Underground Facilities for Low-Energy Neutrino Physics

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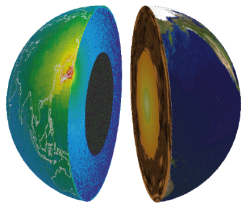
Snowmass on the Mississippi, July 30 2013

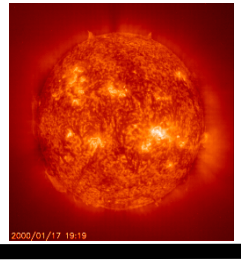
“Low-Energy” Neutrinos

“Wild”

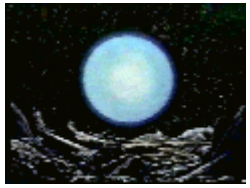
Geo neutrinos



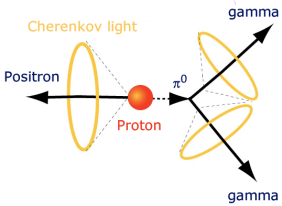
Solar neutrinos

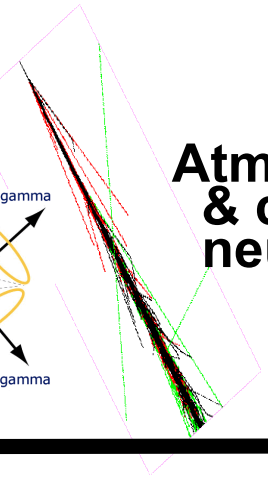


Supernova neutrinos



Proton decay

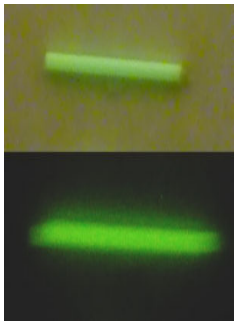




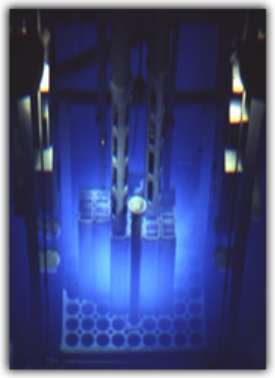
Atmospheric & cosmic neutrinos

keV MeV GeV TeV

“Tame”

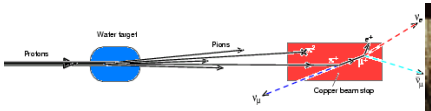


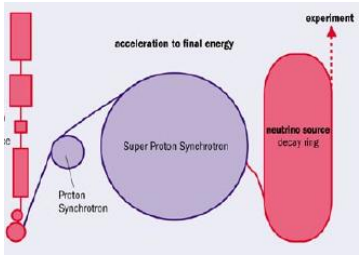
Artificial radioactive neutrino sources



Reactor neutrinos

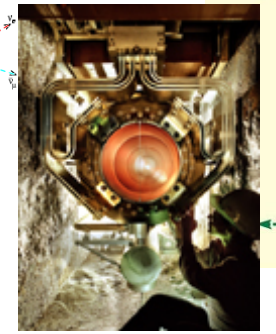
Stopped pion sources



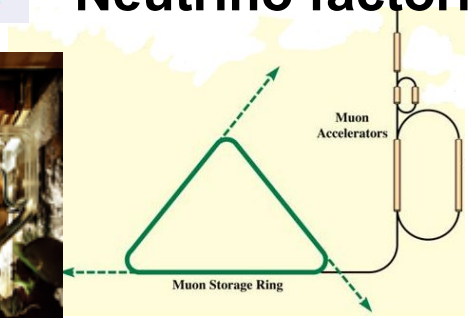


Beta beams

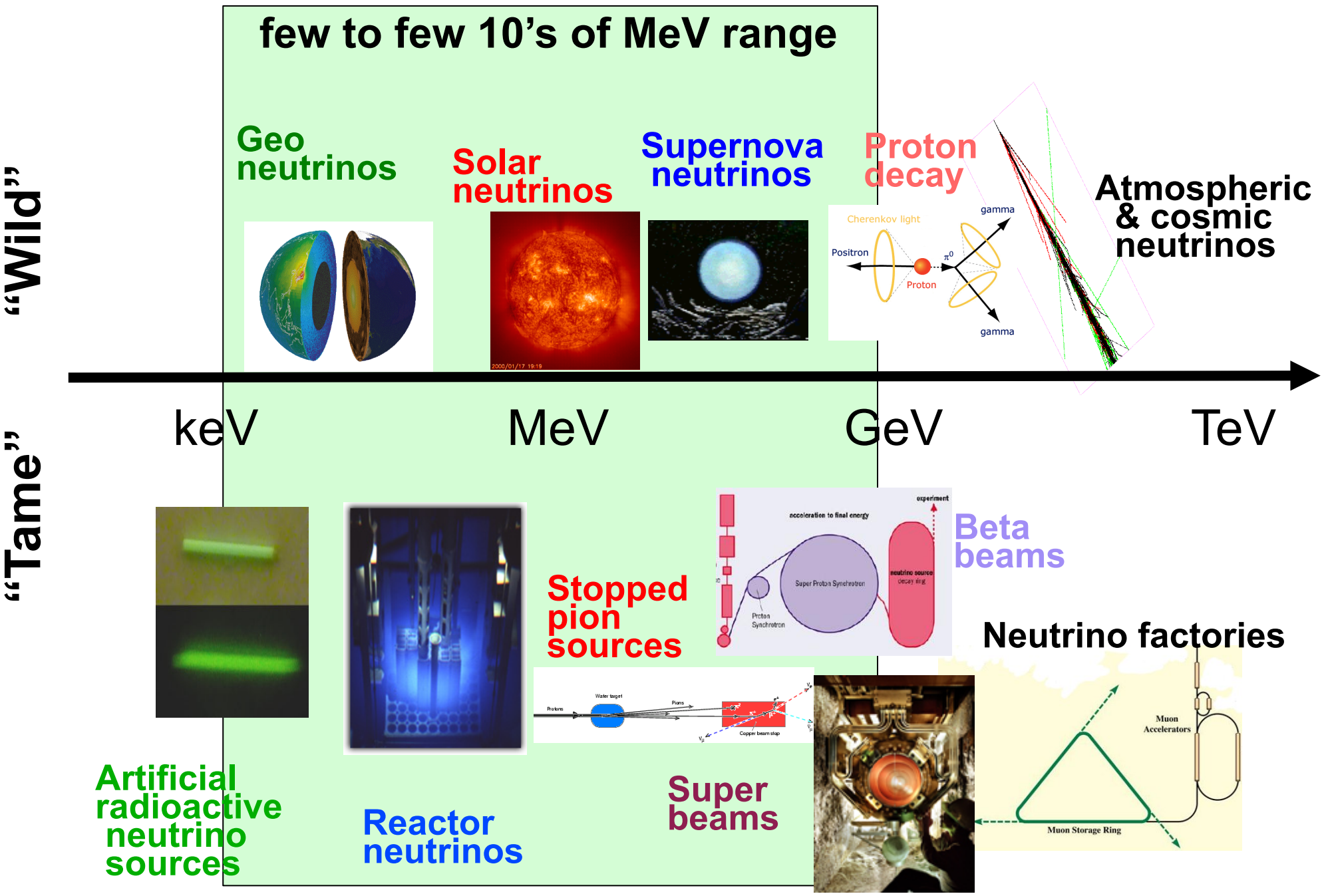
Super beams



Neutrino factories

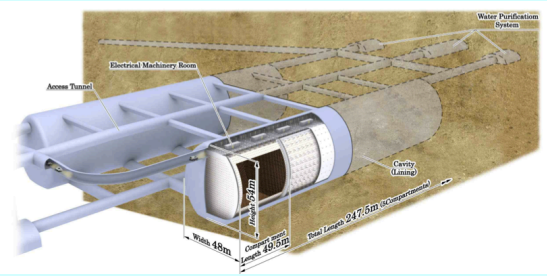


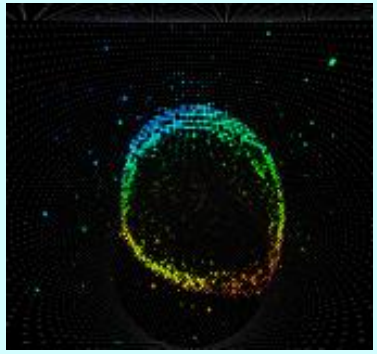
“Low-Energy” Neutrinos



Possible large (multi-kton) detector technologies

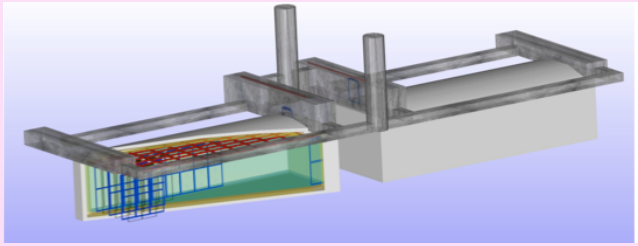
Water Cherenkov

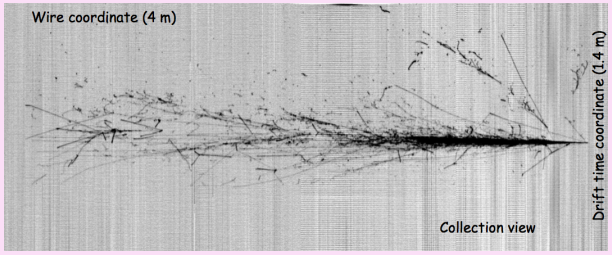




Cheap material, proven at very large scale

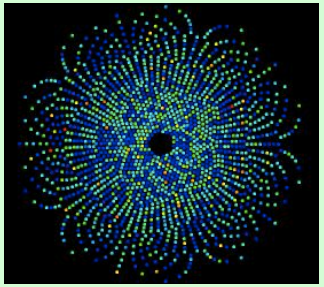
Liquid Argon





Excellent particle reconstruction

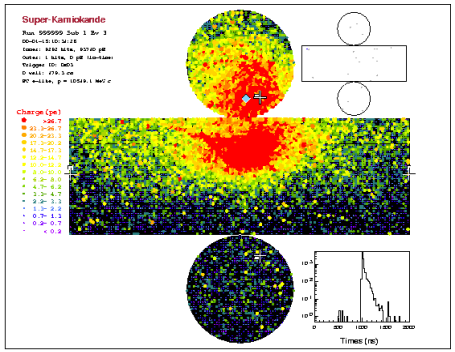
Liquid Scintillator

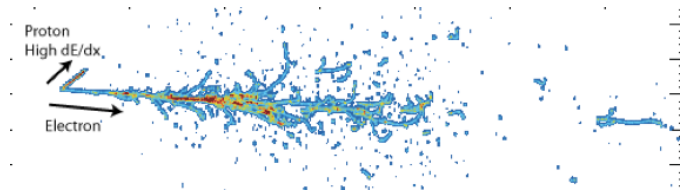


Low energy threshold

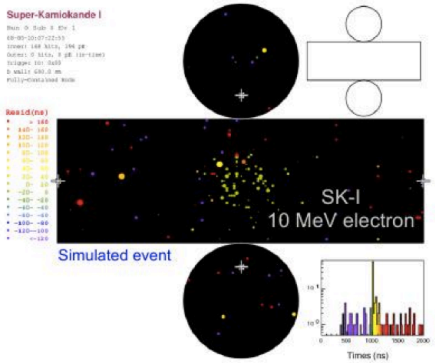
Unlike majestic ~GeV-scale events (atmν, beam, pdk), these are homely (but lovable)

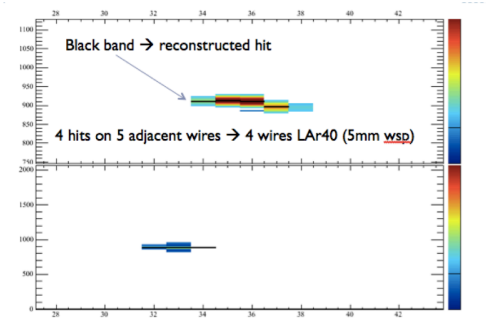
~GeV





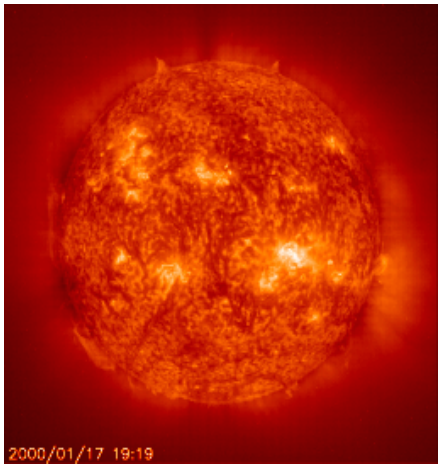
~10 MeV



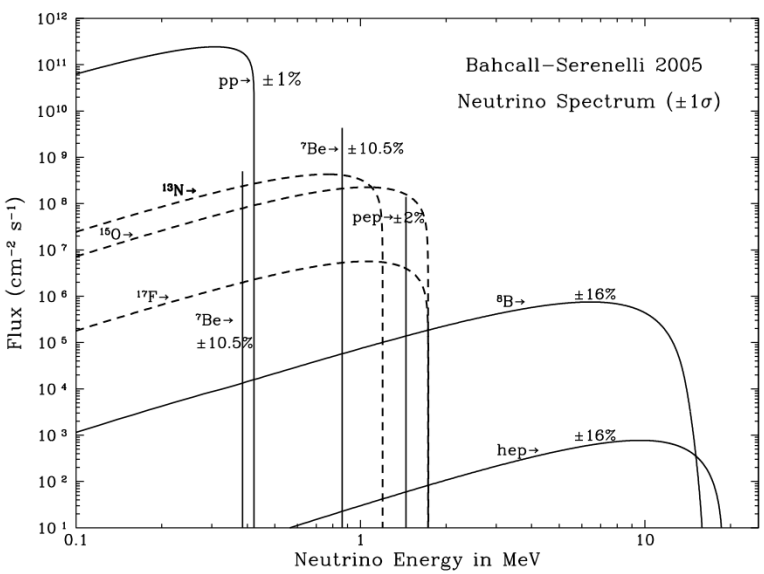


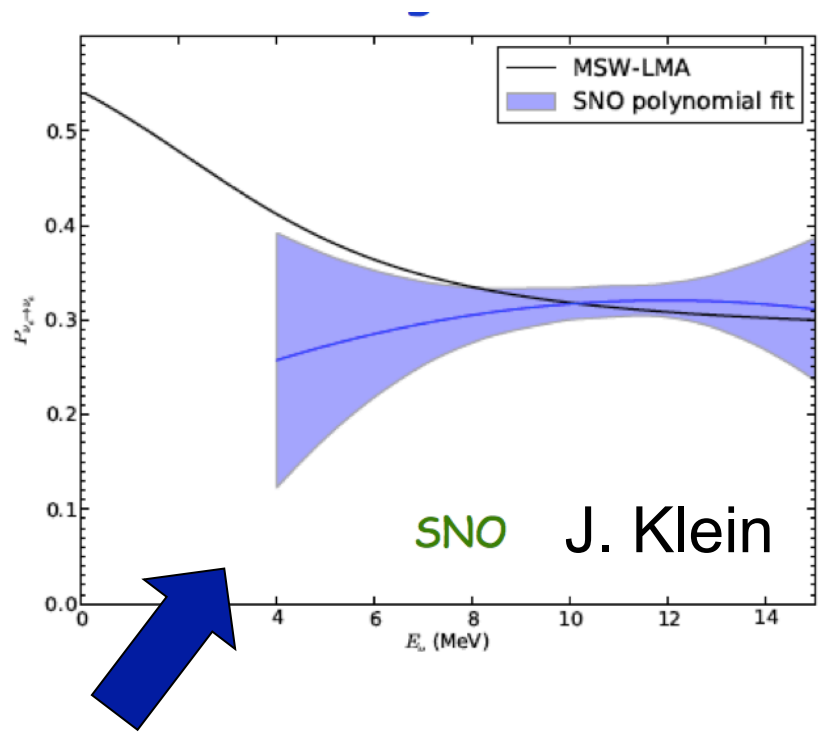
experimental issues are:
light/charge collection,
and *background* (no beam trigger!)

Solar neutrinos



- precision 1-2 oscillation parameters
- probe of exotic physics
- solar physics (metallicity etc.)





- low energy end still interesting!
- real-time measurement of pp flux still a frontier

Neutrinos from core collapse

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

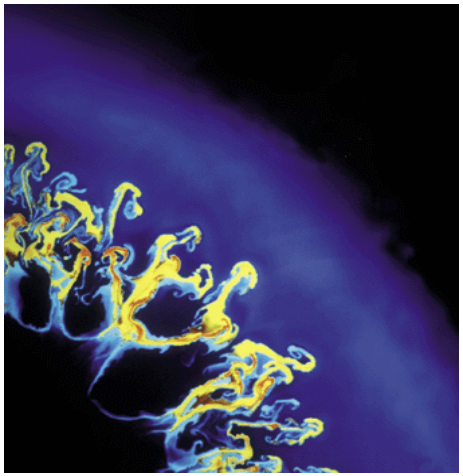
(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

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

~few SNae per century

Physics & astrophysics w/ supernova neutrinos



CORE COLLAPSE PHYSICS

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS

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

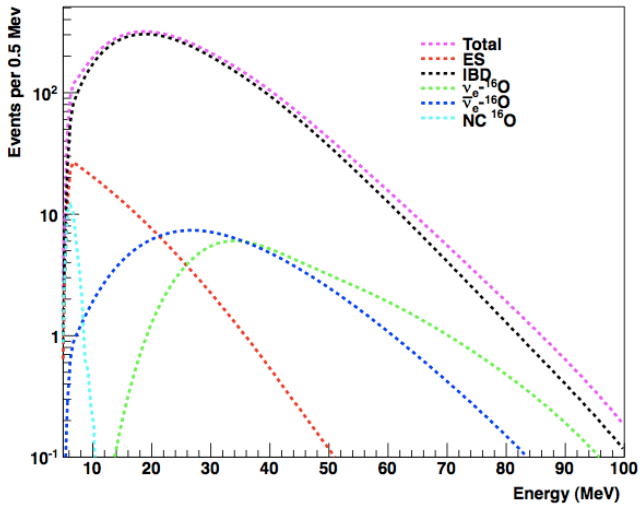
+ EARLY ALERT

sensitivity to different flavors is key

All detector types would observe copious neutrinos... typically "for free"

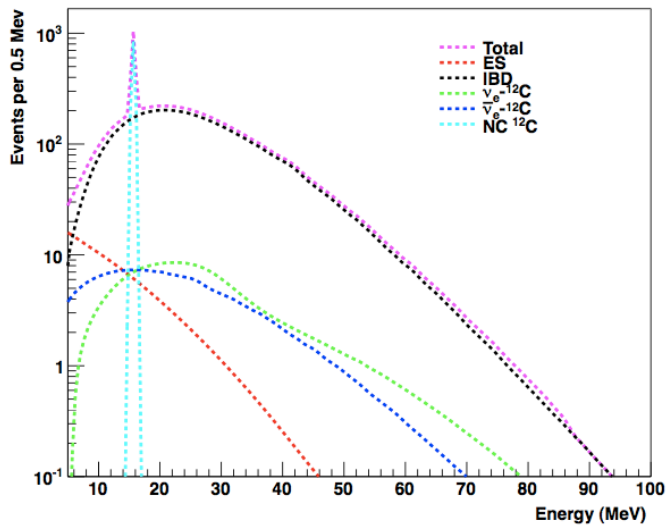
Observed events at 10 kpc

Water
25,000 events in 100 kt



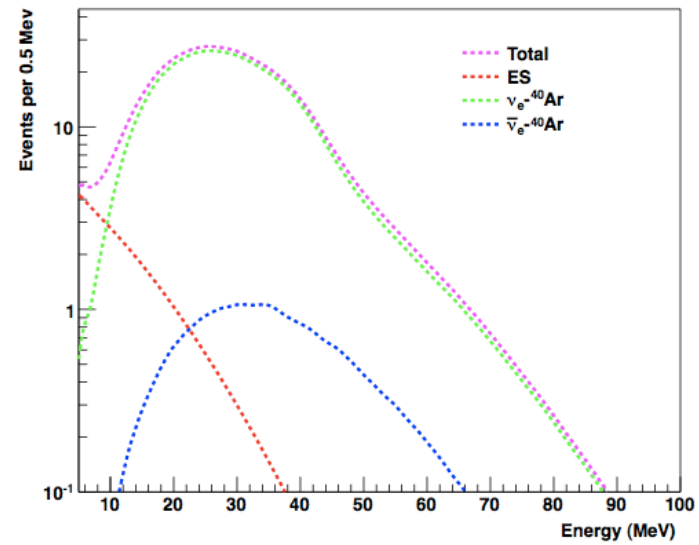
Nearly pure nuebar (inverse beta decay on free protons)

Liquid scintillator
15,000 events in 50 kt



Also nearly pure nuebar, plus NC channels

Liquid argon
1500 events in 17 kt



Nearly pure nue!

Signals are complementary... diversity in flavor sensitivity good for getting physics from the signal!

Current & future 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
Mini-BooNE	Scintillator	USA	0.7	200	(Running)
HALO	Lead	Canada	0.079	20	Running
Icarus	Liquid argon	Italy	0.6	(60)	(Running)
NOνA	Scintillator	USA	15	3000	Turning on
SNO+	Scintillator	Canada	1	300	Under construction
MicroBooNE	Liquid argon	USA	0.17	17	Under construction
LBNE LAr	Liquid argon	USA	34	3000	Proposed
Hyper-K	Water	Japan	540	110,000	Proposed
JUNO	Scintillator	China	20	6000	Proposed
RENO-50	Scintillator	South Korea	18	5400	
LENA	Scintillator	Europe	50	15,000	Proposed

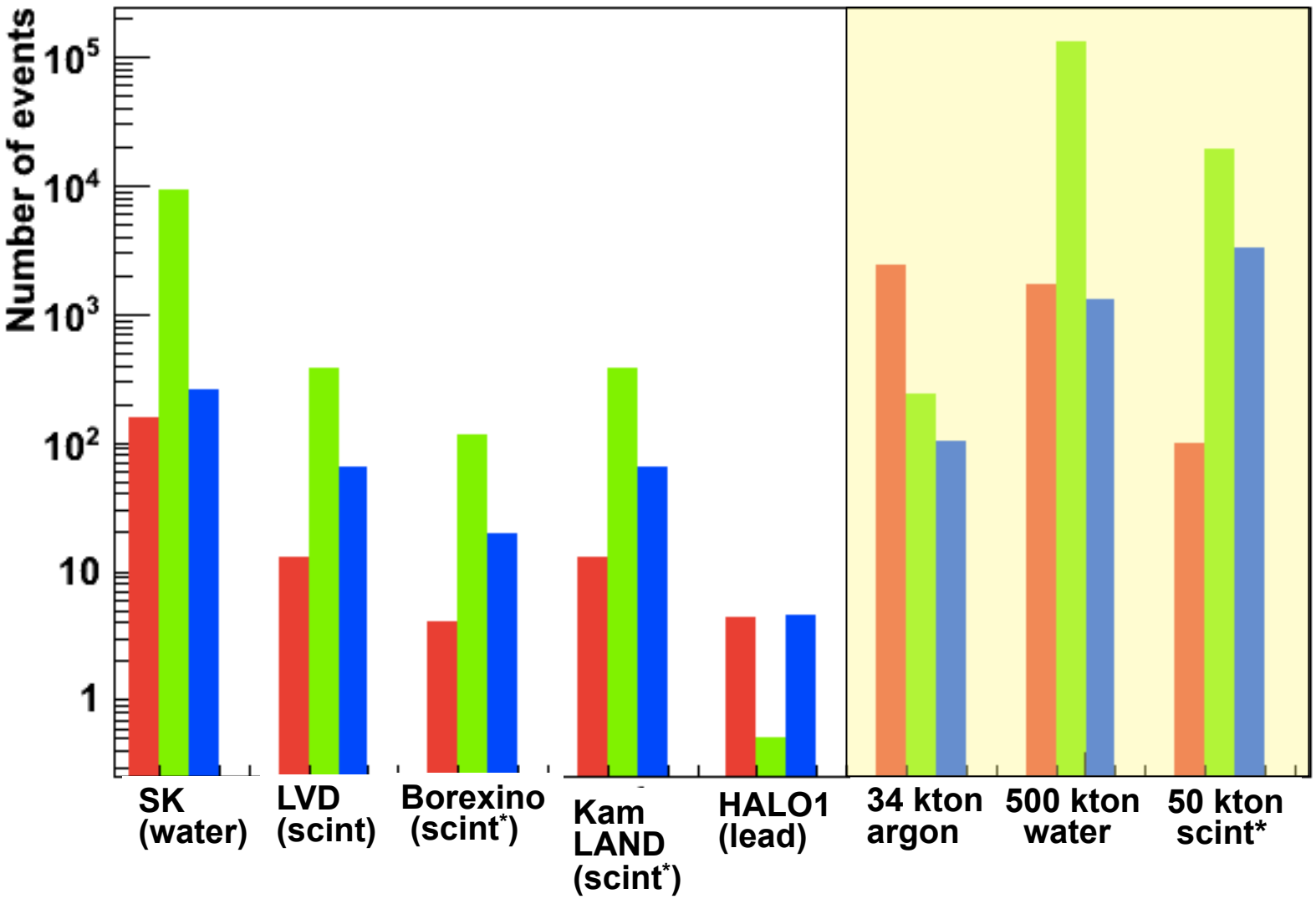
plus reactor experiments, DM experiments...

World SN flavor sensitivity

for largest detectors of each class

Electron neutrino
Electron antineutrino
Muon and tau neutrino and antineutrino

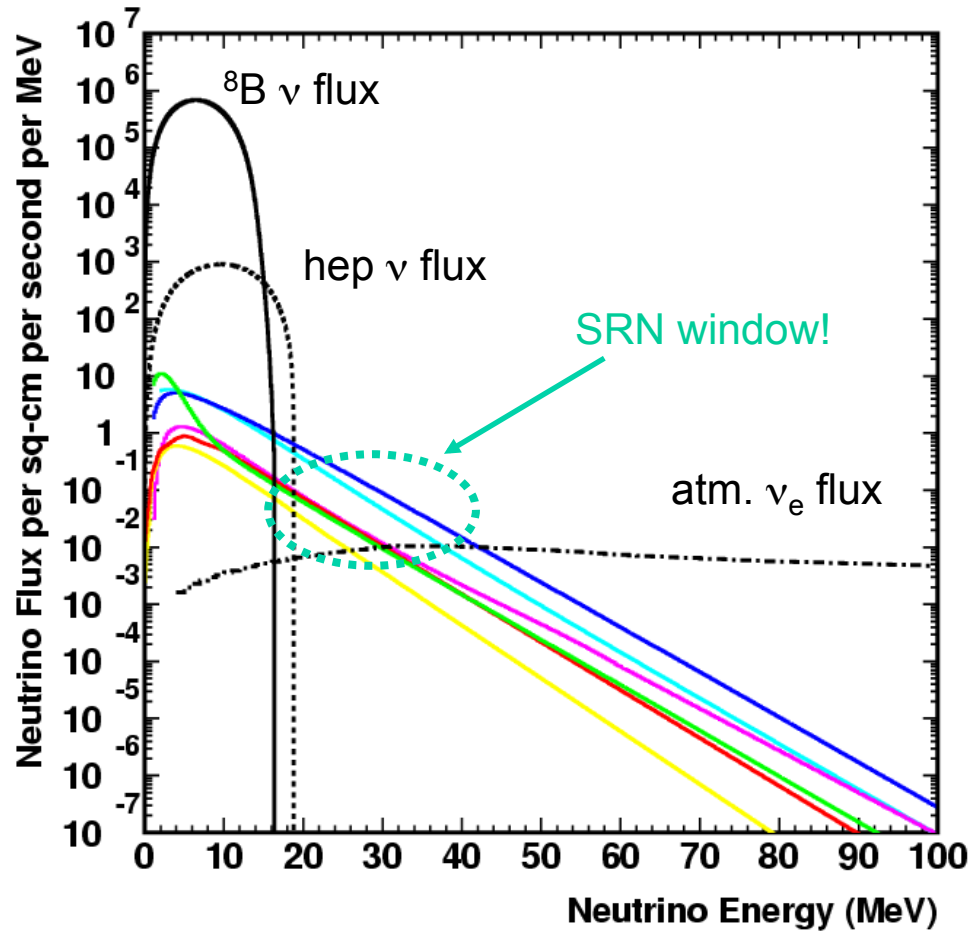
Livermore model
@ 10 kpc



* plus NC ν-p scattering

For the risk-averse: '*relic*' or diffuse SN ν's (DSNB)

Learn about star formation rate, average SN ν emission



Difficulty is tagging ~10-50 MeV ν's (S/B poor if not in burst)

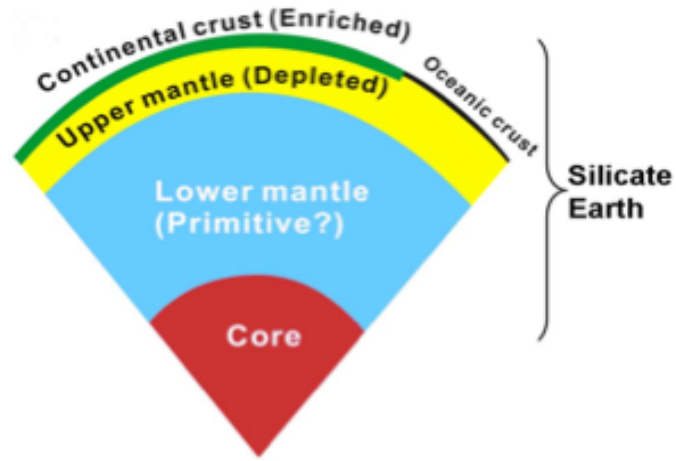
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

- **S/B w/ Gd in water for tagging IBD is promising**
- **Scintillator also good (possible atmospheric ν NC bg)**
- **Argon sees ν_e flux, but low rate, unknown backgrounds**

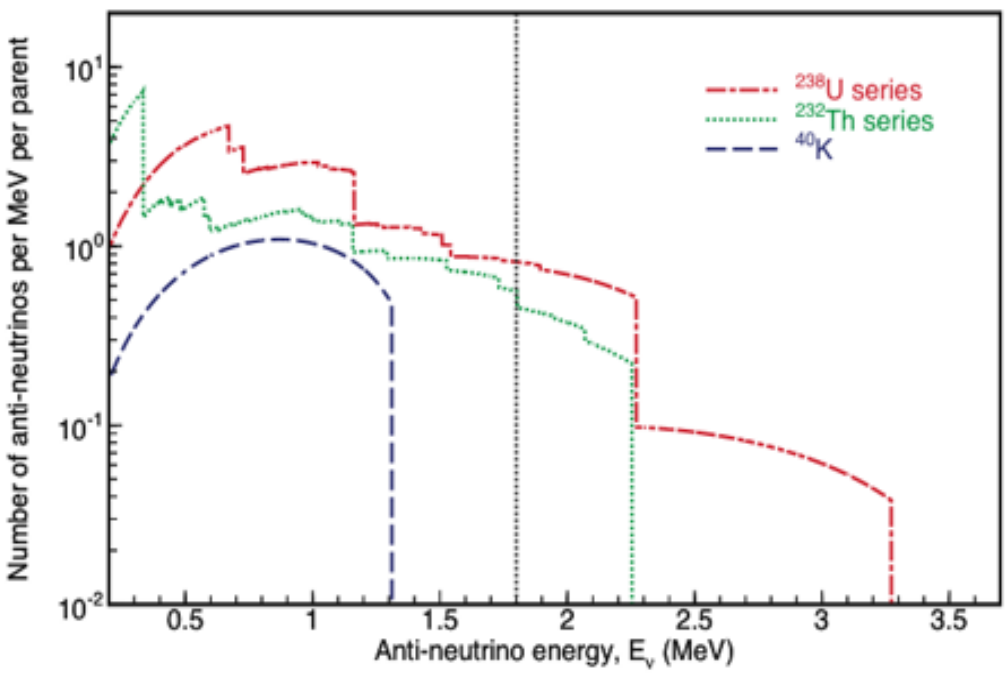
Geo-neutrinos

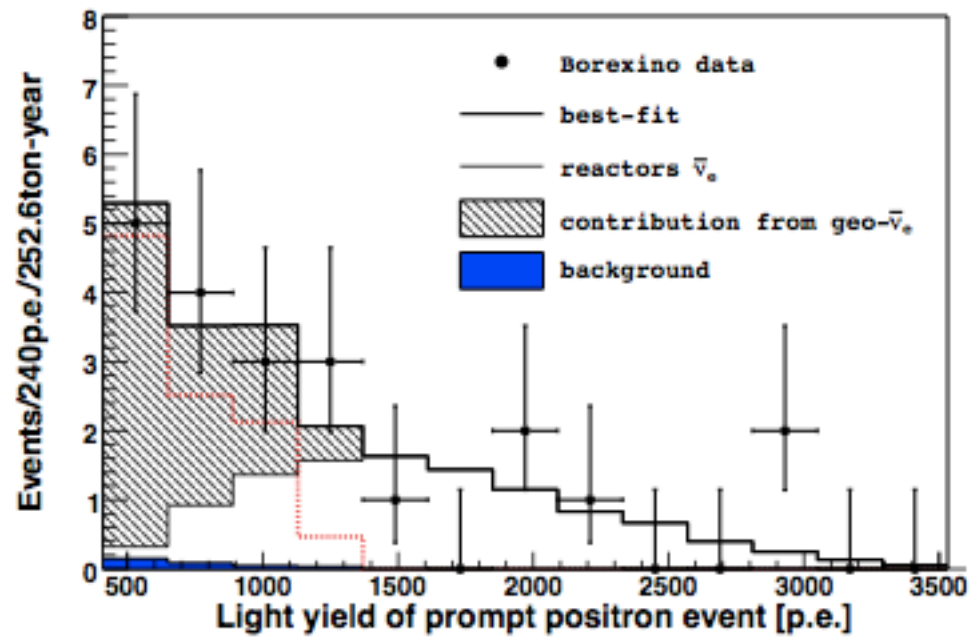
Fraction of Earth's heat from radioactivity is uncertain ... neutrinos can constrain geophysical models, measure U/Th

Recent measurements from KamLAND and Borexino have proven feasibility



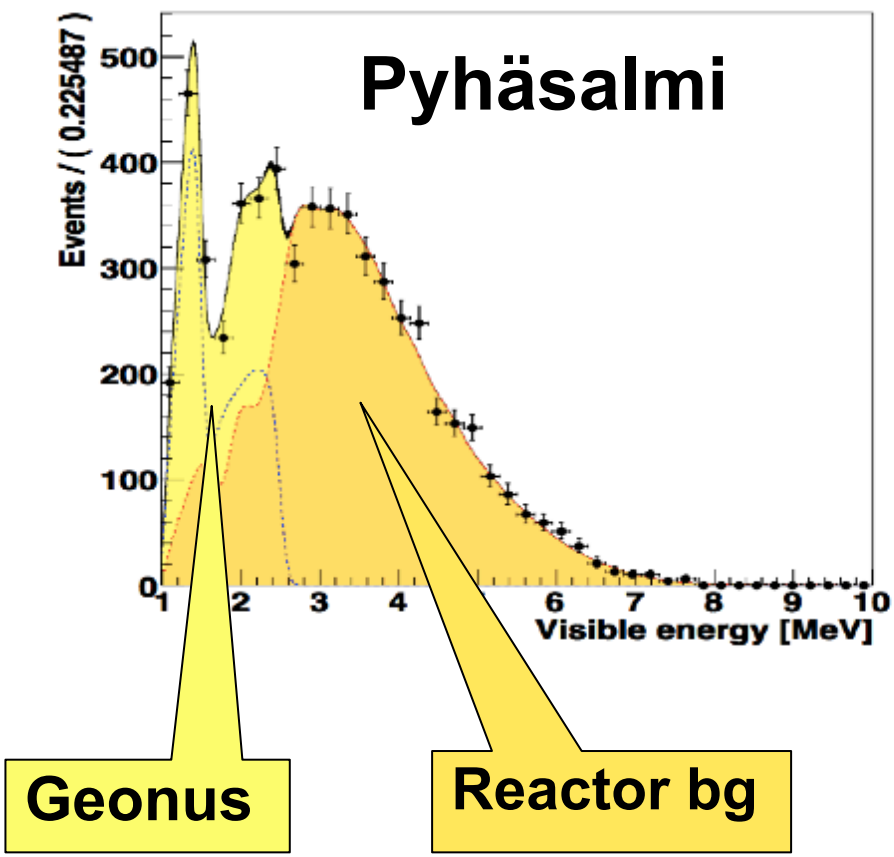
Bulk Silicate Earth model:
~1/2 of U, Th, K in crust
~1/2 of U, Th, K in mantle
~no U, Th, K in core

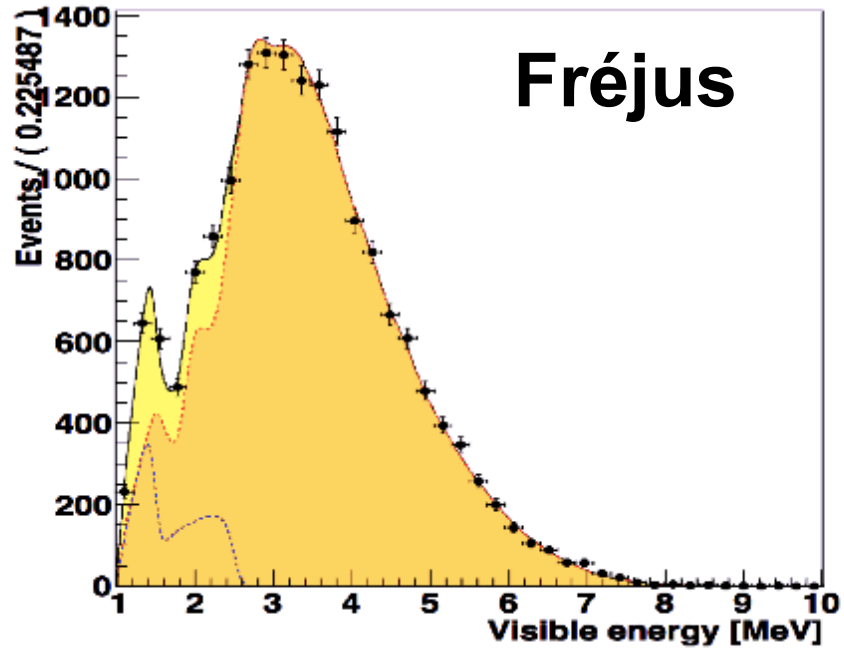




Best bet for geoneutrinos is scintillator, due to low energy threshold, good energy resolution & low radioactive bg

Reactor neutrino bg is the biggest issue

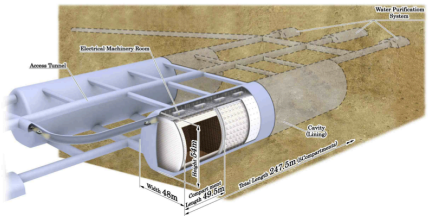


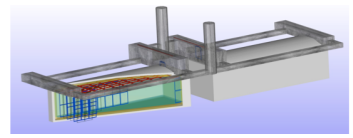


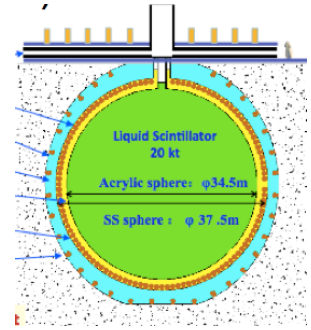
1 year statistics

LENA arXiv.1104.5620

Summary of low-energy neutrinos in large detectors







	Water	Liquid argon	Scintillator
Solar neutrinos	Yes, huge statistics	Difficult, low rate	Yes
Supernova burst	Yes, anti-ν_e, huge statistics, pointing	Yes, ν_e	Yes, anti-ν_e + good NC, good statistics
DSNB	Yes, with Gd	ν_e, unknown bg, low rate	Possibly, bg under evaluation
Geoneutrinos	No	No	Yes

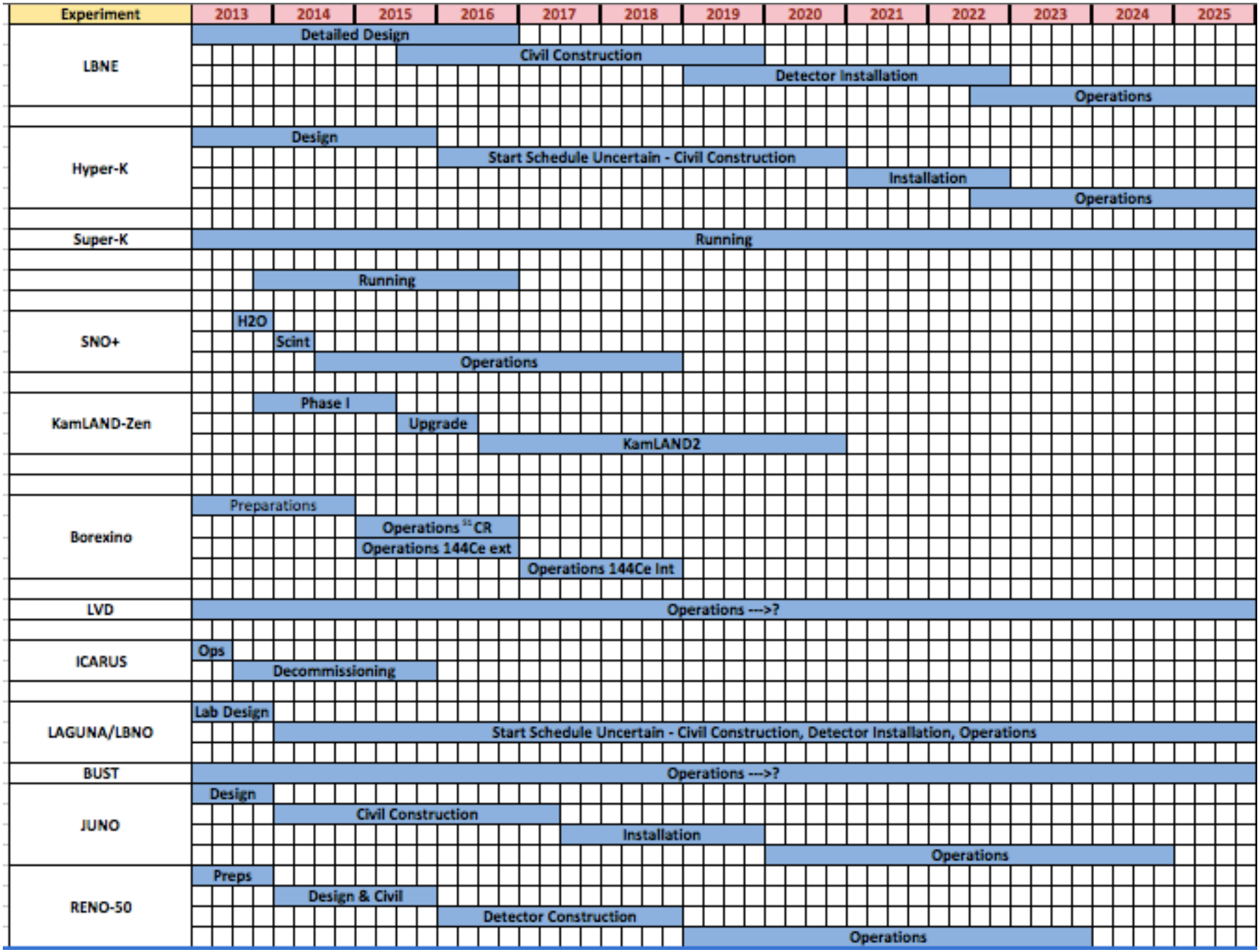
Plus: radioactive sources, neutrinoless double beta decay, stopped-pion neutrinos...

Background an issue for all ➔ need to be underground!

Potential sites

Facility	Location	Overburden (MWE)	Past/Existing Large Underground Detectors	Proposed/Planned Large Underground Detectors	Beam	References
Homestake	USA	4290	Homestake Chlorine Detector	LBNE (LArTPC)	Future from FNAL	EPJ Plus, 127 9 (2012) 107
LNGS	Italy	3800	LVD, Borexino, ICARUS,OPERA		Current from CERN	EPJ Plus, 127 9 (2012) 109
Pyhasalmi	Finland	3900		MEMPHYS, LENA, GLACIER, MIND	Future from CERN	http://laguna.ethz.ch:8080/Plone
SNOLAB	Canada	6010	SNO, SNO+			EPJ Plus, 127 9 (2012) 108
Kamioka	Japan	2700	Kamiokande, Super-K, KamLAND	Hyper-K (Tochibora or Mozumi site)	Current and future beam from J-PARC (T2K, T2HK)	EPJ Plus, 127 9 (2012) 111
Baksan	Russia	850	BUST	BUST upgrade		EPJ Plus, 127 9 (2012) 113
Antares	Mediterranean	2500	ANTARES - 12 String	ORCA		http://antares.in2p3.fr
IceCube	South Pole	1500	IceCube - 86 Strings	PINGU, MICA		http://icecube.wisc.edu

Detector schedules



Summary

Tremendous opportunity for physics and astrophysics from SN burst

- **Many existing & planned detectors; SN capability typically comes "for free" if underground**
- **Very difficult on the surface**
- **Bursts are rare (only every ~30 years): critical to gather as much information as possible**

Other physics opportunities with low-energy neutrinos for underground detectors (solar, DSNB, geo, ...) depending on technology

This is not "competitive"! The more information, the better, especially for SN burst

- **Diverse detector technologies, at different locations around the globe, enhance physics reach**

Underground location important to avoid loss of once-per-career opportunity!

Signal	Energy range	Expected Signal Rate per kton of LAr (s^{-1} $kton^{-1}$)
Beam neutrinos (CP violation/ mass hierarchy)	~ GeV	5×10^{-4} osc ν_e in beam window
Proton decay	~ GeV	$< 2 \times 10^{-9}$
Atmospheric neutrinos	0.1-10 GeV	$\sim 10^{-5}$
Supernova burst neutrinos	few-50 MeV	~3 @ 10 kpc over ~30 secs
Solar neutrinos	few-15 MeV	4×10^{-5}
Supernova relic neutrinos	20-50 MeV	$< 2 \times 10^{-9}$