Open problems in Particle Astrophysics

Questions to be addressed in talks at RICAP 2014

Tom Gaisser
University of Delaware
Noto 30-9-2014

Multi-messenger astrophysics

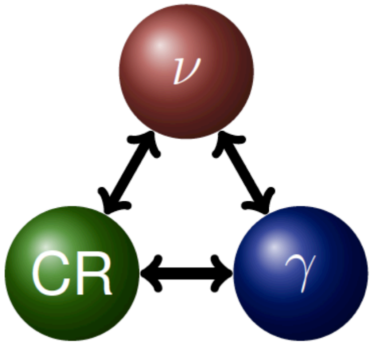
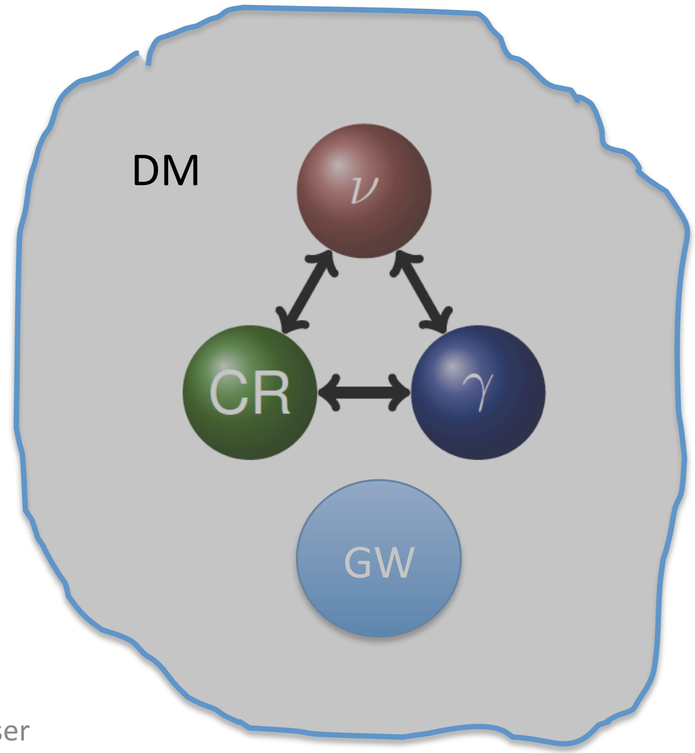


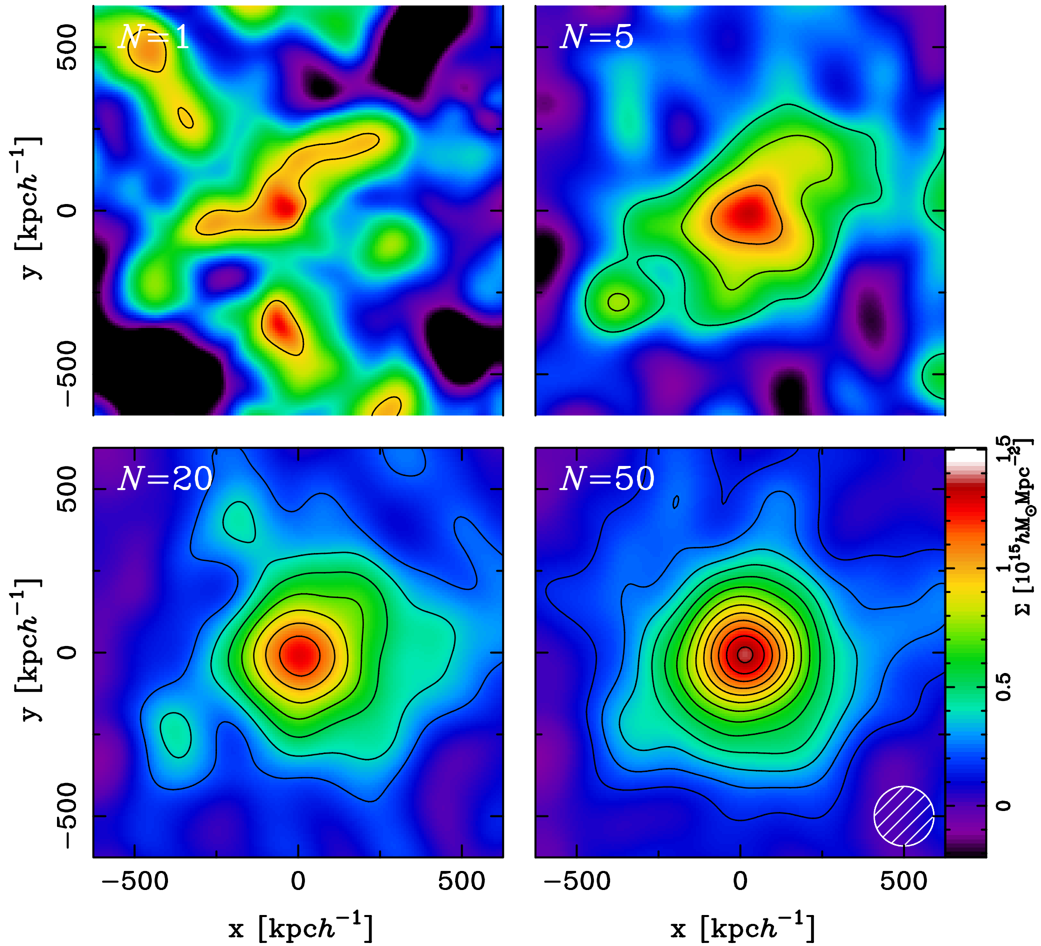
Diagram from Markus Ahlers

Add Gravitational Waves
and dark matter for RICAP



Dark matter in clusters of galaxies

(for example)

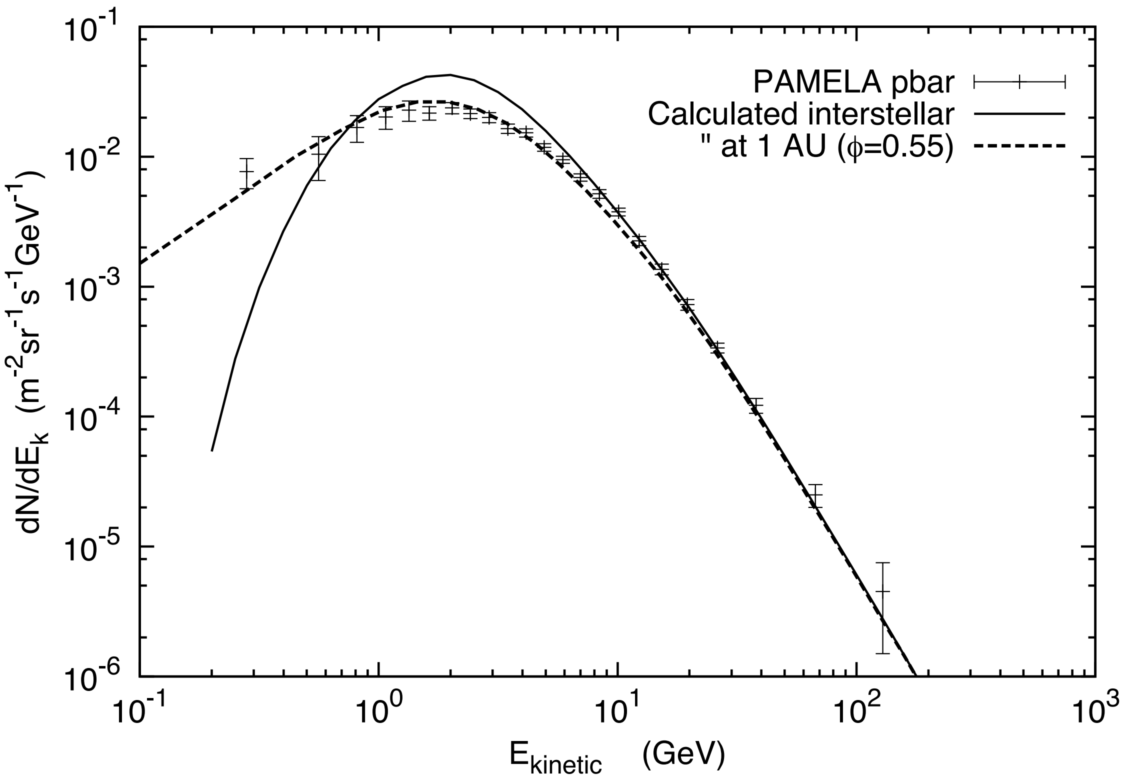


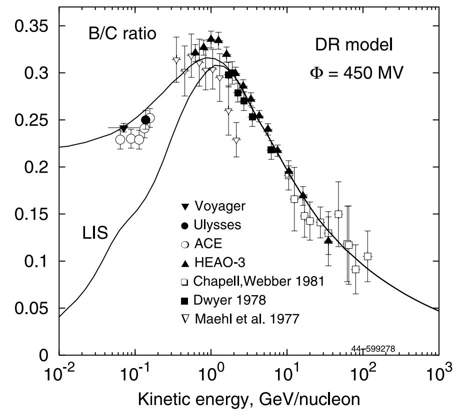
Dark matter distribution in clusters of galaxies measured by weak lensing of background galaxies by SUBARU

N. Okabe et al., Ap.J.Letters 7609:L35 (2013)

Dark Matter

- It can be mapped, but what is it?
- Probably not leptons because:
  - Unnaturally large enhancement needed
  - Positron excess has other explanations
  - Antiprotons are consistent with standard propagation fixed to B/C

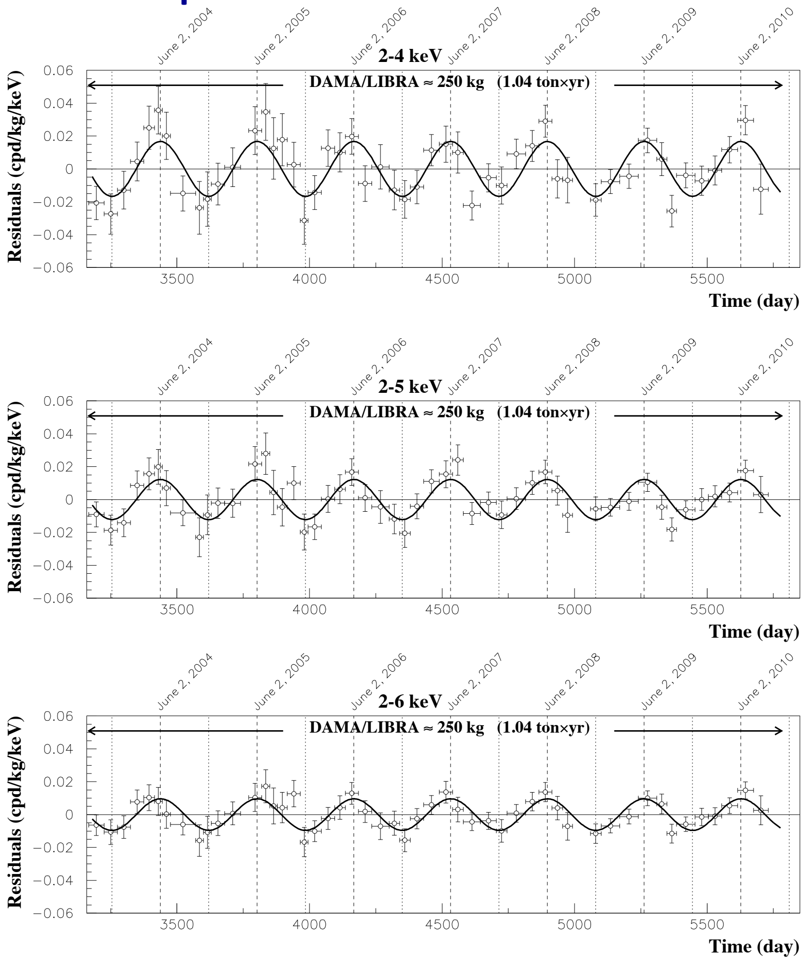




B/C Fig: Ptuskin, APP 39 (2012)

DAMA/LIBRA and DM-ice

DAMA peak rates are in June as expected for motion around Sun



DM-Ice: a scintillator experiment like DAMA planned for South Pole. Seasonal backgrounds peak in January. DM flux peaks in June. A positive result at South Pole would be a spectacular confirmation of DAMA

DAMA/LIBRA, arXiv:1308.5109v2

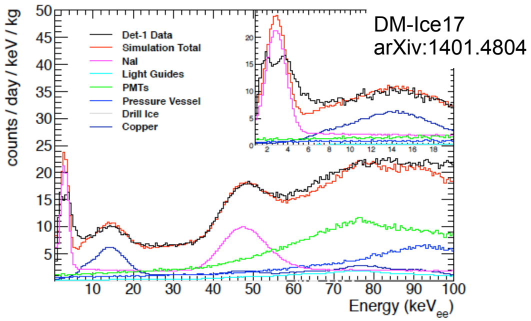
Phased Program for DM-Ice

Reina Maruyama (24/04/2014)

- low-background NaI(Tl) target
- moveable detector array
- access to both Northern & Southern Hemispheres

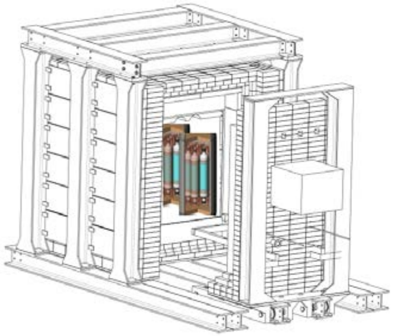
A Phased Experimental Program

DM-Ice17

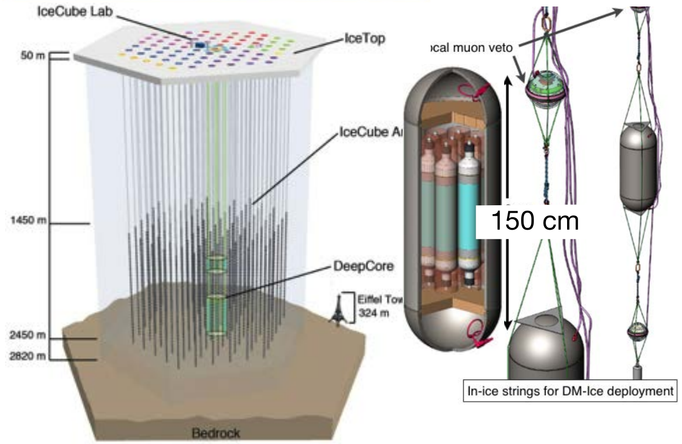
Test Detector at South Pole
17 kg of NaI(Tl) at 2450m depth at South Pole

DM-Ice 250 North



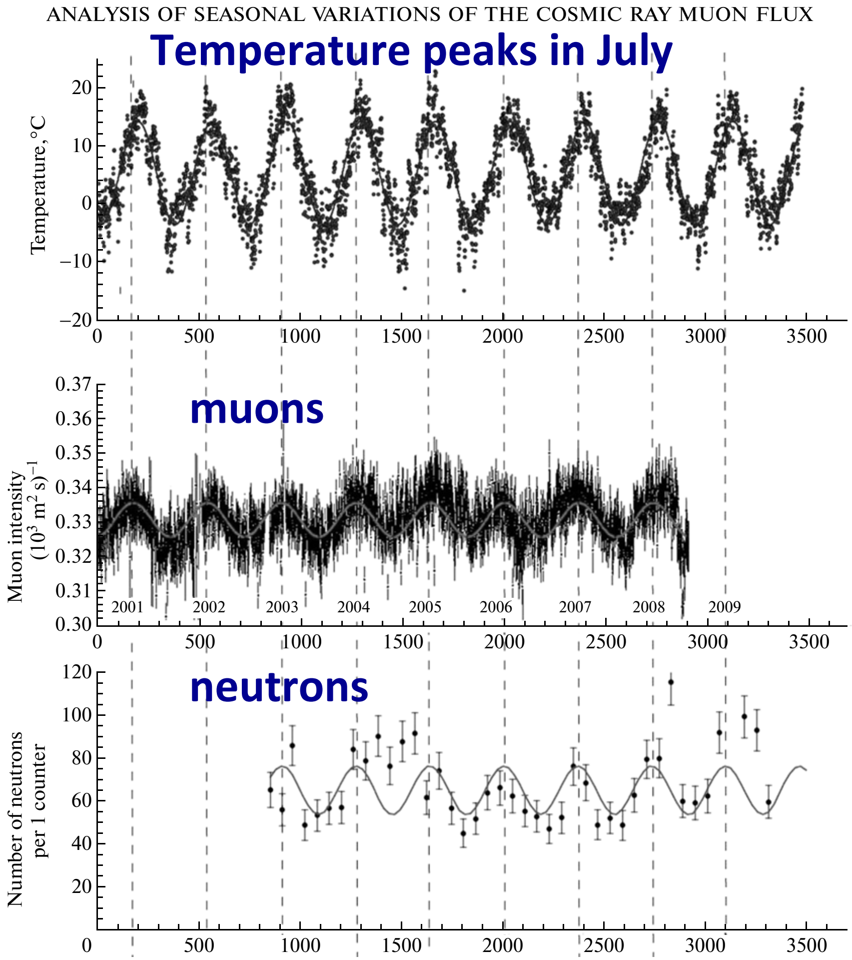
Modulation Search in Northern Hemisphere
portable 250 kg NaI(Tl) detector, first deployment in the Northern Hemisphere

DM-Ice 250 South

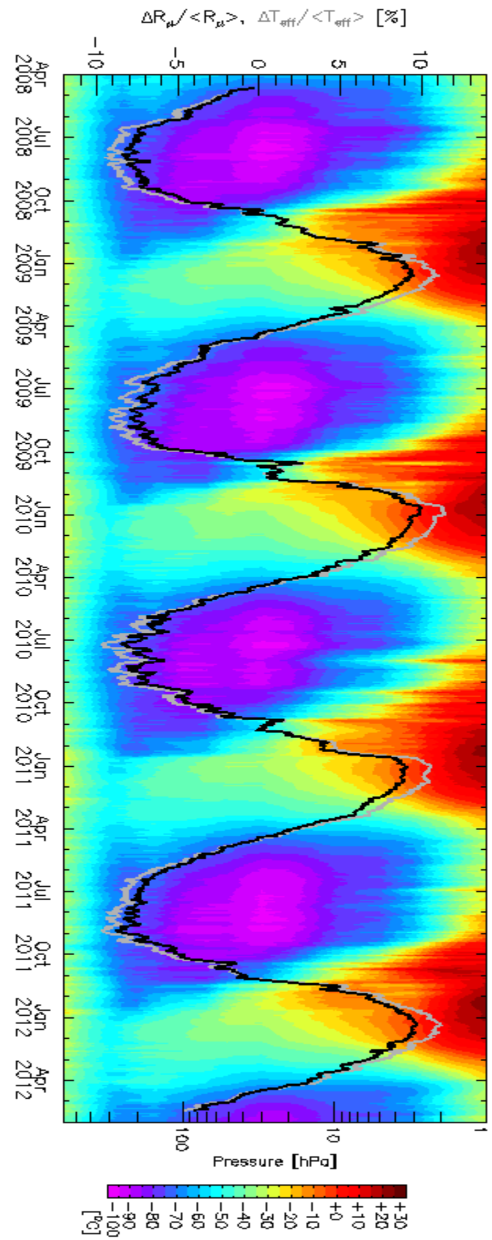


Modulation Search at the South Pole
if modulation seen in North & ice drilling becomes available

Seasonal variations of μ

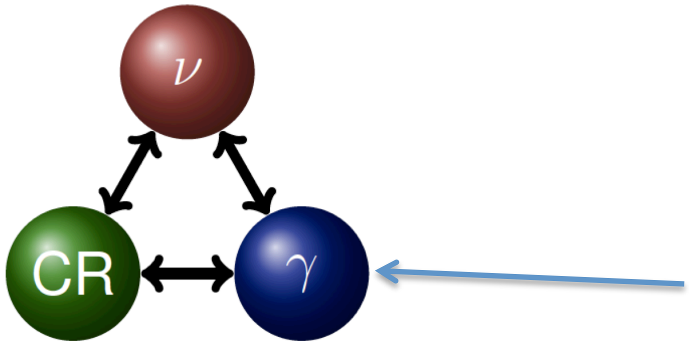


LVD (Bull Russian Acad Sci. **75** (2011) 427



South Pole peaks in January

Gamma-ray astronomy



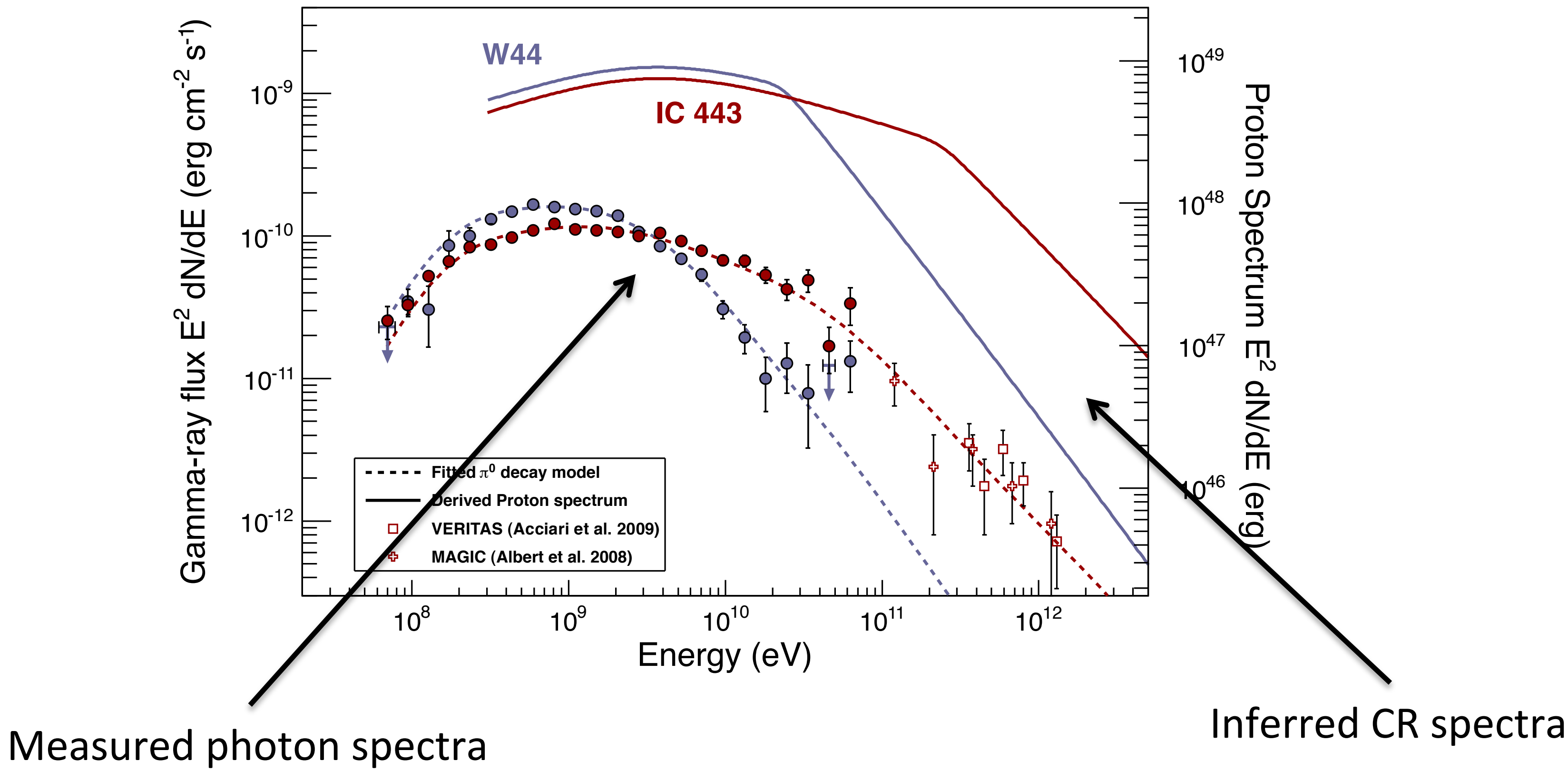
The γ link is the anchor for ν and CR because they are abundant and we can see where they come from.

Two questions:

1. What are the Fermi bubbles? (fossil jets?, minijets?)
2. Why do the proton spectra at W44 and IC443 cut off at such low energy?

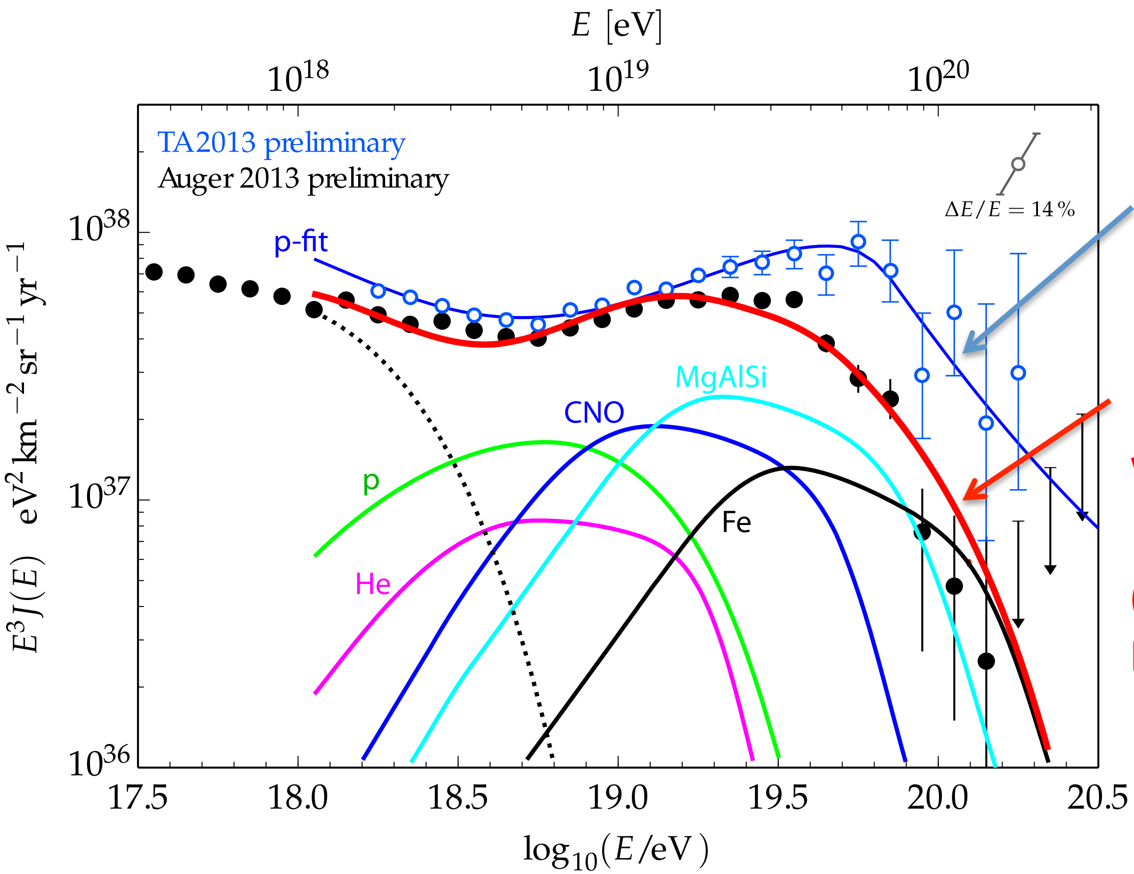
Detection of the Characteristic Pion-decay Signature in Supernova Remnants

Fermi Collaboration   Science Magazine 2013, volume 339, page 807



Ultra-high energy cosmic rays (UHECR)

K.-H. Kampert, P. Tinyakov / C. R. Physique 15 (2014) 318–328



The UHECR dilemma:

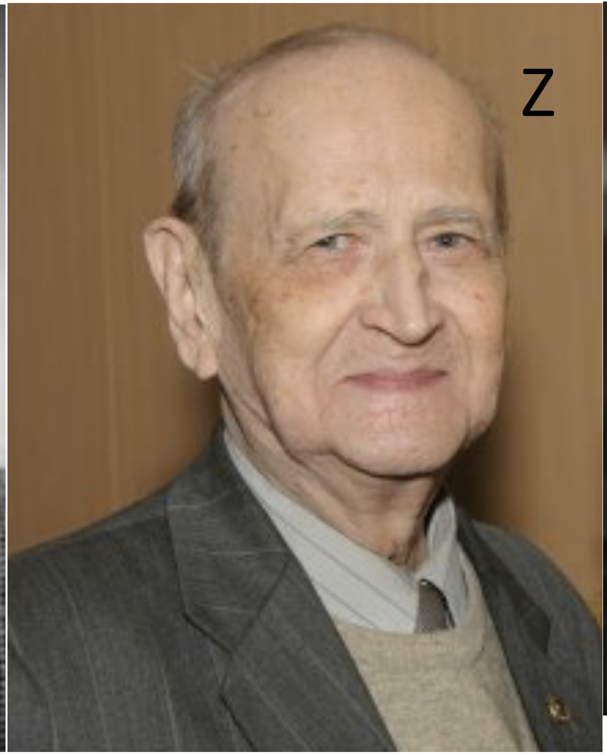
Protons + GZK cutoff

or

Mixed composition with E_{max} at sources

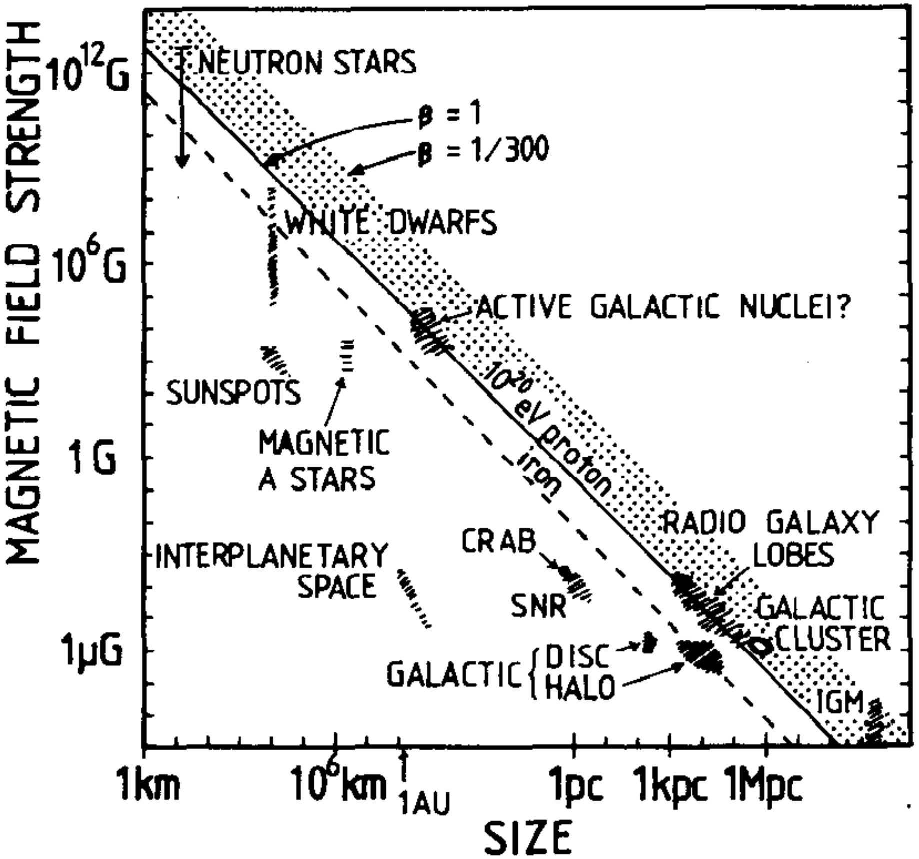
(Model of Aloisio, Berezinsky, Blasi, arXiv:1312.7459)

Greisen and Zatsepin & Kuz'min



$$p + \gamma_{CMB} \rightarrow N + \pi + ...$$

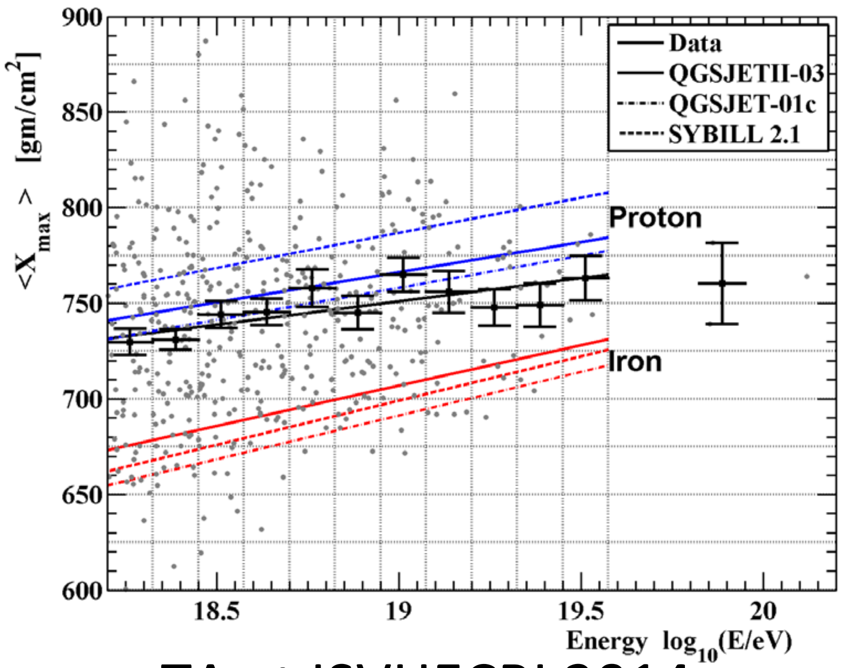
or Hillas cutoff



$$E_{max} = \beta Z e \times B \times R.$$

Are Auger and TA consistent?

Auger Collaboration: mixed composition
arXiv:1409.4809



TA at ISVHECRI 2014

Results are consistent with proton at all energies and inconsistent with iron.

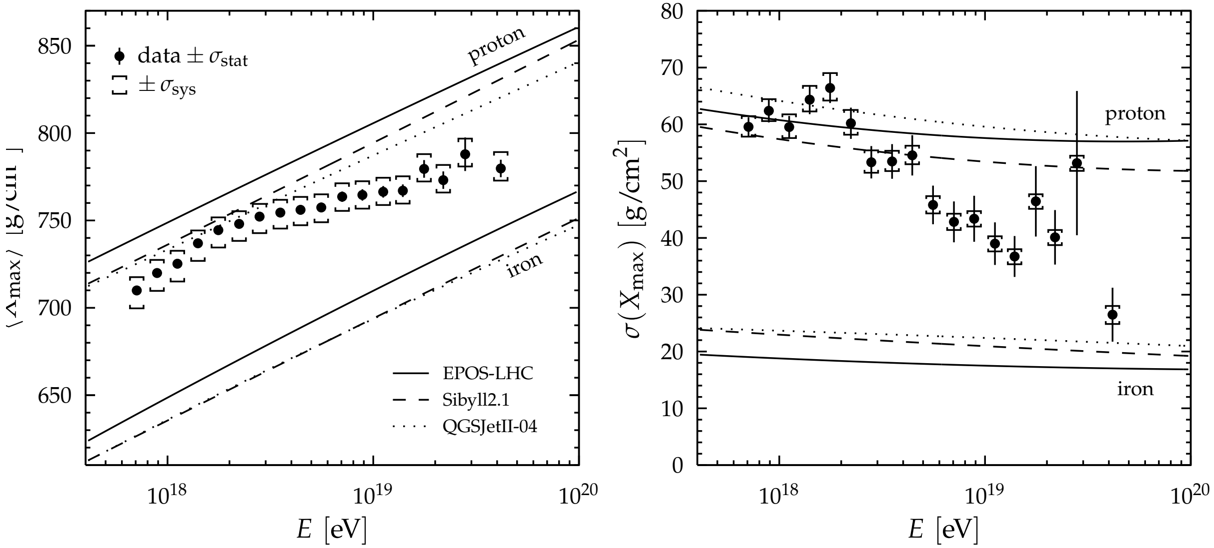


Figure 13: Energy evolution of the first two central moments of the $X_{\rm max}$ distribution compared to air-shower simulations for proton and iron primaries [80, 81, 95–98].

Active working groups

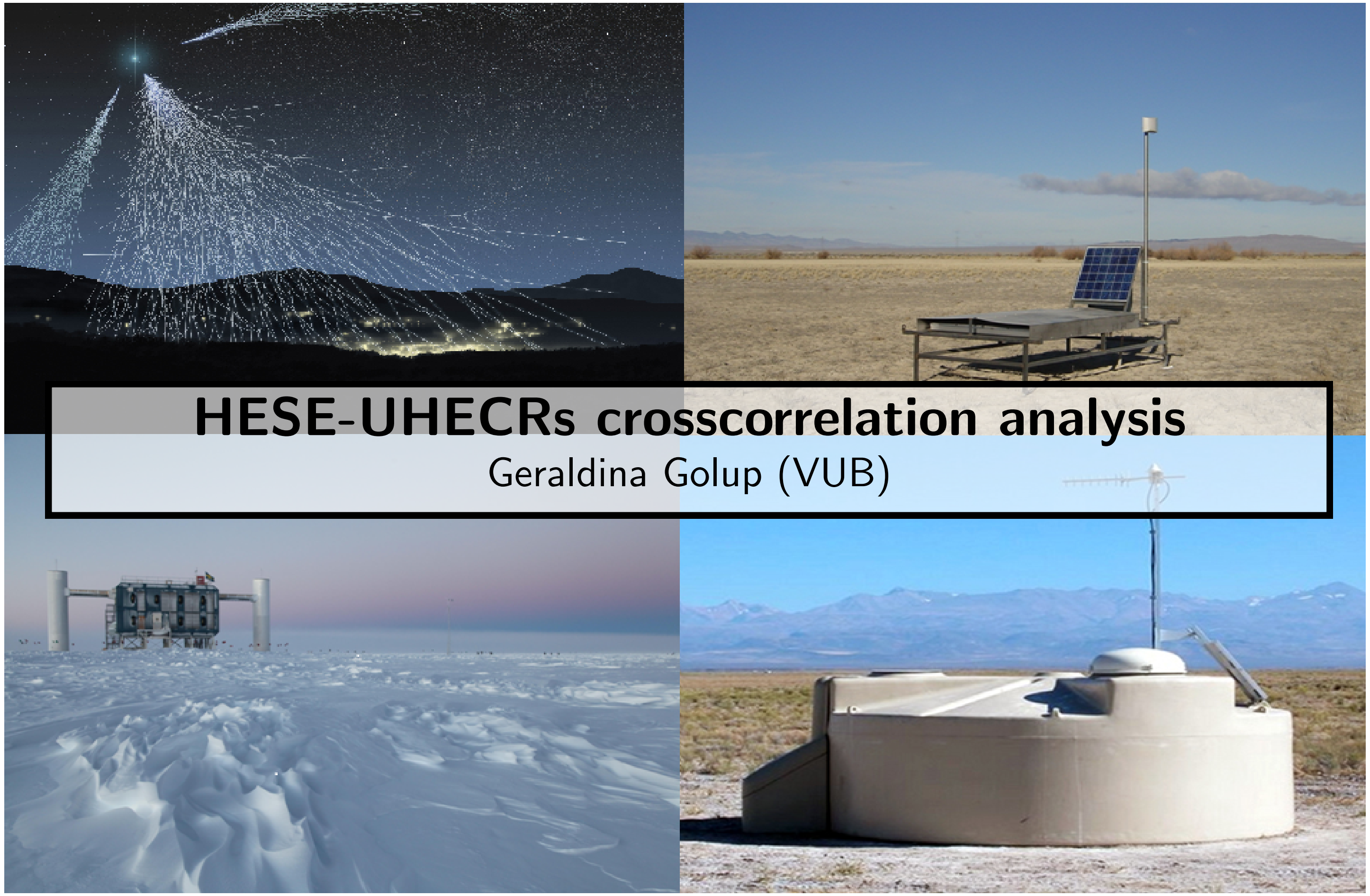
- UHECR energy spectrum
- UHECR anisotropies
- UHECR composition
- Hadronic interactions
  - Now includes PeV –EeV groups, e.g. IceTop

Original 4 working groups –See reports in Proc. UHECR-2012.

- Multi-messenger
  - New, emphasis on IceCube ν + UHECR directions
- Low energy composition
  - New, emphasis on structure in spectrum <EeV
- All groups to report at UHECR-2014, 13-15 Oct.

IceCube-Auger-TA (ν – UHECR)

Will be presented at UHECR 2014



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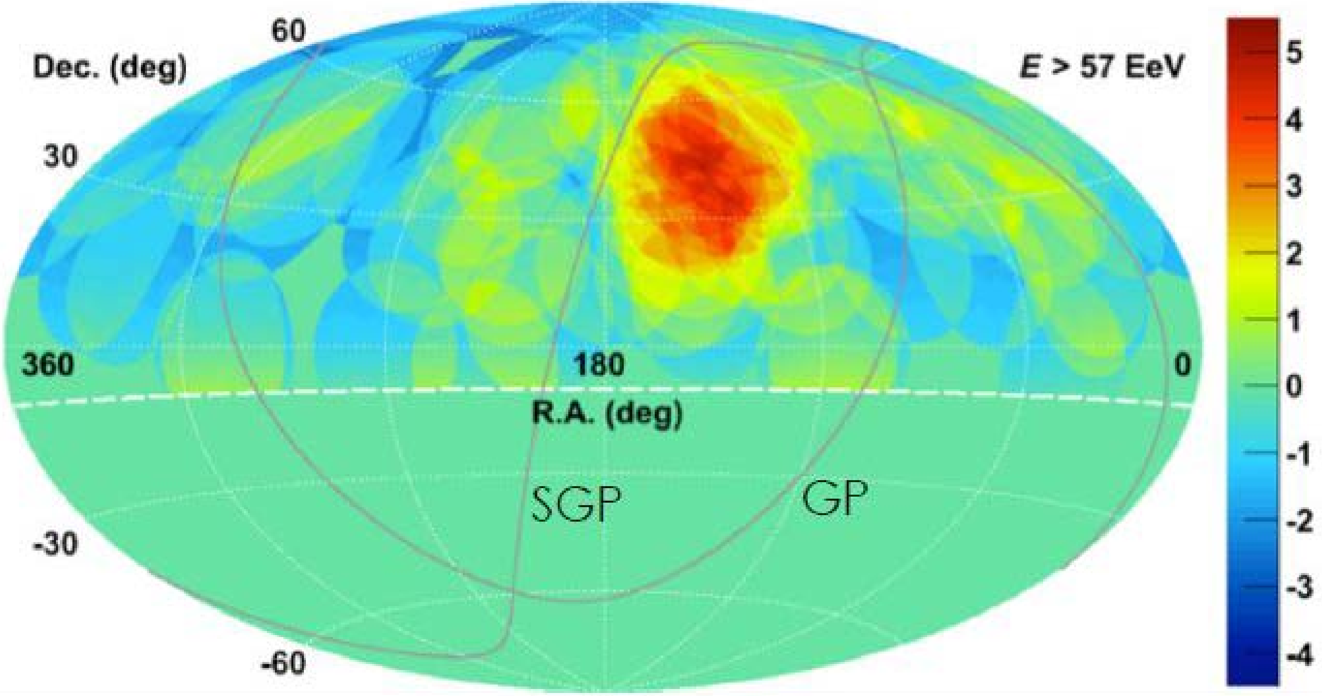
Vrije Universiteit Brussel

TA ISVHECRI 2014

arXiv:1404.5890

Hotspot



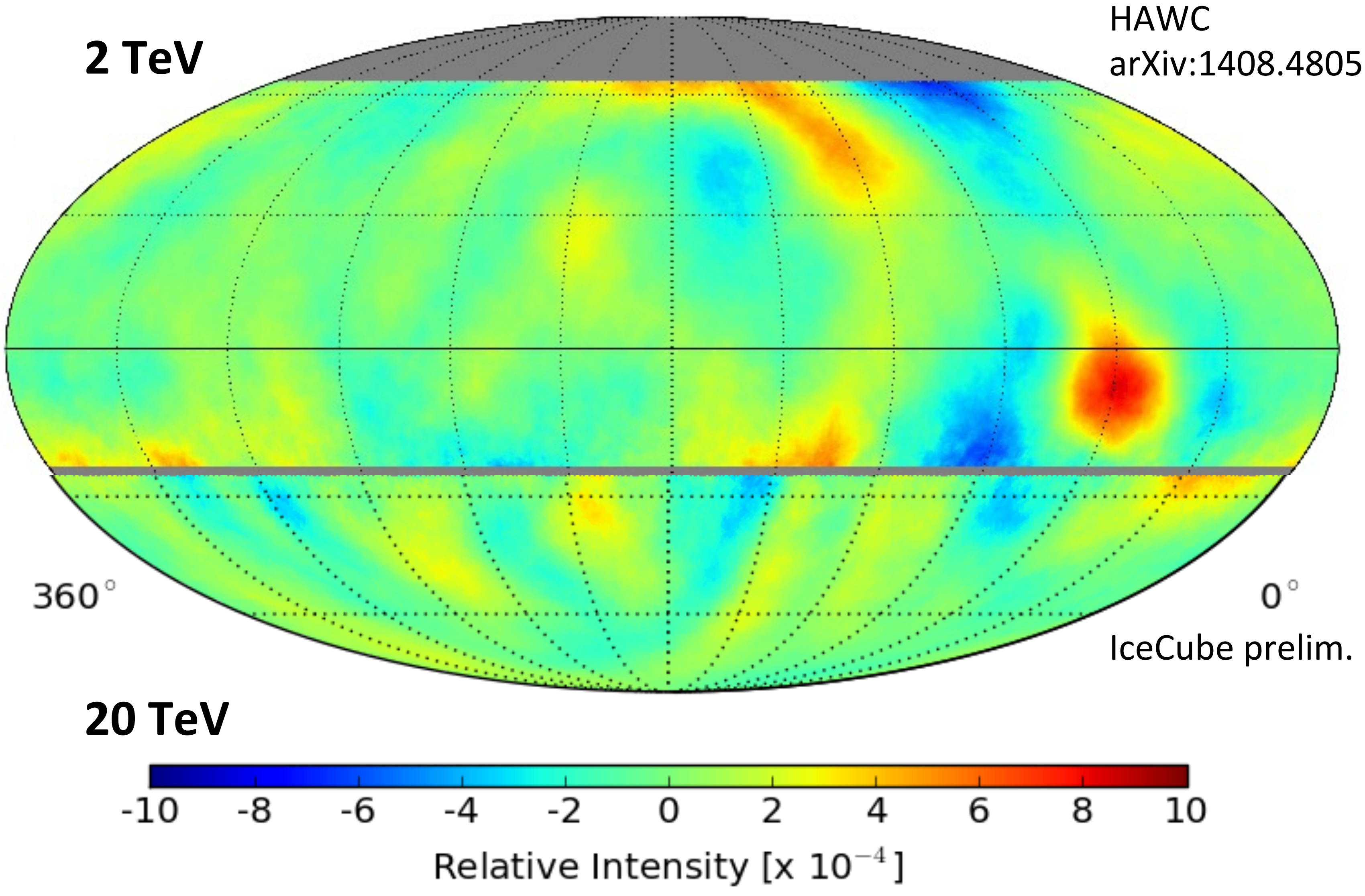
- Loose cut data: 72 events >57EeV, θ<55°, No boundary cut
- Angular resolution does not change very much
- Oversampling with 20°-radius circle

- Hotspot center R.A.=146.7°, Dec. = 43.2° (max. 5.1σ)
- Chance probability from Isotropic sky : 3.7×10^{-4} (3.4 σ)

i.e. 5.1σ enhancement anywhere in TA's FoV & any size r=15, 20,…35°.

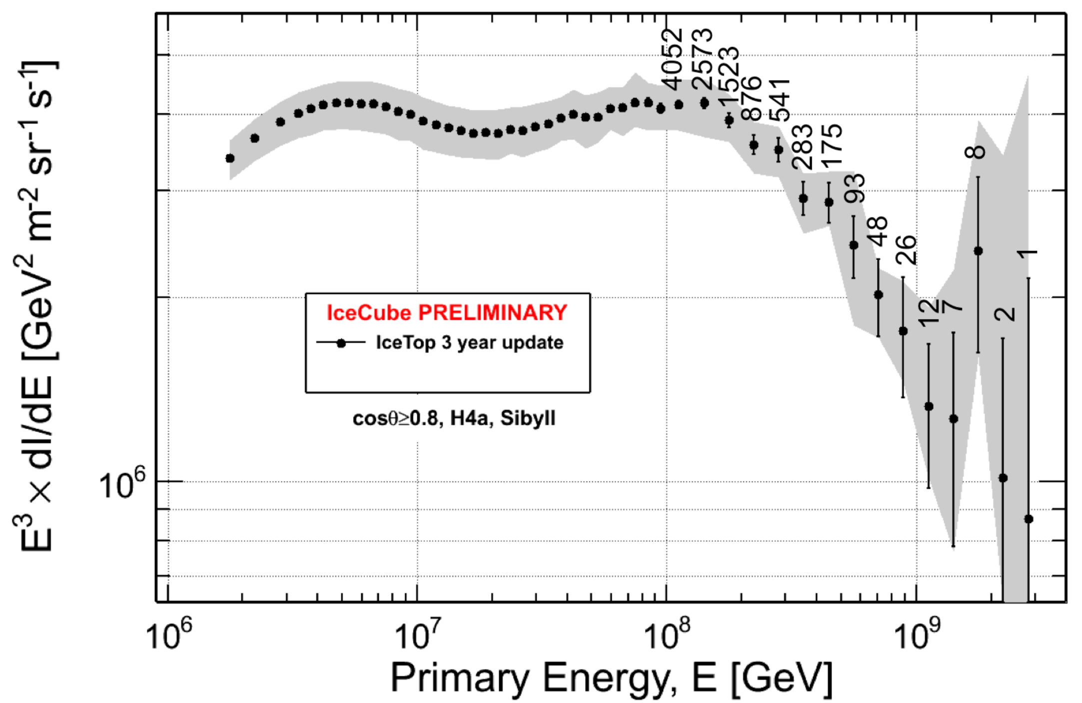
Anisotropy at lower energy

Future HAWC/IceCube Collaboration: Stefan Westerhoff at IC Collaboration meeting

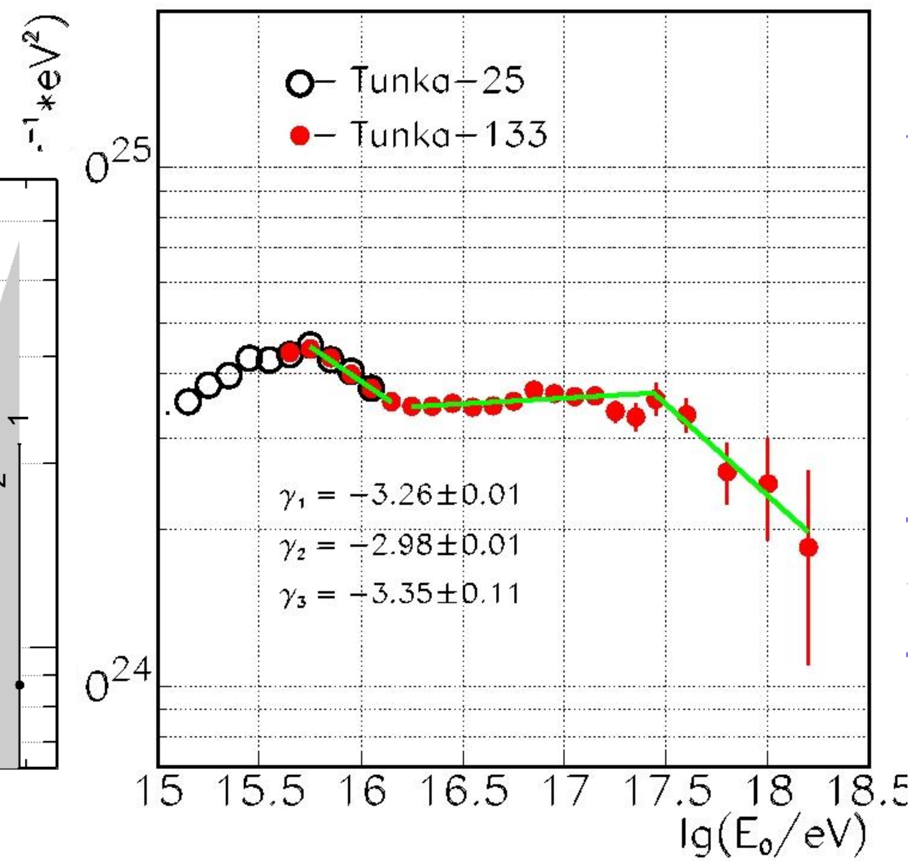


Structure in sub EeV spectrum

IceTop 3 years (preliminary)

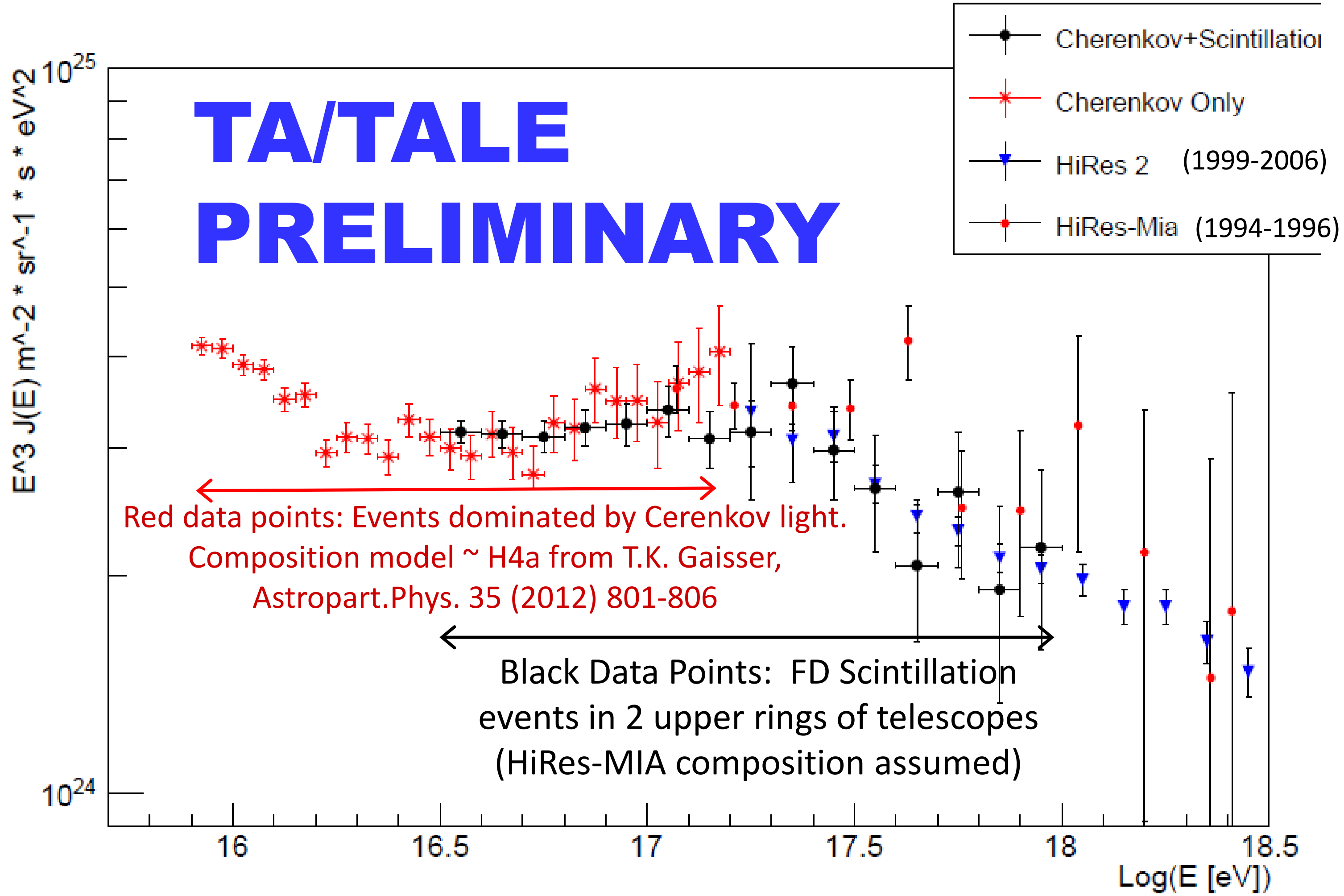


Prosin, TUNKA, ISVHECRI 2014

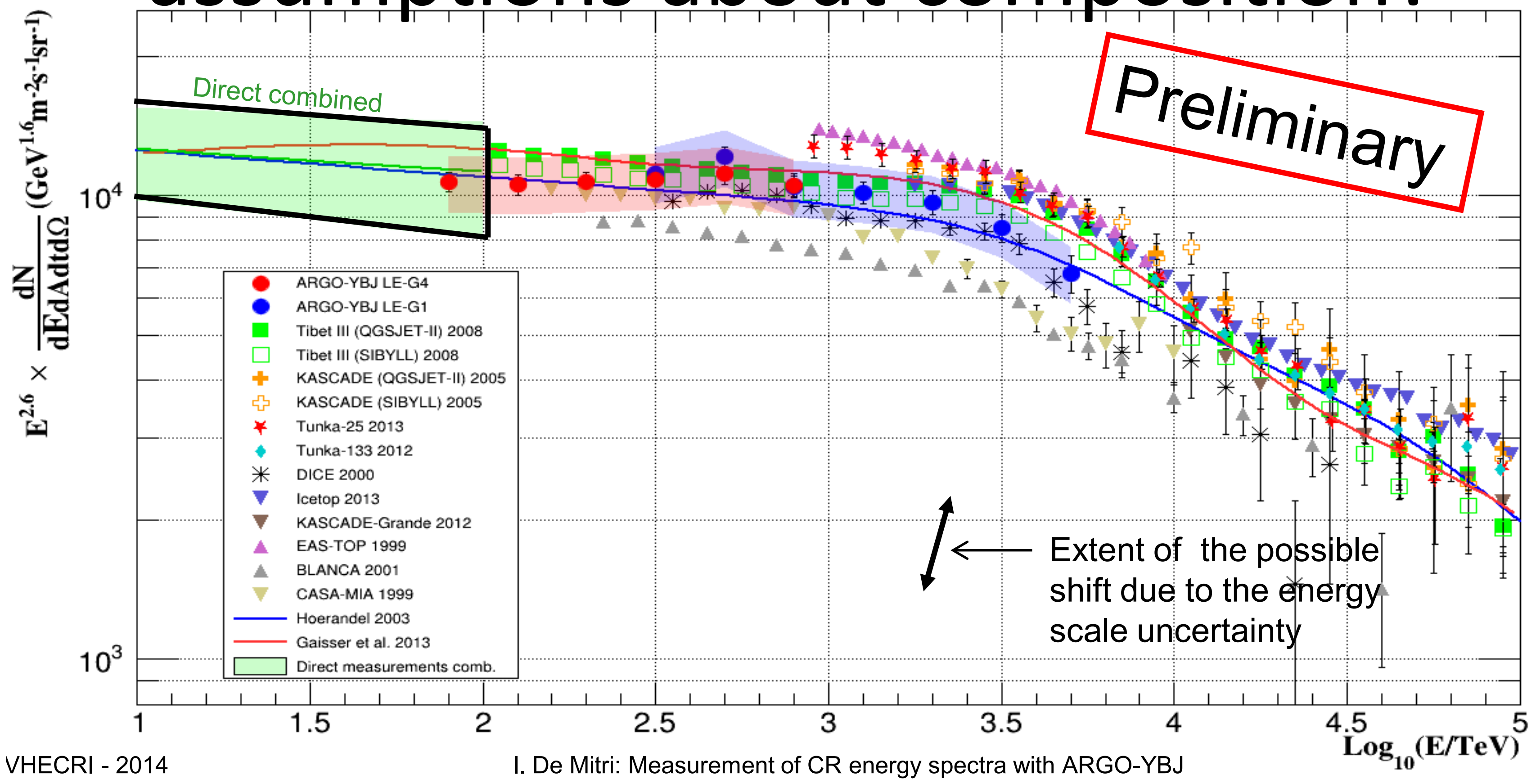


First TALE Monocular Energy Spectrum

~140 hours of data from Fall, 2013   Presented by C. Jui at ICHEP 2014



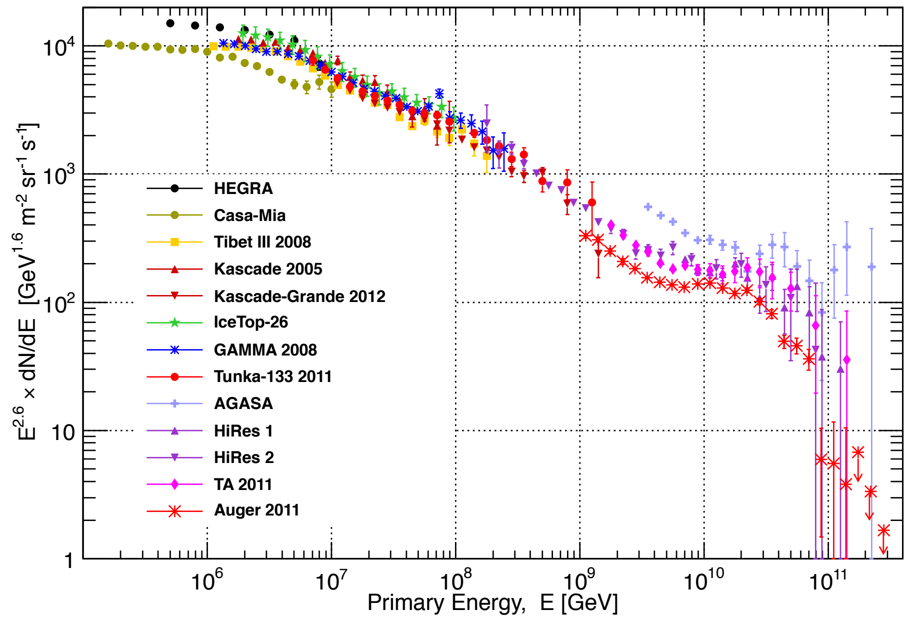
Differences due to systematic shifts in E between experiments? and/or assumptions about composition?



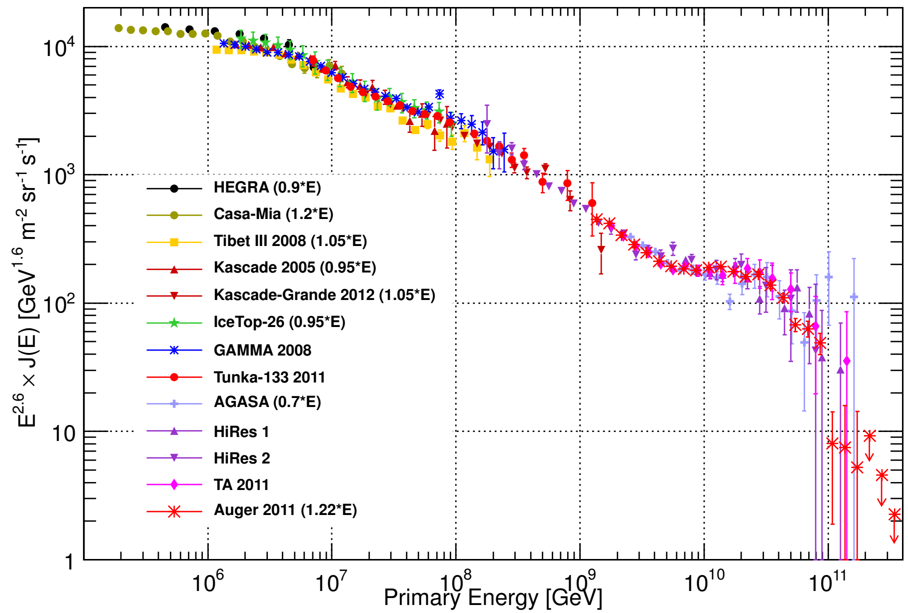
DeMitri: ARGO-YBJ and others, ISVHECRI 2014

Comparisons

Before shifting



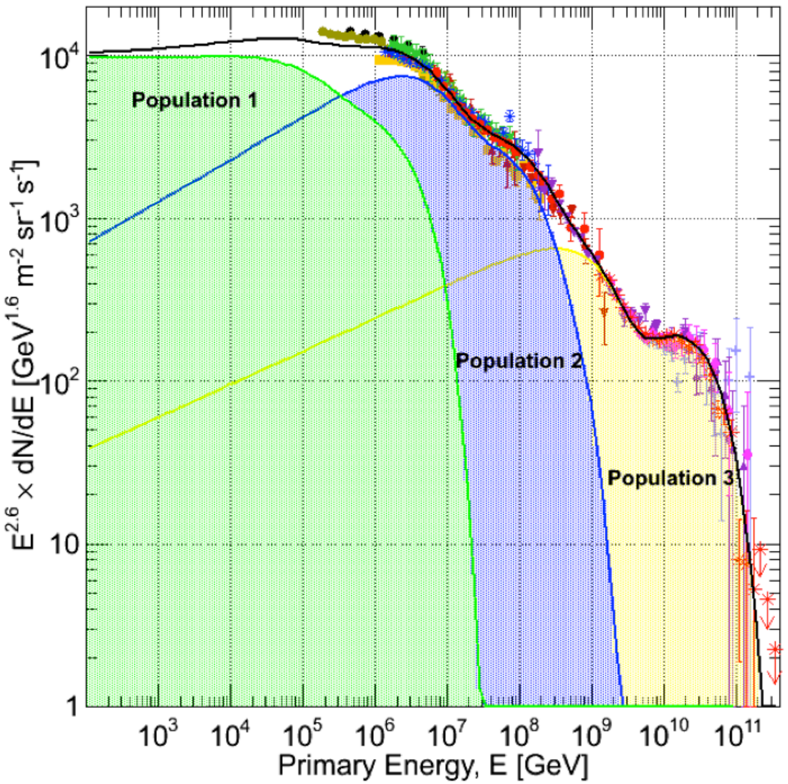
After shifting energy scales by 5 – 20%



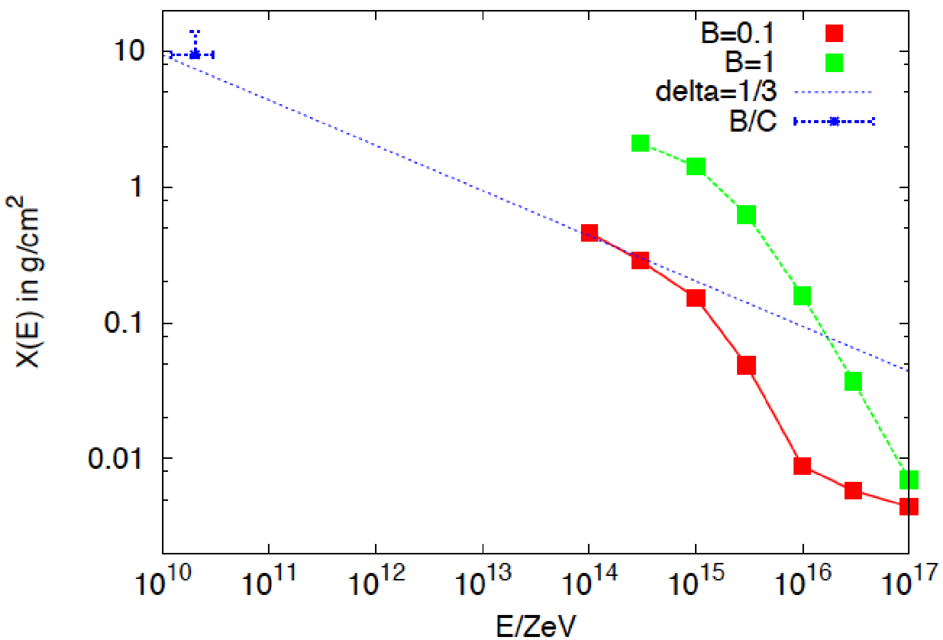
Serap Tilav, ISVHECRI 2014

Is the knee from E_{max} of accelerators or from propagation? (Both depend on rigidity.)

Answer: **both** are important (Paolo Lipari, isvhecri 2014)



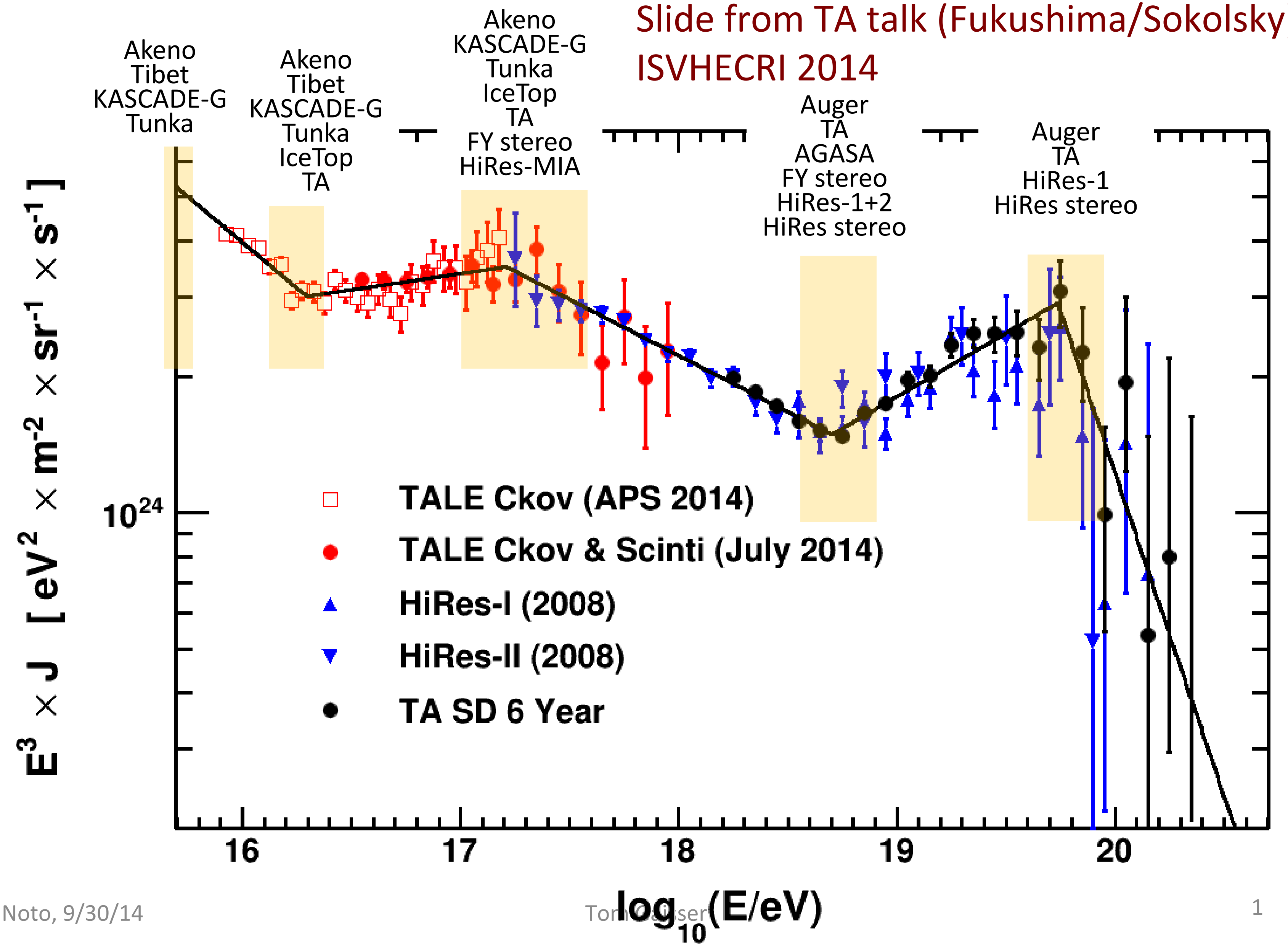
TG, Tilav, Stanev arXiv:1303.3565



D. Semikoz, ISVHECRI 2014 (arXiv:1403.3380

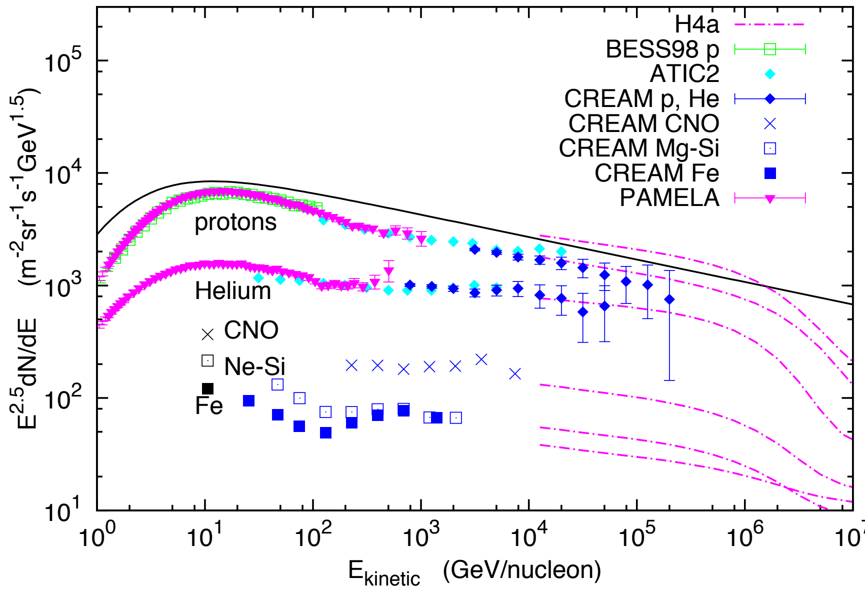
SPECTRUM: from Knee to Cutoff

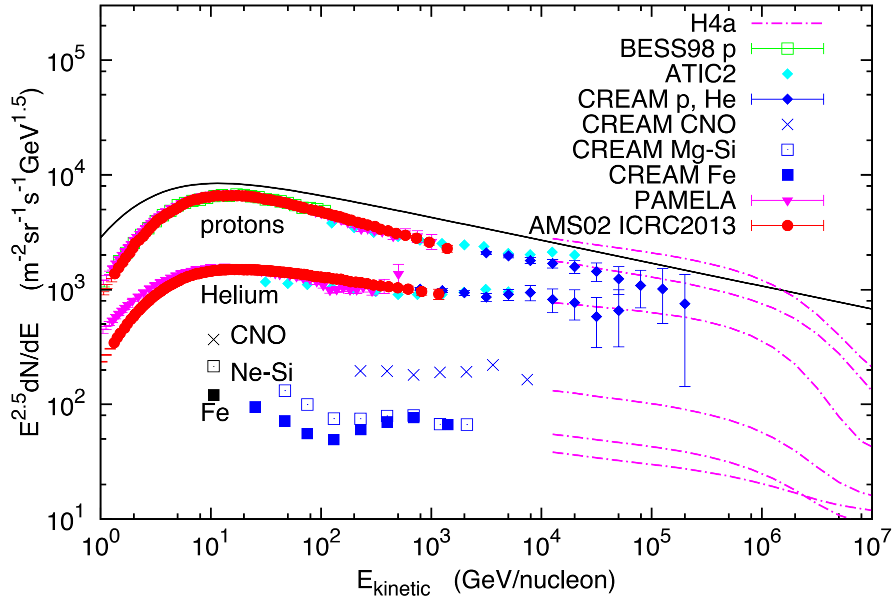
Slide from TA talk (Fukushima/Sokolsky) ISVHECRI 2014



Direct measurements

ATIC, CREAM, PAMELA, AMS02 ...





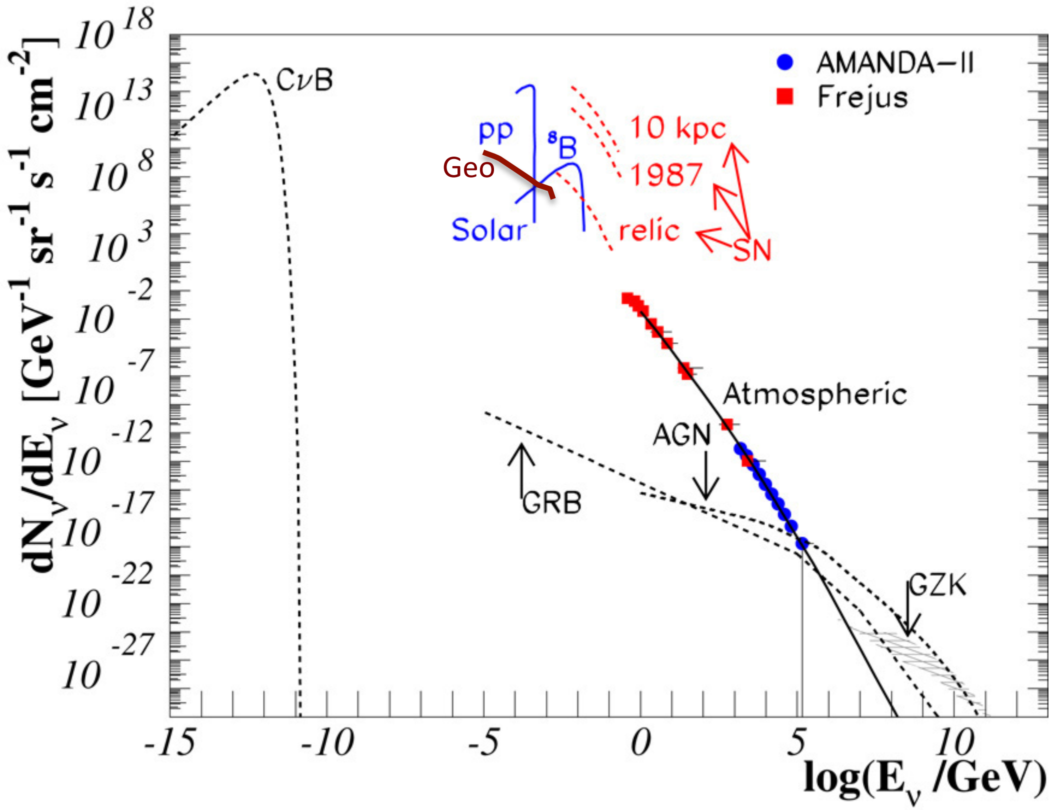
PAMELA, CREAM show hardening around 200 GeV/nucleon

Hardening not seen in preliminary AMS02 data reported at ICRC-2013

What will the final AMS02 analysis show?
(Important for how to extrapolate to the knee.)

Non-accelerator neutrino landscape

J.K. Becker / Physics Reports 458 (2008) 173–246



1987: SN1987A

1998: Atmos ν osc

2000: Solar ν osc

2010: Geo ν

2013: Astro ν

2014: solar pp ν (Borexino)

201? Relic SN ν

20?? Cosmogenic ν (GZK)

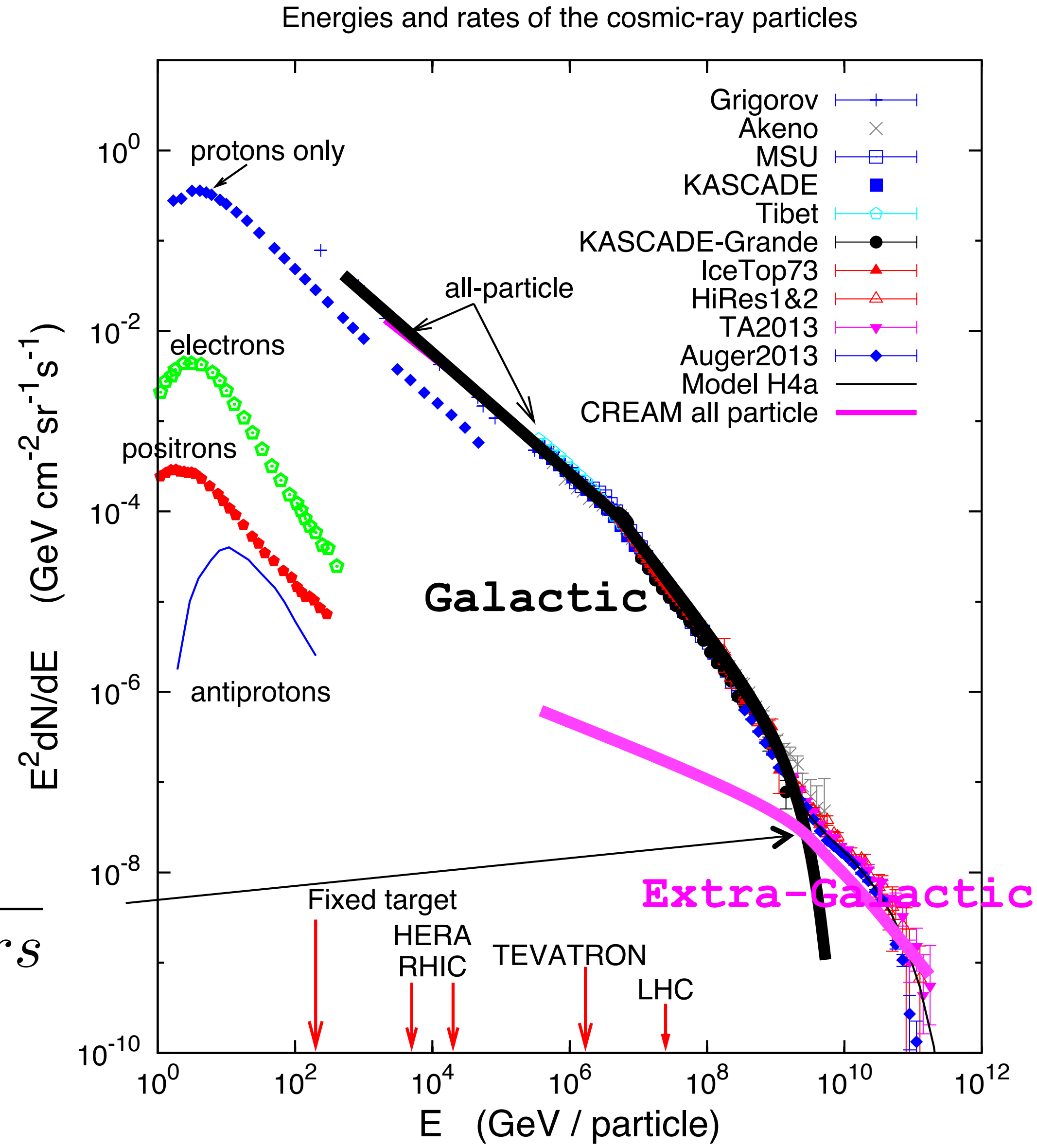
CνB cosmological ν mass?

The cosmic ray – astro-ν connection

- Gassy SN remnants are likely Galactic sources
- Potential extra-galactic sources: AGN, GRB, starburst galaxies …
- Power of extra-galactic CR sources determines level of ν production

$$E\frac{dN}{d\ln E} \approx 3\times 10^{-8}\ \frac{\text{GeV}}{cm^2 srs}$$

$$\text{at } 10^{10}\,\text{GeV}\ (10^{19}\,\text{eV})$$



Generic extra-galactic model I

- UHECR are accelerated in external shocks around active galaxies analogous to SNR
  - See E.G. Berezhko, 0809.0734 & 0905.4785
  - mixed composition (accelerate whatever is there)
  - Low density of target material
  - → lower level of TeV-PeV neutrino production

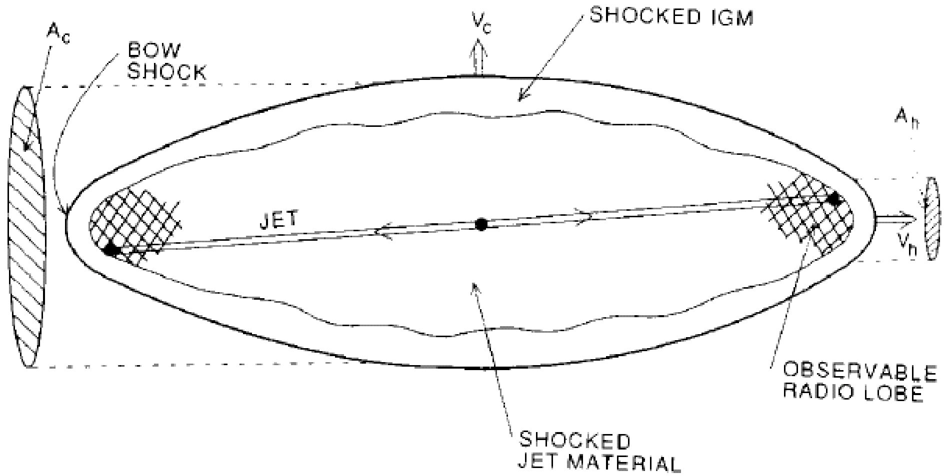
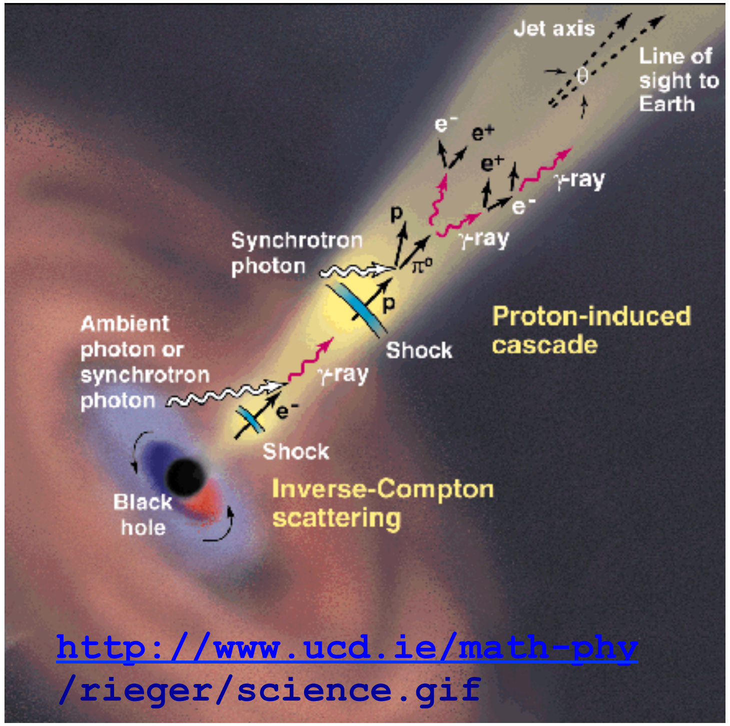


Diagram from Begelman & Cioffi, Ap.J. (1989) L21

Generic model II

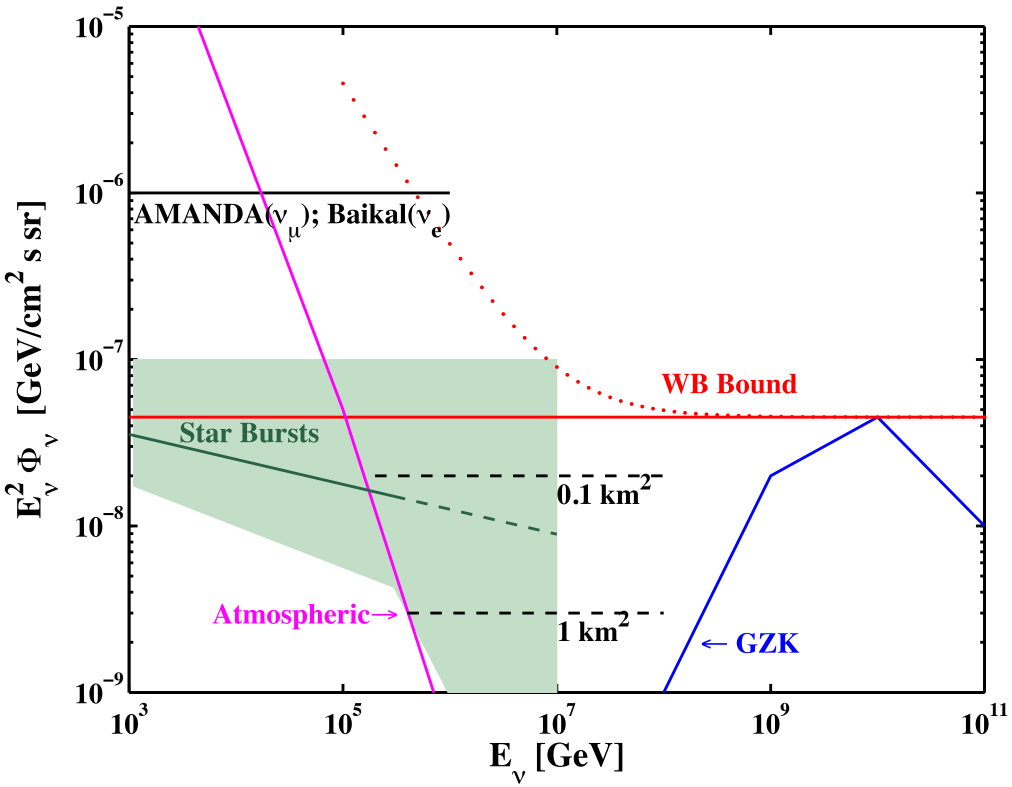
- CR acceleration occurs in jets
  - AGN or GRB
- Intense radiation fields
  - Models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\ \gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR



Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Starburst galaxies as ν sources from CR interactions in dense gas

More info in Eli Waxman's plenary talk tomorrow



Loeb & Waxman, JCAP 0605 (2006) 003

Note: this source class has a maximum $E_\nu < E_{max}$

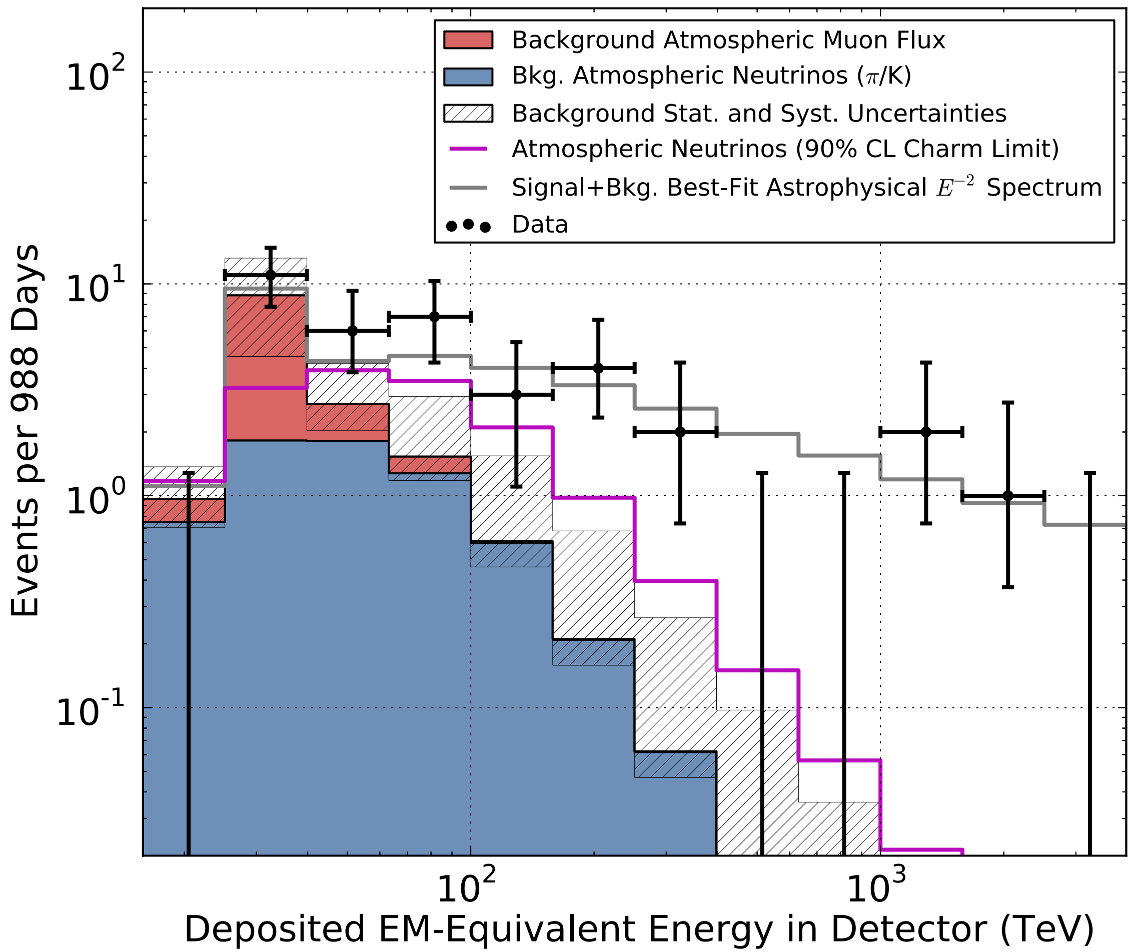
Contrast with AGN or GRB with photon target where $E_\nu > E_{min}$

Question: why are starbursts weak in γ ?

IceCube: Astrophysical ν

IceCube Collaboration, PRL 113.101101 (2014)

See Chad Finley's plenary talk tomorrow



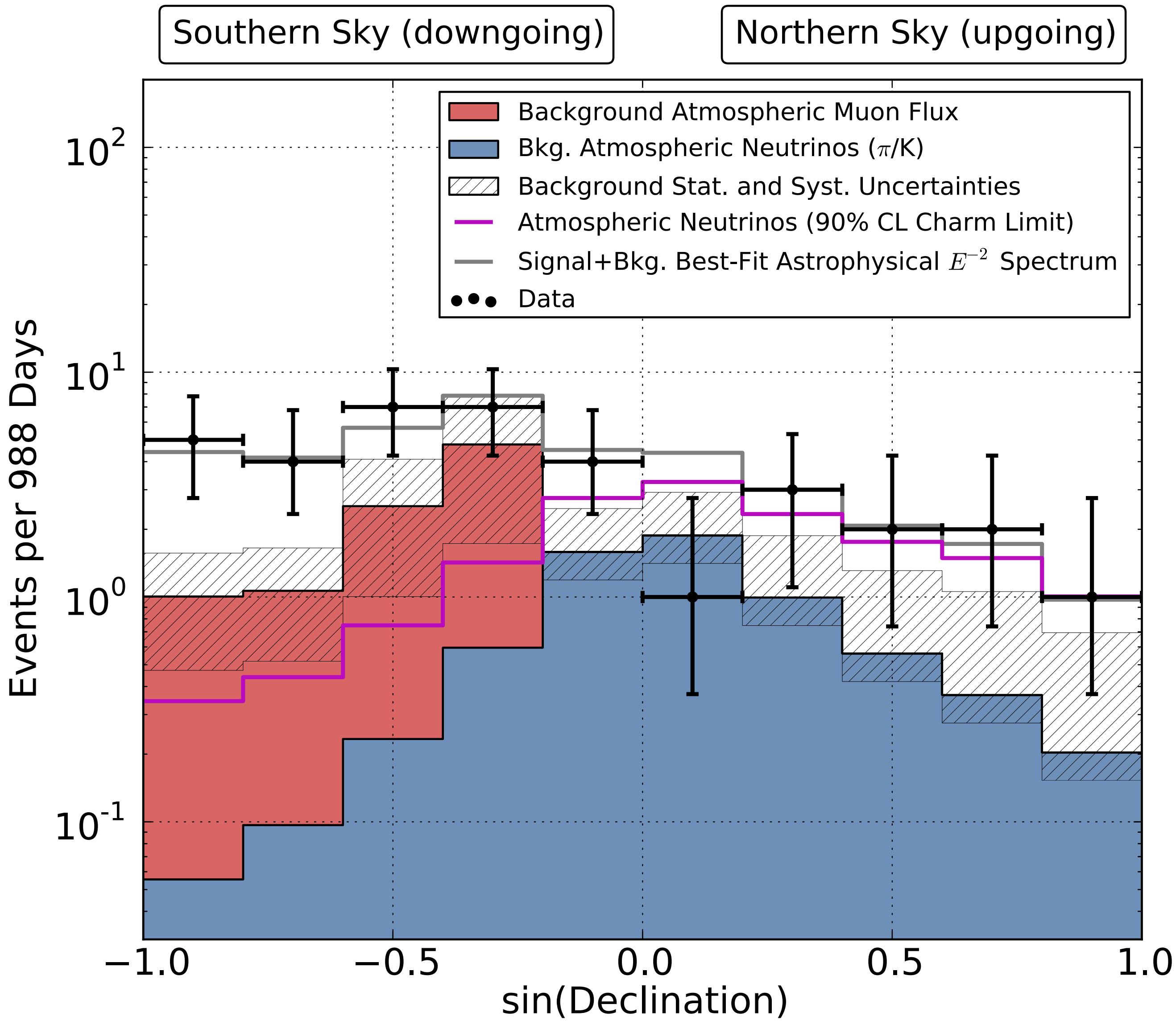
Astrophysical ν spectrum (per flavor)

$$E^2\Phi = 0.9 \cdot 10^{-8} \exp\left(\frac{-E}{2.8\text{PeV}}\right) \text{GeV s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$$

or $E^2\Phi = 1.5 \cdot 10^{-8} \left(\frac{E}{100\text{TeV}}\right)^{-0.3} \text{GeV s}^{-1}\text{sr}^{-1}\text{cm}^{-2}$

or …

Angular distribution

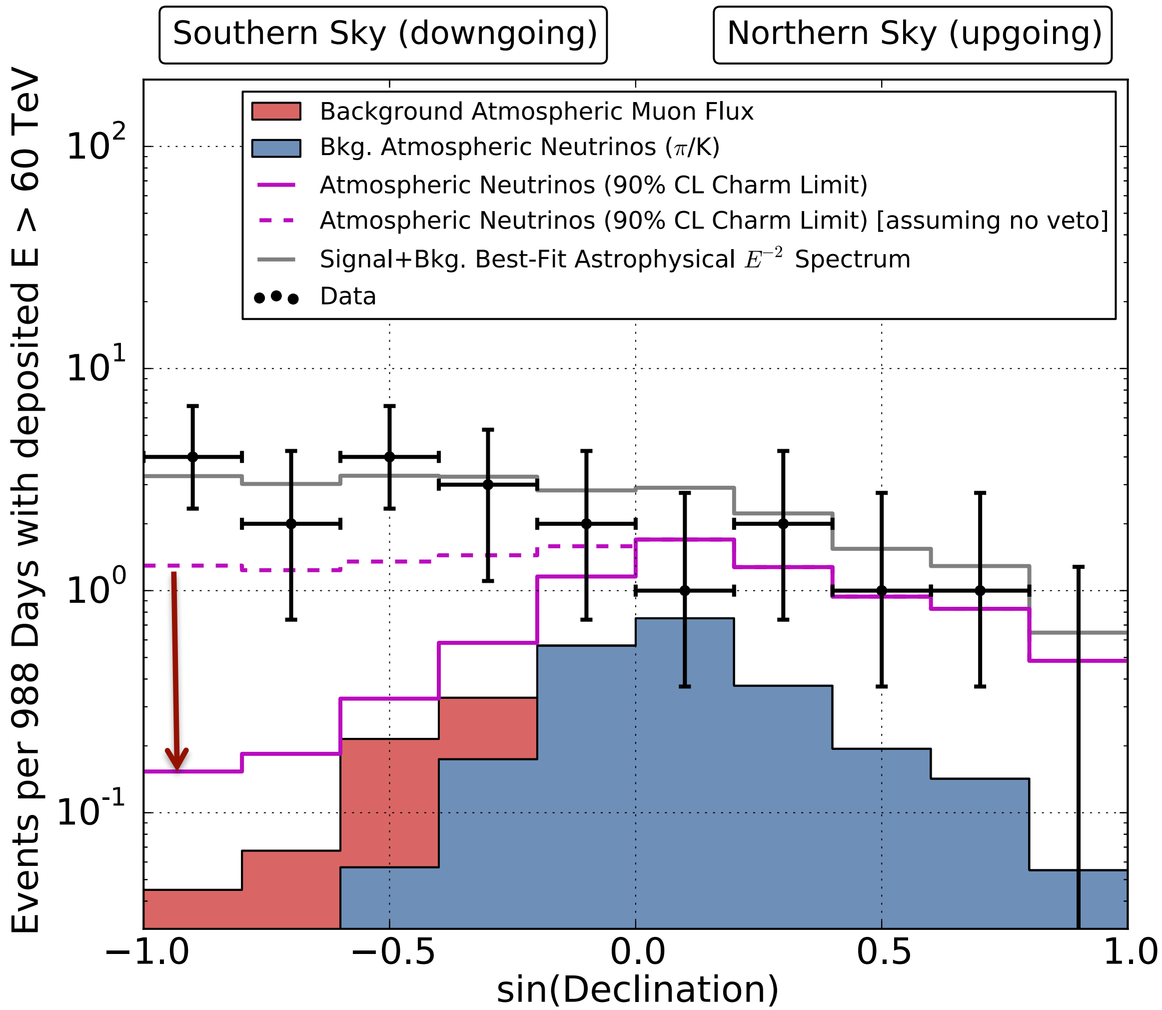


FAQ about IceCube neutrinos

- Why not more background from prompt ν?
- What is the flavor ratio?
- What is the spectrum?
  - Is there an upper cutoff?
  - Is there a gap in energy?
  - Is there a lower cutoff?
- What are the sources?
  - What is the fraction from Galactic sources?
  - Why are point sources not yet identified?

Angular distribution (E> 60 TeV)

Atmospheric ν veto



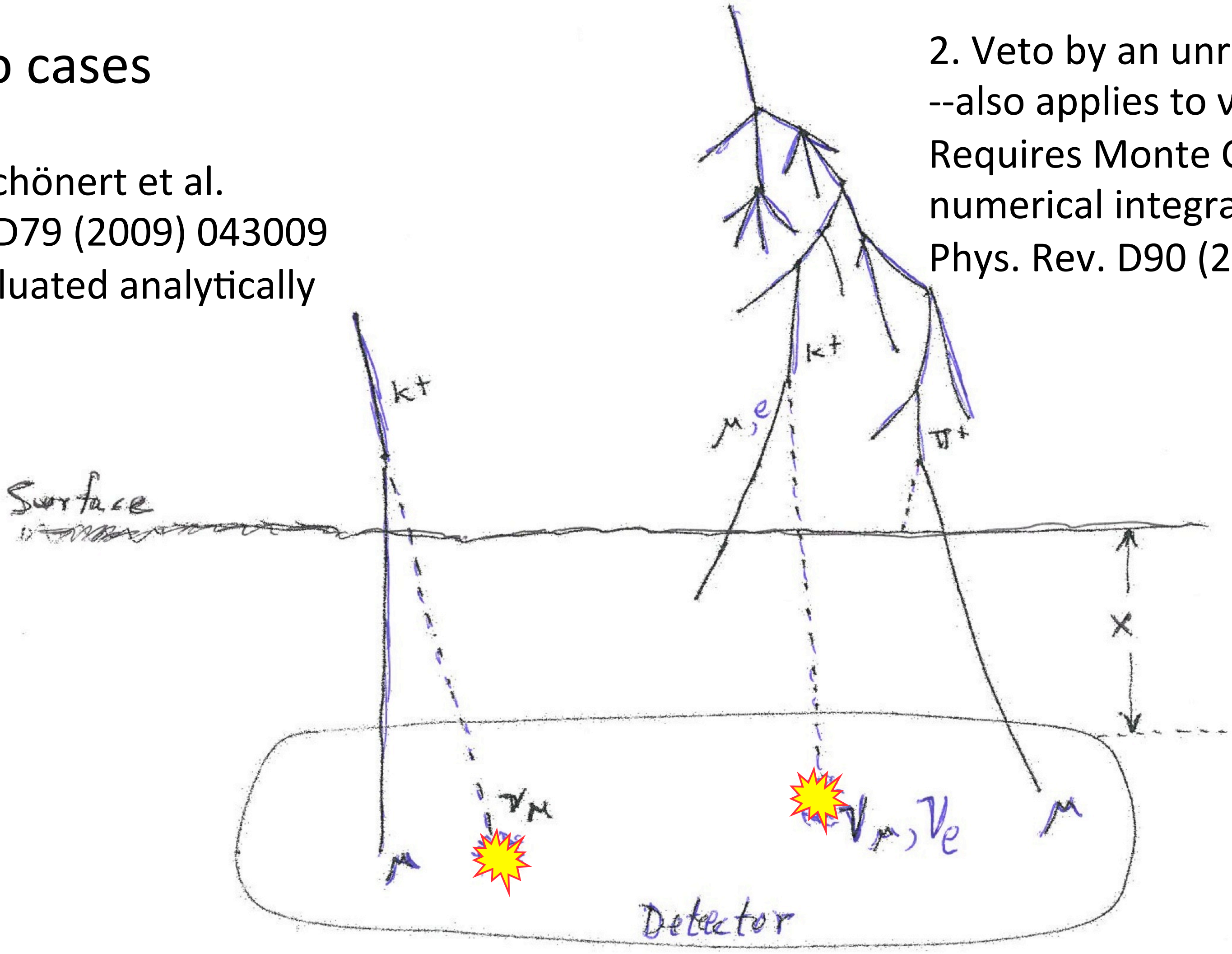
Select E > 60 TeV to get above atmospheric μ background.
Note shape of prompt atmospheric ν background.

Atmospheric neutrino self veto

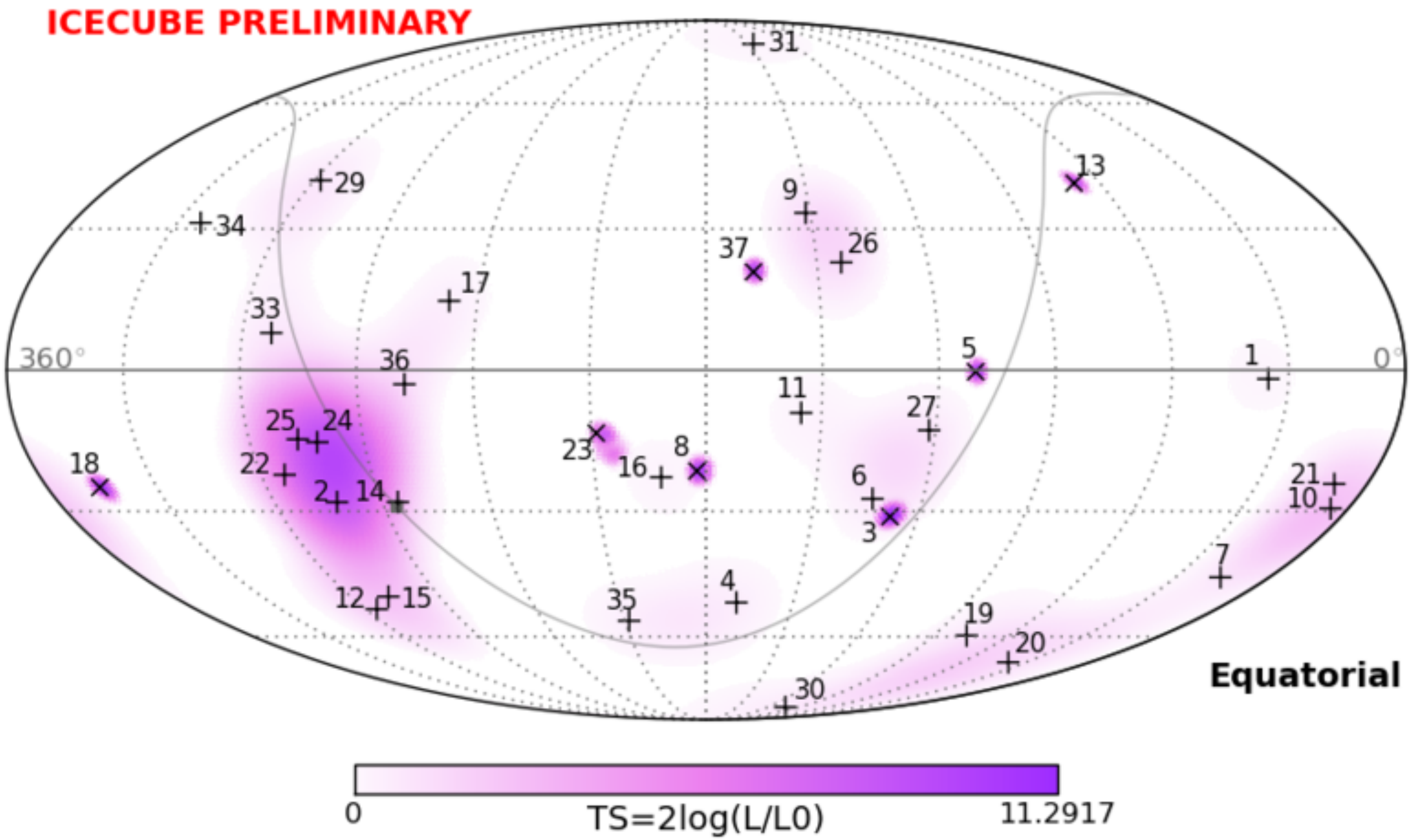
Two cases

1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration
Phys. Rev. D90 (2014) 023009

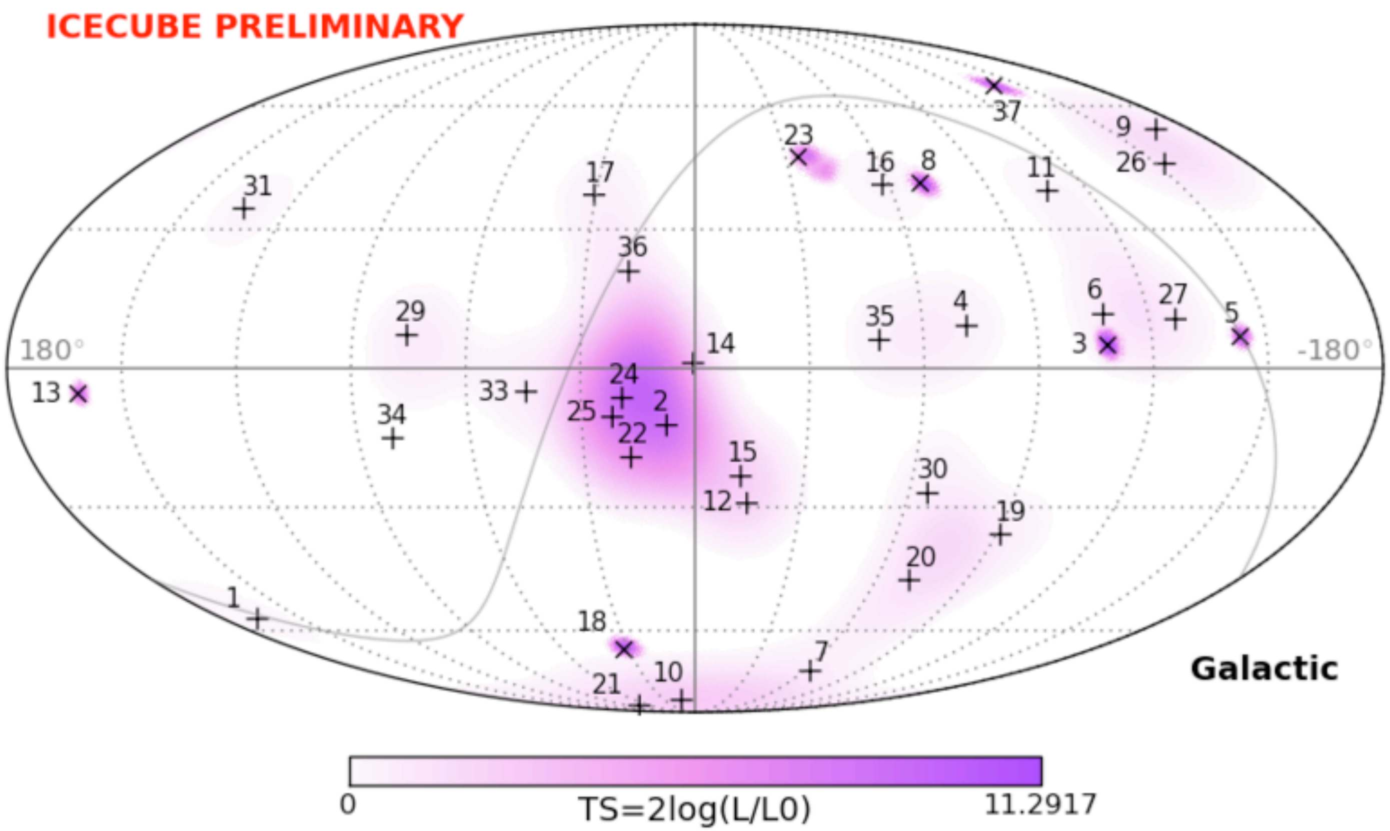


Sky map (equatorial coord.)



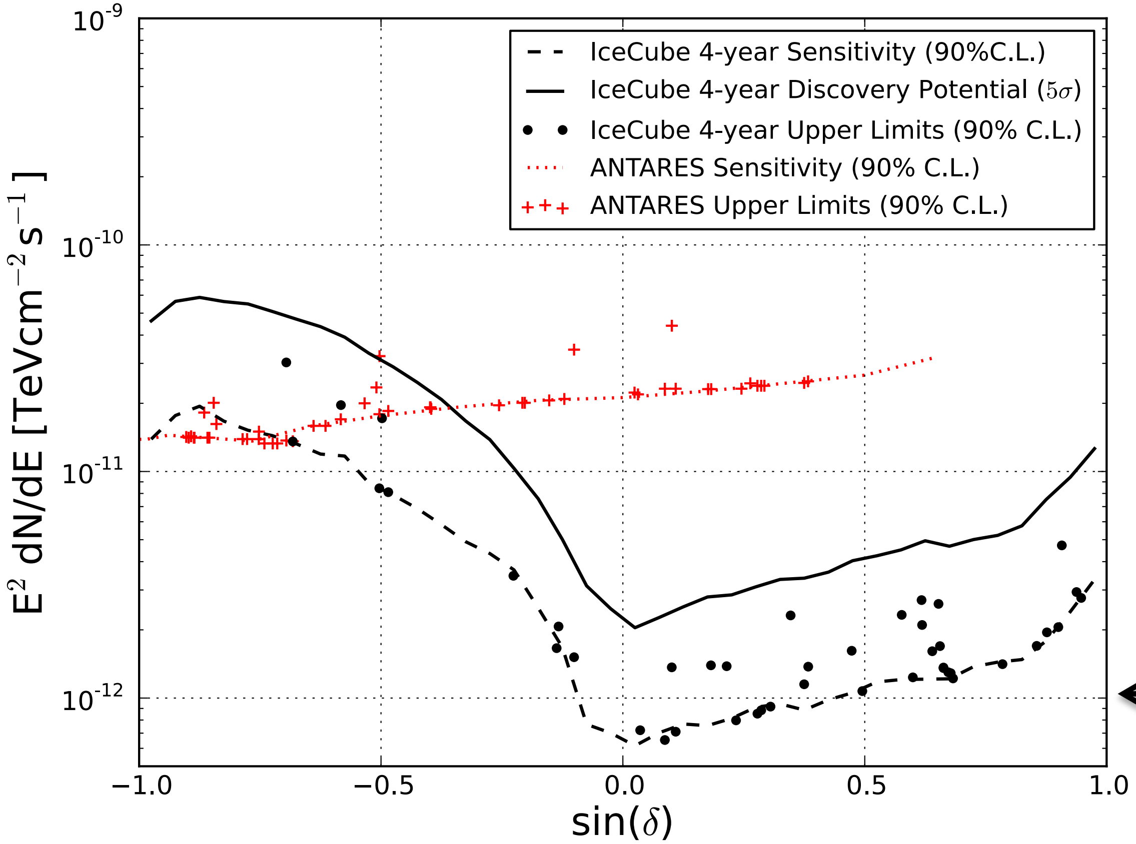
37 – 2 events

Sky map (Galactic coord.)



IceCube point source limits are low

What does this imply for extra-galactic sources?



IceCube: arXiv:1406.6757

$$E^2 \frac{dN}{dE_\nu} < 10^{-9}\,\mathrm{GeV\,cm^{-2}s^{-1}}$$

ν propagate from z>1 without interaction

Integrate all sources out to a Hubble distance c/H_o

(1) $$J_\nu = \xi \frac{L_\nu \, n_s}{4\pi} \frac{c}{H_0}$$

where L_ν is a typical source luminosity and n_s is the density of sources

IceCube measures J_ν around 100 TeV to 1 PeV as

(2) $$J_\nu = \frac{\mathrm{d}N}{\mathrm{d}E_\nu} \sim \frac{2 \times 10^{-8}}{E^2} \, \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

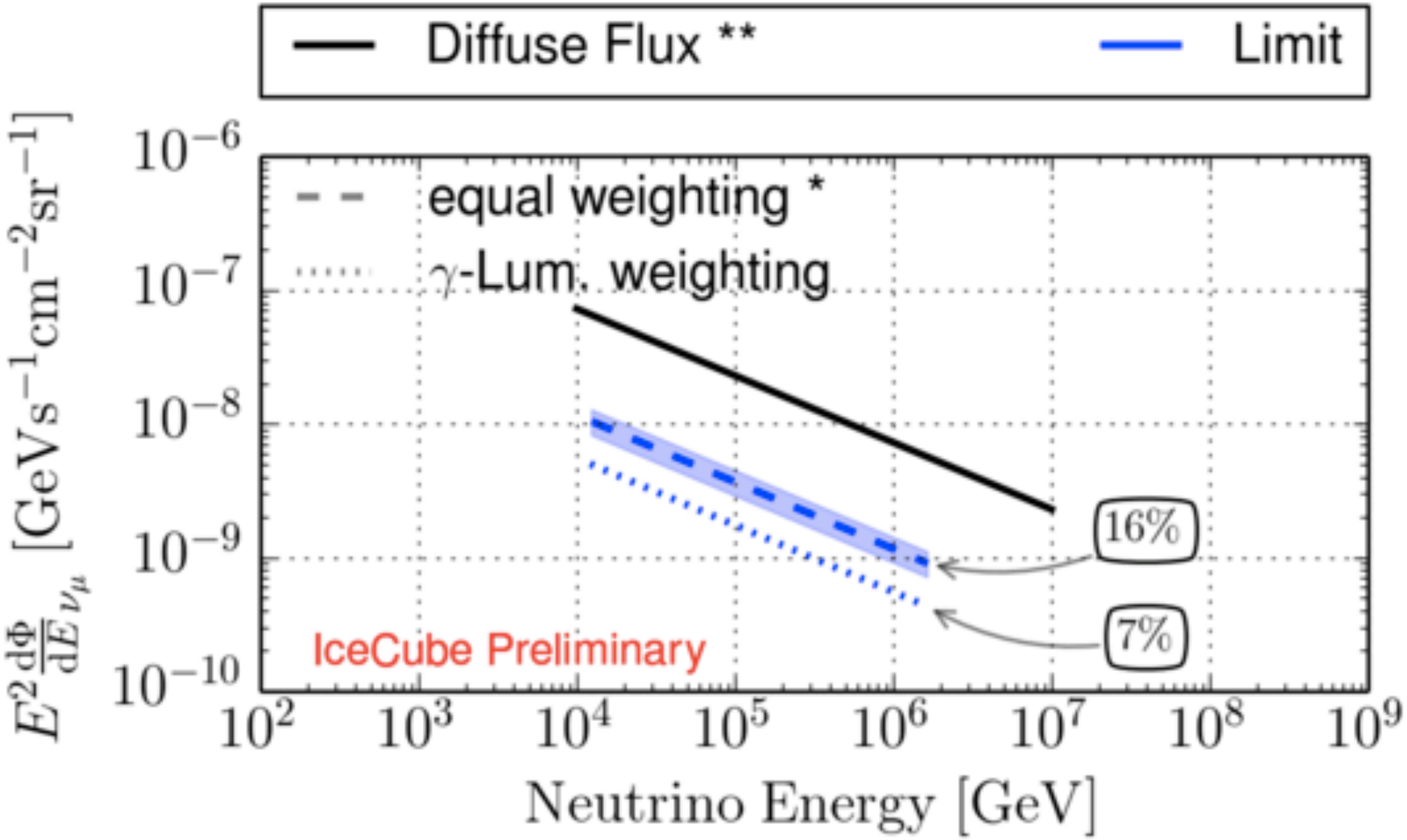
Intensity from a nearby source: $$J_1 = \frac{L_\nu}{4\pi d_1^2} \sim \frac{L_\nu n_s}{4\pi (n_s)^{1/3}}$$

Given a measured flux from (1) and (2), an upper limit on J_1 gives a lower limit on source density

See P. Lipari, PR D 78 083011 (2008) and M. Ahlers & F. Halzen, arXiv:1406.2160

Specific example of blazars

See talk by Thorsten Glüsenkamp in neutrino parallel Session



*) Band denotes central 90 % of outcomes of different realizations from the γ-Luminosity Function.
This limit also holds for all (quasi-)isotropic subpopulations, independent of their gamma emission.

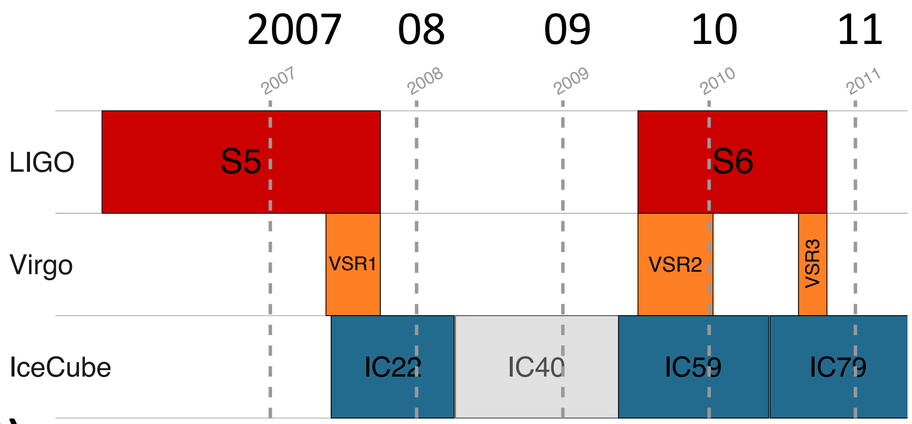
**) 1-flavor fit result, presented at ISVHECRI 2014, see talk by J. van Santen

Fraction of Galactic ν sources?

- Galactic sources may have low E_{max}
- ANTARES more sensitive to Southern hemisphere at low E
  - See talk of Maurizio Spurio (parallel E, Oct 1)
  - Joint IceCube/ANTARES point source search approved at MANTS meeting

Multi-messenger campaigns

- IceCube
  - GW with VIRGO/LIGO
  - γ with MAGIC/VERITAS
  - Alerts to SNEWs, (ROTSE), PTF, SWIFT
- ANTARES
  - with VIRGO/LIGO
  - Optical follow-up
  - … Giulia De Bonis, parallel H



arXiv:1407.1042

IceCube is moving toward publication of near real-time ν events of interest (high energy, good reco)

Future: γ-ray astronomy

C T A

Where?

Future UHECR

- Pierre Auger Observatory
  - Deploy enhanced detectors for $\gamma - \mu$ separation
  - Motivation: composition at highest energy with 100% duty cycle
- Telescope array
  - Increase by factor of 4
  - Motivation: hot spot and UHECR astronomy

TAx4 Proposal

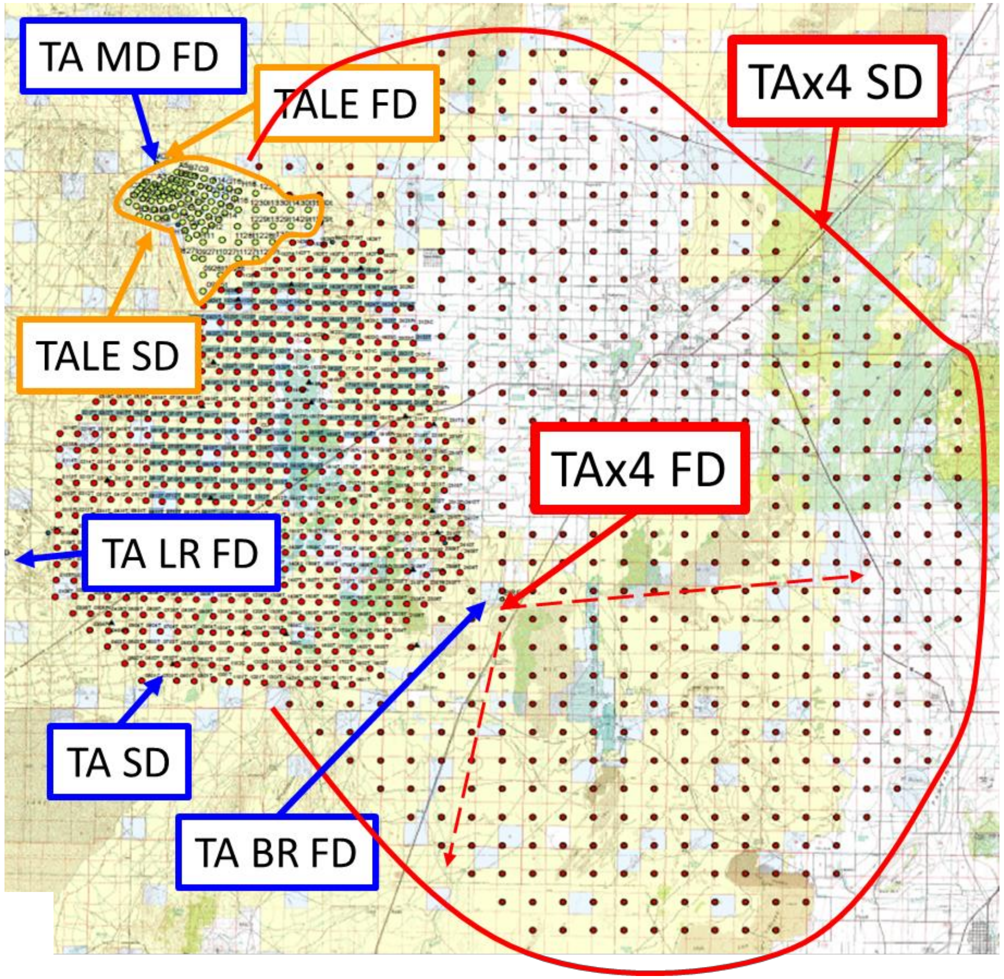
✧ Now there is hint of anisotropy at 3σ level for northern sky.

❖ Plan to expand TA by 4 times (3,000km²)

1. Add 500 scint. counters with 2.1 km spacing
2. 10 refurbished HiRes tels

❖ Science (3-year observation)

1. Study of anisotropy
   → Expect 5σ
2. Xmax at highest energy region
3. UHE photon & neutrino search



Slide from Fukushimi/Sokolsky at ISVHECRI 2014

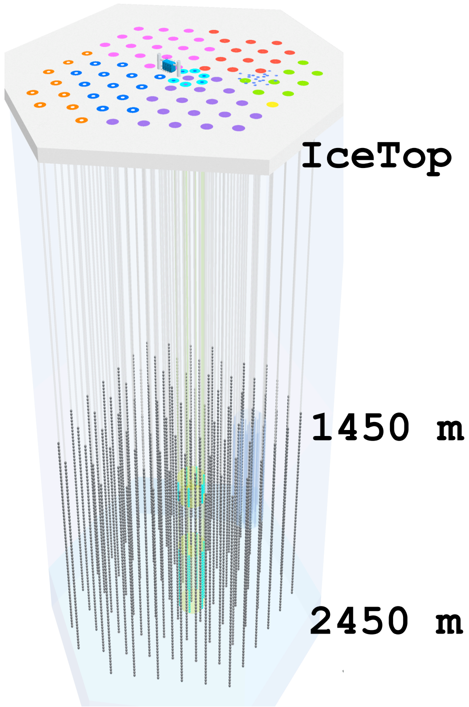
Future neutrino detectors

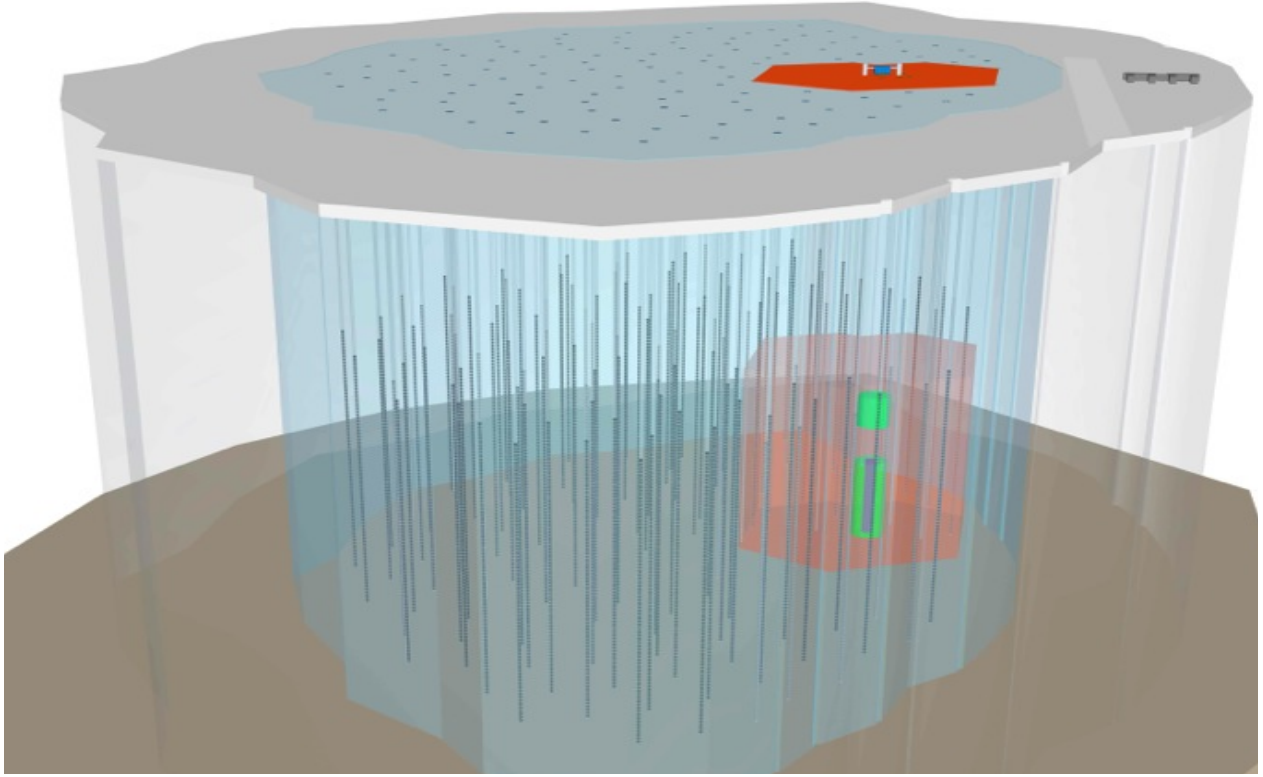
- Mediterranean
  - ORCA
  - KM3NeT
- South Pole
  - PINGU
  - Next generation IceCube
- Lake Baikal
  - GVD

- ORCA, PINGU focus on neutrino physics;
- KM3NeT, NGIC on neutrino astronomy
  - Optimize for Galactic or extra-galactic?
  - Surface veto at NGIC?

Aperture for coincident events: ν, γ, cosmic rays

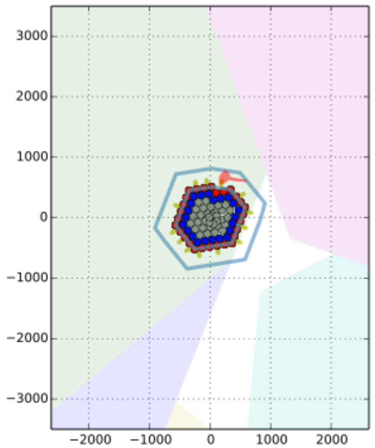
0.26 km^2 sr → ~ 10 km^2 sr





Results

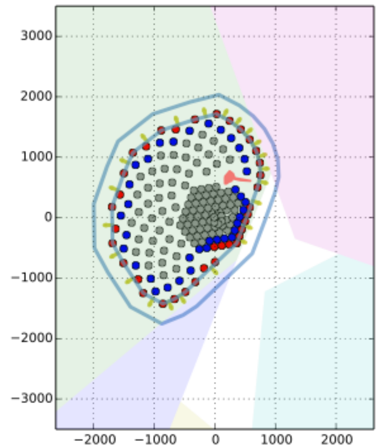
IceCube



strings: IC86

string spacing: ~125m

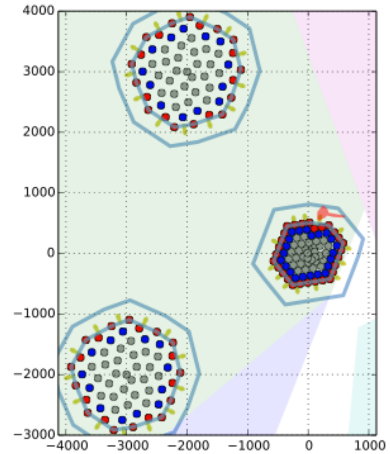
Sunflower 96



strings: IC86+96

string spacing: ~240m

Supercluster



strings: IC86+2x60

string spacing: ~240m

All results are preliminary!

Angular resolution (averages by eye):

IceCube	Sunflower 96	Supercluster
0.5°	0.4°	0.4°

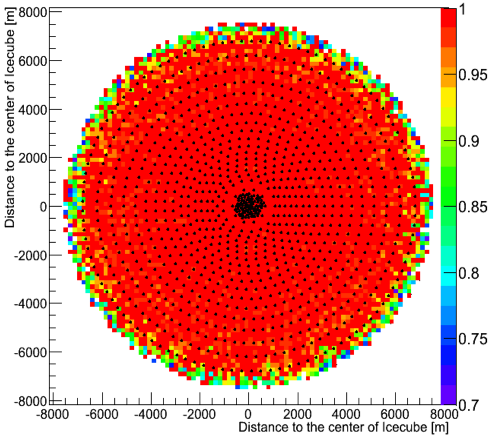
Effective area

IceCube	Sunflower 96	Supercluster
1.6 km^2	5.0 km^2	6.5 km^2

Expand surface veto (IceTop heritage)

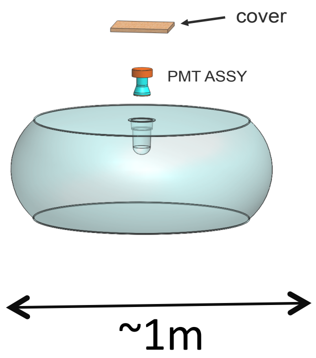
- A surface veto above 1 PeV (cosmic primary) could reject most atmospheric muon AND neutrino background above 100 TeV.
- This is a goal that needs to be demonstrated
- Could work with present IceCube

ν_μ

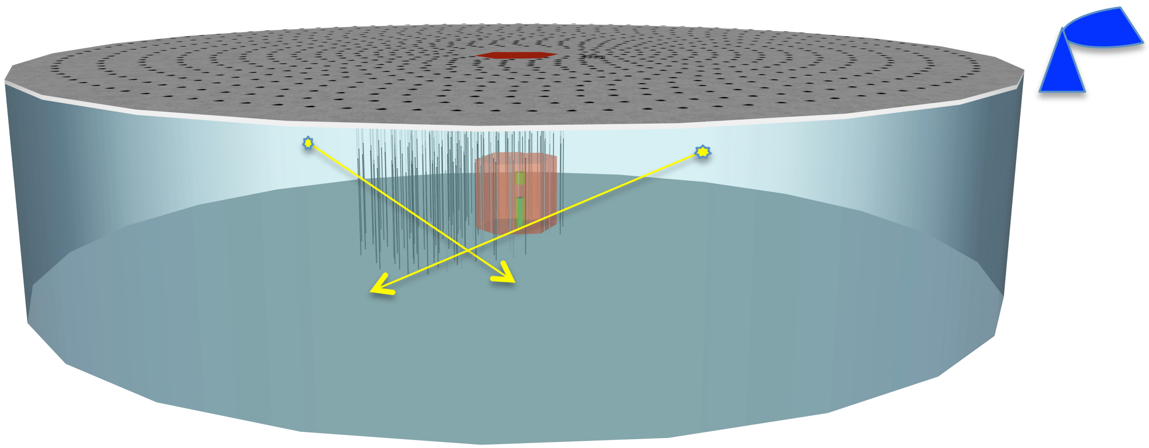


~1000 modules

R&D under way



Air shower veto array



Enjoy RICAP 2014!