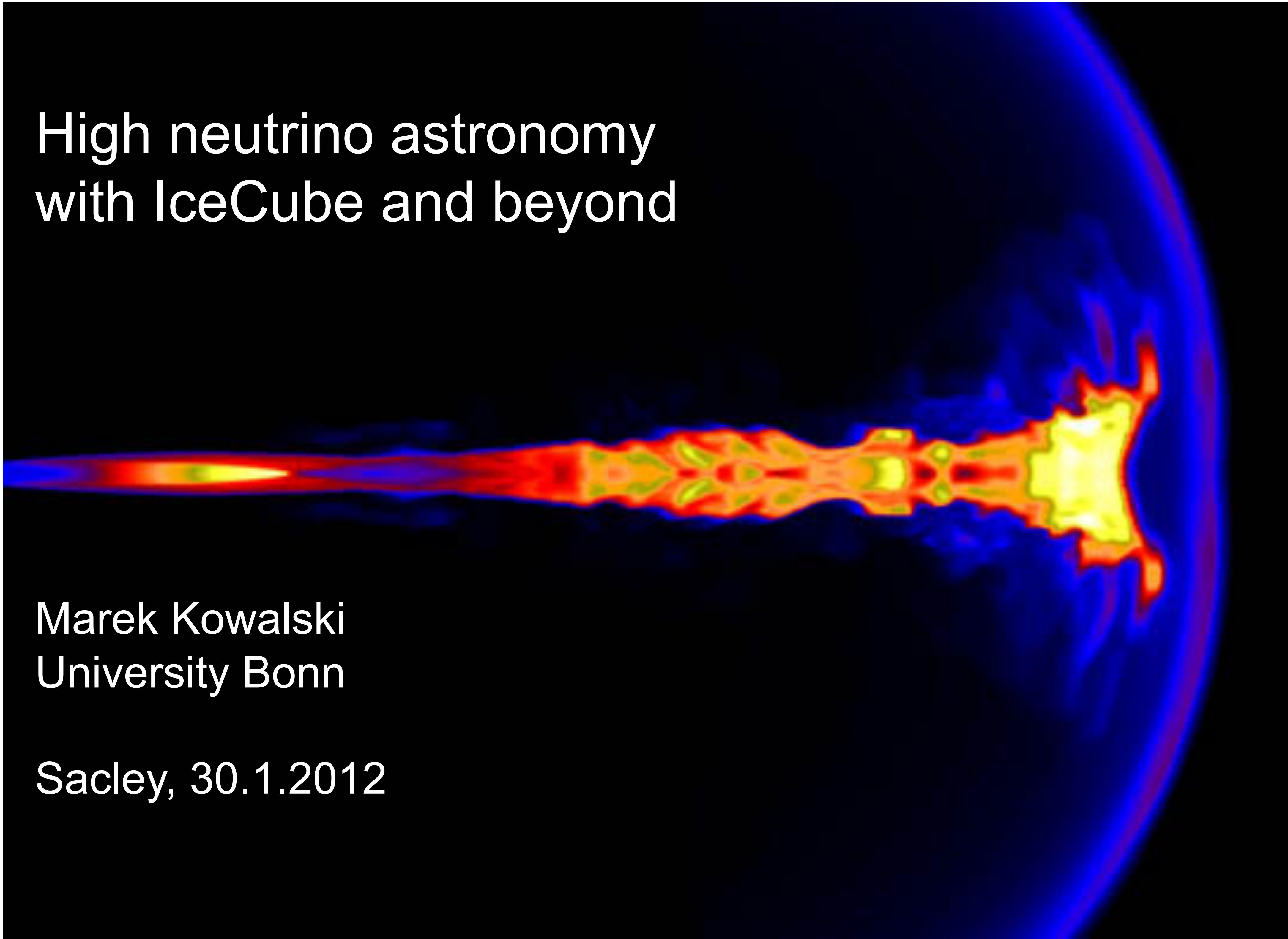
High neutrino astronomy with IceCube and beyond



Marek Kowalski
University Bonn

Sacley, 30.1.2012

Outline

- Introduction to high energy neutrino astrophysics
- The IceCube observatory at the South Pole
- First results from IceCube
- Optical follow-up for the IceCube experiment
- Beyond IceCube

Why do High Energy Neutrino Physics

Astrophysical questions:

Origin of the cosmic rays

Uncovering “invisible” phenomena

Cosmic ray physics

Particle physics:

Search for dark matter

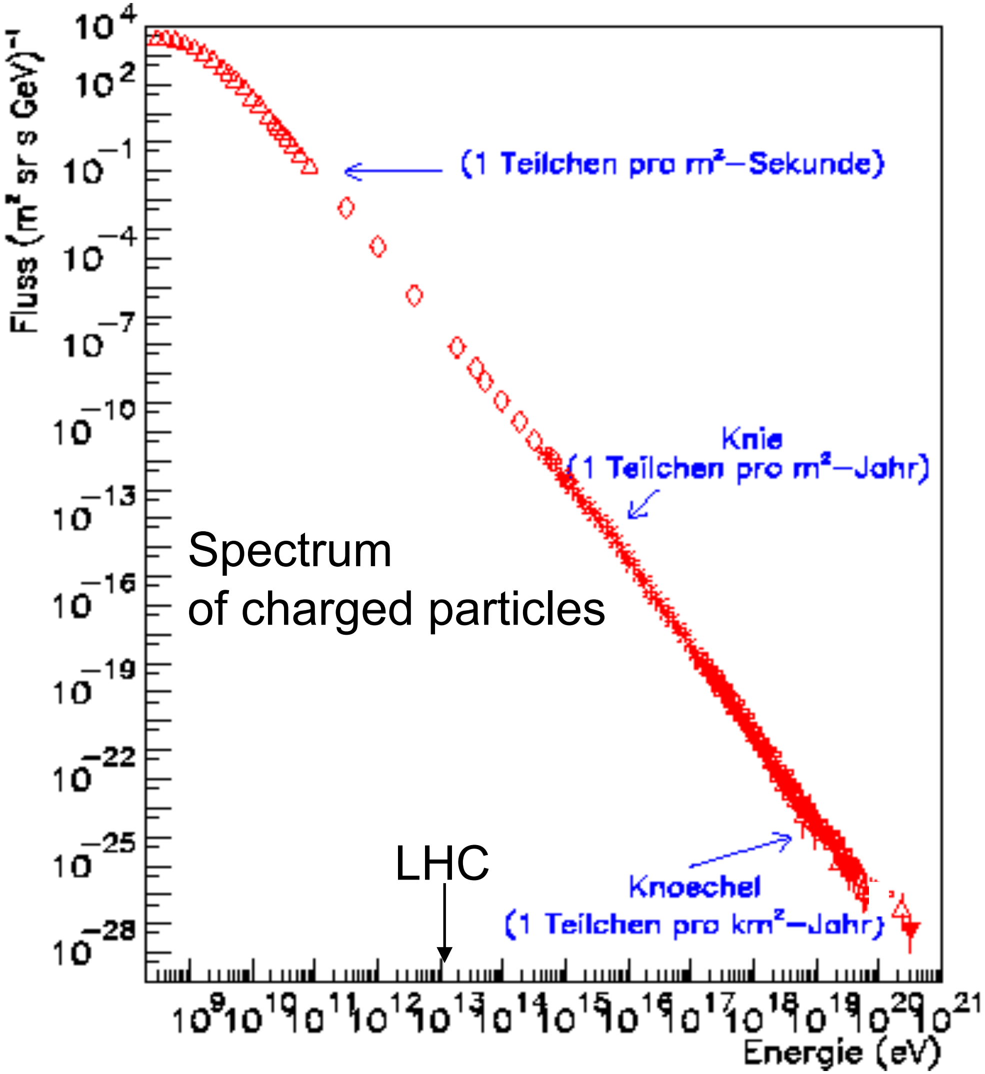
Quantum gravity (and other BSM physics)

Magnetic Monopoles

Neutrino-oscillations

The energetic Universe

Cosmic Rays

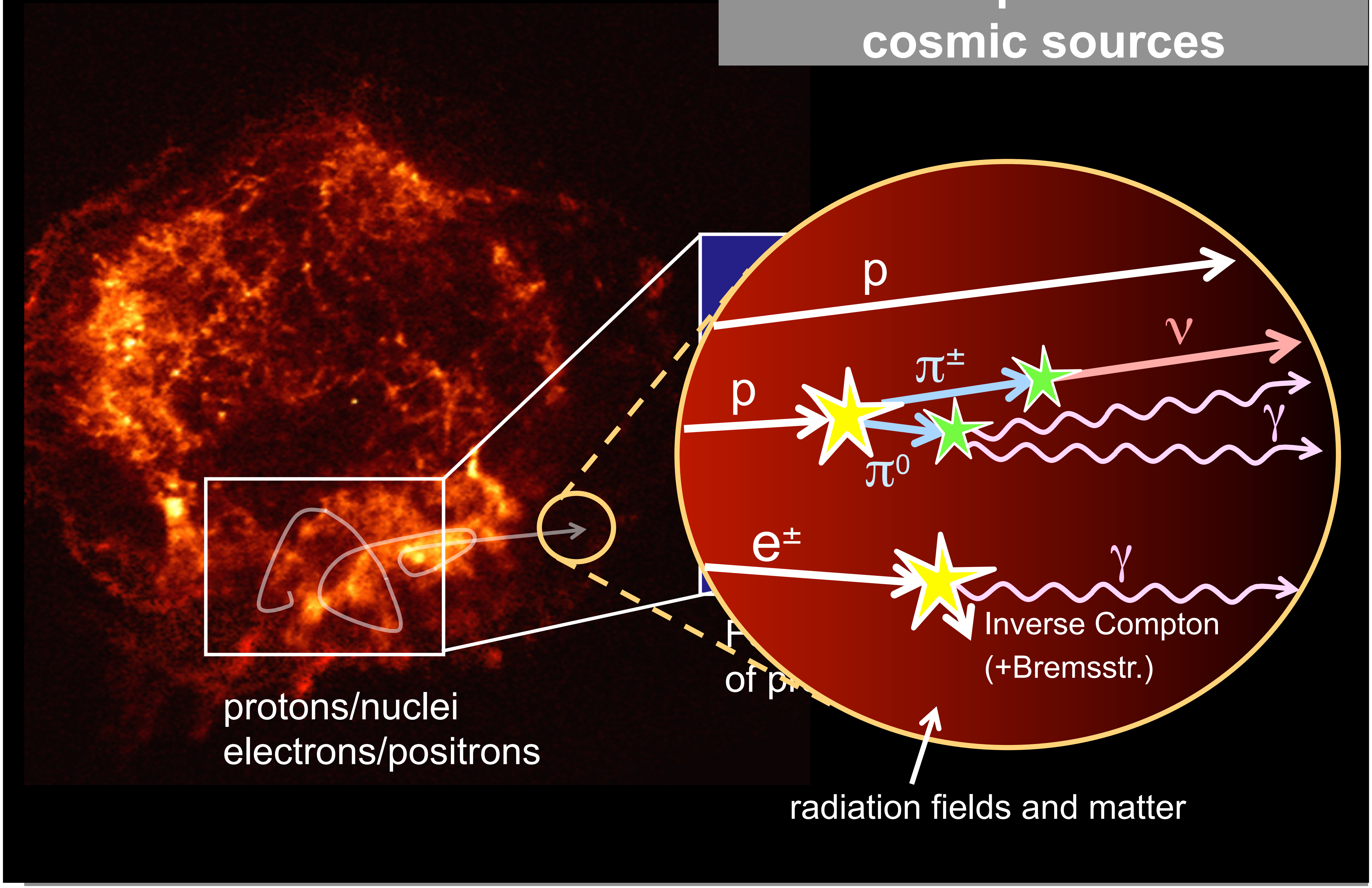


Cosmic rays have been observed up to 10^{20} eV!

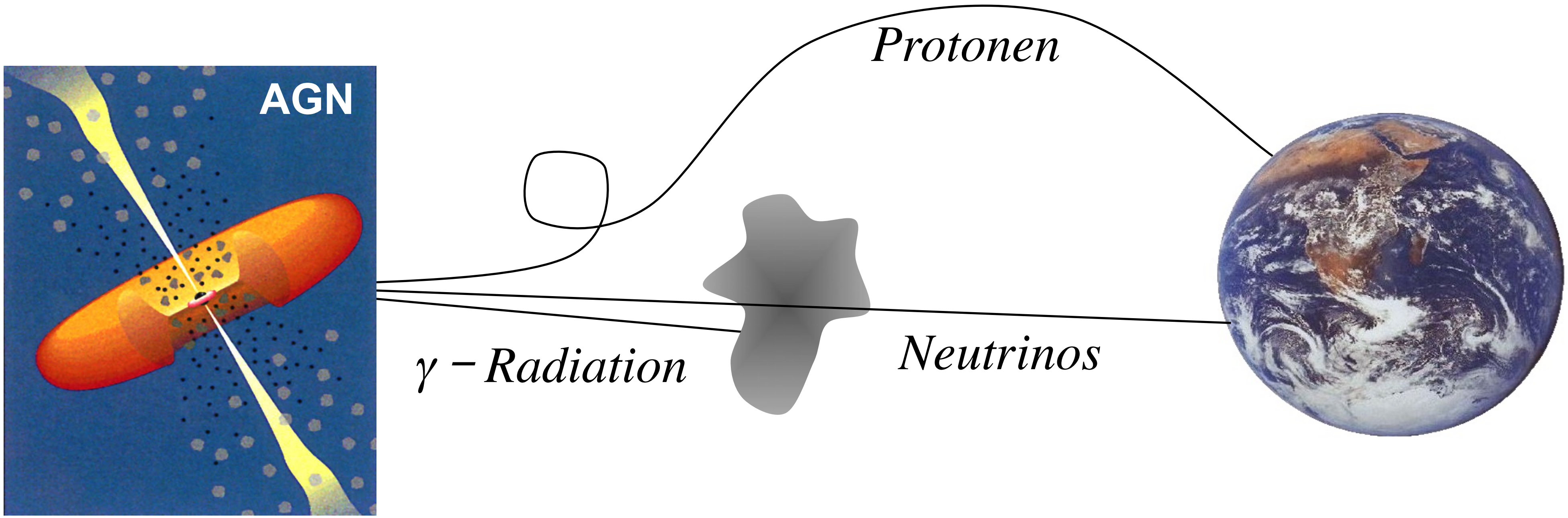
- ❑ What are the sources?
- ❑ How are particles accelerated?

High-energy neutrinos can be important messenger particles.

Neutrino production in cosmic sources



Neutrino propagation



$p + X \rightarrow \pi^{+-} + \pi^{0} + \ldots$

$\hookrightarrow \nu + \mu + \ldots$

Flavor ratio at the source

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 2 : 0$

Neutrino oscillation length:

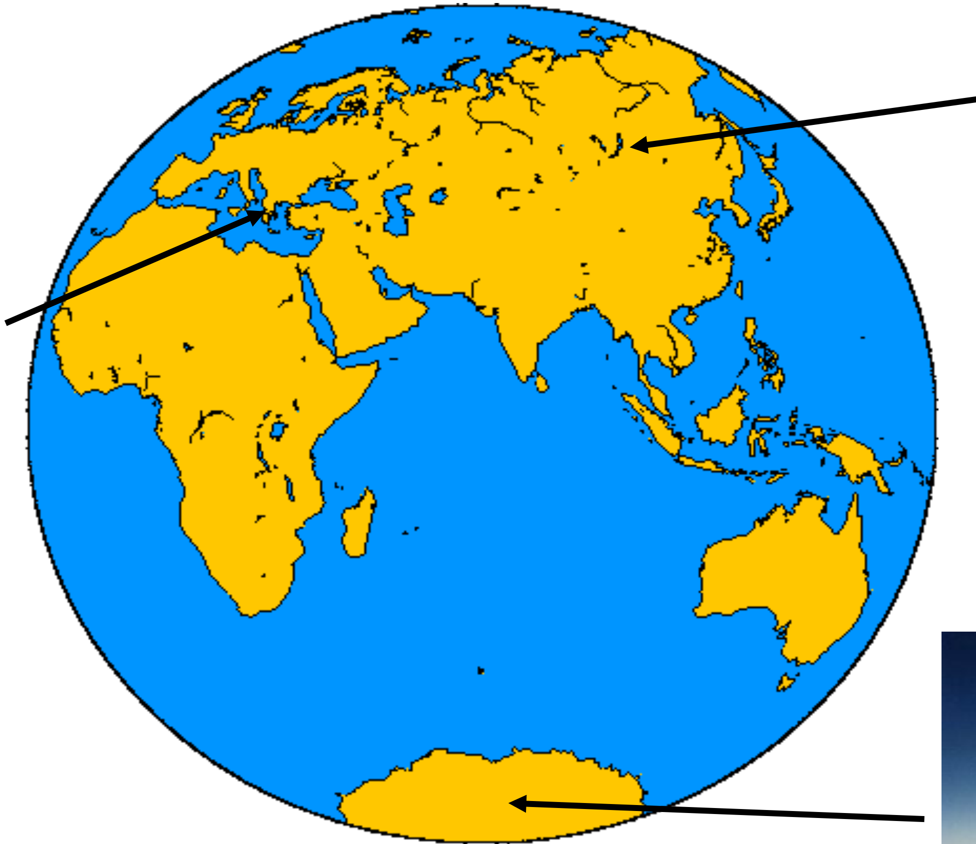
$\lambda_{23} \approx 10^{11}\,(E_\nu/\mathrm{TeV})\,\mathrm{cm}$

Flavor ratio at the Earth:

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

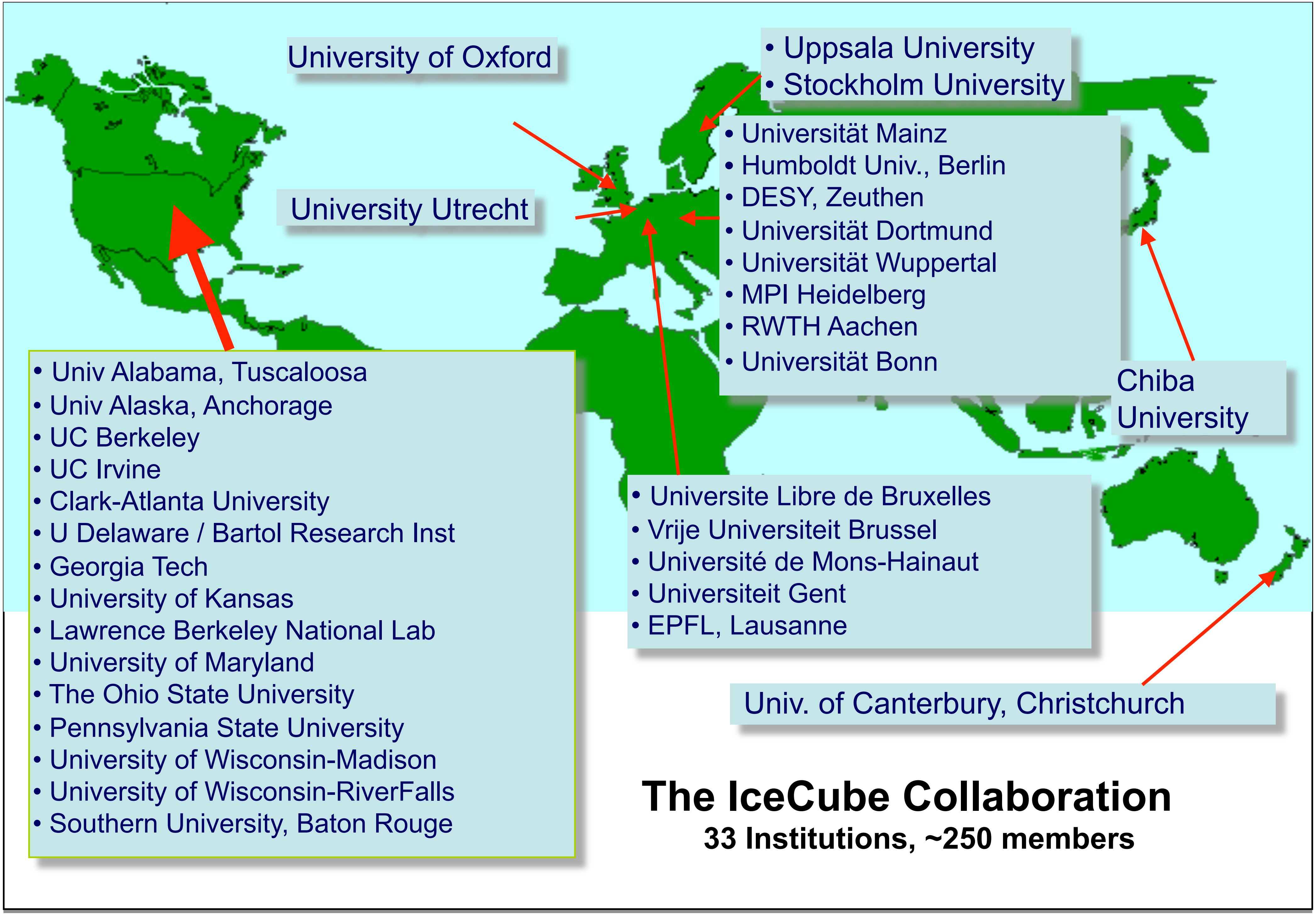
Open water/ice Neutrino Telescopes

Meditarranian:
ANTARES, France
NESTOR, Greece
NEMO, Italy
⇒ KM3Net



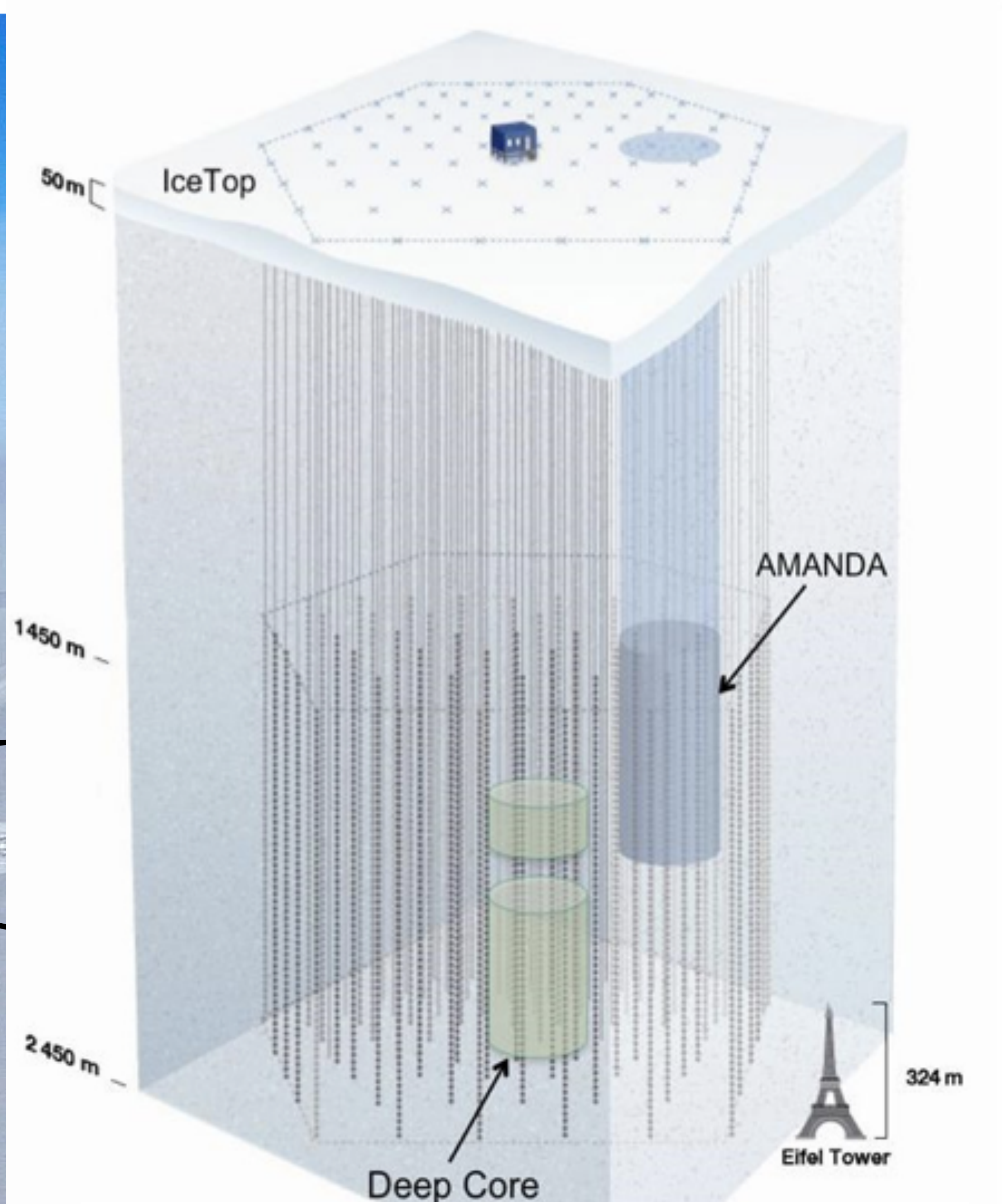
BAIKAL, Sibiria

AMANDA & IceCube, South pole


University of Oxford
• Uppsala University
• Stockholm University
University Utrecht
• Universität Mainz
• Humboldt Univ., Berlin
• DESY, Zeuthen
• Universität Dortmund
• Universität Wuppertal
• MPI Heidelberg
• RWTH Aachen
• Universität Bonn
Chiba University
• Univ Alabama, Tuscaloosa
• Univ Alaska, Anchorage
• UC Berkeley
• UC Irvine
• Clark-Atlanta University
• U Delaware / Bartol Research Inst
• Georgia Tech
• University of Kansas
• Lawrence Berkeley National Lab
• University of Maryland
• The Ohio State University
• Pennsylvania State University
• University of Wisconsin-Madison
• University of Wisconsin-RiverFalls
• Southern University, Baton Rouge
• Universite Libre de Bruxelles
• Vrije Universiteit Brussel
• Université de Mons-Hainaut
• Universiteit Gent
• EPFL, Lausanne
Univ. of Canterbury, Christchurch
The IceCube Collaboration
33 Institutions, ~250 members

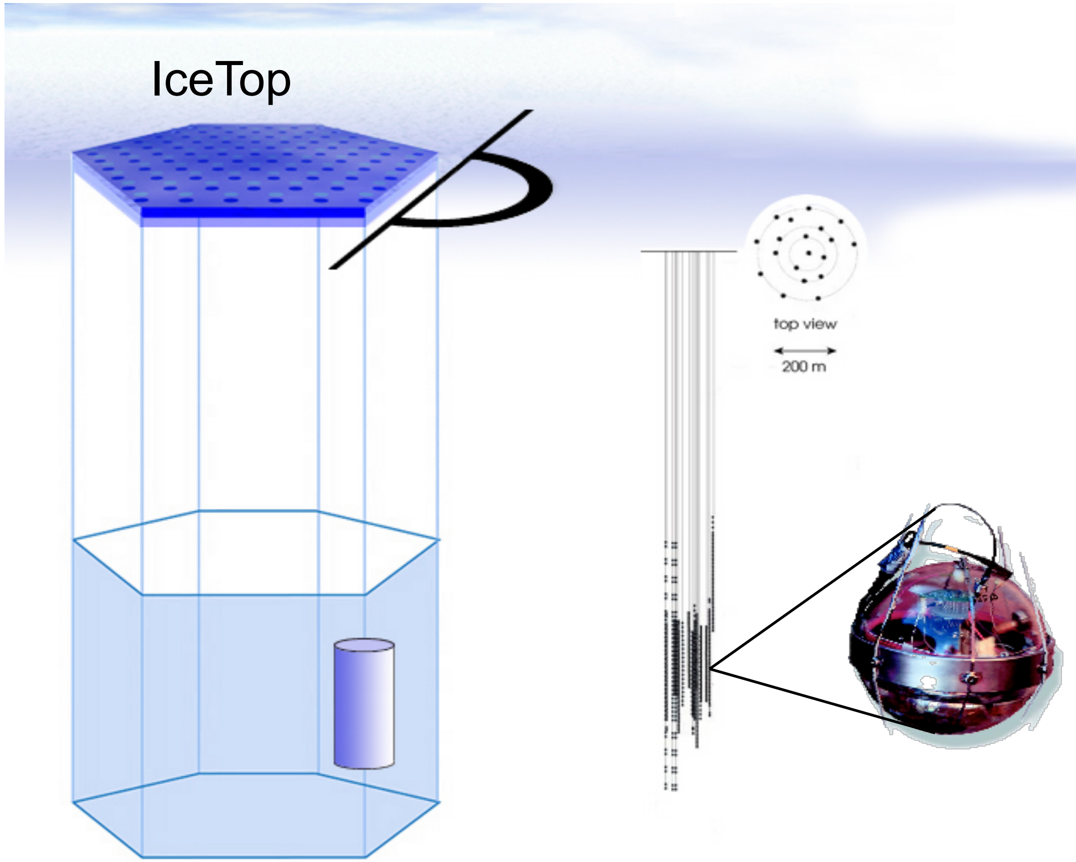
IceCube:
A cubic kilometer neutrino detector

IceCube: A cubic kilometer neutrino detector



70 times larger than AMANDA
20.000 times larger than Super-Kamiokande

The IceCube Detector

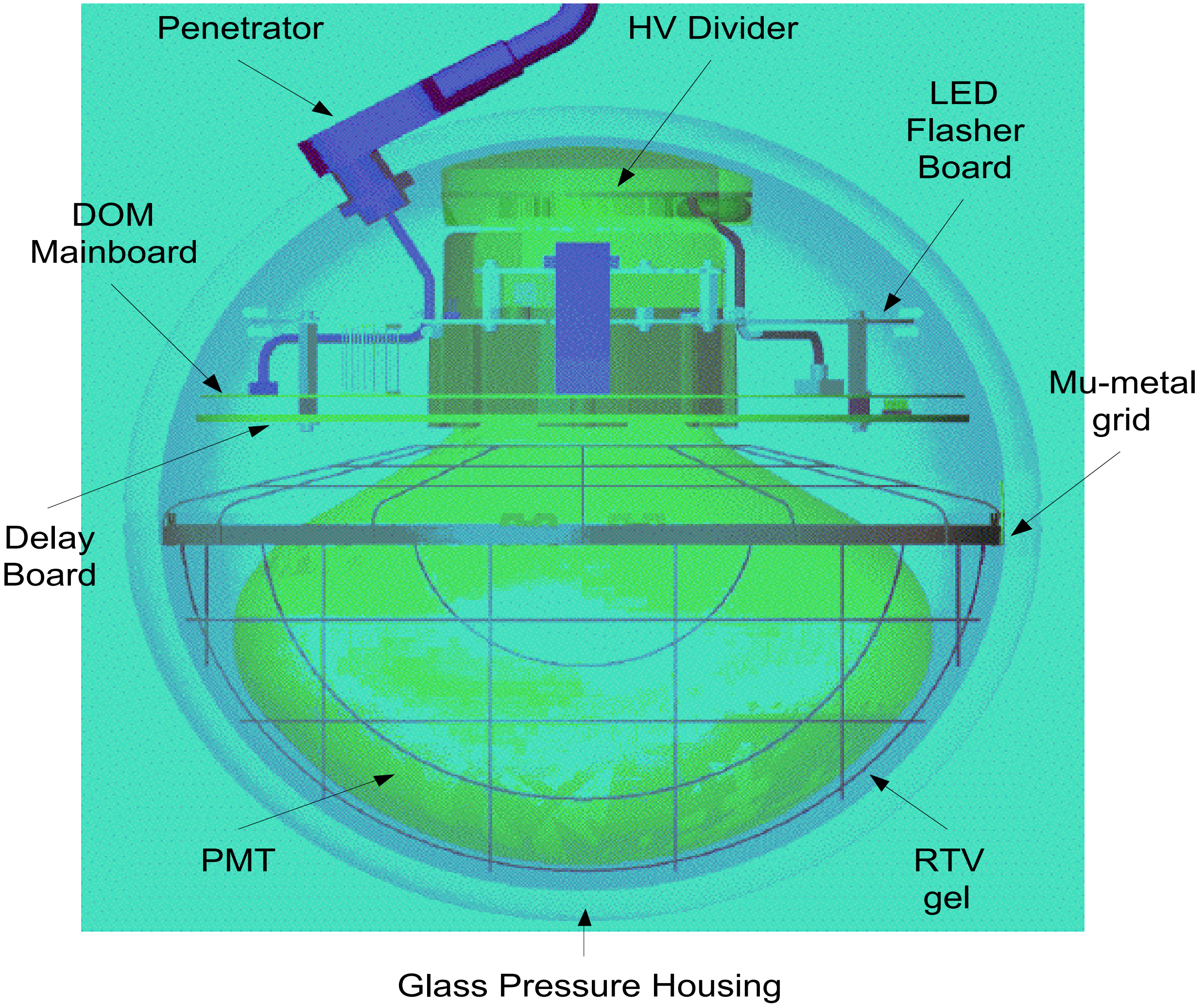


Design Specification

- Digital Optical Modul: *DOM*
- Number of *DOMs* – 5360
- Number of *strings* – 86
- Number of *surface tanks* – 160
- Instrumented volume – 1 km^3
- Angular resolution < 1.0°

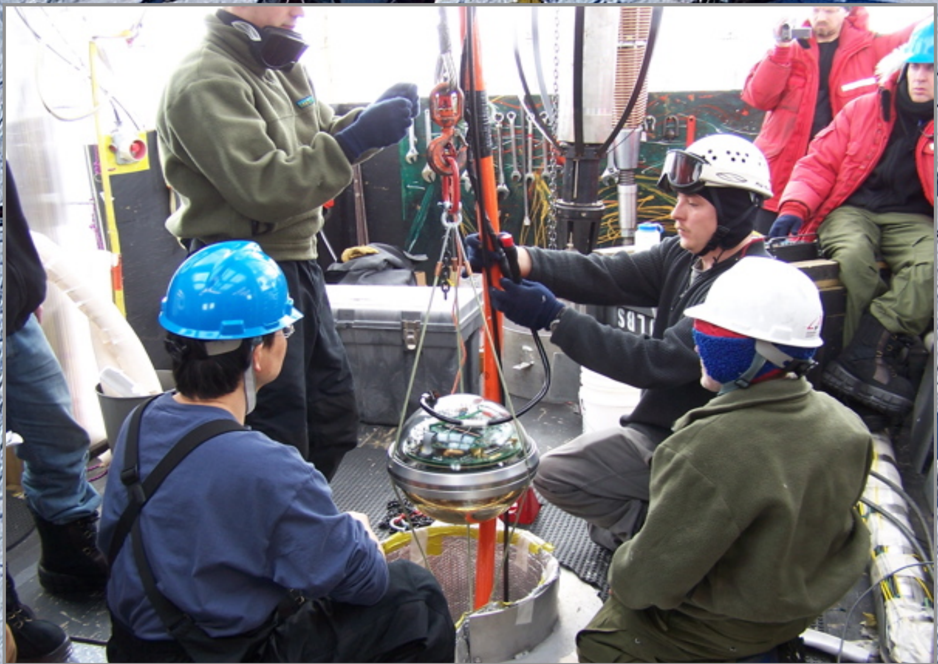
AMANDA construction: 1997 - 2000
IceCube construction: 2005 - 2011

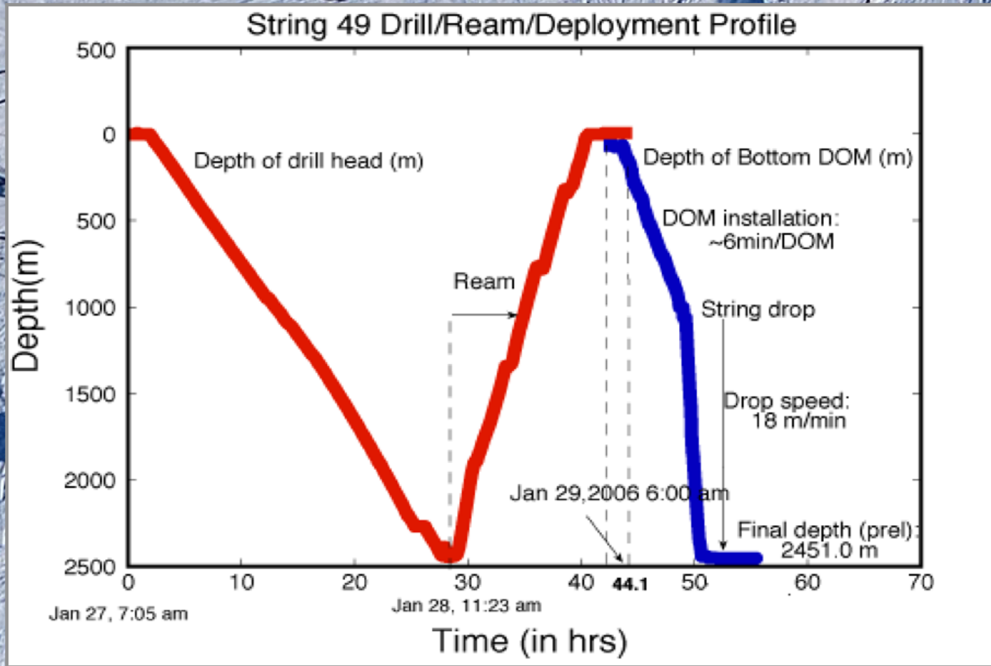
Digital Optical Module



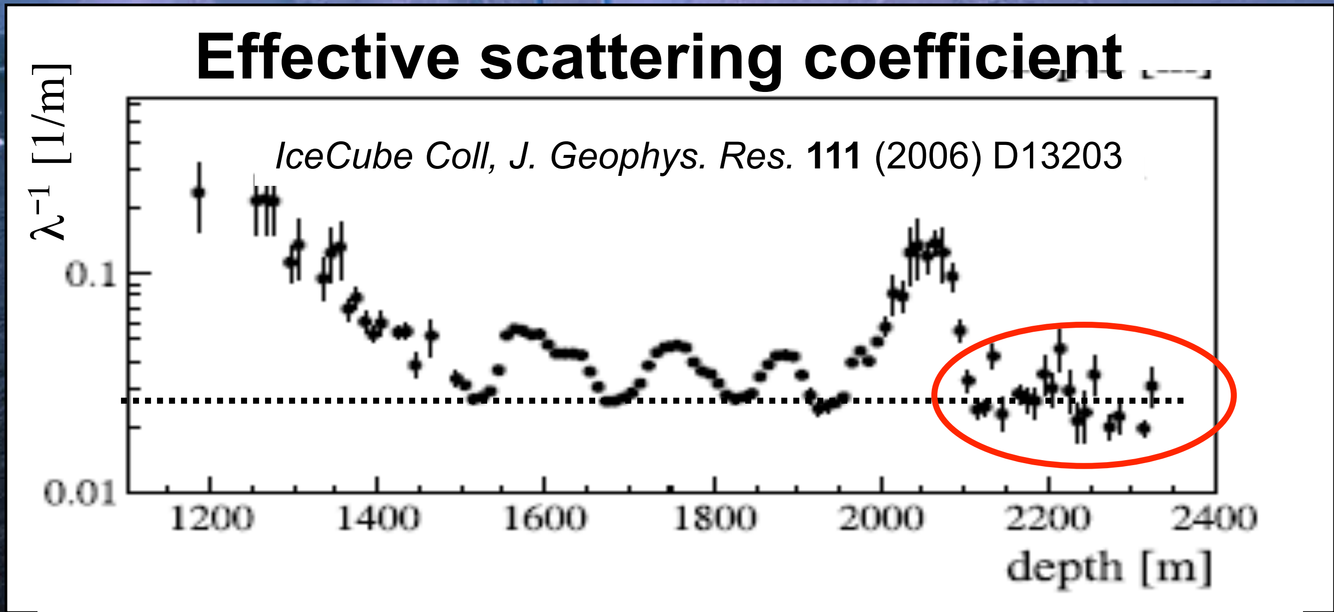
Installation

Installation

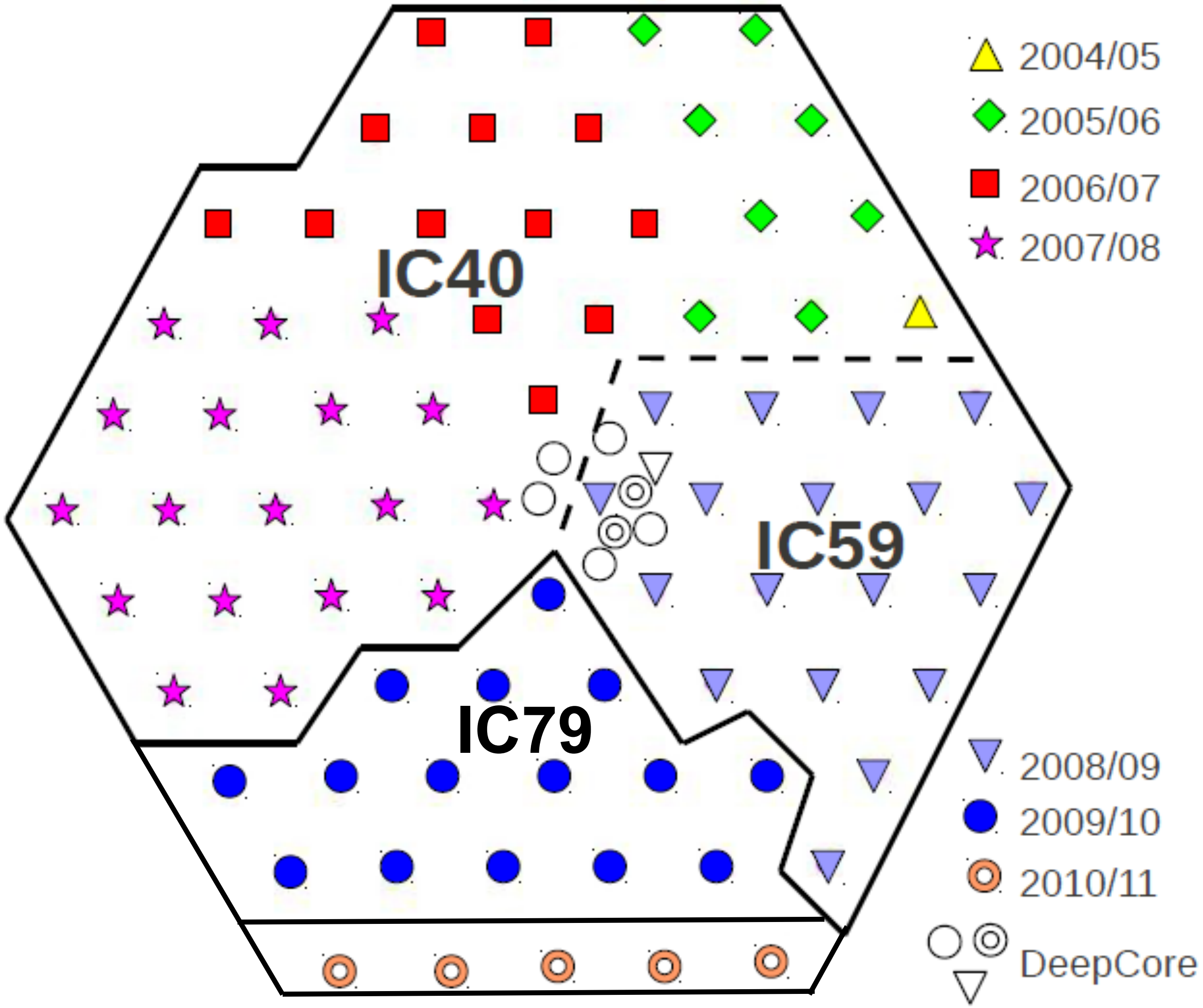




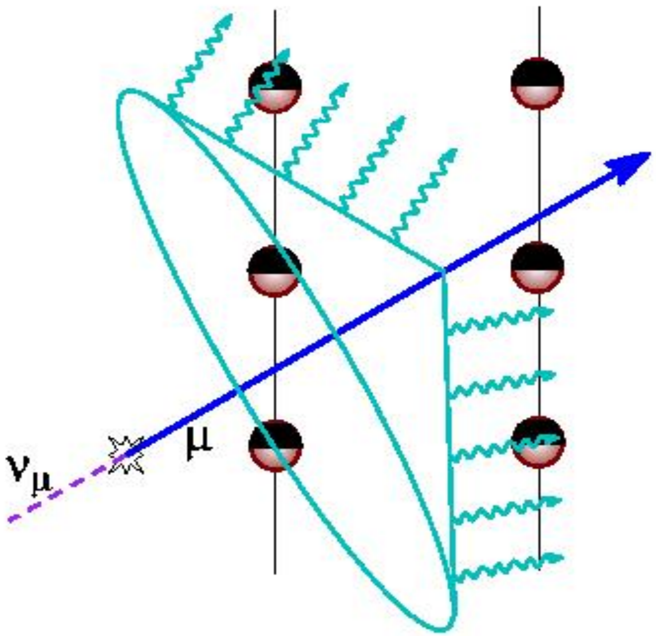
Optical properties of the detection medium



IceCube wtih 86 strings



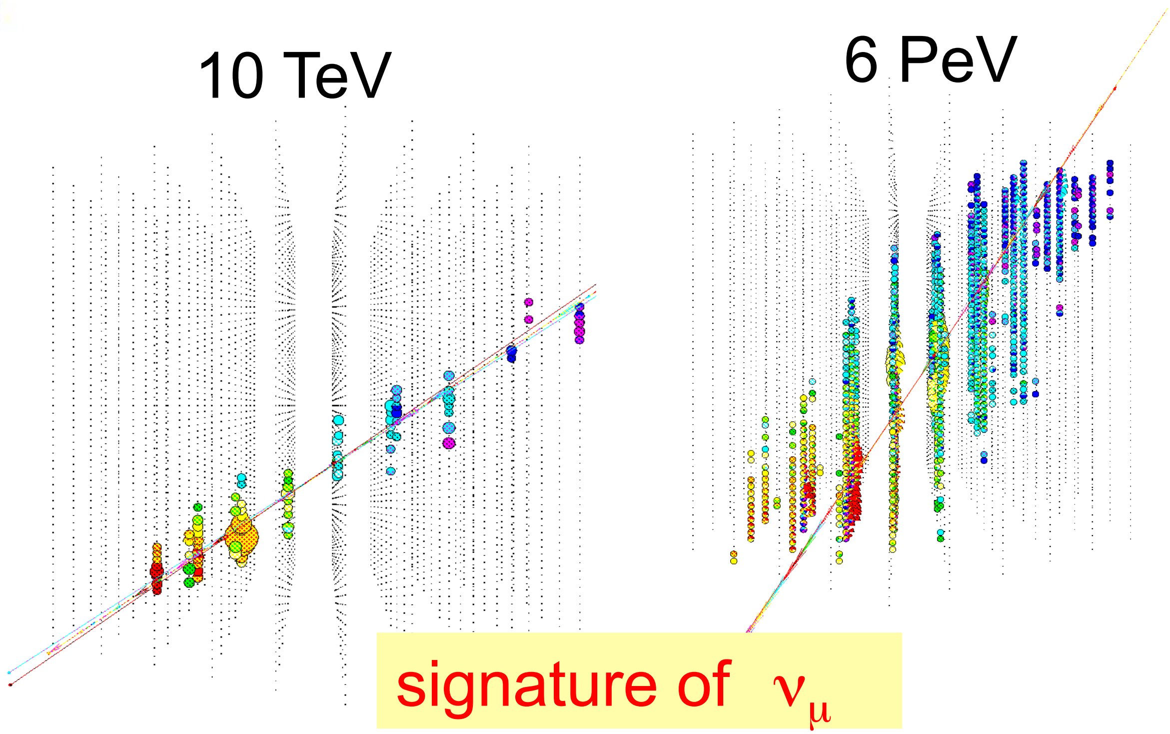
Neutrino signatures



Muon-tracks

+ good pointing (~1 degree)

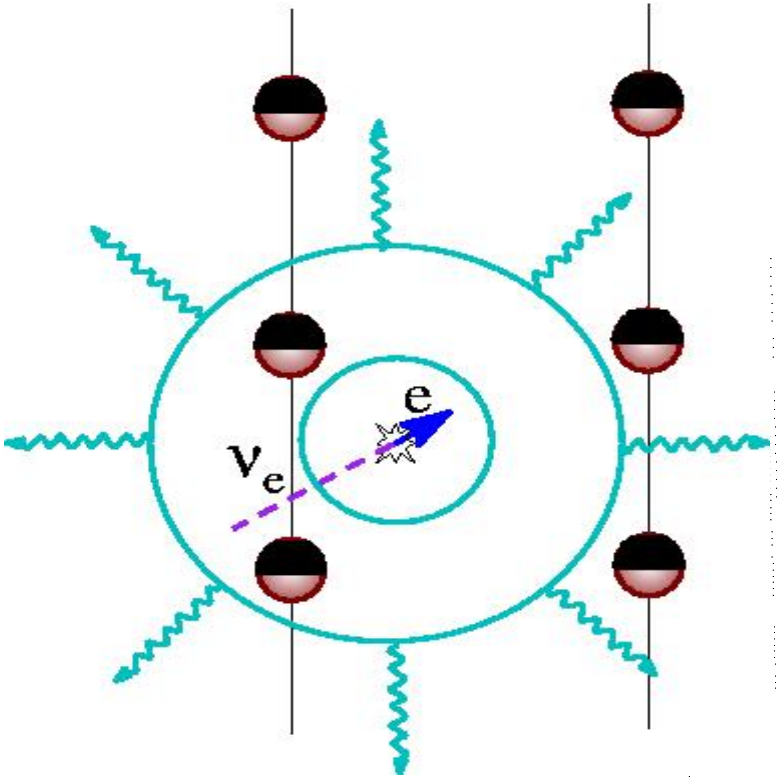
+ large event rates due long muon range

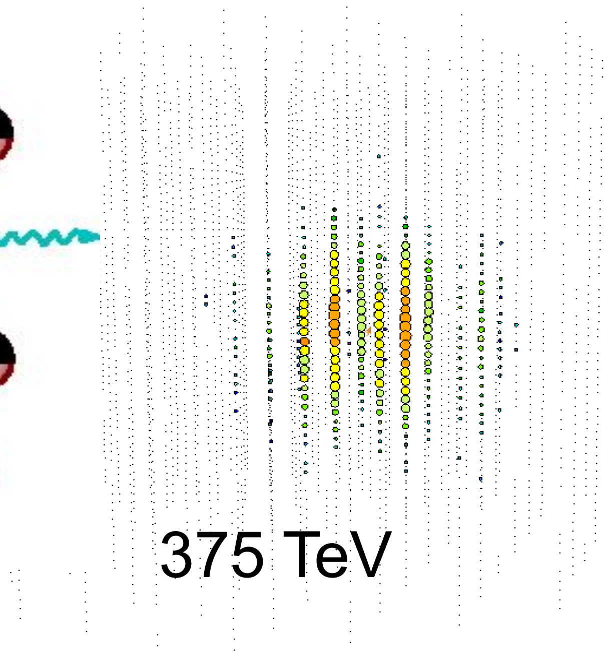


Neutrino signatures

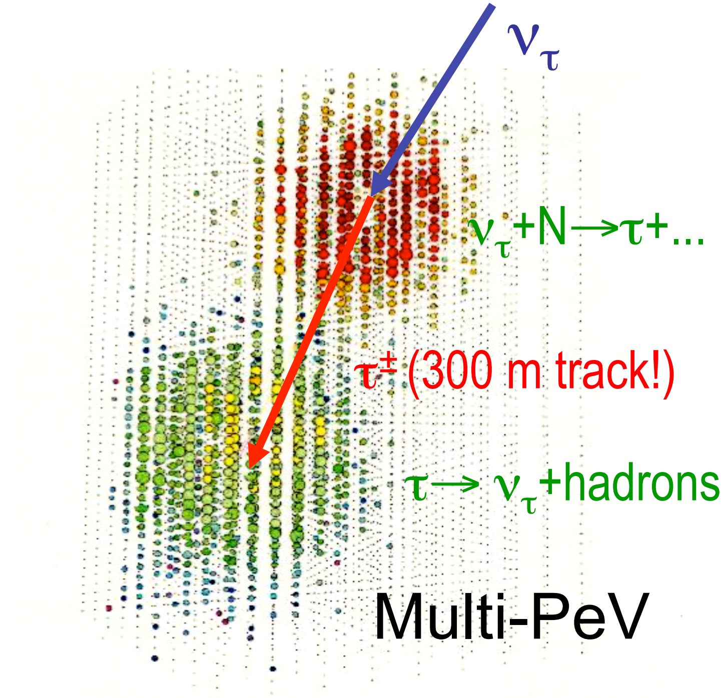
Particle shower (cascade)

\+ $\nu_e, \nu_\tau, (\nu_\mu)$
\+ good energy resolution (~0.2 in logE)
\+ little background

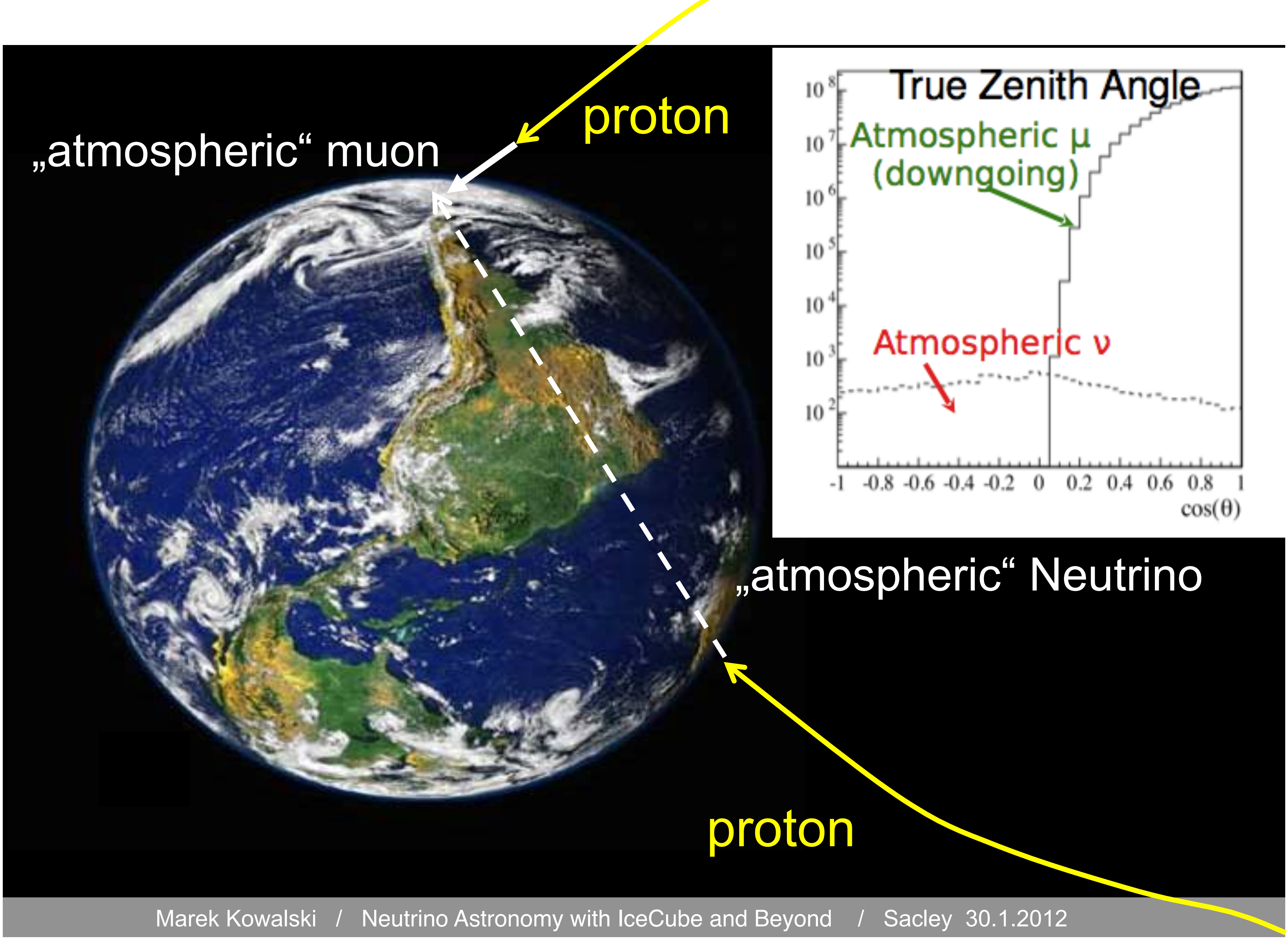




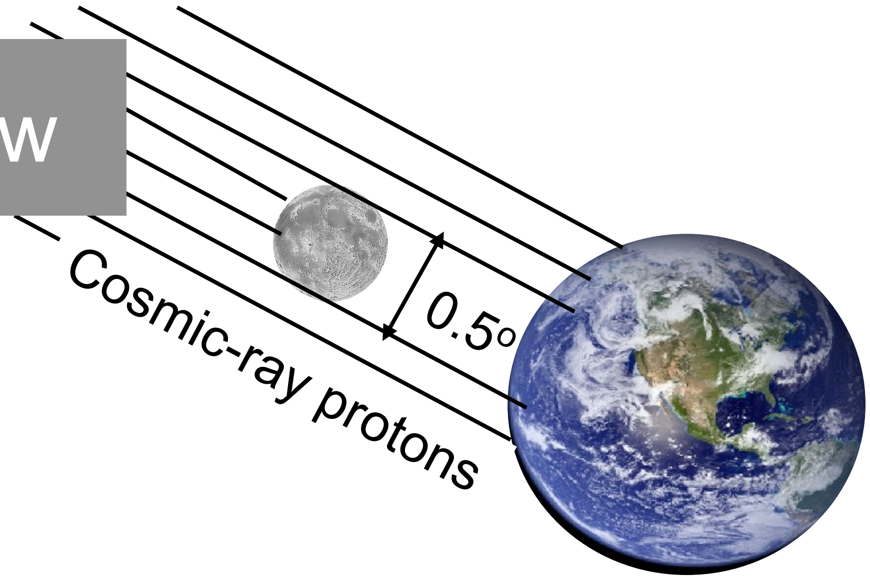
signature of ν_e



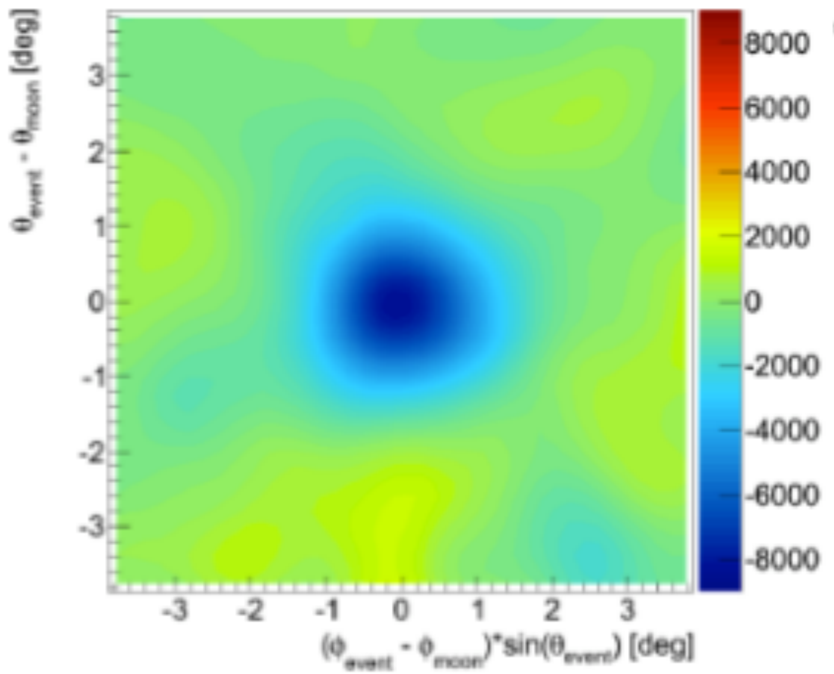
signature of ν_τ


proton
„atmospheric" muon
True Zenith Angle
Atmospheric μ
(downgoing)
Atmospheric ν
cos(θ)
„atmospheric" Neutrino
proton

Observation of moon shadow



59 strings (2009-2010)



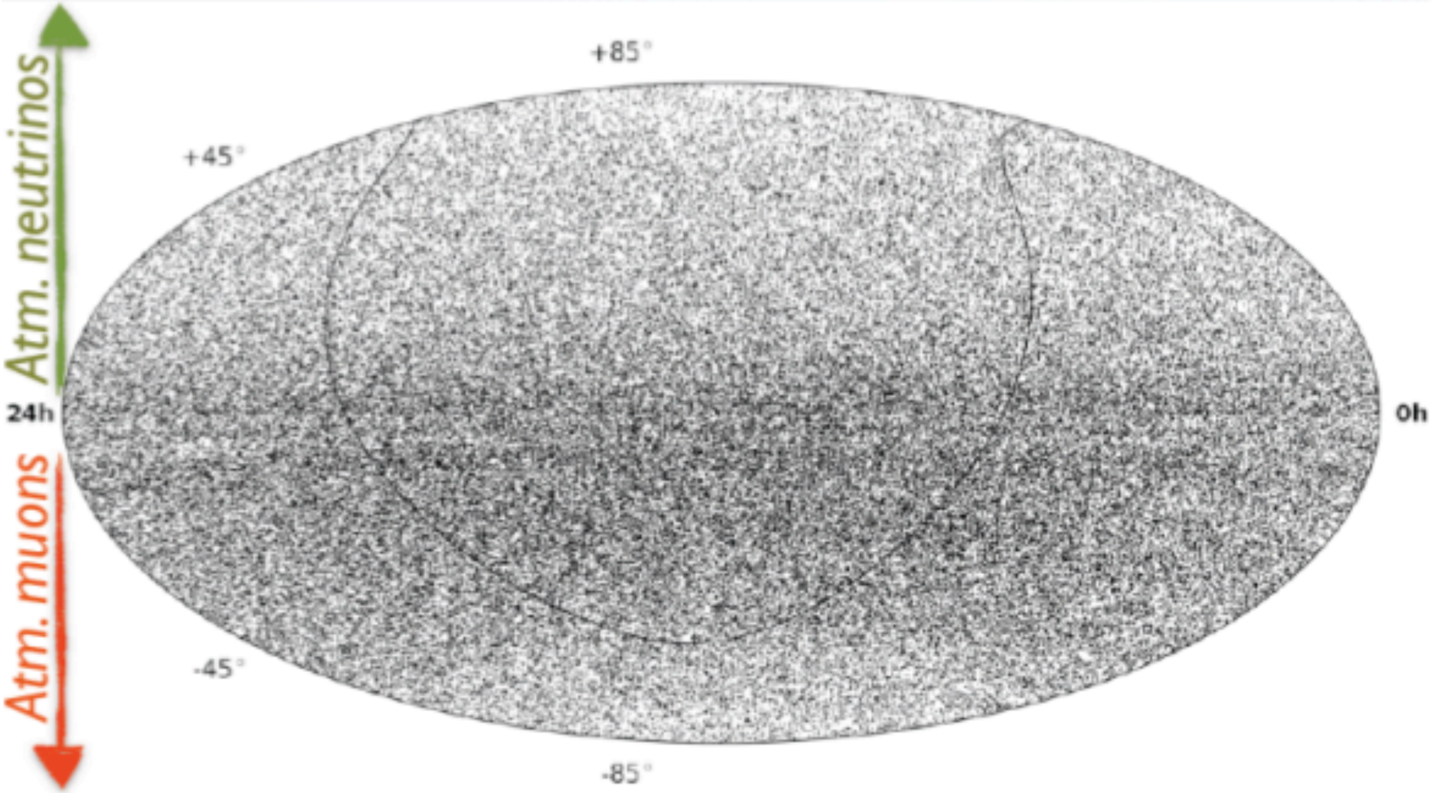
- $n_s^{obs} = -8660 \pm 565 \pm 681$
- $n_s^{exp} = -8192 \pm 91$
- $\vec{x}_s^{obs} = (-0.1^\circ \pm 0.1^\circ, 0.0^\circ \pm 0.1^\circ)$

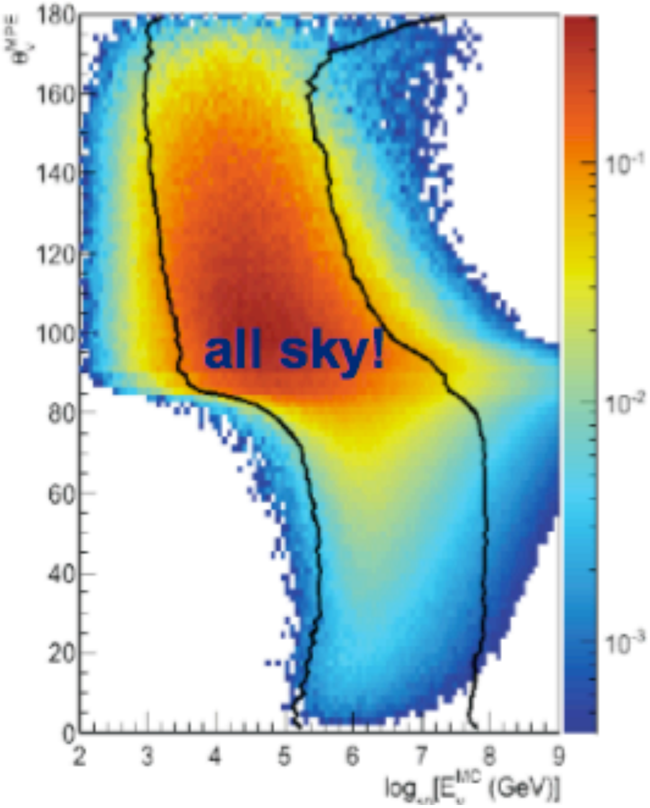
Cosmic rays blocked by the moon lead to a point-like deficit in down-going muons

Point Source Search: IceCube 40 & 59

Northern sky & Southern sky

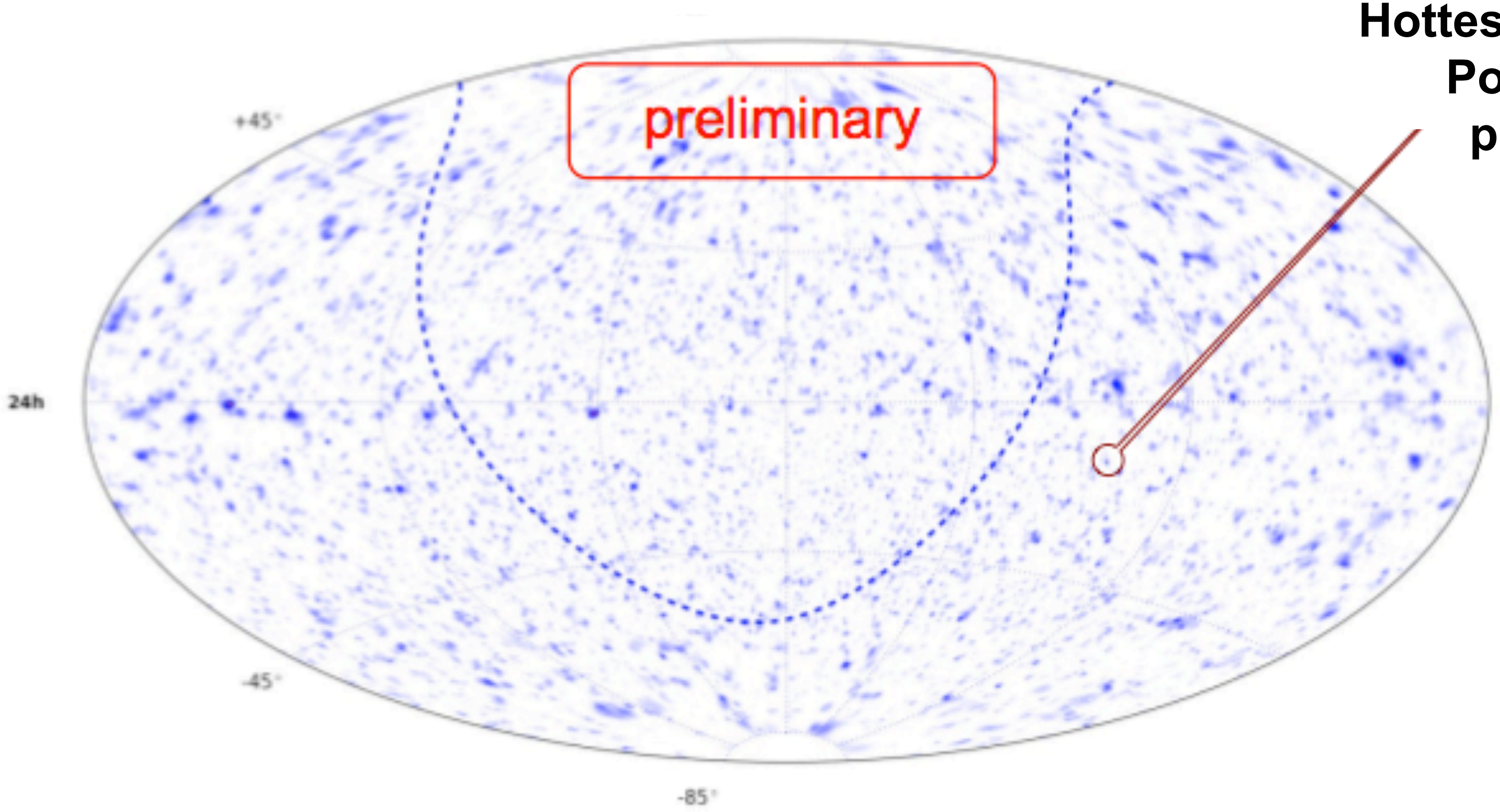
43339 up-going + 64230 down-going from 723 days





Point Source Search: IceCube 40 & 59

Northern sky & Southern sky

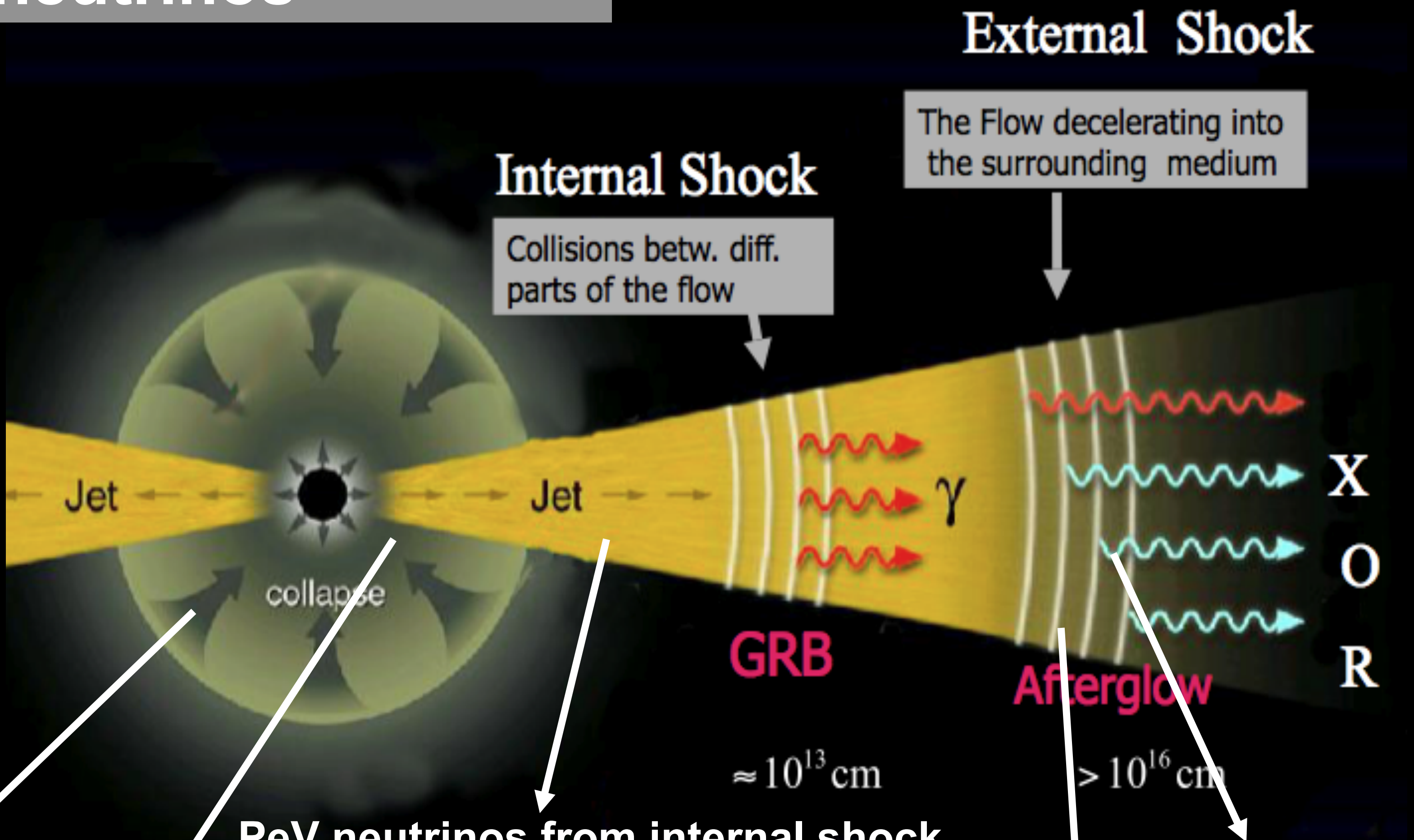


Hottest spot:
Post-trial p-value:
~67%

No evidence for neutrino sources, yet

Gamma Ray Bursts & neutrinos

Fireball model for long GRBs



PeV neutrinos from internal shock

MeV neutrinos at collapse

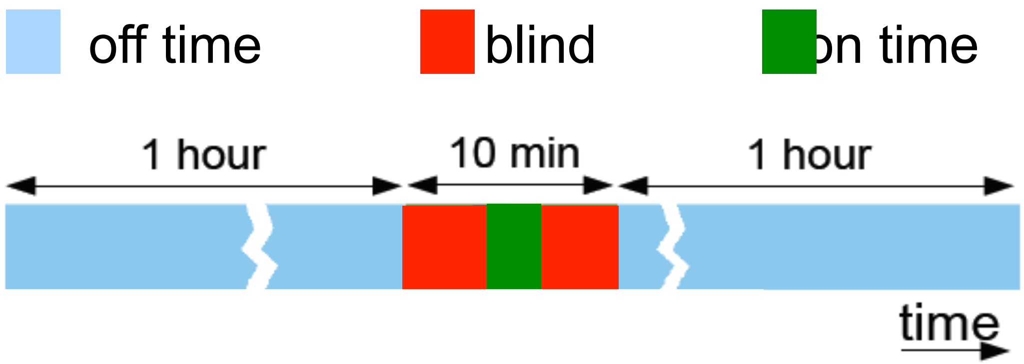
TeV neutrinos from inside the star

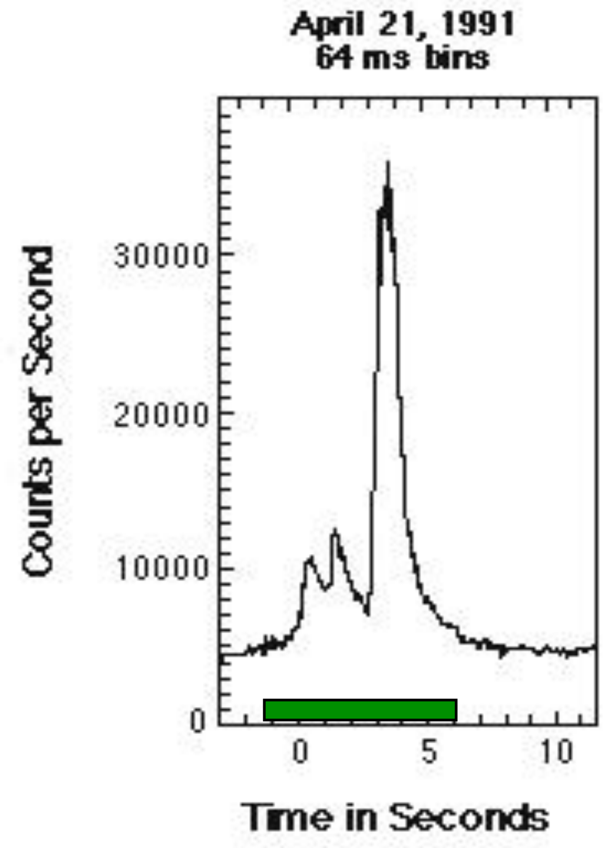
EeV neutrinos from external shocks

PeV-EeV neutrinos from flares

GRBs as neutrino sources

Search results

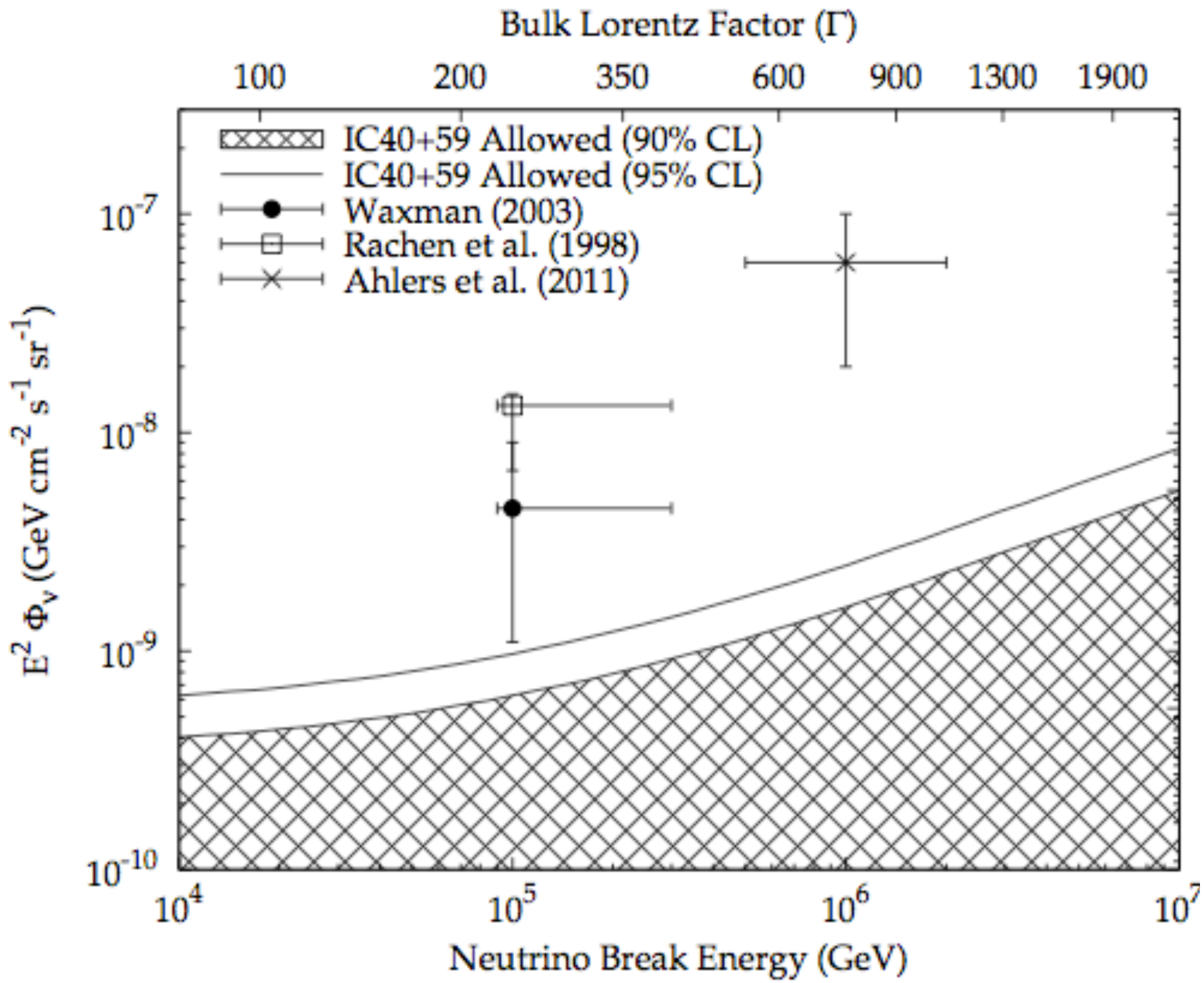




211 northern sky GRBs studied with IC40 & IC59

⇒**no coincident neutrino detected!**
Upper limit from IceCube starts to severely constraints models

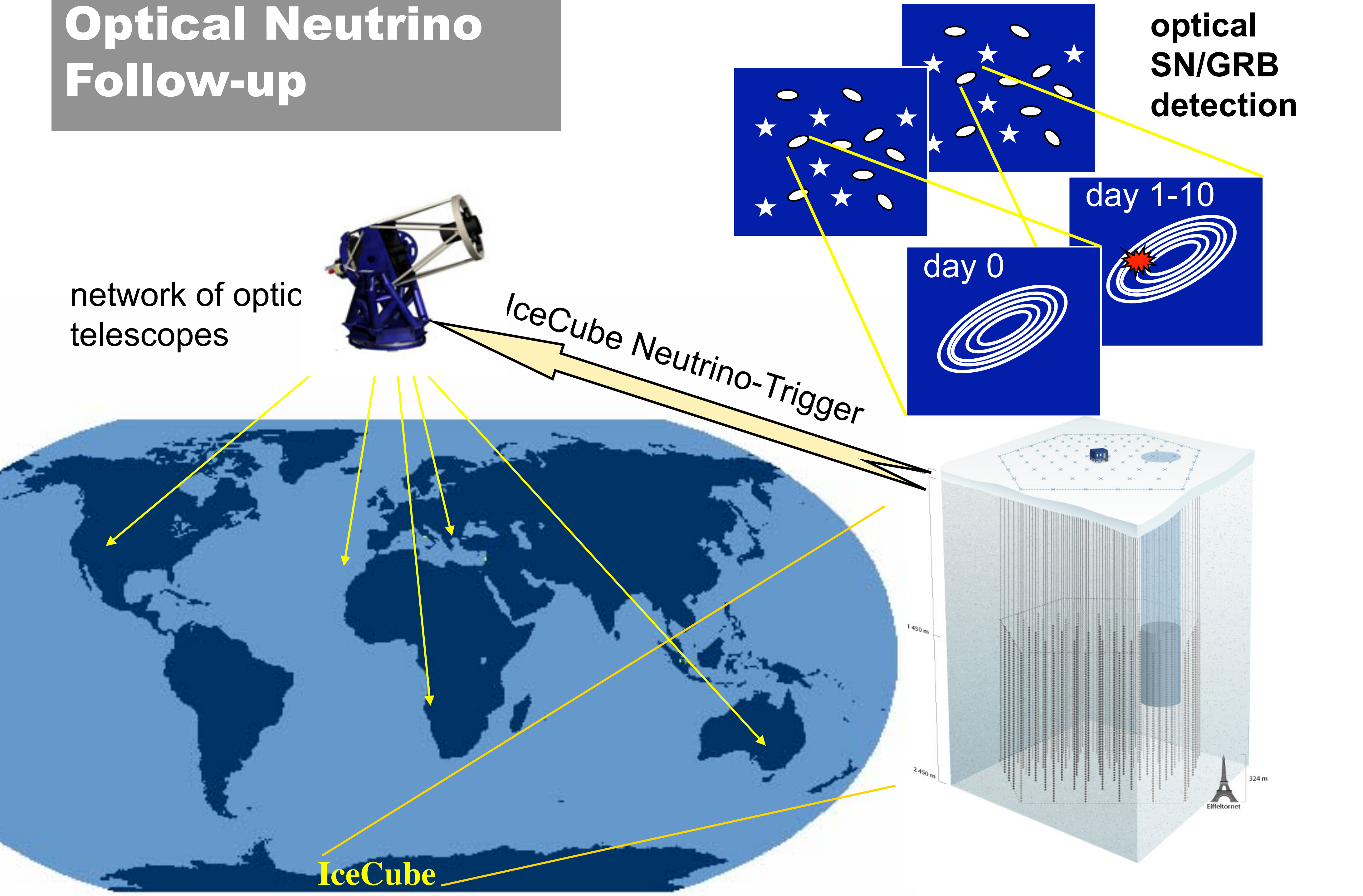
GRBs as neutrino sources



Conventional models appear inconsistent with GRBs as the source of cosmic rays

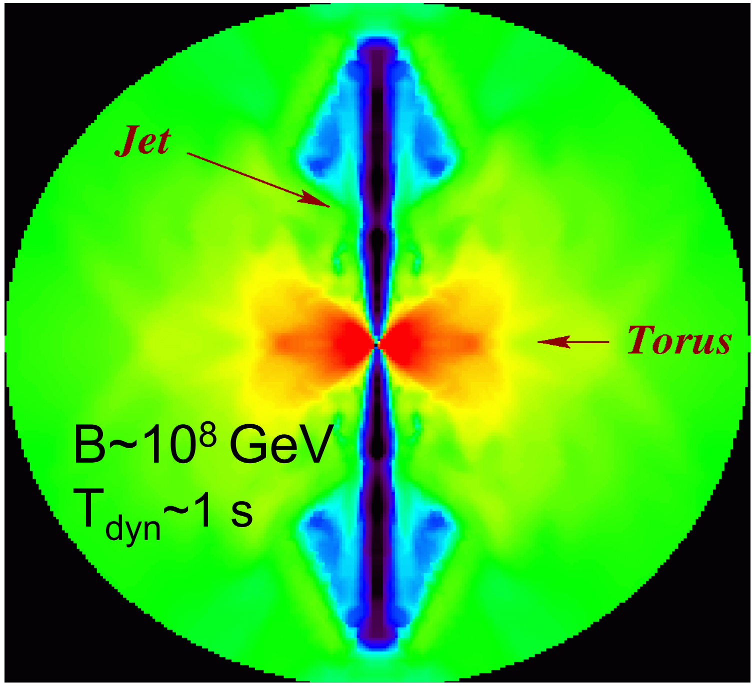
Submitted to Nature

Optical Neutrino Follow-up



Supernovae

Gravitative collaps of a very massive, rotating star (>25 $M_\odot$):



Simulation: MacFadyen (2000)

Source: Core-collapse Supernovae with mildly-relativistic Jets inside, that don't reach the surface.

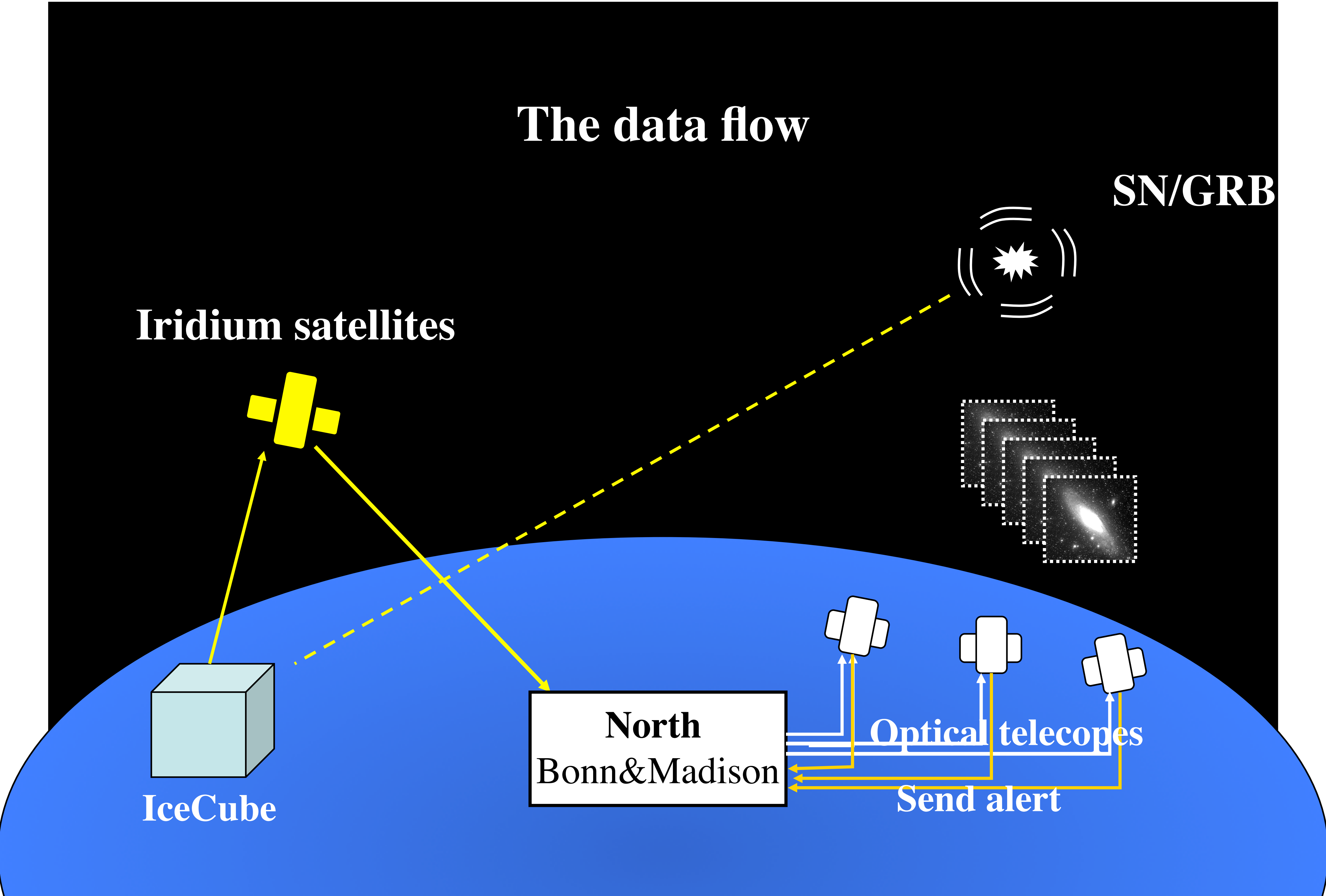
Motivation: Gamma-Ray Bursts, Polarisation & Radio-Observations.

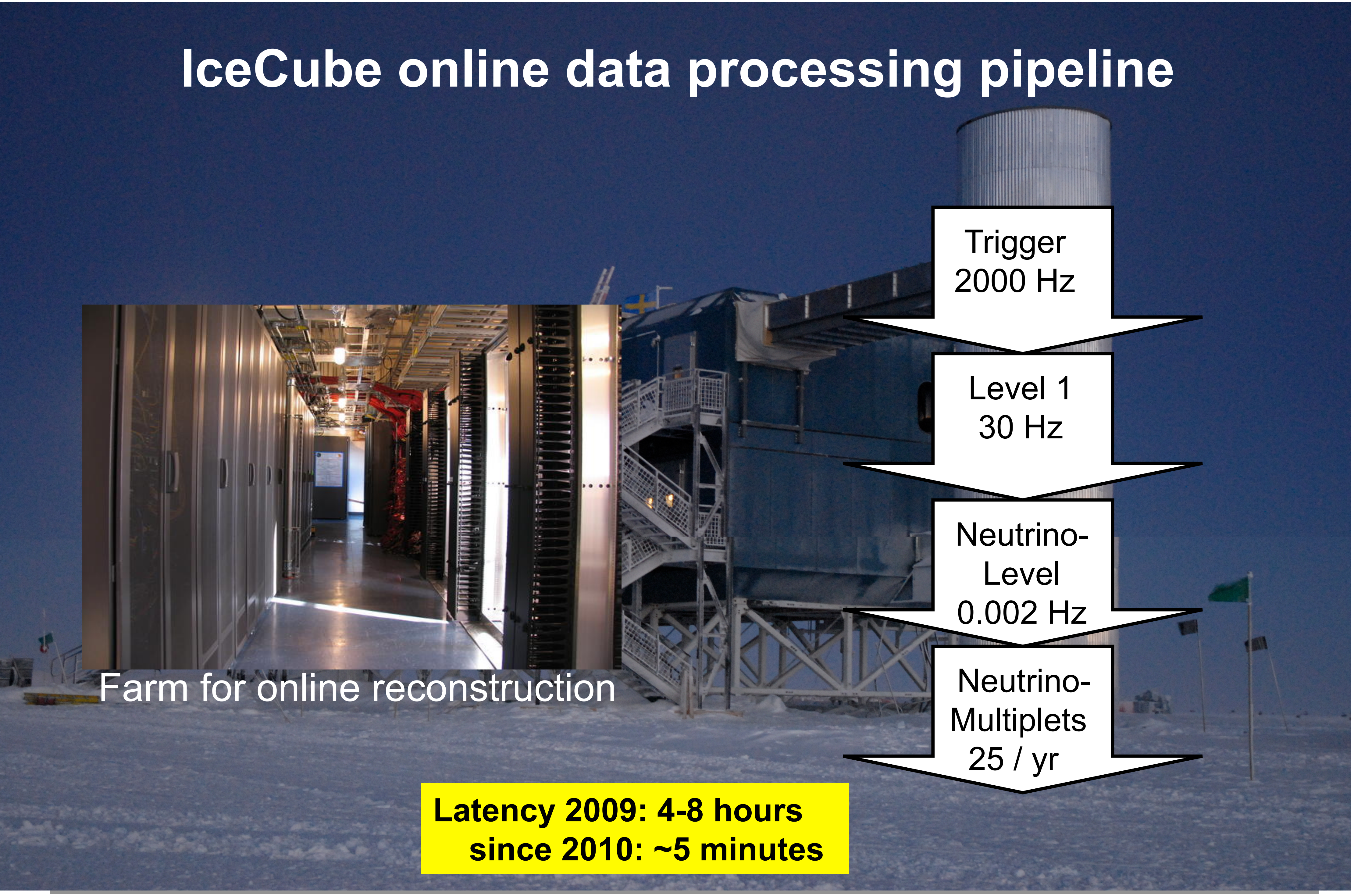
Neutrino prediction:

30 Neutrino-events with E>100 GeV in 10 s in IceCube at a distance of d=10 Mpc.

Ando & Beacom, PRL (2005);

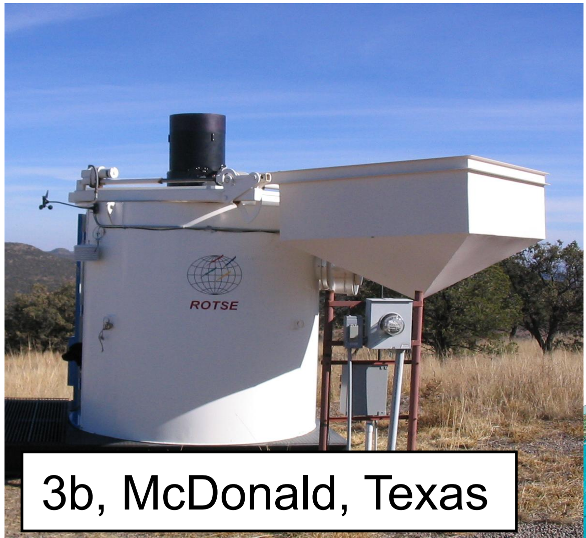
Razzaque, Meszaros & Waxman, PRL (2005).


The data flow
SN/GRB
Iridium satellites
IceCube
North
Bonn&Madison
Optical telecopes
Send alert

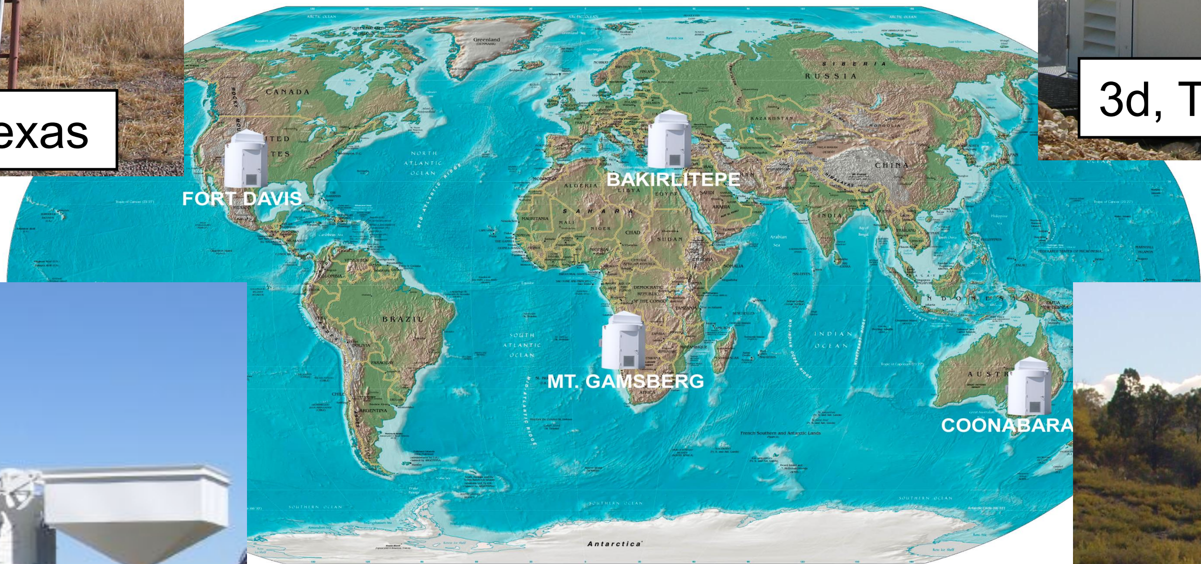

IceCube online data processing pipeline
Trigger
2000 Hz
Level 1
30 Hz
Neutrino-
Level
0.002 Hz
Neutrino-
Multiplets
25 / yr
Farm for online reconstruction
Latency 2009: 4-8 hours
since 2010: ~5 minutes

Optical Neutrino Follow-up

The ROTSE Network



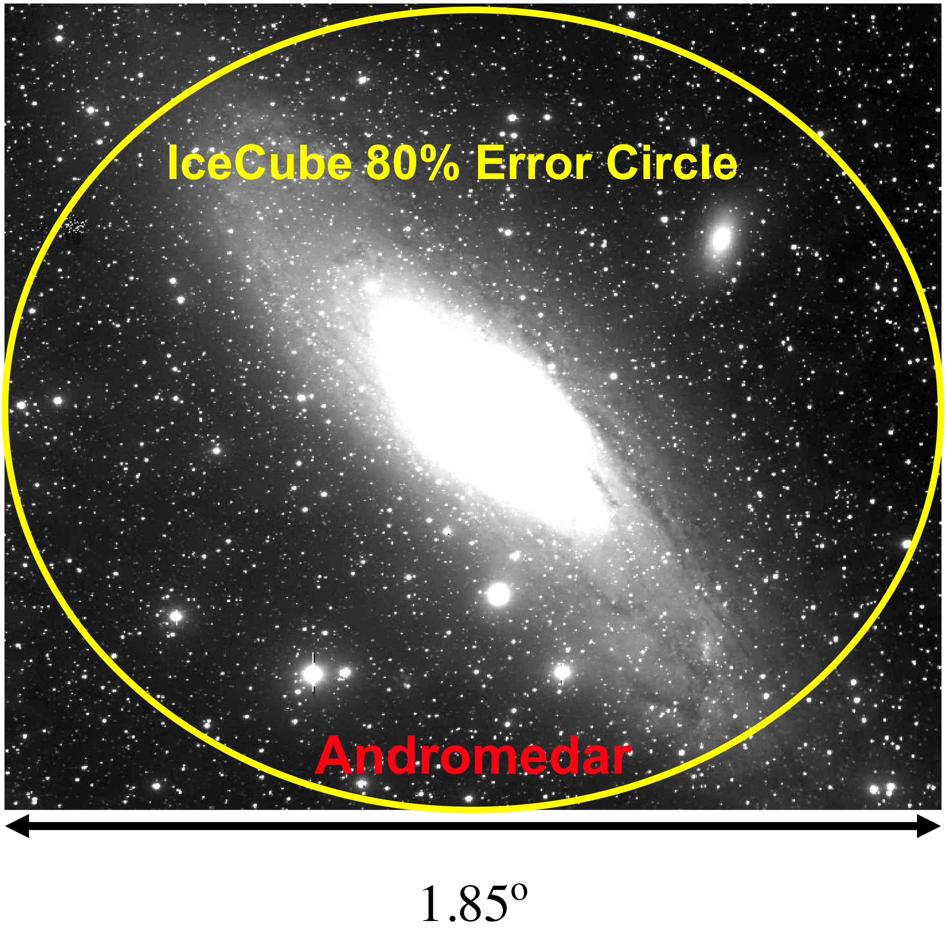
"The sun never rises over the ROTSE empire"



4 x 0.45 m
FoV: 1.85° x 1.85°
fully automated system

Optical Neutrino Follow-up

The ROTSE Telescopes



Optical Neutrino Follow-up

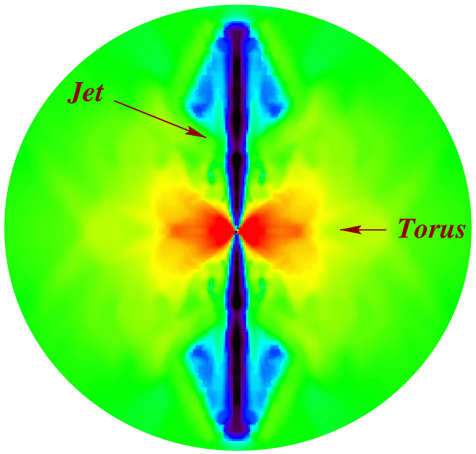
	multiplicity	observed	expected
SNe		0	0.074
IC 40	Doubletts	15	8.55
IC 40	Tripletts	0	0.003
IC 59	Doubletts	19	15.66
IC 59	Tripletts	0	0.004

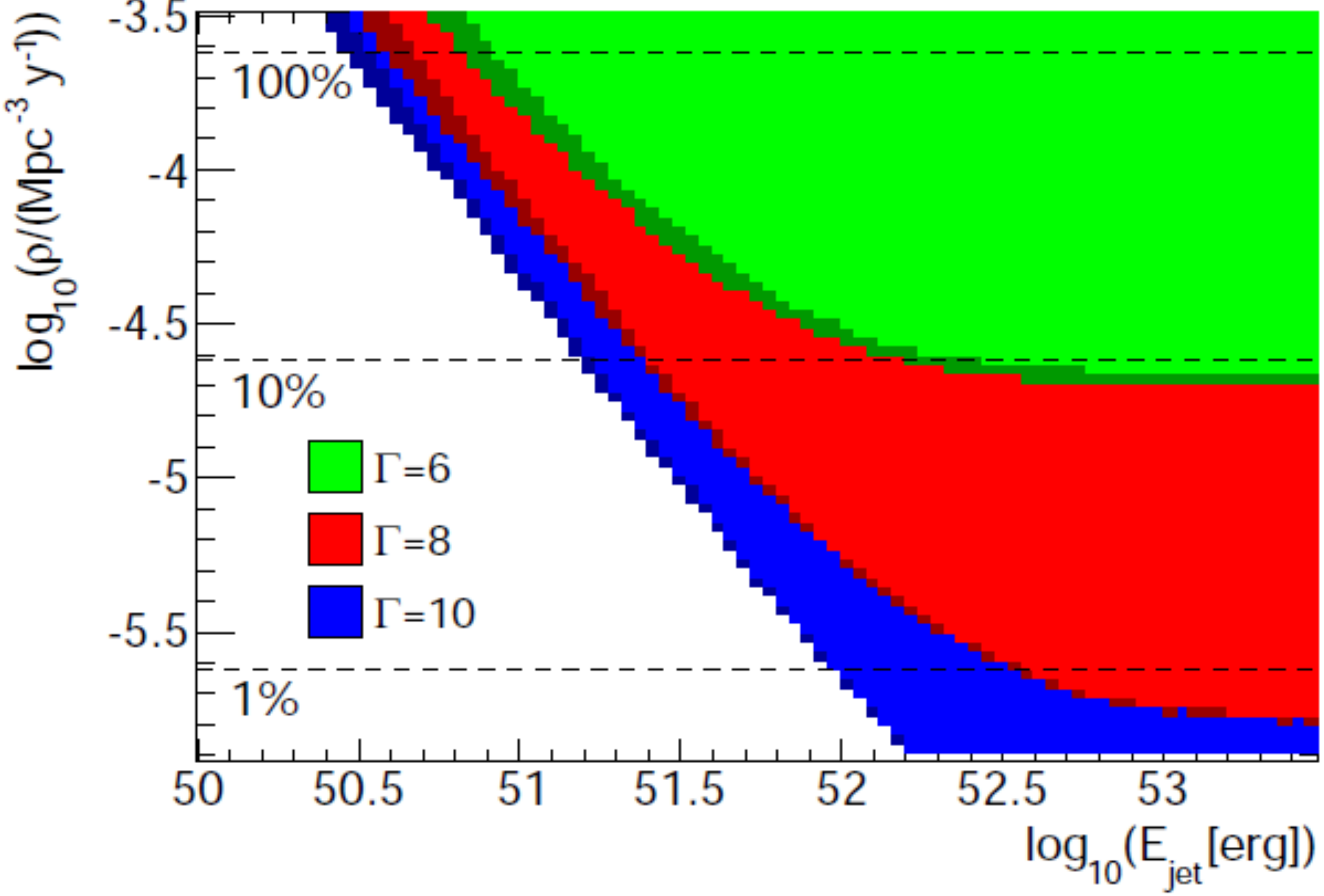
„Neutrino physics is largely an art of learning a great deal by observing nothing“,
Haim Harari

Supernova constraints

Abbasi et al., A&A 2012

Are there GRB-like jets inside of core-collapse supernovae?





Less than 4.2% of all core-collapse SNe contain a jet with $\Gamma = 10$ und $E_{jet} = 3\times10^{51}$erg

PINGU - Precision IceCube Next Generation Upgrade

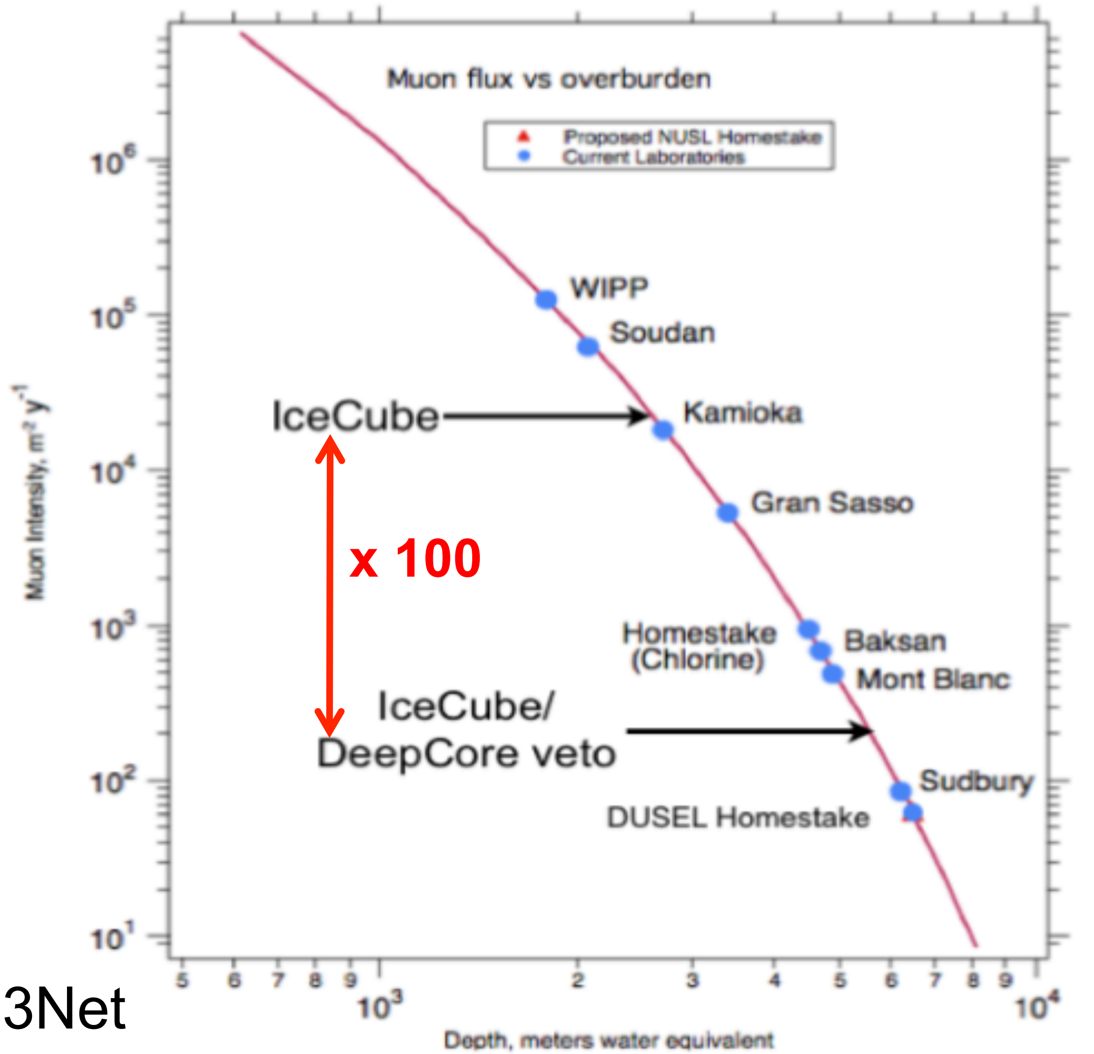
Utilizing existing infrastructure & experience for a large, low energy neutrino-detector

First stage ("PINGU")

- ~18 extra strings for E_{thresh}~1 GeV
- WIMP search, ν-oscillation,...
- test bed for new technologies

Second stage ("MICA")

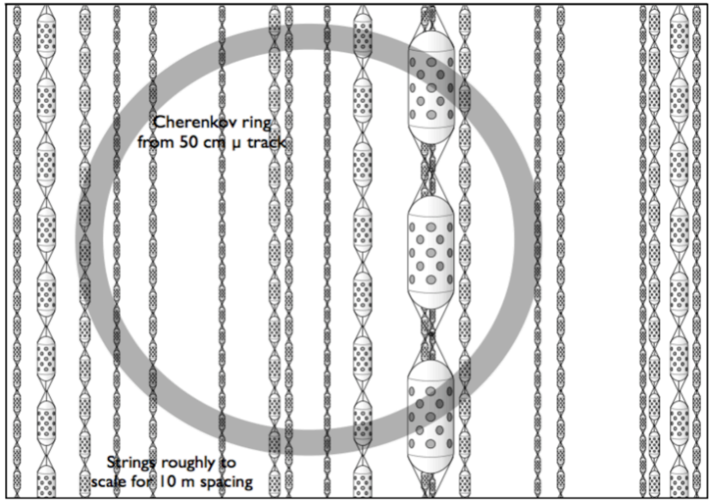
- New photon detection technology, E_{thresh}~ 10 MeV
- proton decay, supernova neutrinos, PINGU-I topics
- Costs comparable to IceCube, KM3Net



MICA – Multi-megaton Ice Cherenkov Array

Goals for 2nd. phase: ~5 MTon scale with energy threshold of ~10 MeV

- IceCube provides active veto
- Physics extraction from Cherenkov ring imaging in the ice

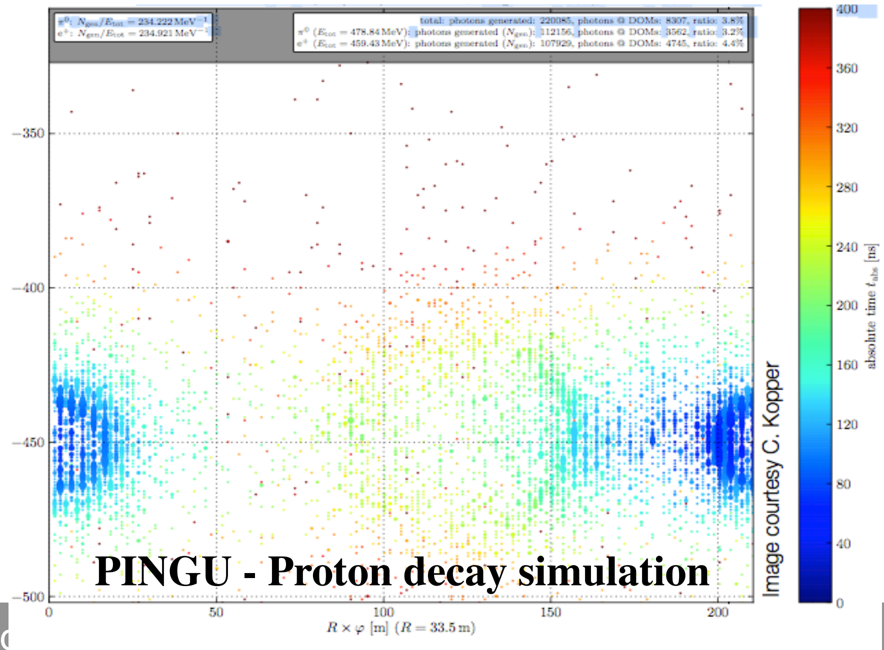


Proton decay:

$\tau_p \sim 10^{35}$ - 10^{36}yr for $p \rightarrow \pi^0 + e^+$ channel.
Probe various SU(5) GUT theories

Supernovae:

Unique sensitivity to nearby extra-galactic Supernovae with rate 1-2/yr



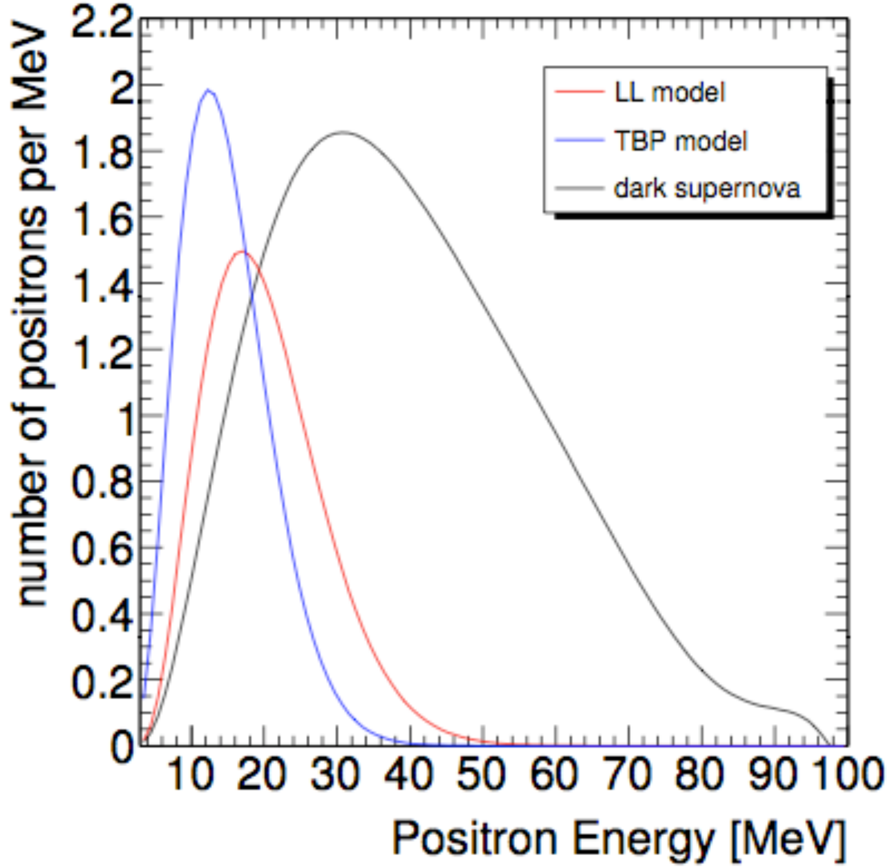
MICA – Multi-megaton Ice Cherenkov Array

- Current ν-detectors sensitive to galactic SNe ⇒1-2 SNe per century

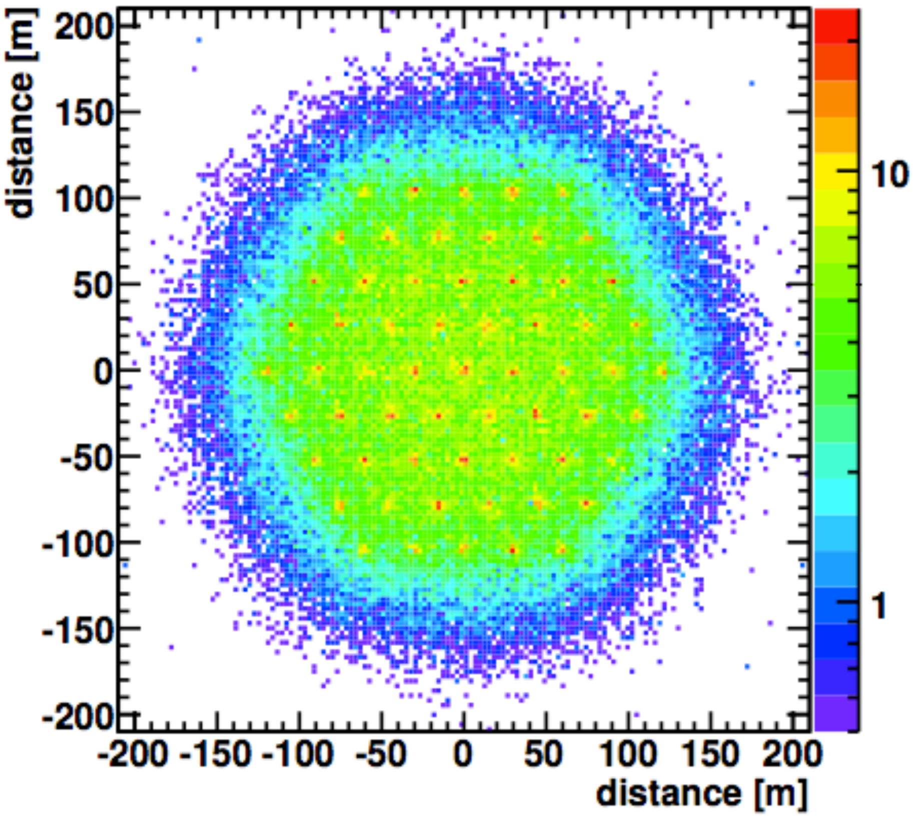
- Within 10 Mpc, **~2 SNe per year ⇒5-10 Mton neutrino detector required**

- Novel science program enabled with routine SNe detection:
  - observing collapse in BH
  - normalizing star formation
  - multi-messenger with grav. waves
  - …

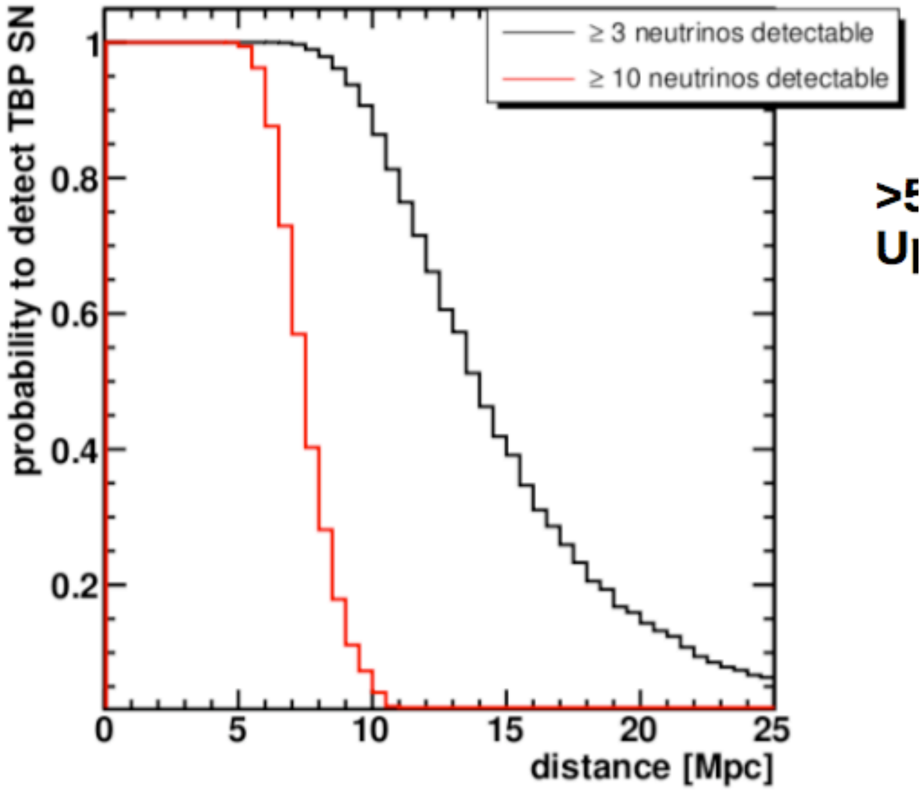
Spectra from core collapse SNe: Neutrino star vs Black Hole



MICA – Mulit-megaton Ice Cherenkov Array



Simulation: dense array with
~90.000 PMTs ⇒10 Mton eff. volume



100 % detection probability tp 10 Mpc

2-3 SNe per year detecteble

Conclusion

- IceCube is now complete and has started collecting data with unprecedented sensitivity.

- A search for point sources and GRBs with the IceCube 40+59 string detector has not brought a discovery yet, many other searches are ongoing.

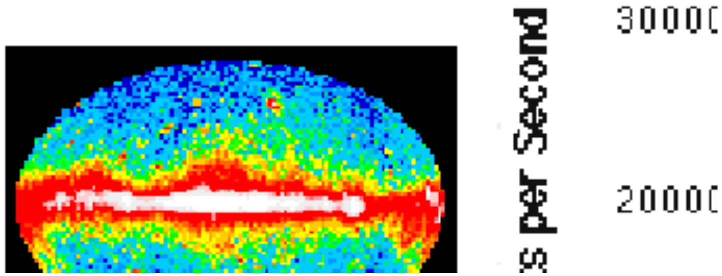
- IceCube has been connected to a network of robotic optical telescopes, as well as to SWIFT that perform automated follow-up observations

- Extension of IceCube principle to lower energies planed, providing significant new scientific opportunities

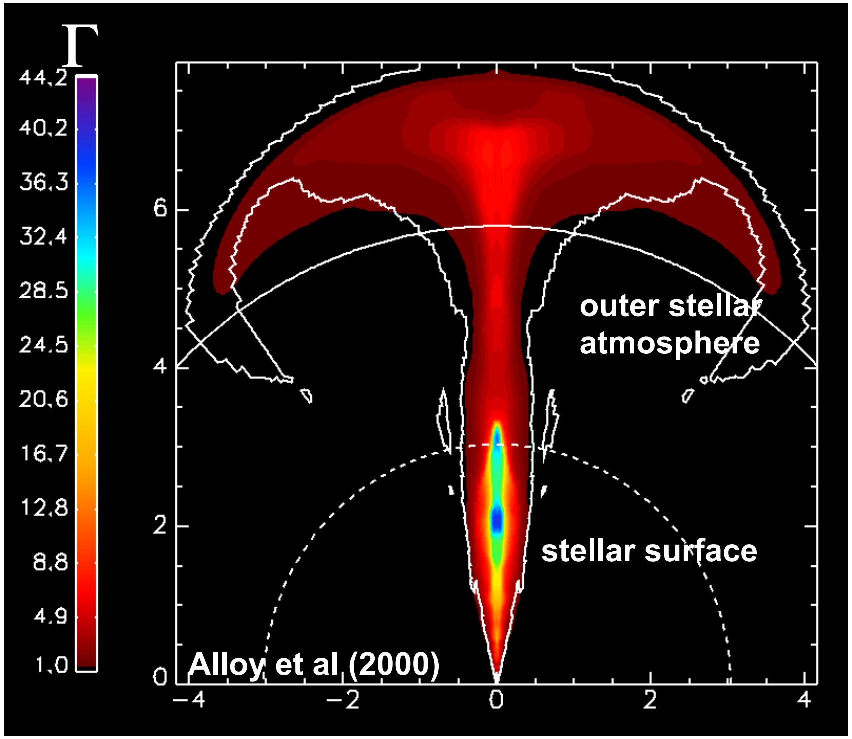

End

Gamma-Ray Bursts

Satelite Detection of keV-MeV photon bursts



Gamma-Ray Bursts

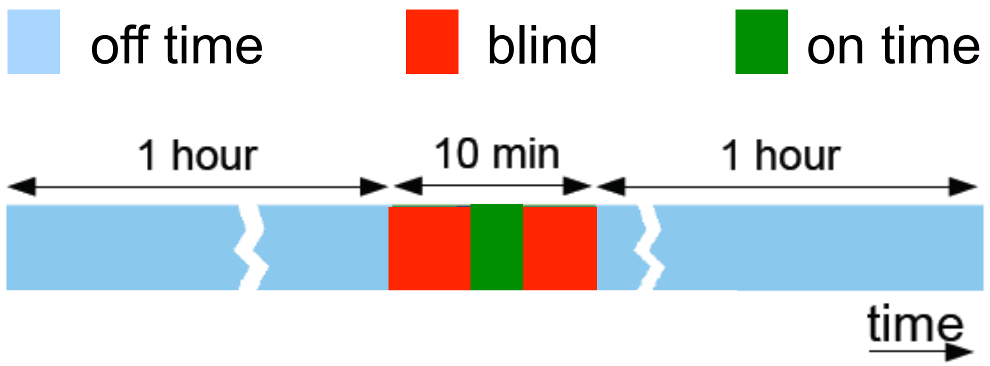


10^{51} ergs (10^{44} J) emitted within few seconds through gamma-rays.
⇒**highly relativistic jets.**

Possible sources of the highest energy cosmic- rays
⇒ **Neutrinoemission.**

Astrophysical neutrino search

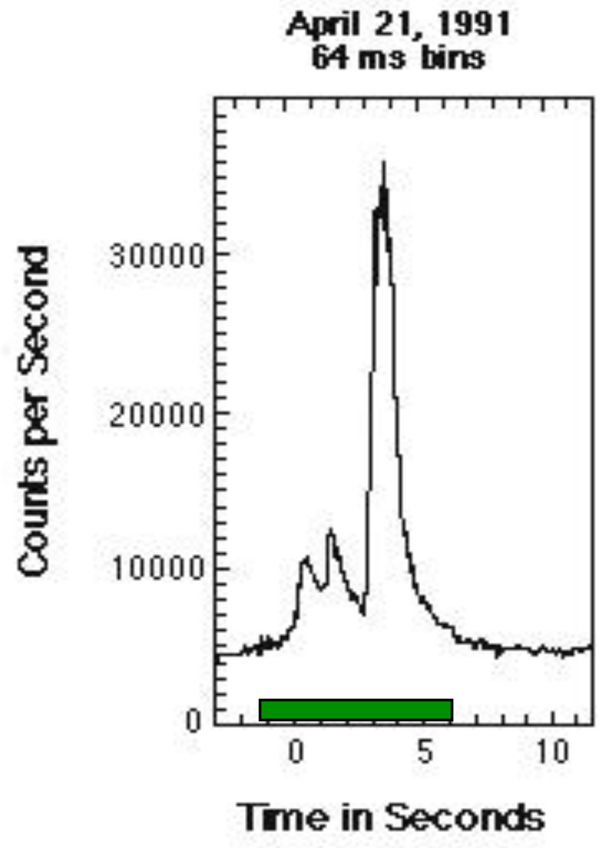
Gamma-Ray Bursts



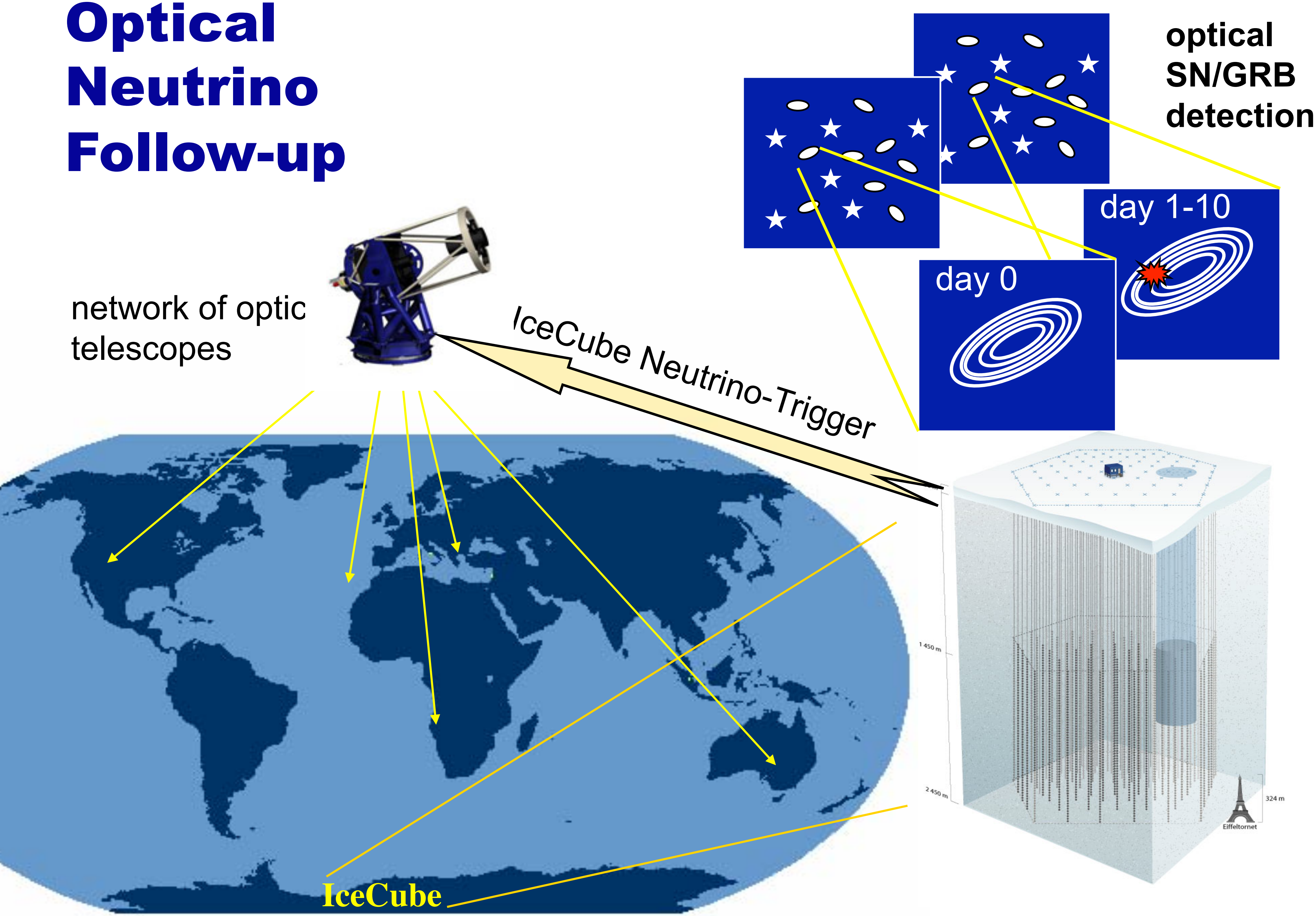
408 GRBs detected with Satelites (1997-2004):

⇒**no coincident neutrino detected!**

Upper limit is within a factor 2 relative to model predictions



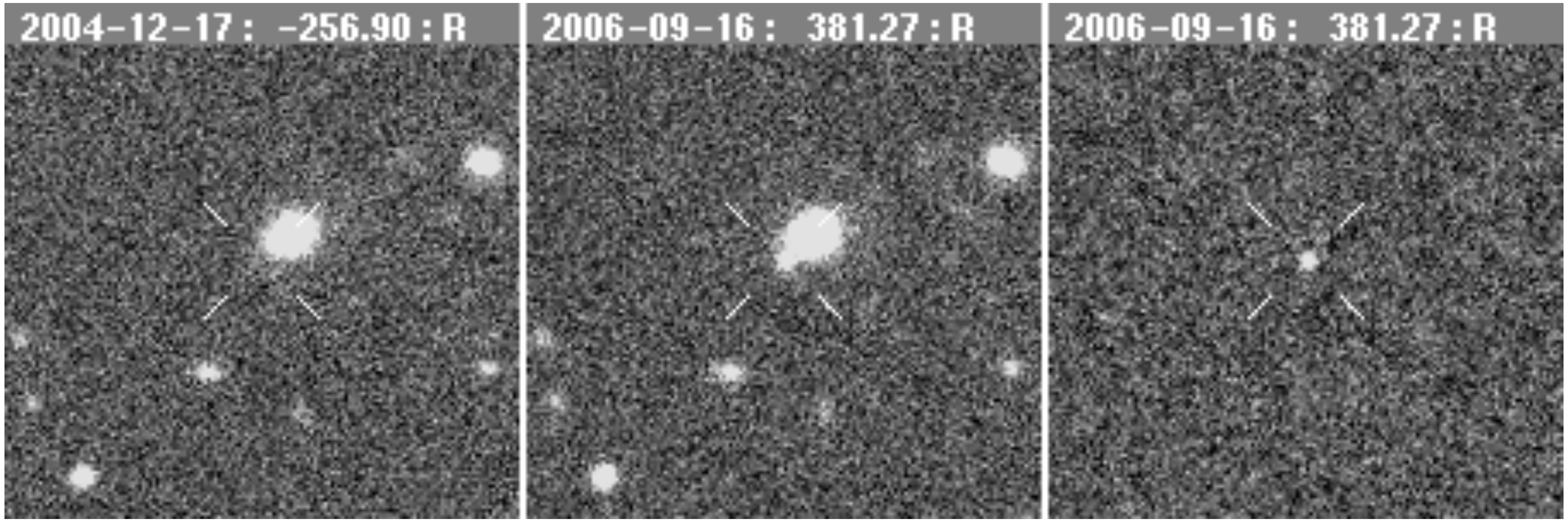
Optical Neutrino Follow-up



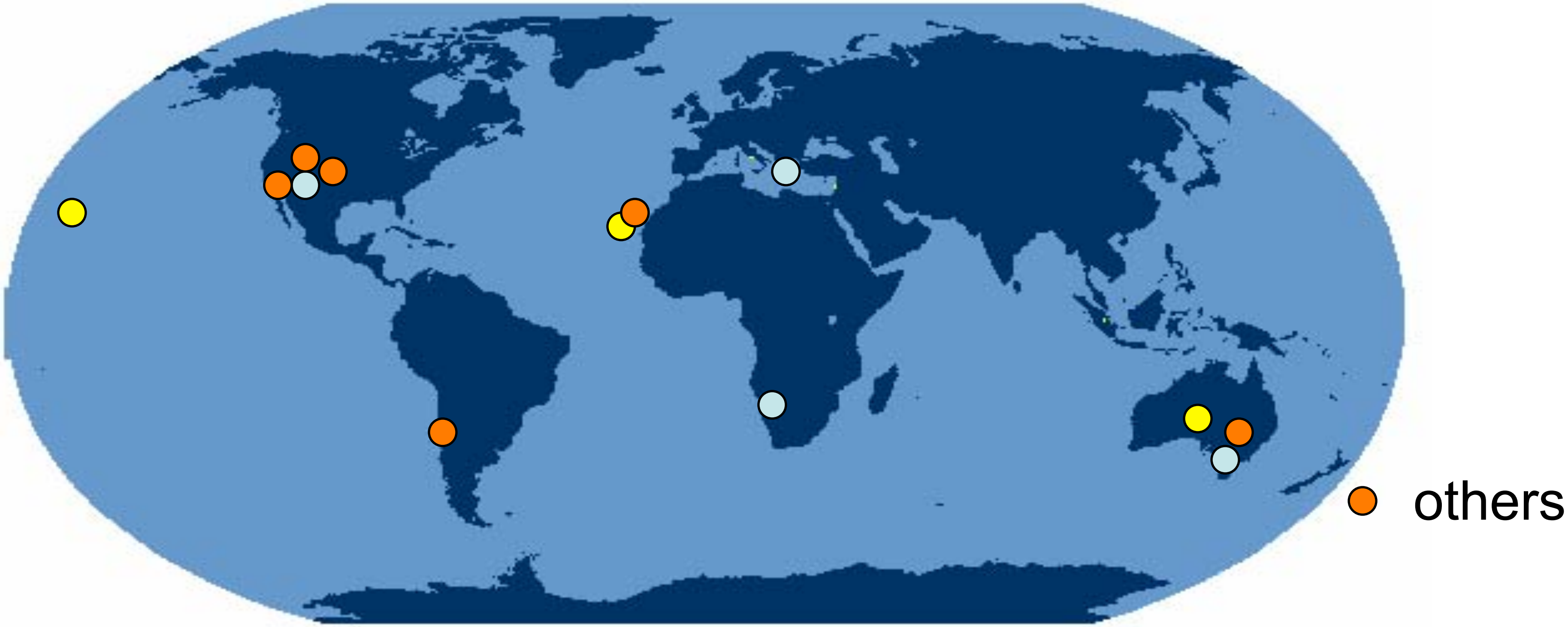
Optical follow-up of neutrino bursts

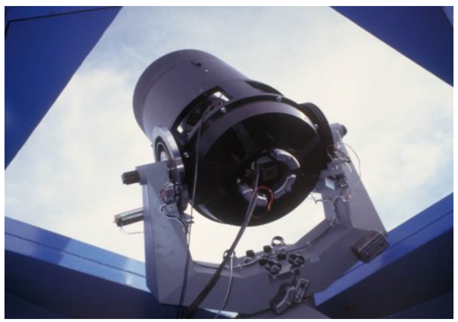
Supernova/GRB detection with optical telescopes

old image - new image = subtraction



Global network of robotic telescopes



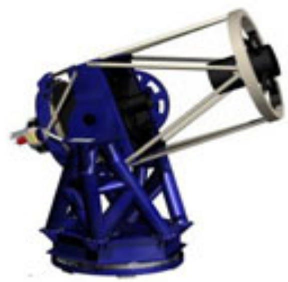


ROTSE III

4 x 0.45 m

FoV: 2° x 2°

rapid ν follow-up



Robonet-1.0

3 x 2.0 m

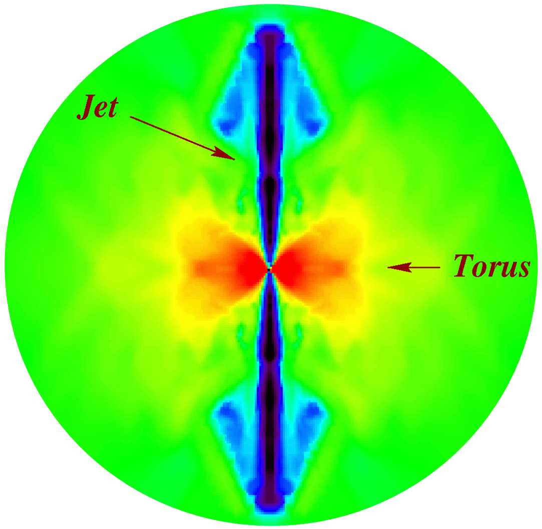
FoV: 0.1° x 0.1°

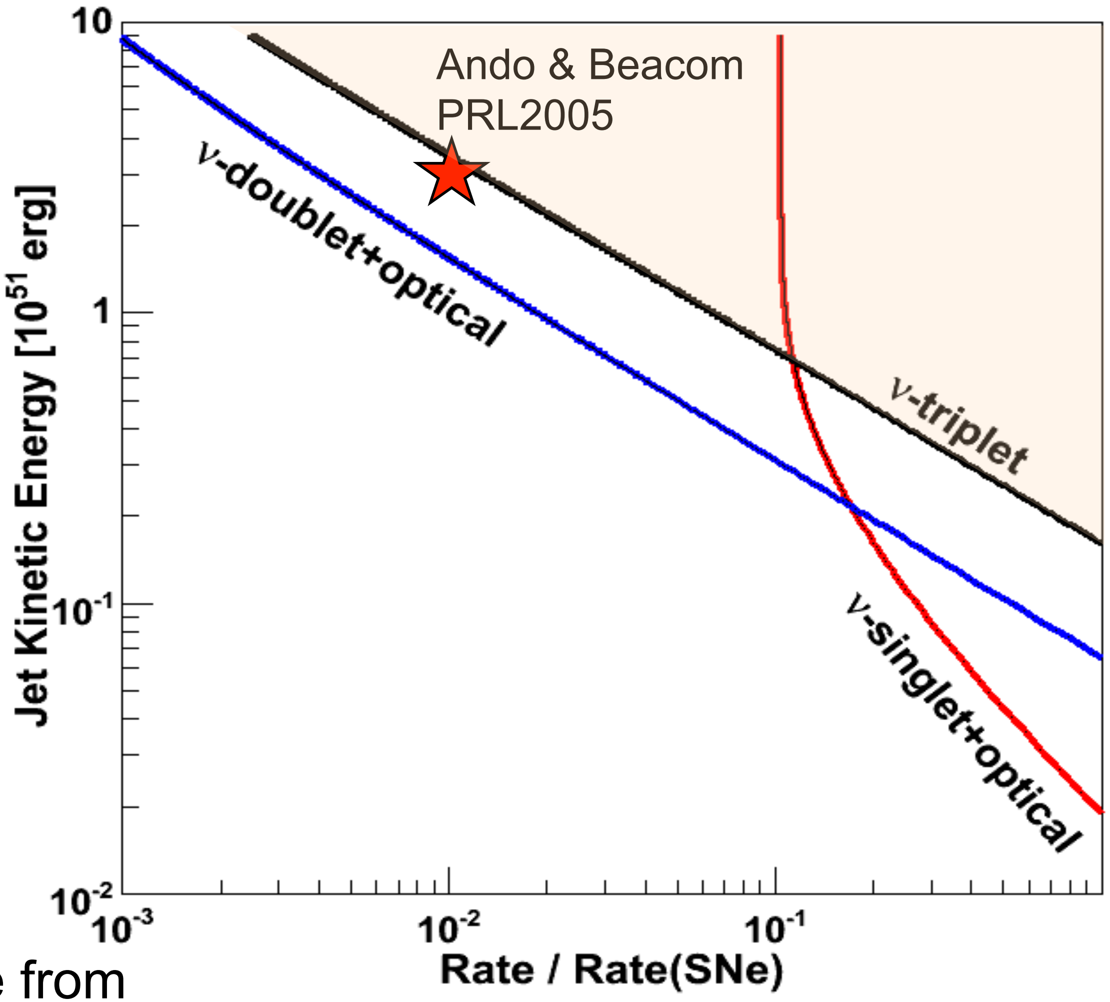
follow-up of ROTSE

Optical follow-up of neutrino bursts

Supernova sensitivity

Are there GRB-like jets inside of core-collapse supernova?





Ando&Beacom:

30 events within 10s in IceCube from a SN @ 10 Mpc distance.

Summary

So far:

- AMANDA has been running since 2000.

- More than 5000 atmospheric neutrinos above 100 GeV energies.

- No indication for an astrophysical neutrino flux.