkov

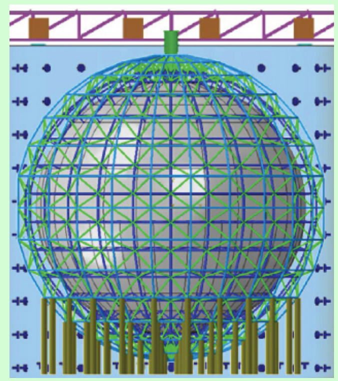


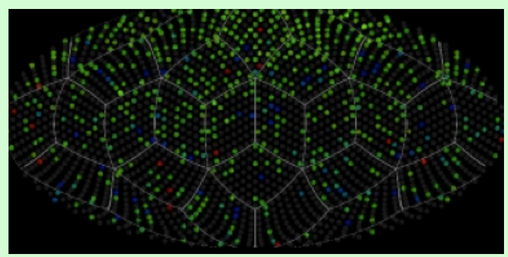


Cheap material, proven at very large scale

Liquid scintillator

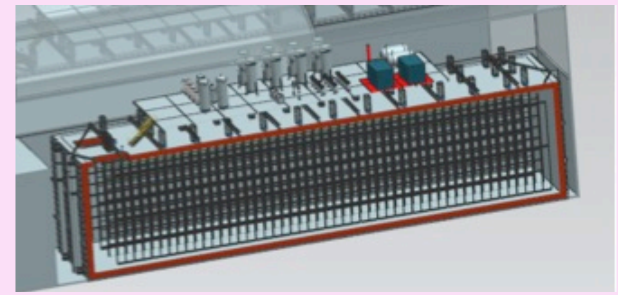
(and water-based LS)

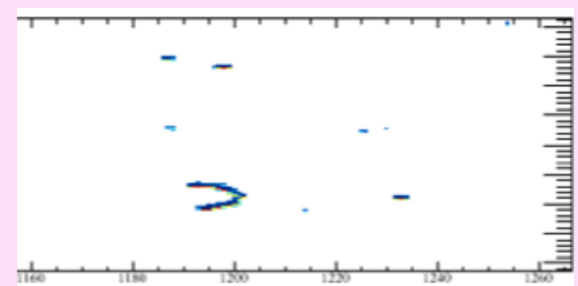




Low threshold, good energy resolution

Liquid Argon



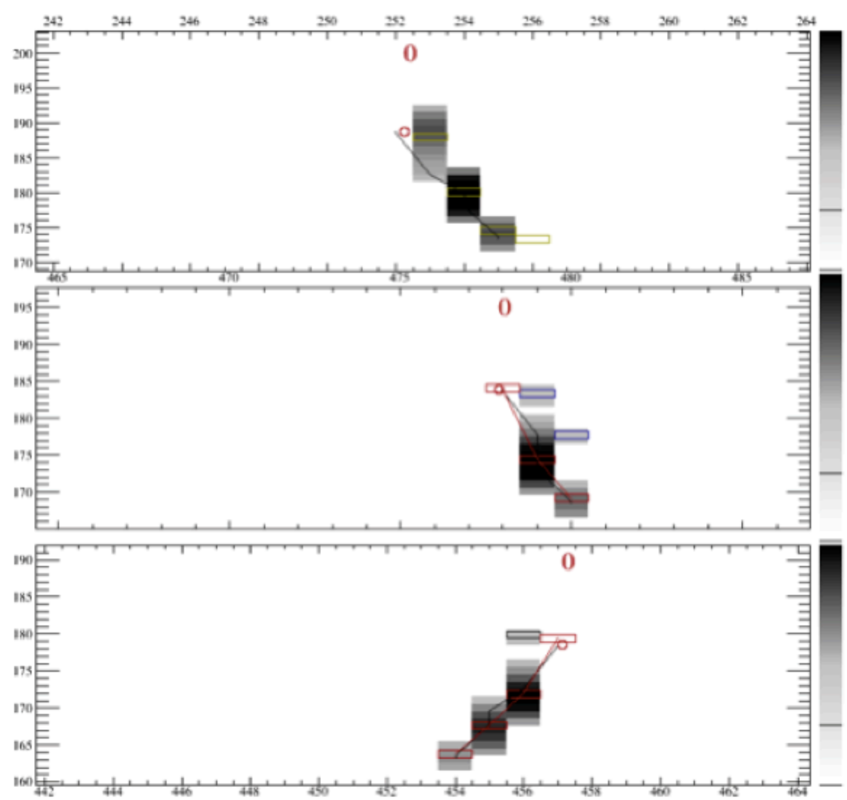


Good particle reconstruction

+ some other detector types for specific uses

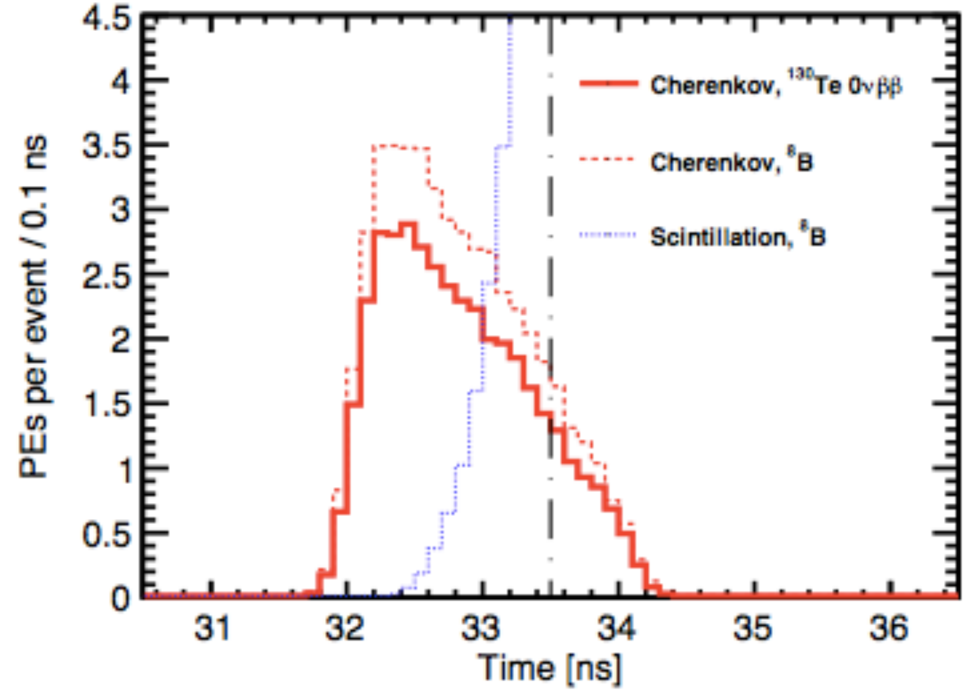
R&D activity important for this regime, too, both for low-energy capabilities of large multi-purpose detectors, and new detectors

Examples: (there are many more!)



Reconstructed 10 MeV electron

LArTPC: backgrounds, photons, reco for low-energy events

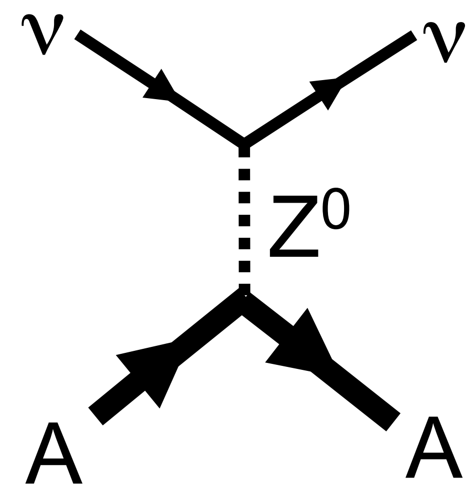


Scintillation vs Cherenkov light separation using fast timing photosensors (arXiv:1609.09865)

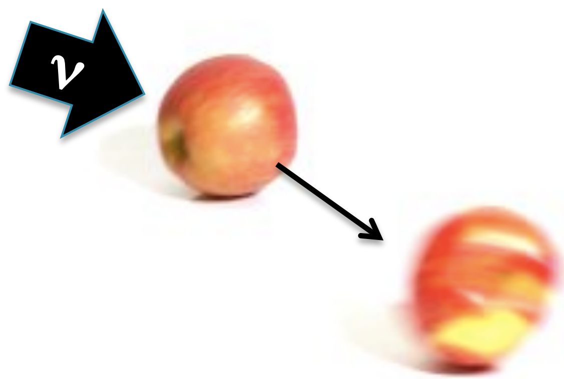
One more example: addresses multiple drivers

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$



A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV

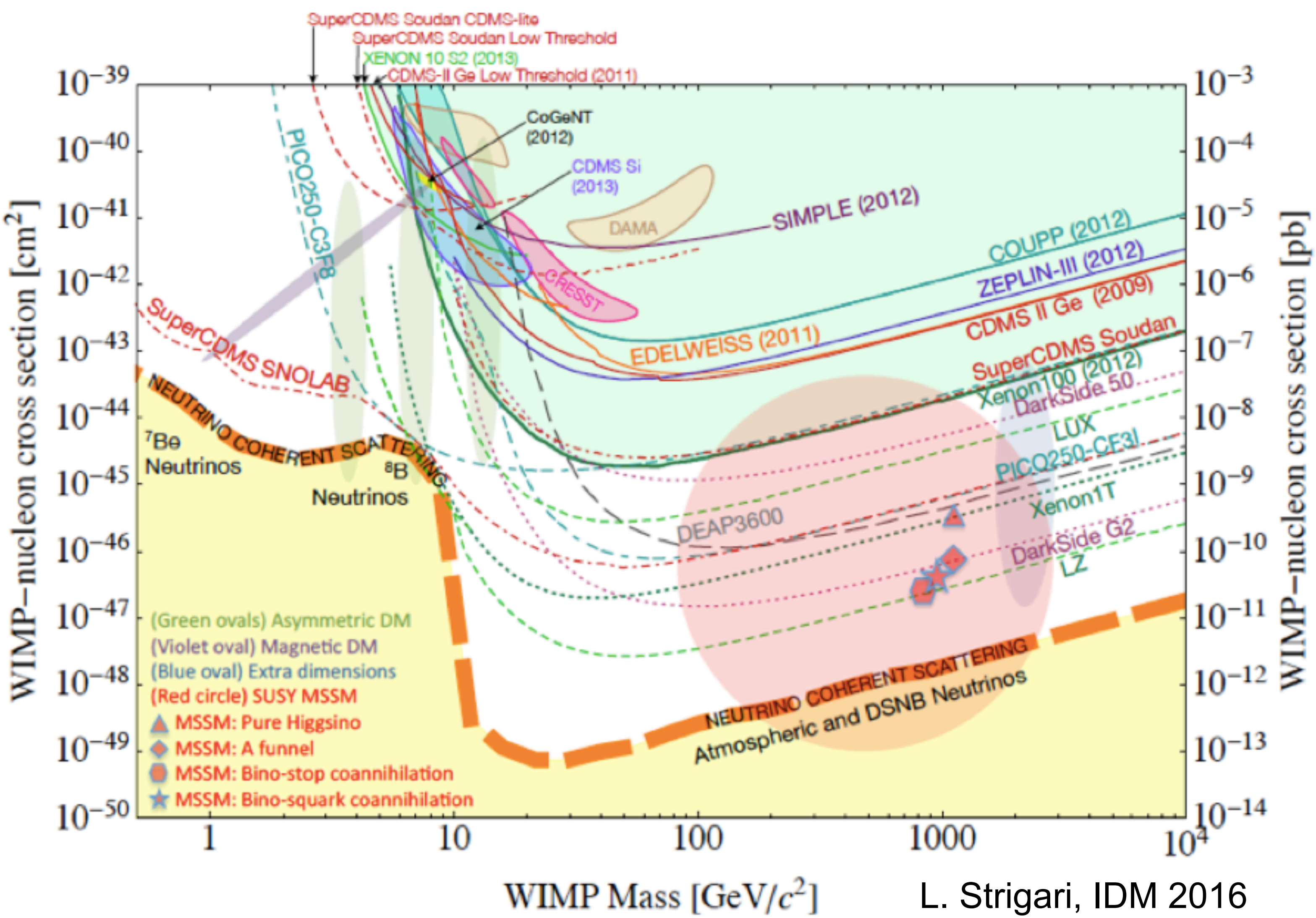


- Important in supernova processes & detection
- Well-calculable cross-section in SM:
  SM test, probe of neutrino non-standard interactions
- Dark matter direct detection background
- Sterile oscillations
- Neutron form factors
- Possible applications (reactor monitoring)

Produces ***very* low-energy recoils** (~10's of keV)

CEvNS from natural neutrinos creates ultimate background for direct DM search experiments

J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

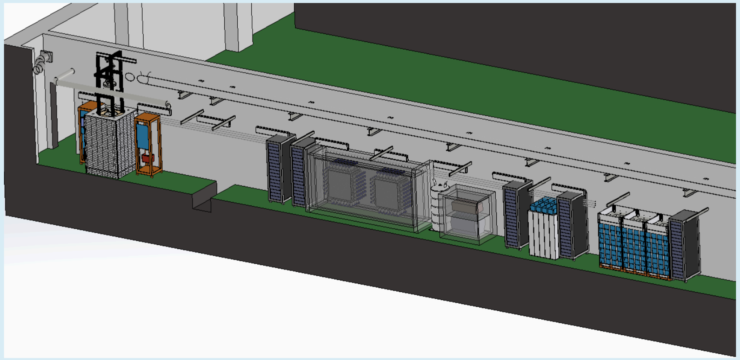


L. Strigari, IDM 2016

Understand nature of background (& detector response)

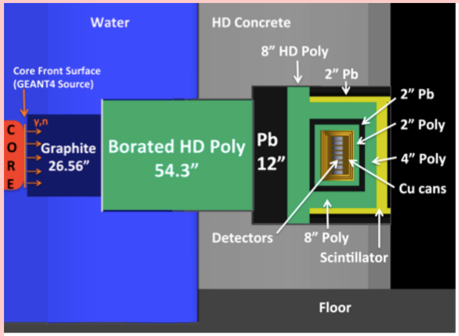
CEvNS experiments at pion DAR sources & reactors

COHERENT:
multiple WIMP/0nbbdk-type detectors @SNS



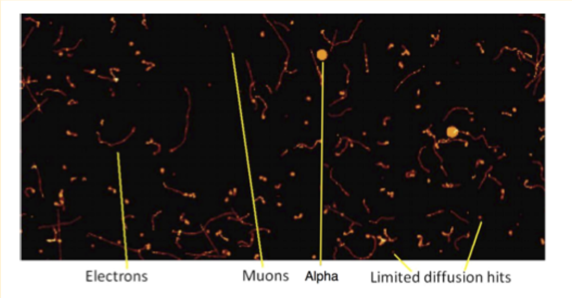
Akimov t et al., arXiv:1509.08702

MINER:
cryogenic Ge @ reactor



Agnolet et al., arXiv:1609.02066

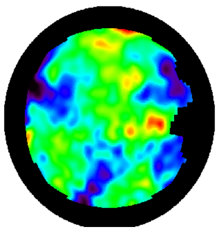
CONNIE:
silicon CCDs @ rectors

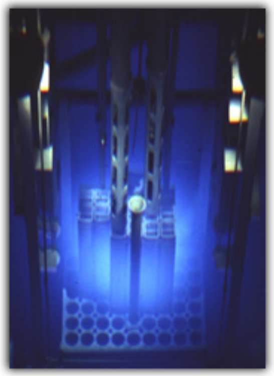


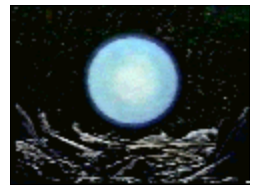
Moroni et al., Phys.Rev. D91 (2015) 7, 072001

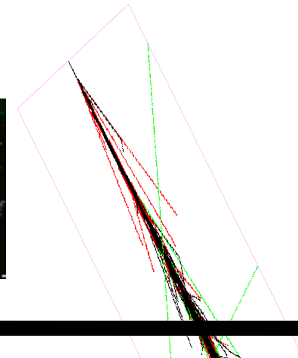
There is strong physics motivation to extend recoil energy threshold to sub-keV (reactor & source ν's)
... backgrounds are the issue

In summary...much exciting physics to explore in broad regimes...
diverse challenges, and connections to other physics drivers

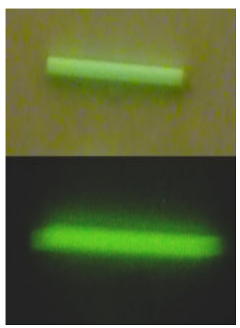


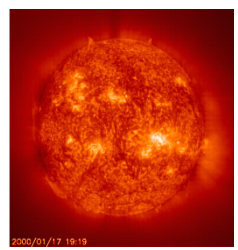


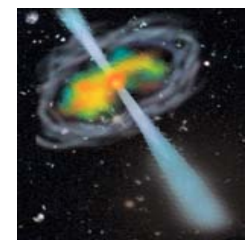


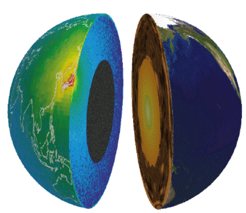


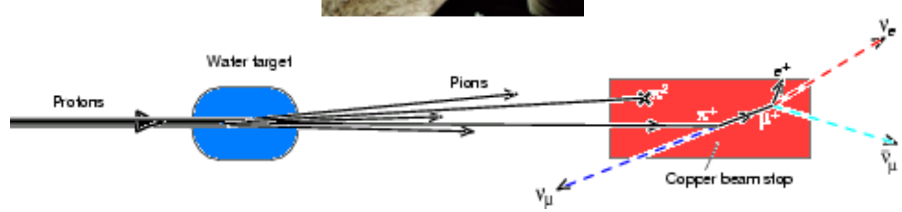
meV eV keV MeV GeV TeV PeV EeV











Many, many things I did not discuss with relevant interesting technology
(0νββdk, absolute ν mass, UHE ν's, reactor expts, xscns, applications,...)

see parallel sessions for more!

Extras/backups

Neutron tagging in water Cherenkov detectors

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

detection of neutron tags event as *electron antineutrino*

- especially useful for DSNB (which has low signal/bg)
- also useful for disentangling flavor content of a burst
  (improves pointing, and physics extraction)

R. Tomas et al., PRD68 (2003) 093013
KS, J.Phys.Conf.Ser. 309 (2011) 012028; LBNE collab arXiv:1110.6249
R. Laha & J. Beacom, PRD89 (2014) 063007

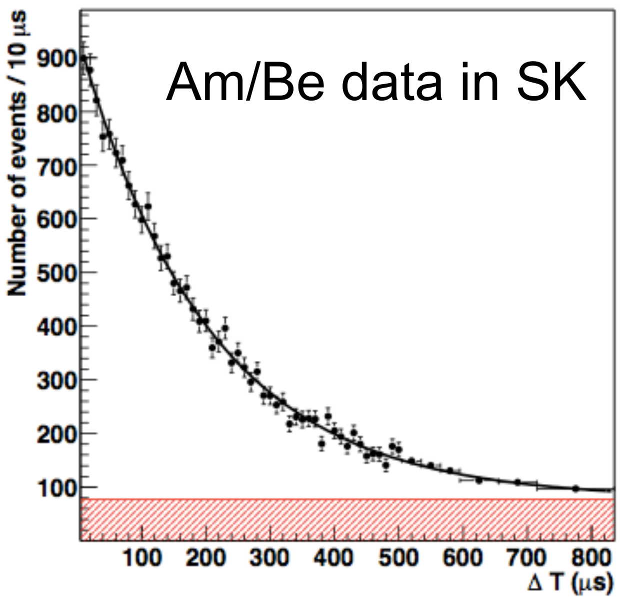
"Drug-free" neutron tagging

$$n + p \rightarrow d + \gamma(2.2\ \mathrm{MeV})$$

~200 μs thermalization & capture, observe Cherenkov radiation from γ Compton scatters

➔ with SK-IV electronics, ~18% n tagging efficiency

SK collaboration, arXiv:1311.3738;



Enhanced performance by doping!

use gadolinium to capture neutrons

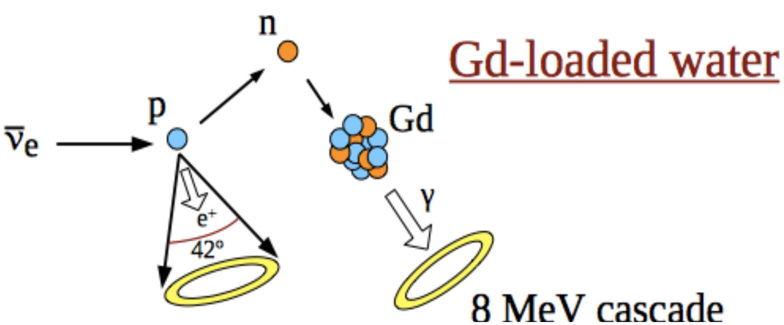
(common strategy for scintillator)

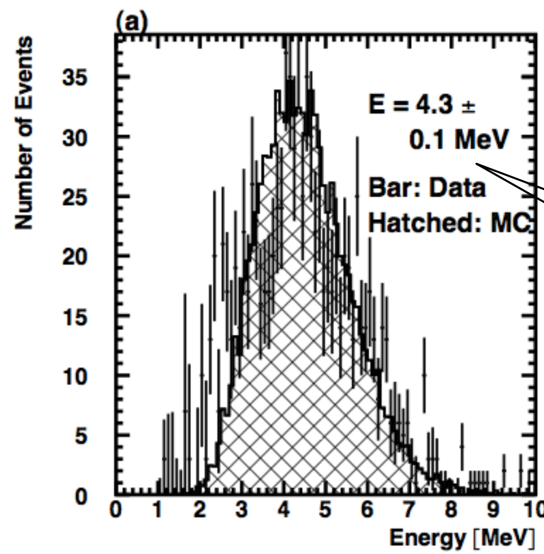
J. Beacom & M. Vagins, PRL 93 (2004) 171101

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

n + Gd → Gd* → Gd + γ

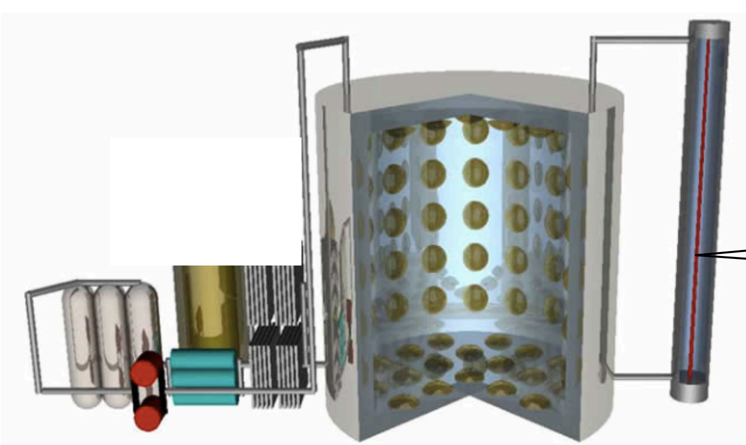
$$\sum E_\gamma = 8\,MeV$$





H. Watanabe et al., Astropart. Phys. 31, 320-328 (2009)

About 4 MeV visible energy per capture; ~67% efficiency in SK



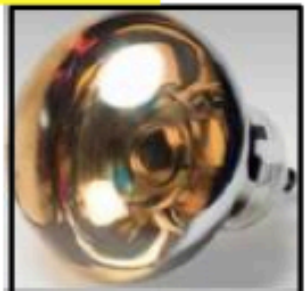
ADS: test tank in the Kamioka mine for R&D

Going forward as "SK-Gd"

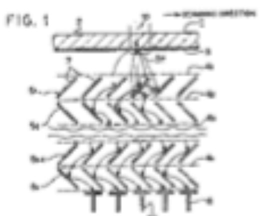
Photosensor Improvements

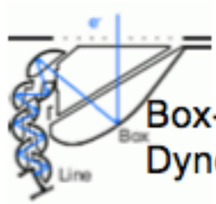
Photo Multipliers (PMTs)


Super-K PMT


50cm HQE Box&Line PMT

Venetian Blind



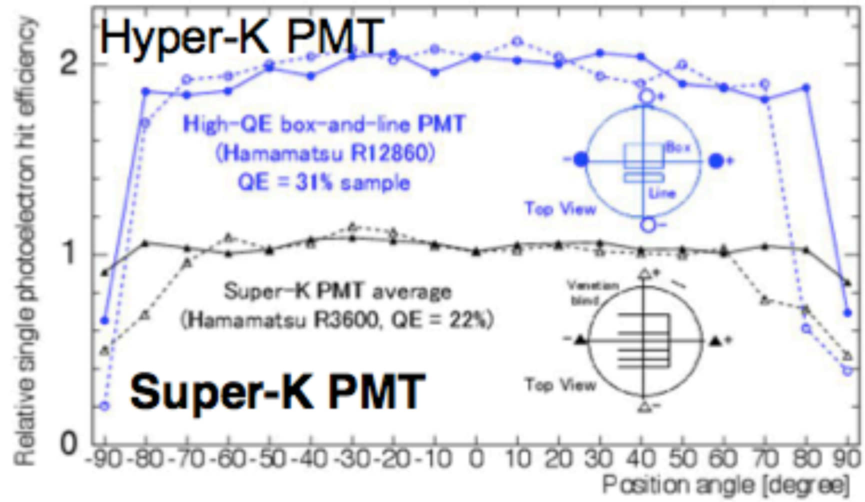


Box-and-Line Dynode

- Efficiency x 2, Timing resolution x 1/2

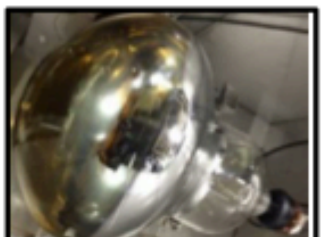
  Pressure tolerance x 2 (>100m)

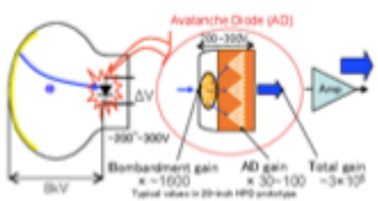
  Enhance p→$\bar{\nu}K^+$ signal, solar ν, neutron signature of np→d+γ(2.2MeV),..



Other Developments:

Hybrid Photo Detectors (HPDs)

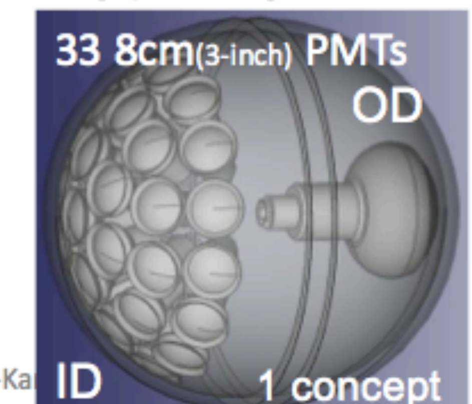

50cm HQE HPD w/ 20mm ϕ AD



Under viability study

The Hyper-Ka

Multi-PMTs



Working concept from KM3NeT but:

- Usage for ID/OD
- lower pressure tolerance required.
- ultrapure water.

International contribut.

F. Di Lodovico, Neutrino 2016

All of this discussion is in the context of the standard 3-flavor picture and testing that paradigm....

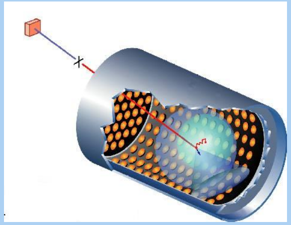
There are already some slightly uncomfortable data that **don't fit that paradigm**...

Open a parenthesis: (

Outstanding 'anomalies'

LSND @ LANL (~30 MeV, 30 m)

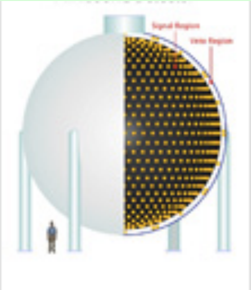
Excess of $\bar{\nu}_e$ interpreted as $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



➔ $\Delta m^2 \sim 1\ eV^2$: inconsistent with 3 ν masses

MiniBooNE @ FNAL ($\nu,\bar{\nu}$ ~1 GeV, 0.5 km)

- unexplained >3 σ excess for E < 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- no excess for E > 475 MeV in neutrinos
  (inconsistent w/ LSND oscillation)
- small excess for E < 475 MeV in antineutrinos
  (~consistent with neutrinos)
- small excess for E > 475 MeV in antineutrinos
  (consistent w/ LSND)
- for E>200 MeV, both nu and nubar consistent with LSND

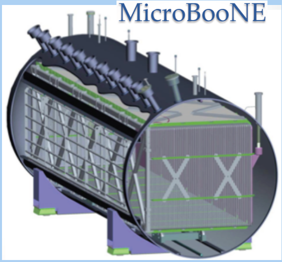


????
more data needed

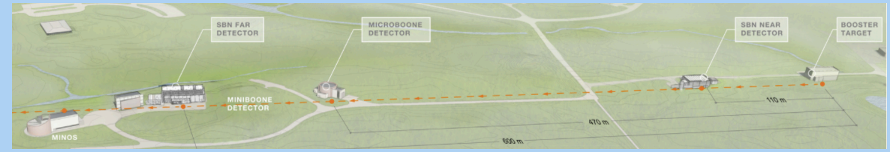
Also: possible deficits of reactor $\bar{\nu}_e$ ('reactor anomaly')
and source ν_e ('gallium anomaly')

Sterile neutrinos?? (i.e. no normal weak interactions)
Some theoretical motivations for this, both from particle & astrophysics
[cosmology w/Planck now consistent w/3 flavors... but allows 4...]
Or some other new physics??

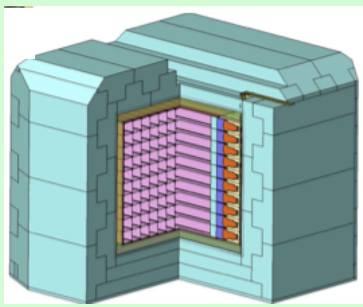
Experimental ideas to address these anomalies...



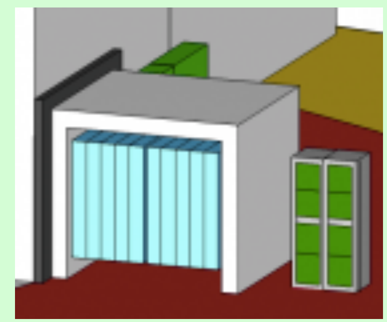
Experiments with beams
(meson decay in flight and at rest)



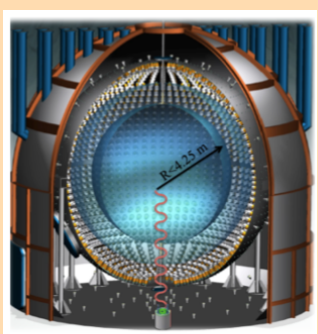
MINOS+, FNAL SBN, OscSNS, J-PARC MLF, ...



Experiments at reactors

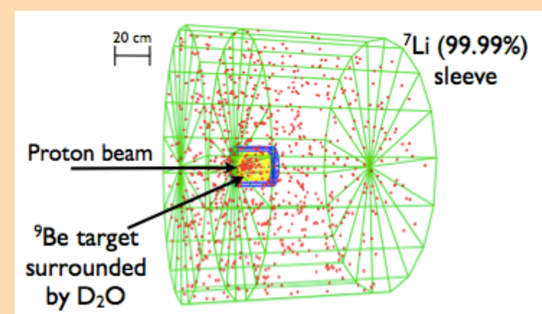


PROSPECT, SoLid, NuLAT, STEREO, DANNS, Neutrino4, Hanaro,..



Experiments with radioactive sources

SOX, CeSOX, IsoDAR, ...

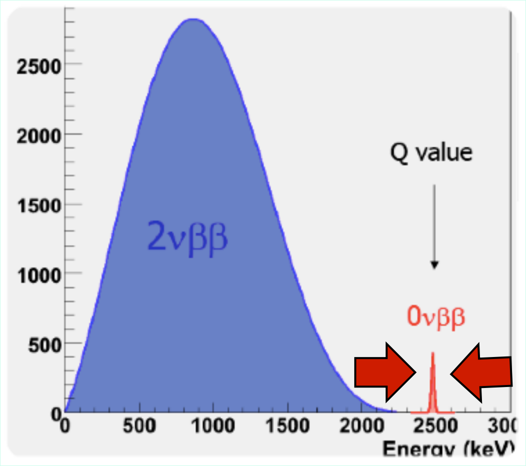
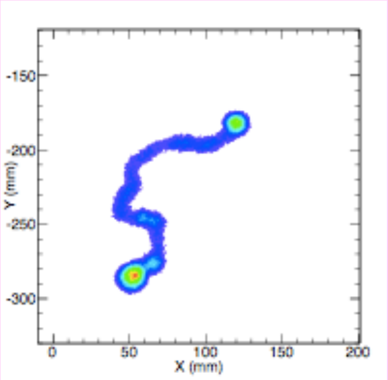


Many more! see e.g., `arXiv:1204.5379` (...already out of date...rapidly evolving)

... parenthesis not closed...

General NLDBD experiment strategies

$$T_{1/2} > \frac{\ln 2 \;\; \varepsilon \cdot N_{source} \cdot T}{UL(B(T) \cdot \Delta E)}$$

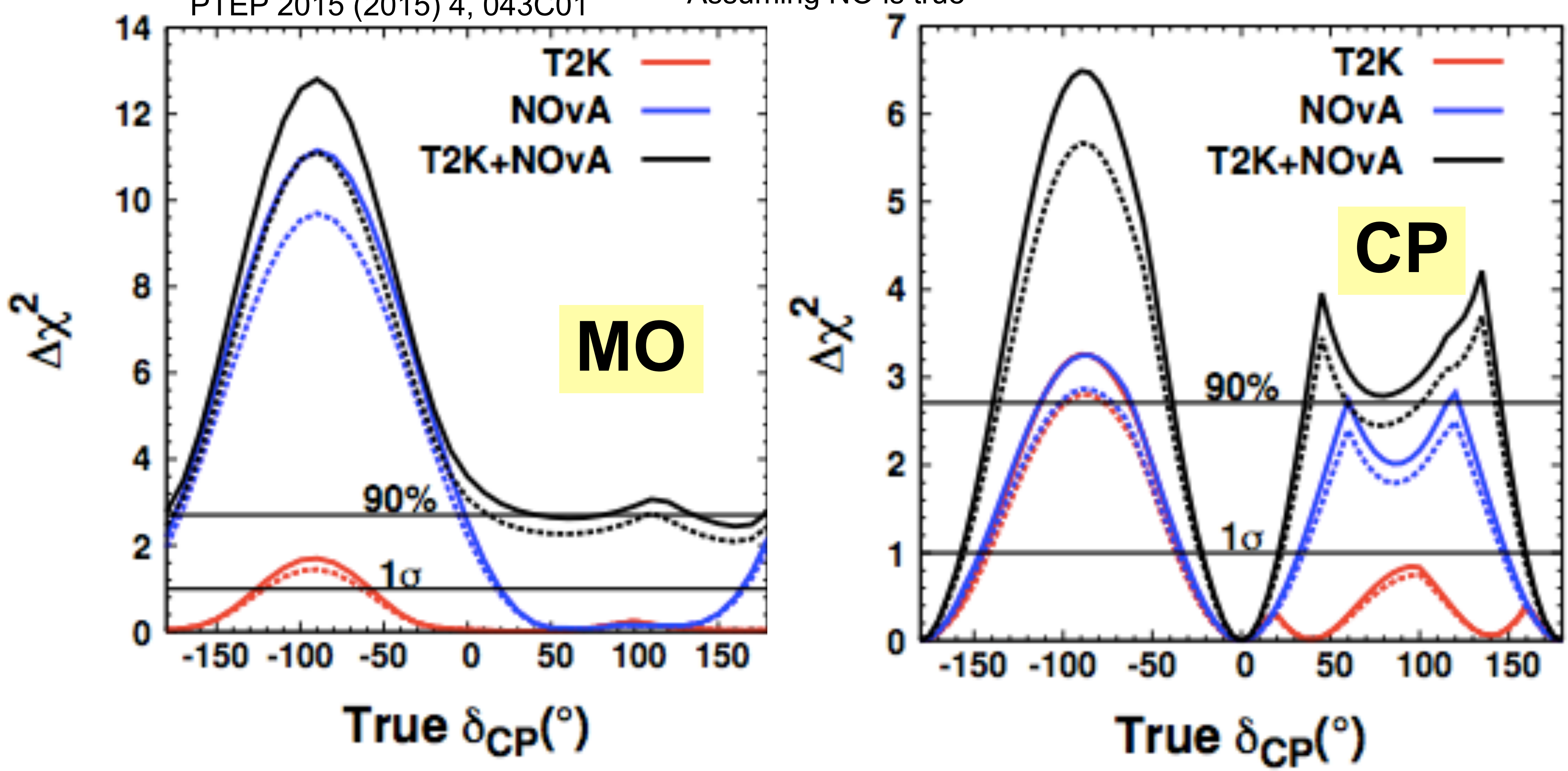
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		
focus on the numerator with a huge amount of material (often sacrificing resolution)	focus on the denominator by squeezing down ΔE (various technologies)	try to make the background zero by tracking or other technique

...some experiments take hybrid approaches...

More data to come from both T2K and NOνA...
...how far will they take us?

PTEP 2015 (2015) 4, 043C01

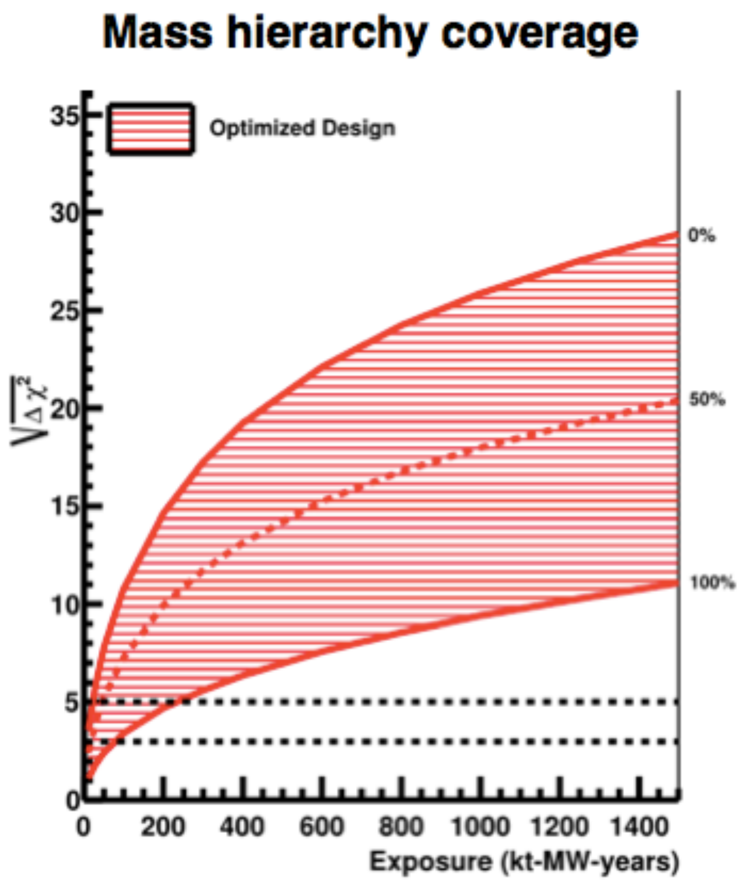
Assuming NO is true

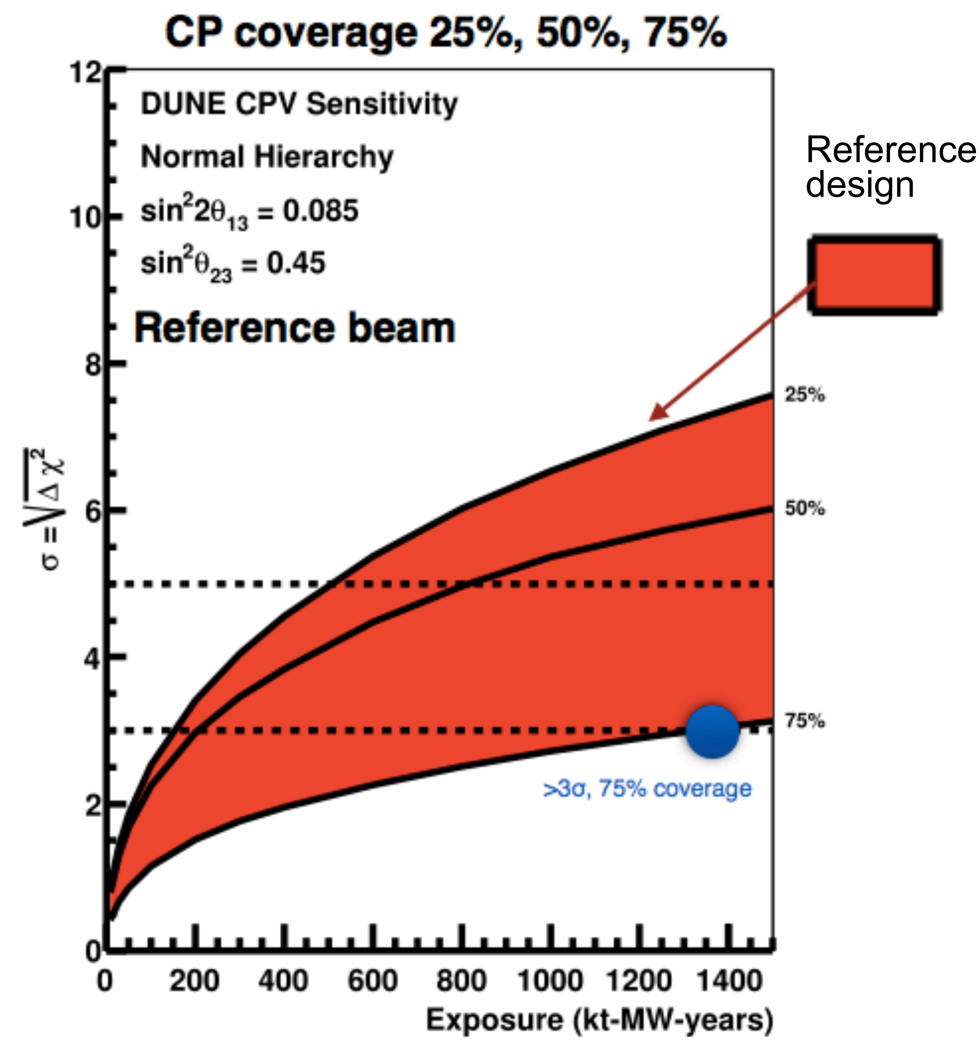


Expected sensitivities for T2K+NOνA
(MO sensitivity driven by NOνA thanks to longer baseline)

➔ Possible "indications" within ~5 years if parameters are lucky (hints so far are in the right direction!)

DUNE sensitivity





Excellent mass ordering reach for all CP values

Decent chance to measure CPV