# ASTROPHYSICAL NEUTRINOS IN SUPER-KAMIOKANDE

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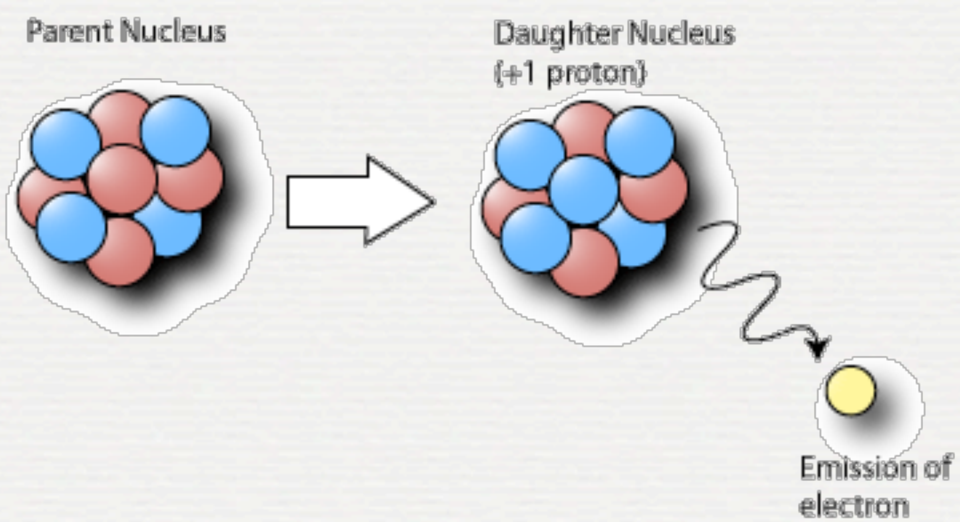
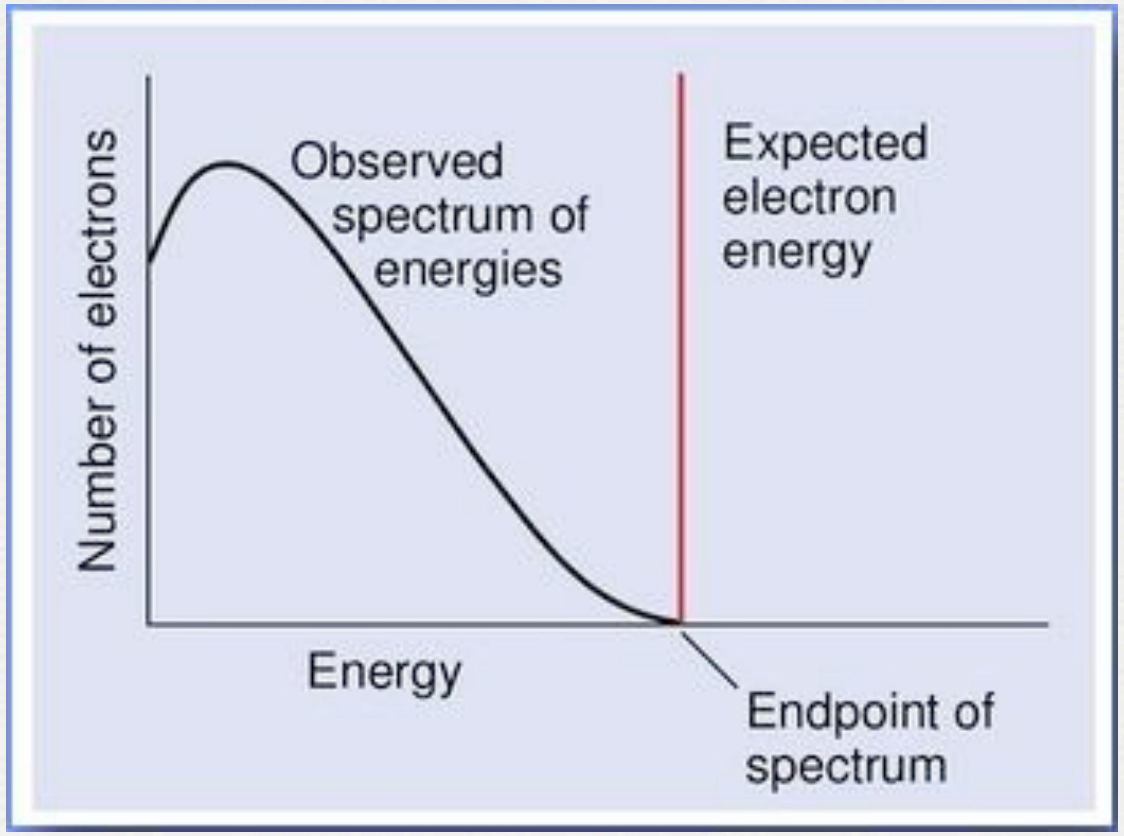
NEUTRINO
NEUTRINO
NEUTRINO

# NEUTRINO TIMELINE

1899: Beta decay is discovered

Beta Decay




A continuous energy spectrum was observed

# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

1899: Beta decay is discovered

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, because of the "wrong" statistics of the N- and Li-6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion principle and that further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and

if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble servant

signed W. Pauli

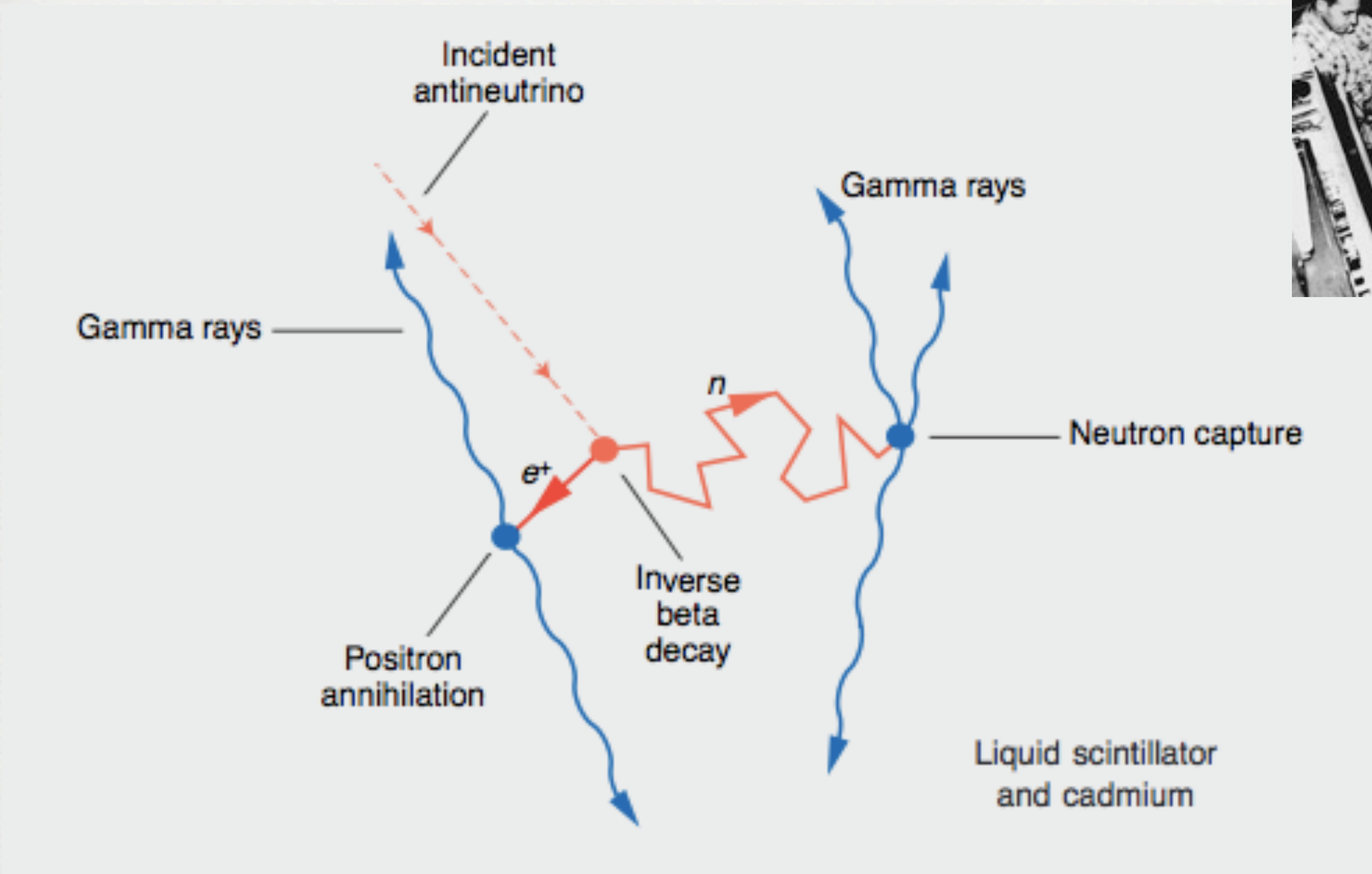
**Wolfgang Ernst Pauli**
(1900 – 1958)

# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

1899: Beta decay is discovered

1959: First measurement of the (anti)neutrino




# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

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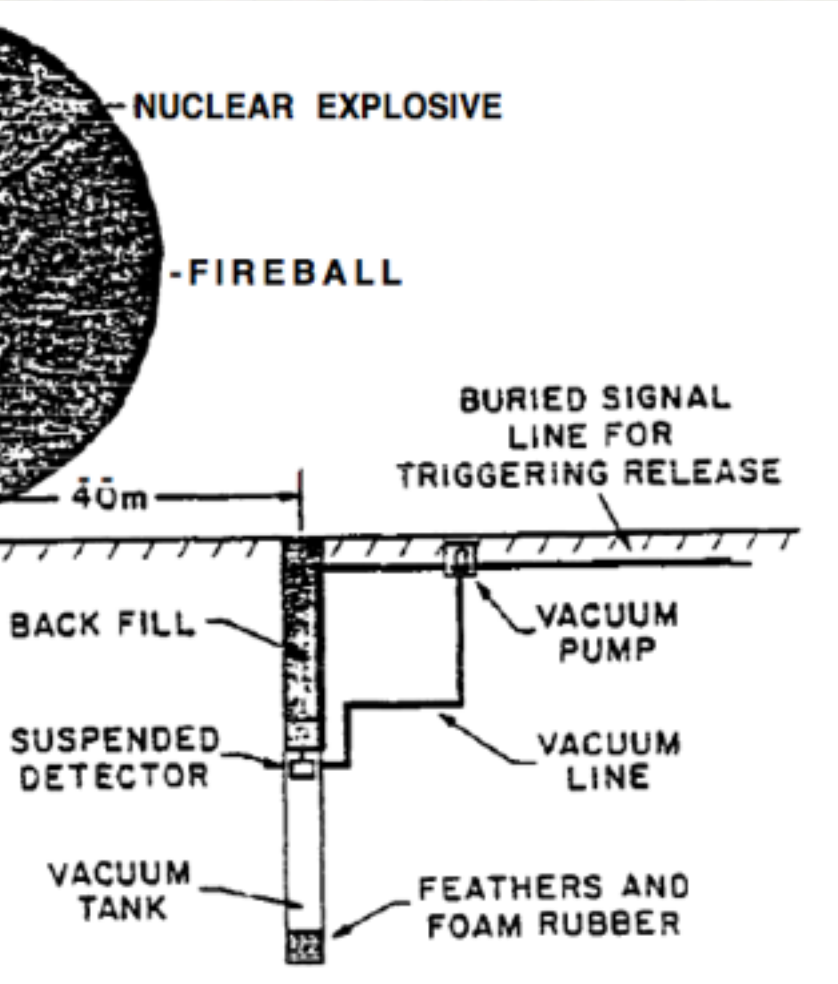
1959: First measurement of the (anti)neutrino

**Plan A: Detonate a nuclear bomb**




**(El Monstro)**

# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

1899: Beta decay is discovered

1959: First measurement of the (anti)neutrino

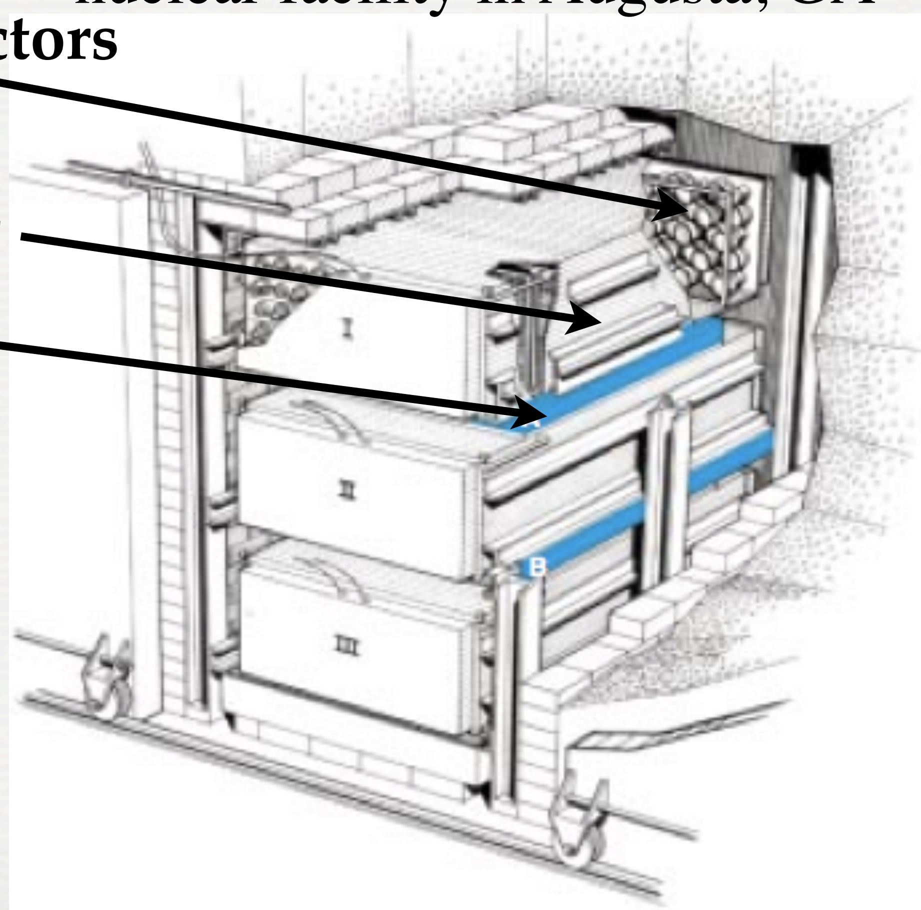
**Plan B: Set up a detector near a nuclear reactor**

Neutrino detector at Savannah River, a nuclear facility in Augusta, GA

**Photodetectors**

**Scintillator**

**Water**



# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

1962: The muon neutrino is discovered

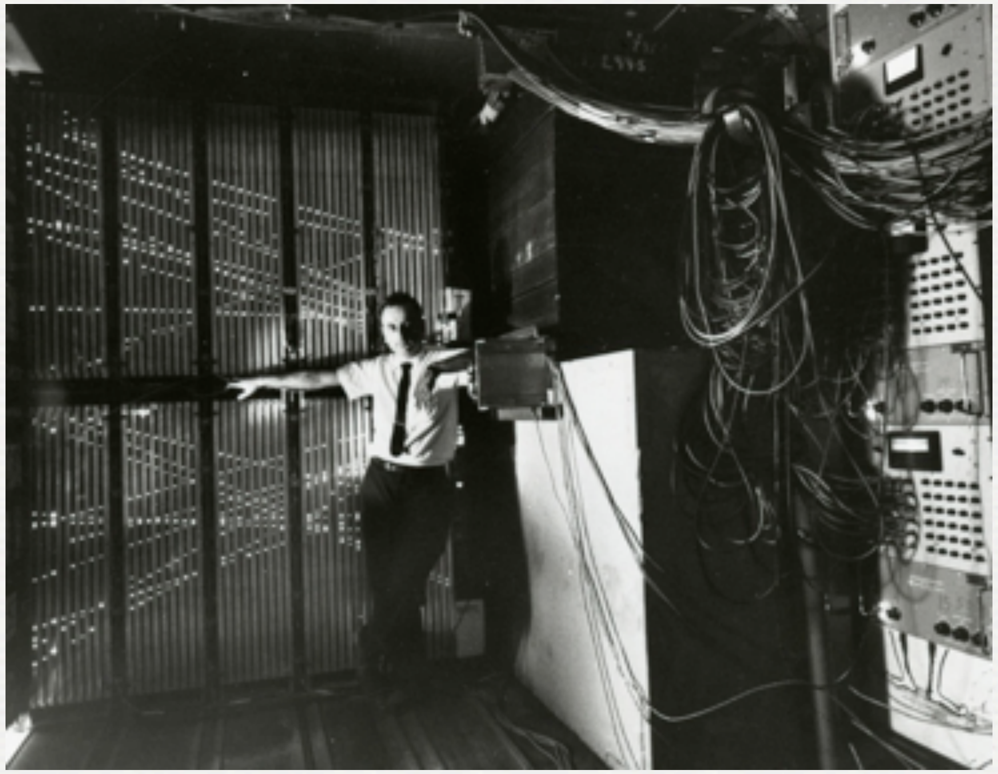
1899: Beta decay is discovered

1959: First measurement of the (anti)neutrino

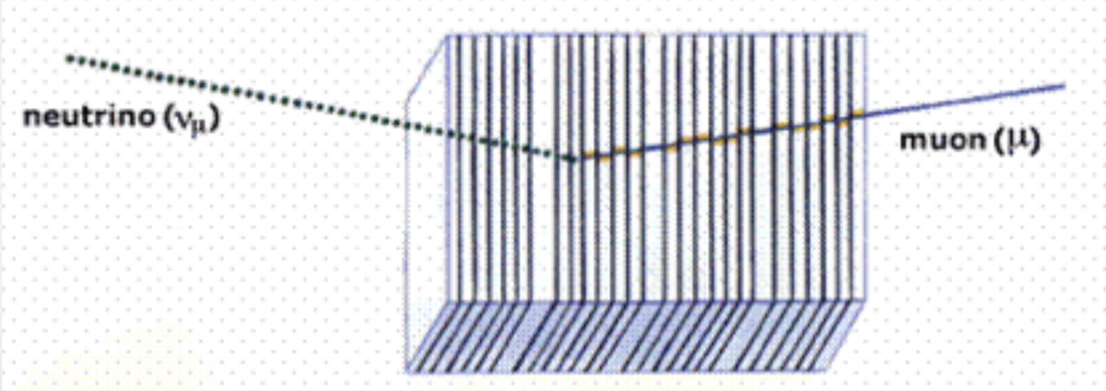
**Melvin Schwartz**
(1932 – 2006)

**Leon Lederman**
(1922 – )

**Jack Steinberger**
(1921 – )



A spark chamber measures a muon produced from a neutrino interaction



# NEUTRINO TIMELINE

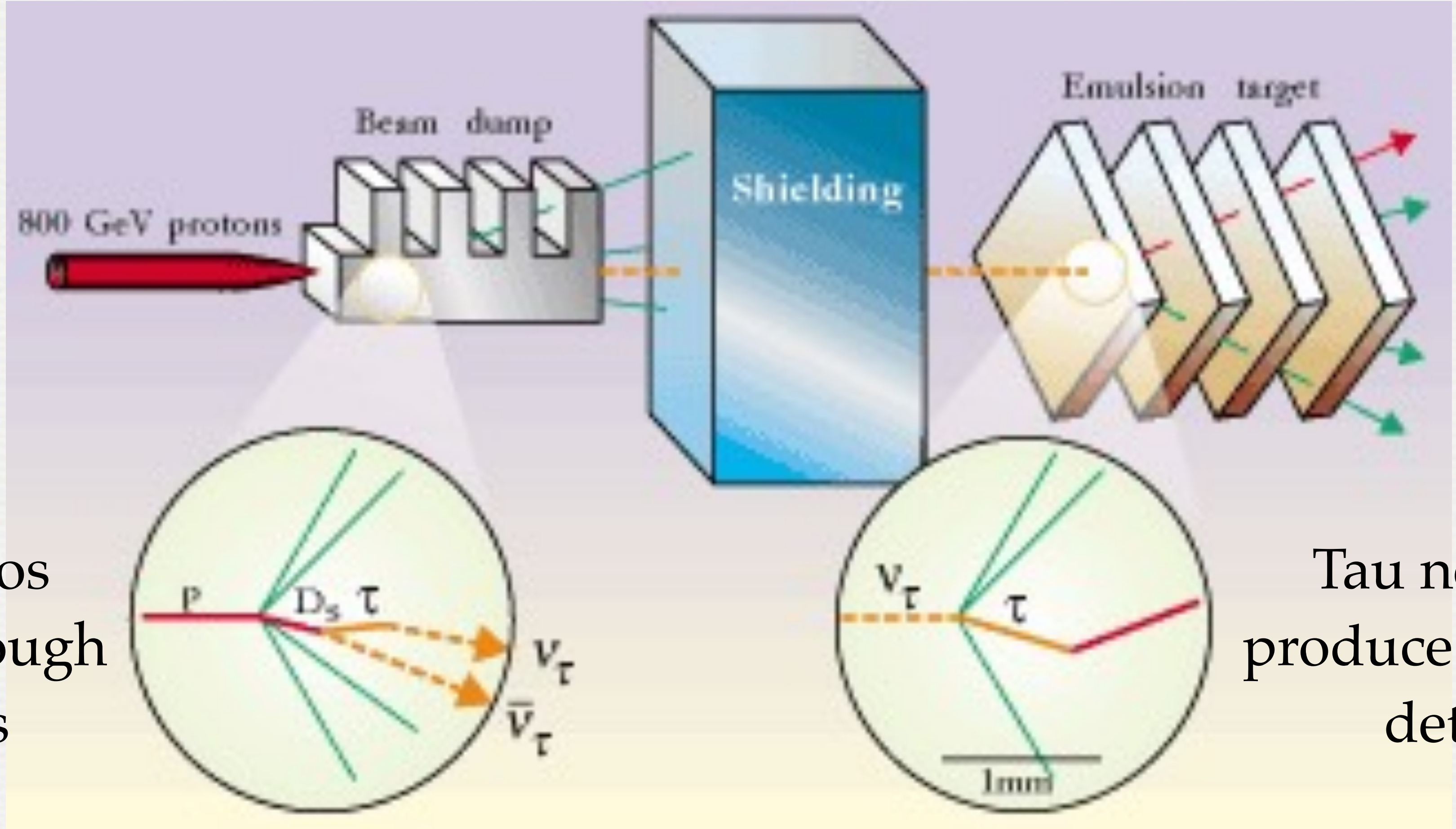
1930: Pauli proposes the neutrino

1962: The muon neutrino is discovered

1899: Beta decay is discovered

1959: First measurement of the (anti)neutrino

2000: The tau neutrino is discovered




Tau neutrinos produced through tau decays

Tau neutrinos produce taus in the detector

# NEUTRINO TIMELINE

1930: Pauli proposes the neutrino

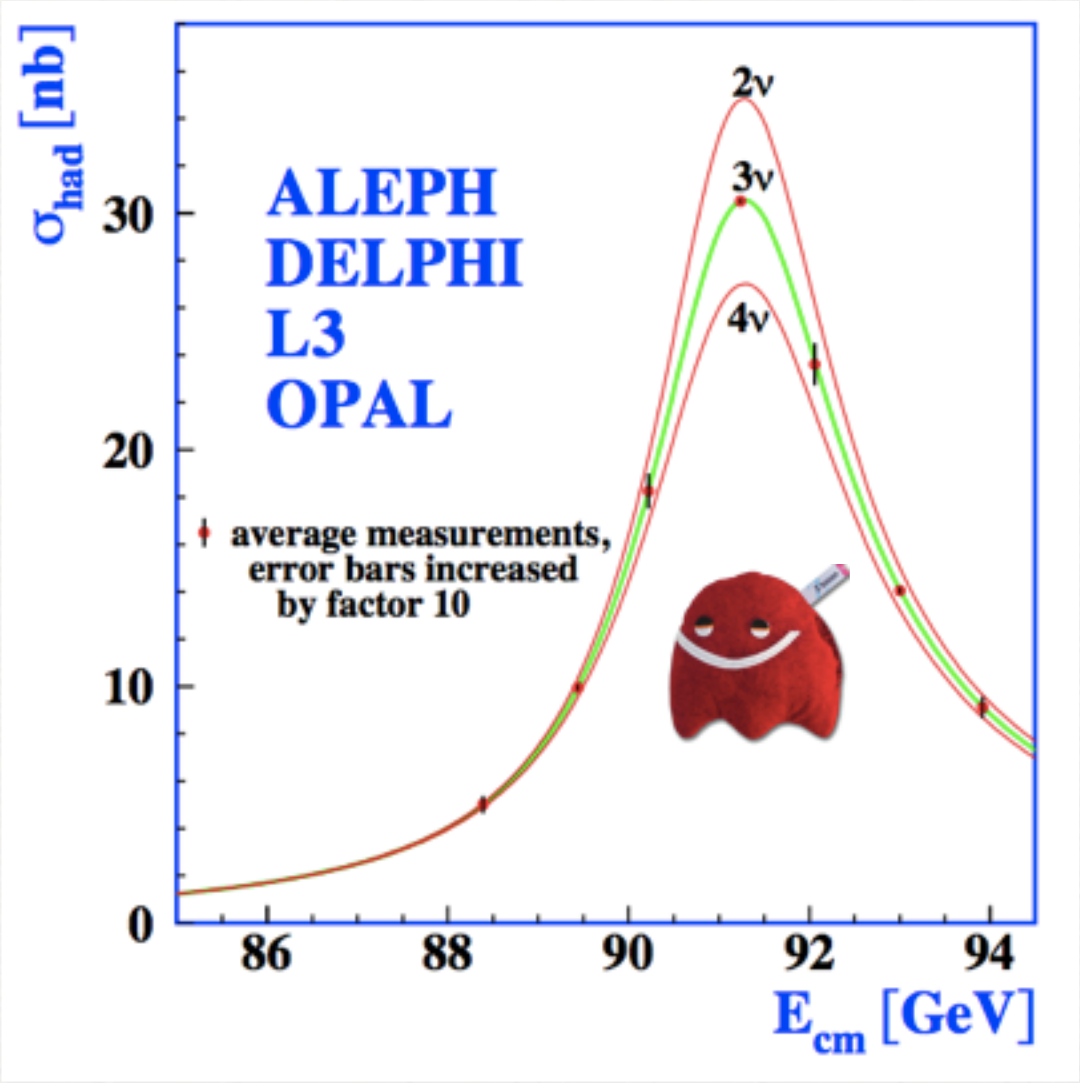
1962: The muon neutrino is discovered

2006: Z boson decay shows that there is only 3 neutrino flavours

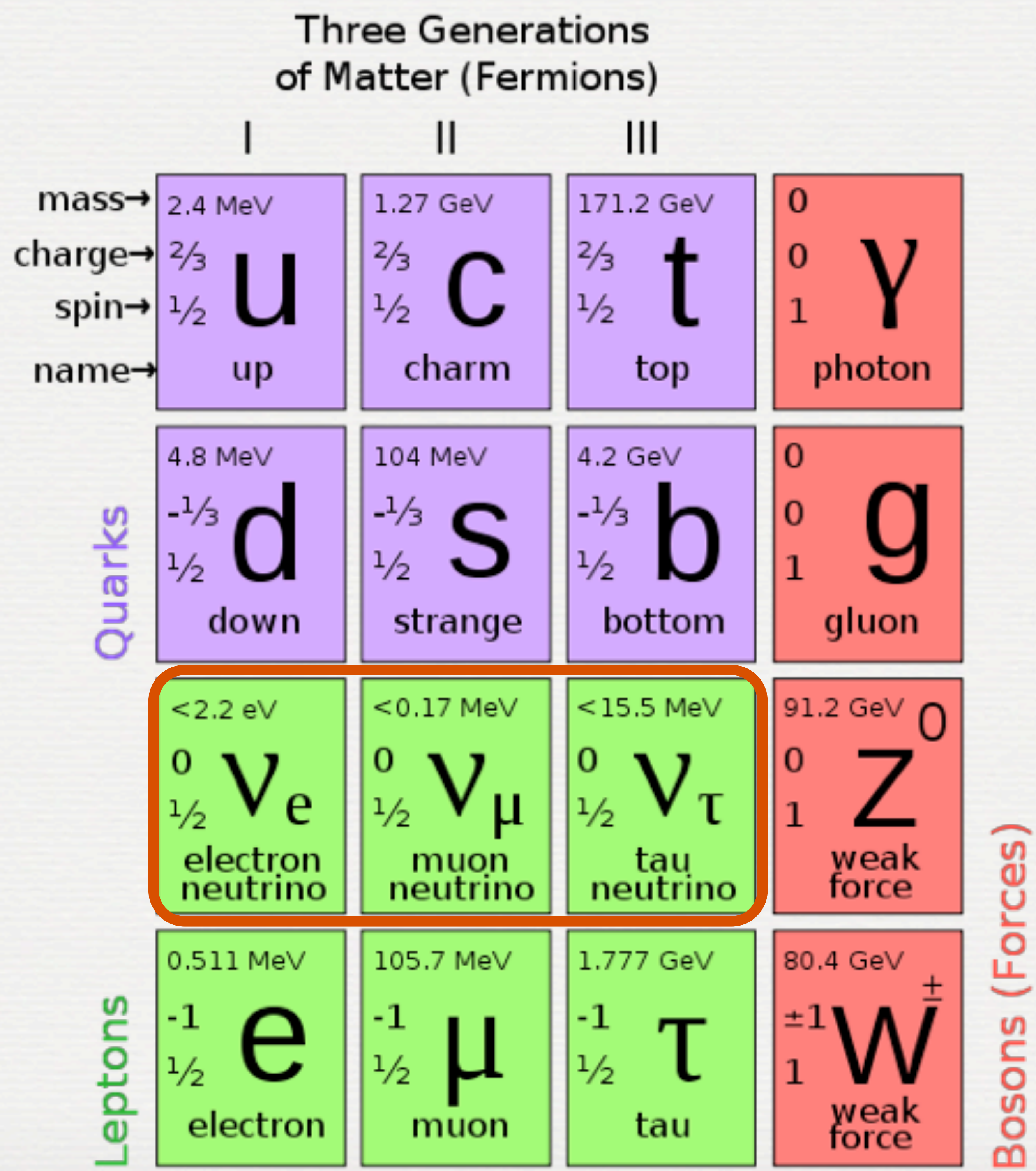
1899: Beta decay is discovered

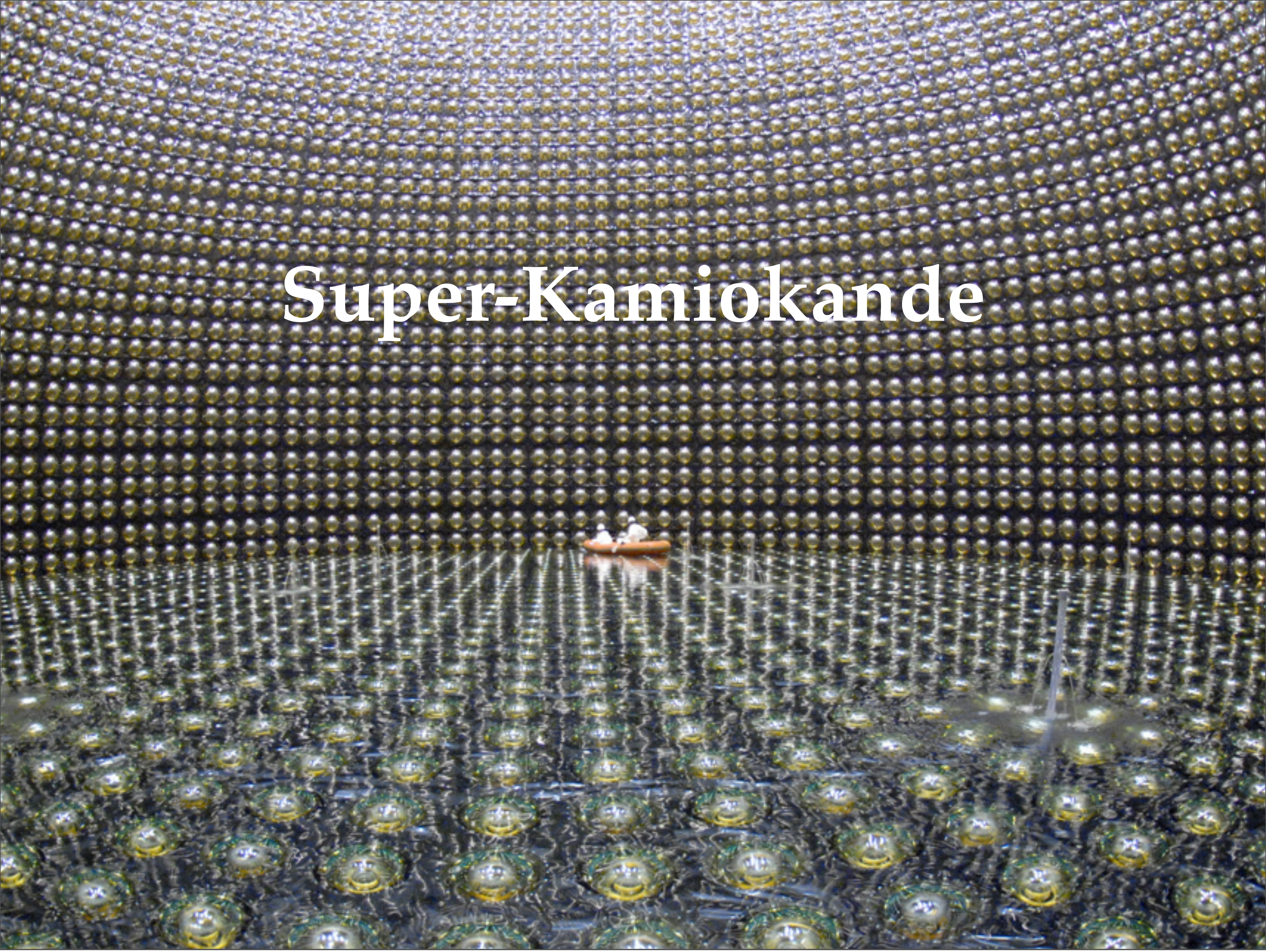
1959: First measurement of the (anti)neutrino

2000: The tau neutrino is discovered

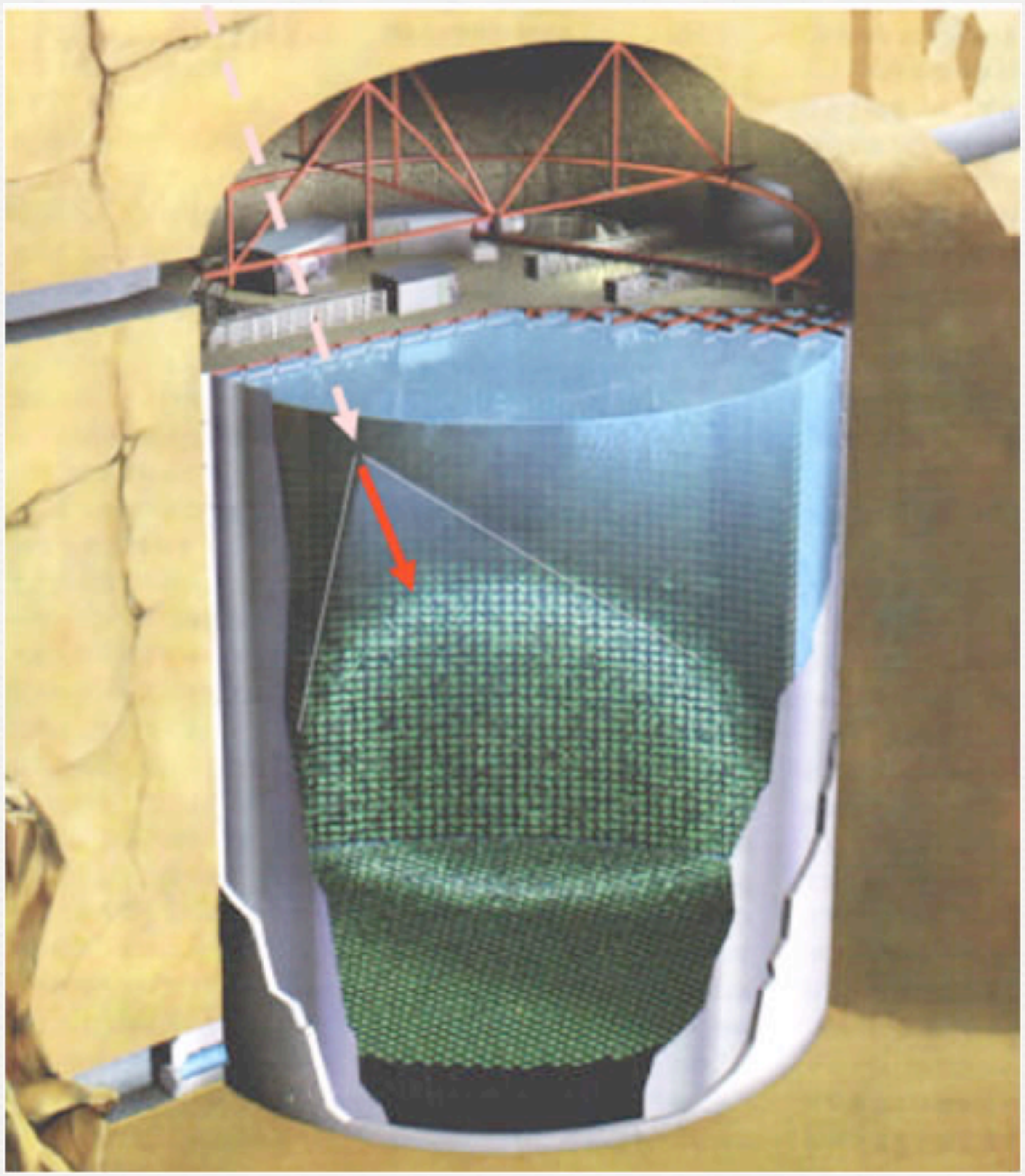


# NEUTRINOS: LIGHT NEUTRAL LEPTONS




Super-Kamiokande

# THE SUPER-KAMIOKANDE DETECTOR



- Located near Toyama, Japan
- 22.5 kton fiducial volume
- Optically separated into inner and outer volumes
- 11,146 20" PMTs (ID) + 1885 8" PMTs (OD)

# SUPER-KAMIOKANDE RUN PERIODS

SK-I (1996-2001)

- Ended with an accident that destroyed ~7000 of the phototubes

SK-II (2003-2005)

- Surviving phototubes + spares (about half the original photocoverage)

SK-III (2005-2008)

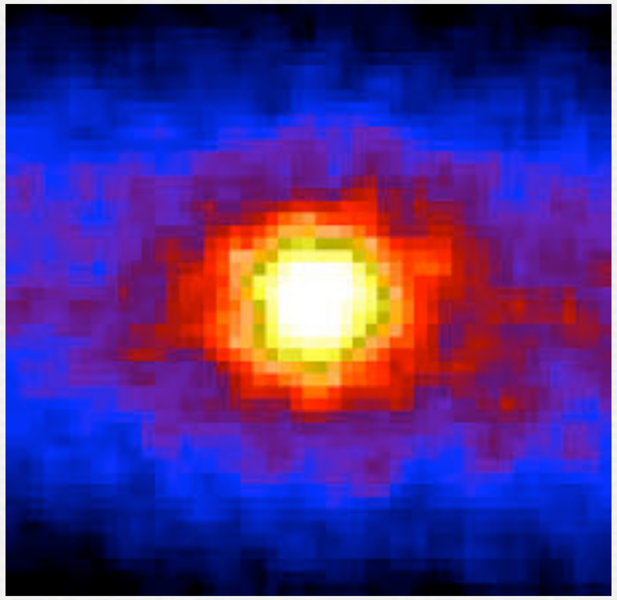
- Refurbish detector to the original photocoverage of SK-I

SK-IV (2008-present)

- New DAQ system which had a larger dynamic range for PMT charge

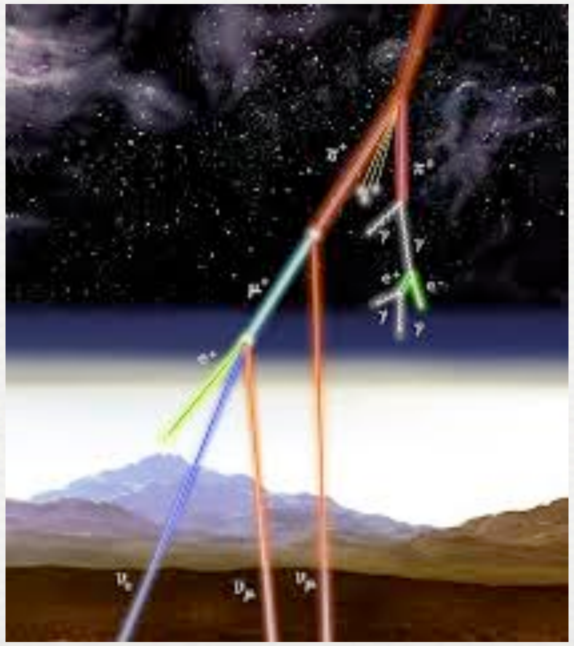
# SUPER-KAMIOKANDE PHYSICS GOALS

Solar neutrinos

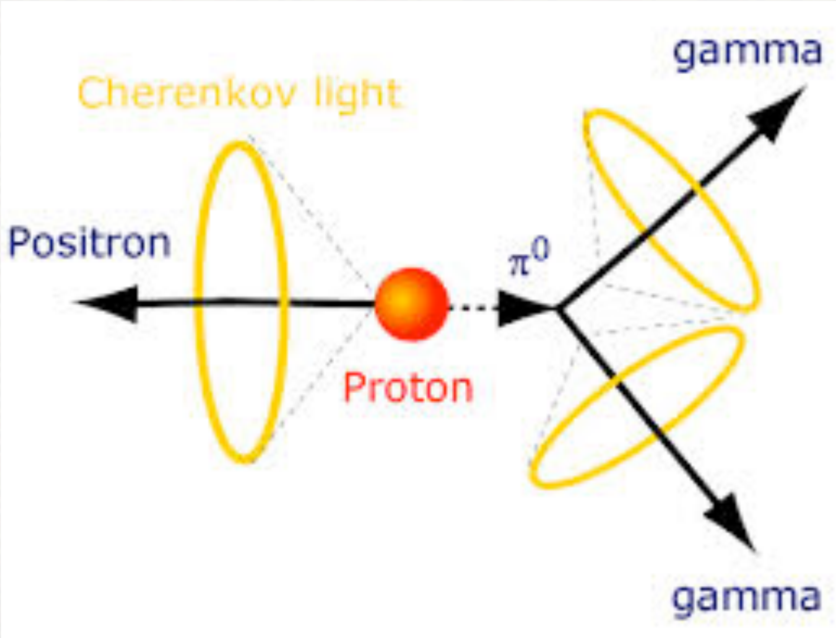


Supernova neutrinos

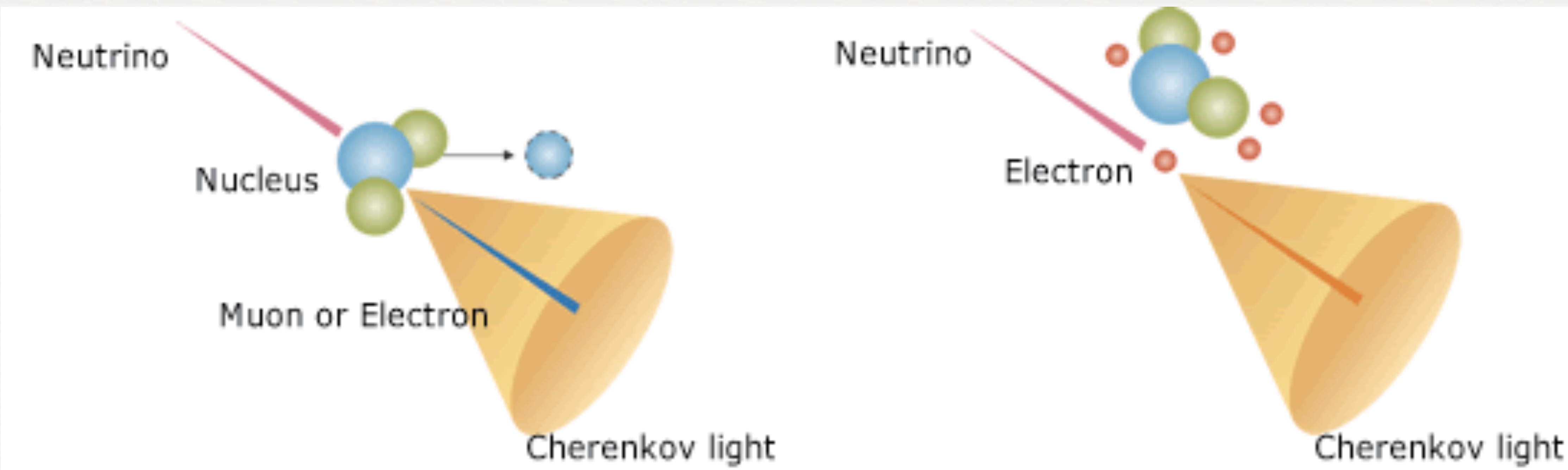
Atmospheric neutrinos



Proton decay

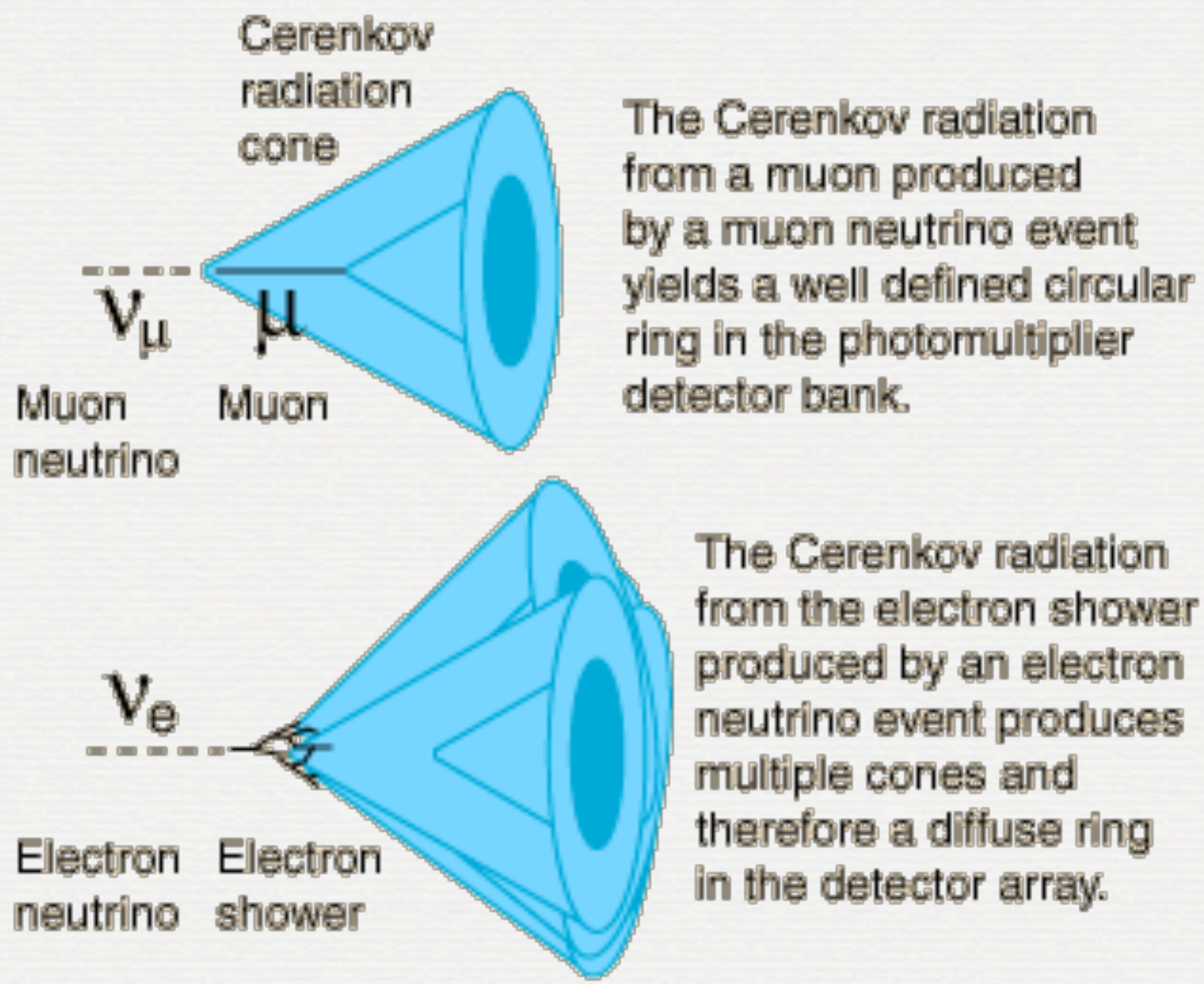


# DETECTING NEUTRINOS IN WATER

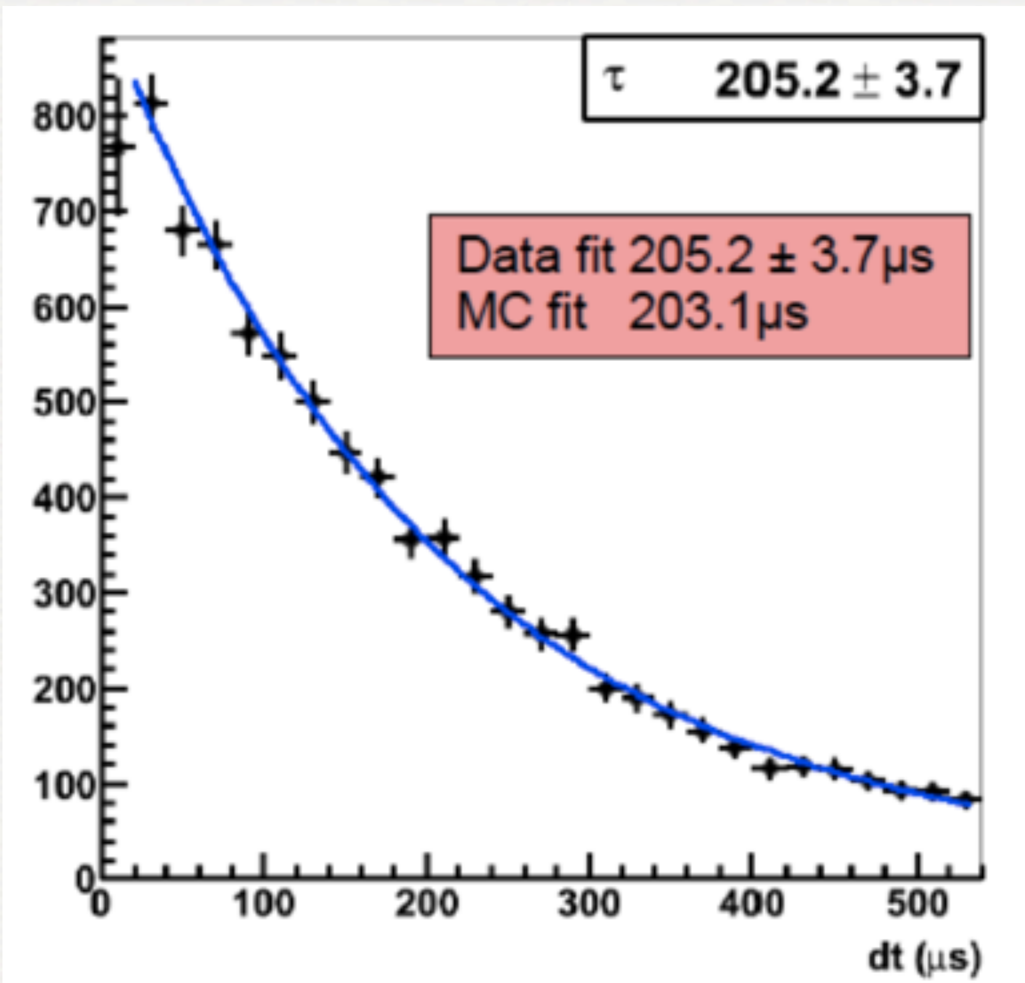



The generated charged particle emits the Cherenkov light.

# PARTICLE ID IN SUPER-KAMIOKANDE

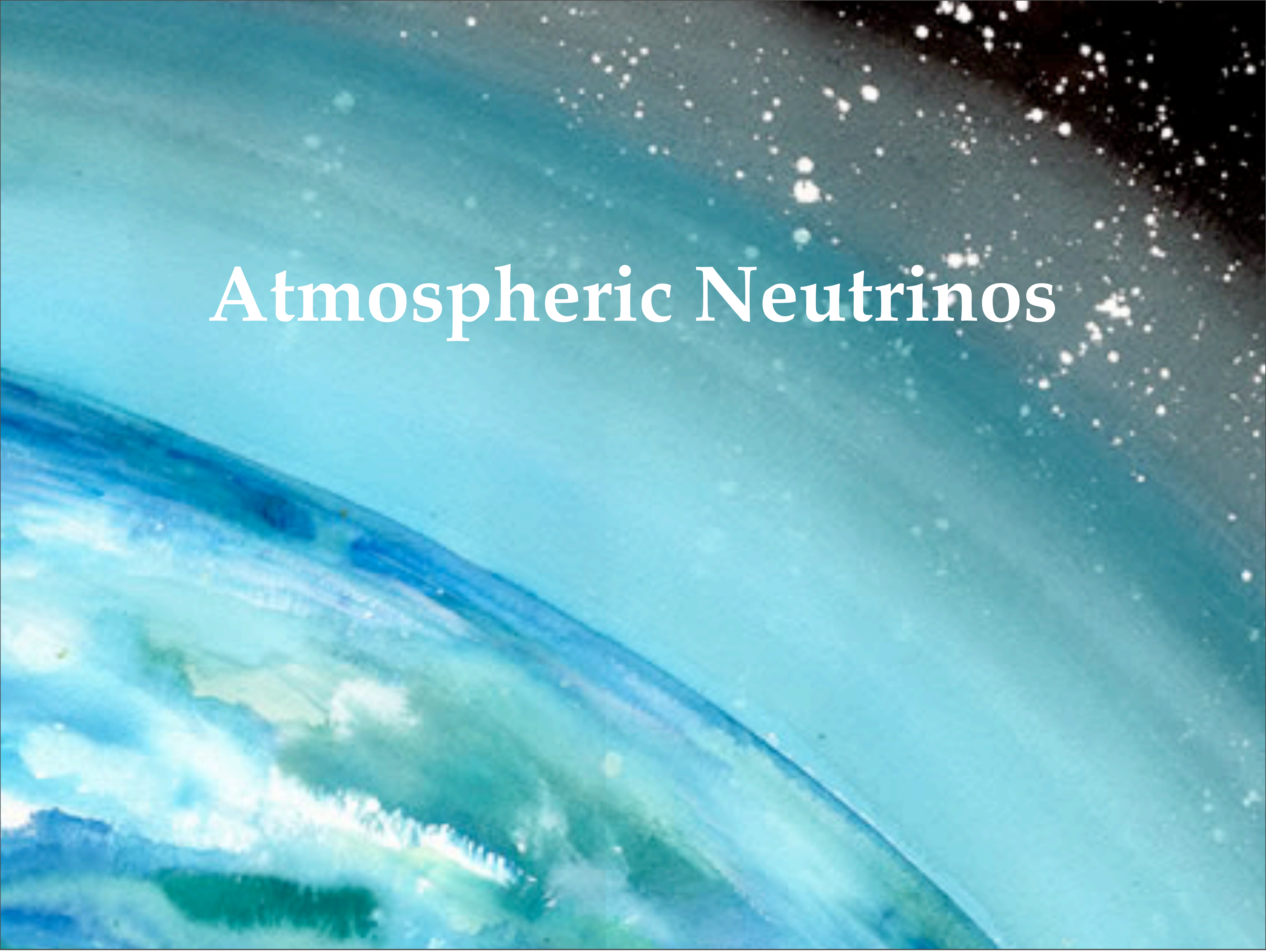


# NEUTRON TAGGING IN SUPER-KAMIOKANDE



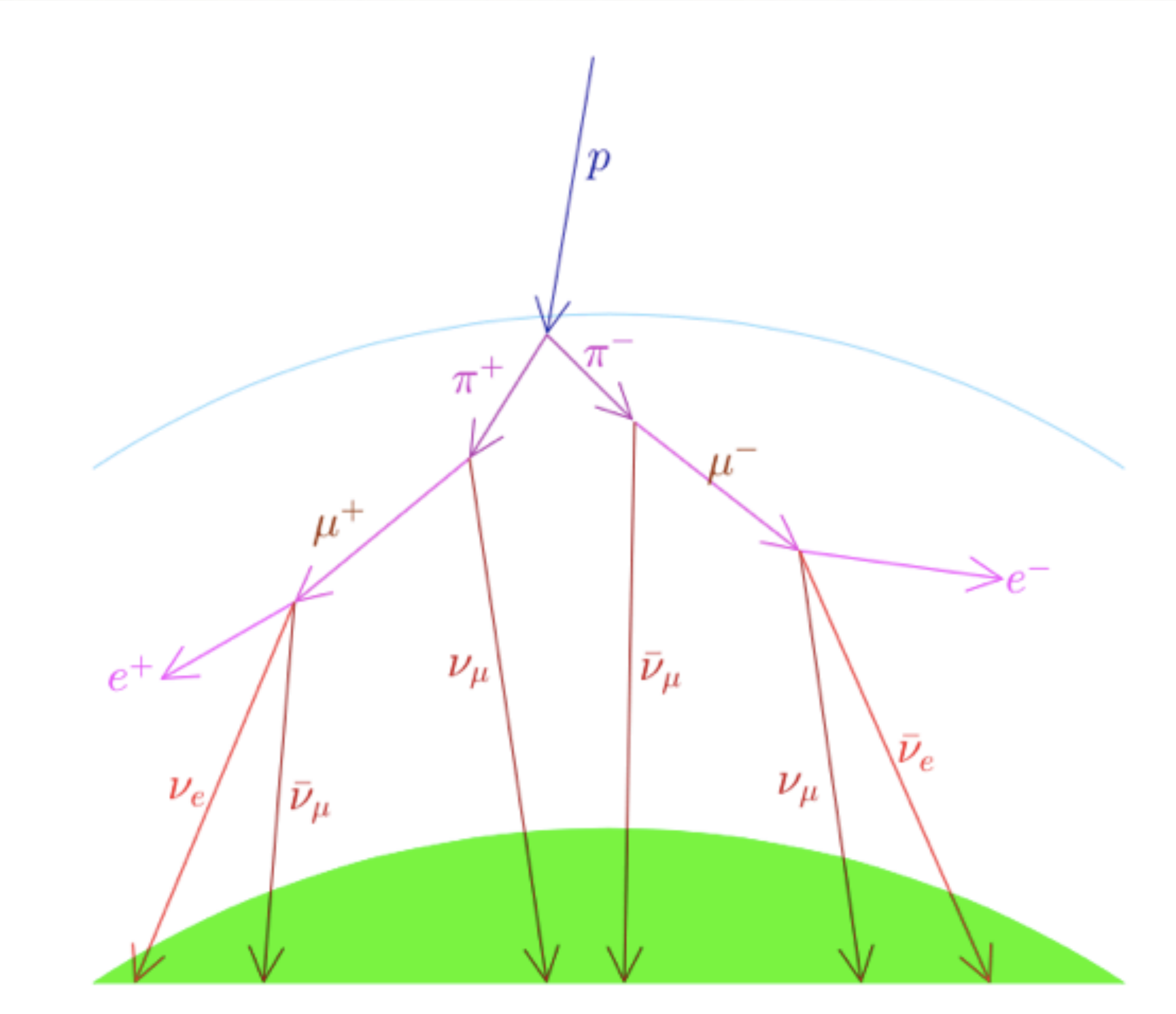

- In SK-IV, we record events 500 microseconds from a trigger
- Search for 2.2 MeV gamma from neutron capture on Hydrogen
- Efficiency ~20%

# Atmospheric Neutrinos



# ATMOSPHERIC NEUTRINOS

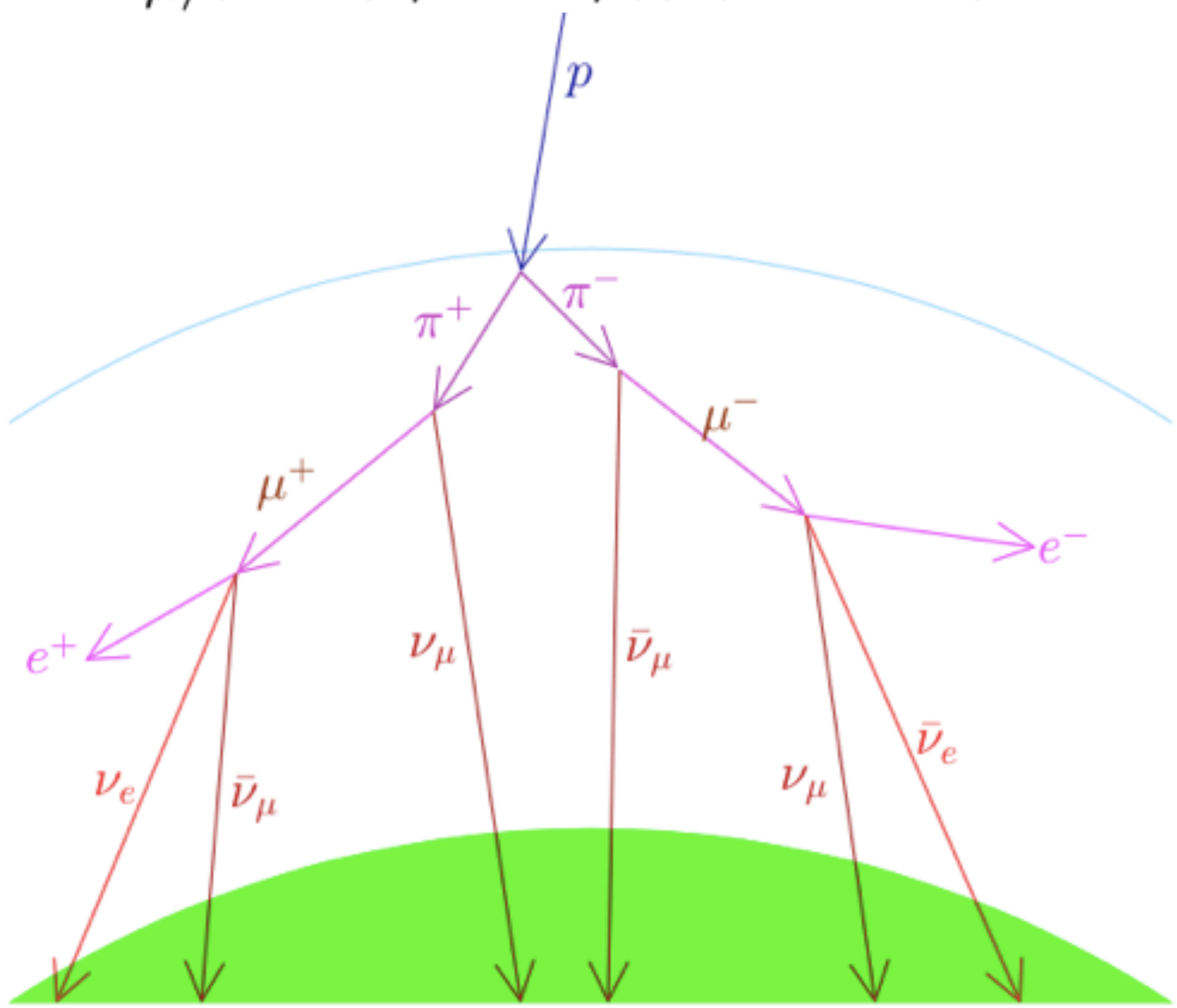
**Atmospheric neutrinos are produced from protons in our atmosphere**



# ATMOSPHERIC NEUTRINO OSCILLATIONS

**Pions produce a set ratio of neutrinos in cosmic ray interactions**

$$R_{\mu/e} \equiv (\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) \simeq \mathbf{2}$$




1998: Super-Kamiokande published a paper (Phys. Rev. Lett. 81 (1998) 1562-1567) that showed:

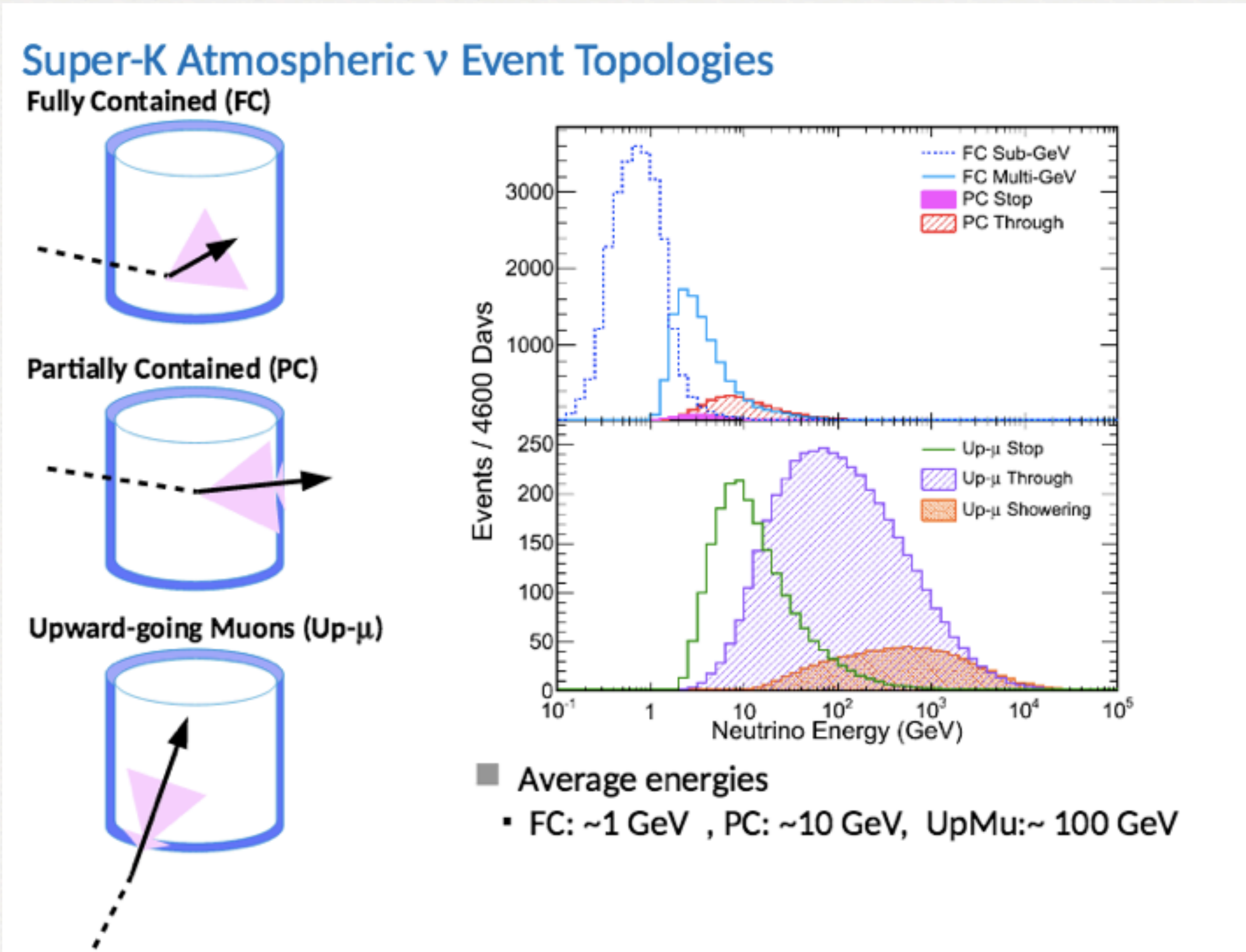
**- the ratio they measure is less than 2** ($R_{data}/R_{expected} \simeq 0.6$)

**- the discrepancy was dependent on neutrino path length** (neutrinos entering the bottom of the detector vs. the top of the detector)

- that the missing neutrinos were muon type neutrinos

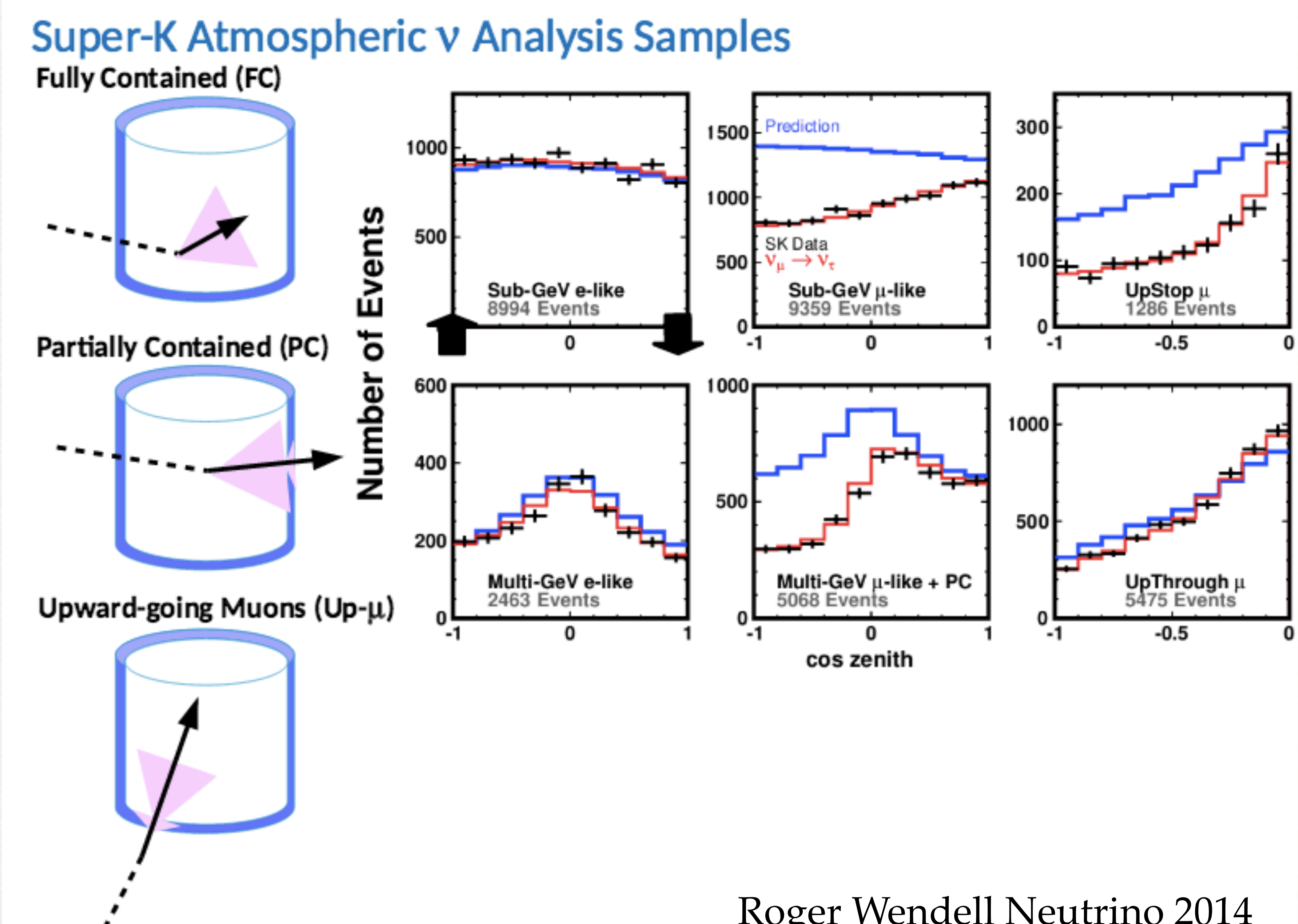
**The paper concluded that the behaviour fit all the hallmarks of neutrino oscillation and they calculated a best fit value for $\nu_\mu \rightarrow \nu_\tau$ mixing parameters**

# CLASSIFYING ATMOSPHERIC EVENTS



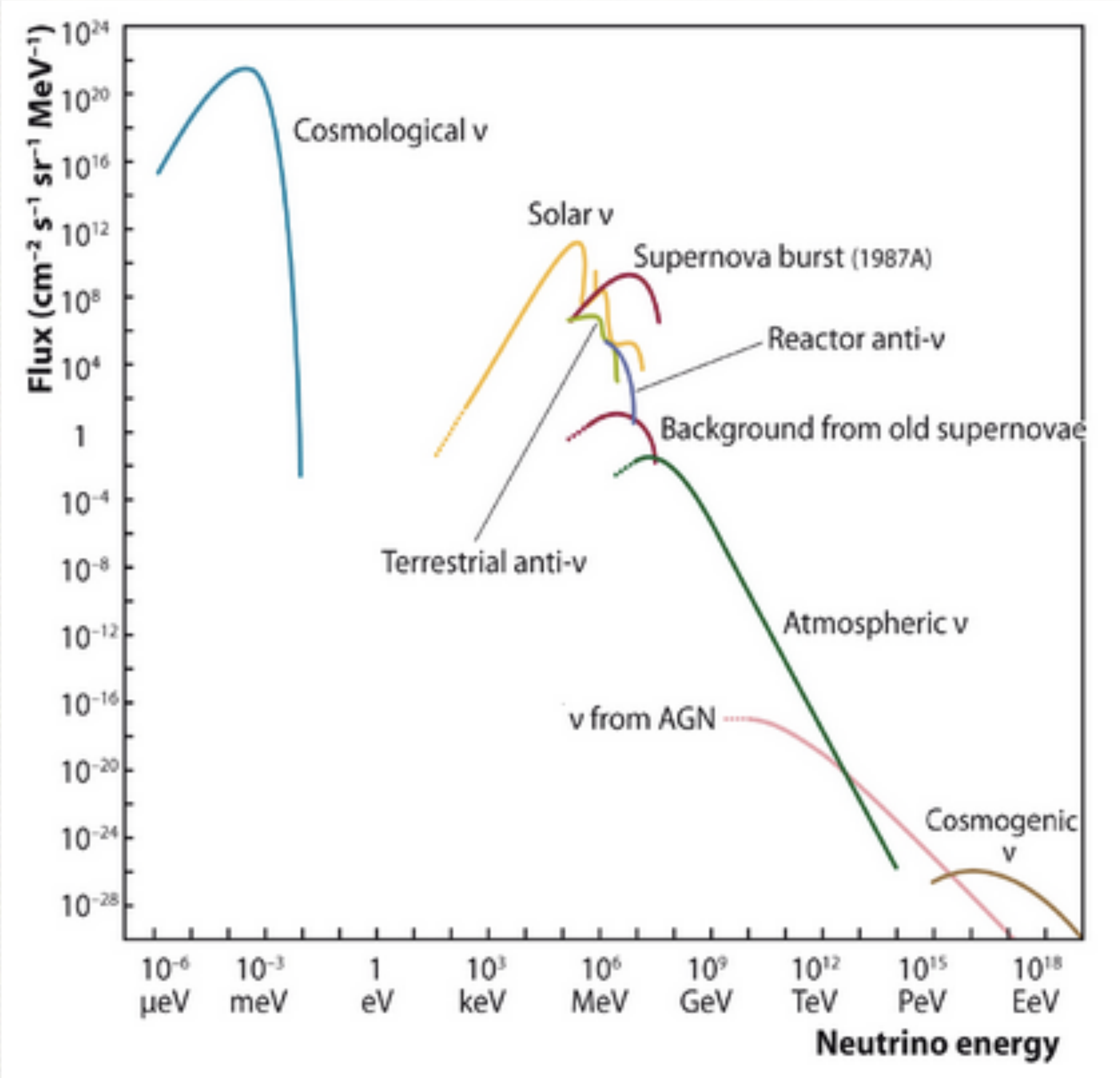

Roger Wendell Neutrino 2014

# CLASSIFYING ATMOSPHERIC EVENTS




Roger Wendell Neutrino 2014

# ATMOSPHERIC NEUTRINOS AS A BACKGROUND FOR ASTROPHYSICAL NEUTRINOS

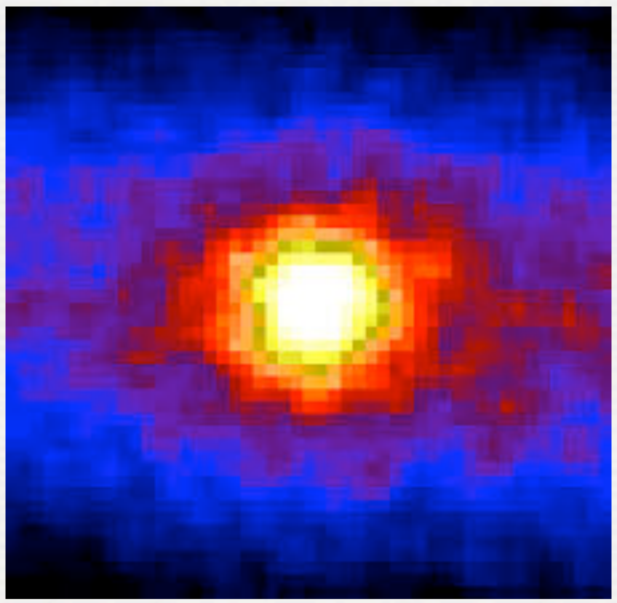


# Astrophysical Neutrinos

# SOURCES OF ASTROPHYSICAL NEUTRINOS

**Known sources**

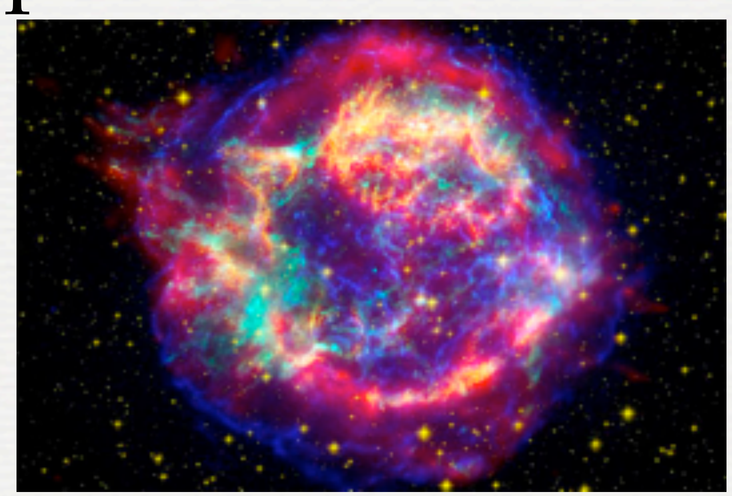
Sun



Supernovae

GRBs

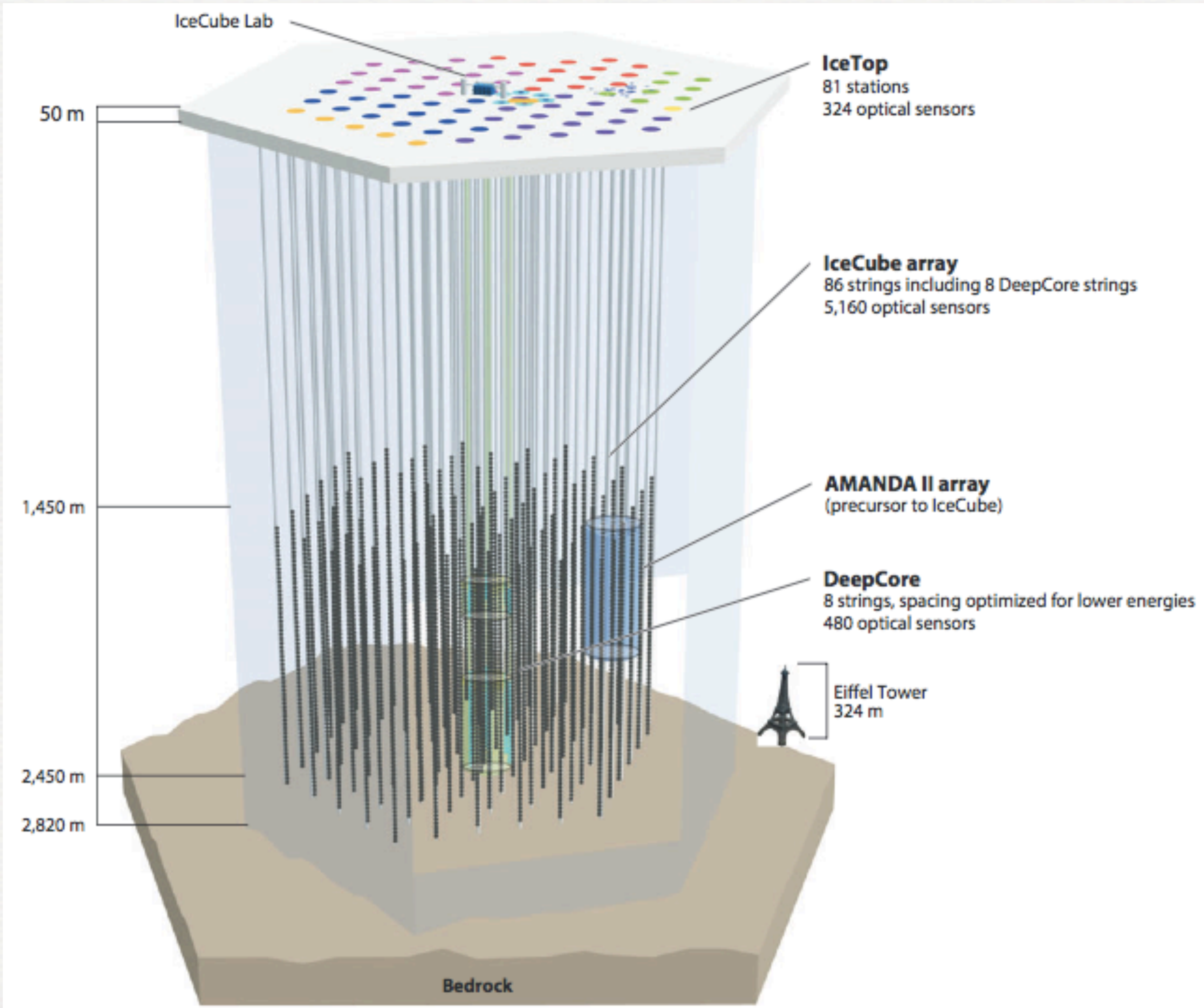
Supernova remnants



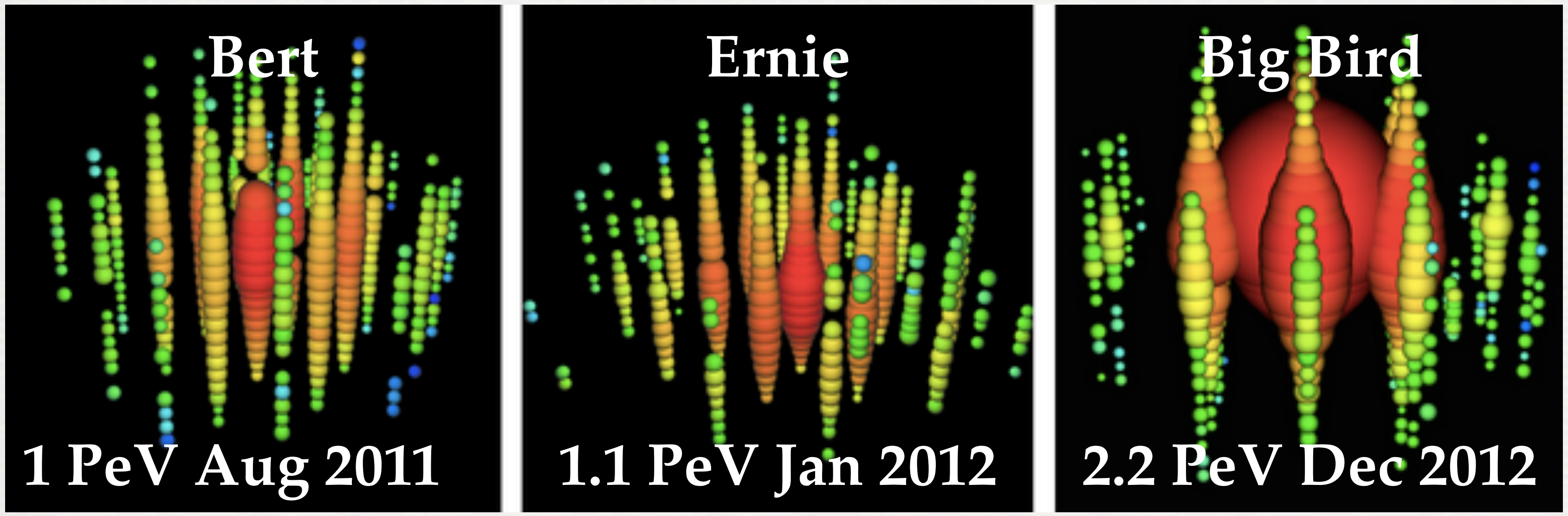
Magnetars

Active galactic nuclei

# ASTROPHYSICS WITH ICECUBE

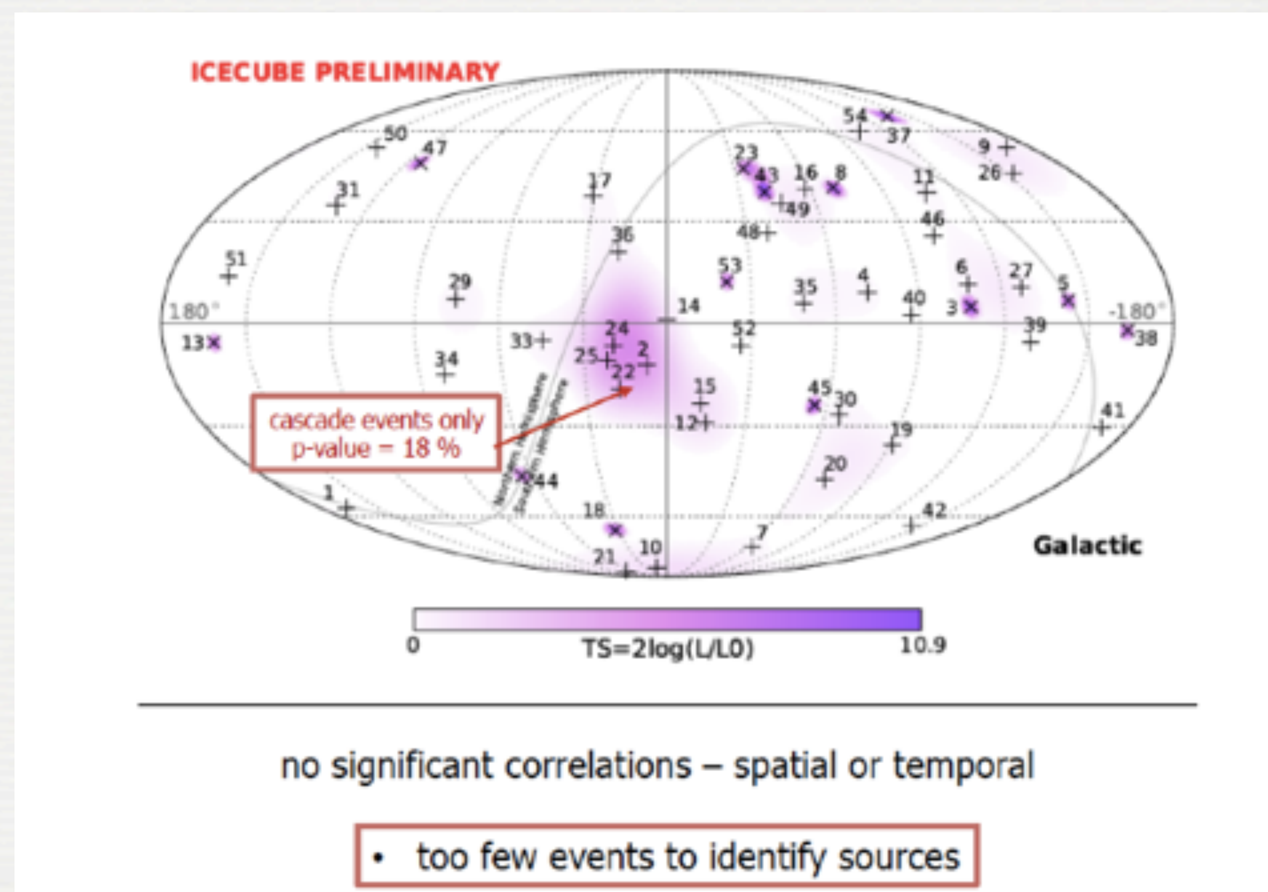


# ASTROPHYSICS WITH ICECUBE

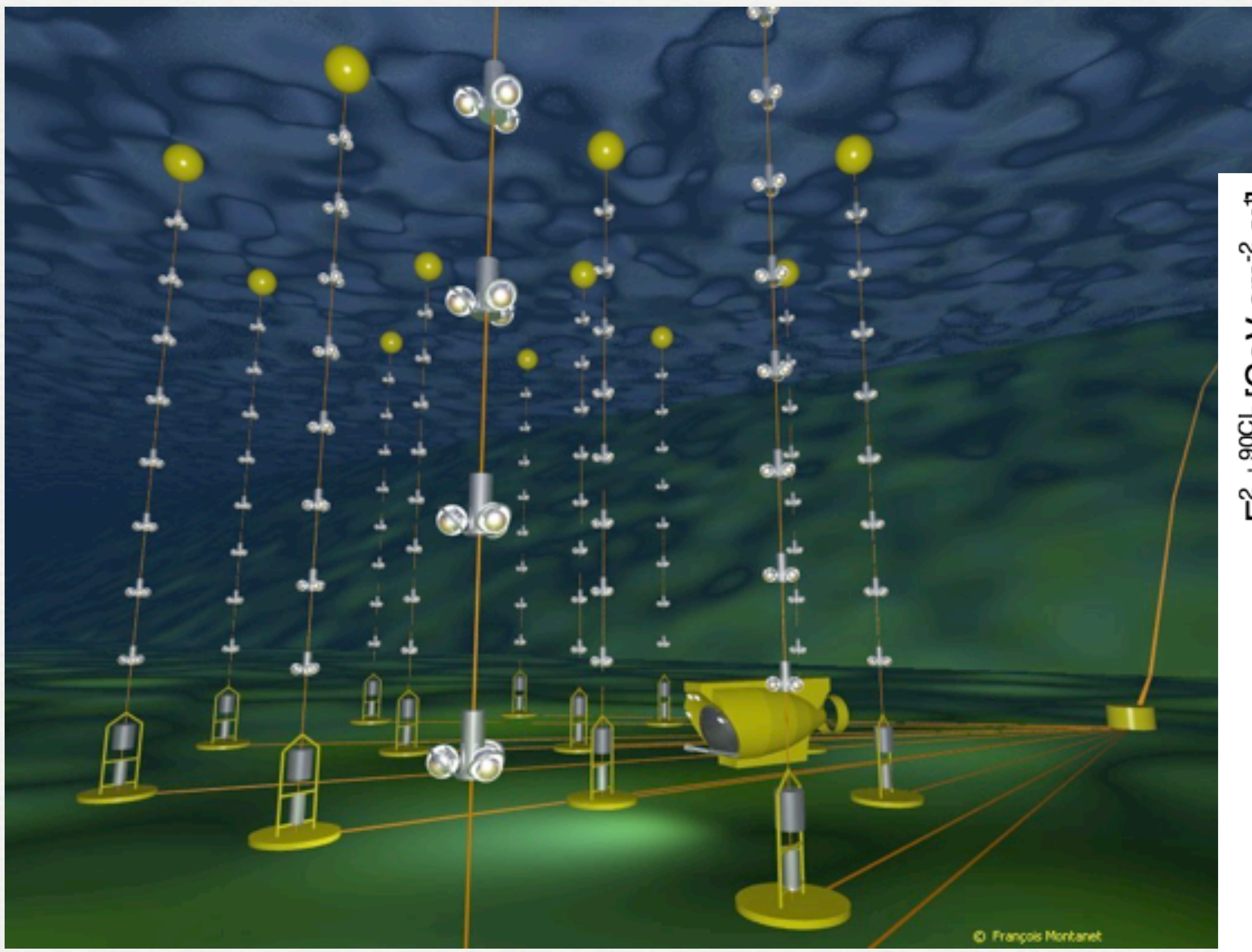


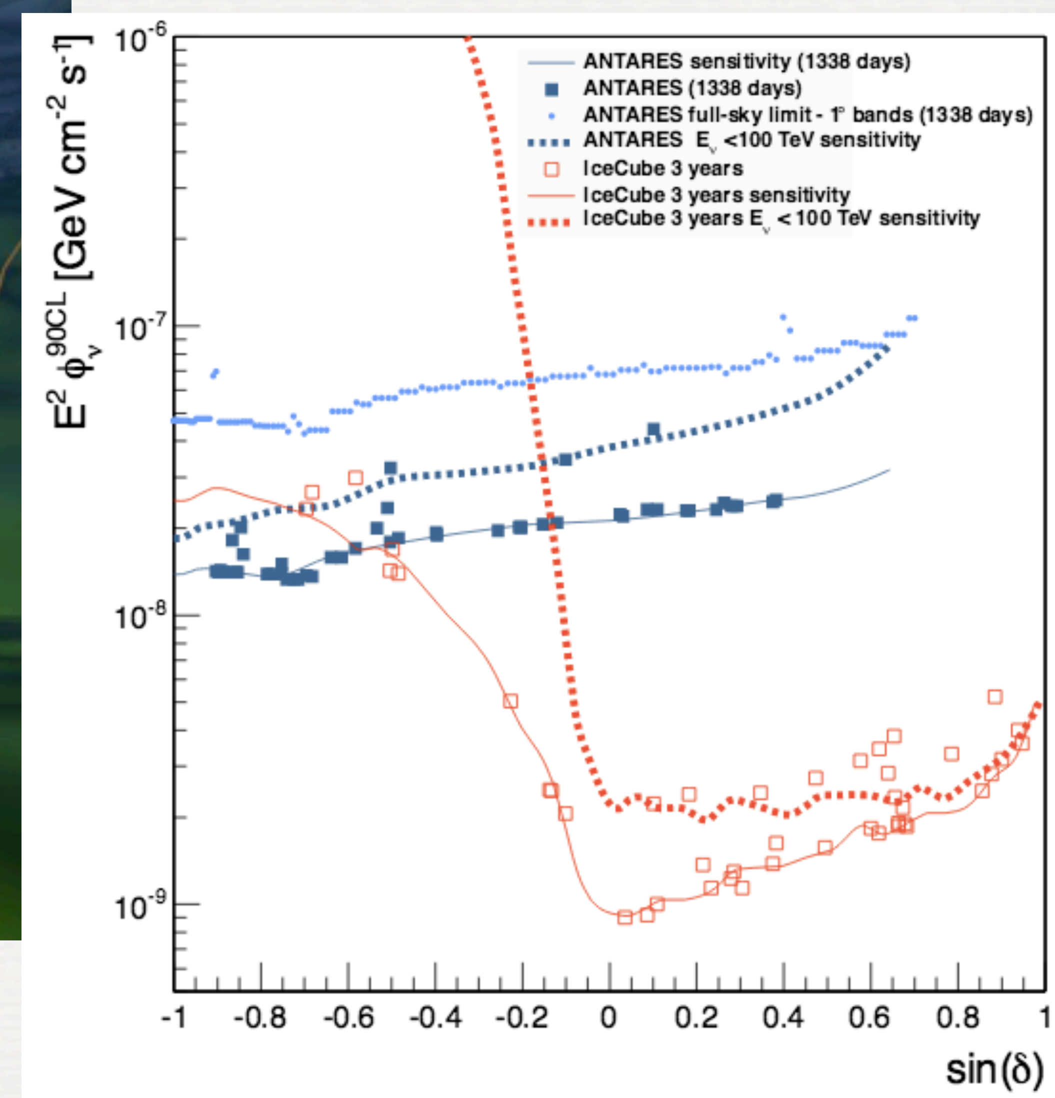

Highest energy neutrinos ever measured

Any significant clustering?
Not yet, need more statistics.



# ASTROPHYSICS WITH ANTARES

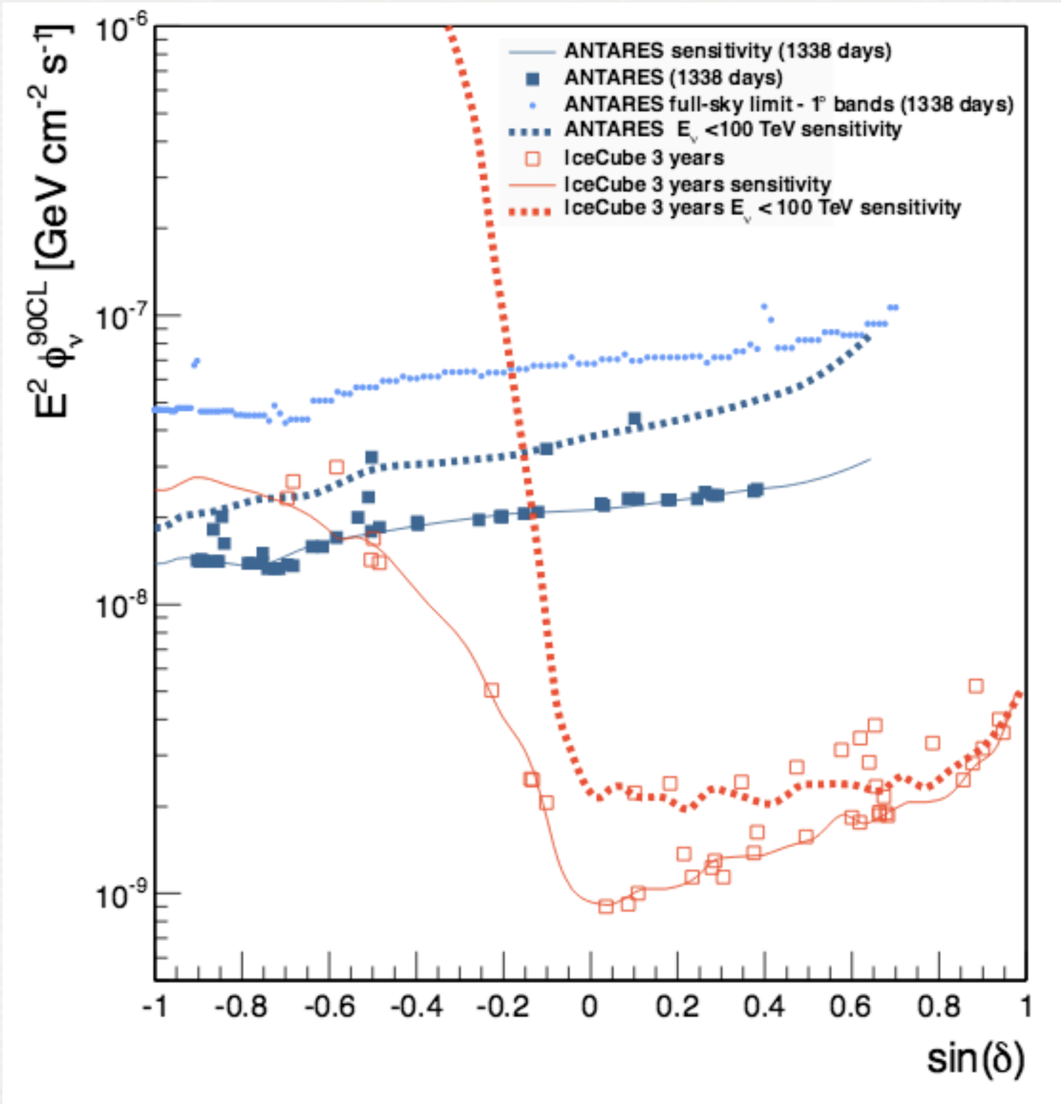



Antares 2015 arXiv: 1402.6182

# WHERE DOES SK FIT IN?

- SK is mainly sensitive to Southern hemisphere events (unlike IceCube). This includes the Galactic centre.
- SK is more sensitive to the lower energy (tens of GeV) than either IceCube or Antares

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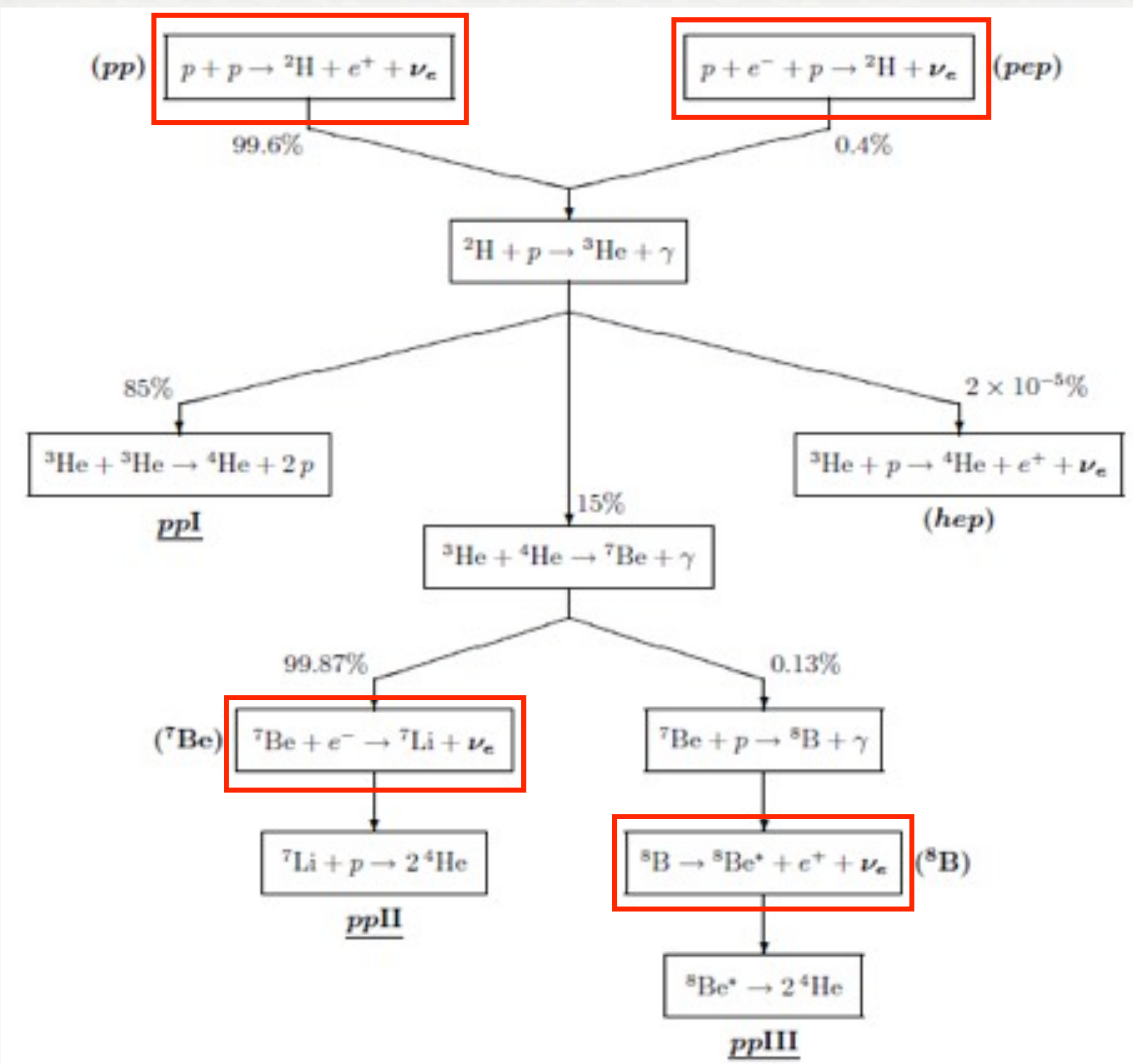
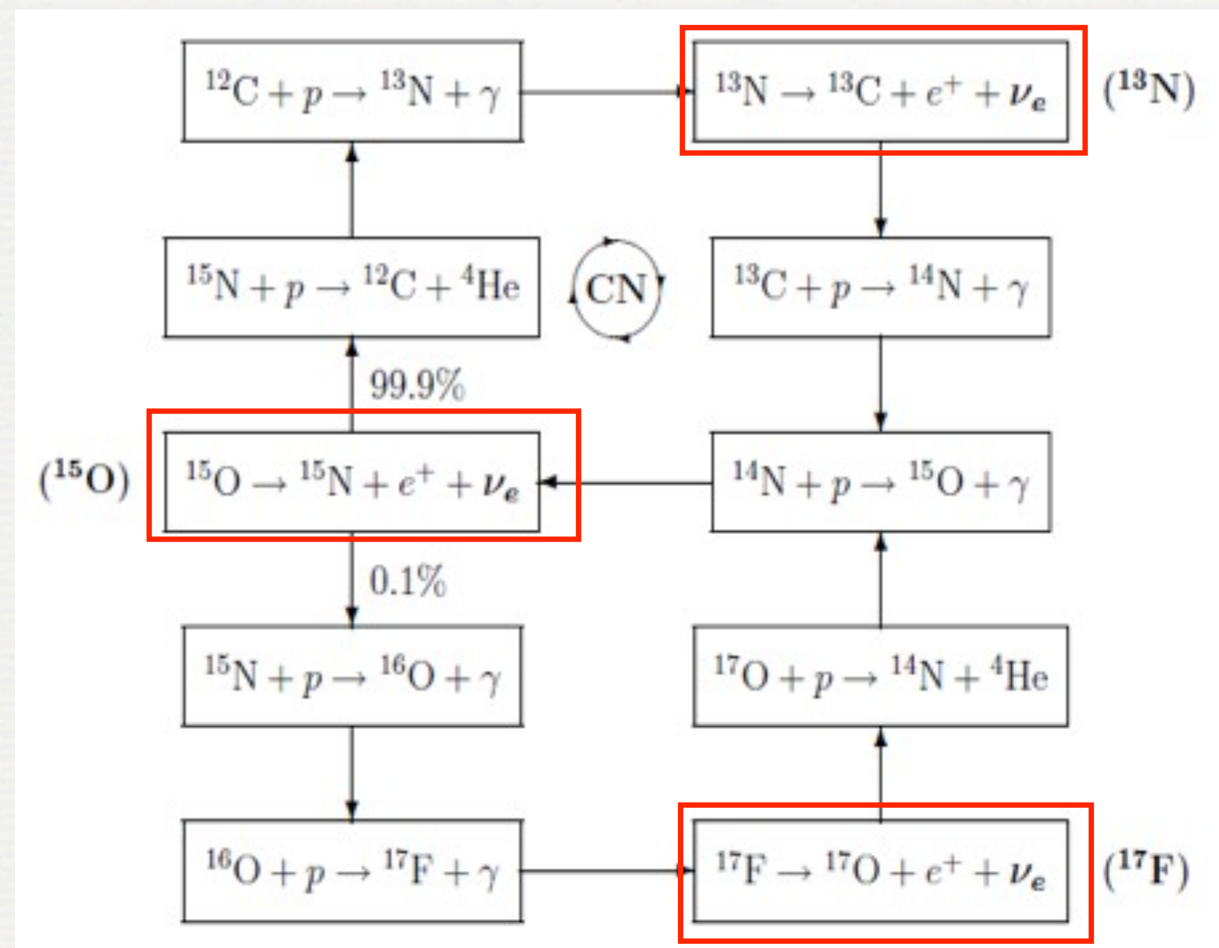
# SOLAR NEUTRINOS

Produced in the thermonuclear reactions in the Sun

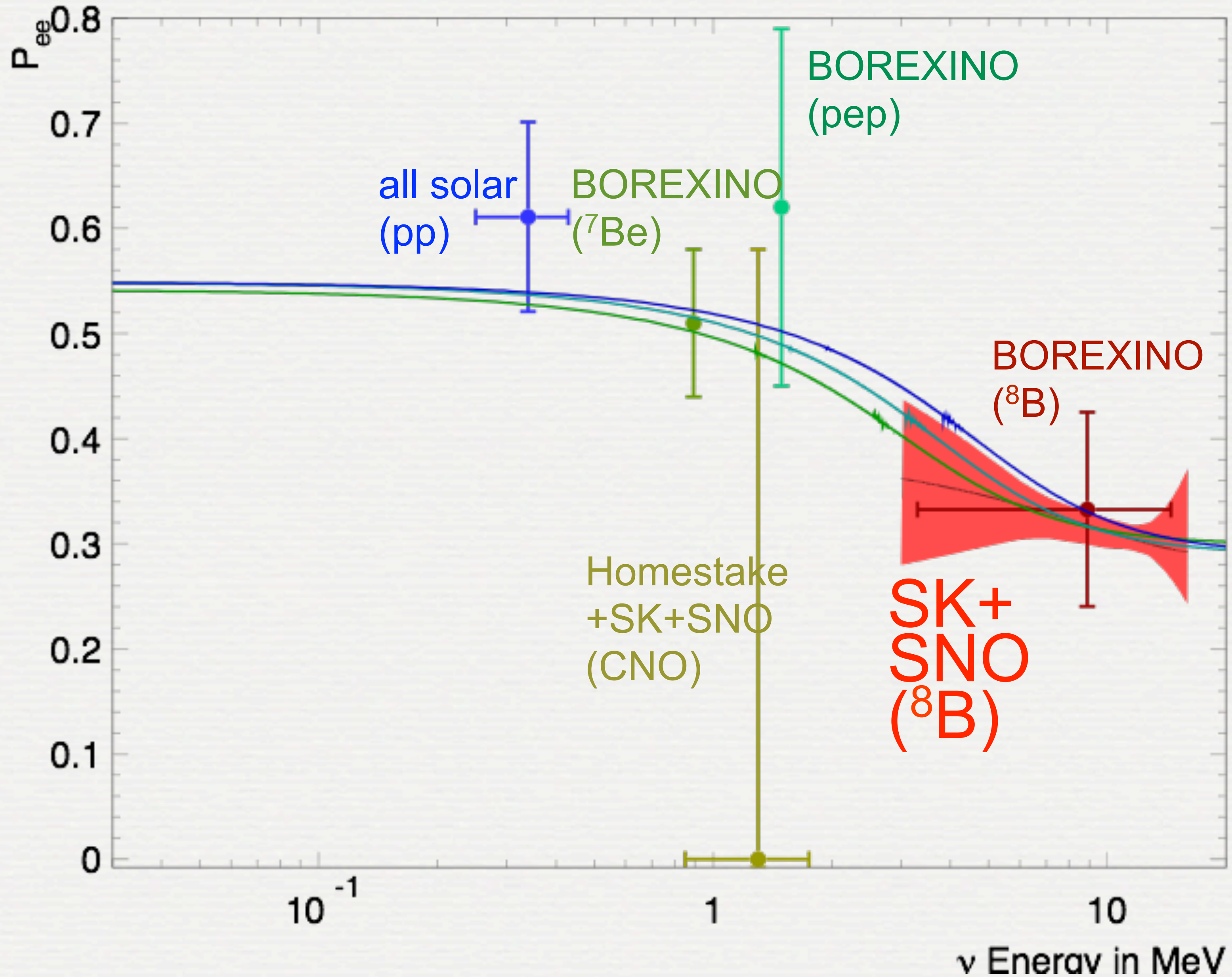
pp chain




CNO cycle

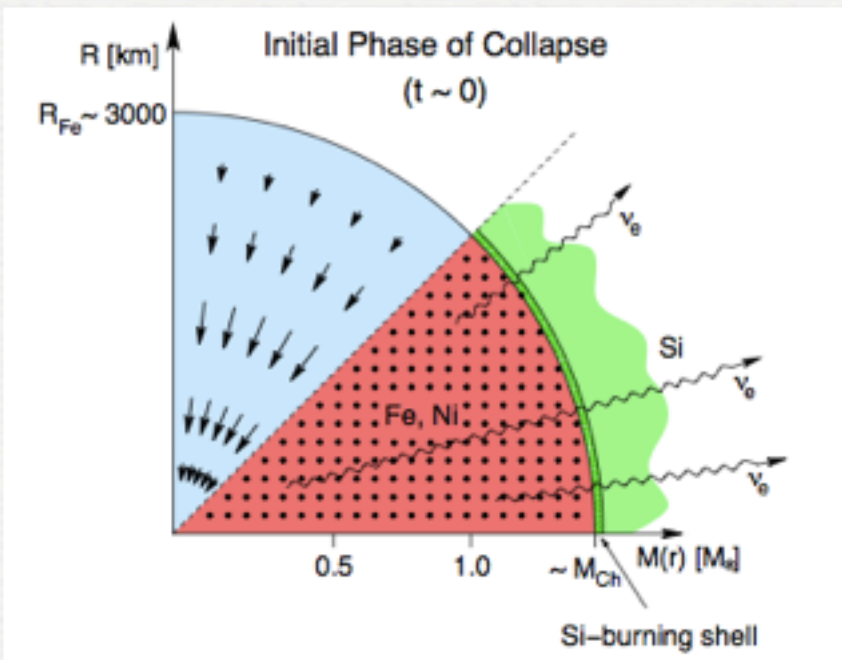


# SOLAR NEUTRINOS IN SK



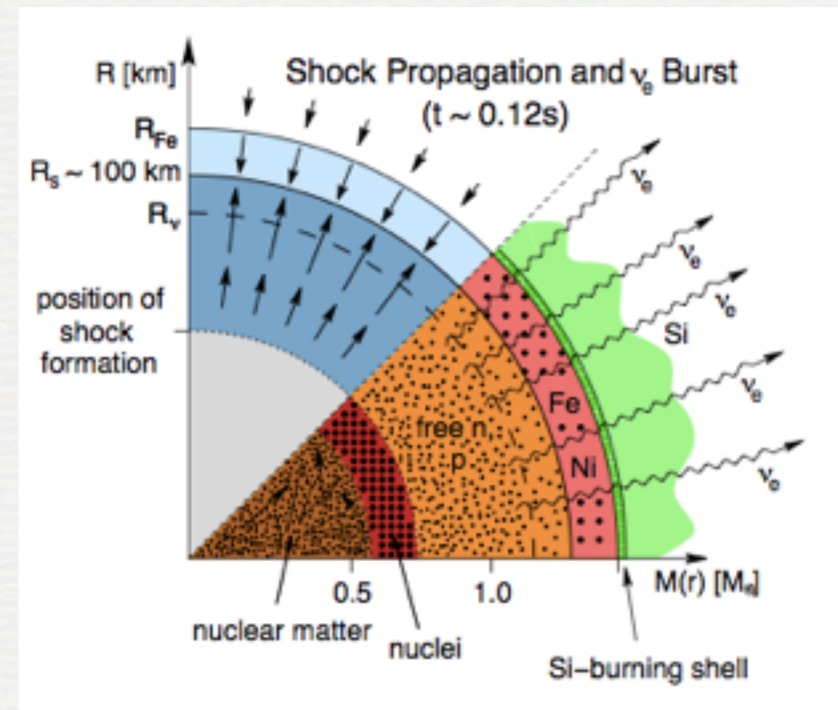
# SUPERNOVA NEUTRINOS

## Infall

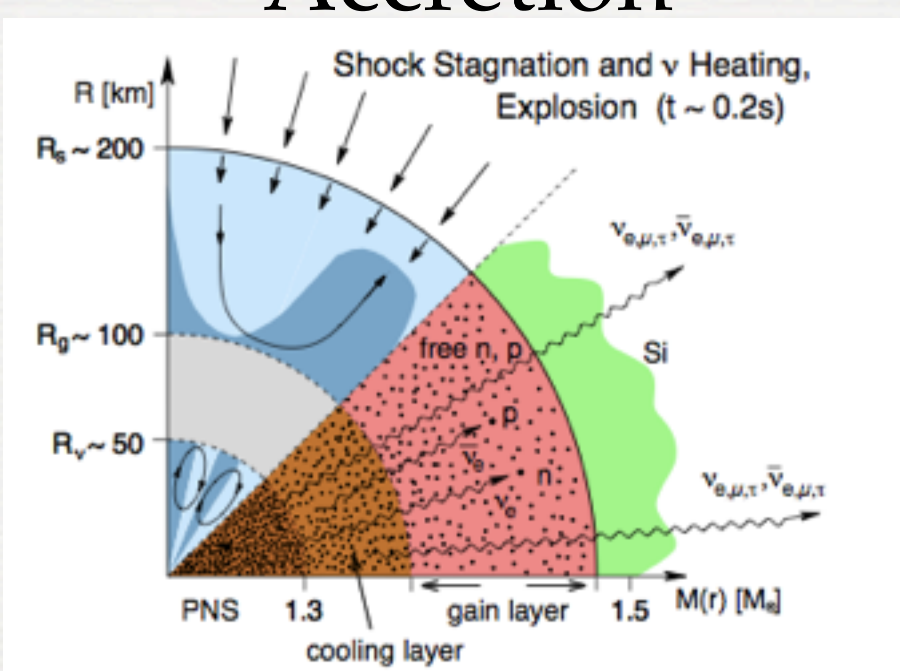



$$p + e^- \rightarrow n + \nu_e$$

## Neutronization burst




## Accretion

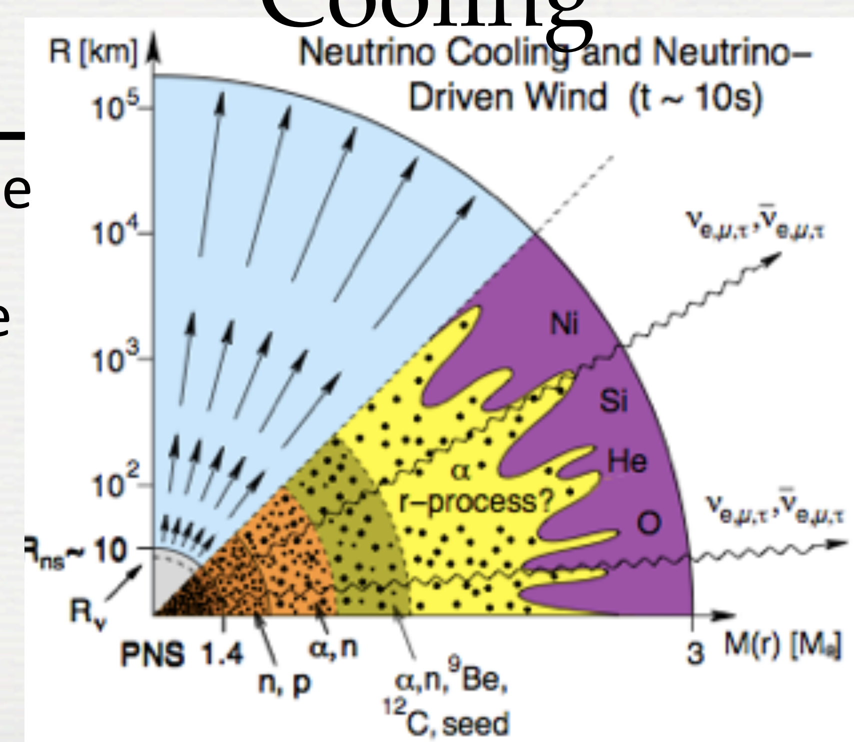



$$n + e^+ \rightarrow p + \bar{\nu}_e$$

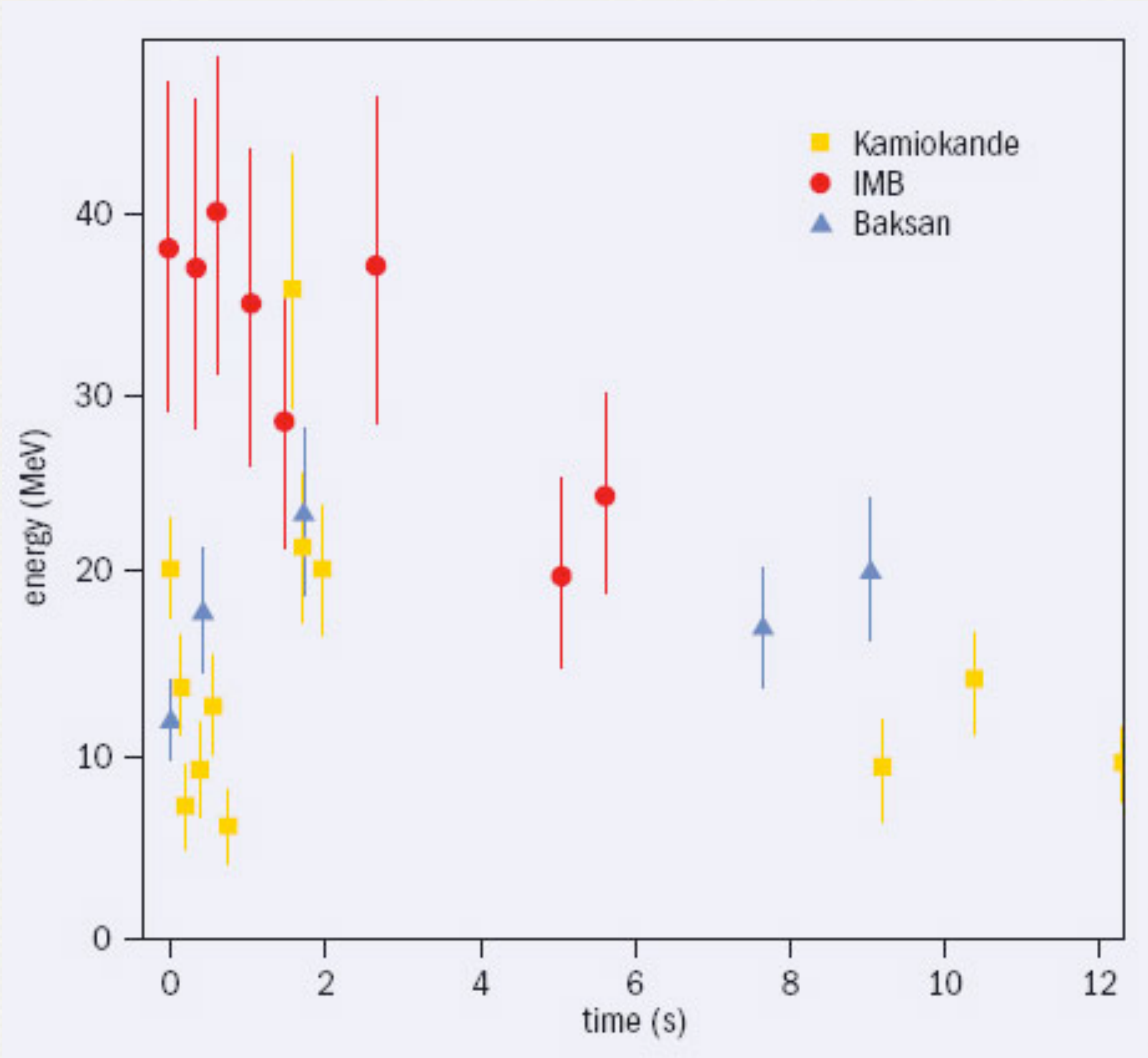
$$p + e^- \rightarrow n + \nu_e$$

$$e^+ + e^- \rightarrow \nu + \bar{\nu}$$

## Cooling



# SUPERNOVA NEUTRINOS IN (S)K



# SUPERNOVA NEUTRINOS IN (S)K

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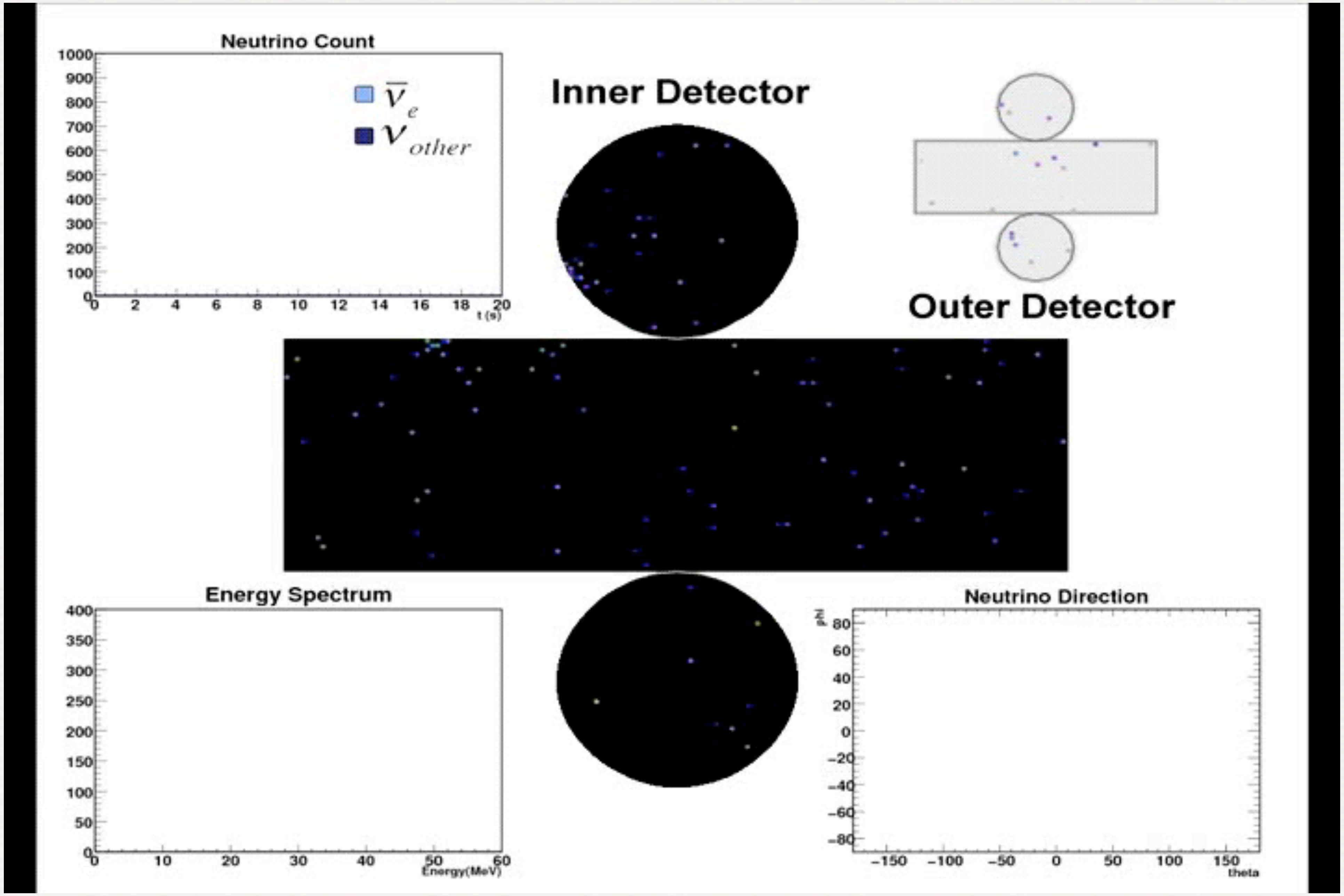
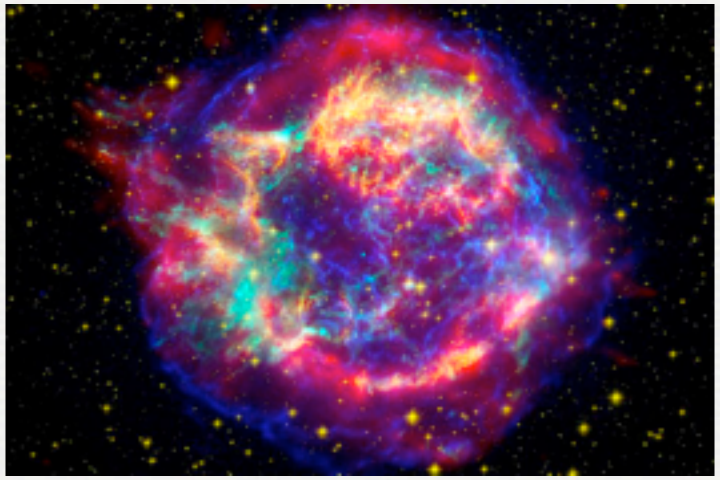


# OTHER EXOTIC SOURCES

Supernova remnants



GRBs

Magnetars

Active galactic nuclei

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

- Step 1: Pick a search direction
- Step 2: Define a cone of 8° around the search direction. (This is large enough to encompass the expected spread of events from a single astro source. )
- Step 3: Record number of events in the search cone, along with their characteristics (angle from search direction, showering/nonshowering).
- Step 4: Perform max likelihood calculation (more about this later).
- Step 5: Choose another search direction. Thrane 2009 used 0.5° steps.

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

$$\underbrace{P}_{\text{Total Probability}} = \underbrace{\alpha}_{\text{Signal strength}} \underbrace{S}_{\text{Describes a signal event}} + (1-\alpha) \underbrace{B}_{\text{Describes a background event}}$$

**Total Probability** — P

**Signal strength** — α

**Describes a signal event** — S

**Describes a background event** — B

**α is the probability an event is due to signal**

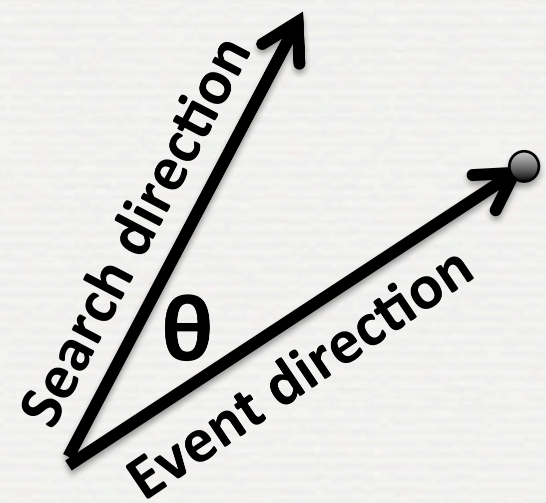
# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

SK Period

Showering/ nonshowering

$$S=S(\theta|m,n,dec)$$

**Point spread function**




**Allows you to characterize the signal as clustered events (vs. background events which are more diffuse)**

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

SK Period

$$S = \underbrace{S(\theta | m, n, dec)}_{\text{Point spread function}} \underbrace{S(n | m, dec)}_{\text{Prob of obs. showering/nonshowering event type (n)}}$$

**Point spread function**

**Prob of obs. showering/ nonshowering event type (n)**

**Allows you to characterize the signal in energy (if you assume signal events are higher in E -> more chance of showering)**

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

**Prob of obs. event in SK phase m**

$$S = S(\theta|m,n,dec)\,S(n|m,dec)\,S(m)$$

**Point spread function** — $S(\theta|m,n,dec)$

**Prob of obs. showering/ nonshowering event type (n)** — $S(n|m,dec)$

**Allows you to consider relative livetimes of SK phases (assumes constant source that would be visible over all phases)**

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

**Total Probability** **Signal strength** **Describes a background event**

$$\overbrace{P} = \overbrace{\alpha}\,\underbrace{S} + (1-\alpha)\,\overbrace{B}$$

**Describes a signal event**

**Likelihood to see N events with those characteristics**

$$\overbrace{L} = P_{poisson}\,\Pi_i^N\,P(\alpha)$$

# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

$$\mathfrak{L}_{(\alpha)} = \overbrace{\frac{e^{-\bar{N}_B/(1-\alpha)}}{N!}\left(\frac{\bar{N}_B}{1-\alpha}\right)^N}^{P_{poisson}} \Pi_i^N P(\alpha)$$

**This is the final likelihood function! Now vary α between 0 and 1 to maximize the likelihood.**

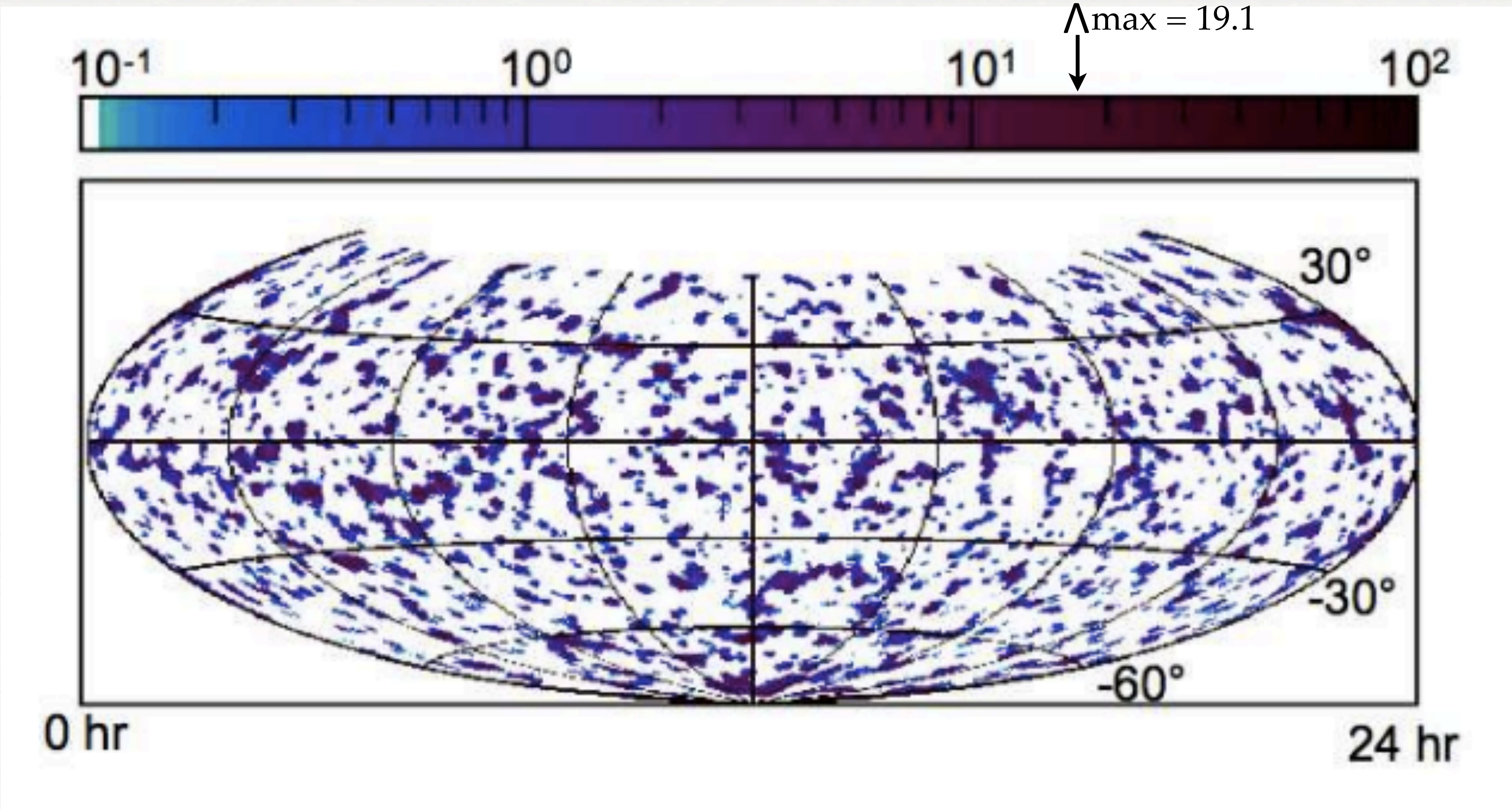
# HOW CAN YOU SEARCH FOR ASTROPHYSICAL NEUTRINOS?

$$\Lambda = 2\log(L(\alpha_{fitted})/L(\alpha=0))$$

**This is final test statistic that determines how much more likely our fitted α is compared with the background only scenario**

# SEARCH FOR OTHER ASTROPHYSICS IN SK

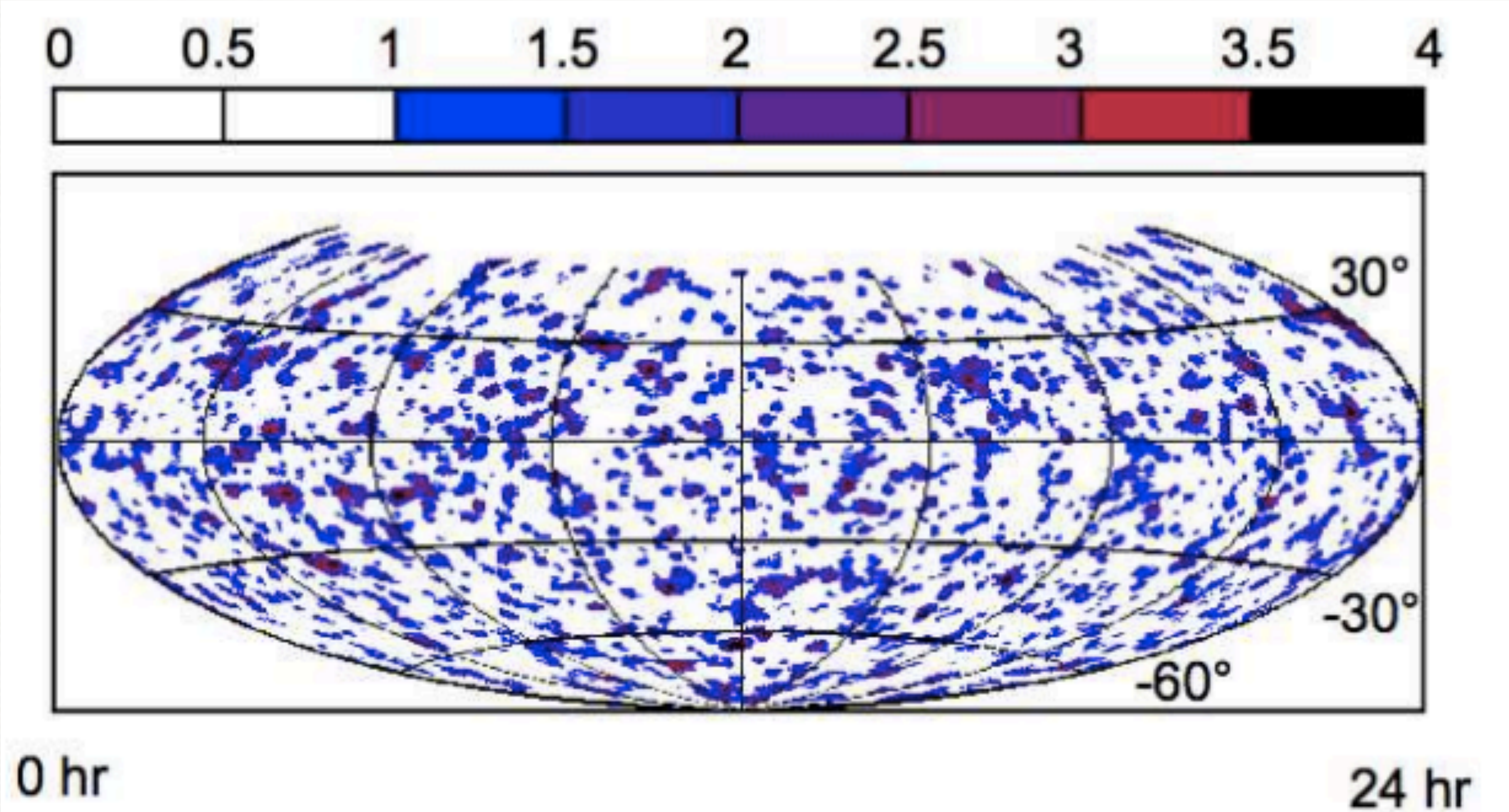
**Sky map of astrophysical neutrino likelihood (Λ) for UPMU neutrinos in SK**




**Thrane 2009 (arXiv 0907.1594v4)**

# SEARCH FOR OTHER ASTROPHYSICS IN SK

**Sky map of astrophysical neutrino significance (in units of σ) for UPMU neutrinos in SK**




**Thrane 2009 (arXiv 0907.1594v4)**

**No statistically significant source found.**

# SEARCH FOR OTHER ASTROPHYSICS IN SK

Thrane 2009 also looked at a catalogue of suspected candidates
- Found two statistically interesting (but not significant) sources: SNR RX J1713.7-3946 (97.5% CL) and GRB 991004D (95.3% CL)

| source | type | (ra,dec) | $\Phi_\nu^{90\%}$ (cm$^{-2}$s$^{-1}$) |
|---|---|---|---|
| SGR 1900+14 | mag | $(286.8^\circ, +9.3^\circ)$ | $1.12 \pm 0.12 \times 10^{-7}$ |
| SGR 0526-66 | mag | $(81.5^\circ, -66.0^\circ)$ | $1.15 \pm 0.13 \times 10^{-7}$ |
| 1E 1048.1-5937 | mag | $(162.5^\circ, -59.9^\circ)$ | $6.71 \pm 0.74 \times 10^{-8}$ |
| SGR 1806-20 | mag | $(272.2^\circ, -20.4^\circ)$ | $1.67 \pm 0.18 \times 10^{-7}$ |
| Crab | pler | $(83.6^\circ, +22.0^\circ)$ | $1.66 \pm 0.18 \times 10^{-7}$ |
| Vela X | pler | $(128.5^\circ, -45.8^\circ)$ | $6.87 \pm 0.76 \times 10^{-8}$ |
| G343.1-2.3 | pler | $(257.0^\circ, -44.3^\circ)$ | $6.81 \pm 0.75 \times 10^{-8}$ |
| MSH15-52 | pler | $(228.5^\circ, -59.1^\circ)$ | $1.12 \pm 0.12 \times 10^{-7}$ |
| RX J1713.7-3946 | SNR | $(258.4^\circ, -39.8^\circ)$ | $2.67 \pm 0.29 \times 10^{-7}$ |
| Vela Jr. | SNR | $(133.2^\circ, -46.3^\circ)$ | $9.16 \pm 1.0 \times 10^{-8}$ |
| MGRO J2019+37 | SNR | $(305.2^\circ, +36.8^\circ)$ | $2.46 \pm 0.27 \times 10^{-7}$ |
| SS433 | MQ | $(288.0^\circ, +5.0^\circ)$ | $1.16 \pm 0.13 \times 10^{-7}$ |
| GX339-4 | MQ | $(255.7^\circ, -48.8^\circ)$ | $5.50 \pm 0.61 \times 10^{-8}$ |
| Cygnus X-3 | MQ | $(308.1^\circ, +40.8^\circ)$ | $1.32 \pm 0.15 \times 10^{-7}$ |
| GRO J1655-40 | MQ | $(253.5^\circ, -39.8^\circ)$ | $1.26 \pm 0.14 \times 10^{-7}$ |
| XTE J1118+480 | MQ | $(169.5^\circ, +48.0^\circ)$ | $1.29 \pm 0.14 \times 10^{-7}$ |

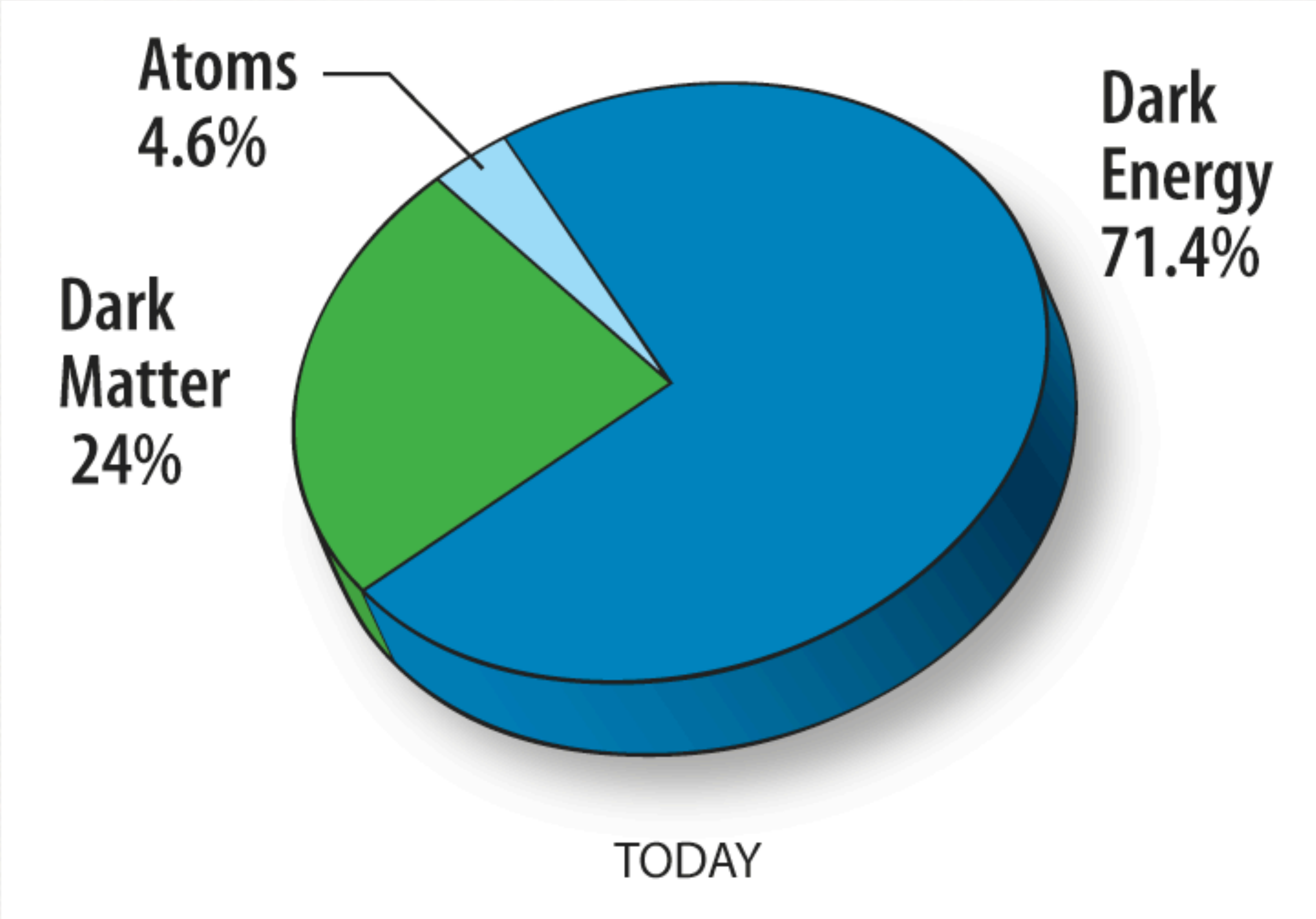
# SEARCH FOR OTHER ASTROPHYSICS IN SK

## Many new sources since 2009

From the Fermi-LAT collaboration (arXiv:1311.5623):
GRB 130427A had the largest fluence, highest-energy photon (95 GeV), longest gamma duration (20 hours), and one of the largest isotropic energy releases ever observed from a GRB.

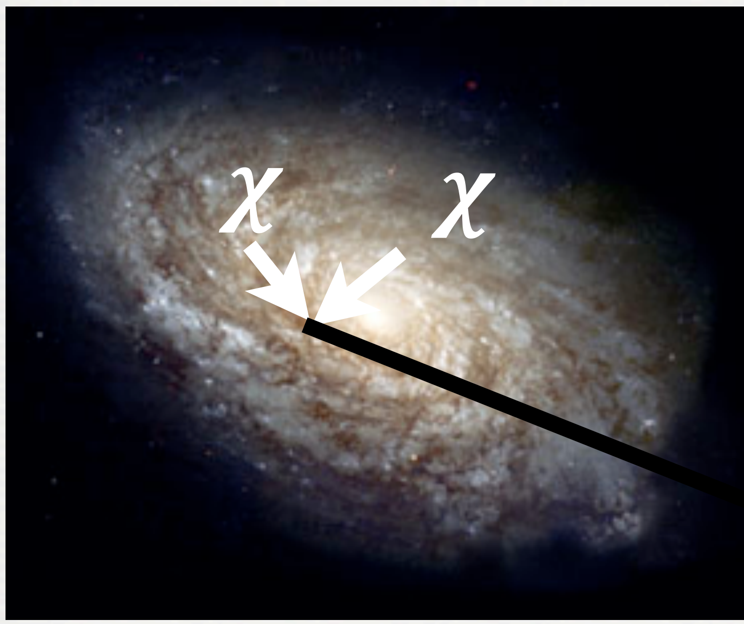
Also might be interesting to see if there are any events correlated with IceCube's UHE neutrinos. We are working on updating this astrophysical analysis.

# DARK MATTER



# DARK MATTER

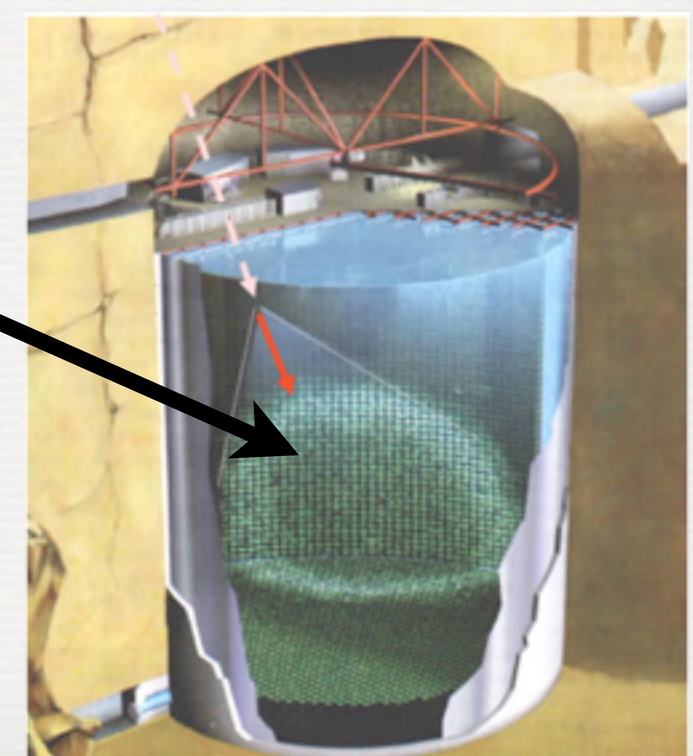
Dark matter collects in the centre of the Galaxy, the Sun, etc




Neutrinos are produced (directly or in a secondary reaction)

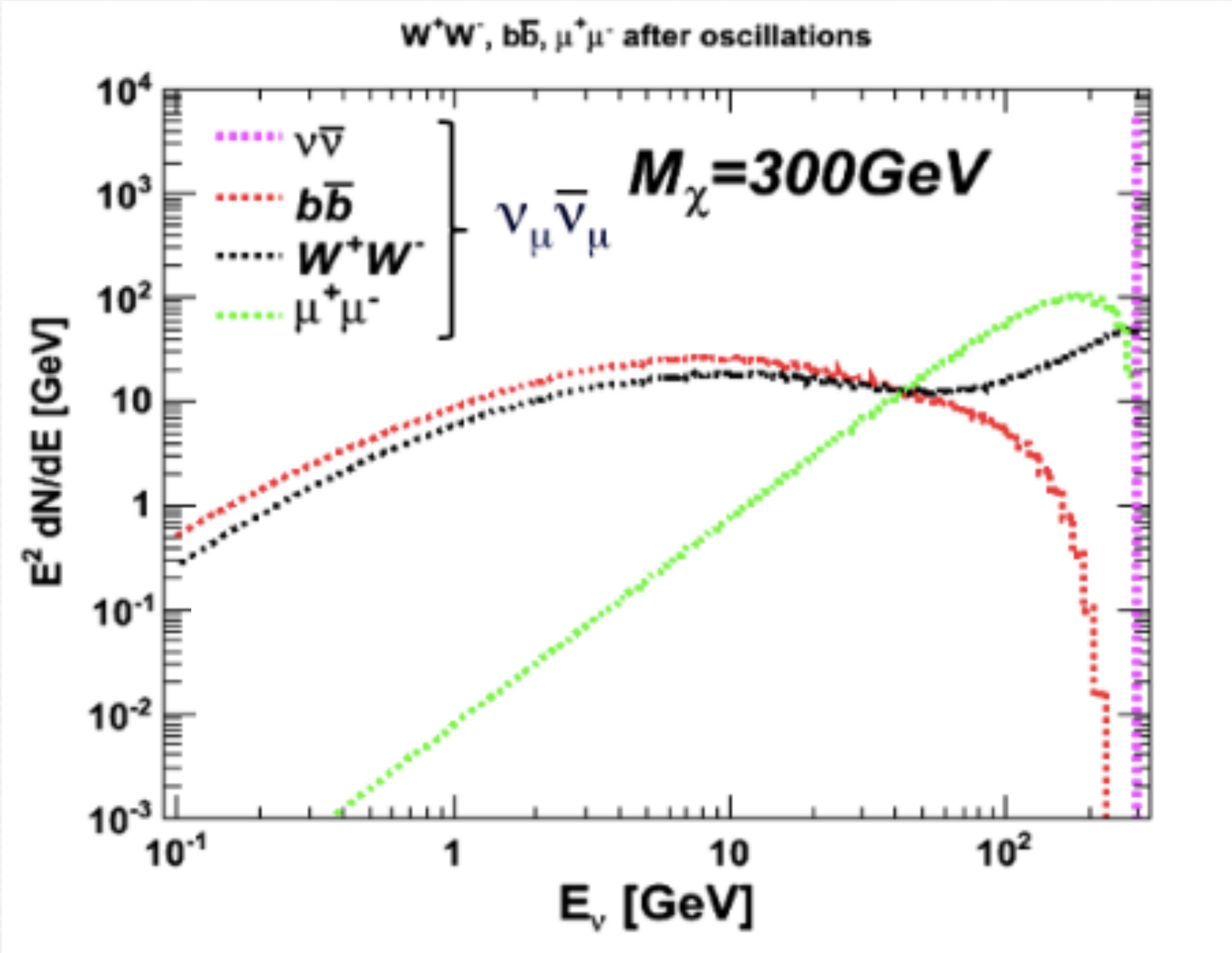
ν

Detect neutrinos in SK

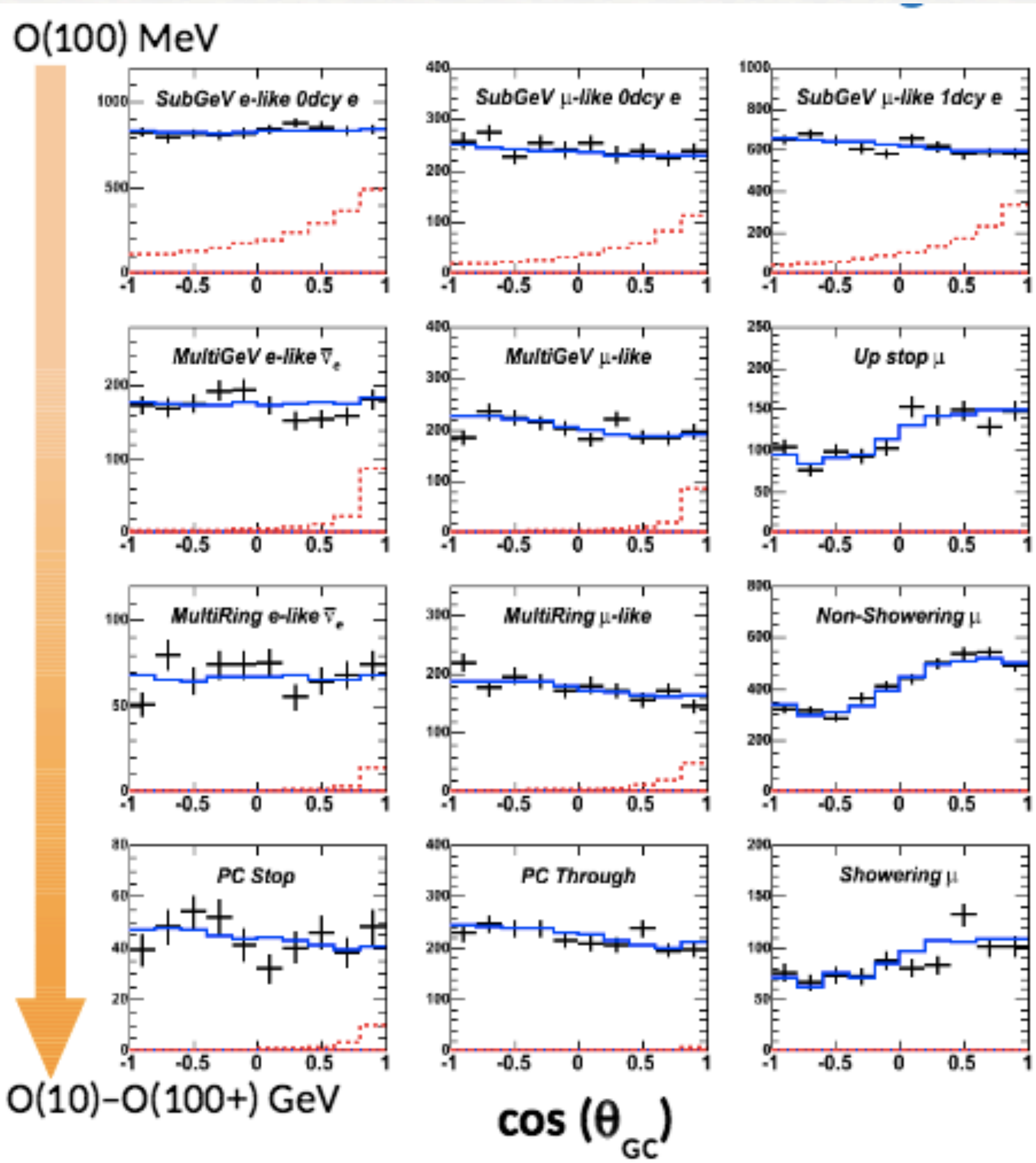


# DARK MATTER SEARCHES IN SK

Use WIMPSIM simulation package to produce expected neutrino spectrum



# DARK MATTER SEARCH FROM GC IN SK




$\chi\chi \rightarrow b\bar{b}$

$M(\chi) =$ 5 GeV / $c^2$

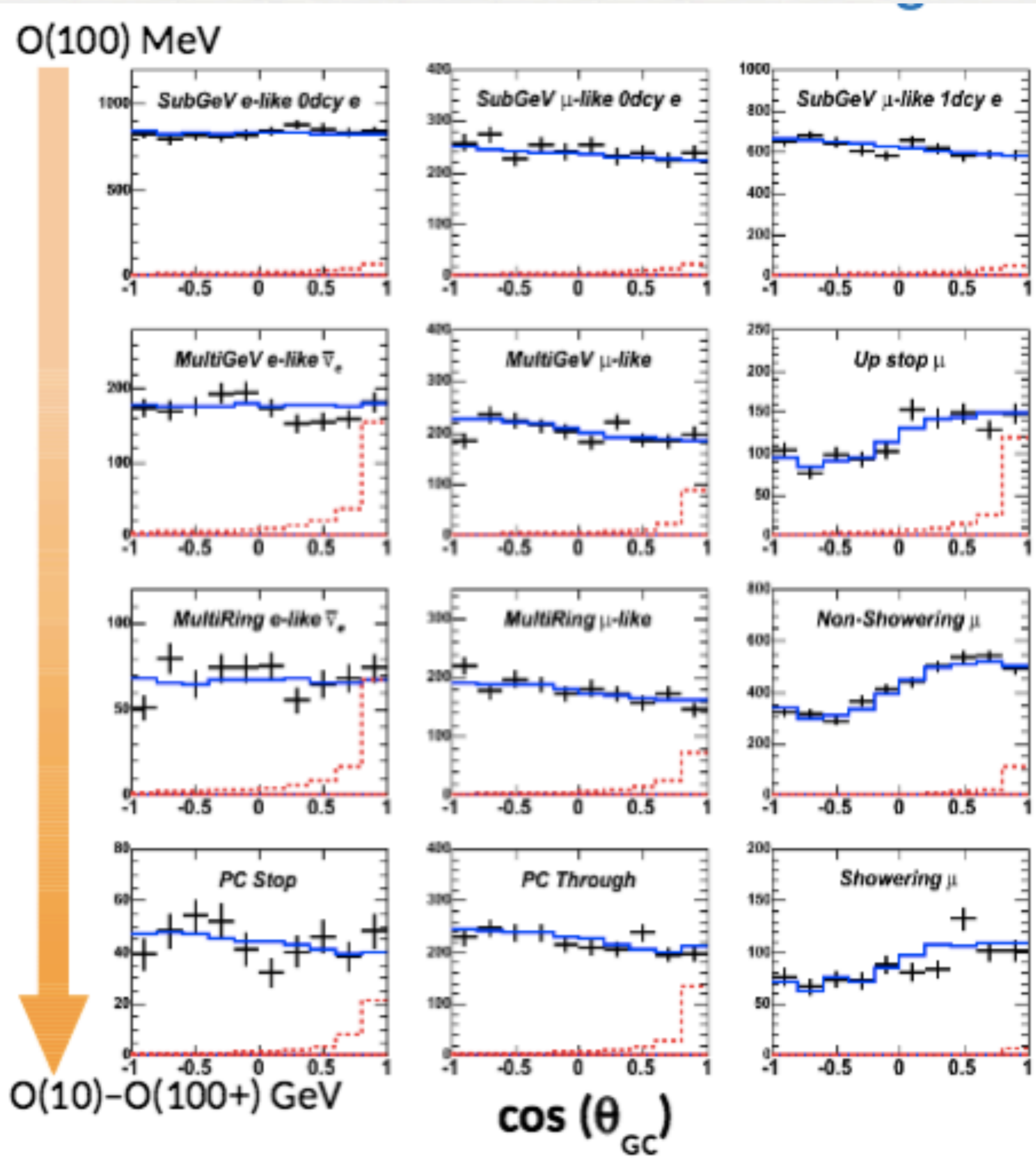
— WIMP Signal, **Best Fit** × 15

— ATM ν Background + WIMP

- Analysis uses all available data
  - Previous analyses used only the upward-going muons
- 100% branching fraction assumed for each tested annihilation channel
- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

Roger Wendell Neutrino 2014

# DARK MATTER SEARCH FROM GC IN SK




$\chi\chi \rightarrow b\bar{b}$

$M(\chi)$ = 100 GeV / $c^2$

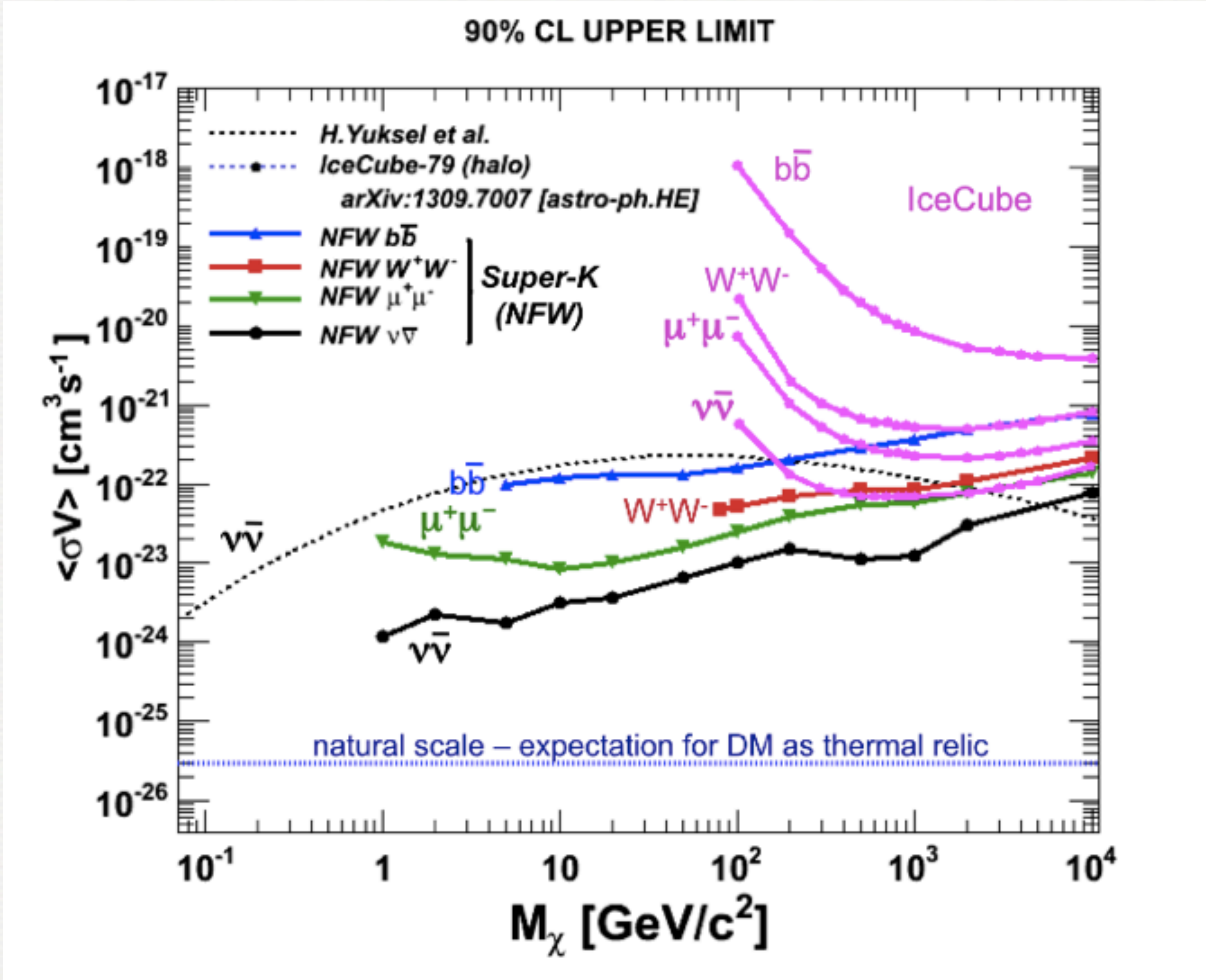
— WIMP Signal, **Best Fit** × 15

— ATM ν Background + WIMP

- Analysis uses all available data
  - Previous analyses used only the upward-going muons
- 100% branching fraction assumed for each tested annihilation channel
- Equal fluxes at detection
  - $\phi(\nu_e) = \phi(\nu_\mu) = \phi(\nu_\tau)$

Roger Wendell Neutrino 2014

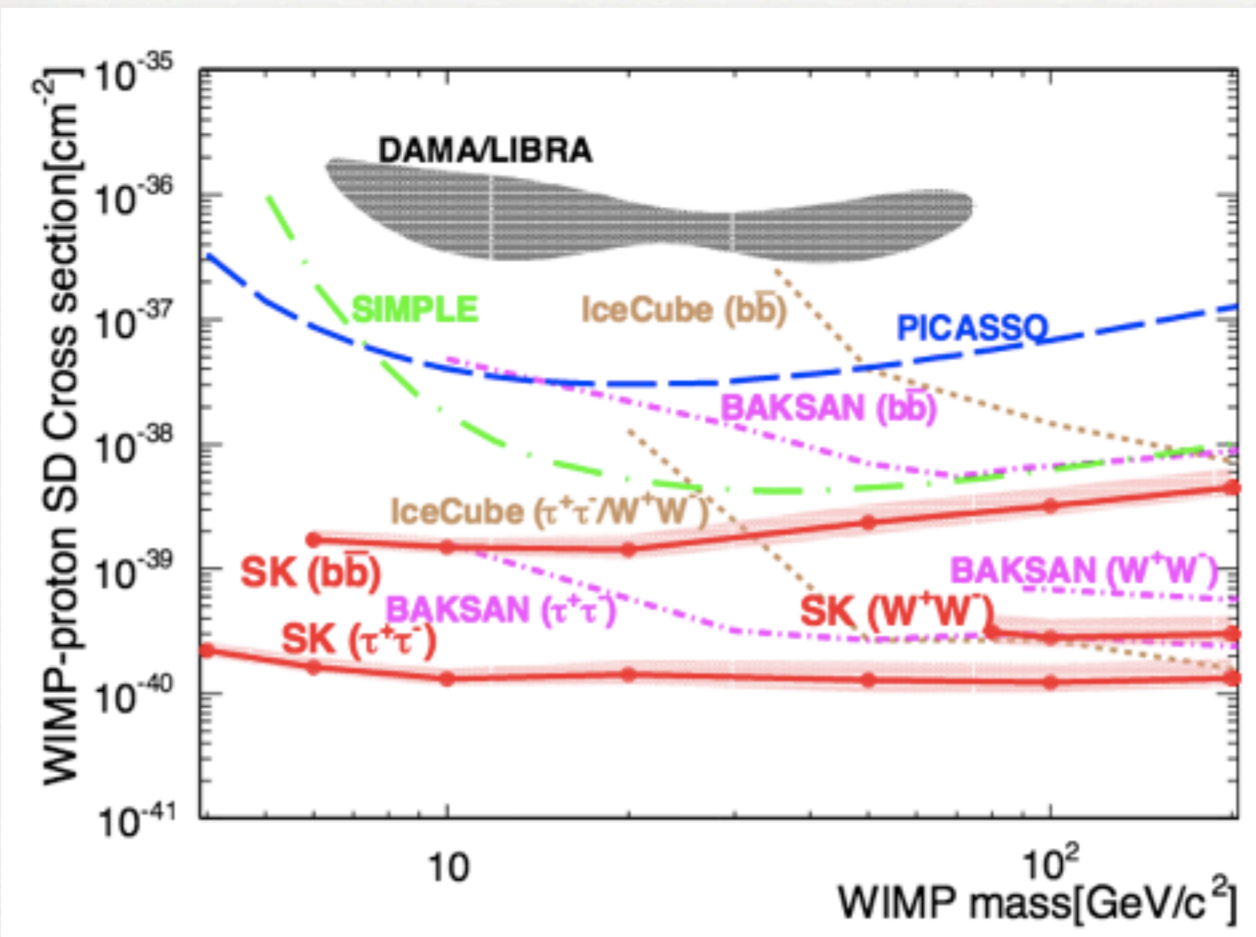
# DARK MATTER SEARCH FROM GC IN SK

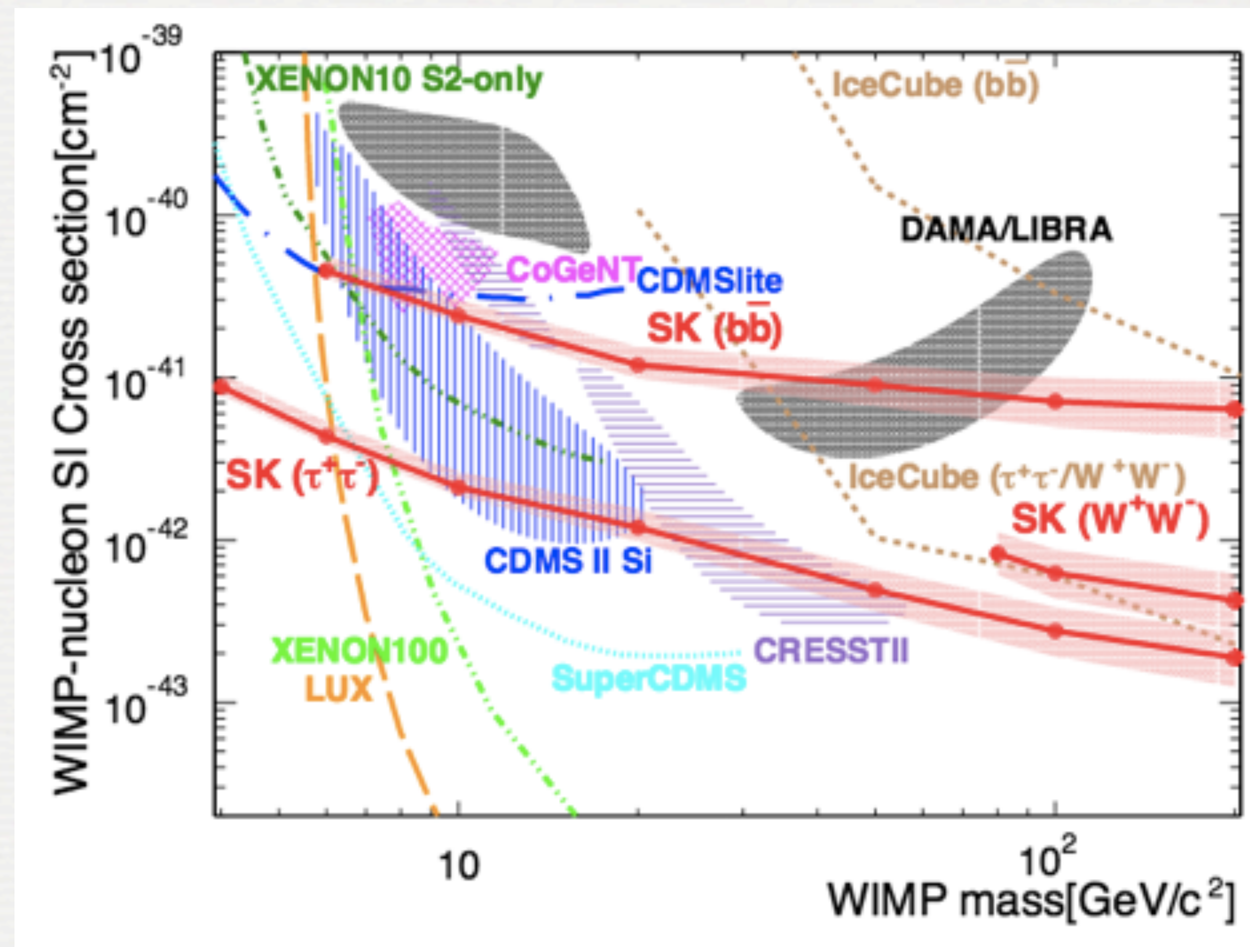





Wednesday, December 2, 15

# DARK MATTER SEARCH FROM THE SUN IN SK




Choi 2015 (arXiv1503.04858v1)

# DARK MATTER SEARCHES FROM OTHER SOURCES IN SK

**Centre of Earth: Analysis is in progress**

**Nearby dwarf galaxies: Analysis is planned**

# CONCLUSIONS

- Super-Kamiokande is a multi-purpose detector that probes both low energy and high energy neutrino physics
- Interesting studies are emerging where the atmospheric neutrinos are a background, namely astrophysical neutrino searches
- Various studies search for astrophysical neutrinos: general point source searches, catalogue searches, dark matter searches
- No significant sources have been found yet in these searches