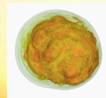
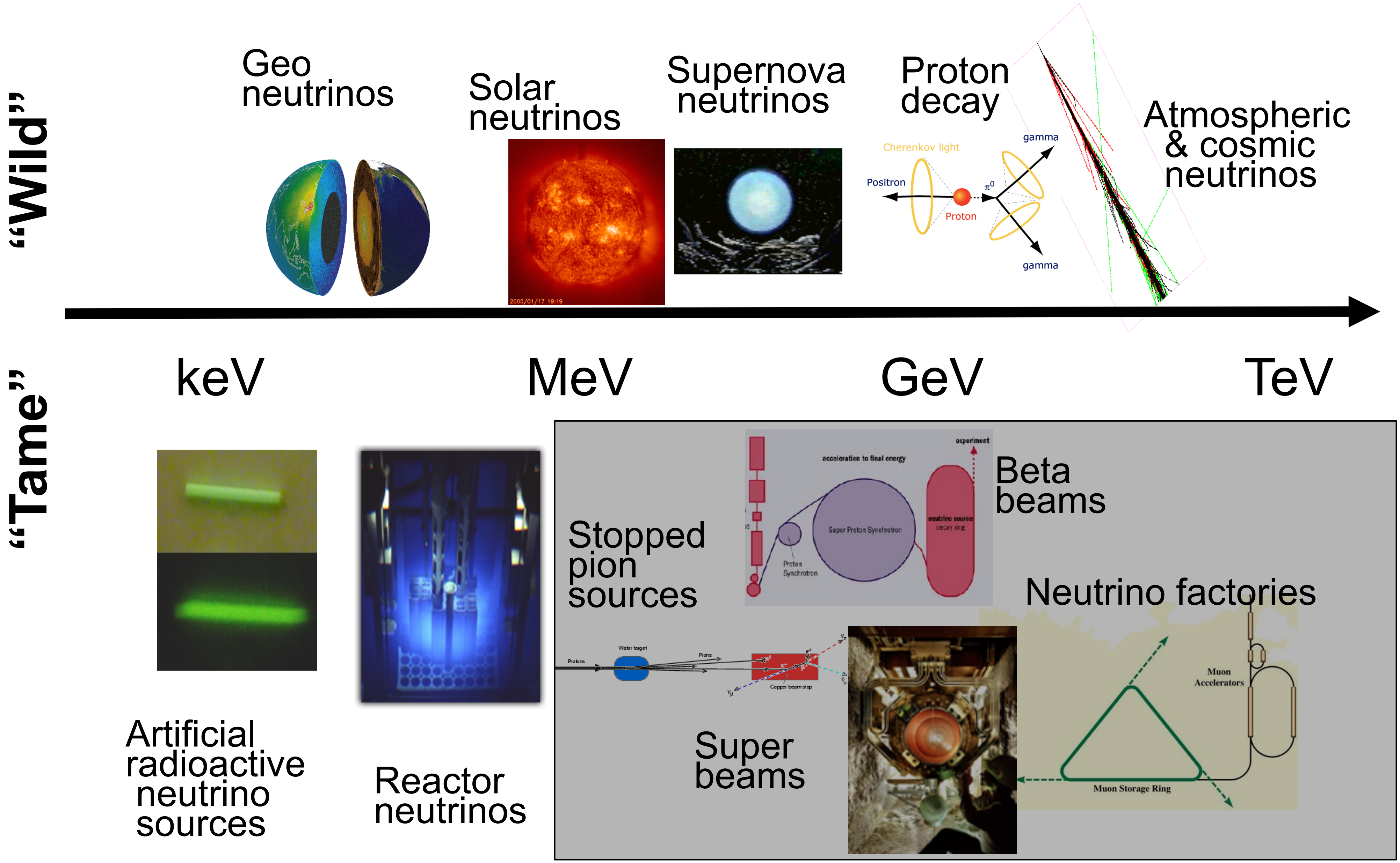
LAr Non-Oscillation Physics



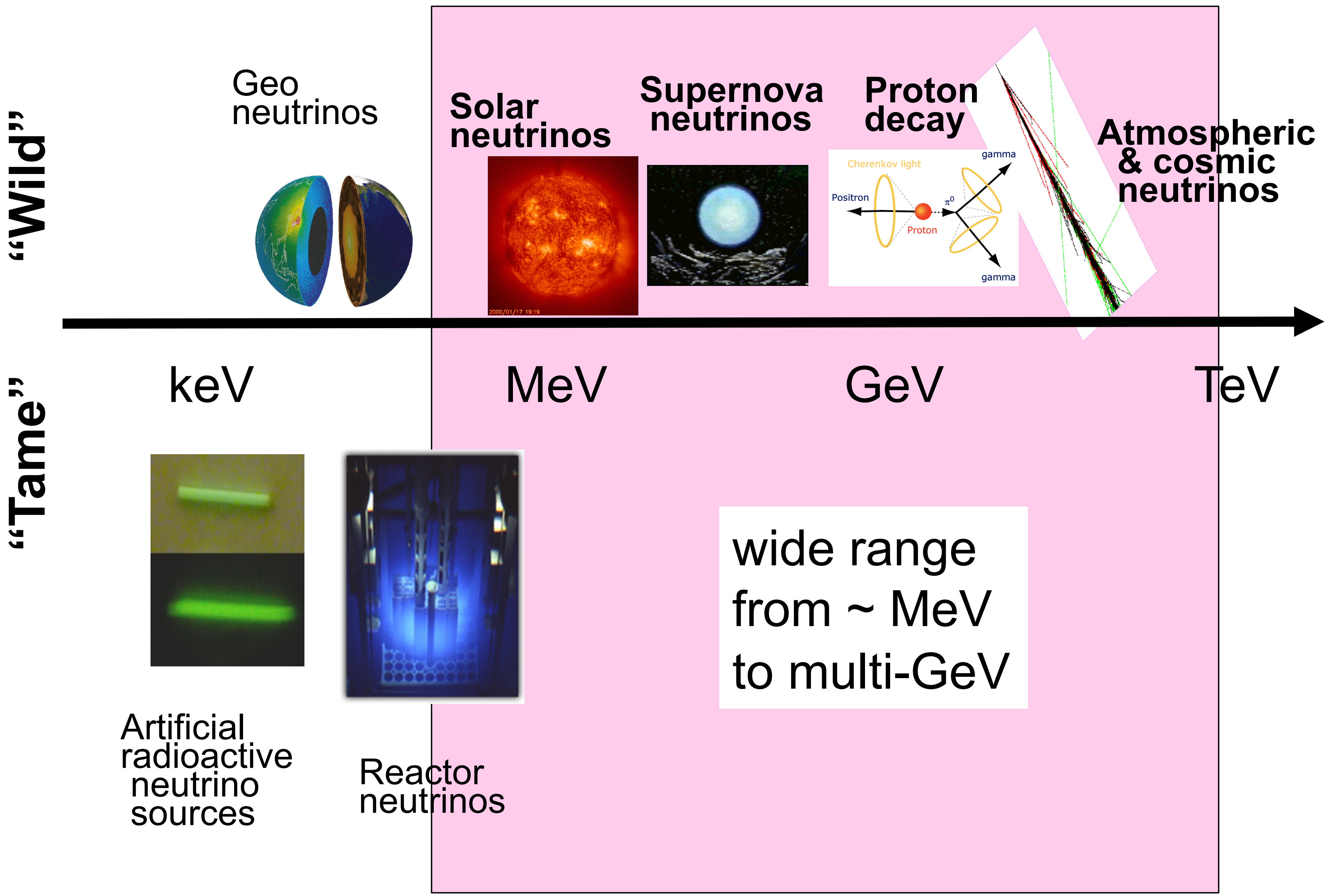
K. Scholberg, Duke University
April 21, 2015
Second International Meeting for Large Neutrino Infrastructures

- Proton decay
- Atmospheric neutrinos
- Supernova burst neutrinos

Non-Accelerator Particle Astrophysics

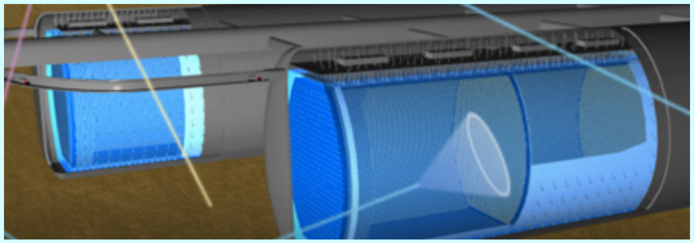


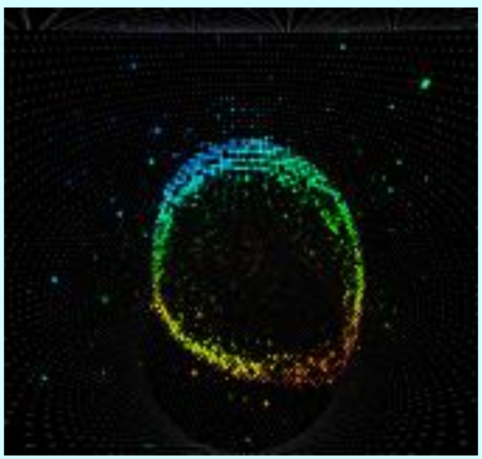
Accessible with LAr



Multi-kiloton detector technologies

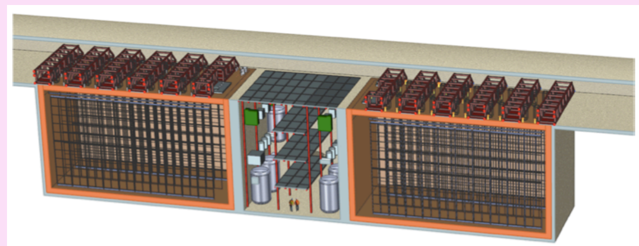
Water Cherenkov

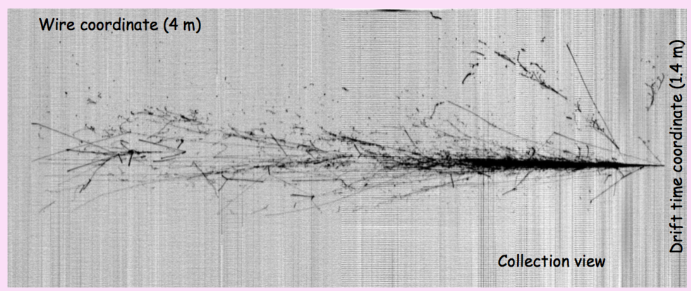




Cheap material,
huge statistics

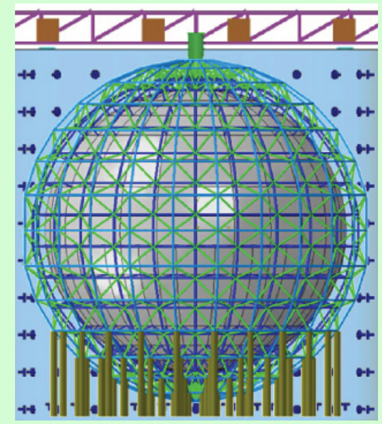
Liquid Argon

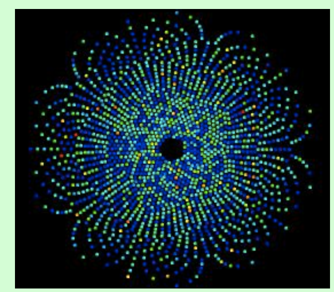




Excellent particle reconstruction

Liquid Scintillator





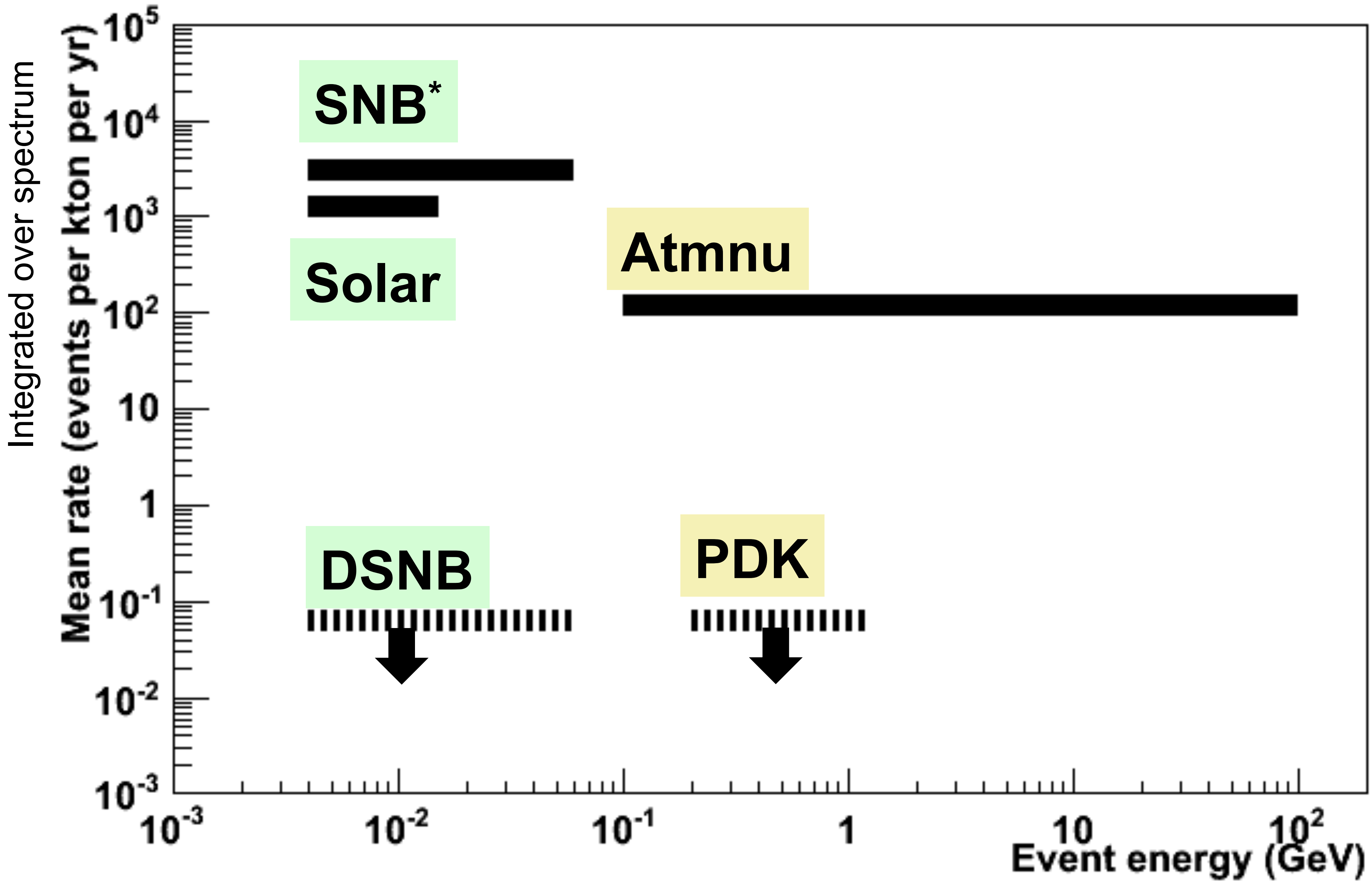
Low energy
threshold,
high resolution
@ low energy

Signal energies and expected rates in LAr

Signal	Energy range	Expected Signal Rate per kton of LAr (yr^{-1} $kton^{-1}$)
Proton decay	~ GeV	< 0.06
Atmospheric neutrinos	0.1-100 GeV	~120
Supernova burst neutrinos	few-50 MeV	~100 @ 10 kpc **over ~30 secs**
Solar neutrinos	few-15 MeV	1300
Supernova relic neutrinos	20-50 MeV	< 0.06

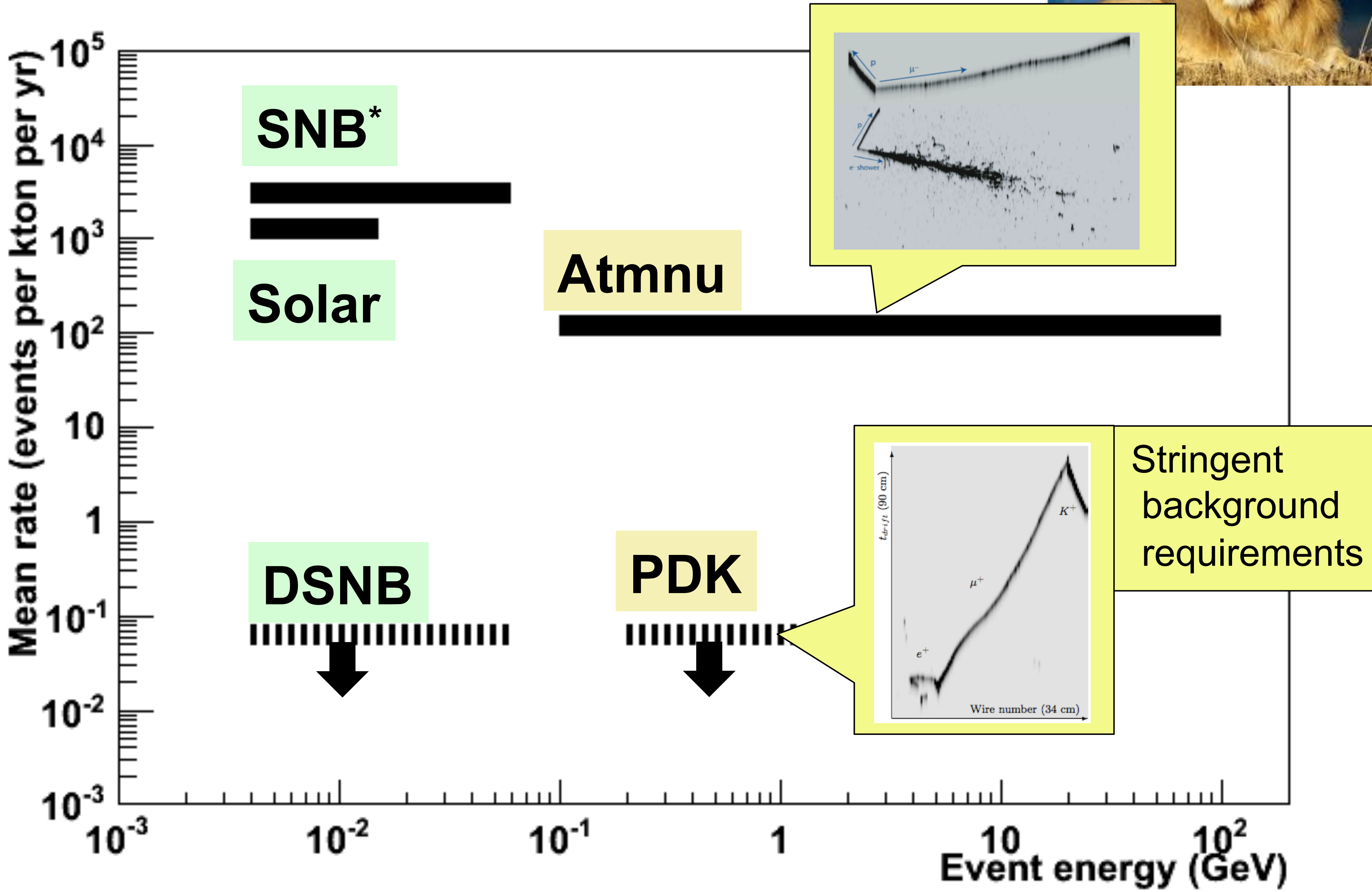
No handy beam trigger, so vulnerable to background, and require attention to triggering

Mean rate vs event energy



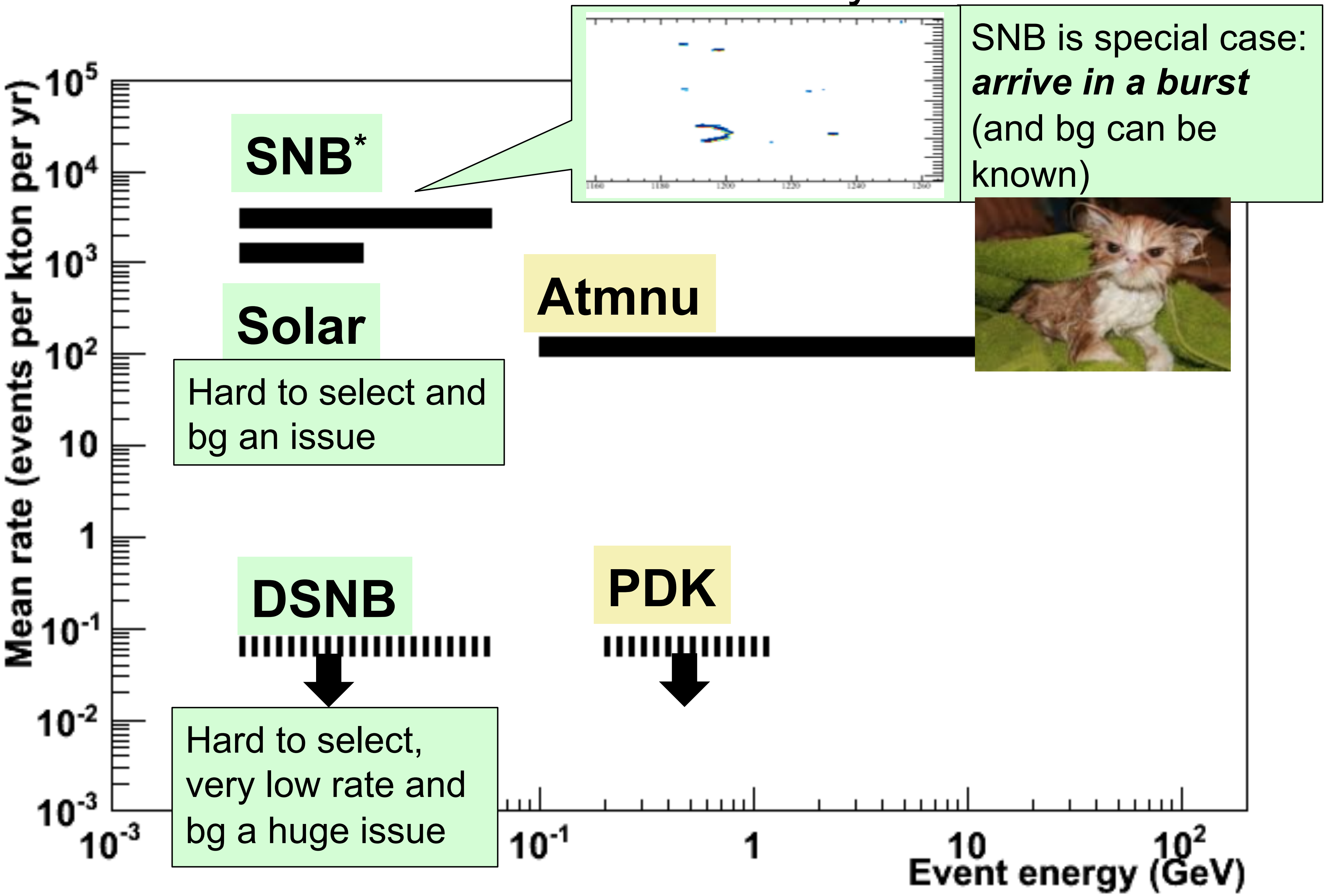
* @1 kpc, 30 s (not steady-state rate)

GeV-scale events: handsome and distinctive



* @1 kpc, 30 s

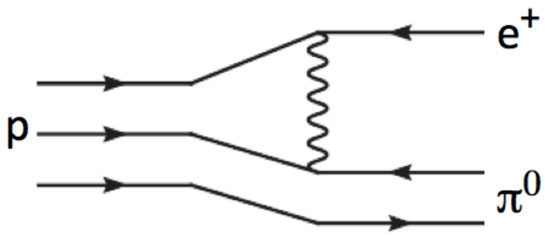
Few tens of MeV-scale events: crummy little stubs



* @1 kpc, 30 s

Baryon Number Violation

$p \rightarrow e^+ \pi^0$

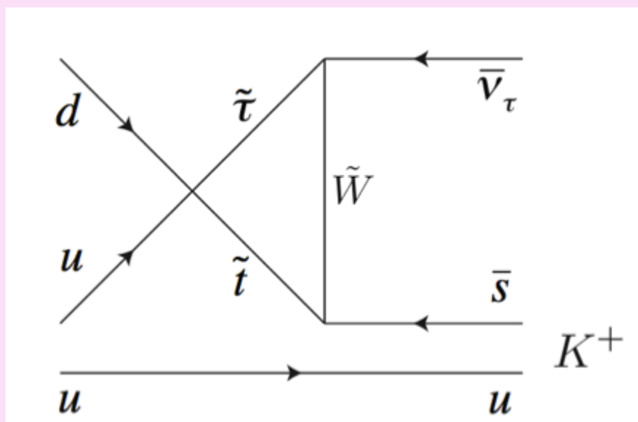


Best limit from SK (1.3×10^{34} yr, 206 kt-yr); water has high-efficiency, clean signal; LAr should be even cleaner but can't compete easily w/ no. of (free) protons in water (still would see fully-reconstructed events)

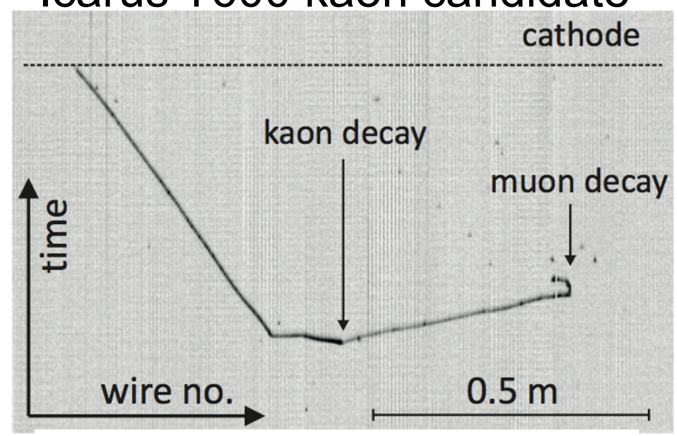
The strength of LAr:

$p \rightarrow K^+ \bar{\nu}$

SUSY
-motivated



Icarus T600 kaon candidate



$K \rightarrow \mu\nu_\mu \quad \mu \rightarrow e\nu_e\nu_\mu$

...and other modes with low efficiency in water

➔ **high quality reconstruction & lack of Cherenkov threshold enable high efficiency & purity**

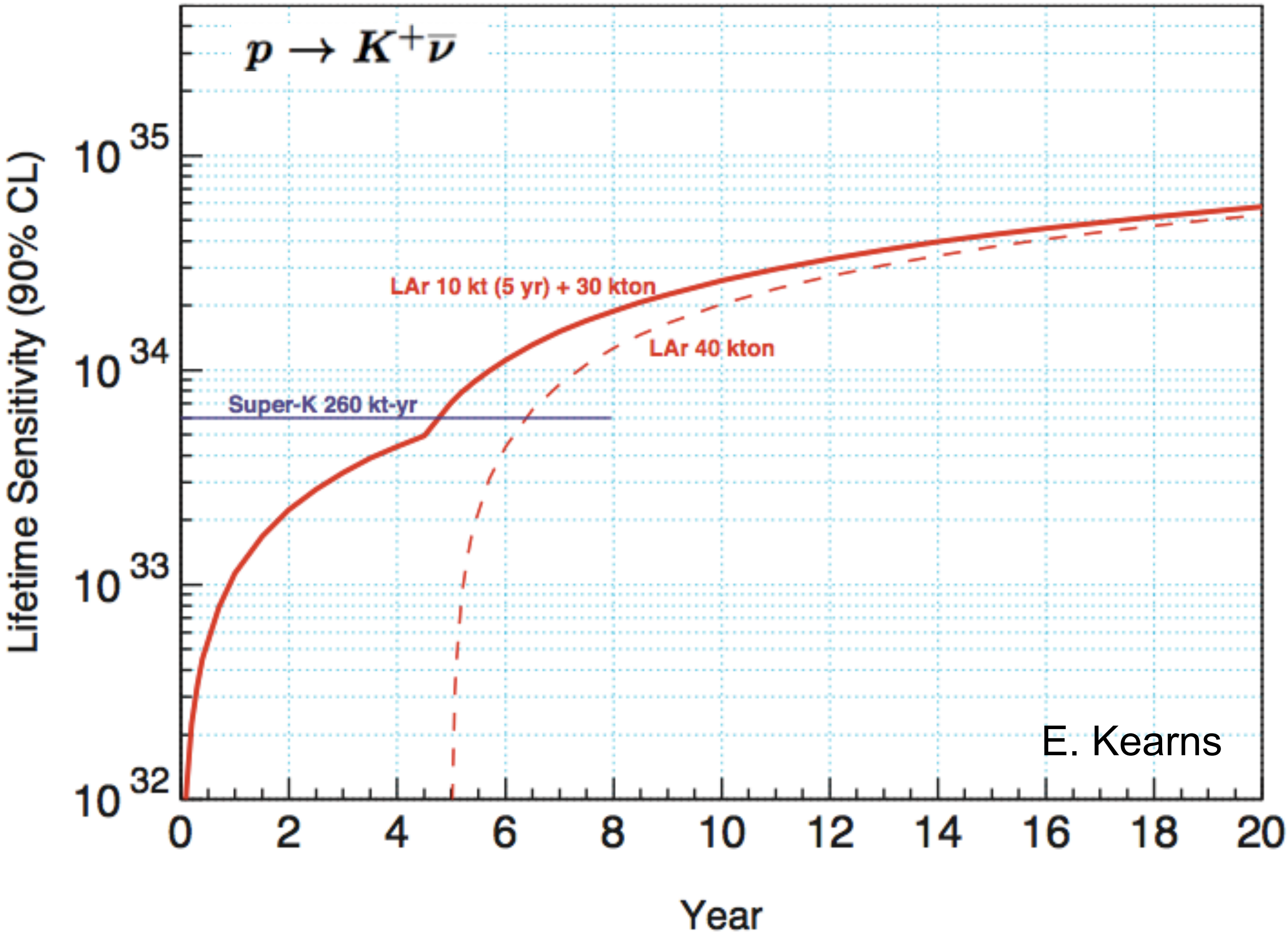
Events per Mton-year in water & argon:

Decay Mode	Water Cherenkov		Liquid Argon TPC	*
	Efficiency	Background	Efficiency	Background
$p \rightarrow K^+\overline{\nu}$	19%	4	97%	1
$p \rightarrow K^0\mu^+$	10%	8	47%	< 2
$p \rightarrow K^+\mu^-\pi^+$			97%	1
$n \rightarrow K^+e^-$	10%	3	96%	< 2
$n \rightarrow e^+\pi^-$	19%	2	44%	0.8

*Dominant bg: sneaky charge-exchanging cosmogenic K^0

High efficiency and low bg in LAr for these modes

LAr Lifetime Sensitivity



97% efficiency, 1 ev/(Mt-yr bg)

LAGUNA/LBNO preliminary studies

90% C.L. Sensitivities, 200 kT*yr

Two depths;
DUNE in between
SNO& Finland

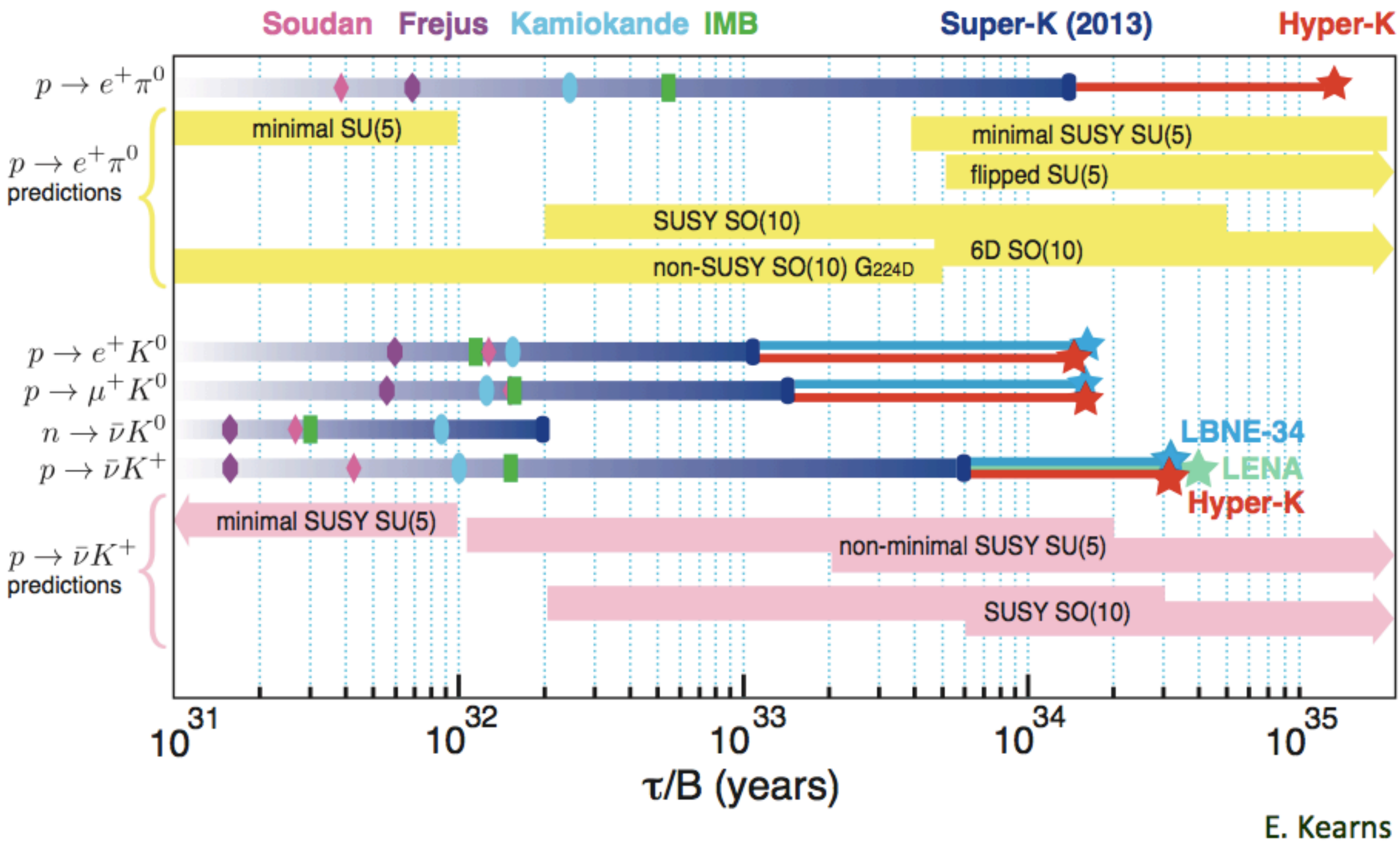
Decay Mode	Selection ε	Atmν Bkg (SNO)	Sensitivity/ 10^{33} yrs	Atmν Bkg (Finland)	Sensitivity /10^{33} yrs
$p \to e^+\pi^0$	0.3334	0.144	7.82	0	7.82
$p \to \mu^+\pi^0$	0.2568	0.047	6.02	0	6.02
$p \to e^+\eta, \eta \to 3\pi^0$	0.1479	0	3.47	0.2	3.47
$p \to \mu^+\eta, \eta \to 3\pi^0$	0.1490	0	3.49	0	3.49
$p \to e^+\rho, \rho \to \pi^+\pi^-$	0.0475	0	1.11	0	1.11
$p \to \mu^+\rho, \rho \to \pi^+\pi^-$	0.0921	0	2.16	0	2.16
$p \to e^+\omega, \omega \to \pi^+\pi^-\pi^0$	0.0424	0	0.99	0	0.99
$p \to \mu^+\omega, \omega \to \pi^+\pi^-\pi^0$	0.0610	<0.001	1.43	0	1.43
$n \to e^+\pi^-$	0.1797	0.76	3.59	0	5.26
$n \to \mu^+\pi^-$	0.1682	0.458	4.82	0	4.82
$p \to \bar{\nu}K^+$	0.7659	0	17.96	3.6	8.3

→ current SK limit 1.3×10^{34} yr (for $p \to e^+\pi^0$)

→ current SK limit 0.6×10^{34} yr (for $p \to \bar{\nu}K^+$)

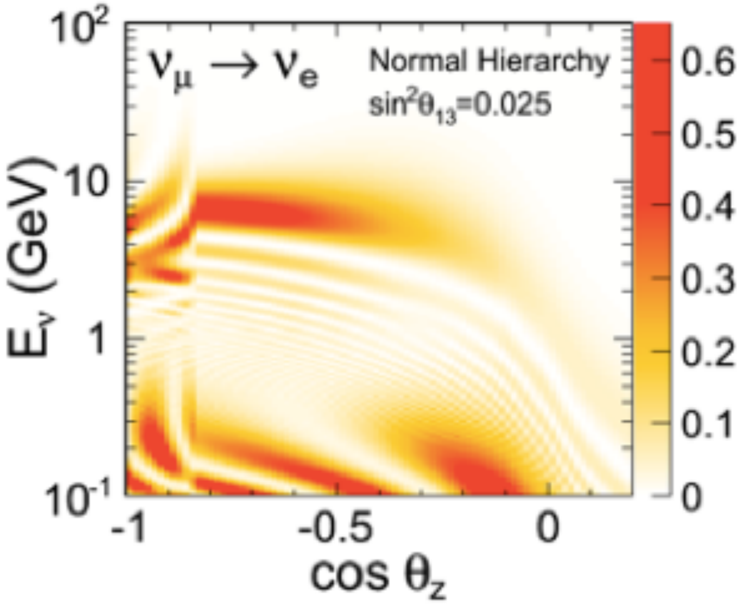
QMUL group, via S. Pascoli, J. Urheim

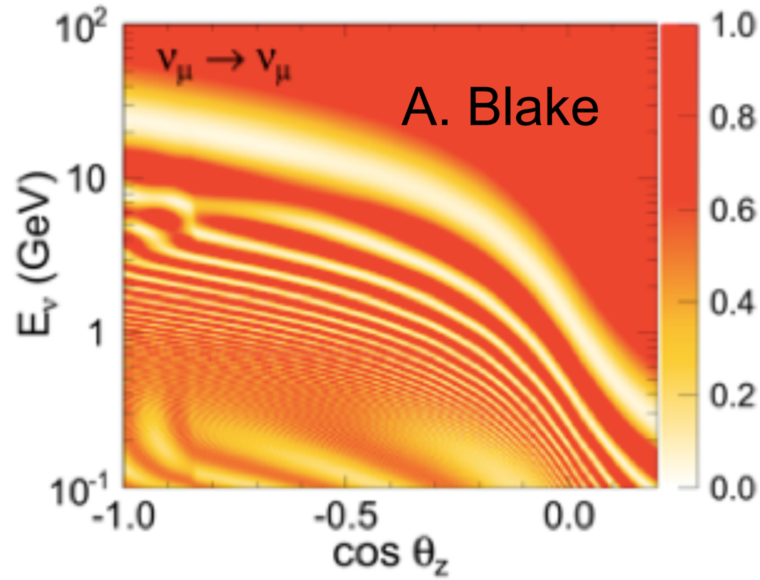
Anticipated limits wrt theory predictions



10 yr run

Atmospheric Neutrinos





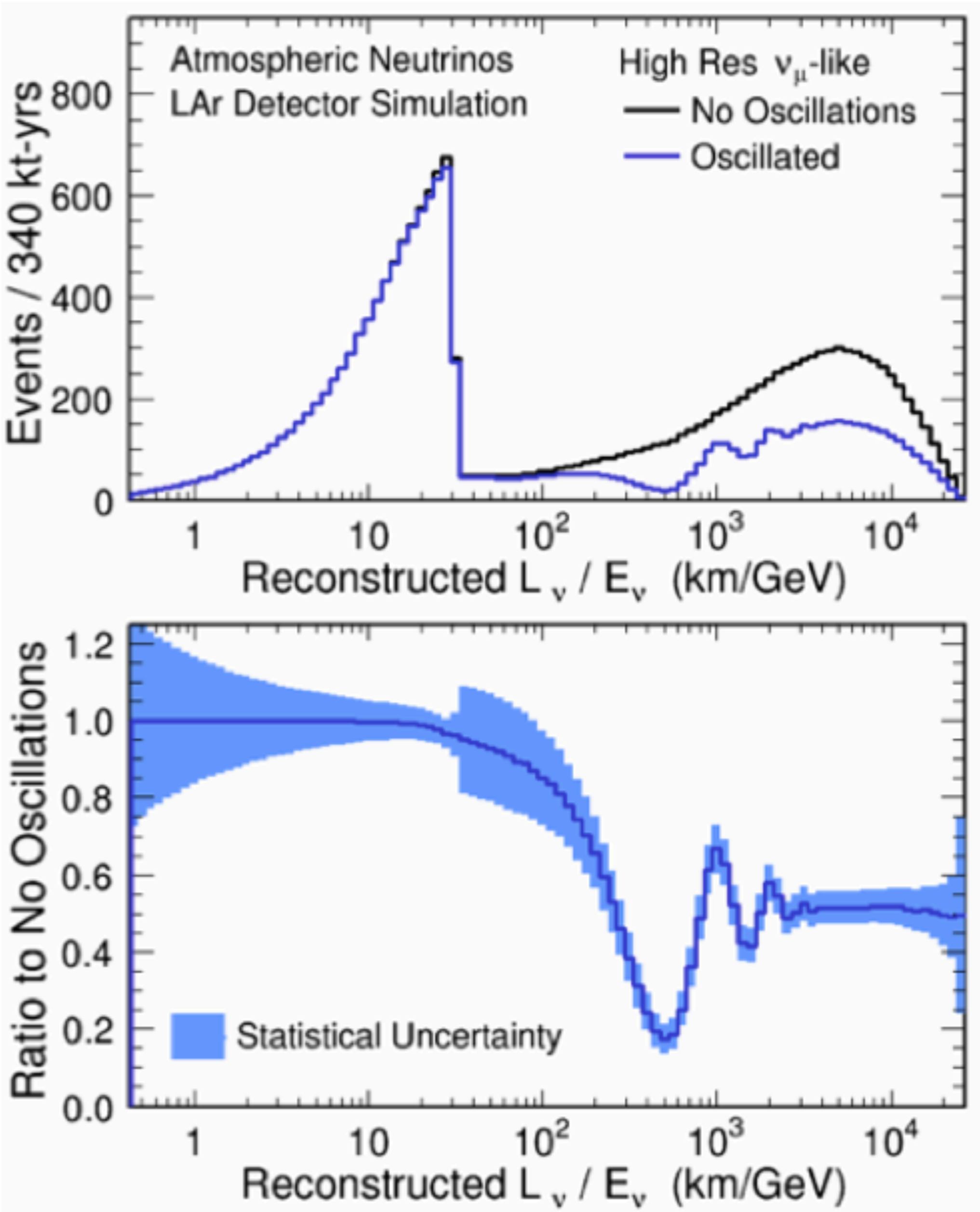
Wide range of angles and energies, sampling matter with both neutrinos and antineutrinos

Sample	Event
fully contained electron-like sample	14,053
fully contained muon-like sample	20,853
partially contained muon-like sample	6,871

in 350 kt-yr

Again, advantage of LArTPC is *precision reconstruction*

Advantage of LArTPC is *precision reconstruction*

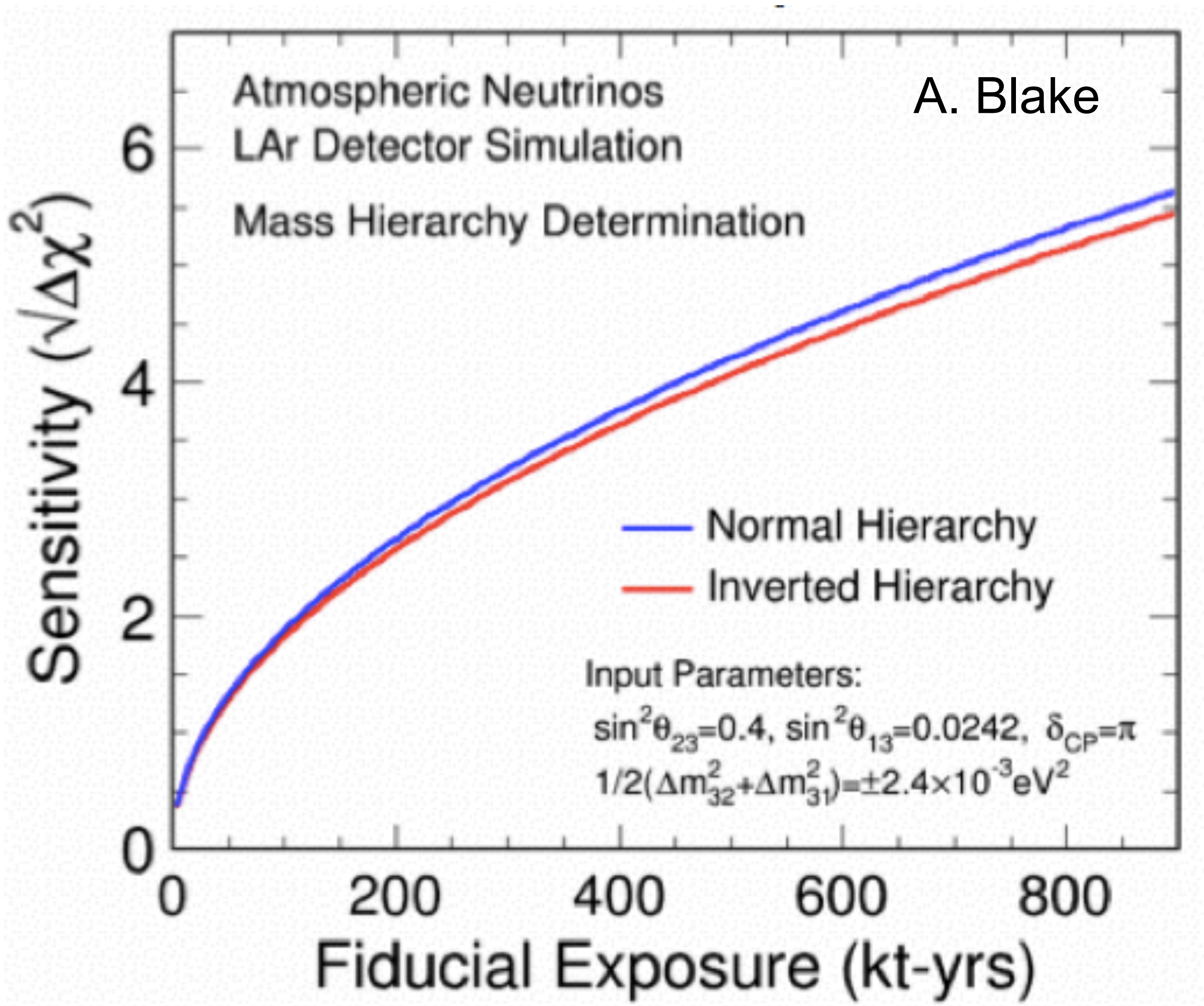


A. Blake

- better L and E
- good **nu vs nubar** separation w/o B field
  (e.g., proton tag, μdk tag)

350 kt-yr, selected sample of high-resolution events

Mass hierarchy sensitivity



- improves with nu vs nubar tagging
- unlike for beam, MH ~independent of CP δ
- also: octant, CP info; complementary to beam osc

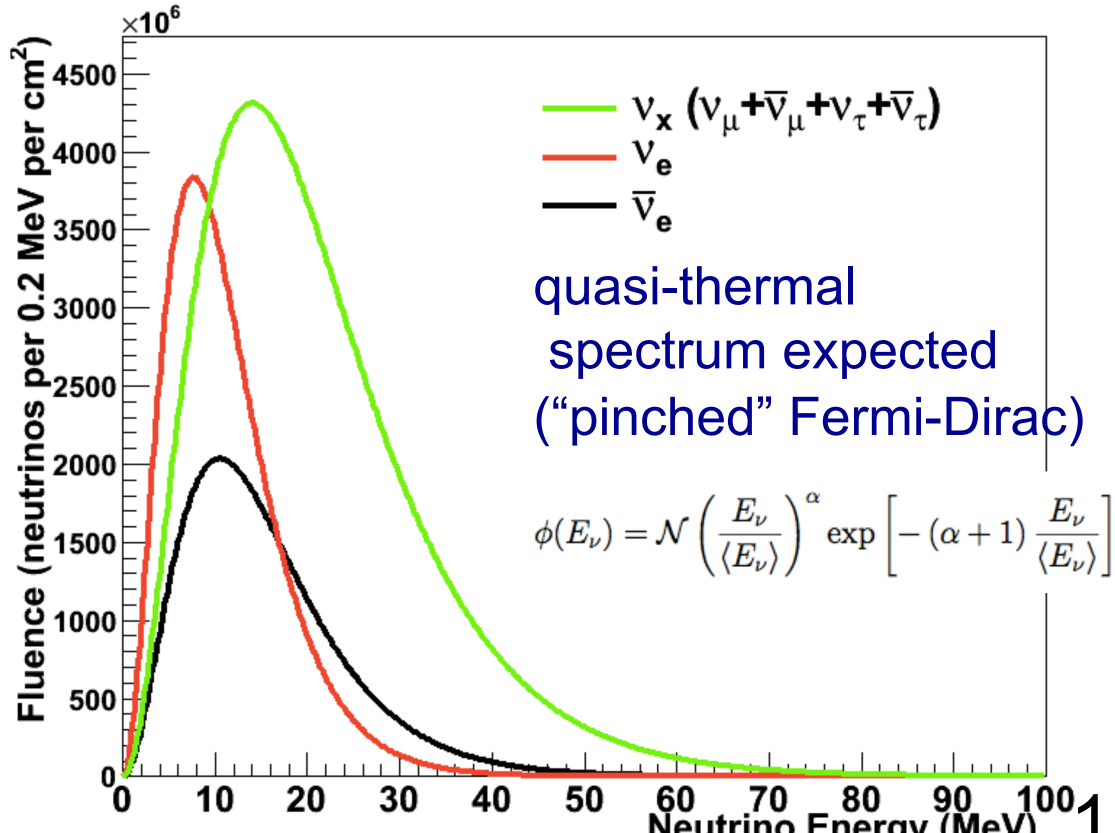
Neutrinos from core collapse

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

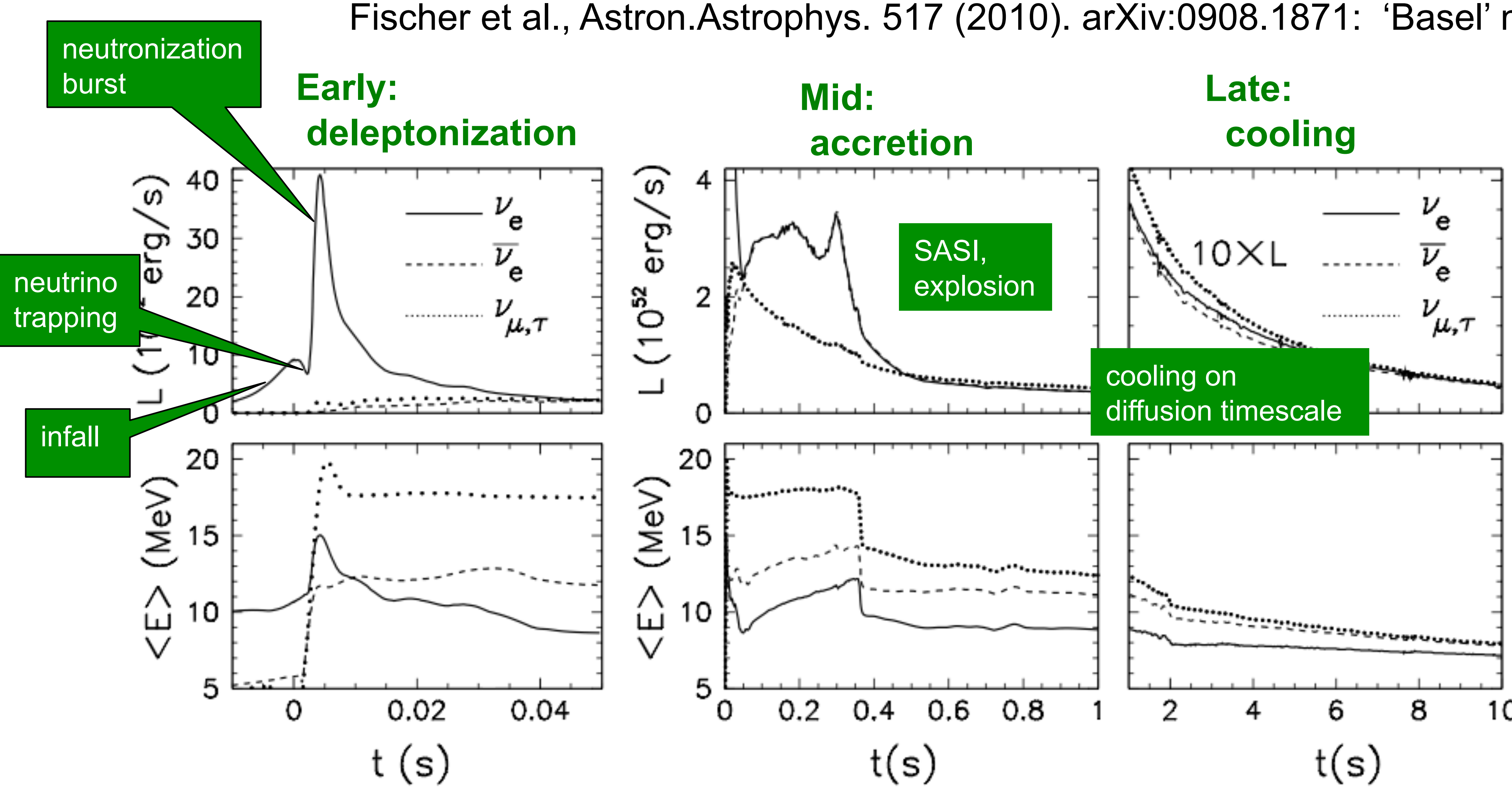
Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Expected neutrino luminosity and average energy vs time

Vast information in the *flavor-energy-time profile*

Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: 'Basel' model



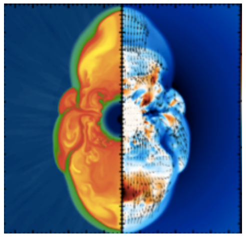
Generic feature:

(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

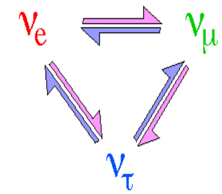
What can we learn from the next neutrino burst?

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

input from photon (GW) observations

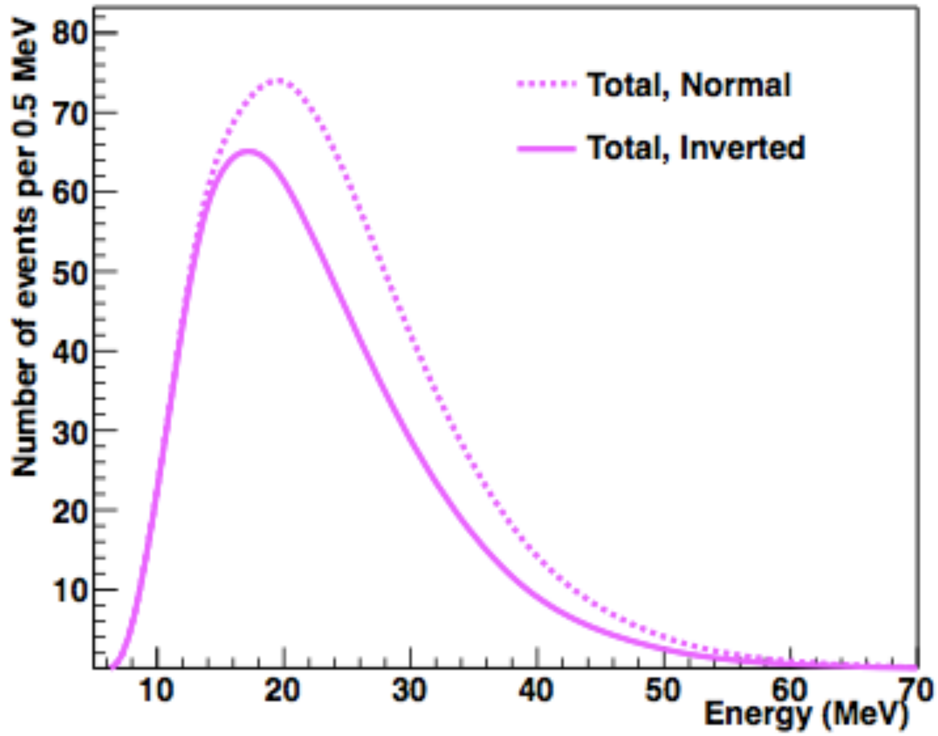
NEUTRINO and OTHER PARTICLE PHYSICS

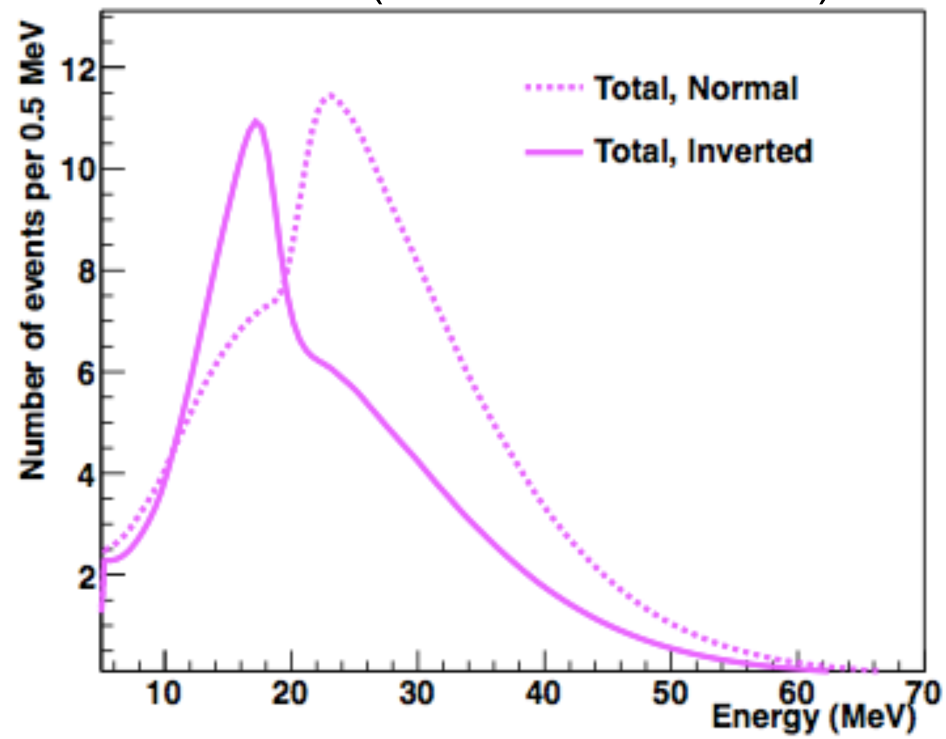
ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth,
collective effects
➔ **mass hierarchy**
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
LIV, FCNC, ...

+ EARLY ALERT

Water | Argon

1-s time slice from Duan model; 100-kt water/ 34-kt LAr (caveat: an anecdote)





mostly $\bar{\nu}_e$

mostly ν_e

Different features in different flavors → ***highly complementary***

Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Not much information in literature

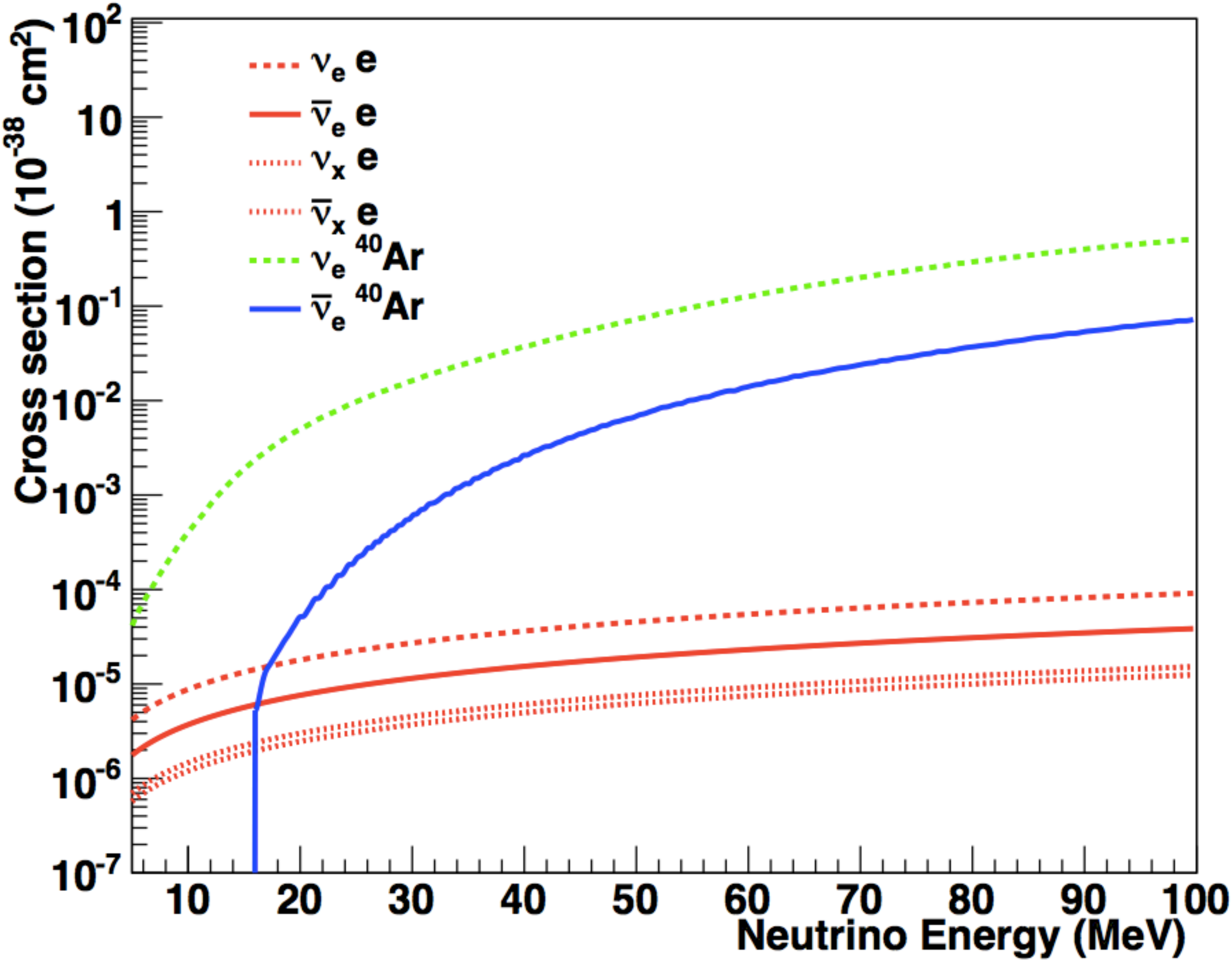
Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

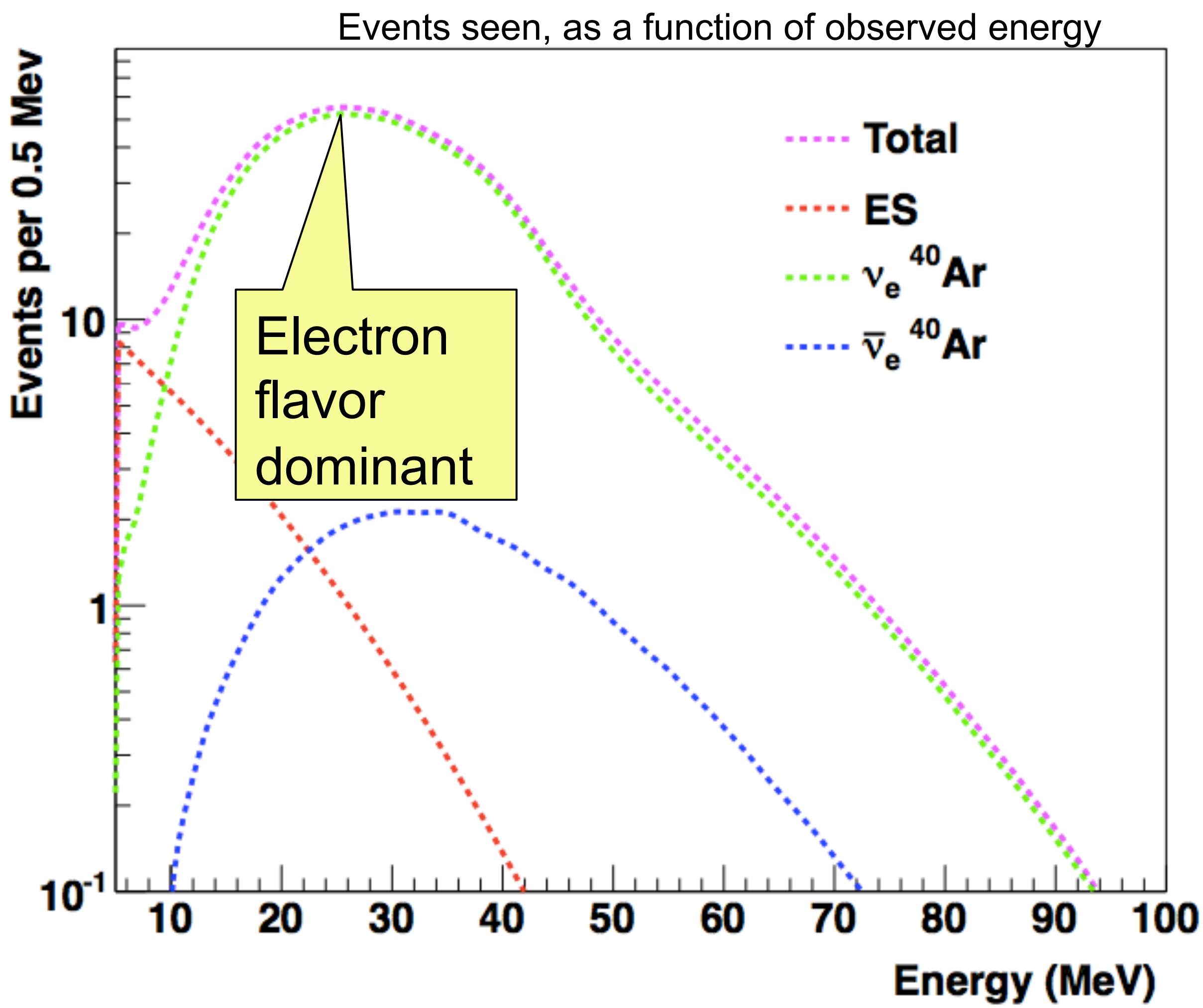
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

Cross sections in argon



Supernova signal in a liquid argon detector



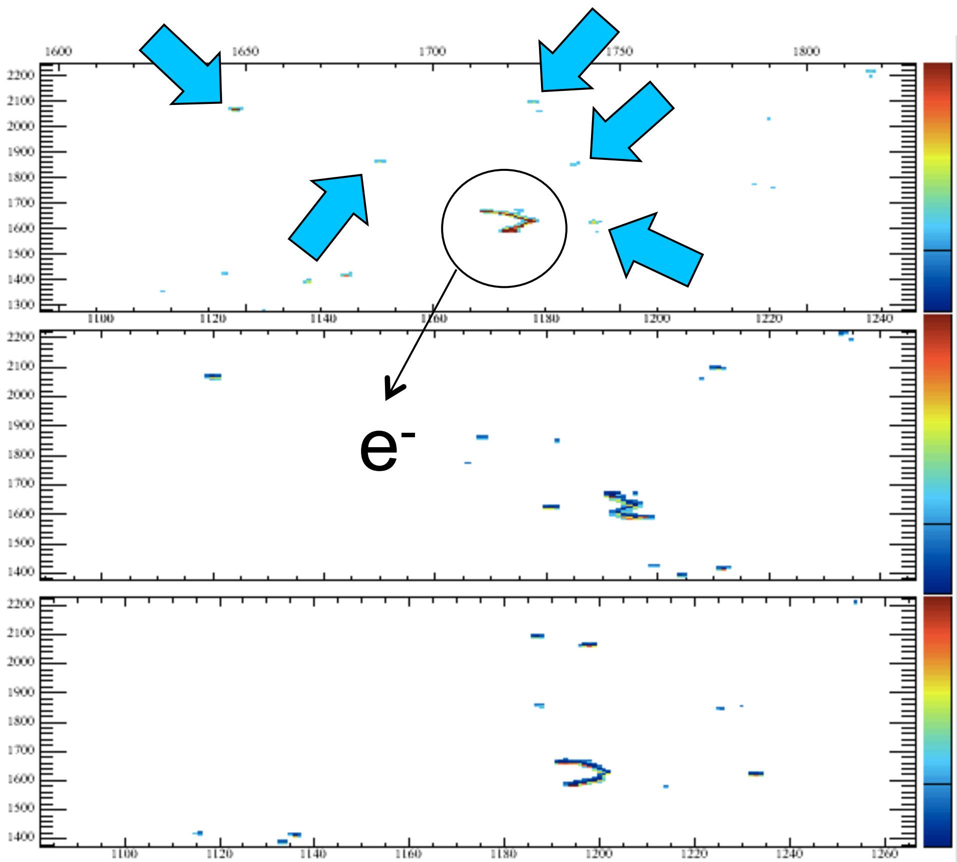
For 34 kton @ 10 kpc,
GKVM model.
ICARUS resolution

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2308	2848
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	194	134
$\nu_x + e^- \rightarrow \nu_x + e^-$	296	178
Total	**2794**	**3160**

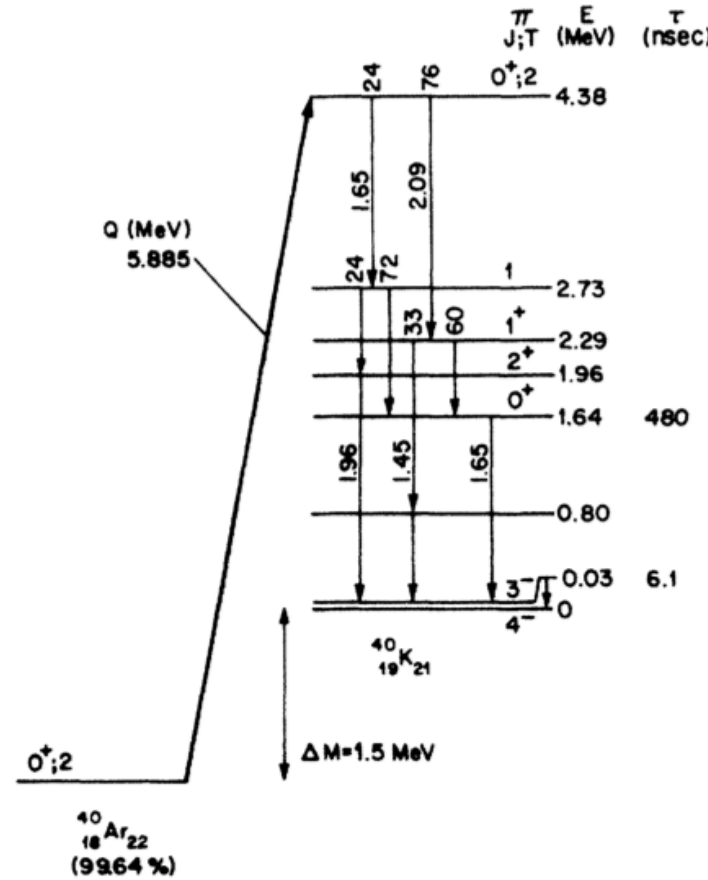
There is significant model variation

Can we tag ν_e CC interactions in argon using nuclear deexcitation γ's?

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



MicroBooNE geometry (LArSoft)



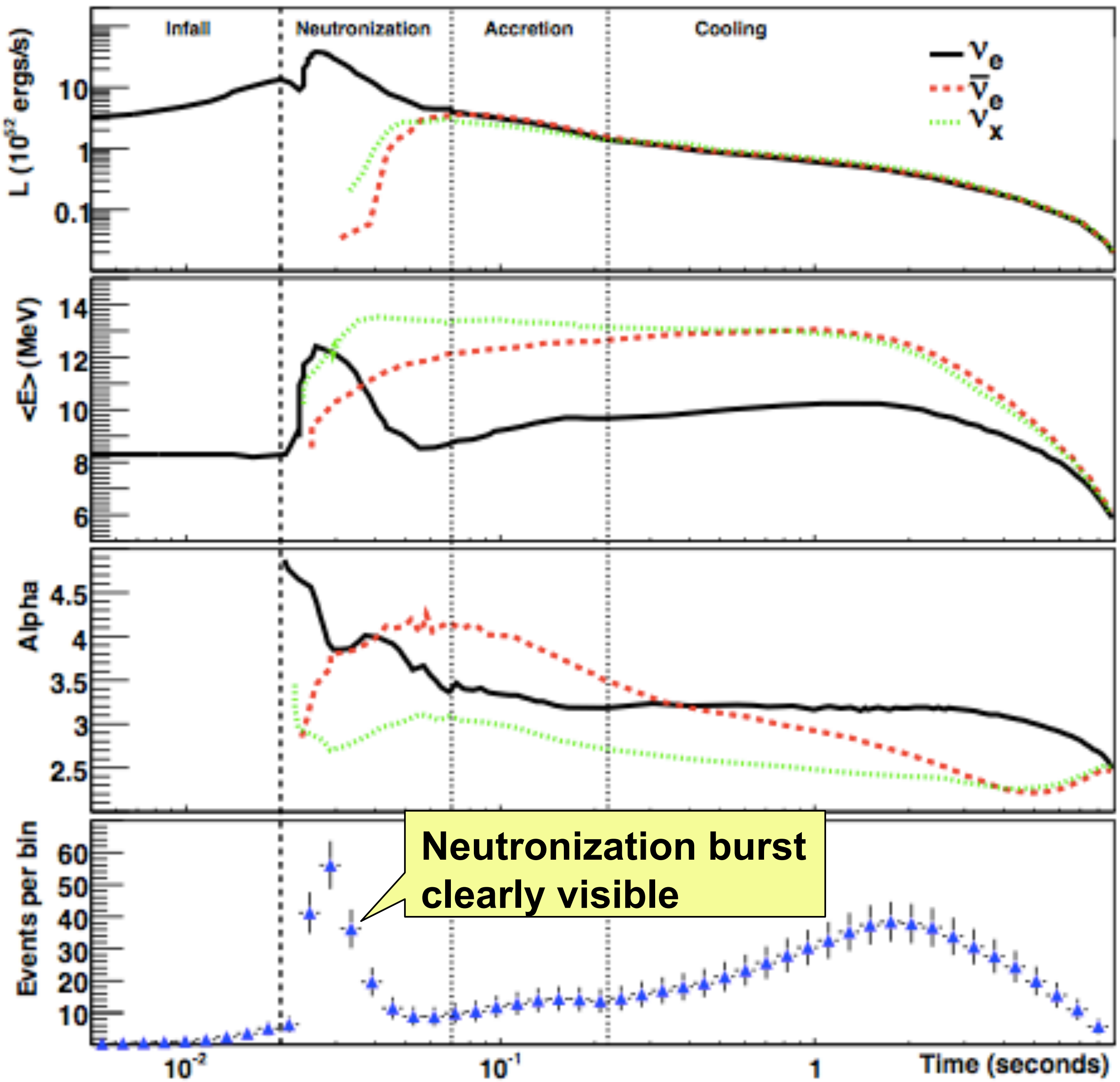
20 MeV ν_e , 14.1 MeV e^-, simple model based on R. Raghavan, PRD 34 (1986) 2088

Improved modeling based on ^{40}Ti (^{40}K mirror) β decay measurements possible

Direct measurements (and theory) needed!

Need to understand efficiency for given technology

Example of supernova burst signal in 34 kton of LAr



luminosity

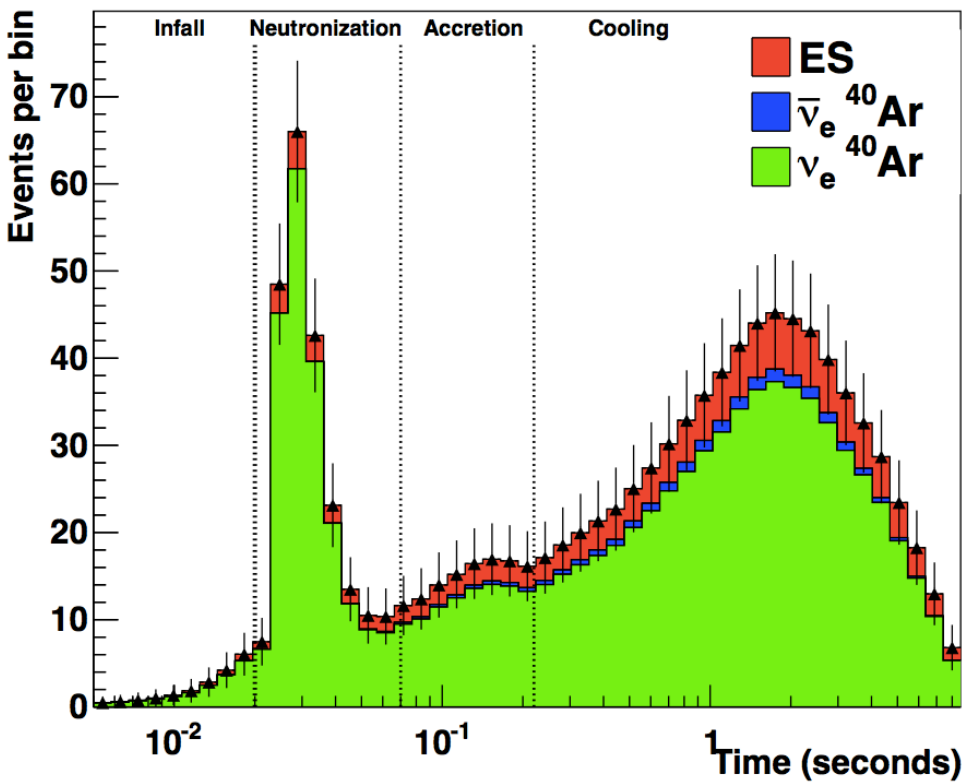
average ν energy

pinching
(large α ➔ suppressed tails)

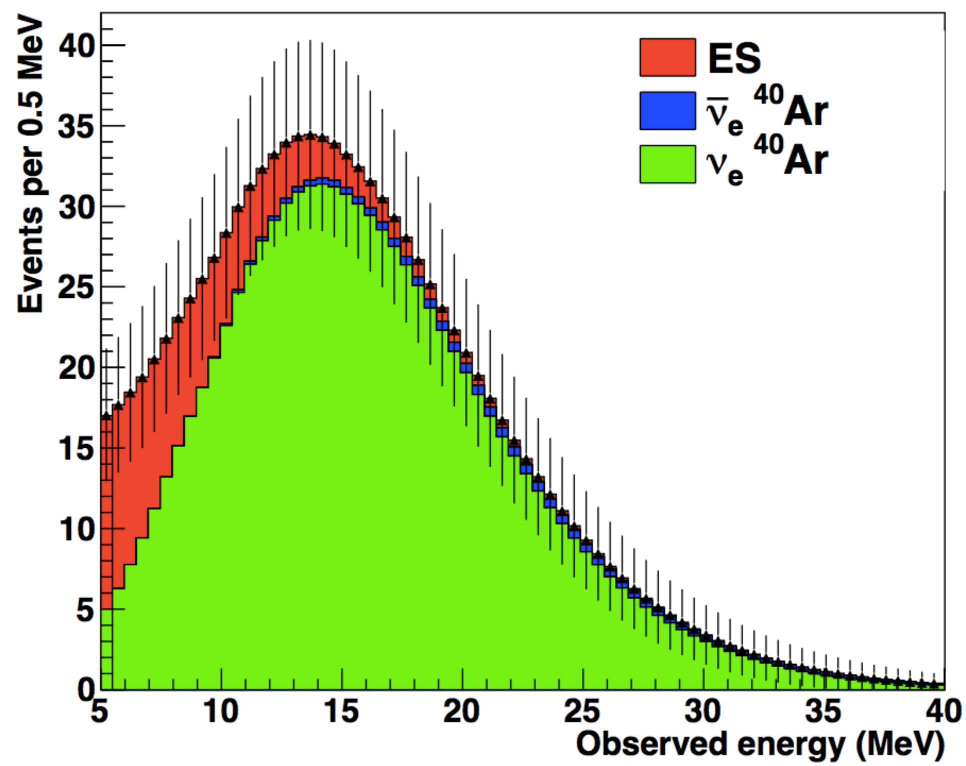
See the ν_e light curve!

Flux from Huedepohl et al., PRL 104 (2010) 251101 ("Garching") @ 10 kpc; assuming Bueno et al. resolution

Flavor composition as a function of time



Energy spectra integrated over time

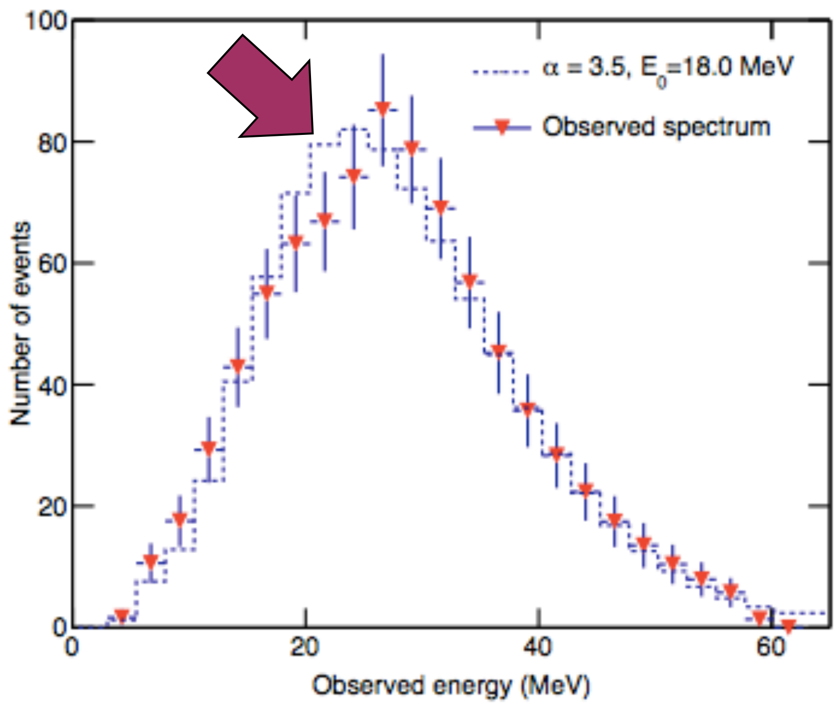


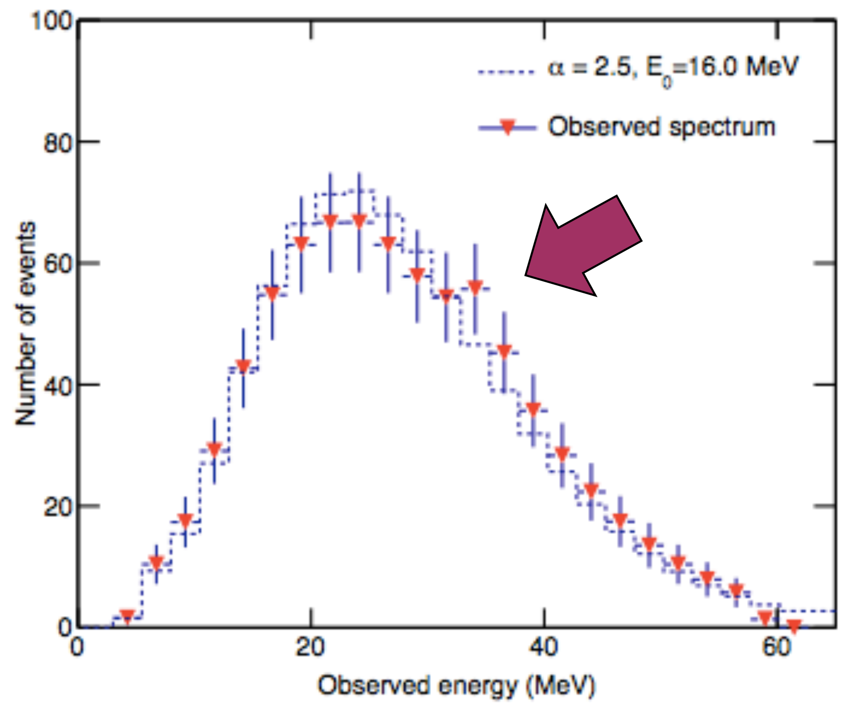
For 40 kton @ 10 kpc,
Garching model

Another anecdote:

A. Friedland, H. Duan, JJ Cherry, KS

1-sec integrated spectra in 34-kton LAr, few sec apart for 10-kpc SN, NMH

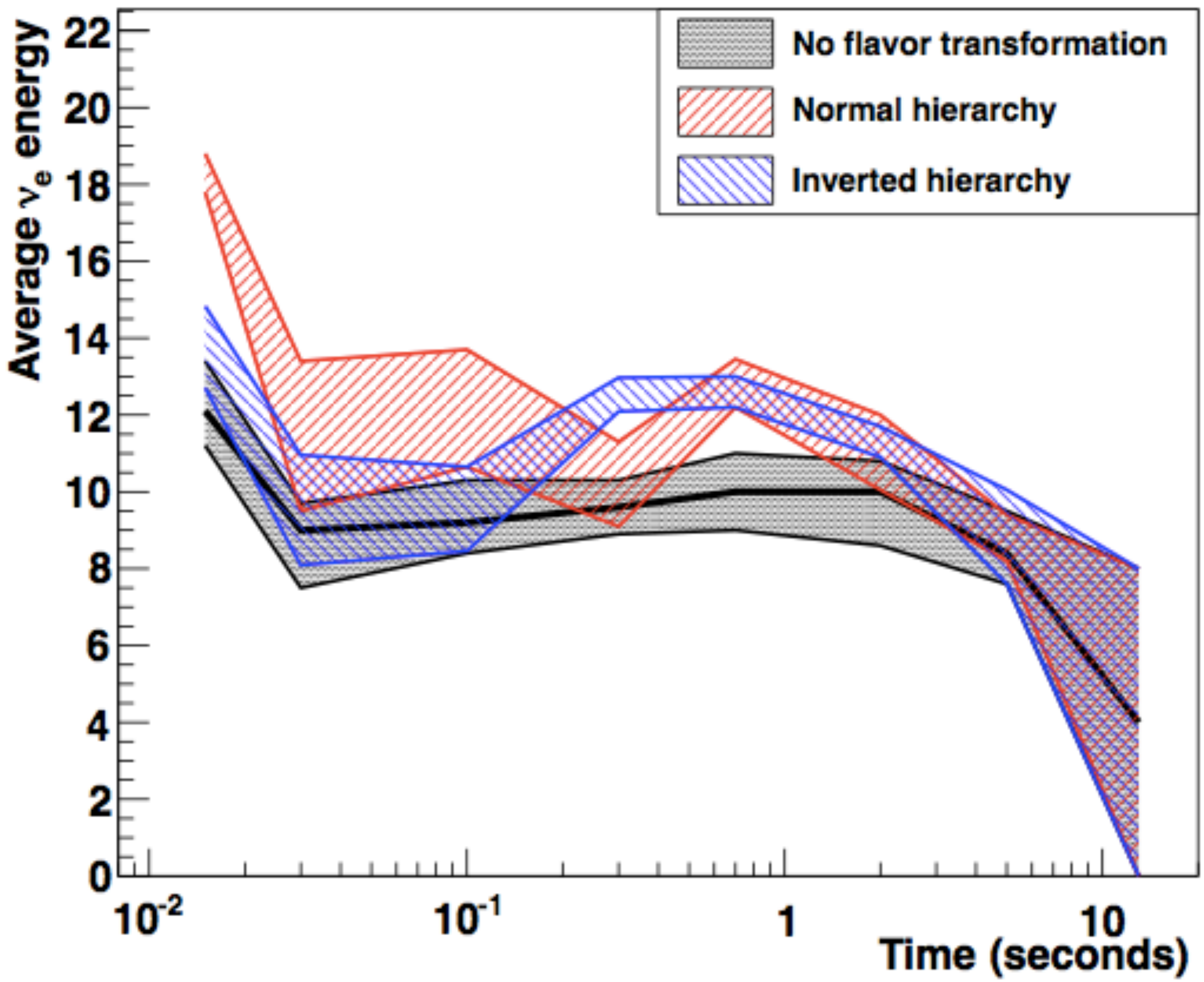




MH-dependent "non-thermal" features clearly visible as shock sweeps through the supernova

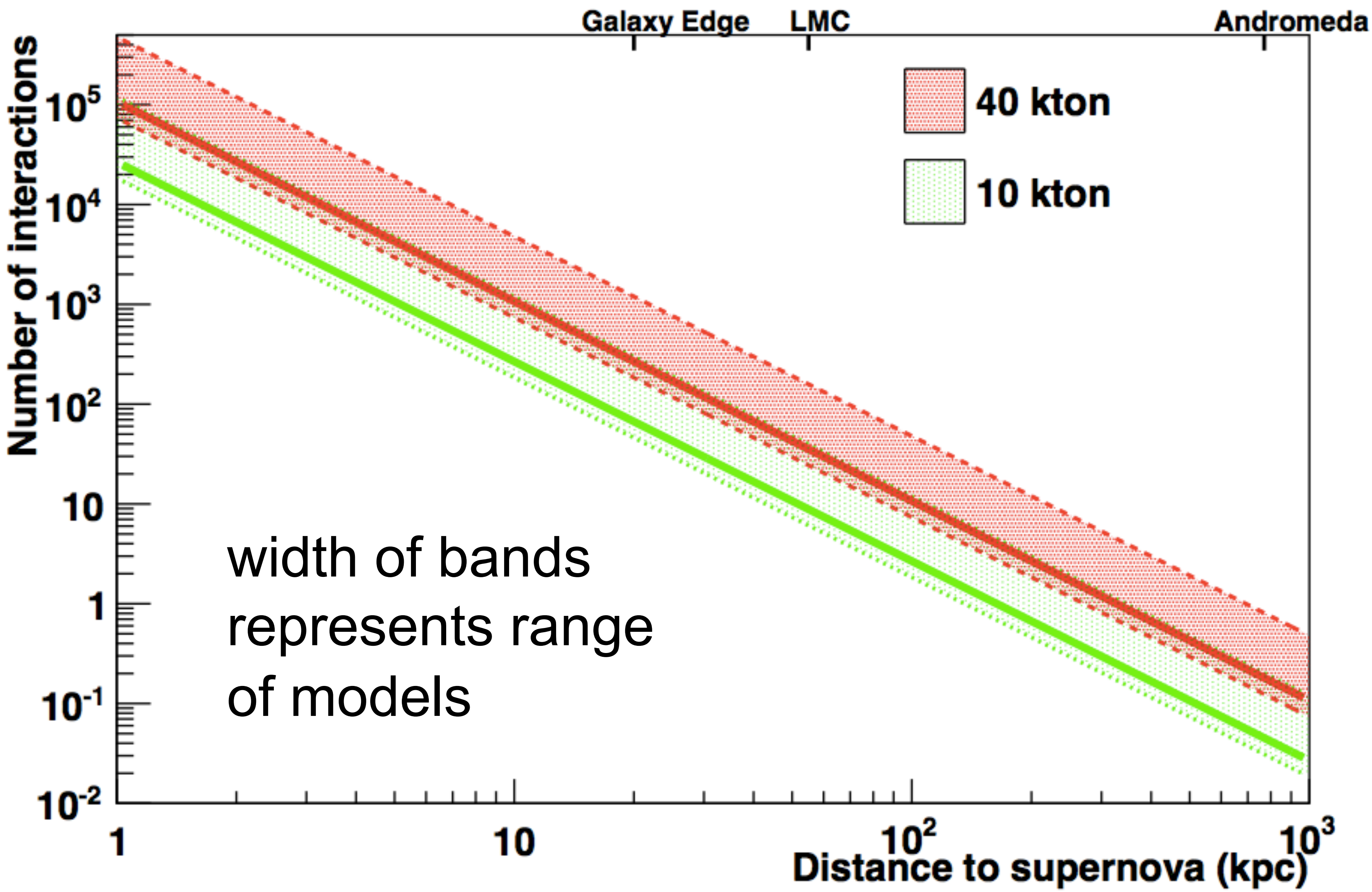
And another:

A. Friedland, H. Duan, JJ Cherry, KS

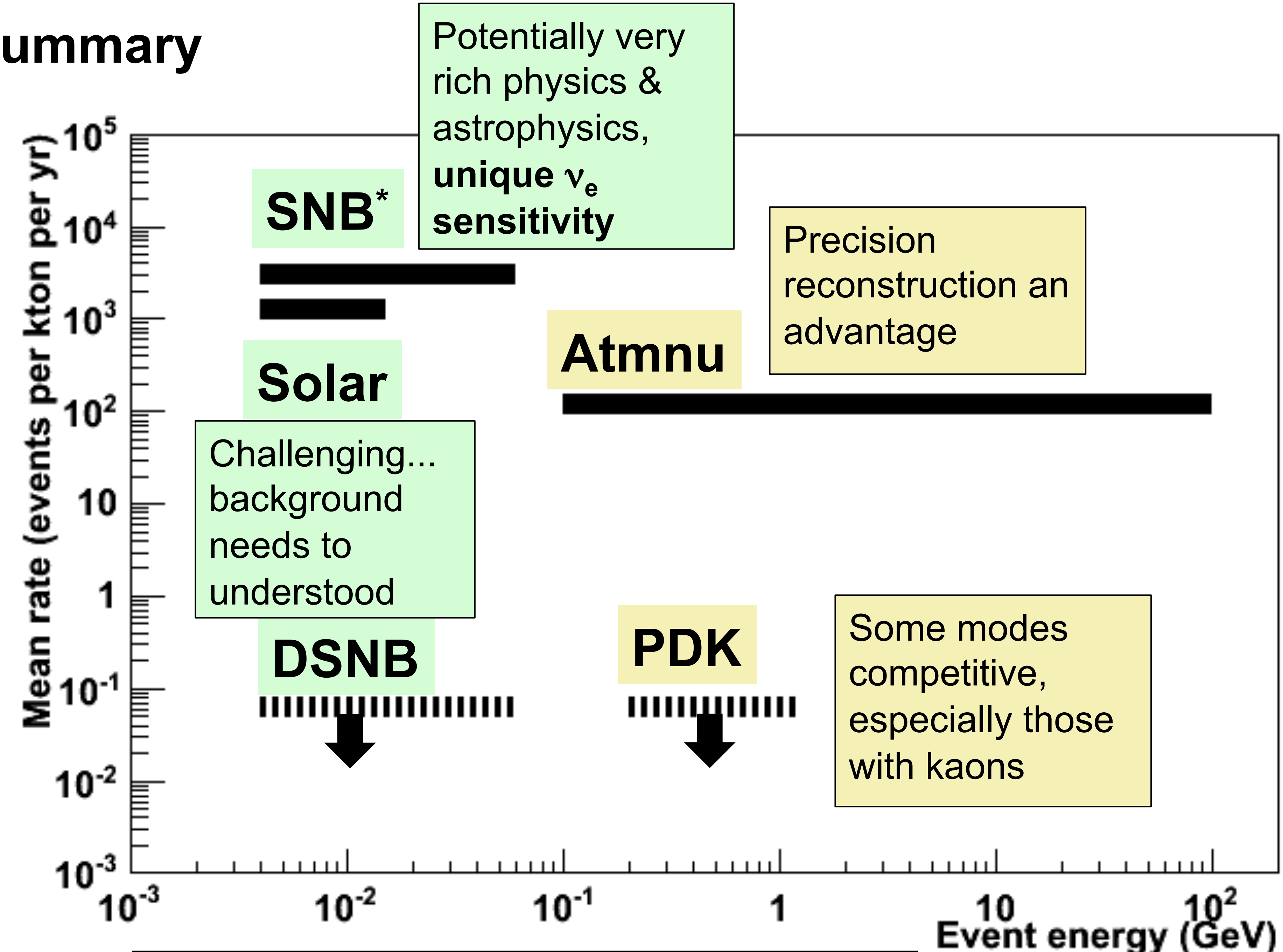


Average ν_e energy from fit to "pinched thermal",
34-kton LAr @ 10 kpc, including collective oscillations ➔
clearly, there's information in the spectral evolution

Events in LAr vs distance



Summary



In all cases, work underway to understand detector capabilities & requirements