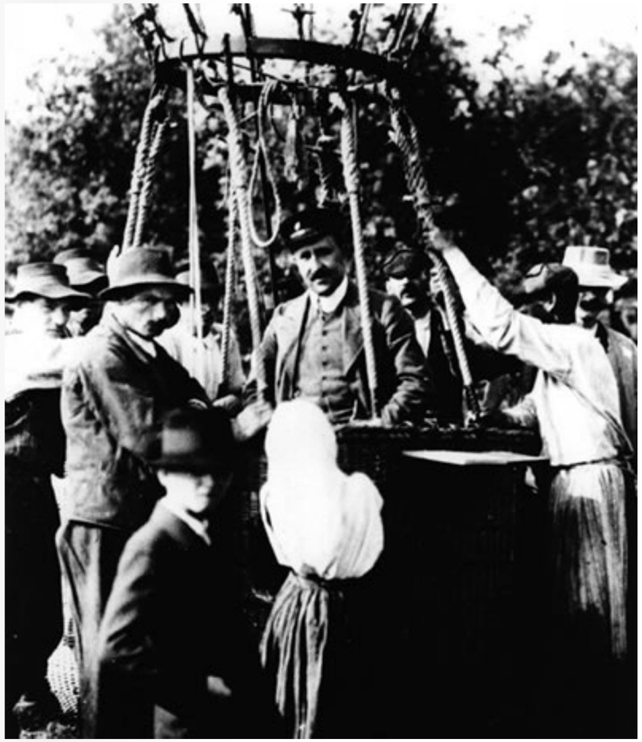
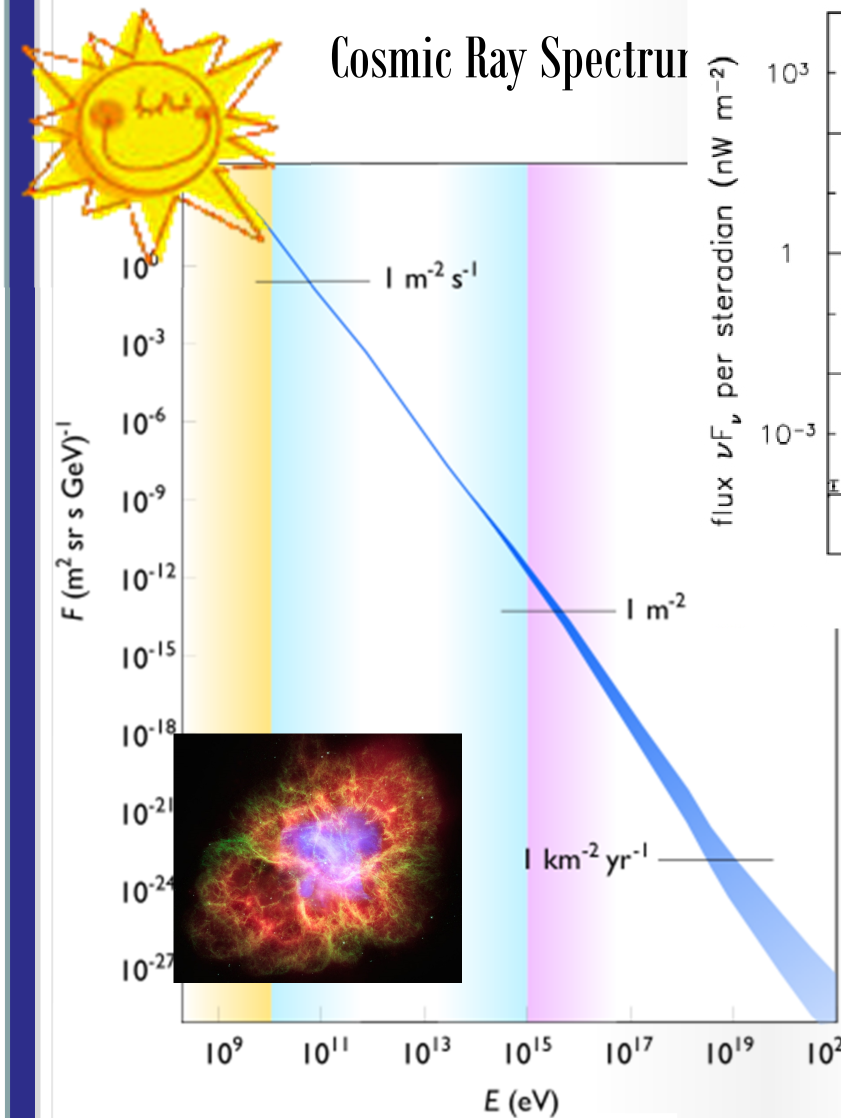
Neutrinos as probes of ultra-high energy astrophysical phenomena

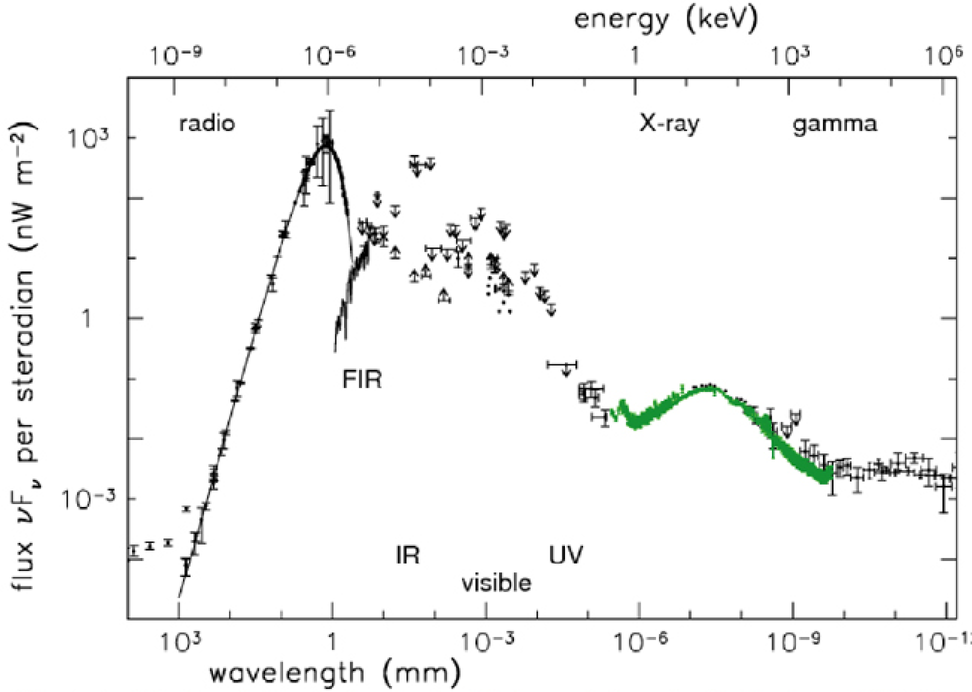
Introduction to Cosmic Rays

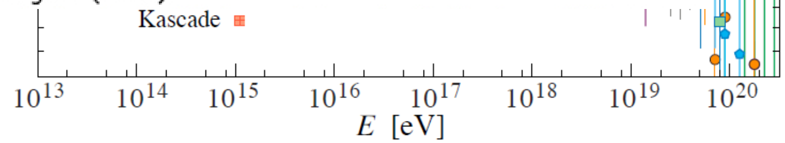


A century-old puzzle

Cosmic Ray Spectru





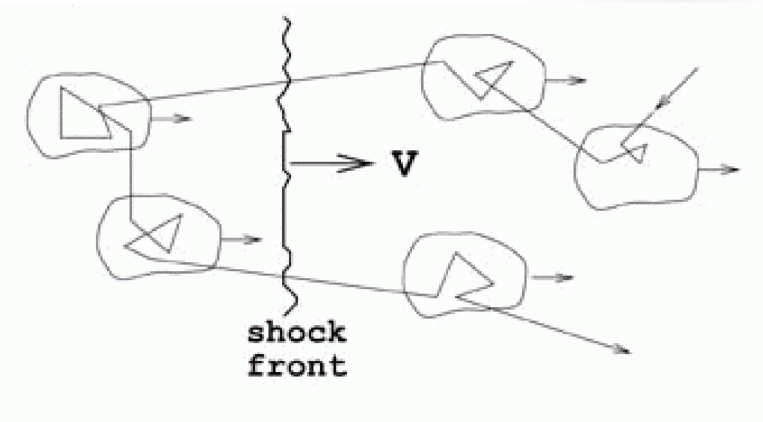


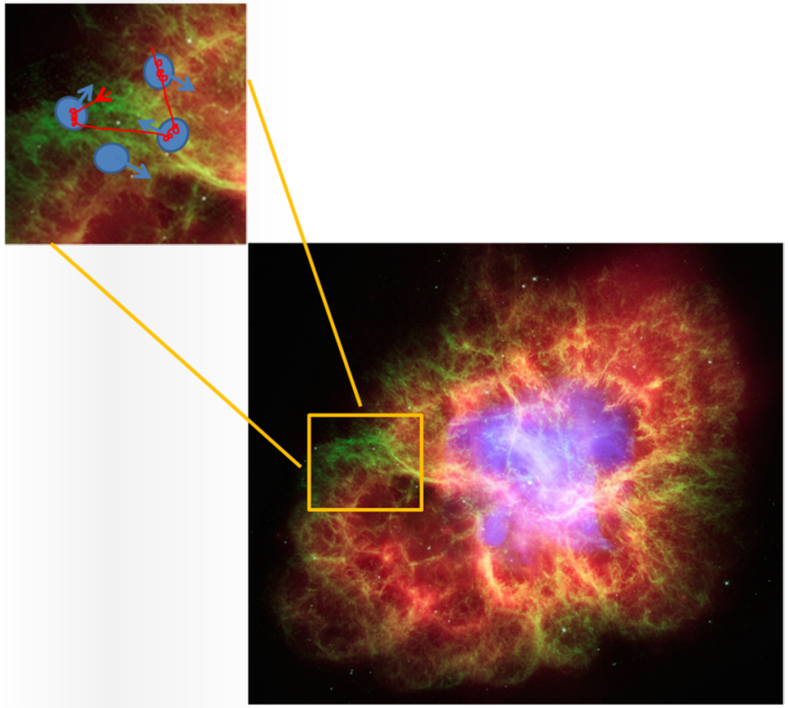
$$\frac{d\Phi}{dE} \propto E^{-2.7}$$

Acceleration of cosmic rays – Fermi diffusive Acceleration

- 1st Order:

acceleration in strong shock waves





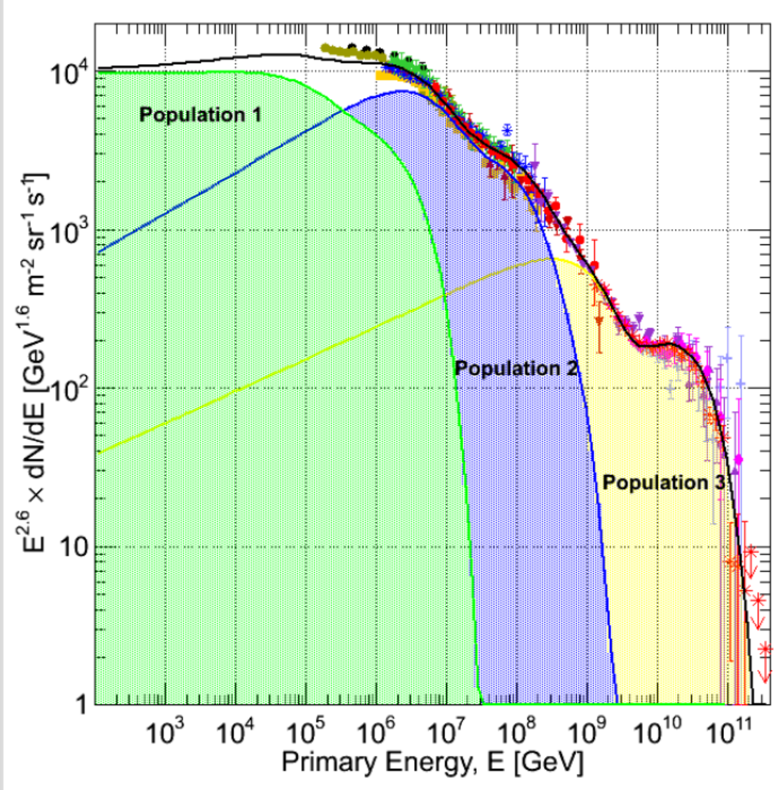
Acceleration Spectrum

$$\frac{dN}{dE} \sim E^{-2}$$

The highest energy that a particular site can accelerate particles to can be estimated through the gyroradius.

That the gyroradius is less than the linear size of the accelerator implies

$$E_{max} \sim \beta ZBr$$



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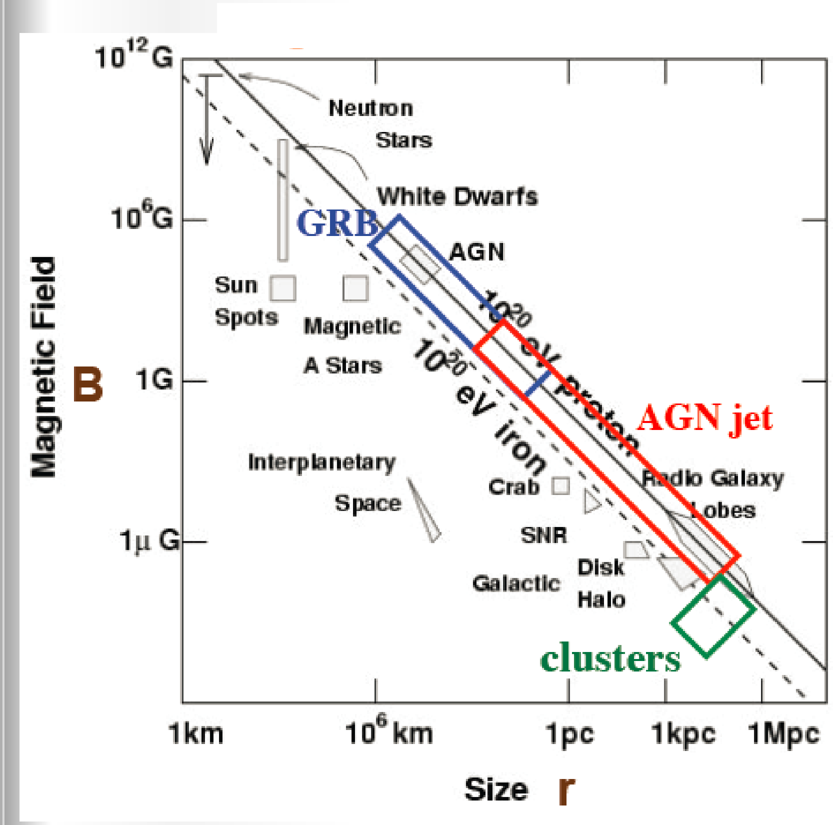
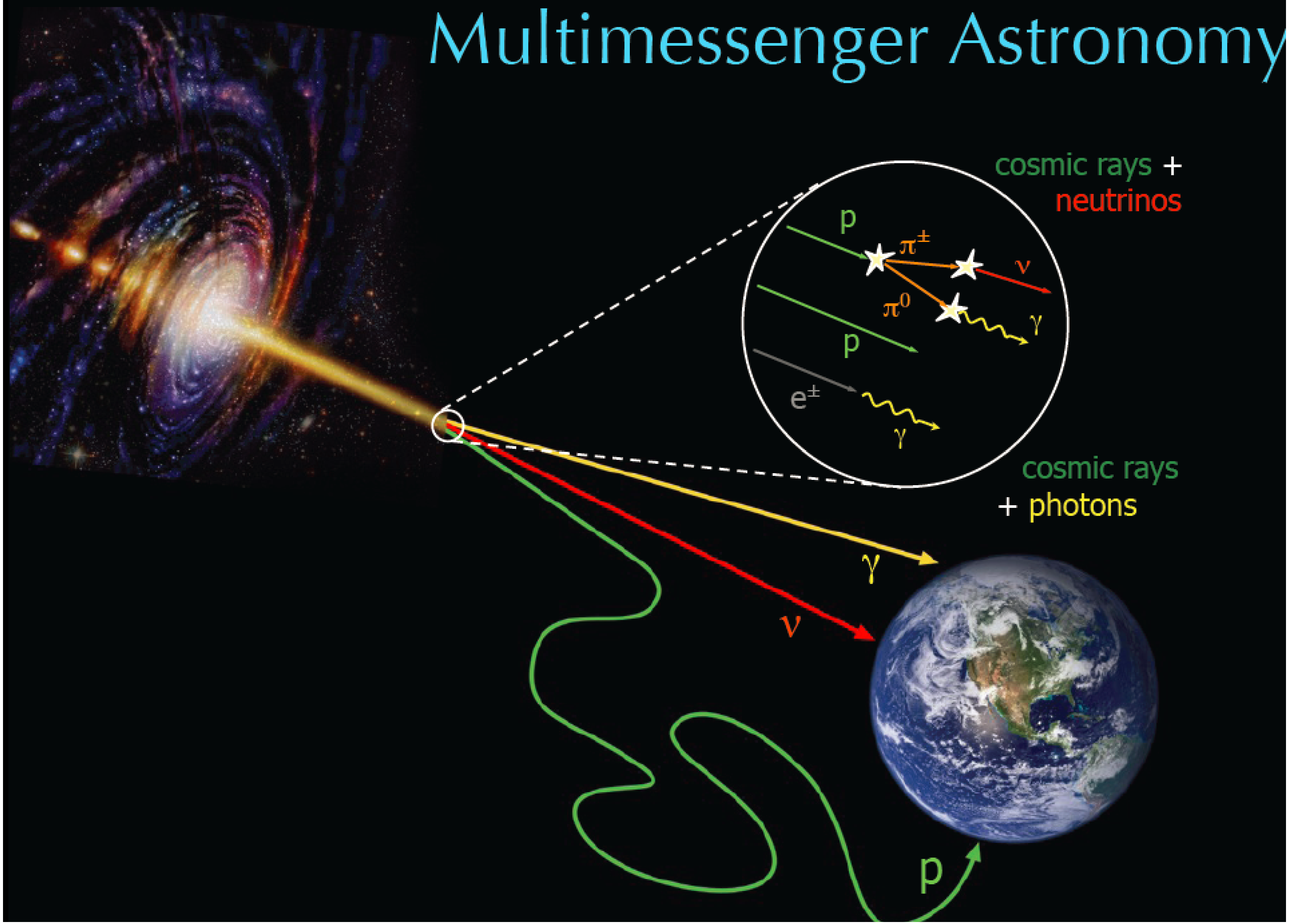
Hillas Plot

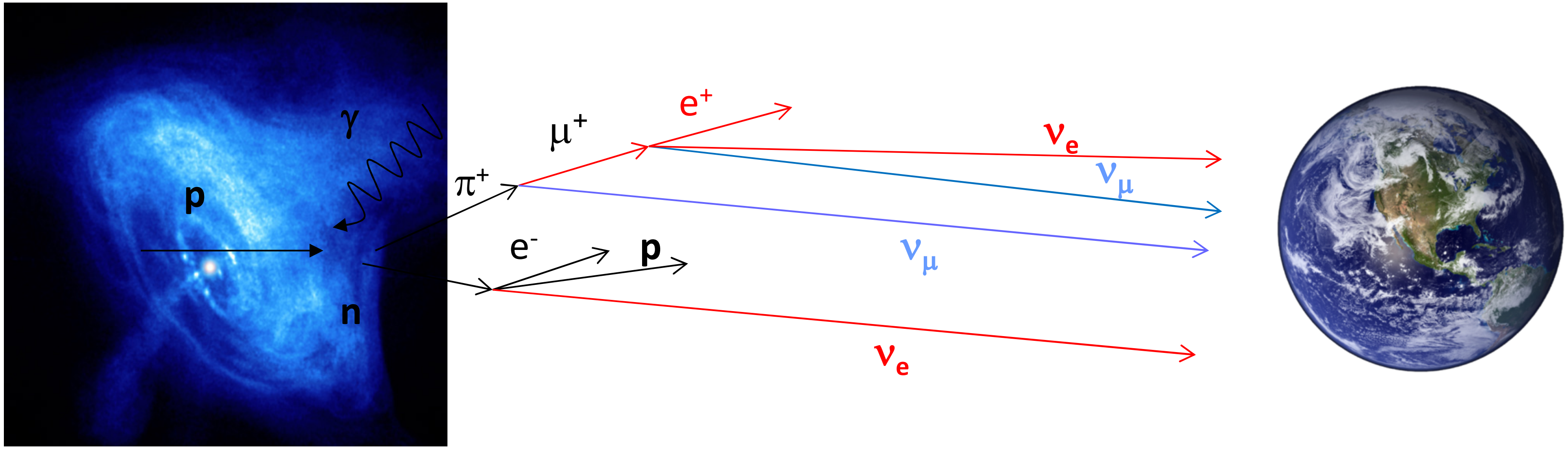


Multimessenger Astronomy



Astrophysical cosmic-ray neutrinos

Neutrinos from cosmic ray interactions at **acceleration site**

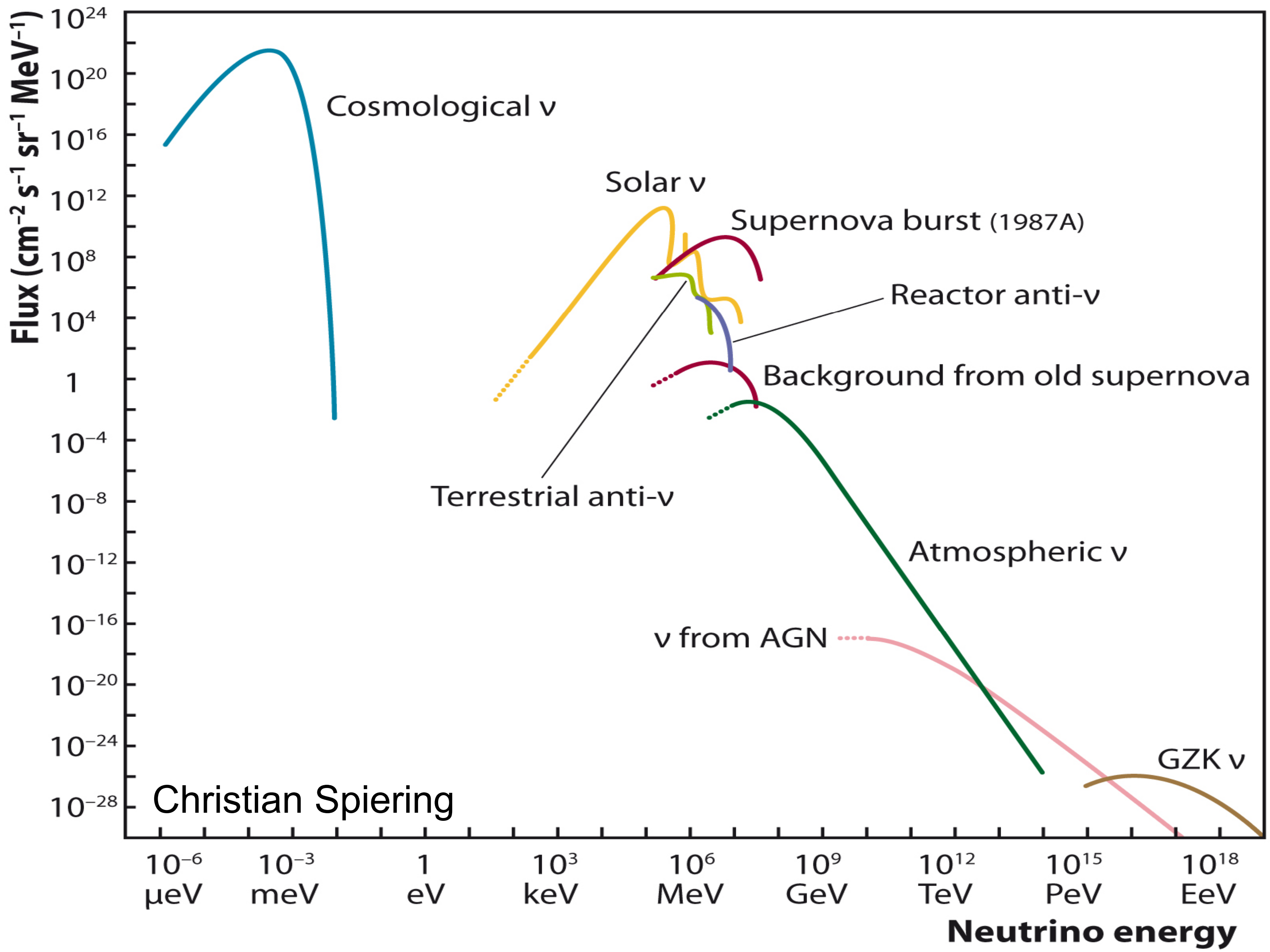


$$\frac{dN_\upsilon}{dE} \sim E^{-2}$$

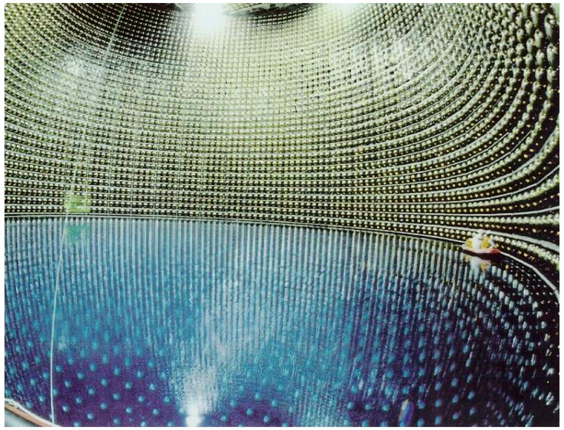
Flavour ratio at source:
$\upsilon_e : \upsilon_\mu : \upsilon_\tau = 1:2:0$

After oscillations flavour ratio at Earth:
$\upsilon_e : \upsilon_\mu : \upsilon_\tau = 1:1:1$

Neutrino source fluxes

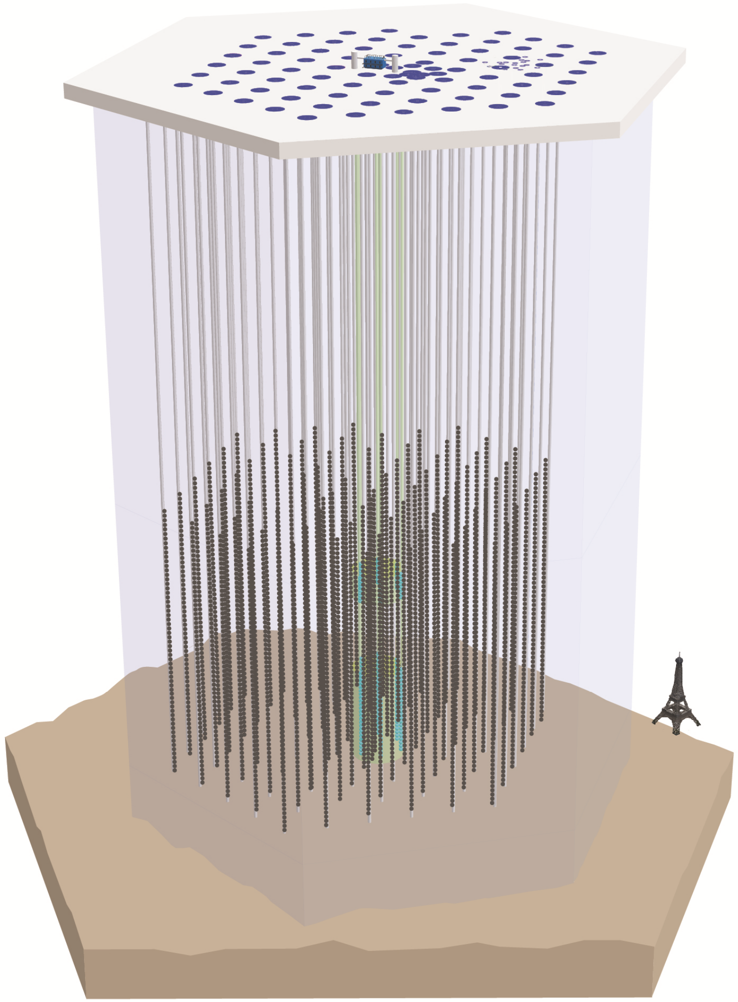


IceCube is a LARGE neutrino detector...

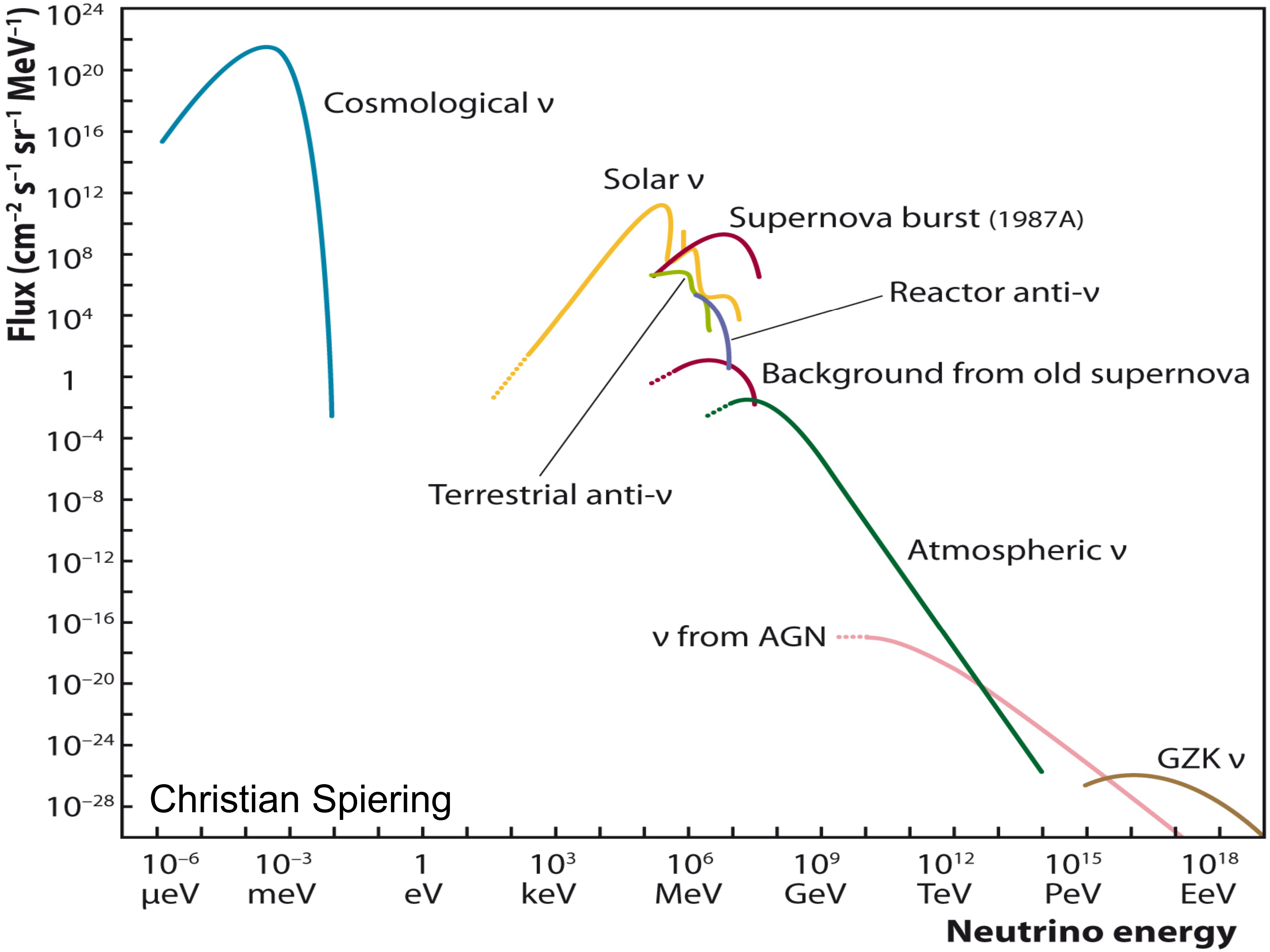


Super Kamiokande

SNO

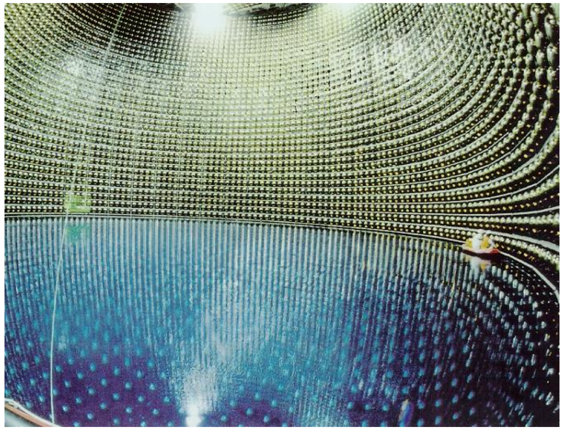


Neutrino source fluxes



IceCube is sparsely instrumented...

The amount of Cherenkov light is proportional to the energy of the neutrino, astrophysical neutrino detectors can have sparse instrumentation.



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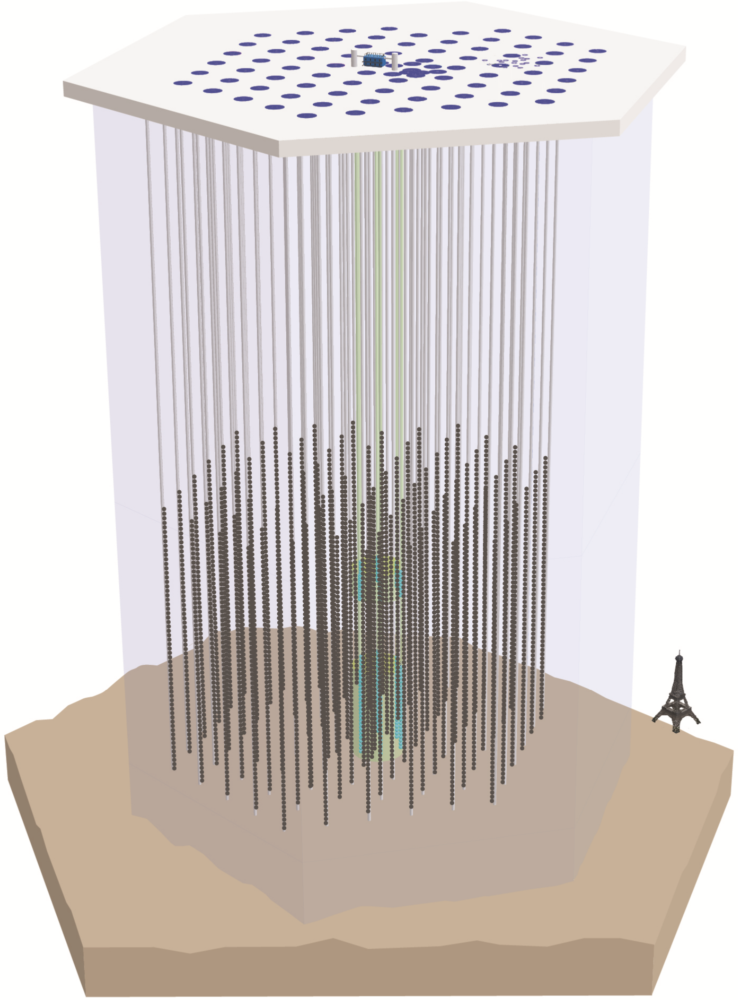
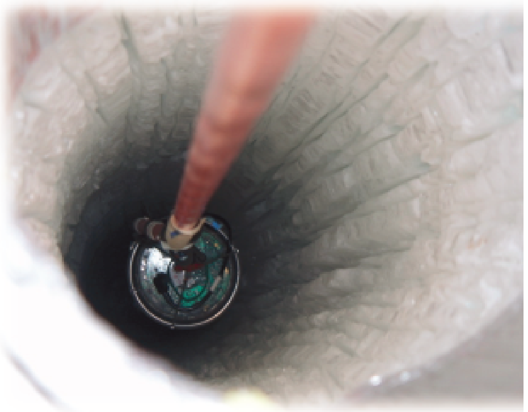
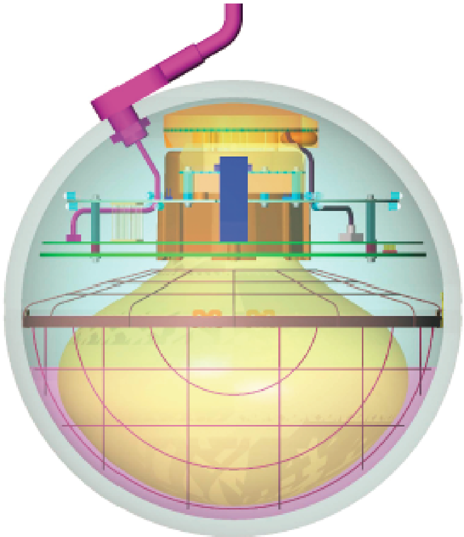
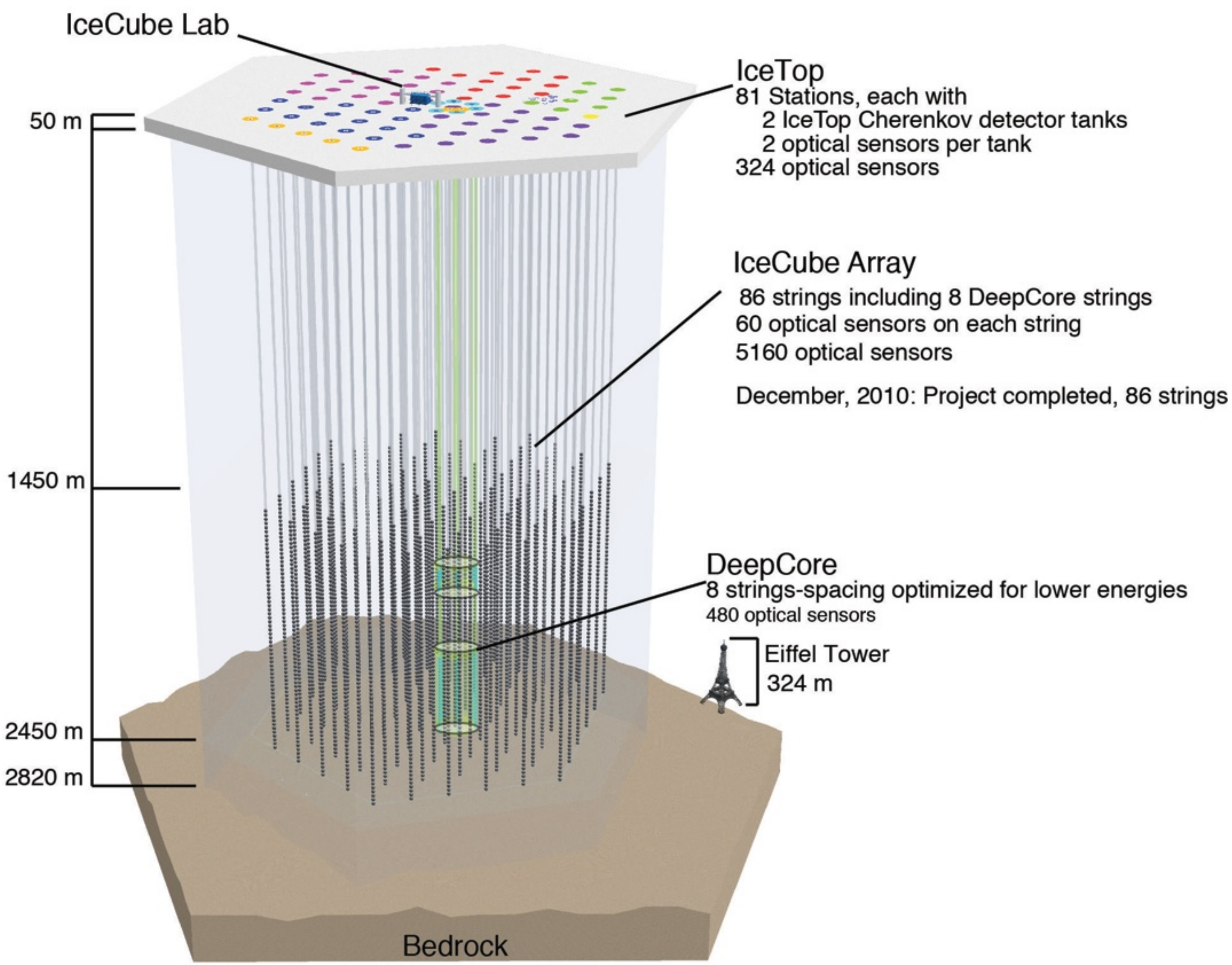


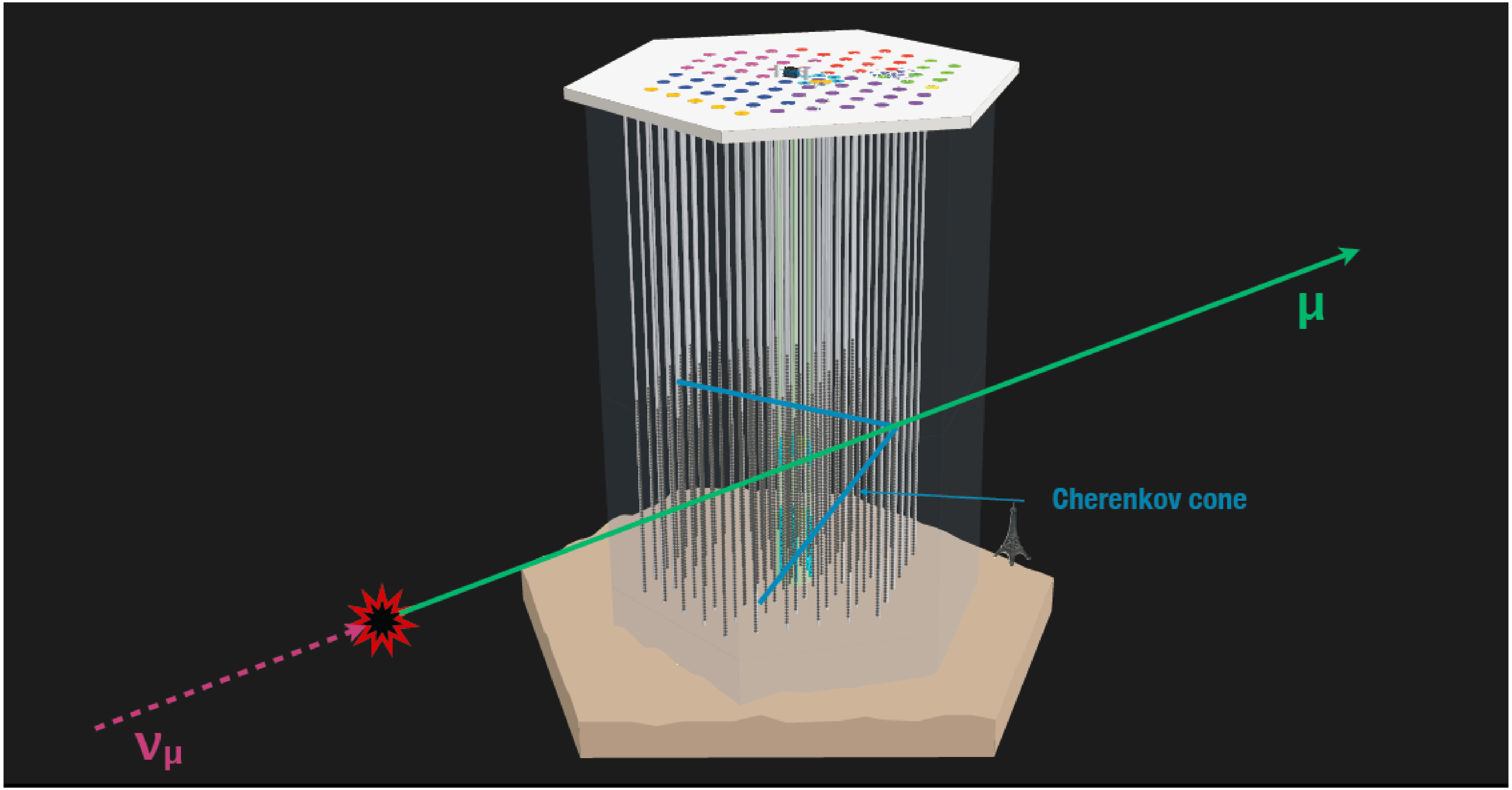
IceCube neutrino detector

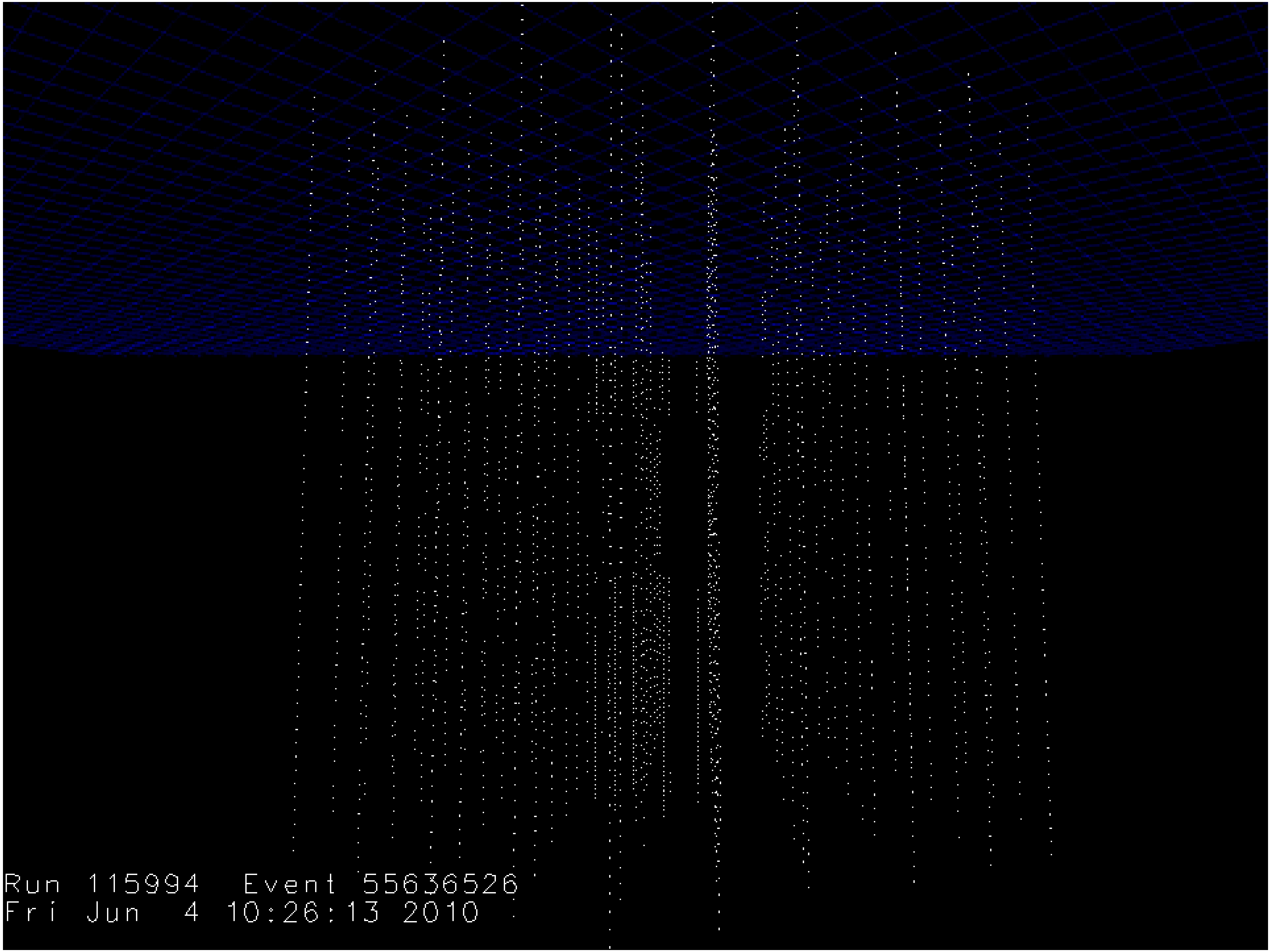






Detection principle

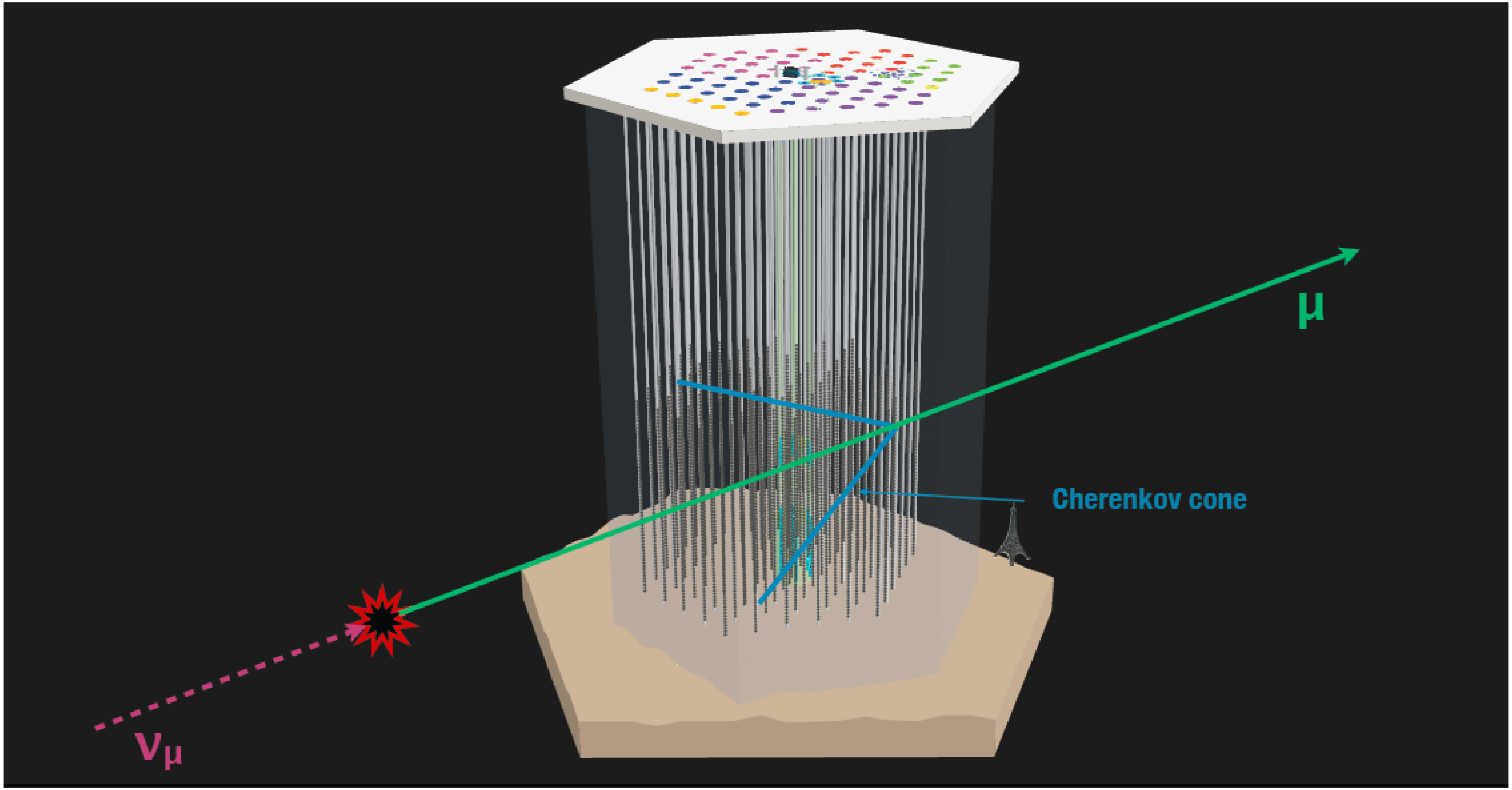



Run 115994 Event 55636526
Fri Jun 4 10:26:13 2010

Neutrino interactions in the ice

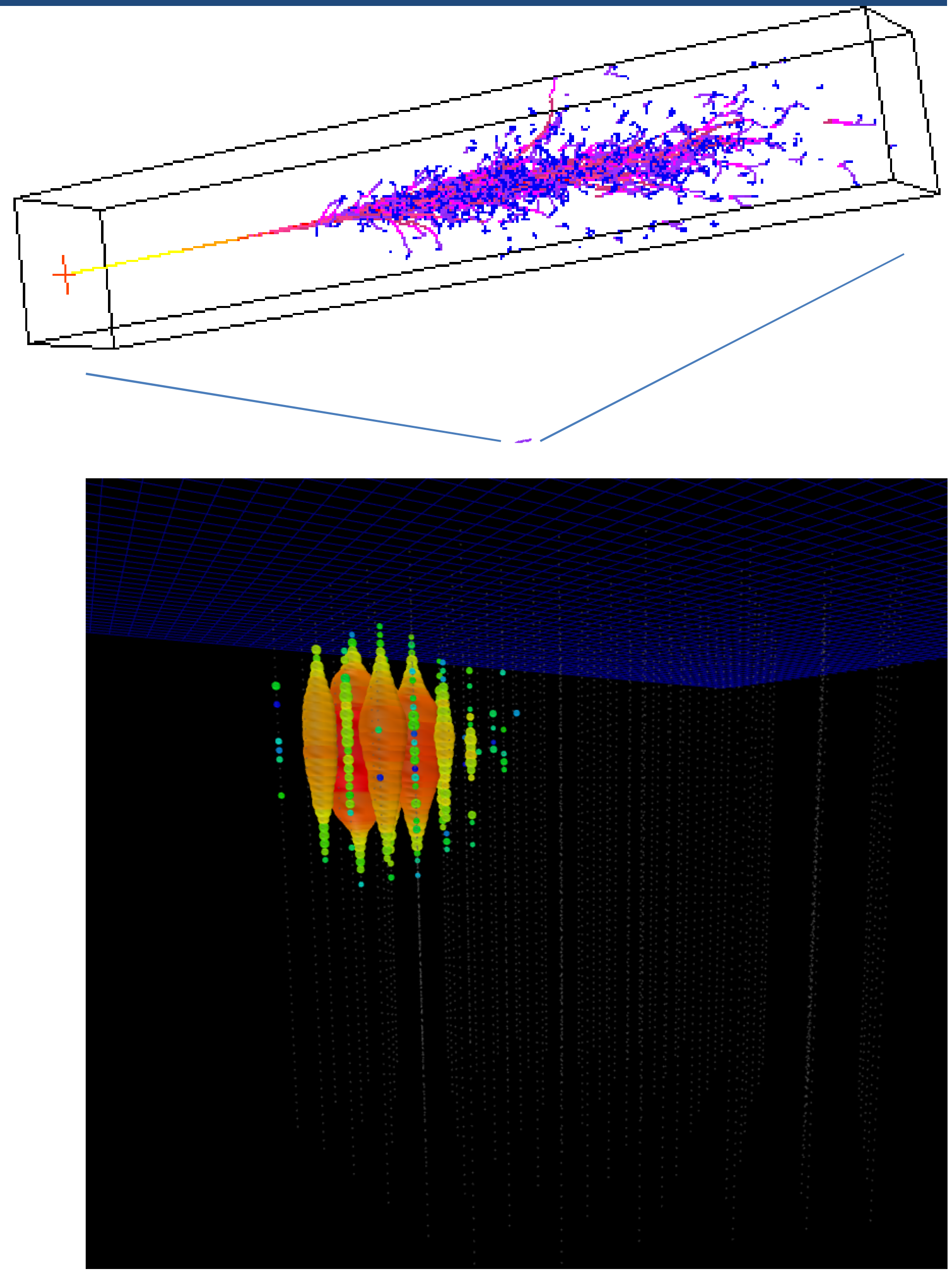
	Charged Current ($W_{+/-}$)	Neutral Current (Z_0)
ν_e	$\nu_e + N \rightarrow e^- + X$	$\nu_e + N \rightarrow \nu_e + X$
ν_μ	$\nu_\mu + N \rightarrow \mu^- + X$	$\nu_\mu + N \rightarrow \nu_\mu + X$
ν_τ	$\nu_\tau + N \rightarrow \tau^- + X$	$\nu_\tau + N \rightarrow \nu_\tau + X$

CC muon neutrino signature

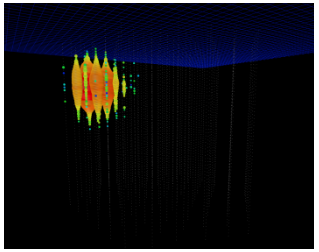


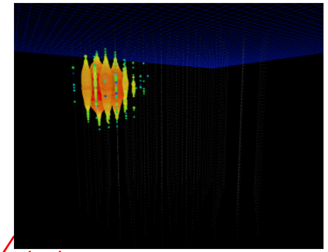
“Cascade” signature

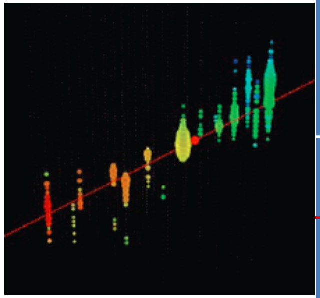
- Particle showers are initiated by 1)electrons and 2)the hadronization of the nuclei debris
- Cherenkov radiation is emitted from all charged particles in a particle shower
- The shower is contained in a volume of less than $5m^3$ (for E < 10PeV)
- Due to scattering the Cherenkov light will have an isotropic distribution around 25m from the shower



Neutrino signatures in the ice







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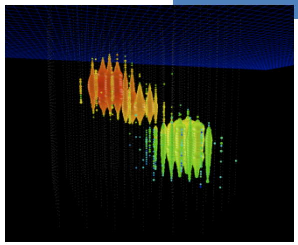
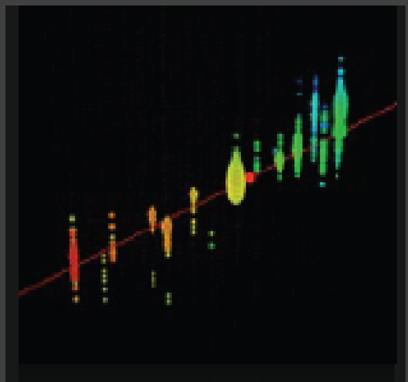


Neutrino event signature summary

CC Muon Neutrino

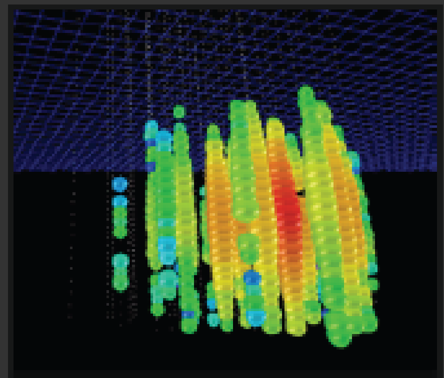


Track (data)

$\nu_\mu + N \rightarrow \mu^- + X$

Factor of 2 ≈ energy resolution
< 1° angular resolution

All flavours NC/
CC Electron Neutrino

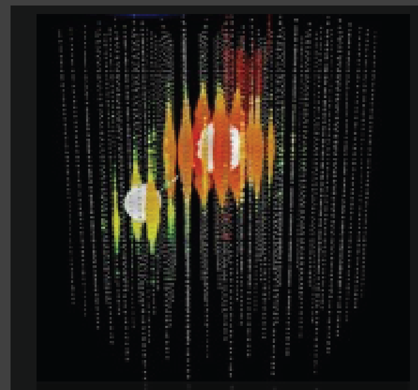


Cascade (data)

$\nu_e + N \rightarrow e^{\square} + X$
$\nu_X + N \rightarrow \nu_X + X$

≈±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≥ 100 TeV)

CC Tau Neutrino

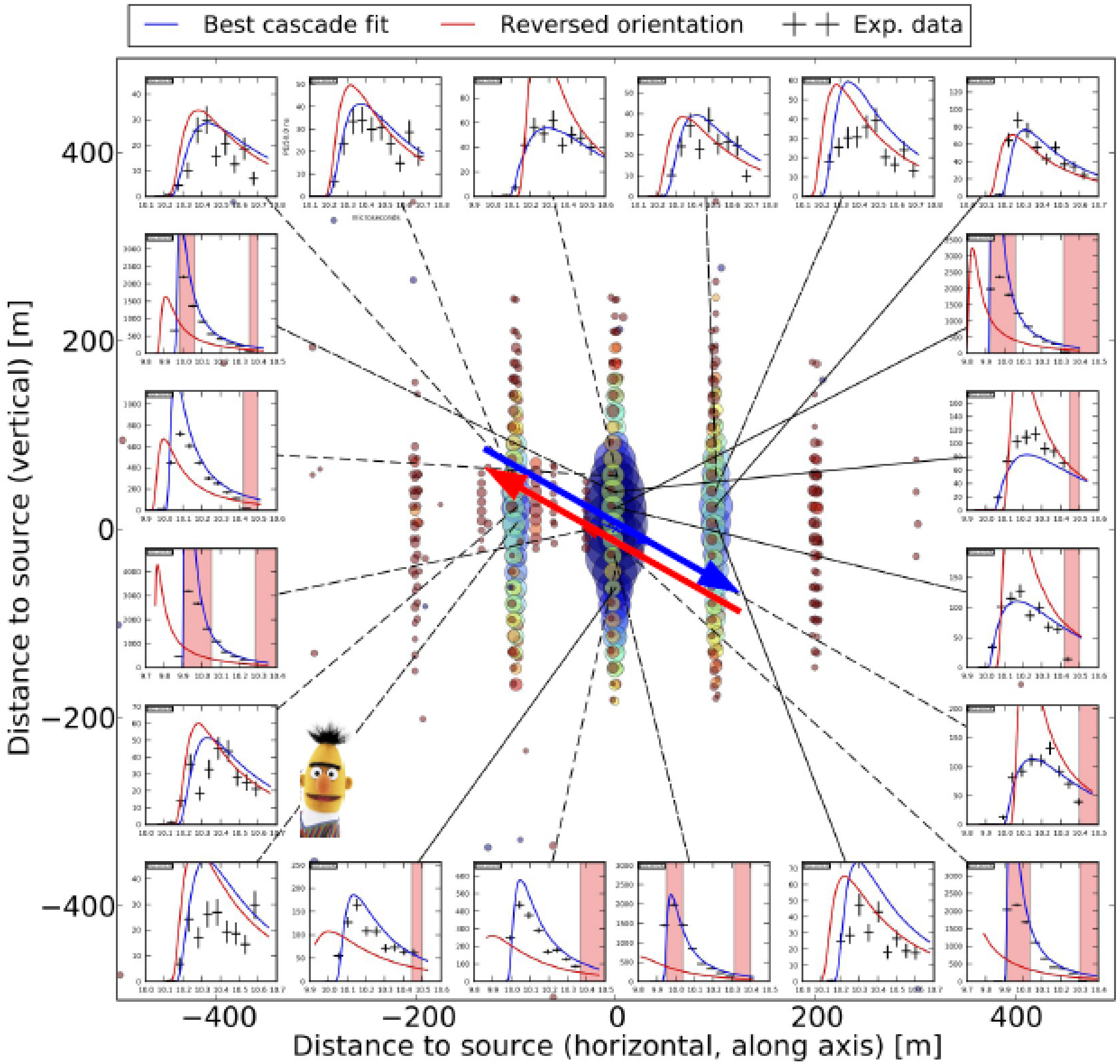


"Double Bang" (simulation)
Other possible event signatures

$\nu_\tau + N \rightarrow \nu_\tau + X$

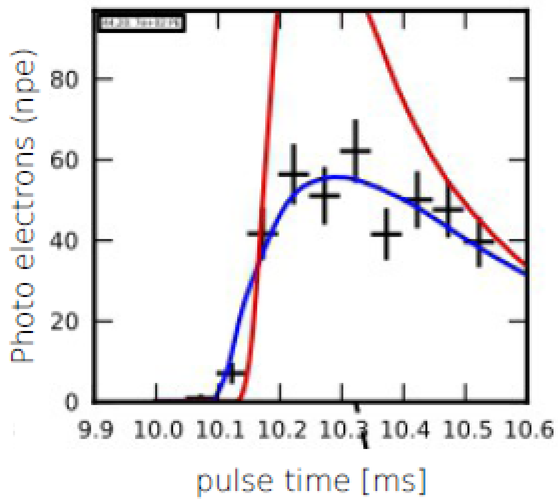
Not yet observed

Cascade angular resolution



Width of waveform related to direction of Cherenkov cone

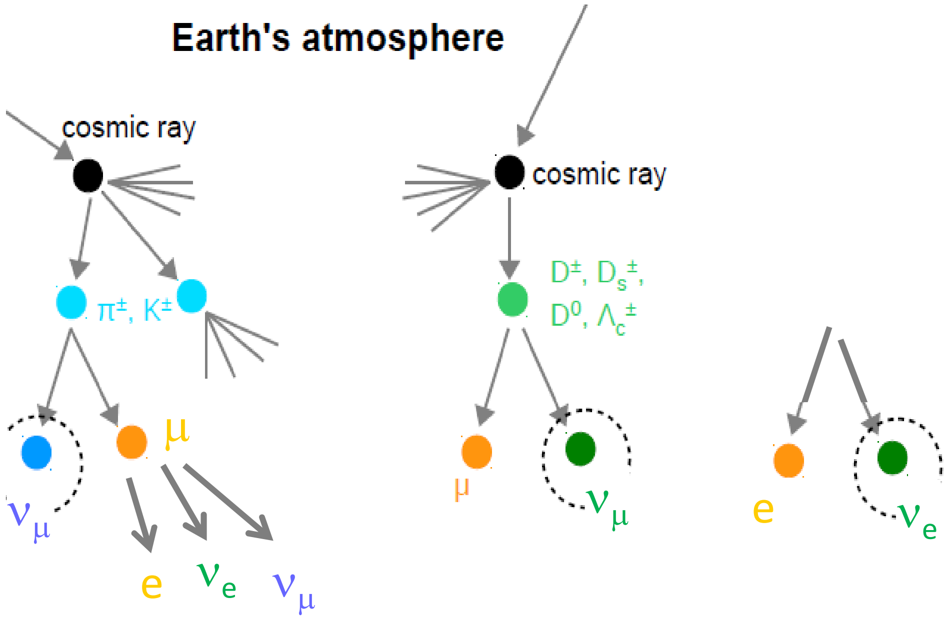
Height proportional to energy



Backgrounds

Cosmic rays – interacting in the Earth's atmosphere

– source of atmospheric neutrinos and muon background



- "Conventional"
- From π / K decay
- $\Phi \sim E^{-3.7}$

- "Prompt"
- From charmed meson decay
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- Undetected so far

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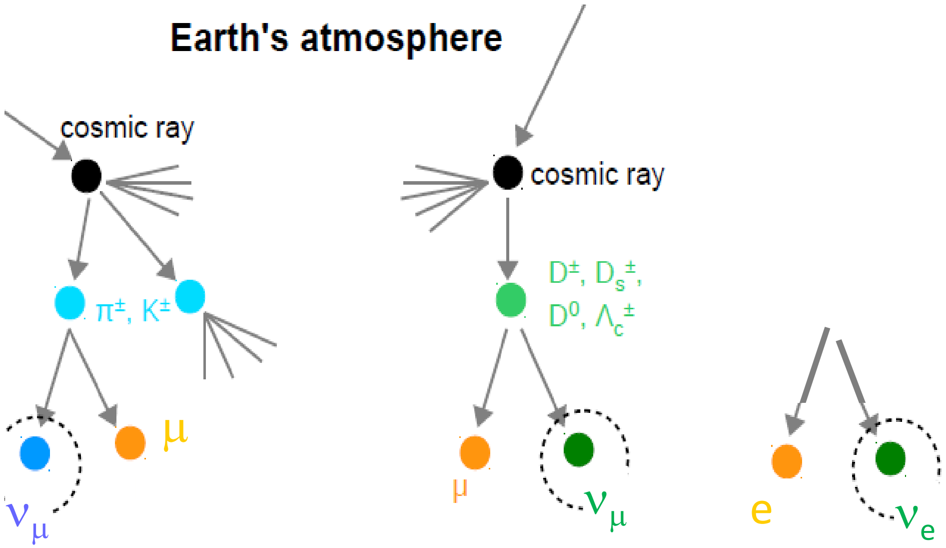

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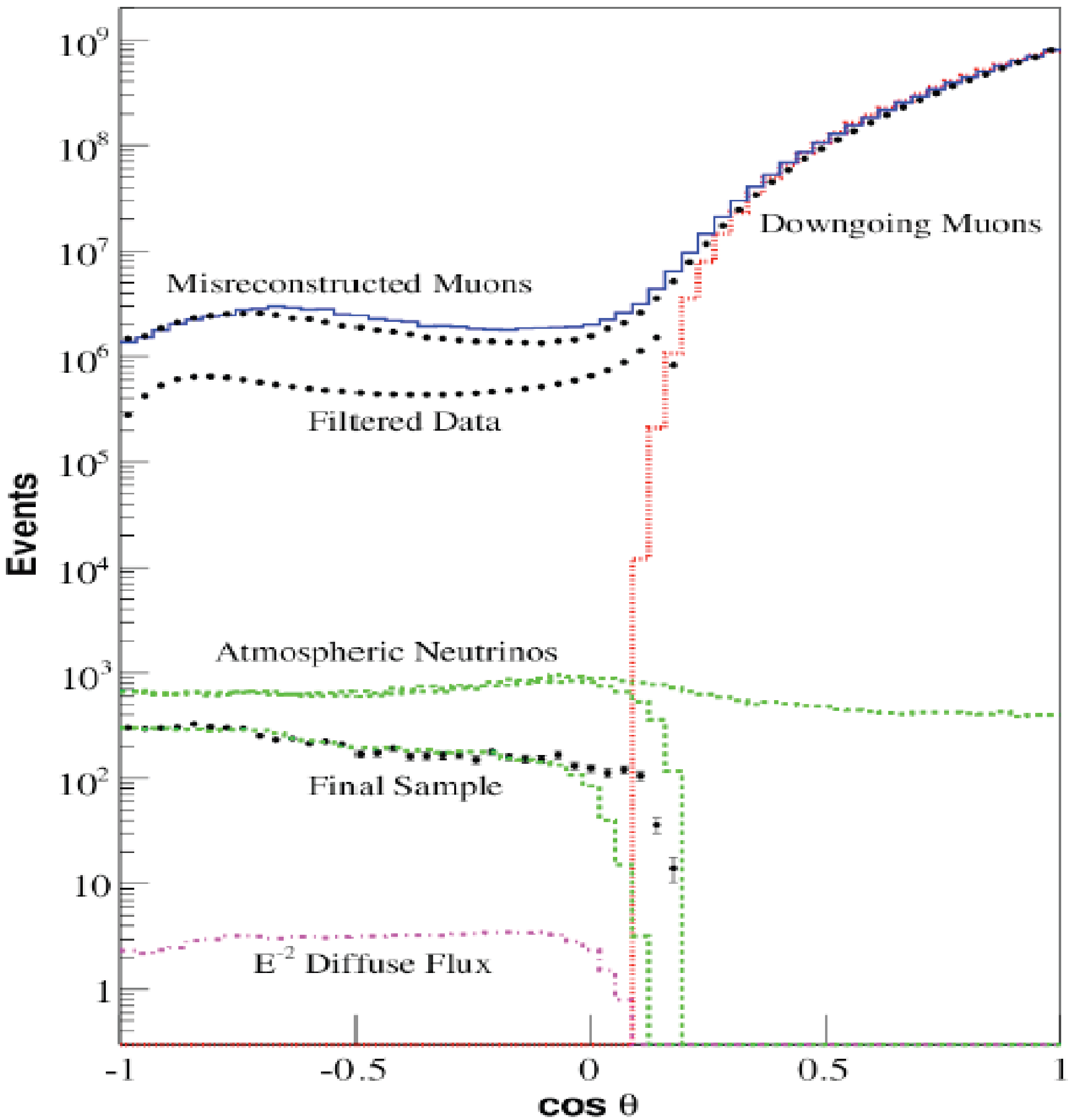
Muon rate:
In ice: ~3000 Hz

Atmospheric neutrinos:
~1 neutrino/10 minutes

Neutrino Detection:
Requires 10^6 background rejection

Backgrounds



Background rejection

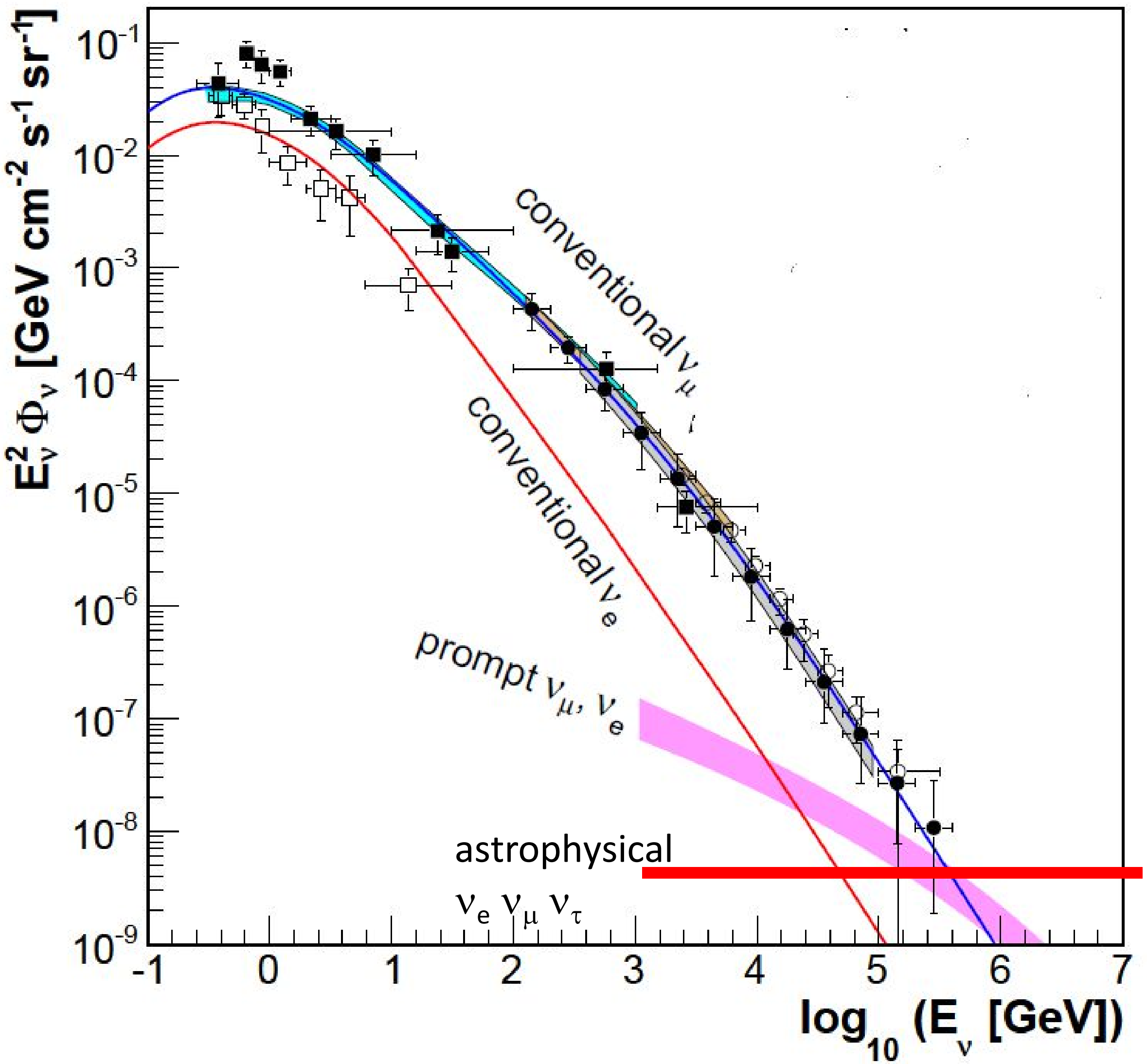
Astrophysical and Atmospheric neutrinos

Reduce background by:

- Looking for upward going tracks
- Look for cascade signature
- Looking for events that "start" in the detector
- Looking for point sources
  - Look for hot spots
  - Look for correlations with astrophysical objects (including in time for transient objects)

Astrophysical neutrinos

Diffuse search strategy

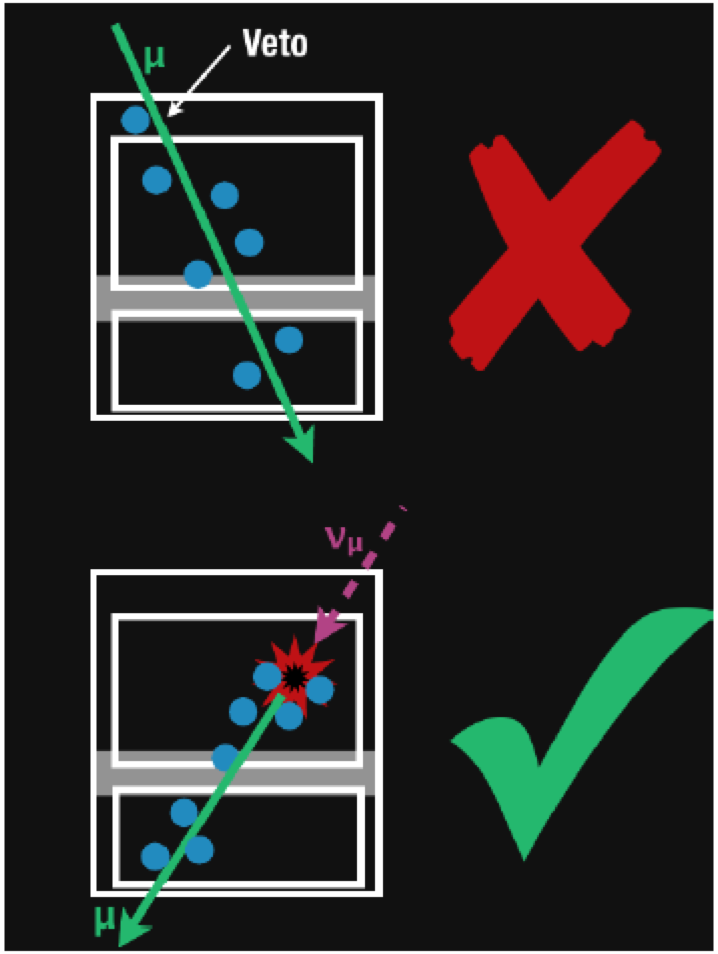


High Energy Starting Event Strategy

High Energy Starting Event Strategy

Look for **high-energy**, **starting events** in the detector

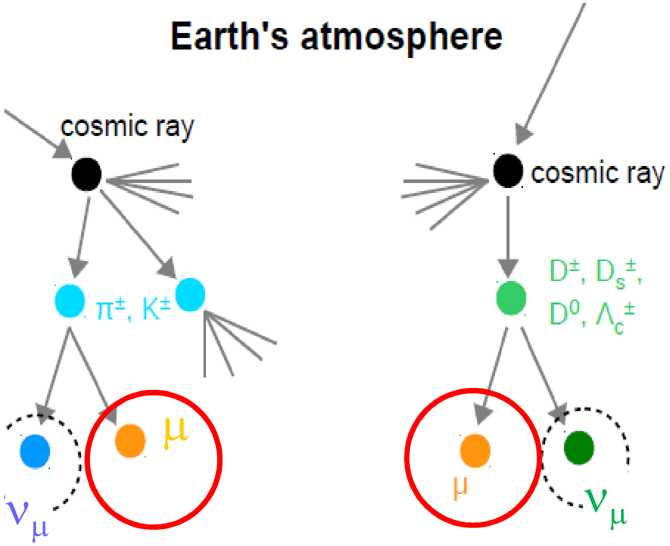
Use outer parts of the detector as a veto-region



IceCube,Science 342, 1242856 (2013)

“Self-veto”

Veto criteria reduces both muon **and southern hemisphere atmospheric neutrinos**



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- Undetected so far

Accompanying muon trips the veto

See:

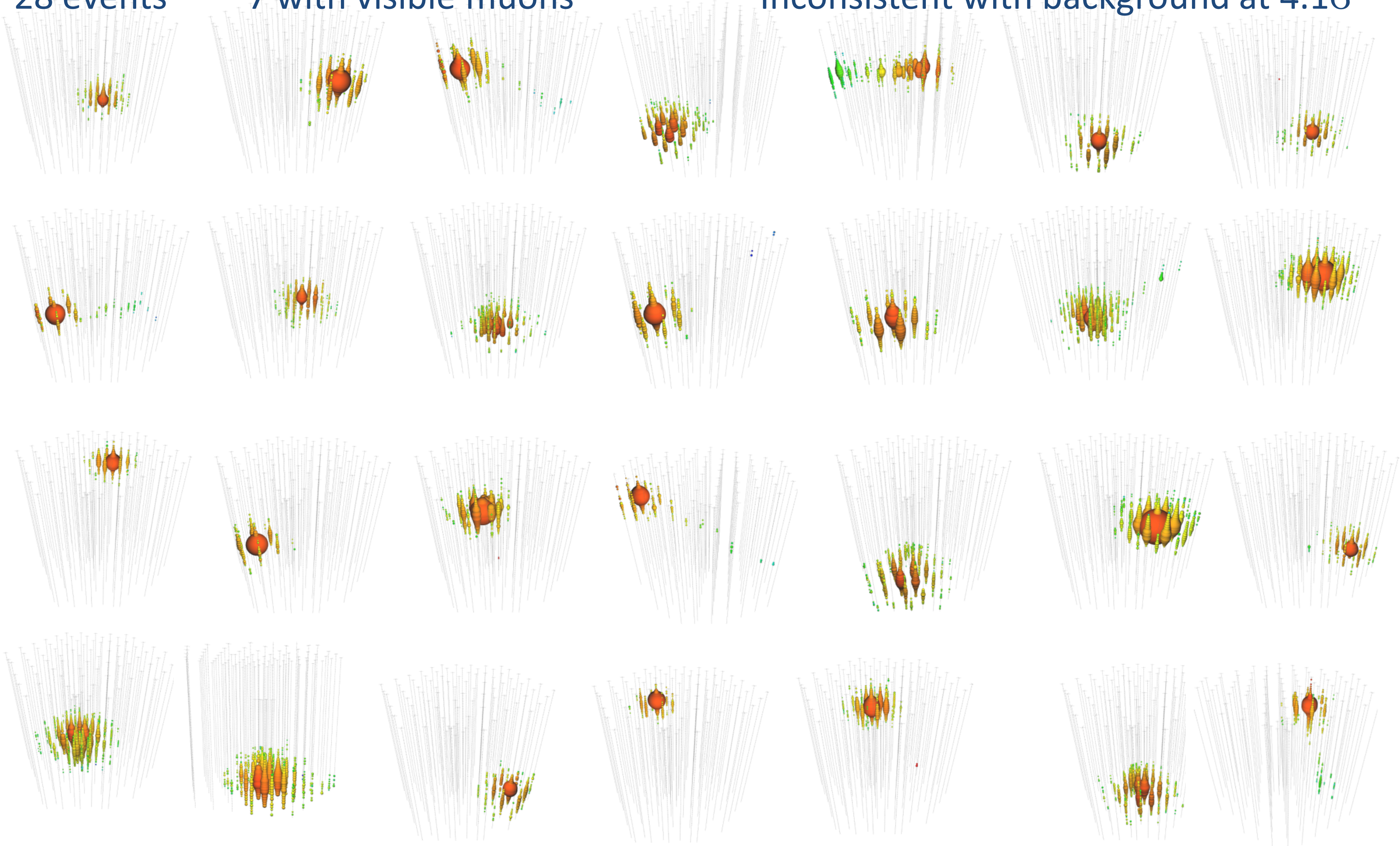
Gaisser, Jero, Karle and van Santen arXiv: 1405.0525

Schonert, Gaisser, Resconi, Schulz arXiv: 0812.4308

for efficiency estimates

2 Year Search Results

28 events   7 with visible muons   Inconsistent with background at 4.1σ



Atmos ν background: 4.6 + 3.7/-1.2   Atmos μ background: 6 +/- 3.4

3 year search results

37 events

9 with visible muons and 28 cascade events

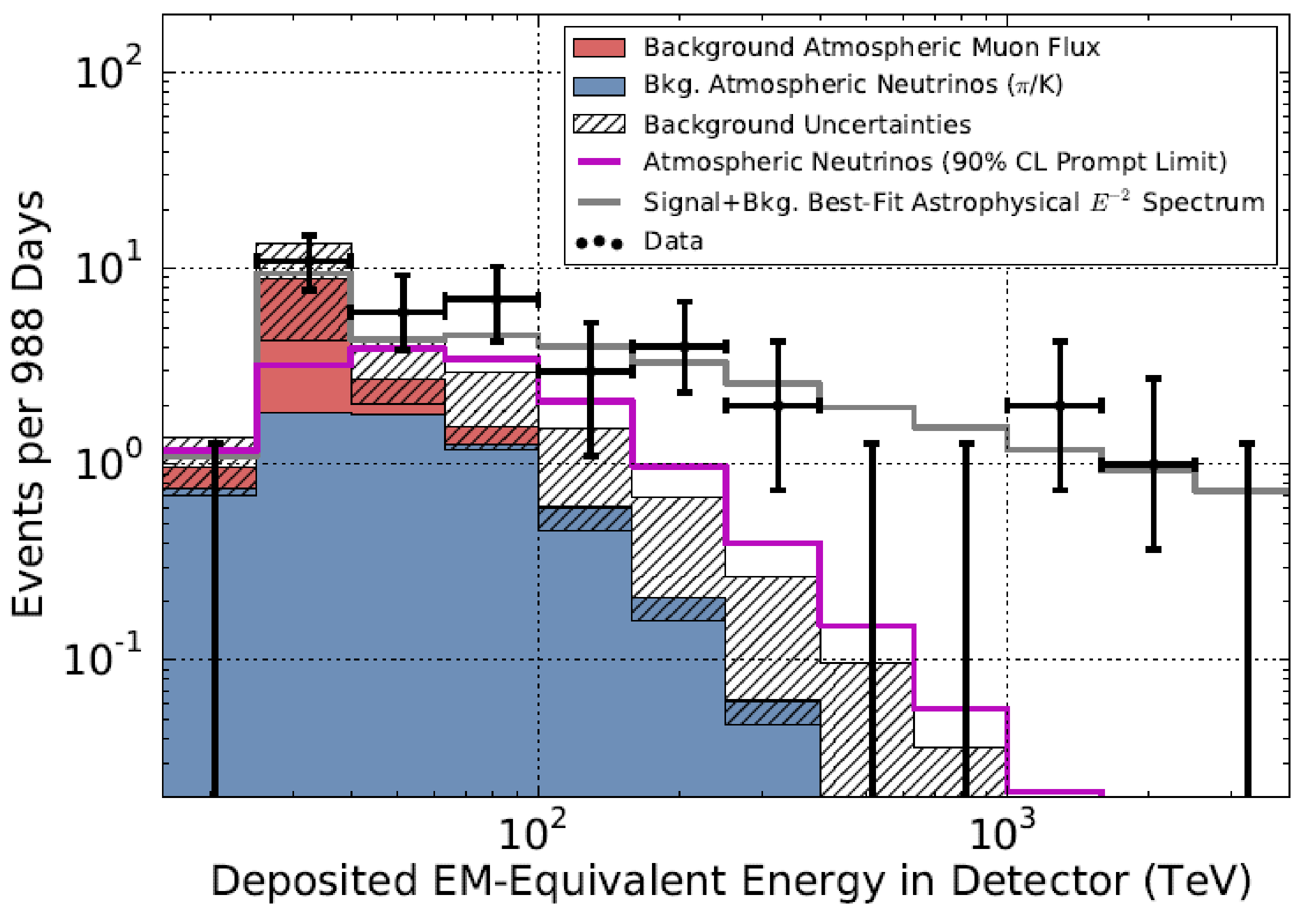
Atmos ν background: 6.6 + 5.9/-1.6

Atmos μ background: 8.4 +/- 4.2

Inconsistent with background at 5.7s

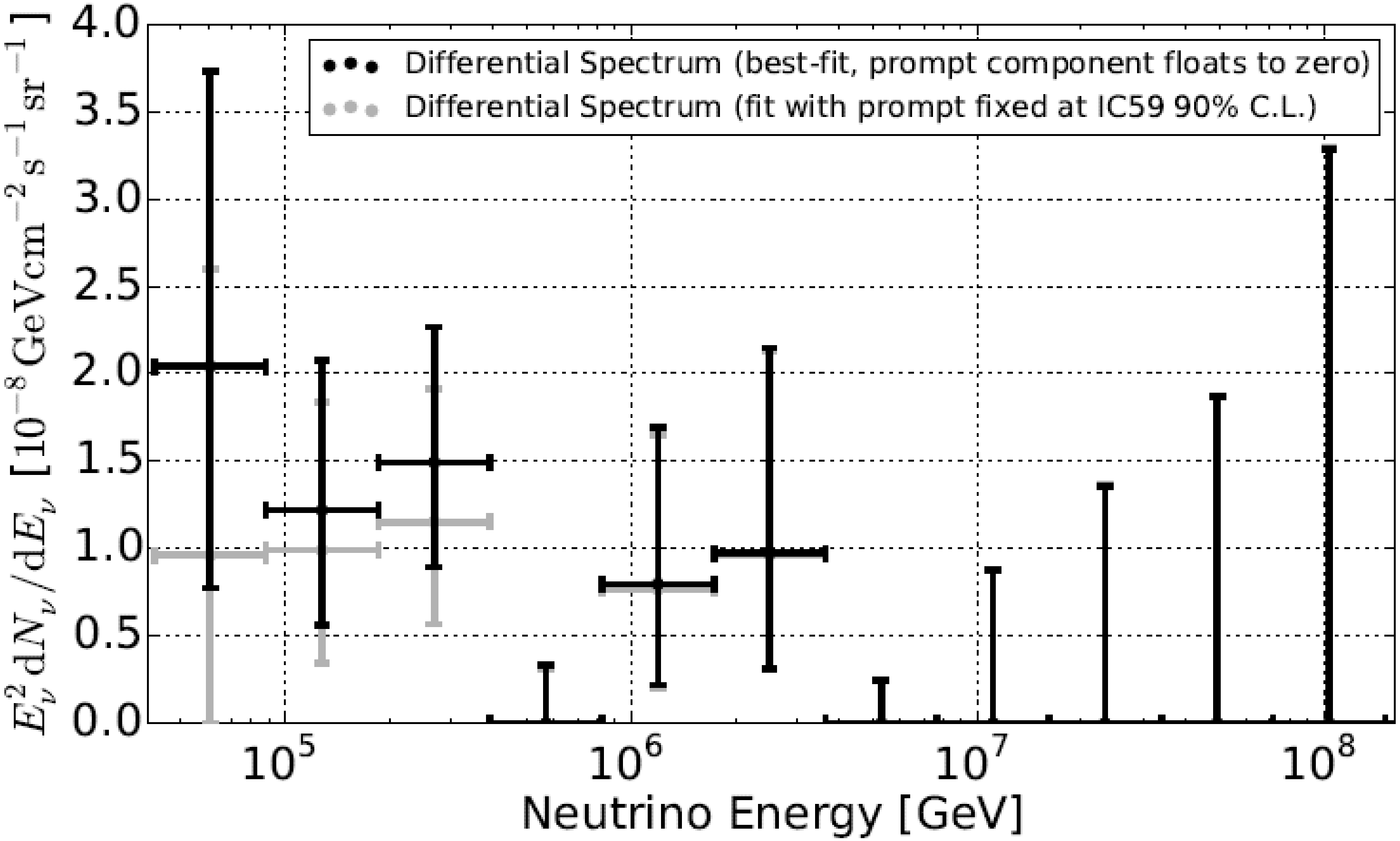
Energy spectrum

- Harder than expected from atmospheric backgrounds
- Merges well into backgrounds at low energies



IceCube, arxiv:1405.5303

Neutrino flux



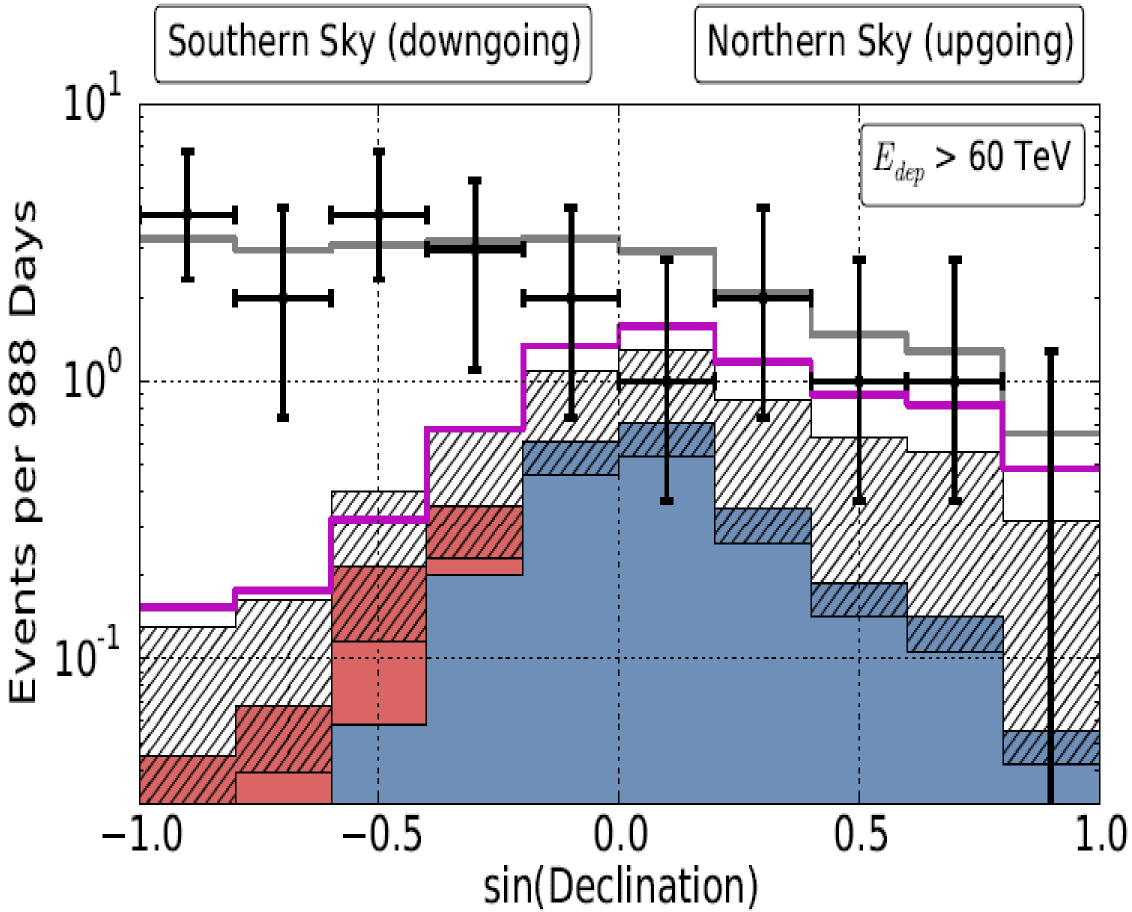
Best fit flux:

$$E^2\phi(E) = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

IceCube, arxiv:1405.5303

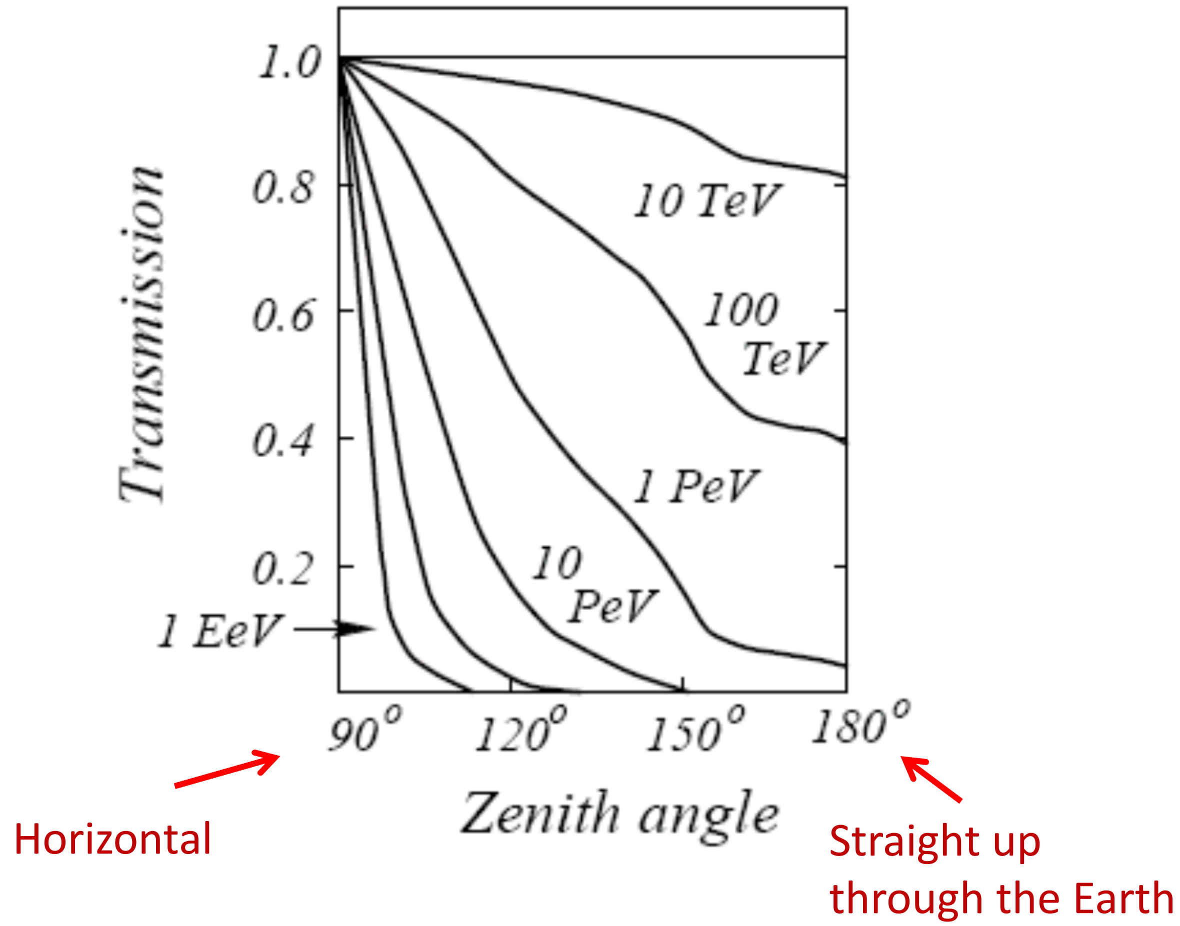
Zenith distribution

- Compatible with isotropic
- Northern hemisphere events attenuated by the earth
- Slight excess from the south but not significant



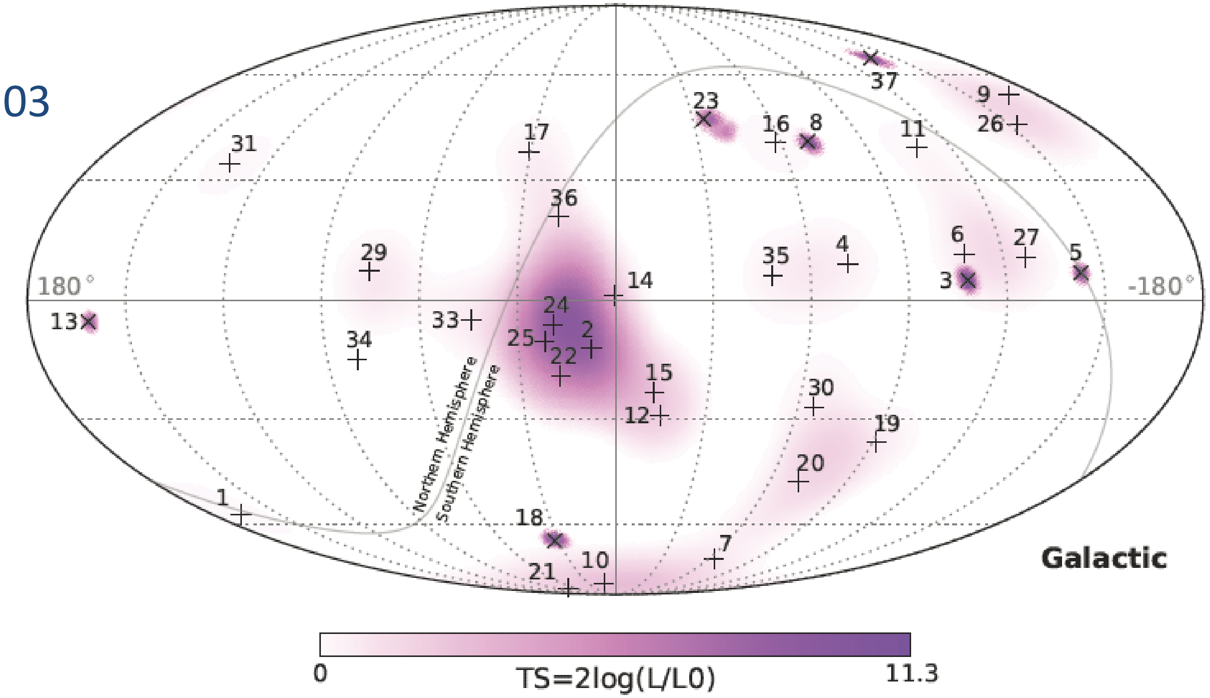
IceCube, arxiv:1405.5303

Earth attenuation E>TeV



Sky Map

IceCube,
arxiv:1405.5303



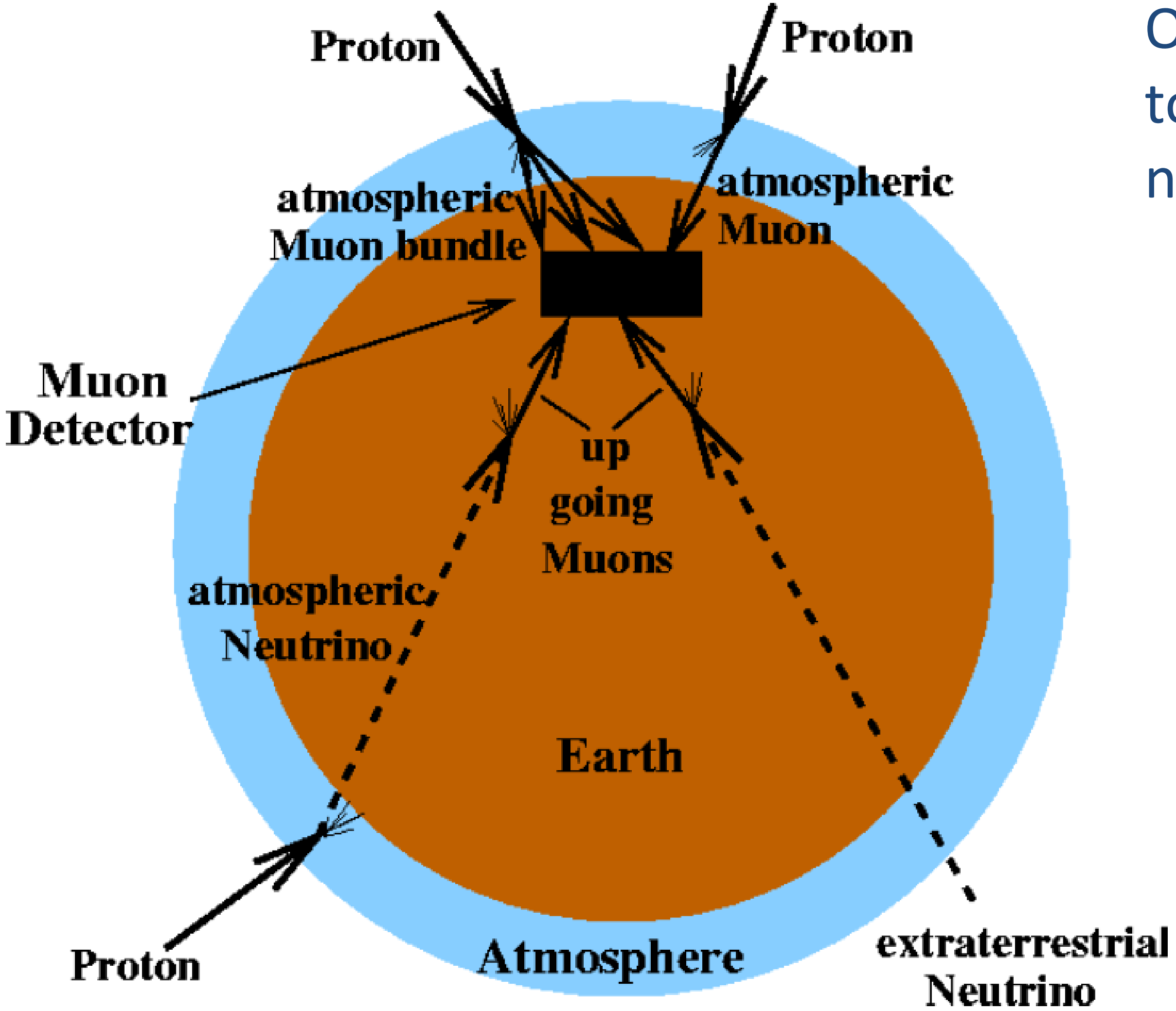
Spot with the highest TS value has 28% significance – 28% of randomised maps contain a spot with similar or higher TS value

Correlation searches with:

- Galactic plane
- point-source catalogue
- GRBs

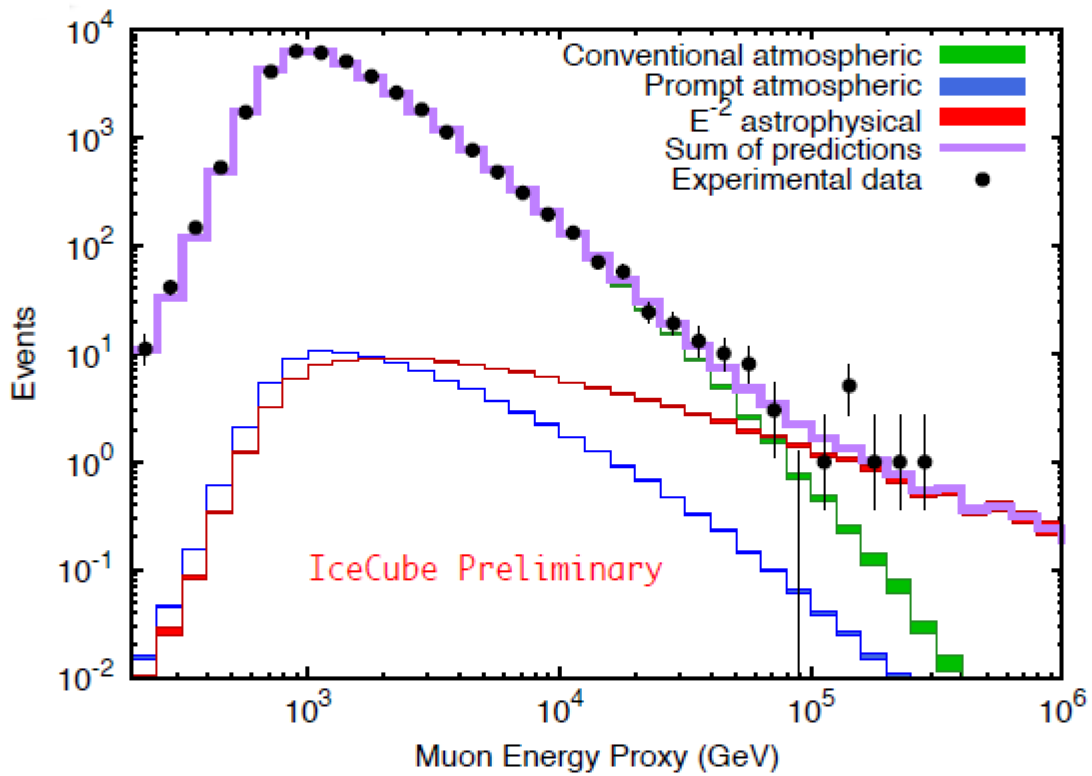
Show no significance

Upward Track Strategy for Background Removal



Only sensitive to muon neutrinos

Upward Track Strategy – latest results



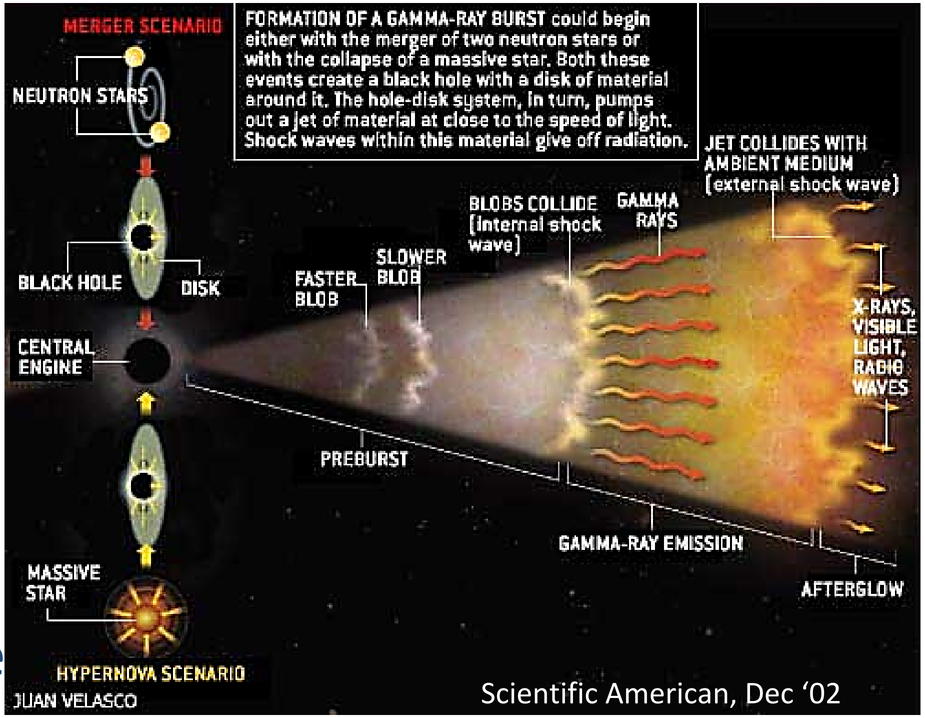
- The best-fit astrophysical flux is 1.01×10^{-8} GeV^{-1} cm^{-2} s^{-1} sr^{-1}
- The atmospheric-only hypothesis is disfavored at 3.9σ.

- Consistent with HESE flux
- Support for 1:1:1 flavour ratio

Point source strategy

- transient point sources
- localized in space and time

- data from incomplete IceCube
 (April 2008 – May 2010)
 ~ 300 GRBs
 constrained models
- upper limit
  ~ a factor 3 below
 predictions for neutrinos from the
 cosmic ray fireball model



Scientific American, Dec ‘02

IceCube, Nature 484 (2012) 351
IceCube, arXiv:1204.4219v2

CONCLUSION:

GRBs alone cannot account for the flux of very-high energy CRs

OR

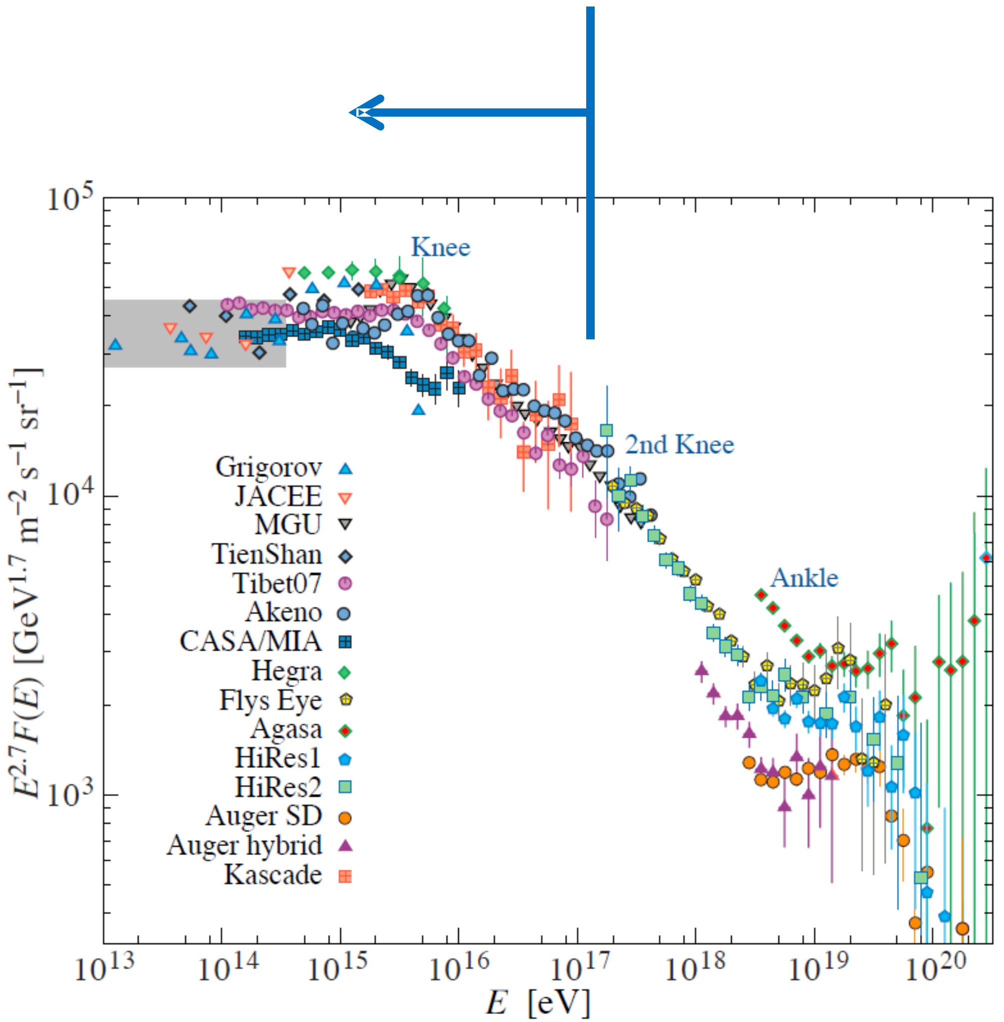
the efficiency of neutrino production much lower than expected

What can we say so far...

- Galactic or extra-galactic?
  - Probably a mixture... Likely extra-galactic component
- Extragalactic candidates:
  GRBs, AGNs, Starburst galaxies...
  - GRB neutrinos make up at most 10-20% of the observed flux (caveats..)
  - Anisotropy searches favour common, weaker sources
- Spectrum probably softer that E^{-2} and/or has a break

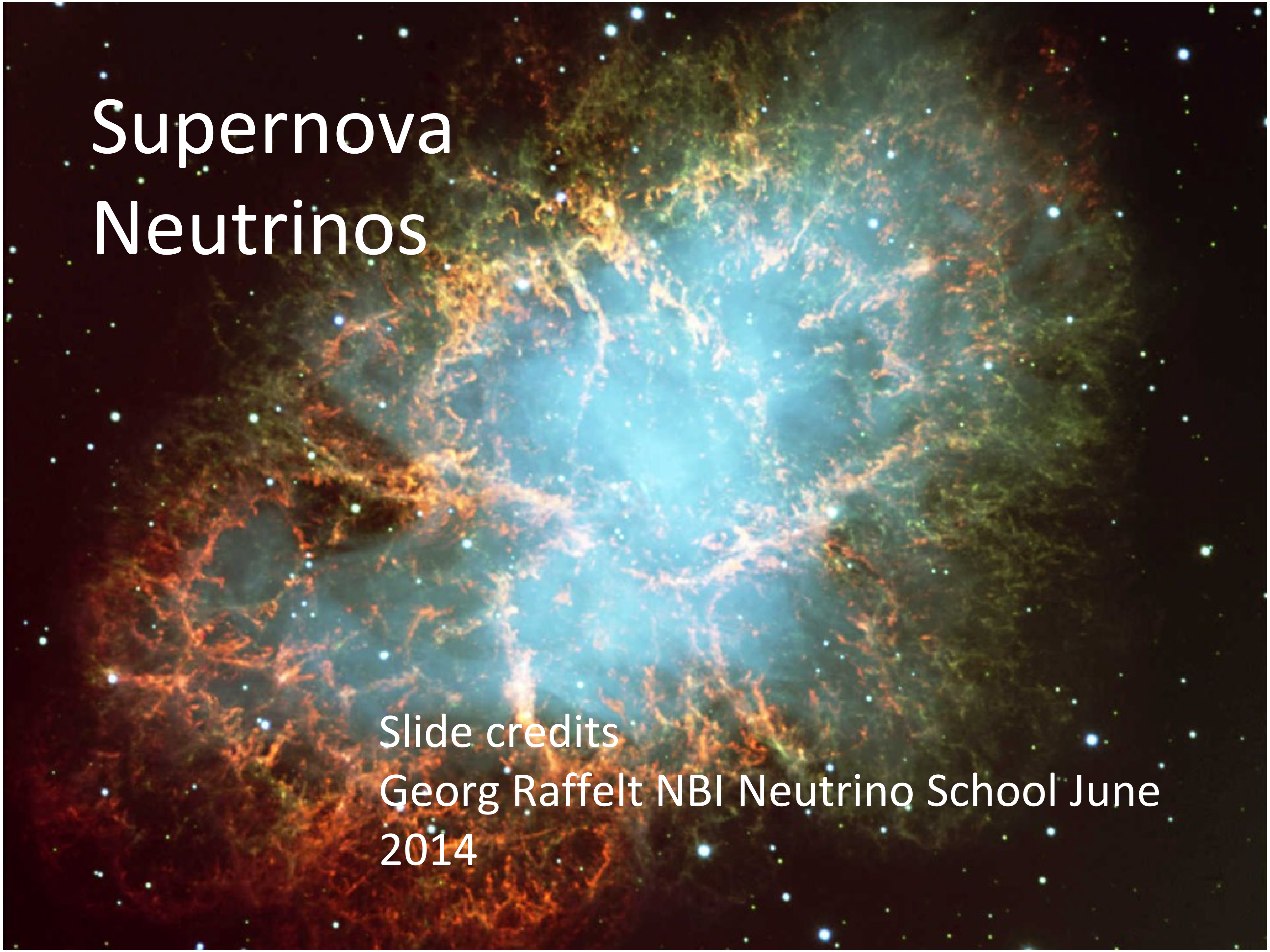
Energy range not compellingly extra-galactic

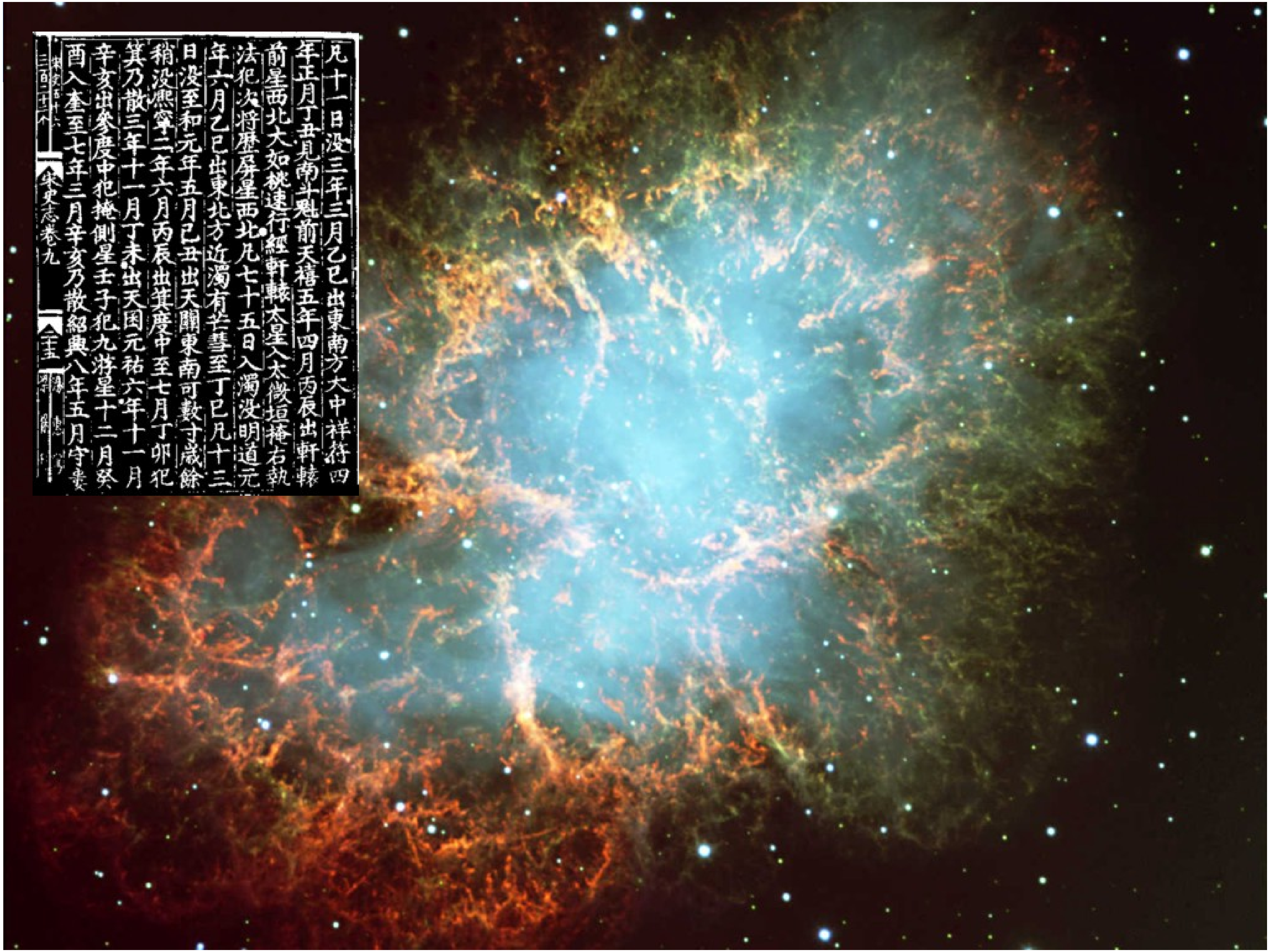
Neutrinos observed are from cosmic rays E < 10^{17} eV



Next steps

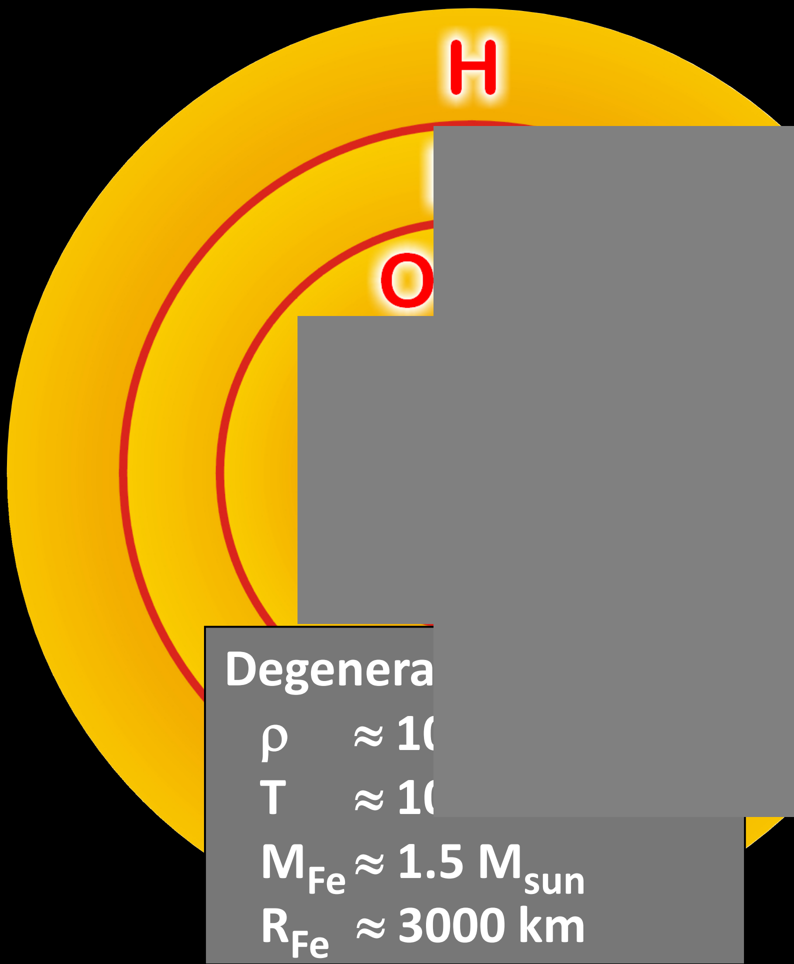
- Further observations to determine spectrum properties
  - Spectral index
  - Is there a break?
- Source identification.....?


Supernova
Neutrinos
Slide credits
Georg Raffelt NBI Neutrino School June
2014

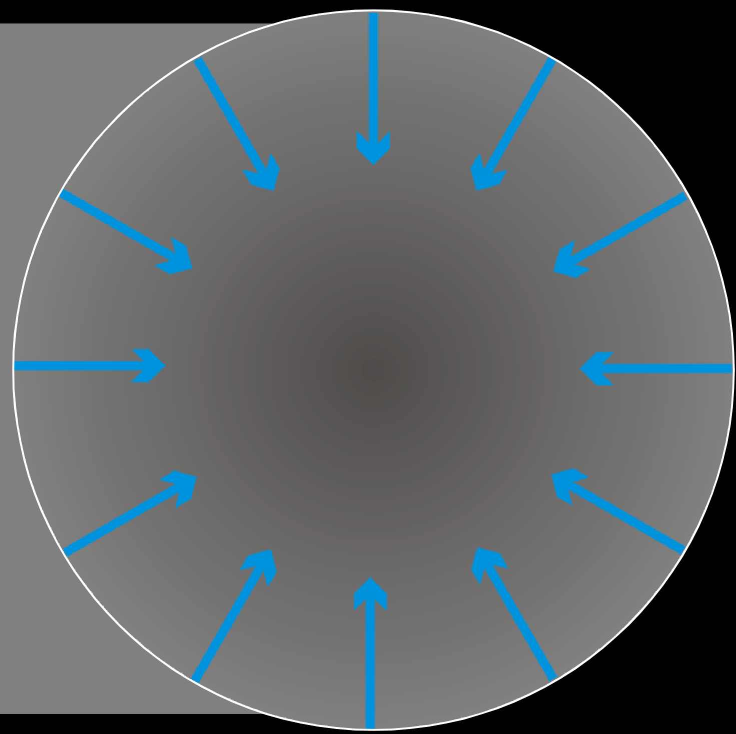

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

Stellar Collapse and Supernova Explosion

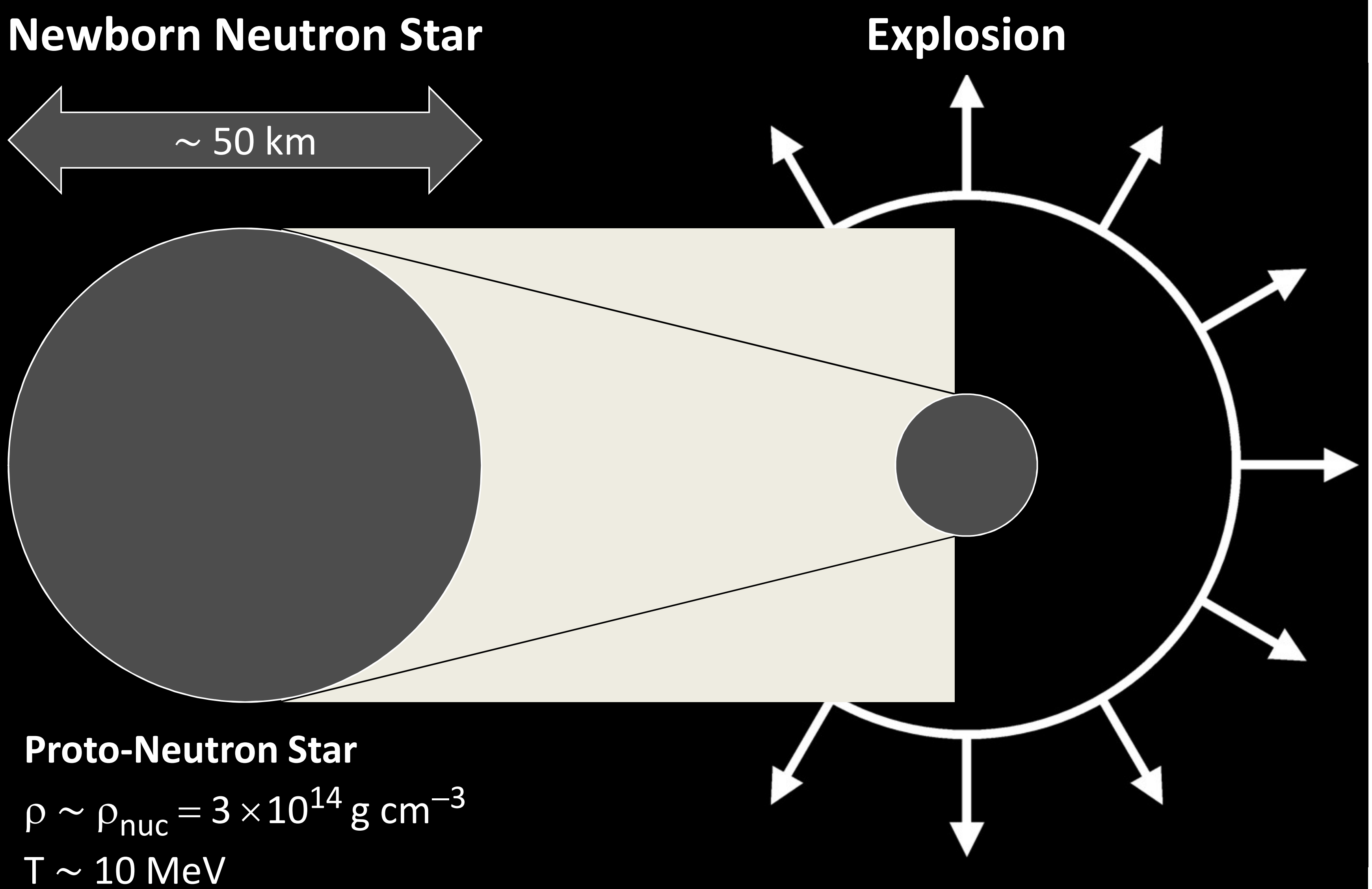
Onion structure



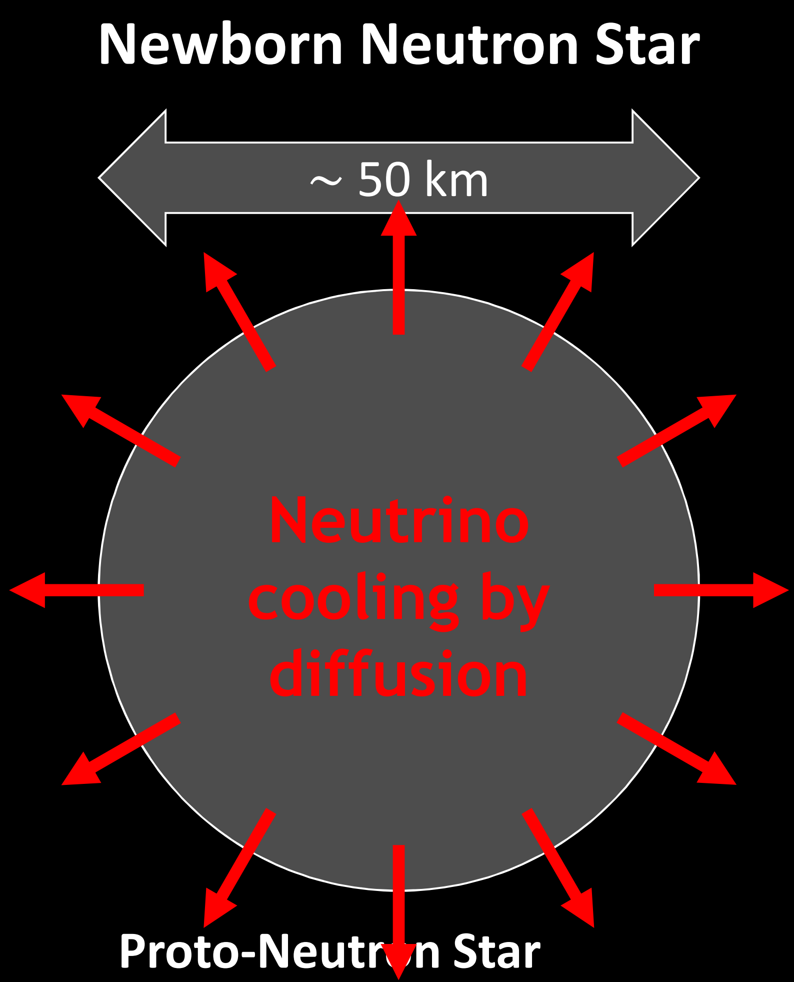
Collapse (implosion)



Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion



$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 10$ MeV

Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

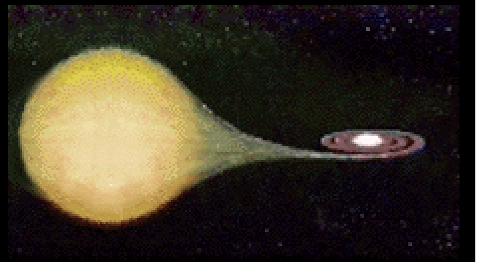
Neutrino luminosity

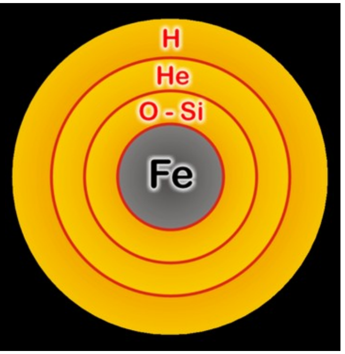
$$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$$
$$\sim 3 \times 10^{19}\ L_{SUN}$$

While it lasts, outshines the entire visible universe

Thermonuclear vs. Core-Collapse Supernovae

Thermo-nuclear (Type Ia)	Core collapse (Type II, Ib/c)
• Carbon-oxygen white dwarf (remnant of low-mass star) • Accretes matter from companion	• Degenerate iron core of evolved massive star • Accretes matter by nuclear burning at its surface





Chandrasekhar limit is reached — $M_{Ch} \approx 1.5\, M_{sun}\, (2Y_e)^2$

COLLAPSE SETS IN

Nuclear burning of C and O ignites $\to$ Nuclear deflagration ("Fusion bomb" triggered by collapse)	Collapse to nuclear density Bounce & shock Implosion $\to$ Explosion
Powered by nuclear binding energy	Powered by gravity
Gain of nuclear binding energy $\sim$ 1 MeV per nucleon	Gain of gravitational binding energy $\sim$ 100 MeV per nucleon 99% into neutrinos

Comparable "visible" energy release of $\sim 3 \times 10^{51}$ erg

Spectral Classification of Supernovae

Spectral Type	Ia	Ib	Ic	II
Spectrum	No Hydrogen			Hydrogen
	Silicon	No Silicon		
		Helium	No Helium	
Physical Mechanism	Nuclear explosion of low-mass star	Core collapse of evolved massive star (may have lost its hydrogen or even helium envelope during red-giant evolution)		
Light Curve	Reproducible	Large variations		
Neutrinos	Insignificant	$\sim 100 \times$ Visible energy		
Compact Remnant	None	Neutron star (typically appears as pulsar) Sometimes black hole		
Rate / h^2 SNu	0.36 ± 0.11	0.14 ± 0.07		0.71 ± 0.34
Observed	Total $\sim$ 6400 as of 2014 (Asiago SN Catalogue)			

1 SNu = 1 supernova per century per 10^{10} $L_{B(\text{solar*})}$

Neutrino Diffusion in a Supernova Core

Main neutrino reactions	Electron flavour $\nu_e + n \to p + e^-$ $\bar{\nu}_e + p \to n + e^+$ All flavours $\nu + N \to N + \nu$
Neutral-current scattering cross section	$\sigma_{\nu N} = \frac{C_V^2 + 3C_A^2}{\pi} G_F^2 E_\nu^2 \approx 2 \times 10^{-40}\mathrm{cm}^2 \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Nucleon density	$n_B = \frac{\rho_{\mathrm{nuc}}}{m_N} \approx 1.8 \times 10^{38}\ \mathrm{cm}^{-3}$
Scattering rate	$\Gamma = \sigma n_B \approx 1.1 \times 10^9\ \mathrm{s}^{-1} \left(\frac{E_\nu}{100\ \mathrm{MeV}}\right)^2$
Mean free path	$\lambda = \frac{1}{\sigma n_B} \approx 28\ \mathrm{cm} \left(\frac{100\ \mathrm{MeV}}{E_\nu}\right)^2$
Diffusion time	$t_{\mathrm{diff}} \approx \frac{R^2}{\lambda} \approx 1.2\ \mathrm{sec} \left(\frac{R}{10\ \mathrm{km}}\right)^2 \left(\frac{\mathrm{E}_\nu}{100\ \mathrm{MeV}}\right)^2$

What Determines the Neutrino Energies?

Hydrostatic equilibrium (virial equilibrium)

$$-\frac{1}{2}\langle\Phi_{\text{grav}}\rangle = \langle E_{\text{kin}}\rangle = \frac{3}{2}k_{\text{B}}T$$

Assume SN core is homogeneous sphere with

$$M = 1.5\,M_{\odot}, \quad \rho = \rho_{\text{nuc}} = 3\times 10^{14}\,\text{g/cm}^3, \quad R = 13.4\,\text{km}$$

Gravitational potential of nucleon at centre

$$\Phi_{\text{grav}} = -\frac{3}{2}\,\frac{\mathrm{G_N M_{core} m_p}}{\mathrm{R}} \sim -234\,\text{MeV}$$

For non-interacting and non-degenerate nucleons implies

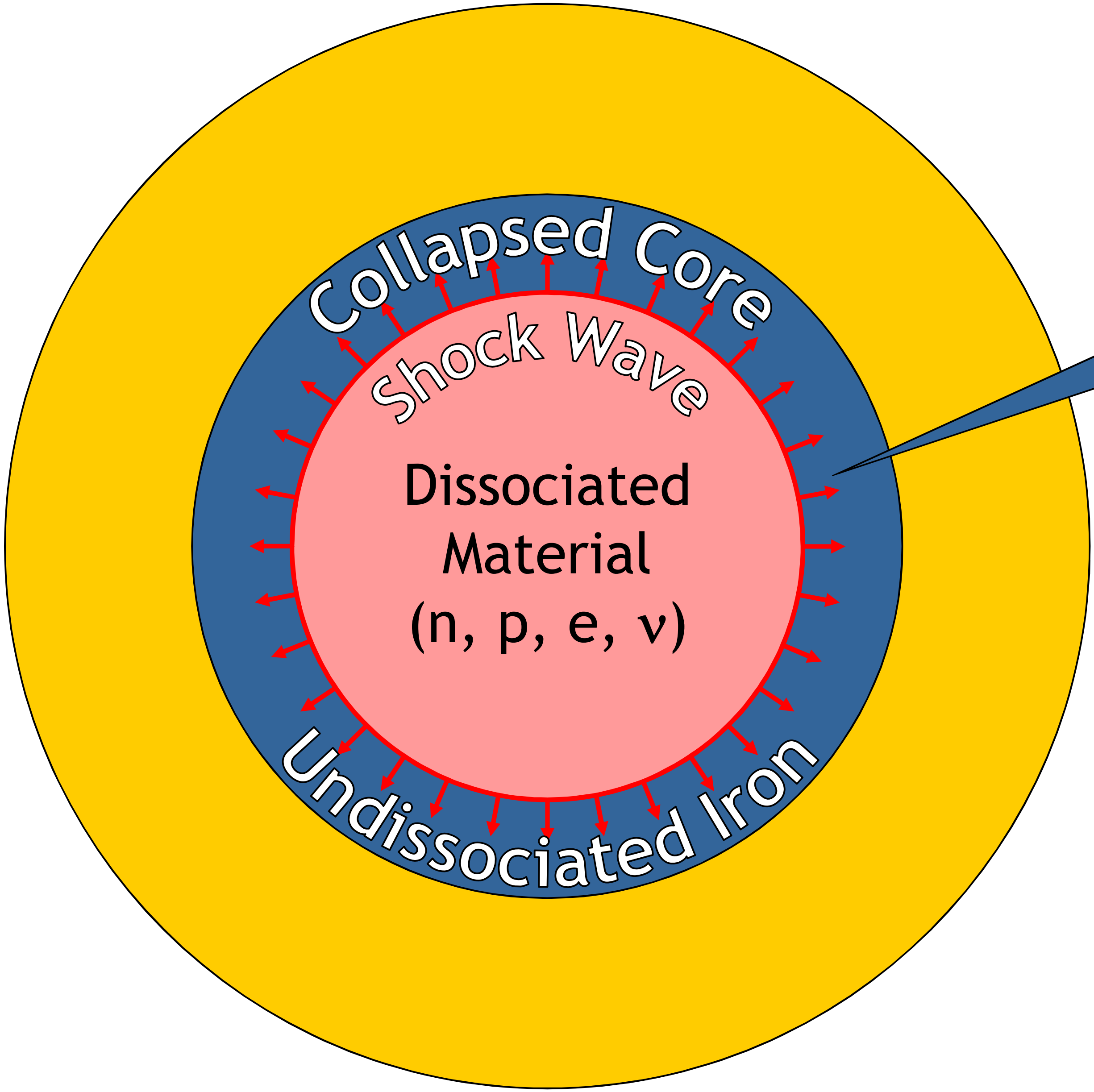
$$T \sim 80\,\text{MeV}$$

More realistic, nuclear equation-of-state dependent values

$$T \sim 20\text{–}40\,\text{MeV}$$

Energy scale in the multi-10 MeV range set by gravitational potential

Why No Prompt Explosion?



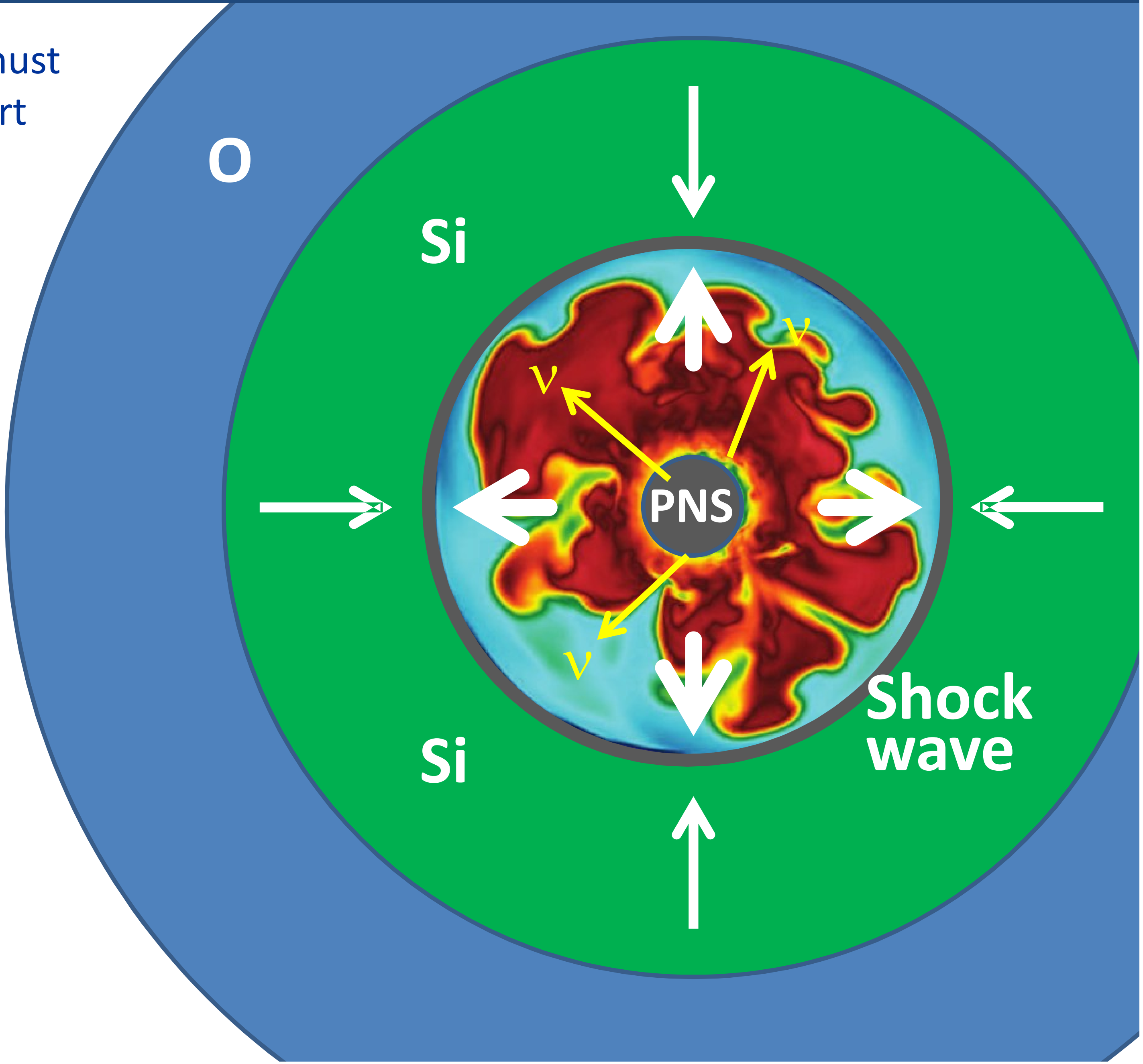
- 0.1 M_{sun} of iron has a nuclear binding energy $\approx 1.7 \times 10^{51}$ erg
- Comparable to explosion energy

- **Shock wave forms within the iron core**
- **Dissipates its energy by dissociating the remaining layer of iron**

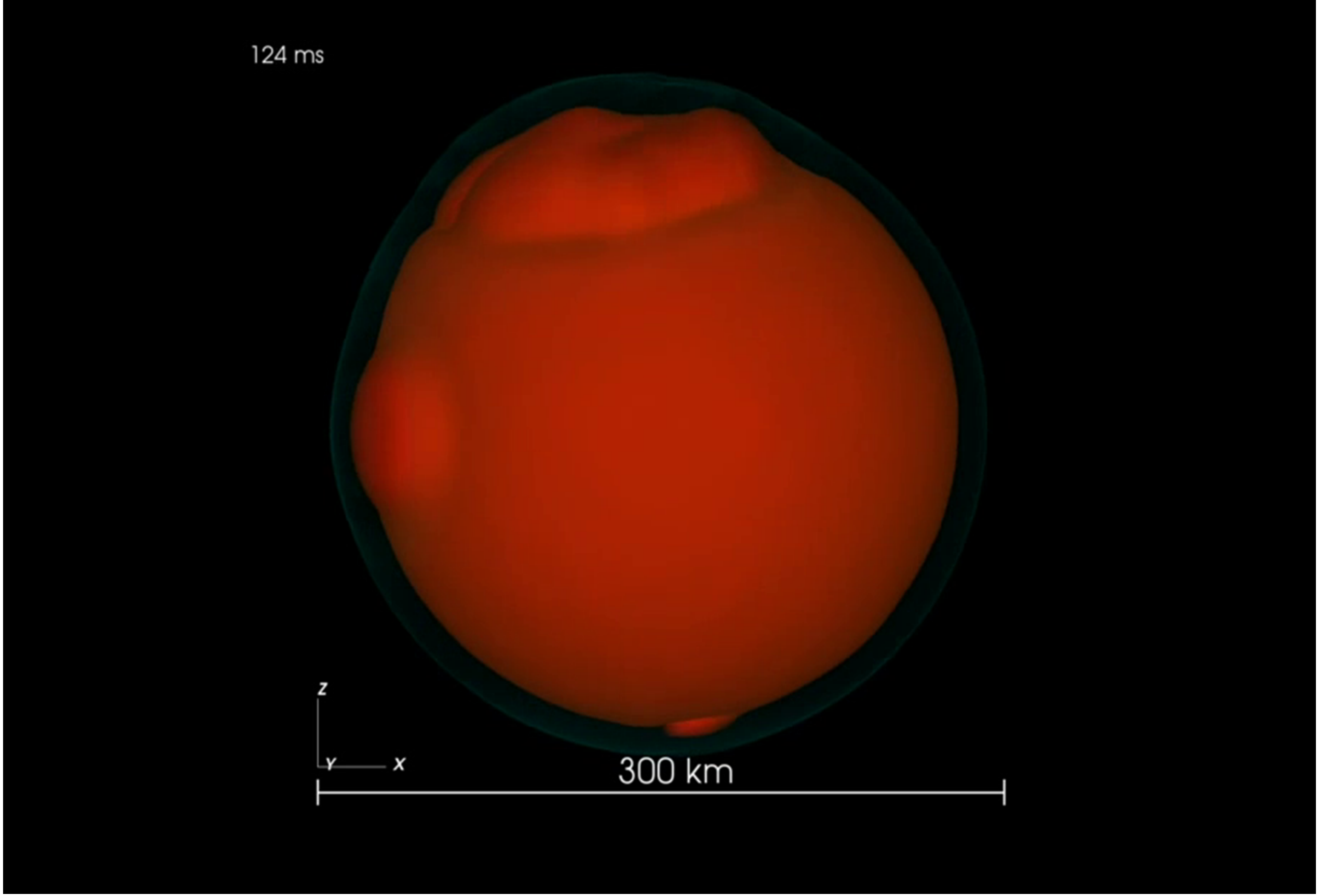
Shock Revival by Neutrinos

Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

Shock can receive fresh energy from neutrinos!



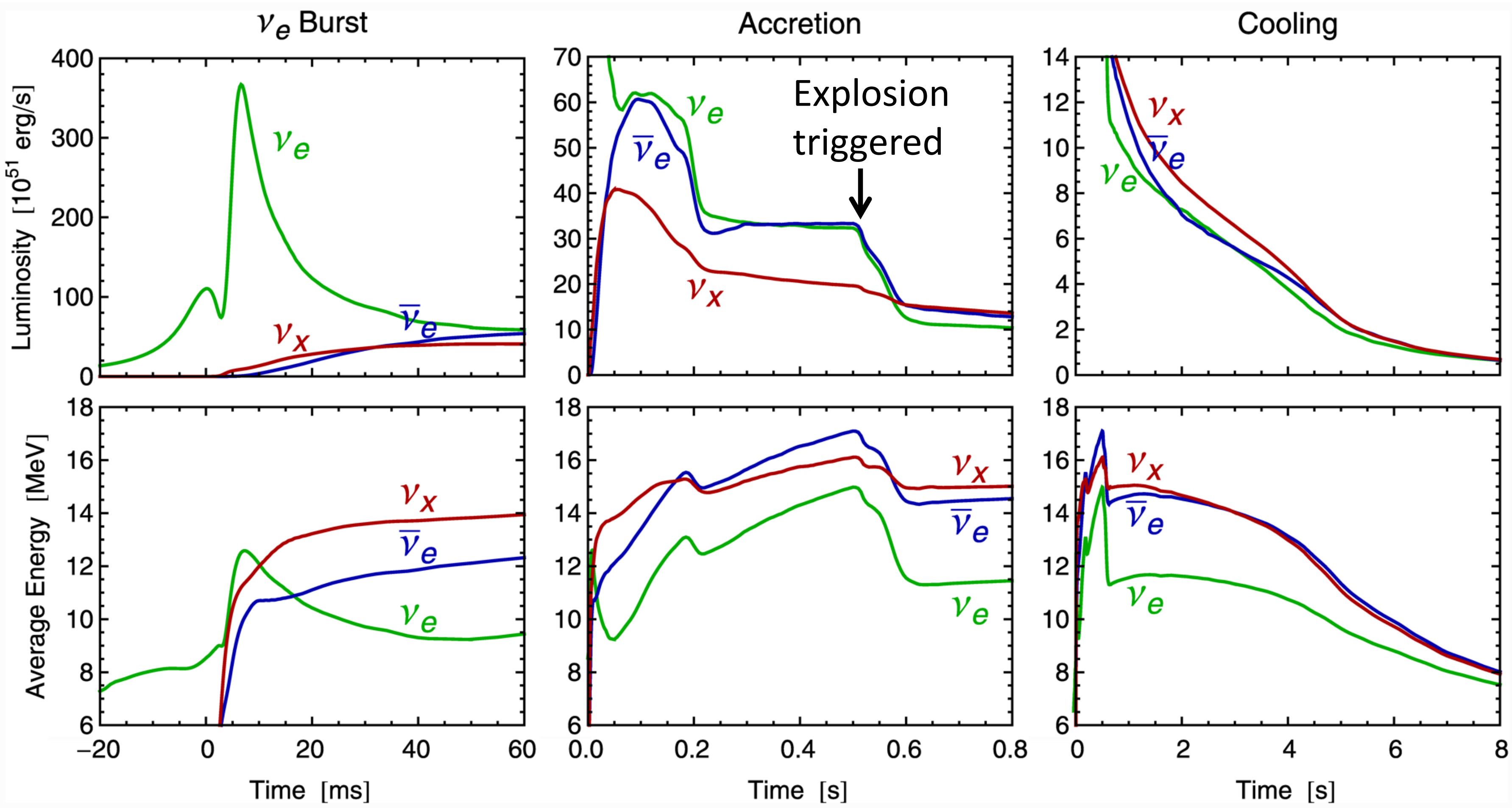
First Realistic 3D Simulation (27 $M_\odot$ Garching Group)



Summary Explosion Mechanism

- Standard paradigm for many years:
  Neutrino-driven explosion (delayed explosion, Wilson mechanism)
- Numerical explosions ok for small-mass progenitors in 1D
  (spherical symmetry)
- Numerical explosions ok for broad mass range in 2D
  (axial symmetry)
- 3D studies only beginning – no clear picture yet
  Better spatial resolution needed?
- Strong progenitor dependence? 3D progenitor models needed?

Three Phases of Neutrino Emission



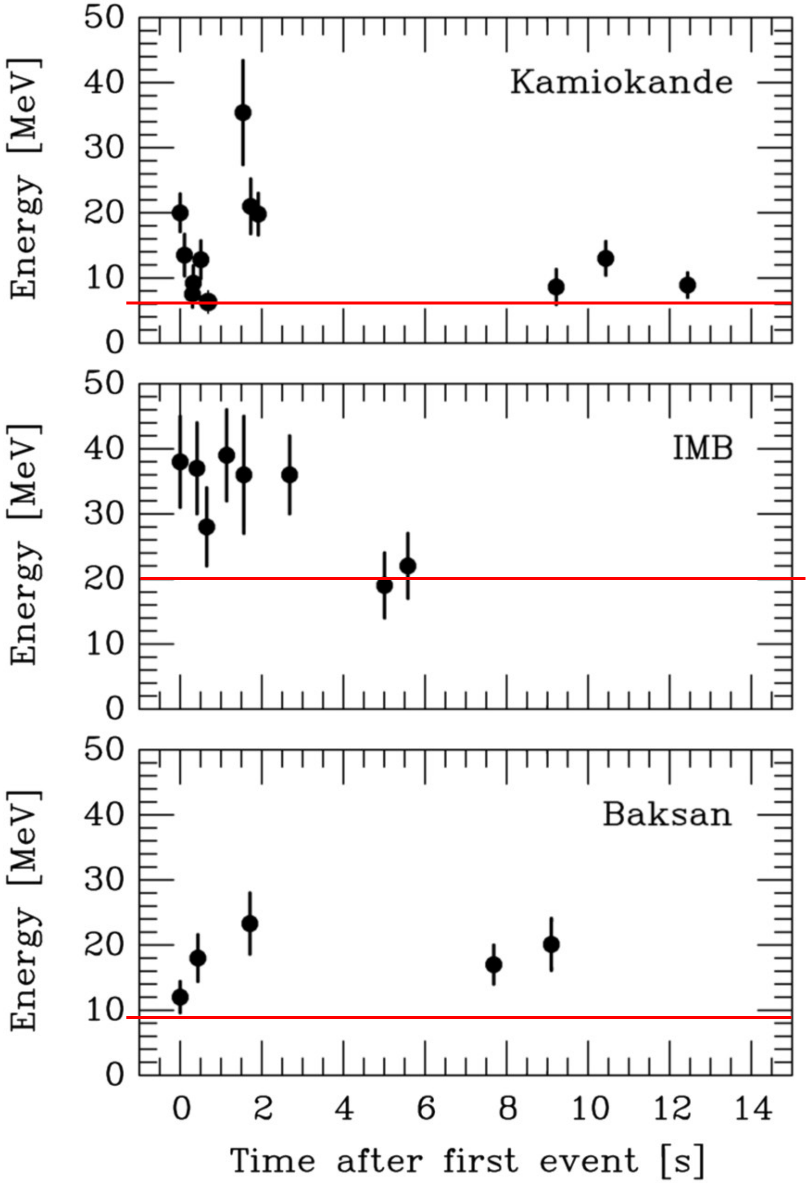
- Shock breakout
- De-leptonization of outer core layers

- Shock stalls ~ 150 km
- Neutrinos powered by infalling matter

Cooling on neutrino diffusion time scale

Spherically symmetric Garching model (25 $M_\odot$) with Boltzmann neutrino transport

Neutrino Signal of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/–54 s

Within clock uncertainties,
all signals are contemporaneous

What did we learn?

- Luminosity ≈ total energy budget
  - Energy emitted is of *gravitational* nature:

    $L_\nu \approx G\, M^2{}_f/R_f - G\, M^2{}_i/R_i \sim 3\ 10^{53}$ ergs ✓ ($R_f \sim 10$ Km)

- Energy spectrum: ~ *Fermi Dirac (thermal)*
  - $E \approx 3.15\ T \sim$ 15-20 MeV ✓

- Duration of neutrino burst ~ diffusion time
  - Time ≈ (size^2)/(mean free path) ~ 10 s ✓

What could we learn?

- Much about the physics of supernova – information about shock waves, accretion, cooling, possible formation of exotic matter, and further collapse to a black hole imprinted on the neutrino spectrum.
- Neutrino sector information: mass and oscillation parameters, hierarchy
- Other particle physics as energy loss constrains other exotic channels

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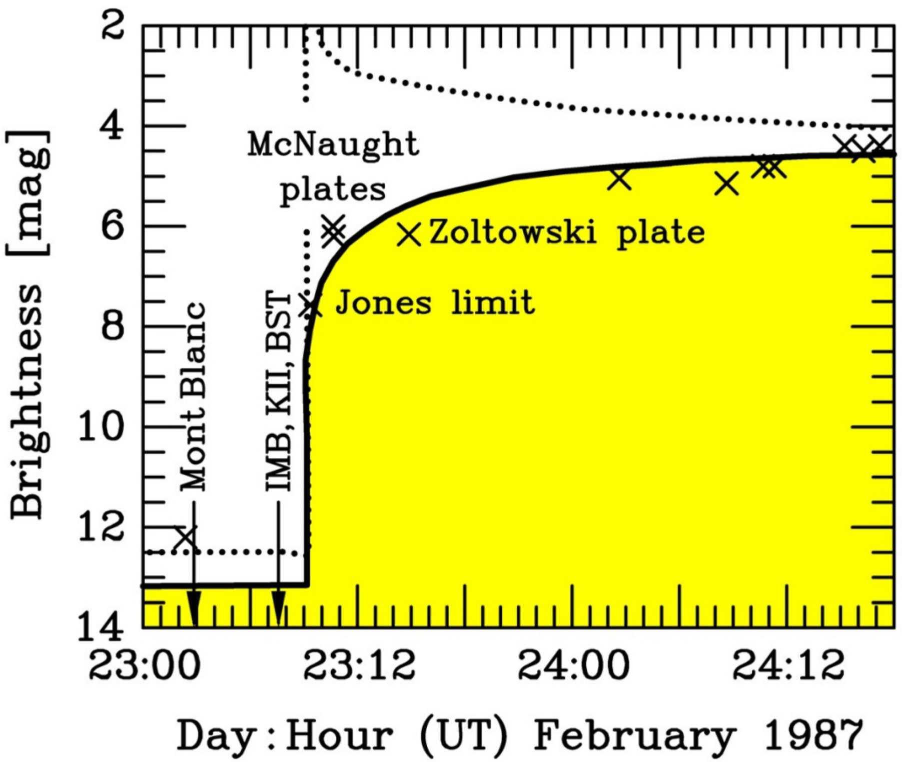
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A



http://snews.bnl.gov

- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance