"Collider Physics": 2nd Symposium of the Division for Physics of Fundamental Interactions of the Polish Physical Society, 13-15 May 2016, Katowice

Astrophysical searches with neutrino detectors

Piotr Mijakowski
Narodowe Centrum Badań Jądrowych, Warszawa

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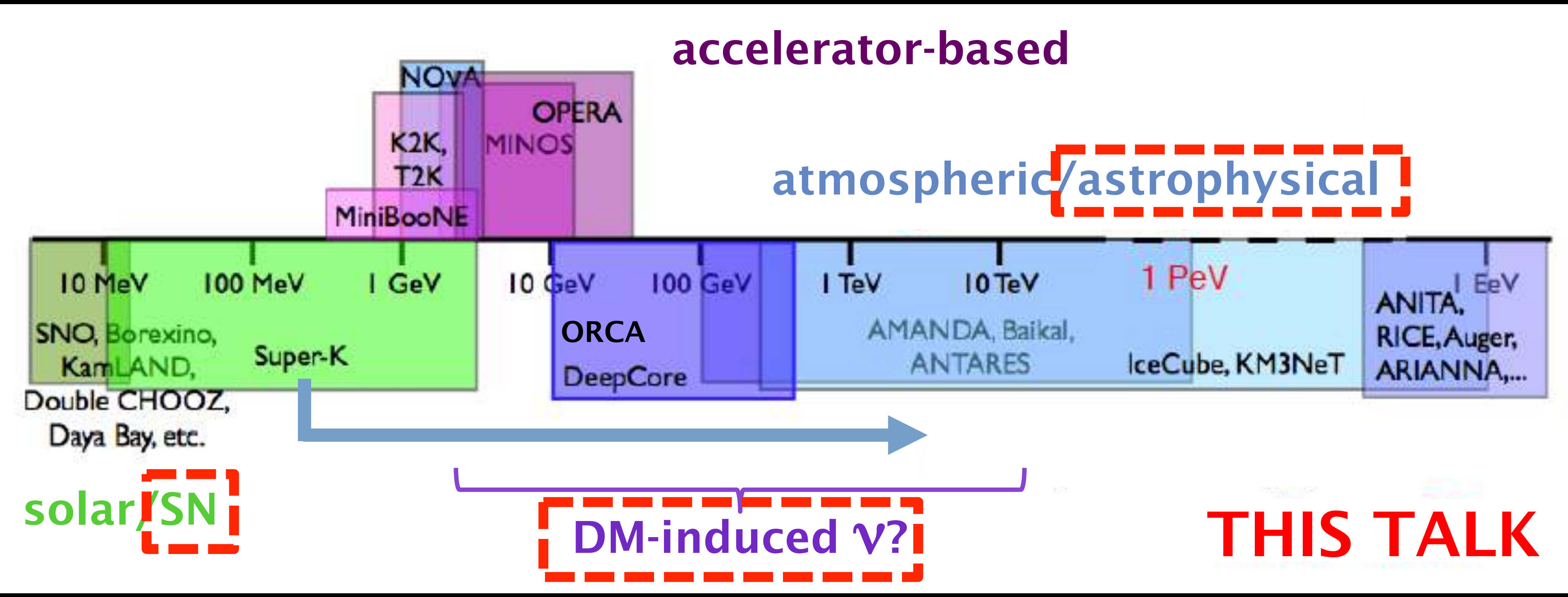
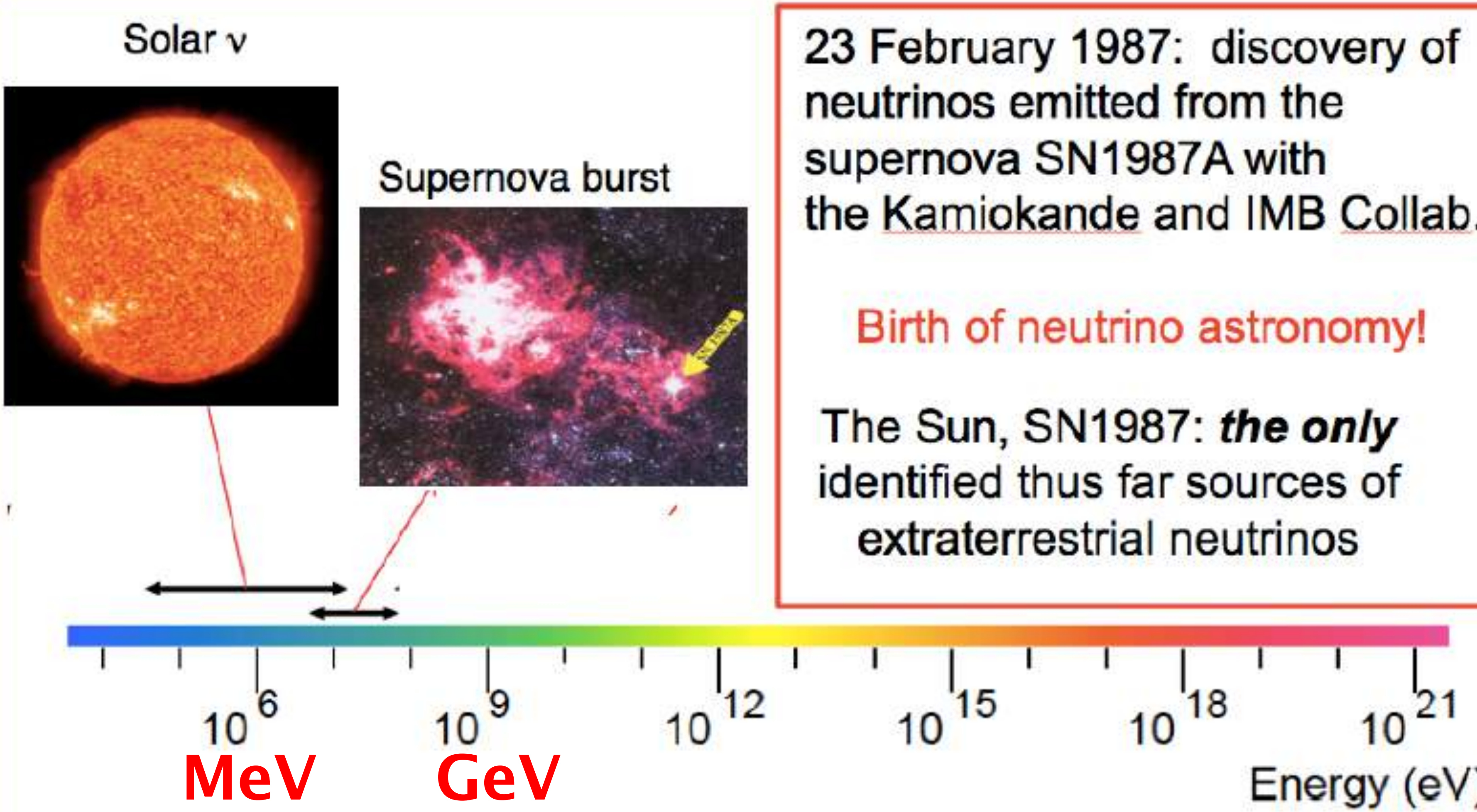
neutrino experiments and their energy range



neutrino sources/energies



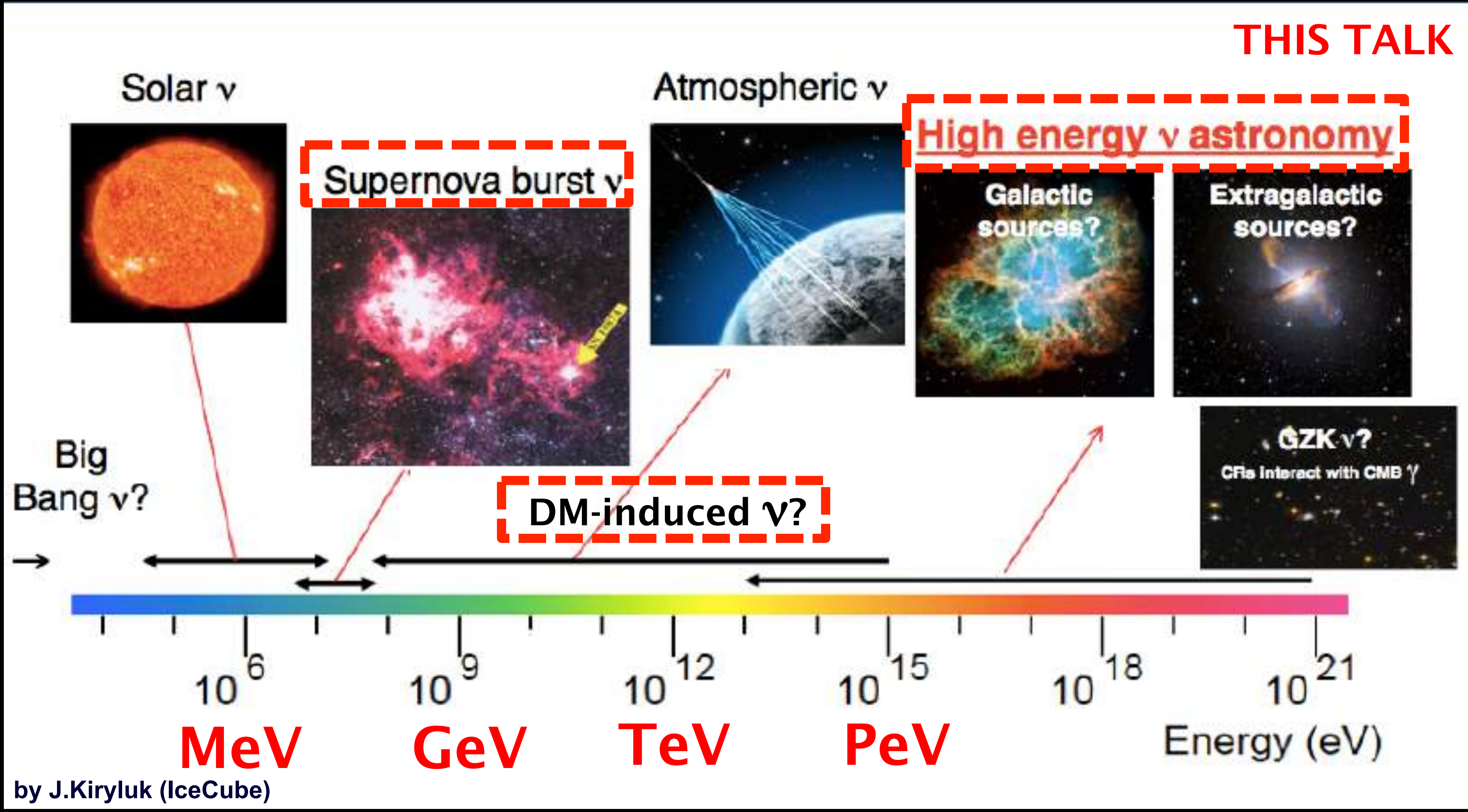
23 February 1987: discovery of neutrinos emitted from the supernova SN1987A with the Kamiokande and IMB Collab.

Birth of neutrino astronomy!

The Sun, SN1987: ***the only*** identified thus far sources of extraterrestrial neutrinos

by J.Kiryluk (IceCube)

neutrino sources/energies



OUTLINE

- Neutrinos as cosmic messengers
- Neutrino telescopes
- Selected results:
  - Indirect search for dark matter — based on **Super-K**
  - Diffuse flux of cosmic neutrinos — **IceCube**
  - Point source searches — **Antares**
- Future projects **Km3NeT, SK-Gd, Hyper-K…**

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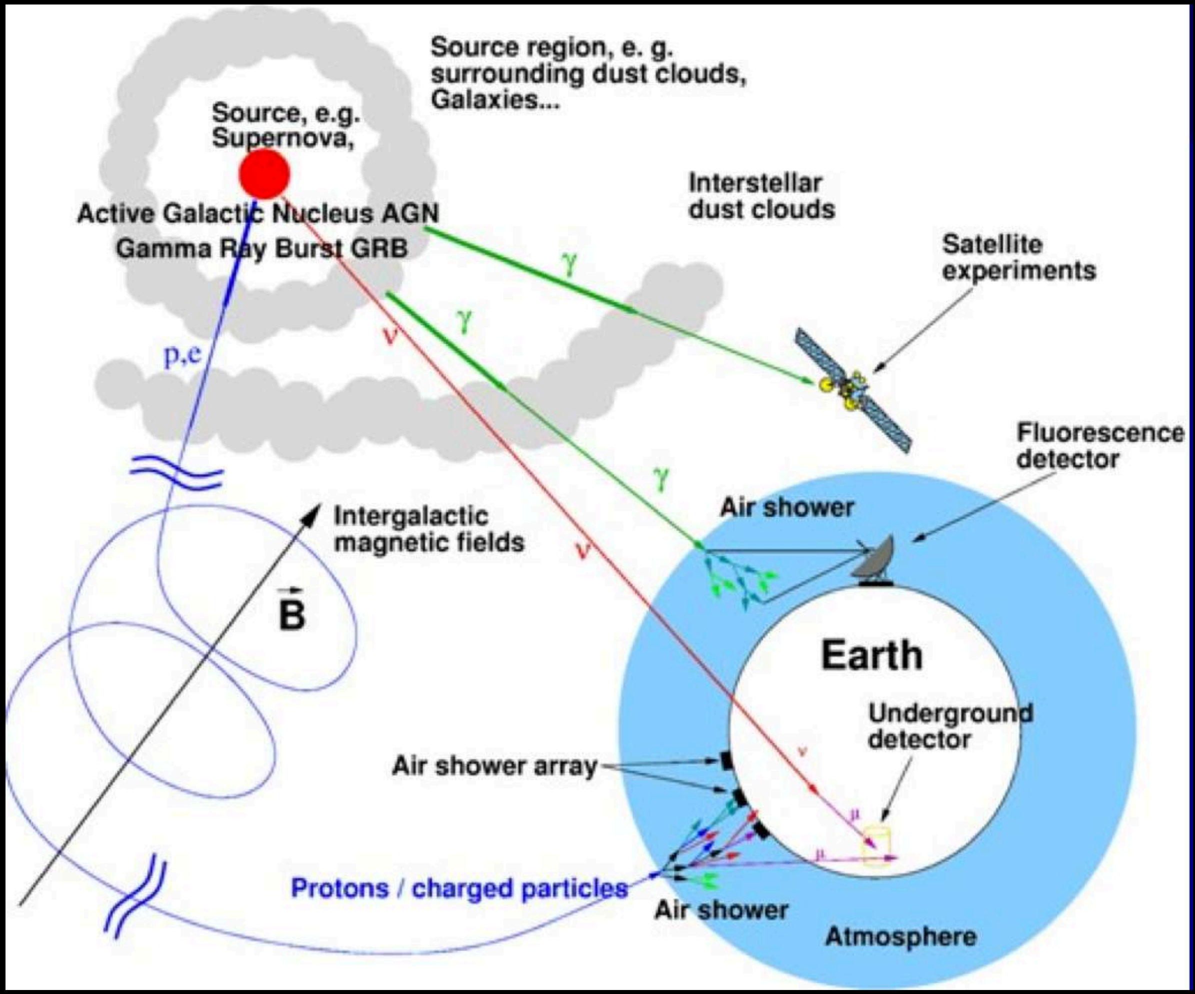
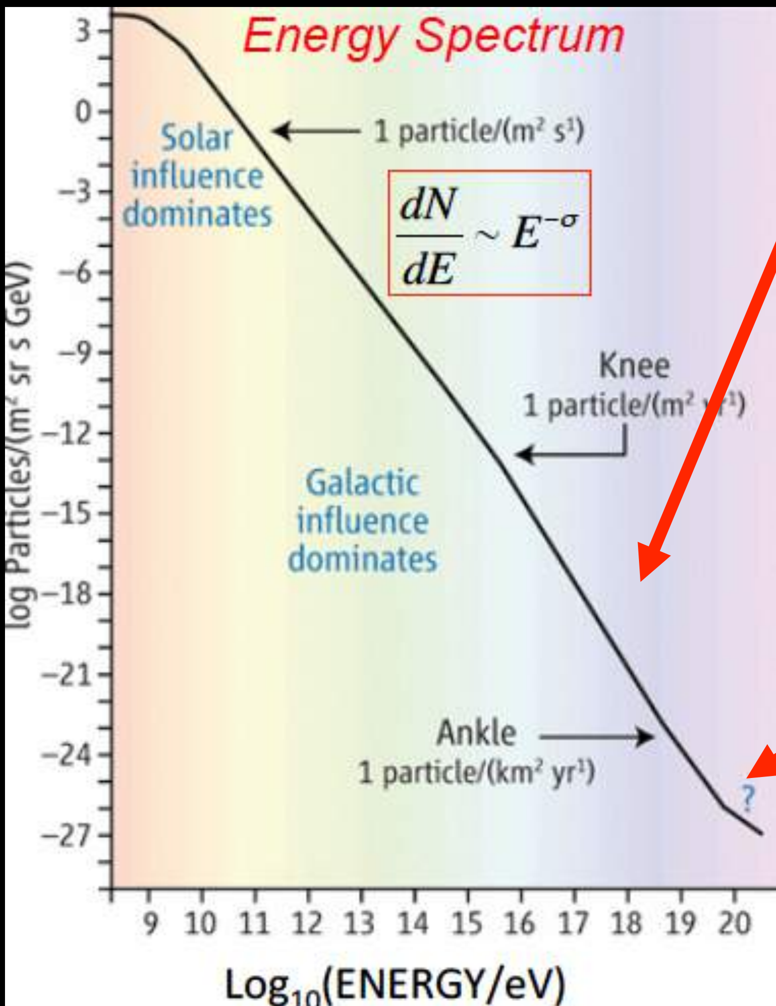
Neutrinos as cosmic messengers

- We would like to understand origin of UHE cosmic rays
- Multi-messenger approach: protons, γ-rays & neutrinos
- protons: directions scrambled by magnetic fields
- γ-rays: direction straight-line, but reprocessed in the sources and asborbed >1TeV
- neutrinos: not affected by magnetic fields, could pass through dense regions, carry original energy information → excellent probe of the Universe



Motiviation

- We would like to understand origin of UHE cosmic rays



Cosmic accelerators:

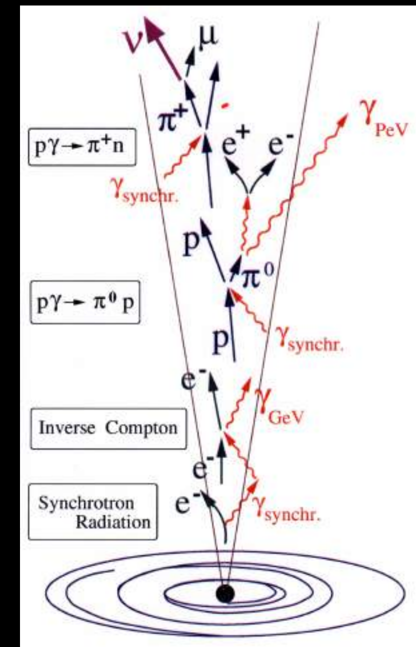
Active galactic nuclei (AGN),

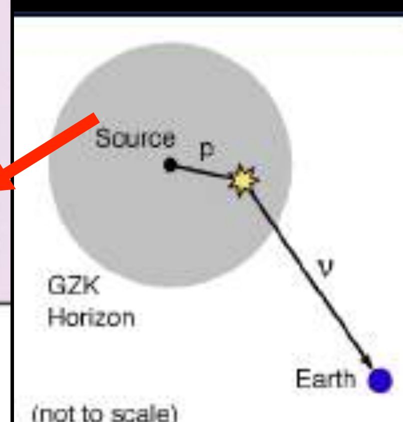
Gamma ray bursts (GRBs),

SN remnants,
Pulsars,

Microquasars

…





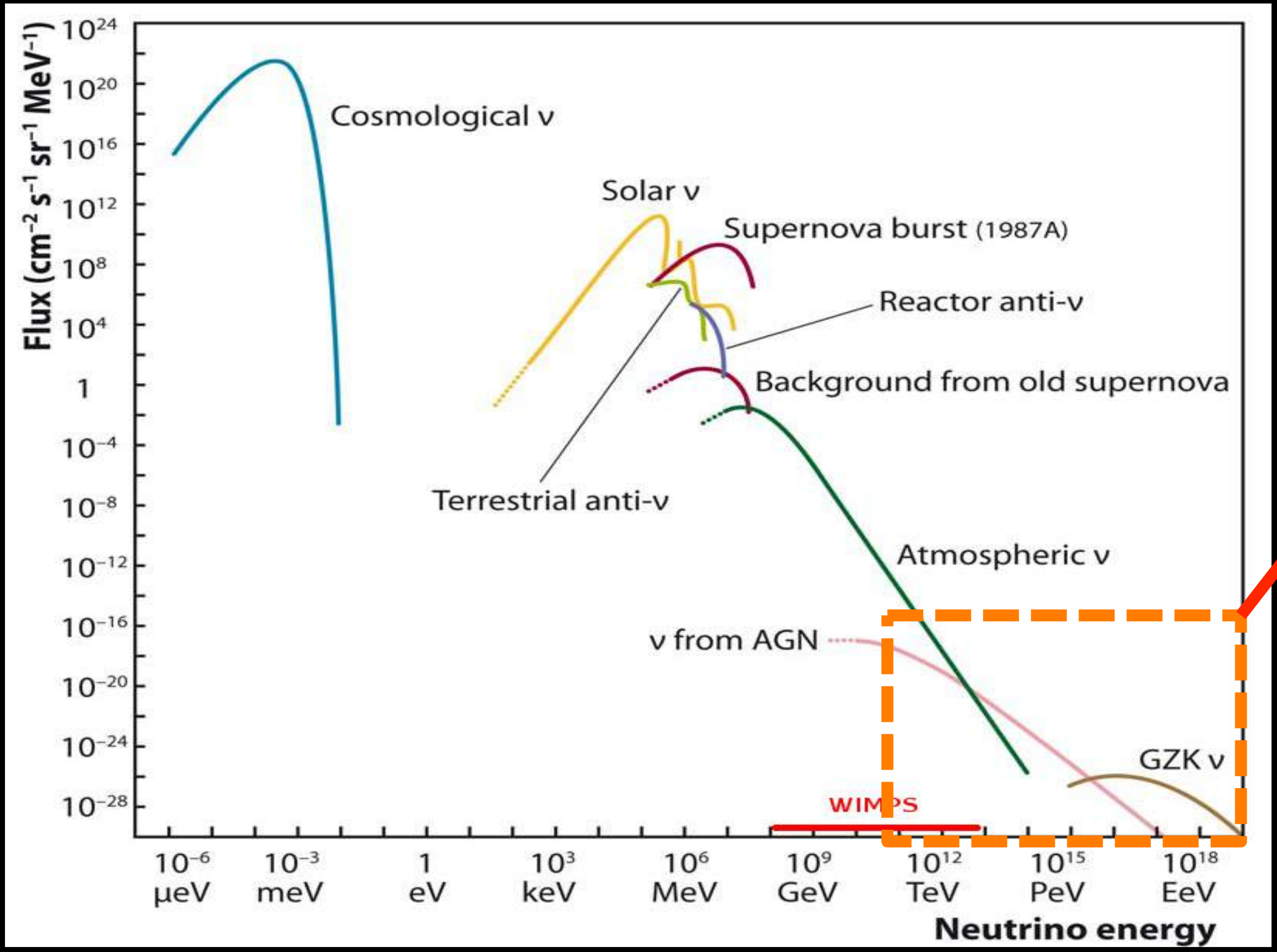
Greisen–Zatsepin–Kuzmin (GZK) limit

expect ~1evt/km2/year

$$E_p > 6\times10^{19}\,eV:$$
$$p+\gamma_{CMB} \rightarrow \Delta \rightarrow \pi + n \rightarrow \nu + \ldots$$

Motiviation

- We would like to understand origin of UHE cosmic rays



Theoretically predicted cosmic neutrino fluxes: very small at high energies

Low ν fluxes and small ν interaction cross section: need for km3 scale detectors

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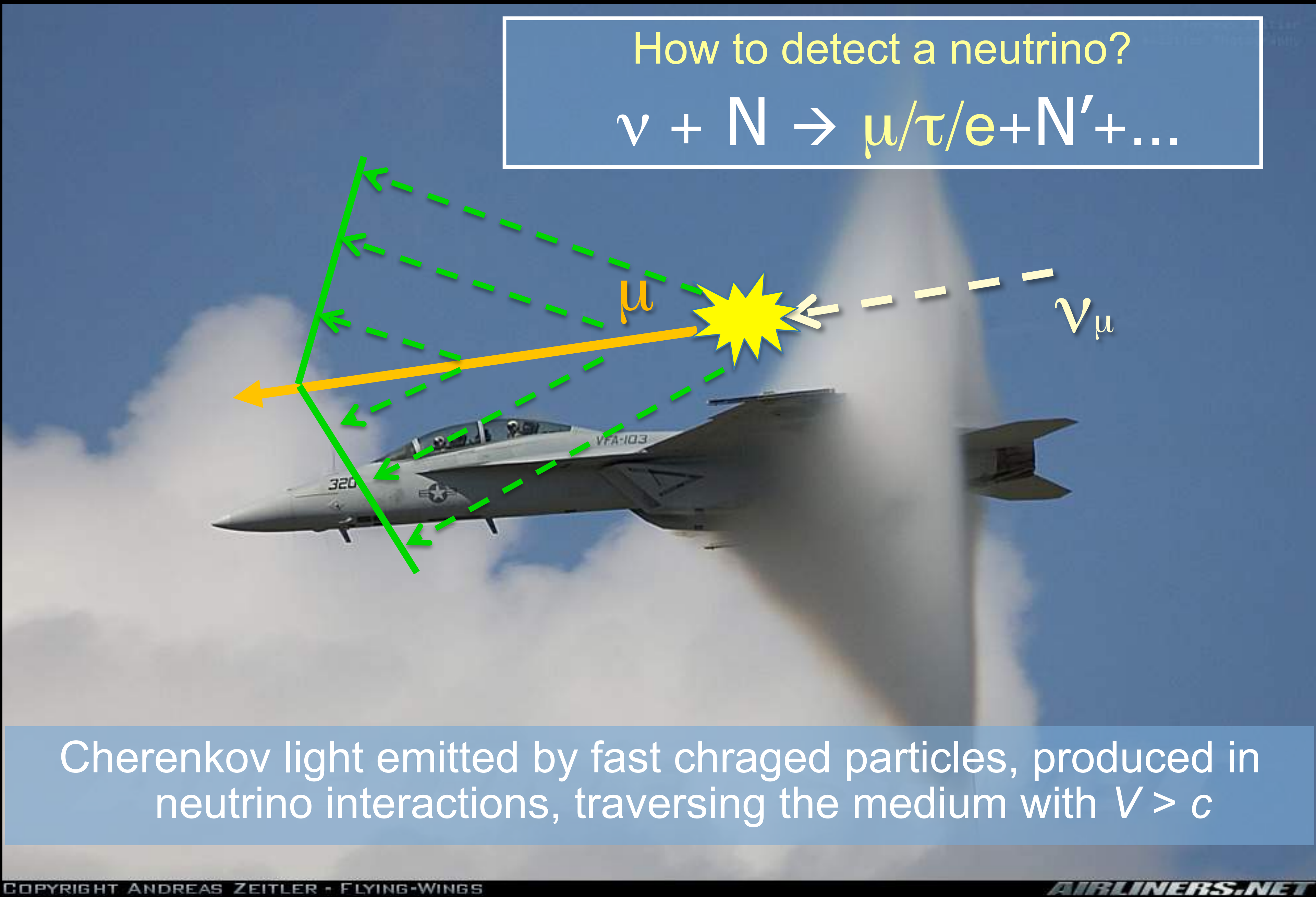
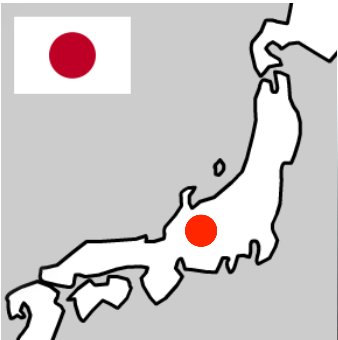
How to detect a neutrino?

$$\nu + N \rightarrow \mu/\tau/e + N' + \ldots$$

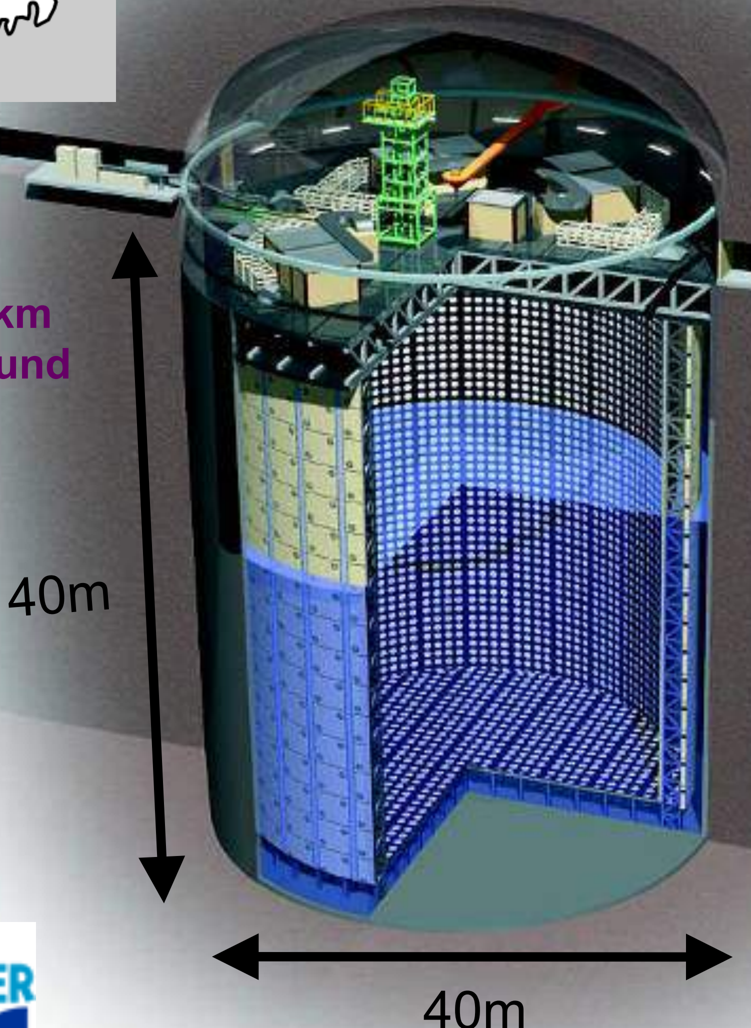


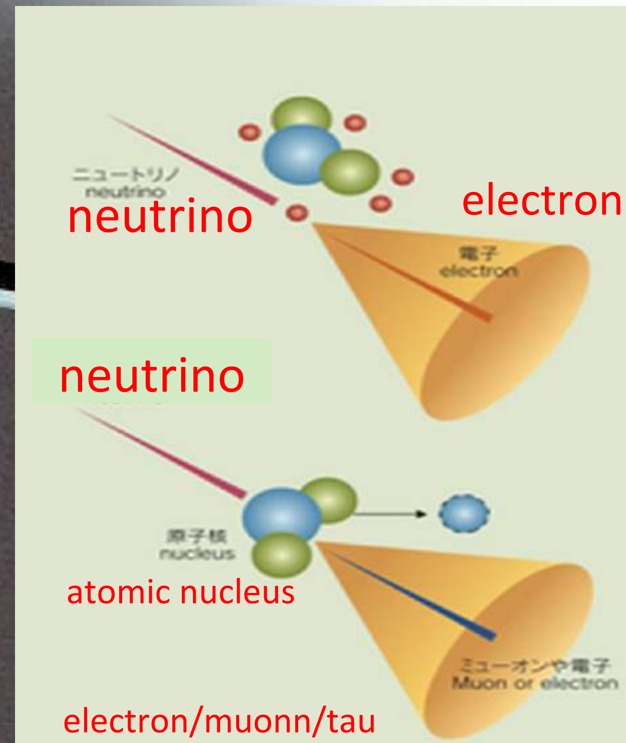
Cherenkov light emitted by fast chraged particles, produced in neutrino interactions, traversing the medium with $V > c$

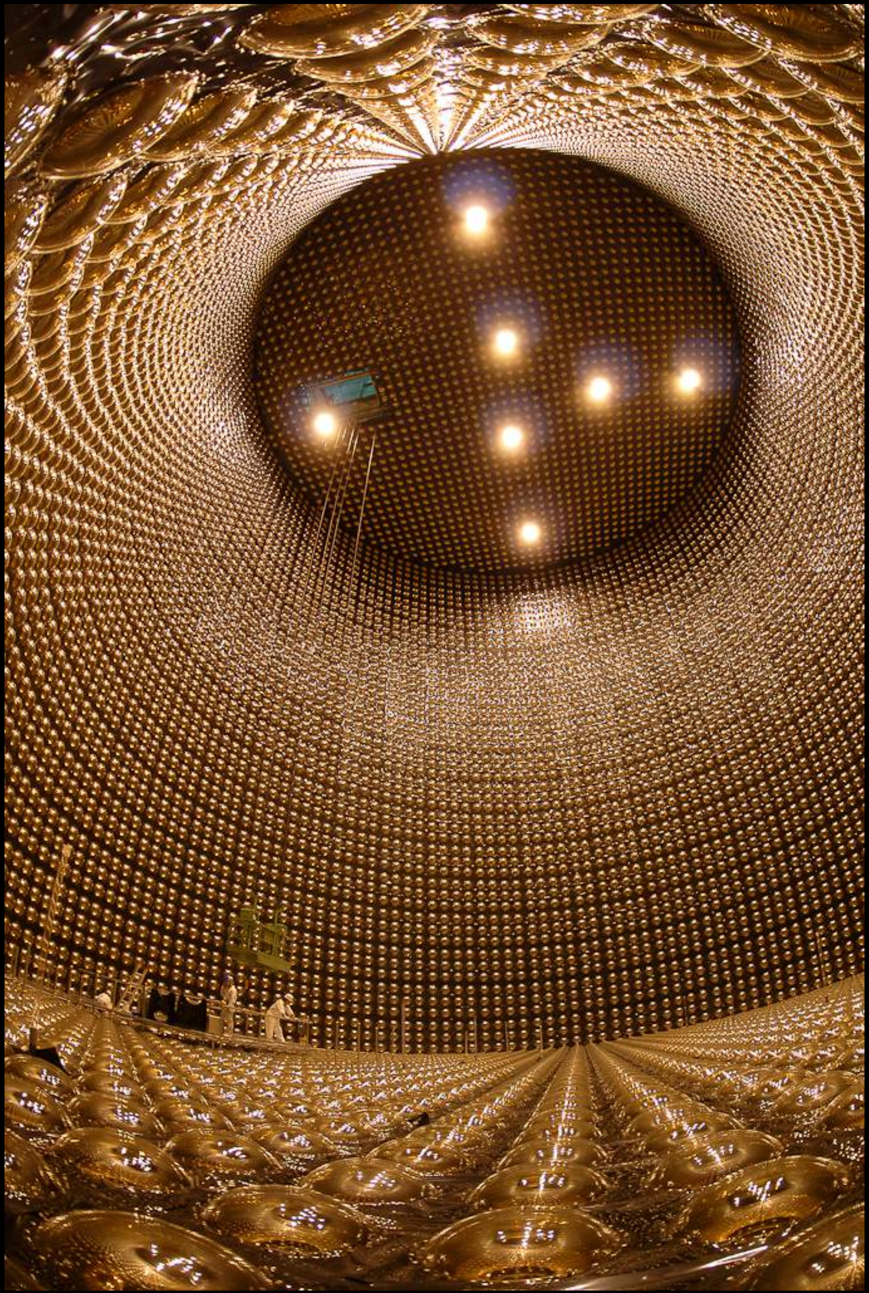
How does it work in practice? based on Super-Kamiokande detector



located 1km underground

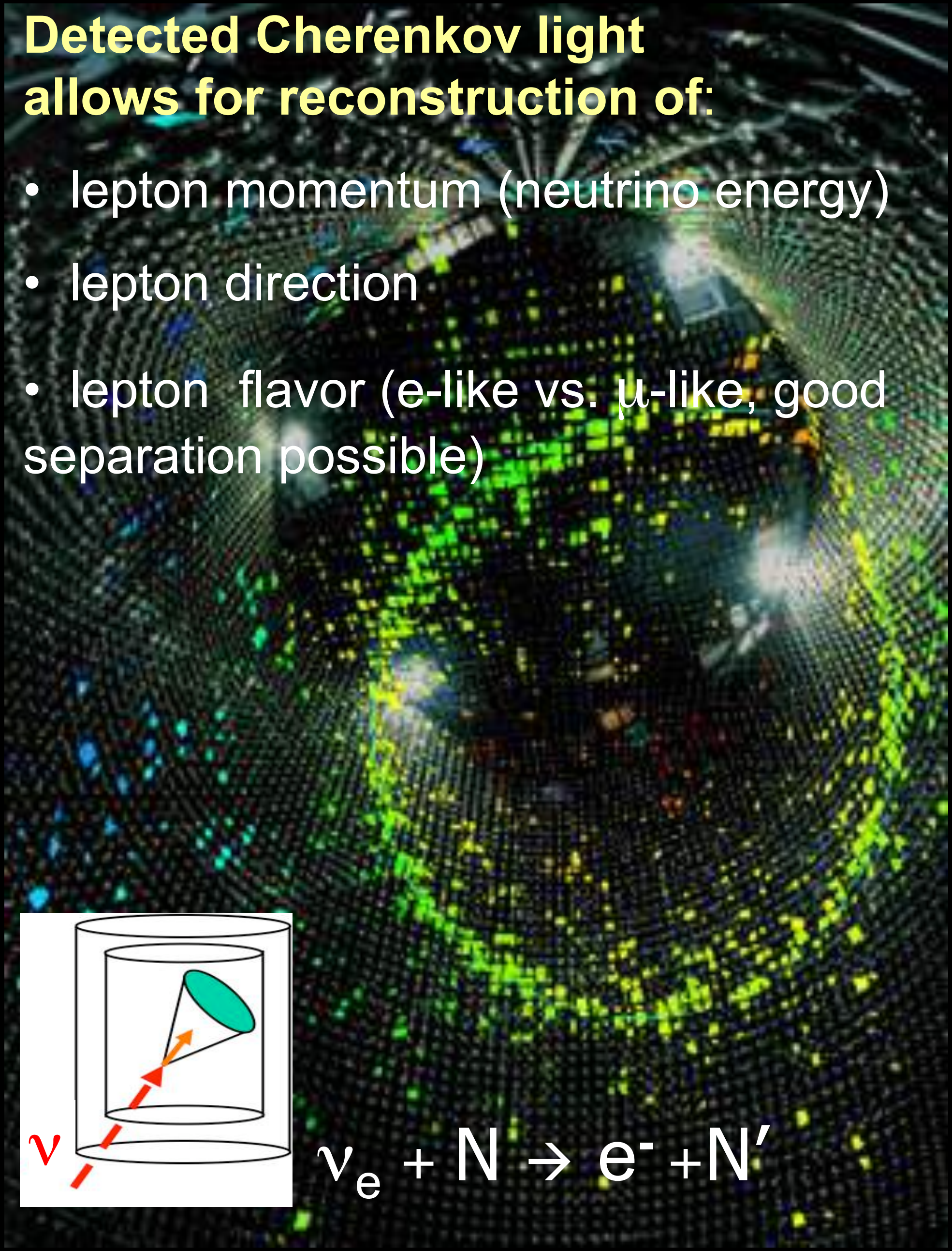






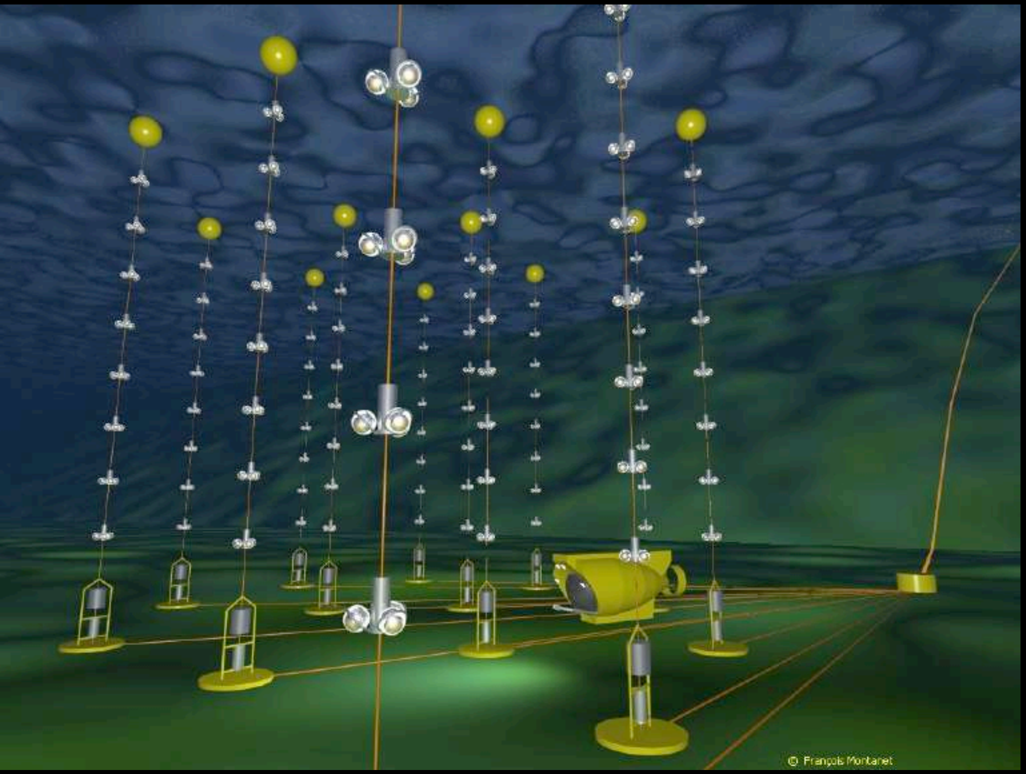
Detected Cherenkov light allows for reconstruction of:

- lepton momentum (neutrino energy)
- lepton direction
- lepton flavor (e-like vs. μ-like, good separation possible)

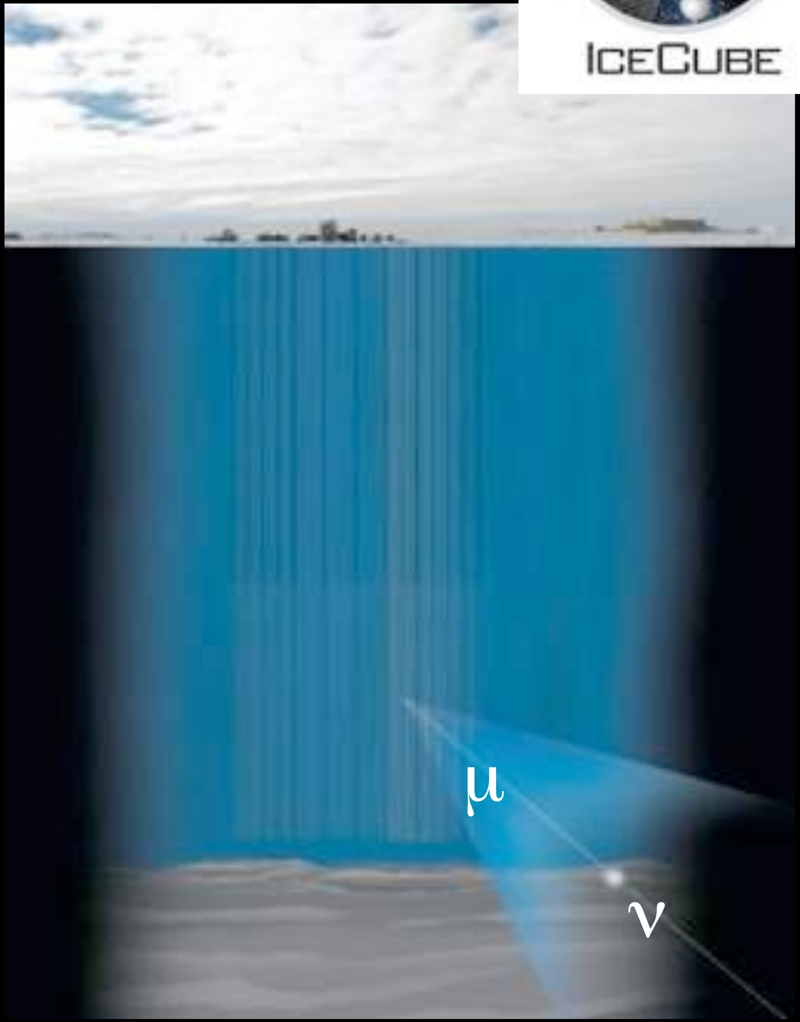


$\nu_e + N \rightarrow e^- + N'$

neutrino detection in Mediterranean Sea

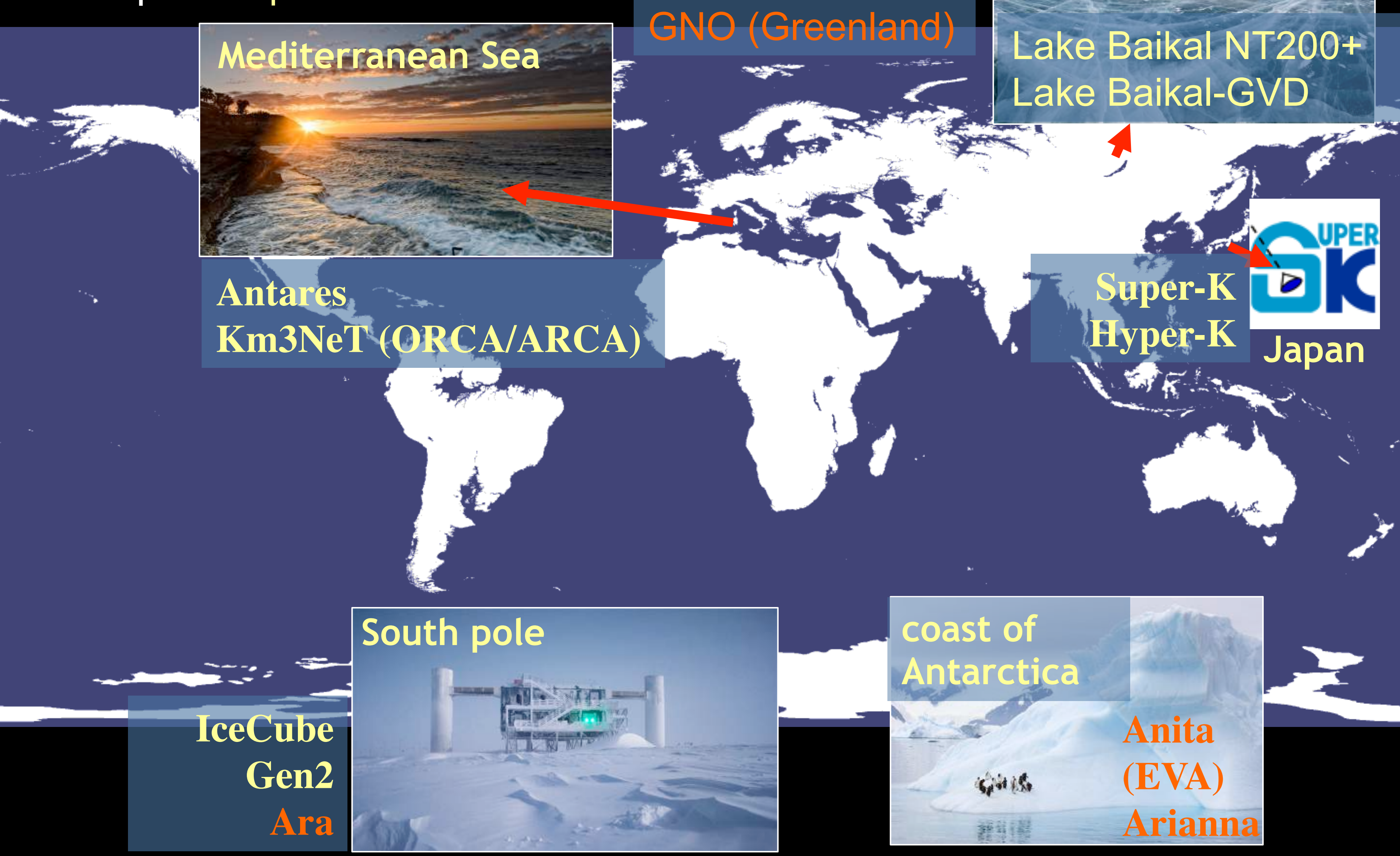


neutrino detection in ice@South Pole



neutrino telescopes

techniques: optical /radio detection



BIG players: HE optical neutrino observatories (in operation)

NT-200+

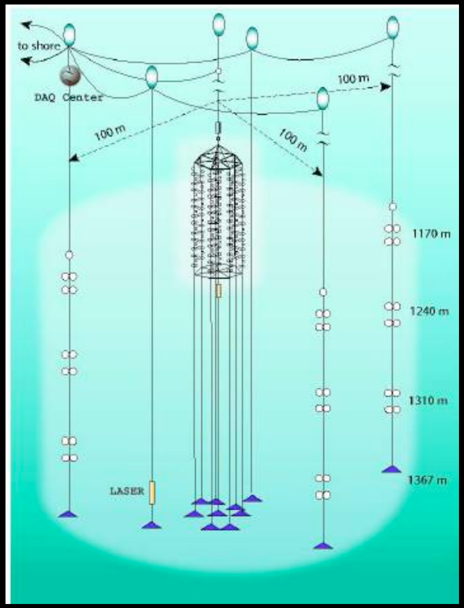
- 8+3=11 strings
- 192+36=228 PMTs
- 1/2000 km3 of volume
- Medium: Lake Baikal
- Northern hemisphere

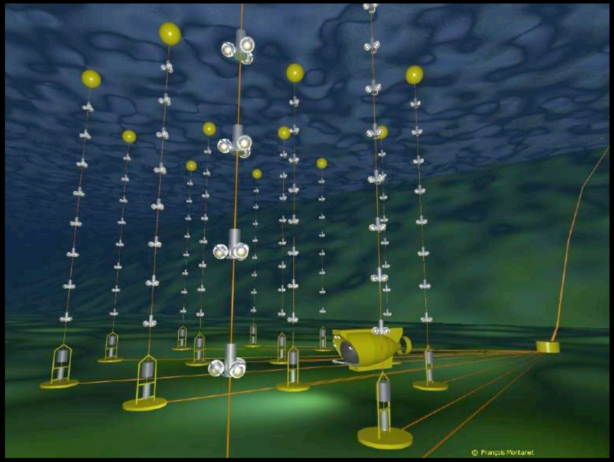
ANTARES

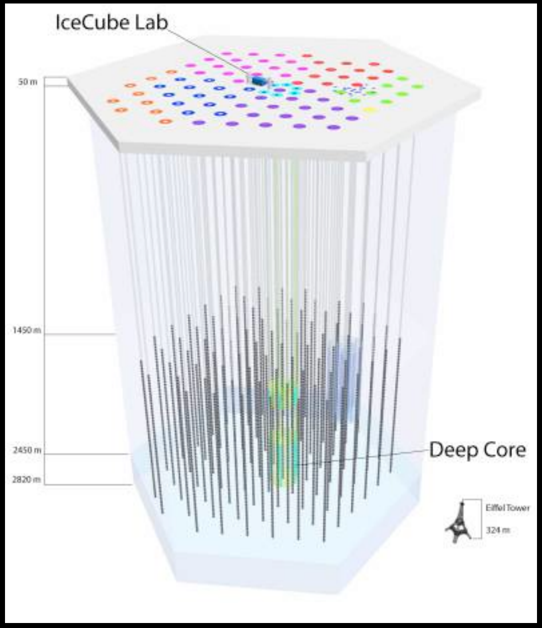
- 12 strings
- 885 PMTs
- 1/100 km3 of volume
- Medium: Mediterranean Sea
- Northern hemisphere

IceCube

- 86 strings
- 5160 PMTs
- 1 km3 of volume
- Medium: South Polar Ice
- Southern hemisphere

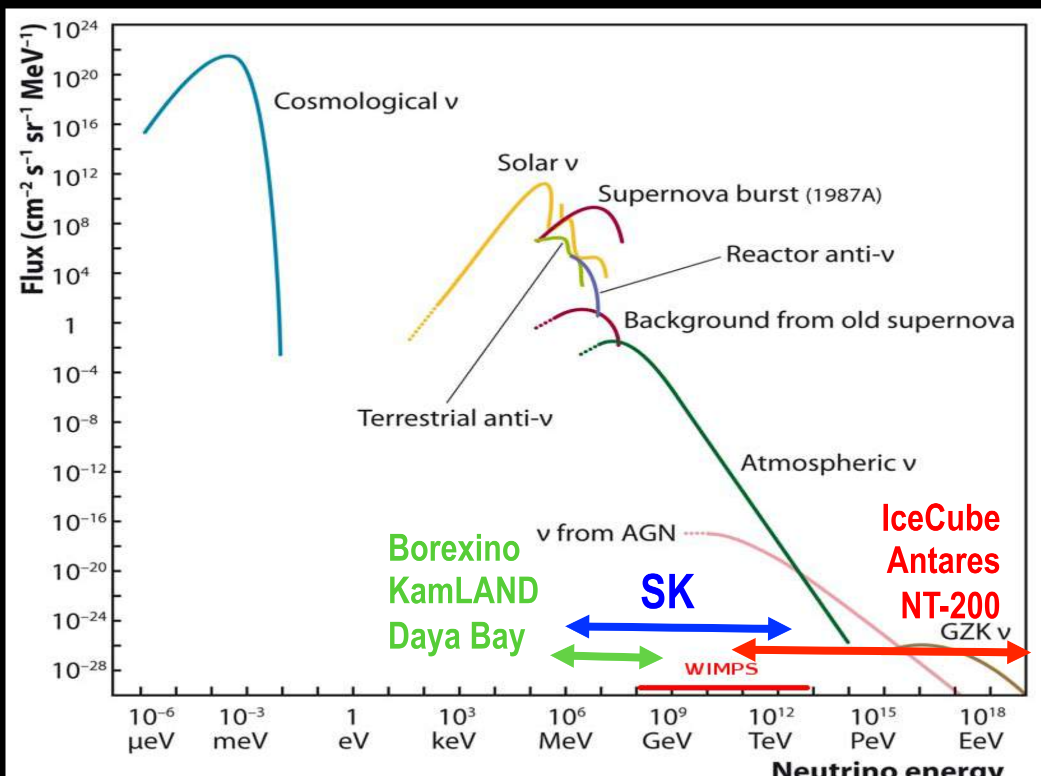






smaller players: Super-Kamiokande, Borexino, KamLAND, Daya Bay…

- NT-200/Antares/IceCube: sensitive from ~100GeV
- … smaller detectors, with MeV sensitivity, suitable for SN neutrinos



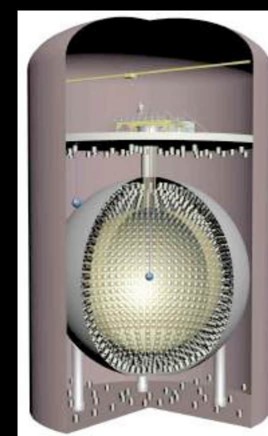
Borexino

Italy

Daya Bay

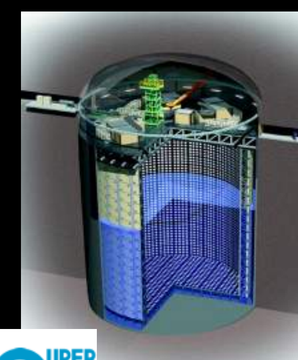
China

KamLAND



Japan

Super-K

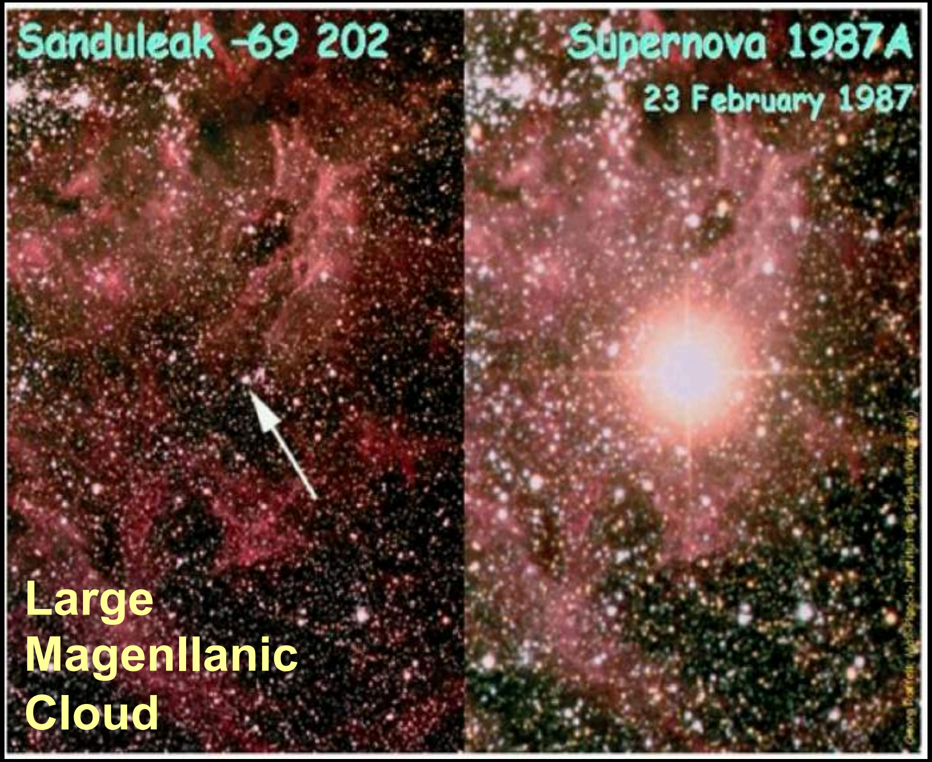


Japan

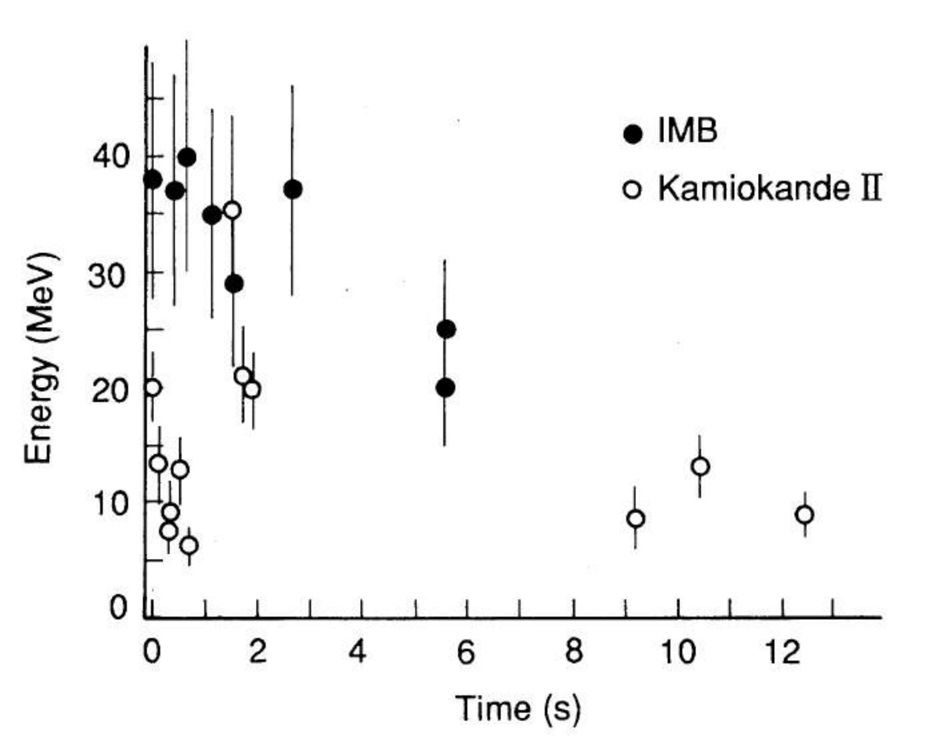
- Super-K best samples at GeV scale →possible also to search for DM
  - … upward going muon directional information even up to TeV scale

Supernova neutrinos, SN1987A

- February 23, 1987: birth of neutrino astronomy!
- expecting ~2-3 SN bursts/century in Milky Way (last visible one in year 1604)



SN1987A neutrino events

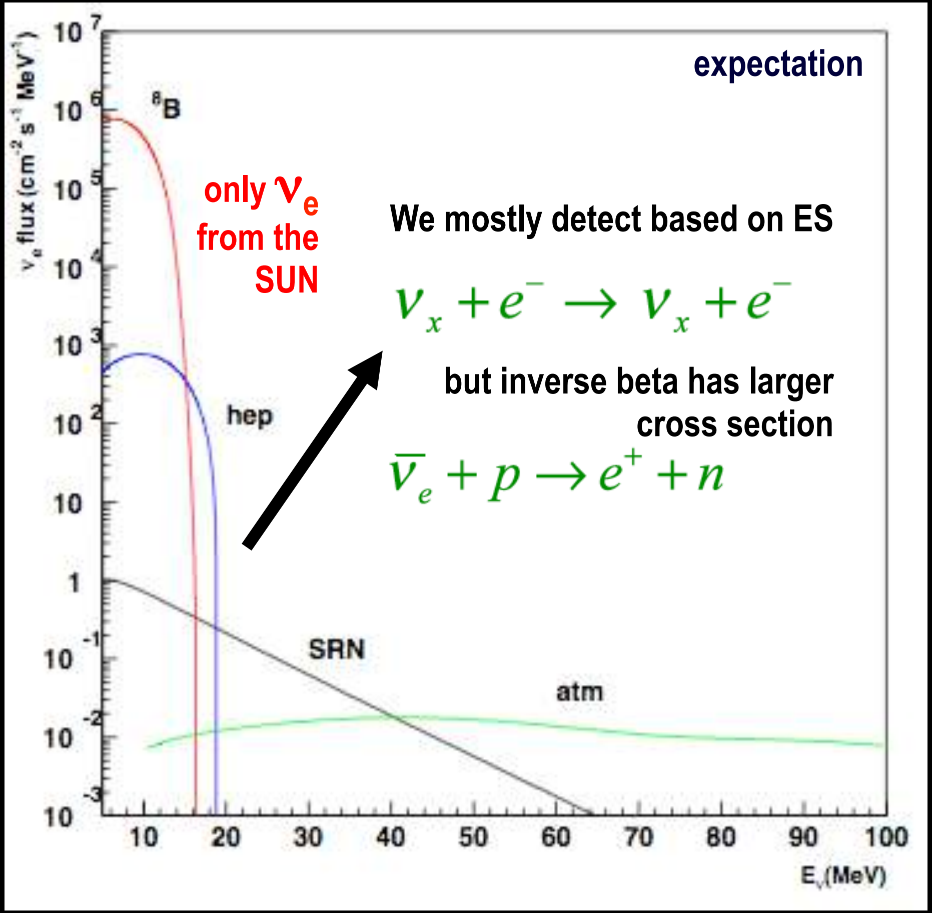


- neutrinos arrived 3hrs earlier than photons!
- SNEWS (SuperNova Early Warning System): Borexino, Daya Bay, KamLAND, HALO, IceCube, LVD, Super-Kamiokande

Supernova relic neutrinos

- Observation of a single SN relies on a very brief signal – trivial separation from background but a very rare event
- But Universe is full of neutrinos from all previous SN flying around
- Need to separate them from backgrounds
- … next generation of neutrino detectors like SK-Gd or Hyper-K may be the first one to discover and measure the spectrum of SRNs

challenge: SN relic ν (SNR)



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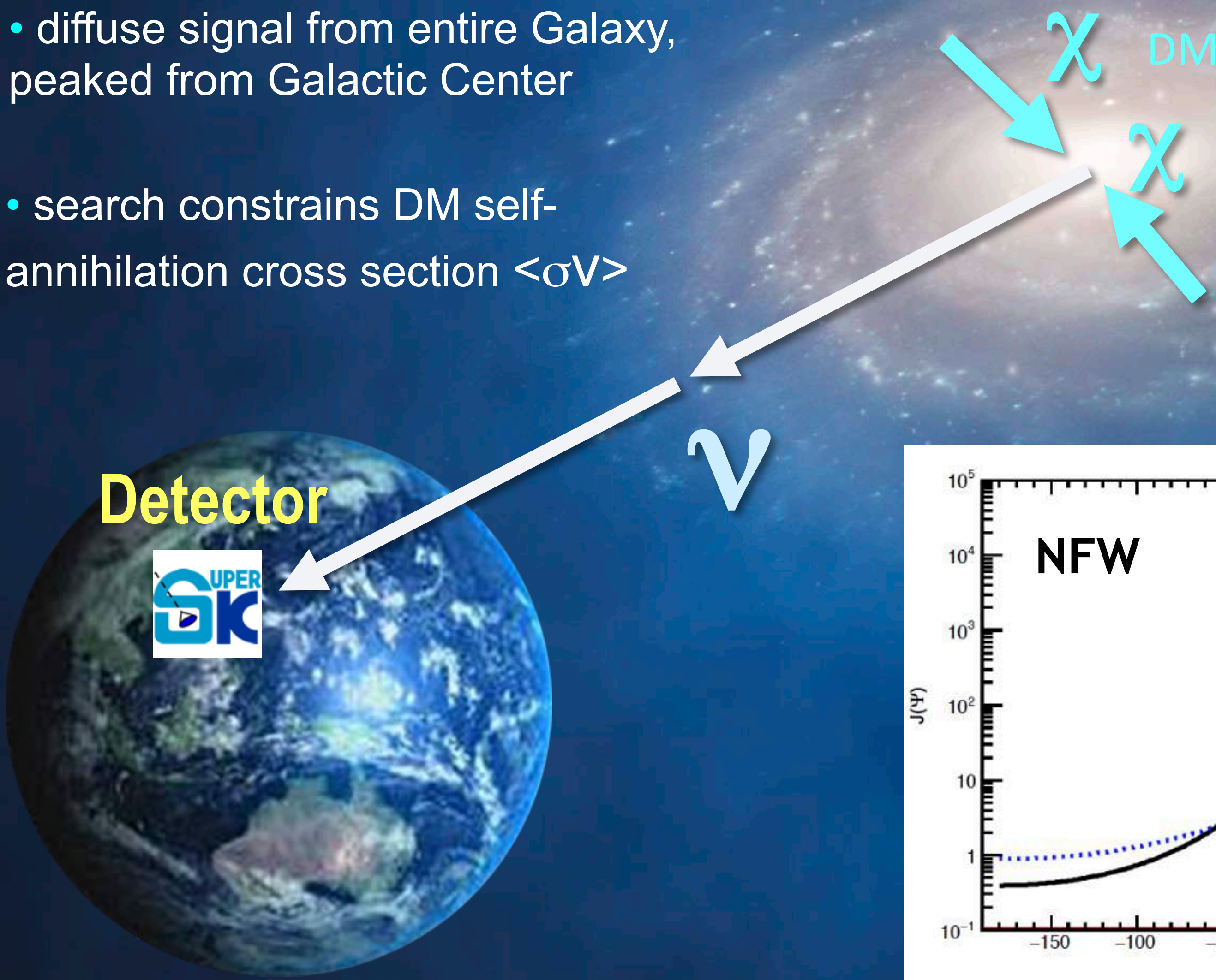
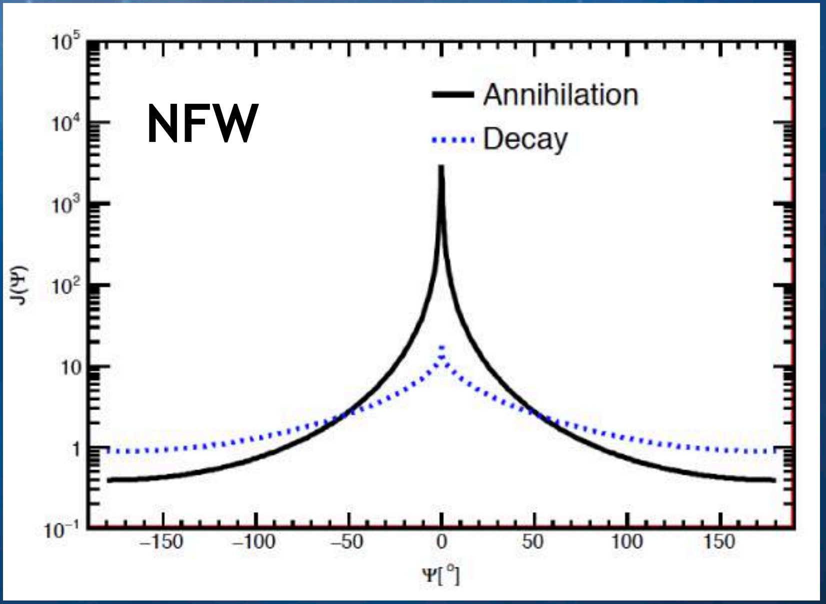
Indirect search for DM from the Galaxy

- diffuse signal from entire Galaxy, peaked from Galactic Center
- search constrains DM self-annihilation cross section <σV>

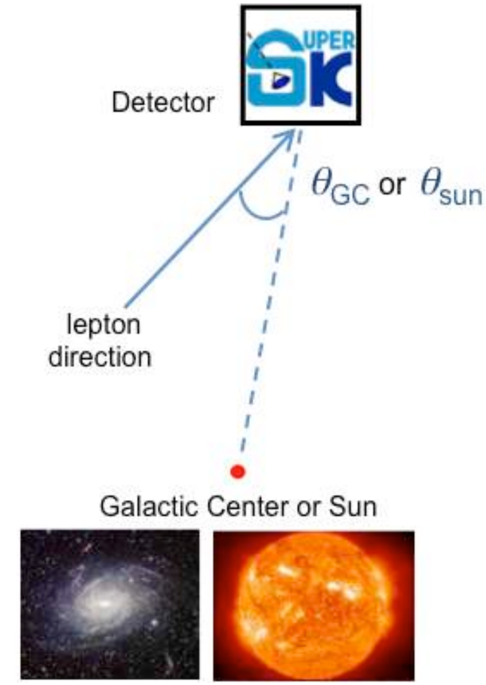




Expected signal intensity

Idea of dark matter searches at Super-K

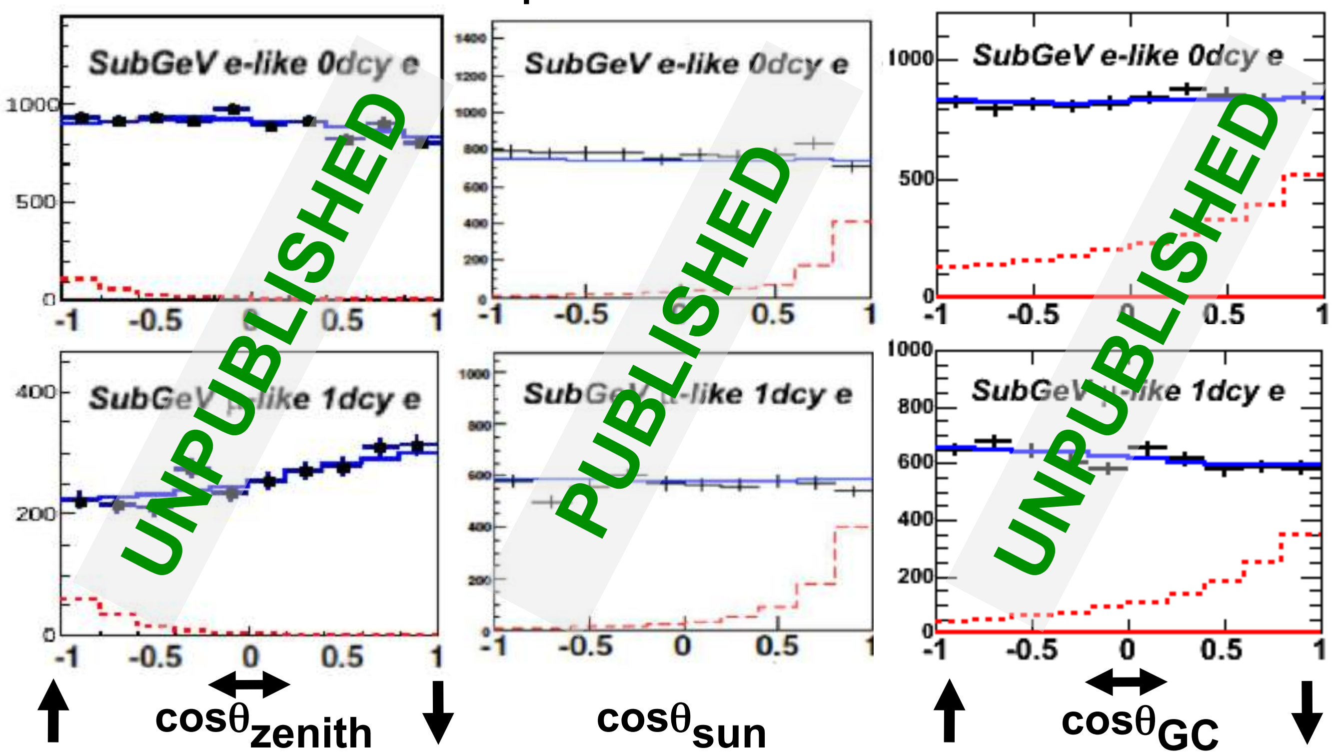
- Search for excess of neutrinos form **Earth/Sun/Milky Way**
- **FIT:** for each tested WIMP mass, find configuration of ATM ν + DM signal that would match DATA the best



Earth WIMP search
diffuse search

Solar WIMP search
point-like search

Galactic WIMP search
diffuse search



Example: $b\bar{b}$ signal before fit shown in 2 data samples

SK DATA

ATM MC (BKG) with oscillations

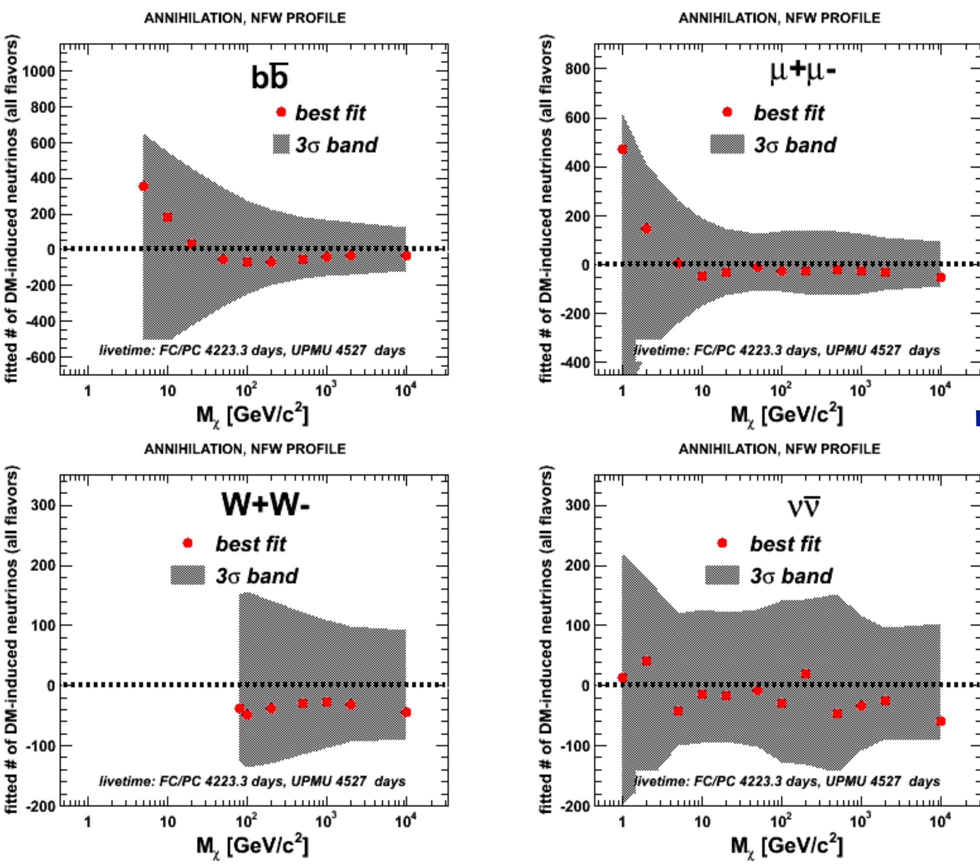
DM signal shape enhanced for illustration

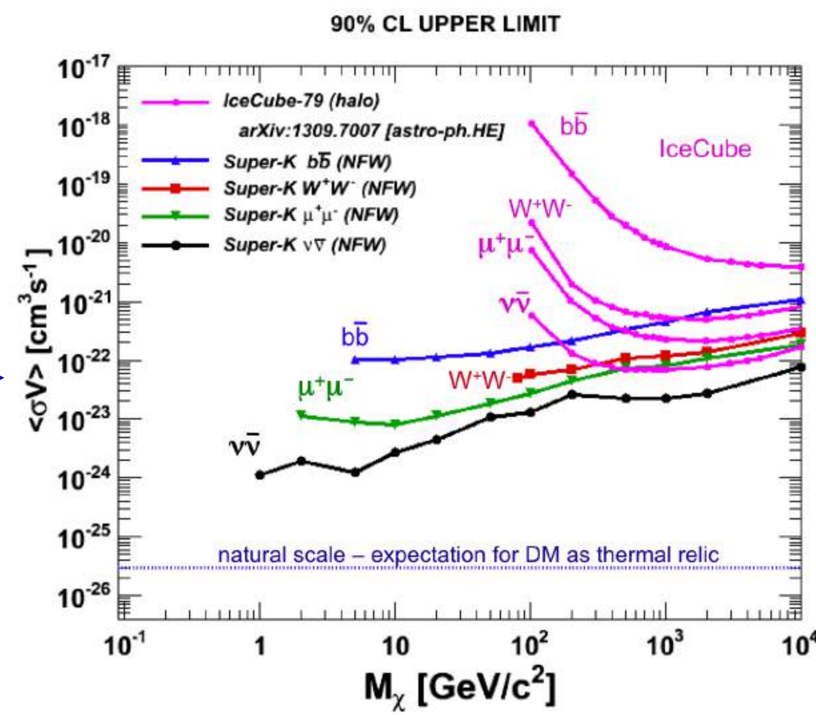
- **In these coordinate systems signal is easy to distinguish from atmospheric neutrino background**

Super-K galactic WIMP search result

100% branching ratio to given annihlation channel is assumed

- FIT based on lepton mom. & $\cos\theta_{GC}$ distributions, 4223 days of SK data used (1996-2014)
- NFW halo model is assumed
- Since fit results consistent with zero we can derive the limit on DM self-annihilation cross section $\langle\sigma V\rangle$

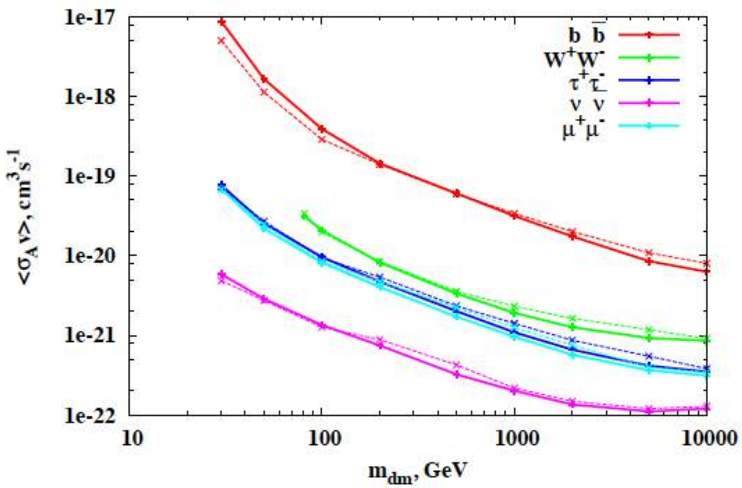




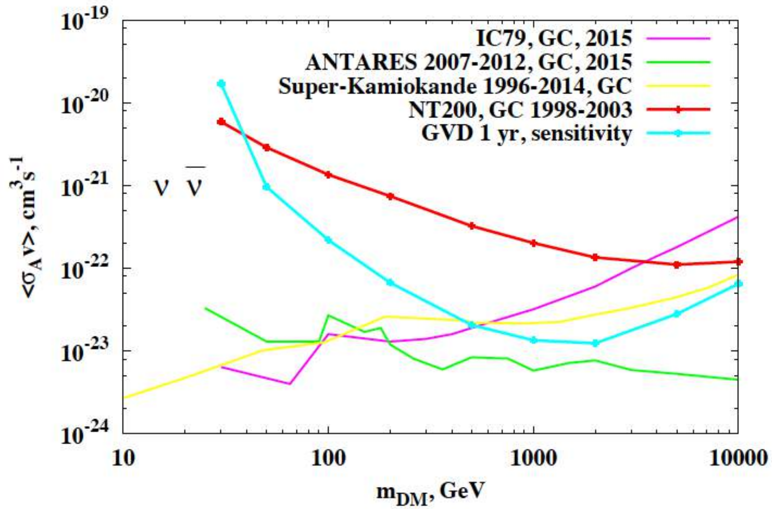
- We still investigate regions <1GeV
- ~150 syst. uncertainty terms included in fit

Limits on DM self-annihilation cross section: other experiments

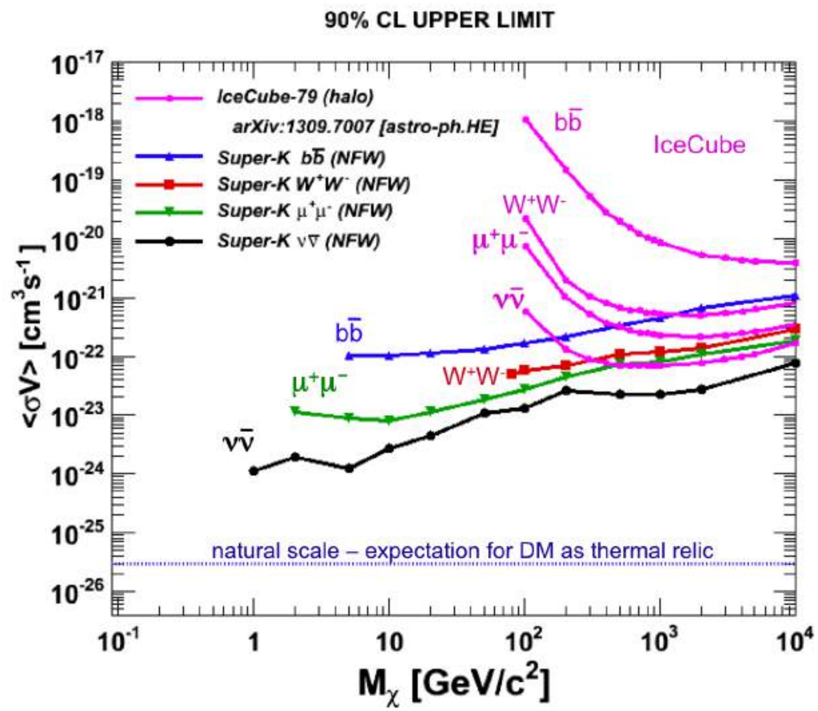
BAIKAL NT-200 limit (Dec'2015)



only for νν-bar

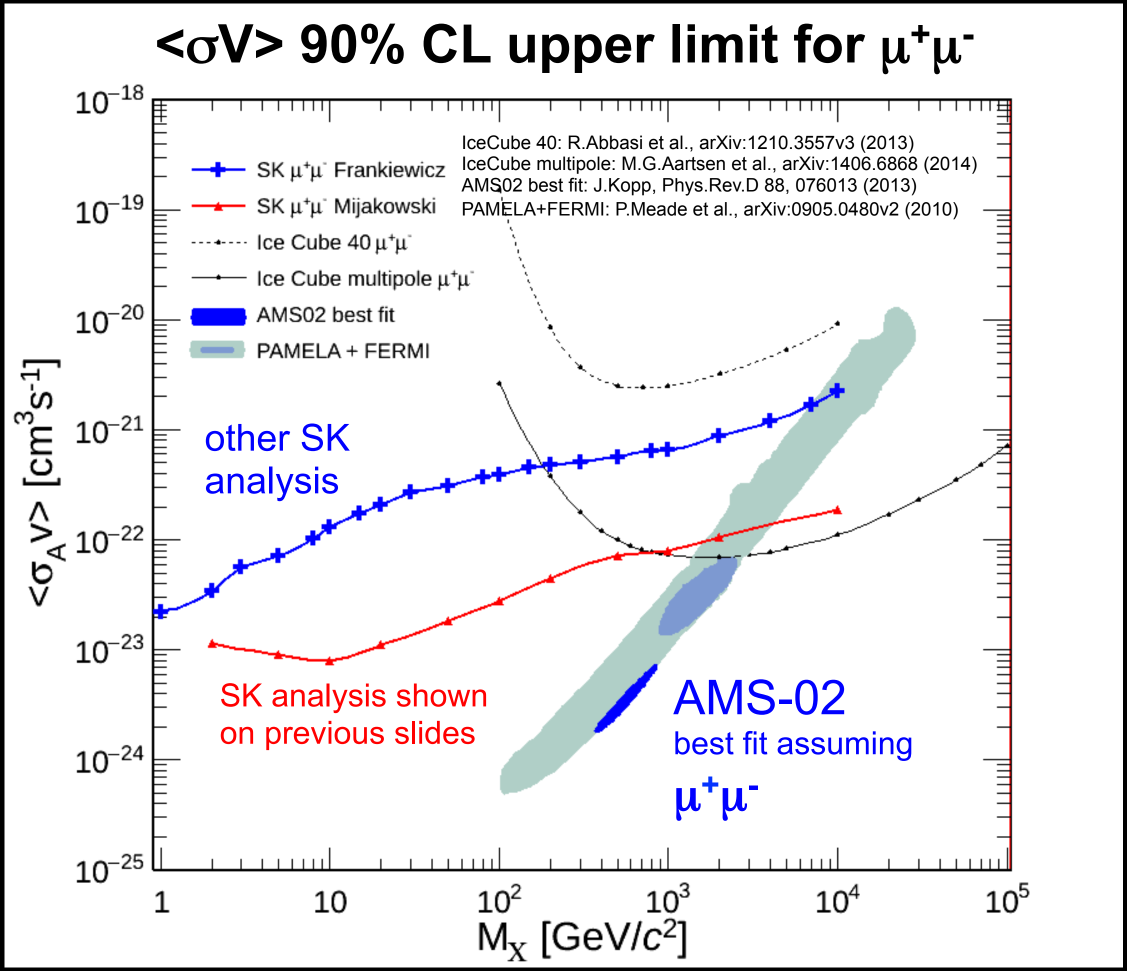


Super-K



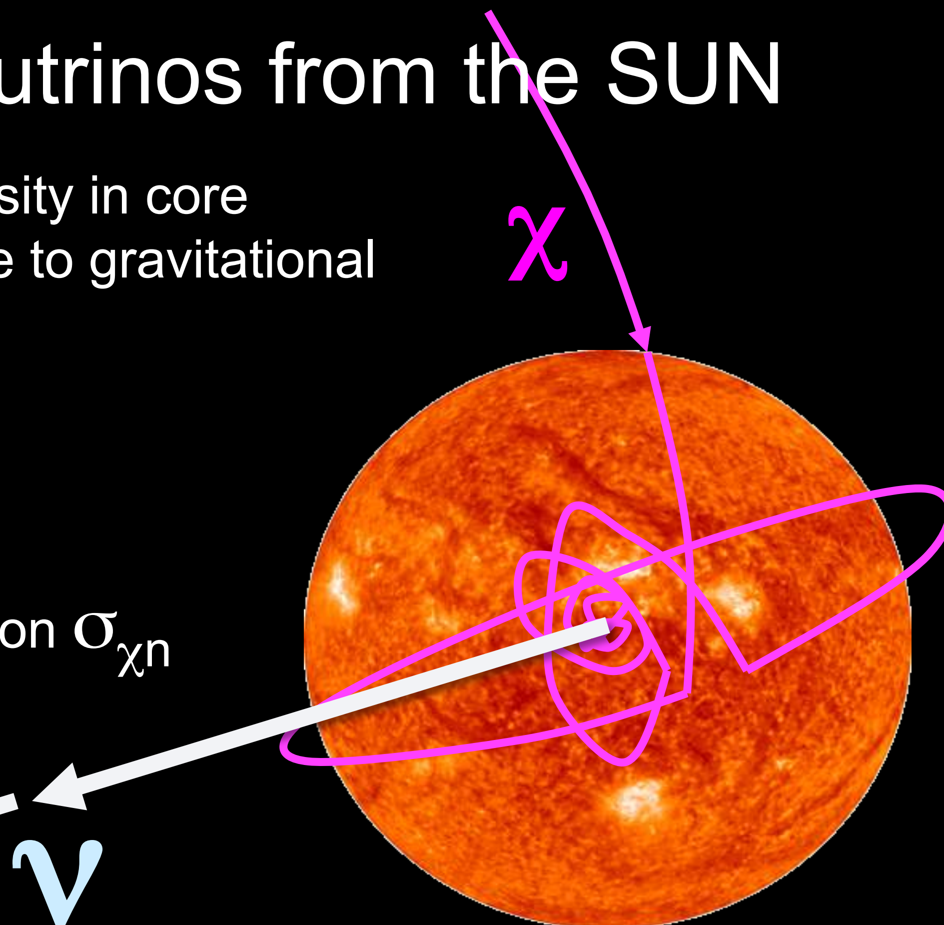
Comparison with AMS-02

- DM annihilation into $\mu^+\mu^-$ may explain positron excess seen by PAMELA/FERMI/ AMS-02
- SK limits for DM ann. in the Milky Way come along



DM-induced neutrinos from the SUN

- expected increased WIMP density in core of massive celestial objects due to gravitational capture
- equilibrium between capture & annihilation rate
- constrain scattering cross section $\sigma_{\chi n}$



related HOT TOPICS: low $M\chi$ positive signal by CoGeNT, Cresst, DAMA

WIMP elastic scattering cross section $\sigma_{\chi N}$ limit
(spin dependent)

- GLOBAL FIT of simulated DM-ind signal to all SK samples → same as in case of galactic search
- Elastic scattering of χ on hydrogen in SUN (spin dependent)
- Equilibrium between χ capture and annihilation rate in the SUN

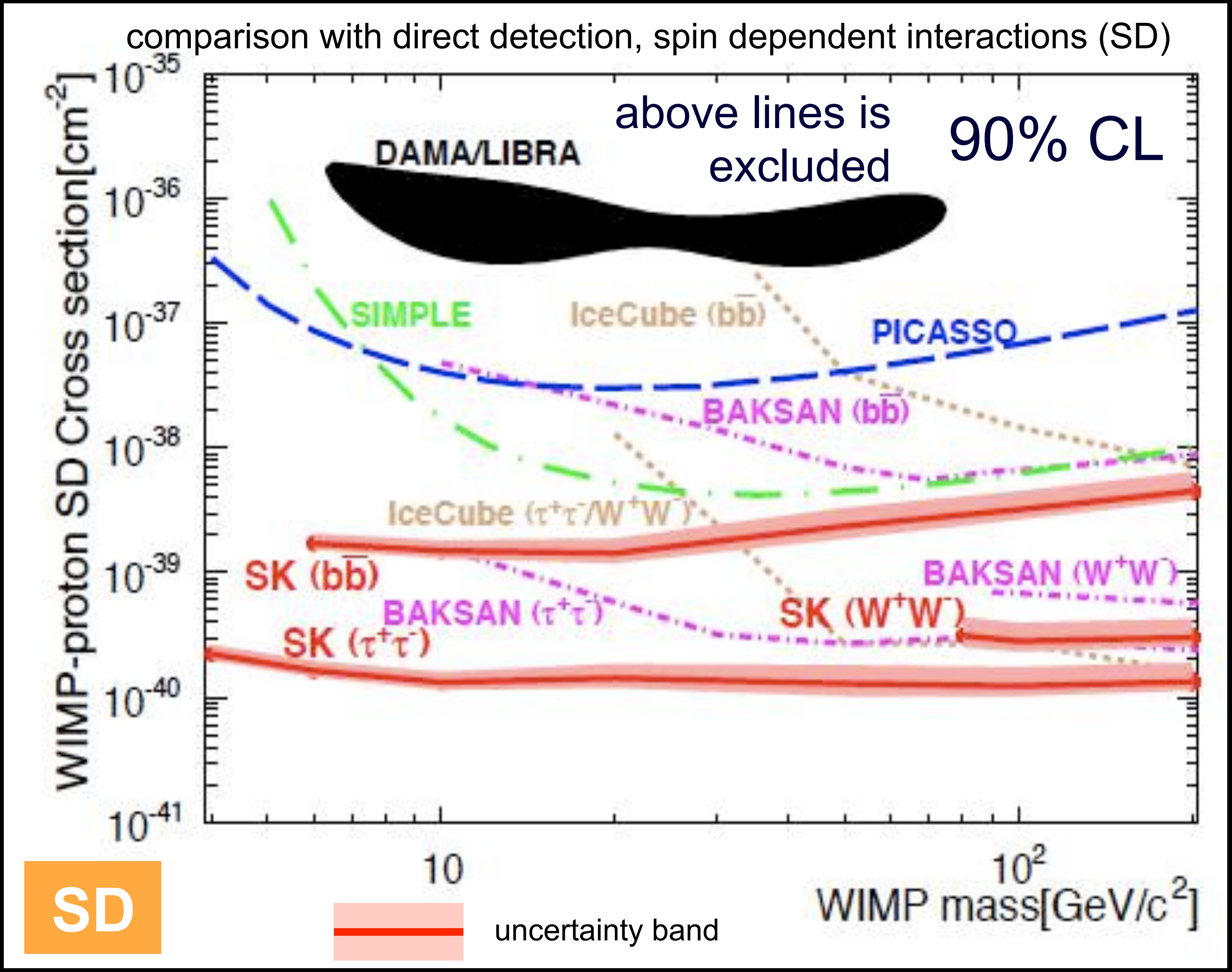
capture = annihilation

↓

depends on $\sigma_{\chi N}$

more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

- DAMA excluded



reference: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

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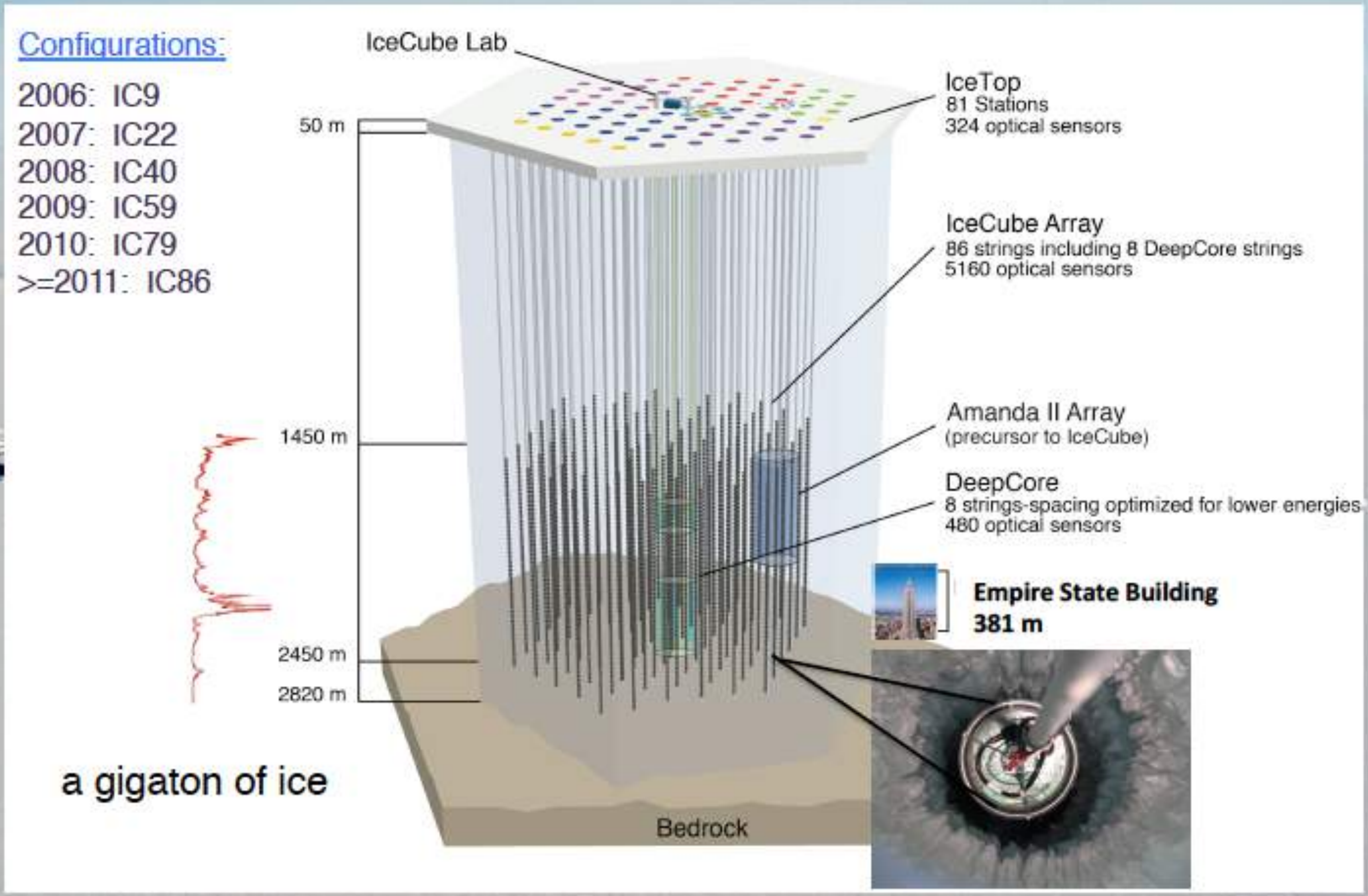
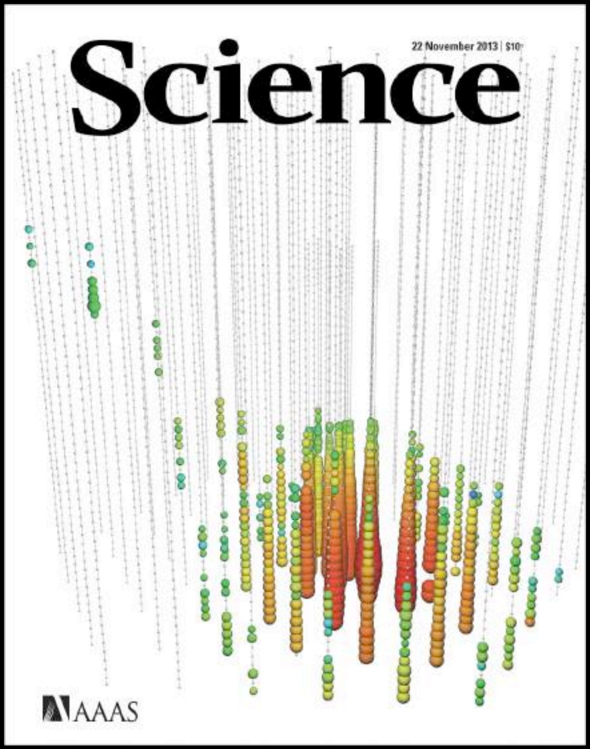
IceCube South Pole Neutrino Observatory

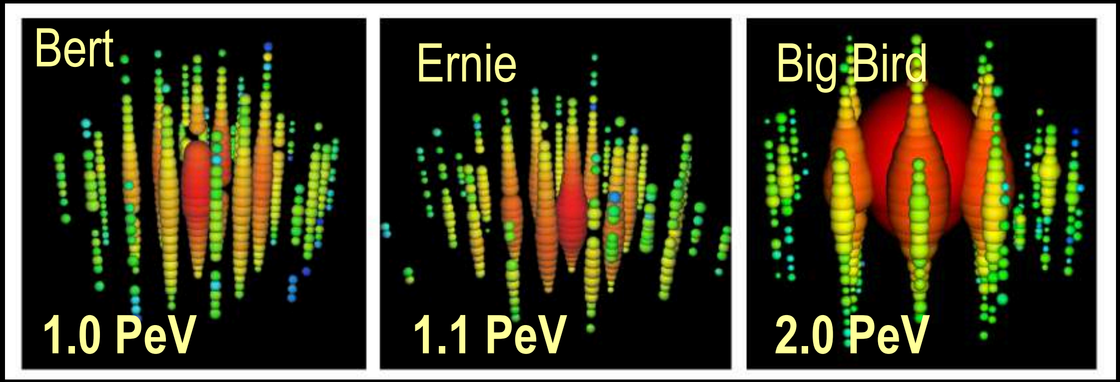
1 km^3 volume of ice, instrumented with optical modules to detect neutrinos



„Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector” Nov/2013

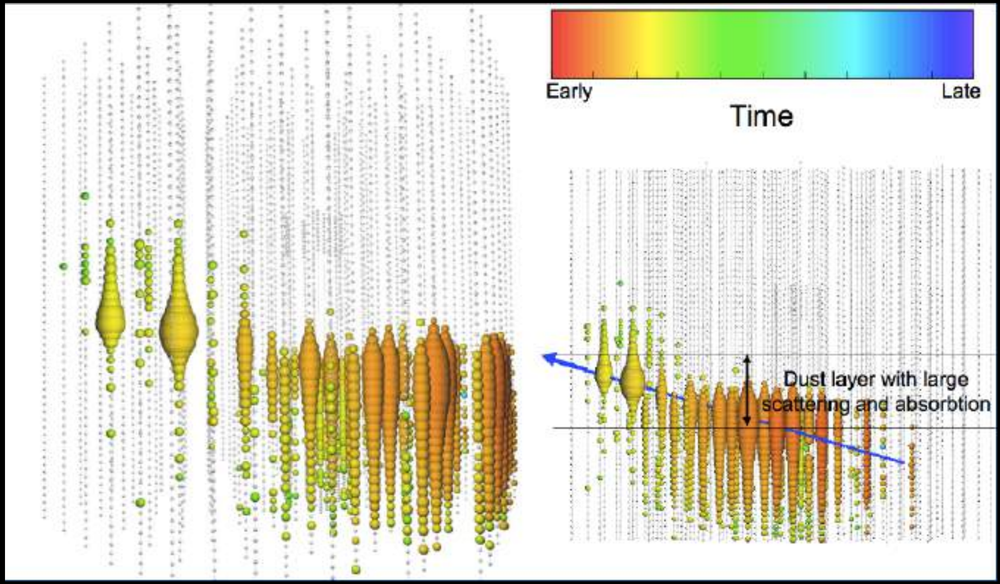


first UHE cosmic neutrinos



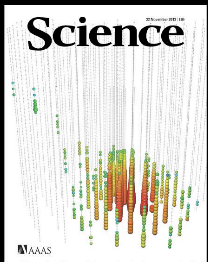
Aug 2011 Jan 2012 Dec 2012

highest energy event (June/11 2014)



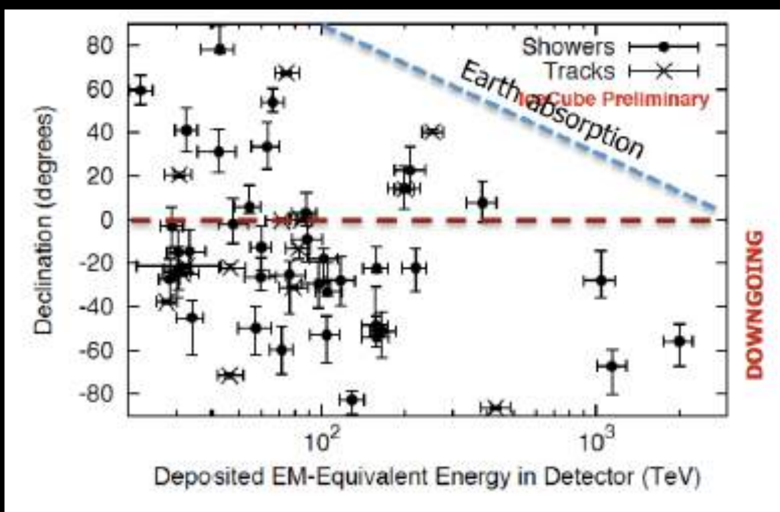
- Deposited energy 2.6±0.3 PeV (lower limit)

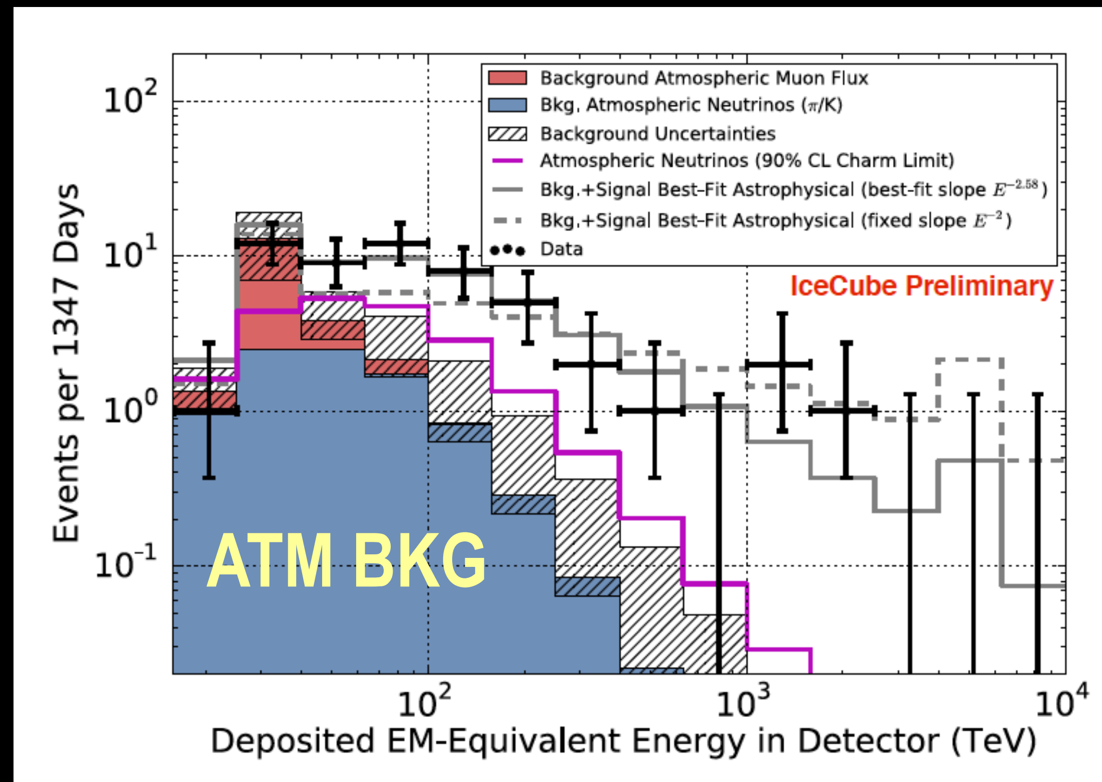
Discovery of Cosmic Neutrinos with IceCube



IC79+IC86 analysis of **2010-2014 data (4 years)** to search for "High Energy Starting Events" (HESE) all-flavor neutrinos

IceCube (4yr) C. Kopper et al, ICRC2015
IceCube (3 yr), Phys. Rev. Lett.; arXiv:1405.5303
IceCube (2 yr), Science 22 Vol. 342 no. 6161

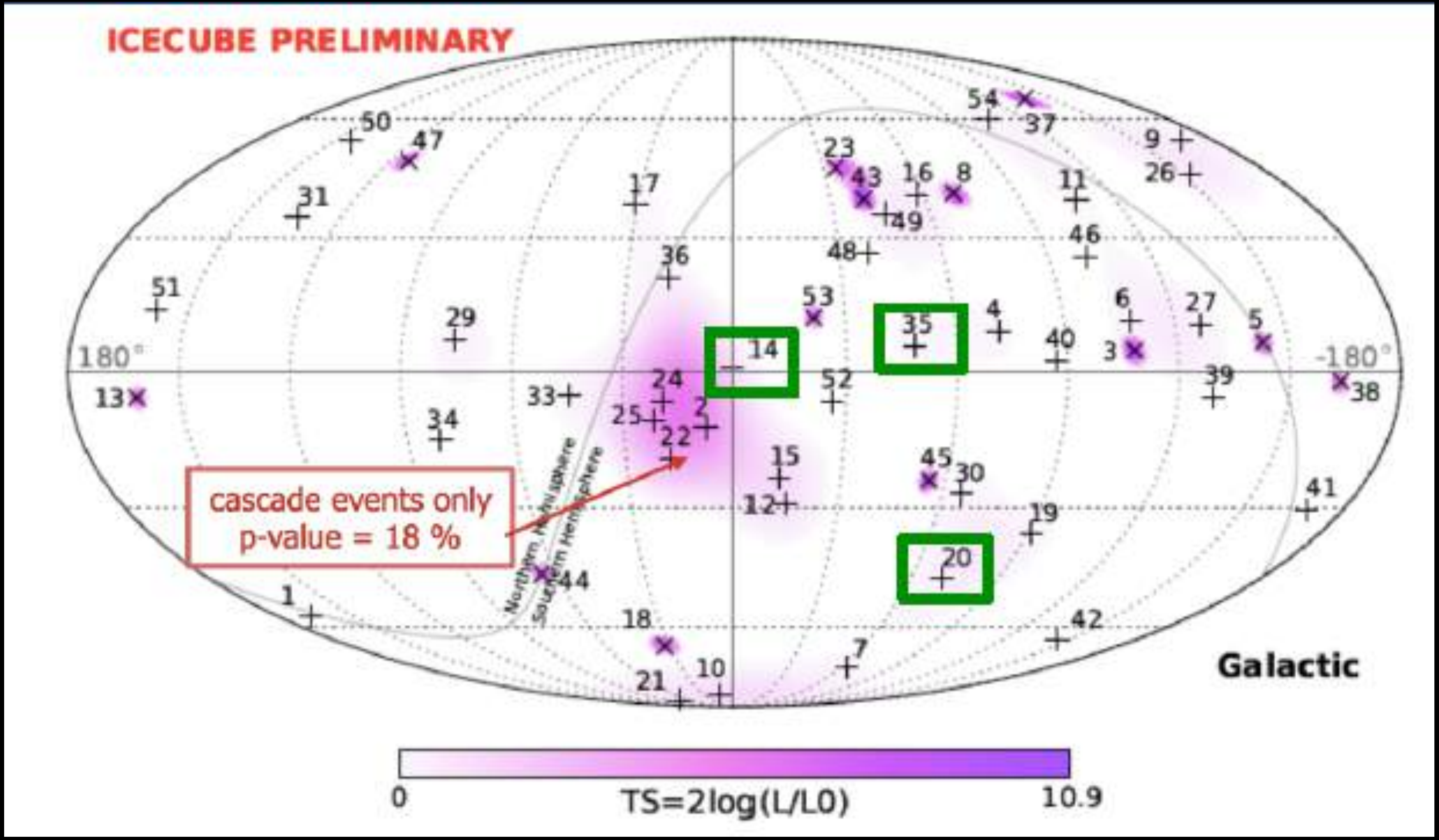




- **54** events in 1347 days (4yr)
- Astro. signal dominates at E > 60 TeV
- Significance: **7σ**

Discovery of Cosmic Neutrinos with IceCube: where are they coming from?

IceCube (4yr) C. Kopper et al, ICRC2015
Observed 54 events (tracks and cascades)

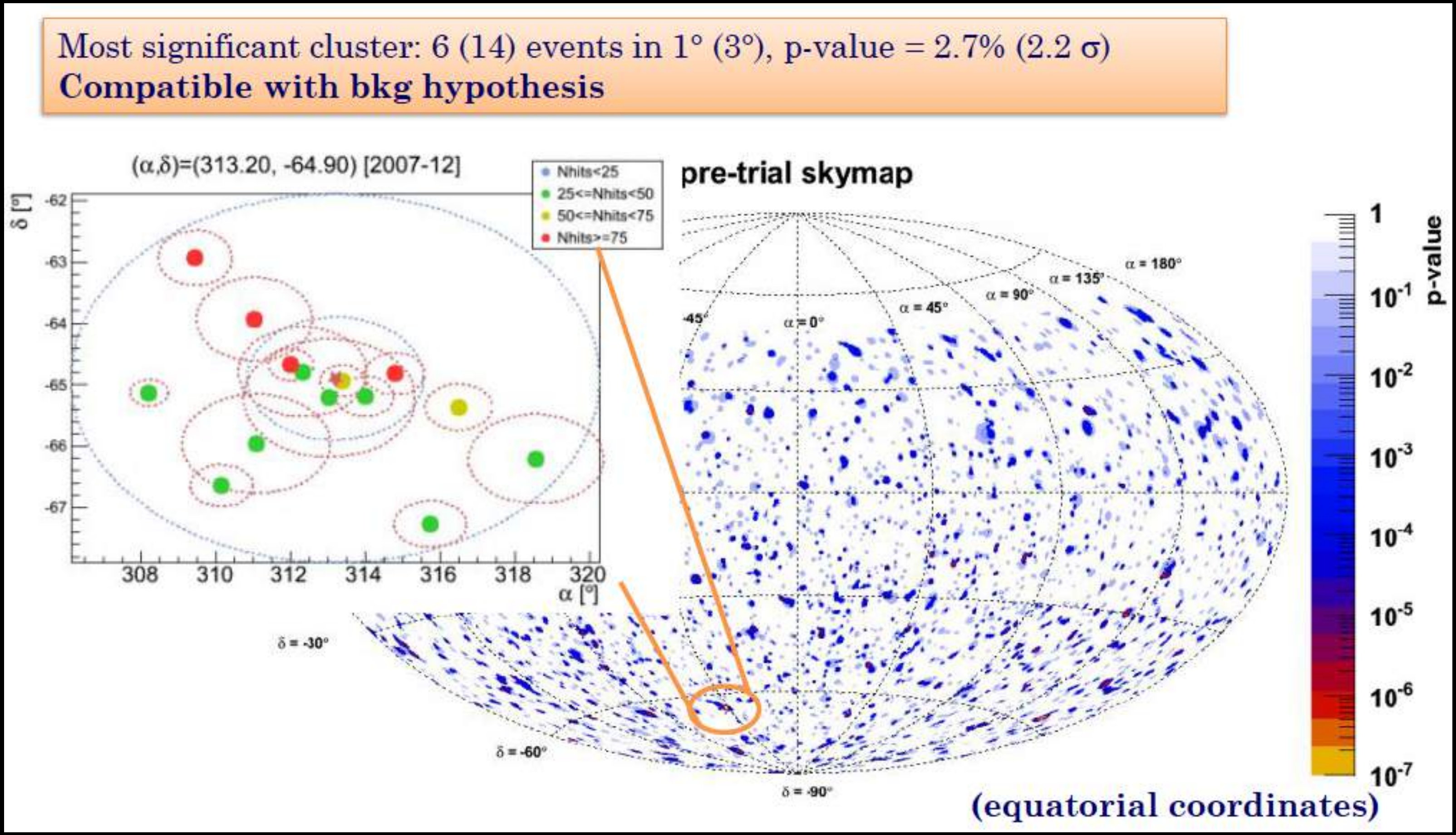


- No evidence of (significant) correlation (neither spacial nor temporial e.g. GRB's)

Point-like source neutrino searches

All-Sky search: Search for excess of astrophysical ν from a common direction over the background of atmospheric ν

ANTARES (2007-2012)



- Cosmic neutrinos observed at IceCube
- No evidence for a point / extended source

Questions:

- Where are the point sources?
- What is their spectrum? Production mechanism? What is the flavor composition?
- GZK neutrinos?

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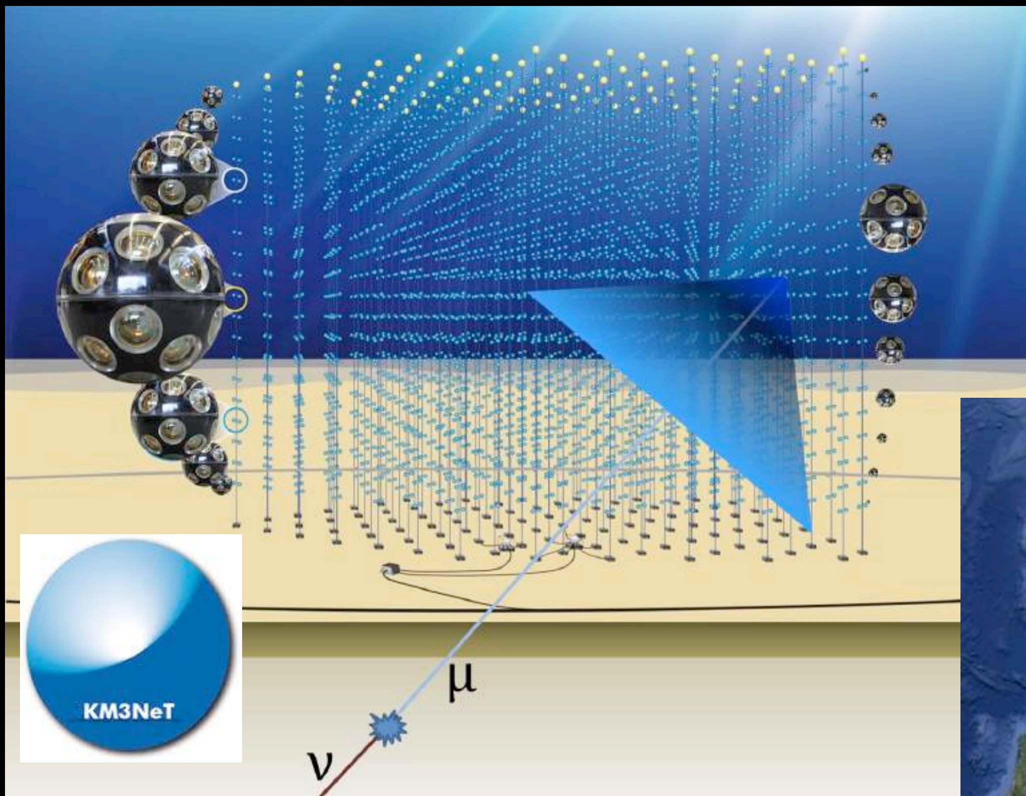
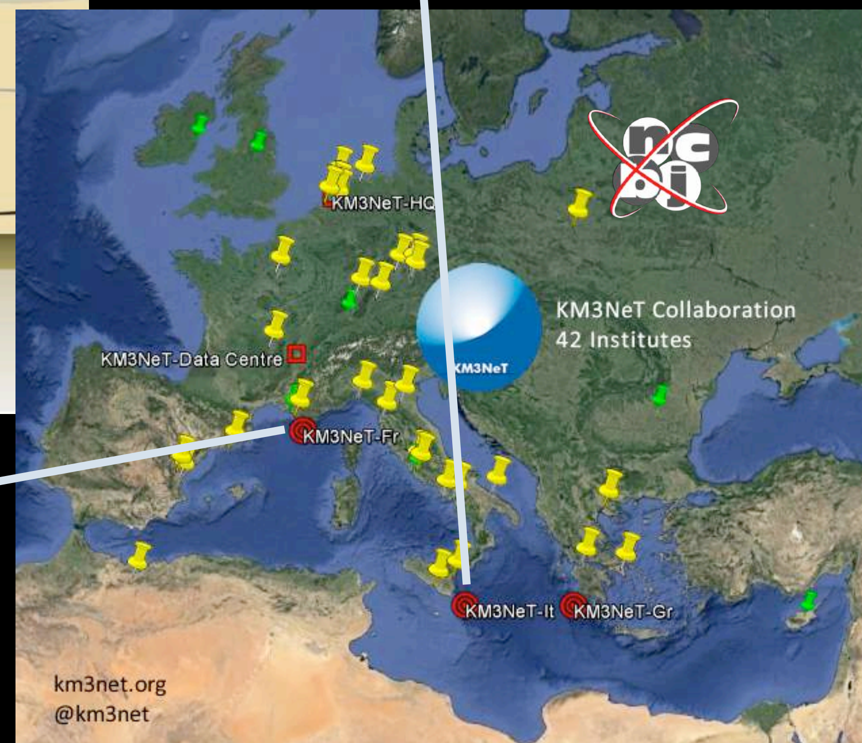
Future: KM3NeT

- Modular neutrino research infrastructure the Mediterranean Sea (aim for several km^3)
- 2 parts: ARCA & ORCA
- ARCA: Astroparticle Research with Cosmics in the Abyss, IT





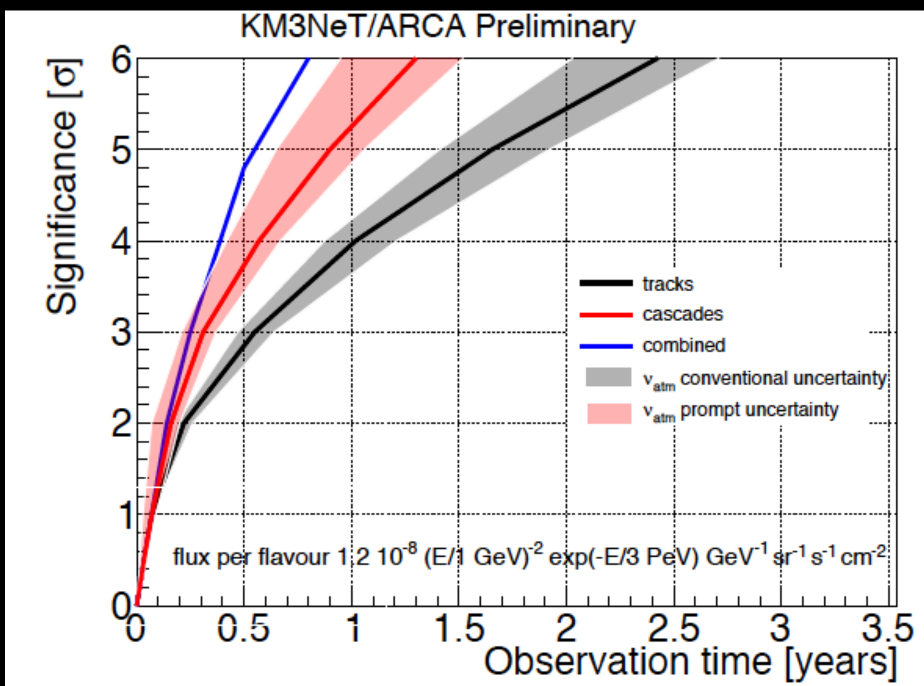
- ORCA: Oscillation Research with Cosmics in the Abyss, near FR coast
- KM3NeT selected for the 2016 ESFRI Roadmap!
- Open positions in our group to work on this project!

Future: KM3NeT

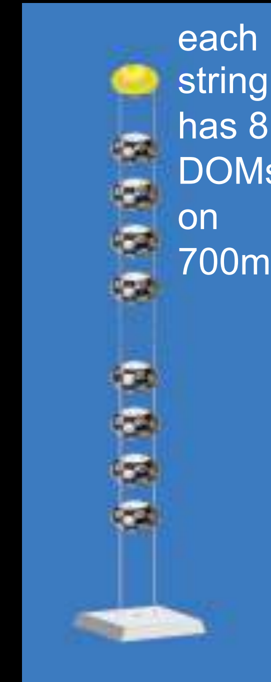
ARCA

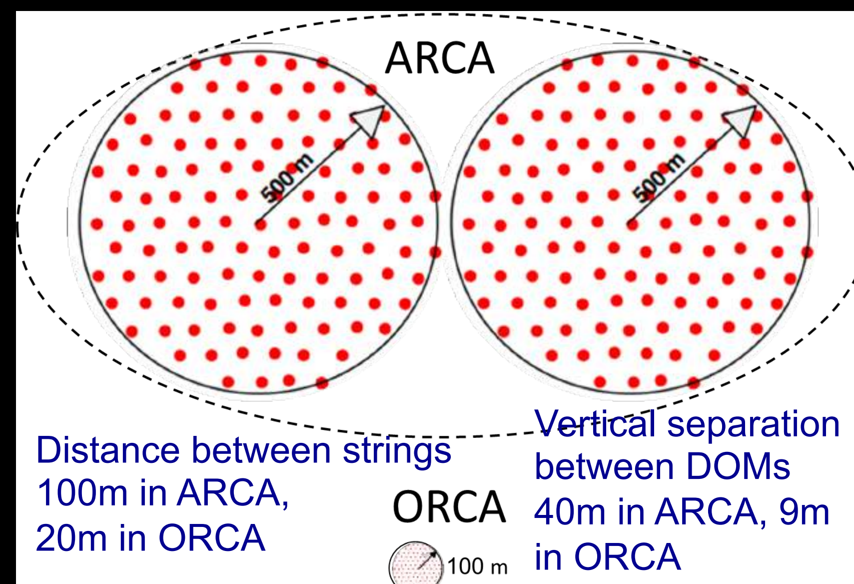
- HE ν astronomy
- 1st stage: 30 strings in KM3NeT-IT (Sicily) already funded, 3rd string under deployment! $0.1 km^3$
- next stage: 2x115 strings, $1 km^3$, final: several km^3

expected confirmation of IceCube cosmic neutrino diffuse flux observation



each Digital Optical Module (DOM) contains 31 PMTs





Distance between strings 100m in ARCA, 20m in ORCA

Vertical separation between DOMs 40m in ARCA, 9m in ORCA

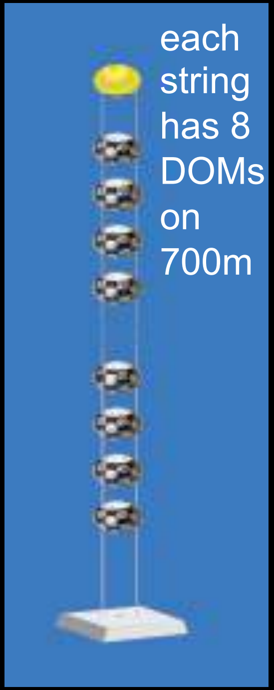
Future: KM3NeT

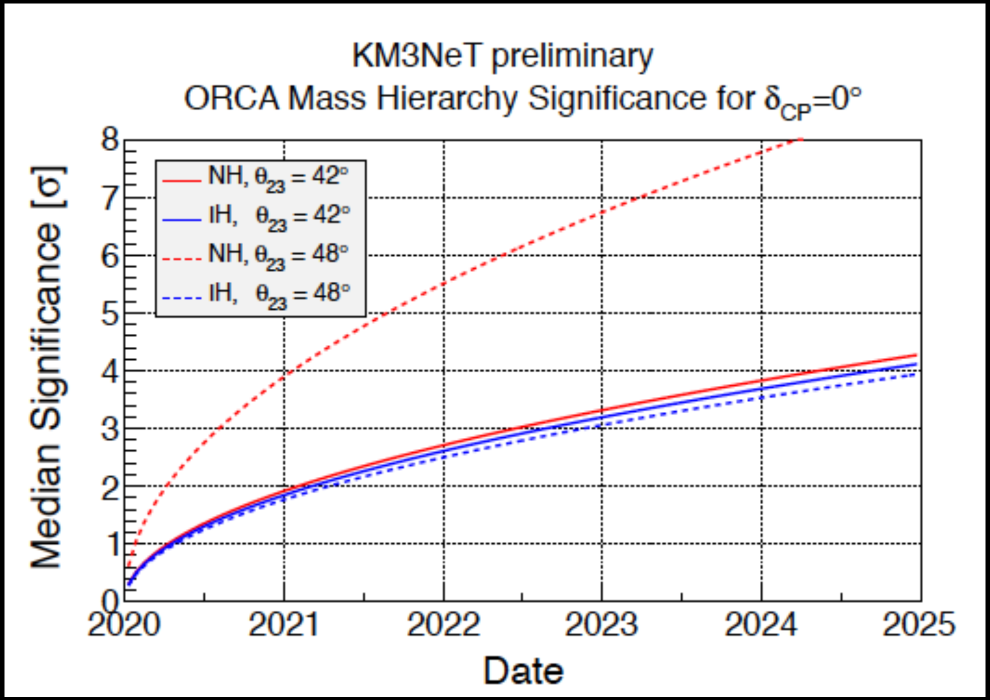
ORCA

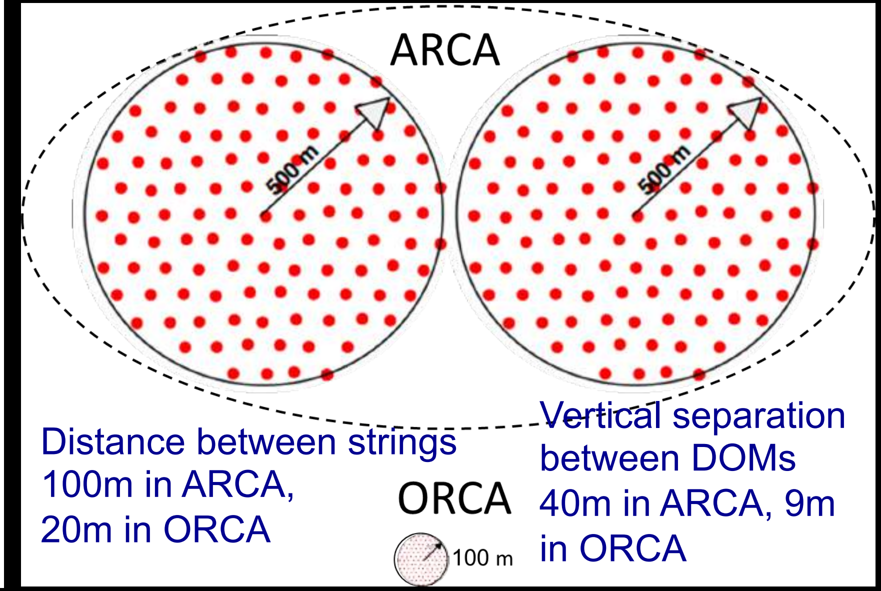
- study of atmospheric ν
- 1st stage: 7strings in KM3NeT-FR (Toulon) already funded and under construction
- next phase: 115 strings, $0.5km^3$, 3.7Mton

If fully funded, ORCA could be the first experiment to determine neutrino mass hierarchy

each Digital Optical Module (DOM) contains 31 PMTs



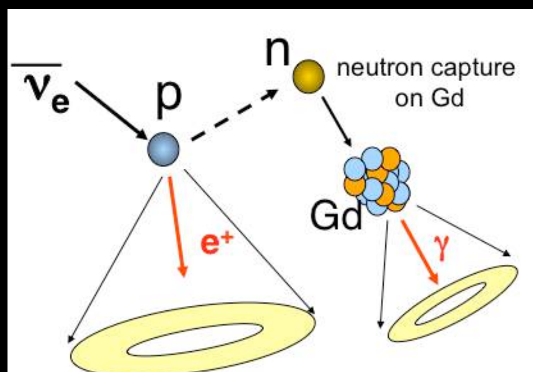




Future: SK-Gd/Gadzooks!

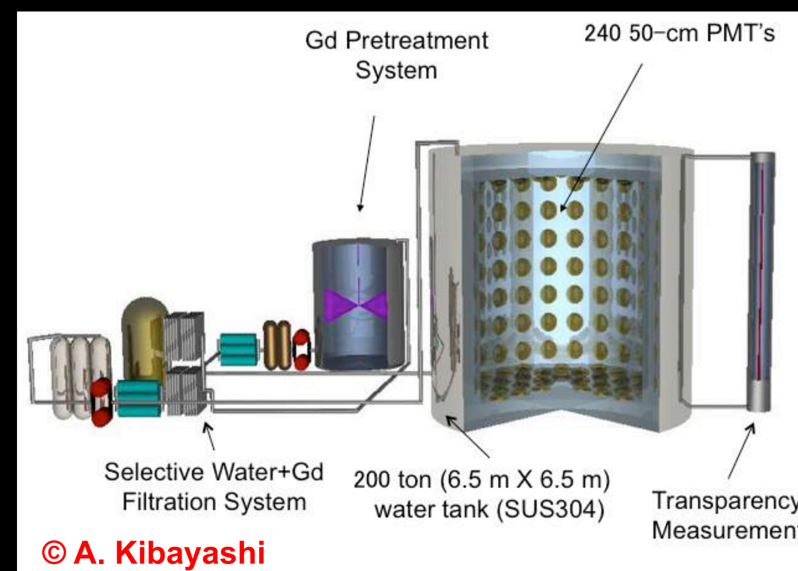
Project approved by Super-K collaboration in June/2015! Join us to work on it!

- Disolve Gd compound in Super-K water, that will increase sensitivity to SN anti-ν which is limited currently by background



- Possibility to discover diffuse SN background neutrinos by coincidence reaction with n capture (up to ~5 events/ year at Super-K & ~800 evts at Hyper-K)
- Precision measurement of reactor neutrinos (constrains on Δm^2_{12})
- Test facility EGADS already taking data

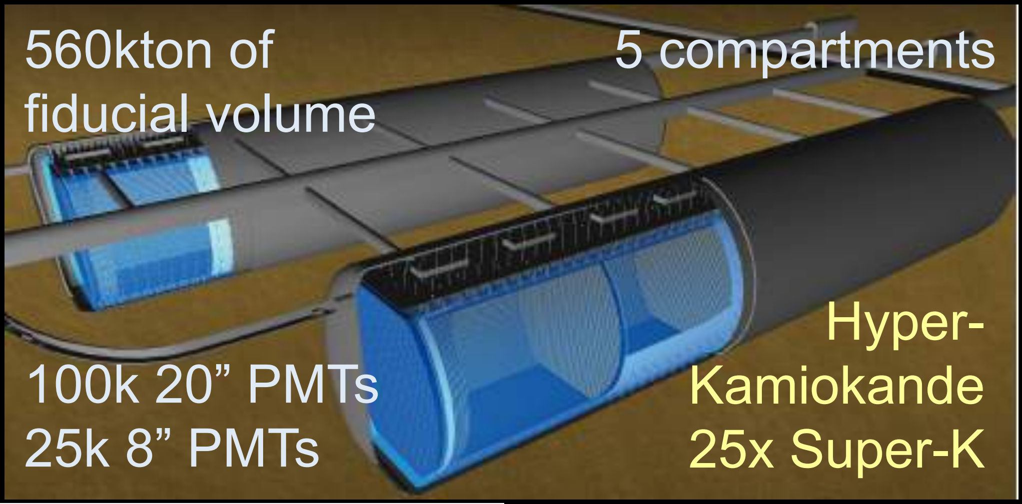
EGADS facility already in operation at Kamioka Obs.



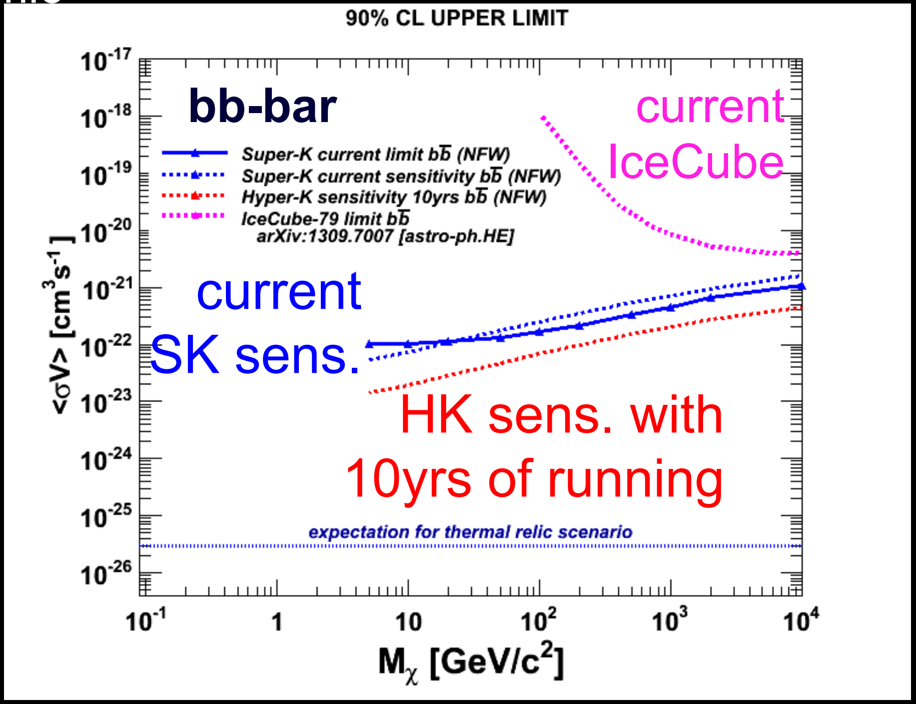
Future: Hyper-Kamiokande

Hyper-Kamiokande

- start 2024 (after 7 years construction)
- main goal: neutrino mass hierarchy and δCP
- some astro potential: SN, DSNB (~2evts per day), WIMPs, cosmic neutrinos



- In galactic WIMP search sensitivity ~1 order of magnitude improvmnt after 10 yrs of Hyper-K running



SN physics: Hyper-K will be sensitive to neutrinos from Galactic SN (~250k evts in ~10 s for SN burst at the GC happening a few times/ century), nearby supernovae (~25 interactions for SN at Andromeda) and distant supernovae (~100 interactions/year, up to Z ~ 1)

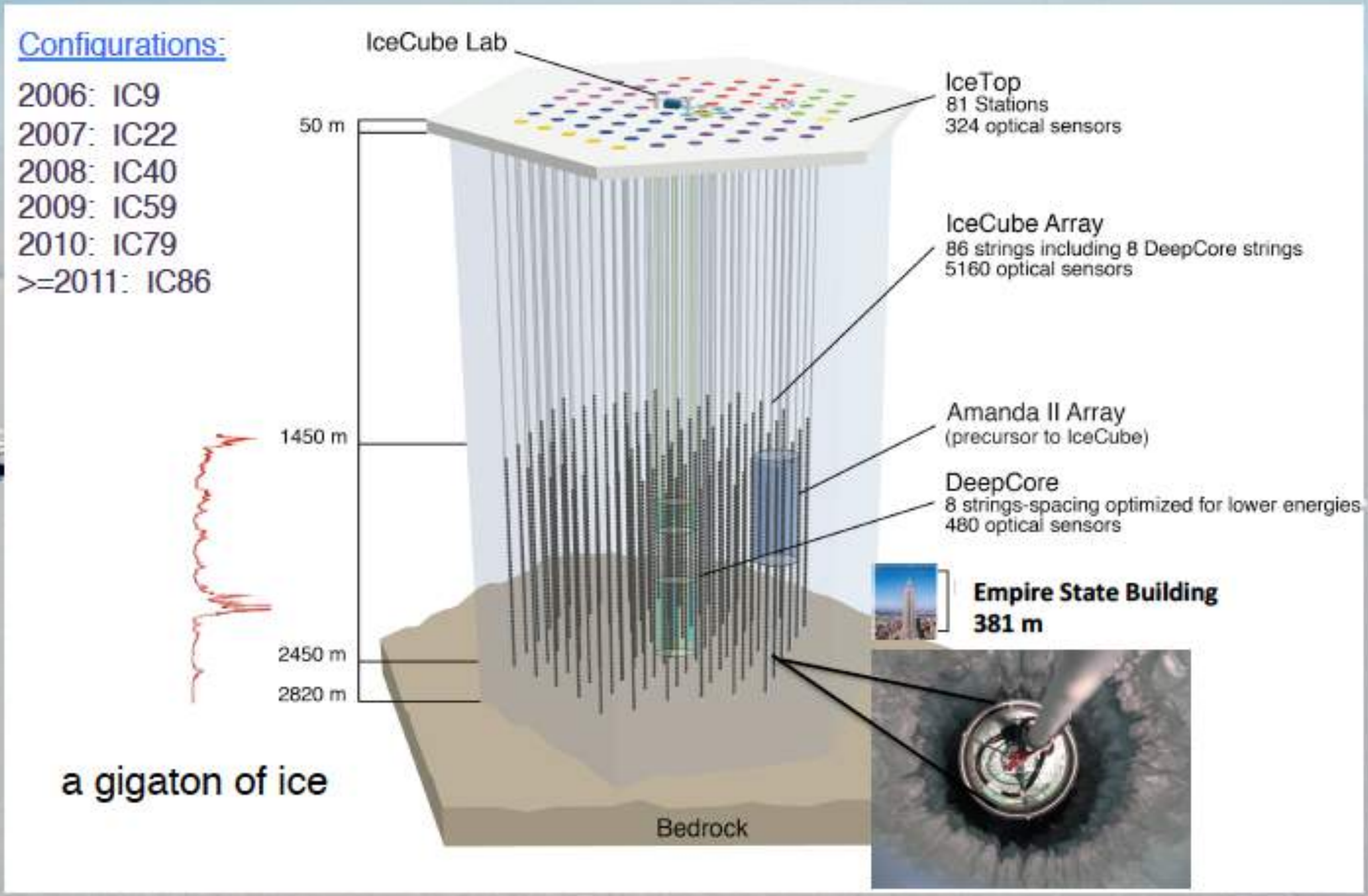
Summary

- Neutrinos open a new window to the Universe
- Exciting experiments ongoing and even more exciting in preparation
- Join us in this activities: open positions in Warsaw Neutrino Group (NCBJ) for post-doc and PhD students (SONATA BIS) for work at Super-Kamiokande/Hyper-K & KM3NeT (mostly DM-indirect searches)

supplementary
slides

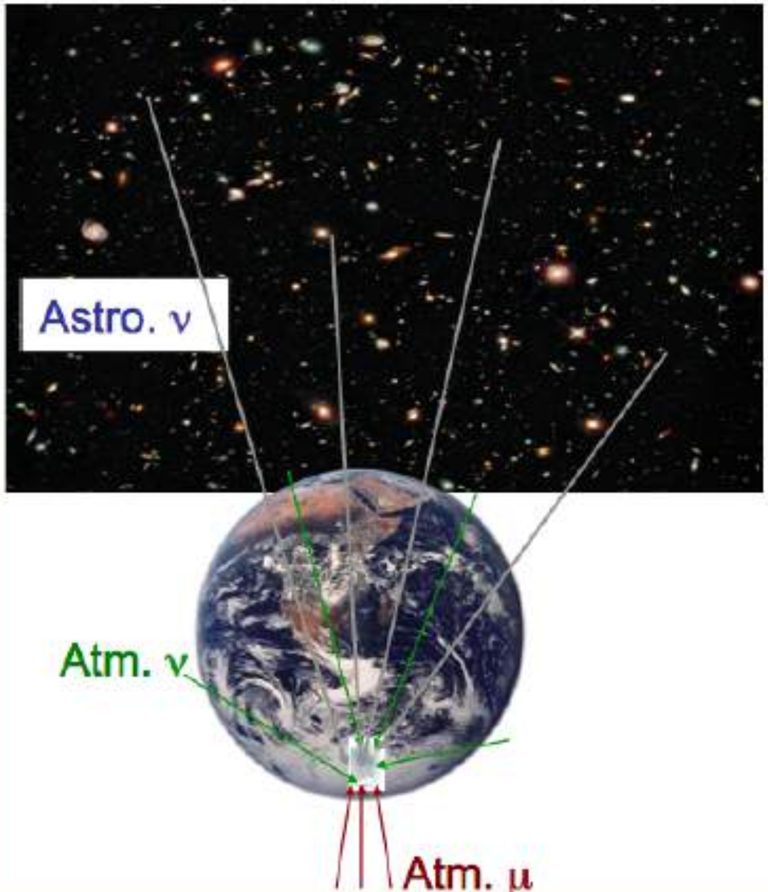
IceCube South Pole Neutrino Observatory

1 km^3 volume of ice, instrumented with optical modules to detect neutrinos

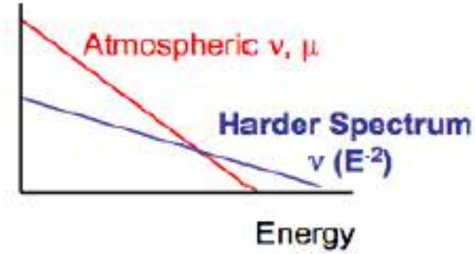


Neutrino diffuse cosmic flux search method

Diffuse flux = *effective sum from all (unresolved) extraterrestrial sources (e.g.AGNs)*
Possibility to observe diffuse signal even if flux from an individual source is too small to be detected by point source techniques.



- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos using energy and direction (self-veto)

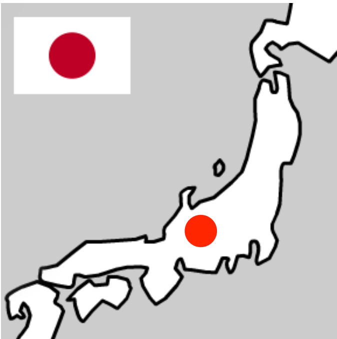


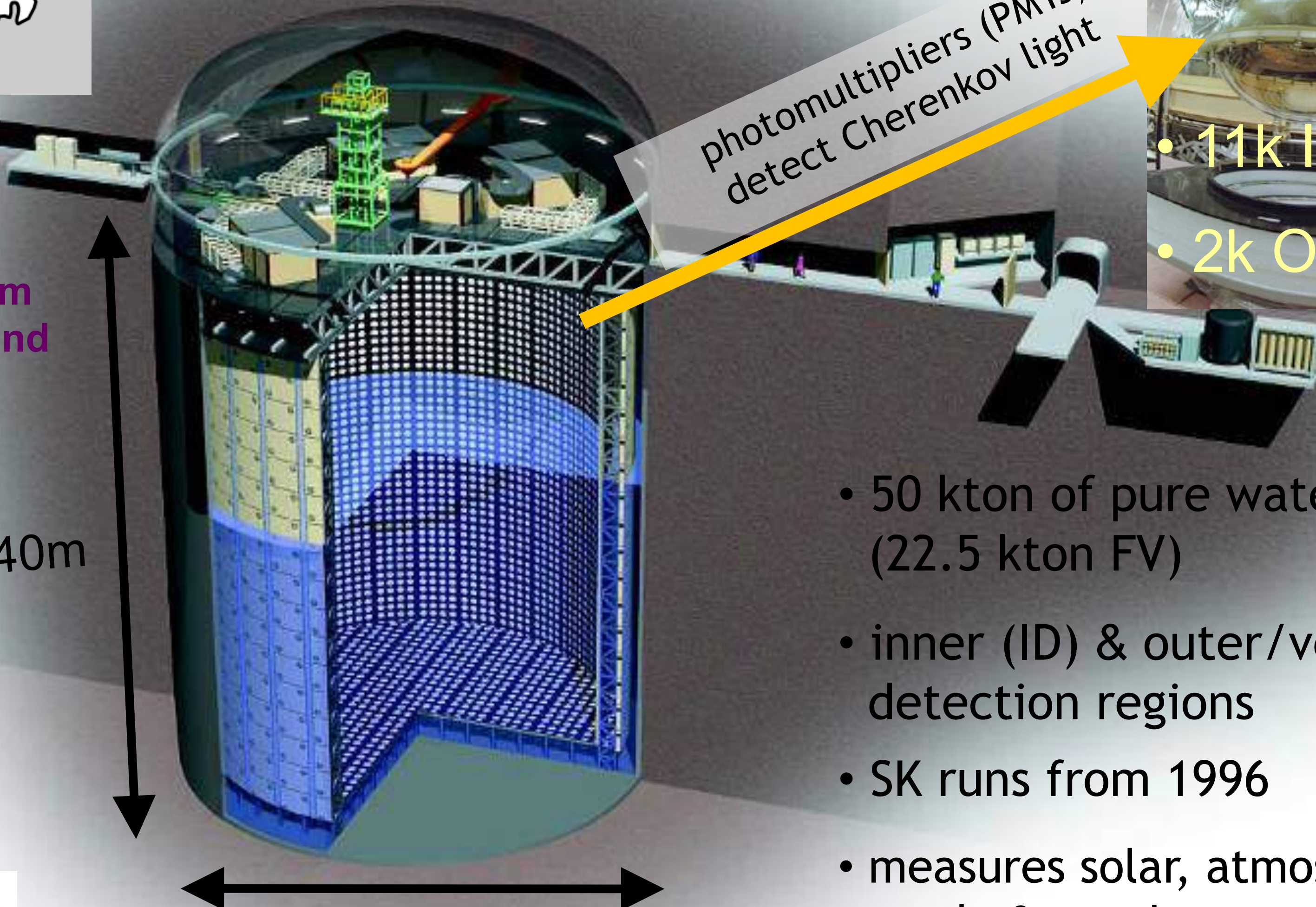
- Advantage over point source search: can detect weaker fluxes
- Sensitive to all three flavors of neutrinos
- Disadvantage: high background
  solution: containment cut / veto technique

by J.Kiryluk (IceCube)

Super-Kamiokande

@ Kamioka Observatory (ICRR, University of Tokyo), Japan



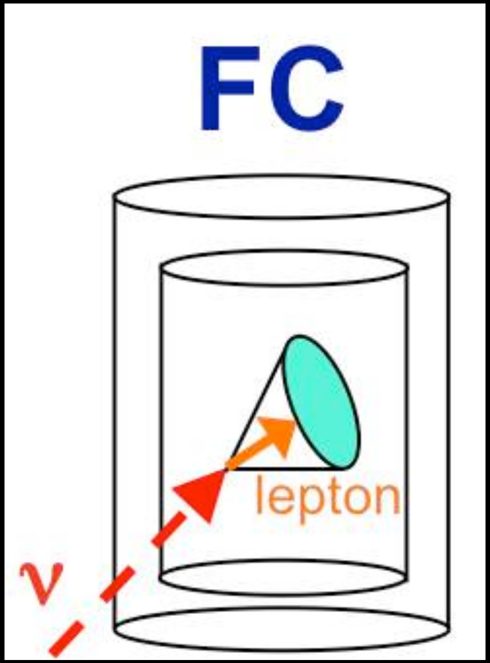


located 1km underground

- 50 kton of pure water (22.5 kton FV)
- inner (ID) & outer/veto (OD) detection regions
- SK runs from 1996
- measures solar, atmospheric, cosmic & accelerator neutrinos
- Far detector of **T2K**

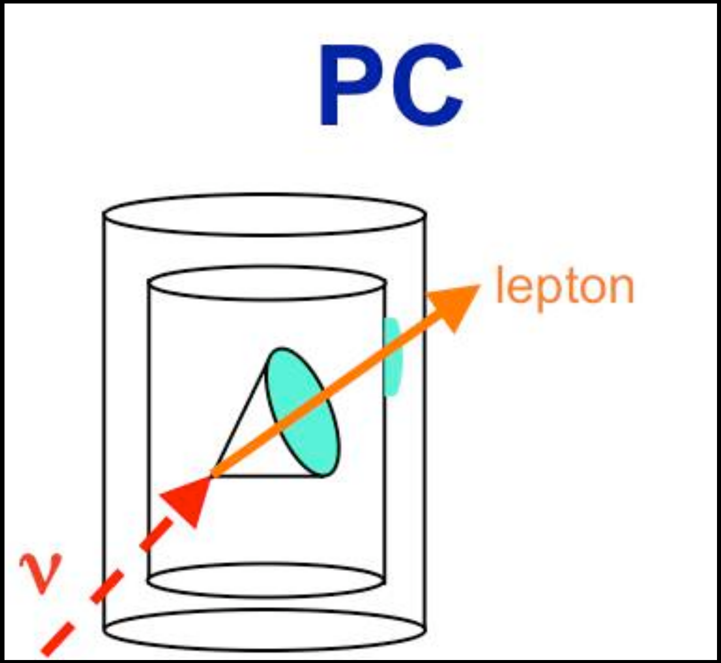
Super-K data samples

Fully-contained



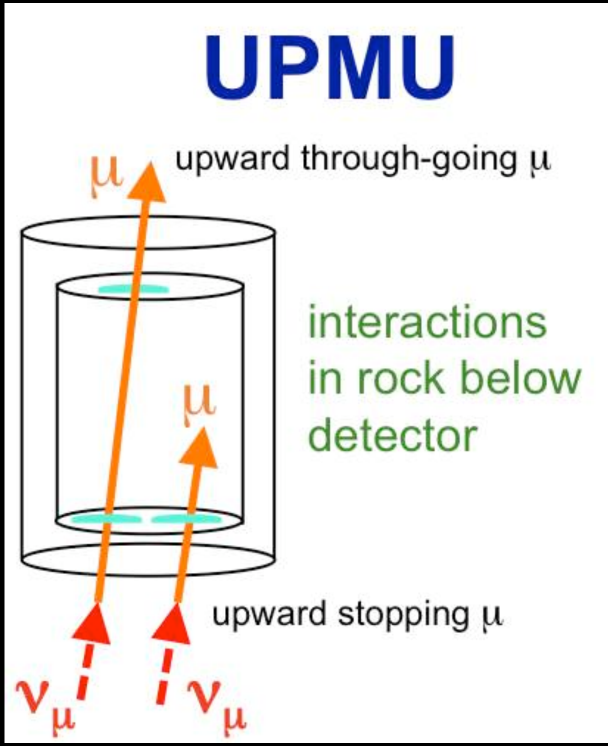
- » ν energy reconstruction
- » ν direction info
- » e/μ identification possible

Partially-contained



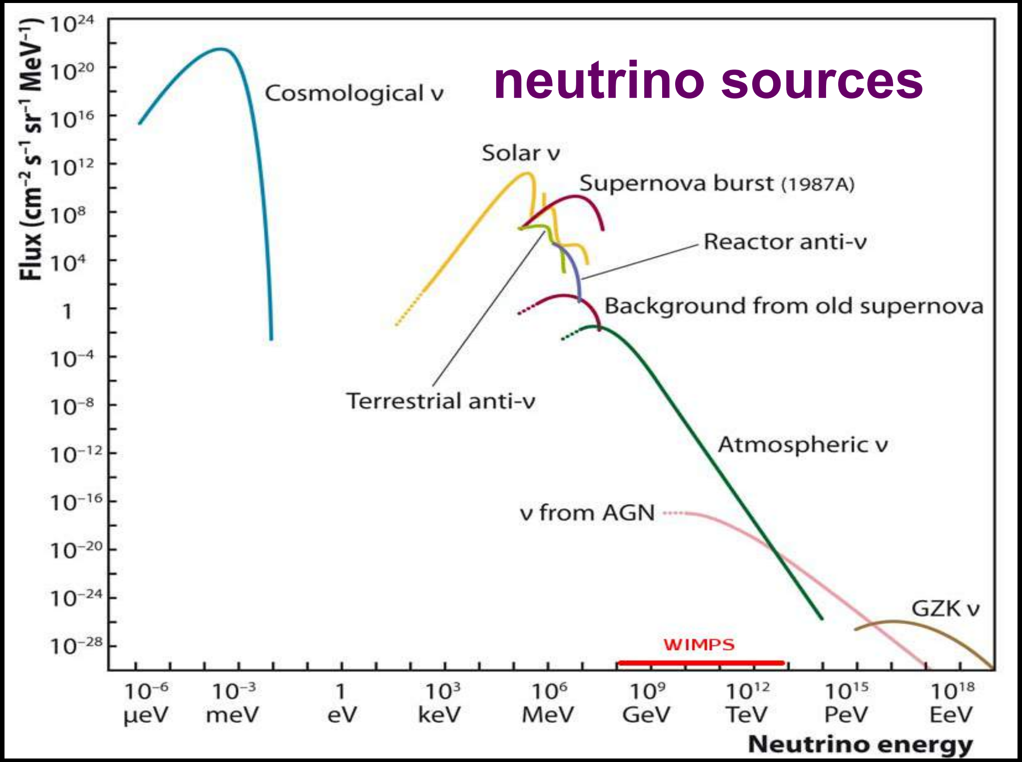
- » partial E_ν info (lepton leaves detector)
- » ν direction info

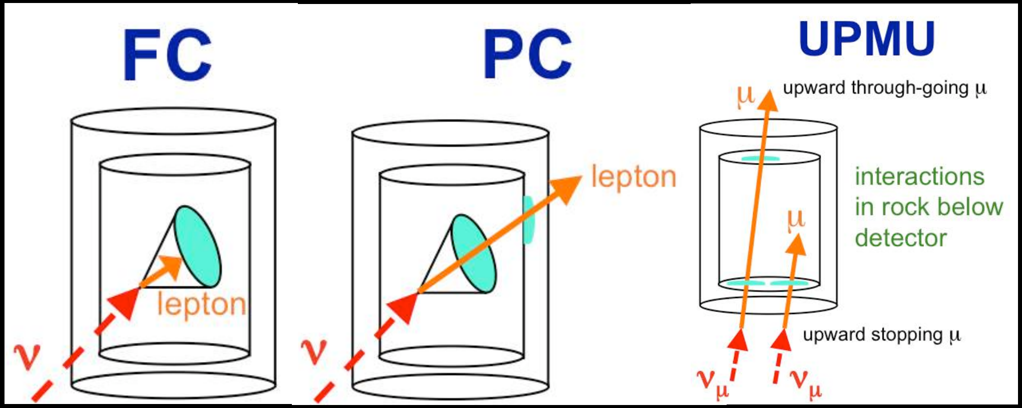
Upward-going muons



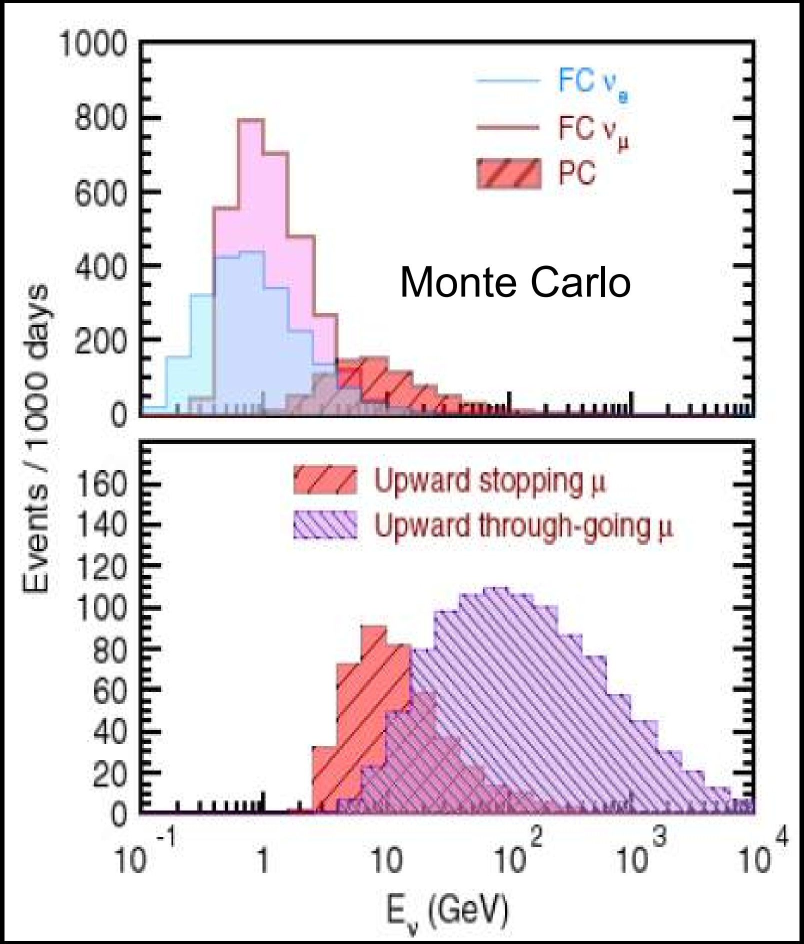
- » no E_ν info
- » excellent ν direction info
- » downward-going muons are neglected (mainly cosmic ray μ)

Atmospheric neutrinos: main background in DM-induced ν searches





atmospheric neutrinos at SK



~10 events/day

~40k evts collected 1996-2014

WIMP elastic scattering cross section $\sigma_{\chi N}$ limit
(spin independent)

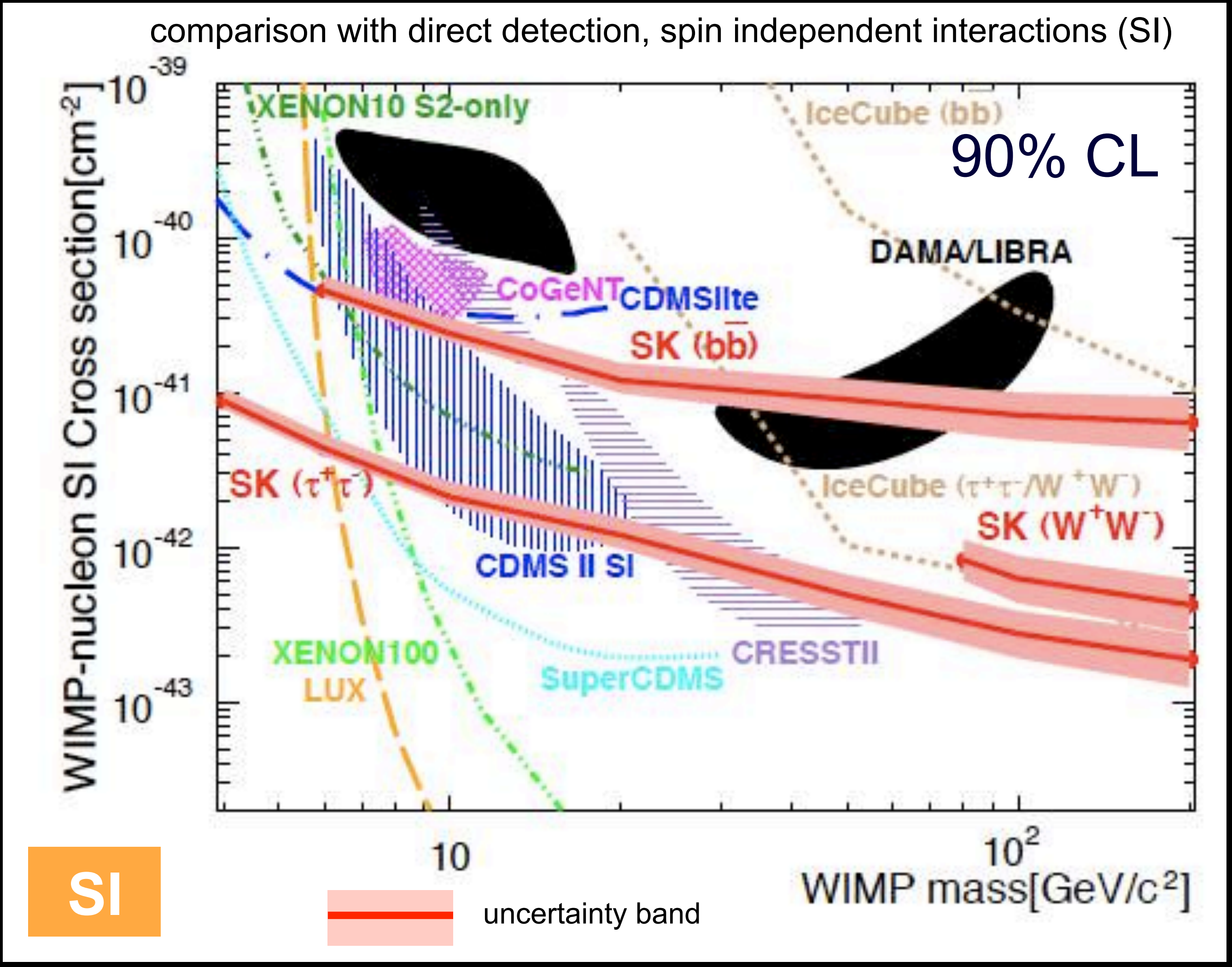
- GLOBAL FIT of simulated DM-ind signal to all SK samples → same as in case of galactic search

- Equilibrium between χ capture and annihilation rate in the SUN

capture = annihilation
↓
depends on $\sigma_{\chi N}$

more: G.Wikström, J.Edsjö JCAP 04, 009 (2009)

- exclusions in the „confusion zone" of positive results

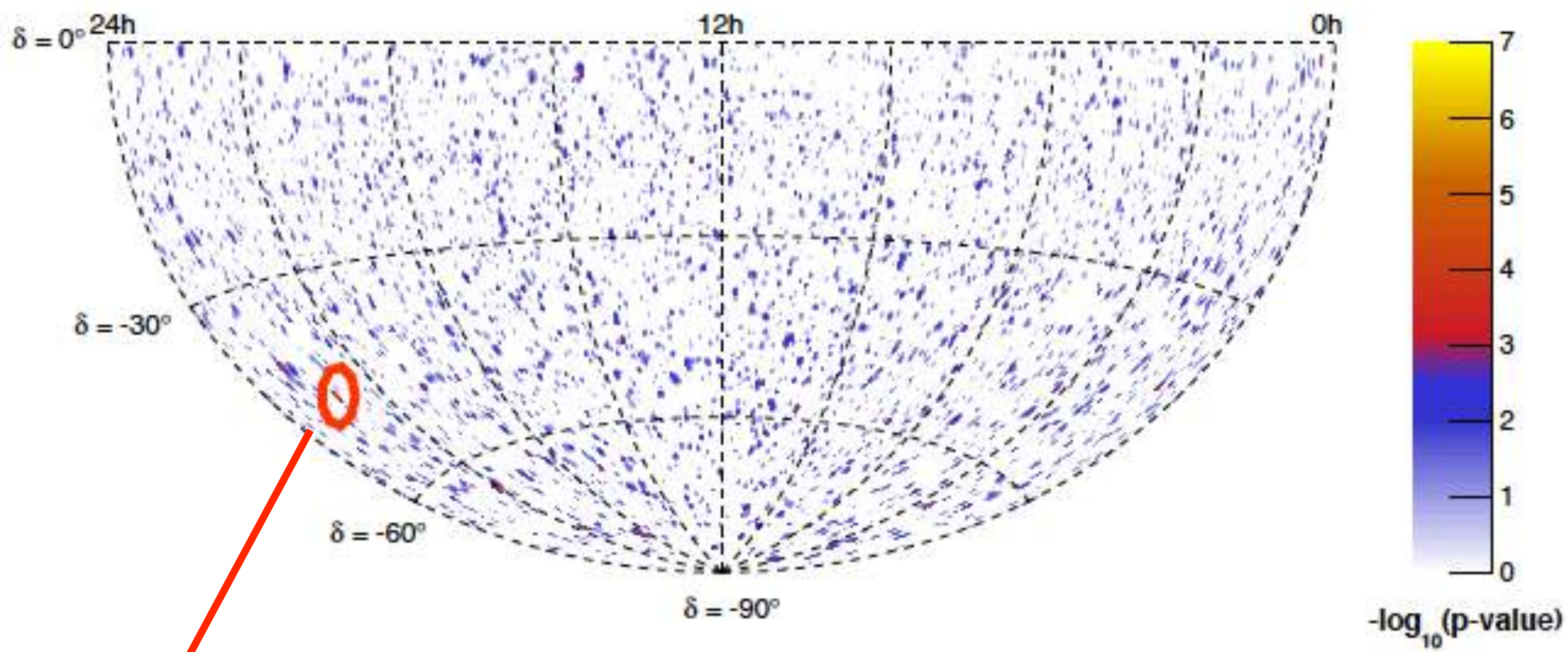


reference: K.Choi et al., Phys. Rev. Lett. 114, 141301 (2015)

Point-like source neutrino searches

All-Sky search: Search for excess of astrophysical ν from a common direction over the background of atmospheric ν

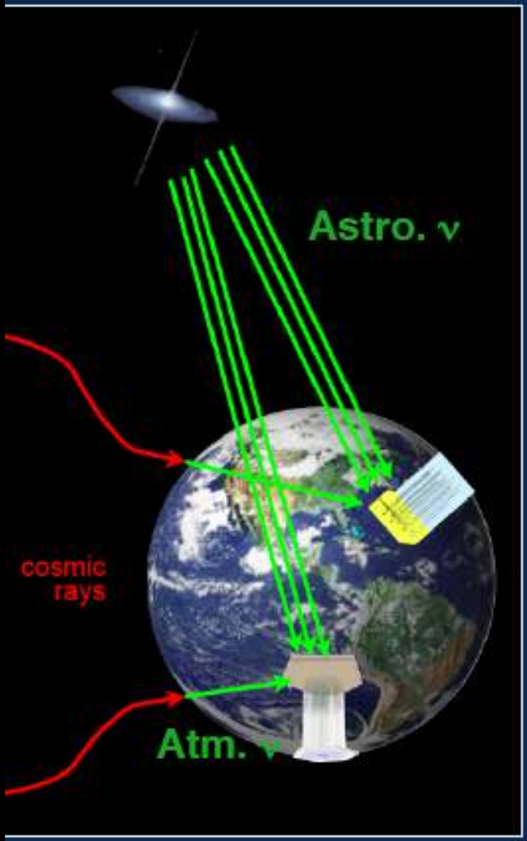
ANTARES (2007-2012) + IceCube (2008-2011)



Significance 0.7σ

point-like searches

All-Sky search: Search for excess of astrophysical ν from a common direction over the background of atmospheric ν (IceCube: Northern Sky) or μ (IceCube: Southern Sky)

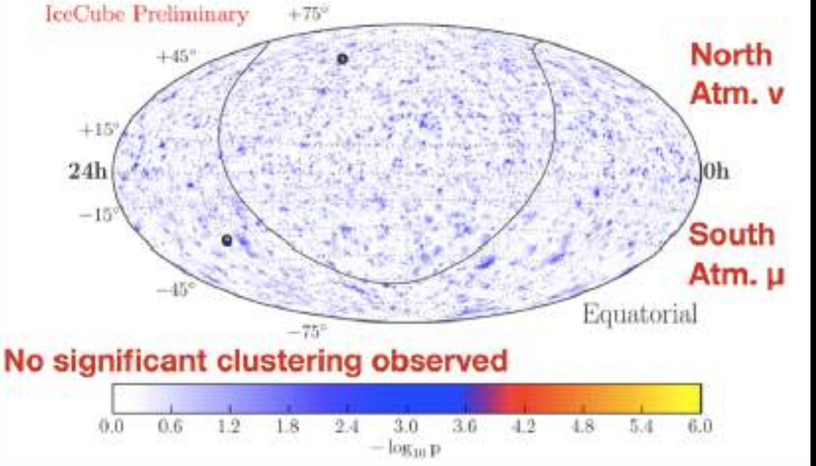


IceCube:

6yr data (2008-2014)
Hottest spots: not significant

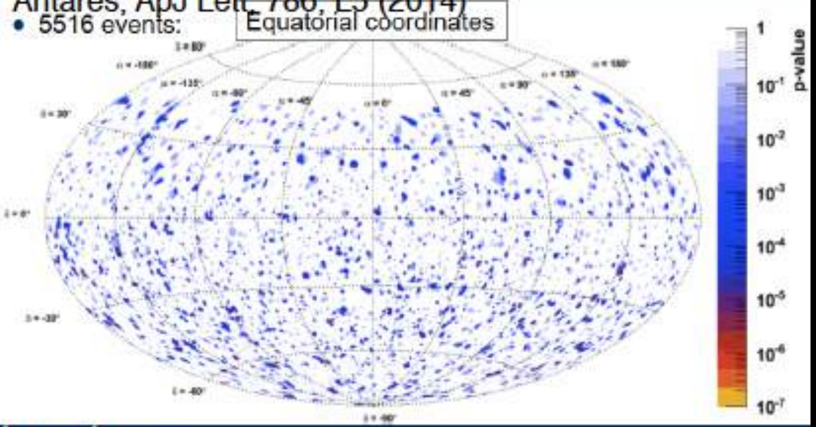
e.g. Northers Sky: 35 % of trials have significance > hottest spot

S. Coenders (IceCube) ICRC2015



Antares:

Antares, ApJ Lett, 786, L5 (2014)



… a mostly uniform structure …

by J.Kiryluk (IceCube)