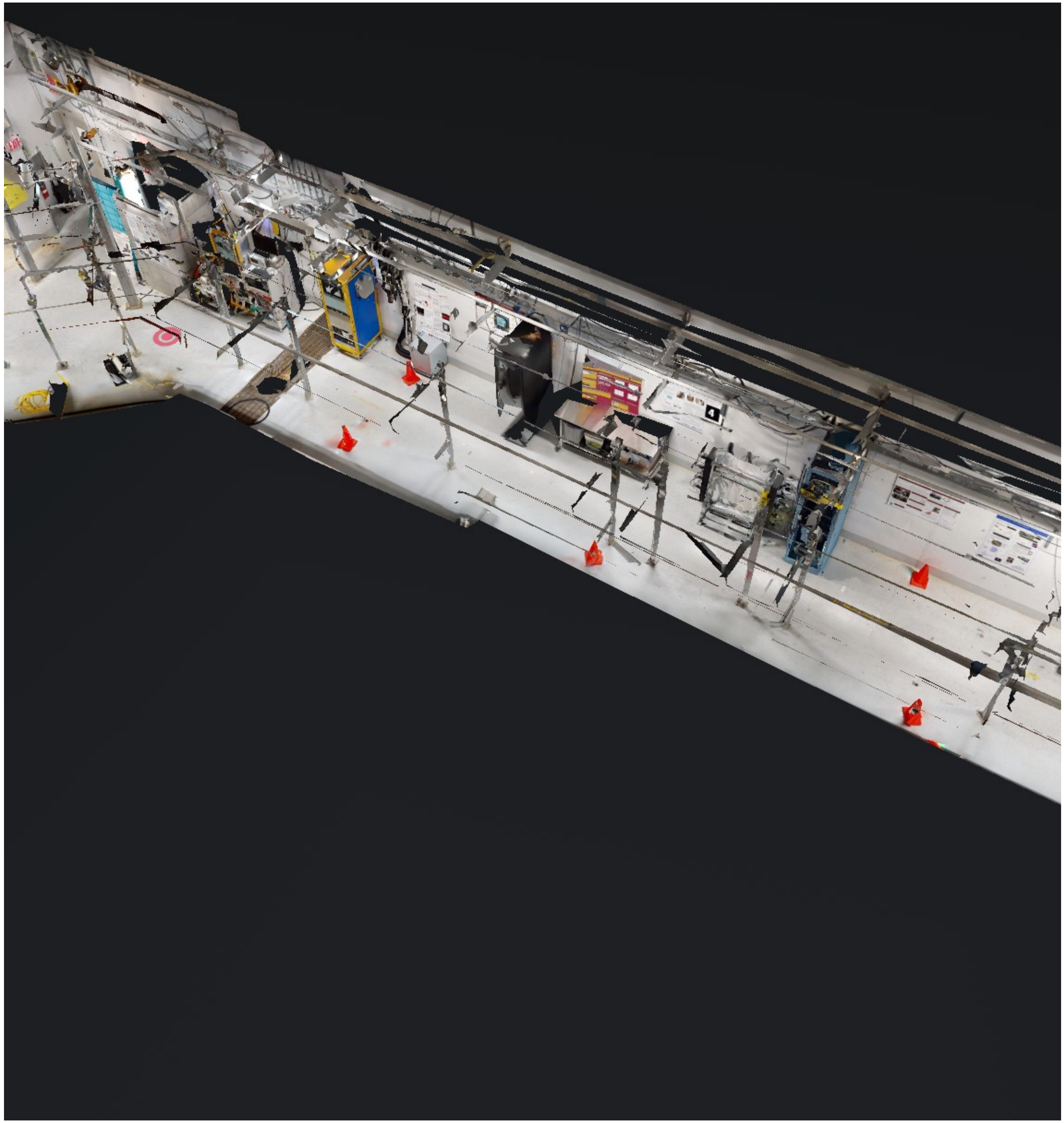
Neutrino Interactions



Kate Scholberg,
Duke University

MPA Summer School 2021:

Fundamental Interactions in Particle, Hadron and Nuclear Physics

September 2021

Outline of Lecture Topics

General overview

Specific example

- Neutrino sources
- Neutrino interactions with matter
- Particle detection techniques

Mon

- Physics with neutrinos in the ~1-100 MeV range
- Physics with stopped-pion neutrino sources

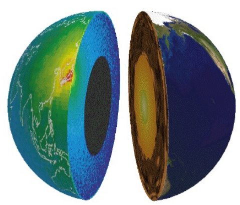
Tue

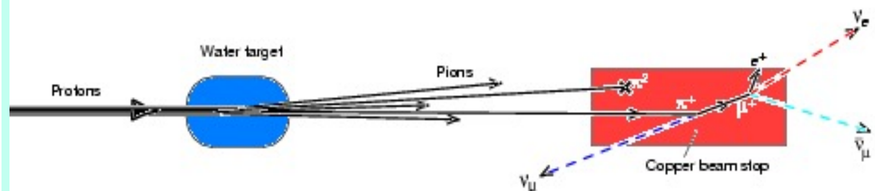
- Physics in Neutrino Alley at the Spallation Neutron Source
- The COHERENT Experiment
- Future prospects

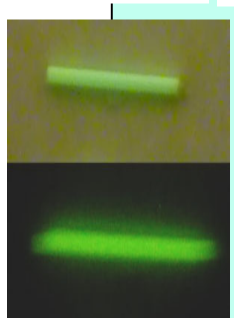
Thu

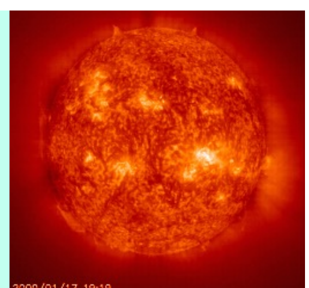
Zoom in
to the
~ MeV to few tens of MeV energy
range

eV keV MeV GeV TeV



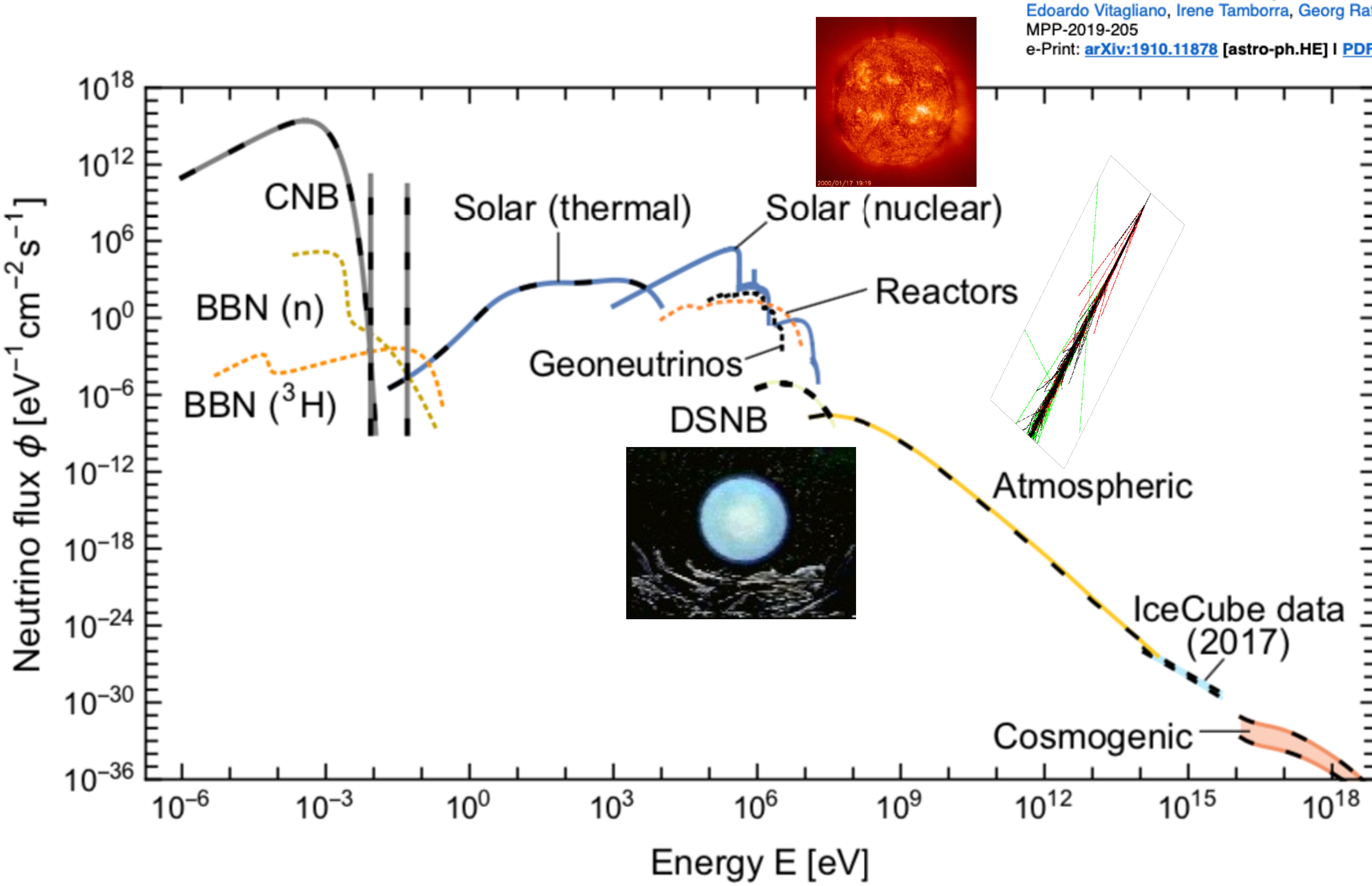






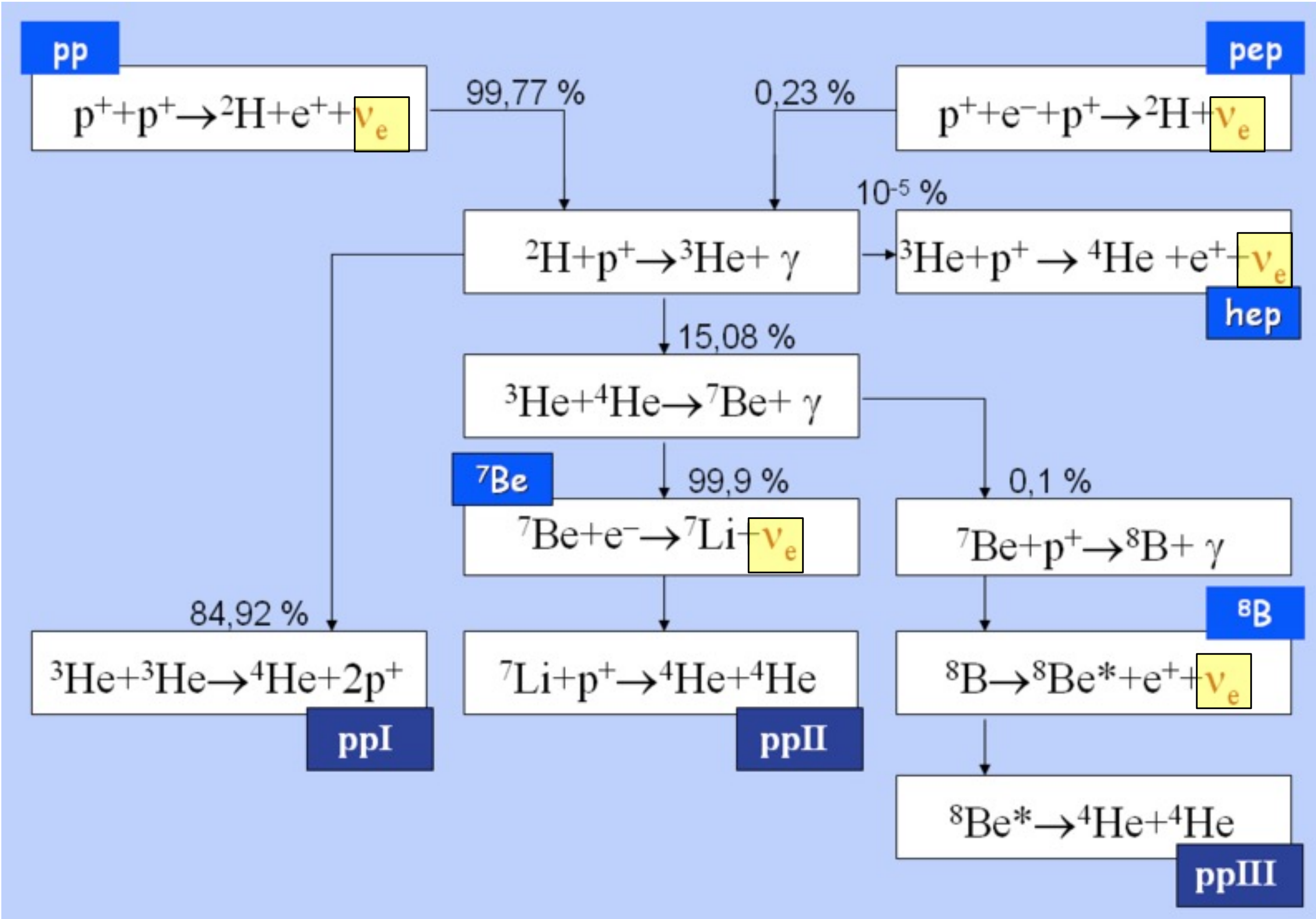
Many interesting sources!

Grand Unified Neutrino Spectrum at Earth
Edoardo Vitagliano, Irene Tamborra, Georg Raffelt. Oct 25, 2019. 54 pp.
MPP-2019-205
e-Print: arXiv:1910.11878 [astro-ph.HE] | PDF

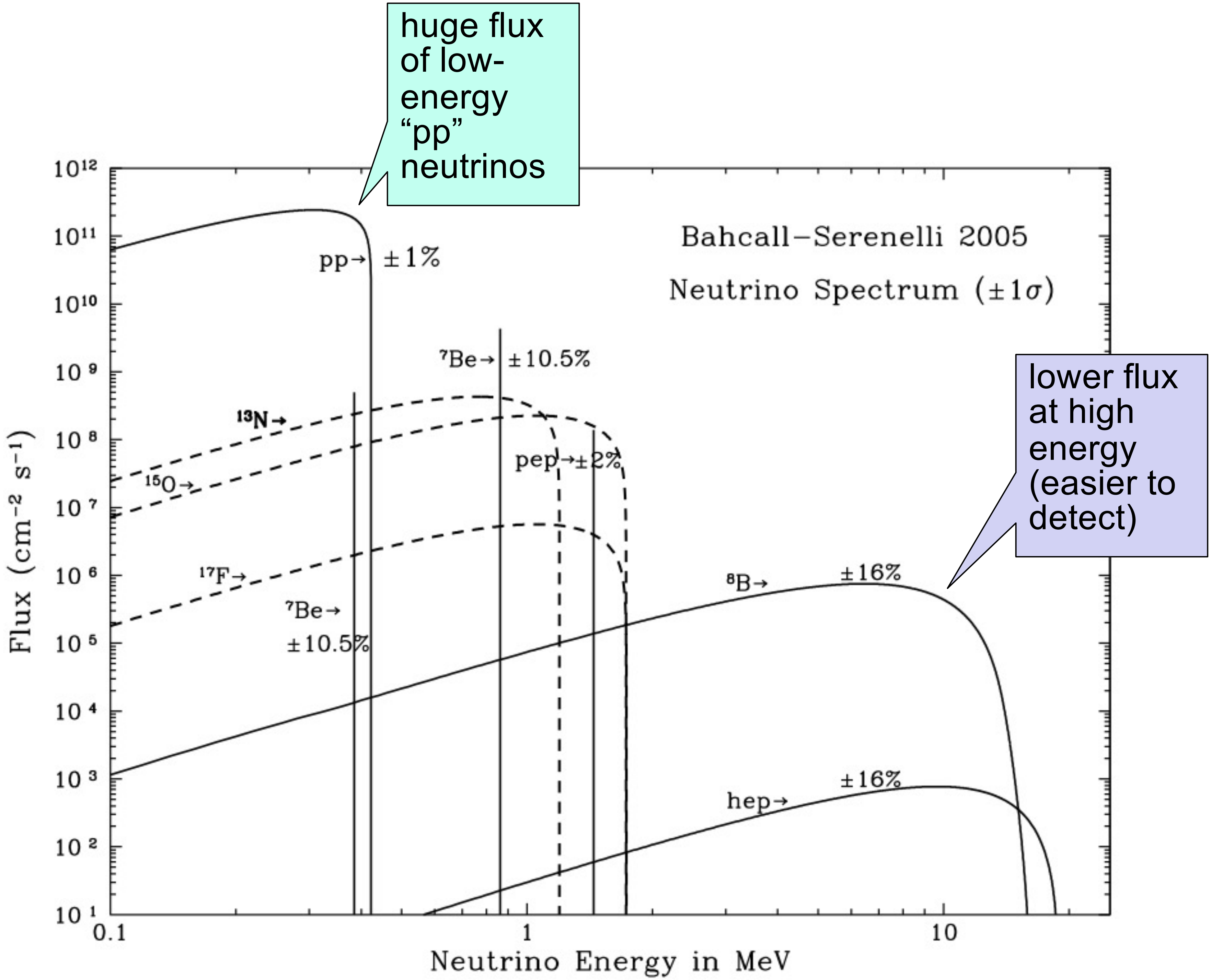


Will consider **solar** and **supernova** neutrinos

Detecting solar neutrinos



Electron flavor neutrinos generated in solar fusion; spectrum is pretty well understood from weak physics



huge flux of low-energy "pp" neutrinos
lower flux at high energy (easier to detect)
Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
⁷Be→ ±10.5%
pep→±2%
⁸B→ ±16%
hep→ ±16%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV

What fraction of the Sun's produced energy goes into neutrinos?

A. 0.001%

B. 0.1%

C. 3%

D. 30%

E. 60%

F. 99%

Homestake chlorine radiochemical detector

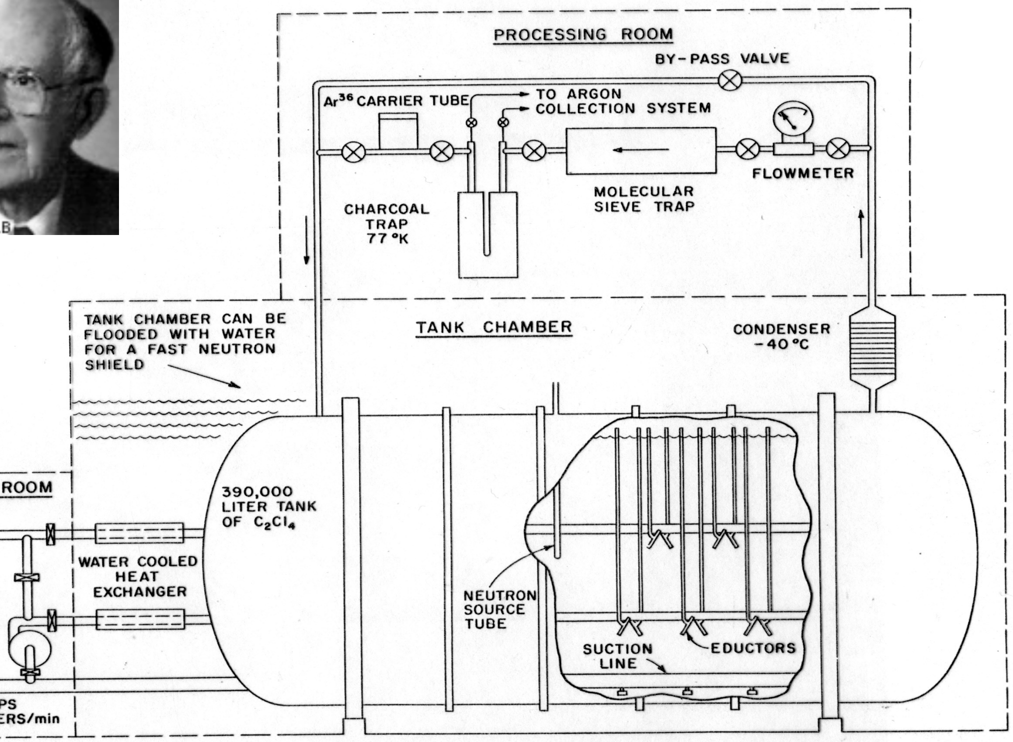


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

600 tons of cleaning fluid

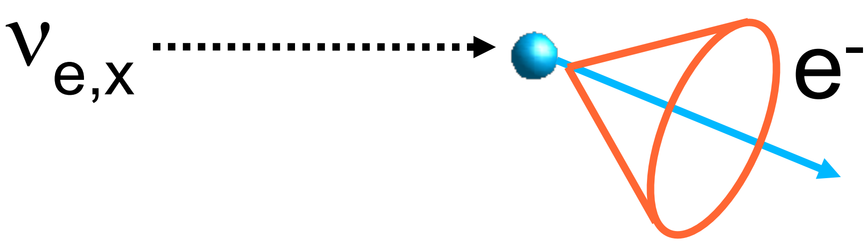
Threshold: 0.81 MeV

Extract atoms of ^{37}Ar every few months
and count decays (35-day half life): ~ 12 per month!

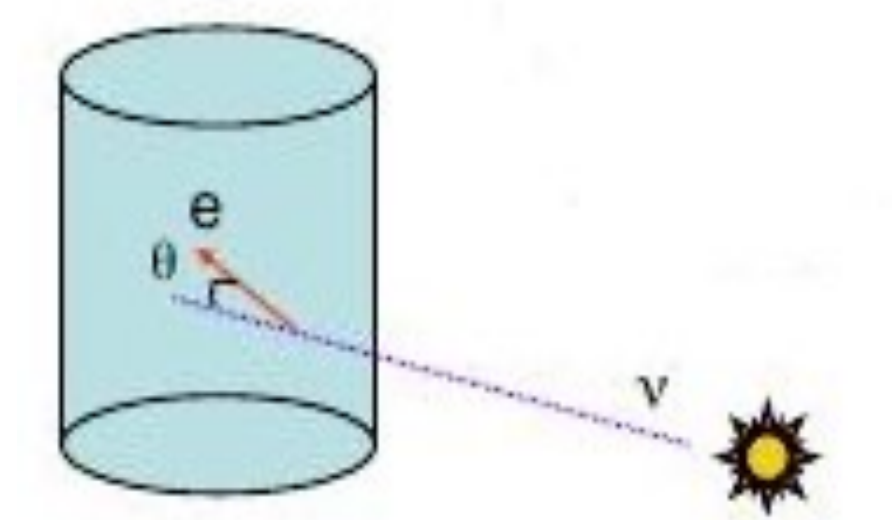
Water Cherenkov detectors for solar neutrinos

Elastic scattering of ~MeV solar ν's on electrons

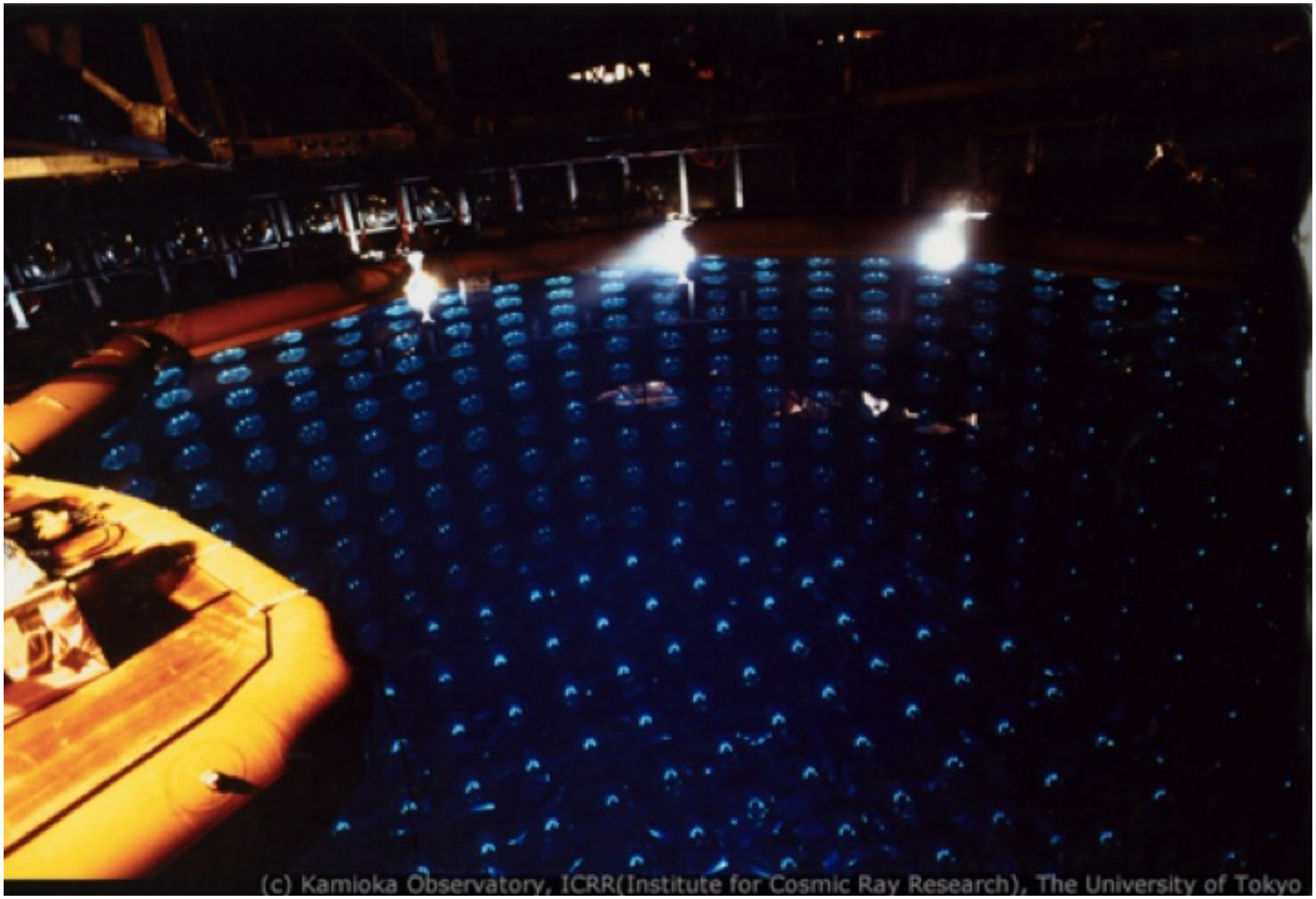
real time detection, with *directionality*

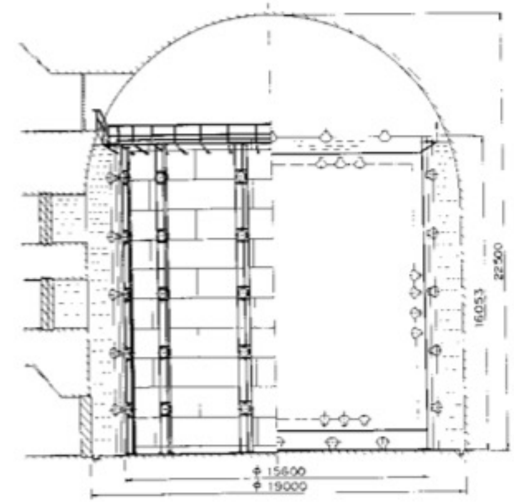


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

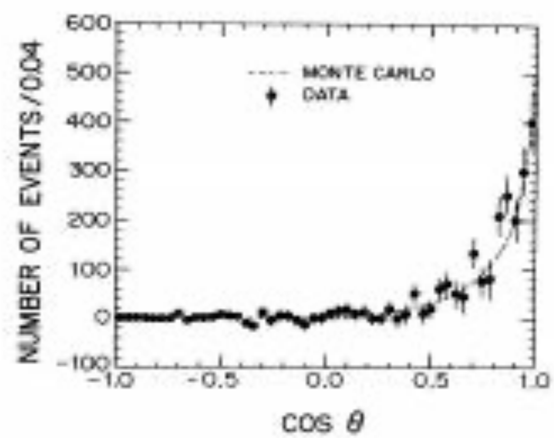


Kamiokande II in Japan
(original motivation: search for proton decay)





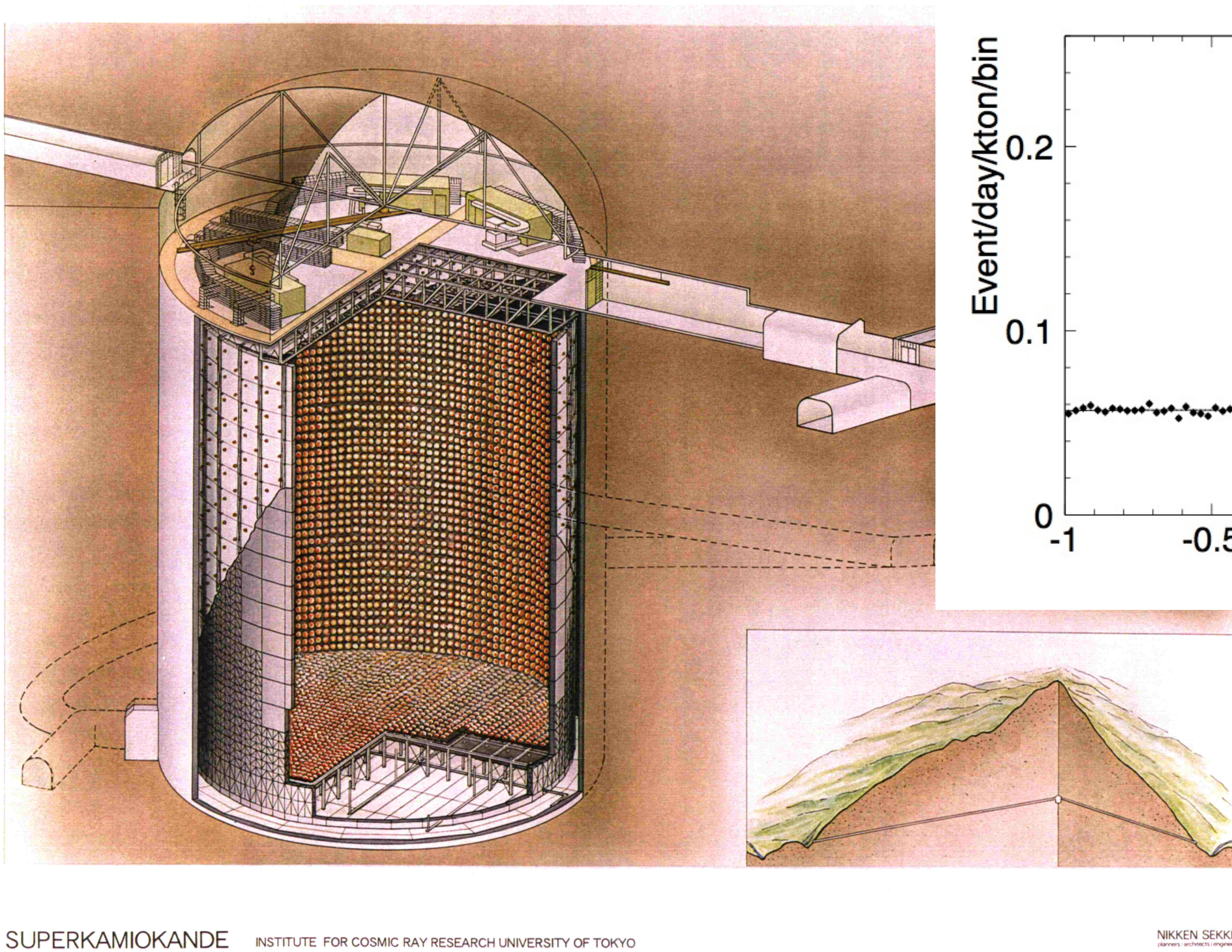
2.1 kton

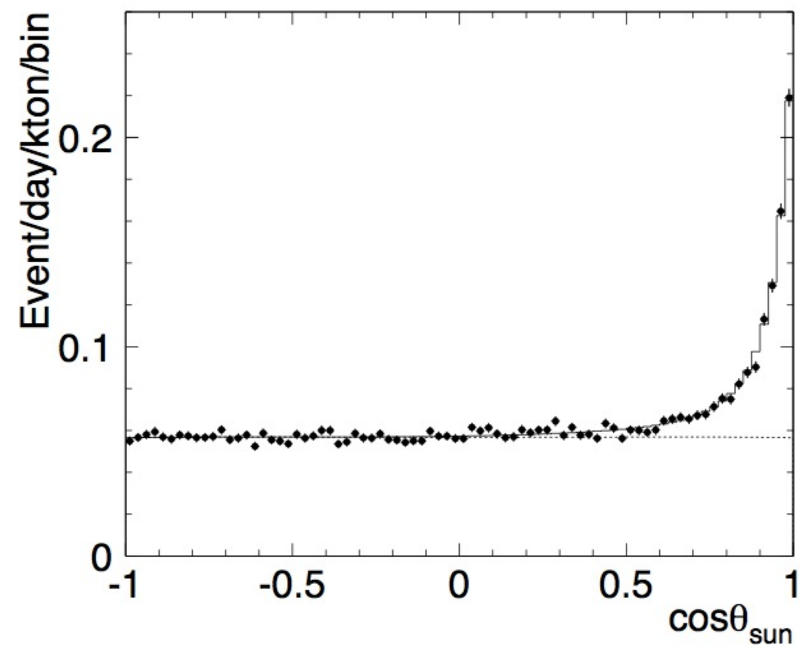


E>~7 MeV : sensitive to ^{8}B tail of spectrum

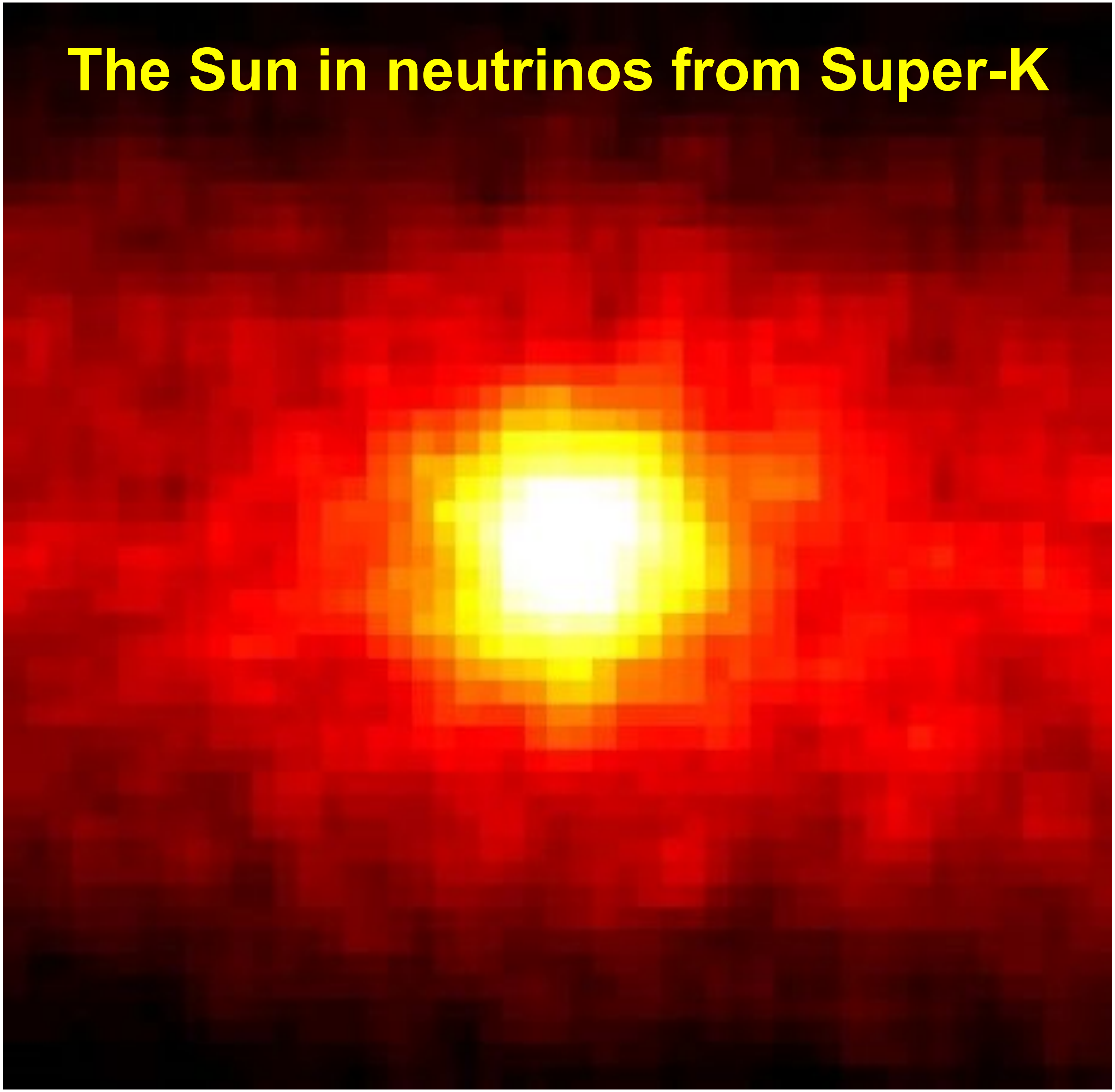
Later: significant improvement from Super-K

(consistent with earlier results)

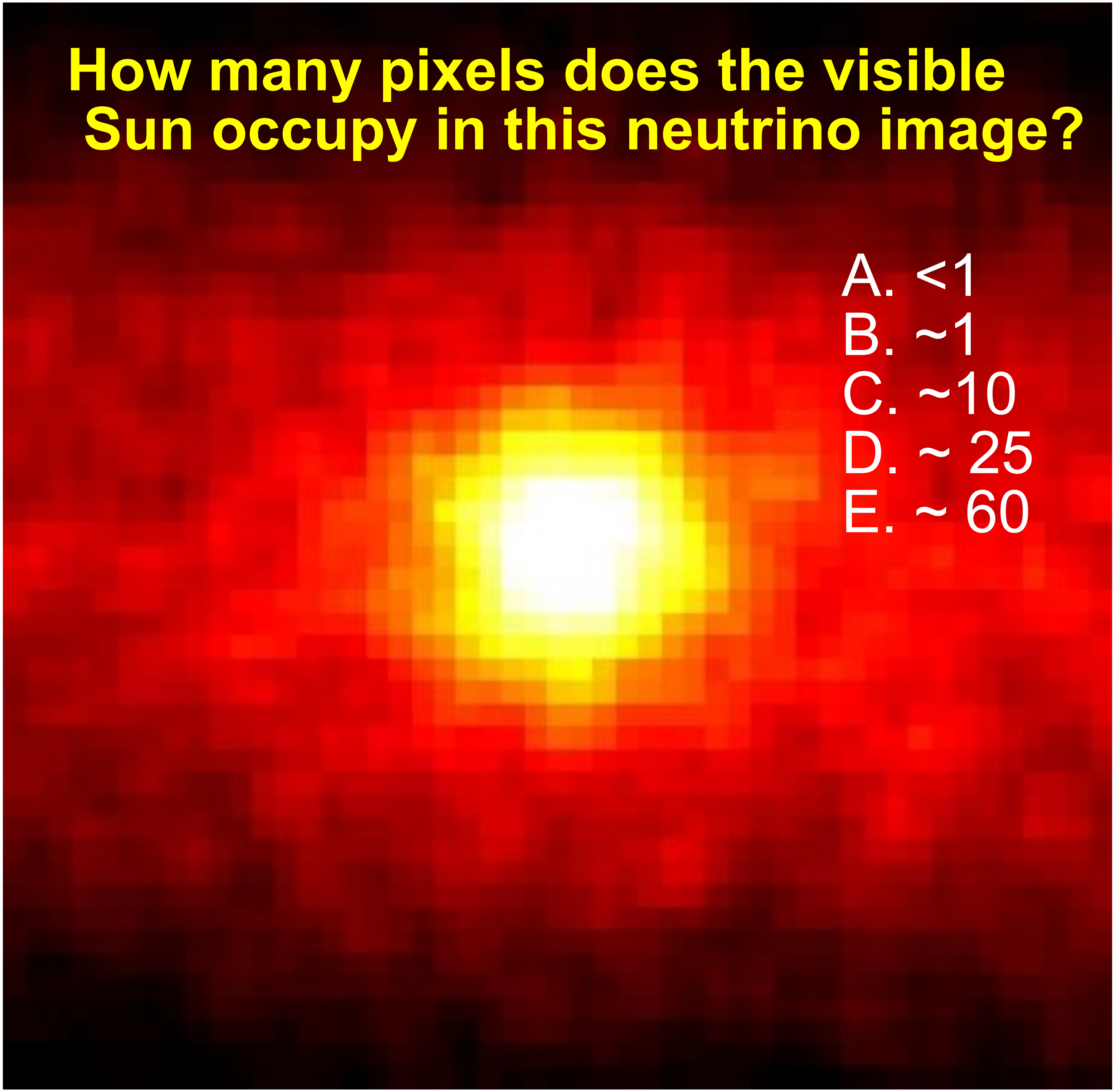




22.5 kton, <~ 5 MeV threshold

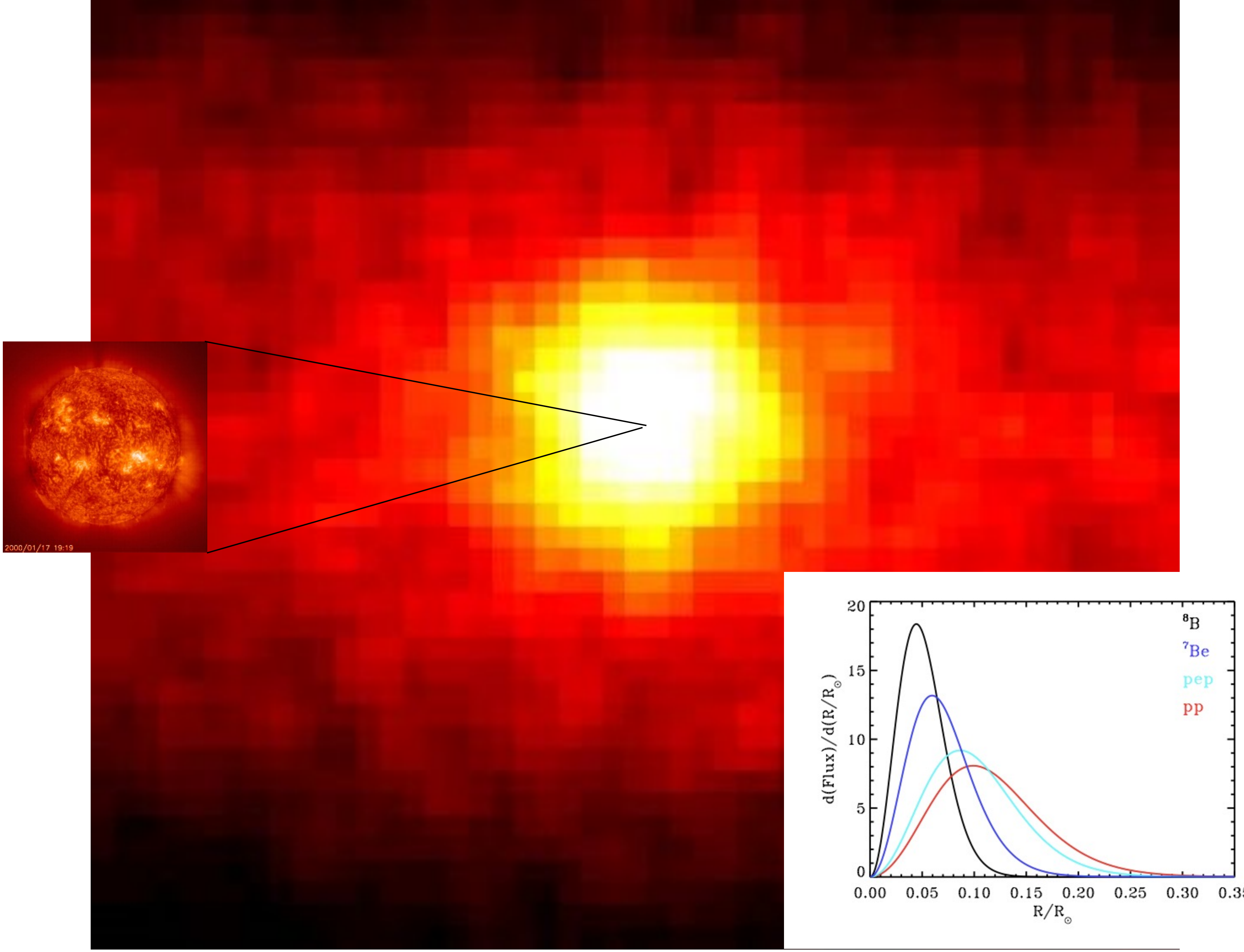

The Sun in neutrinos from Super-K

How many pixels does the visible Sun occupy in this neutrino image?



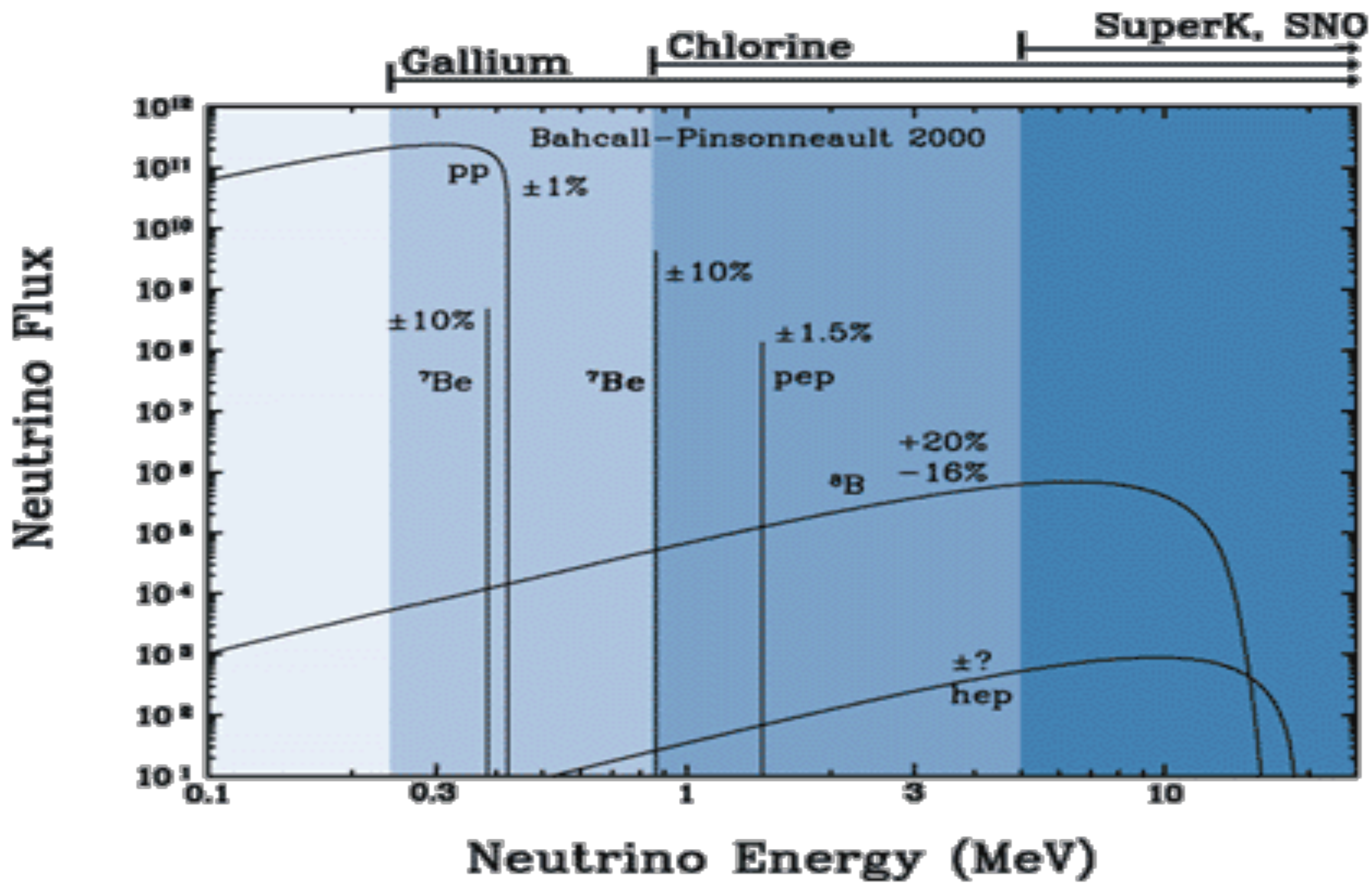
A. <1
B. ~1
C. ~10
D. ~ 25
E. ~ 60

Disclaimer: the visible Sun occupies < 1 pixel,
and neutrinos emerge from an even smaller region!



Another radiochemical experiment: gallium

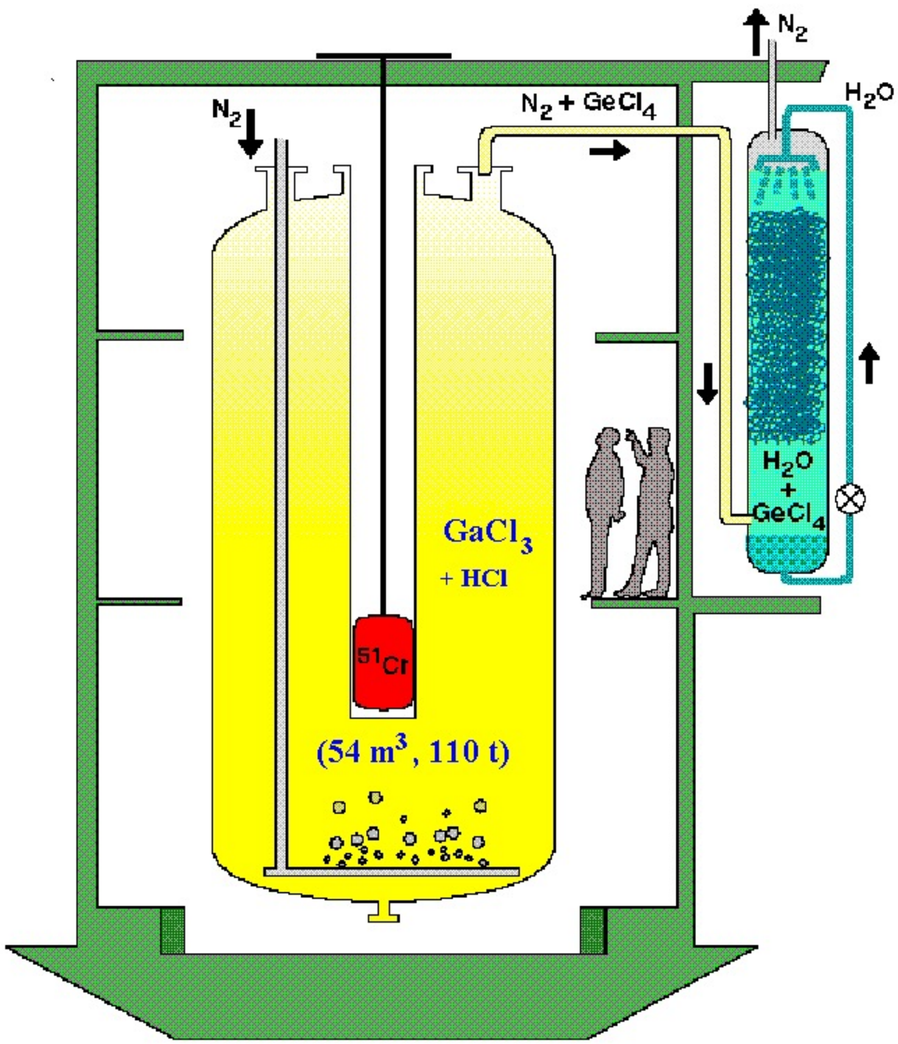
$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$



Threshold: 0.23 MeV, 11 day half-life

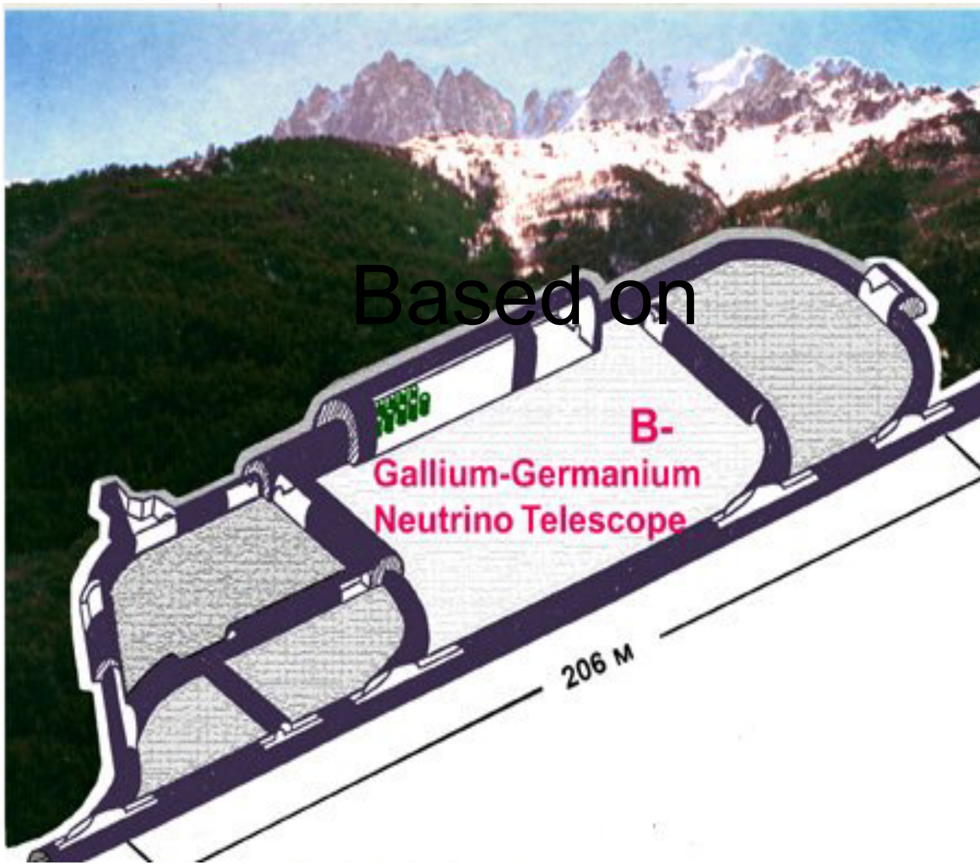
Sensitive to *pp neutrinos*

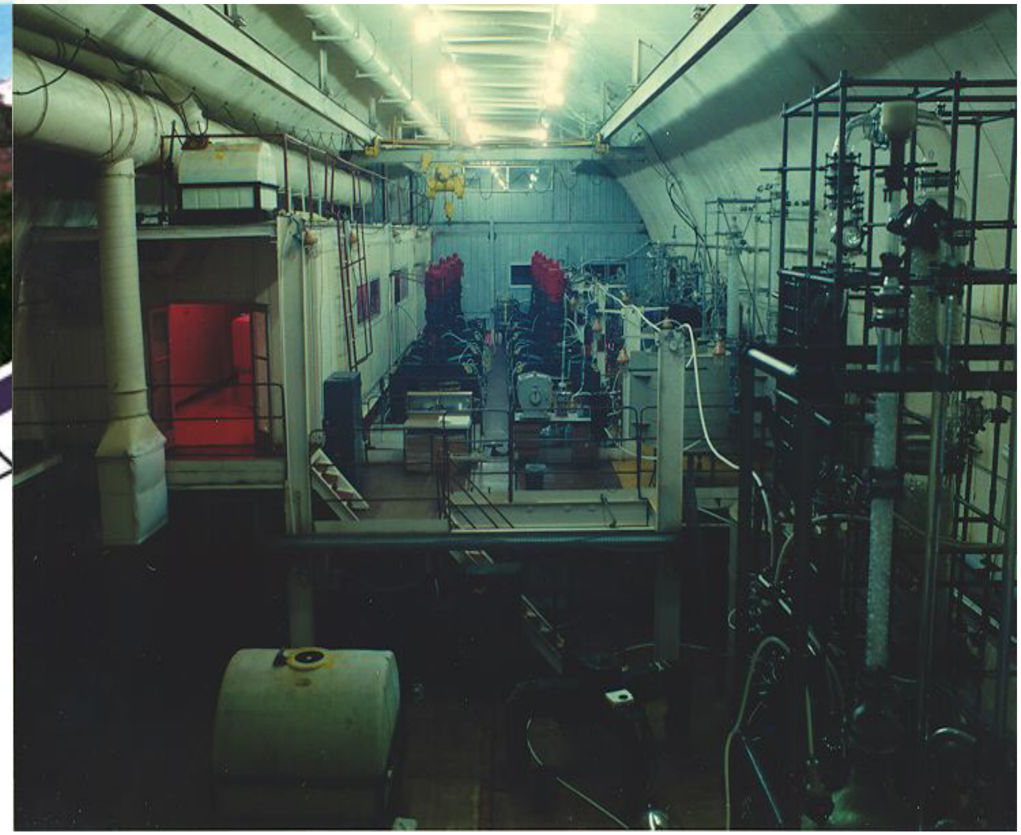
Gallex/GNO (Gallium Neutrino Observatory)
at LNGS, Italy: 1991-2006



Used gallium chloride (30 tons of Ga)

The SAGE Experiment





Caucasus mountains, Russia

Based on liquid gallium
50 tons

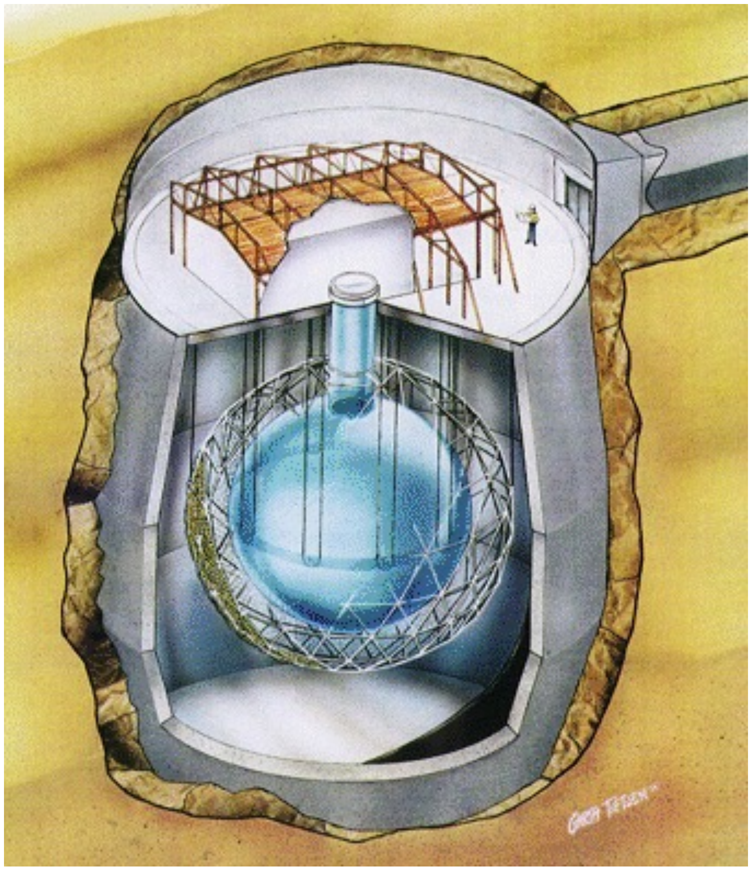
1990-2007

For many years: the "solar neutrino problem"

... ν_e's disappearing...

How do we know for sure they are oscillating?

The Sudbury Neutrino Observatory



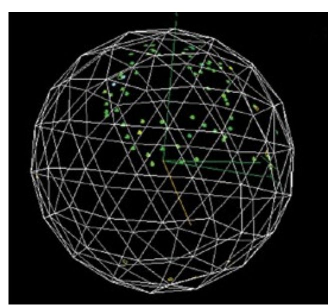
Sudbury, Canada

1 kton D_2O, 1.7 kton H_2O

$\nu_e + d \rightarrow p + p + e^-$ CC

$\nu_x + d \rightarrow \nu_x + p + n$ NC

$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$ Elastic scattering (CC, NC)



Cherenkov light from e^- and **neutron detection** for NC

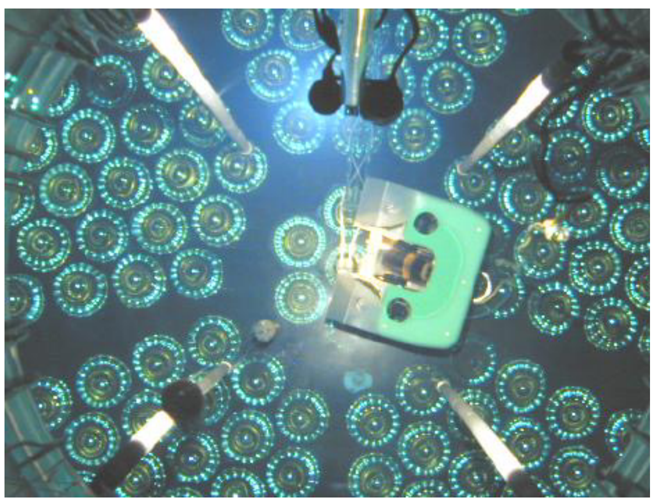
SNO's unique feature: NC detection

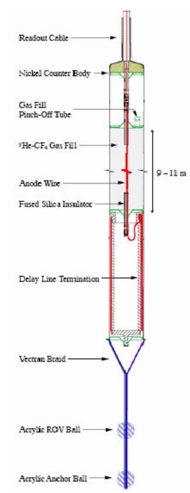
$$\nu_x + d \rightarrow \nu_x + p + n$$

flavor-blind

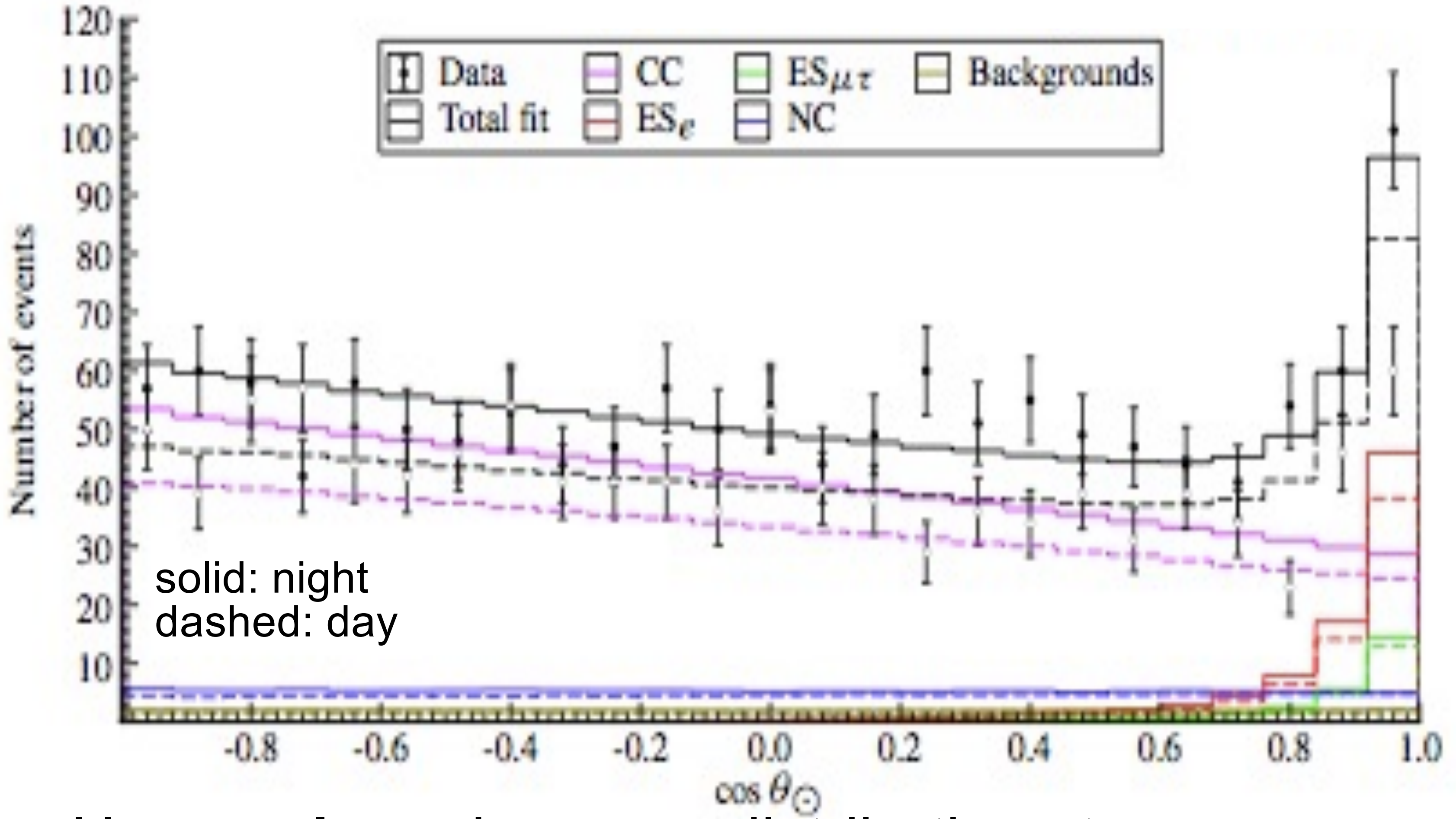
Tag NC via detection of neutron

- Phase I: capture on d (D_2O) $\quad n + d \rightarrow t + \gamma + 6.25$ MeV
- Phase II: capture on Cl (salt, NaCl) $\quad n + {}^{35}Cl \rightarrow {}^{36}Cl + \gamma + 8.6$ MeV
- Phase III: neutron detectors (NCD) $\quad n + {}^{3}He \rightarrow p + t + 0.76$ MeV





SNO data



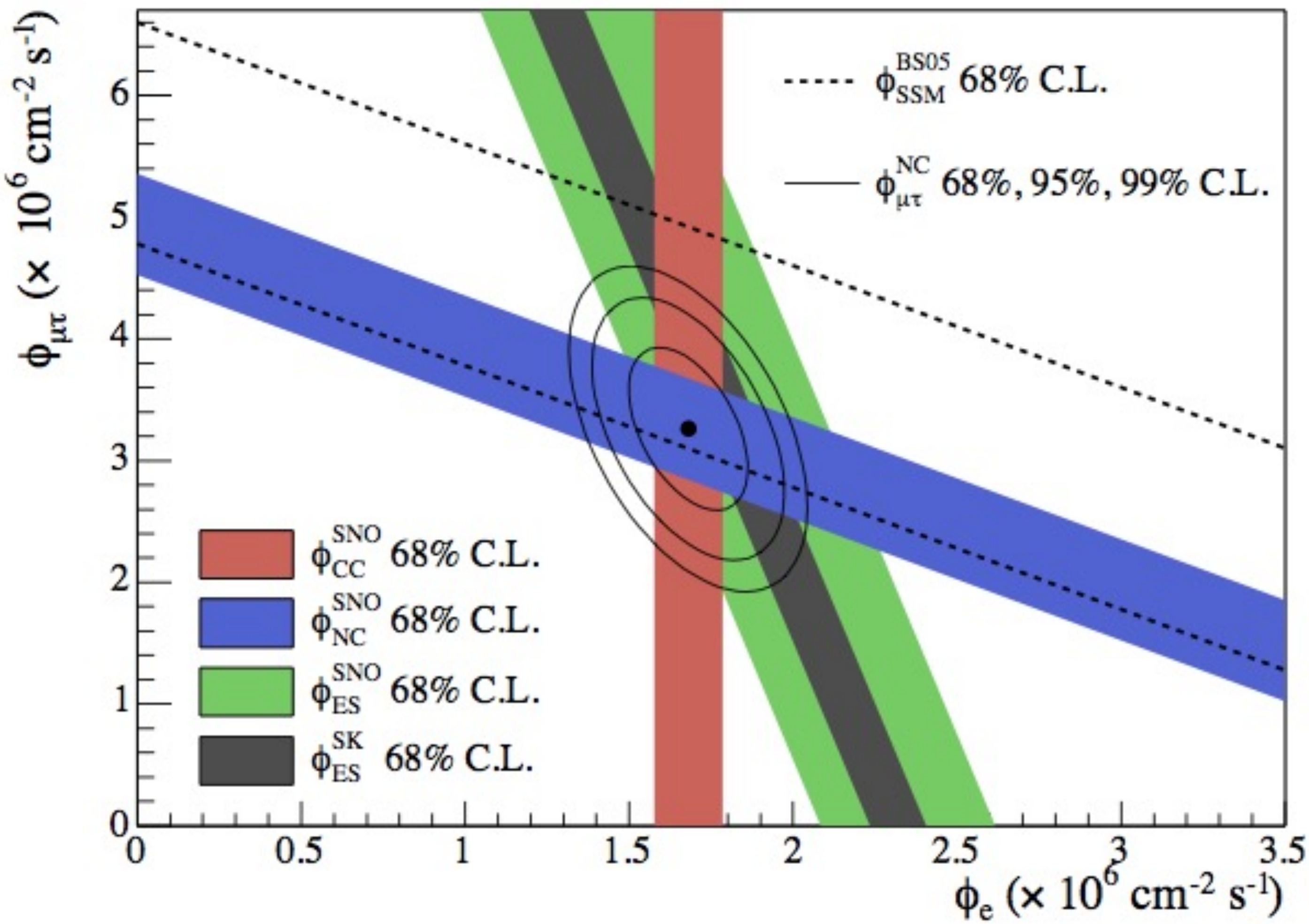
Use **angle** and **energy** distributions to fit data for CC, NC, ES components

slightly backscattered

isotropic

forward scattered

Clear evidence from SNO for oscillation to $\nu_{\mu,\tau}$



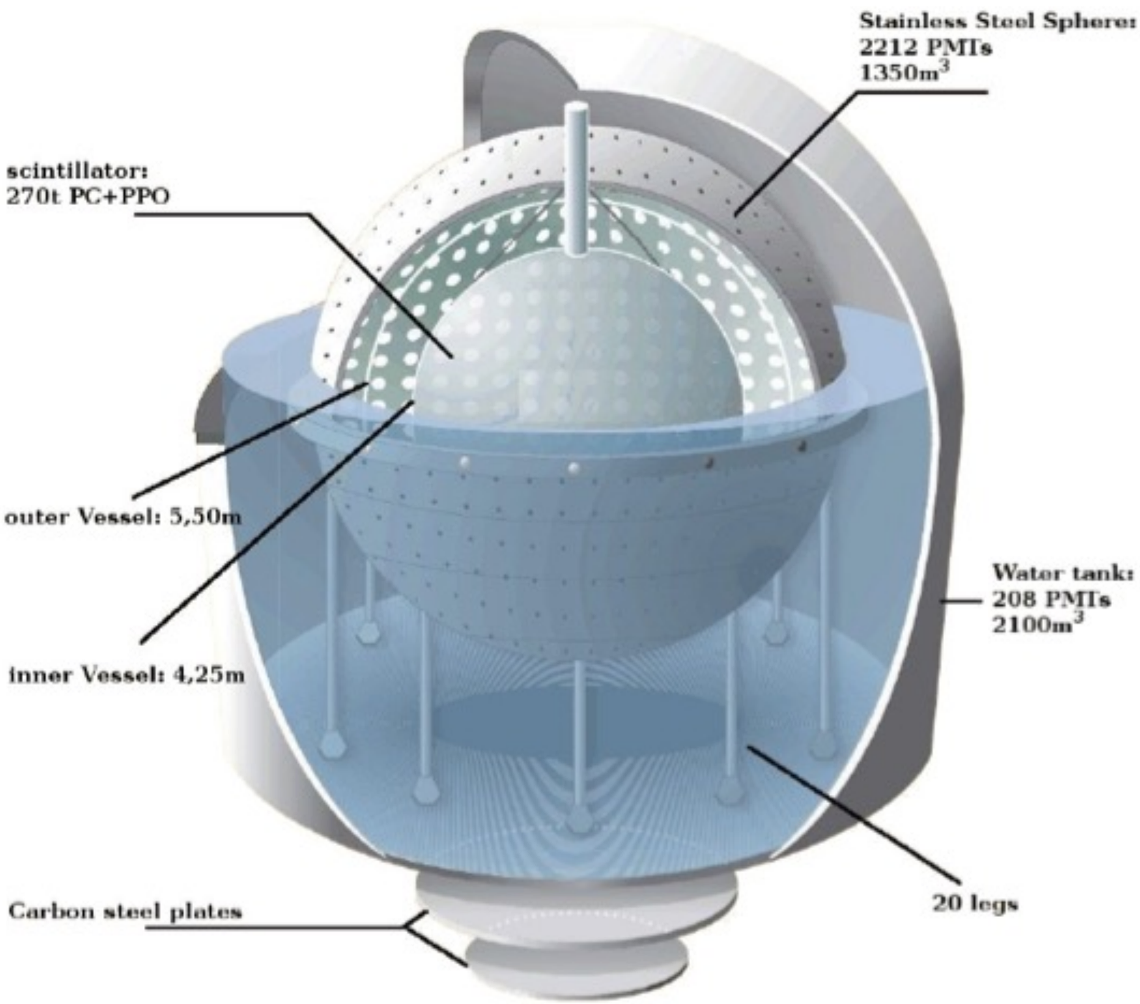
$\phi_{CC}=\phi(\nu_e)$

$\phi_{NC}= \phi(\nu_e) + \phi(\nu_{\mu,\tau})$ ~ total flux

$\phi_{ES}=\phi(\nu_e) + 0.15\phi(\nu_{\mu,\tau})$

But there's more: **the Borexino Experiment**

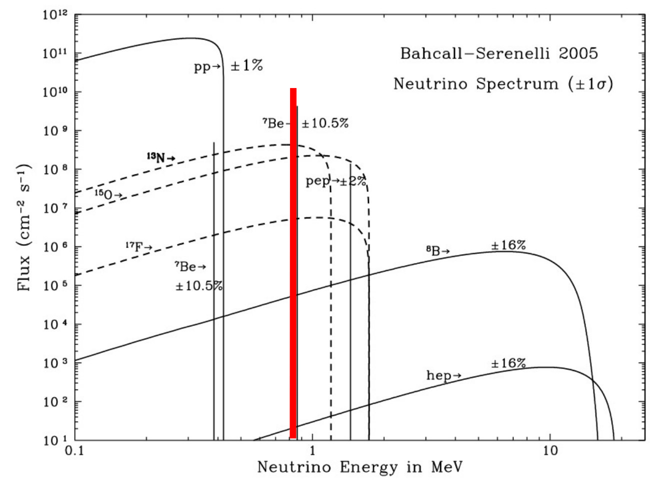
Gran Sasso, Italy

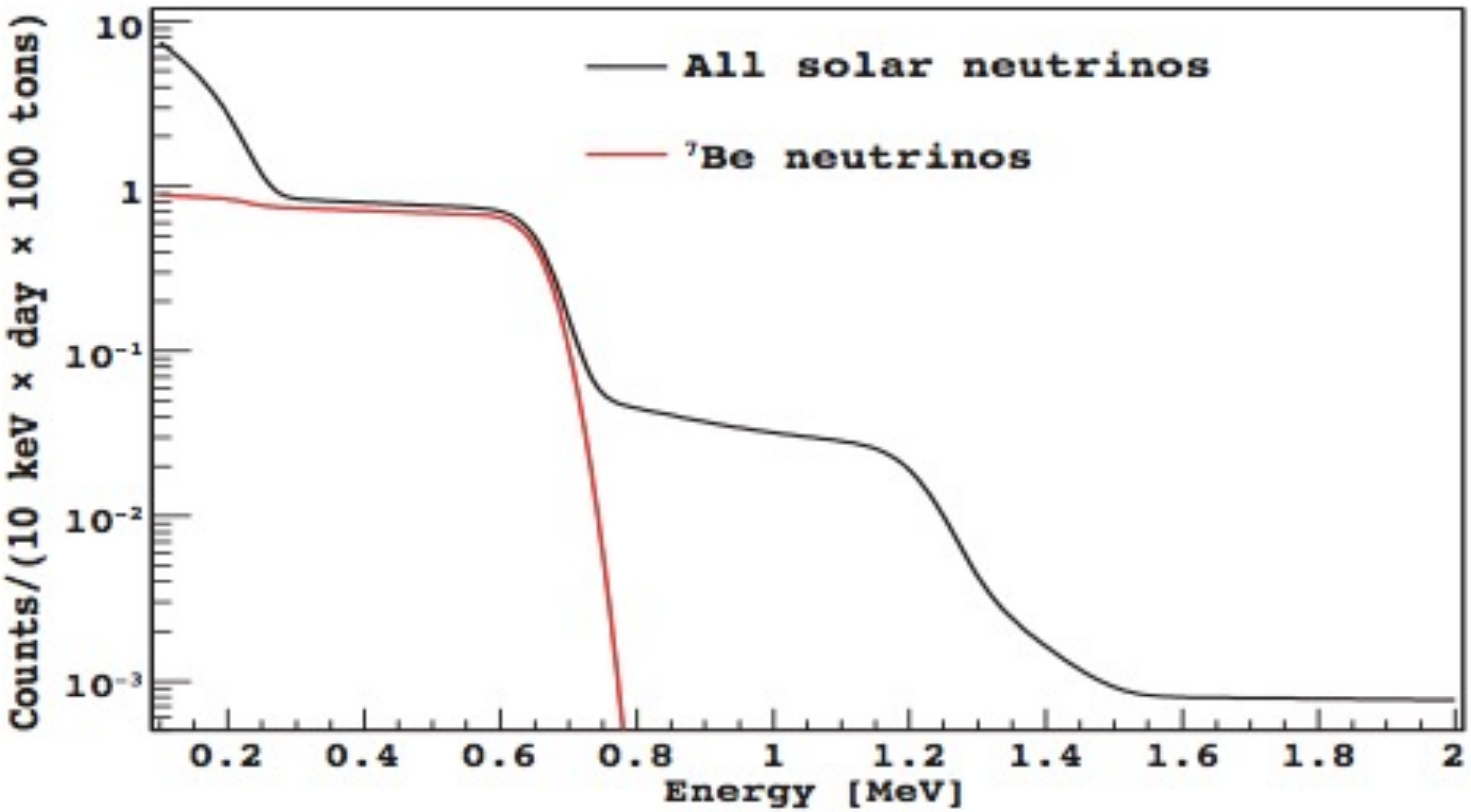


$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

- Scintillator (300 ton)
- Very low threshold (down to ~200 keV)
- Very low radioactivity
- Real time

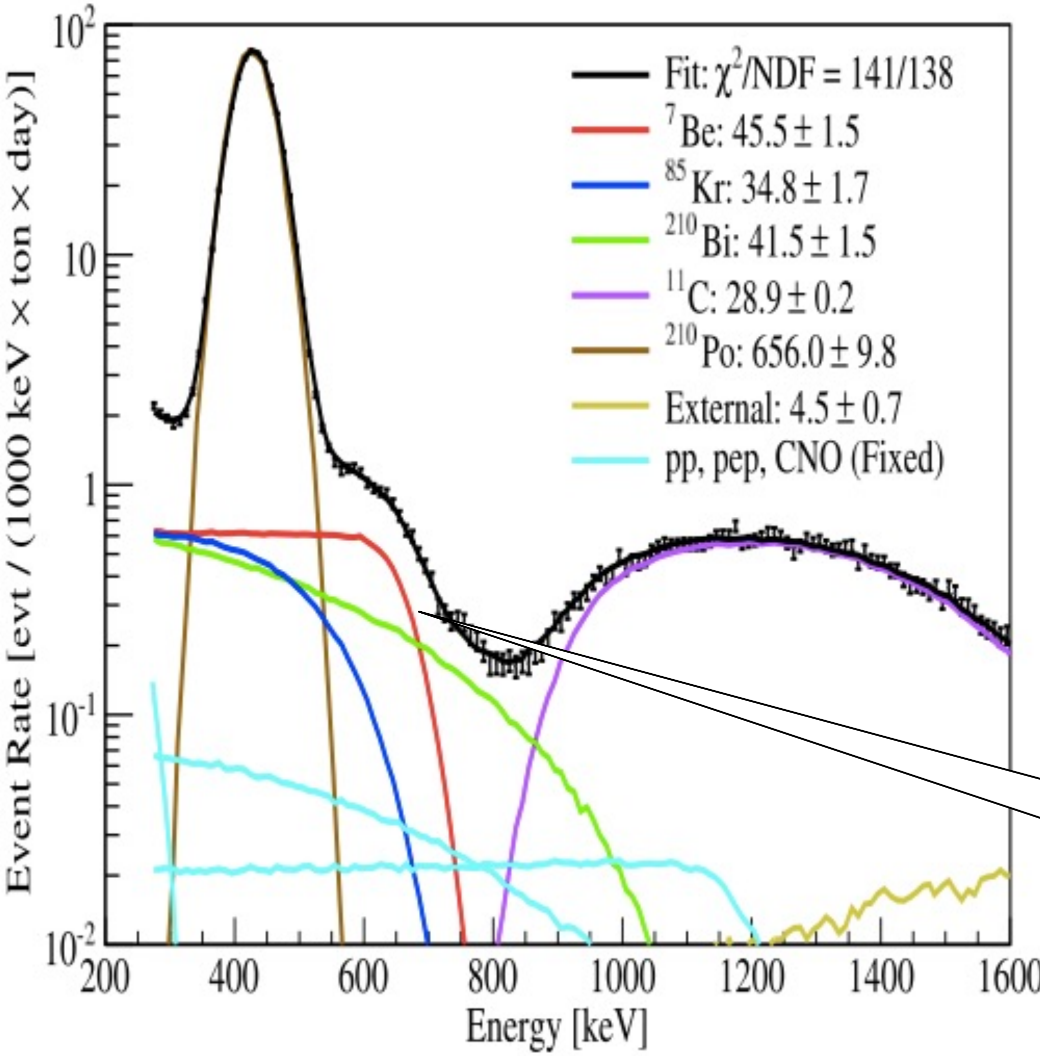
Go after recoil
electrons
from the ^{7}Be line





...

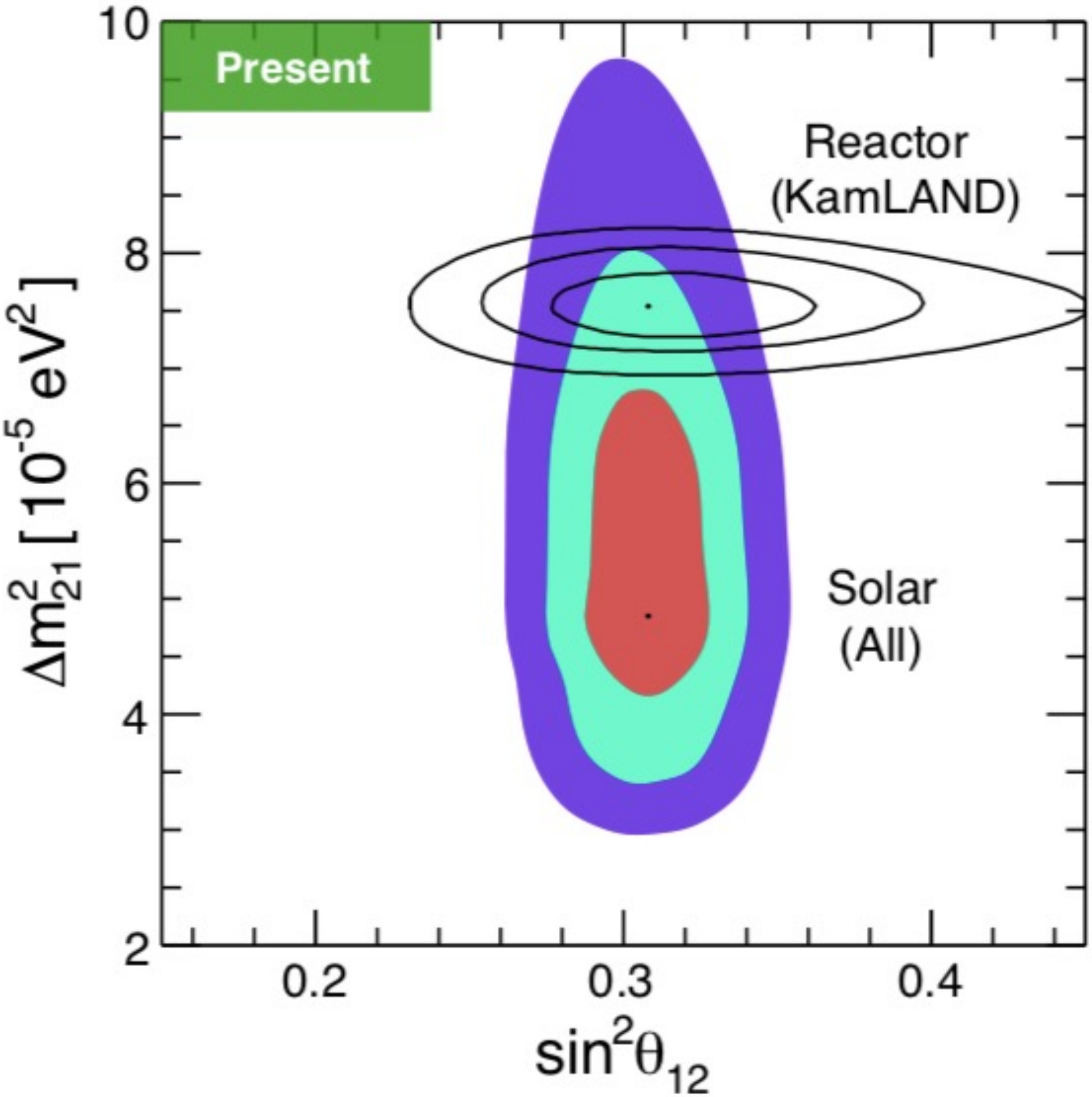
Heroic (and successful) struggle with radioactive (ambient & cosmogenic) backgrounds



^{7}Be neutrinos identified

it's all about the backgrounds

"Solar" neutrino oscillation parameters

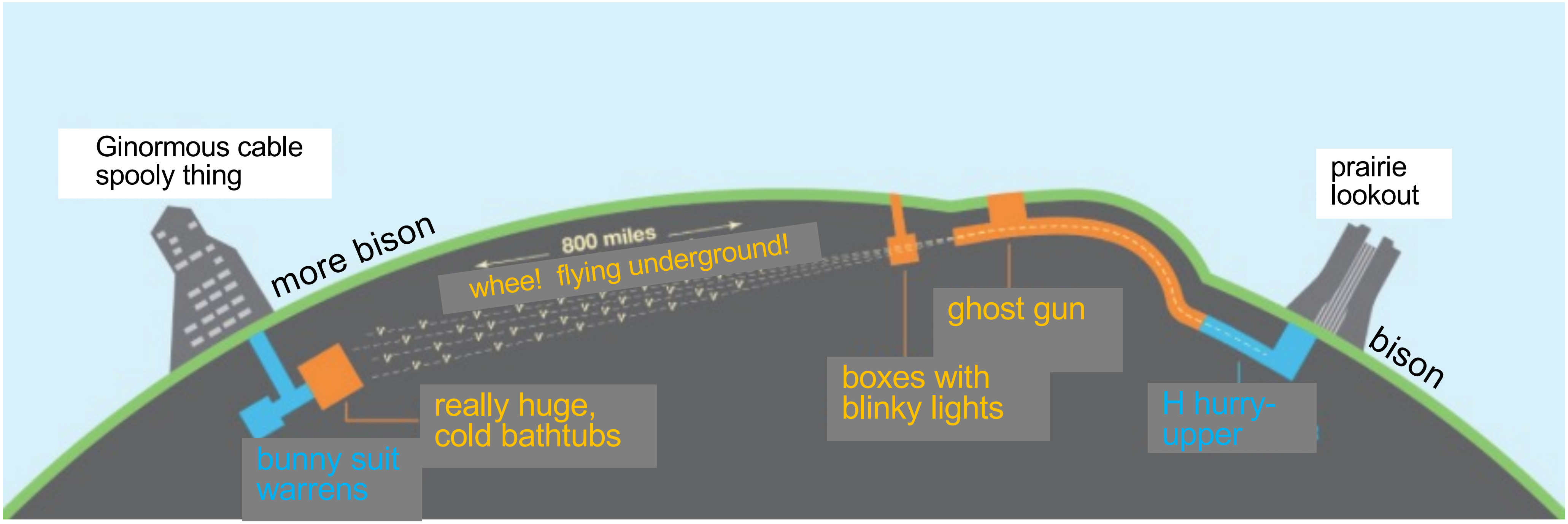


mild tension
w/ reactor
measurement

Capozzi et al., 2019

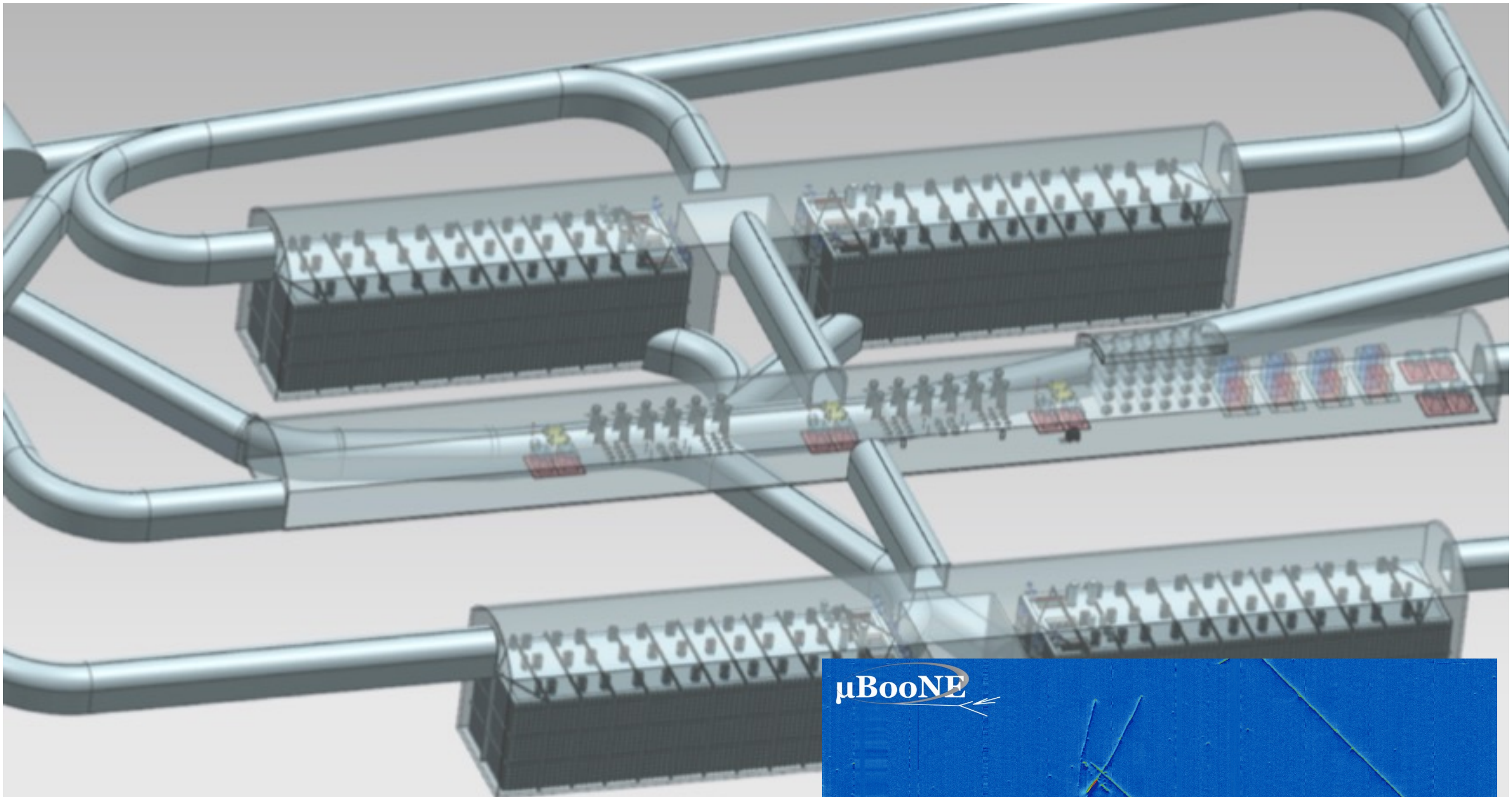
Deep Underground Neutrino Experiment/ Long Baseline Neutrino Facility

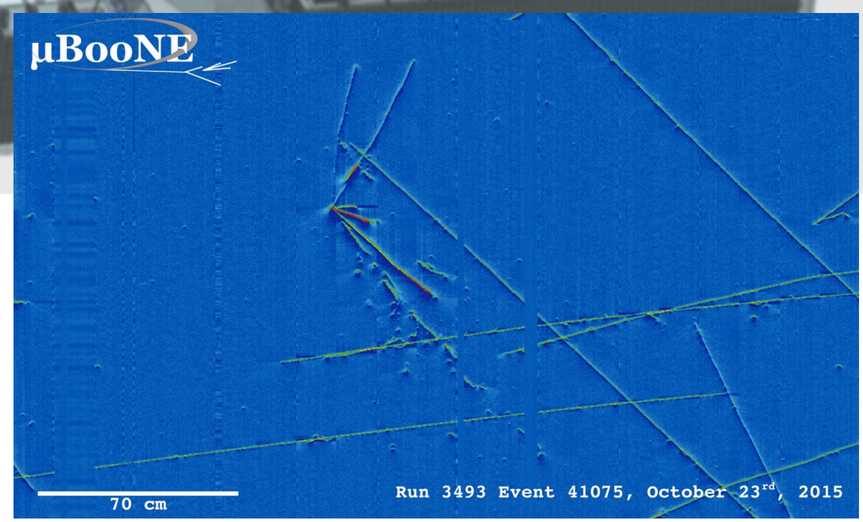
next big US-based international particle physics project



- new 1.2 MW beam, Fermilab to SD
- 40-kton fiducial
  liquid argon TPC far detector
- Also proton decay,
  supernova, atmospheric neutrino
  physics ...

The DUNE far detector: 70,000 tons of liquid argon



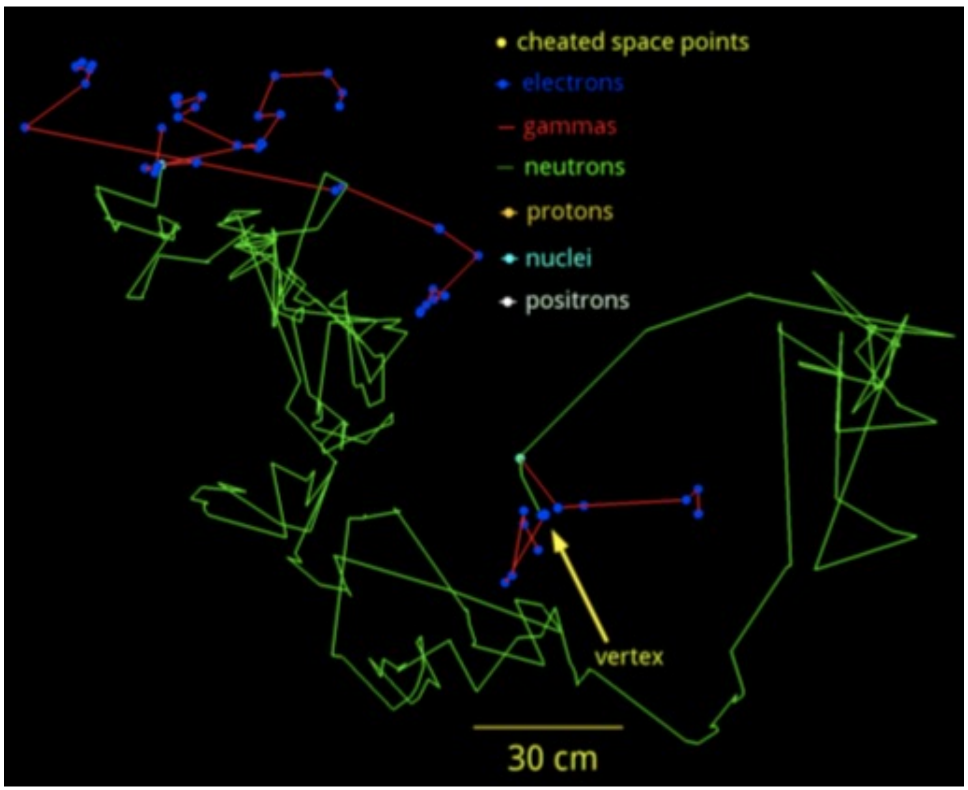


- exquisitely precise tracking
- single-phase and dual-phase technology under consideration (prototypes @ CERN)

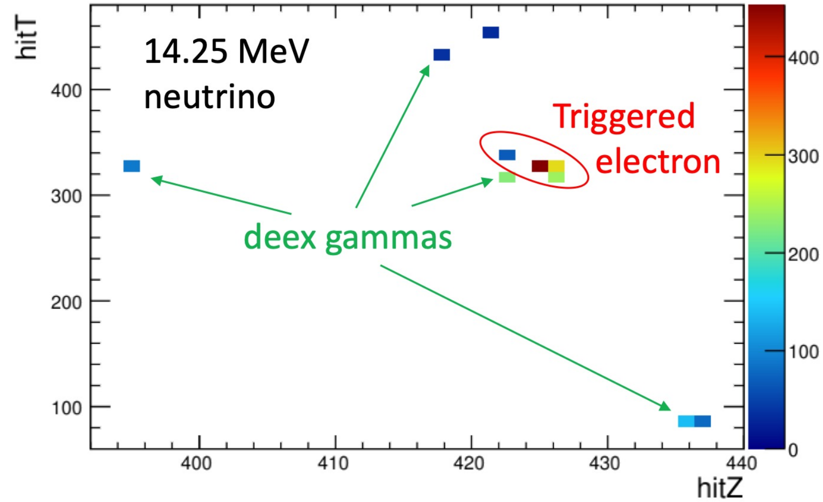
Solar neutrinos in DUNE

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

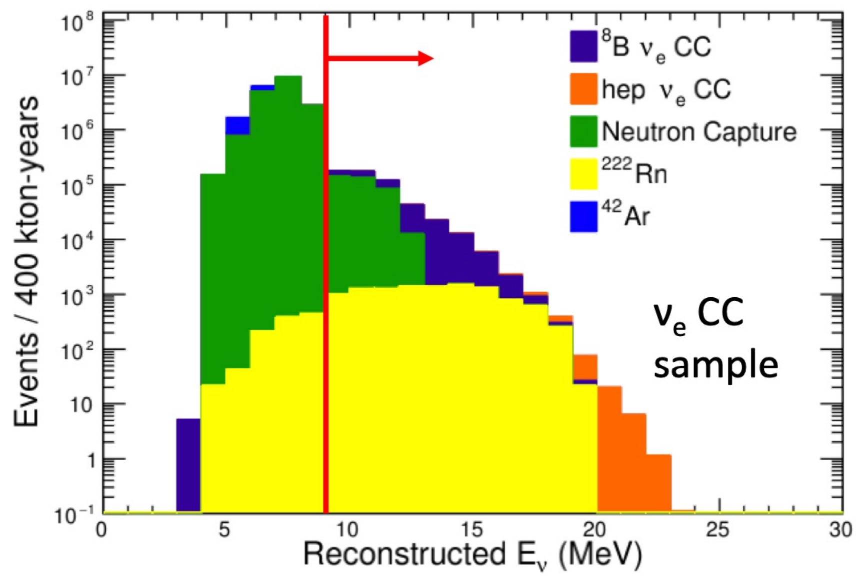
ν_eCC has distinctive topology in a LArTPC



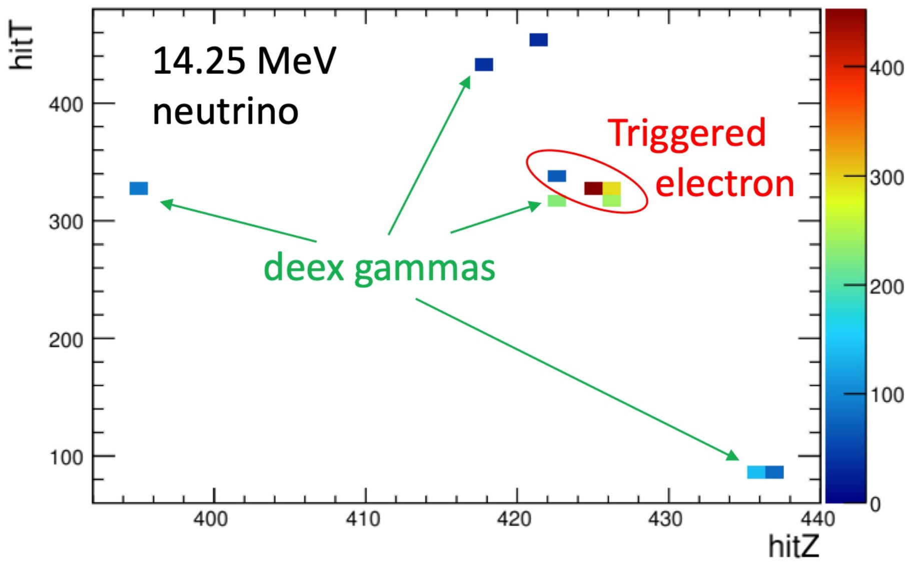
MARLEY



D. Pershey DUNE preliminary



What are the deex gammas?



A. Photoelectrons

B. Compton scatters

C. Produced e+e- pairs

D. Sparkles

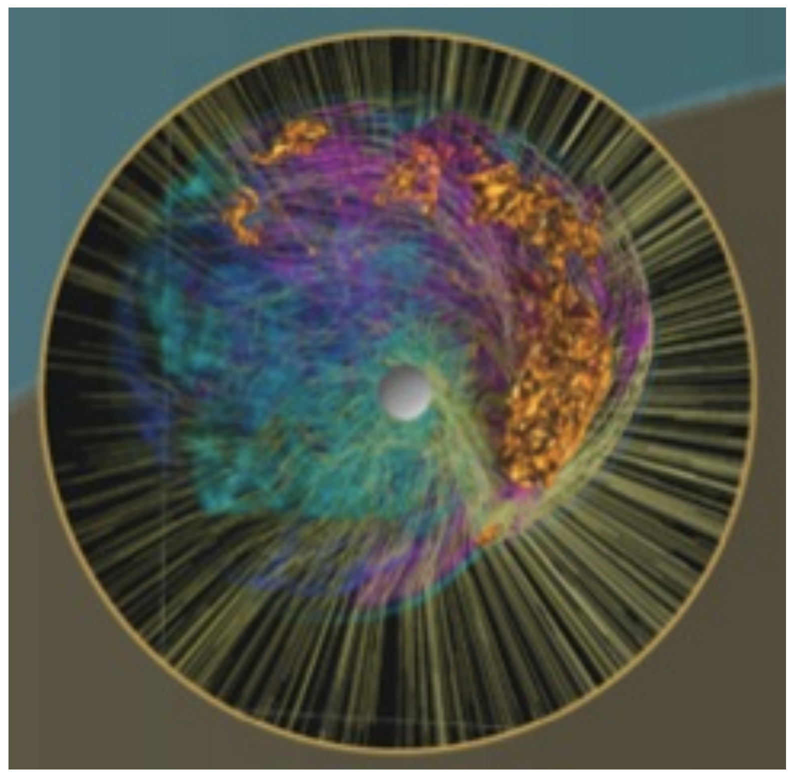
The core-collapse neutrino signal

When a star's core collapses,
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



What fraction of the binding energy is released in the the form of neutrinos?

A. 0.1%

B. 1%

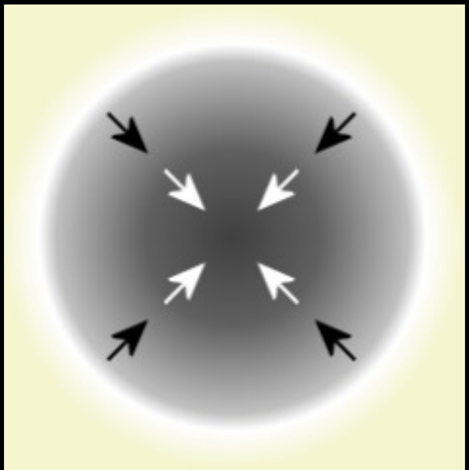
C. 10%

D. 50%

E. 99%

Neutrinos from core collapse

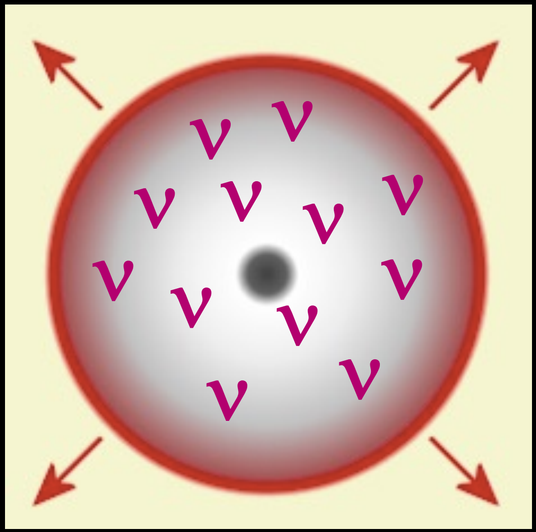
Just as gravitational potential energy turns
into kinetic (and thermal) energy
when an object falls,



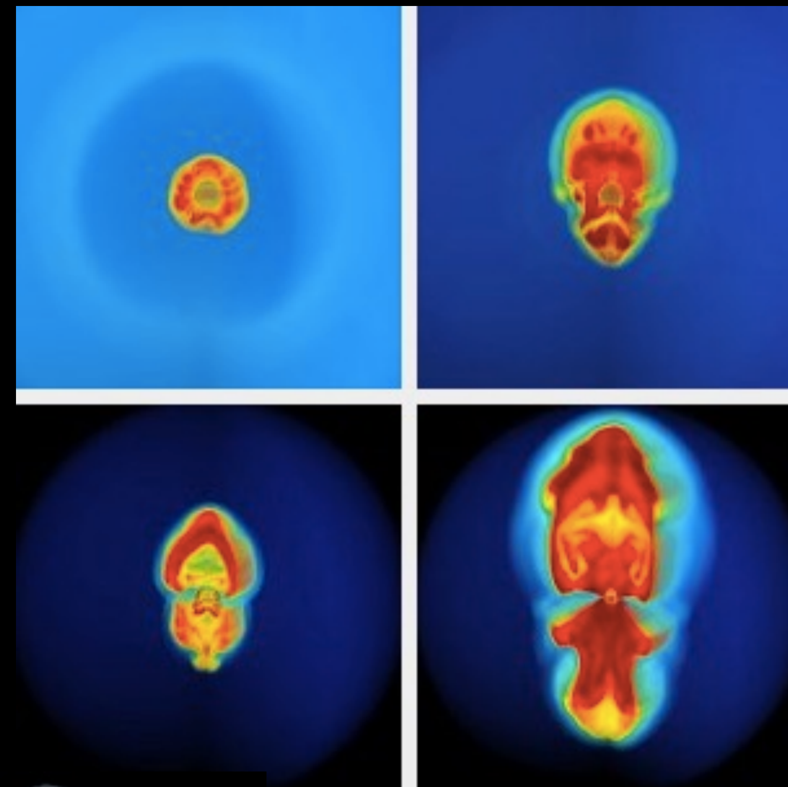
.... as the star falls inward, the gravitational energy *must go somewhere*...

The energy *can* escape via neutrinos, thanks to the weakness of the neutrino interactions

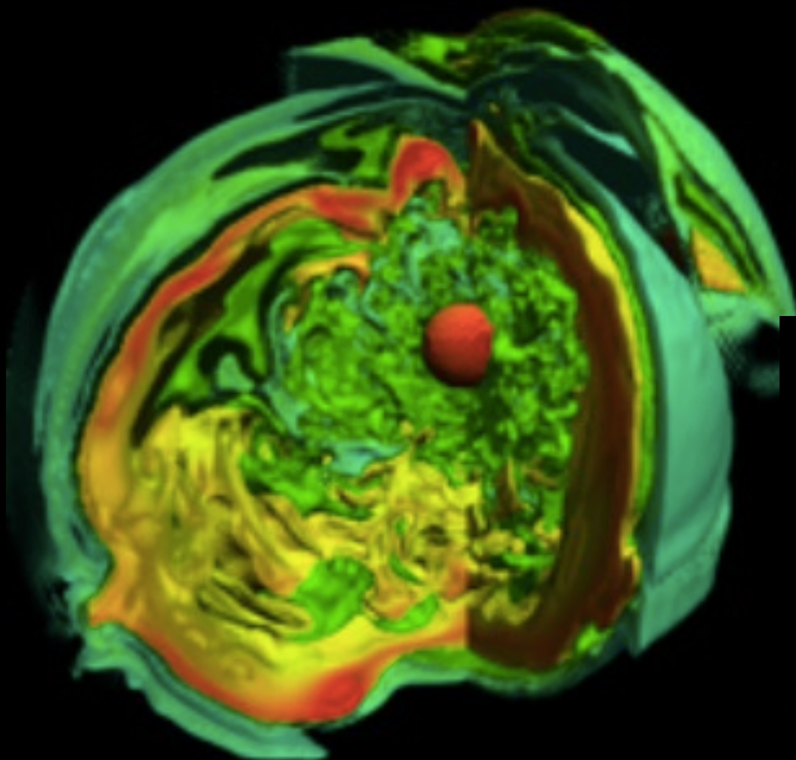
~99% of the vast binding energy of the proto-neutron star is shed within ~10 seconds in the form of *neutrinos and antineutrinos of all flavors*



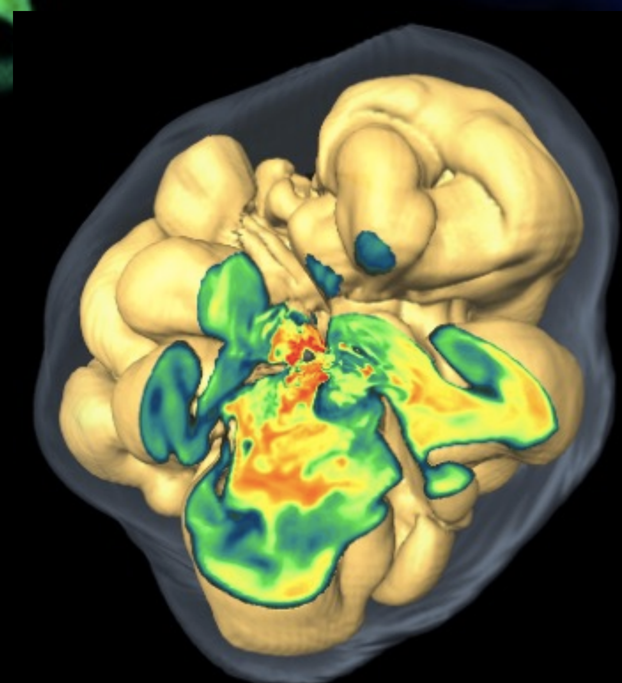
The core-collapse supernova explosion is still not well understood... numerical study ongoing



Marek & Janka

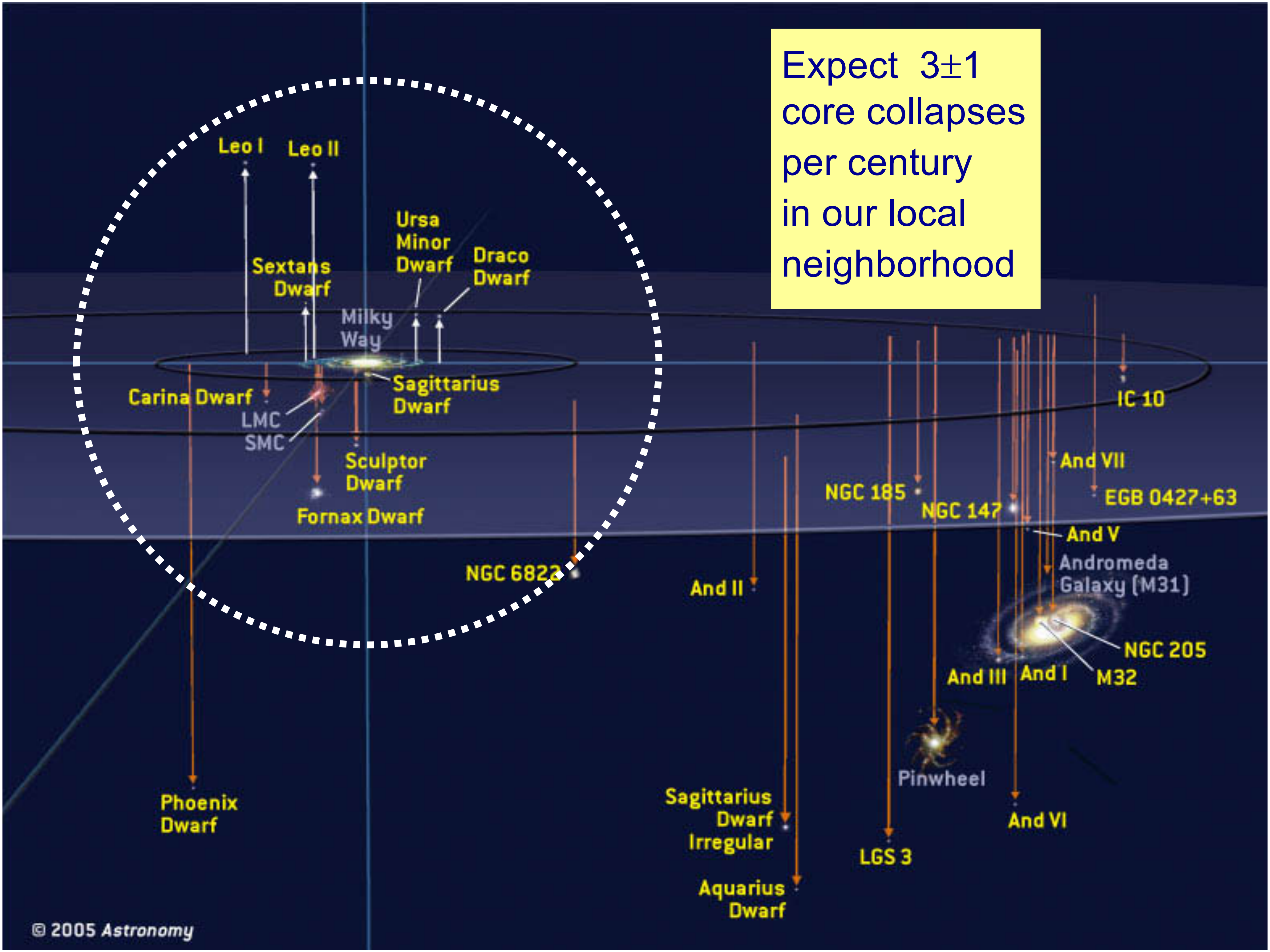


Blondin, Mezzacappa, DeMarino



Neutrinos are intimately involved

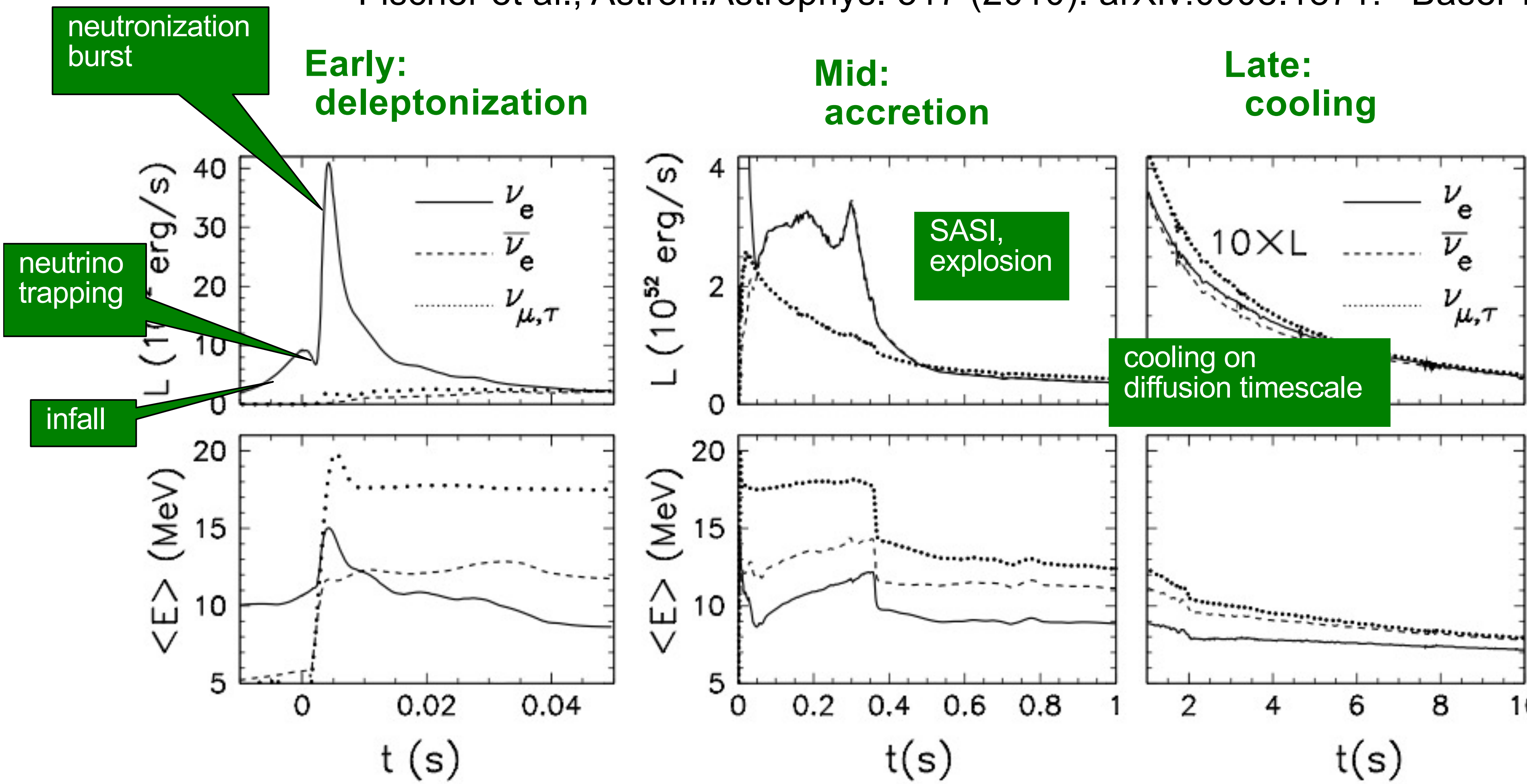
Expect 3±1 core collapses per century in our local neighborhood



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's the physics reason for this energy hierarchy?

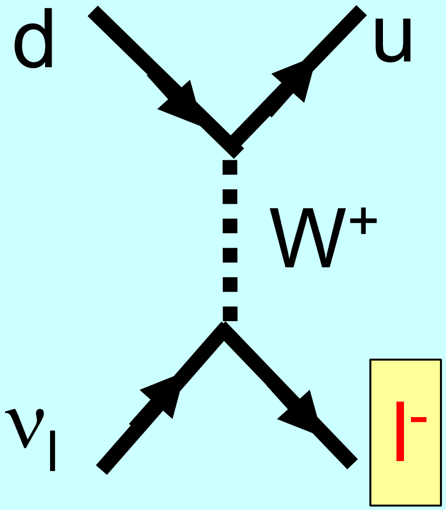
$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

Reminder on Neutrino Interactions with Matter

Neutrinos are aloof but not *completely* unsociable

Charged Current (CC)

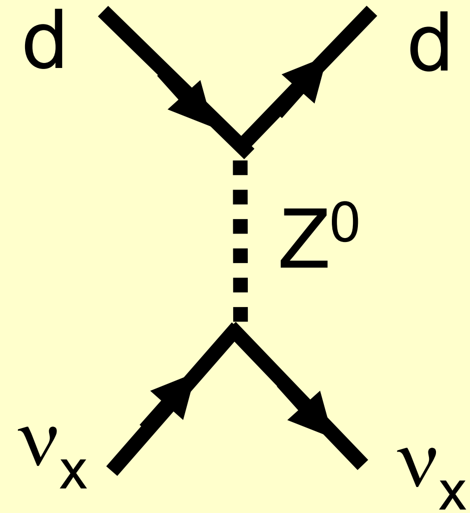


$$\nu_l + N \rightarrow l^{\pm} + N'$$

Produces lepton
with flavor corresponding
to neutrino flavor

(must have enough energy to make lepton)

Neutral Current (NC)



Flavor-blind

What’s the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

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

ν_x NC only

What’s the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

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

CC

ν_x NC only

Hint #2: what’s the proto-neutron star made of?

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

$\nu_e + n \to e^- + p$
$\bar{\nu}_e + p \to e^+ + n$ CC

ν_x NC only

Hint #2: what's the proto-neutron star made of? neutrons!

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

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

ν_x NC only

Hint #2: what's the proto-neutron star made of? neutrons!

Hint #3: which flavors have more interactions?

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$
CC

ν_x NC only

Hint #2: what's the proto-neutron star made of?

neutrons!

Hint #3: which flavors have more interactions?

ν_e has most
then bar-ν_e
ν_x has least

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$
CC

ν_x NC only

Hint #2: what's the proto-neutron star made of?

neutrons!

Hint #3: which flavors have more interactions?

ν_e has most
then bar-ν_e
ν_x has least

Hint #4: "neutrinosphere" is the surface at which neutrino mean-free-path is infinity

...where are the neutrinospheres for each flavor?

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$
CC

ν_x NC only

Hint #2: what's the proto-neutron star made of?

neutrons!

Hint #3: which flavors have more interactions?

ν_e has most
then bar-ν_e
ν_x has least

Hint #4: "neutrinosphere" is the surface at which neutrino mean-free-path is infinity
...where are the neutrinospheres for each flavor?

ν_e is farthest out
then bar-ν_e
ν_x is deepest

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

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

ν_x NC only

Hint #2: what's the proto-neutron star made of?

neutrons!

Hint #3: which flavors have more interactions?

ν_e has most
then bar-ν_e
ν_x has least

Hint #4: "neutrinosphere" is the surface at which neutrino mean-free-path is infinity
...where are the neutrinospheres for each flavor?

ν_e is farthest out
then bar-ν_e
ν_x is deepest

Hint #5: how does temperature vary with radius?

What's the physics reason for this energy hierarchy?

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

Hint #1: what kind of interactions does each flavor have with the medium at <~ 50 MeV energies?

$$\nu_e + n \to e^- + p$$
$$\bar{\nu}_e + p \to e^+ + n$$
CC

ν_x NC only

Hint #2: what's the proto-neutron star made of?

neutrons!

Hint #3: which flavors have more interactions?

ν_e has most
then bar-ν_e
ν_x has least

Hint #4: "neutrinosphere" is the surface at which neutrino mean-free-path is infinity
...where are the neutrinospheres for each flavor?

ν_e is farthest out
then bar-ν_e
ν_x is deepest

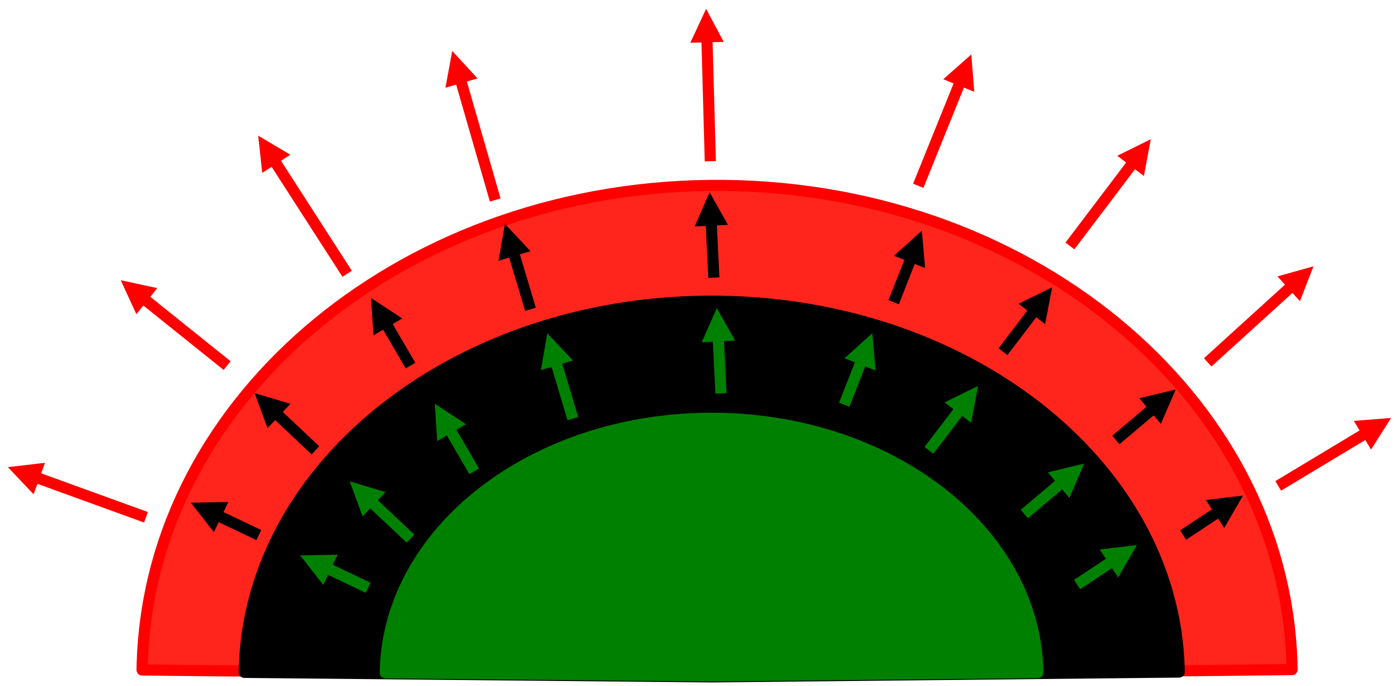
Hint #5: how does temperature vary with radius?

the deeper, the higher the temperature

Nominal expected flavor-energy hierarchy

Fewer interactions
w/ proto-nstar
$\Rightarrow$ deeper ν-sphere
$\Rightarrow$ hotter ν's

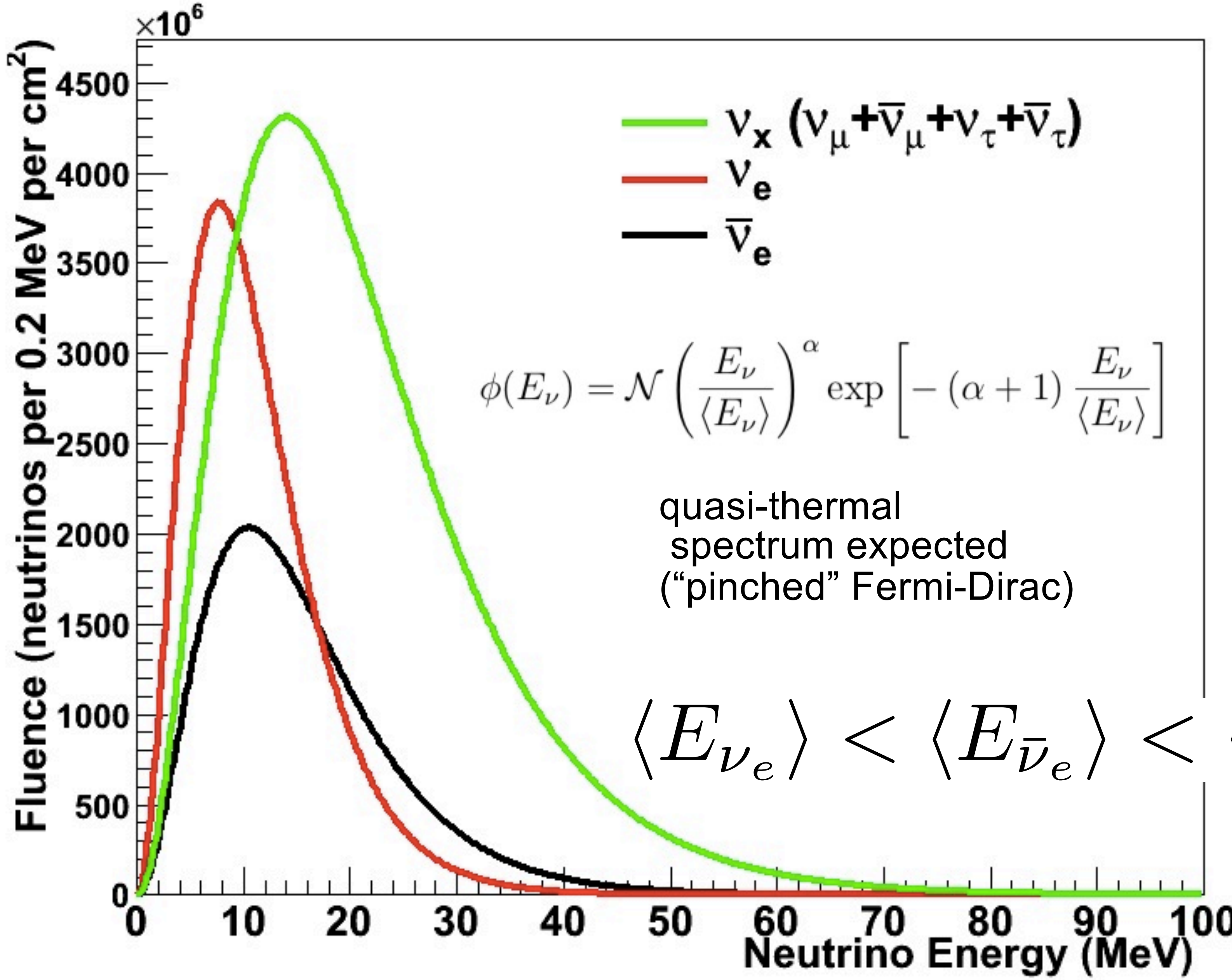
$\langle E_{\nu_e} \rangle \sim$ 12 MeV
$\langle E_{\bar{\nu}_e} \rangle \sim$ 15 MeV
$\langle E_{\overset{(-)}{\nu}_{\mu,\tau}} \rangle \sim$ 18 MeV



May or may not be robust...

Neutrino flavor oscillations (governed by fundamental neutrino parameters) will modify the spectra

Neutrino spectrum from core collapse



$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

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

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

Supernova 1987A

in the Large Magellanic Cloud (55 kpc away)

~two dozen neutrino interactions observed!

What is a kiloparsec (kpc)?

A. A unit of distance equal to about 3260 light years

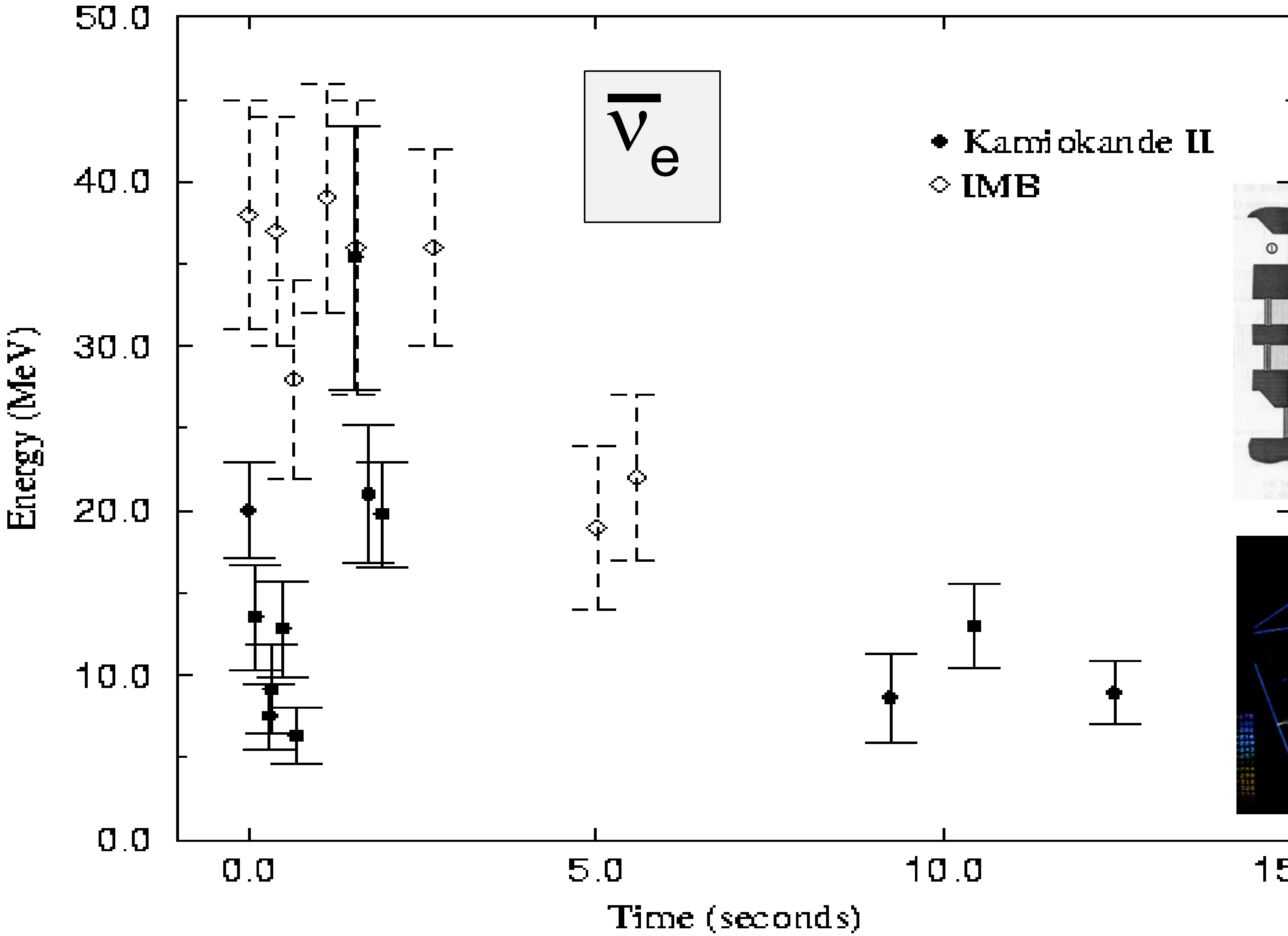
B. A unit of time equal to about 3260 years

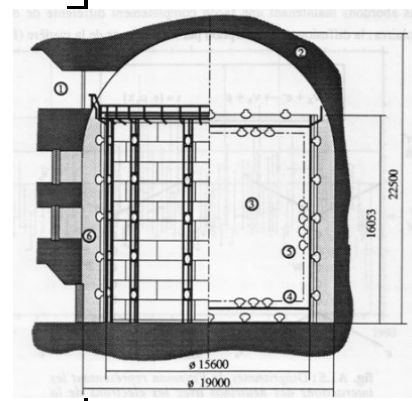
C. Approximately the distance to Betelgeuse

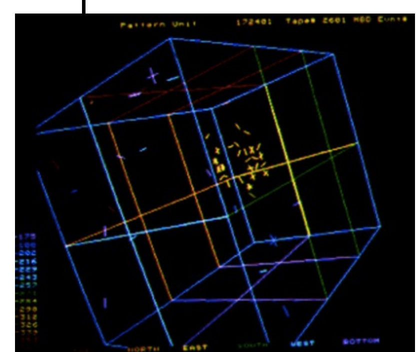
D. A leisurely amount of time to complete the Kessel Run

SN1987A in LMC

ν's seen ~2.5 hours before first light

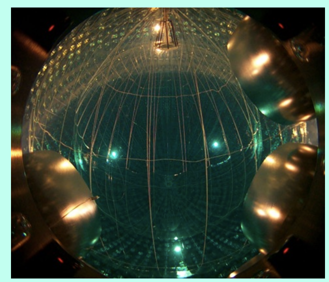
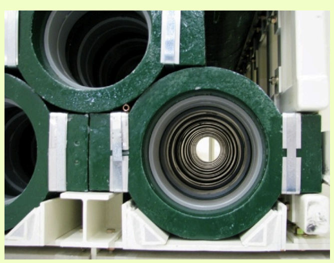
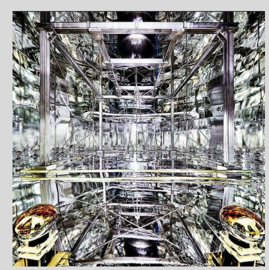




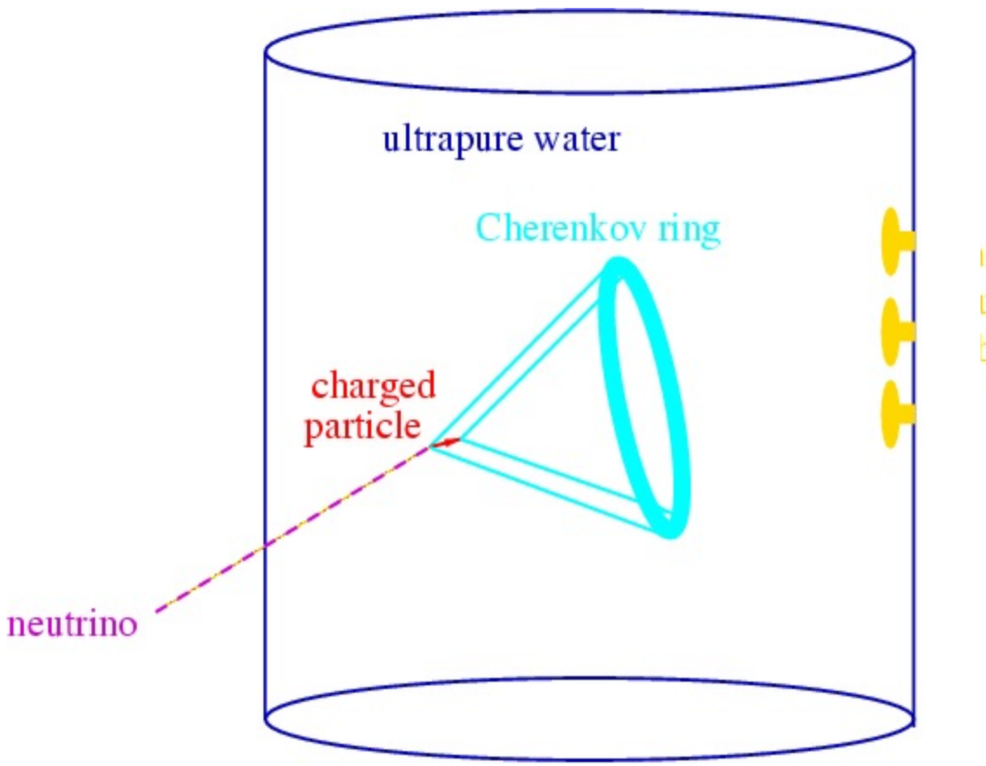


Confirmed baseline model... but still many questions

Supernova neutrino detector types

Water  $\overline{\nu}_e$	**Water, long-string**  $\overline{\nu}_e$
Argon  ν_e	**Scintillator**  $\overline{\nu}_e$
Lead  ν_e	**DM (Noble liquid)**  ν_x

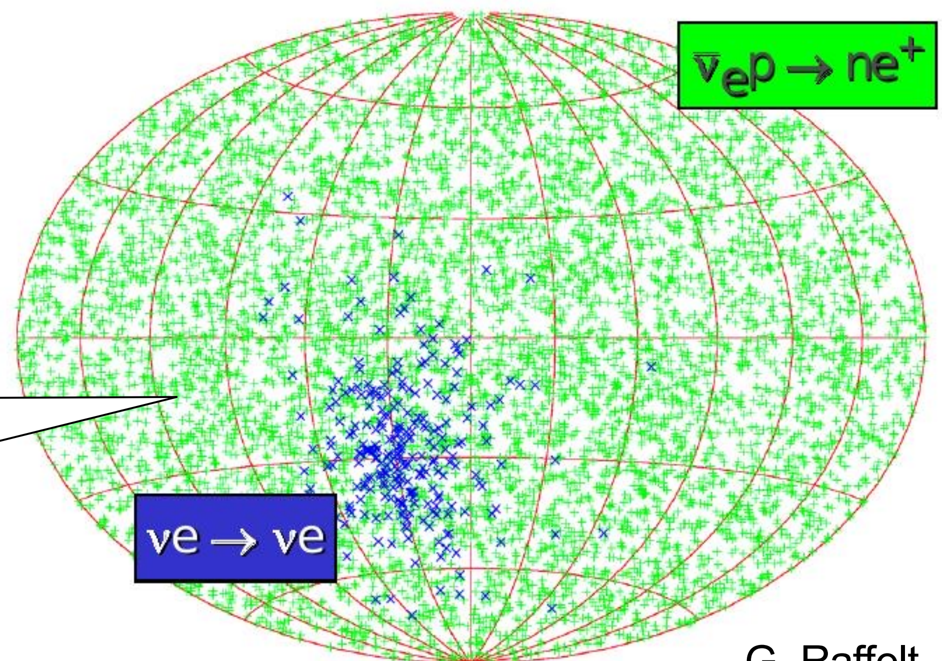
Water Cherenkov detectors



Inverse Beta Decay (CC)

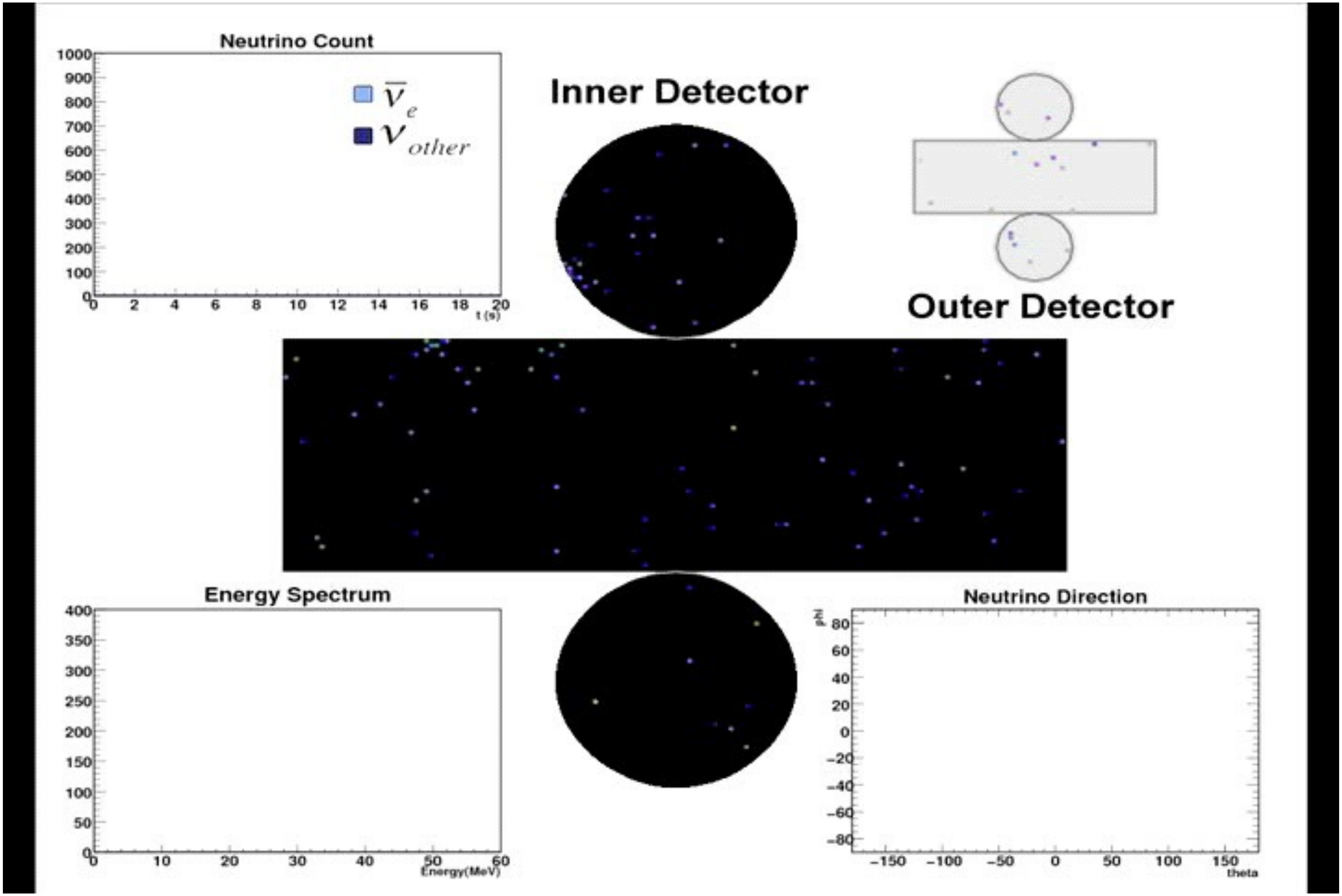
$\bar{\nu}_e + p \rightarrow e^+ + n$ **dominates**

E_{thr}=1.8 MeV



Pointing from neutrino-electron elastic scattering

G. Raffelt



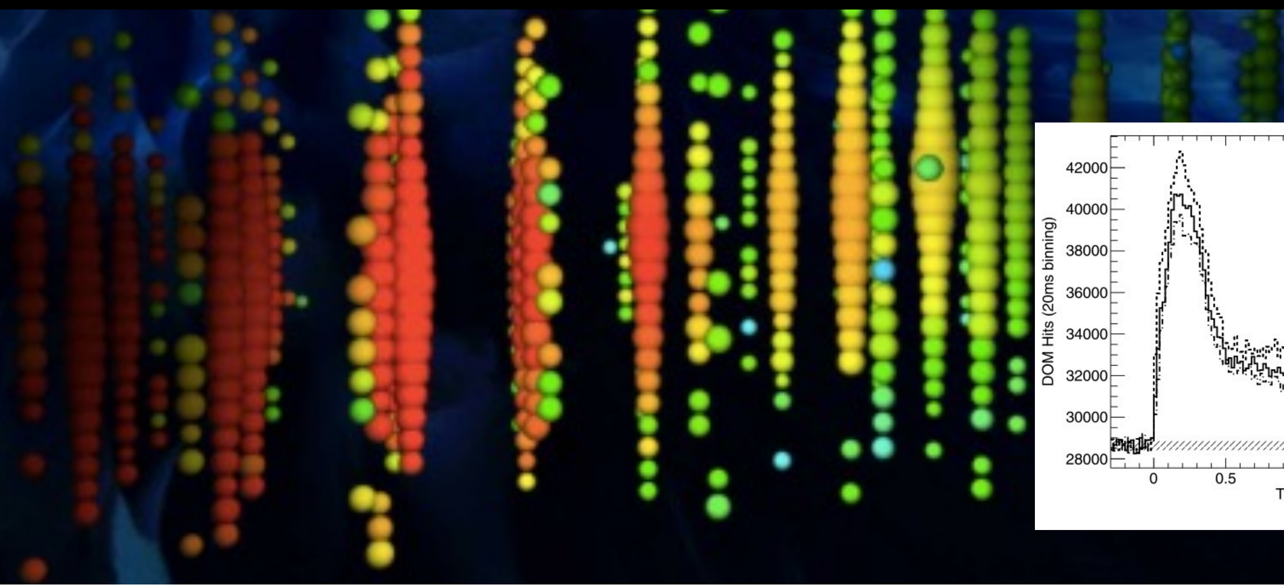
http://snews.bnl.gov/snmovie.html

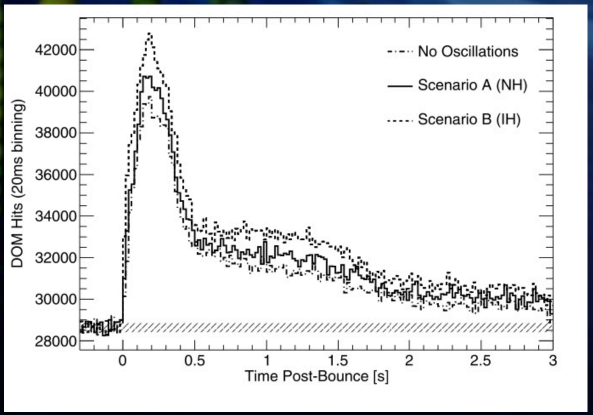
Long string water Cherenkov detectors

~kilometer long
strings of PMTs
in very clear water
or ice (IceCube, ANTARES)

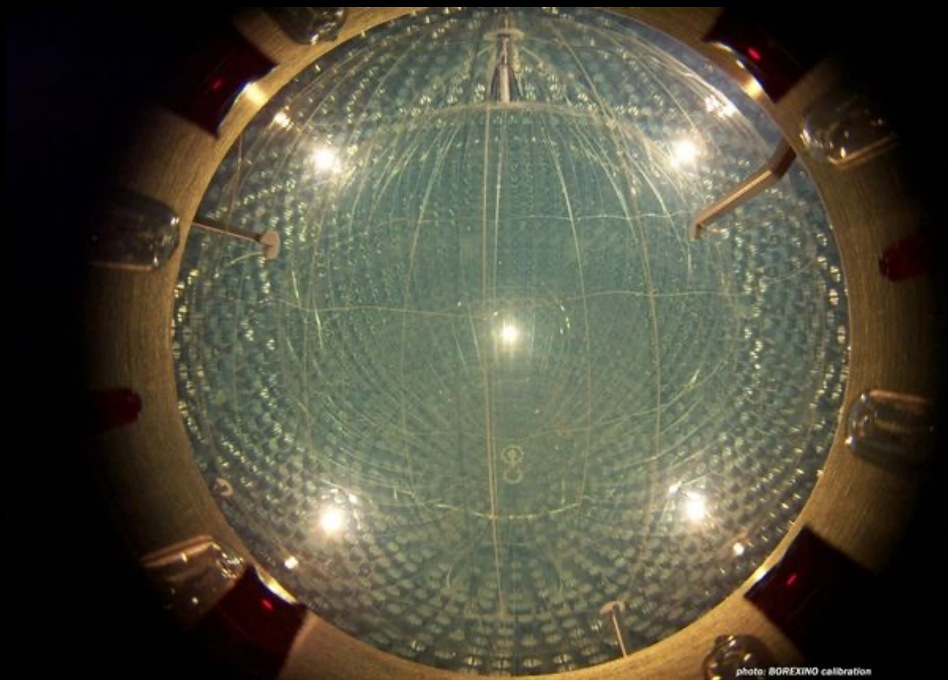
Nominally multi-GeV energy threshold...
but, may see burst of low energy (anti-) ν_e's as
coincident increase in single PMT count rate

Map overall time structure of burst by tracking the single-PMT hit glow





Scintillation detectors

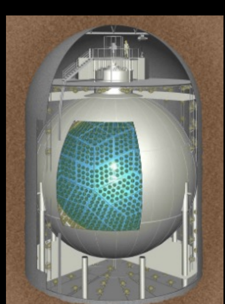


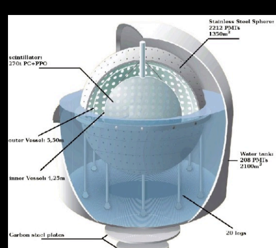
Liquid hydrocarbon (C_nH_{2n}) that emits (lots of) photons when charged particles lose energy in it

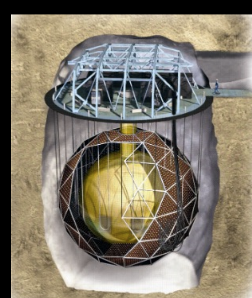
Will see supernova **electron antineutrinos**, with good energy resolution

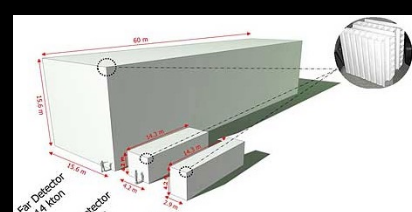
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Many examples worldwide of current and future detectors

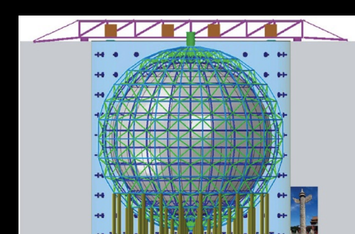




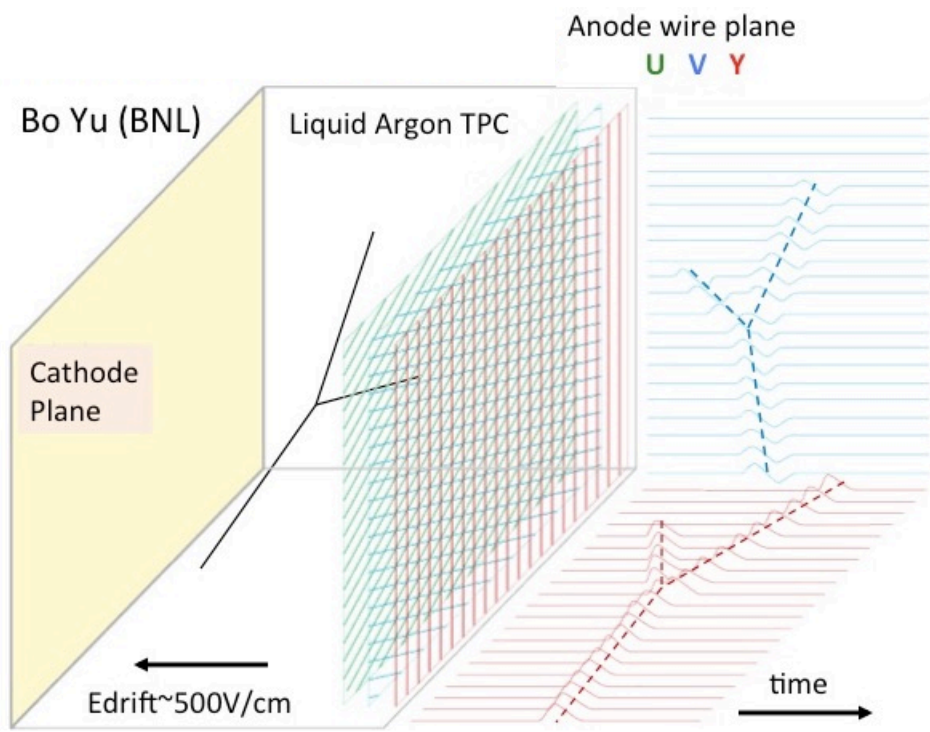




JUNO, 20 kt



Liquid argon time projection chambers

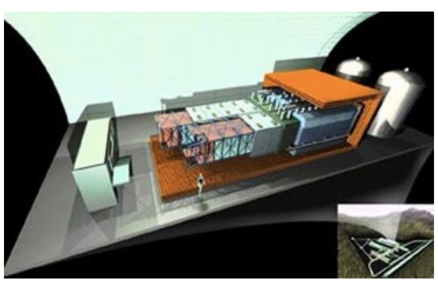


fine-grained trackers
ionization + scintillation photons

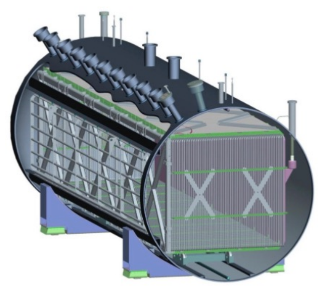
sensitive to **electron neutrinos**
(as opposed to antineutrinos)

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

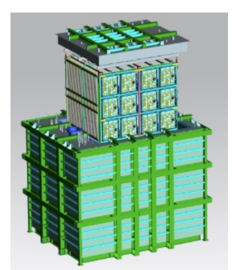
ICARUS
(Italy→USA)
0.6 kton



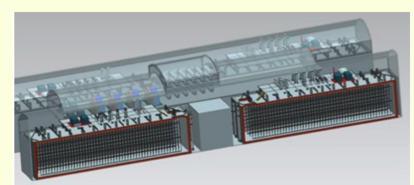
MicroBooNE
(USA)
0.2 kton



SBND
(USA)
0.112 kton



DUNE
(USA)
40 kton



Summary of 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
HALO	Lead	Canada	0.079	20	Running
Daya Bay	Scintillator	China	0.33	100	Running
NOvA	Scintillator	USA	15	3000	Running
SNO+	Scintillator	Canada	1	300	(Running)
MicroBooNE	Liquid argon	USA	0.17	17	Running
DUNE	Liquid argon	USA	40	3000	Future
Hyper-K	Water	Japan	540	110,000	Future
JUNO	Scintillator	China	20	6000	Future
IceCube Gen-2	Long string	South pole	(600)	(10^6)	Future

plus reactor experiments, DM experiments...

How many events are expected in DUNE for a core collapse in Andromeda (700 kpc)?

A. <<1

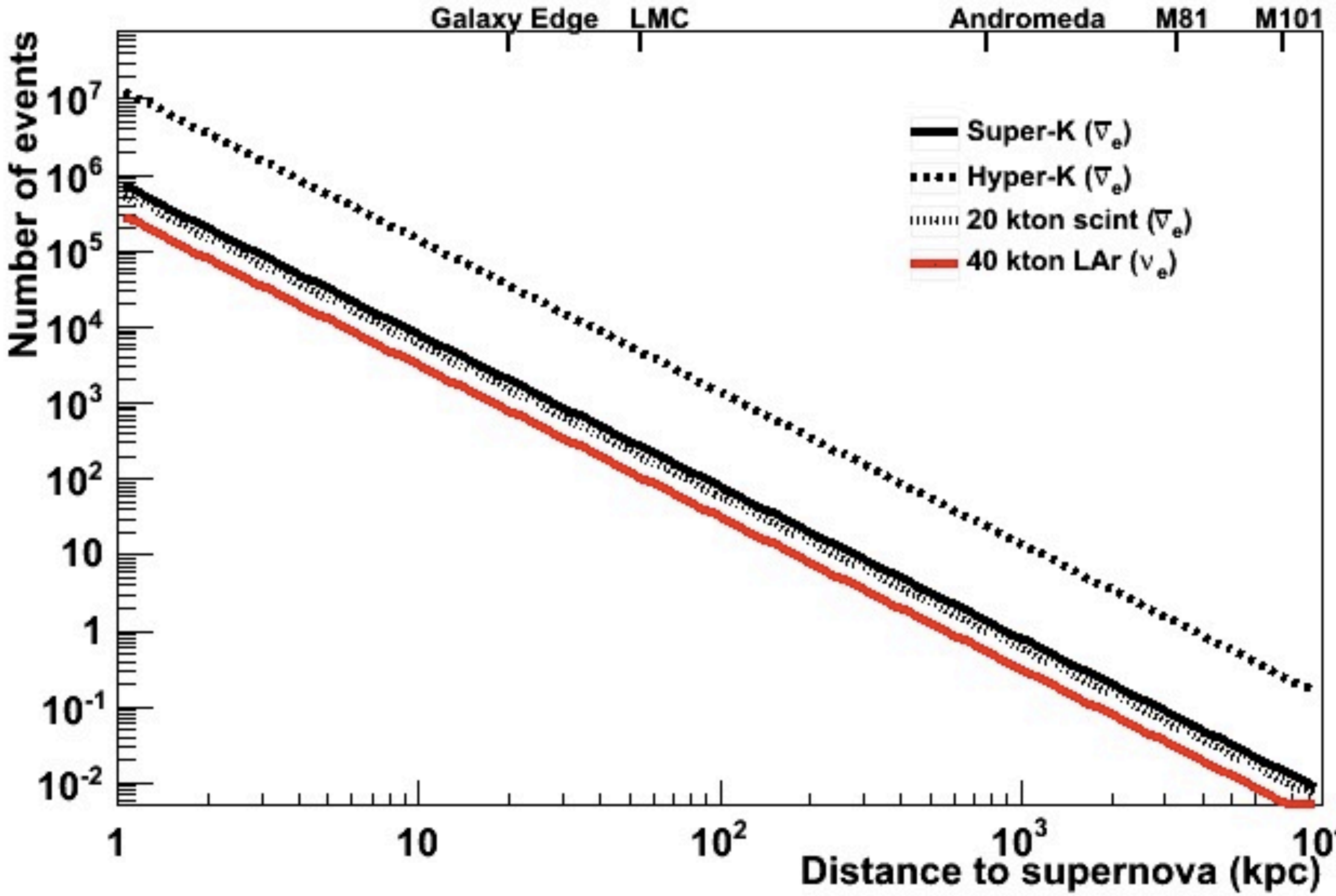
B. 1

C. 10

D. 100

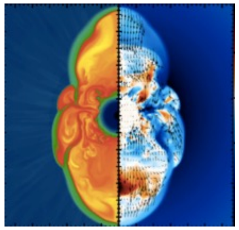
E. 1000

Distance reach for future detectors



What can we learn from the next neutrino burst?

CORE COLLAPSE PHYSICS

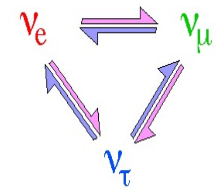


explosion mechanism
proto nstar cooling,
quark matter
black hole formation
accretion, SASI
nucleosynthesis
....

input from photon (GW) observations

from flavor, energy, time structure of burst

input from neutrino experiments



NEUTRINO and OTHER PARTICLE PHYSICS

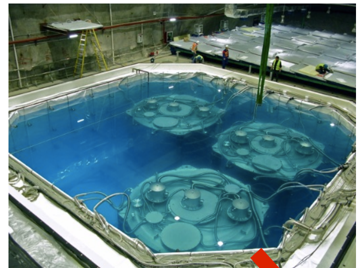
ν absolute mass (not competitive)
ν mixing from spectra:
flavor conversion in SN/Earth
(mass hierarchy)
other ν properties: sterile ν's,
magnetic moment,...
axions, extra dimensions,
FCNC, ...

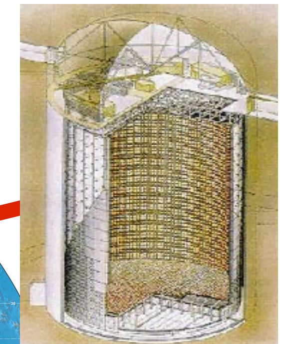
+ EARLY ALERT

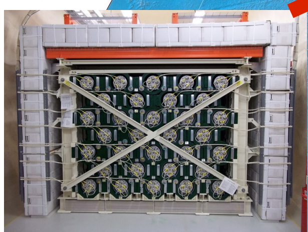
SNEWS: SuperNova Early Warning System

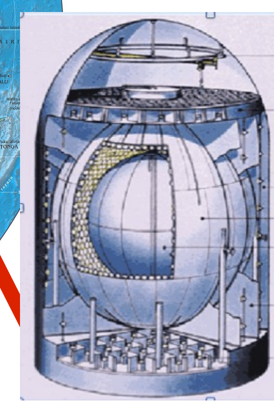
snews.bnl.gov


LVD

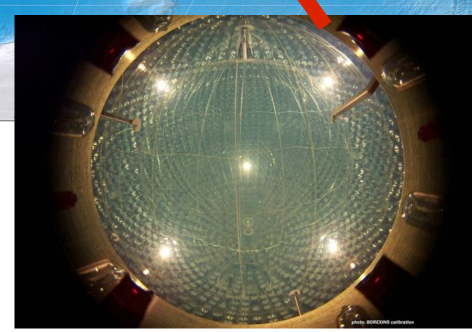

(Daya Bay)

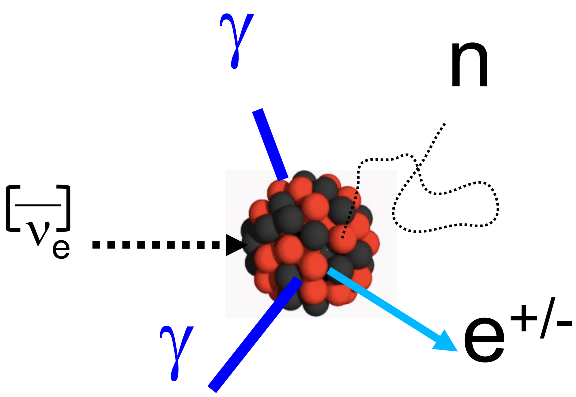

Super-K


HALO


KamLAND


IceCube

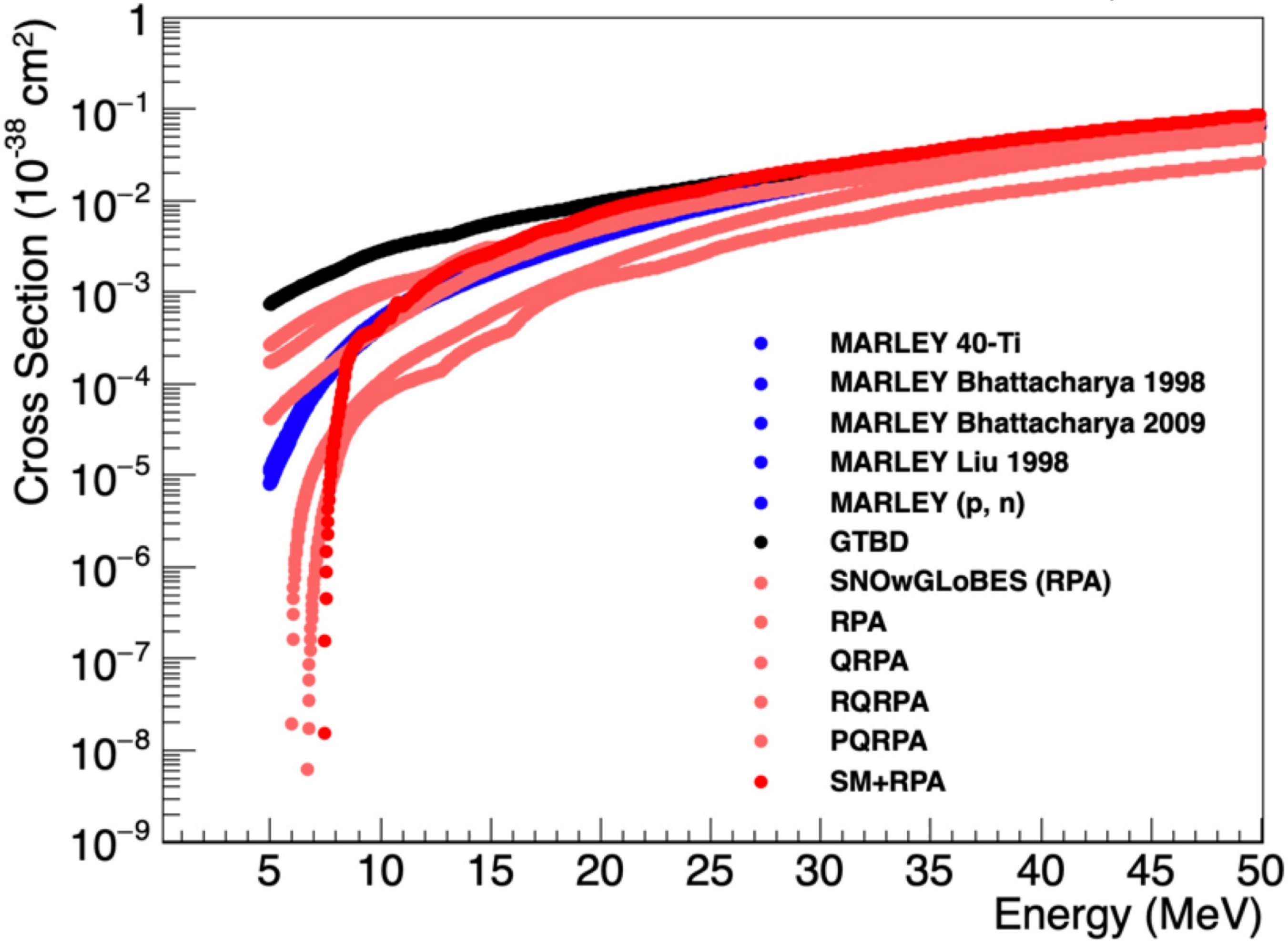

Borexino



Inelastic interactions of neutrinos with nuclei (cross sections & interaction products) **quite poorly understood**... sparse theory & experiment (*only* measurements at better than ~50% level are for ^{12}C)

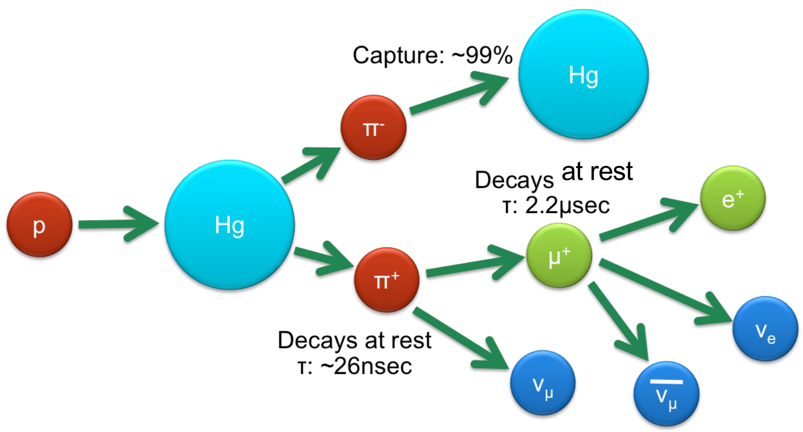
Example of variation in theory predictions at low energy

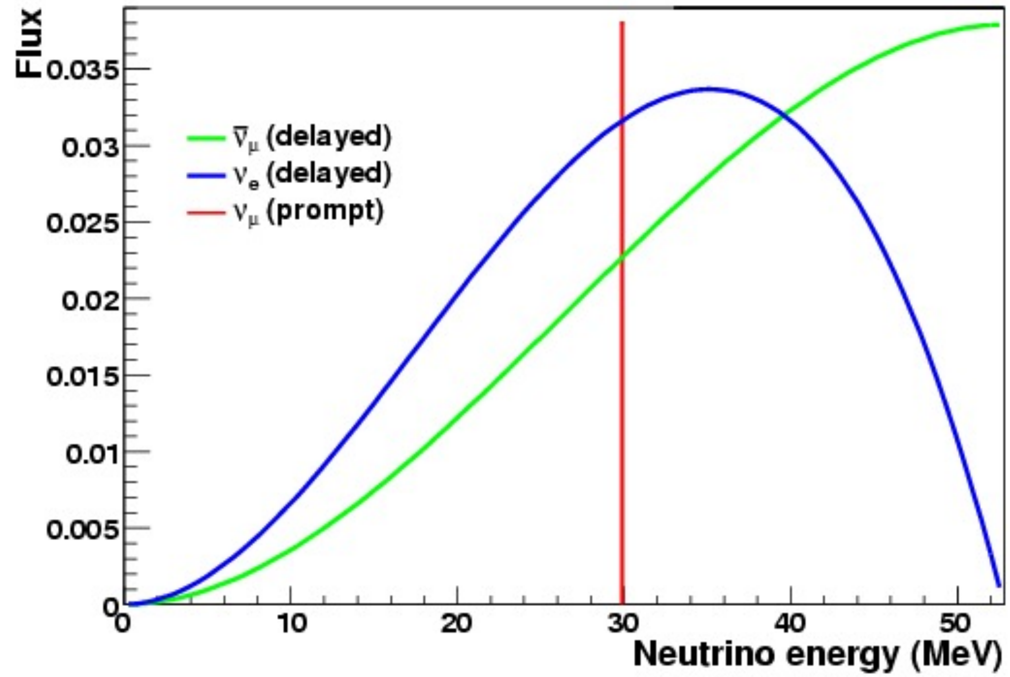
E. Conley, S. Gardiner



This is for ν_eCC on Ar, but gives an idea of (large) uncertainties for these kinds of calculations... need better info to interpret an SNB observation!

Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$

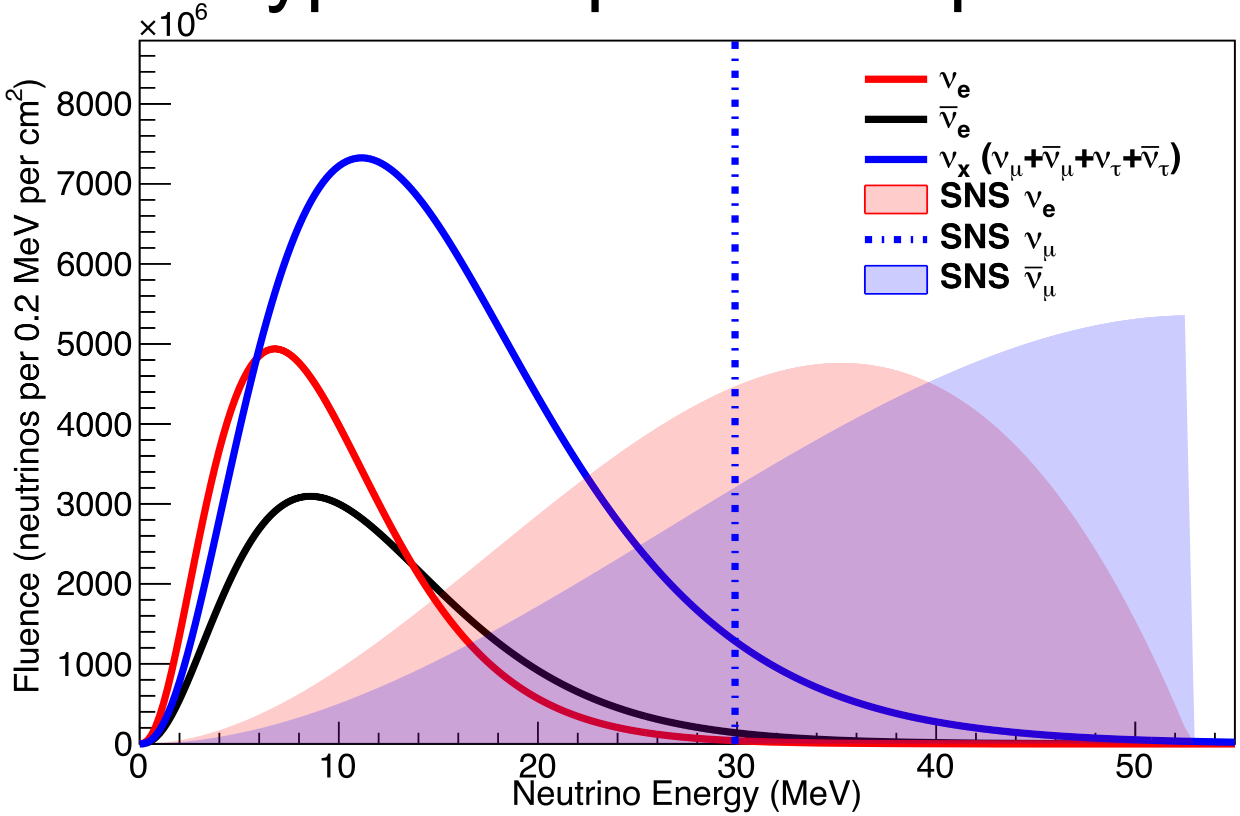
2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

$$\mu^+ \longrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

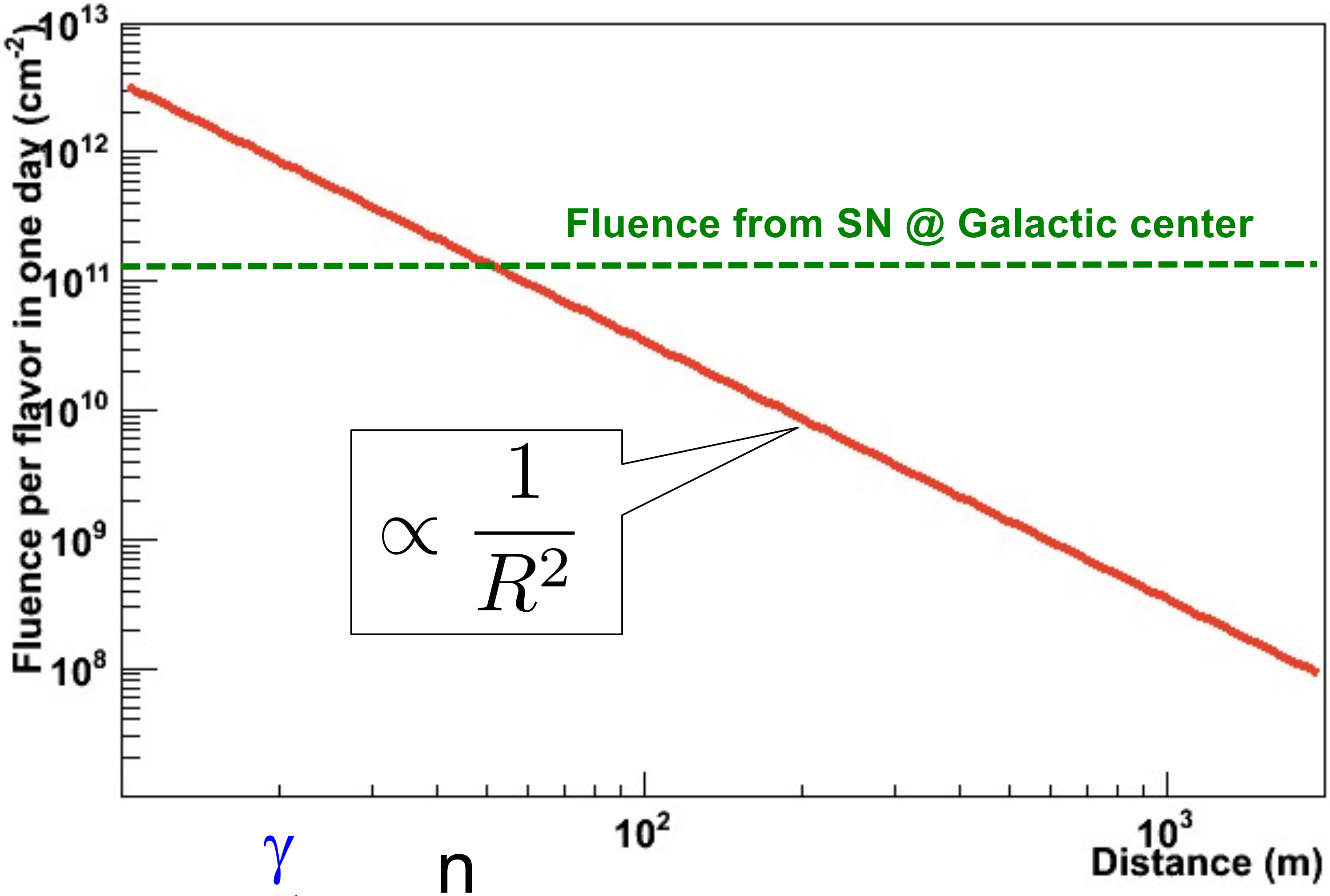
Neutrinos from stopped pions overlap with the typical supernova spectrum

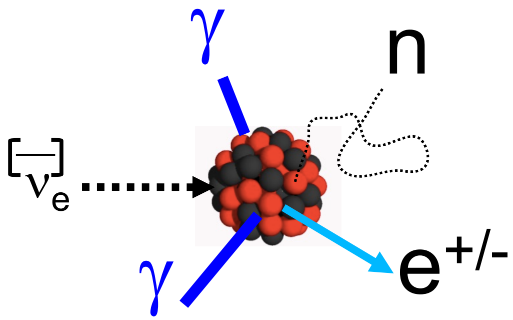


Available at the Spallation Neutron Source

Fluence at ~50 m from the stopped pion source amounts to ~ a supernova a day!

(or 0.2 microsupernovae per pulse, 60 Hz of pulses)





This is an excellent opportunity to study poorly understood neutrino-nucleus interactions in the supernova energy range

Take-away points from today

- Solar neutrinos:
    - up to ~15 MeV, huge rate of pp below ~1 MeV
    - interesting to measure in DUNE with ν_eCC

- Supernova neutrinos:
    - all flavors, up to ~50 MeV, 10 second burst
    - very rich physics and astrophysics
    - multiple detectors worldwide

- Inelastic neutrino interactions have big uncertainties!

→ **We need to *measure* the cross sections**

- Stopped-pion neutrino sources are "synthetic supernovae"

... more on this Thursday!

Outline of Lecture Topics

General overview

Specific example

- Neutrino sources
- Neutrino interactions with matter
- Particle detection techniques

- Physics with neutrinos
  in the ~1-100 MeV range
- Physics with stopped-pion
  neutrino sources

- Physics in Neutrino Alley at the
  Spallation Neutron Source
- The COHERENT Experiment
- Future prospects

Mon

Tue

Thu