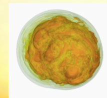
Detection of Supernova Neutrinos in DUNE



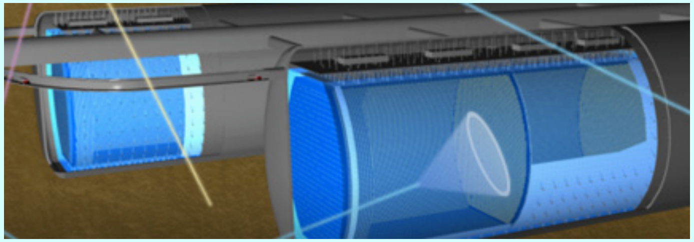
Determining detector requirements for SNB physics

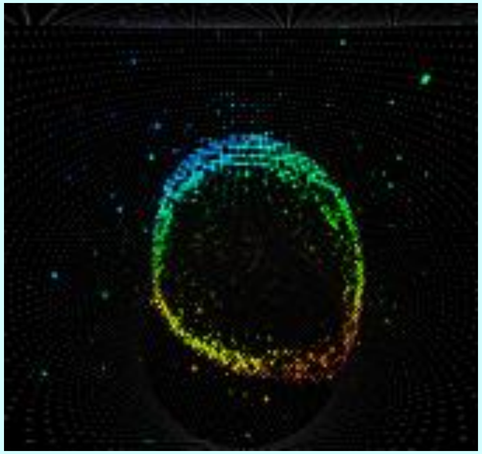
K. Scholberg, Duke University

SN@DUNE Workshop
Virginia Tech, March 2016

Multi-kiloton detector technologies

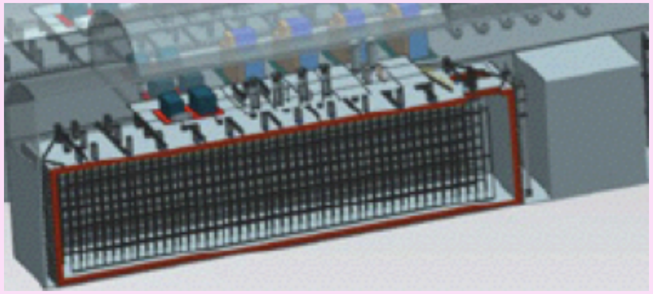
Water Cherenkov

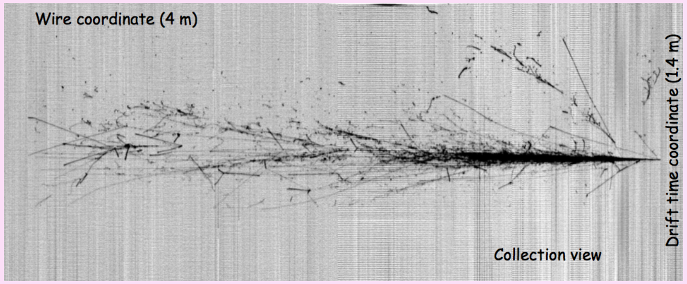




Cheap material, huge statistics

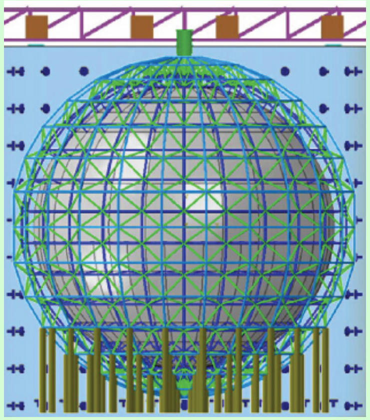
Liquid Argon

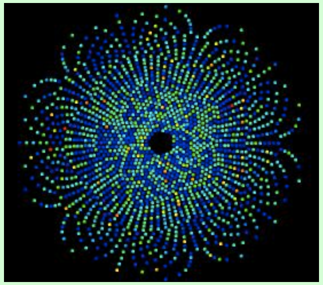




Excellent particle reconstruction

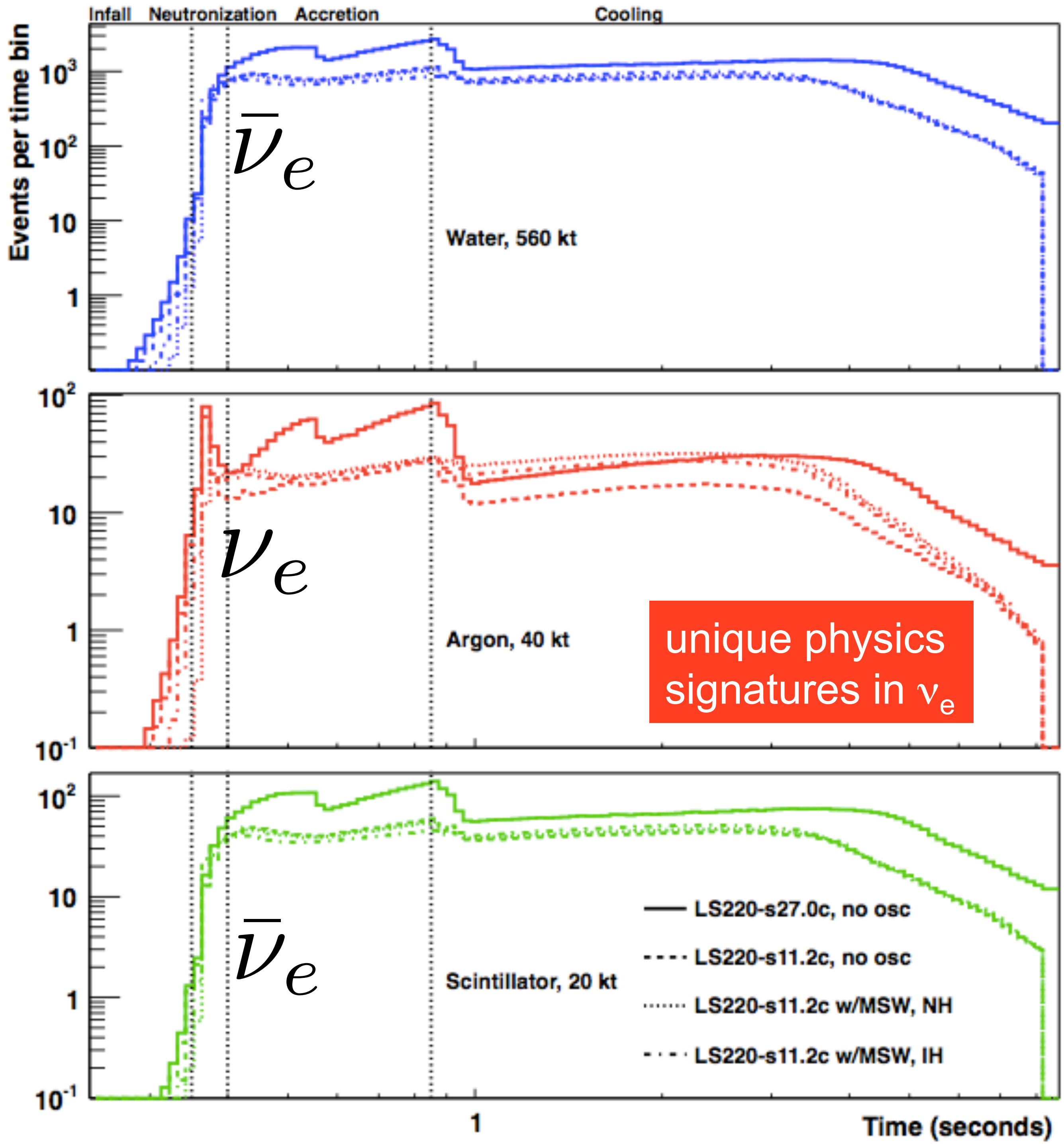
Liquid Scintillator

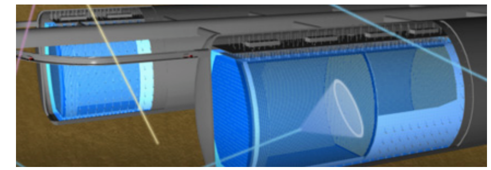


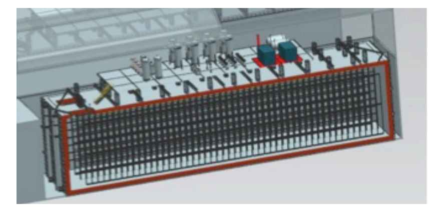


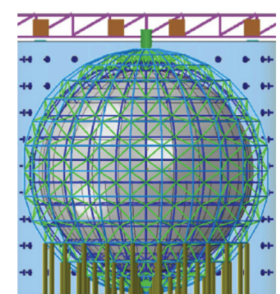
Low energy threshold, high resolution @ low energy

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









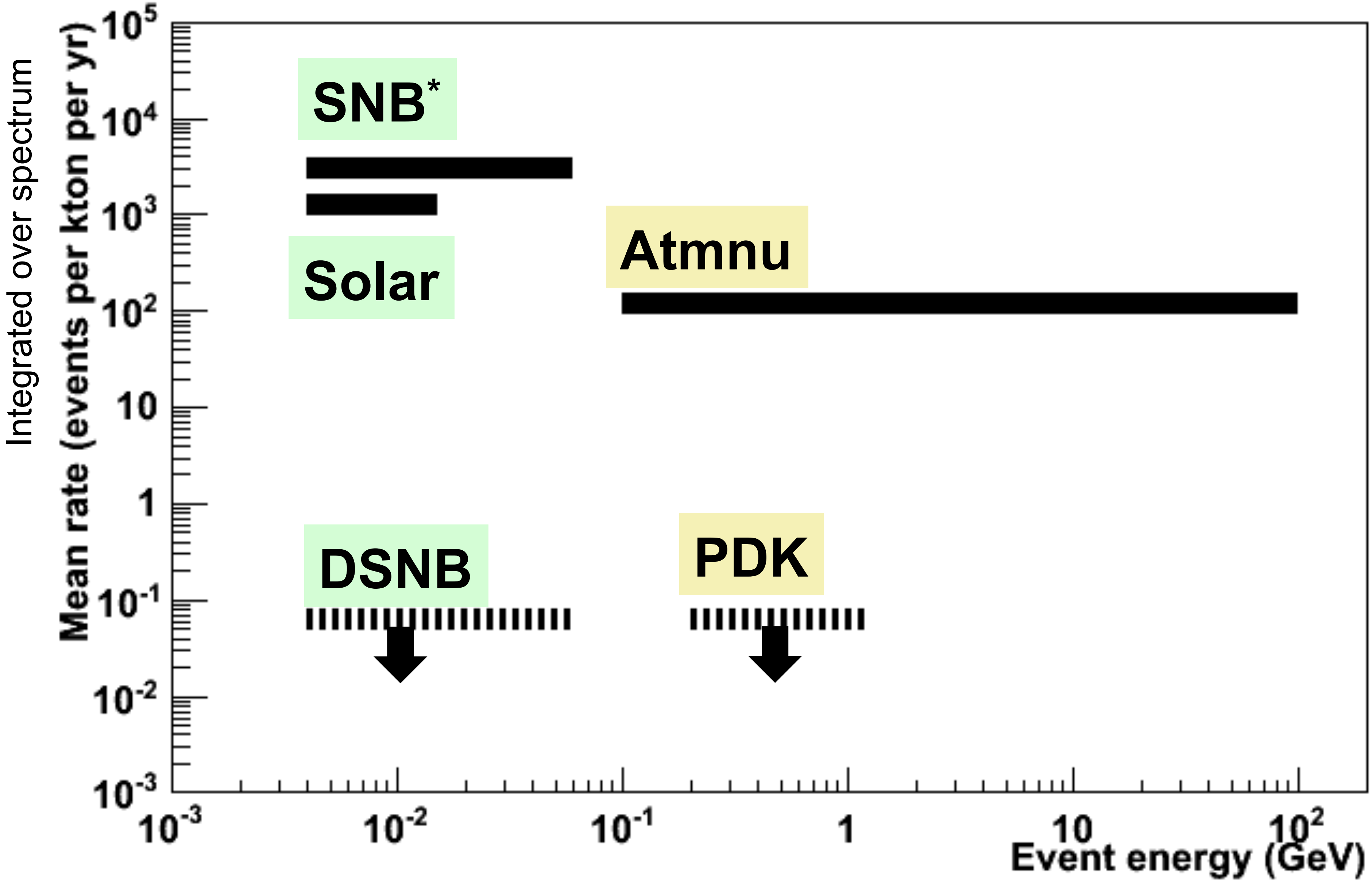
arXiv:1508.00785

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

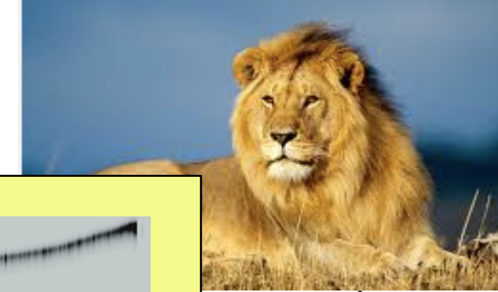
No handy beam trigger, so vulnerable to background, and require attention to triggering

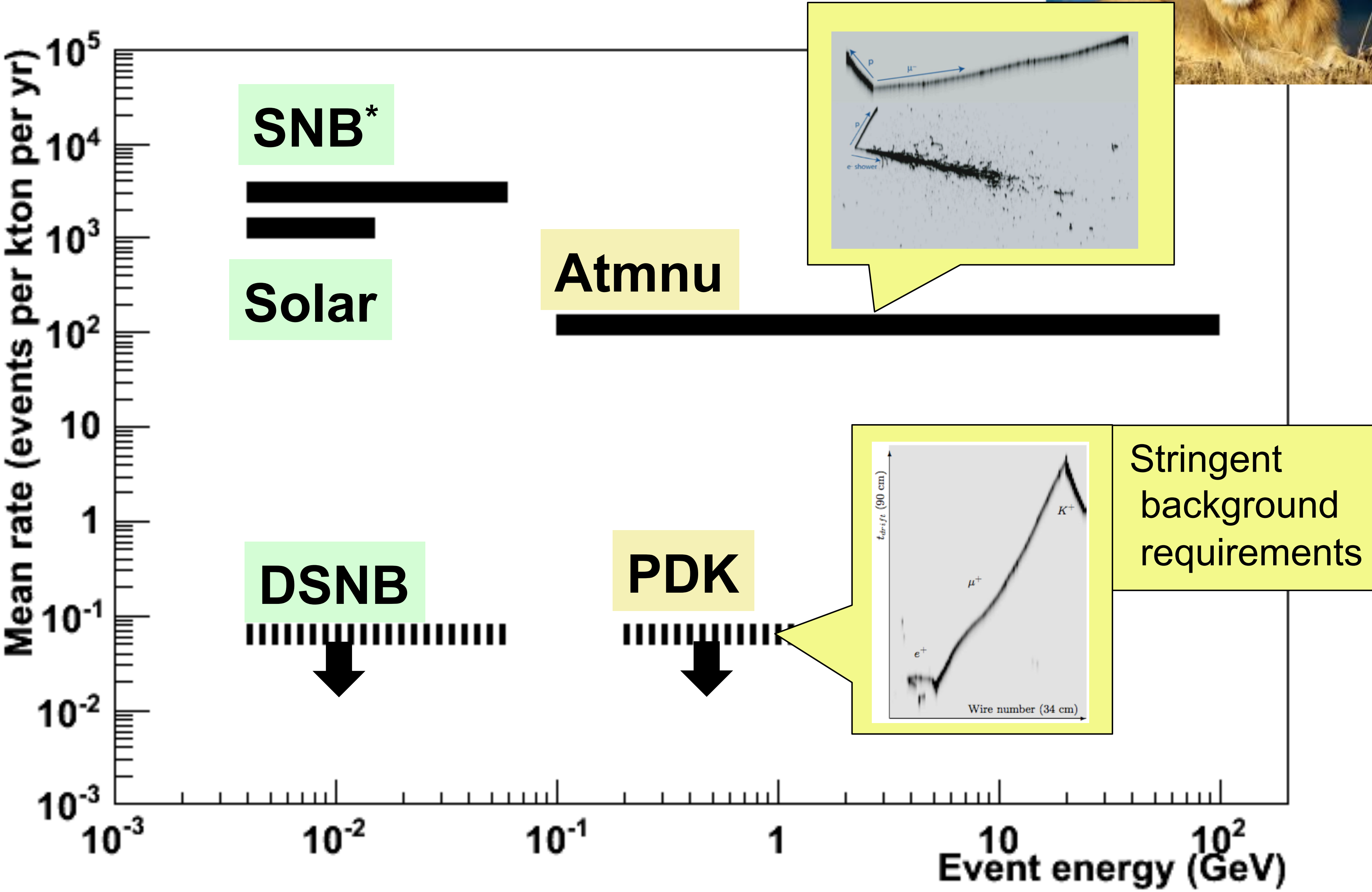
Mean rate vs event energy



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

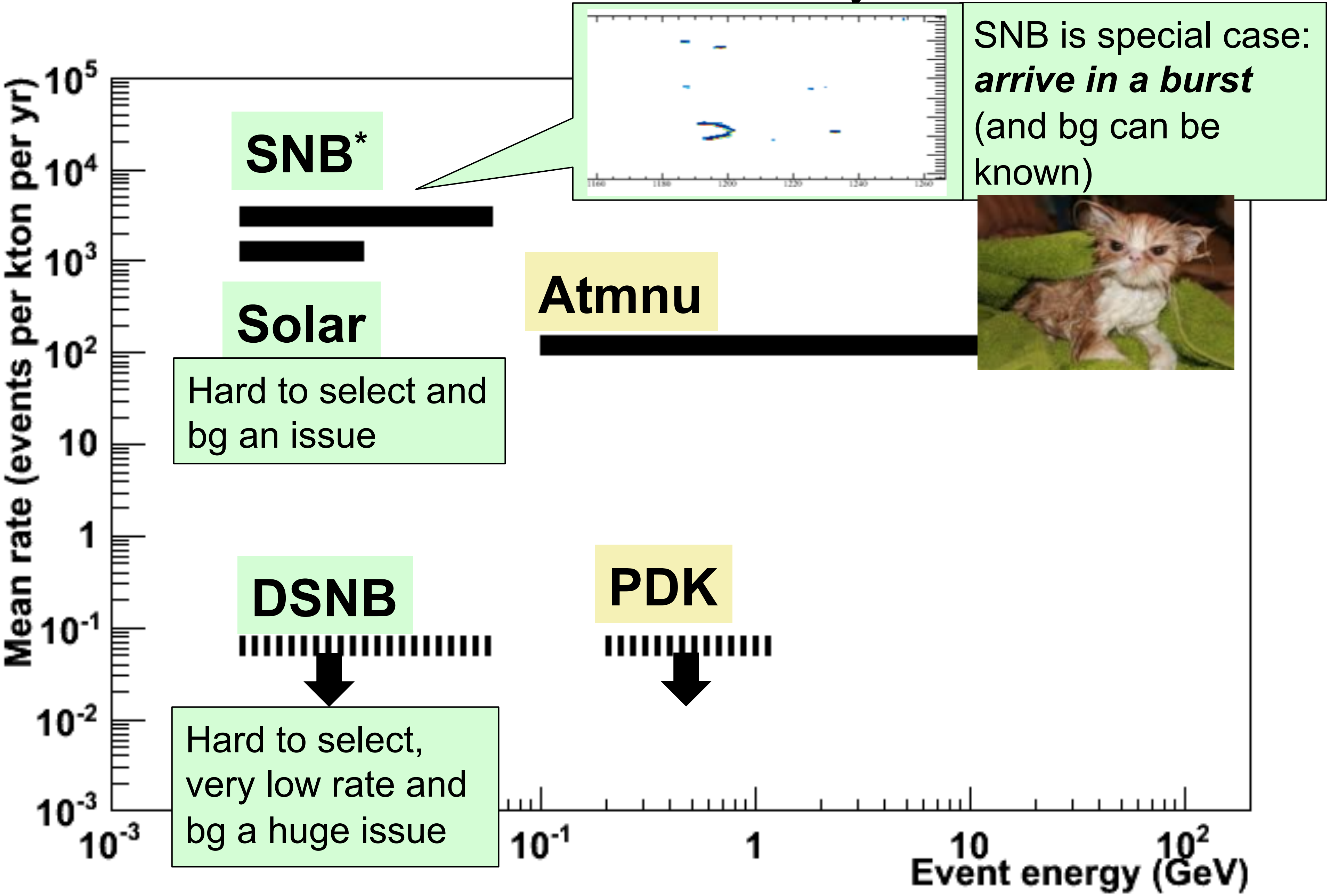
GeV-scale events: handsome and distinctive





* @1 kpc, 30 s

Few tens of MeV-scale events: crummy little stubs



* @1 kpc, 30 s

Current key tasks of the DUNE SNB/LE group

What are the detector requirements?

Ines has covered low-energy capabilities

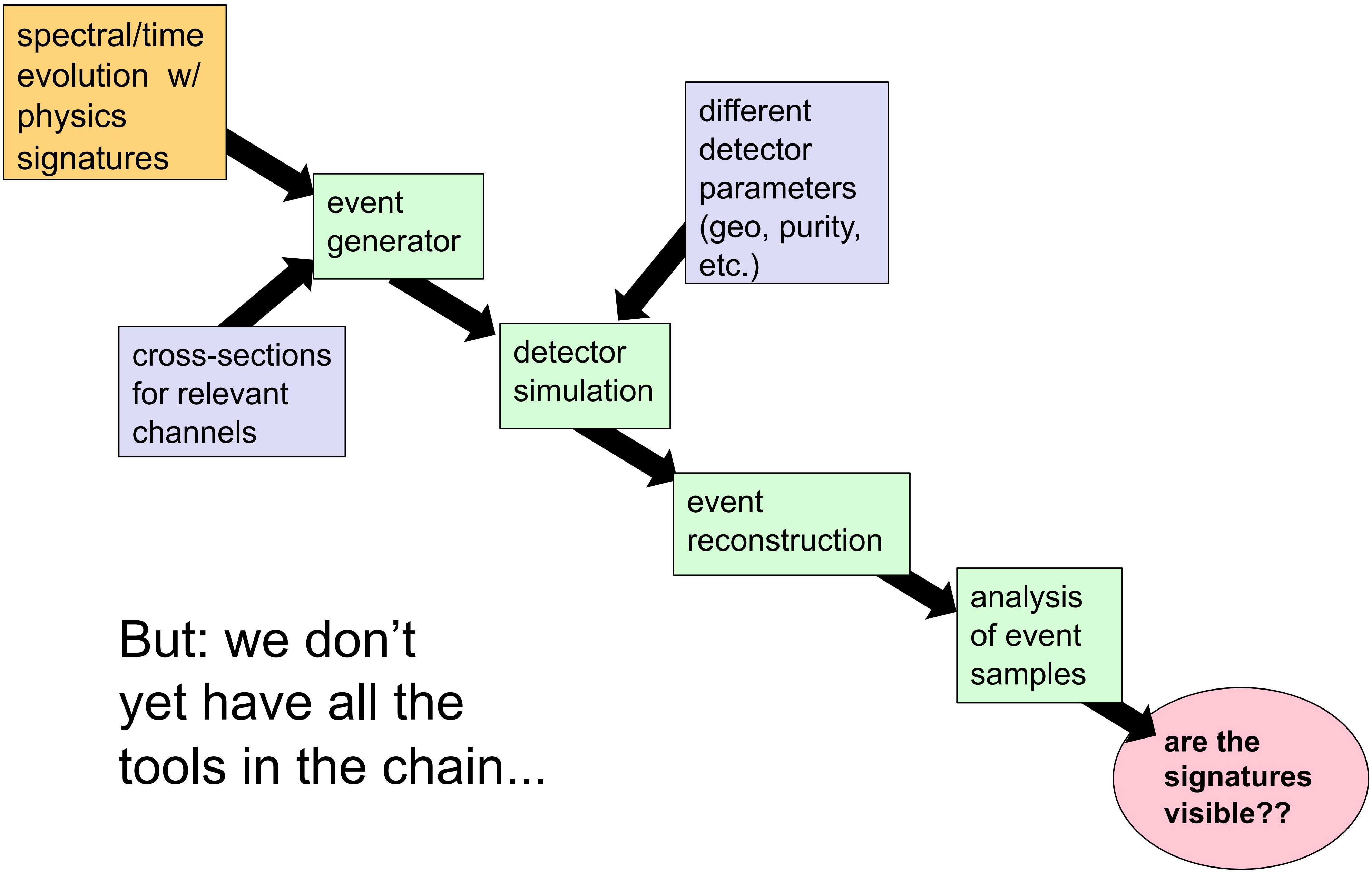
We would like to **tie the low-energy requirements to physics signatures**

... what resolutions, efficiencies are needed,
to drive detector design?

(a potentially sprawling task... need to identify **robust signatures**...)

The “ideal” way to determine requirements

full simulation with different detector parameters + full analysis chain



But: we don’t yet have all the tools in the chain...

Use SNOwGLoBES as fast tool

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

spectral/time evolution w/ physics signatures

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

use sim for refined estimate, or simple resolutions

SNOw GLoBES

interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

are the signatures visible??

In either case, critical input from theory needed here: **what are the signatures?**

spectral/time evolution w/ physics signatures

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

use sim for refined estimate, or simple resolutions

SNOwGLoBES

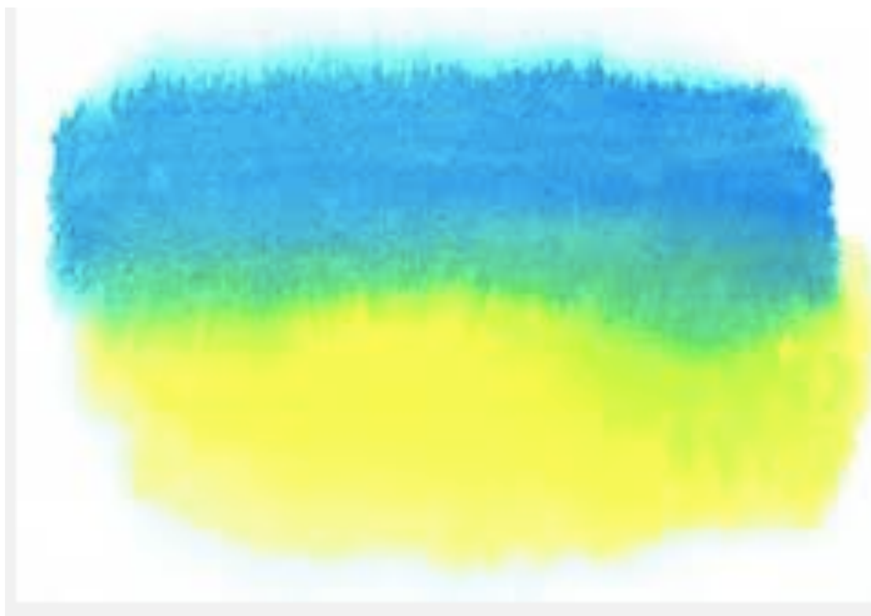
interaction rates, as a function of neutrino energy

‘smeared’ rates as a function of detected energy

are the signatures visible??

Some studies for SNB requirements
can be done using broad-brush information,

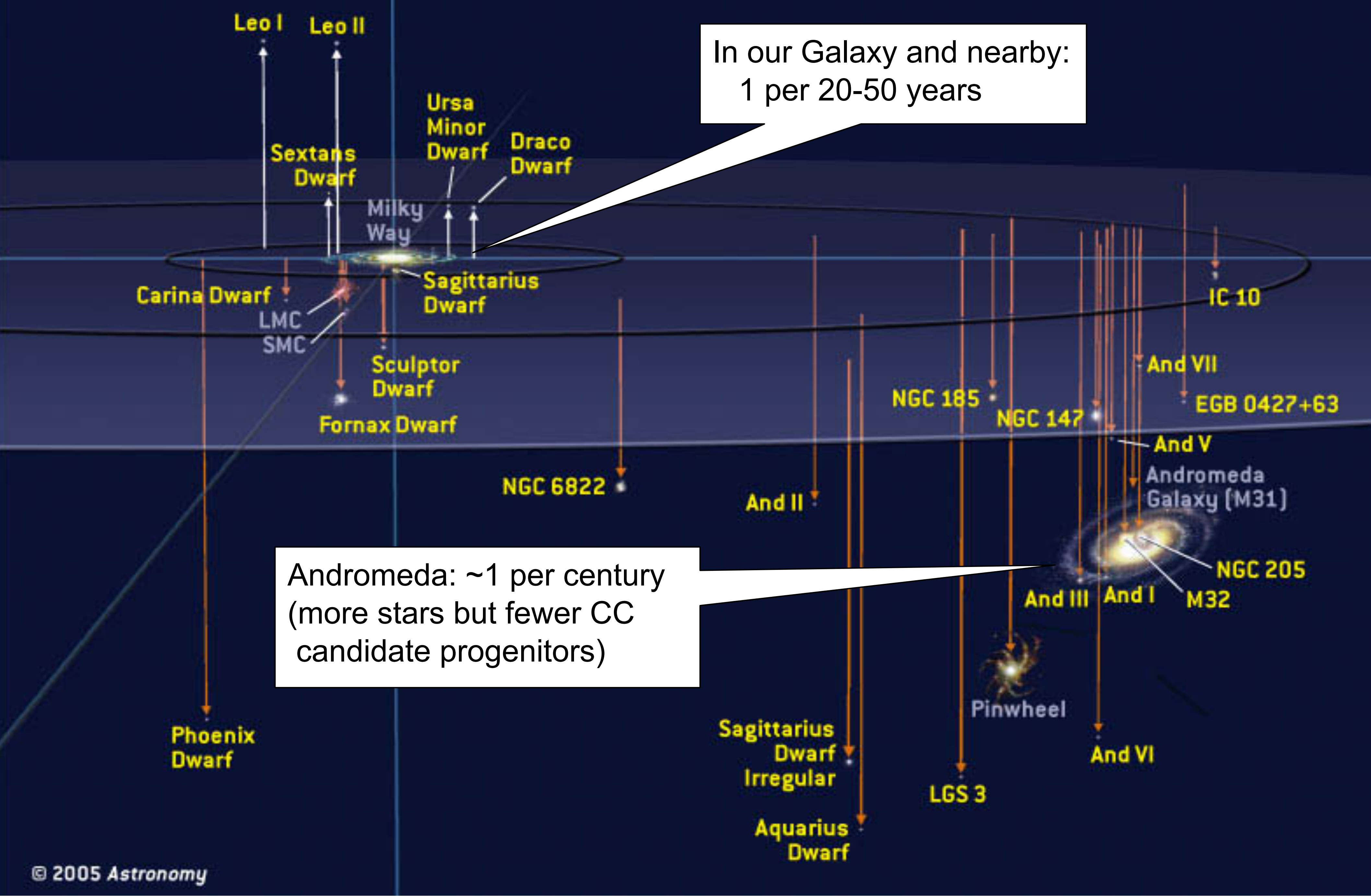
e.g., general requirements on DAQ



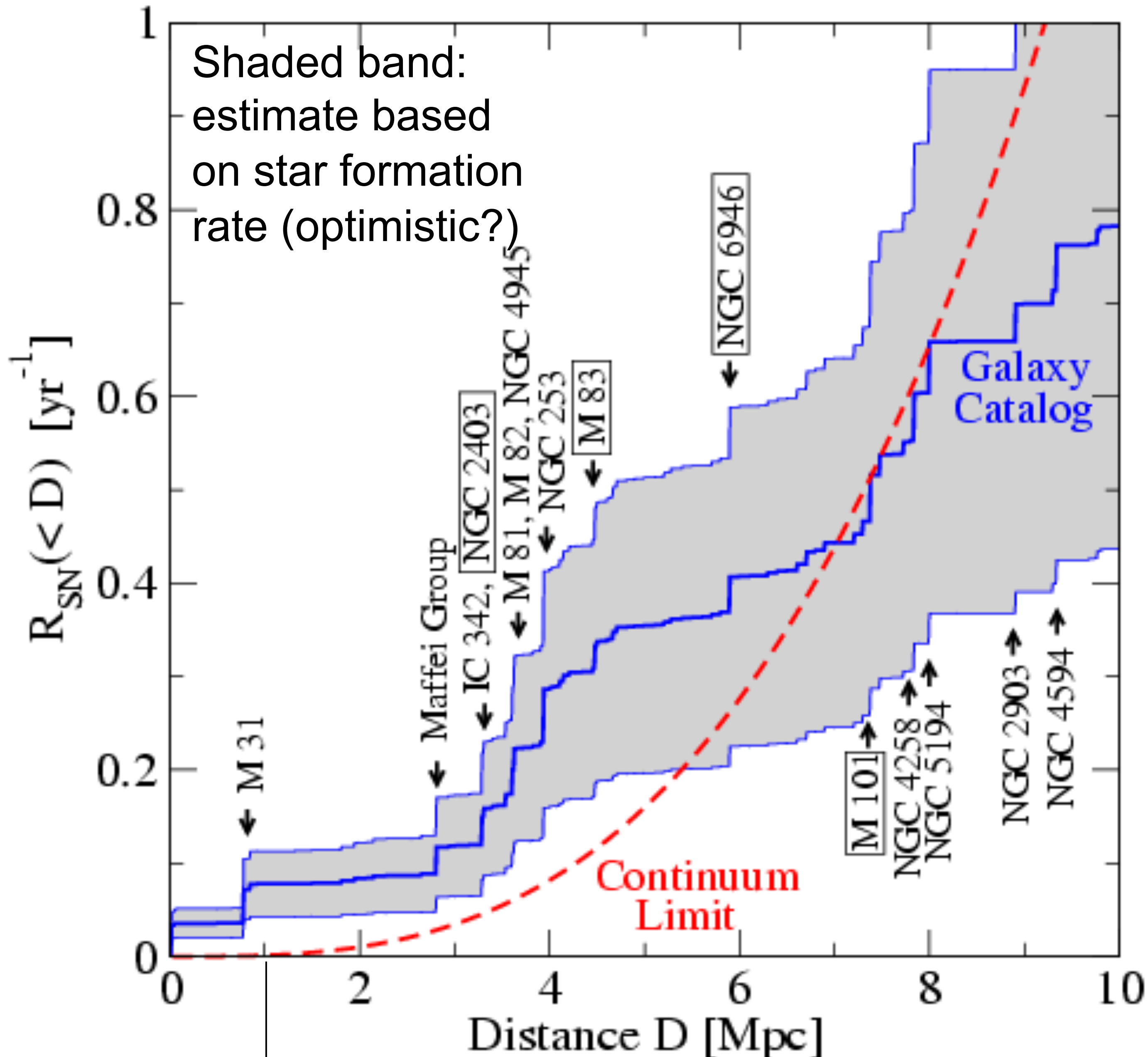
How often do core collapse supernovae happen?

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

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



Looking beyond: number of sources α D^3

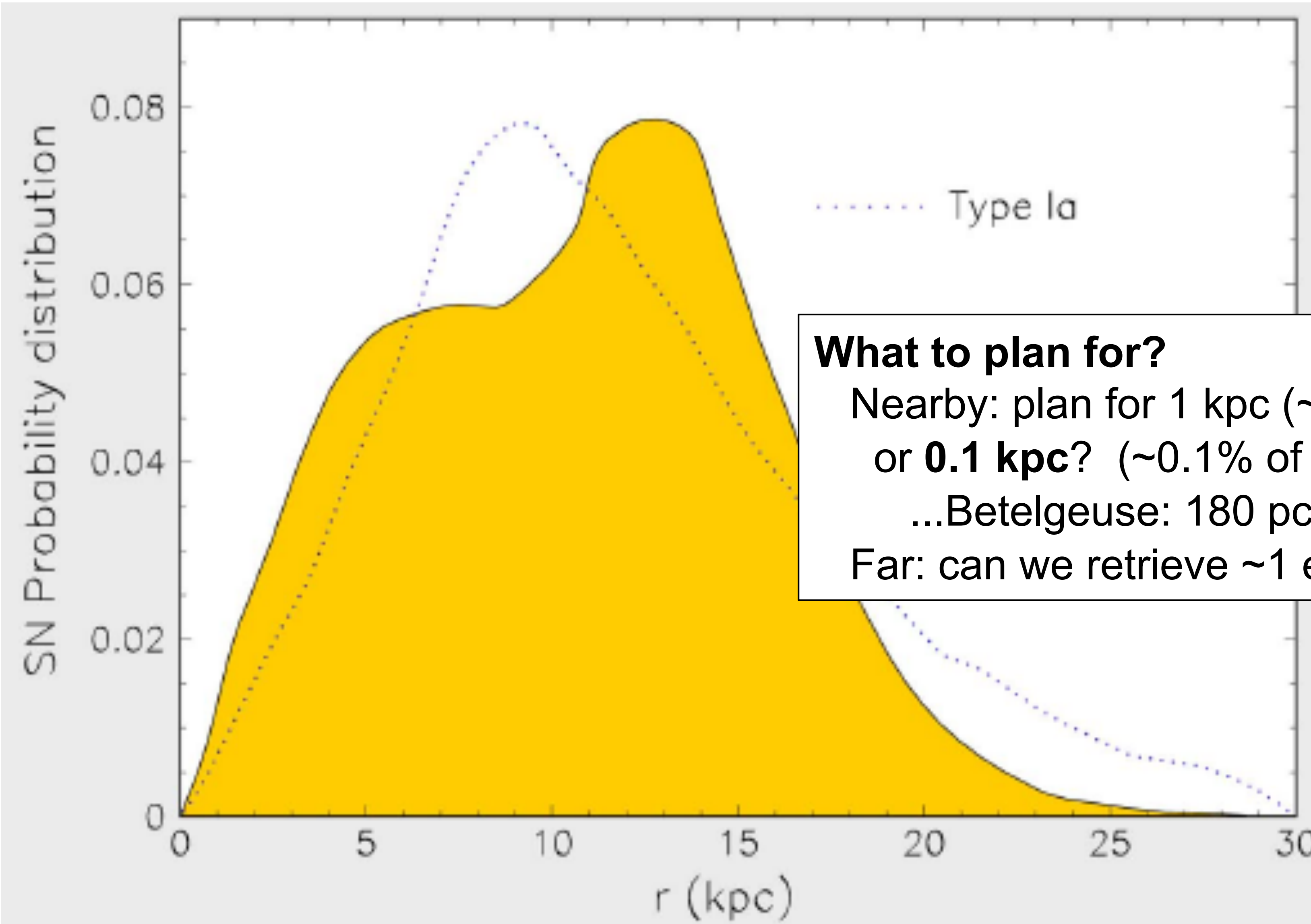


S. Ando et al.
astro-ph/0503321

expect < 1 event in 40-kt LAr

Typical distance from us: ~10-15 kpc

(10 kpc is “standard distance”)

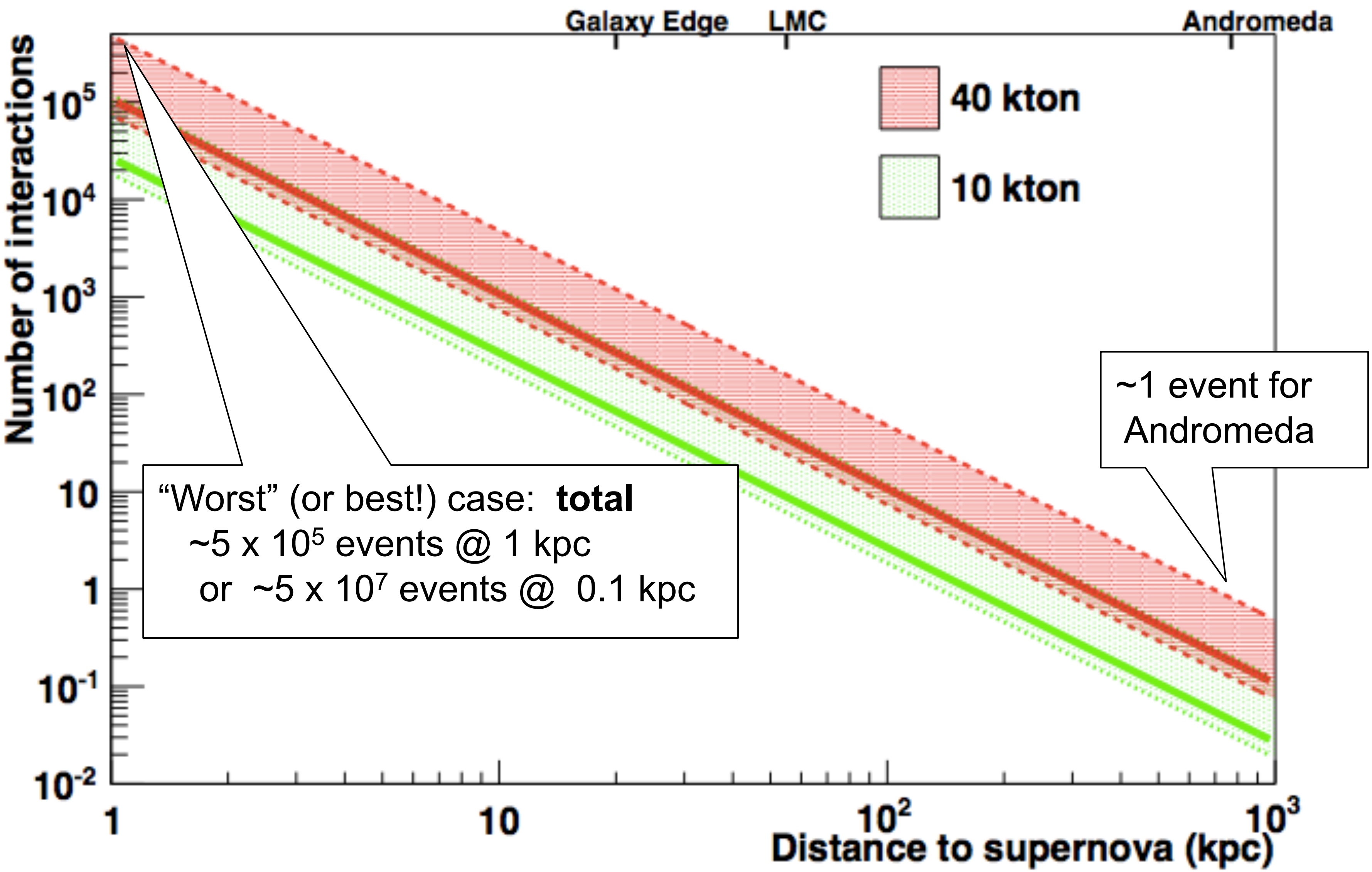


What to plan for?
Nearby: plan for 1 kpc (~1% of CCSN)?
or **0.1 kpc**? (~0.1% of CCSN?
...Betelgeuse: 180 pc)
Far: can we retrieve ~1 event??

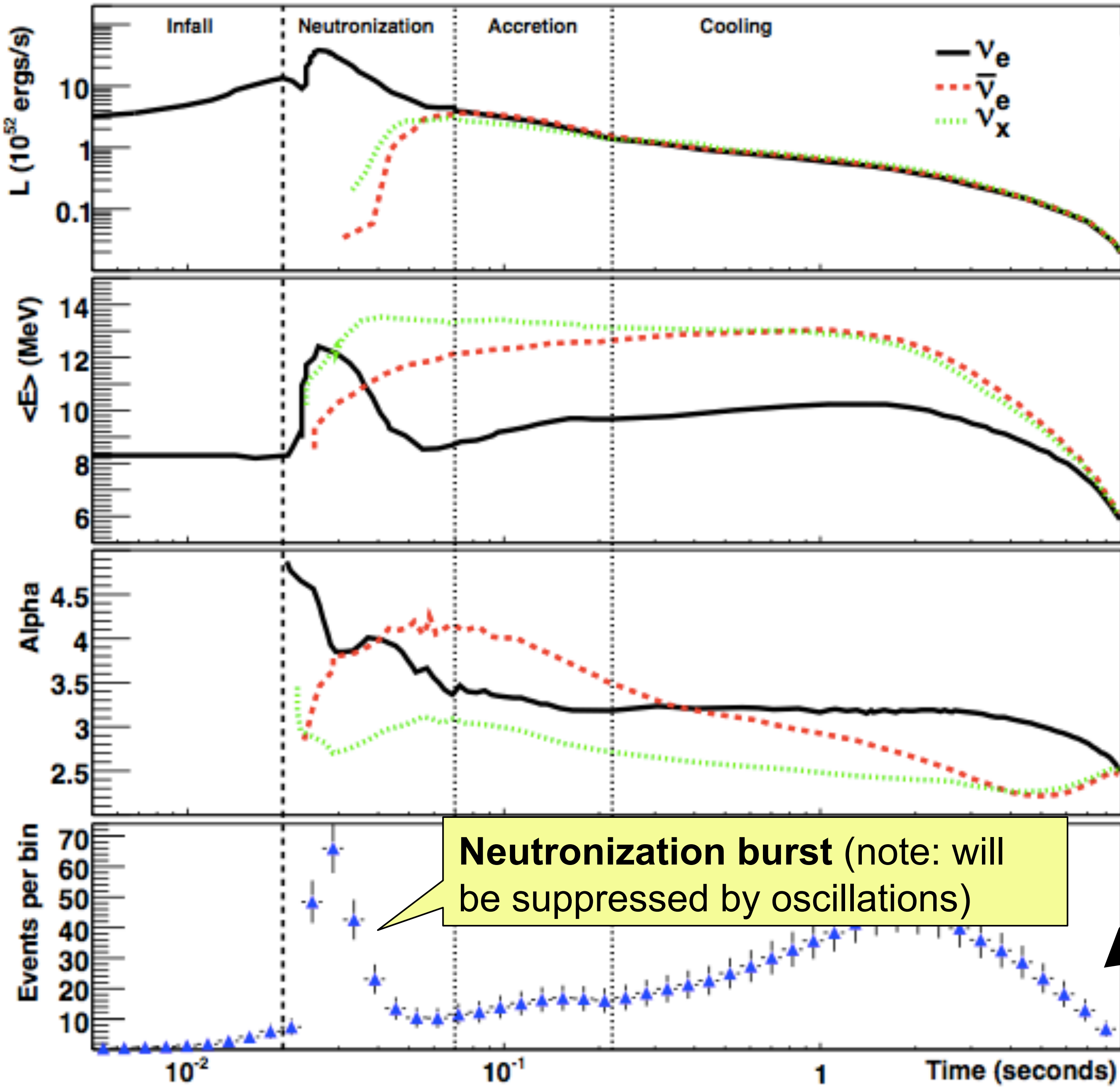
Mirizzi, Raffelt and Serpico , astro-ph/0604300

Events vs distance
(α $1/R^2$)

- band represents range of models (factor of ~10 in rate)
- solid line: “Garching” model



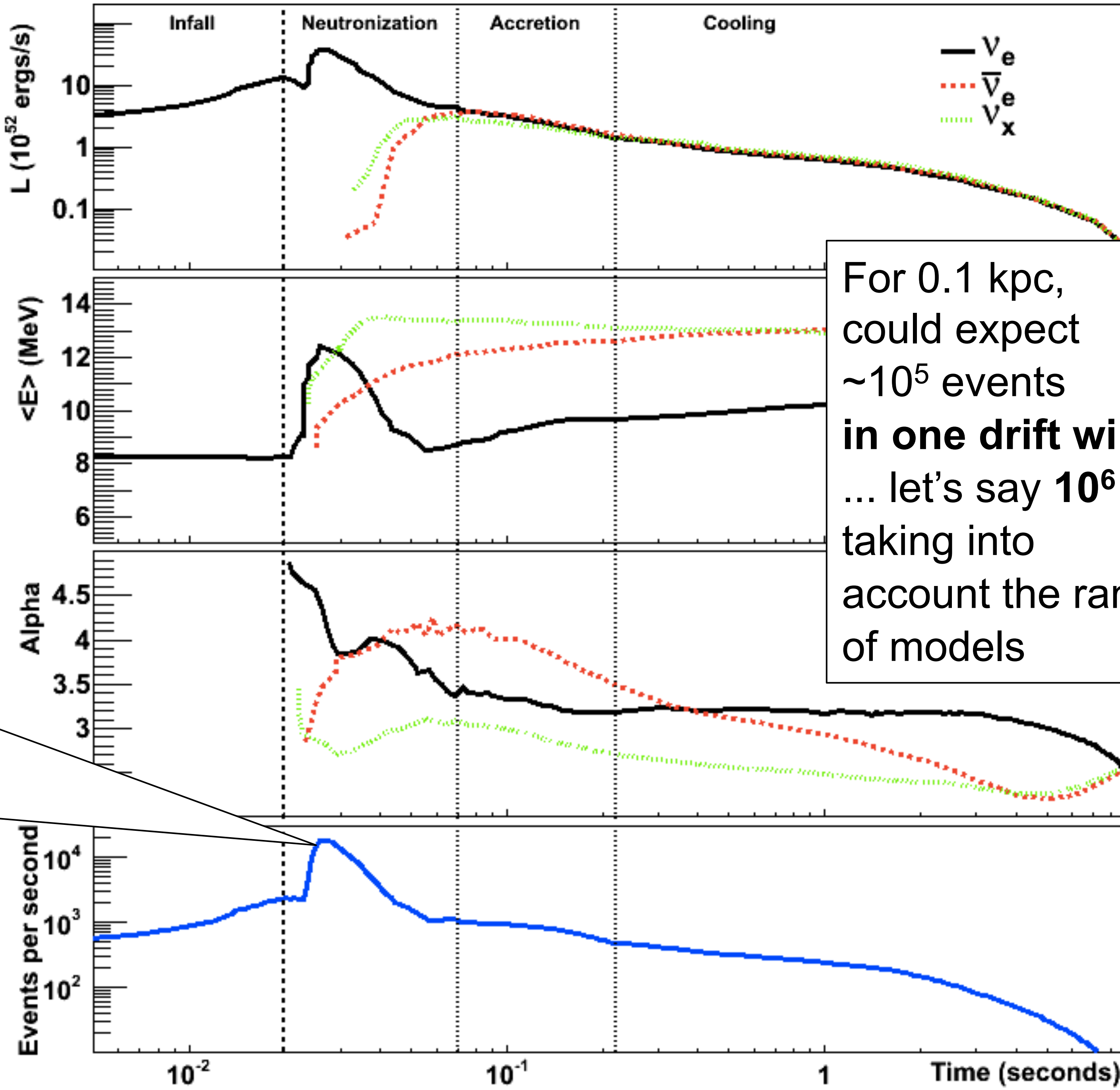
How are these events distributed in time? Maximum rate?



Plot from DUNE CDR of example model... but these are **unequal time bins**

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

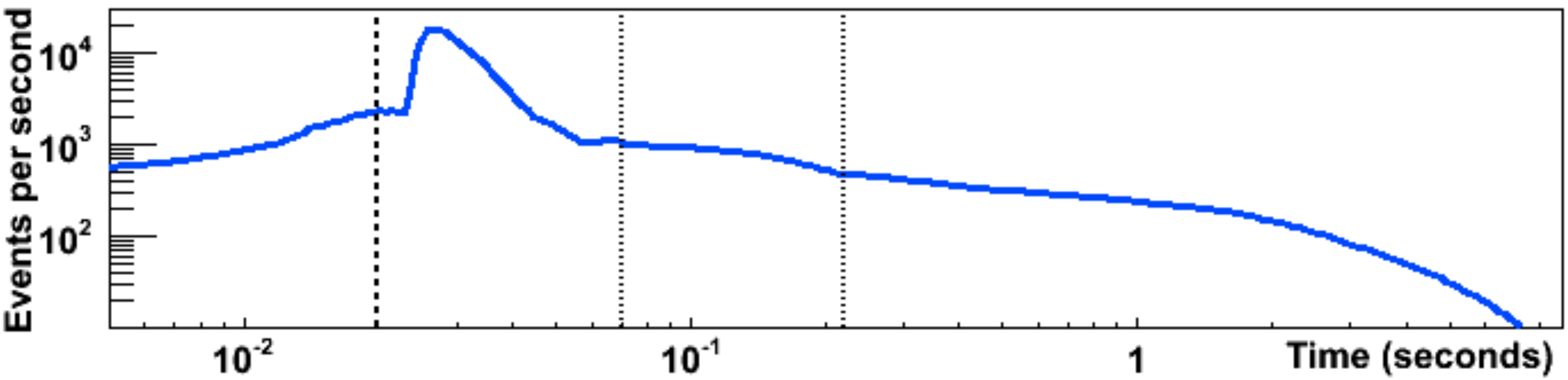
Redone as **rate** profile (same “Garching” model, 10 kpc)



~2 x 10^4 events per second in highest rate ~4 ms time bins @ 10 kpc (~80 events)

For 0.1 kpc, could expect ~10^5 events **in one drift window** ... let’s say **10^6** taking into account the range of models

How long is the burst? How long to make the burst time window to keep all interesting information?

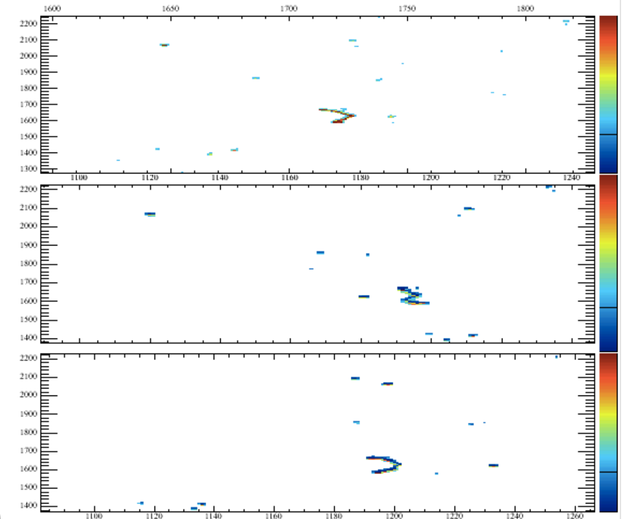


???

Answer: don't really know! Models go out to ~10 seconds (only a few that far)

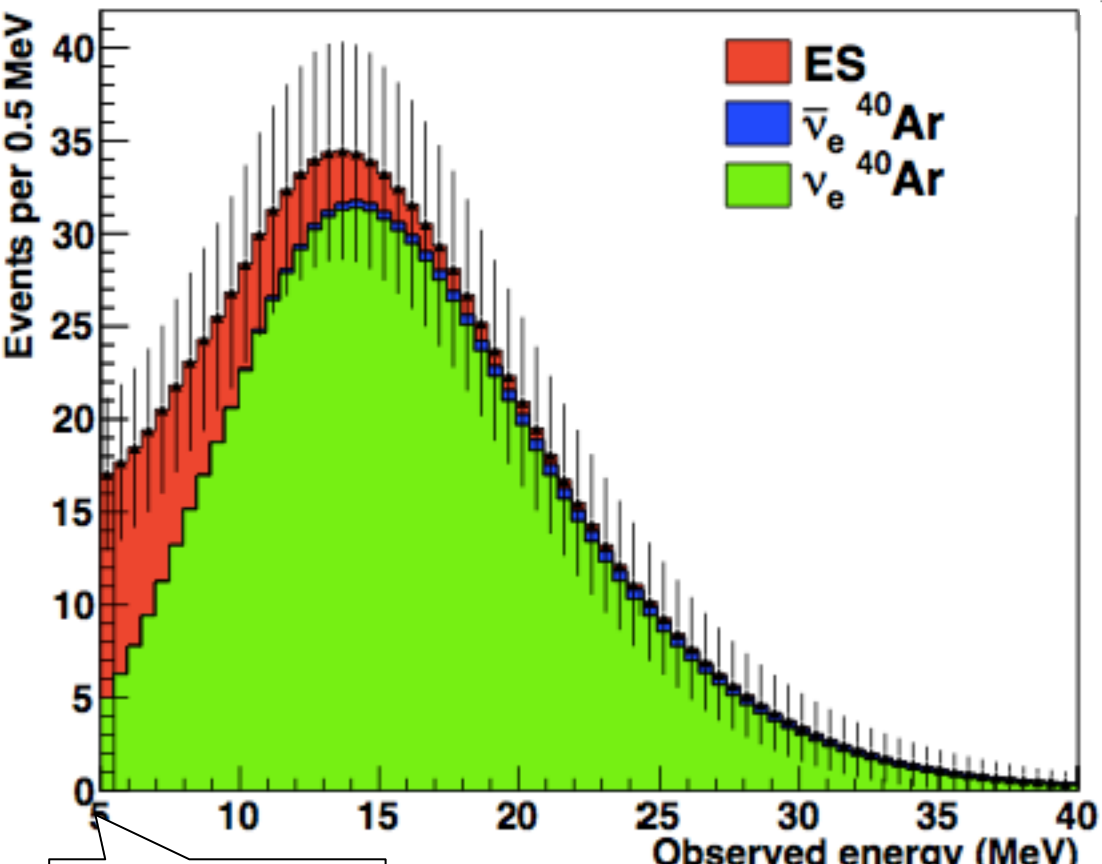
Good to keep information as long as possible for proto-nstar cooling information, other physics signatures

What do events look like?



20 MeV ν, ~60 cm size

Energy spectrum

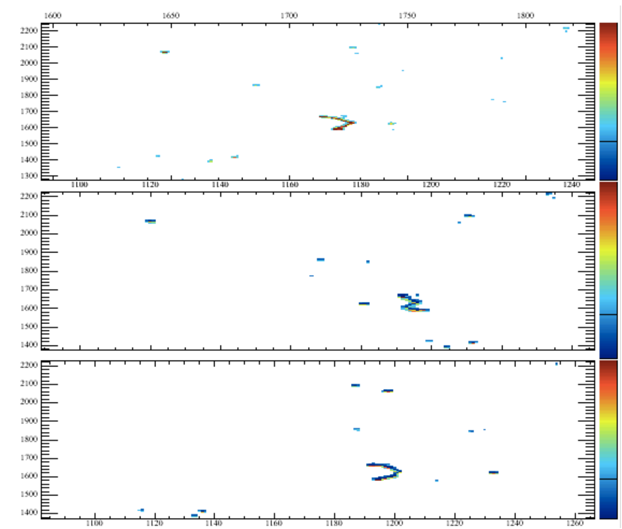


Events down to 5 MeV and lower

This assumes final state energy is fully collected, which is probably a poor approximation for CC events (some γ energy may be collected but for CC events, n, p energy may not be observed)

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)

SNB considerations for DAQ

If we plan for 0.1 kpc:
could have 5 x 10^7 total events,
possibly ~10^6 in one drift time window

Excitement happens within 10 secs, but
should plan for as long a window as tolerable

Spatial overlap becomes an issue < 1 kpc
only during highest-rate neutronization burst time bin

Should plan for ~5 MeV events (lower if possible!)

Backgrounds the main issue to understand
since resources to handle steady-state background
will constrain DAQ capabilities for signal

Triggering and data taking opportunities for SN in current design

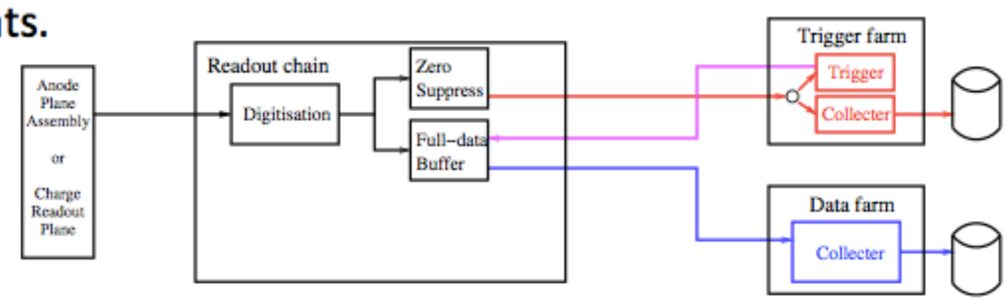
Important: this current design can change after our discussion – we have tried to be as flexible as possible, but will certainly think again if this falls short.

- Trigger primitives (a.k.a. Zero suppressed hits) collected in trigger-farm computer. Can be stored in long-term storage. Suitable for making searches for supernova activity coincident with some external event reported hours or days after the data are collected.

- Trigger based on the trigger primitives sent back to full-data-buffers, can contain location and trigger type information. So it is possible to design an algorithm where we pick up low energy depositions around the thing that triggered. Constrained by bandwidth budget.

- The supernova-burst trigger: This also uses the trigger primitives and the trigger farm. It is designed to detect neutrinos from a supernova burst in our galaxy and allow the maximum info to be saved over the 10 sec window. Also want to minimize the dead-time for being receptive to such events.

One dead-time minimization technique is to make the DAQ in the four caverns independent.



Giles Barr

Backgrounds

This is the most important and least well known,
and obviously will constrain what we can do...
determines distance reach

Sources:

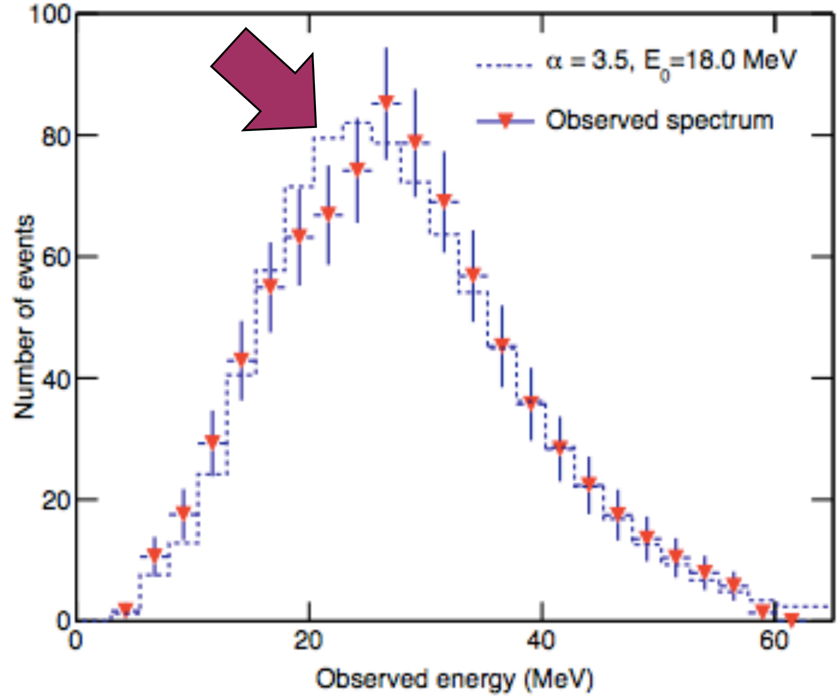
Radiologicals... ^{39}Ar, ...
Cosmogenics: muons, spallation products
Noise
...

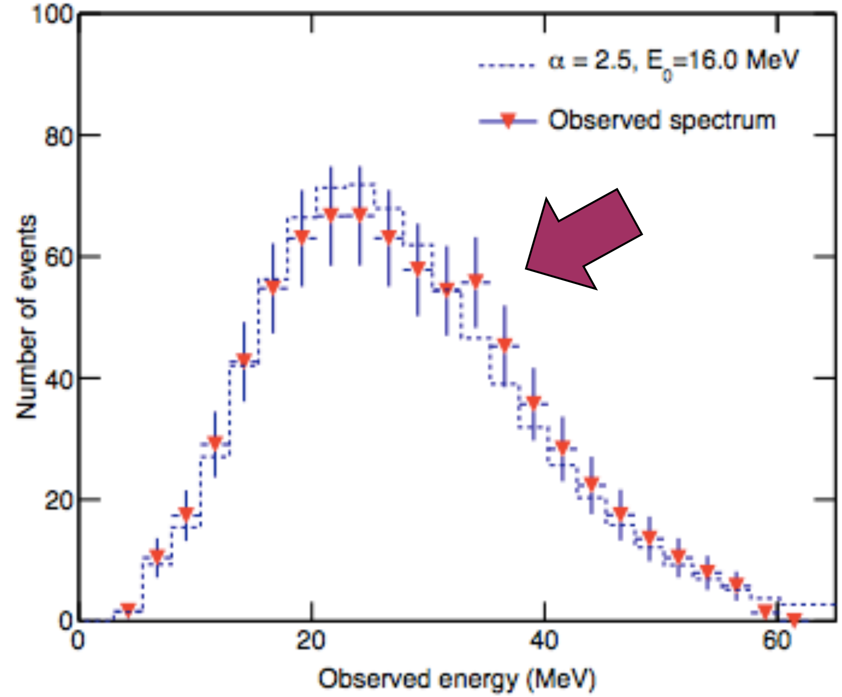
More fine-grained expectations required
to understand other detector requirements
(energy, time, angular resolution...)

Example study (an 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

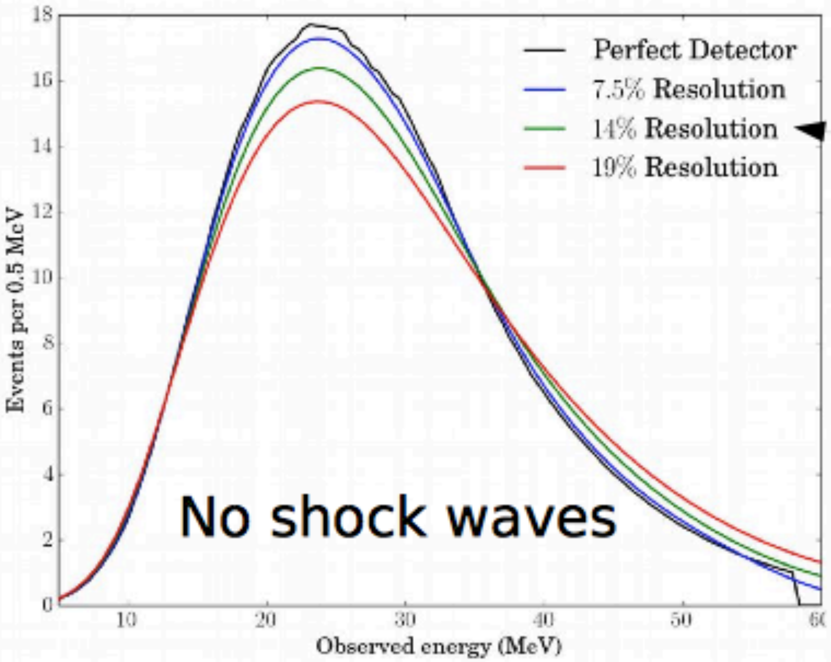
In this case, using standard SNOwGLoBES:
Icarus resolution, assume all gamma energy retrieved
(and no energy lost via nucleon emission! probably poor assumption...)

Energy resolution studies (Gleb Sinev)

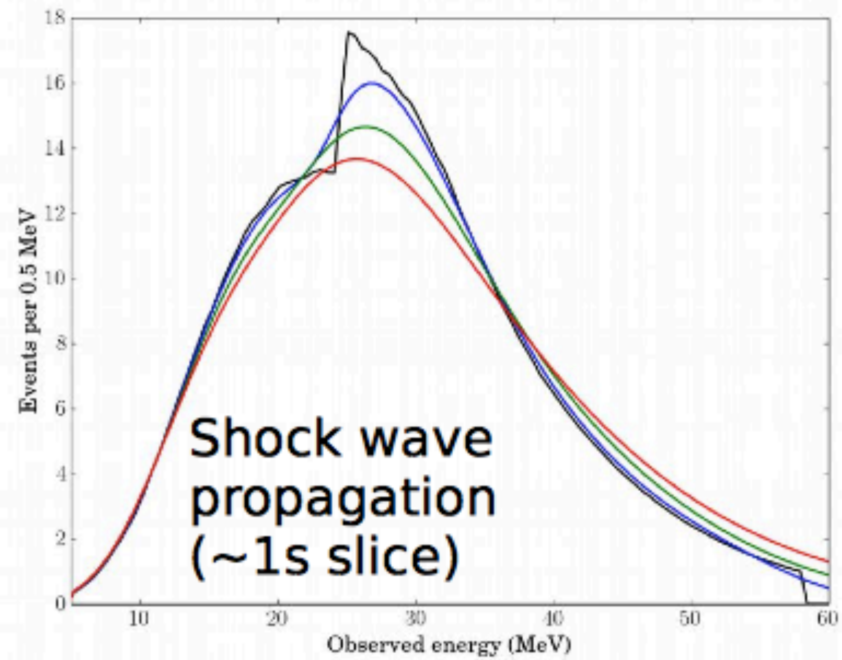
Energy resolution Shock-wave signatures

Gaussian smearing indep of energy

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

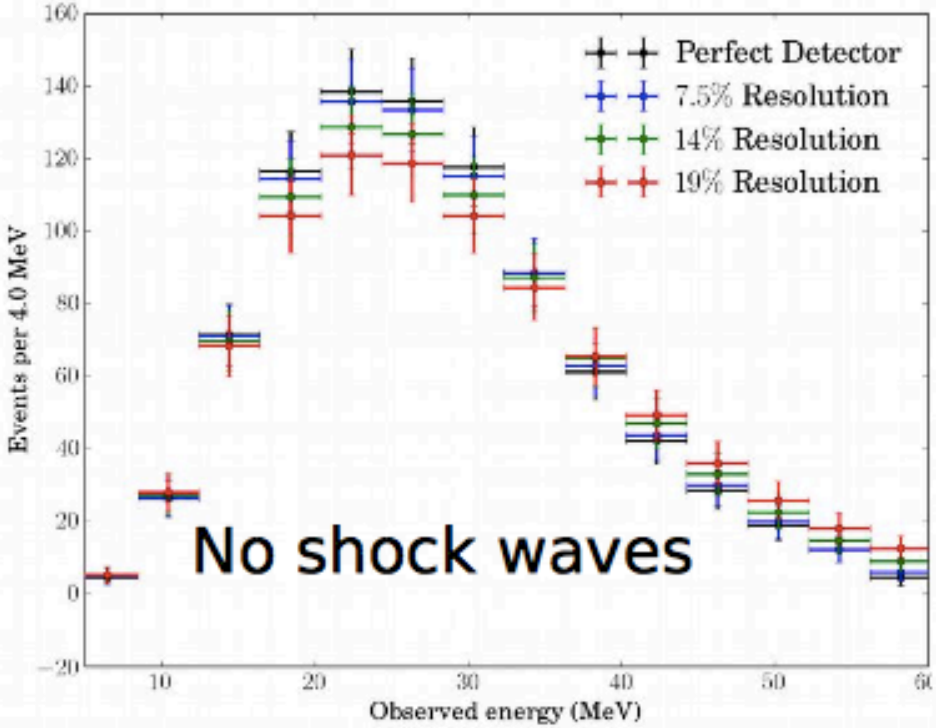


Detector simulation



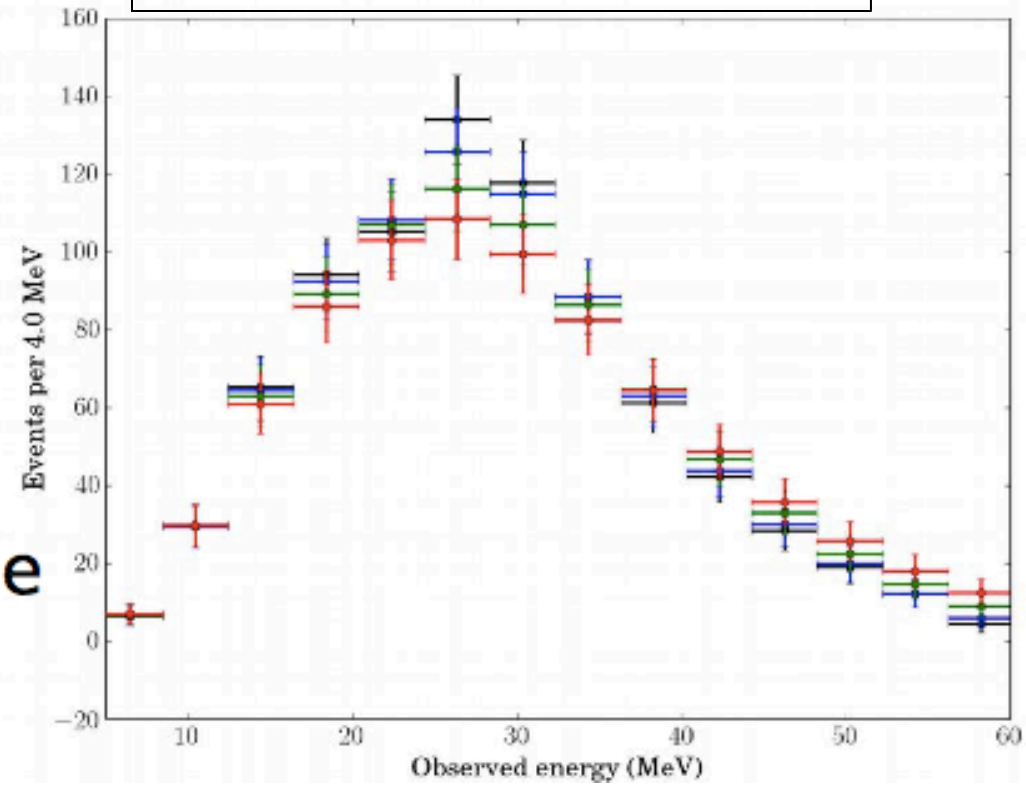
“Anecdotal” spectral feature from A. Friedland

Adding statistics (supernova 10 kpc away)



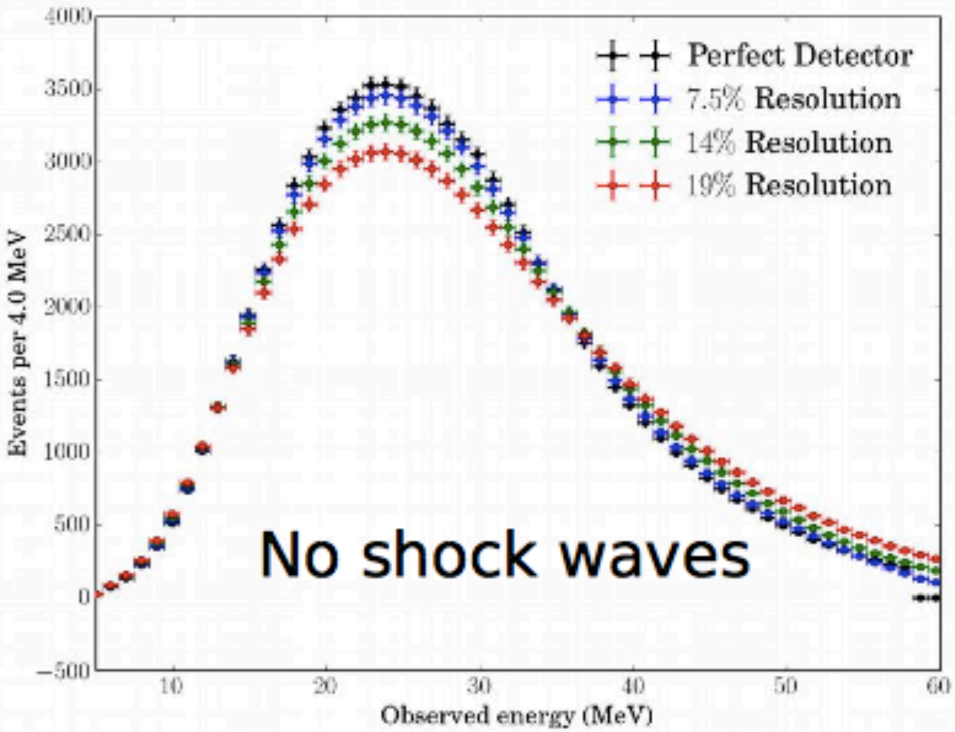
No shock waves

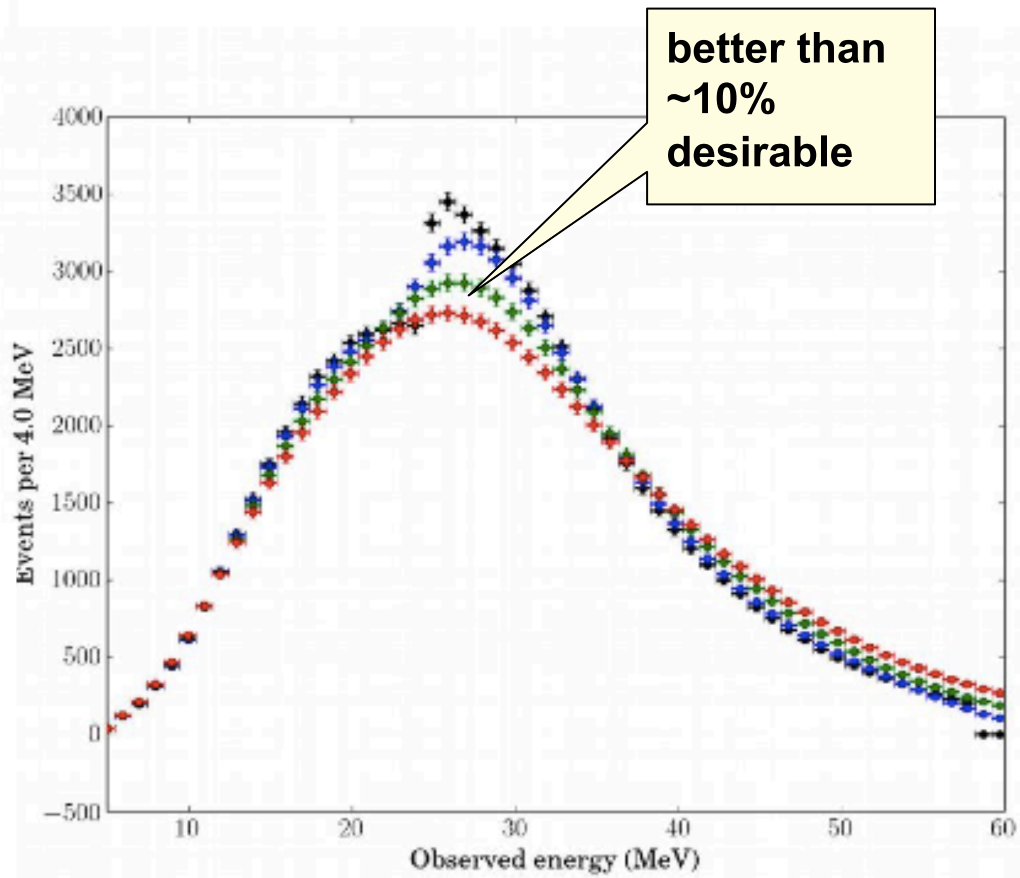
Resolution doesn't help much if you don't have sufficient statistics...
(note: may still be able to quantify non-smooth/thermal)



Features are indistinguishable

Adding statistics (supernova 1 kpc away)

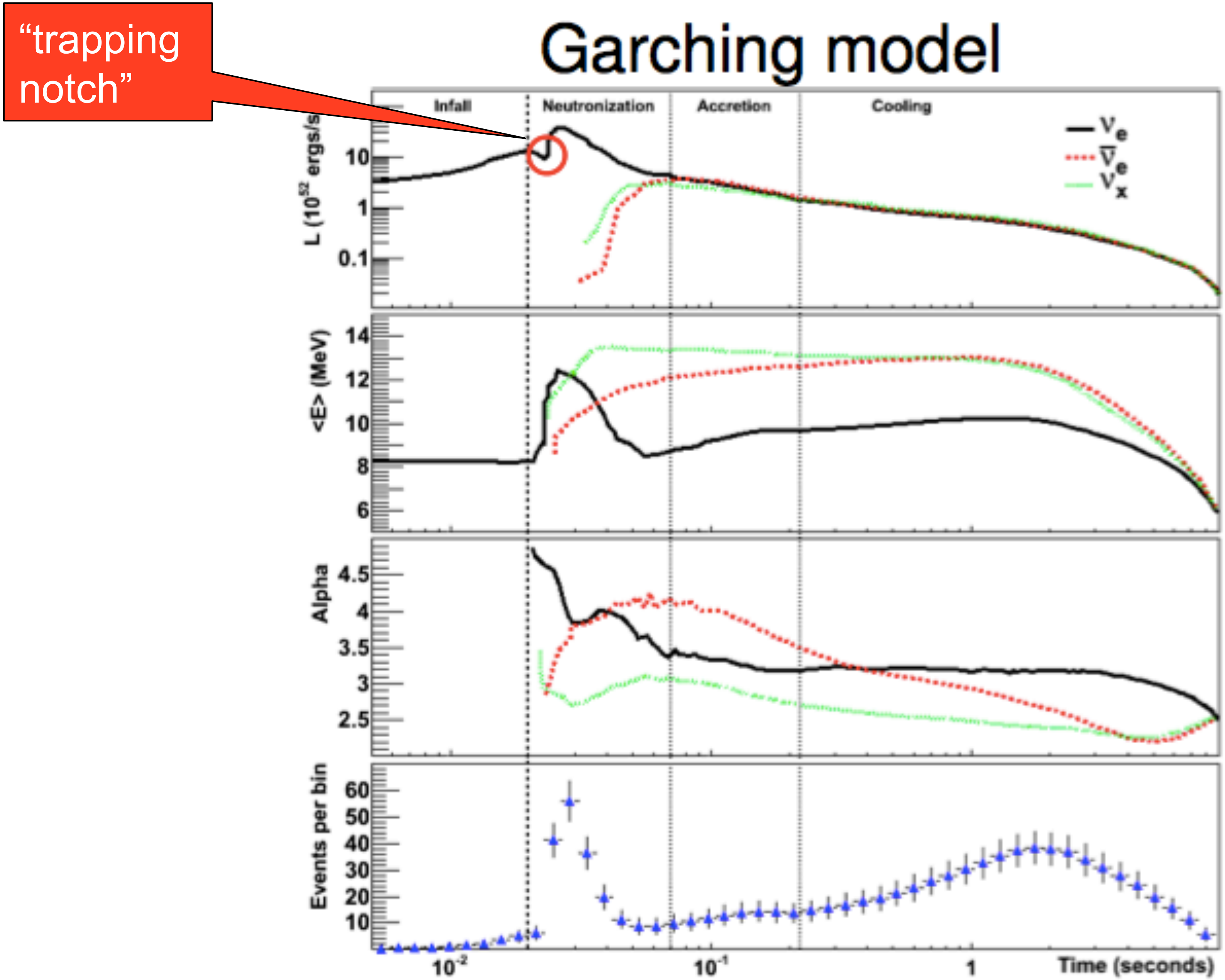




Conclusion: this shock feature **observability is statistics-limited** for much of the Galaxy, but if we have a close supernova, we'll be sorry

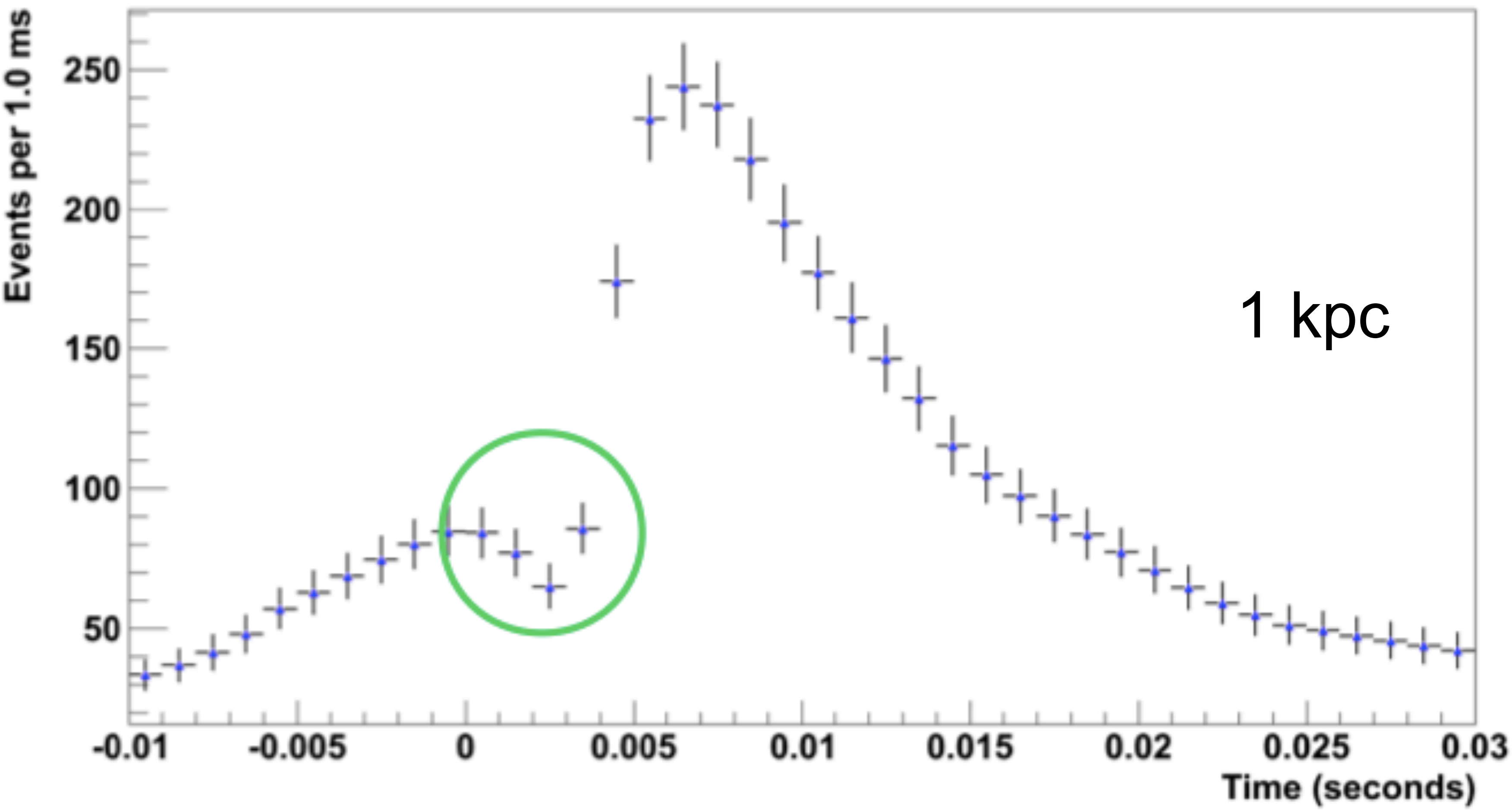
(of course, it's a judgment call how much to spend for a rare case..)

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]

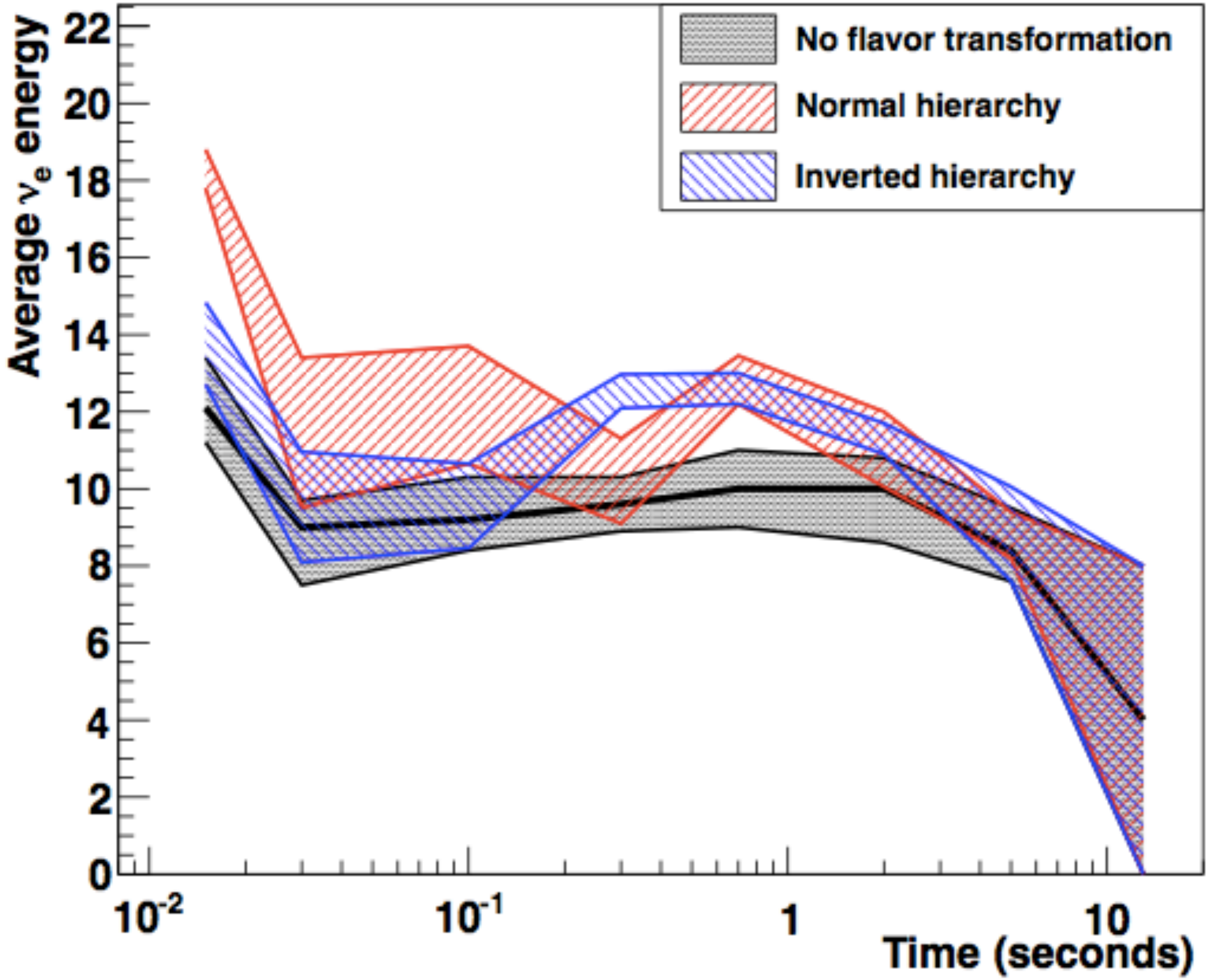
Model from Evan O’Connor



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

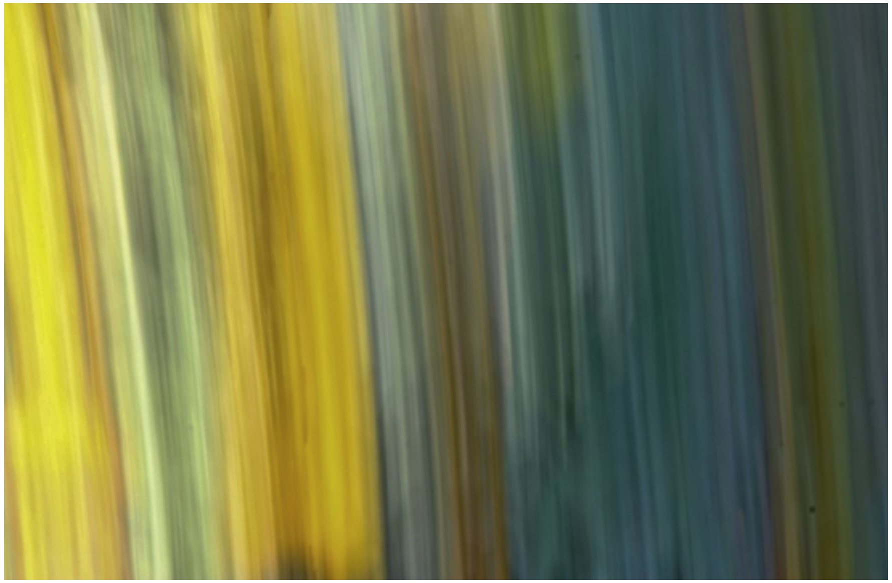
And another anecdote:

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

More, more fine-grained
and robust, signatures needed...



http://stanford.edu/~alexfr/SN4DUNE/Nov2015/SN_theory_for_DUNE.htm

Small theory meeting at SLAC

November 2015

organized by
Alex Friedland,
Bob Svoboda

Physics drivers for requirements on energy, time, cross-section, etc.

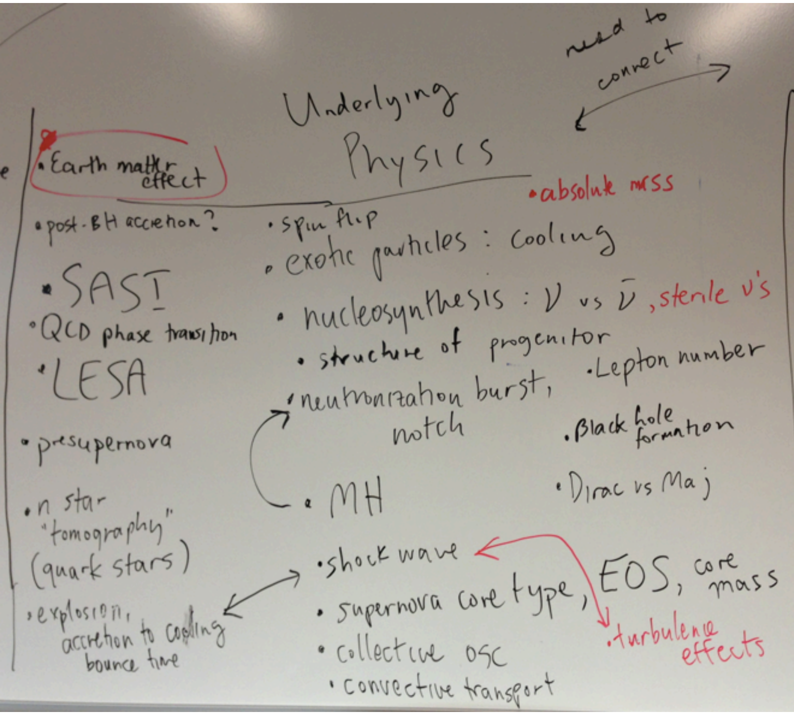
Monday, November 23

Session	Time	Discussion Lead	Co-Leads
Breakfast, informal discussion	8:45-9:15		
Introduction, experimental questions	9:15-10:00	Svoboda, PPTX, 14 MB	Himmel, Scholberg
Status of simulations	10:00-11:00	Ott, PDF, 8 MB	Messer, Kasen
Simulations and neutrino fluxes	11:00-noon	Messer, PDF, 9 MB	Ott, Kasen
Lunch	12:30-2:00		
Nuclear equation of state and neutrinos	2:00-3:00	Reddy, PDF, 5 MB	Fuller, Messer, Kasen, Ott
Nucleosynthesis and neutrino signal. Effect of sterile	3:00-4:00	Fuller	Friedland, Kasen, Ott
Diffuse SN background	4:00-5:00	Lunardini, PPTX, 9 MB	Friedland, Fuller, Duan, Shalgar

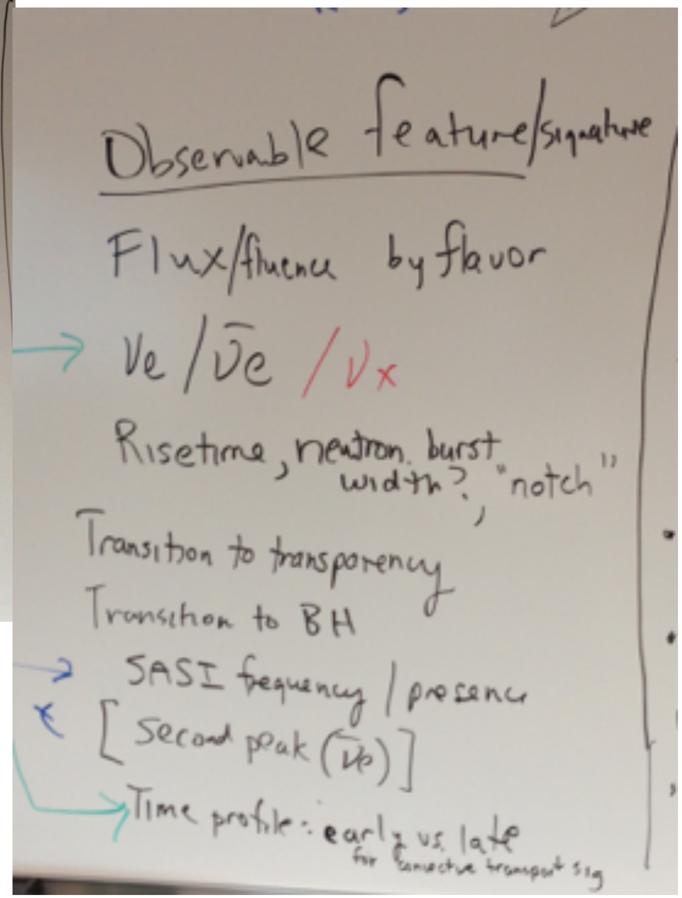
Tuesday, November 24

Session	Time	Speaker	Title
Breakfast, informal discussion	8:45-9:15		
Summary so far	9:15-10:00	Fuller	Friedland, Scholberg
Oscillation dynamics: overview	10:00-11:00	Friedland	Duan, Fuller, Lunardini, Shalgar
Collective oscillations	11:00-noon	Duan	Friedland, Fuller, Shalgar
Lunch	12:30-2:00		
Detector characteristics: overview	2:00-3:00	Himmel	Scholberg
Translating physics into detector specifications	3:00-4:30	Everybody -- discussion	
Summary	4:30-5:00	Friedland	Everybody

The Whiteboard from the November Meeting

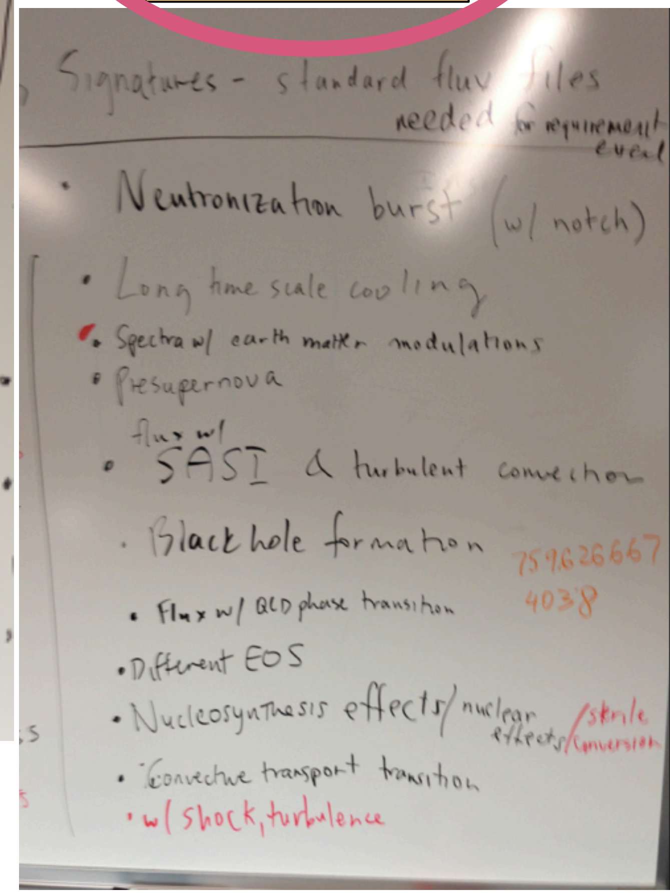


Underlying Physics



Observable Features/ Signatures

spectral/time evolution w/ physics signatures



Flux Files Needed

Finding robust physics signatures for setting requirements

Underlying Physics

Neutrino Physics/Particle Physics:

Absolute neutrino mass
Mass hierarchy
Collective oscillations
Spin flip
Exotic particles
Majorana vs Dirac
Collective oscillations
Sterile neutrinos
Earth matter effect

Supernova Physics:

Presupernova evolution
Progenitor structure
Neutronization, trapping
Shock waves, turbulence effects
Supernova core type, core mass, EOS
Convective transport
Black hole formation
Explosion
Accretion to cooling transition
SASI
LESA
Neutron star "tomography"
Quark stars
QCD phase transition
Lepton number
Post BH accretion

Other:

Nucleosynthesis

Many topics!

Observable Features

Note some of these may be correlated

Flux/fluence: spectra as a function of flavor/time (nue, nuebar, nux)
Time profile of cooling (early vs late)
Risetime
Features of neutronization burst
"Notch"
Transition to black hole
Transition to transparency
SASI presence/frequency
Second peak (QCD transition?)

Connect to multiple physics topics

Fluxes with signatures we need to evaluate

Presupernova
Neutronization burst, w/ second peak/notch (and oscillations)
Long time scale cooling
With SASI and turbulent convection
Black hole formation
With shock wave, turbulence
With collective effects
With different EOS
With Earth matter modulation
With QCD phase transition
With nucleosynthesis effects/nuclear effects/sterile conversion
With convective transport transition

What we hope theorists can provide

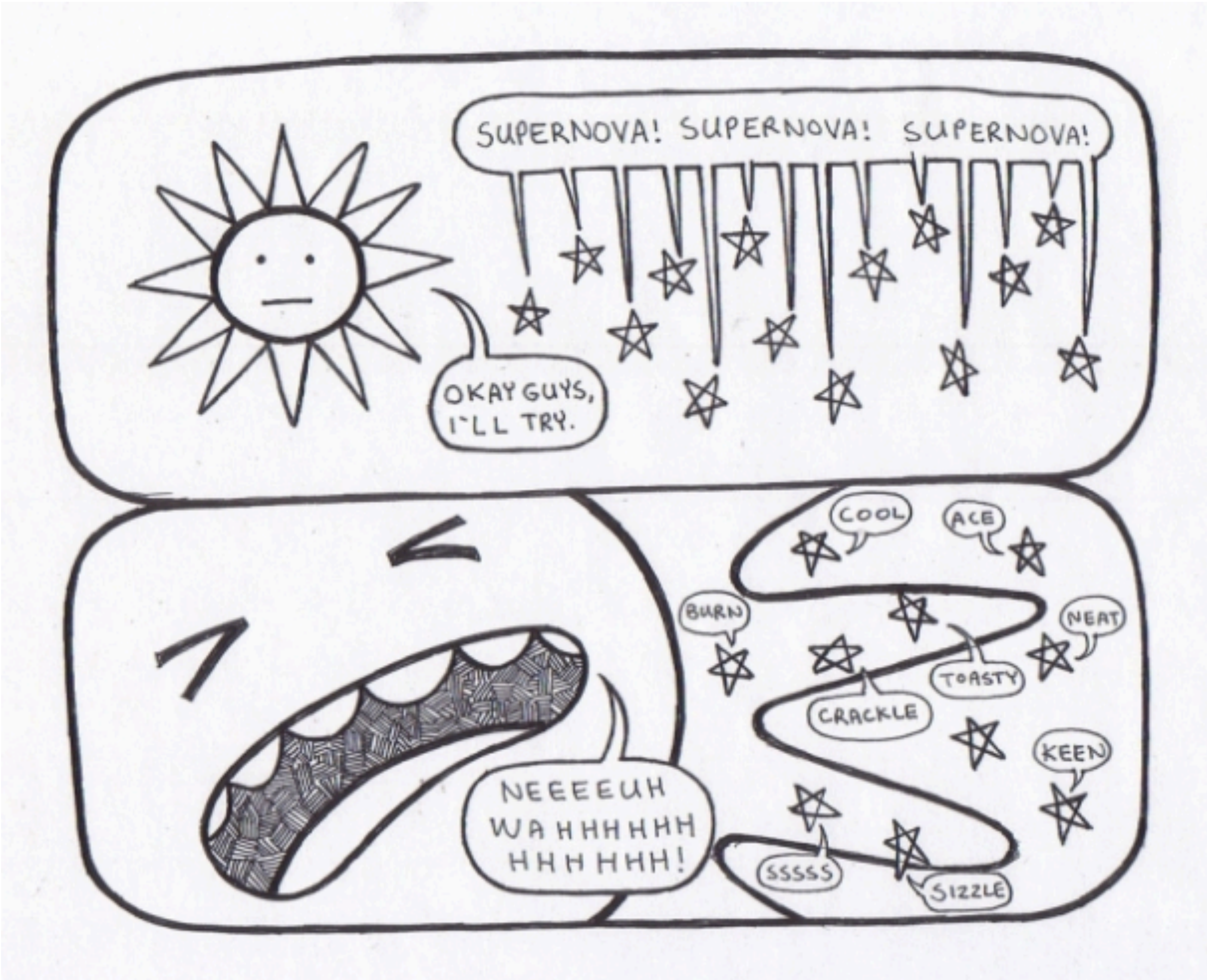
spectral/time evolution w/ physics signatures

Picking a few things from the smorgasbord...

- neutronization burst
- black hole formation
- cooling time scale
- ...

Take-Away Messages

- Specific **detector requirements need to be defined** for low-energy events in DUNE
- Need **robust physics signatures** to develop quantitative criteria
    - some requirements can be set based on broad-brush knowledge (e.g., trigger, DAQ)
    - have some anecdotal studies (useful but limited)
    - more still needed: **"benchmark" fluxes desired**
    - many sensitivities will be statistically limited
- Much more work still needed on experimental side
    - reconstruction algorithms, PID, generators
    - background studies
    - ...


SUPERNOVA! SUPERNOVA! SUPERNOVA!
OKAY GUYS, I'LL TRY.
NEEEEUH WAHHHHHH HHHHHH!
COOL
ACE
BURN
NEAT
TOASTY
CRACKLE
KEEN
SSSSS
SIZZLE

Will Krause

Extras/Backups

SNB Event Generators

NueCC event generator (by AJ Roeth, LBNE-doc-8225-v1)

- ν_eCC w/ deexcitation γ's $\nu_e + {}^{40}\mathrm{Ar} \rightarrow {}^{40}\mathrm{K}^* + e^-$
- model deexcitations based on mirror-nucleus measurements
- integrated into LArSoft by G. Sinev `NueAr40CCGenerator`
- uses realistic SNB spectrum
- samples made for MC Challenge 5

MARLEY (Davis group)

- more sophisticated model taking into account nucleon emission
- generated samples posted