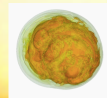
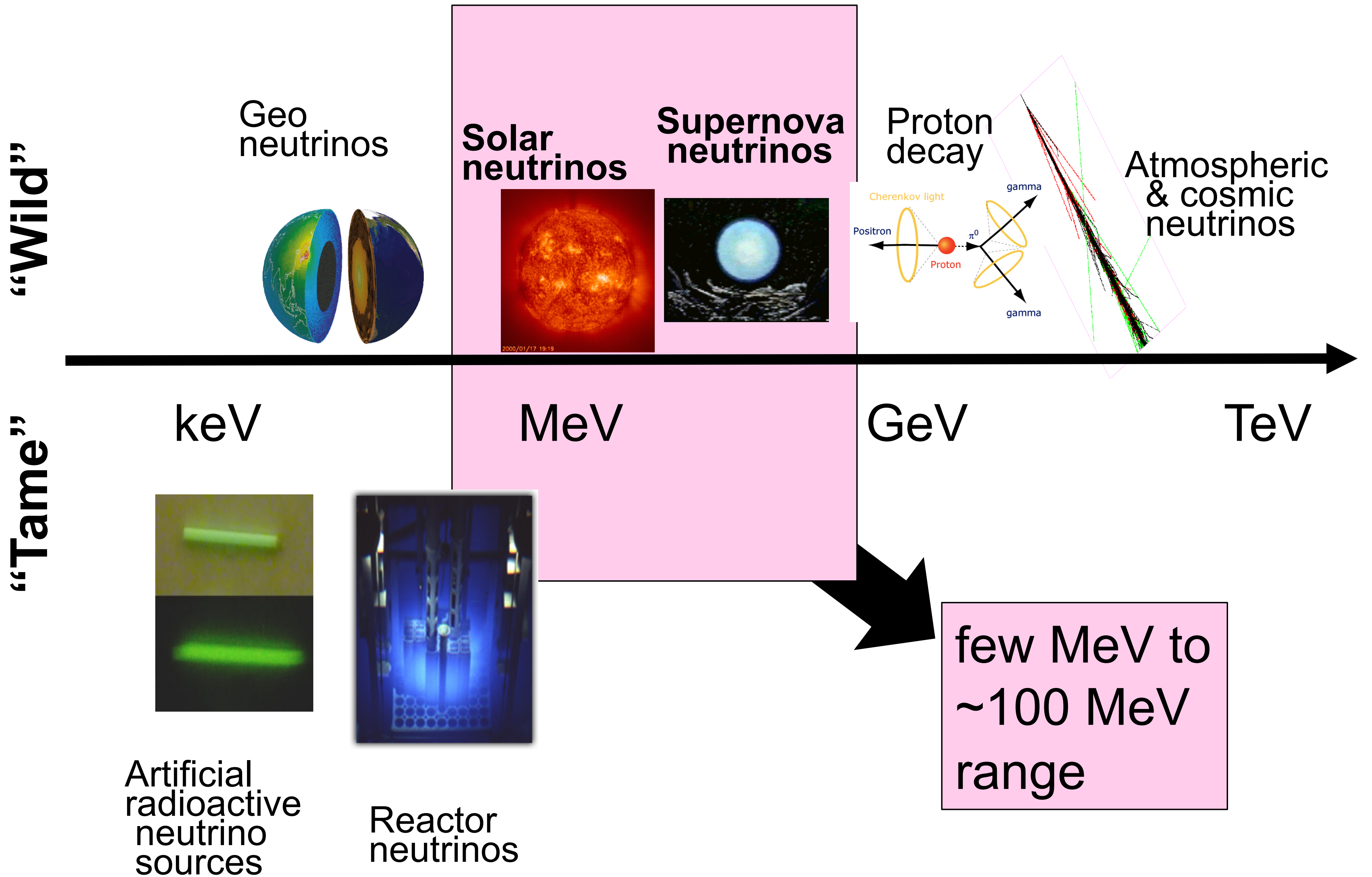
Supernova Neutrinos in DUNE

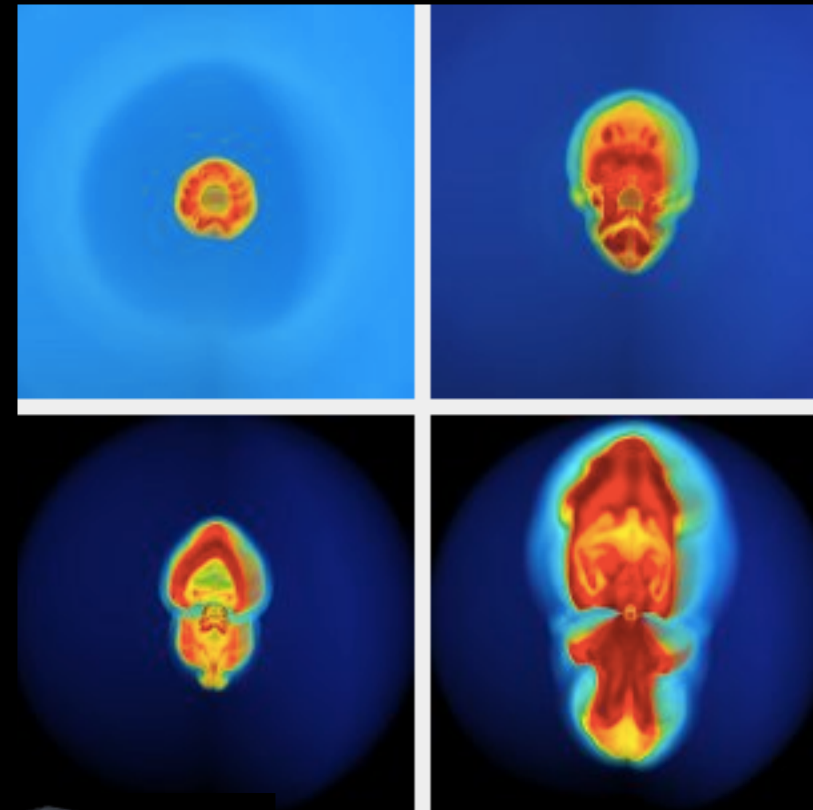


K. Scholberg, Duke University
April 28, 2016
Neutrino Latin America Workshop
Fermilab

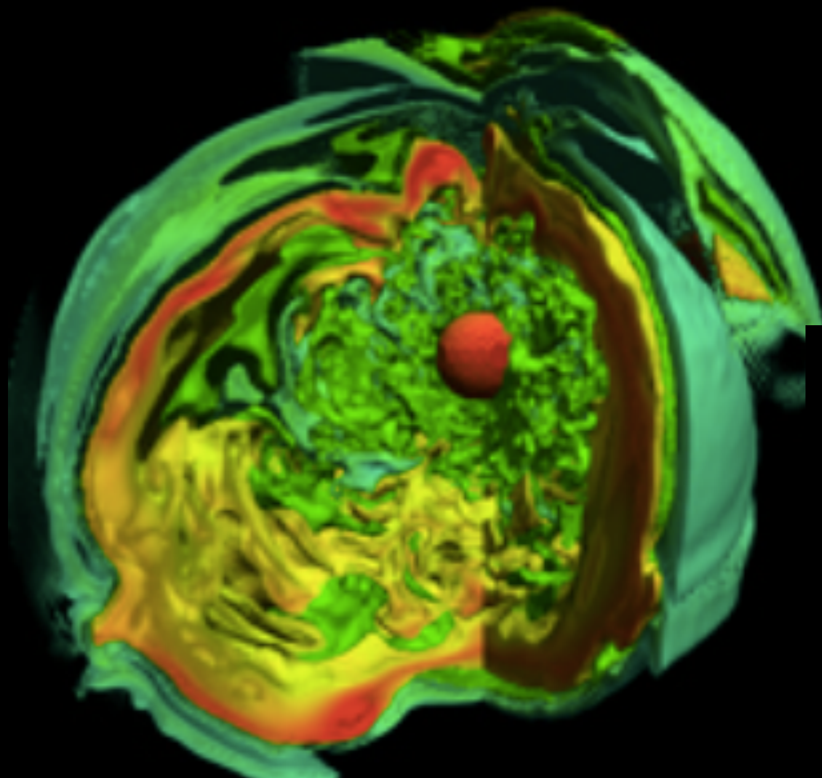
Signals accessible underground



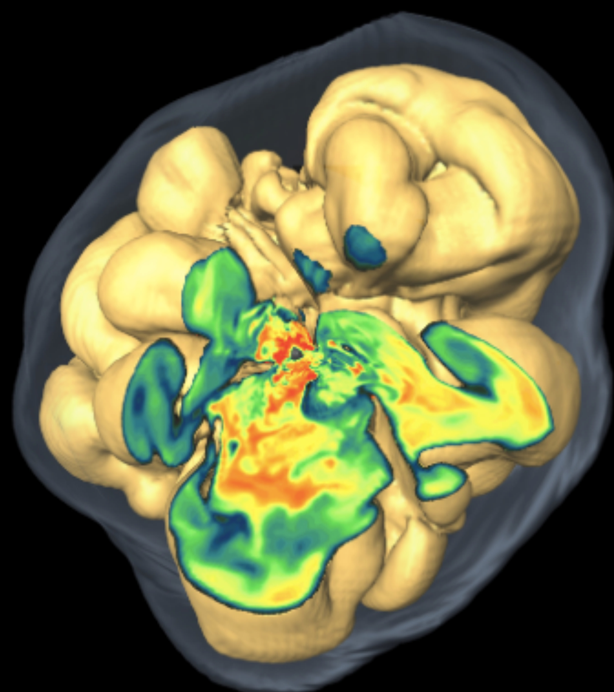
The core-collapse supernova explosion is still not well understood... numerical study ongoing



Marek & Janka



Blondin, Mezzacappa, DeMarino



Neutrinos are intimately involved

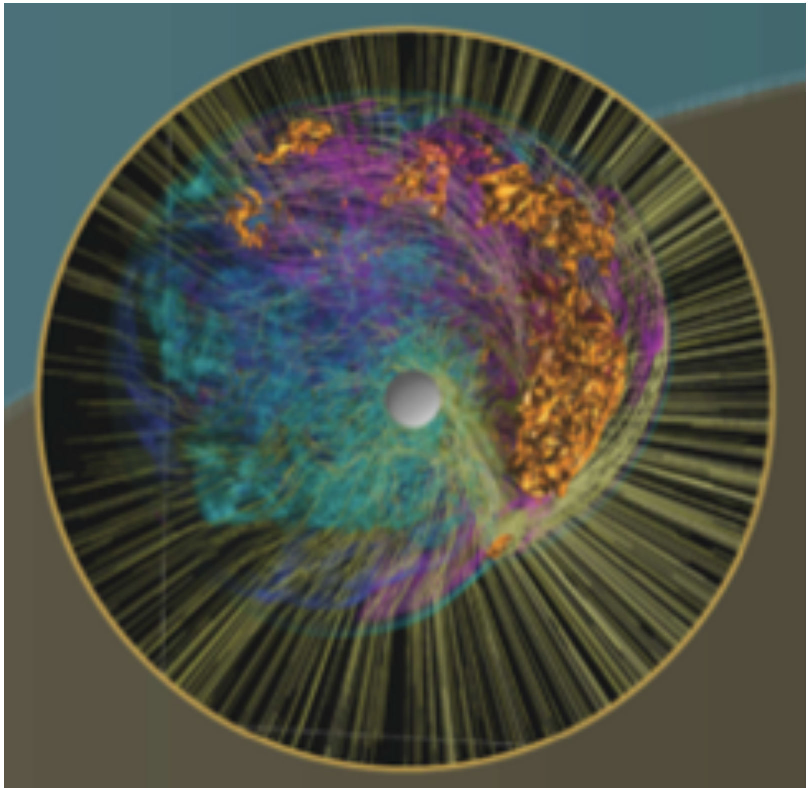
Neutrinos from core collapse

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

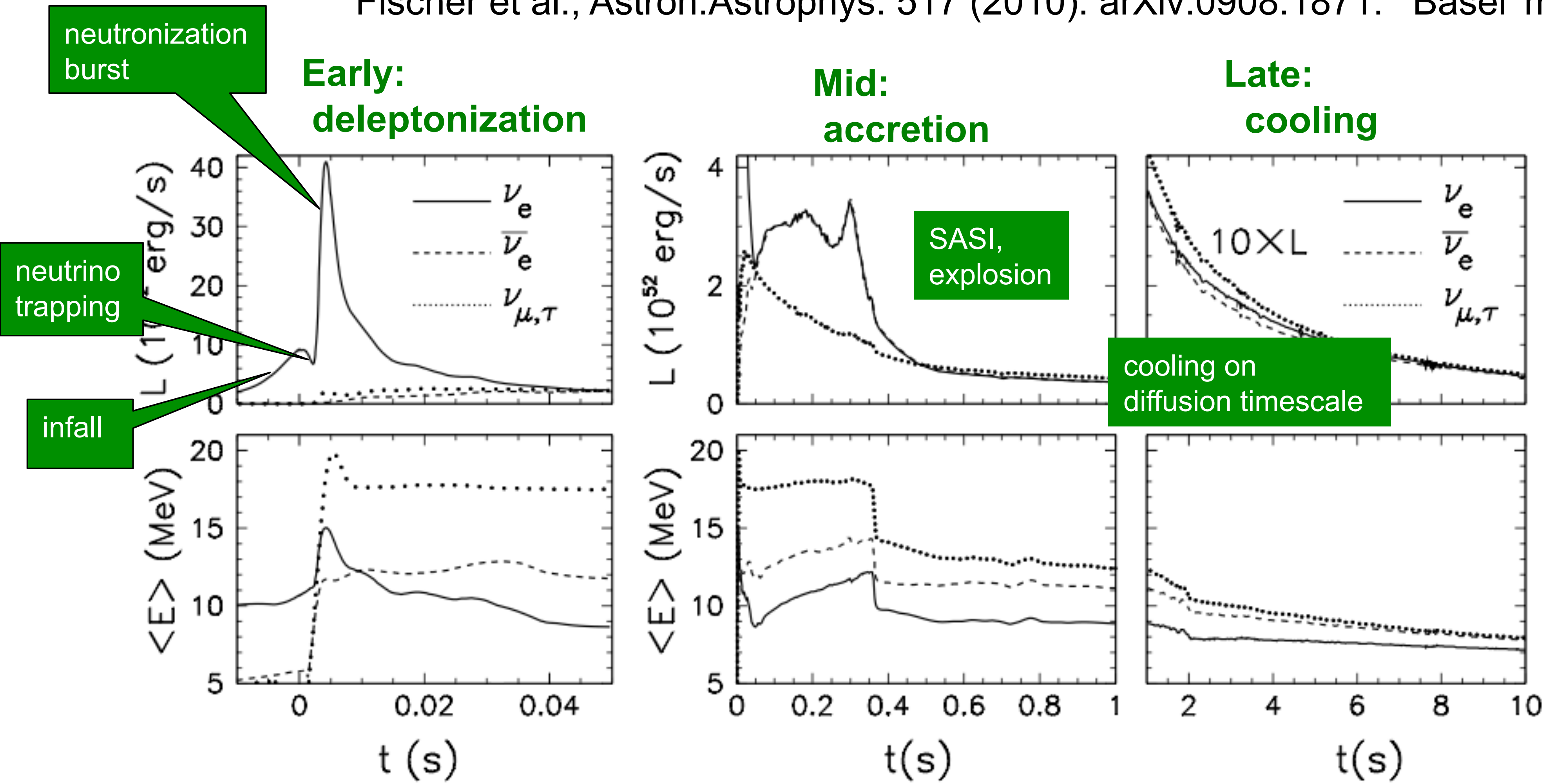
Timescale: *prompt* after core collapse, overall Δt~10's of seconds



Expected neutrino luminosity and average energy vs time

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

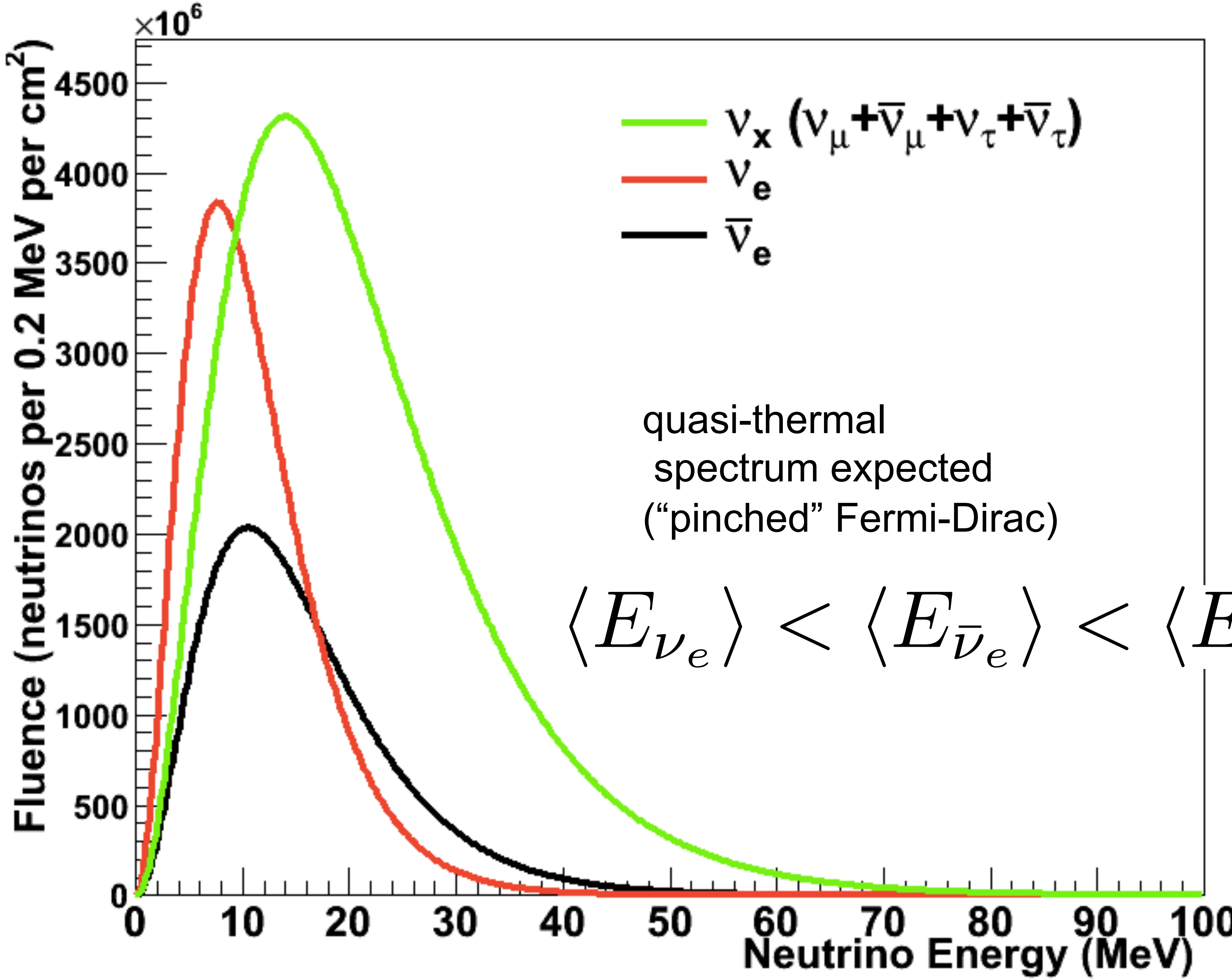
Fischer et al., Astron.Astrophys. 517 (2010). arXiv:0908.1871: ‘Basel’ model



Generic feature:
(may or may not be robust)

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

Neutrino spectrum from core collapse

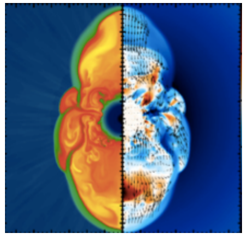


quasi-thermal
spectrum expected
("pinched" Fermi-Dirac)

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

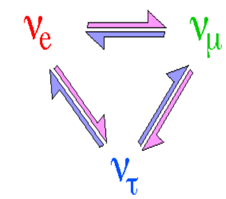
What can we learn from the next neutrino burst?

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

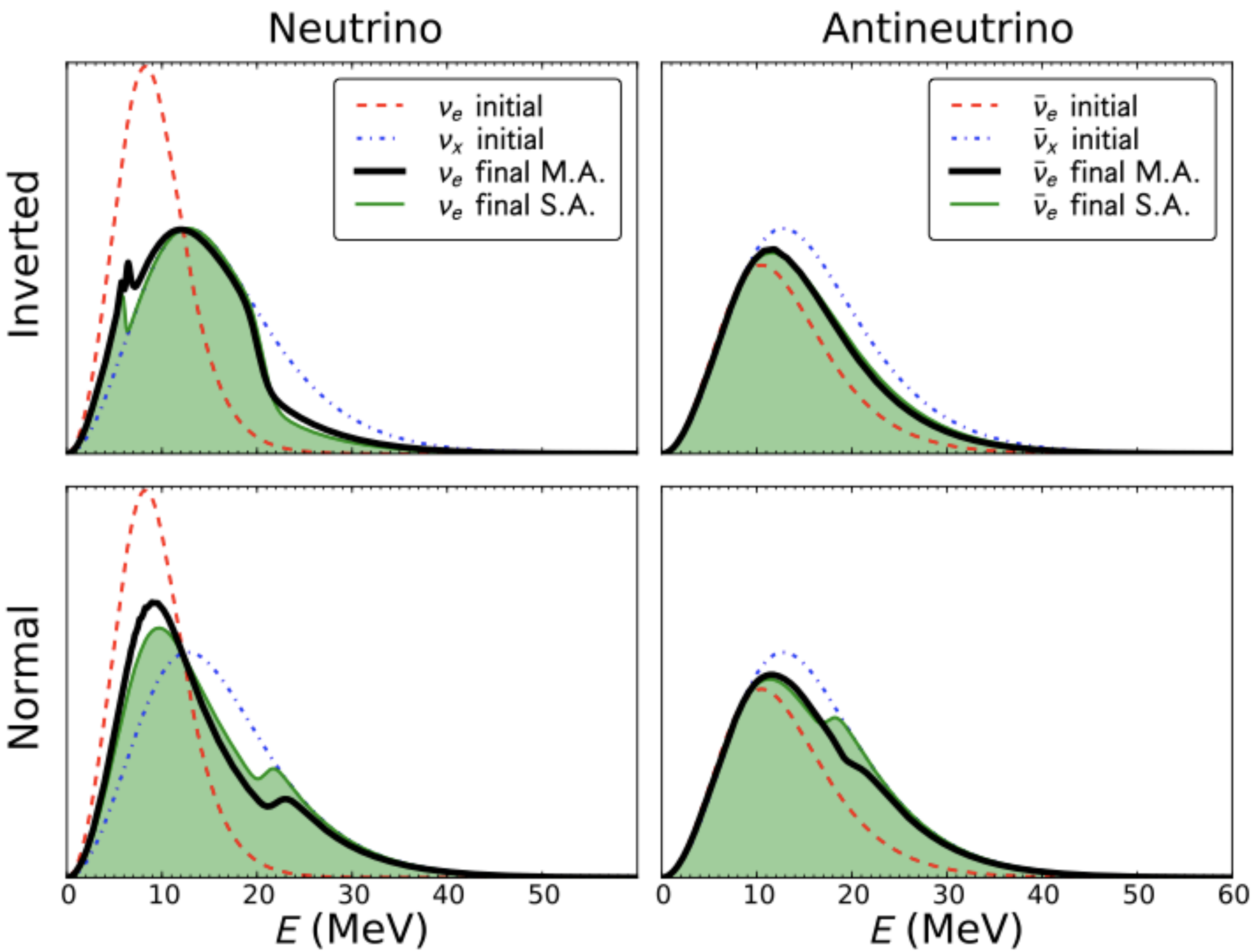
NEUTRINO and OTHER PARTICLE PHYSICS

ν absolute mass
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, ...

input from photon (GW) observations

+ EARLY ALERT

Example of oscillation effects: Duan & Friedland, arXiv:1006.2359

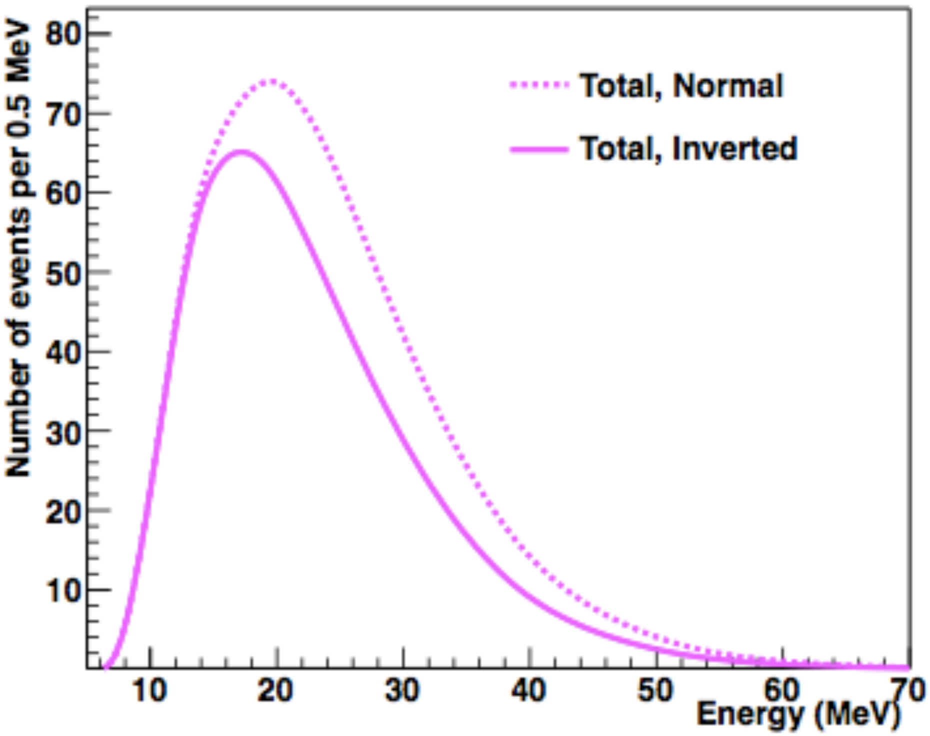


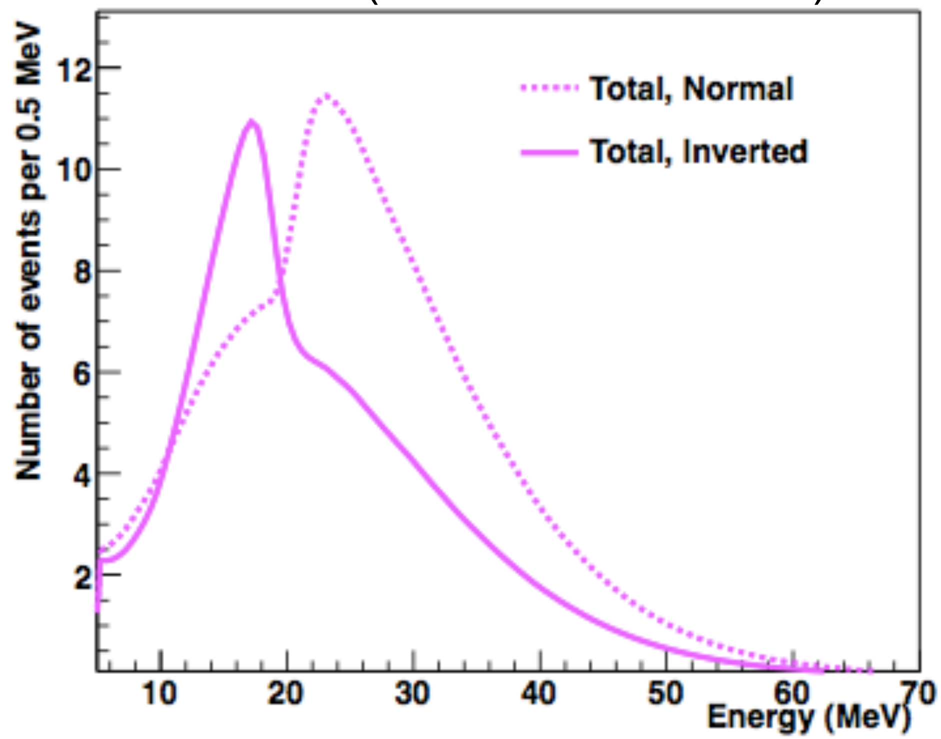
Distinctive spectral swap features depend on neutrino mass hierarchy, for neutrinos vs antineutrinos

Experimentally, can we tell the difference?

Water | **Argon**

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

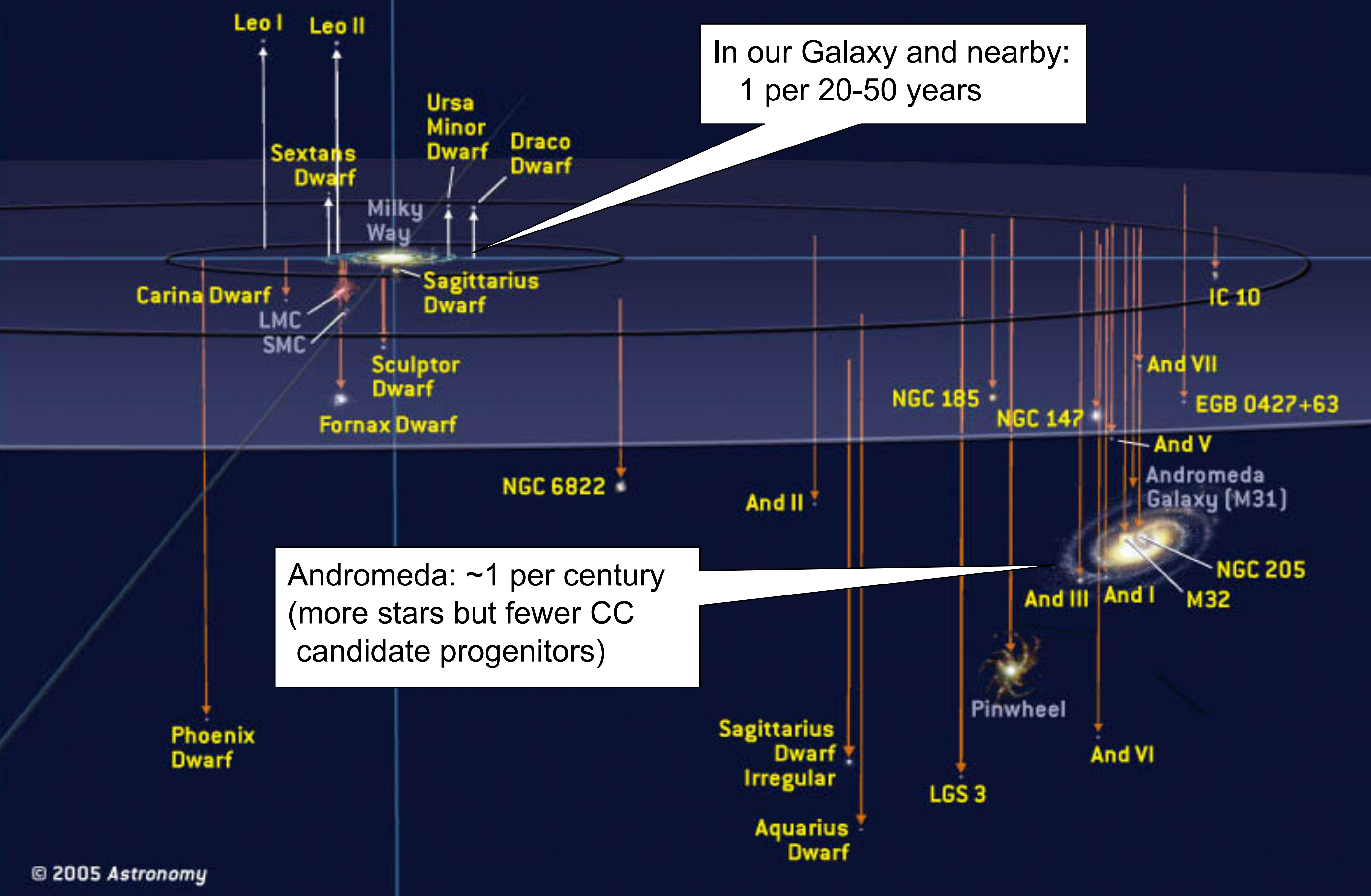




mostly $\bar{\nu}_e$ | **mostly** ν_e

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

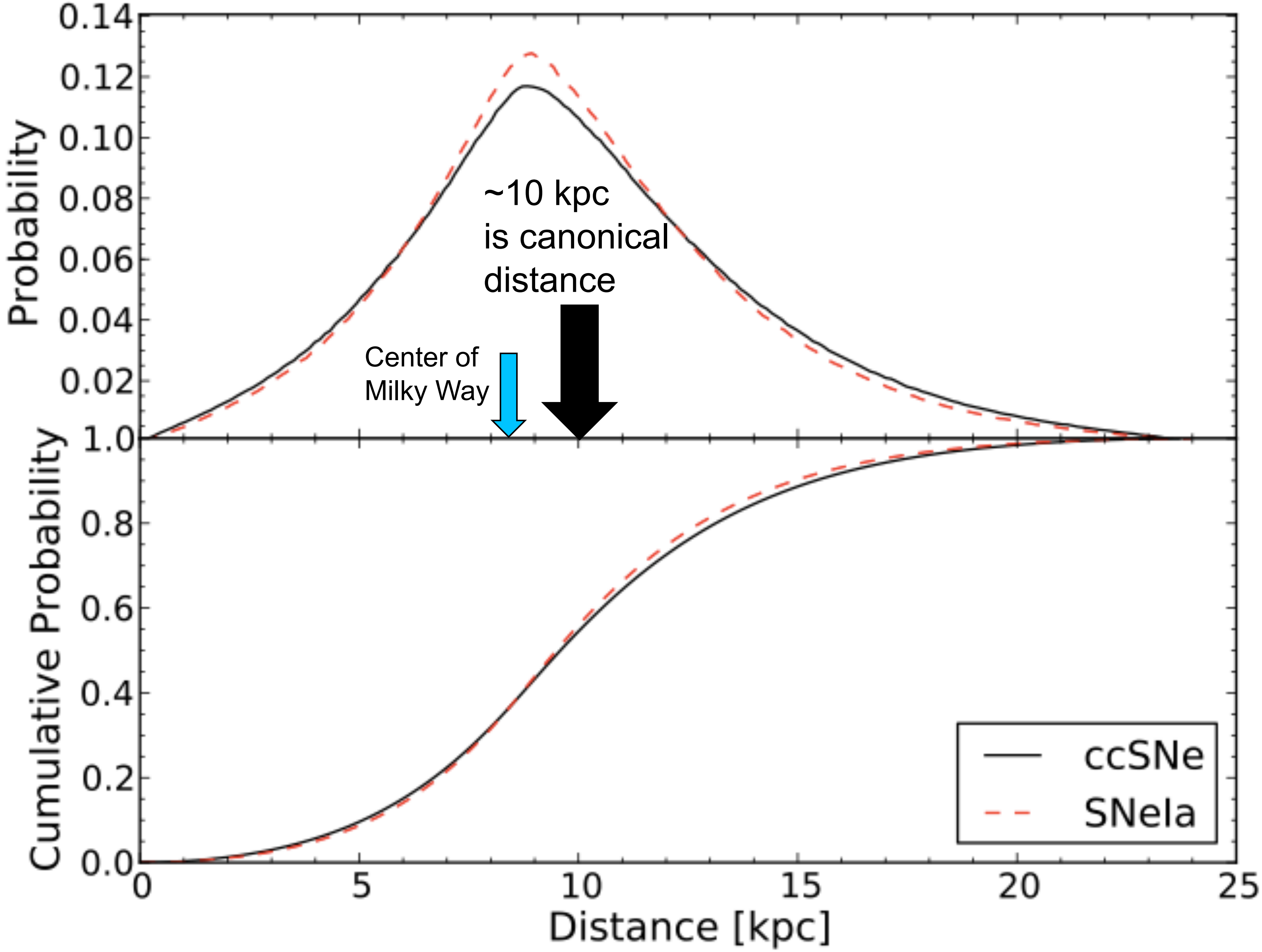
How often do core collapse supernovae happen?



In our Galaxy and nearby:
1 per 20-50 years

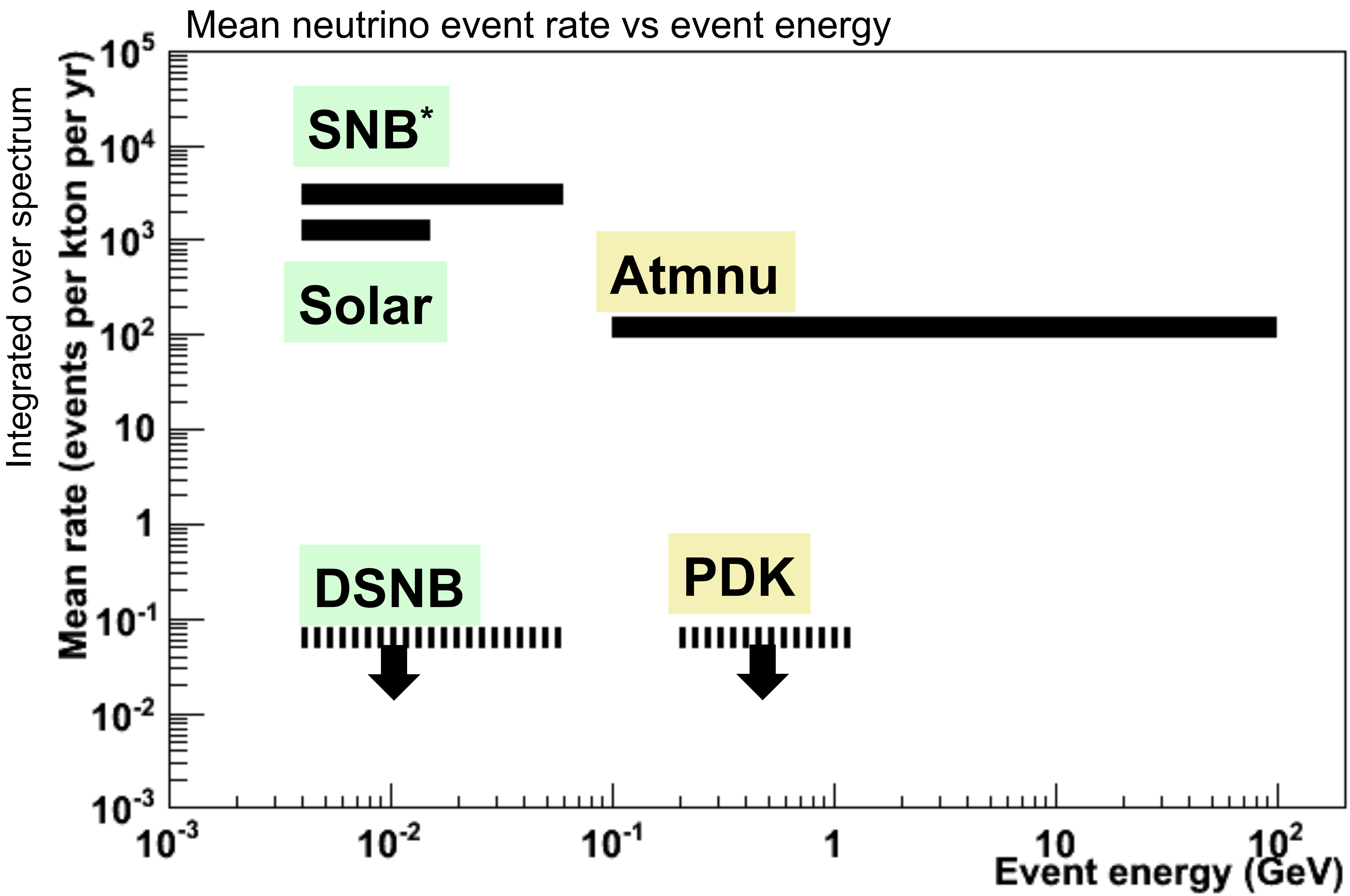
Andromeda: ~1 per century
(more stars but fewer CC candidate progenitors)

Distribution of supernova distances



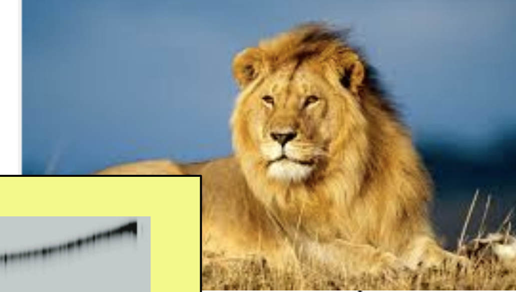
Adams et al., arXiv:1306.0559

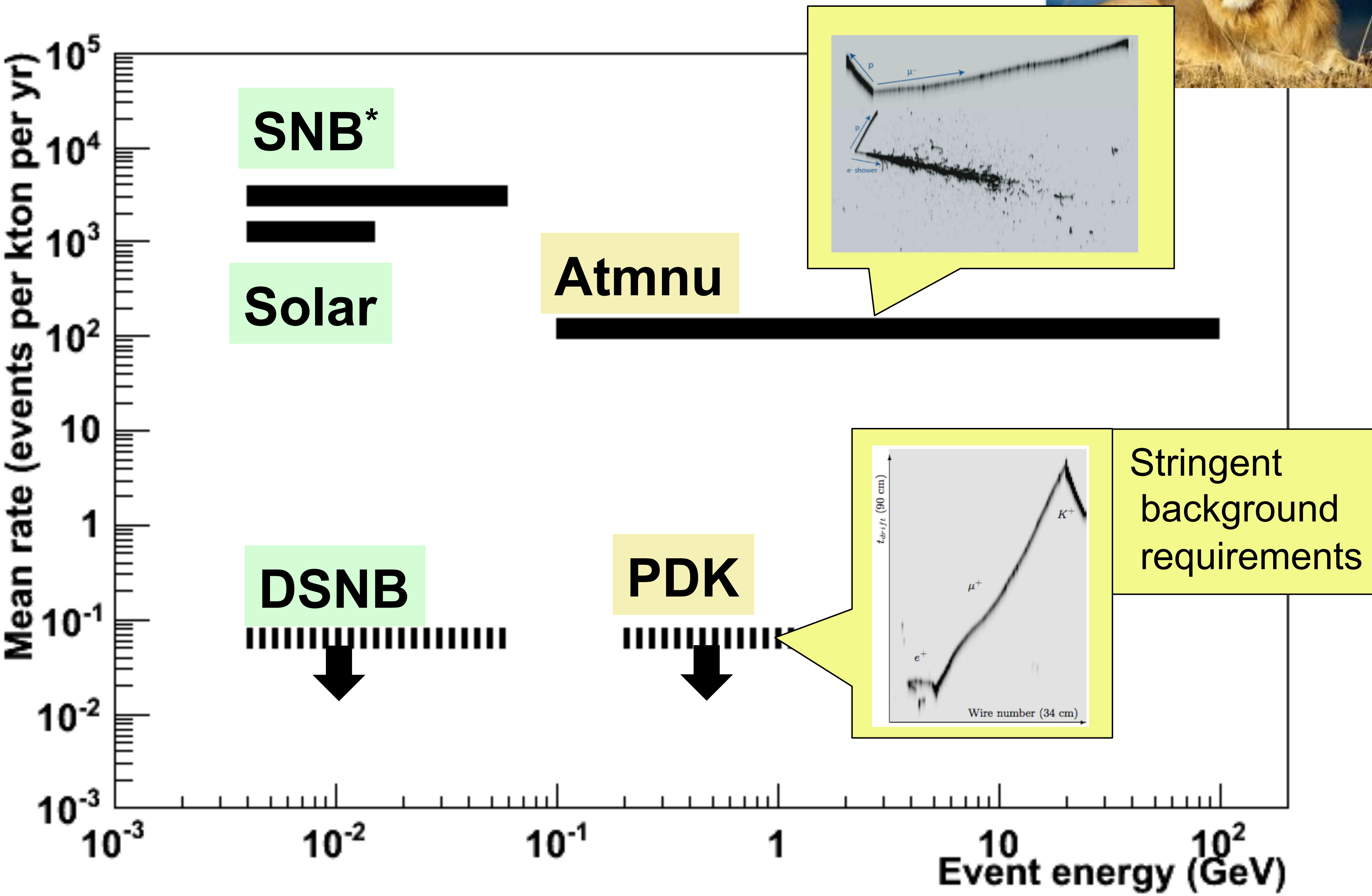
Detecting Low Energy Events



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

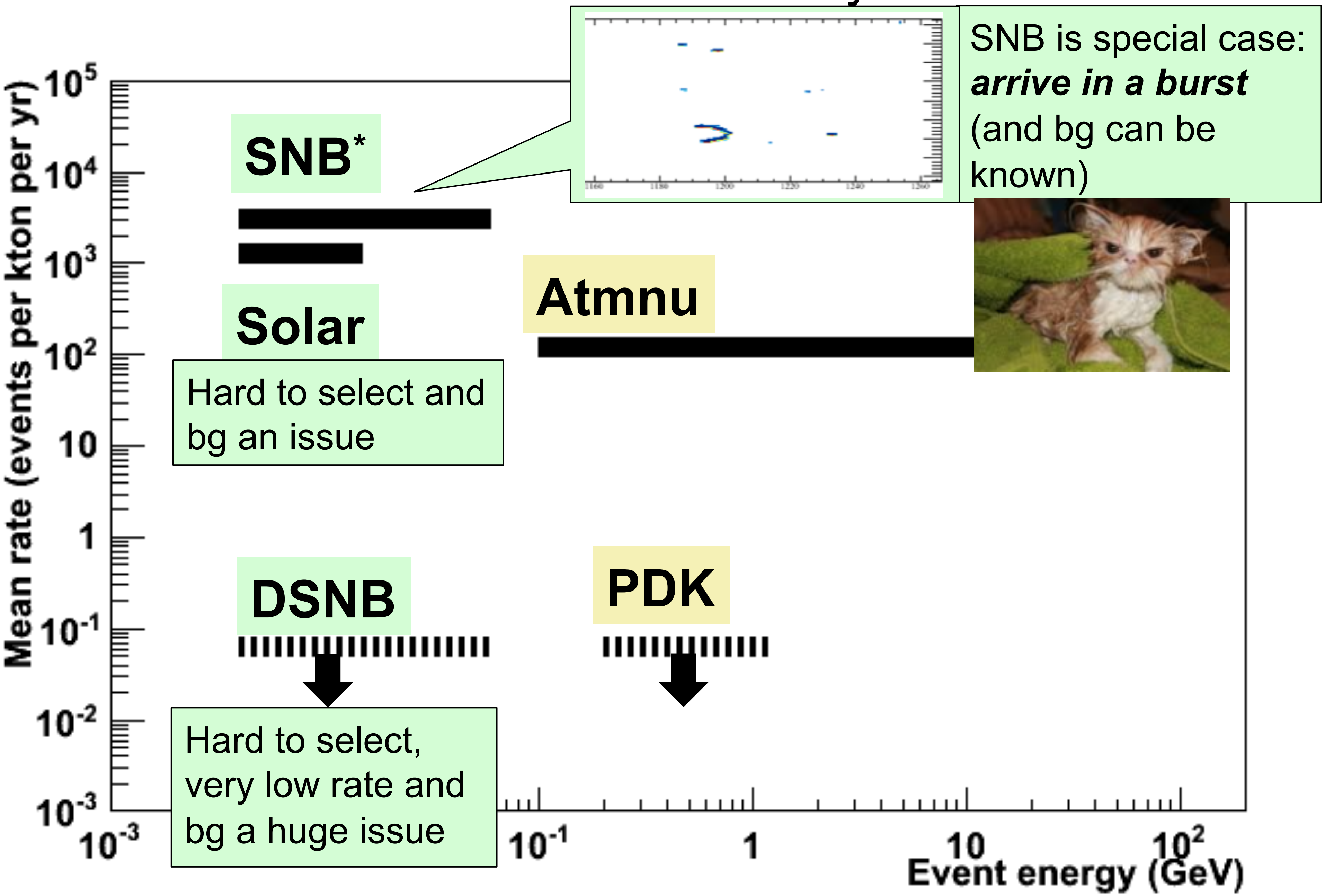
GeV-scale events: handsome and distinctive





* @1 kpc, 30 s

Few tens of MeV-scale events: crummy little stubs



* @1 kpc, 30 s

Low energy neutrino interactions in argon

Charged-current absorption

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

Dominant

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

Neutral-current excitation

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

Not much information in literature

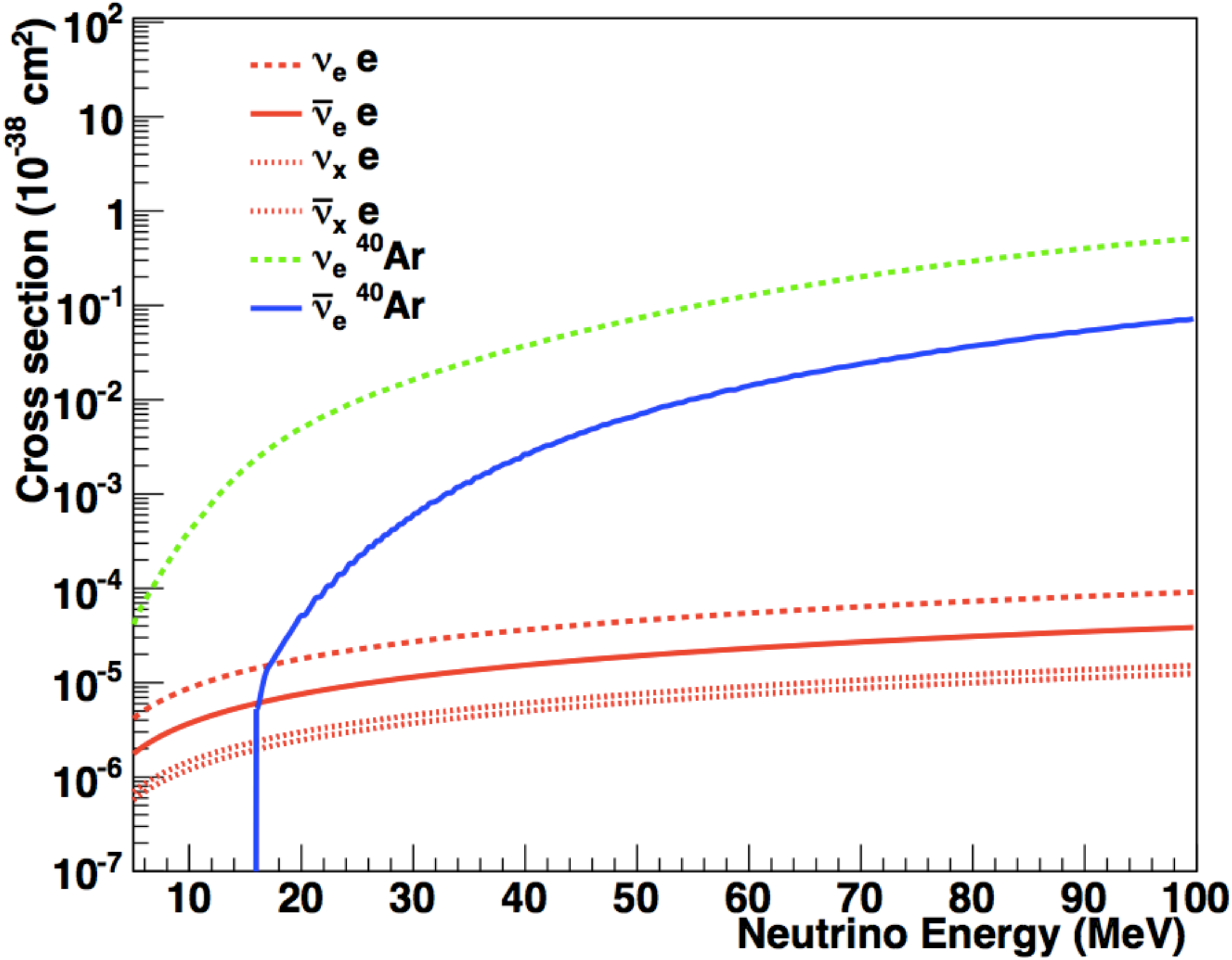
Elastic scattering

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

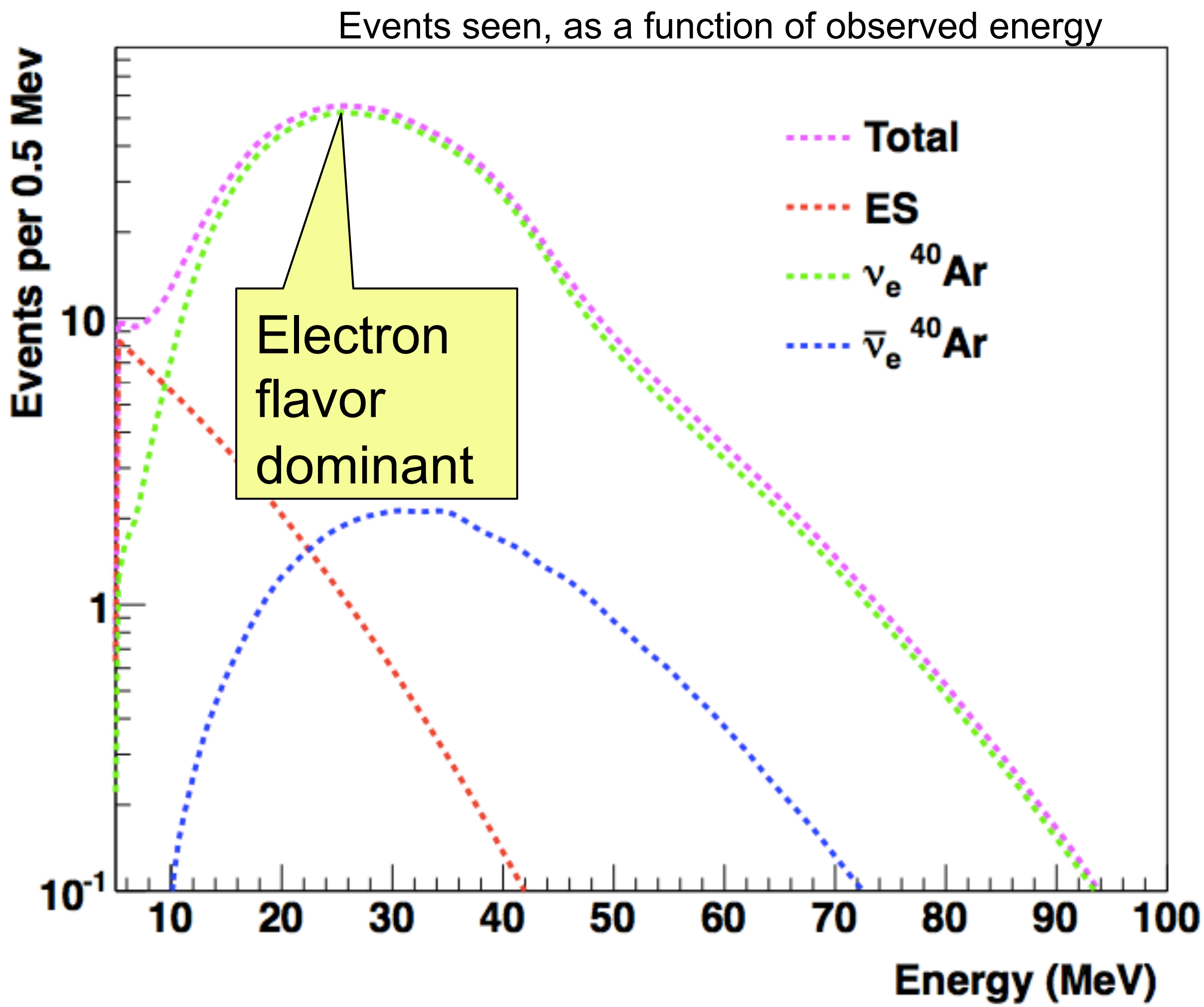
Can use for pointing

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

Cross sections in argon



Supernova signal in a liquid argon detector



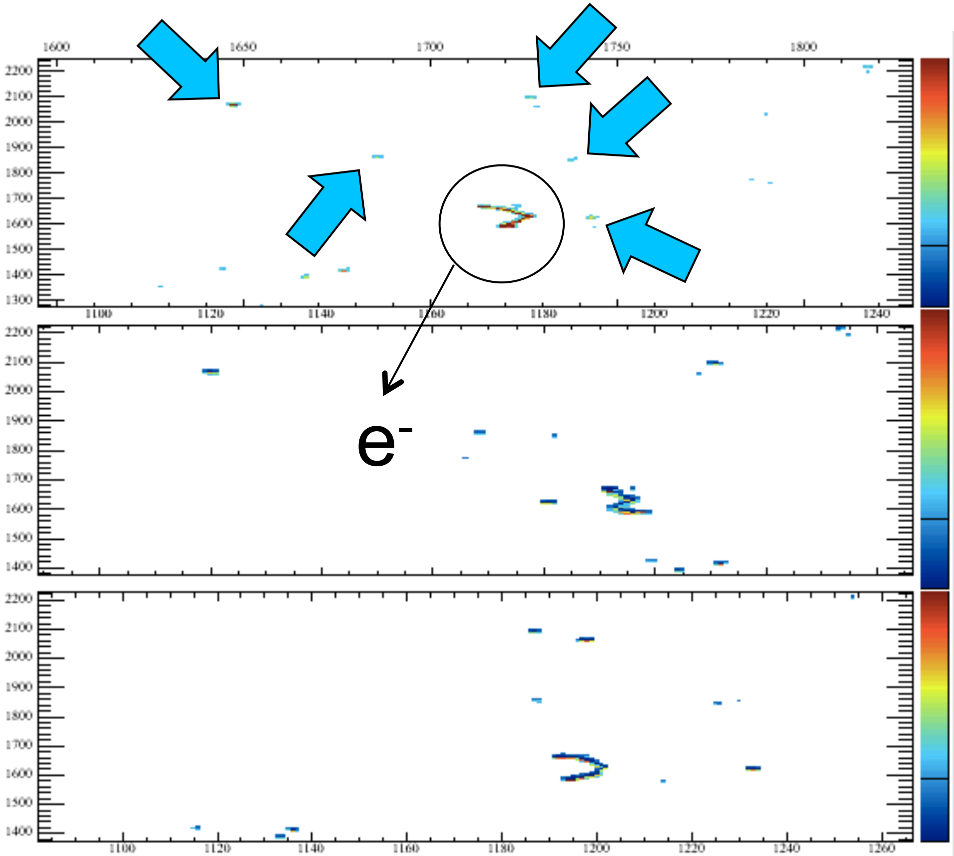
For 34 kton @ 10 kpc,
GKVM model.
ICARUS resolution

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**

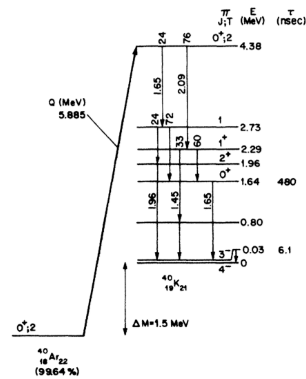
There is significant model variation

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

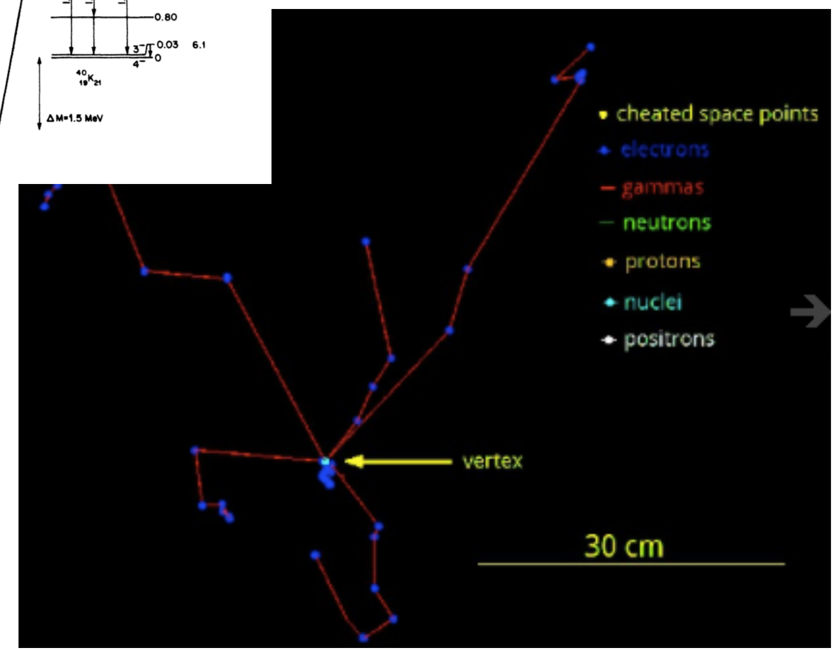
$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$



MicroBooNE geometry (LArSoft)



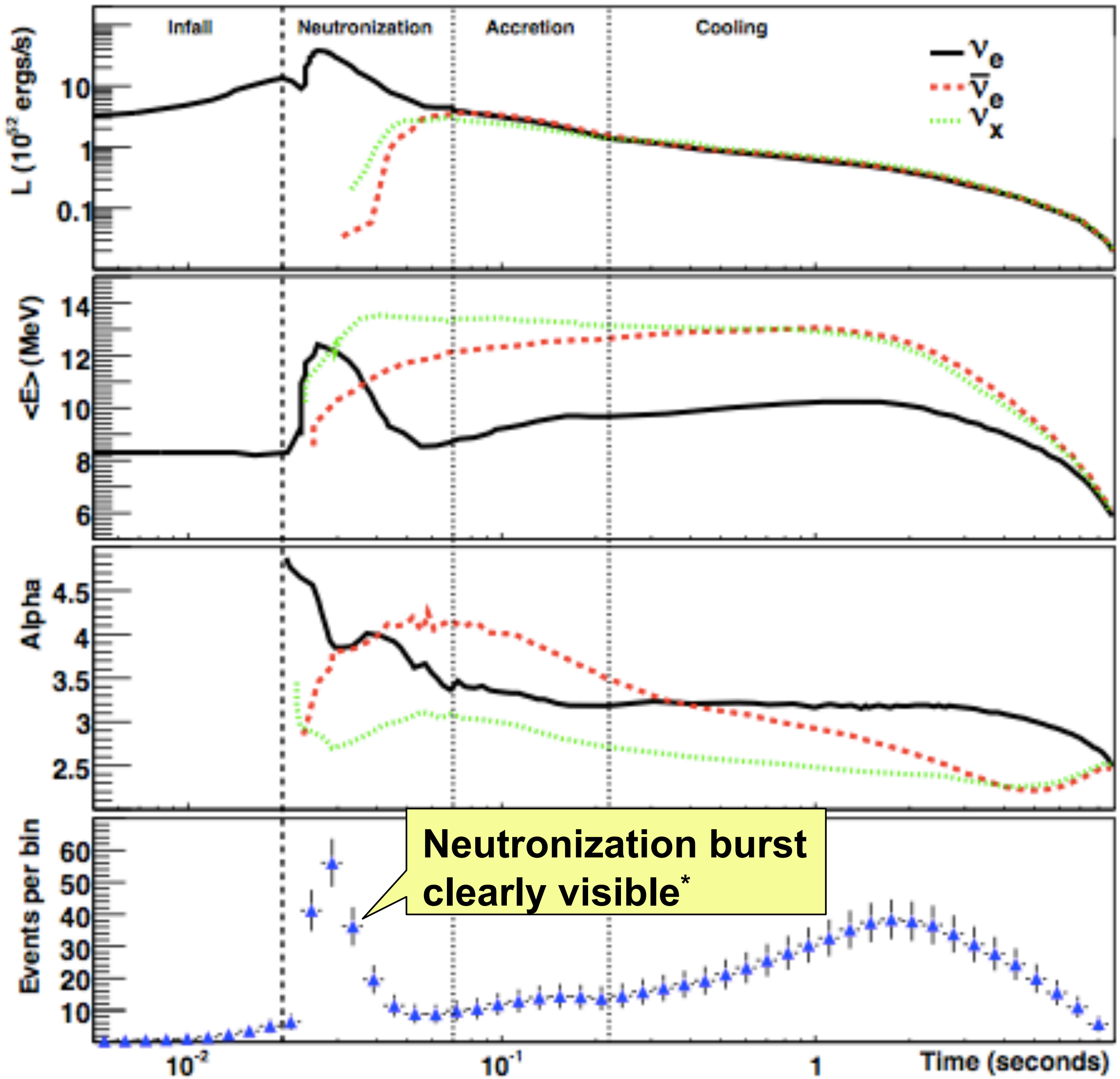
S. Gardiner,
APS April meeting



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 + theory
Direct measurements (and theory) needed!

Need to understand efficiency for given technology

Example of supernova burst signal in 40 kton of LAr



luminosity

average ν energy

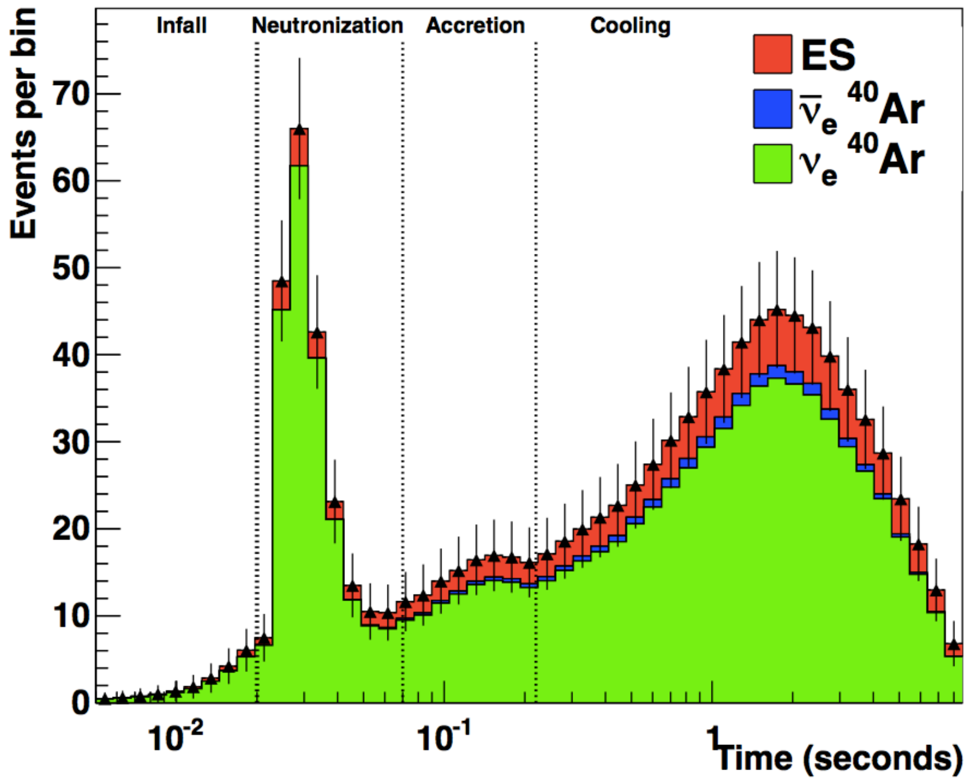
pinching
(large α ➔ suppressed tails)

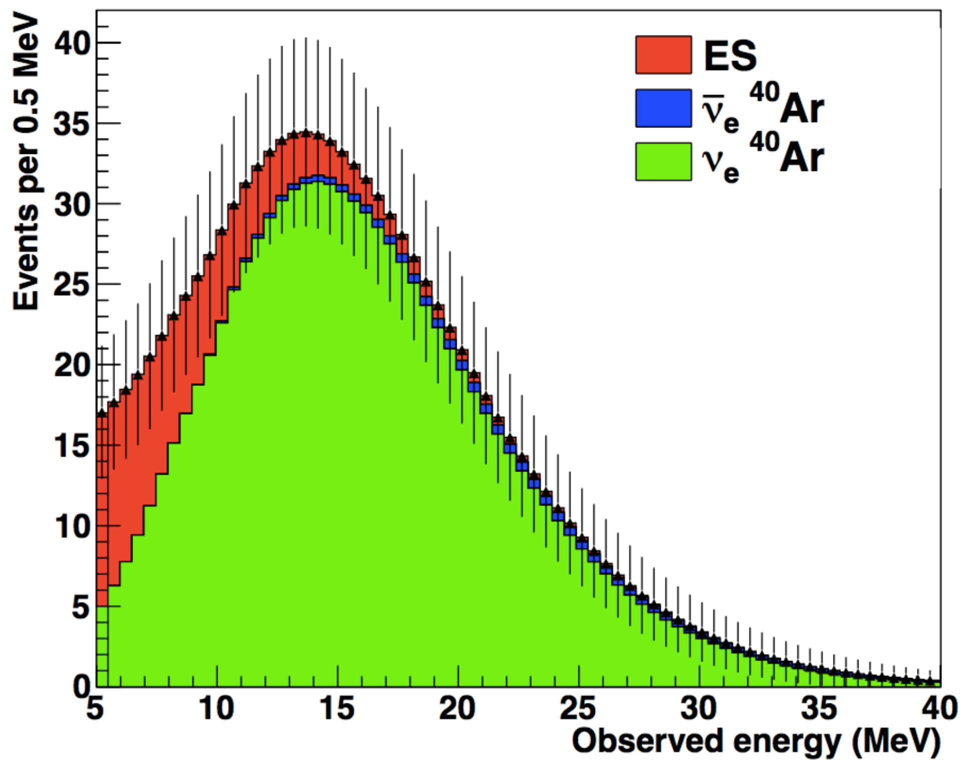
See the ν_e light curve!

Flux from Huedepohl et al., PRL 104 (2010) 251101 ("Garching") @ 10 kpc;
assuming Bueno et al. resolution, *no oscillations

Flavor composition as a function of time

Energy spectra integrated over time



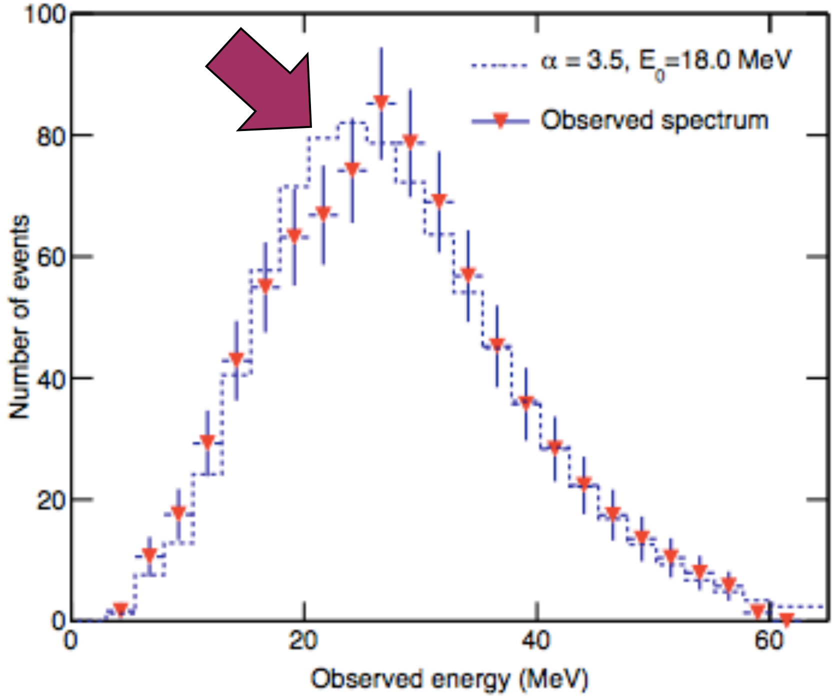


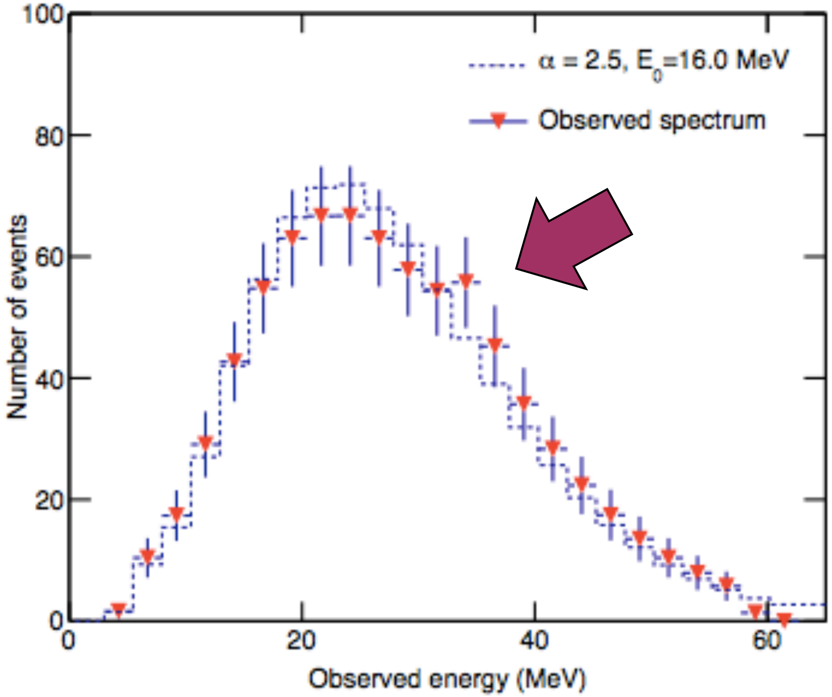
For 40 kton @ 10 kpc,
Garching model
(no oscillations)

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

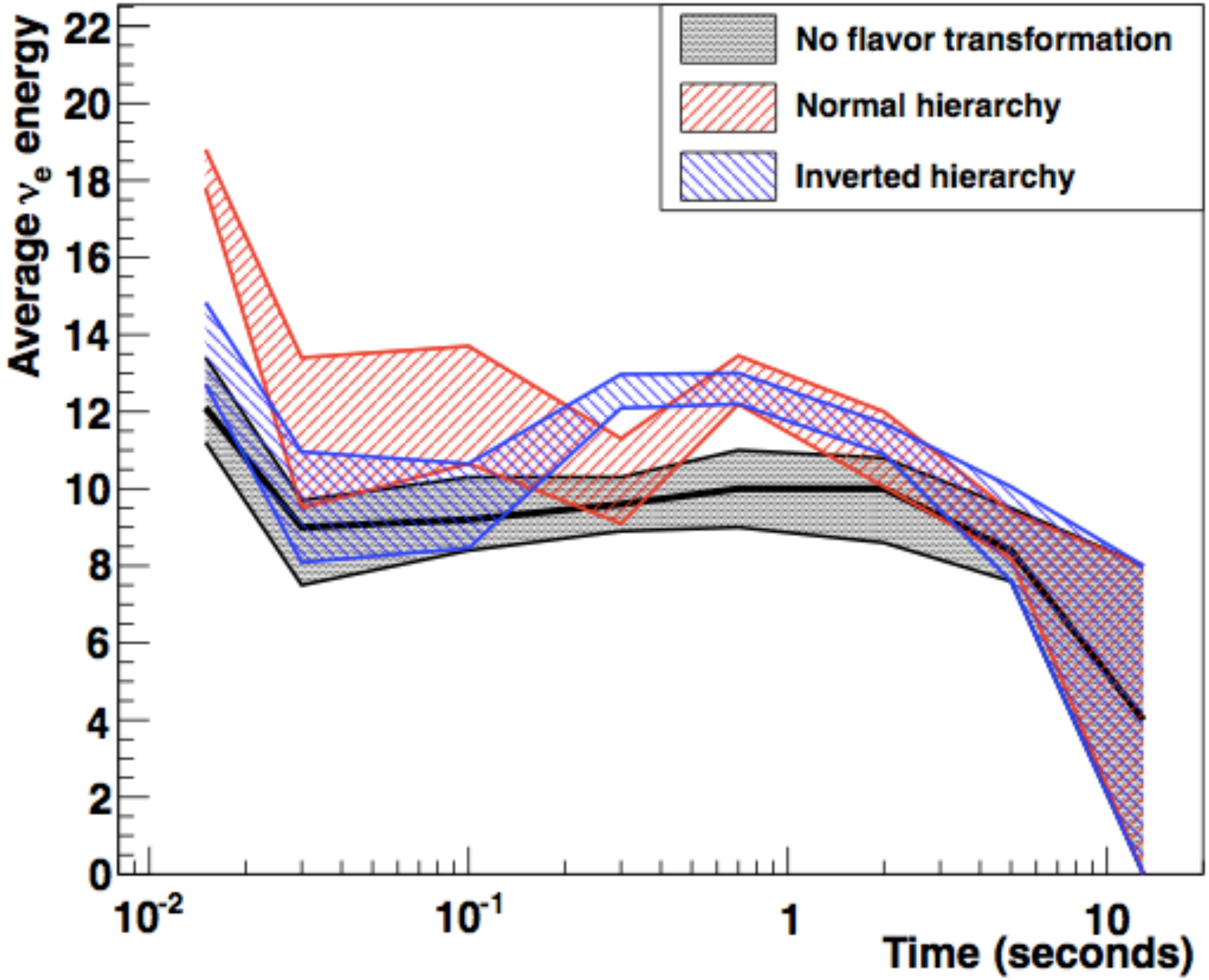




MH-dependent "non-thermal" features clearly visible as shock sweeps through the supernova

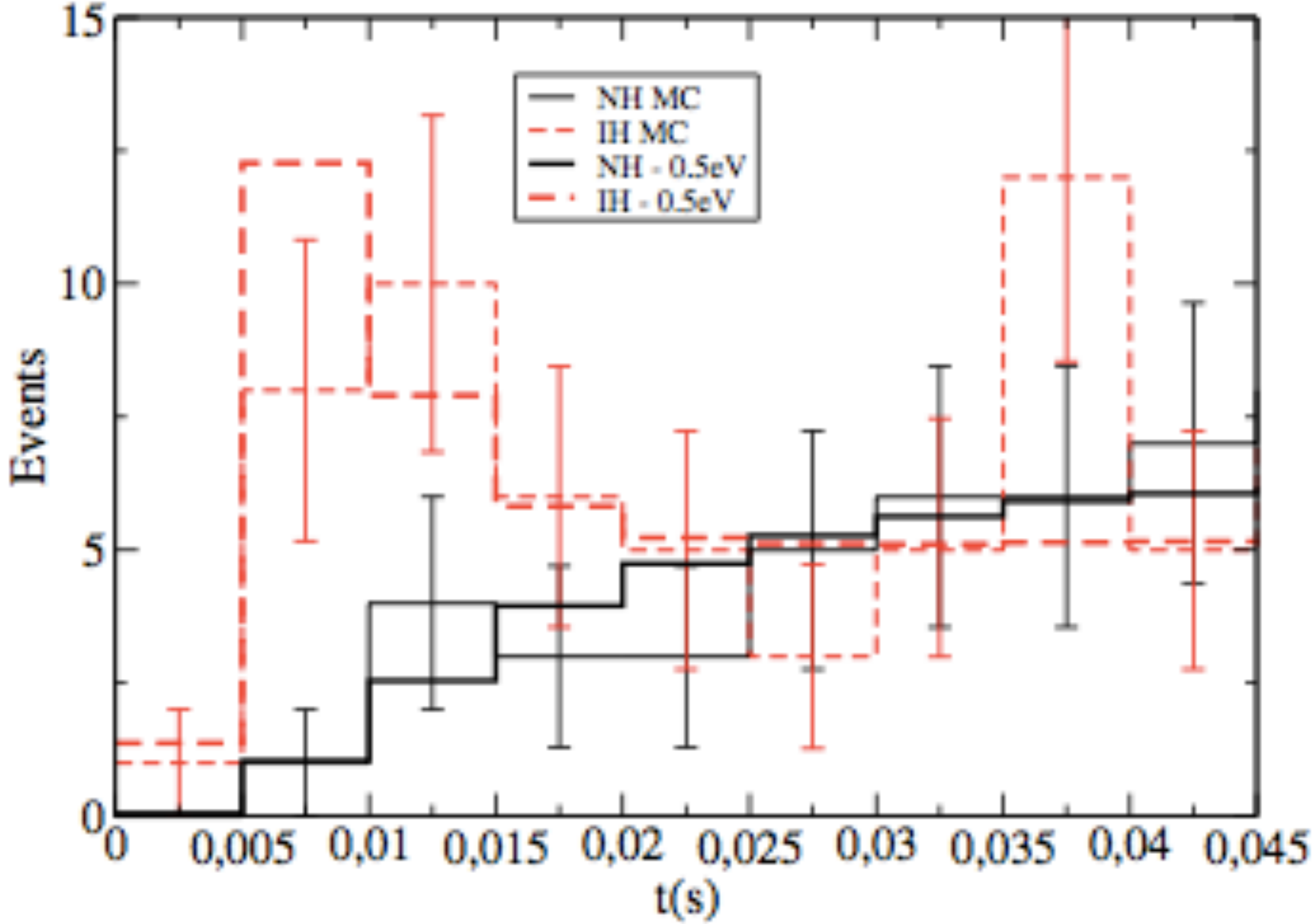
And another:

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



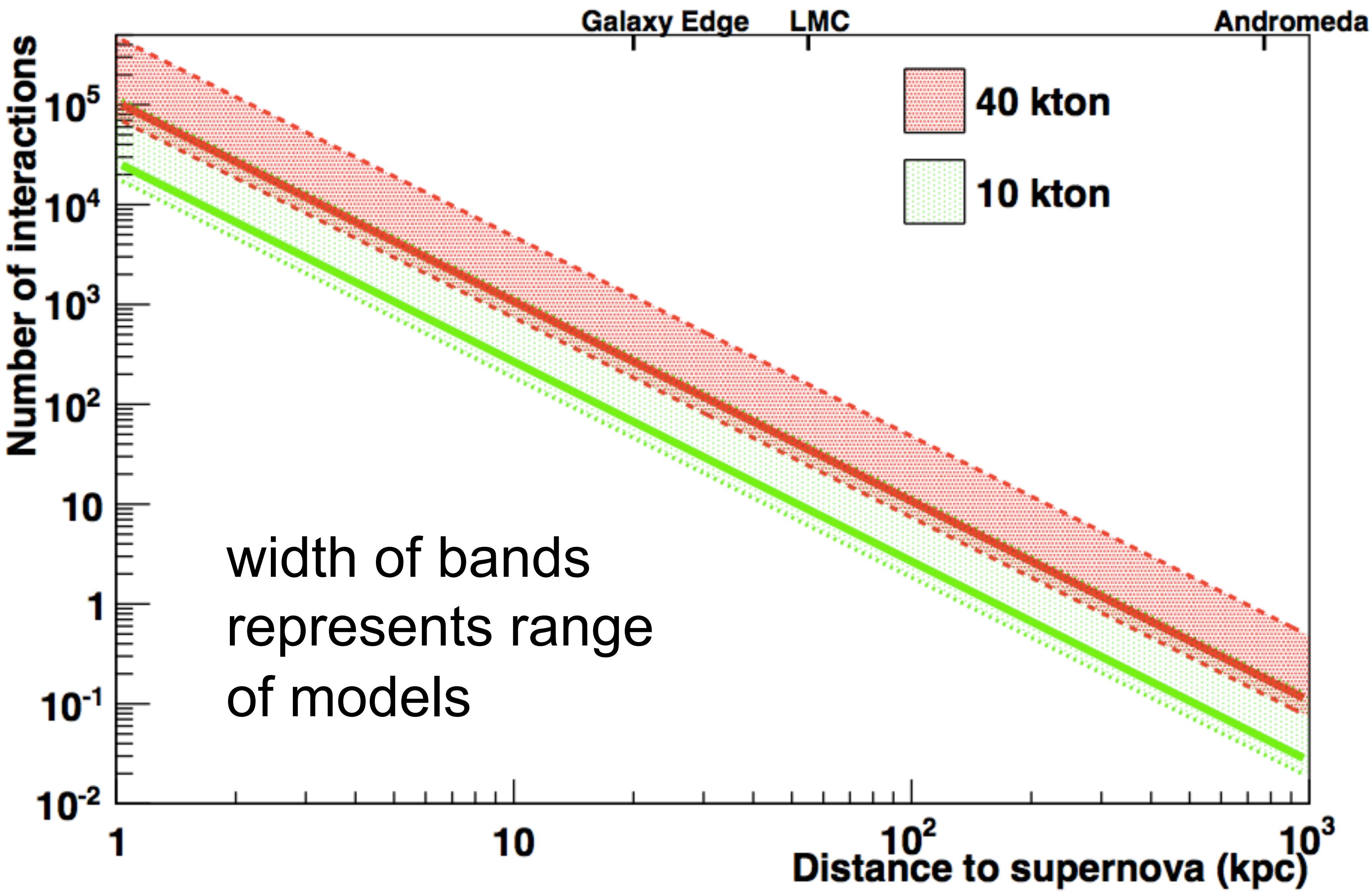
Average ν_e energy from fit to "pinched thermal",
34-kton LAr @ 10 kpc, including collective oscillations ➔
clearly, there's information in the spectral evolution

And another: MH & absolute mass effect on neutronization burst



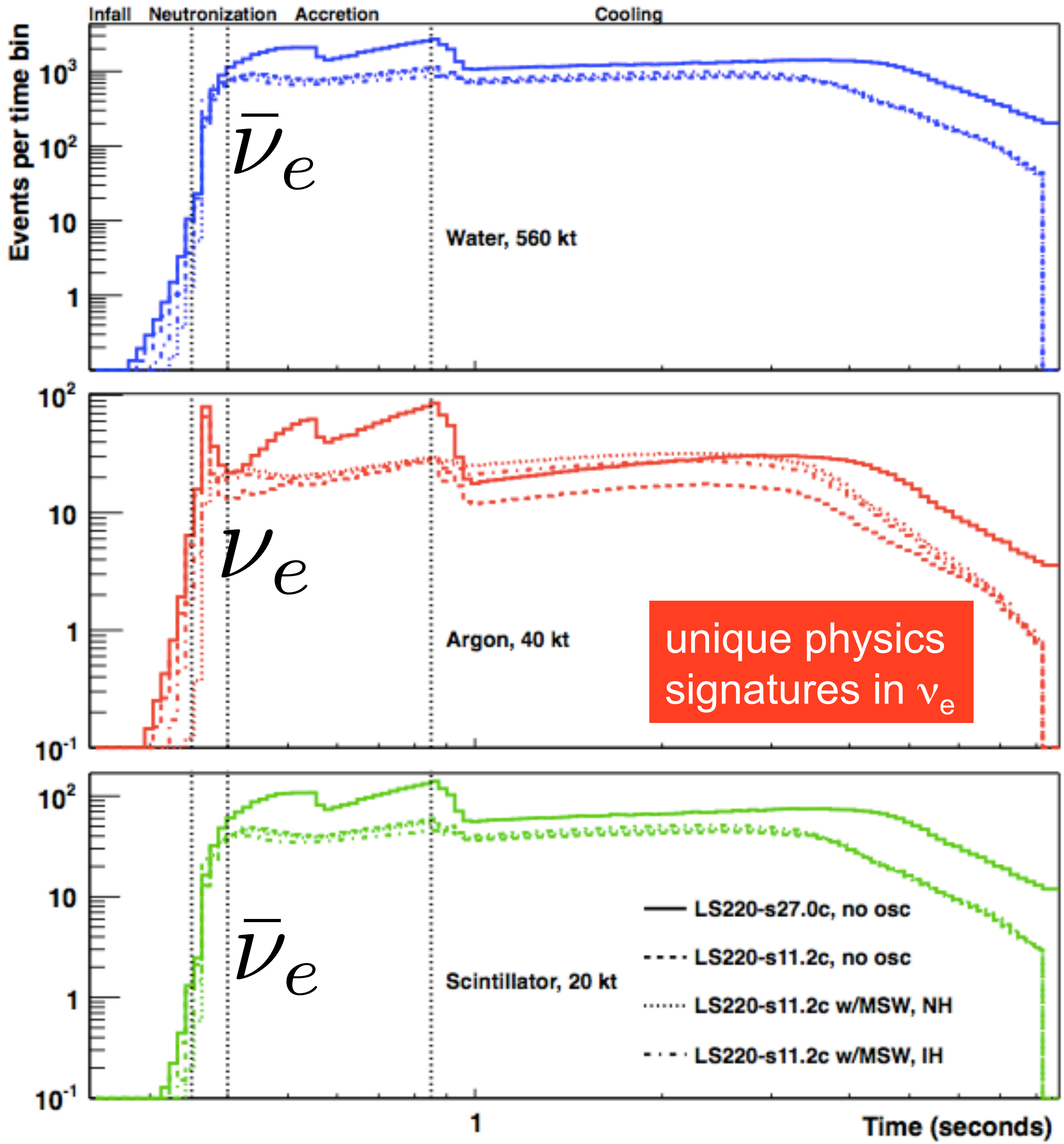
F. Rossi-Torres, M. M. Guzzo, E. Kemp, arXiv:1501.0045

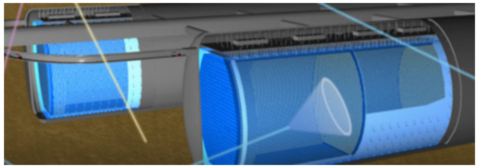
Events in LAr vs distance

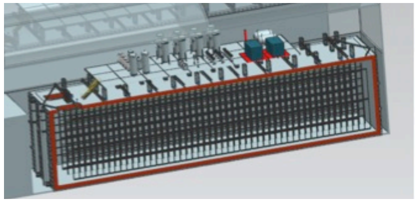


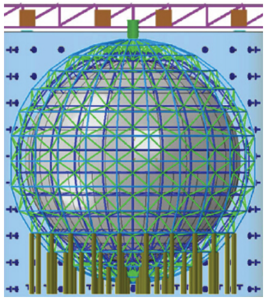
For supernova neutrinos, the more the merrier!

Two models (11.2 and 27.0 solar masses, NH/IH for former)









arXiv:1508.00785

In DUNE SNB/LE (Supernova Burst/Low Energy) **group:**

Work underway to refine understanding of physics sensitivities and optimize detector requirements/design

- energy/time/angular resolution
- tagging of interaction channels
- cross sections, event generators
- DAQ/trigger issues
- role of photon detectors
- backgrounds (cosmogenic, radiologicals)
- ...

SNB 'Hack Days' July 25-27

Summary

A Galactic core collapse would be the event of a career!

Vast information to be collected... the more observations, the richer the spoils

DUNE will provide **unique ν_e information**

Lots of work to be done to understand and optimize detector response!

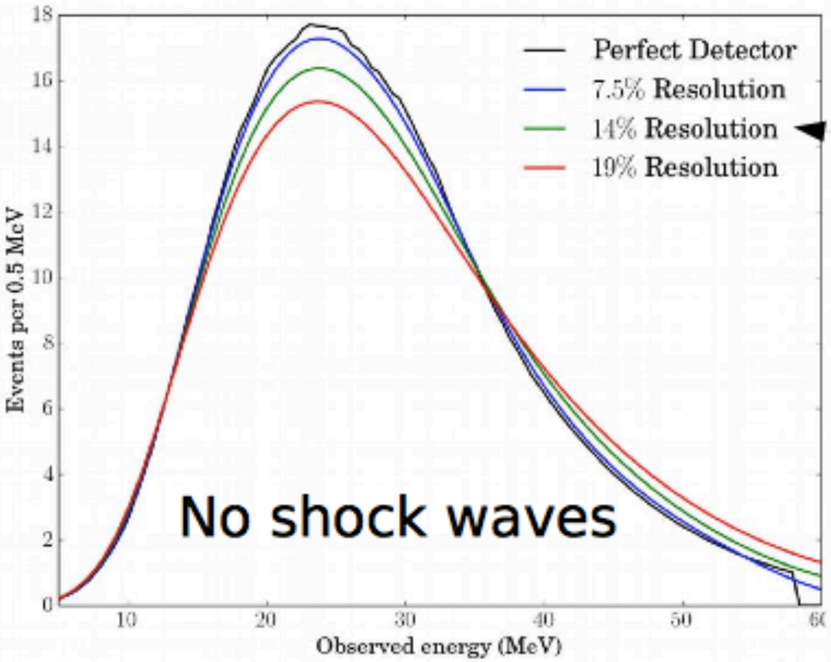
Extras/Backups

Gleb Sinev energy resolution studies

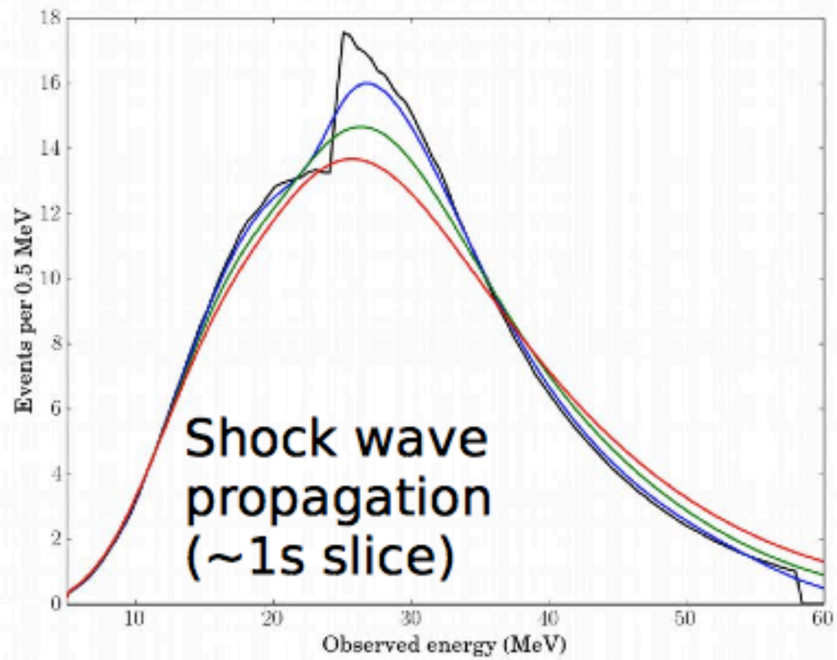
Energy resolution
Shock-wave signatures

Gaussian smearing indep of energy

Using SNOwGLoBES, what resolution do we need to see the shock wave feature?

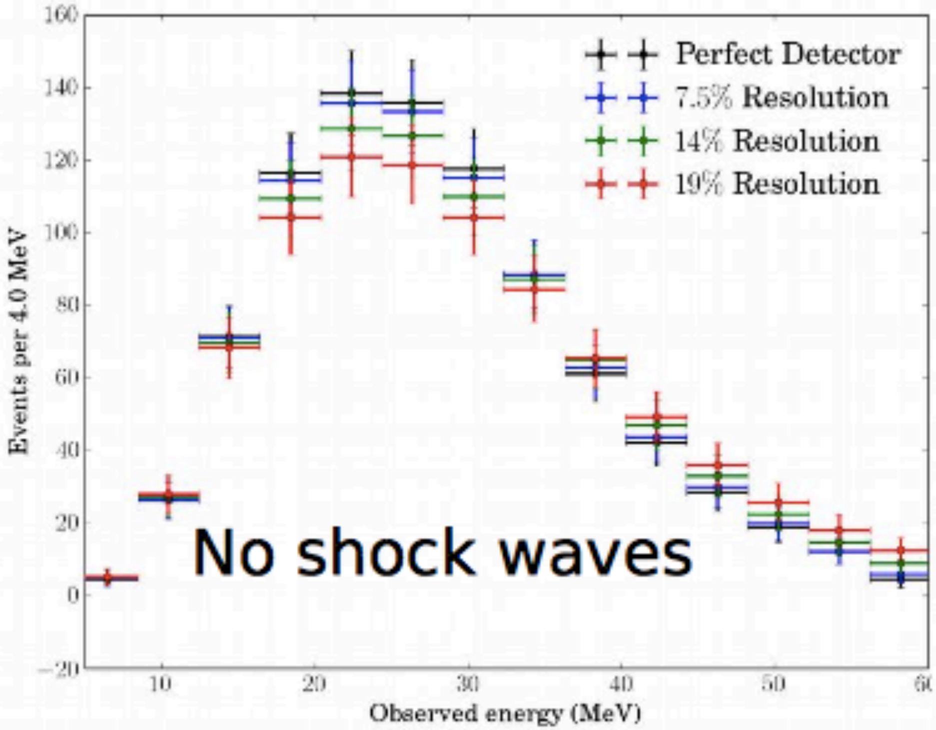


Detector simulation



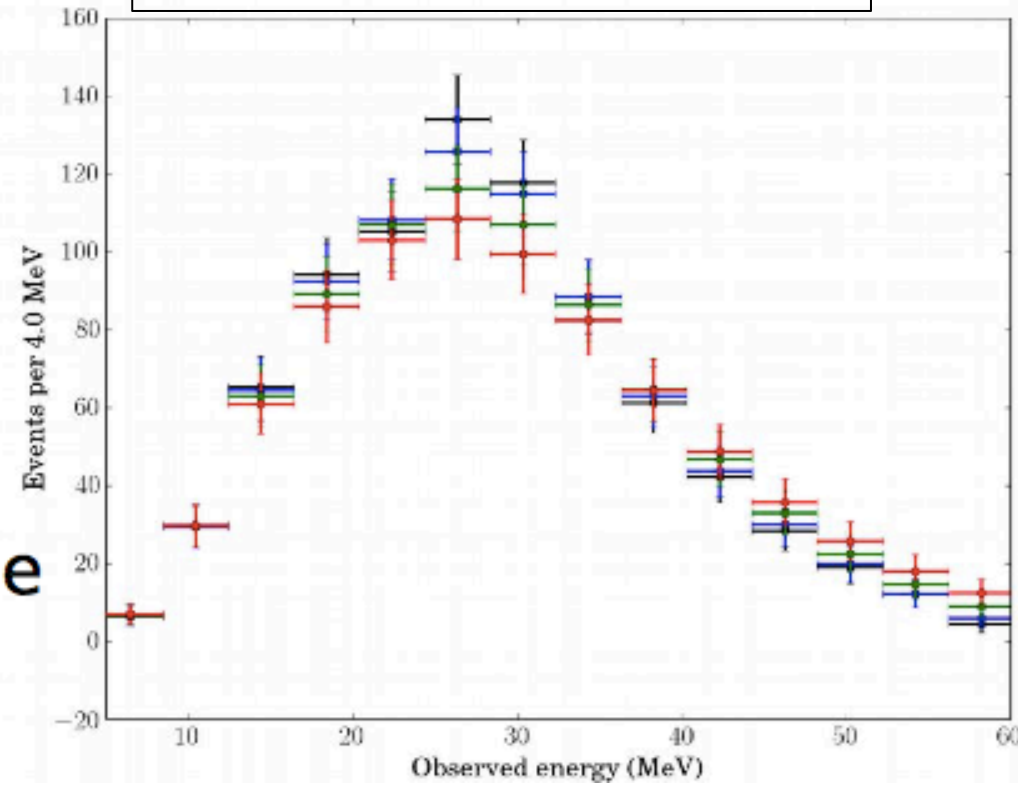
“Anecdotal” spectral feature from A. Friedland

Adding statistics (supernova 10 kpc away)

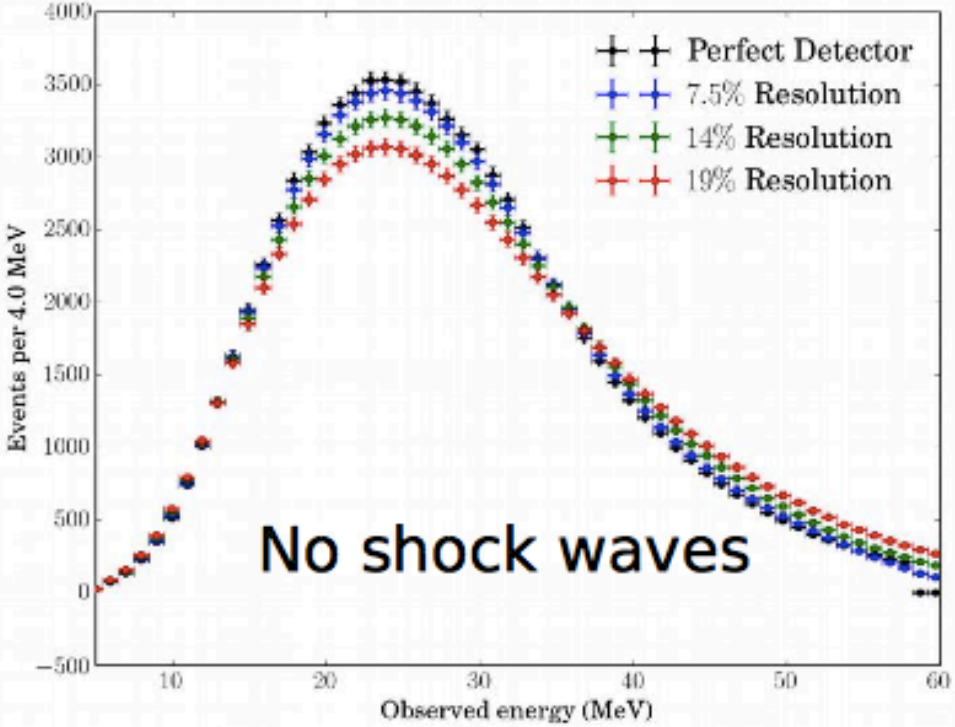


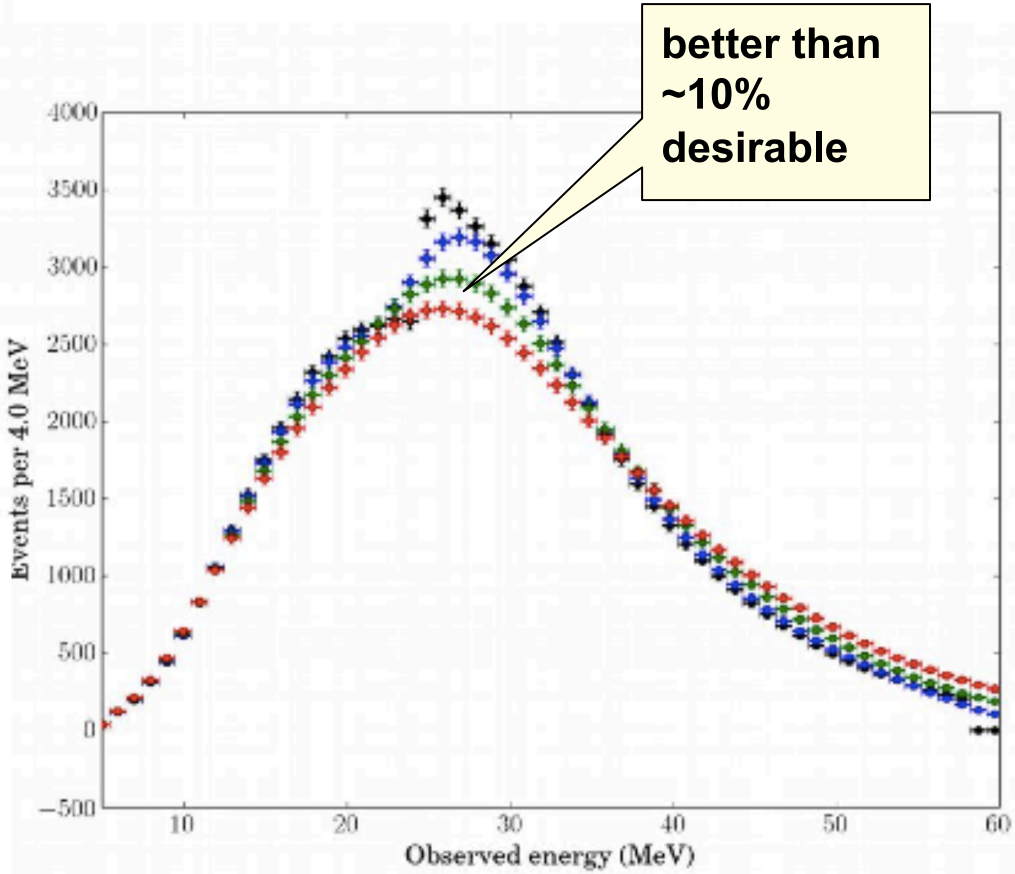
Resolution doesn't help much if you don't have sufficient statistics...
(note: may still be able to quantify non-smooth/thermal)

Features are indistinguishable



Adding statistics (supernova 1 kpc away)

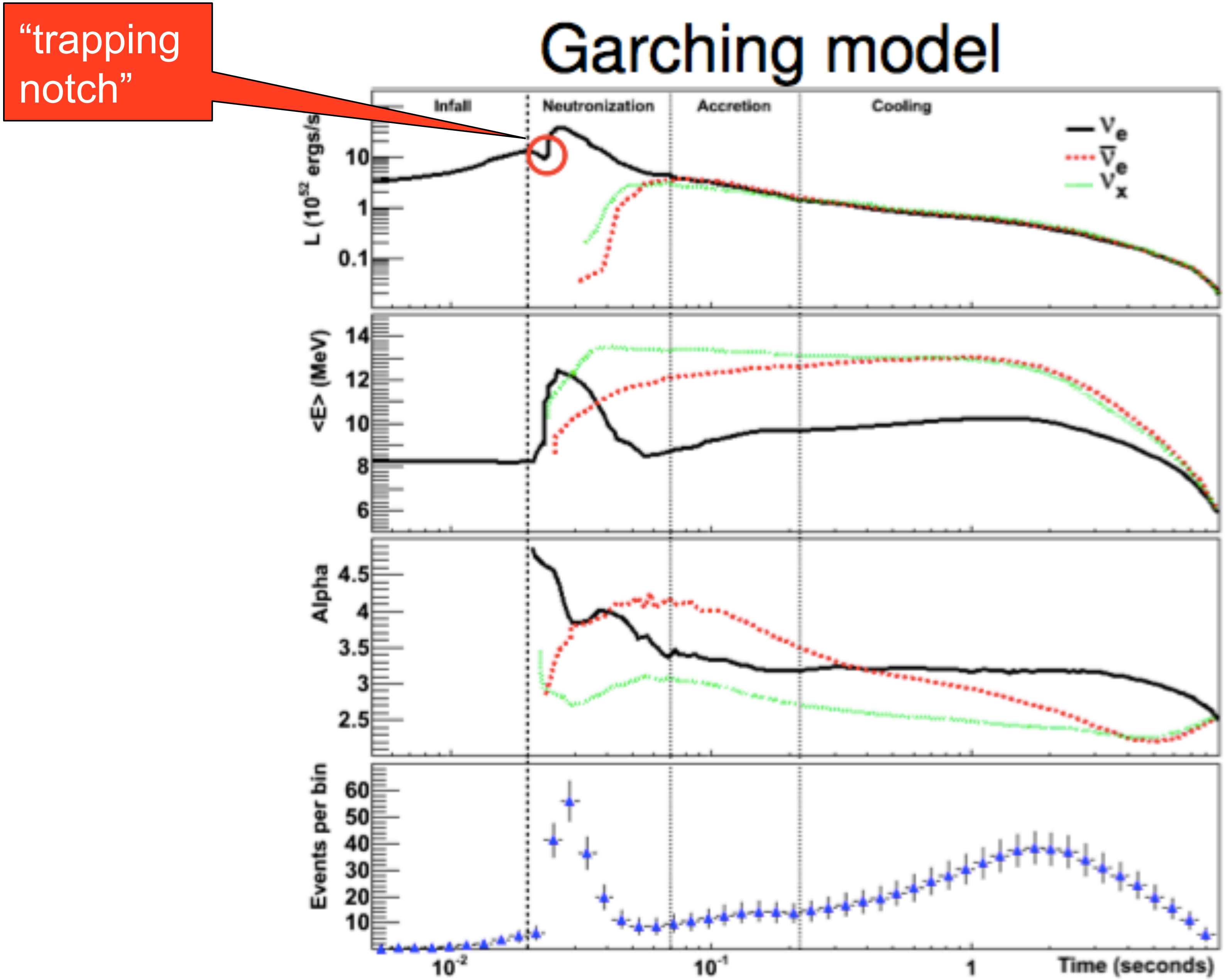




Conclusion: this shock feature **observability is statistics-limited** for much of the Galaxy, but if we have a close supernova, we'll be sorry

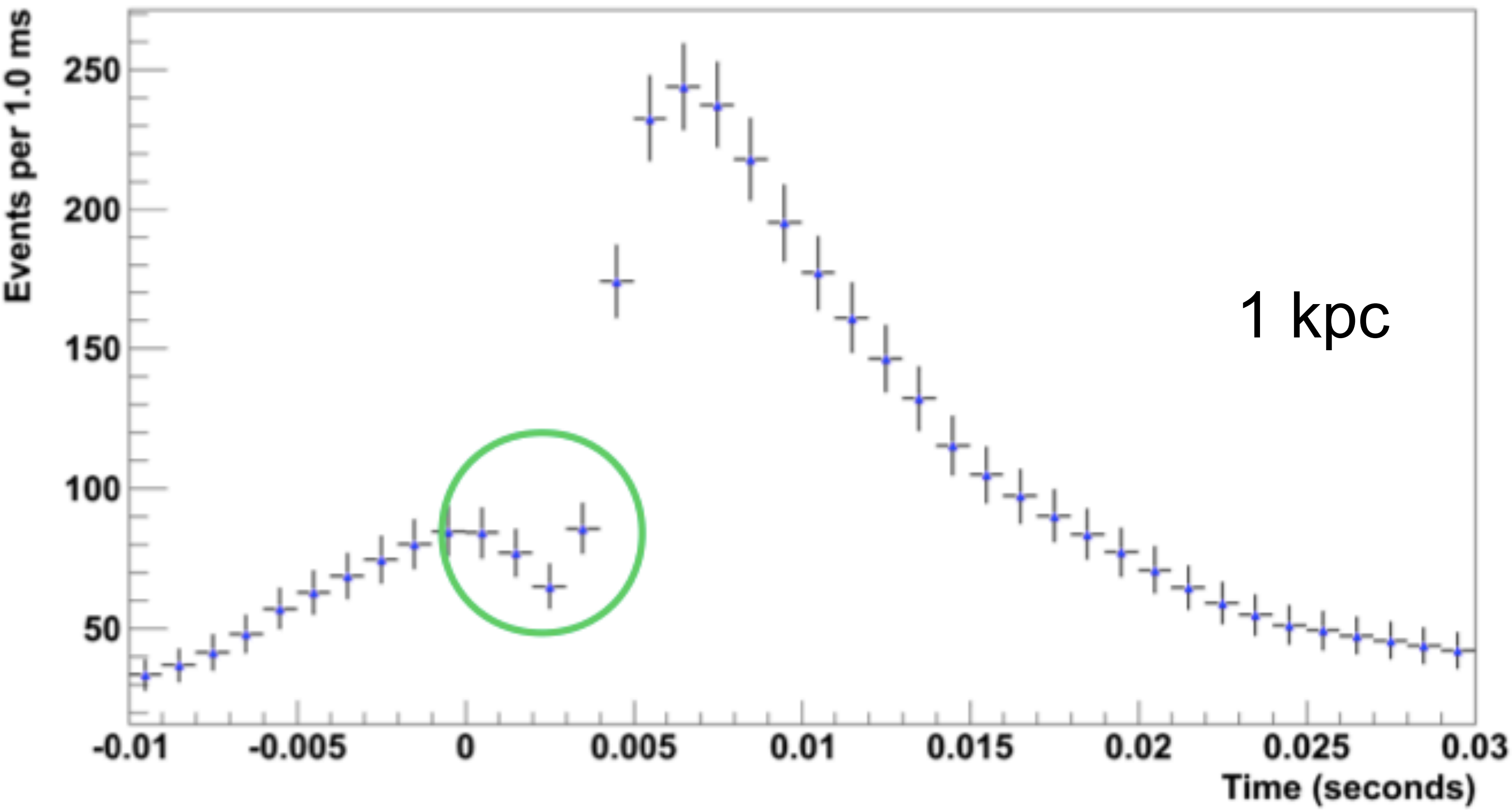
(of course, it's a judgment call how much to spend for a rare case..)

Another anecdote: what time resolution is required?



L. Hudepohl, B. Muller, H.-T. Janka, A. Marek, and G. Raffelt, "Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling," Phys.Rev.Lett. 104 (2010) 251101, arXiv:0912.0260 [astro-ph.SR]

Model from Evan O'Connor



Need <~ ms resolution to observe the notch..
but also require large statistics

Parallel session this meeting: SNB/LE/DAQ

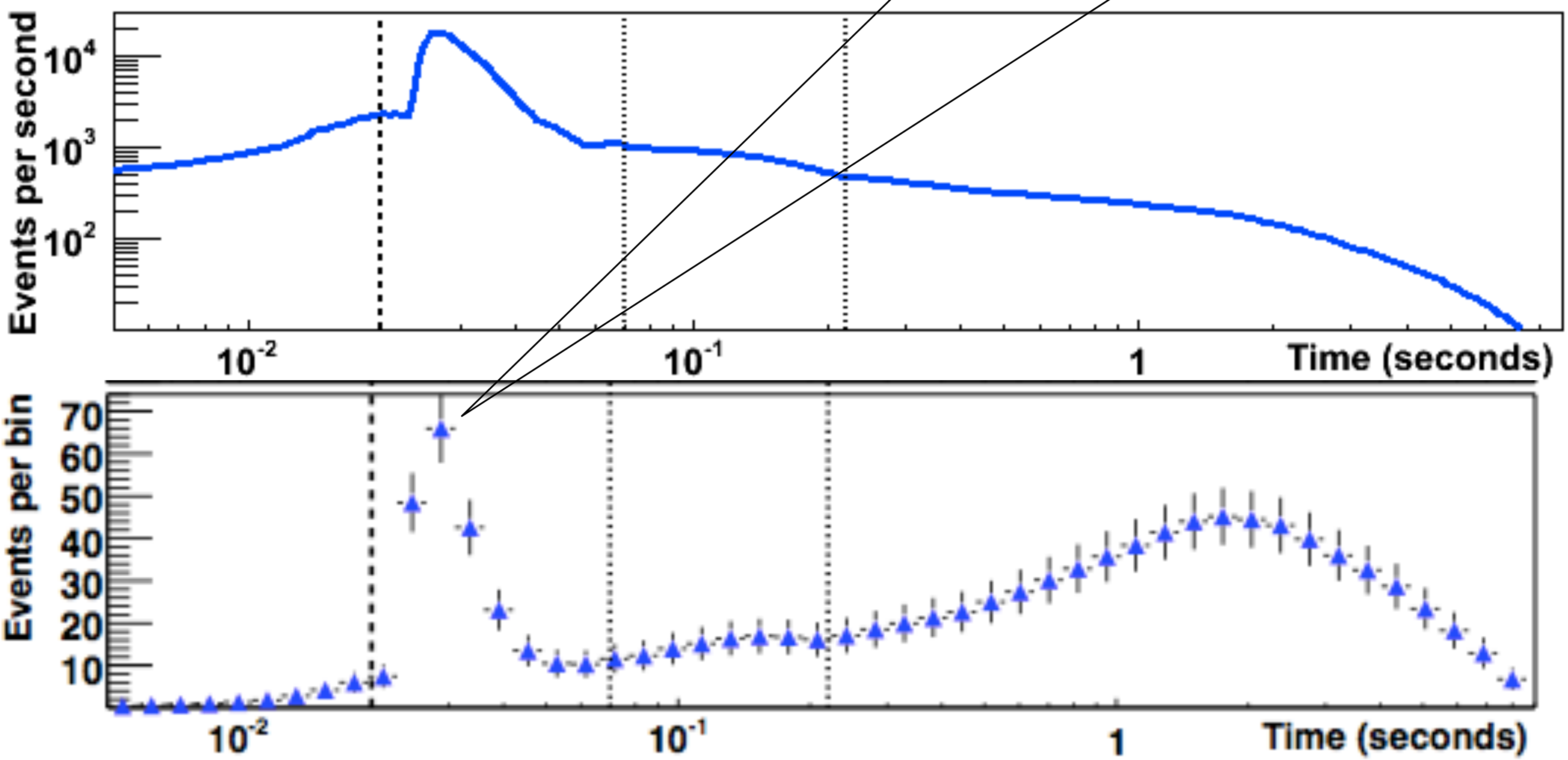
DAQ/Computing architecture for Supernova/Low Energy Neutrinos: ReadyTalk 4066631

Session to address the needs of the Supernova/Low Energy neutrino physics in relation to data rates, DAQ architecture, background rates, etc. highlighting the connections to DAQ and cleanliness requirements.

Convener: Dr. Ines Gil-Botella (CIEMAT Madrid), Kate Scholberg (Duke University), Giles Barr (Oxford University), Dr. Jacques MARTEAU (IPN Lyon), Dr. Thomas Junk (Fermilab), Dr. Amir Farbin (University of Texas at Arlington)

Extreme case: during highest-rate part of burst, expect ~80 events @10 kpc in **one drift time** (~4 ms) ➔ **~10⁵-10⁶ events** @ 0.1 kpc

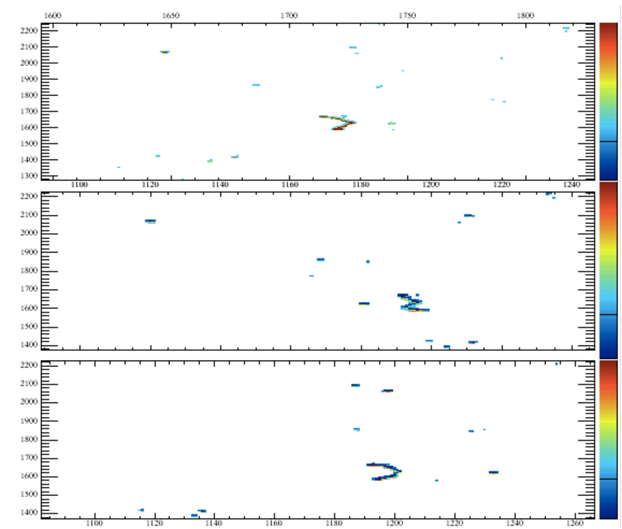
"Garching" model (cool)



(note: neutronization peak will be suppressed by oscillations)

Will there be spatial overlap during the drift time?

<u>Back of the envelope:</u>



20 MeV ν, ~60 cm size

- Typical event size: cube ~few 10’s of cm on a side,

say **~1 m^3 per event**

- 40 kton is 3 x 10^4 m^3 of LAr

- In *highest rate drift window* during neutronization burst

~10^6 events would mean

- 10^6 / 3 x 10^4 ~ **33 events per m^3** at 0.1 kpc (crowded!)
- **0.3 events per m^3** at 1 kpc (minor overlap)
- **0.003 events per m^3** at 10 kpc (minimal overlap)

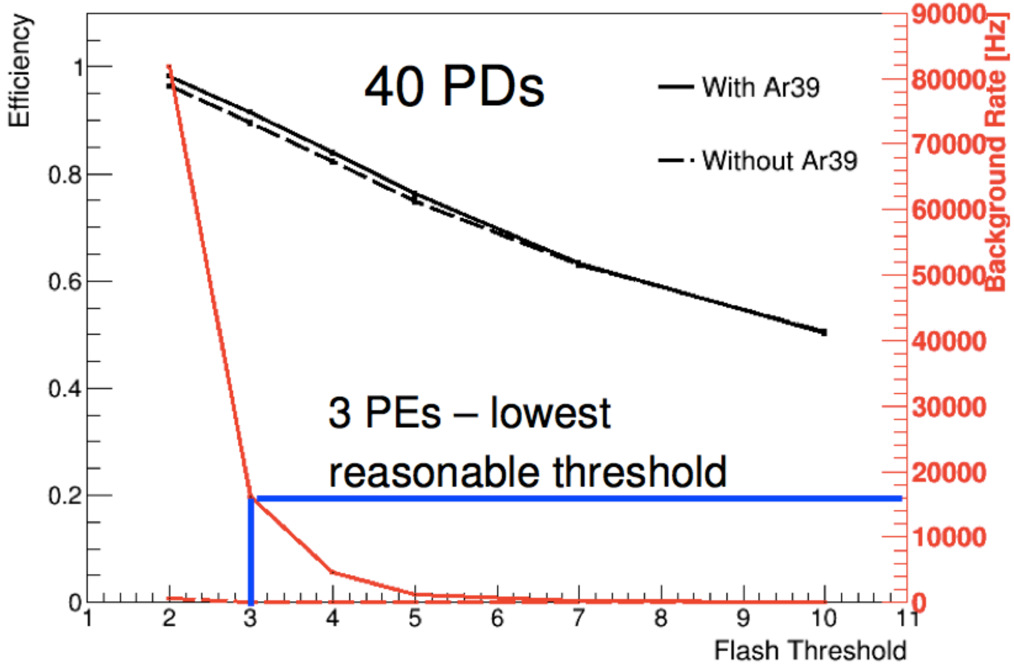
Pileup only a serious problem in ~Betelgeuse case

(for cooler model + osc suppression, down by factor of ~10)

Gleb Sinev

Low-Energy Background Simulations

From last meeting: ^{39}**Ar** study in photon detectors (Sinev, Himmel)



~3 kHz/PD

New ongoing work (w/purity group):

^{222}**Rn**

5.5 MeV α-particles
Preliminary look:
~35 kHz/PD

Needs more study to understand limitations & potential mitigation