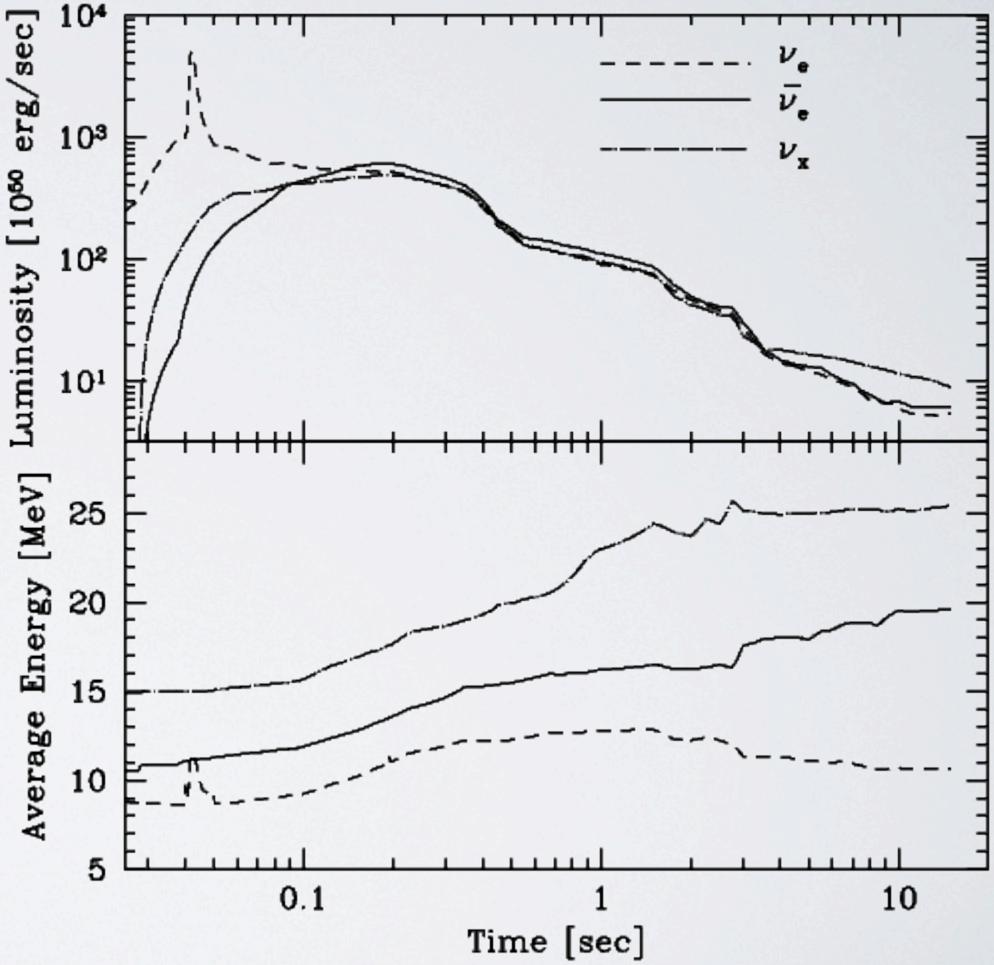
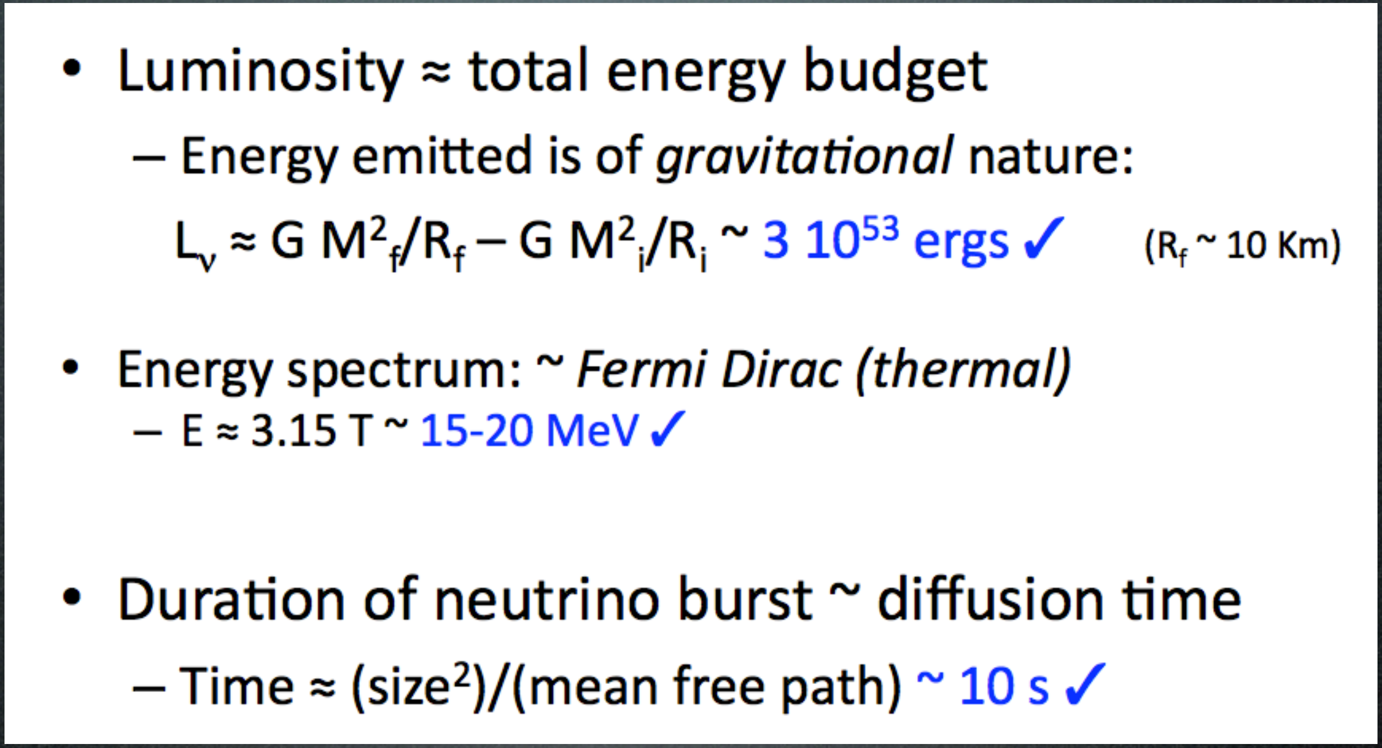
NEUTRINOS FROM SN COLLAPSE

Neutrino collapse and neutrino production
Detection of a galactic supernova: SN 1987A
Current detectors

(Hubble image)



What did we learn?



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

    $L_\nu \approx G\,M^2_f/R_f - G\,M^2_i/R_i$ ~ 3 10^{53} ergs ✓ (R_f ~ 10 Km)
- Energy spectrum: ~ *Fermi Dirac (thermal)*
  - E ≈ 3.15 T ~ 15-20 MeV ✓
- Duration of neutrino burst ~ diffusion time
  - Time ≈ (size^2)/(mean free path) ~ 10 s ✓

Limit on neutrino masses now well overcome:

$$v = \frac{p}{E} = \frac{\sqrt{E^2 - m^2}}{E} \approx 1 - \frac{1}{2}\frac{m_\nu^2}{E_\nu^2}$$

$$t_a - t_e = d \times \left(1 + \frac{1}{2}\frac{m_\nu^2}{E_\nu^2}\right)$$

propagation time = arrival - emission time

$$|\Delta t_a - \Delta t_e| = \frac{1}{2} d\, m_\nu^2 \frac{|E_1^2 - E_2^2|}{E_1^2 E_2^2}$$

Measure energy of 2 events and the t
dispersion between the 2 events =>

$$m_{\nu_e} \lesssim 20\,eV$$

$$F(\bar\nu_e) = (1-p)\cdot F_0(\bar\nu_e) + p\cdot F_0(\bar\nu_\mu).$$

The anti-ν_e spectrum is a mixture of the 2 original spectra for anti-ν_e, ν_μ permutation factor < 35% (99%CL)

SN detectors

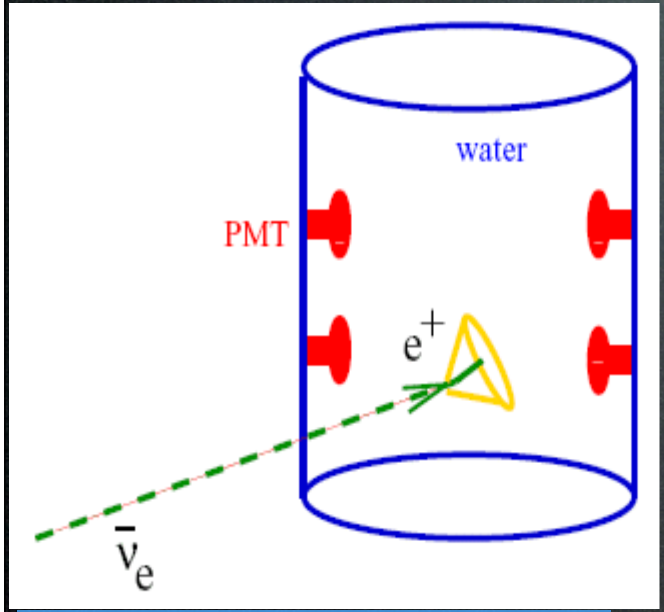
Detector	Type	Location	Mass (ton)	Events @ 8kpc	Status
Super-K	Water	Japan	32000	8000	Running (SK IV)
LVD	Scintillator	Italy	1000	300	Running
KamLAND	Scintillator	Japan	1000	300	Running
Borexino	Scintillator	Italy	300	100	Running
IceCube	**Ice**	**South Pole**	**600000**	**1 million**	**Running**
Baksan	Scintillator	Russia	330	50	Running
Mini-BOONE	Scintillator	USA	700	200	Running
HALO	Lead	Canada	76	85	Under construction
Icarus	Liquid argon	Italy	600	230	Almost ready
NOvA	Scintillator	USA	15	3000	Construction started
SNO+	Scintillator	Canada	1000	300	Funded
Lena	Scintillator	?	50000	$\bar{\nu}_e$: 15000 ν_e: 800 ν_x: 6000	Design study 08-10
Hyper-K	Water	DUSEL	300000	$\bar{\nu}_e$: 70000 ν_e: 3000 ν_x: 3000	Design study S4-funded 10 events Andromeda

Adapted from K. Scholberg, TAUP 2009, and G. Raffelt, Erice 2009

Detection

SN ν interactions inverse beta in Water Čerenkov

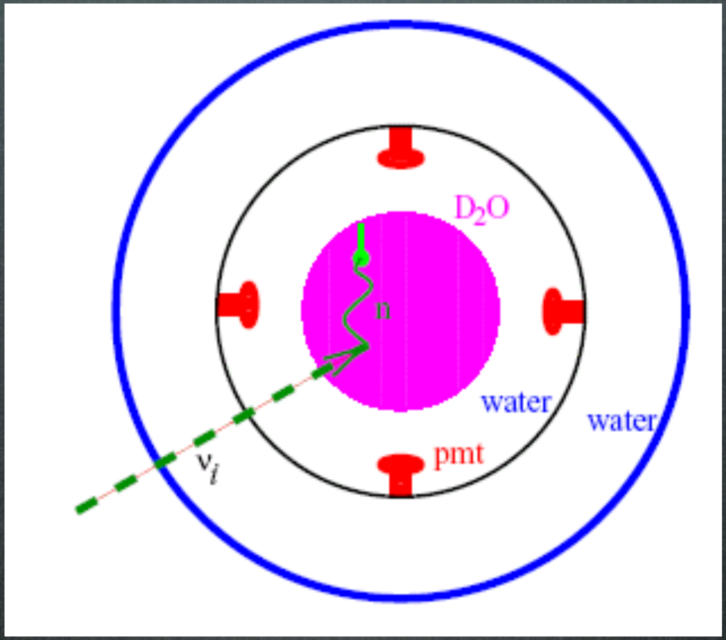
SK, IceCube



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

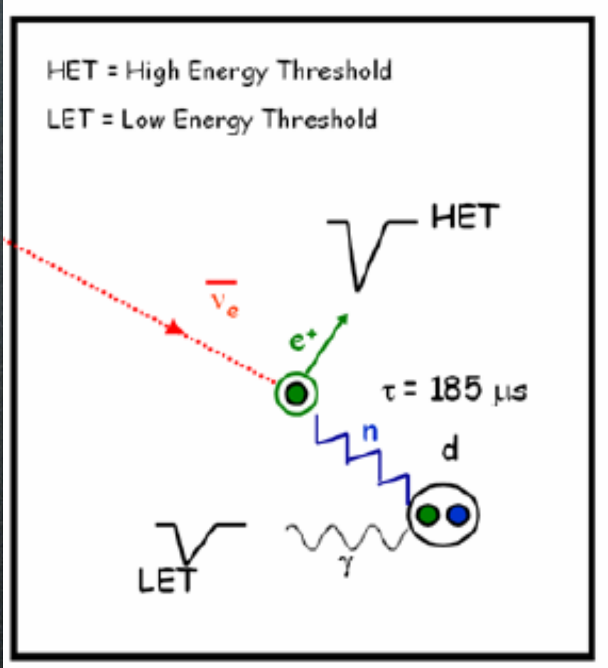
SN ν interactions in heavy water Čerenkov

SNO



SN ν interactions in Liquid Scintillator

LVD, LENA, Borexino, SNO+



1. **Deep underground location**
2. **Using low radioactivity materials**
3. **Anti-coincidence system**
4. **Using reactions with good signature**
5. **Coincidence of signals**

The SN Early Warning System system

Distribution of alerts from experiments looking for SN burst
(currently LVD, SK, SNO, IceCube)

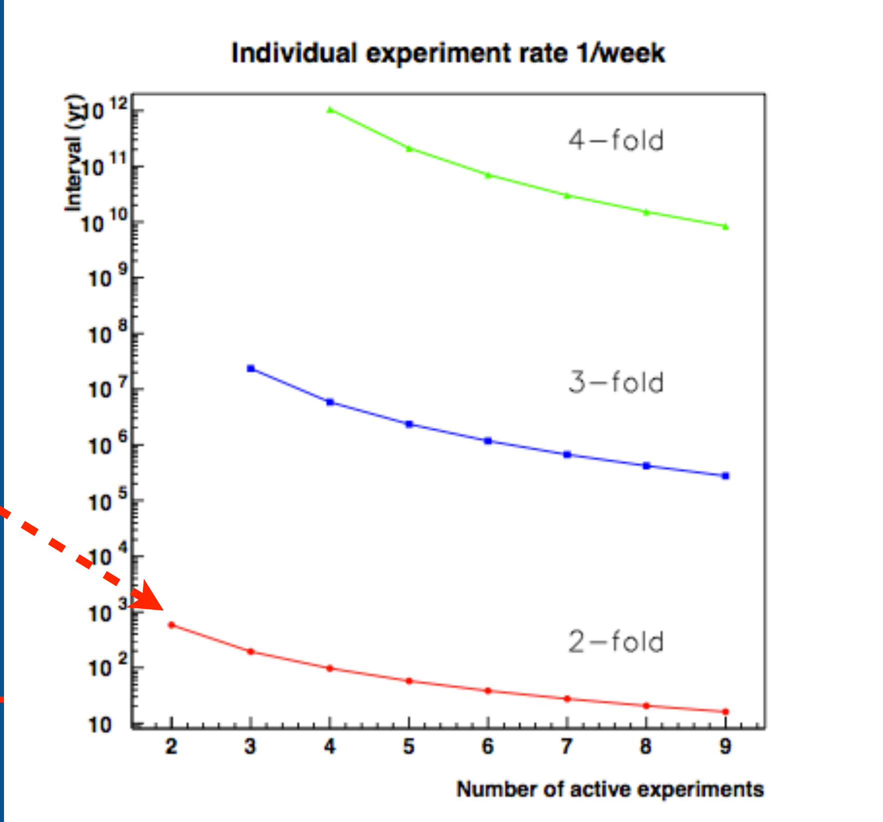
The combination of information allows to reduce the false allarm rate and possibly to make a triangulation between detectors. Triangulation is difficult because only

$$\nu + e^- \to \nu + e^-$$

has directional capabilities but it is not dominant in any detector (only in SK is 2% of signal).

Every experiment looks for SN burst and sends alarms at average rate of 1/week. The average interval of time between accidental alerts for a 2-fold coincidence in 10 s for 2 active experiments with this alarm rate is about 500 yrs!

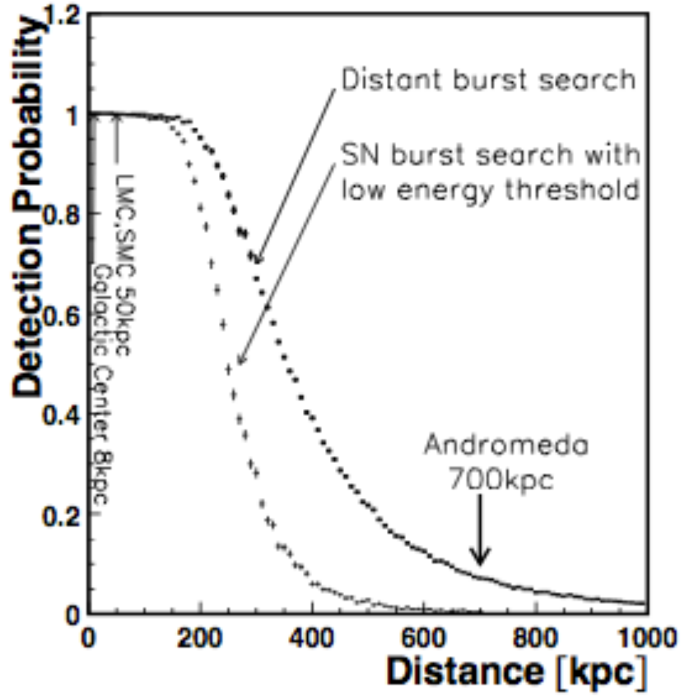
Prompt information to astronomical community



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

SK

http://arxiv.org/pdf/0706.2283v1



$$
\begin{array}{ll}
\bar{\nu}_e + p \to n + e^+ & (88\%/89\%)\,, \\
\nu_e + e^- \to \nu_e + e^- & (1.5\%/1.5\%)\,, \\
\bar{\nu}_e + e^- \to \bar{\nu}_e + e^- & (<1\%/<1\%)\,, \\
\nu_x + e^- \to \nu_x + e^- & (1\%/1\%)\,, \\
\nu_e + {}^{16}O \to e^- + {}^{16}F & (2.5\%/<1\%)\,, \\
\bar{\nu}_e + {}^{16}O \to e^+ + {}^{16}N & (1.5\%/1\%)\,, and \\
\nu_x + {}^{16}O \to \nu_x + O^*/N^* + \gamma & (5\%/6\%)\,,
\end{array}
$$

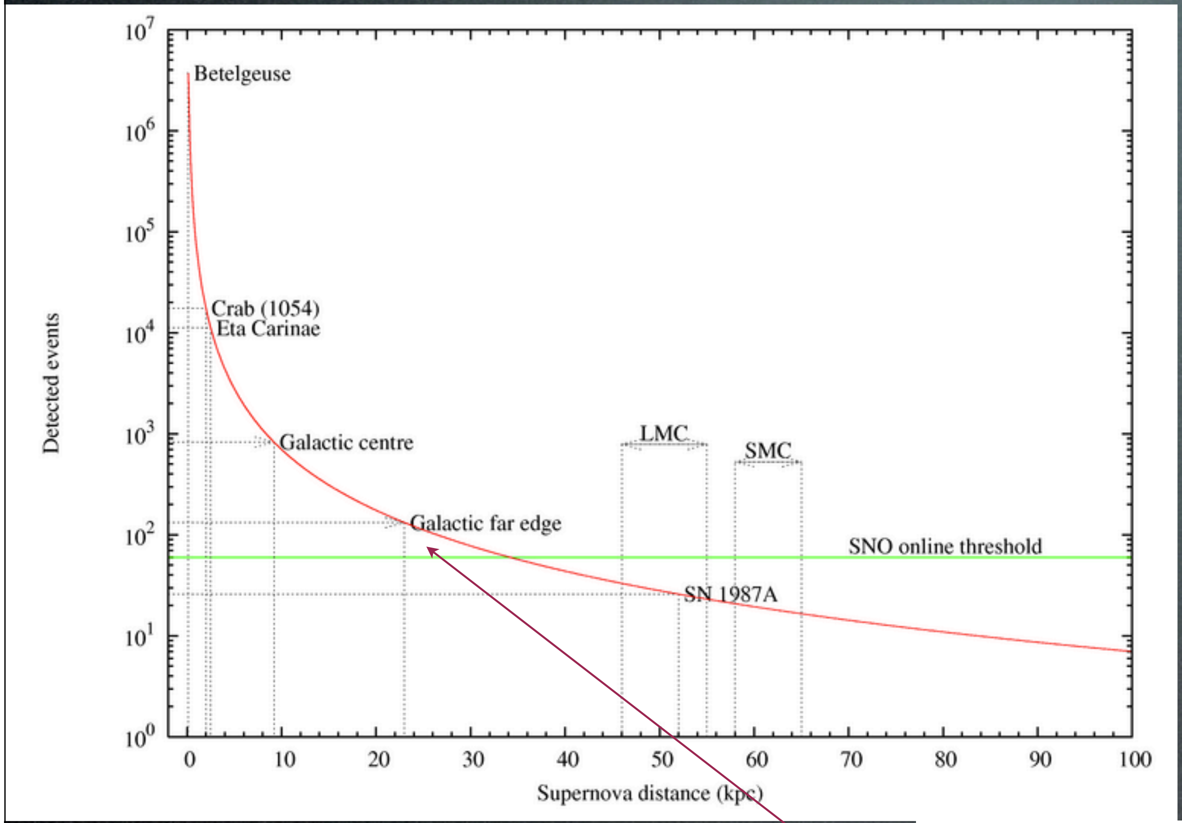
Signal from SN at 10 kpc: 10^4 events
100% efficient out to 100 kpc.
upper limit 0.32 SN yr^{-1} for 2589 d
IceCube: 2.6 yr^{-1} AMANDA 1997-2004
Baksan (best): 0.093 yr^{-1}

EGADS – **Evaluating Gadolinium's Action on Detector Systems:** a dedicated Gd test facility of 200 ton built to explore feasibility of adding Gd to SK water for efficient anti-electron neutrino tagging.

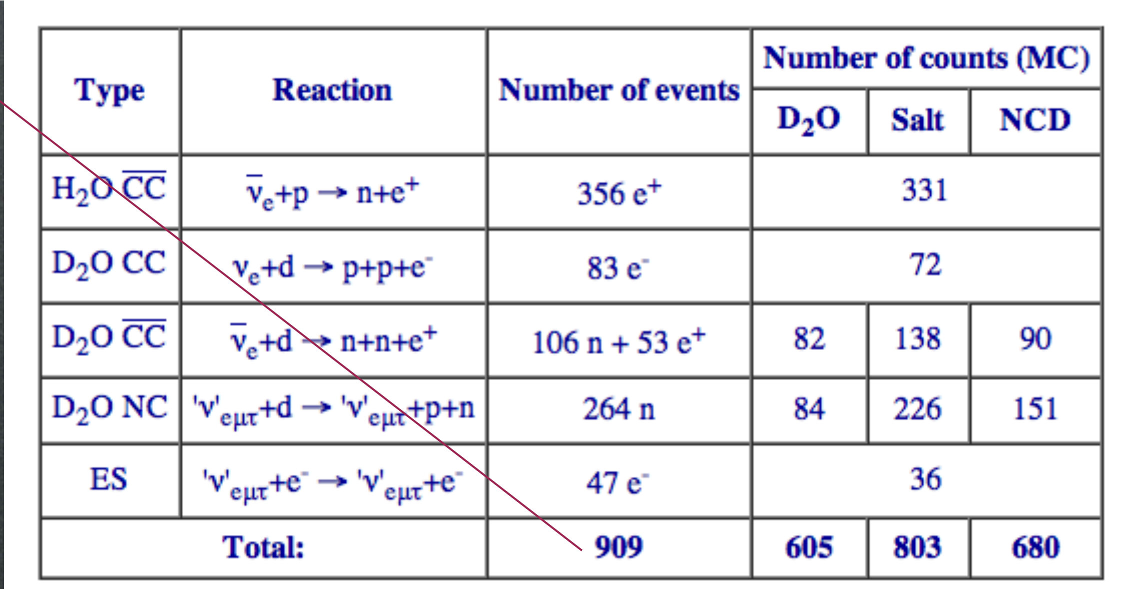
[see Beacom and Vagins, *Phys. Rev. Lett.*, **93**:171101, 2004]

The cross section for thermal neutron capture on natural Gd is 49,000 barns, compared to 0.3 barns on free protons. With 0.2% $GdCl_3$ in water, 90% of n captures are on Gd with gamma decay of 8 MeV, 0.2% on Cl with gamma of 8.6 MeV and the rest on H (gamma 2.2 MeV not detectable in SK)

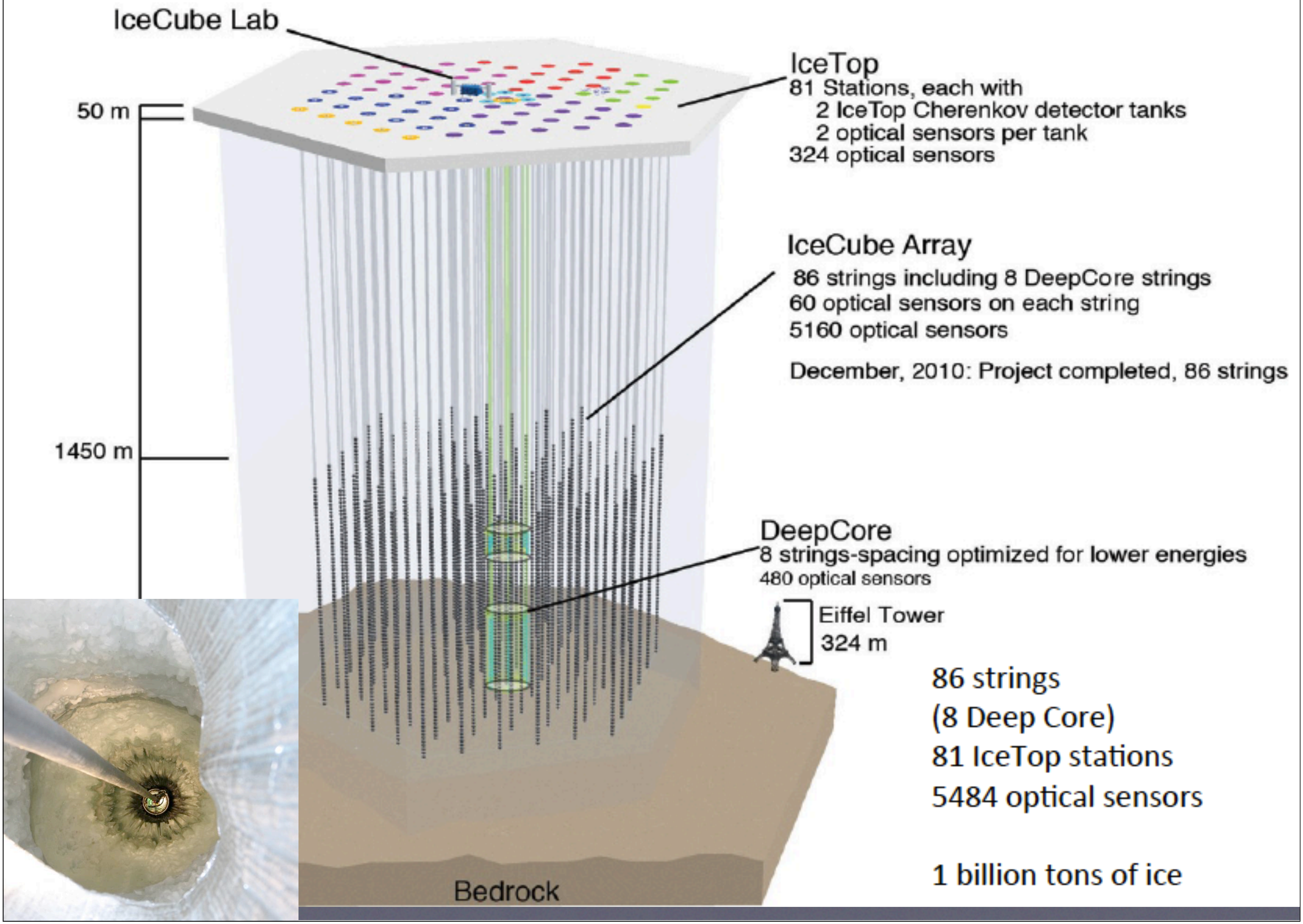
SNO



14 kt, 1 kt of D_2O, H_2O



Type	Reaction	Number of events	Number of counts (MC)		
			D_2O	Salt	NCD
H_2O $\overline{CC}$	$\bar{\nu}_e+p \rightarrow n+e^+$	356 e^+	331		
D_2O CC	$\nu_e+d \rightarrow p+p+e^-$	83 e^-	72		
D_2O $\overline{CC}$	$\bar{\nu}_e+d \rightarrow n+n+e^+$	106 n + 53 e^+	82	138	90
D_2O NC	$'\nu'_{e\mu\tau}+d \rightarrow {}'\nu'_{e\mu\tau}+p+n$	264 n	84	226	151
ES	$'\nu'_{e\mu\tau}+e^- \rightarrow {}'\nu'_{e\mu\tau}+e^-$	47 e^-	36		
Total:		**909**	**605**	**803**	**680**



IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors

1 billion tons of ice

IceCube

Halzen, Jacobsen & Zas
astro-ph/9512080

5160 Optical Modules between 1450-2450 m -43 /-20 °C with dark count rates of about 540 Hz (approximately 16 Hz from muons, 10 Hz thermal emission from photocathode, 30 Hz afterpulses and the rest is a radioactive decays of ^{40}K, U, Th). The rate is reduced enforcing an artificial dead time after each count to 280 Hz at the cost of 13% dead time for signal.

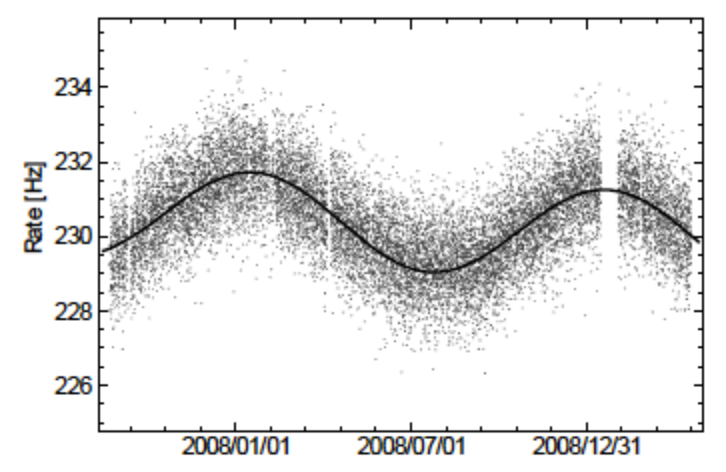
The contribution due to muons shows an annual modulation.

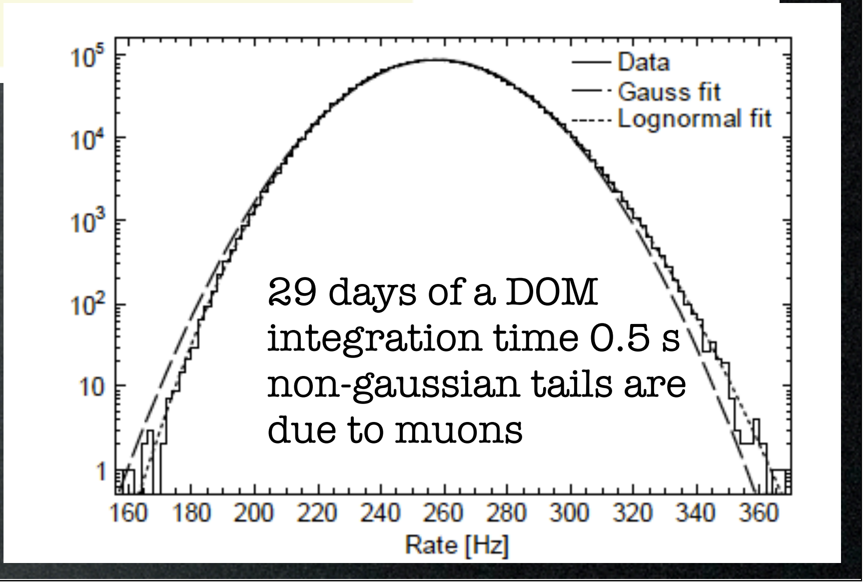
IceCube's advantages:

- Best detector for fine details in neutrino light curve for close supernovae
  - location far from other supernova detectors (triangulation, earth effect differences)

IceCube's disadvantages:

- no information on direction, neutrino type, energy, reach limited to 50 kpc
  - currently limited time resolution
  - limited sensitivity to ν_e

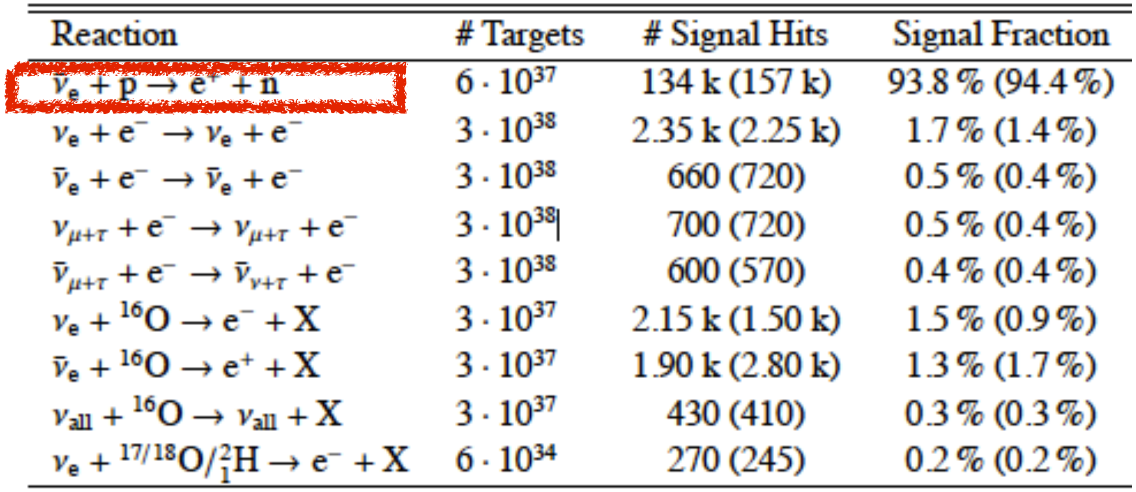




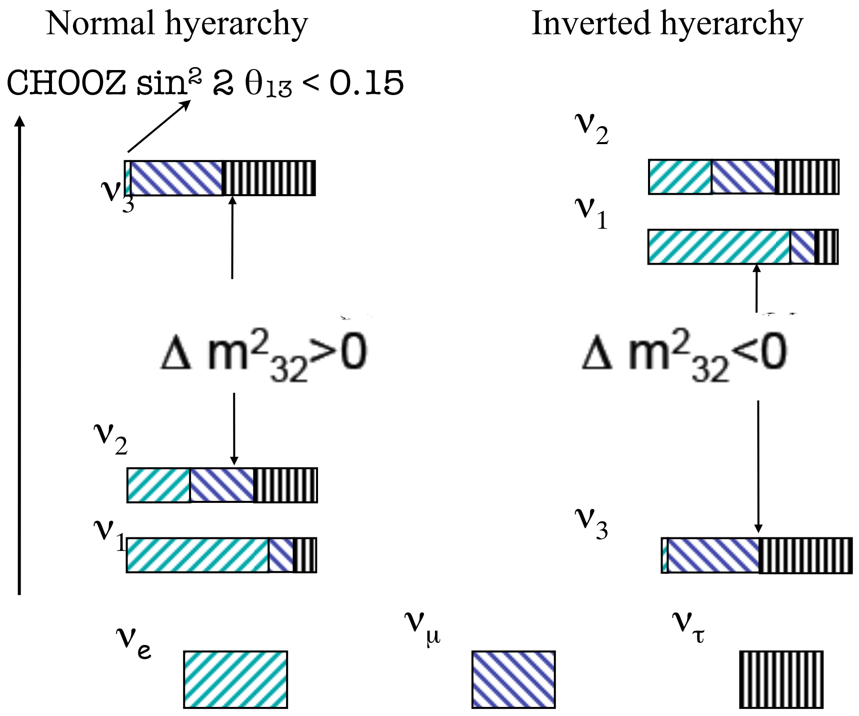
29 days of a DOM
integration time 0.5 s
non-gaussian tails are
due to muons

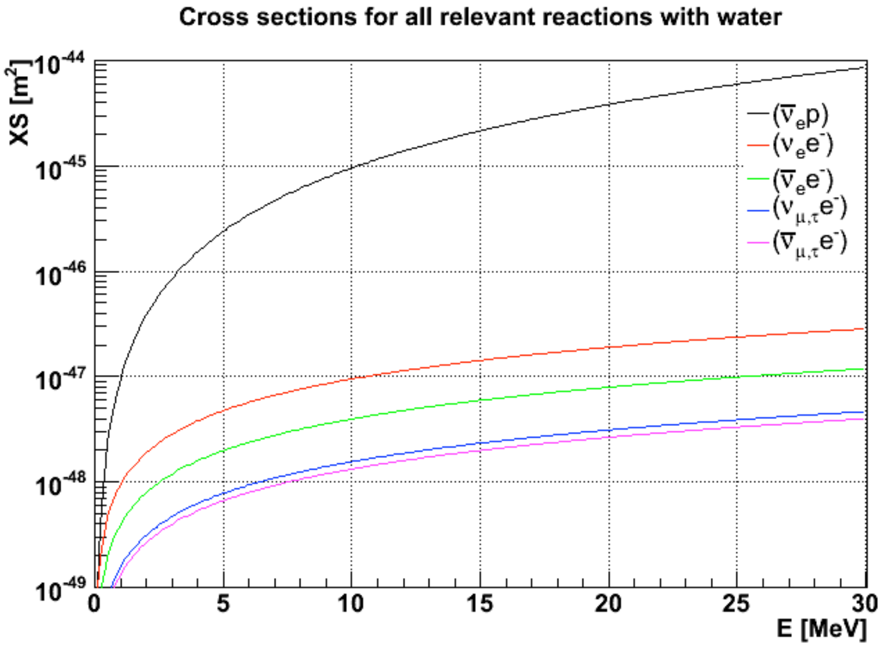
Signal rates and x-section for inverse beta and electron scattering

1 km3 of ice for Normal (NH) and Inverted (IH) Hierarchy for SN1987A at 10 kpc



Reaction	# Targets	# Signal Hits	Signal Fraction
$\bar{\nu}_e + p \rightarrow e^+ + n$	$6 \cdot 10^{37}$	134 k (157 k)	93.8 % (94.4 %)
$\nu_e + e^- \rightarrow \nu_e + e^-$	$3 \cdot 10^{38}$	2.35 k (2.25 k)	1.7 % (1.4 %)
$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$	$3 \cdot 10^{38}$	660 (720)	0.5 % (0.4 %)
$\nu_{\mu+\tau} + e^- \rightarrow \nu_{\mu+\tau} + e^-$	$3 \cdot 10^{38}$	700 (720)	0.5 % (0.4 %)
$\bar{\nu}_{\mu+\tau} + e^- \rightarrow \bar{\nu}_{\nu+\tau} + e^-$	$3 \cdot 10^{38}$	600 (570)	0.4 % (0.4 %)
$\nu_e + {}^{16}O \rightarrow e^- + X$	$3 \cdot 10^{37}$	2.15 k (1.50 k)	1.5 % (0.9 %)
$\bar{\nu}_e + {}^{16}O \rightarrow e^+ + X$	$3 \cdot 10^{37}$	1.90 k (2.80 k)	1.3 % (1.7 %)
$\nu_{all} + {}^{16}O \rightarrow \nu_{all} + X$	$3 \cdot 10^{37}$	430 (410)	0.3 % (0.3 %)
$\nu_e + {}^{17/18}O/{}^{2}_{1}H \rightarrow e^- + X$	$6 \cdot 10^{34}$	270 (245)	0.2 % (0.2 %)




Cross sections for all relevant reactions with water

Inverse beta on p dominates

$E_{th} = (m_n - m_p + m_e)\,c^2 = 1.8$ MeV

Reactions on Oxygen have Eth > 10 MeV.

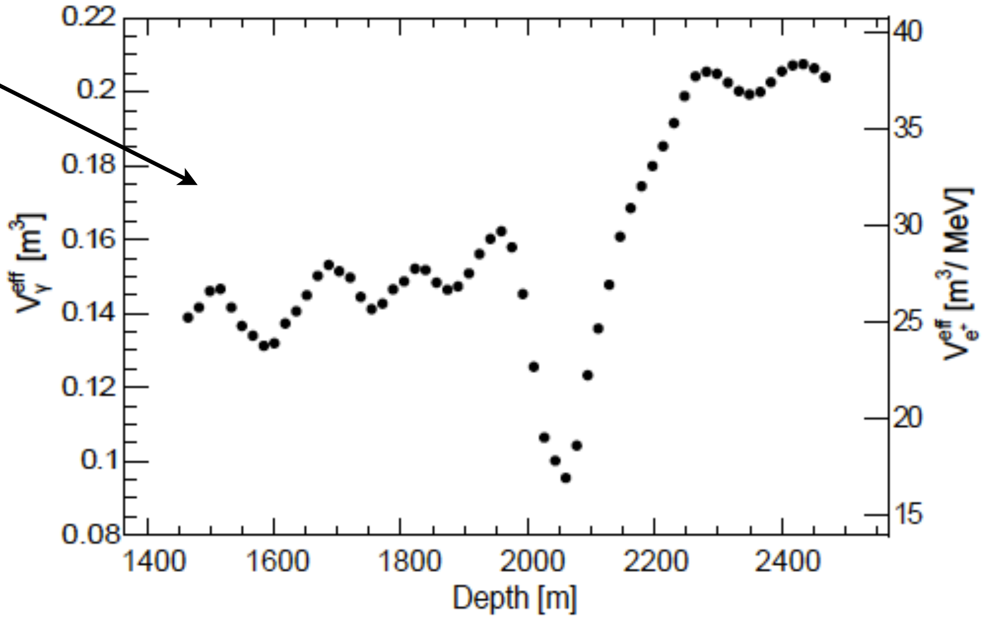
Rate

$$R(t) = \epsilon_{\text{deadtime}} \frac{n_{\text{target}} L^{\nu}_{\text{SN}}(t)}{4\pi d^2 \overline{E_\nu}(t)} \int_0^\infty dE_{\text{e}} \int_0^\infty dE_\nu \times \frac{d\sigma}{dE_{\text{e}}}(E_{\text{e}}, E_\nu)\, N_\gamma(E_{\text{e}})\, V_\gamma^{\text{eff}}\, f(E_\nu, \overline{E_\nu}, \alpha_\nu, t)\,,$$

Effective Volume/PMT per single photon detection and for positrons

Average over all DOMs

$$V_\gamma^{\text{eff}} = 0.160 \pm 0.004\,(\text{stat.}) \pm \underline{0.020}\,(\text{syst.})\,\text{m}^3$$



number of radiated Cherenkov photons ≈ 188 E_e in 300-600 nm

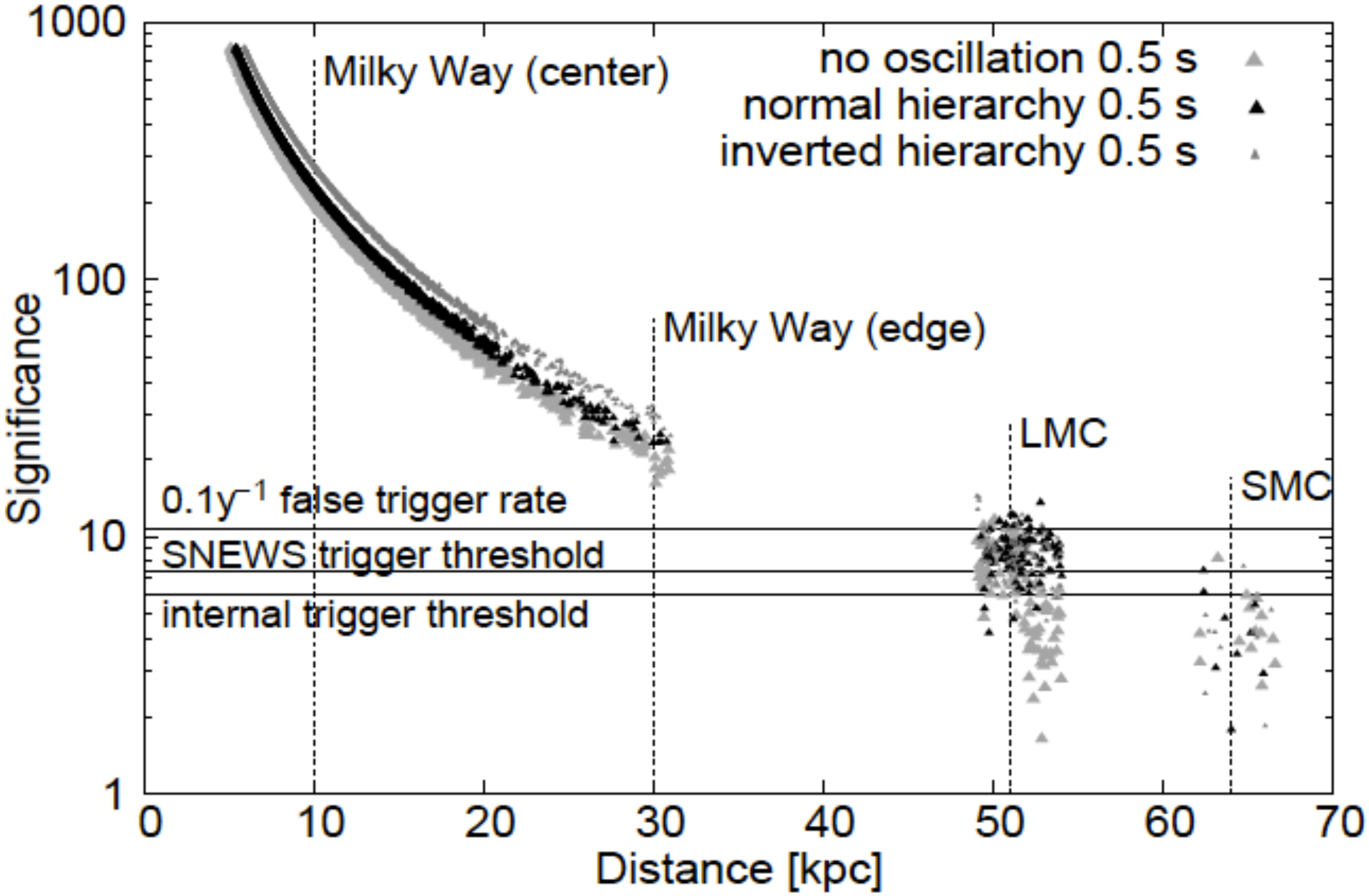
Mean positron track length with v > c/n

$$\bar{x}_e(E_e) = (0.579 \pm 0.017)\text{cm} \cdot E_e/\text{MeV}$$

$$\frac{d^2}{d\lambda dx} N_{\gamma_C} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n_{ice}^2}\right)$$

$$\bar{N}_{\gamma_C} = 2\pi\alpha\left(1 - \frac{1}{\beta^2 n_{ice}^2}\right)\bar{x}_e \int \frac{1}{\lambda^2} d\lambda = 325.4 \frac{\bar{x}_e}{\text{cm}} = (188.3 \pm 5.5) \cdot E_e/\text{MeV}$$

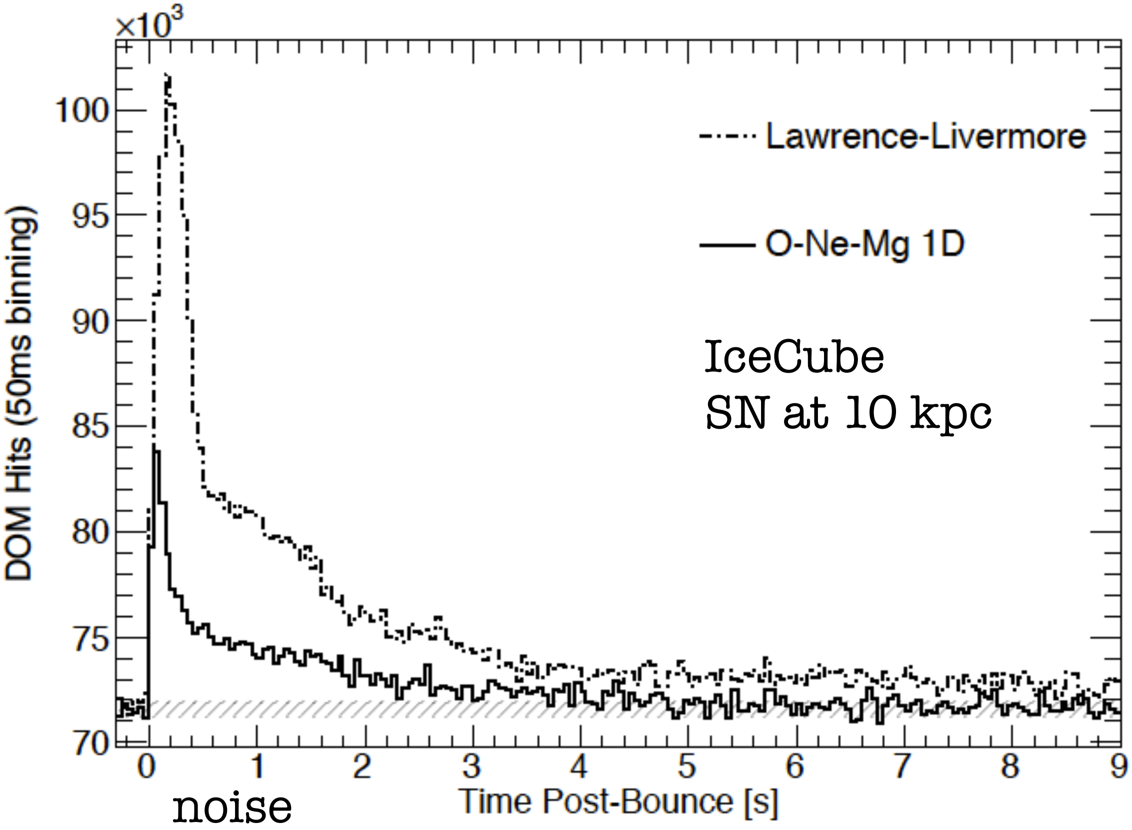
Significance



The significances are increased by neutrino oscillations in the star by typically 15% in case of a normal hierarchy and 40% in case of an inverted hierarchy

Astrophysics: SN core

Neutrinos can distinguish between a SN with iron core (Fe-core SN) and one with an oxygen-neon-magnesium core (ONeMg-core or low mass core SN), for which the density distribution and the shock propagation are completely different. Stars with 8-10 MSun are expected to develop ONeMg cores, which may undergo gravitational collapse before Ne ignition due to rapid electron captures on Mg and Ne (electron-capture supernovae)



IceCube
SN at 10 kpc

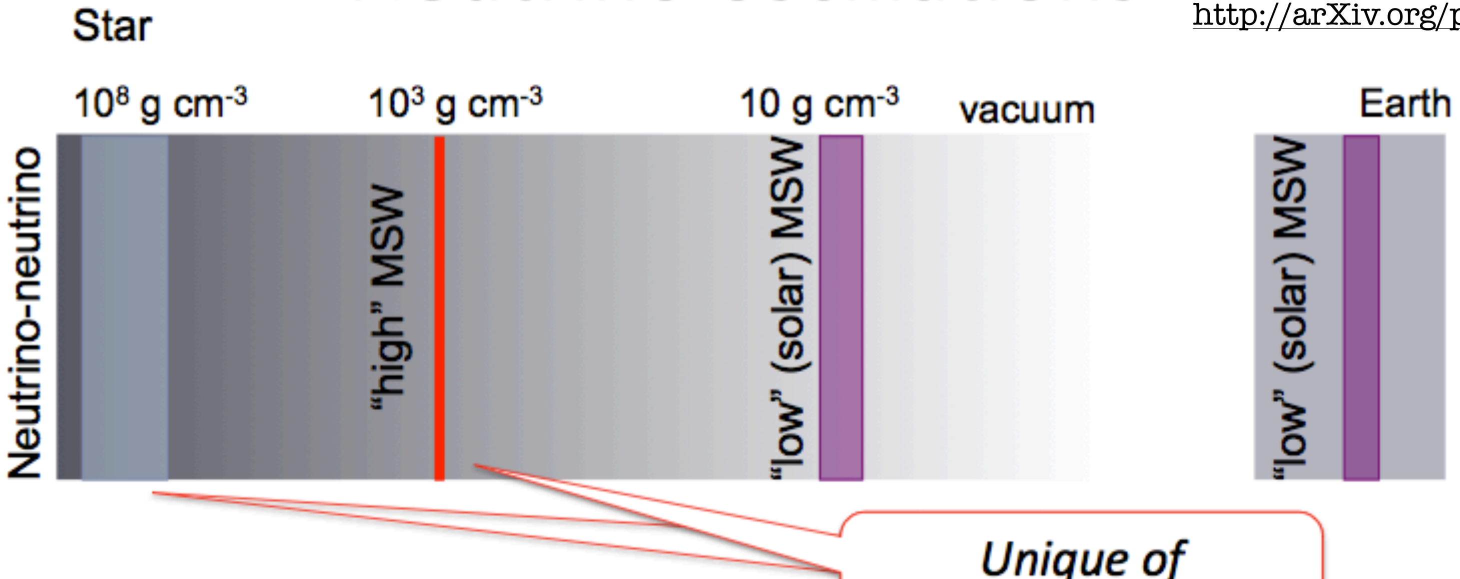
noise

Models: Garching 8.8 solar masses ONeMg core – arXiv:0912.0260 0.3M neutrinos
Reference: Lawrence-Livermore (“classic” model with 20 solar masses) 1M neutrinos

http://arXiv.org/pdf/0712.3000

Neutrino oscillations

http://arXiv.org/pdf/hep-ph/9907423



Unique of supernovae!

- **Matter effects:**

Given what we know of mixing parameters,

$$\sin^2\theta_{12} = 0.32, \Delta m^2_{21} = 8\times 10^{-5}\ \mathrm{eV}^2,\ |\Delta m^2_{31}| = 3\cdot 10^{-3}\ \mathrm{eV}^2,\ \sin\theta_{13} \leq 2\cdot 10^{-2}$$

neutrinos encounter the MSW resonant density in the star that produce a distortion of spectra and reduction of the neutronization peak. The effect depends on the sign of

Δm^2_{31} and the value of θ_{13} (we ignore δ_{CP})

$$F_e = pF_e^0 + (1-p)F_x^0$$
$$F_{\bar{e}} = \bar{p}F_{\bar{e}}^0 + (1-\bar{p})F_{\bar{x}}^0$$

p = survival probability of neutrinos
$\bar{p}$ = surv. prob. of anti-neutrinos

http://arxiv.org/pdf/hep-ph/0302033

RESONANCE

$$\Delta m^2 \cos 2\theta = 2\sqrt{2} G_F E N_e$$

#electrons/nucleon

$$N_e = \frac{\rho Y_e}{m_N}$$

nucleon mass

$$\rho_{res} \approx \frac{1}{2\sqrt{2}G_F} \frac{\Delta m^2}{E} \frac{m_N}{Y_e} \cos 2\theta$$

Density of resonance layer

$$\rho_{res} \sim 1.4 \times 10^6 \text{ g/cc} \left(\frac{\Delta m^2}{1 \text{ eV}^2}\right) \left(\frac{10 \text{ MeV}}{E}\right) \left(\frac{0.5}{Y_e}\right) \cos 2\theta$$

H resonance

In a SN there are two resonance layers, one at higher densities corresponding to atmospheric neutrinos $\Delta m^2_{atm} \sim 2.5 \times 10^{-3}$ eV^2

$$\rho_H \sim 10^3 - 10^4 \text{ g/cc}$$

and the other at lower densities (far from the core) corresponding to Δm^2_{sol}

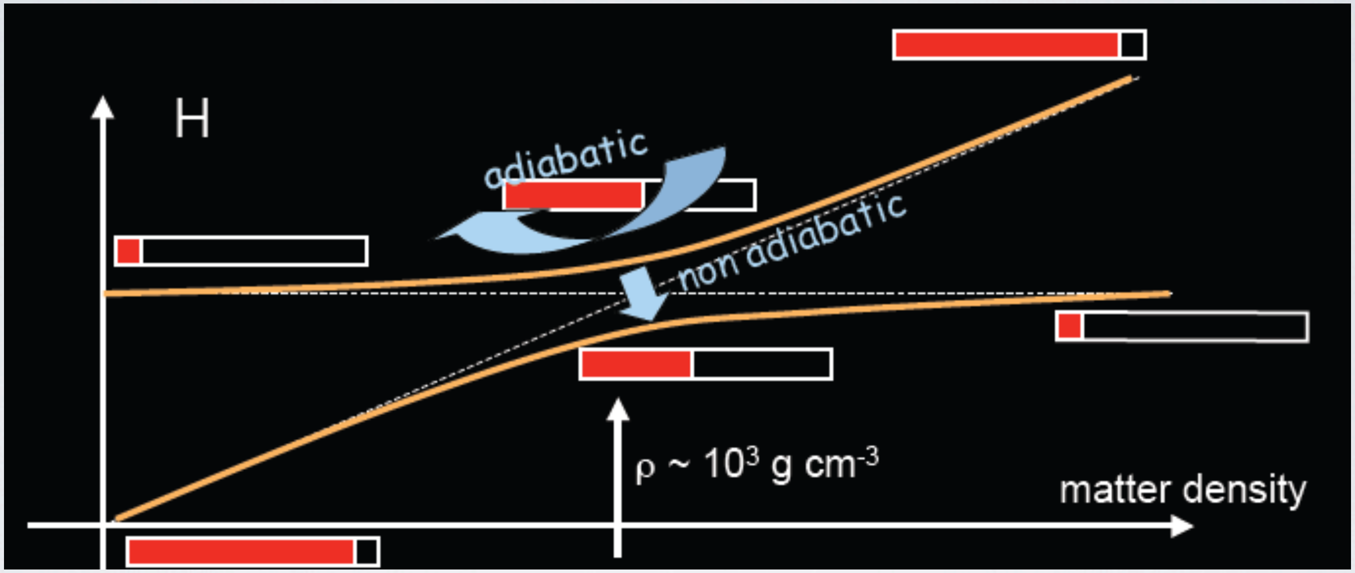
$$\rho_L = \begin{cases} 5 - 15 & \text{g/cc} \quad \text{for SMA} \\ 10 - 30 & \text{g/cc} \quad \text{for LMA} \\ < 10^{-4} & \text{g/cc} \quad \text{for VO} \ . \end{cases}$$

L resonance

Mikheev, Smirnov, Wolfenstein (1985,1978)

http://arxiv.org/pdf/hep-ph/0302033

ADIABATICITY



when the matter density changes the adiabaticity parameter governs the dynamics of the conversion

$$\gamma \equiv \frac{\Delta m^2}{2E}\,\frac{\sin^2 2\theta}{\cos 2\theta}\,\frac{1}{(1/N_e)(dN_e/dr)}$$

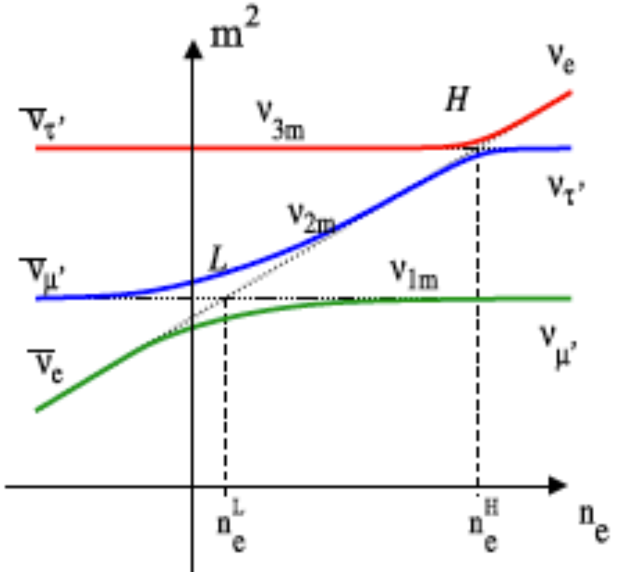
Jumping prob. that a neutrino in one matter eigenstate jumps to another.

$$P_f = exp\left(-\frac{\pi}{2}\gamma\right)$$

Υ>>1 $P_f = 0$ adiabatic resonance: if the density changes slowly => strong flavor conversion (neutrino stays in mass state and flavor conversion occurs)
Υ<<1 $P_f = 1$ non adiabatic, little flavor conversion

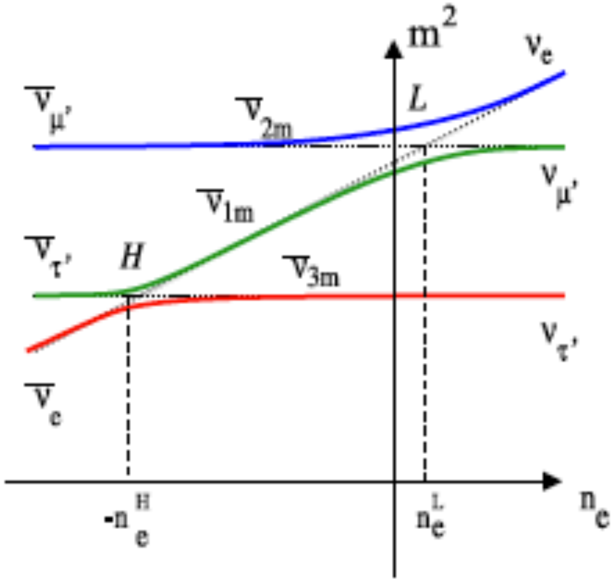
Inside a SN

Normal mass ordering



negative Ne is to show the case for anti-neutrinos

Inverted mass ordering



AD, A.Smirnov, PRD62, 033007 (2000)

H resonance: $(\Delta m^2_{\text{atm}}, \theta_{13})$, $\rho \sim 10^3$–10^4 g/cc

- In $\nu(\bar{\nu})$ for normal (inverted) hierarchy
- Adiabatic (non-adiabatic) for $\sin^2\theta_{13} \gtrsim 10^{-3} (\lesssim 10^{-5})$

L resonance: $(\Delta m^2_{\odot}, \theta_{\odot})$, $\rho \sim 10$–100 g/cc

- Always adiabatic, always in ν

Inside a SN

The H resonance 'jumping probability' is:

$$P_H = \exp\left[-\left(\frac{E_{na}}{E}\right)^{2/3}\right] ,$$

$$E_{na} \simeq 1.08 \cdot 10^7\ \mathrm{MeV} \left(\frac{|\Delta m^2_{32}|}{10^{-3}\ \mathrm{eV}^2}\right) C^{1/2} \sin^3\theta_{13}$$

for the SN density profile $\rho \propto r^{-3}$:

$$\rho(r) = 10^{13}\, \underset{1\text{-}15}{C} \left(\frac{10\ \mathrm{km}}{r}\right)^3\ \mathrm{g}\cdot\mathrm{cm}^{-3}$$

- for θ_{13} small => $P_H \sim 1$ and for both mass hierarchy

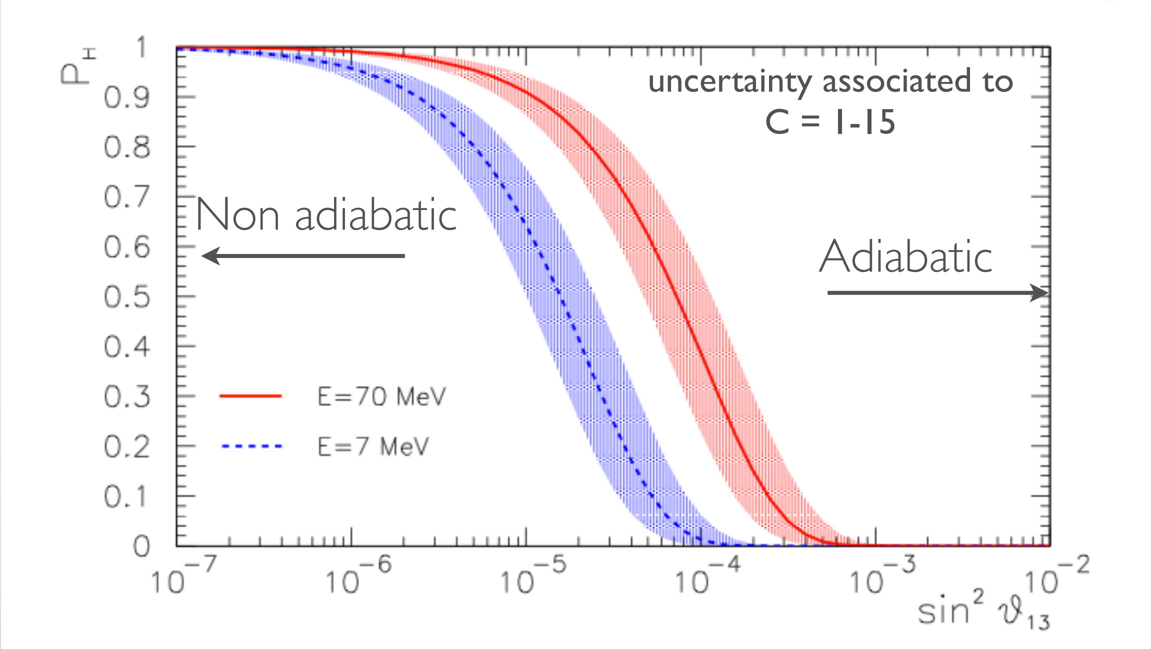
$$p \simeq \sin^2\theta_{12}, \quad \bar{p} \simeq \cos^2\theta_{12}$$

- for θ_{13} large => $P_H \sim 0$ (adiabatic conversion)

$$p \simeq \sin^2\theta_{13}\ , \quad \bar{p} \simeq \cos^2\theta_{12}(1-\sin^2\theta_{13}) \approx \cos^2\theta_{12} \qquad \text{(n.h.)}\ ,$$

and

$$p \simeq \sin^2\theta_{12}(1-\sin^2\theta_{13}) \approx \sin^2\theta_{12}\ , \quad \bar{p} \simeq \sin^2\theta_{13} \qquad \text{(i.h.)}$$



sensitivity to θ_{13} to about 10^{-5}!

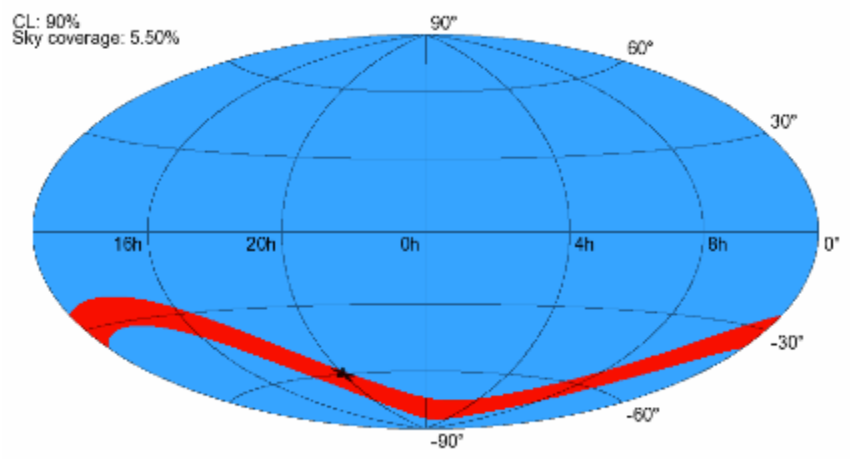
Matter oscillations in the Earth and triangulation

Scholberg et al., http://arxiv.org/pdf/0910.3174v1

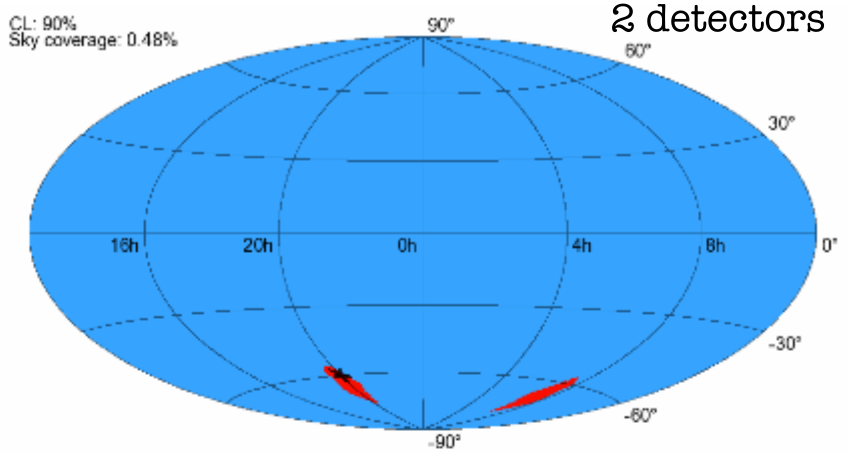
Earth matter effects can be identified comparing signals in detectors, when the shadowing by the earth in different. Since the frequency of oscillations in energy depends on the pathlength traveled by the neutrinos in the Earth, an observed energy spectrum contains information about the SN direction.

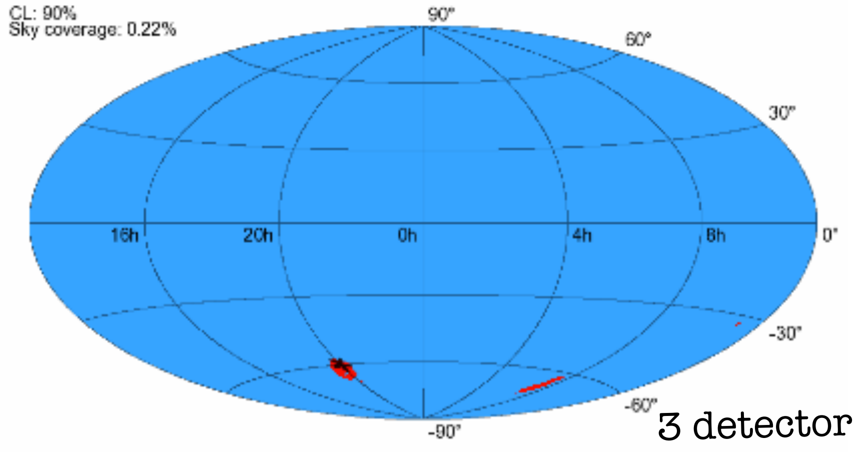
90%CL allowed region for SN position indicated by the black star

1 detector with good energy resolution



2 detectors





3 detectors

Neutrino properties

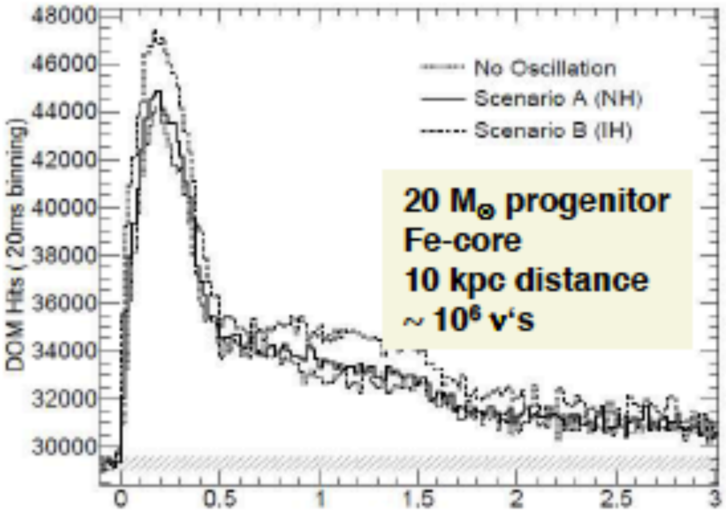
- learn about neutrino hierarchy and θ_{13} mixing angle from, various forms of ν-oscillations

MSW-oscillation in star

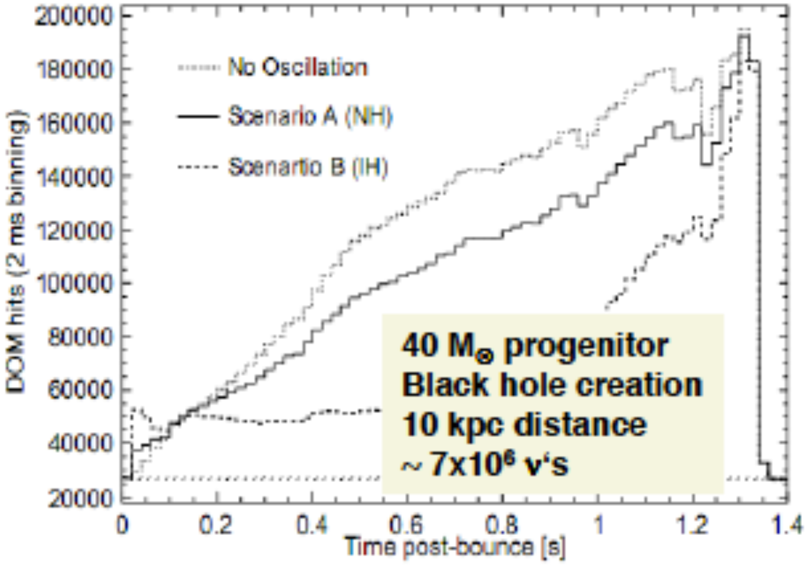
and Earth

Large shape differences between Normal and inverted hierarchies

IceCube simulation following Totani et al. (1997)



20 $M_\odot$ progenitor
Fe-core
10 kpc distance
~ 10^6 ν's



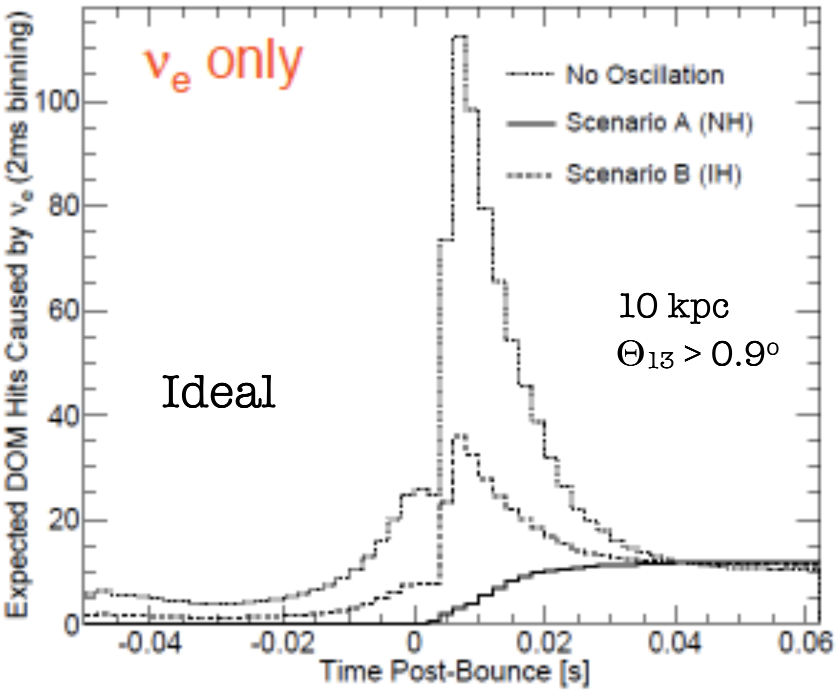
40 $M_\odot$ progenitor
Black hole creation
10 kpc distance
~ 7×10^6 ν's

Deleptonization peak and oscillations (< 10 ms)

Detected by the elastic scattering reaction dominantly $\nu_e + e^- \rightarrow \nu_e + e^-$

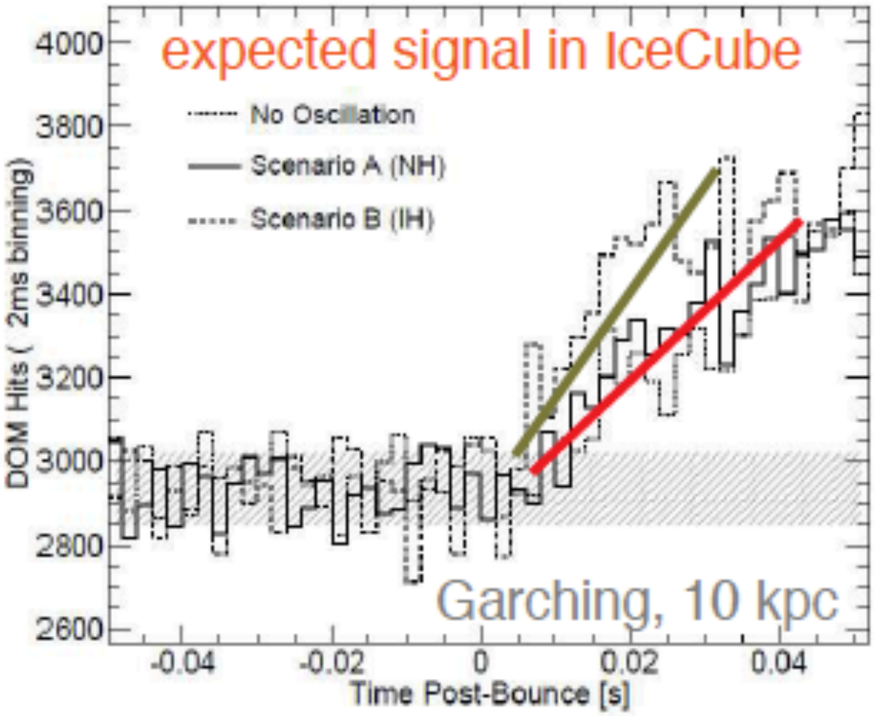
smaller cross section x number of targets by 50 compared to inverse-β

2 ms time bin



Ideal

10 kpc
$\Theta_{13} > 0.9^o$

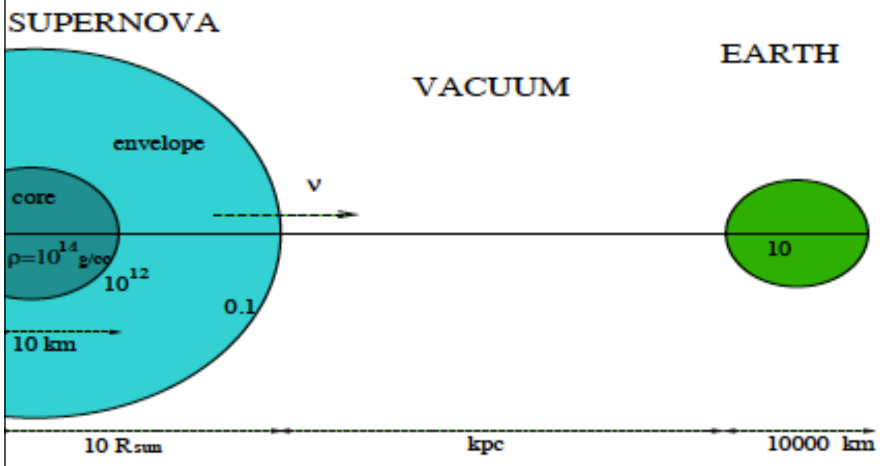


With noise: features are washed out but

signal visible up to a couple kpc distance … however, rising slope bears information on ν hierarchy (3σ up to 6 kpc)

Collective effects and MSW resonance

Dighe et al, http://arXiv.org/pdf/0904.3542



Inside the SN: ***flavour conversion***

Collective effects and MSW matter effects

Between the SN and Earth: ***no flavour conversion***

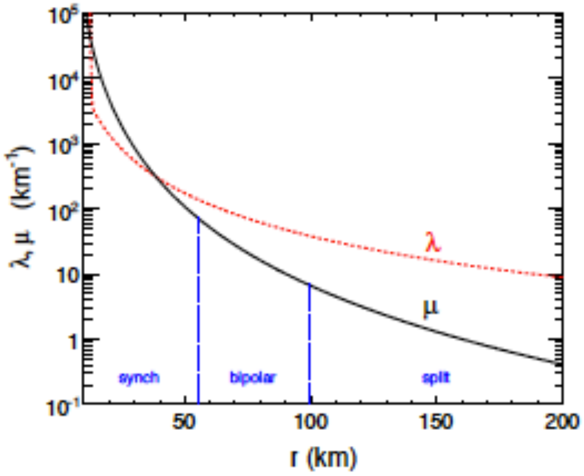
Mass eigenstates travel independently

Inside the Earth: ***flavour conversion***

MSW matter effects (*if detector is on the other side*)

Collective effects (non-linear ν oscillations + neutrinos-neutrinos interactions) produce exchanges of ν_e (anti-ν_e) spectra with ν_x (anti-ν_x) in some energy ranges and introduce spectral distorsions for NH and IH

- $\mu \equiv \sqrt{2}G_F(N_\nu + N_{\bar{\nu}})$
- $\lambda \equiv \sqrt{2}G_F N_e(r)$ MSW

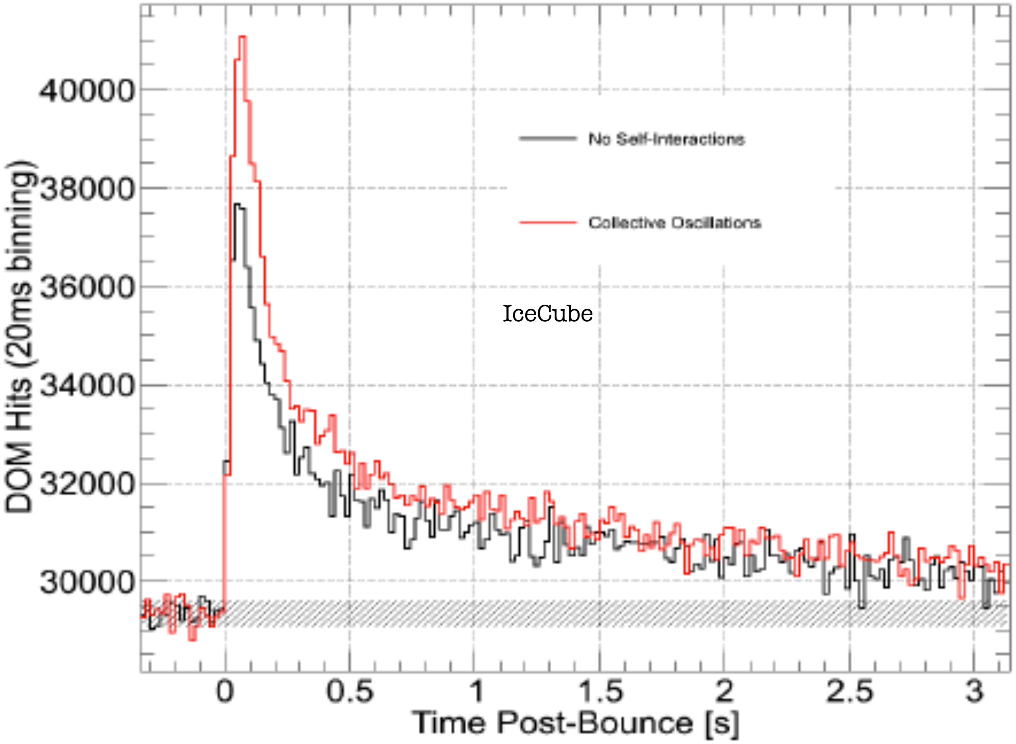


- $r \lesssim 200$ km: collective effects dominate
- $r \gtrsim 200$ km: standard MSW matter effects dominate

G.L.Fogli, E. Lisi, A. Marrone, A. Mirizzi, JCAP 0712, 010 (2007)

Neutrino self-interactions

Test model: Garching 8.8 solar masses ONeMg core



Future: LAGUNA

Order of 10,000 events from SN at 10 kpc

Glacier, LANNDD LAr TPC 100 kt

CC

$$\nu_e +^{40} Ar \rightarrow^{40} K^* + e^- + \text{gamma decay}$$

2.5e4

$$\bar{\nu}_e +^{40} Ar \rightarrow^{40} Cl^* + e^+$$

540

NC

$$\nu_\alpha +^{40} Ar \rightarrow^{40} Ar^* + \nu_\alpha + \text{gamma decay}$$

3e4

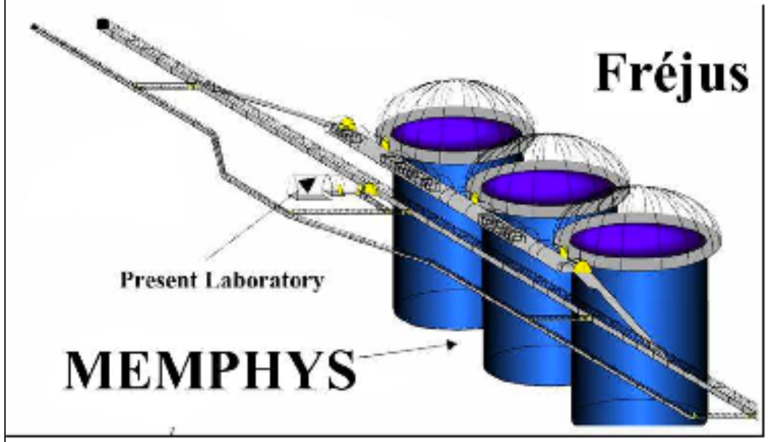
ES

$$\nu + e^- \rightarrow \nu + e^-$$

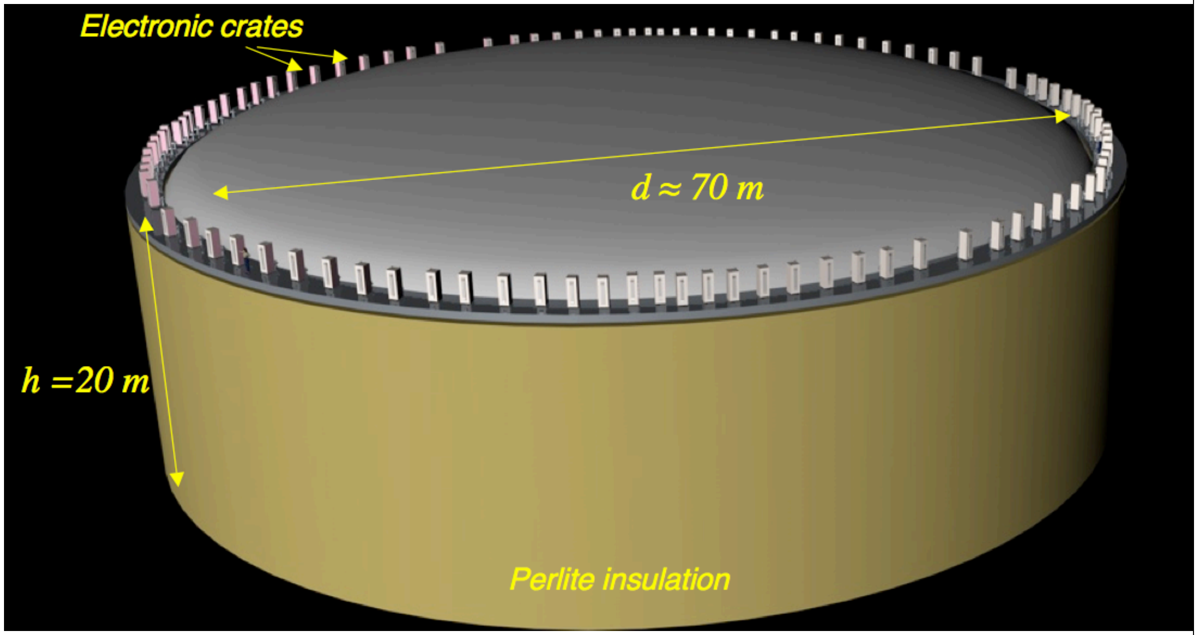
1e3

http://arXiv.org/pdf/0705.0116v2

WC 750 kt



DUSEL



Future: LENA or Hano Hano

Cavern
height: 115 m, diameter: 50 m
shielding from cosmic rays: ~4,000 m.w.e.

Muon Veto
plastic scintillator panels (on top)
Water Cherenkov Detector
3,000 phototubes
100 kt of water
reduction of fast
neutron background

Steel Cylinder
height: 100 m, diameter: 30 m
70 kt of organic liquid
30,000 – 50,000 phototubes

Buffer
thickness: 2 m
non-scintillating organic liquid
shielding from external radioactivity

Nylon Vessel
separating buffer liquid
and liquid scintillator

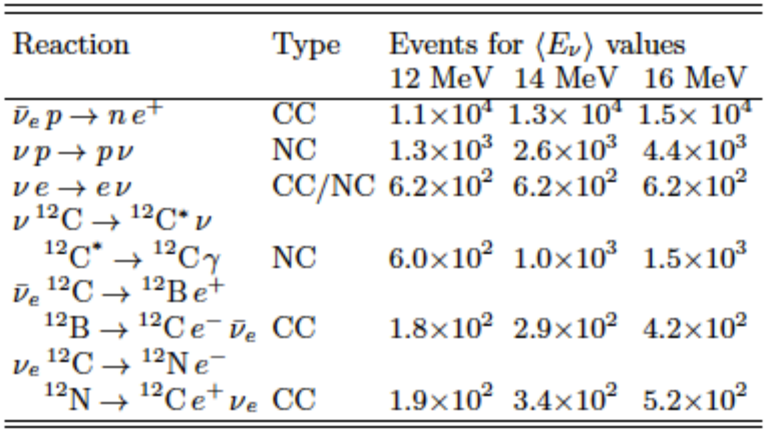
Target Volume
height: 100 m, diameter: 26 m
50 kt of liquid scintillator

70 kt of liquid scint.

Golden channel:

$$\bar{\nu}_e + p \rightarrow n + e^+ \text{ inverse-}\beta$$

$$n + p \rightarrow d + \gamma(2.2\text{MeV}) \text{ after an average of } 250\ \mu s$$



Reaction	Type	Events for $\langle E_\nu \rangle$ values 12 MeV	 14 MeV	 16 MeV
$\bar{\nu}_e\, p \rightarrow n\, e^+$	CC	1.1×10^4	$1.3\times\ 10^4$	$1.5\times\ 10^4$
$\nu\, p \rightarrow p\, \nu$	NC	1.3×10^3	2.6×10^3	4.4×10^3
$\nu\, e \rightarrow e\, \nu$	CC/NC	6.2×10^2	6.2×10^2	6.2×10^2
$\nu\, {}^{12}\text{C} \rightarrow {}^{12}\text{C}^*\, \nu$				
${}^{12}\text{C}^* \rightarrow {}^{12}\text{C}\, \gamma$	NC	6.0×10^2	1.0×10^3	1.5×10^3
$\bar{\nu}_e\, {}^{12}\text{C} \rightarrow {}^{12}\text{B}\, e^+$				
${}^{12}\text{B} \rightarrow {}^{12}\text{C}\, e^-\, \bar{\nu}_e$	CC	1.8×10^2	2.9×10^2	4.2×10^2
$\nu_e\, {}^{12}\text{C} \rightarrow {}^{12}\text{N}\, e^-$				
${}^{12}\text{N} \rightarrow {}^{12}\text{C}\, e^+\, \nu_e$	CC	1.9×10^2	3.4×10^2	5.2×10^2

E_{tot} = 3 x 10^{53} erg for a SN at 10 kpc, equipartitioned among all neutrino species, and Maxwell-Boltzmann spectra with <Eν> = 12, 14 and 16 MeV

Three charged-current (CC) reactions measure ν_e and anti-ν_e fluxes and spectra while three neutral-current (NC) processes, sensitive to all flavors, give information on the total flux.

http://arxiv.org/pdf/1104.5620

Selected topics on high energy neutrino astrophysics

→ cosmic ray -gamma - neutrino connection

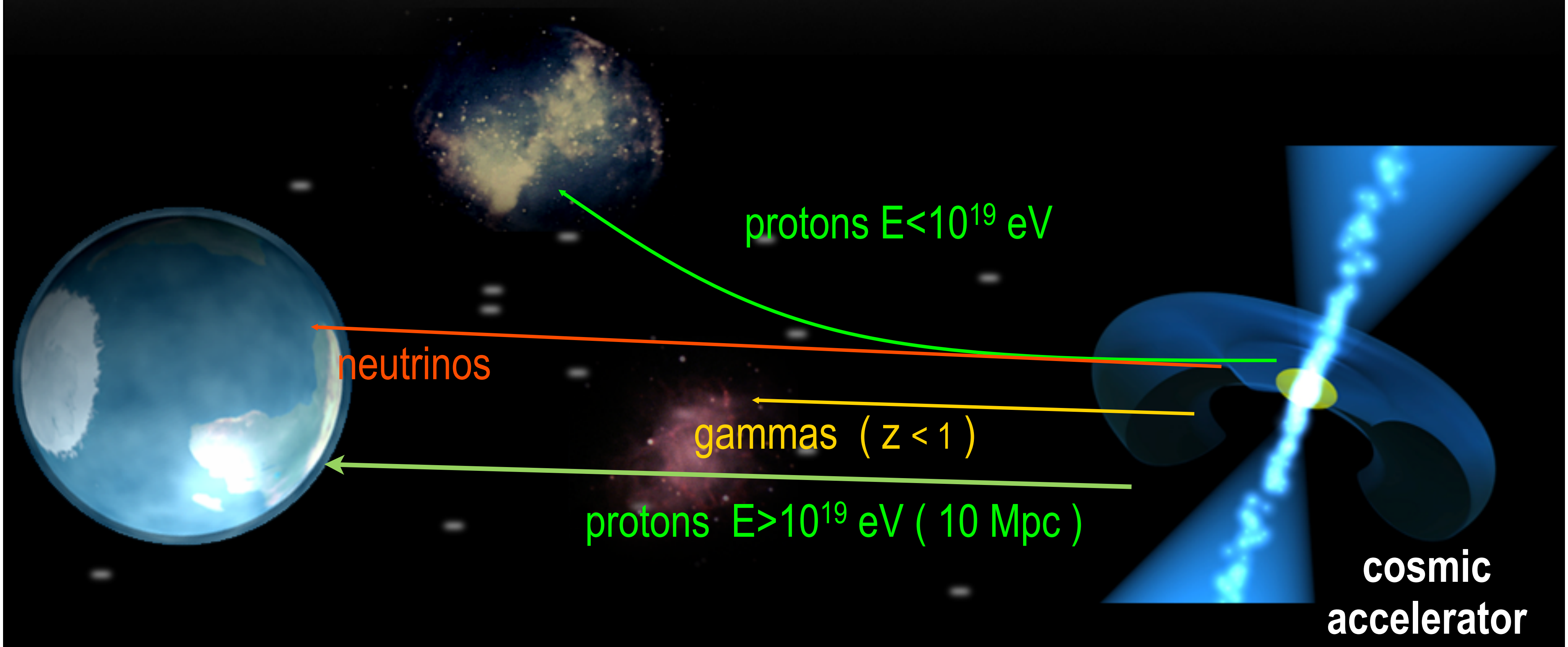
→ GRBs as an instructive example

→ UHE neutrinos

→ Neutrino - gamma connection

MESSENGERS FROM THE UNIVERSE

Discovery messengers: Neutrinos and Gravitational Waves



photons: absorbed on dust and radiation; reprocessed at source

protons/nuclei: deviated by magnetic fields, absorbed on radiation (GZK)

OBSERVABLE UNIVERSE

10^3 TeV photons barely reach us from the Galactic Centre

$$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$$

Proton horizon (GZK cut-off):

$$p\gamma_{2.7K} \rightarrow \Delta^+ \rightarrow \pi^+ n$$

$$L_p = \frac{1}{\sigma_{p-\gamma_{CMB}} n_\gamma} \sim \frac{1}{10^{-28}\text{cm}^2 \times 400\text{cm}^{-3}} \sim 10\ \text{Mpc}$$

The neutrino horizon is comparable to the universe!

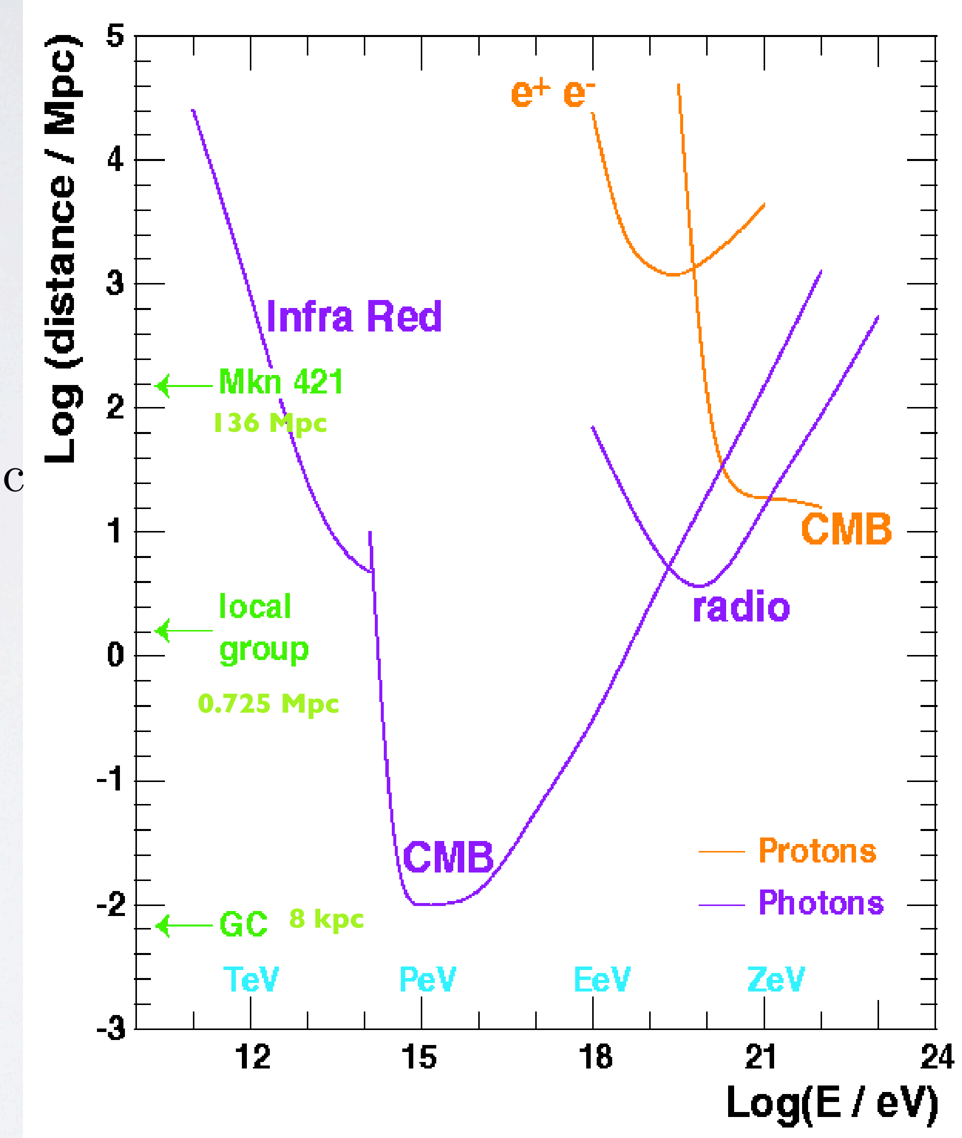
$$\bar{\nu}\nu_{1.95K} \rightarrow Z \rightarrow X$$

$$E_{res} = \frac{M_Z^2}{2m_\nu} \cong 4 \times 10^{21}\left(\frac{1\text{eV}}{m_\nu}\right)\text{eV}$$

$$L_\nu = \frac{1}{\sigma_{res} \times n} = \frac{1}{5 \times 10^{31} cm^2 \times 112 cm^{-3}} \approx 6Gpc$$

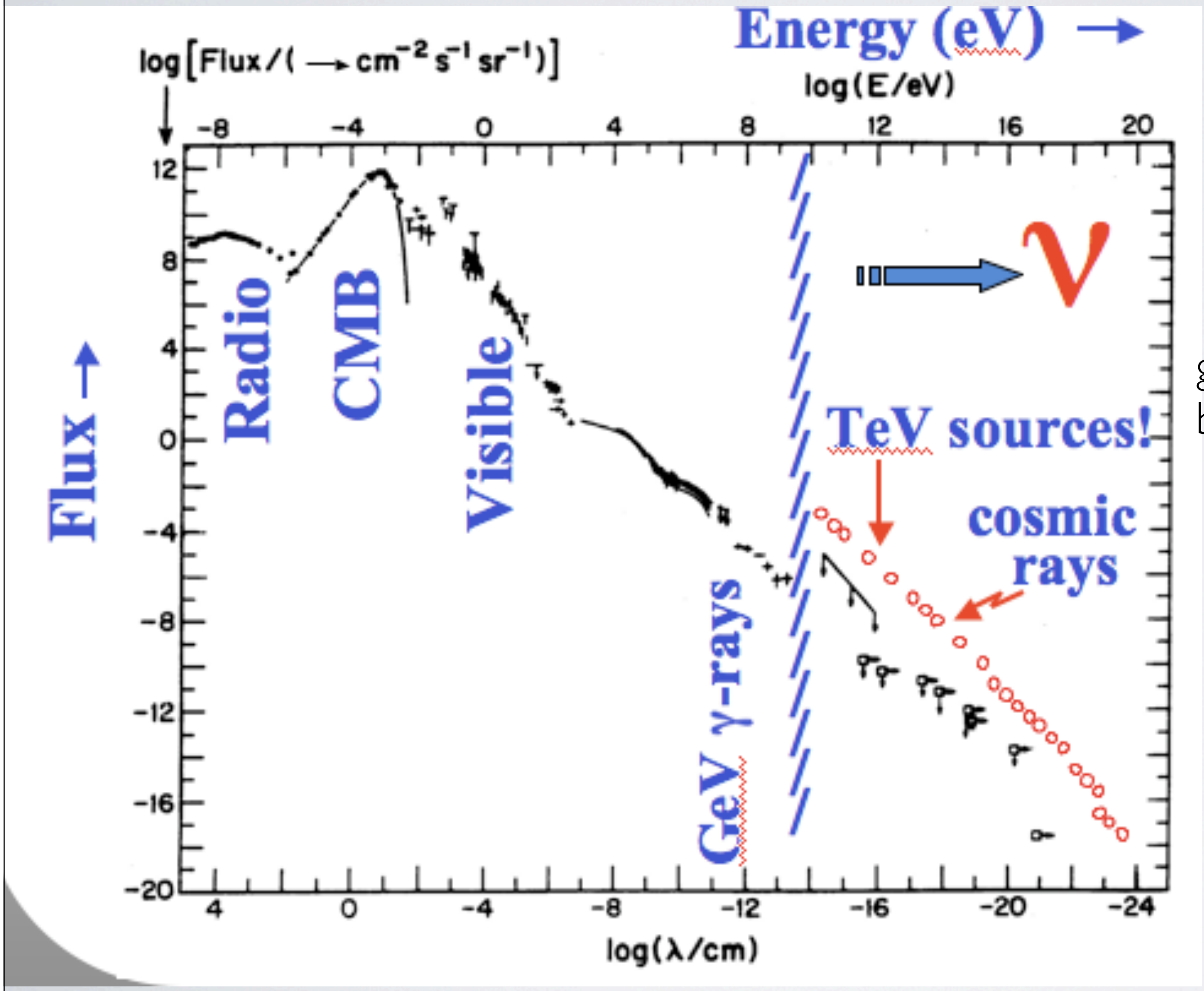
Particle horizon about 14 Gpc

1Mpc = 3.26 Mly = 3.1 10^{24} cm



T. J. Weiler, Phys. Rev. Lett. 49, 234 (1982)

UNDERSTANDING ACCELERATION PROCESSES IN THE UNIVERSE



Gamma astronomy

< 100 TeV

$\gamma + \gamma_{CMB} \longrightarrow e^+ + e^-$

gamma are absorbed on backgrounds

Neutrino astronomy

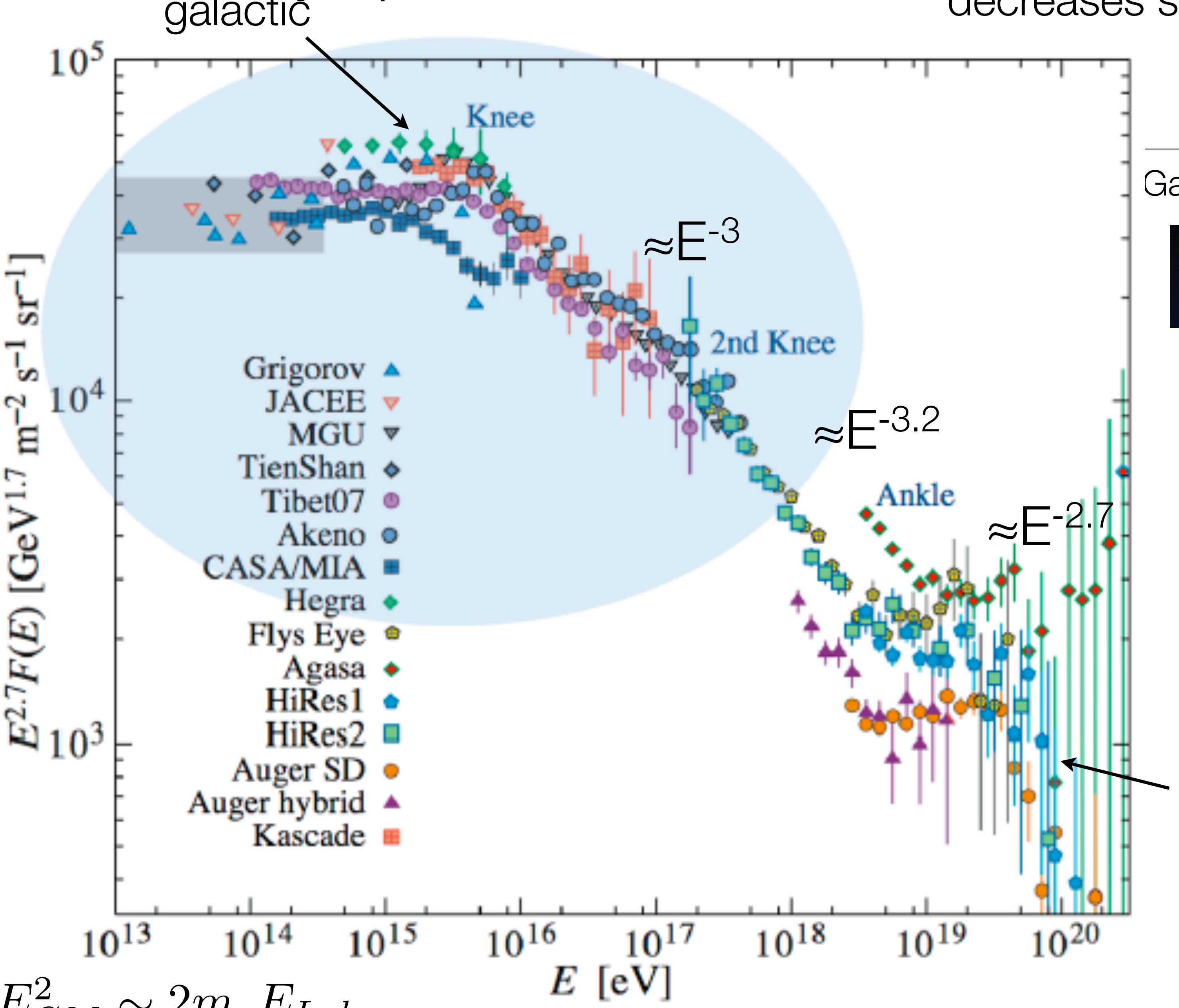
> 10 EeV

$$p\gamma_{CMB} \rightarrow \Delta^+ \rightarrow \pi^+ n$$
$$\pi^0 p$$

Proton astronomy

Cosmic Ray Spectrum

Luminosity of the CR beam decreases steeply with energy



extra-galactic

Galaxy containment (B ~ 4 uG)

R ~ 400 pc @ 10^{18} eV
R ~ 0.4 pc @ 10^{15} eV

$$E_{CM}^2 \sim 2 m_p E_{Lab}$$

For LHC: $E_{CM} = 14$ TeV, $m_p \sim 1$ GeV $\rightarrow E_{Lab} \sim 10^{17}$ eV

POWER OF SOURCES OF COSMIC RAYS

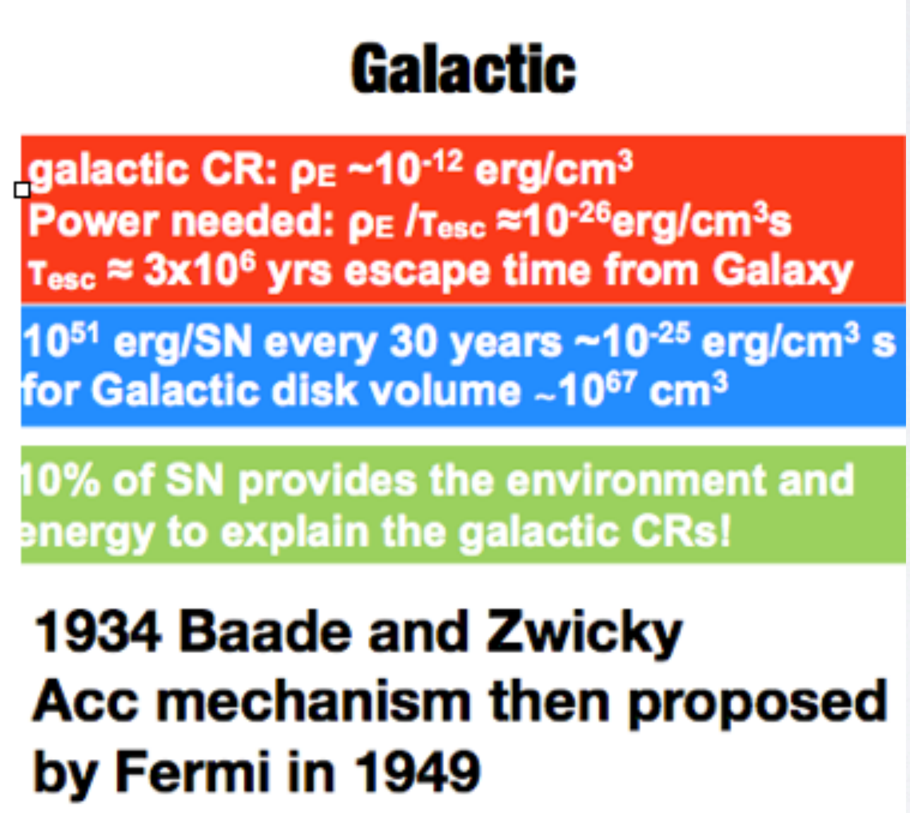
energy density flux = velocity x density

$$4\pi \int dE \left(E \frac{dN}{dE} \right) = c\, \rho_E$$

$$1)\, p + \gamma \rightarrow \Delta^+ \rightarrow p\pi^0$$

$$2)\, p + \gamma \rightarrow \Delta^+ \rightarrow n\pi^+$$

Waxman & Bahcall, PRD59, 1999 and PRD64, 2001)



Galactic

galactic CR: $\rho_E \sim 10^{-12}$ erg/cm^3
Power needed: $\rho_E / T_{esc} \approx 10^{-26}$ erg/cm^{3}s
$T_{esc} \approx 3\times10^6$ yrs escape time from Galaxy

10^{51} erg/SN every 30 years ~10^{-25} erg/cm^3 s
for Galactic disk volume ~10^{67} cm^3

10% of SN provides the environment and energy to explain the galactic CRs!

1934 Baade and Zwicky
Acc mechanism then proposed by Fermi in 1949

Extragalactic

Above the ankle:

$$E\left\{E\frac{dN_{\rm CR}}{dE}\right\} = \frac{3\times10^{10}\,{\rm GeV}}{(10^{10}\,{\rm cm}^2)(3\times10^7\,{\rm s})\,{\rm sr}} = 10^{-7}\,{\rm GeV\ cm^{-2}\,s^{-1}\,sr^{-1}}$$

Energy density in extra-galactic CRs:

$$\rho_E = \frac{4\pi}{c}\int_{E_{min}}^{E_{max}} \frac{10^{-7}}{E}\, dE\, \frac{GeV}{cm^3} \sim 3\times10^{-19}\,\frac{erg}{cm^3}$$

$$E_{max}/E_{min} \sim 10^3$$

Power needed by a population of sources of p with E^{-2} to generate ρ_E over the Hubble time = 10^{10} yrs $\approx 10^{44}$ erg Mpc^{-3} yr^{-1}

3×19^{39} erg/s per galaxy
3×10^{42} erg/s per cluster of galaxies
2×10^{44} erg/s per AGN
2×10^{52} erg per cosmological GRB.

300 GRB per Gigaparsec^3 per year for 10^{10} years (Hubble time)

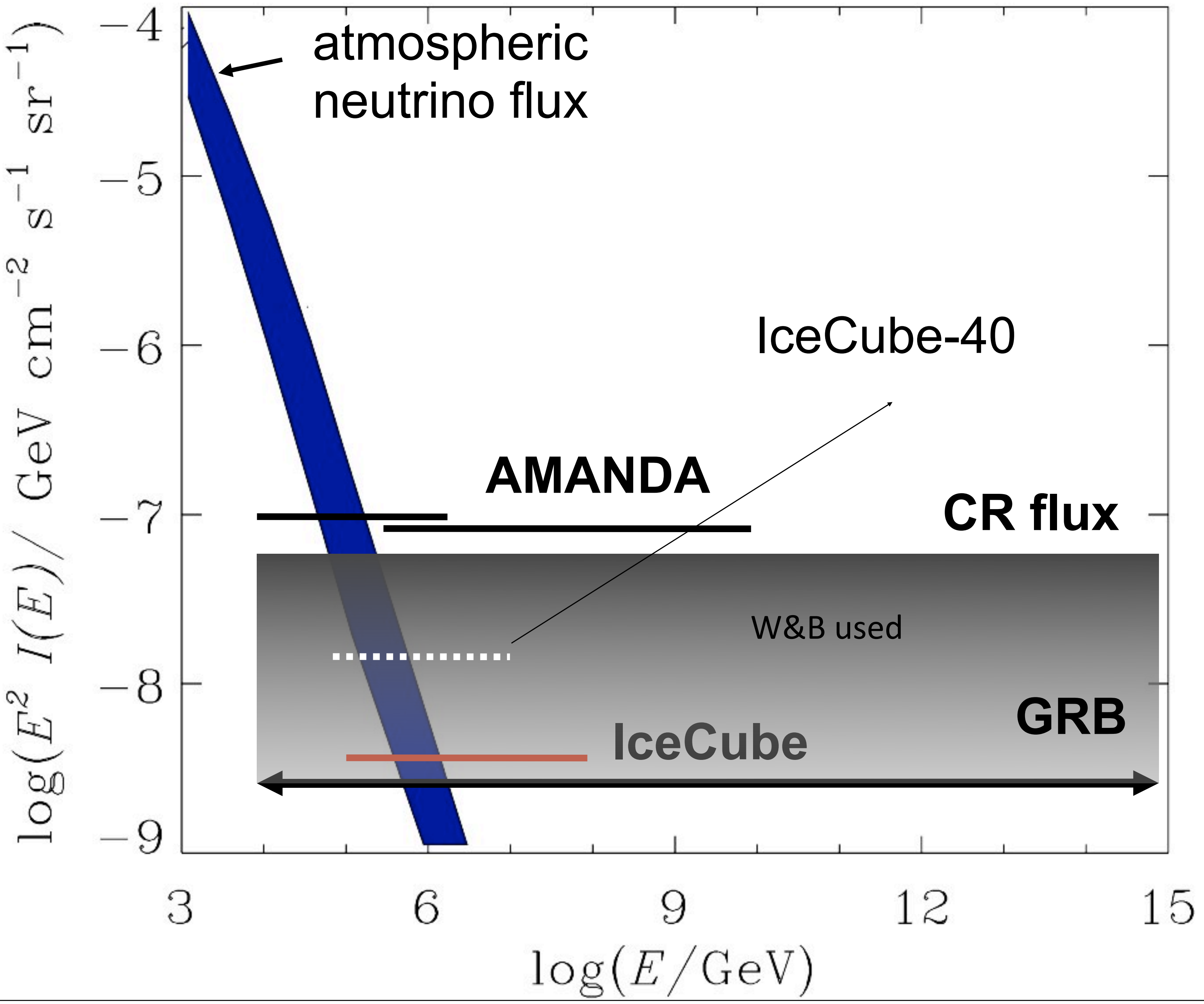
$$2\times10^{51}\,erg\times\frac{300}{Gpc^3\ \ yr}\times10^{10}\,yr = 3\times10^{-19}\,\frac{erg}{cm^3}$$

$$1\,Gpc^3 = 2.9\times10^{82}\,cm^3 \qquad Hubble\ time = 10^{10}\ \ years$$

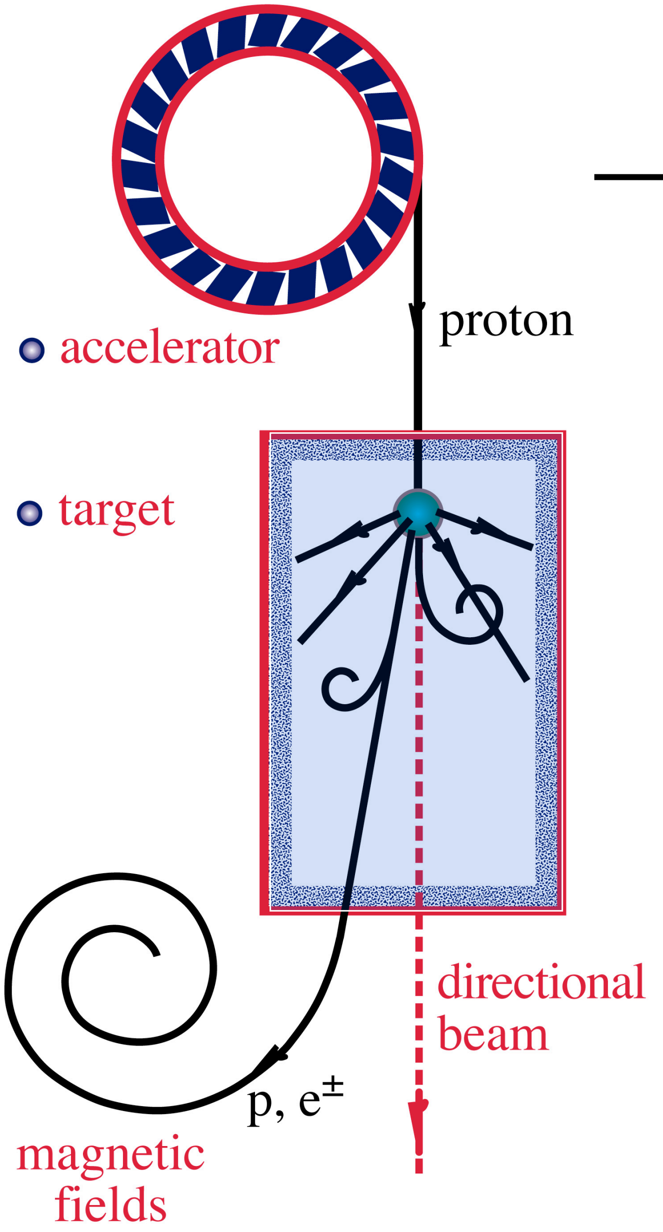
observed energy
density of extragalactic
CRs:

~ 10^{-19} erg / cm^3

neutrinos associated with extragalactic cosmic rays



ν and γ beams : heaven and earth



→ **black hole**

→ **radiation and dust**

$p + \gamma \rightarrow n + \pi^{+}$

~ cosmic ray + neutrino

$\rightarrow p + \pi^{0}$

~ cosmic ray + gamma

Neutrino production: Threshold

$$\gamma + p \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$ → gamma rays

$$\gamma + p \rightarrow \Delta^{+} \rightarrow n + \pi^{+}$$ → neutrinos

IN CM

$$E'_p > \frac{m_\Delta^2 - m_p^2}{4E'_\gamma}$$

$$s = E_{CM}^2 = E_\gamma^2 + E_p^2 - 2 \times (E_p E_\gamma - p_p E_\gamma \cos\theta) = m_p^2 - 2E_p E_\gamma (1 - \cos\theta)$$

For opposite beams cos(theta) = -1. The threshold is calculated for final states at rest:

$$m_\Delta^2 = m_p^2 - 4E_p E_\gamma$$

In the comoving proton frame
and in the observer frame

$$E_p > 1.4 \times 10^{16}\mathrm{eV}\left(\frac{\gamma}{300}\right)^2\left(\frac{1\mathrm{MeV}}{\mathrm{E}_\gamma}\right)$$

a gamma for each energy

$$\mathrm{E}_\nu = 1/4 < \mathrm{X_F} > \mathrm{E_p} \simeq 1/20\ \mathrm{E_p} \simeq 700\ \mathrm{TeV}$$

Fraction of proton energy in pions $< X_F > \sim 0.2$ that is equally distributed in leptons. Flux in neutrinos from fraction of energy into a neutrino and total energy in CRs

$$\frac{dN_\nu}{dE} \sim n_{int} \times \frac{1}{x_\nu} \times \frac{dN_{CR}}{dE}\left(\frac{E_{CR}}{x_\nu}\right)$$

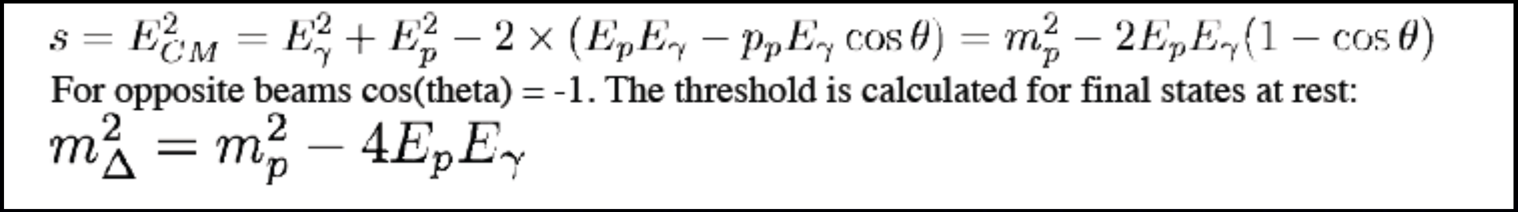
$$x_\nu \sim \frac{1}{4} x_F \sim \frac{1}{20}$$

$$n_{\mathrm{int}} \cong 1\ \textit{for GRB fireball}$$

FRACTION OF PROTON ENERGY IN NEUTRINOS, x_F p -> pion

The neutrino - proton connection

p-gamma interactions (require higher threshold than pp and ambient photons)



$$s = E_{CM}^2 = E_\gamma^2 + E_p^2 - 2 \times (E_p E_\gamma - p_p E_\gamma \cos\theta) = m_p^2 - 2E_p E_\gamma (1 - \cos\theta)$$

For opposite beams cos(theta) = -1. The threshold is calculated for final states at rest:

$$m_\Delta^2 = m_p^2 - 4E_p E_\gamma$$

Isospin conservation: Delta production produces pions that share 1/3 of p energy

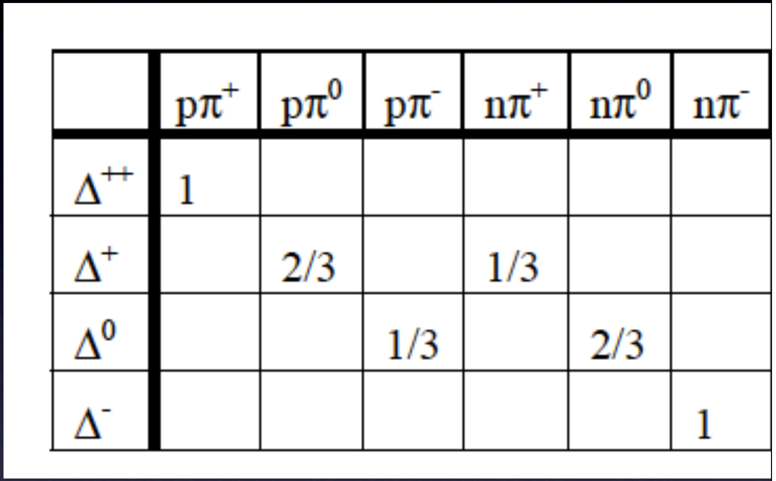
$$p + \gamma \rightarrow \Delta \rightarrow n + \pi^+ \qquad (1/3)$$

$$p + \gamma \rightarrow \Delta \rightarrow p + \pi^0 \qquad (2/3)$$

$$\pi^0 \rightarrow \gamma + \gamma \quad (1/2)$$

$$\pi^+ \rightarrow \nu_\mu + (e + \nu_e + \nu_\mu) \; (1/4)$$

← *muon* →



	$p\pi^+$	$p\pi^0$	$p\pi^-$	$n\pi^+$	$n\pi^0$	$n\pi^-$
Δ^{++}	1					
Δ^+		2/3		1/3		
Δ^0			1/3		2/3	
Δ^-						1

$$x_\nu = \frac{E_\nu}{E_p} = \frac{1}{4} < x_F > = \frac{1}{20}$$

0.2

$$x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{2} < x_F > = \frac{1}{10}$$

$$\frac{dN_\nu}{dE_\nu} = 2 \times \frac{1}{3} \frac{1}{x_\nu} \frac{dN_p}{dE_p}(E_p)$$

$$\frac{dN_\nu}{dE_\gamma} = 2 \times \frac{2}{3} \frac{1}{x_\gamma} \frac{dN_p}{dE_p}(E_p)$$

$$dE_\nu = x_\nu dE_p$$

$$dE_{\nu,\gamma} = x_{\nu,\gamma} dE_p$$

The neutrino - gamma connection

Assuming an E^{-2} spectrum of protons we have for the p spectrum

$$E_p = \frac{E_\nu}{x_\nu} \Rightarrow \frac{dN_p}{dE_p}(E_p) \propto E_\nu^{-2} x_\nu^2 \Rightarrow$$

$$\frac{dN_\nu}{dx_\nu} \propto 2 \times \frac{1}{3} \times \frac{1}{20} E_\nu^{-2}$$

$$\frac{dN_\gamma}{dx_\gamma} \propto 2 \times \frac{2}{3} \times \frac{1}{10} E_\gamma^{-2}$$

$$\frac{dN_\nu}{dE} \sim \frac{1}{4} \frac{dN_\gamma}{dE}$$

factor of 8 between gamma and nu fluxes (no oscillations)

Kelner and Aharonian for a full calculation http://prd.aps.org/abstract/PRD/v78/i3/e034013

Galactic SNR and pp

In Galactic SN shocks CRs interact with the H in the Galactic disk (pp interactions, lower threshold than p-gamma)

$$p + p \rightarrow \pi^{+} : \pi^{-} : \pi^{0}$$

$$E_{p,th} = \frac{(2m_p+m_\pi)^2-2m_p^2}{2m_p} \sim 1.23\ \mathrm{GeV}$$

if all muons decay and for E^{-2} p spectrum:

2 pions x 1/3

$$\frac{dN_\nu}{dE} \sim 2 \times \frac{2}{3} \times \frac{1}{20}$$

$$\frac{dN_\gamma}{dE} \sim 2 \times \frac{1}{3} \times \frac{1}{10}$$

Assume always:

$$x_\nu = \frac{E_\nu}{E_p} = \frac{1}{4} < x_F >= \frac{1}{20}$$

0.2

$$x_\gamma = \frac{E_\gamma}{E_p} = \frac{1}{2} < x_F >= \frac{1}{10}$$

Ignoring oscillations there is a factor of about 1 between the gamma and neutrino flux.

For a full calculation see: http://arxiv.org/pdf/astro-ph/0606058for pp

relation between pionic gamma rays and neutrinos robust (after oscillations)

$$\frac{dN_\nu}{dE} = \frac{1}{2}\frac{dN_\gamma}{dE} \quad for\ p + p$$

$$\frac{dN_\nu}{dE} = \frac{1}{8}\frac{dN_\gamma}{dE} \quad for\ \gamma + p$$

E^{-2} *assumed*

NEUTRINO OSCILLATION REMINDER

Conversion probability (3 neutrino flavors and in vacuum):

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - \sum_{j\neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \left(1 - e^{-i\Delta E_{jk} L}\right)$$

Kayser's lectures

Where the mixing matrix is:

solar U_{e1}, U_{e2} ↔ θ_{12} CHOOZ U_{e3} ↔ θ_{13}

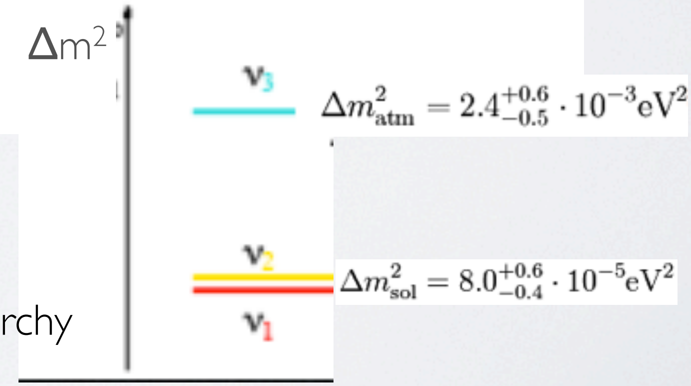
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

atmospheric U_{e3} ↔ θ_{13} $U_{\mu 3}$, $U_{\tau 3}$ ↔ θ_{23}

$$s_{ij} \equiv \sin\theta_{ij},\ c_{ij} \equiv \cos\theta_{ij}.$$

Observed values of oscillation parameters

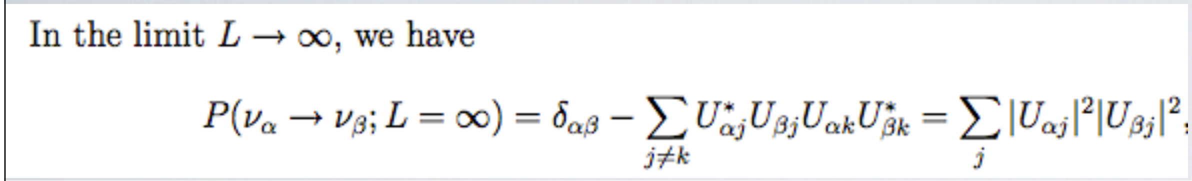
- $\sin^2(\theta_{13}) < 0.032$ at 95% confidence level ($\theta_{13} < 10.3°$) [4] CHOOZ
- $\tan^2(\theta_{12}) = 0.45^{+0.09}_{-0.07}$. This corresponds to $\theta_{12} \equiv \theta_{\rm sol} = 33.9°^{+2.4°}_{-2.2°}$ ("sol" stands for solar) [6]
- $\sin^2(2\theta_{23}) = 1^{+0}_{-0.1}$, corresponding to $\theta_{23} \equiv \theta_{\rm atm} = 45 \pm 7°$ ("atm" for atmospheric)[7]
- $\Delta m^2_{21} \equiv \Delta m^2_{\rm sol} = 8.0^{+0.6}_{-0.4} \cdot 10^{-5}{\rm eV}^2$ [6]
- $|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{\rm atm} = 2.4^{+0.6}_{-0.5} \cdot 10^{-3}{\rm eV}^2$[7]



direct hierarchy

inverted hierarchy

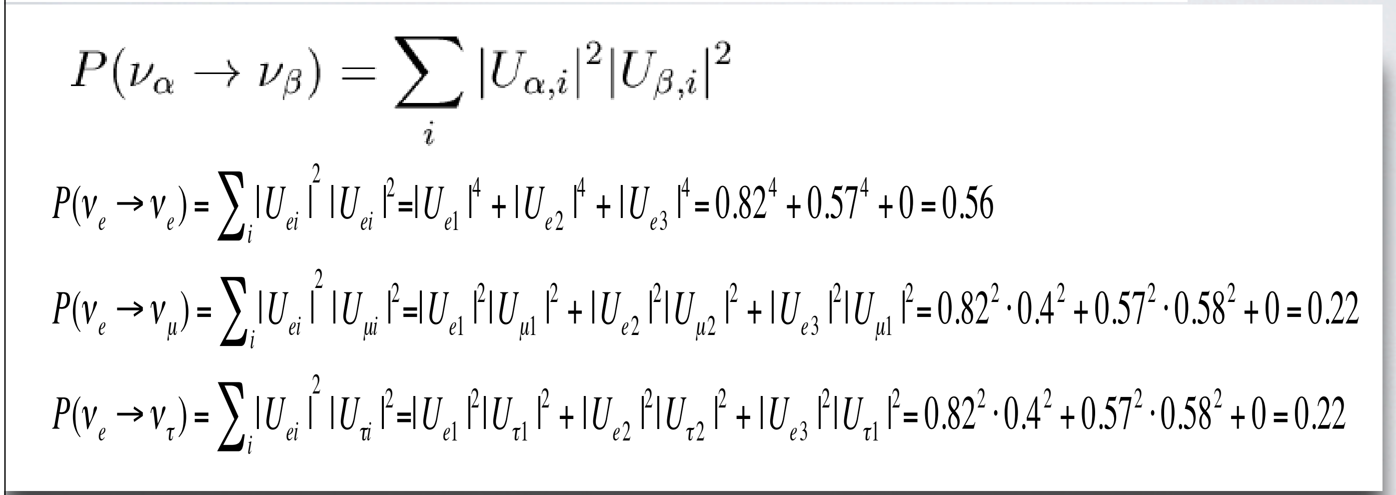
ASTROPHYSICAL NEUTRINO OSCILLATIONS



In the limit $L \to \infty$, we have

$$P(\nu_\alpha \to \nu_\beta; L=\infty) = \delta_{\alpha\beta} - \sum_{j\neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2,$$

average over rapid oscillations



$$P(\nu_\alpha \to \nu_\beta) = \sum_i |U_{\alpha,i}|^2 |U_{\beta,i}|^2$$

$$P(\nu_e \to \nu_e) = \sum_i |U_{ei}|^2 |U_{ei}|^2 = |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 = 0.82^4 + 0.57^4 + 0 = 0.56$$

$$P(\nu_e \to \nu_\mu) = \sum_i |U_{ei}|^2 |U_{\mu i}|^2 = |U_{e1}|^2 |U_{\mu 1}|^2 + |U_{e2}|^2 |U_{\mu 2}|^2 + |U_{e3}|^2 |U_{\mu 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$$P(\nu_e \to \nu_\tau) = \sum_i |U_{ei}|^2 |U_{\tau i}|^2 = |U_{e1}|^2 |U_{\tau 1}|^2 + |U_{e2}|^2 |U_{\tau 2}|^2 + |U_{e3}|^2 |U_{\tau 1}|^2 = 0.82^2 \cdot 0.4^2 + 0.57^2 \cdot 0.58^2 + 0 = 0.22$$

$\nu_\alpha \backslash \nu_\beta$	ν_e	ν_μ	ν_τ
ν_e	60%	20%	20%
ν_μ	20%	40%	40%
ν_τ	20%	40%	40%

At source: $\nu_e : \nu_\mu : \nu_\tau \sim 1:2:0$

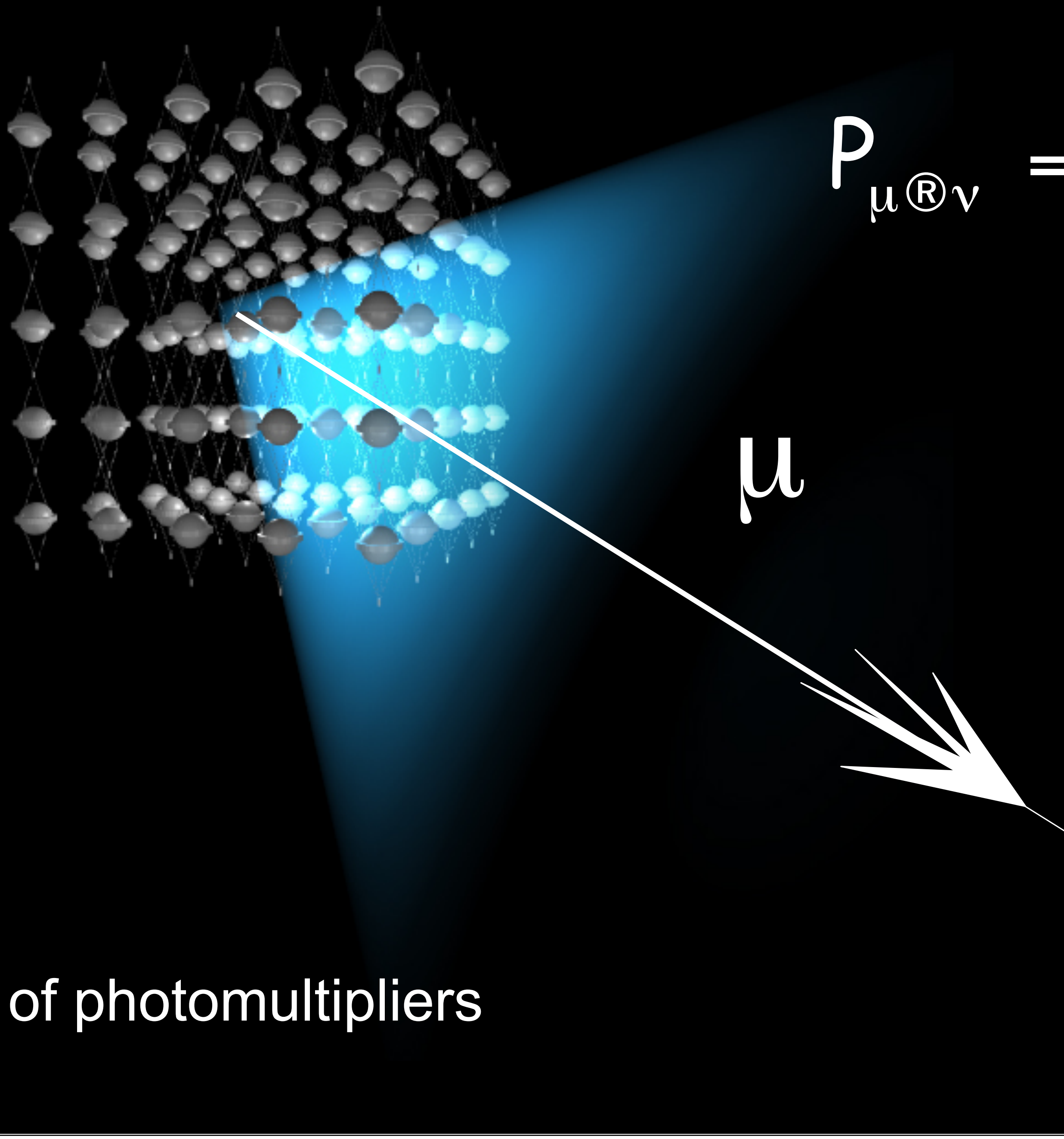
60% of ν_e survive and 2x20% come from 2xν_μ = 100%
2x40%=80% of 2xν_μ survive and 20% come from ν_e= 100%
20% of ν_τ come from ν_e and 2 x 40% from ν_μ= 100%

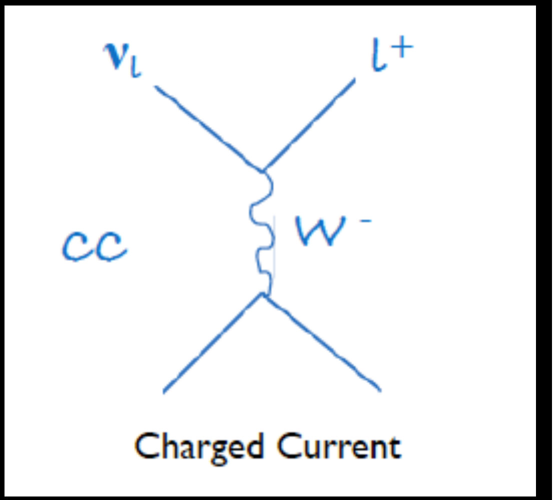
At Earth: 1: 1: 1

http://arXiv.org/pdf/hep-ph/0005104

- shielded and optically transparent medium

$$P_{\mu \circledR \nu} = \frac{\lambda_\mu}{\lambda_\nu} = nR_\mu \sigma_\nu$$





- lattice of photomultipliers

Effective area

$$N_\mu = \int A^\nu_{eff}(E_\nu, \theta_\nu, \phi_\nu)\, \frac{d\Phi_\nu}{dE_\nu\, d\Omega_\nu}\, dE_\nu\, d\Omega_\nu$$

Neutrinos flux model

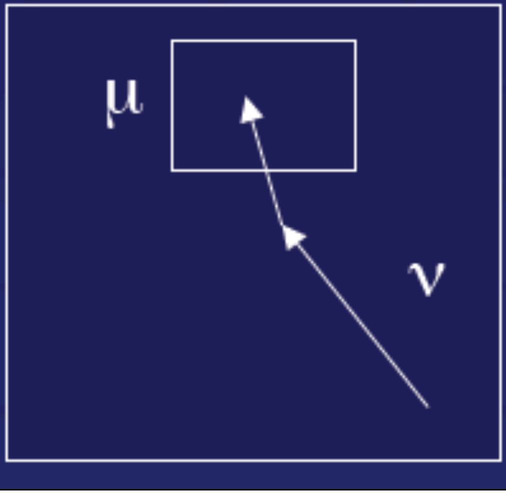
Target nucleon density

Neutrino-nucleon cross-section

$$A^\nu_{eff} = V_{gen} \times \frac{N_{xxx}(E_\nu, \Theta_\nu, \phi_\nu)}{N_{gen}(E_\nu, \Theta_\nu, \phi_\nu)} \times (\rho\ N_A)\ \sigma(E_\nu) \times P_{earth}(E_\nu, \Theta_\nu)$$

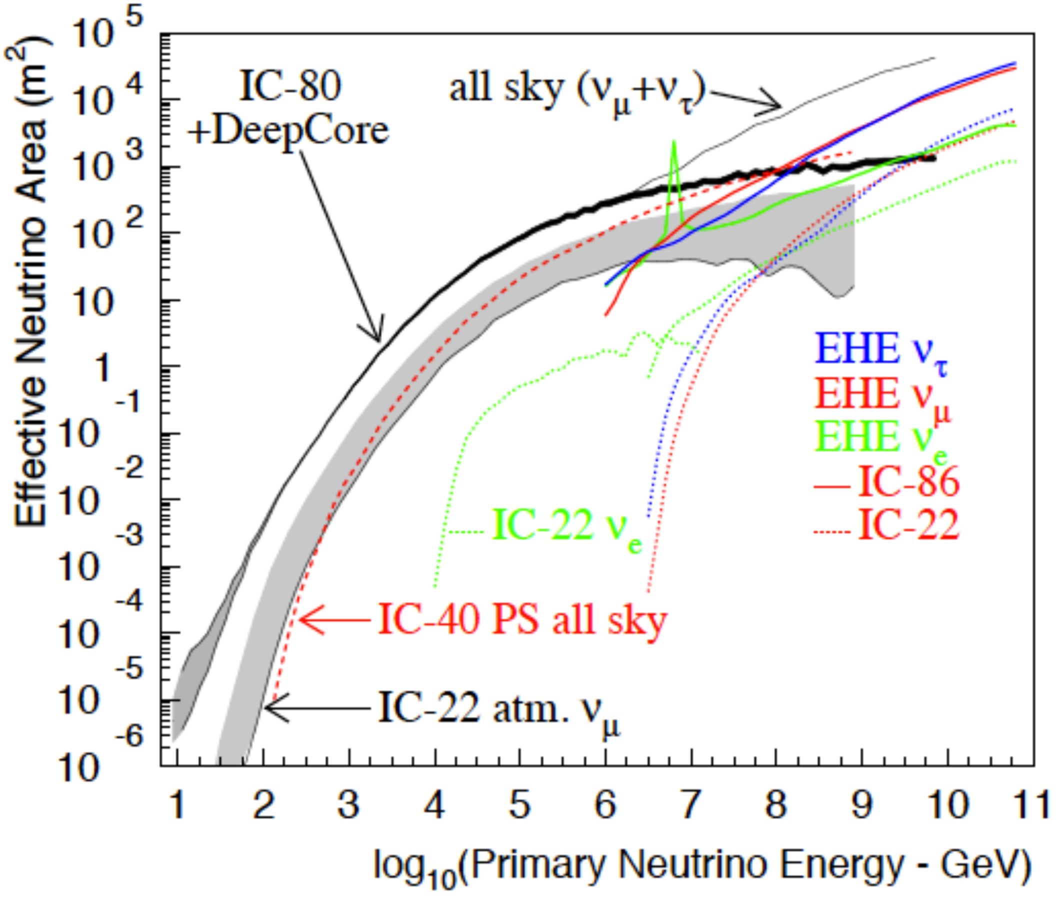
$$P_{earth}(E_\nu, \Theta_\nu) = e^{-N_A\ \sigma(E_\nu) \int \rho\, dl}$$

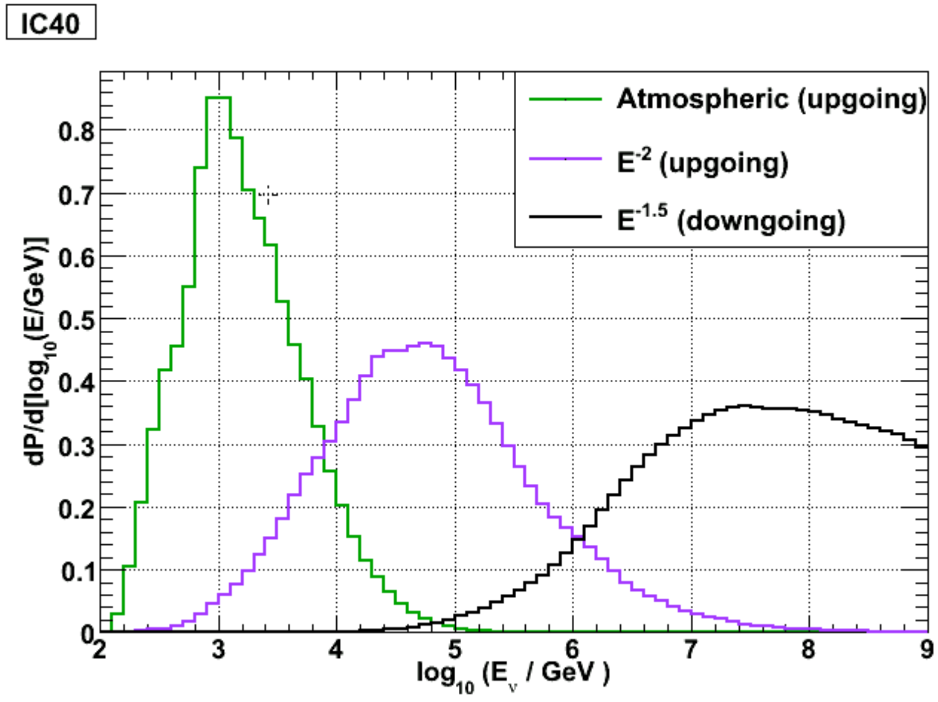
Shadowing effec



V_{gen} = generation volume of all neutrino interaction that potentially would produce the signal in the detector

Effective area (useful for rates)



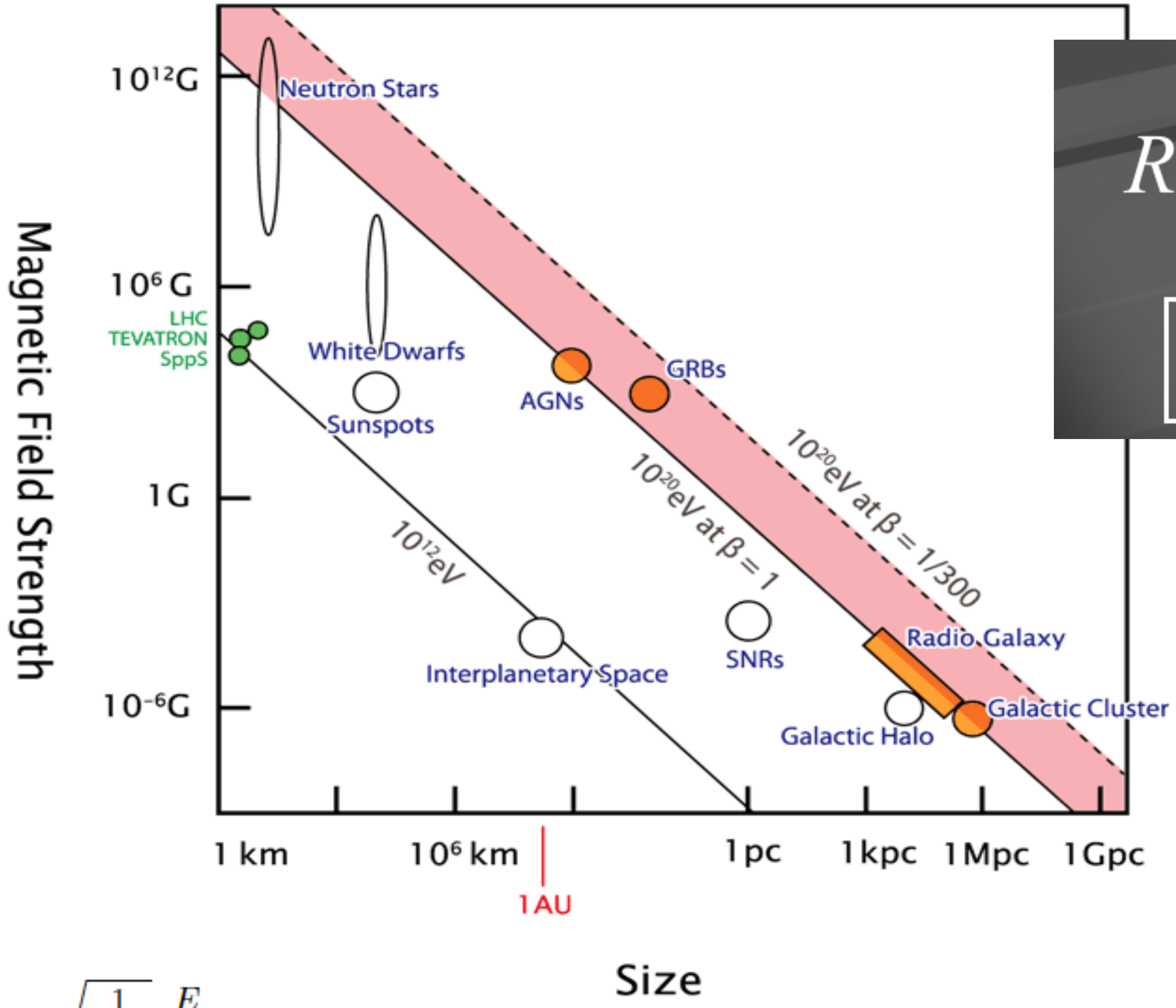


you get it from the generation volume and it is analysis dependent

$$A^{\nu}_{eff}(E_\nu,\theta_\nu) = V_{eff}(E_\nu,\theta_\nu)\times(\rho N_A)\times\sigma(E_\nu)\times P_{Earth}(E_\nu,\theta_\nu \qquad V_{eff}(E_\nu,\theta_\nu) = \frac{N_{selected}(E_\nu,\theta_\nu)}{N_{generated}(E_\nu,\theta_\nu)}\times V_{generation}$$

you use it to get the event rate $$\int_{E_{\nu,min}}^{E_{\nu,max}} dE\, A^{\nu}_{eff}(E_\nu,\delta_{source})\frac{dN}{dE}dE_\nu$$

ACCELERATION: HILLAS' PLOT



$$R_{gyro}\left(=\frac{E}{vqB}\right)\leq R$$

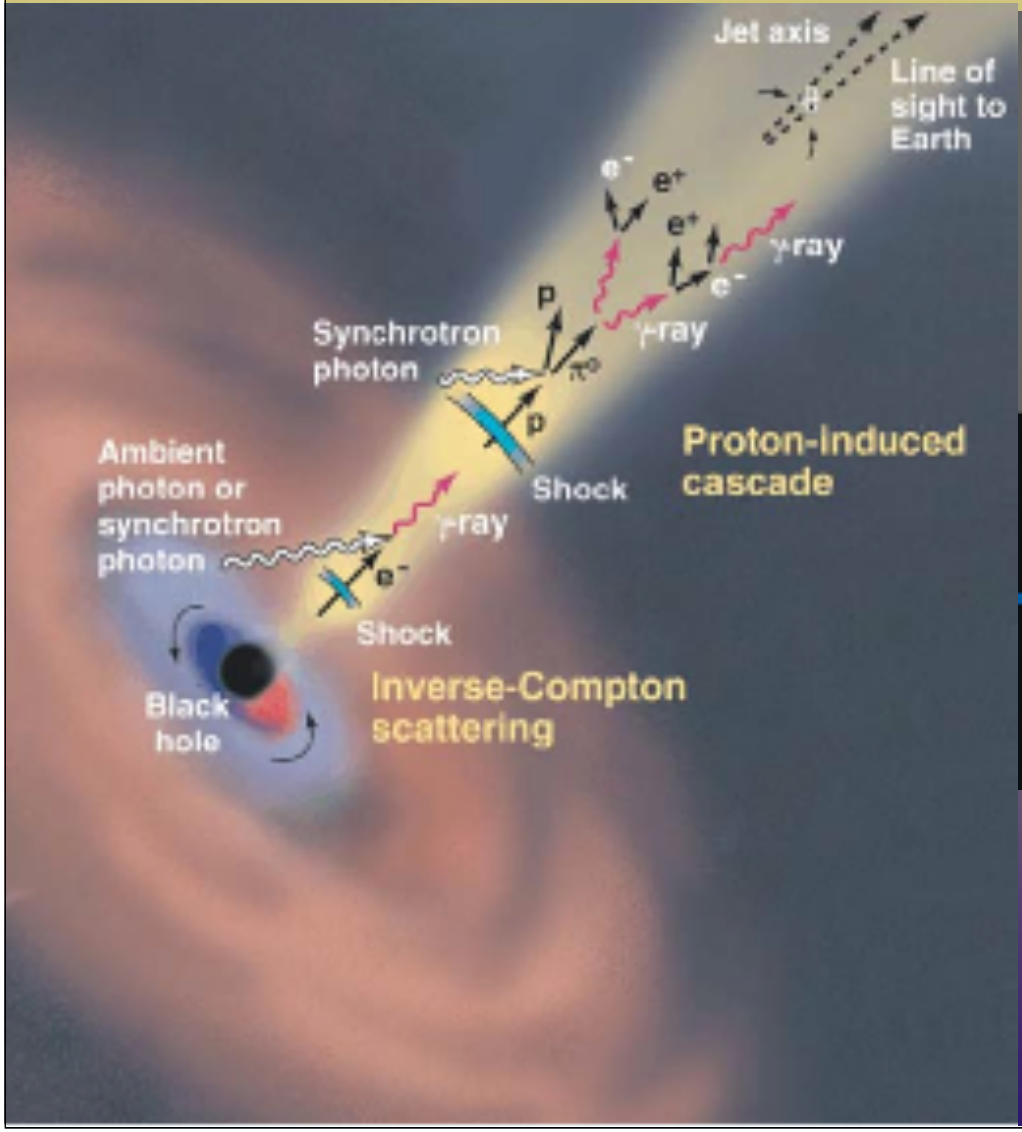
$$\boxed{E\leq v\,qBR}$$

$$\begin{aligned} r_L &= \sqrt{\frac{1}{4\pi\alpha}}\frac{E}{ZeB} \\ &= \frac{1.1}{Z}\left(\frac{E}{\mathrm{EeV}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1}\mathrm{kpc}\,. \end{aligned}$$

$$E_{\max}\simeq Z\left(\frac{B}{\mu\mathrm{G}}\right)\left(\frac{R_{\mathrm{source}}}{\mathrm{kpc}}\right)\times 10^{9}\ \mathrm{GeV}\,.$$

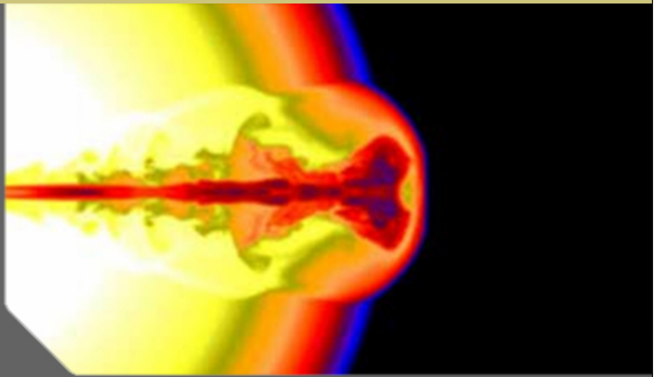
Extragalactic sources

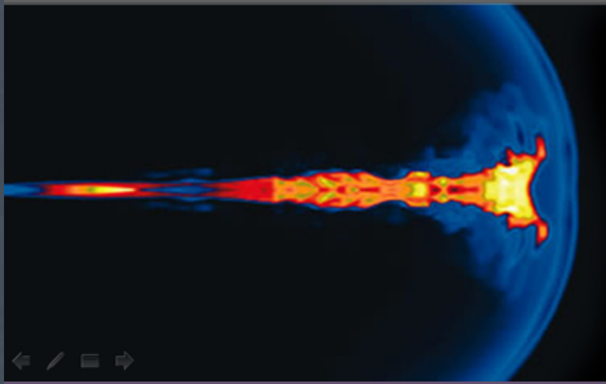
AGN’s



gamma ray bursts

collapse of massive star produces a spinning black hole (long bursts)



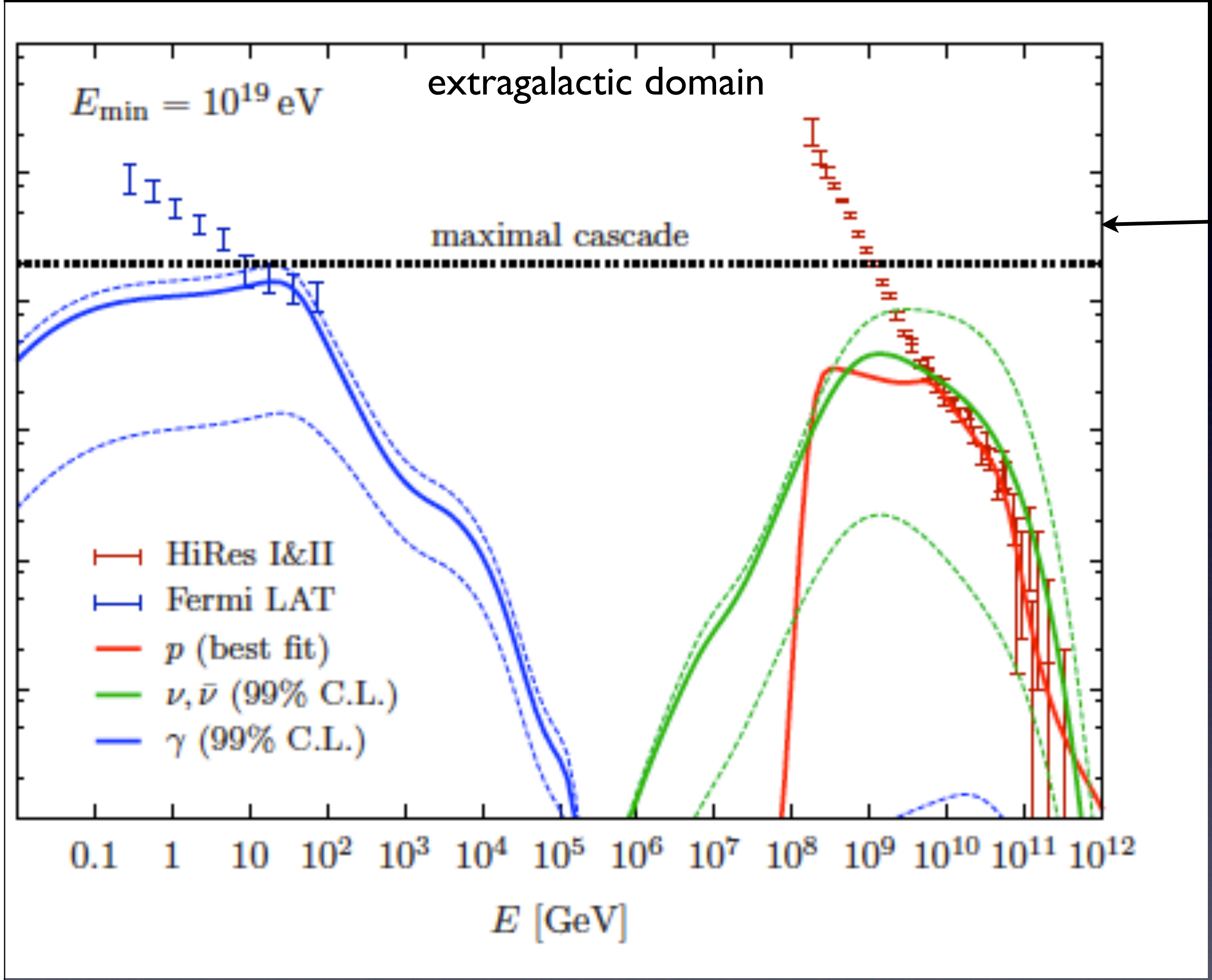


shocks produced in the outflow of the spinning black hole: electrons and protons ?

Associated to SN

compact binary mergers (short bursts)

Fermi-LAT extragalactic photon background - UHECR - neutrino connection



gamma flux in GeV-TeV saturating the total EM radiation energy density from proton energy losses

normalization to Fermi diffuse flux is tricky because gamma cascading and galactic point source flux subtraction.

$p + \gamma \rightarrow n + \pi^+$

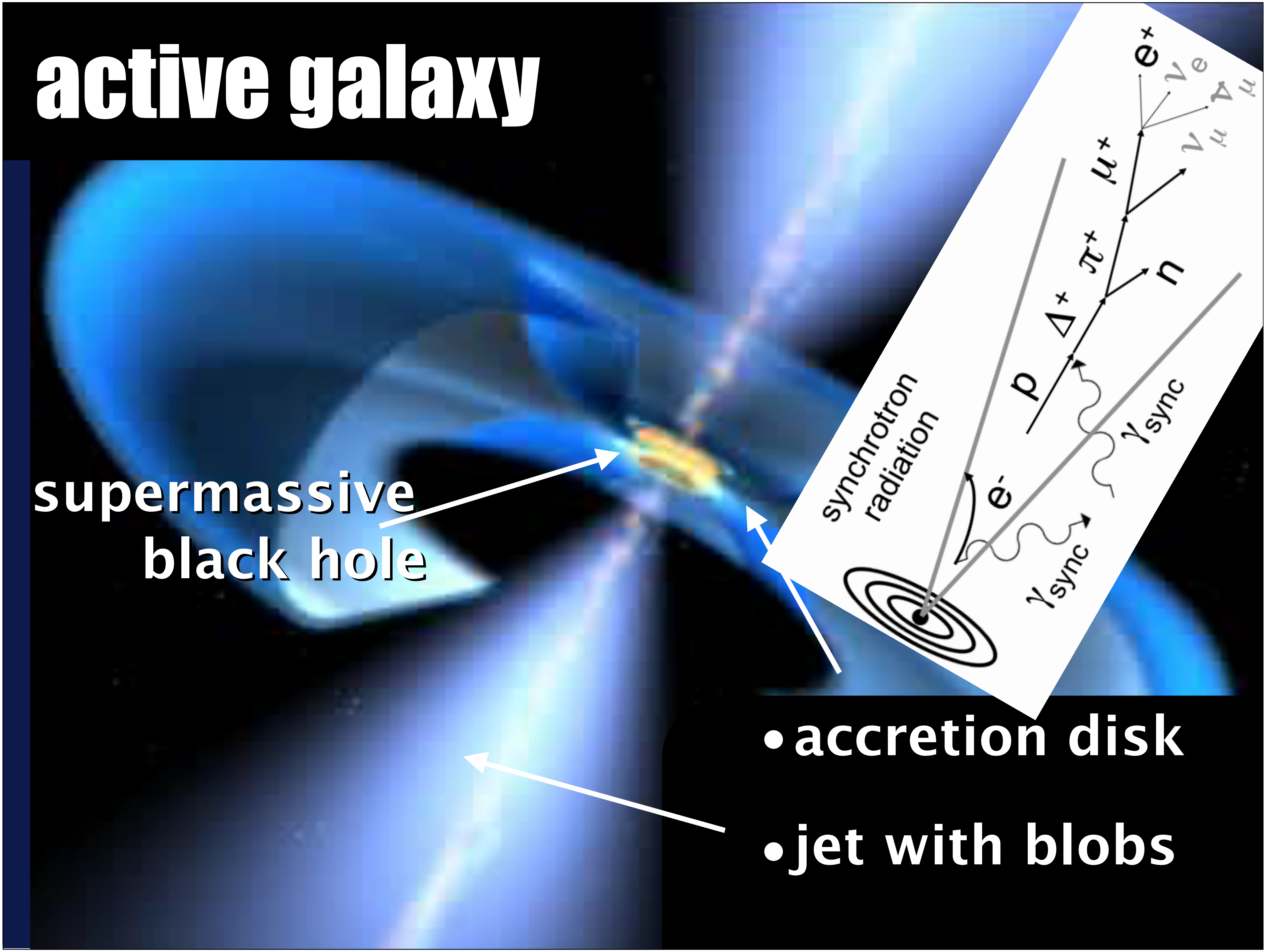
$\rightarrow p + \pi^0$

~ cosmic ray + neutrino

~ cosmic ray + gamma

Ahlers et al, arXiv:1005.2620

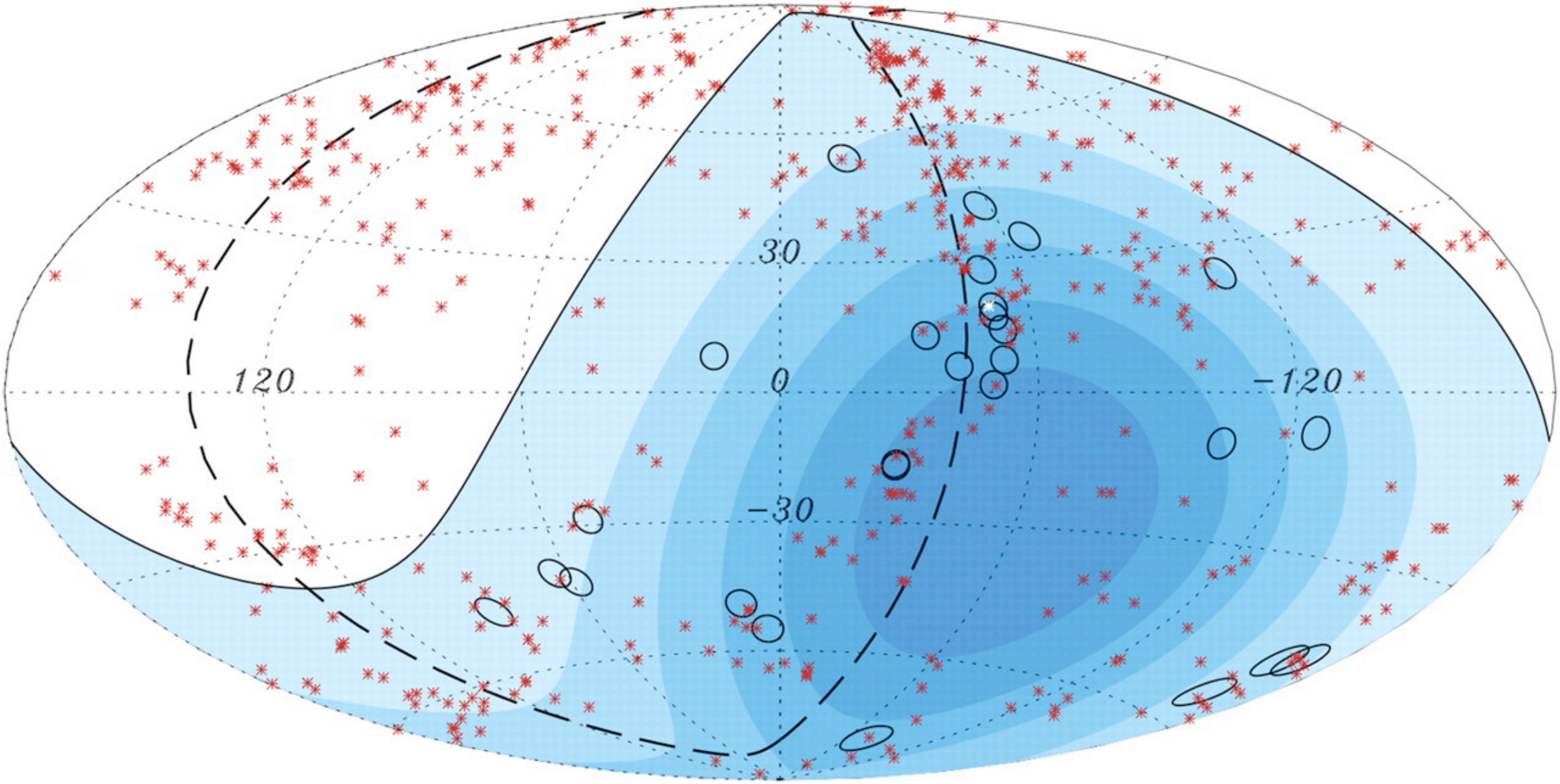
active galaxy



supermassive
black hole

- accretion disk
- jet with blobs

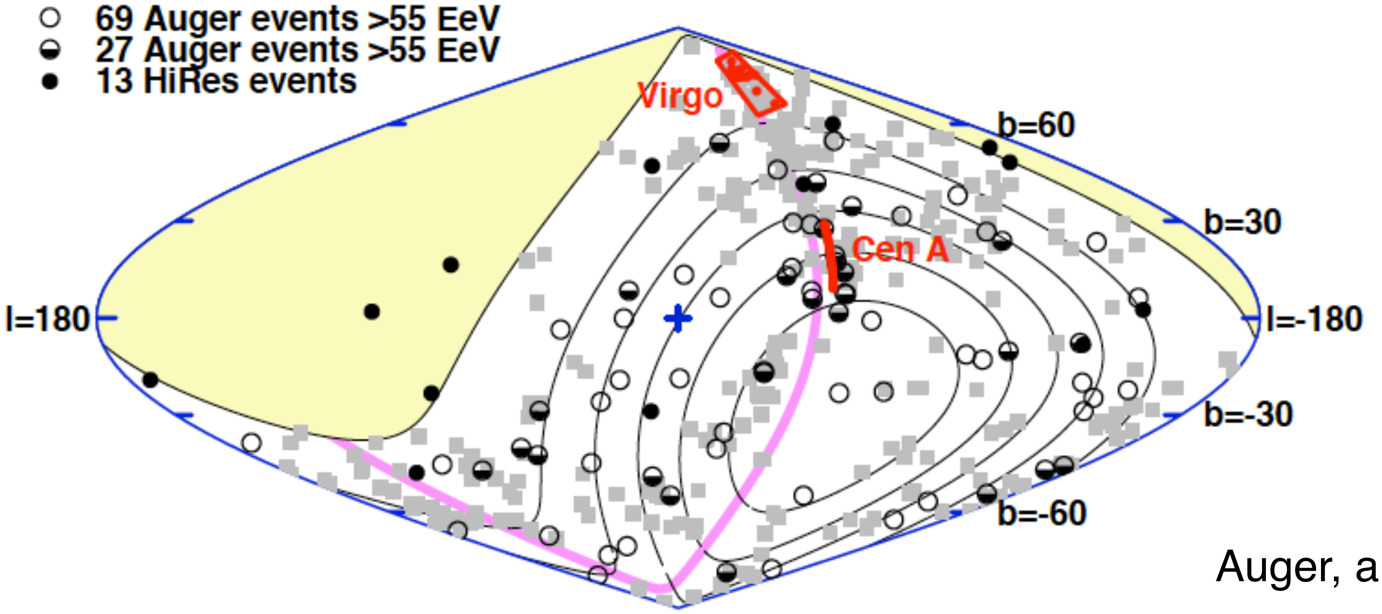
Proton astronomy?



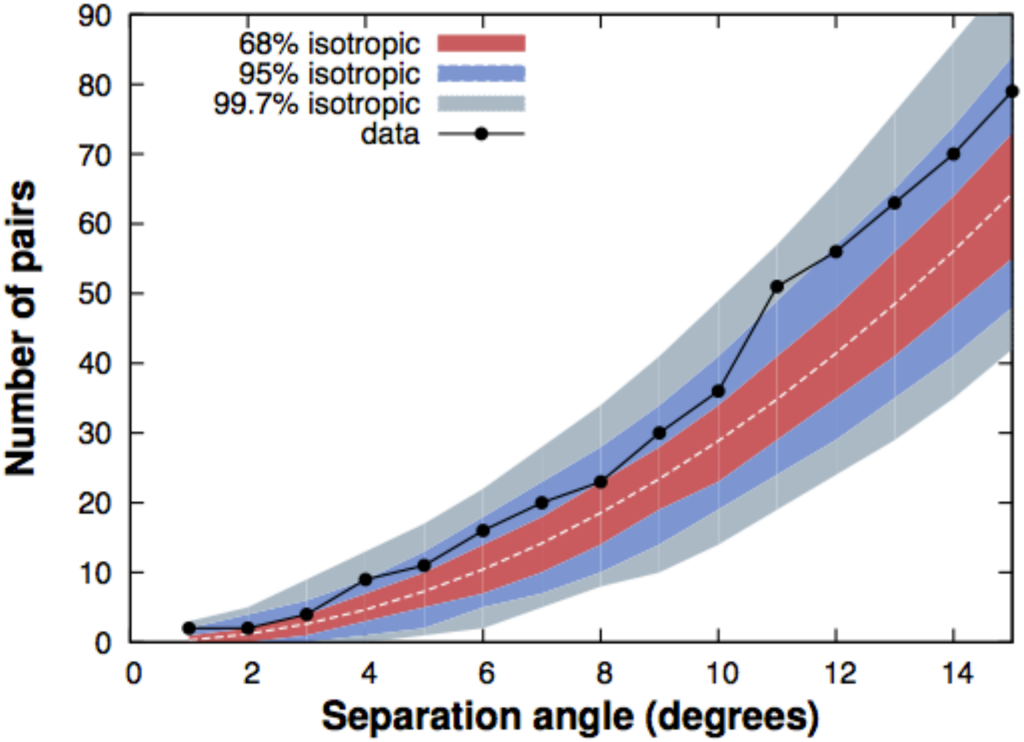
$$\theta \cong \frac{d}{R_{gyro}} = \frac{dB}{E}$$

$$\frac{\theta}{1^o} \sim \frac{(d/10\mathrm{Mpc})(\mathrm{B}/10^{-9}\mathrm{Gauss}}{E/3\times10^{20}\mathrm{eV}}$$

The sources revealed: AGNs?



Auger, arXiv:1009.1855



Auger: correlating fraction of E>55 EeV events with AGN close-by catalogue decreased from 69% to 37% (21% expected to occur by chance for an isotropic flux).

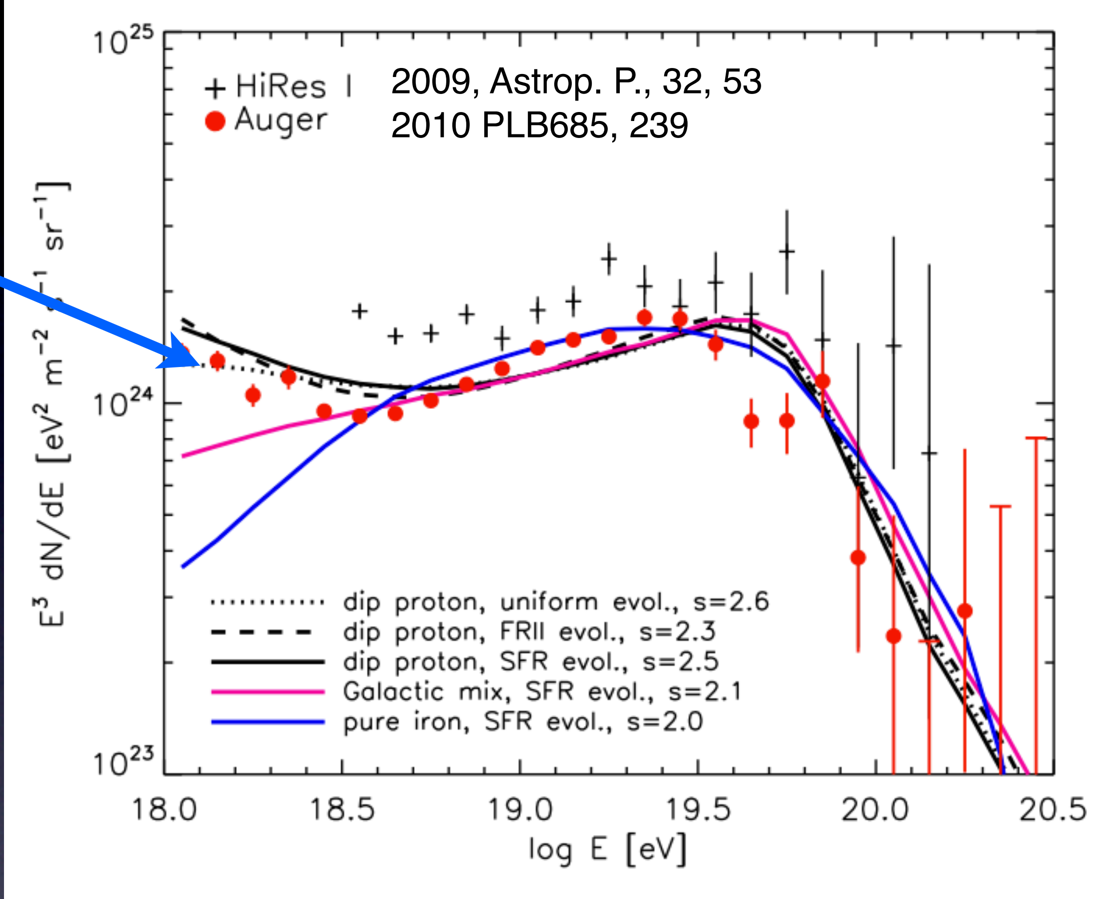
18% of 69 events are inside 18^{o} from Cen A but no event from M87.

Autocorrelation function: largest deviation from isotropic distribution at 11^{o}.

For an isotropic distribution 1.3% pairs of the 69 events have 51 or more pairs inside 11^{o}.

The lack of knowledge of B-fields prevents to establish if UHECR astronomy is possible.

GZK-cut off proved



2009, Astrop. P., 32, 53
2010 PLB685, 239

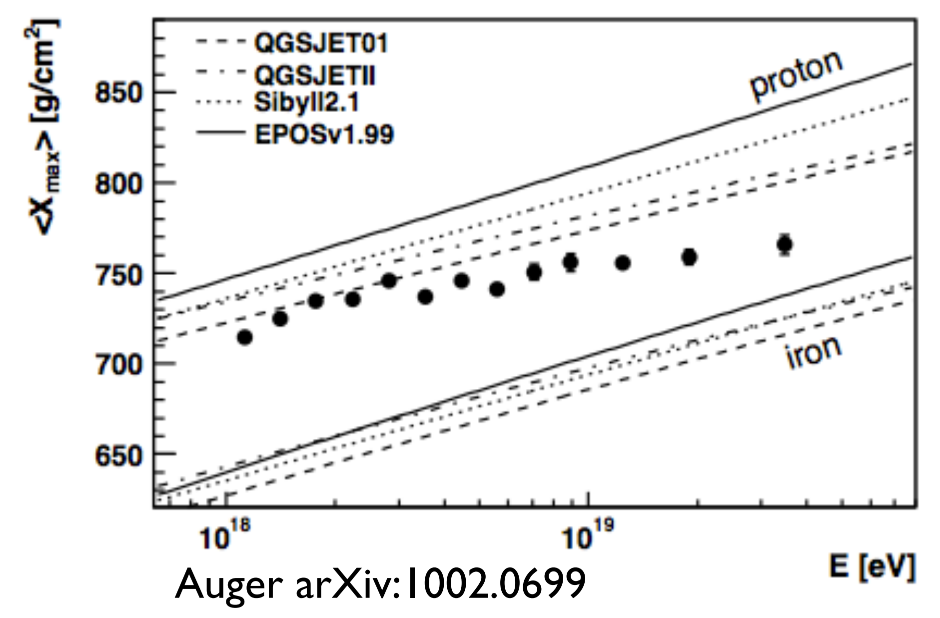
Where is the galactic - extra-galactic transition?

Nature trick: spectrum shows same feature for p and Fe.
While jets can easily accelerate Fe ($E_{max} \propto Z$), Fe would not survive photo-disintegrations when injected in extra-galactic accelerators such as a GRB fireball.

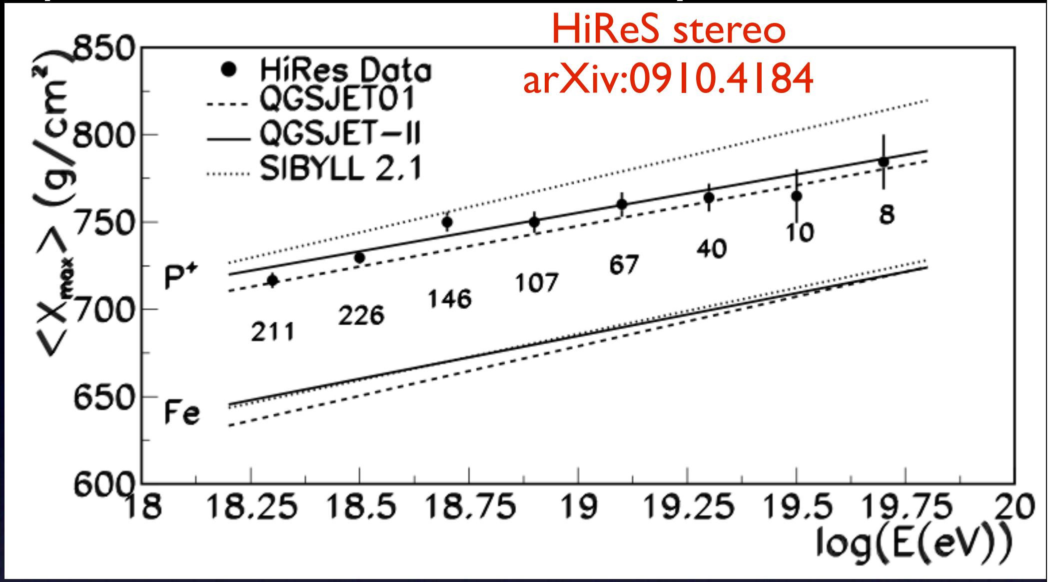
Kotera, Olinto's review arXiv: 1101.4256

Heavy/light composition?

In a heavy composition scenario anisotropies would be washed out by B-fields.

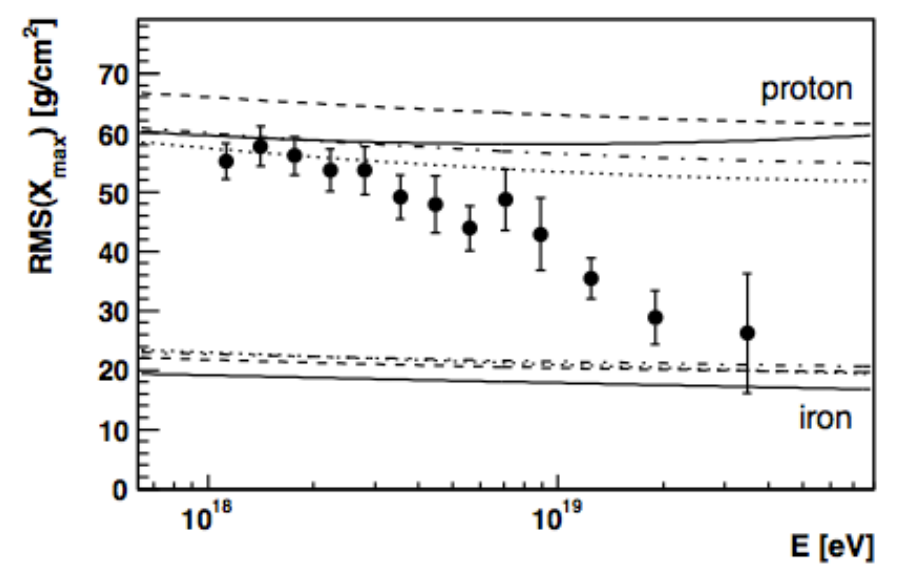


Auger arXiv:1002.0699



HiReS stereo
arXiv:0910.4184

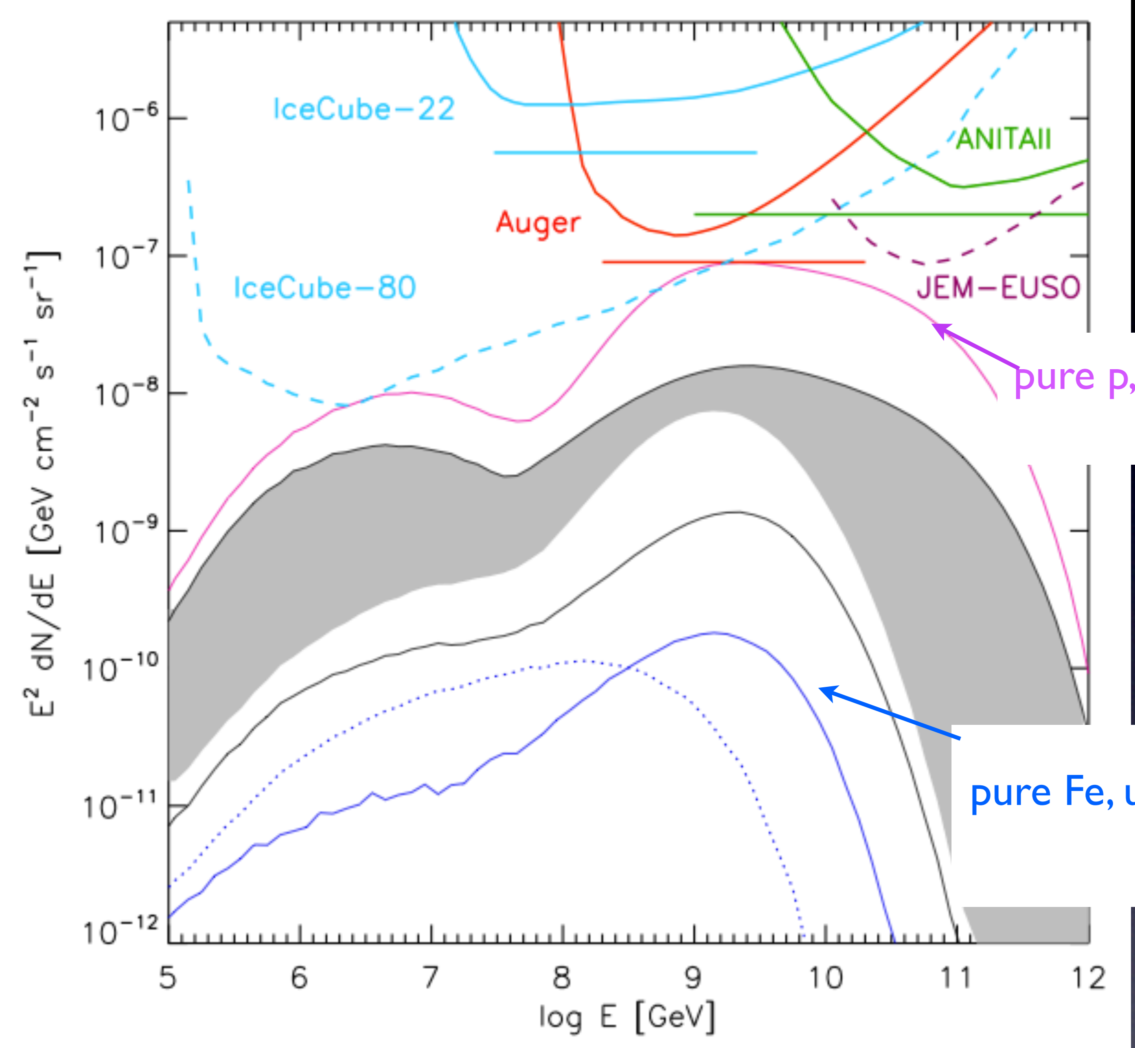
HiReS and Auger X_{max} are not directly comparable due to fiducial cuts.



An evidence of neutrinos in coincidence with UHECR would indicate that the extra-galactic sources are not GRBs because p take much longer than neutrinos. It would also indicate a p-dominated composition.

IceCube: no correlation evidence in 40-strings, 40+59 strings to be presented at ICRC 2011

Fluxes of UHECR neutrinos



pure p, strong evolution, E_{max} = 3
10^{21} eV

pure Fe, uniform evolution, E_{max} =
Z x 100 EeV

The diffuse extragalactic background measured by Fermi can be used as a constraint accounting for photon cascading.

UHECR neutrino fluxes depend on:
1) the transition energy between galactic and extra-galactic CRs
2) Emax
3) injection spectrum and source evolution

Kotera, Olinto's review arXiv:
1101.4256

Useful references

Halzen and Hooper, Rept.Prog.Phys.65:1025-1078,2002
http://arxiv.org/abs/astro-ph/0204527v2
Anchordoqui & TM, Annual Review of Nuclear and Particle Science (2009) 60
Anchordoqui, arXiv:1104.0509v1
J. Becker, High-energy neutrinos in the context of multimessenger astrophysics
Neutrino unbound
Textbooks:
T.K. Gaisser book on CRs
Longair, High Energy Astrophysics
Berezinski, Neutrino Astrophysics 1995