DI LUCIA SIMION

Neutrino Astronomy with the IceCube Observatory

Implications for Astroparticle Physics

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University of Wisconsin - Madison

Vulcano Workshop May 30, 2008

outline

neutrinos

cosmic rays

gamma rays

neutrino astronomy

particle physics

toward a km^3 Observatory

AMANDA & IceCube

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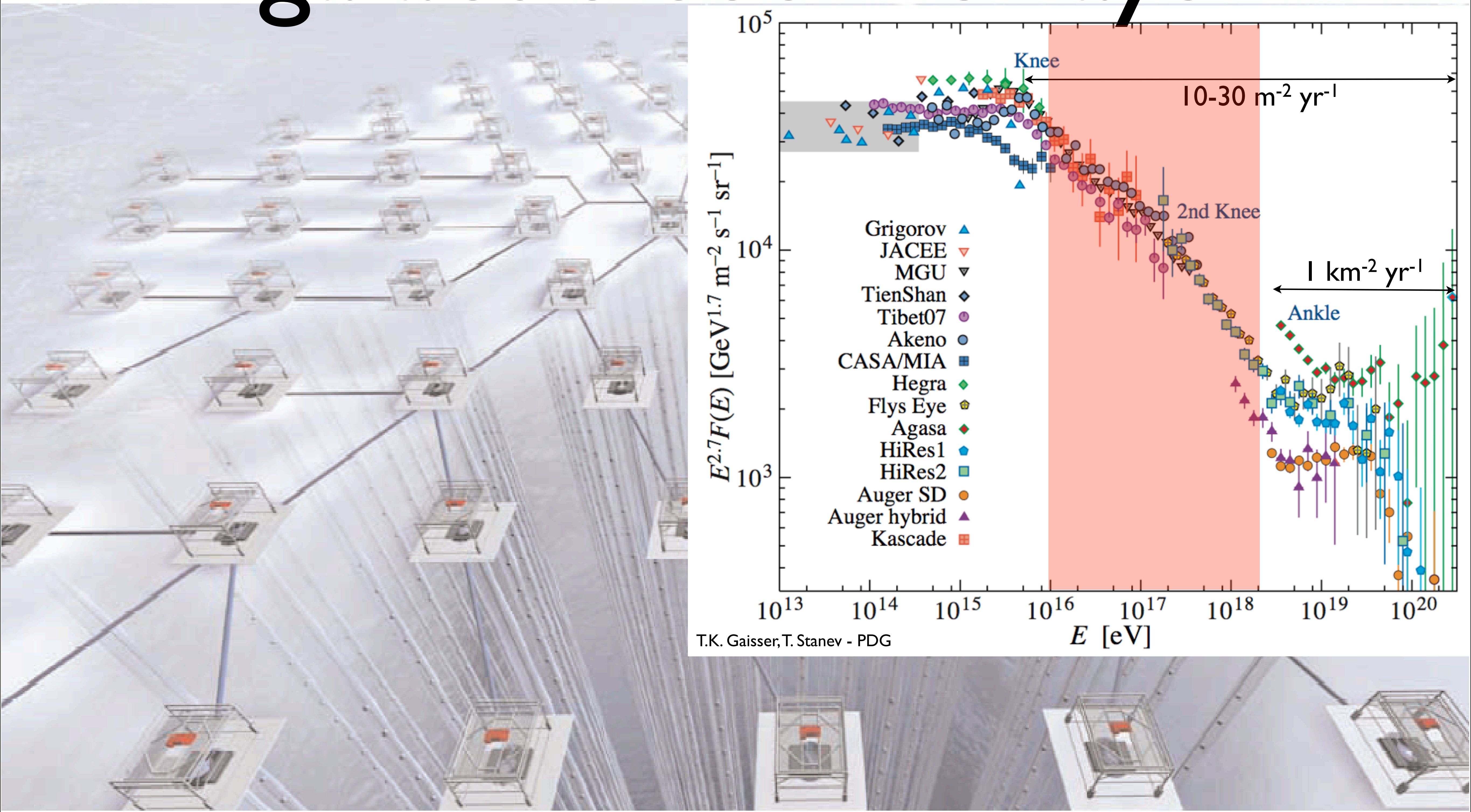
galactic cosmic rays



T.K. Gaisser, T. Stanev - PDG

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galactic cosmic rays

observed energy density

$\rho \sim 10^{-12}$ erg/cm^3

$\backsimeq$

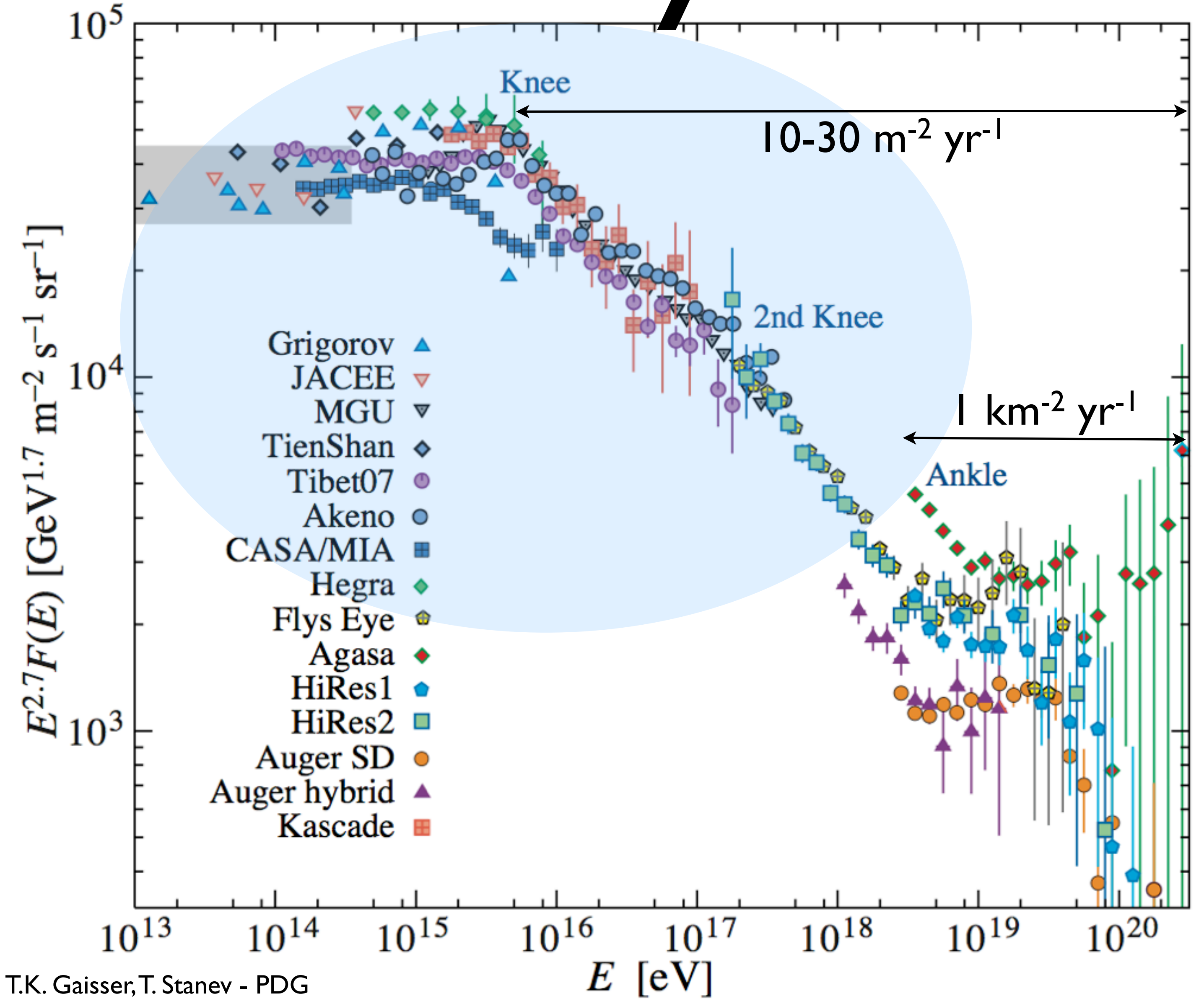
supernova remnants

$\sim 10^{50}$ erg / 50 years

$\rho \sim 10^{-12}$ erg/cm^3

$\Downarrow$

SNR as sources of galactic cosmic rays

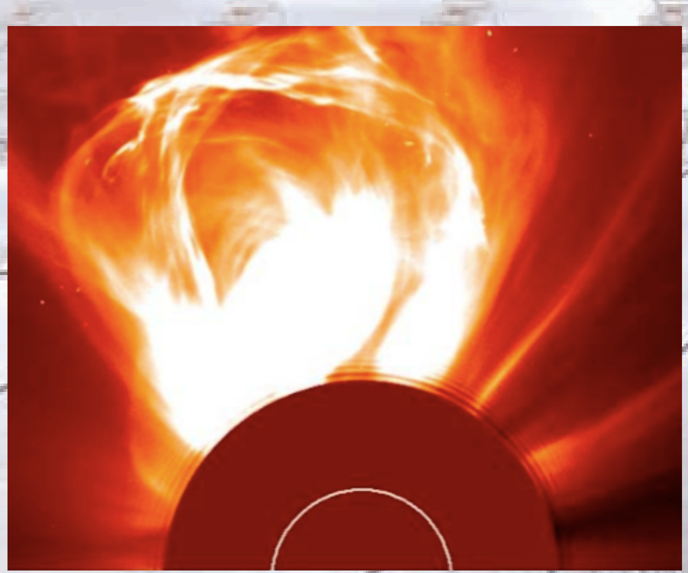


T.K. Gaisser, T. Stanev - PDG

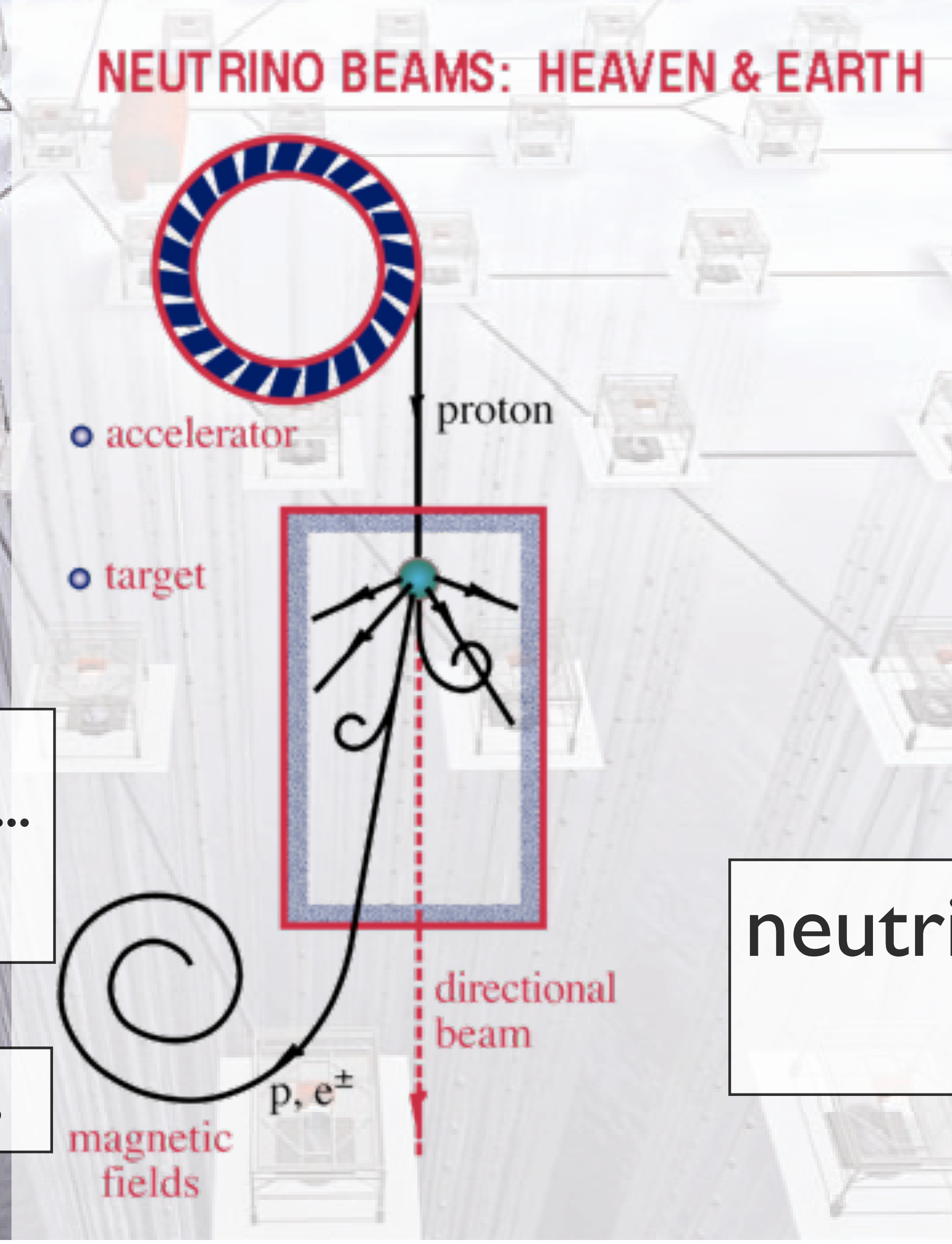
$\Rightarrow$ shock front from Supernovæ ... PeVatrons

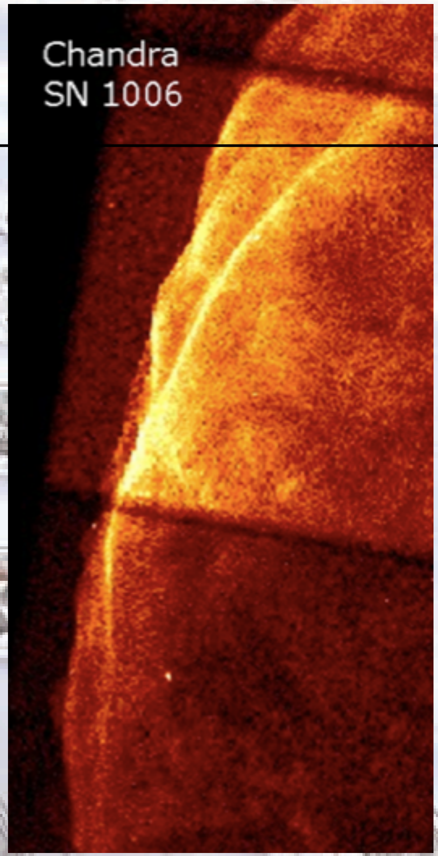
shock acceleration

solar shock acceleration
well known



observed shocks in SNR





$p + (p \text{ or } \gamma) \rightarrow \pi^{\pm} + X \rightarrow \nu_e, \nu_\mu + X$ neutrinos ...

$\rightarrow \pi^{o} + X \rightarrow \gamma\,\gamma + X$ gamma rays ...

Flux $\sim E_p^{-2}$ (Fermi acceleration)

protons @ knee produce ~ 300 TeV γ rays

neutrino and gamma
connection

γ ray observations

HESS/Magic observations ≲ 10'sTeV

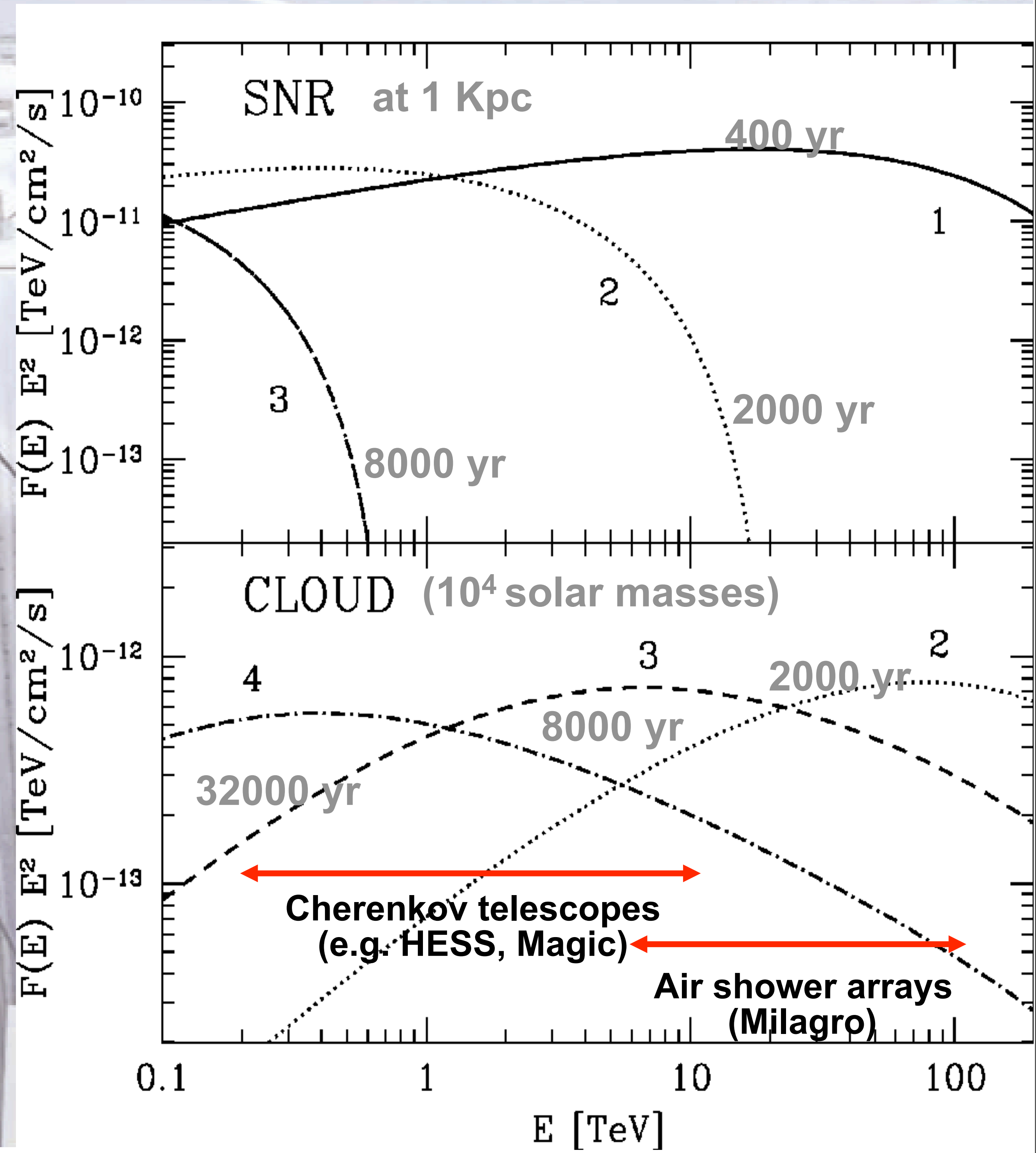
PeV particles escape within ~1,000 yr

low energy particles mostly confined and released in later times

only young SNR (≲1,000 yr) emit >10 TeV γ rays and ν

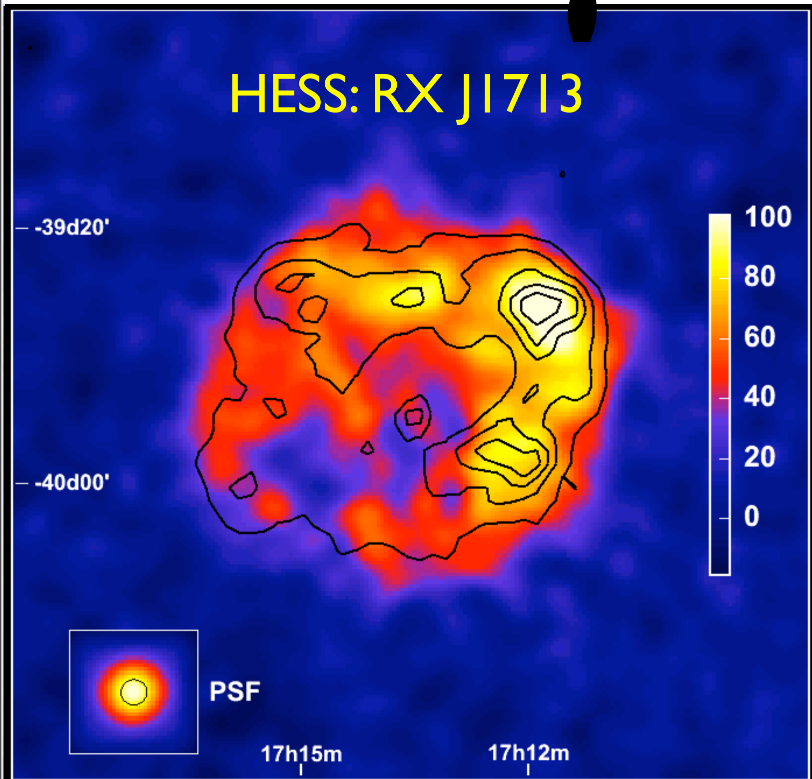
PeV particles hitting molecular clouds can produce *delayed* multi-TeV γ rays and ν

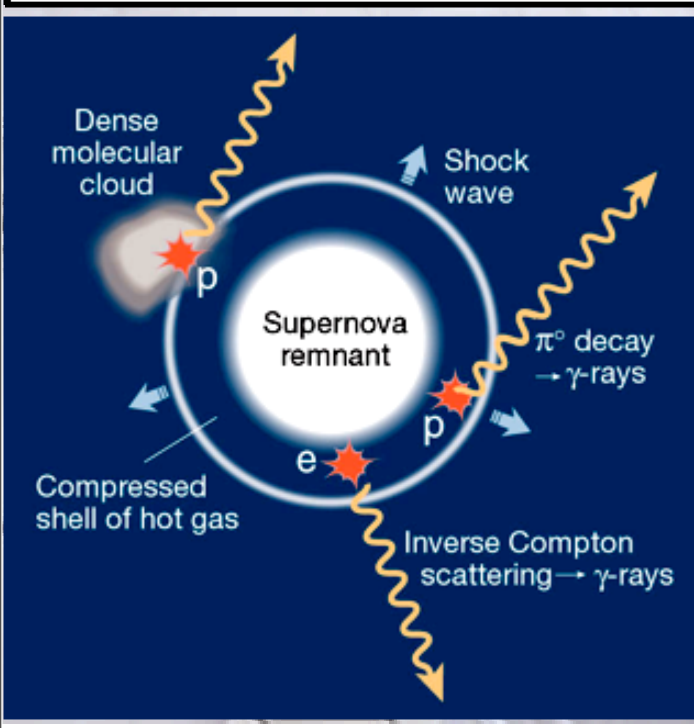
hard spectra because not yet steepened by diffusion



Gabici, Aharonian, arXiv:0705.3011

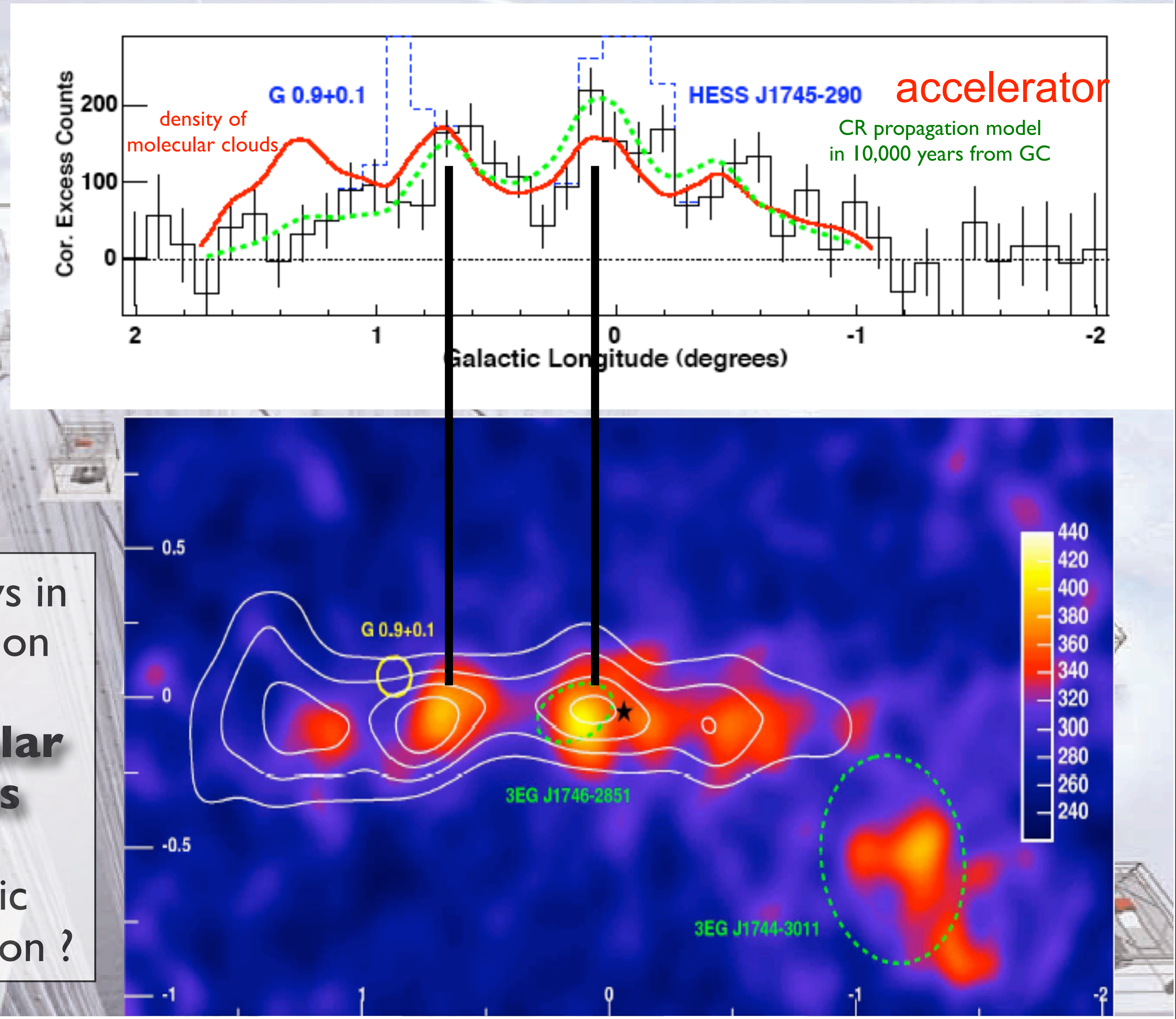
γ ray observations





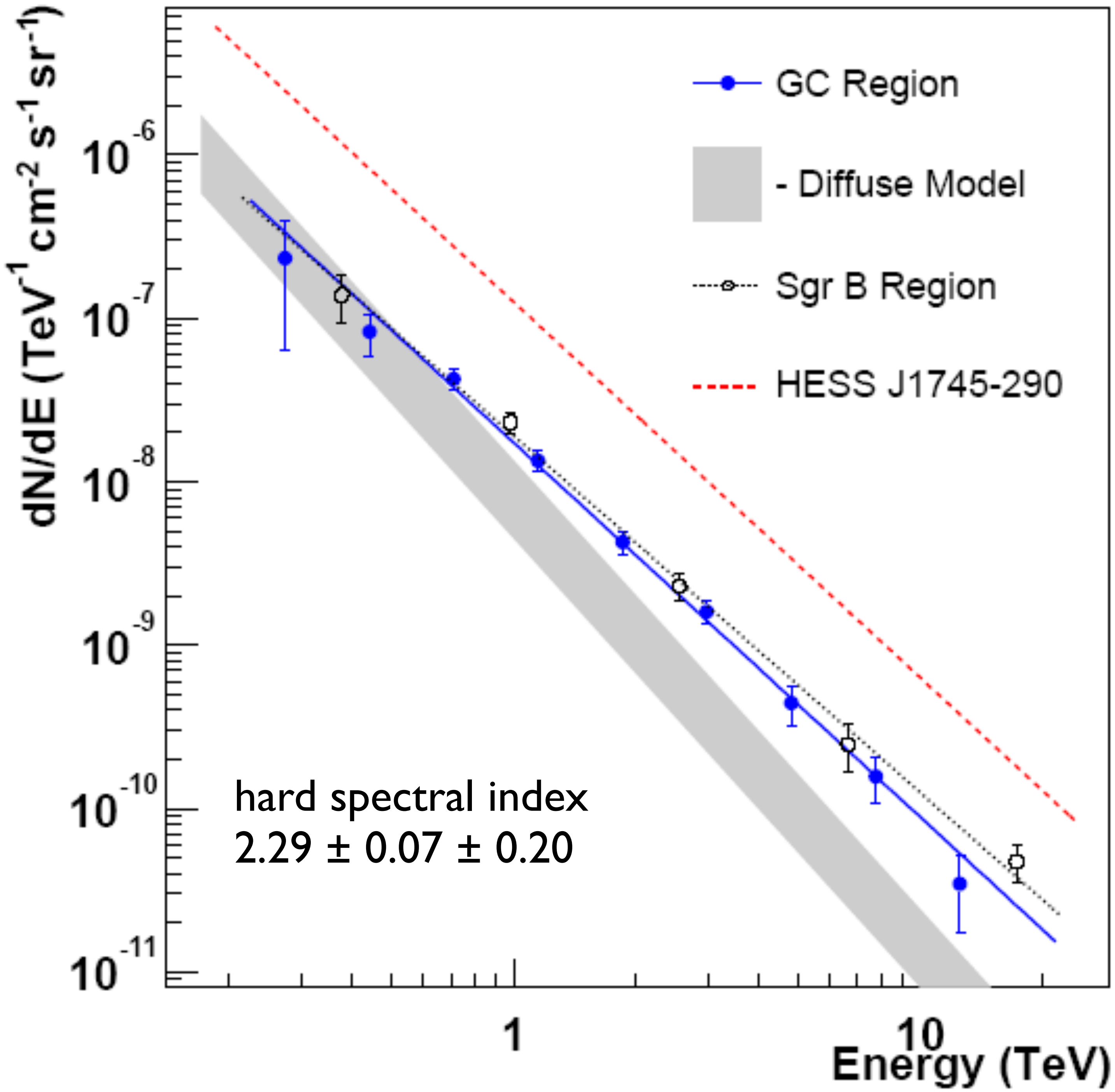
TeV γ rays in correlation with **molecular clouds**

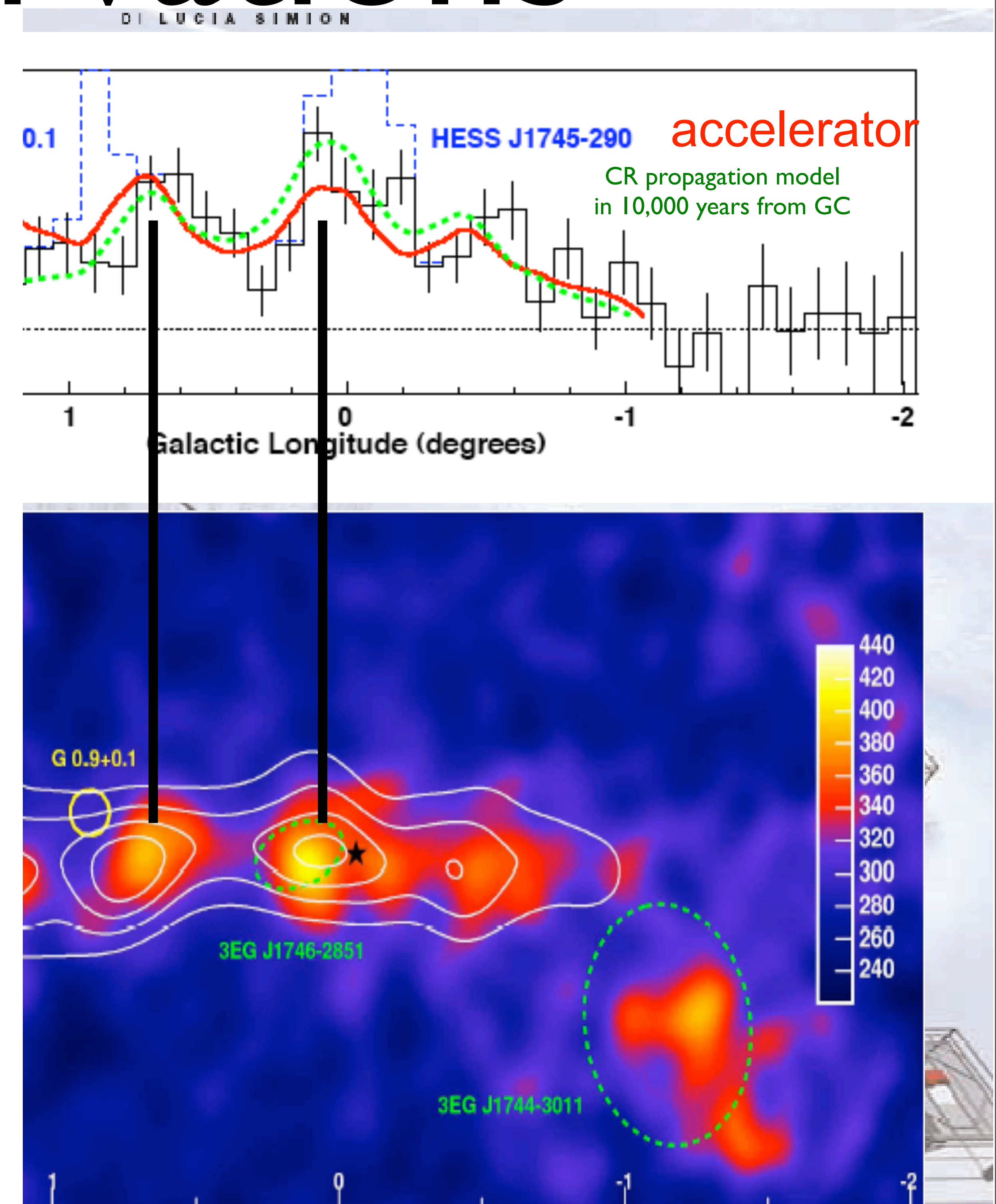
hadronic acceleration ?



Aharonian et al., Nature 439 (2006), 695

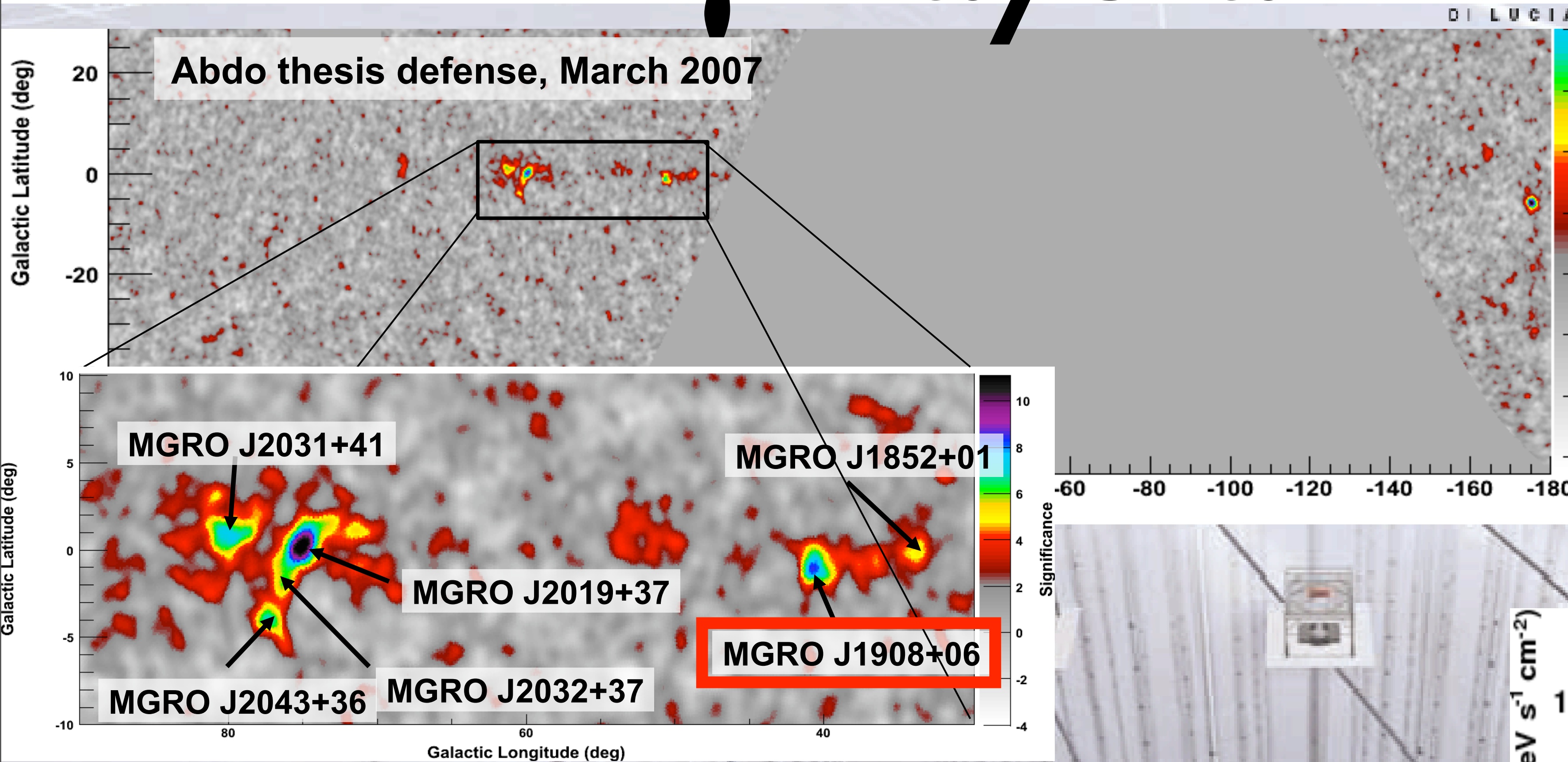
γ ray observations

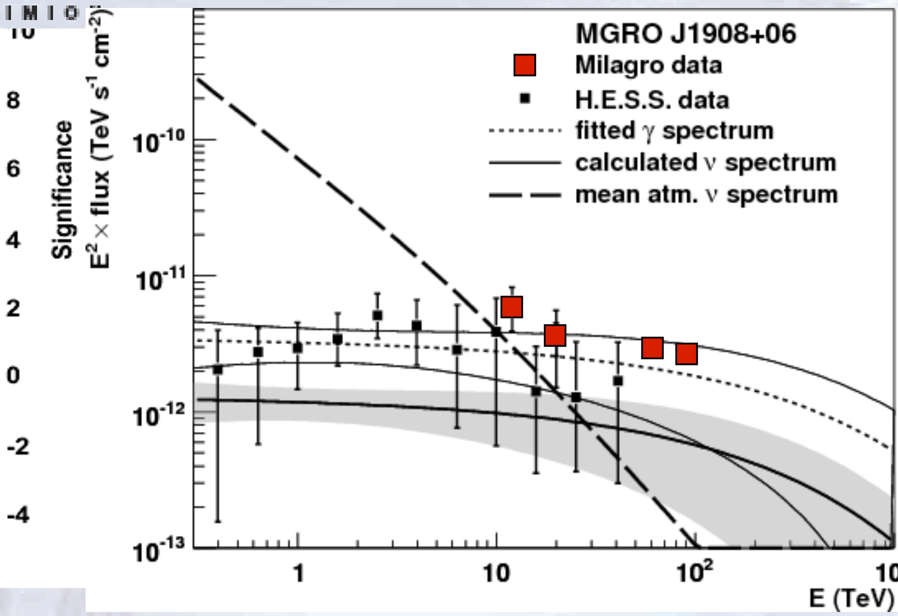




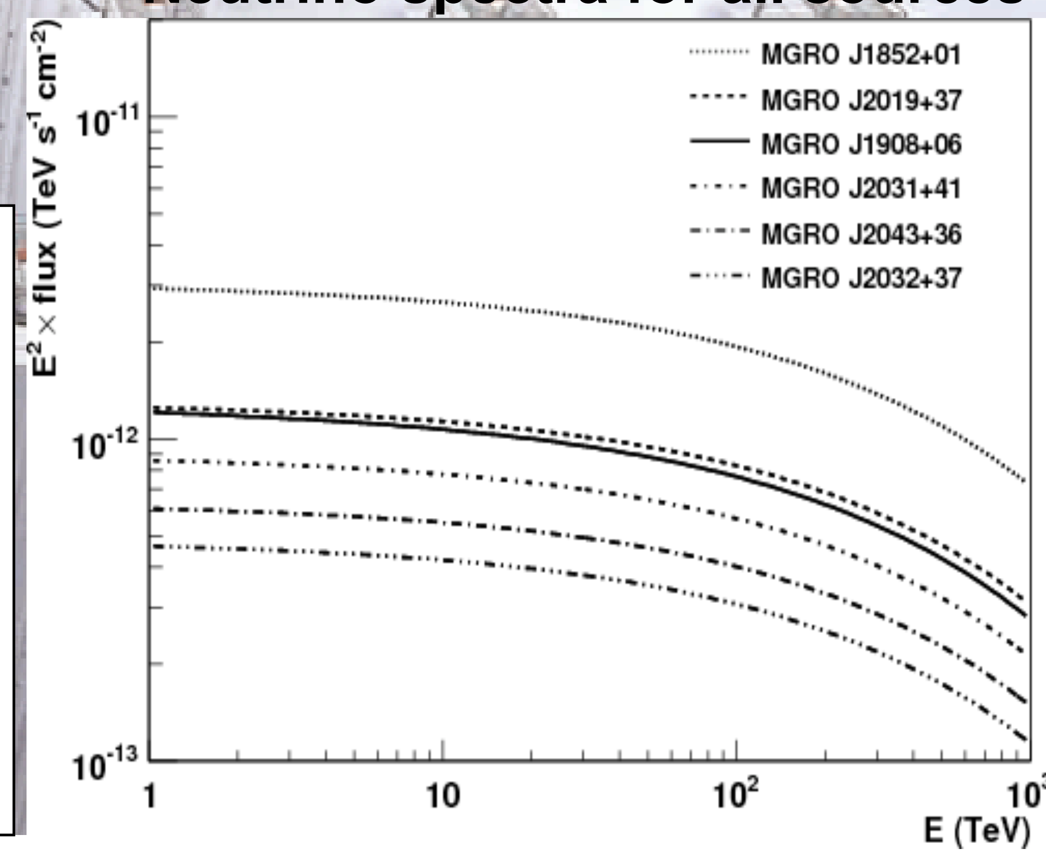
Aharonian et al., Nature 439 (2006), 695

γ rays and ν’s





Neutrino spectra for all sources



Halzen, Kappes, O’Murchadha arXiv:0803.0314

Milagro measurement at ~100 TeV

strong indication of proton acceleration

ν’s as uncontroversial sign of hadronic acceleration
⇒ Neutrino Telescopes

extra-galactic cosmic rays

observed energy density

$\rho \sim 3\times10^{-19}$ erg/cm^3 ($\times10^{10}$y)

$\rho \sim 10^{44}$ erg/yr/Mpc^3

≃

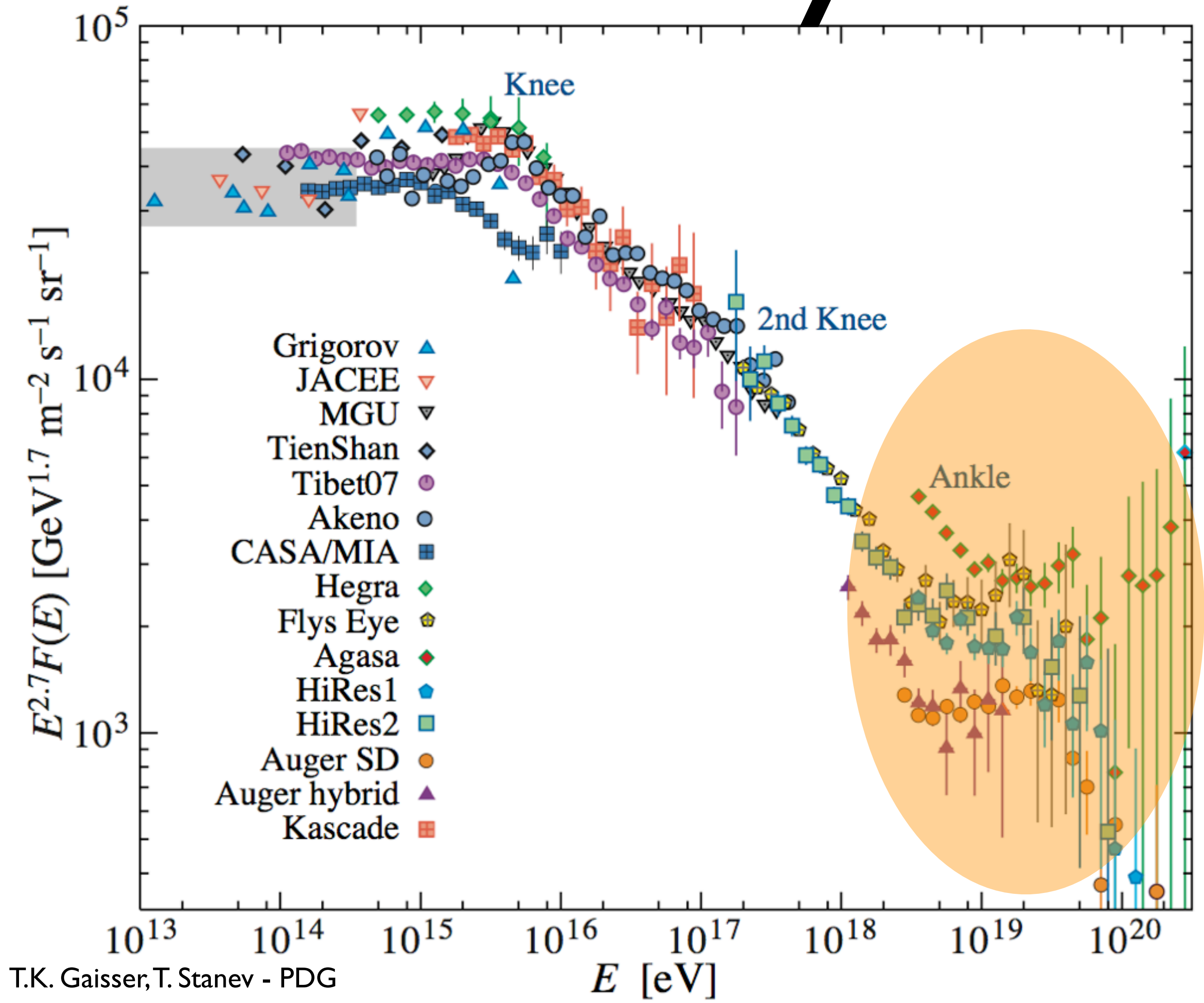
GRB

$\sim10^{51}$ erg$\times$300/y/Gpc^3

$\rho \sim 10^{44}$ erg/yr/Mpc^3

⇓

GRB/AGN as source candidates of extra-galactic cosmic rays



T.K. Gaisser, T. Stanev - PDG

⇒ large sizes and intense magnetic fields

cosmic ray astronomy ?

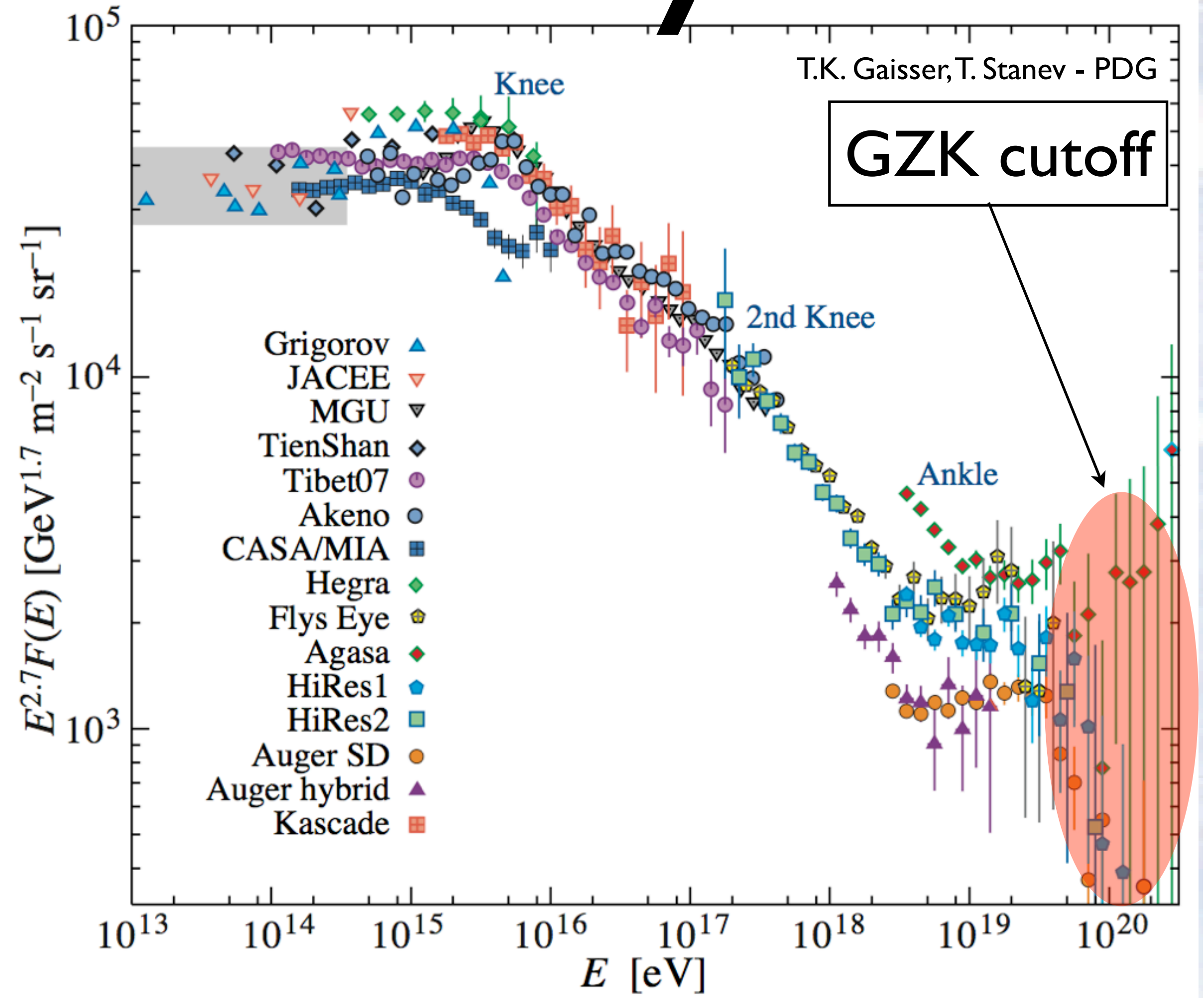
protons with E > 10^{19} eV almost un-deflected

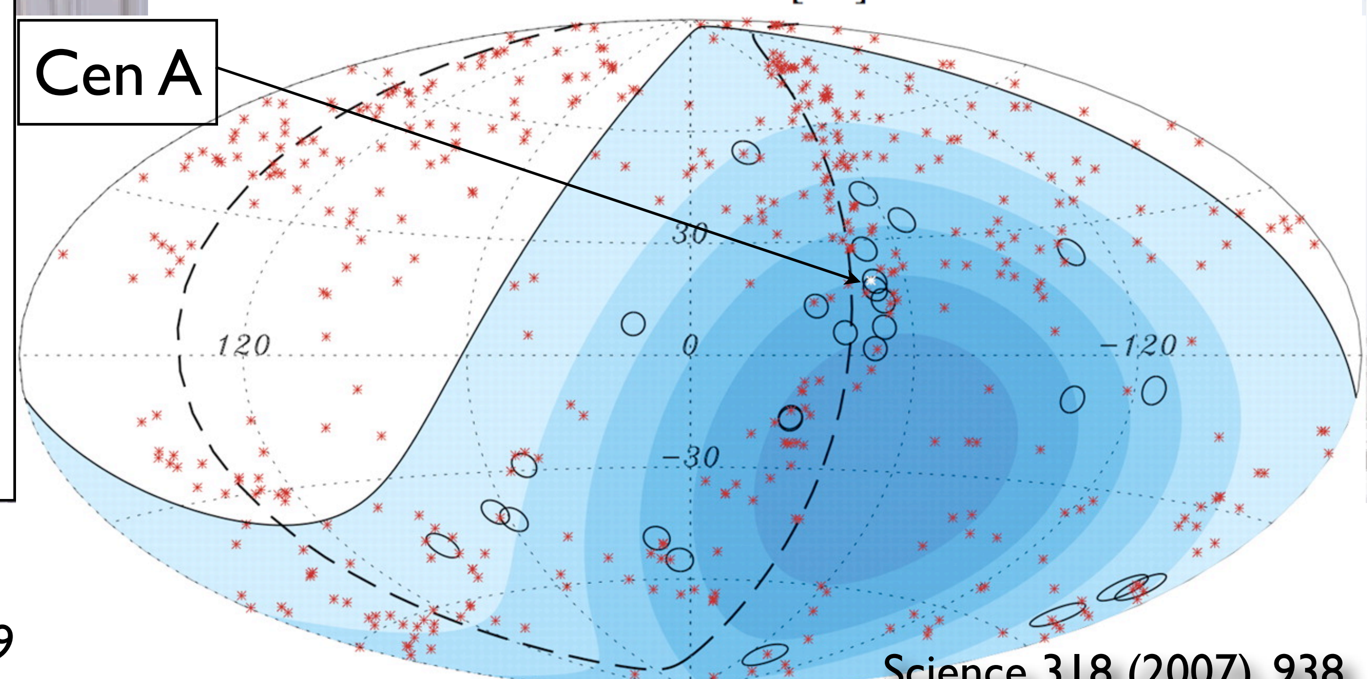
cosmic rays above 6×10^{19} eV

consistent with GZK cutoff

protons from nearby AGN sources with p-value = 1.7×10^{-3}

to be confirmed with more experimental data





Science 318 (2007), 938

neutrinos and cosmic rays

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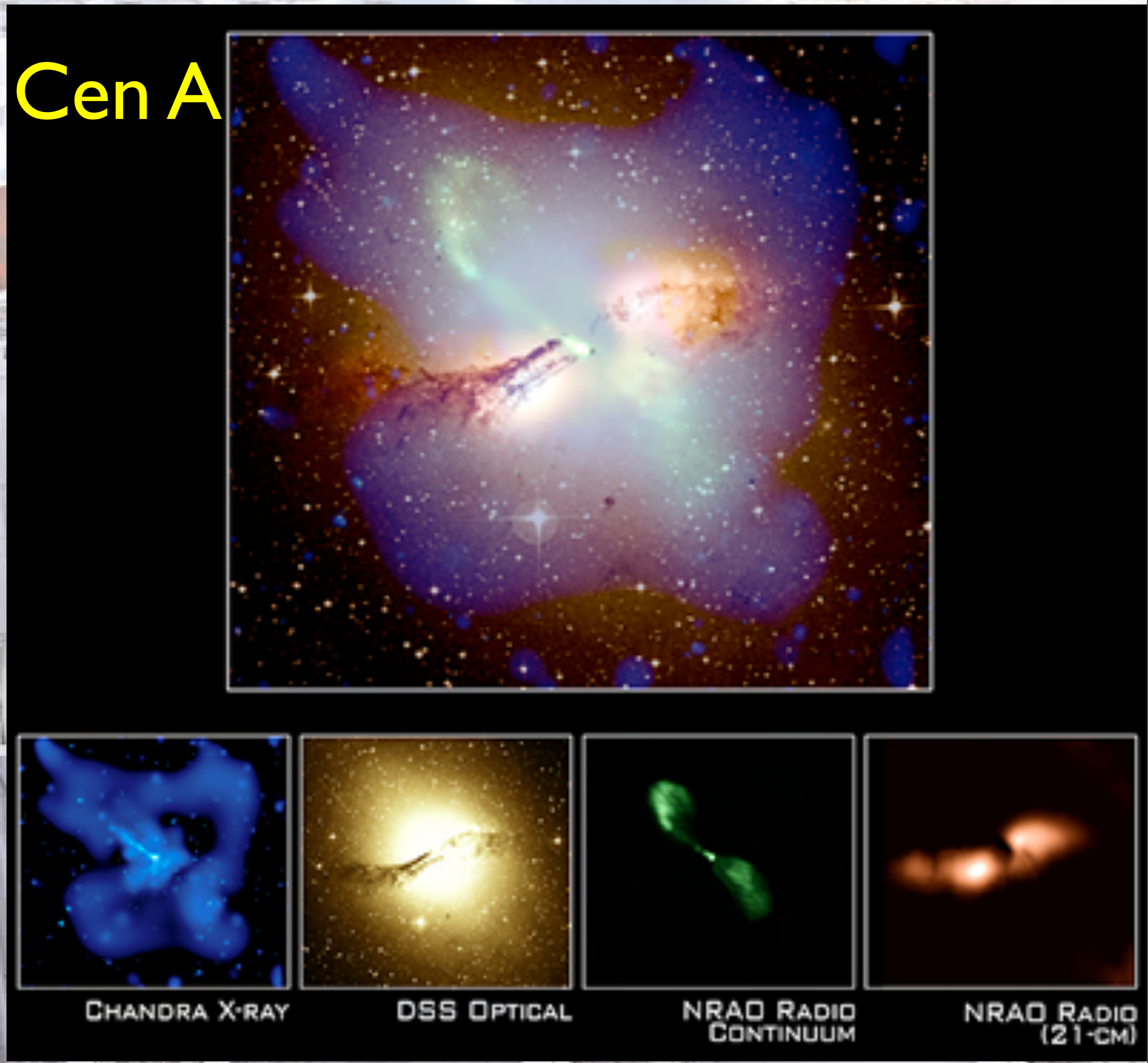
nearby AGN (as Cen A) possible hadronic acceleration sites and sources of TeV γ rays

if γ rays flux from Cen A is from π and normalizing to Auger observation

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-2} \text{TeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}$$

$$\Downarrow$$

$$\frac{dN_\nu}{dE}_{\text{diff}} = 2 \times 10^{-9} \left(\frac{E}{\text{GeV}}\right)^{-2} \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$$



Halzen, O'Murchadha arXiv:0802.0887v2

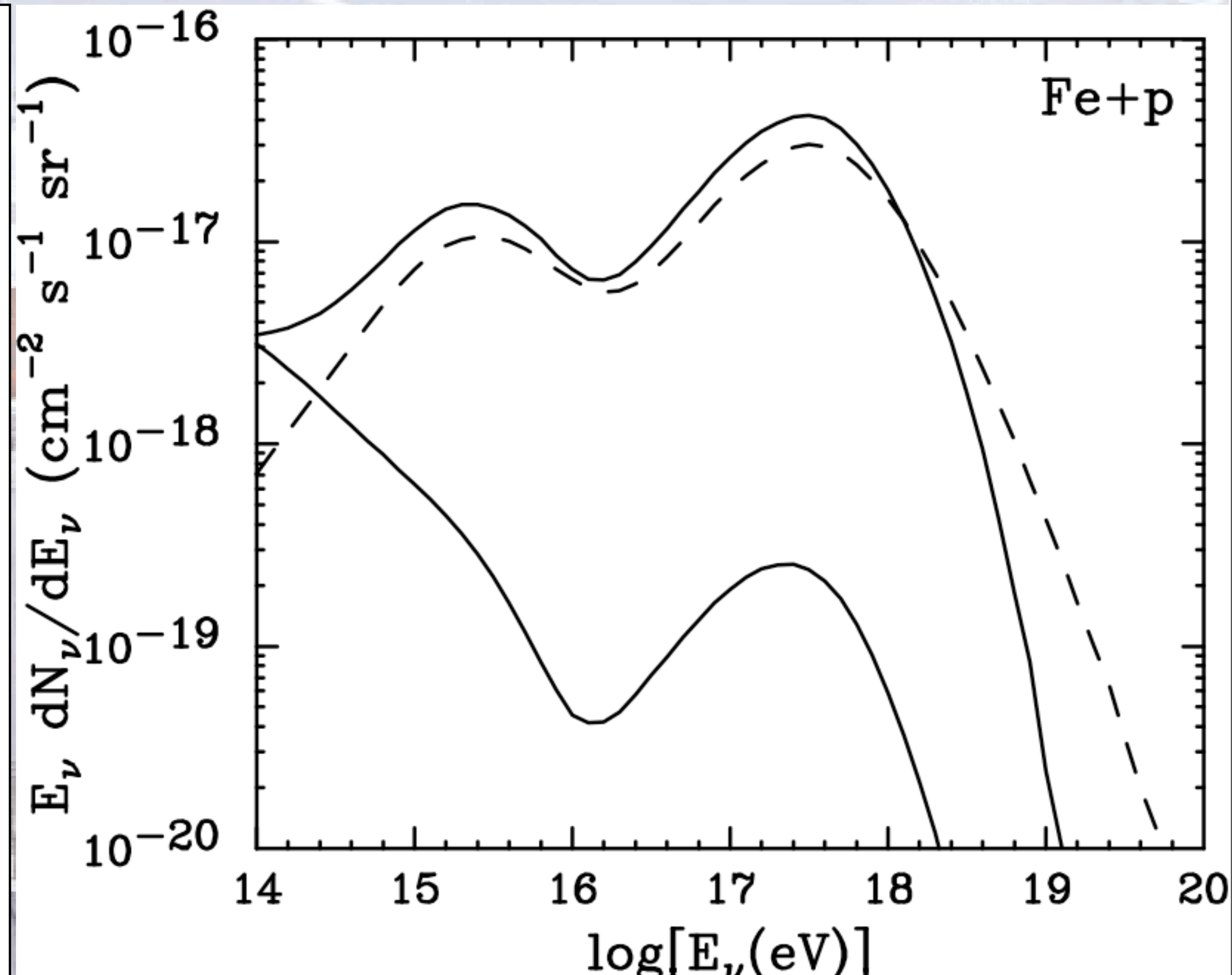
neutrinos and GZK cutoff

Auger suggests a CR composition heavier than pure H $\gtrsim 10^{19}$ eV

even if dip at ~ 10^{19} eV is signature of $p\gamma_{CMB} \longrightarrow e^+e^-$

if heavy CR then cosmogenic ν's are suppressed

Auger spectrum & composition consistent with ~CNO masses or p+Fe mixture. But NOT consistent with injected p/He only.



50% Fe, 50% p	1.6-2.1	10^{22} eV	0.15-0.043	0.11-0.034
10% Fe, 90% p	1.4-1.9	10^{21} eV	0.14-0.10	0.11-0.080
3% Fe, 97% p	2.1	10^{22} eV	0.68	0.51
1% Fe, 99% p	1.4-1.9	10^{21} eV	0.74-0.53	0.59-0.43
100% p (for comparison)	2.2	10^{22} eV	0.76	0.60

L.A. Anchordoqui, et al., arXiv:0709.0734v1

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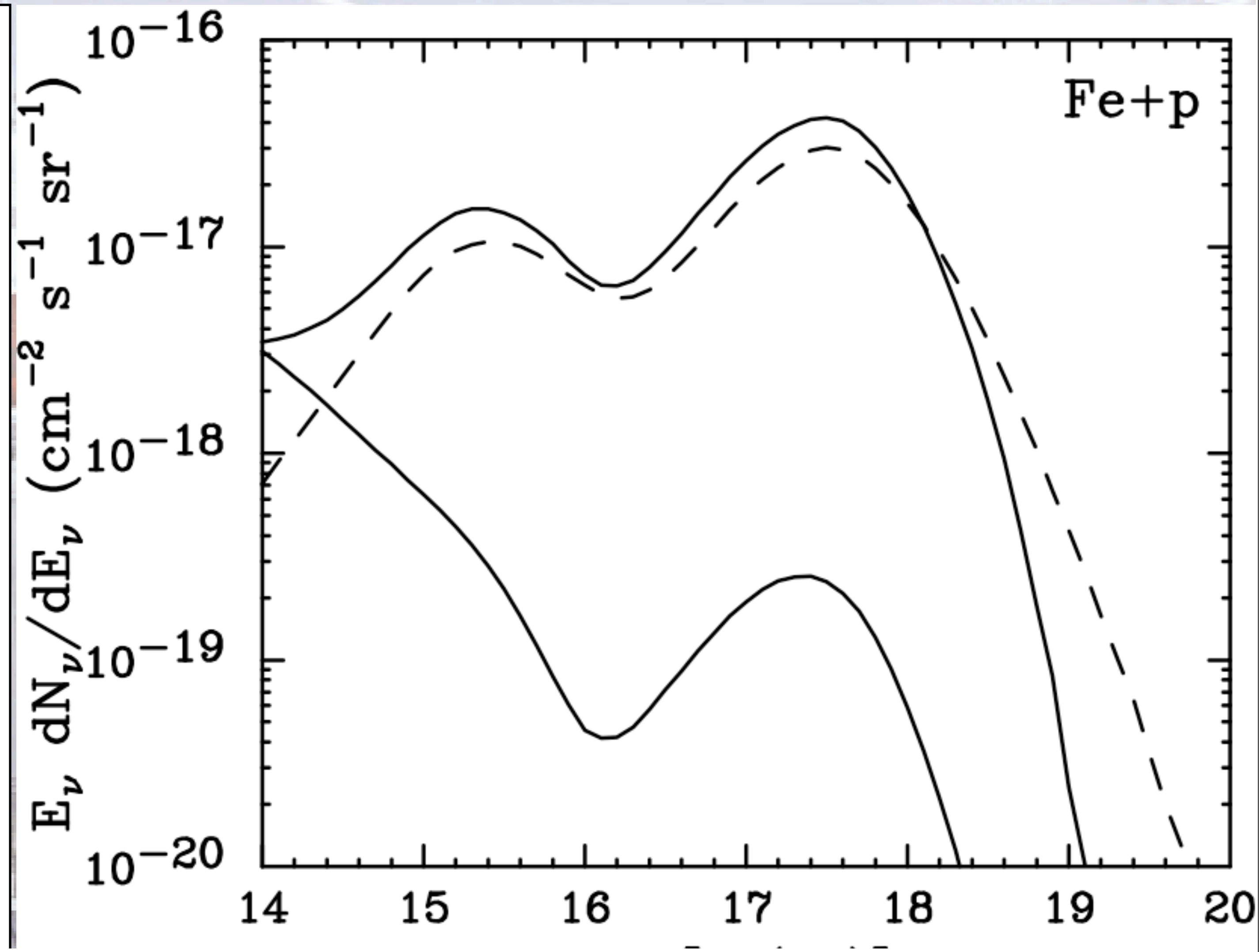

Auger sp

consister

p+Fe mix

with injected p/He only.

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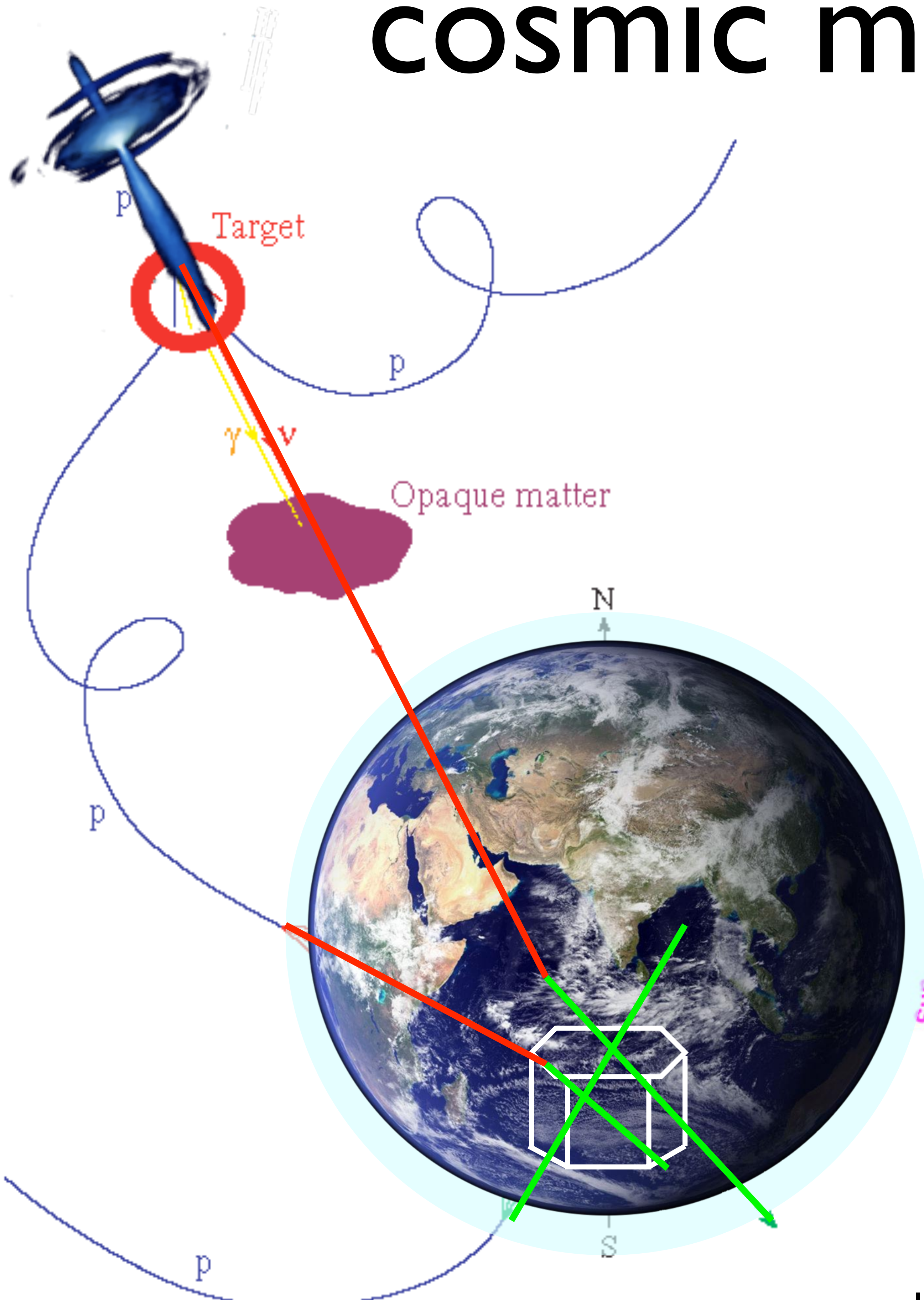
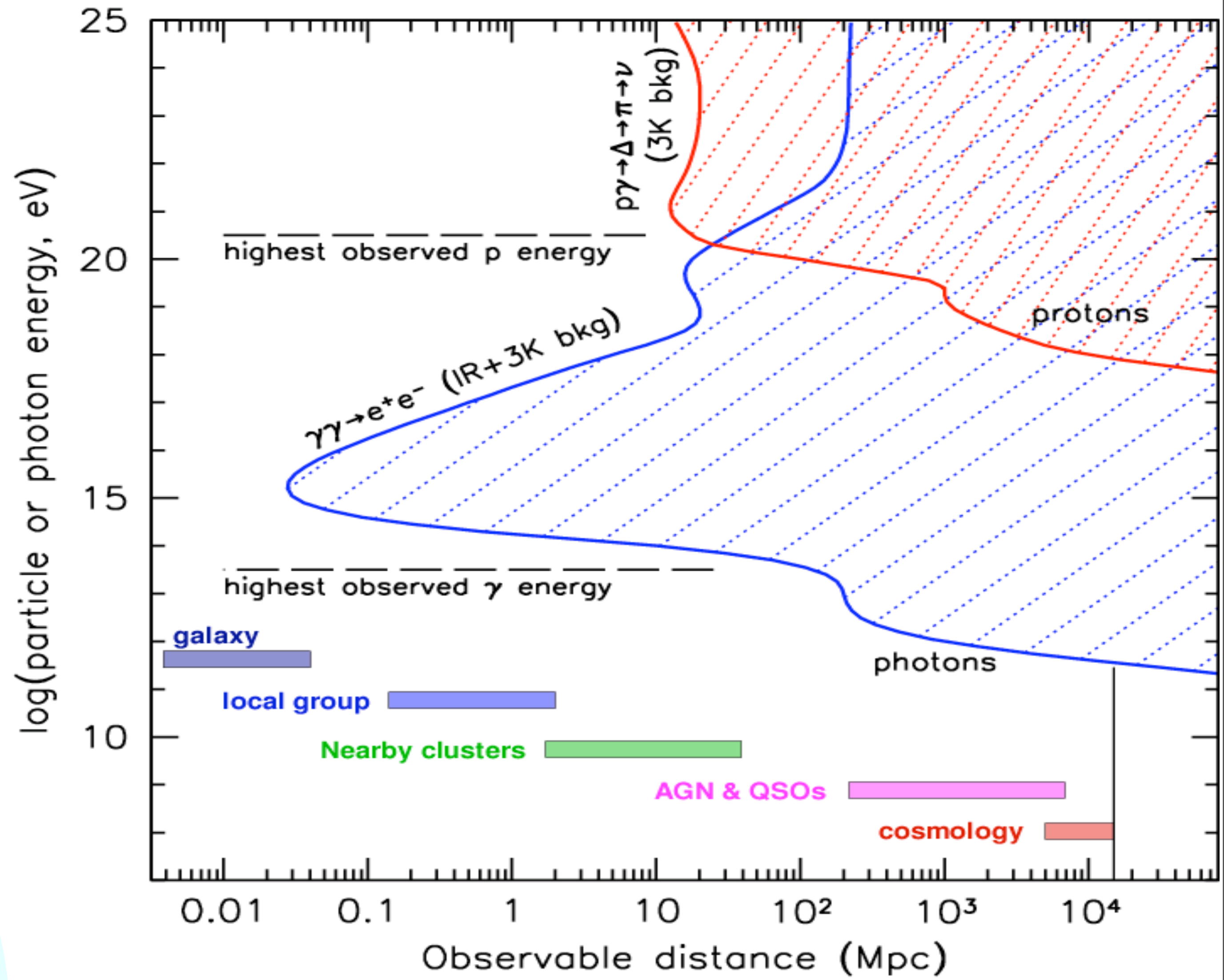
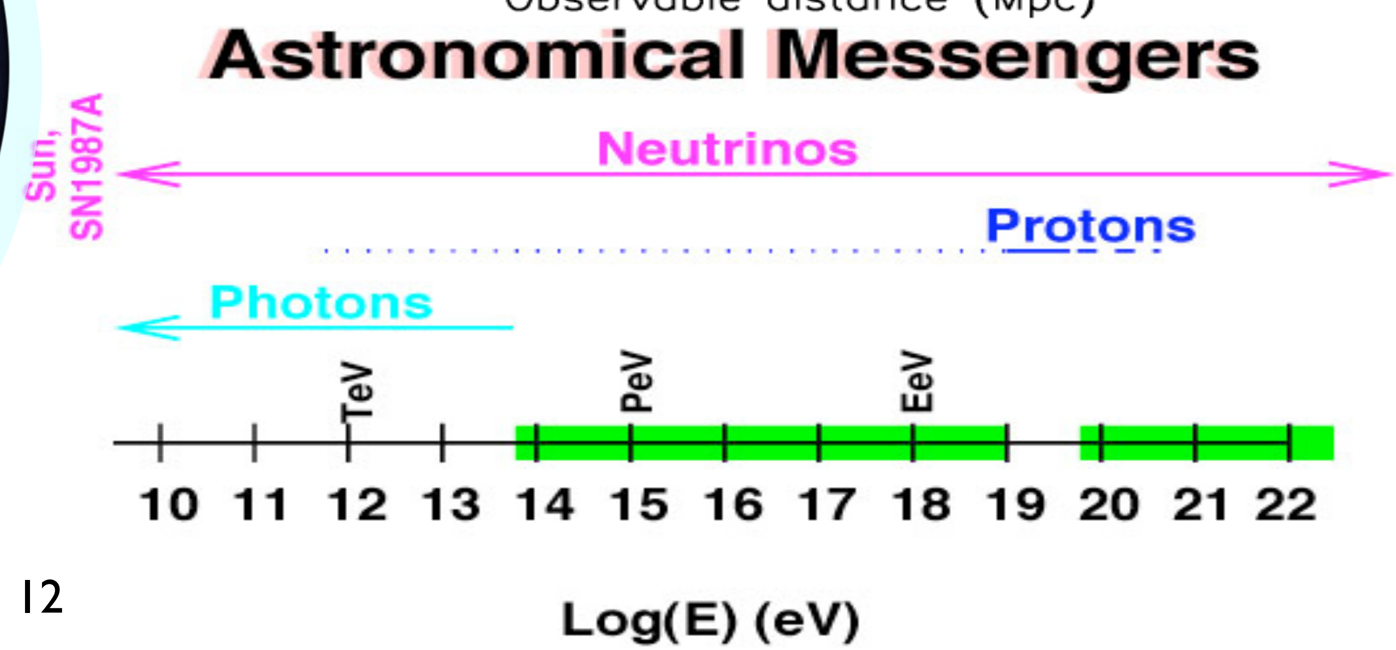
cosmic messengers







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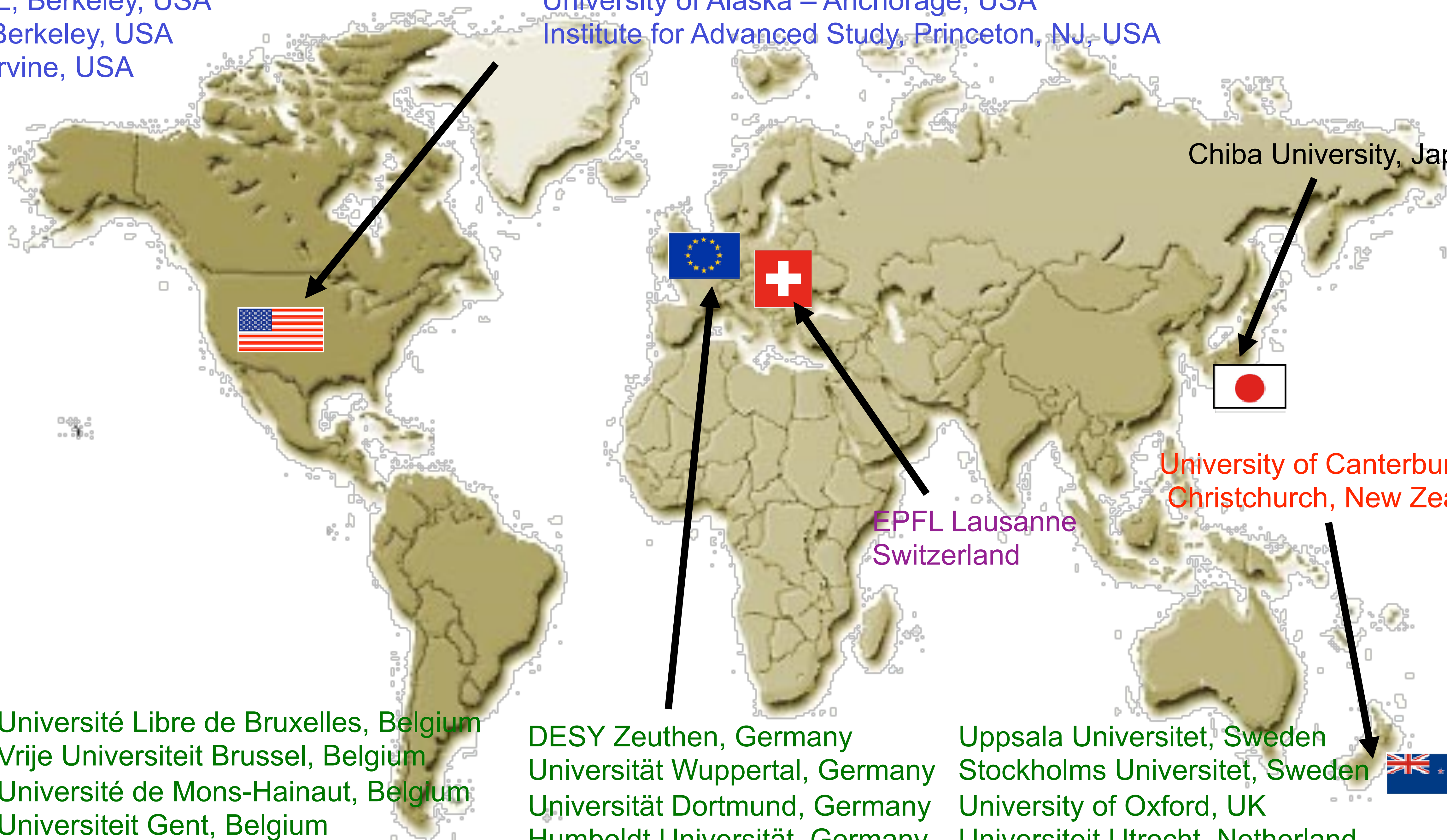
Who is in IceCube ?

Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA

Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
University of Alaska – Anchorage, USA
Institute for Advanced Study, Princeton, NJ, USA



Chiba University, Japan

University of Canterbury, Christchurch, New Zealand

EPFL Lausanne Switzerland

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
RWTH Aachen Universität, Germany

DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany
Humboldt Universität, Germany
MPIfK Heidelberg, Germany

Uppsala Universitet, Sweden
Stockholms Universitet, Sweden
University of Oxford, UK
Universiteit Utrecht, Netherland

Amundsen-Scott Station, Antarctica

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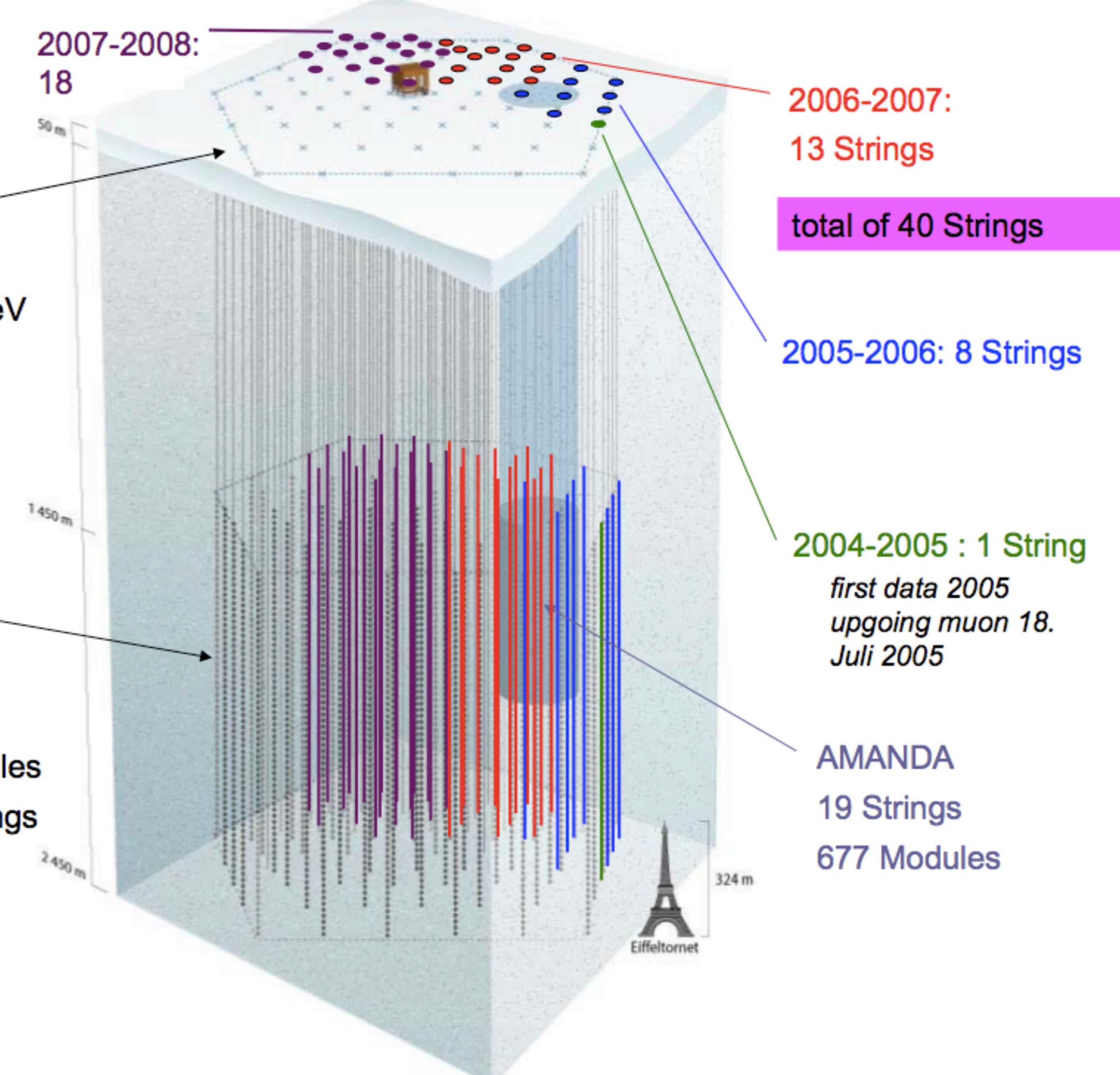
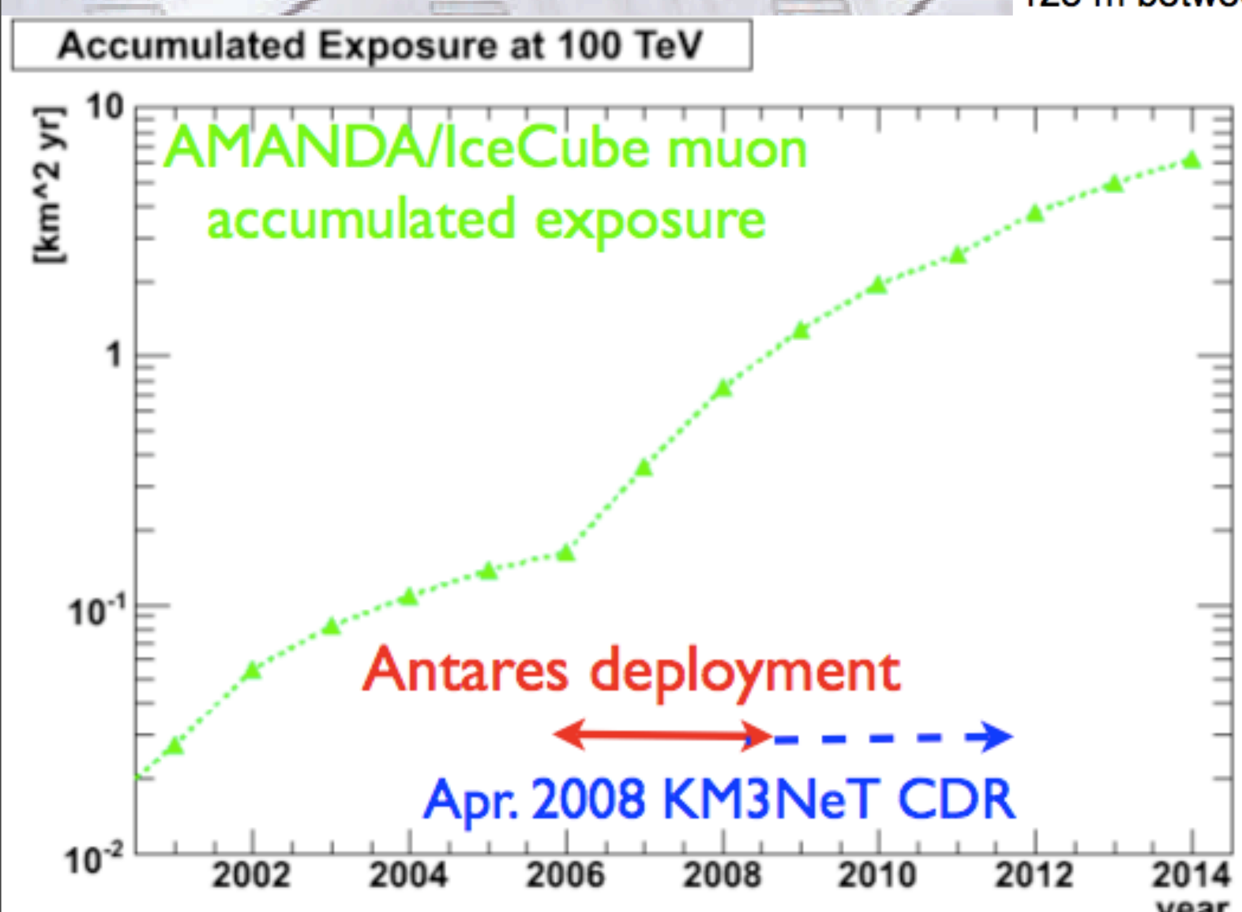
IceCube Observatory

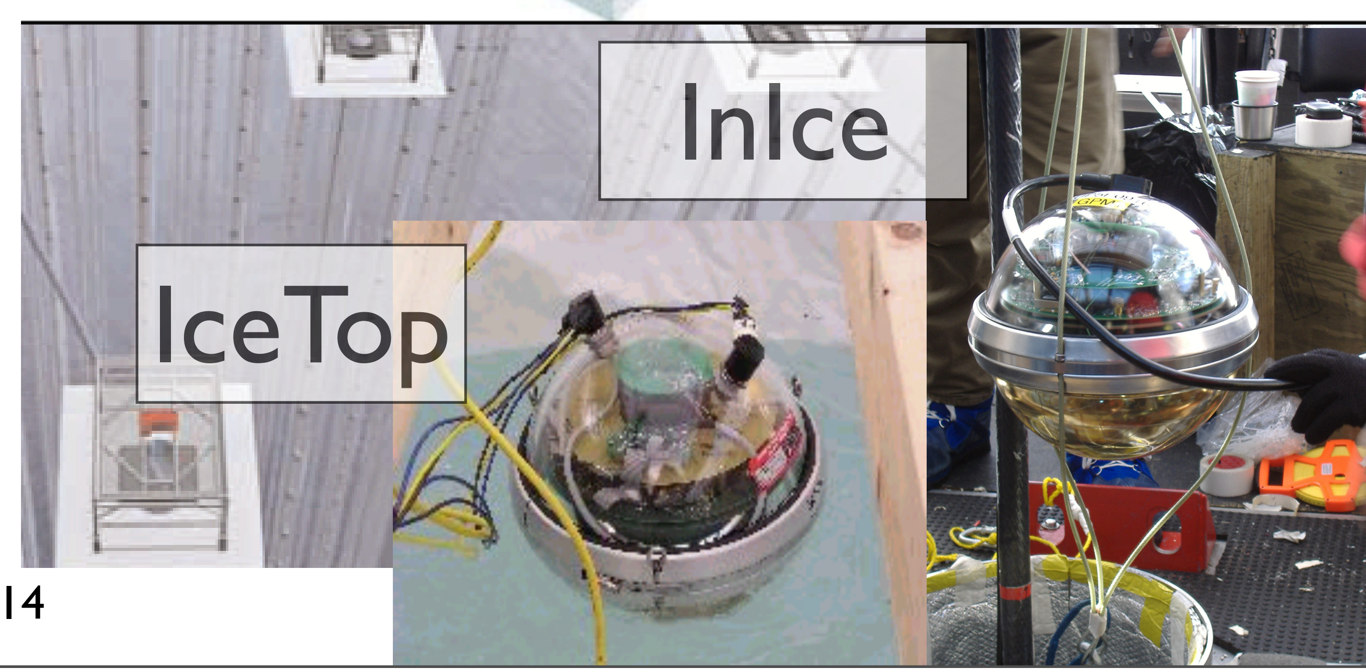
km^3
neutrino telescope

IceTop
Air shower detetor
threshold ~ 300 TeV

InIce
70-80 Strings ,
60 Optical Modules
17 m between Modules
125 m between Strings







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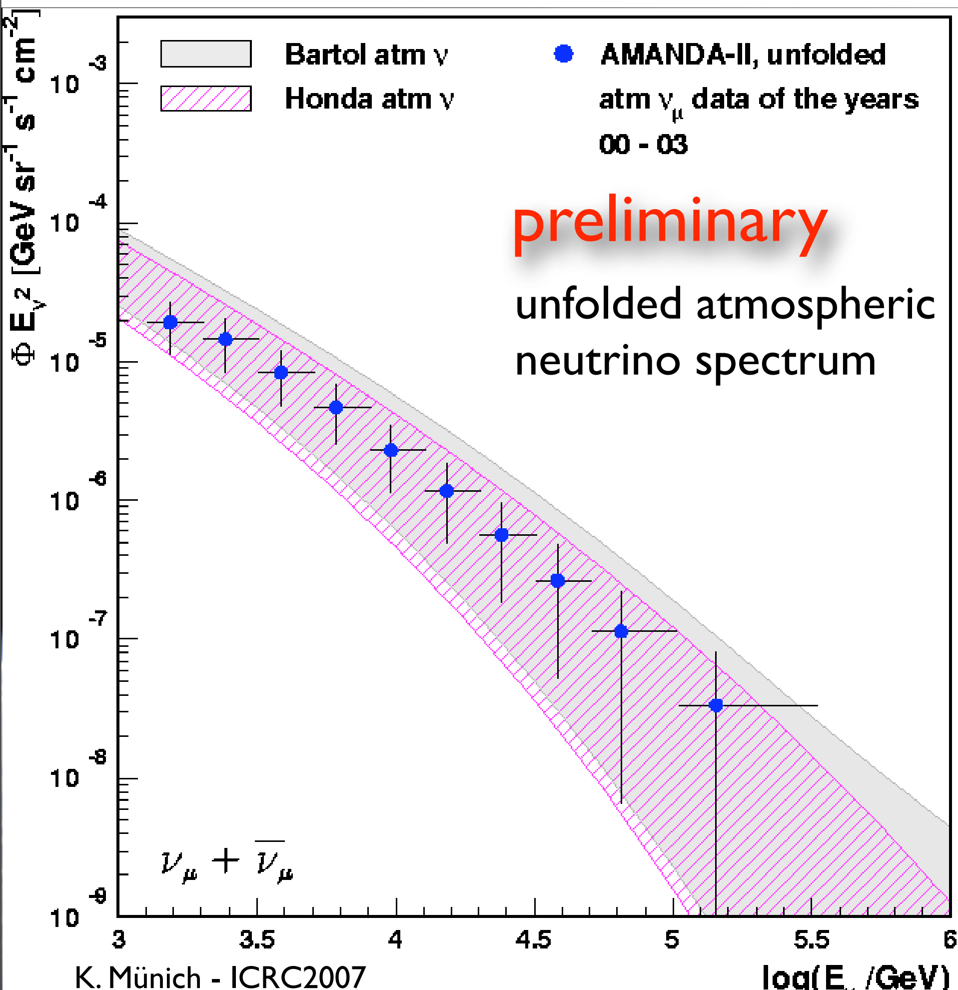
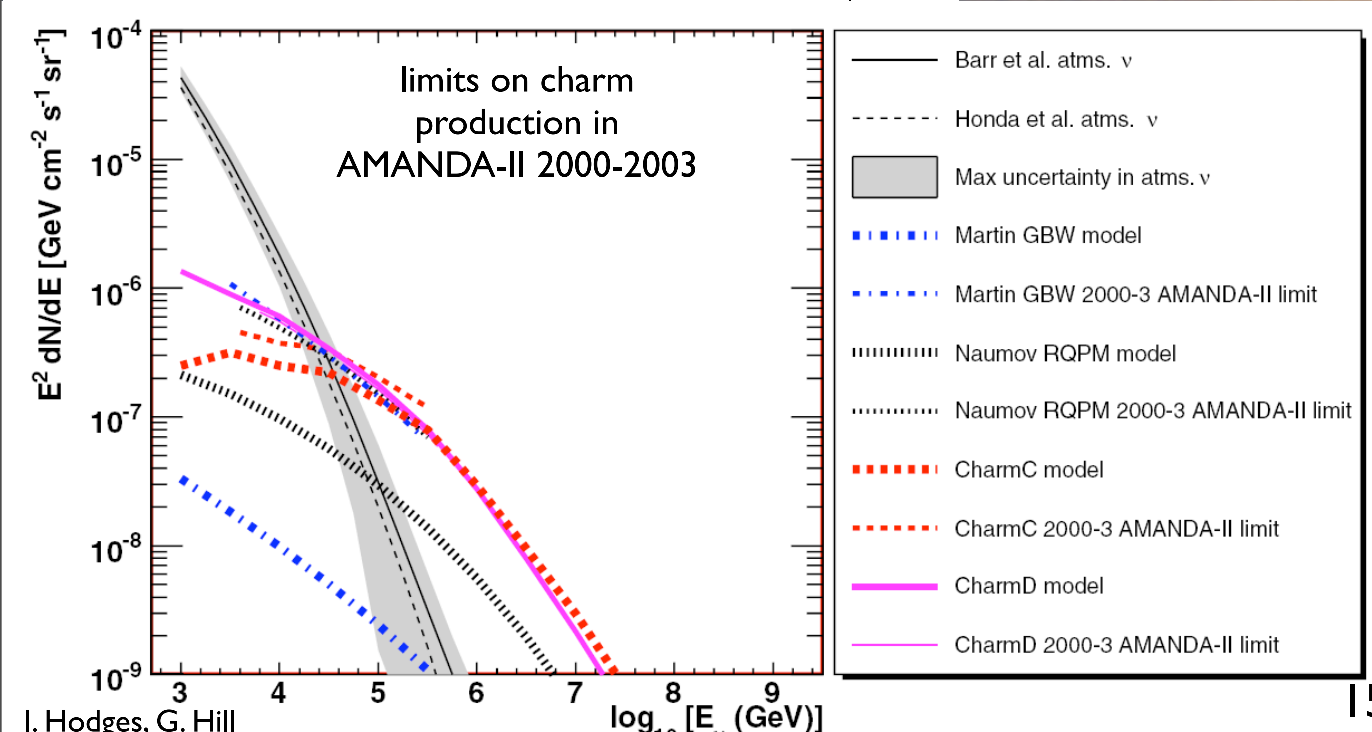
detecting neutrinos





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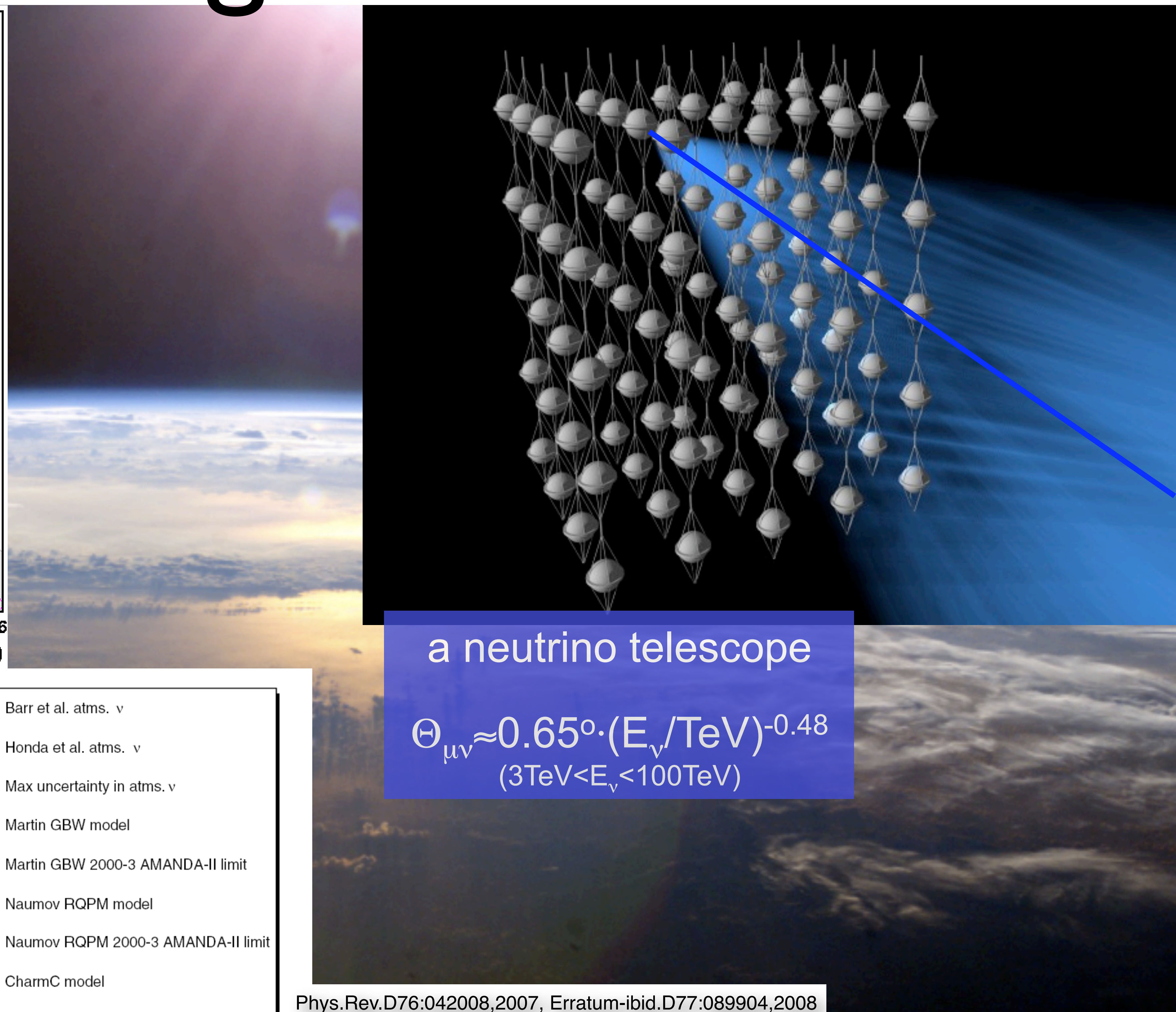
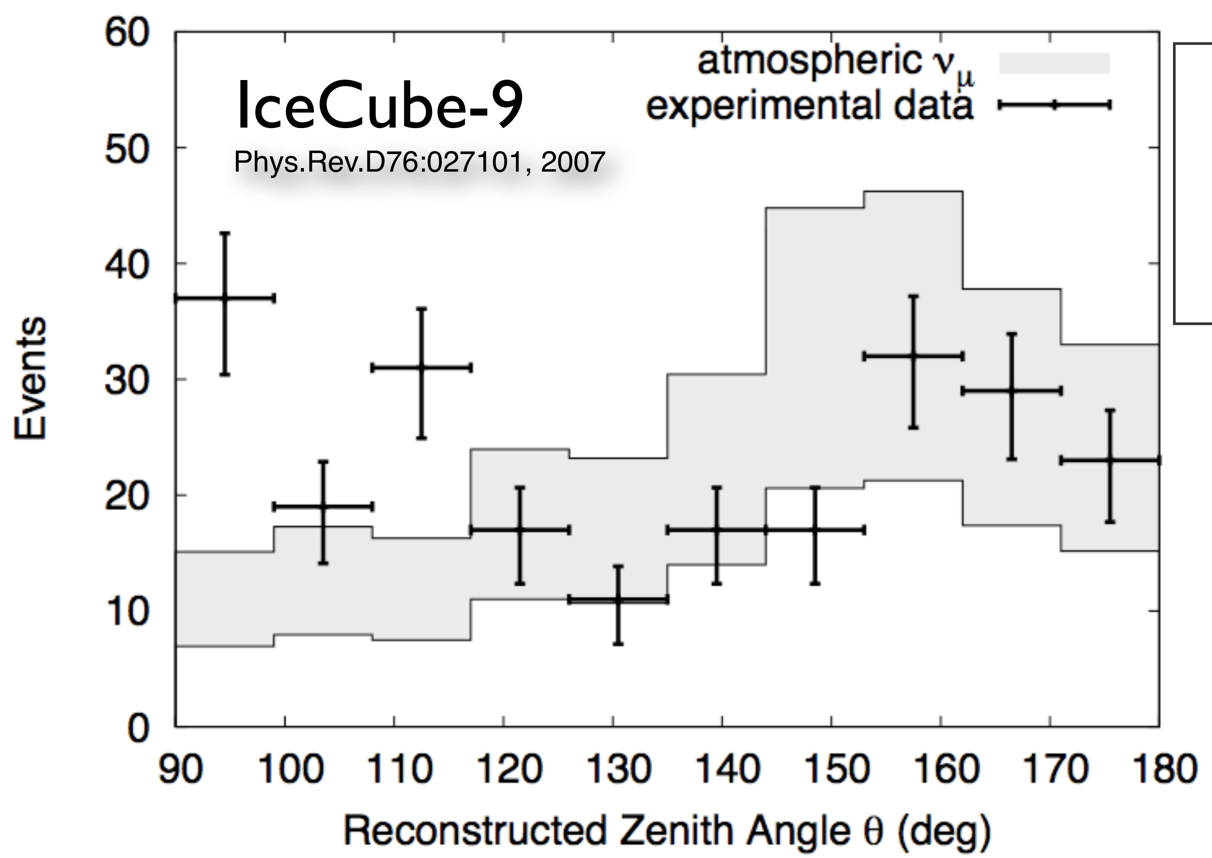
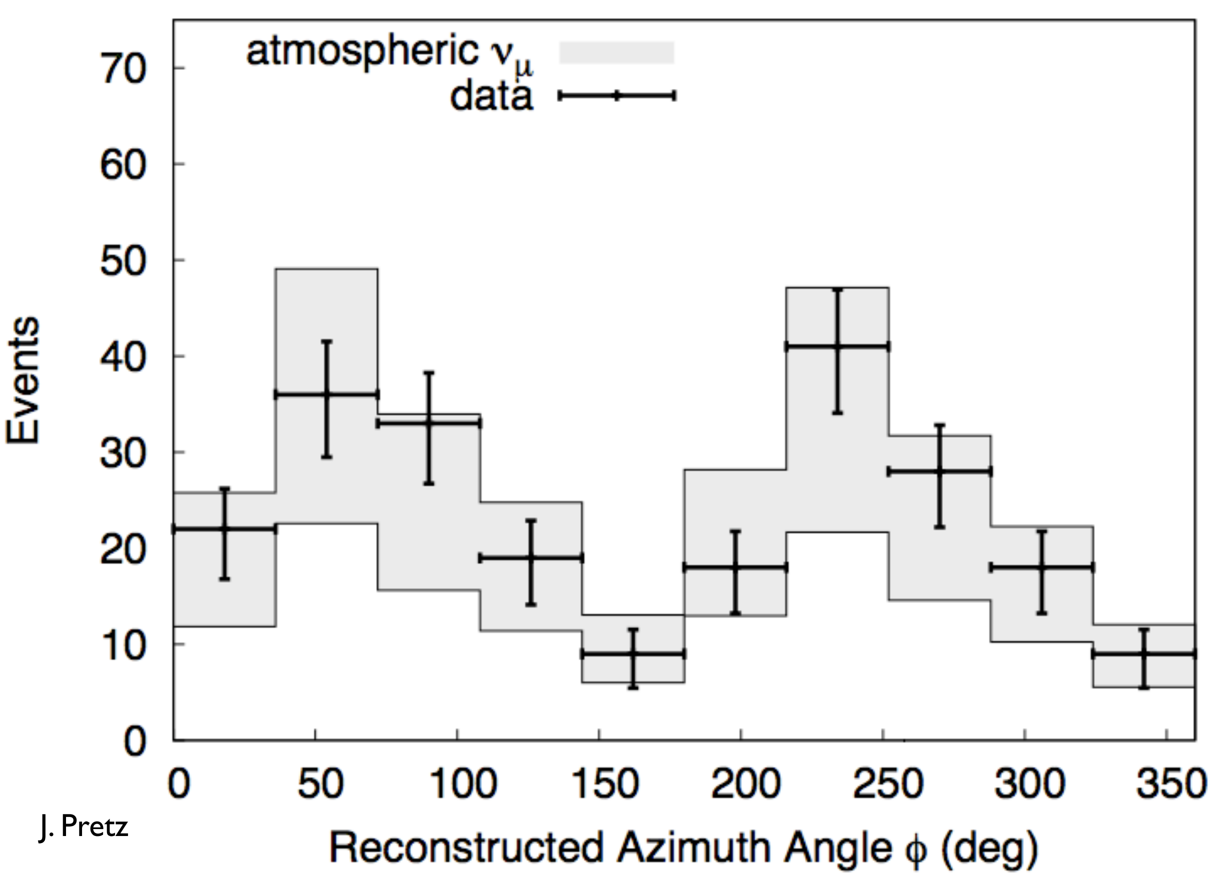


Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008

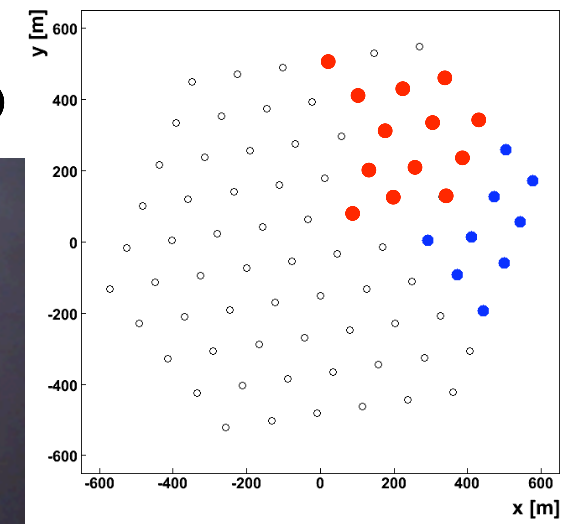
detecting neutrinos



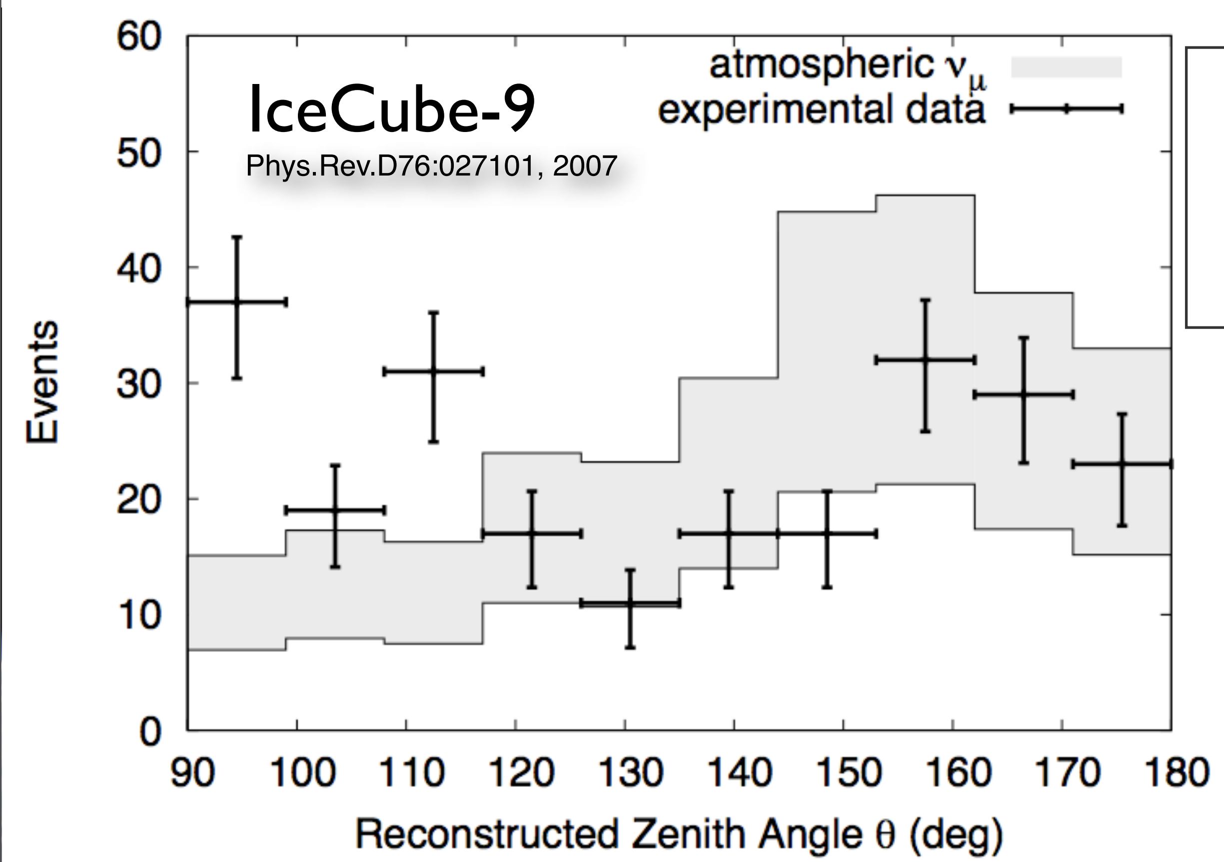


1.7 events / day
3% efficiency @ 90% purity

exp : 234 events (θ>100°)
sim : 211±76.1(syst)±14.5(stat)



detecting neutrinos



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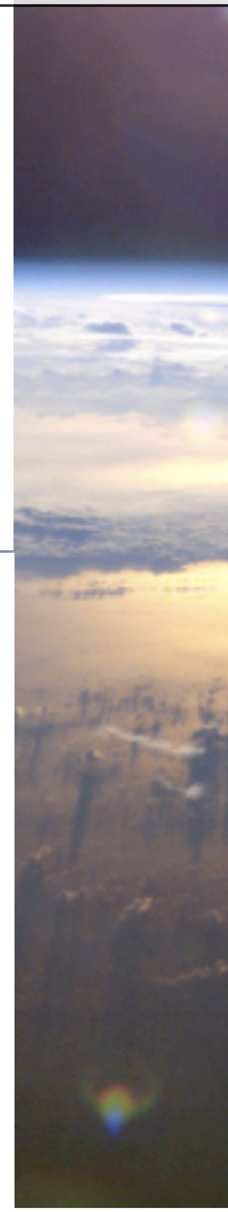

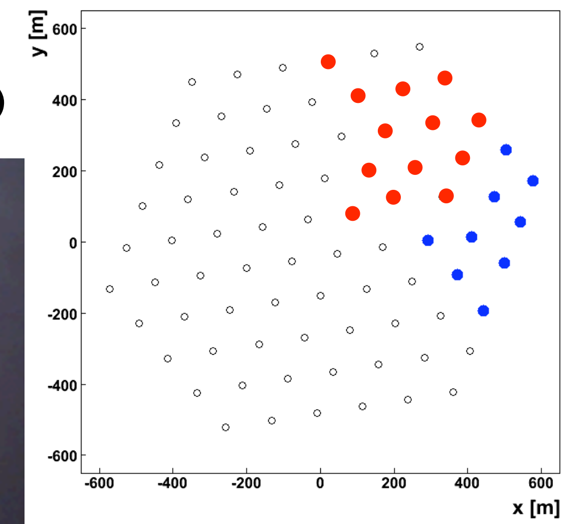

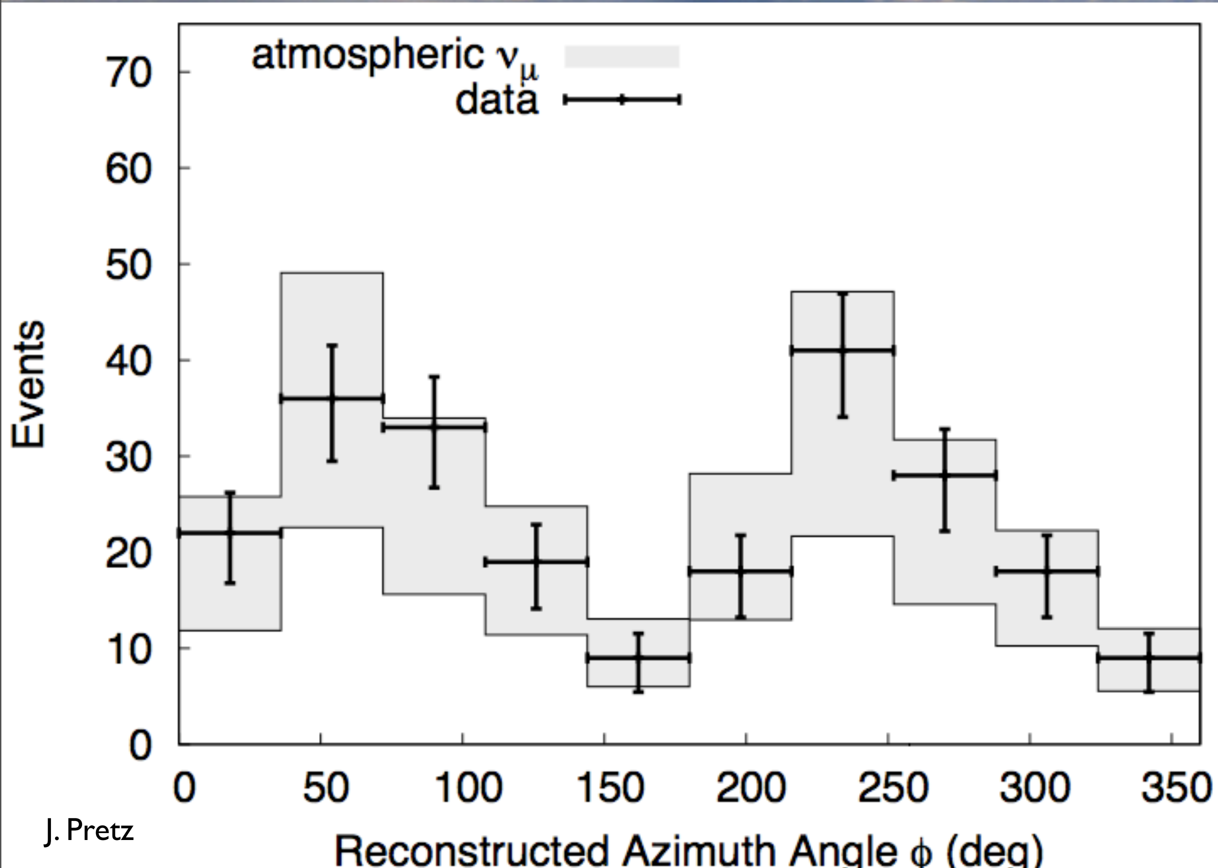

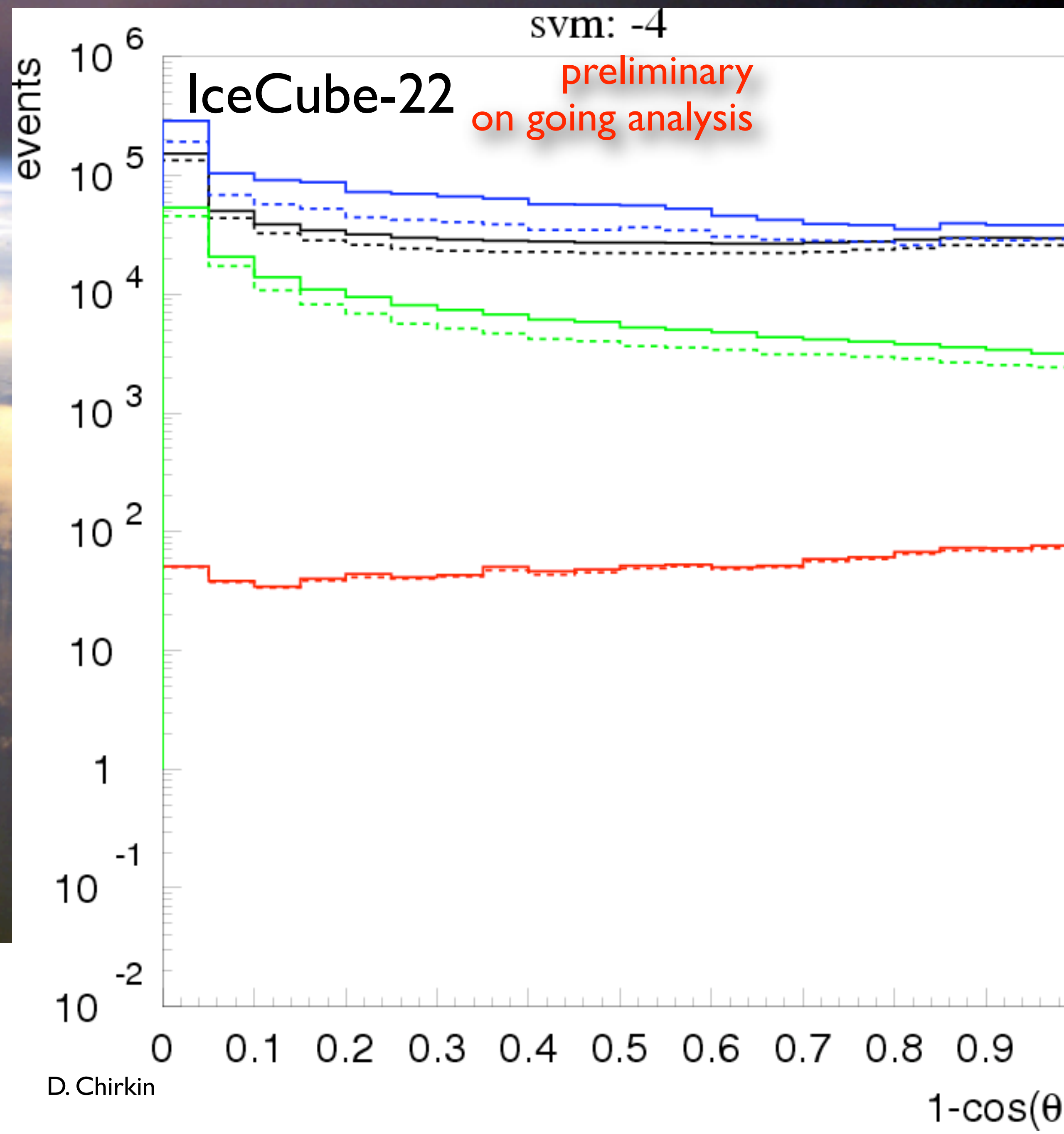

J. Pretz

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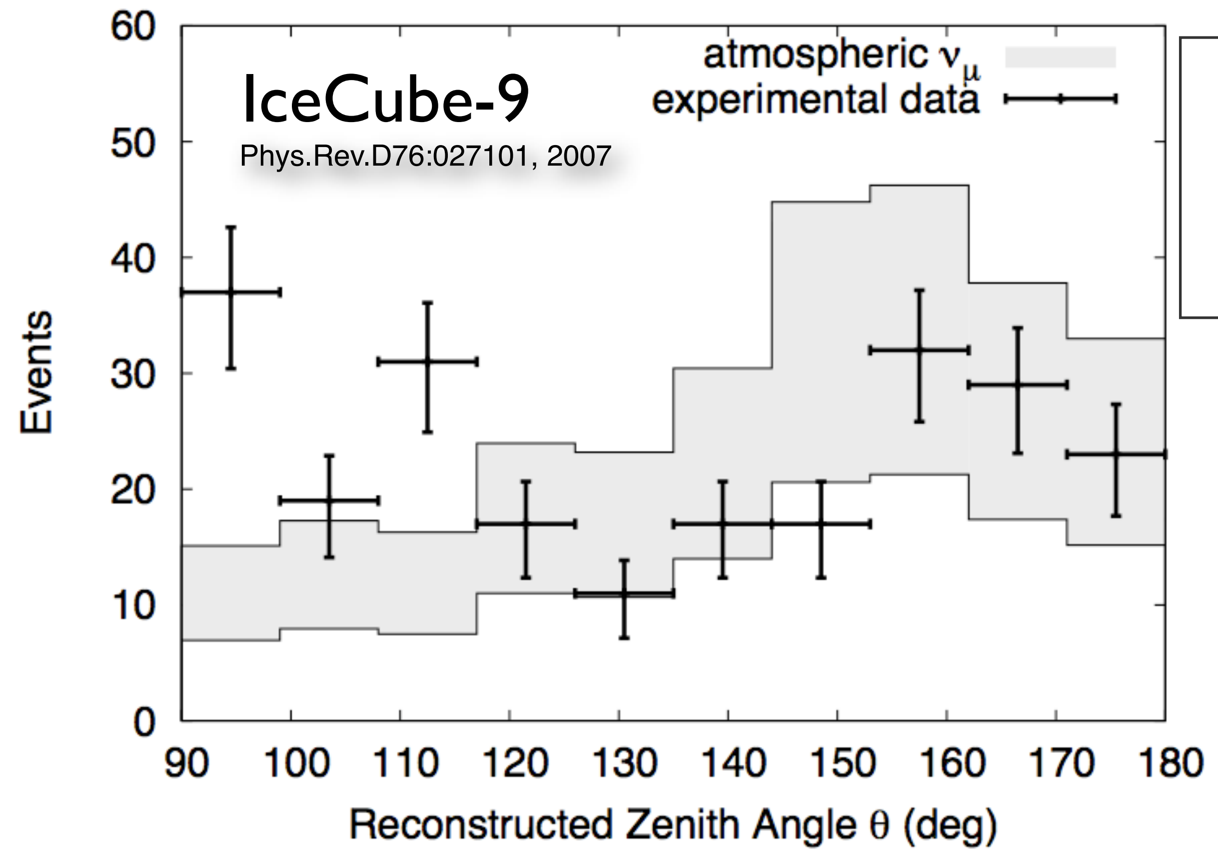
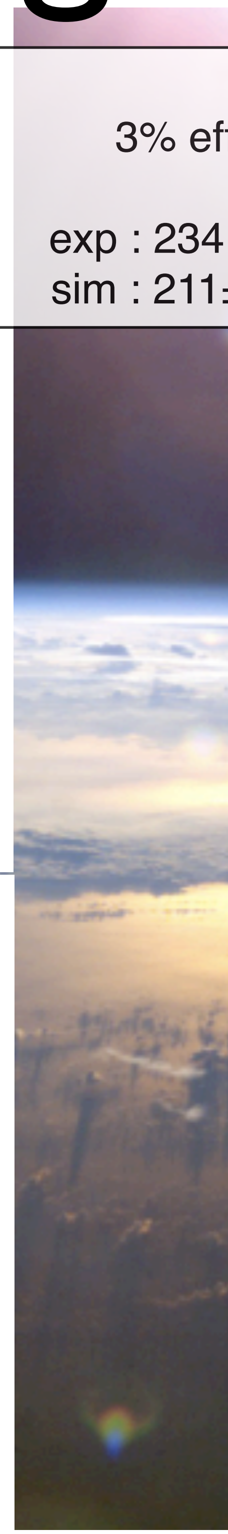
D. Chirkin

detecting neutrinos





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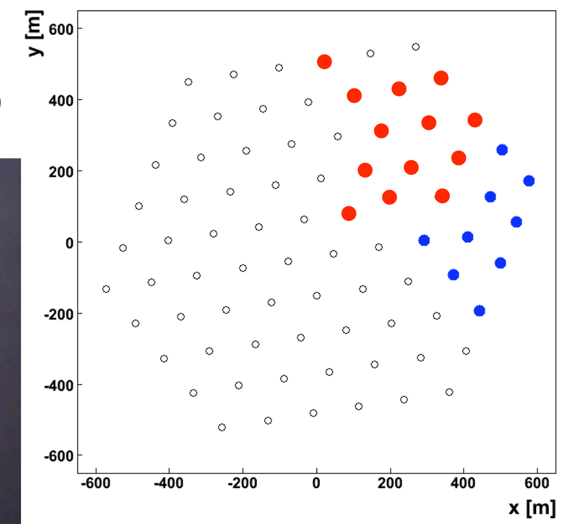
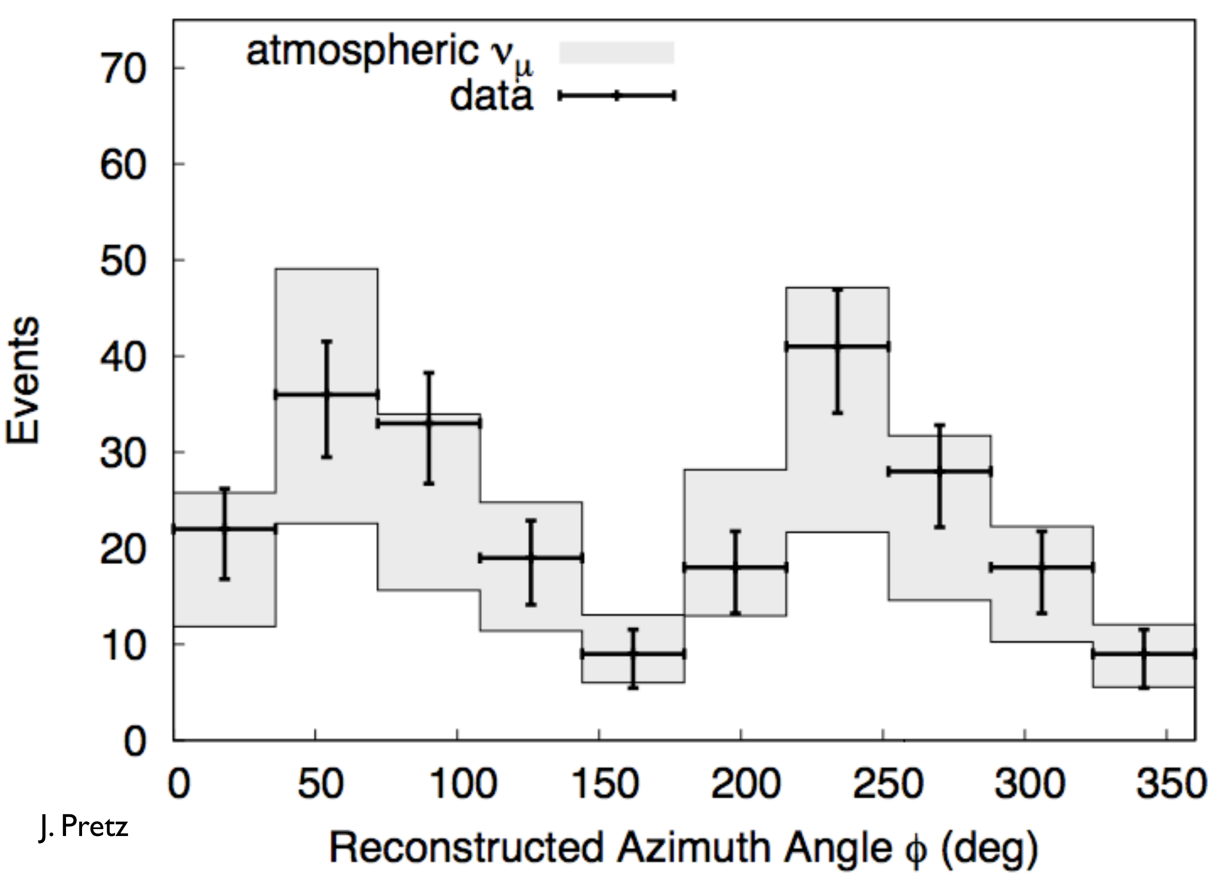
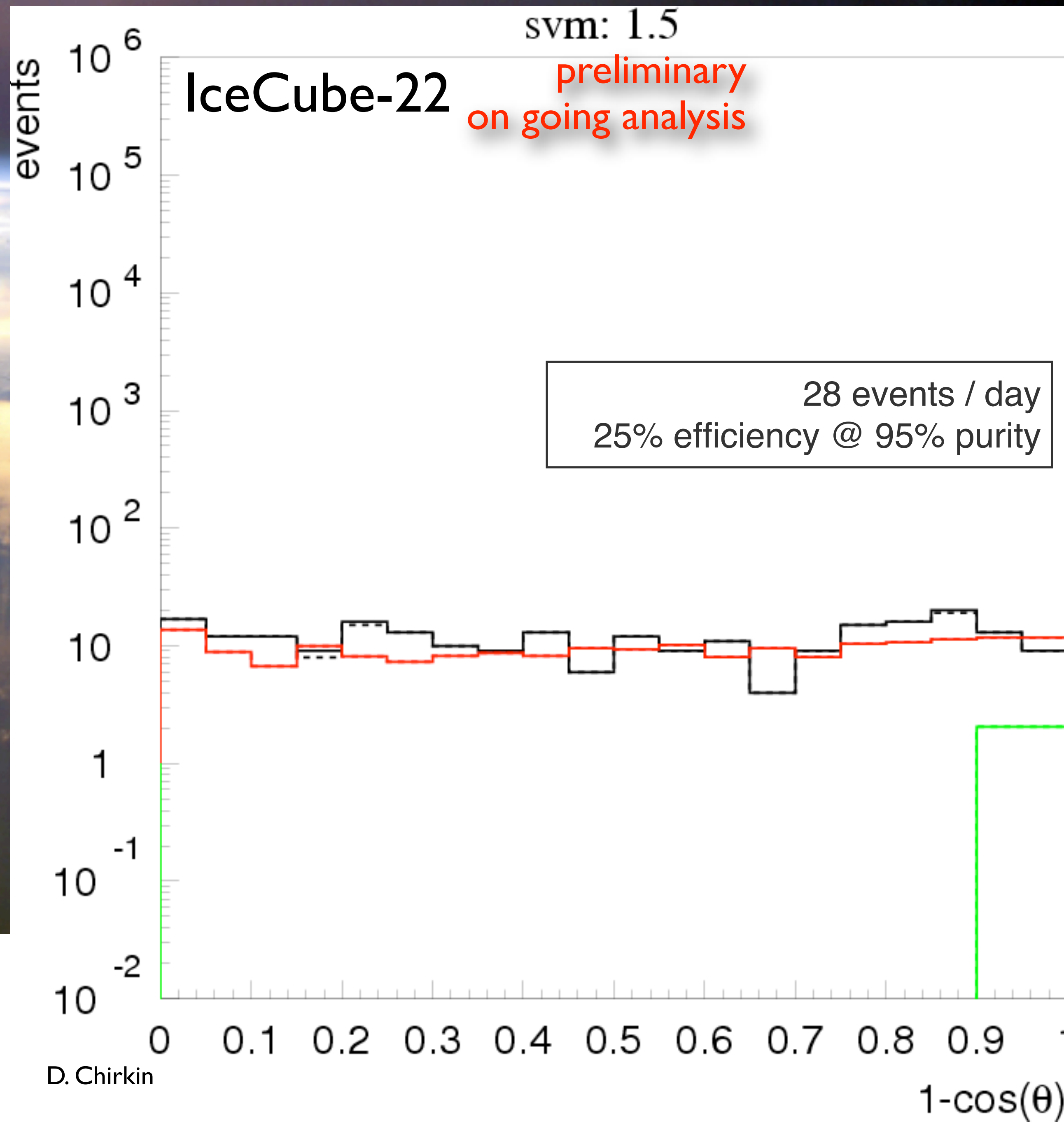
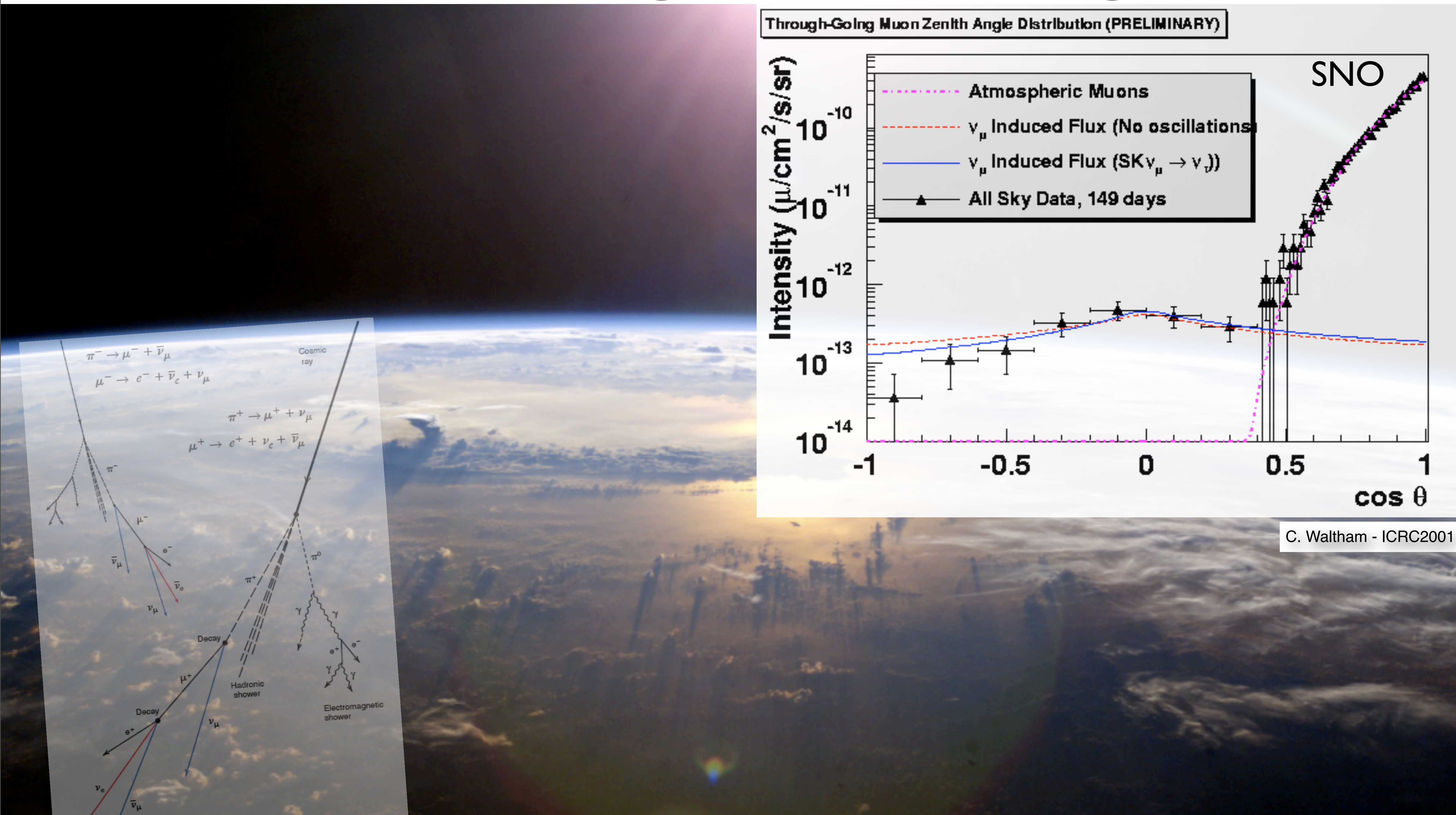


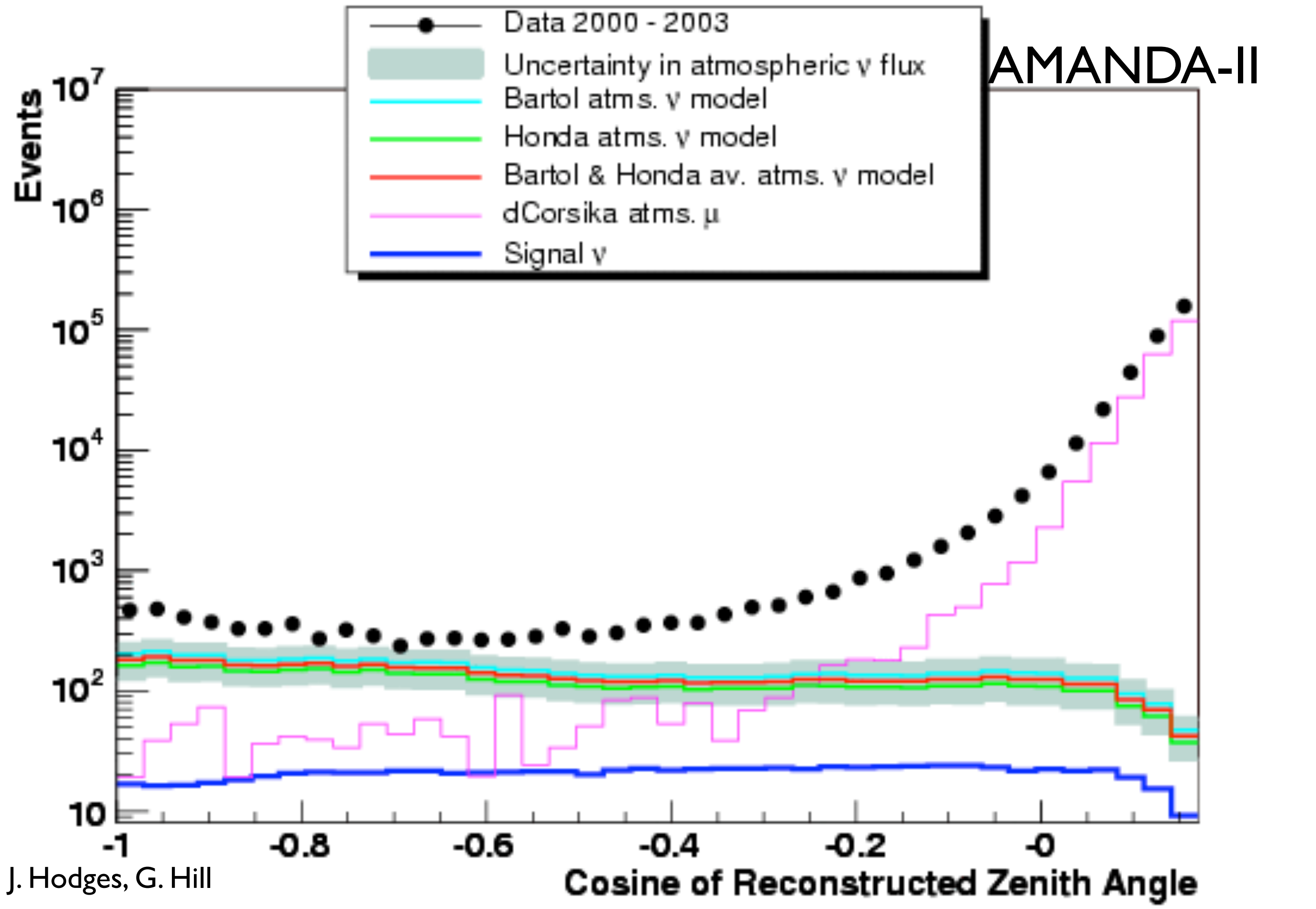




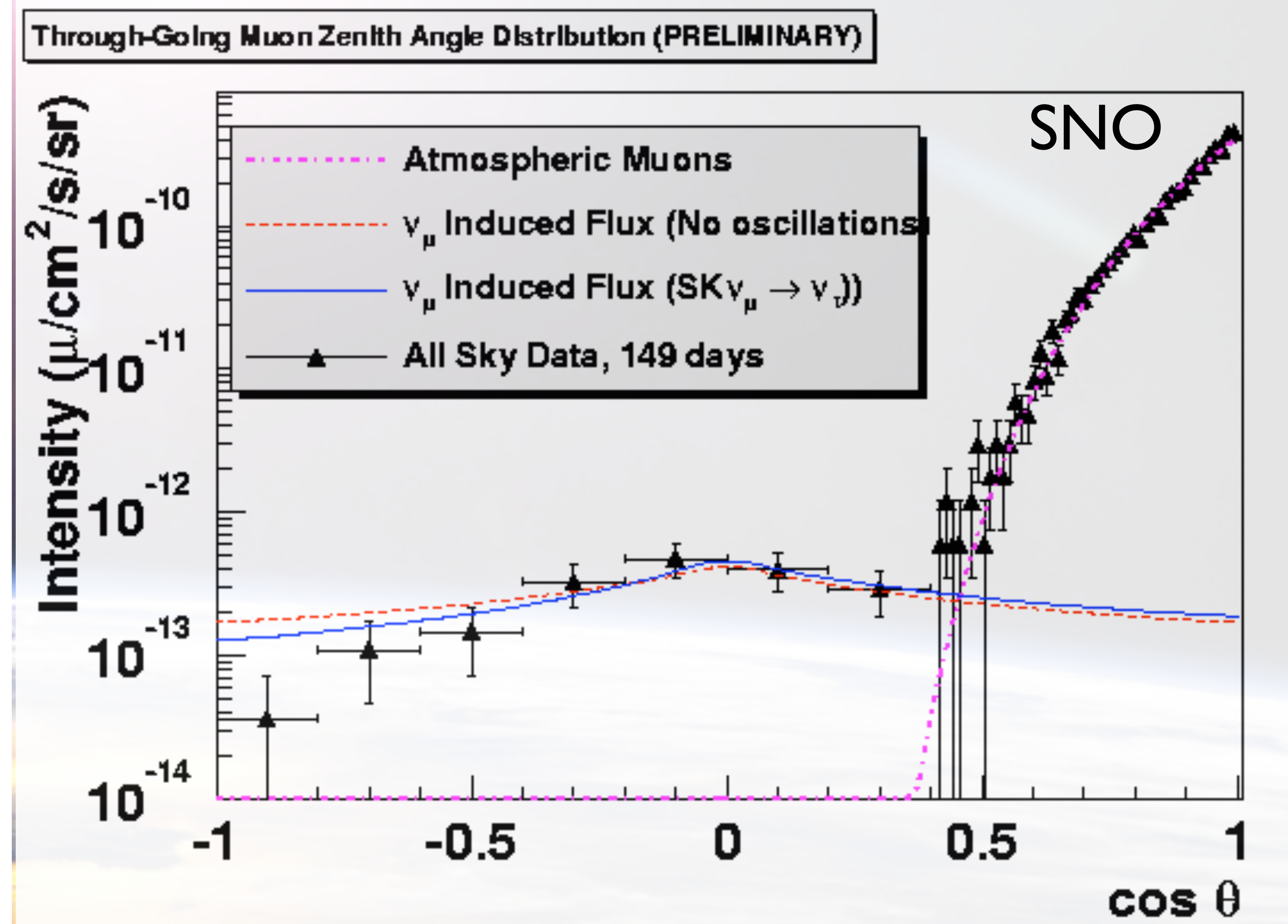
understanding the background



understanding the background

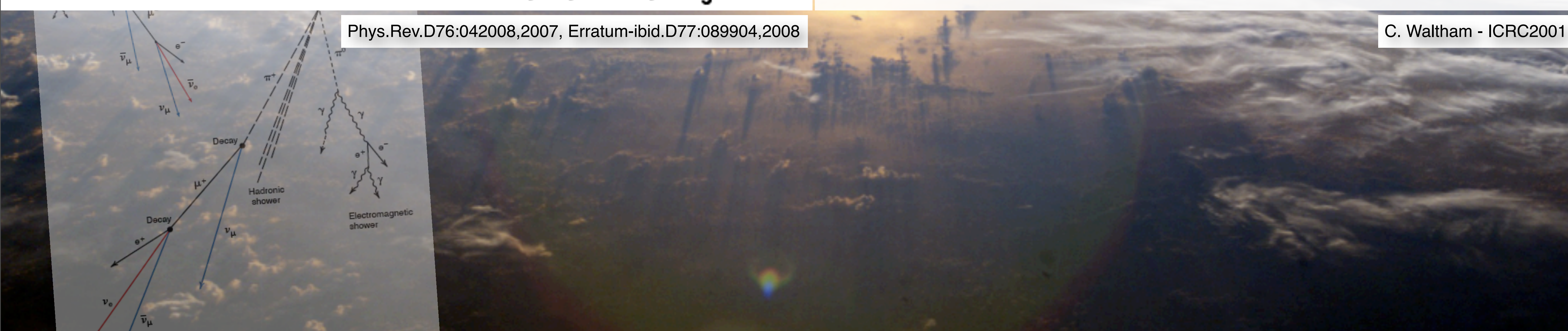


J. Hodges, G. Hill

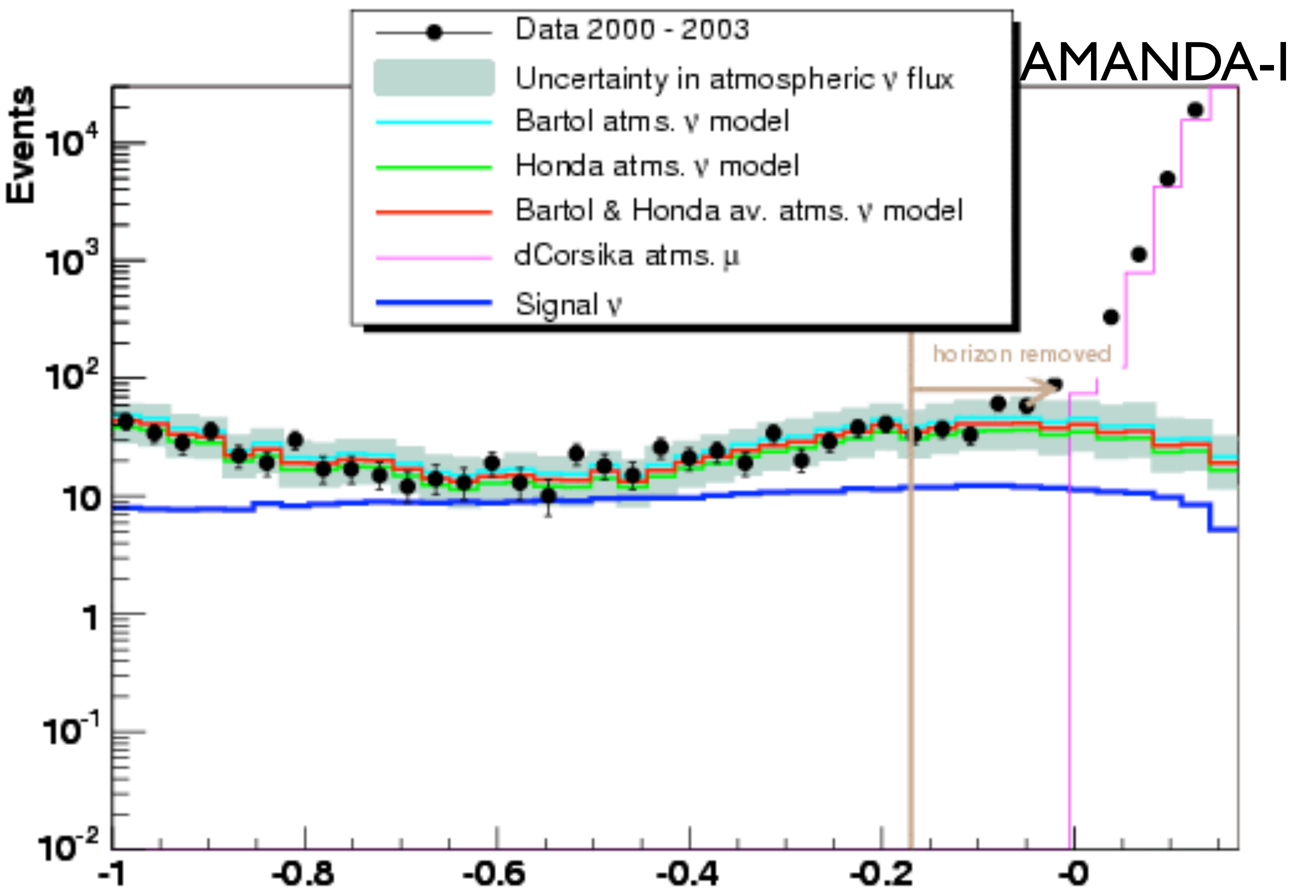


Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008

C. Waltham - ICRC2001



understanding the background



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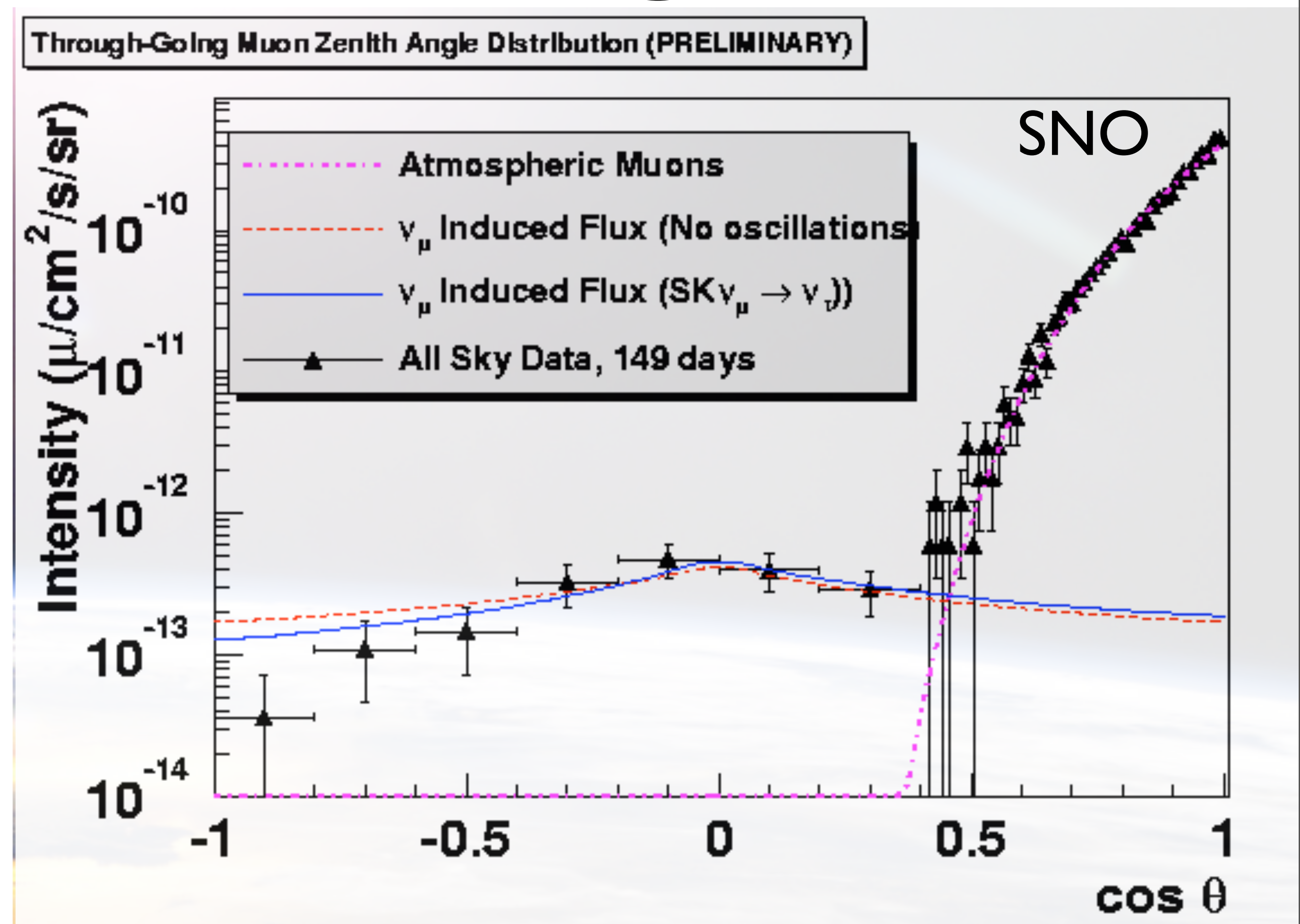

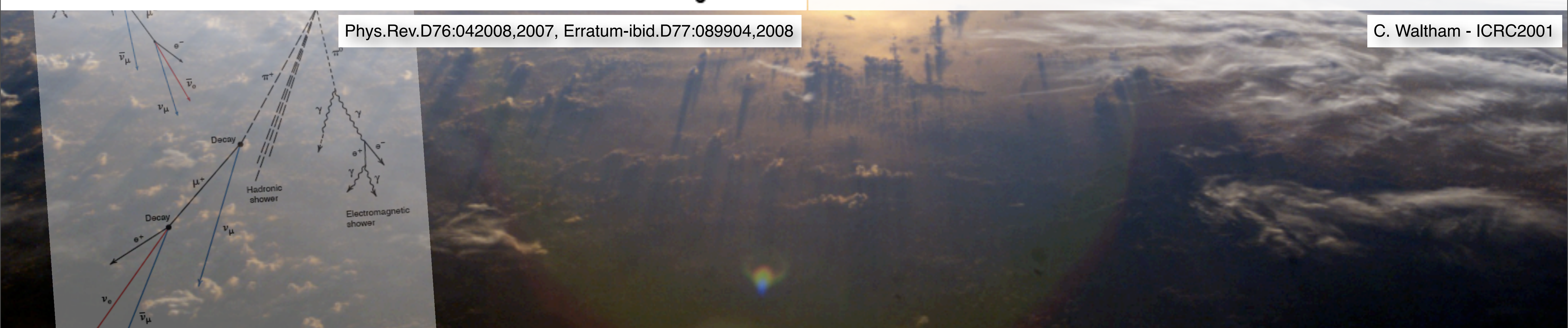

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C. Waltham - ICRC2001

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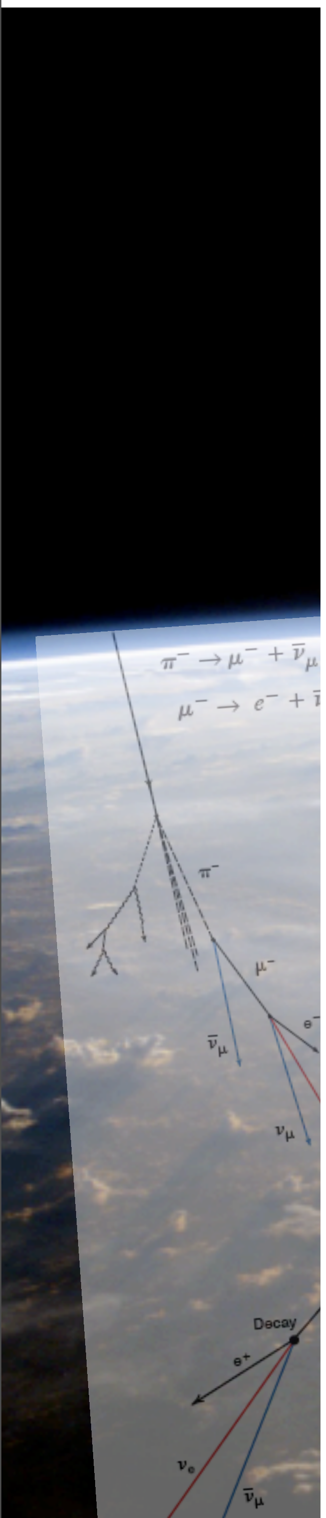

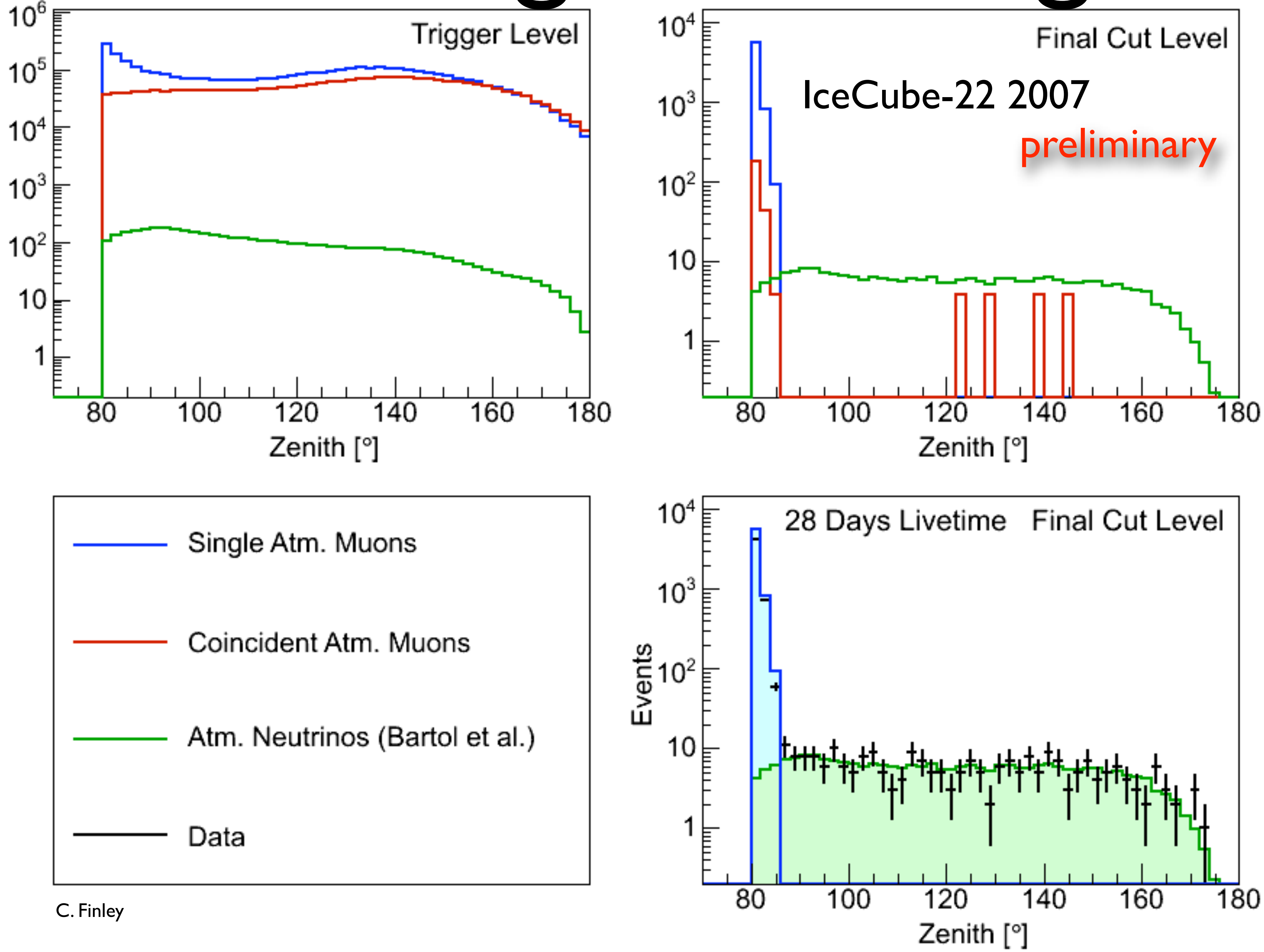

C. Finley

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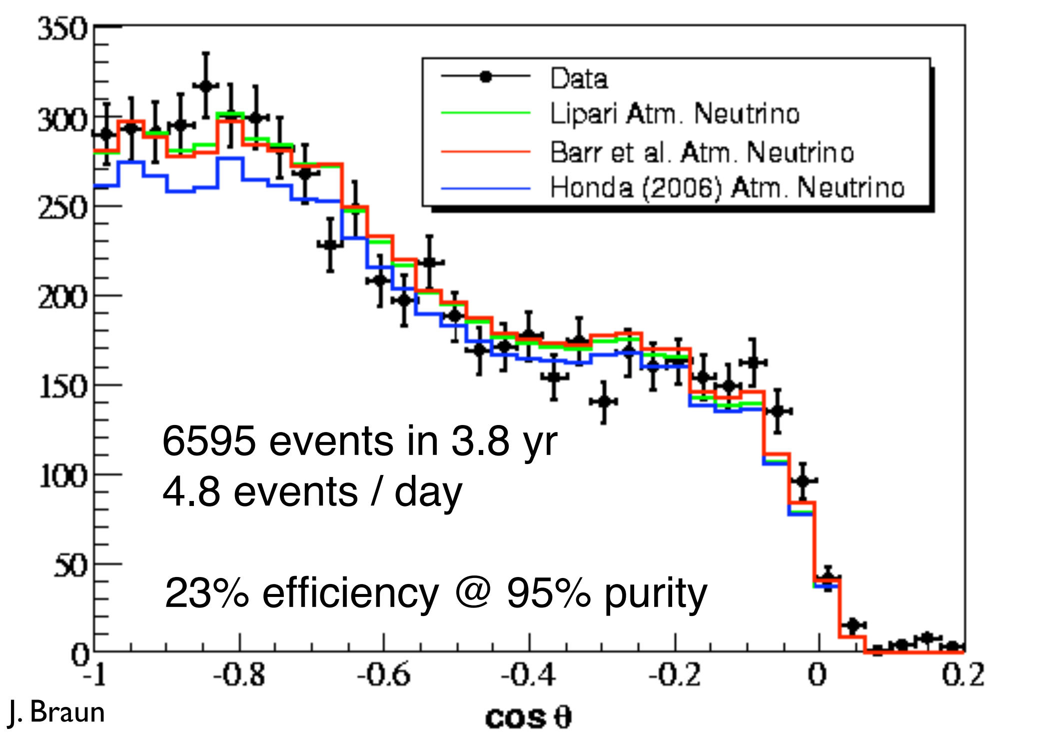
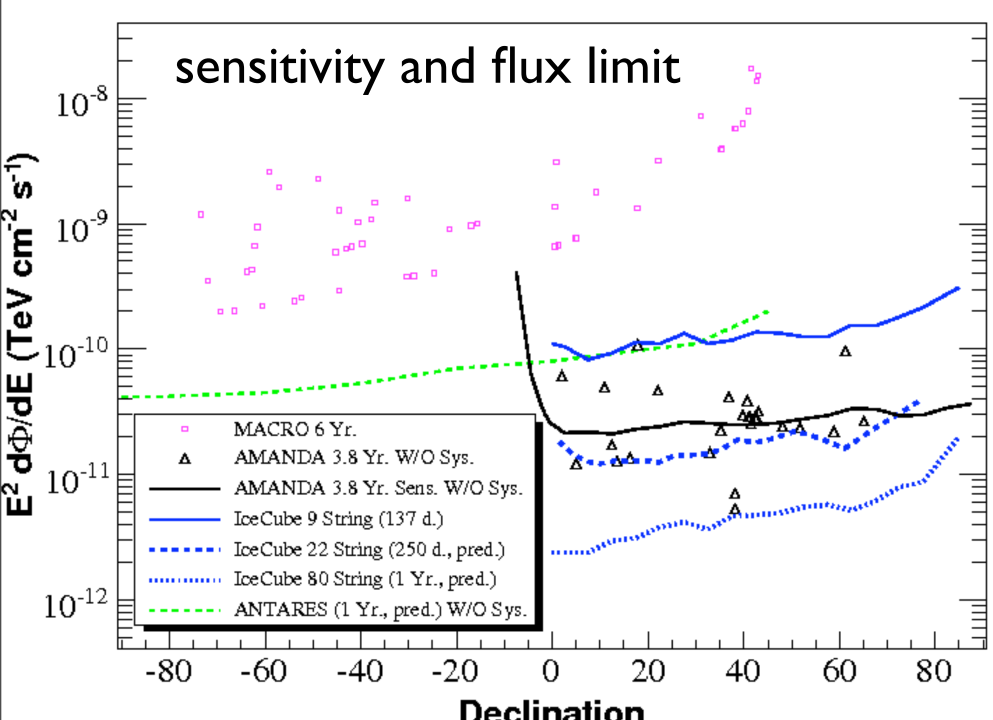
astrophysical neutrinos: point sources

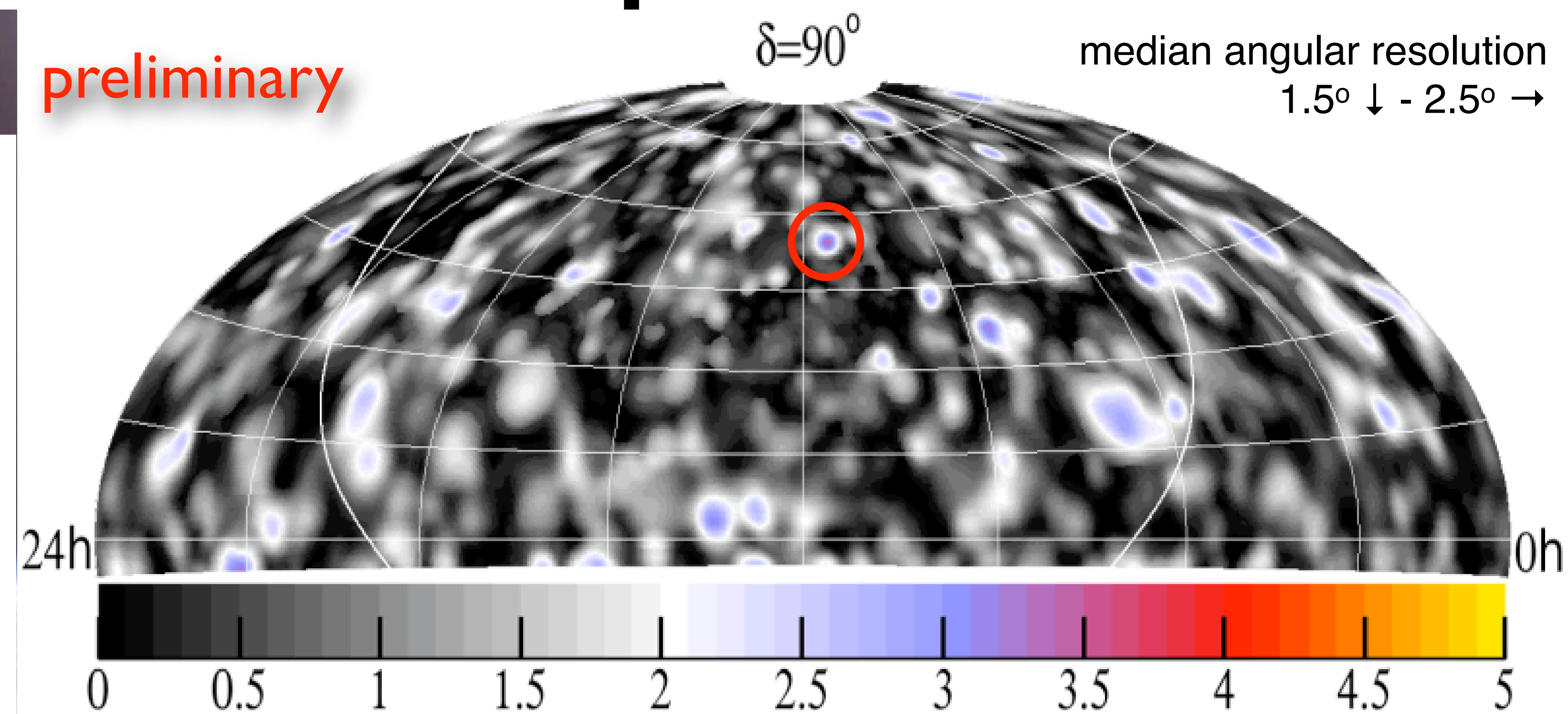
AMANDA-II 2000-2006





preliminary

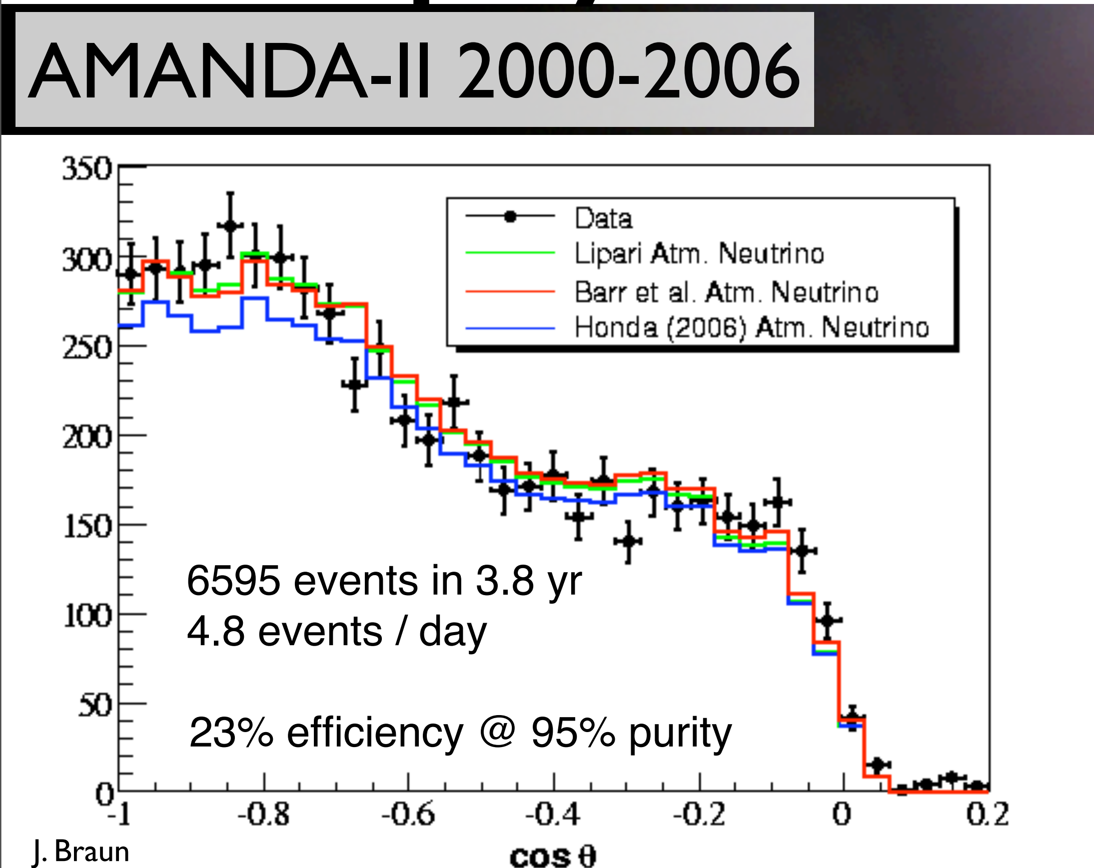
median angular resolution
1.5° ↓ - 2.5° →

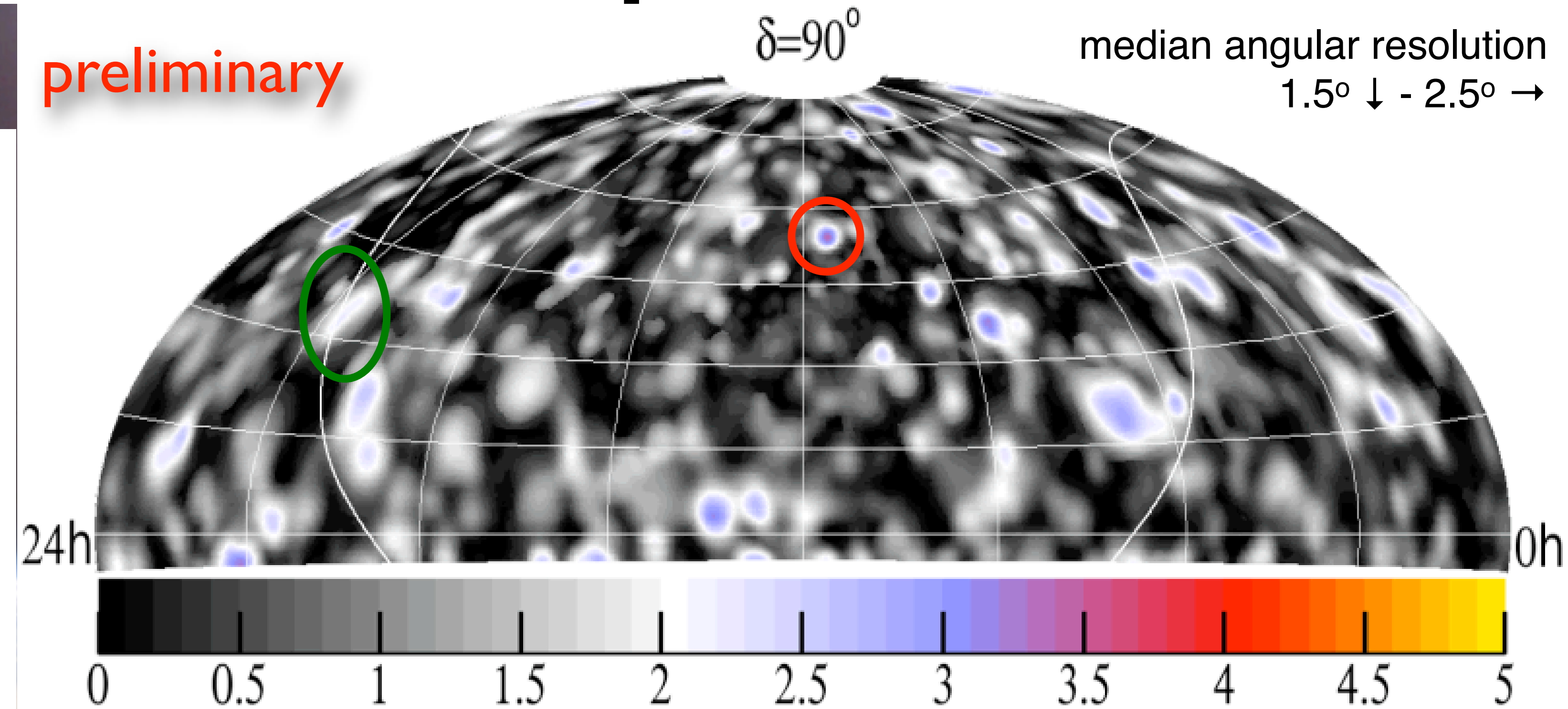


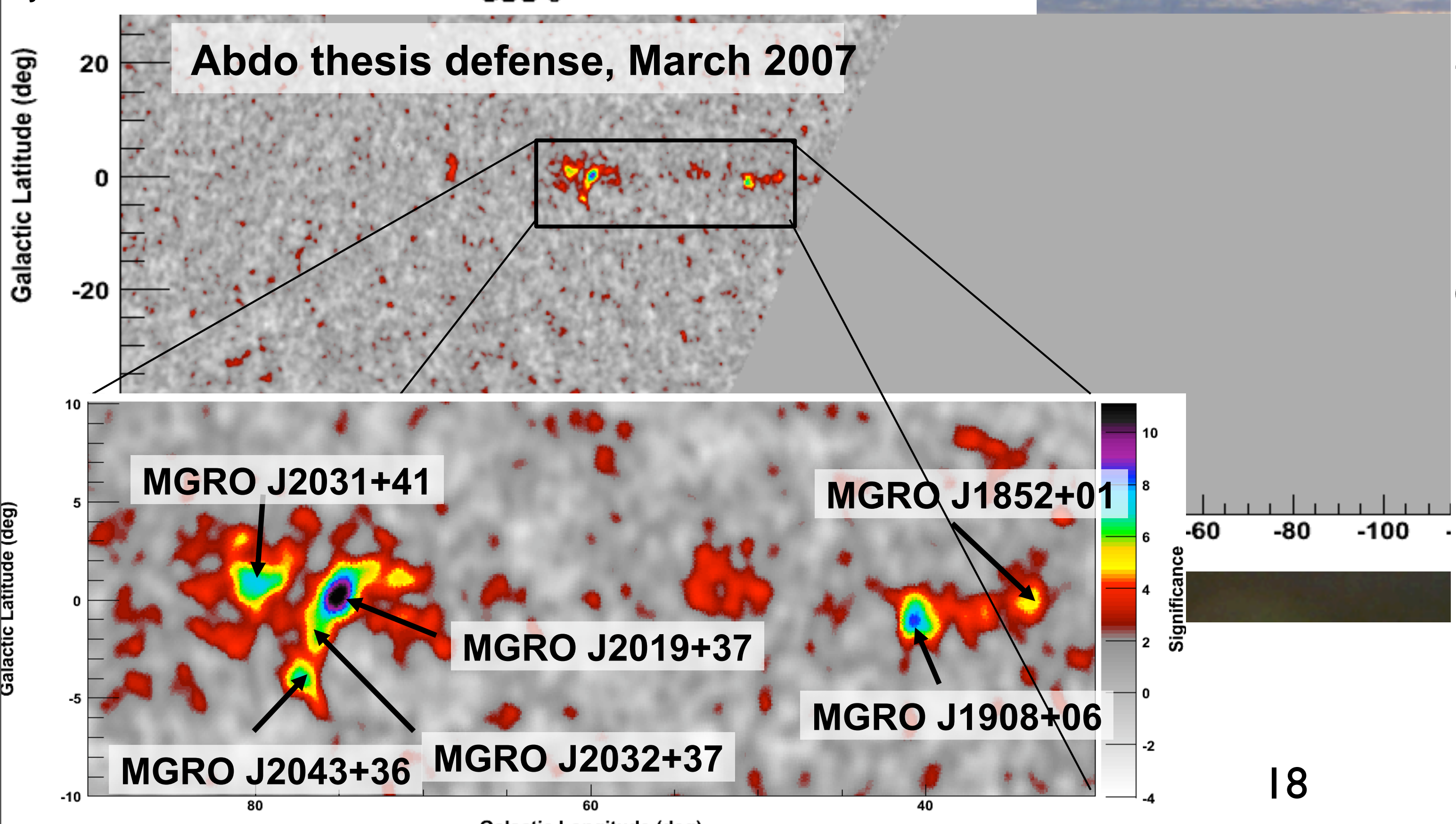
Maximum significance = **3.38σ** near **(11.4h, +54°)**

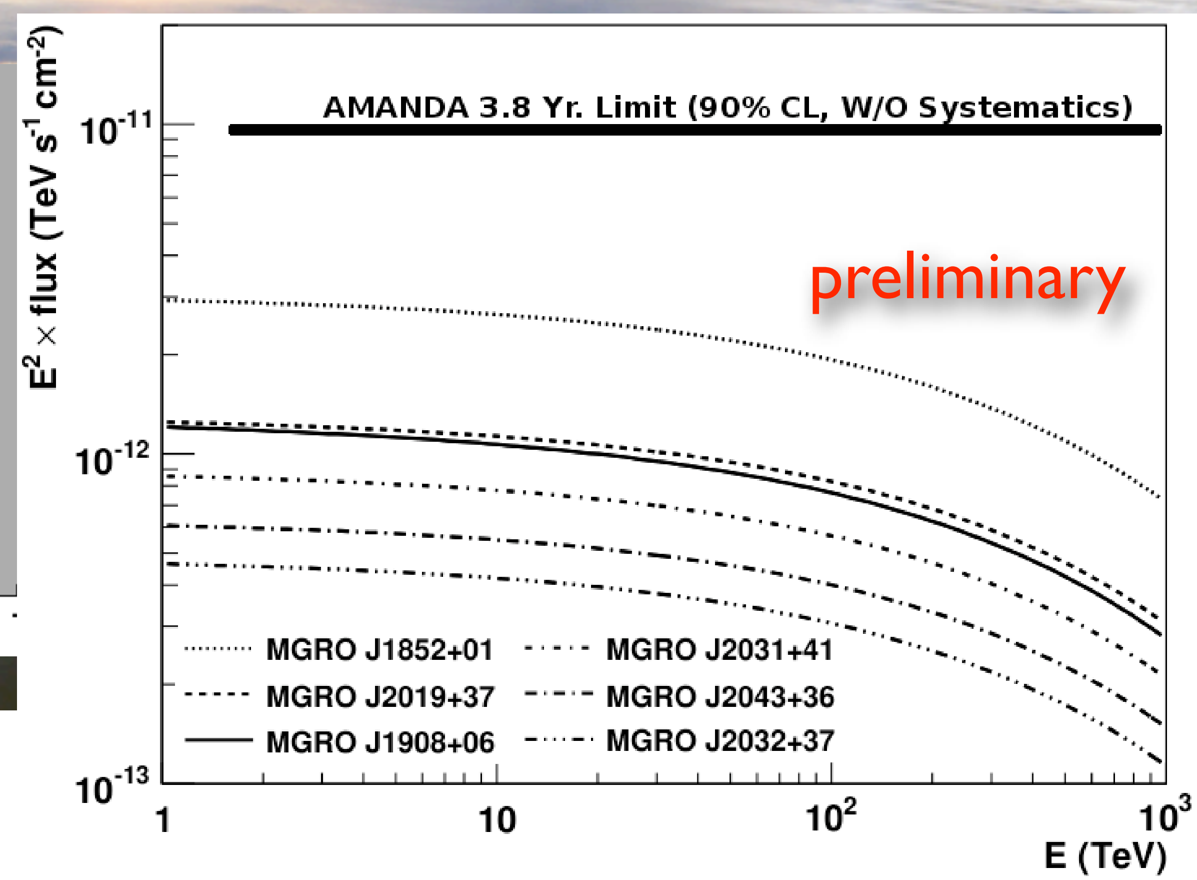
95% chance to obtain maximum significance ≧ 3.38σ in random skymaps

astrophysical neutrinos: point sources









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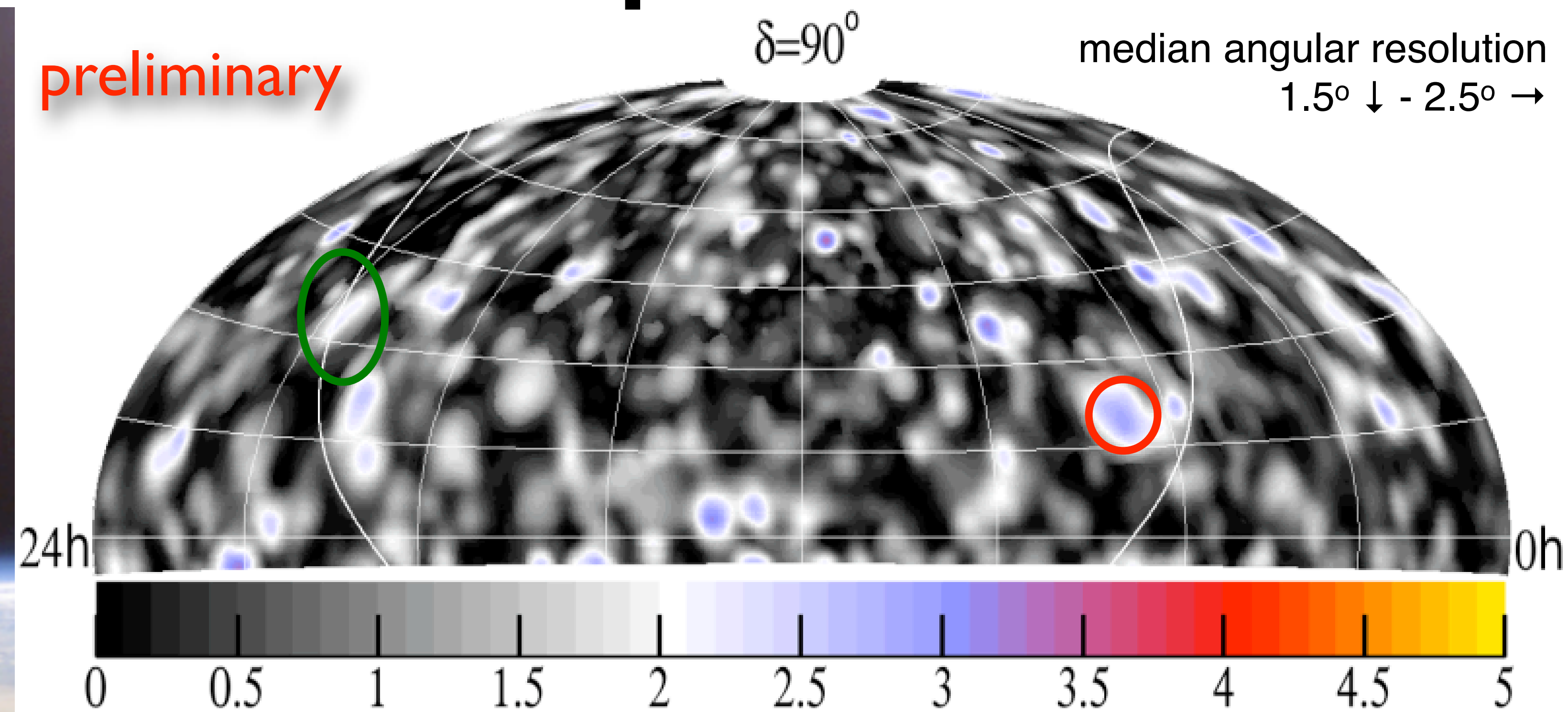
astrophysical neutrinos: point sources

AMANDA-II 2000-2006

Object	Dec°	RA°	μ_{90}	P-value
MGRO J2019+37	36.83	304.83	4.75	0.077
Cyg OB2	41.32	308.29	3.16	0.30
Mrk 421	38.21	166.11	1.26	0.82
Mrk 501	39.76	253.47	3.56	0.22
1ES 1959+650	65.15	300	3.38	0.44
1ES 2344+514	51.71	356.77	2.84	0.44
H 1426+428	42.68	217.14	2.82	0.36
BL Lac (QSO B2200+420)	42.28	330.68	2.54	0.38
3C66A	43.04	35.67	3.93	0.18
3C 454.3	16.15	343.49	1.27	0.73
4C 38.41	38.14	248.82	1.10	0.85
PKS 0528+134	13.53	82.74	1.60	0.64
3C 273	2.05	187.28	4.17	0.086
M87	12.39	187.71	2.18	0.43
NGC 1275 (Perseus A)	41.51	49.95	2.24	0.47
Cyg A	40.73	299.87	4.50	0.095
SS 433	4.98	287.96	1.57	0.64
Cyg X-3	40.96	308.11	3.28	0.29
Cyg X-1	35.2	299.59	2.00	0.57
LS I +61 303	61.23	40.13	7.21	0.033
GRS 1915+105	10.95	288.8	3.73	0.11
XTE J1118+480	48.04	169.55	2.61	0.50
GRO J0422+32	32.91	65.43	1.40	0.76
Geminga	17.77	98.48	6.07	0.0086
Crab Nebula	22.01	83.63	4.47	0.10
Cas A	58.82	350.85	1.93	0.67



the probability of obtaining a p-value = 0.0086 for at least one of the 26 sources is 20%.

Source	l	b	δ	α
MGRO J2019+37	75.0	0.2	36.72°	305.03°
MGRO J1908+06	40.4	-1.0	6.18°	287.18°
MGRO J2034+41	80.3	1.1	41.57°	308.04°
C1 (MGRO J2043+36)	77.5	-3.9	36.3°	310.98°
C2 (MGRO J2032+37)	76.1	-1.9	36.52°	307.75°
MGRO J1852+01	33.5	0.0	0.51°	283.12°

stack Milagro sources : upward fluctuation with p-value = 0.19

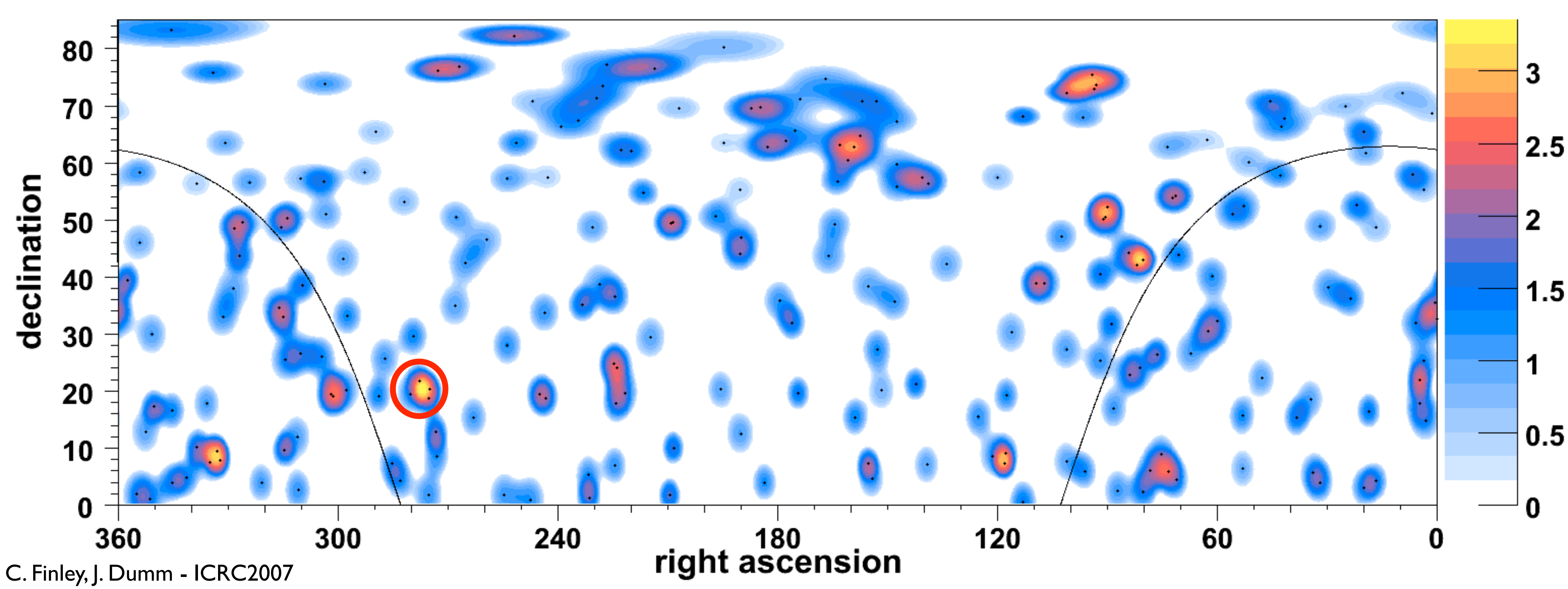
the 90% confidence level limit on the per-source flux for the six sources, excluding systematics, is $9.6*10^{-12}$ TeV cm^{-2} s^{-1} over the energy region 1.8 TeV - 2.1 PeV

astrophysical neutrinos: point sources

IceCube-9 2006

234 events in 137.4 days
1.7 events / day

median angular resolution ~ 2°



C. Finley, J. Dumm - ICRC2007

maximum significance = **3.35σ** near **(18.4h, +20.4°)**

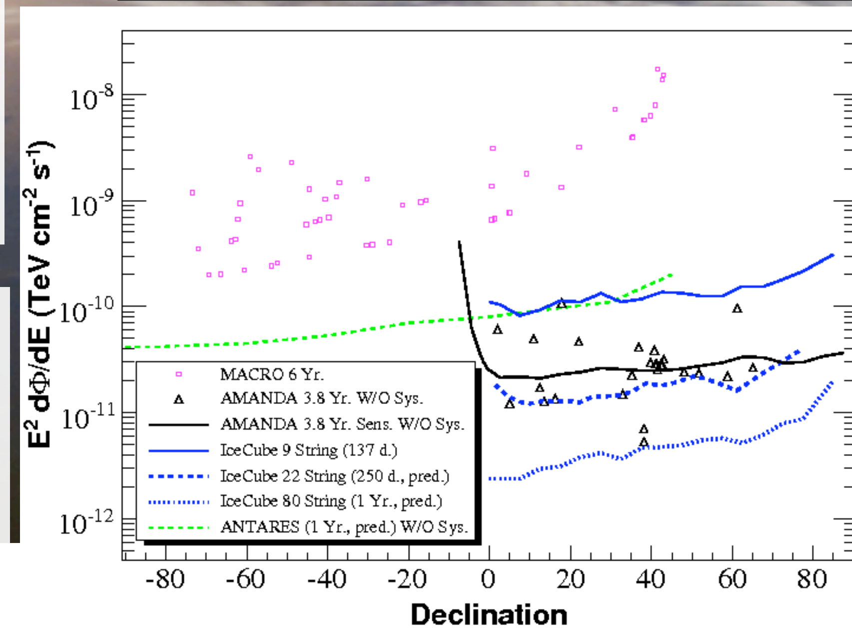
60% chance to obtain maximum significance ≧ 3.35σ in random skymaps

highest fluctuation on the list of 26 sources is σ = 1.77 (p-value = 0.04) in the direction of Crab Nebula

the probability for a p-value = 0.04 for at least one of the 26 sources is 65%.

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-2} \text{TeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}$$

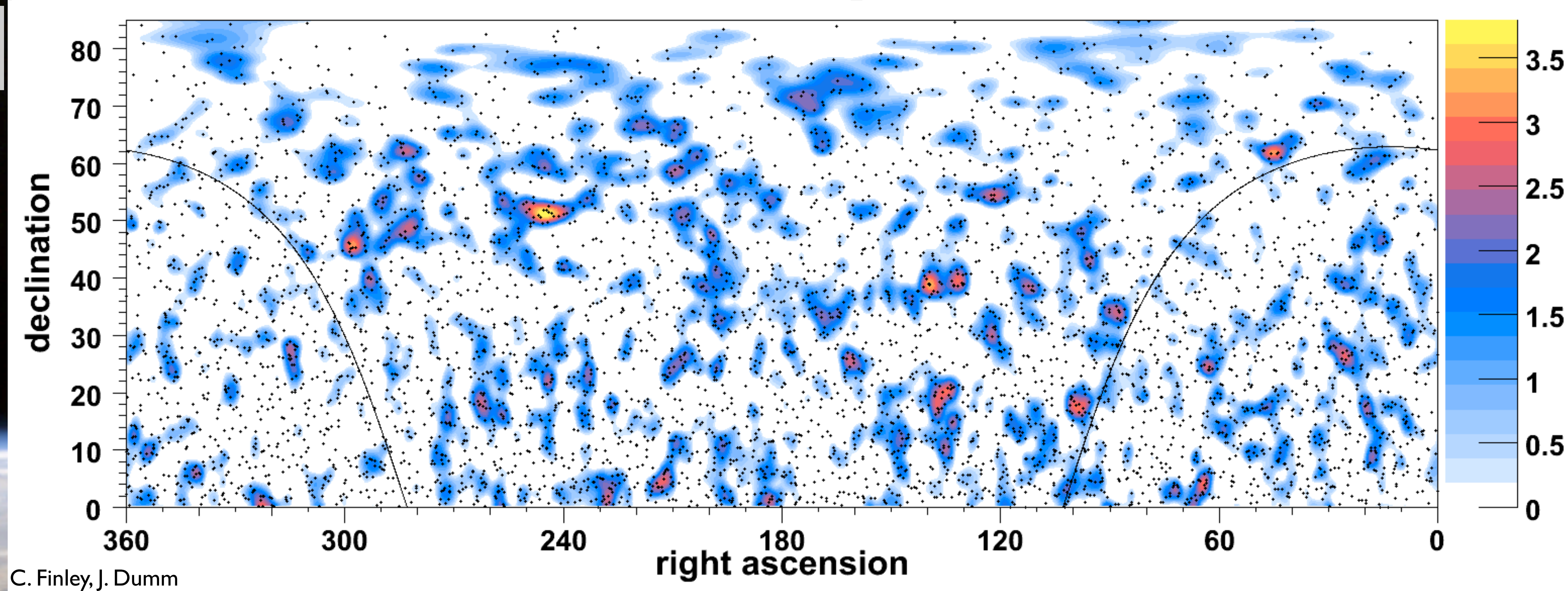
→ Auger - CenA as reference



astrophysical neutrinos: point sources

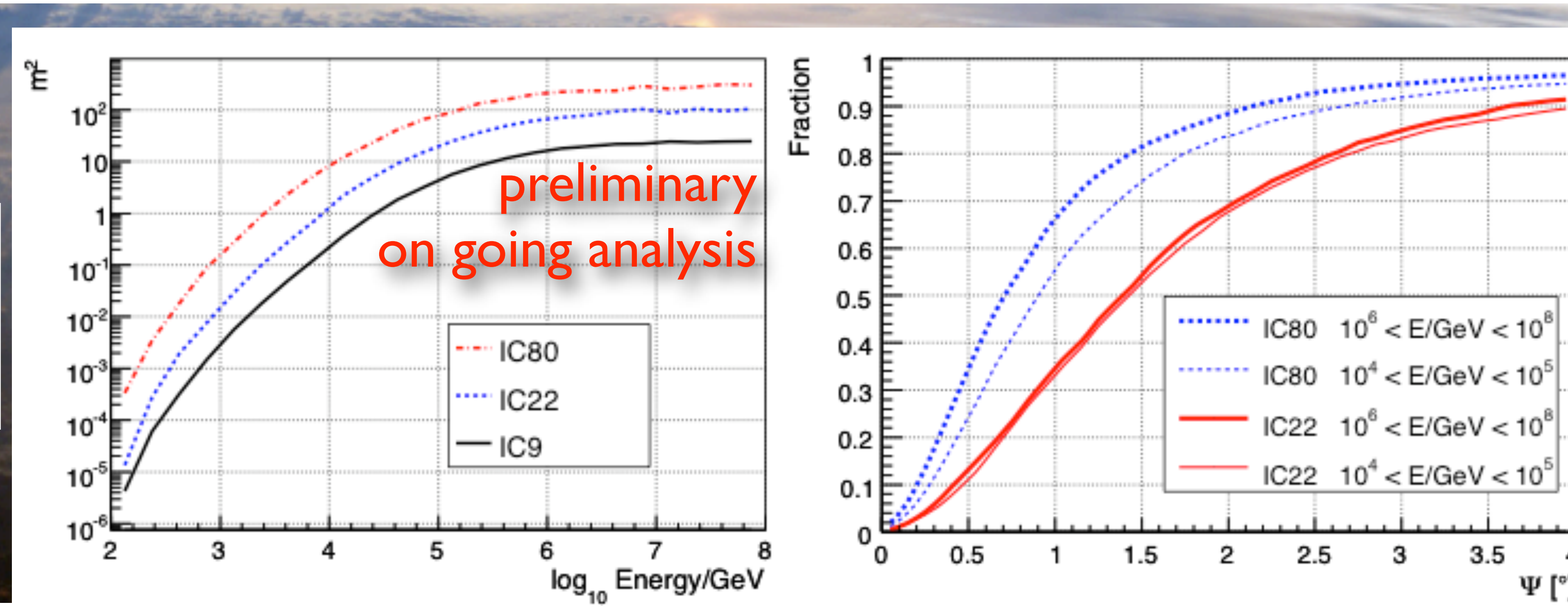
IceCube-22 2007

simulated skymap



285 days livetime
20-30 events / day

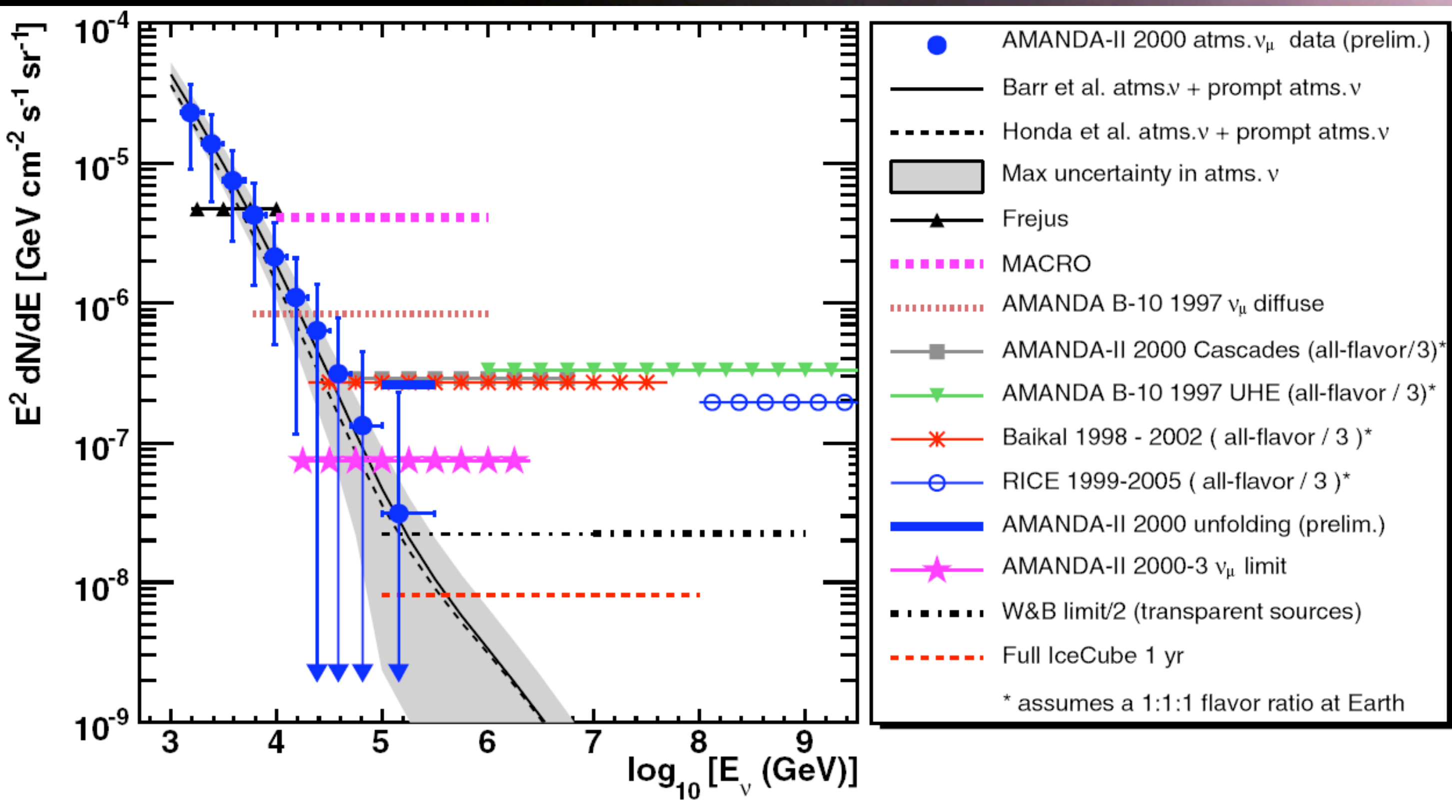
median angular resolution ~ 1.5°

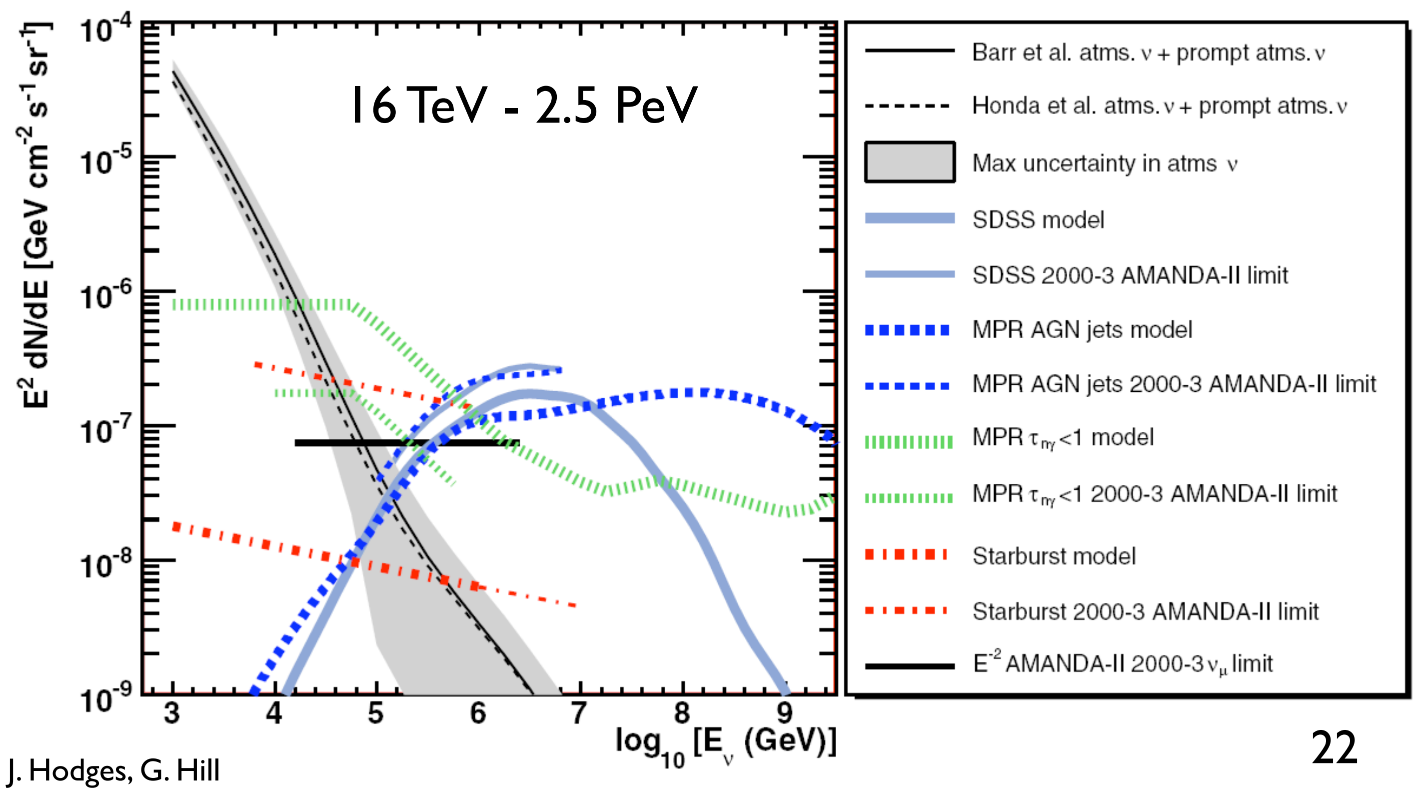


IC-22 expected to be x5 more efficient & x7 more sensitive than IC-9

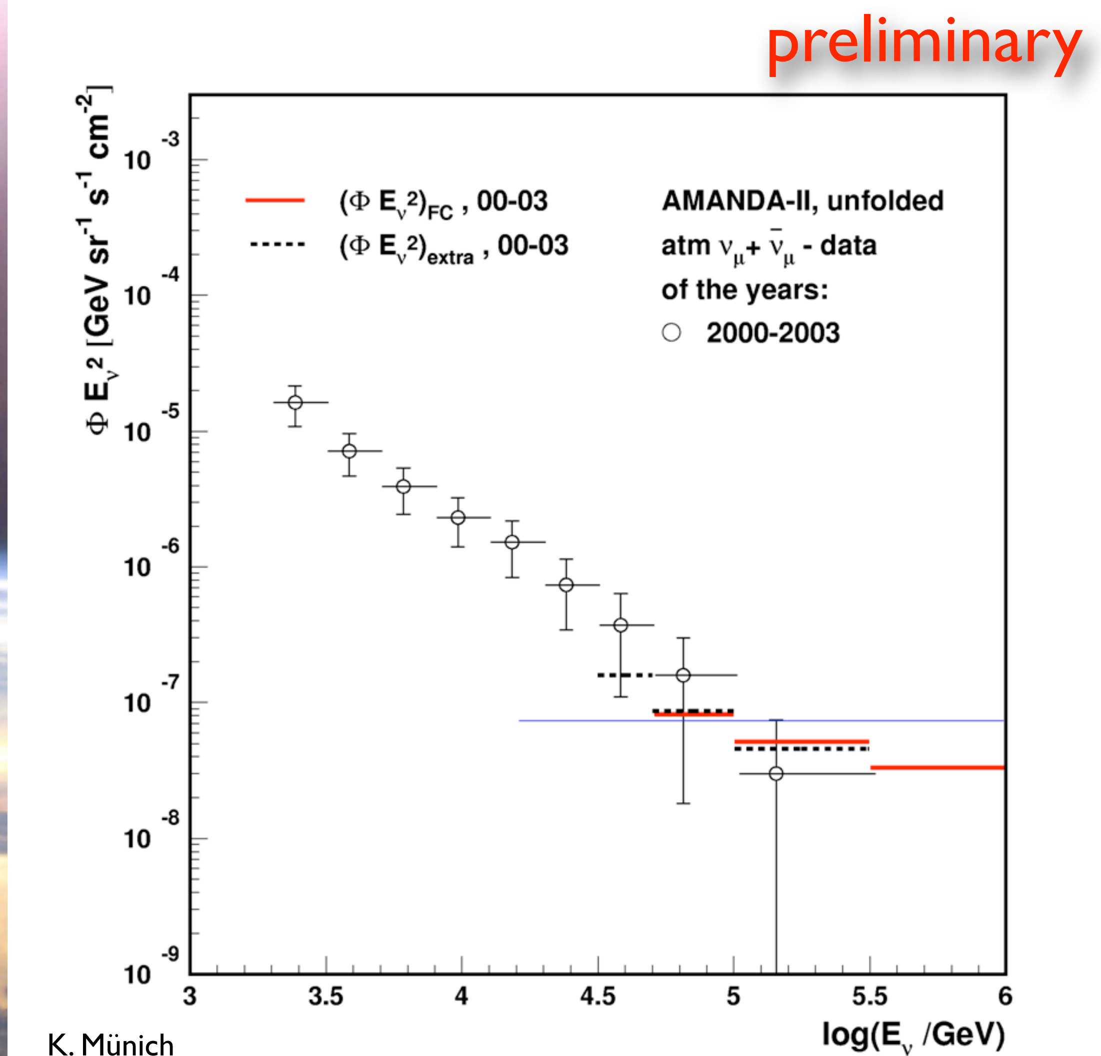
astrophysical neutrinos: diffuse sources

AMANDA-II 2000-2003 $\Longrightarrow$ IceCube





J. Hodges, G. Hill



K. Münich

$E^2 \Phi < 7.4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

$$\frac{dN_\nu}{dE}_{\rm diff} = 2 \times 10^{-9} \left(\frac{E}{\rm GeV}\right)^{-2} {\rm GeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}\,{\rm sr}^{-1}$$

→ Auger - diffuse as reference

Phys.Rev.D76:042008,2007, Erratum-ibid.D77:089904,2008

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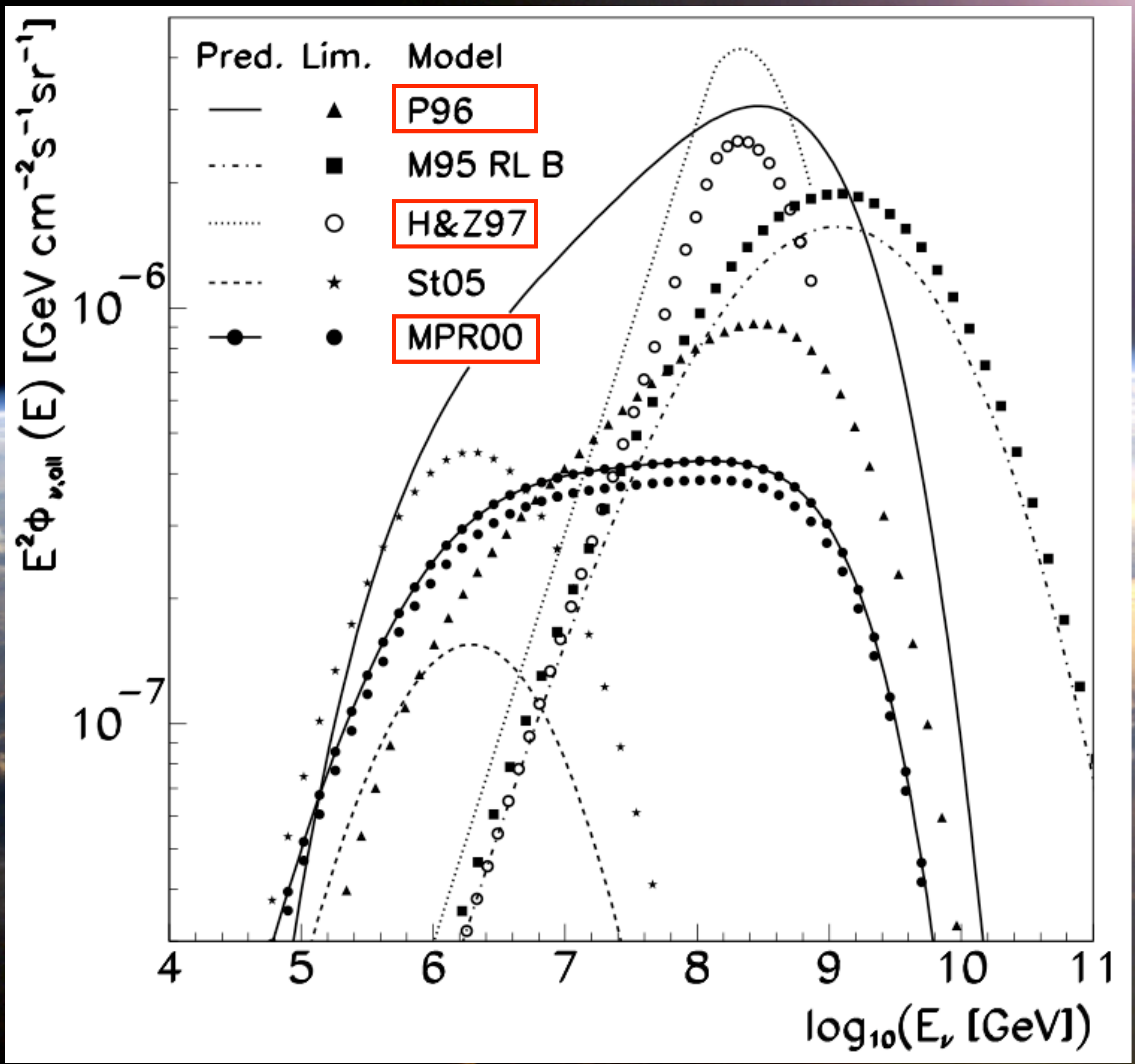
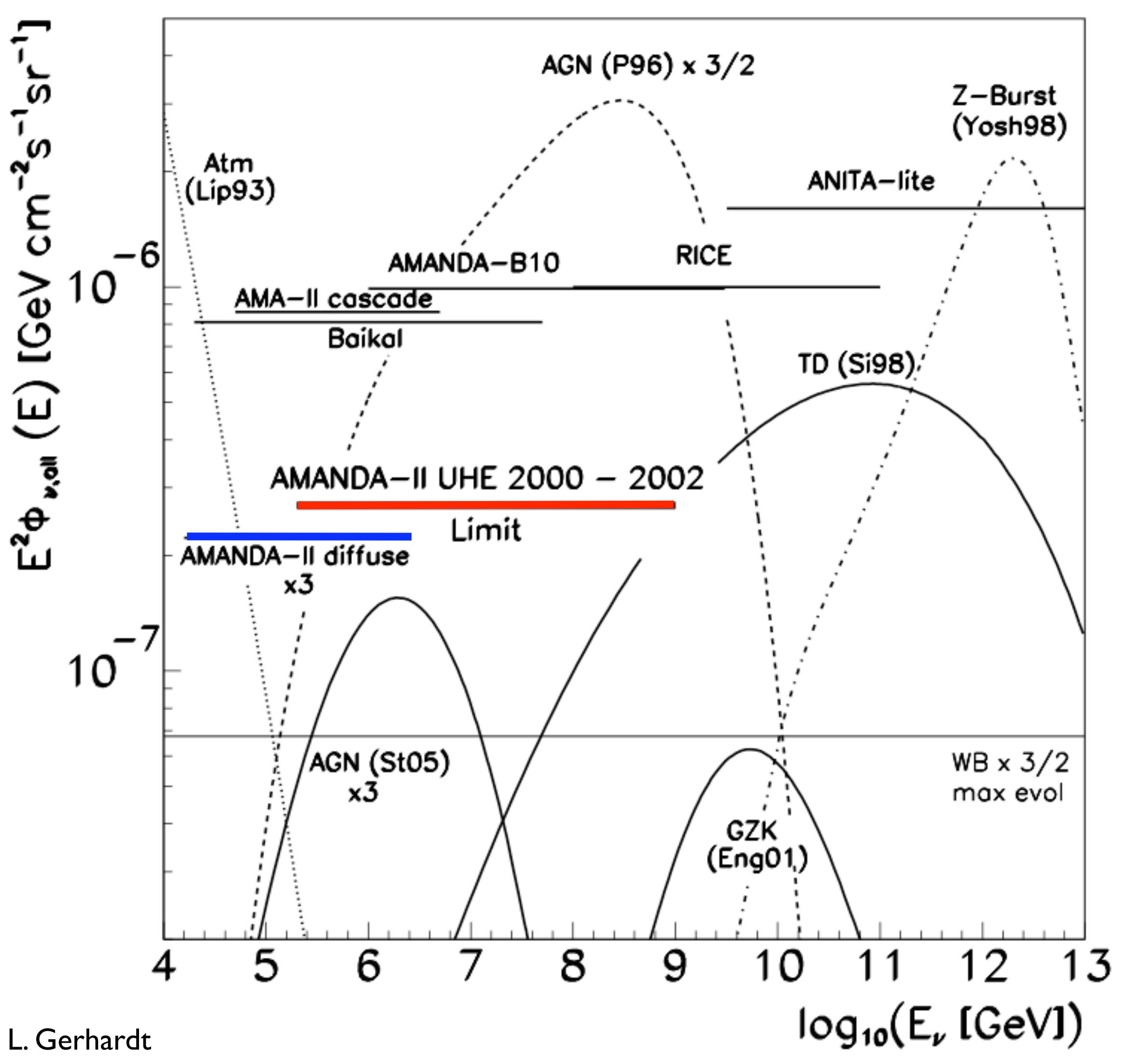
astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2000-2002

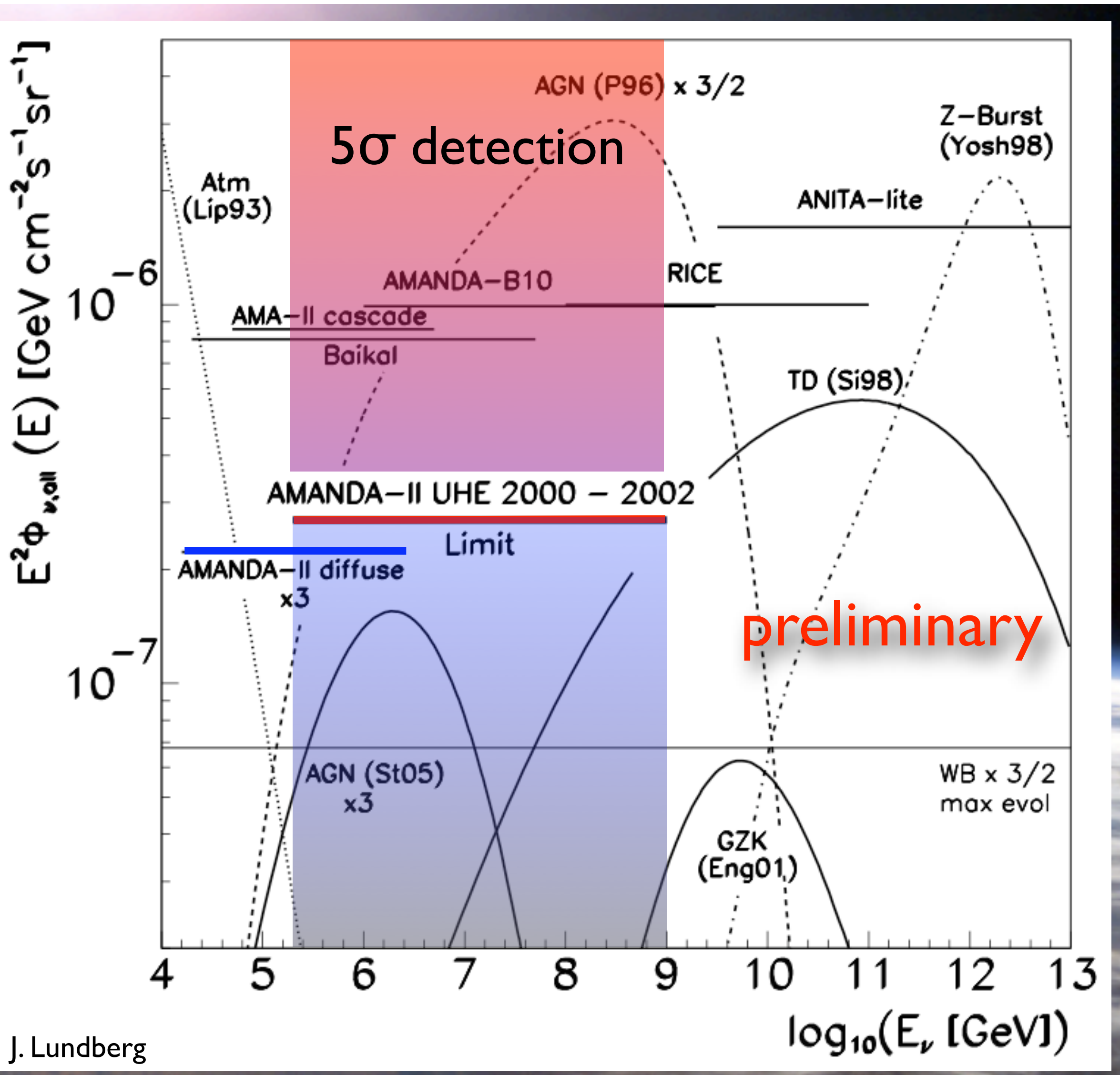




Astrophysical Journal 675 (2008) 1014-1024

astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2003-2004 $\Longrightarrow$ IceCube



Astrophysical Journal 675 (2008) 1014-1024

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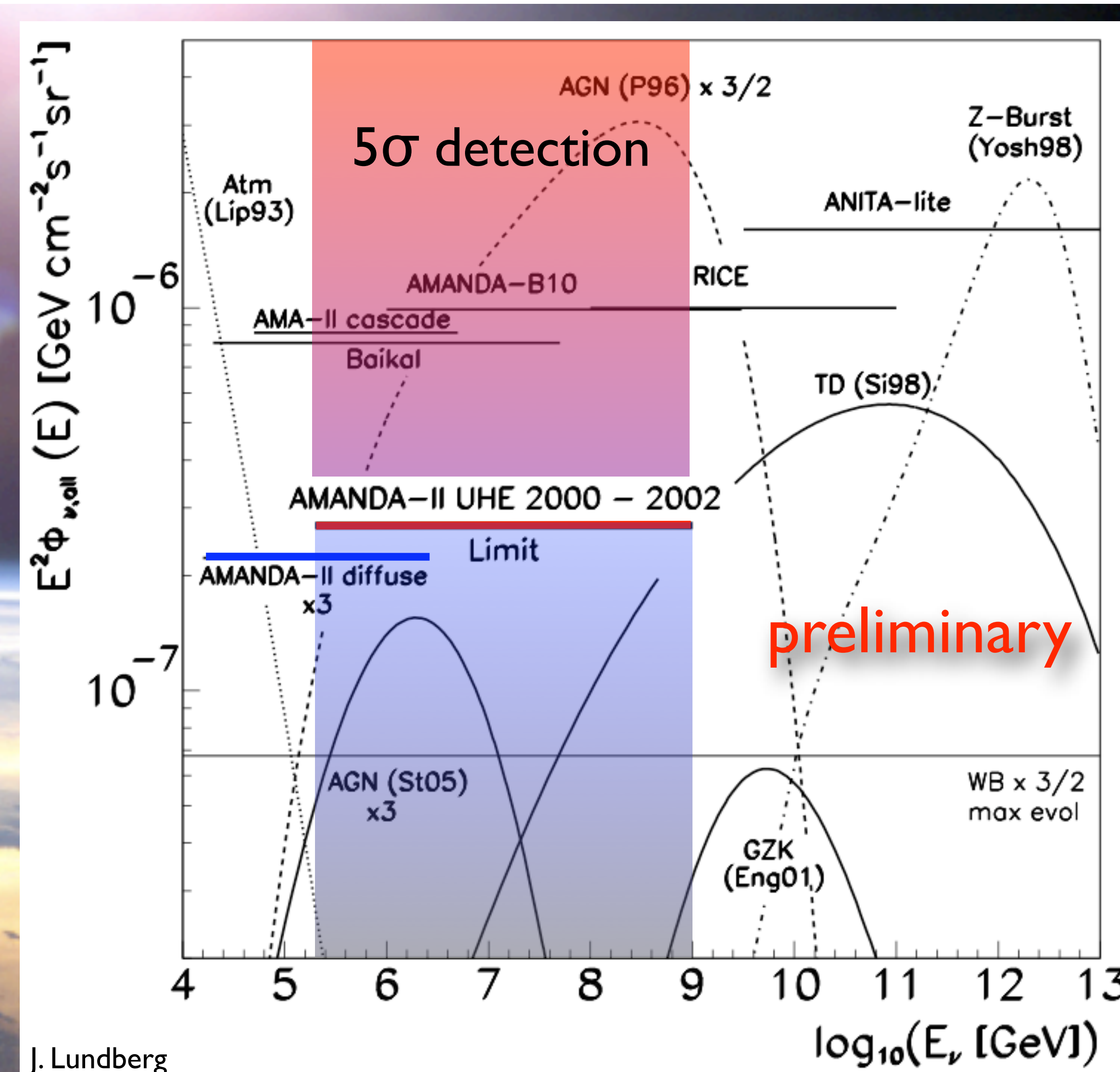
astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2003-2004 ⟹ IceCube

analyzing IceCube data to detect diffuse HE/UHE/EHE neutrinos

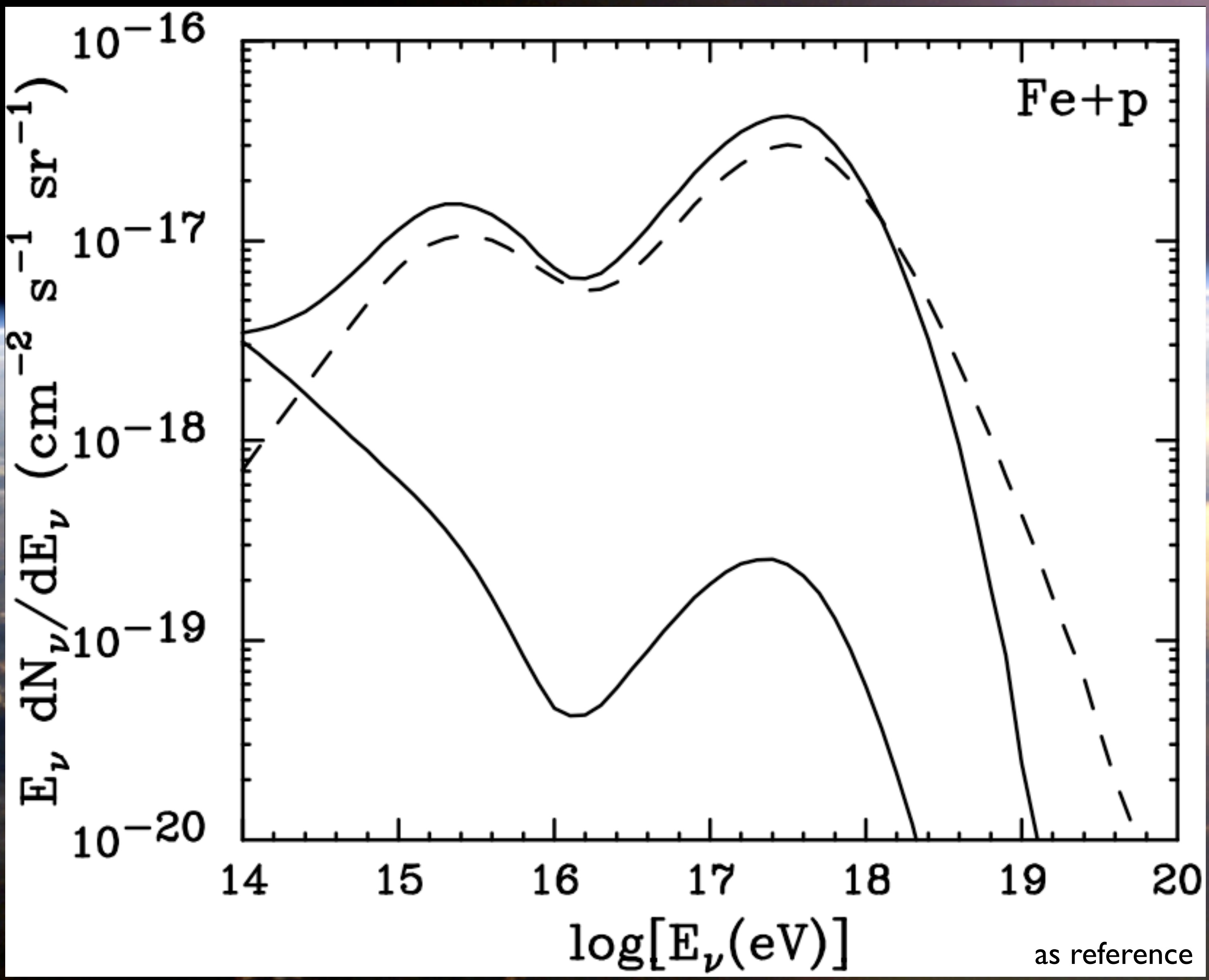
IceCube-80 predicted to improve sensitivity by at least x10

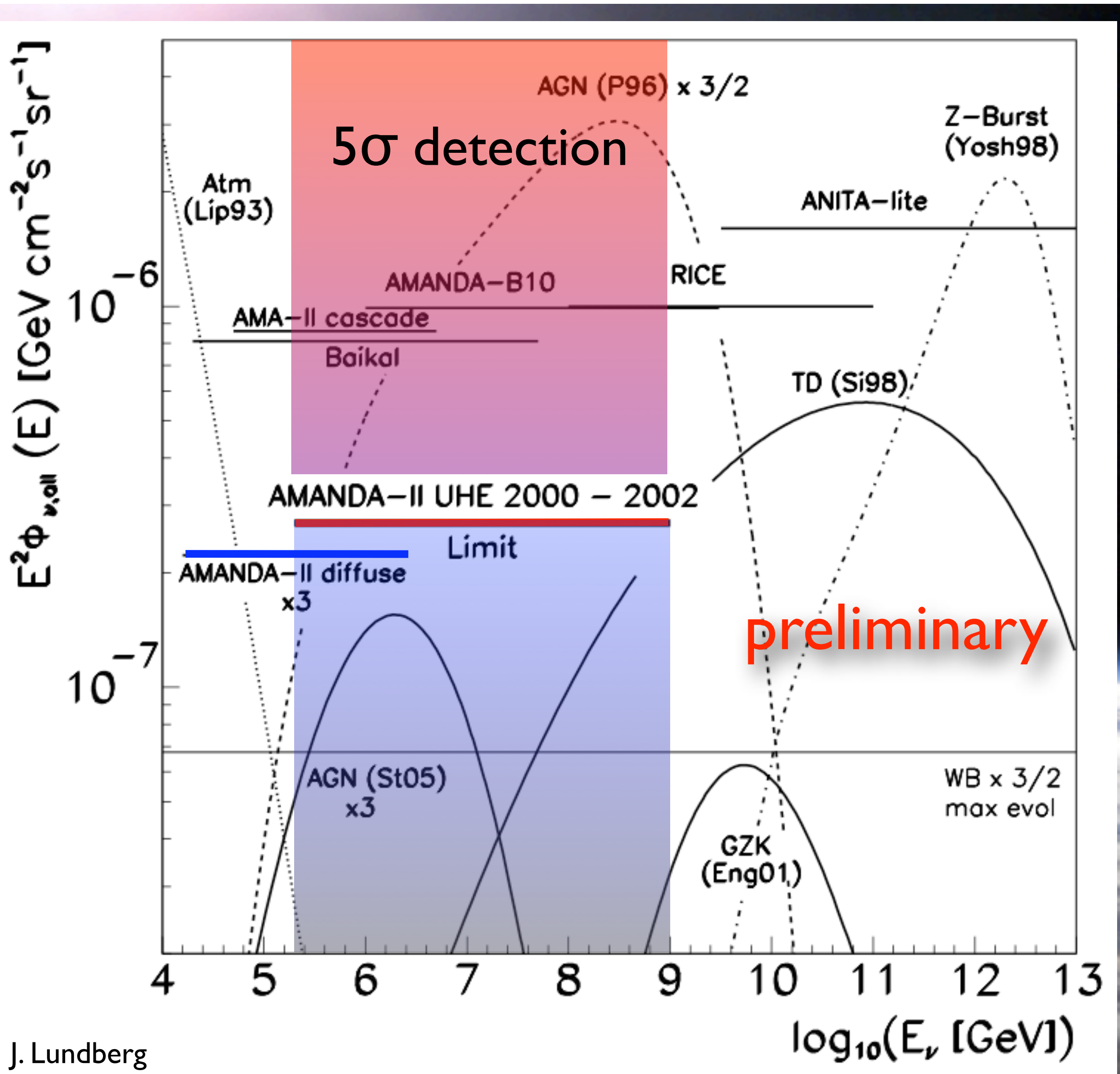


Astrophysical Journal 675 (2008) 1014-1024

astrophysical neutrinos: UHE diffuse sources

AMANDA -II 2003-2004 ⟹ IceCube





Astrophysical Journal 675 (2008) 1014-1024

conclusions

- AMANDA has had an excellent role in developing neutrino telescopes
- a km^3 neutrino observatory is under construction at the South Pole
- will collect unprecedented statistics of neutrinos
- sensitivities closer to neutrino predictions
  - origin of cosmic ray and gamma ray connection
  - smoking gun for hadronic processes in CR sources
  - probe GZK neutrinos
- planning multi-messenger campaigns
- IceCube data filtered online and processed North for short-term analysis
- will be complete in 2011: 4,800 DOMs InIce and 320 DOMs @ IceTop

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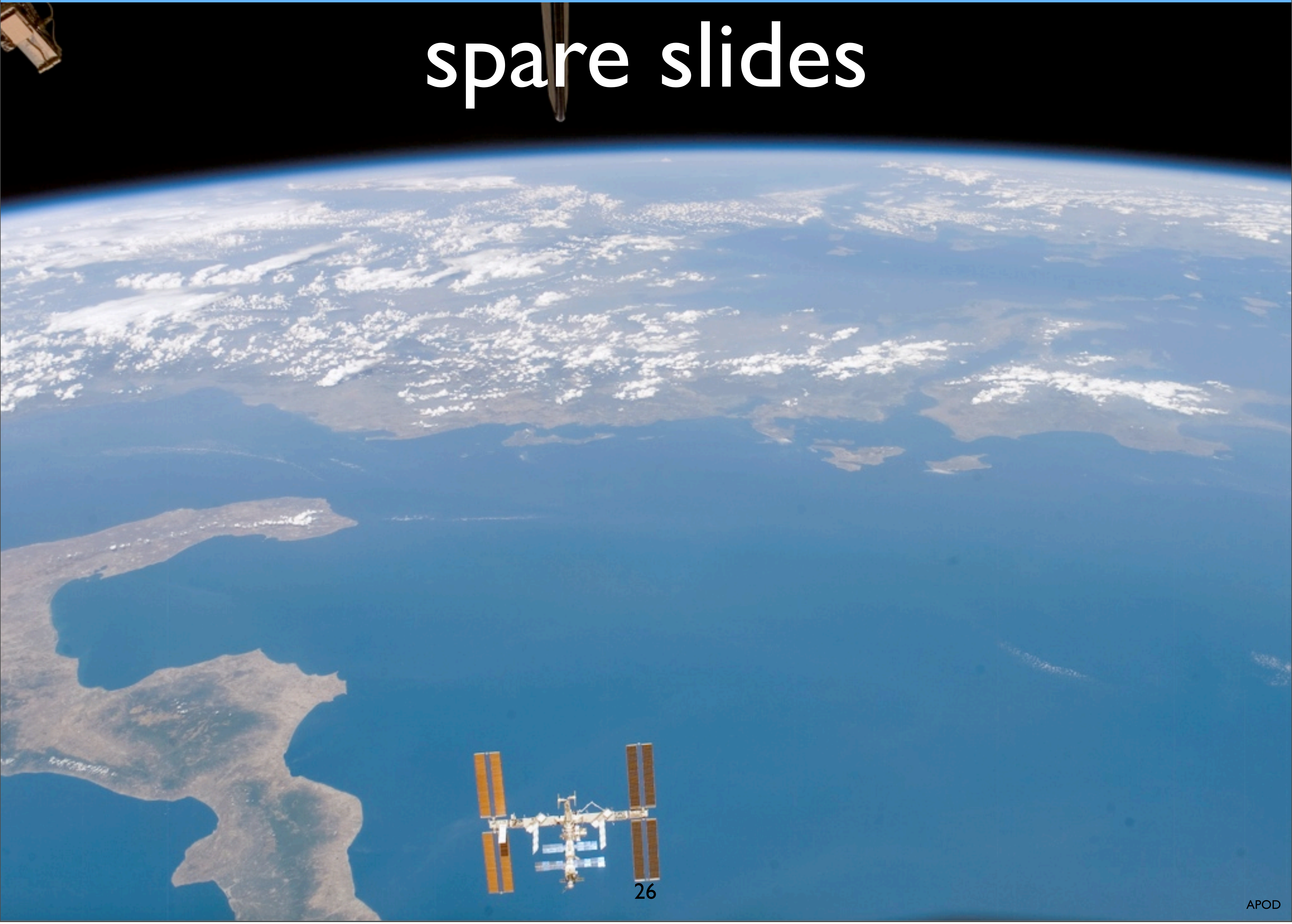
spare slides



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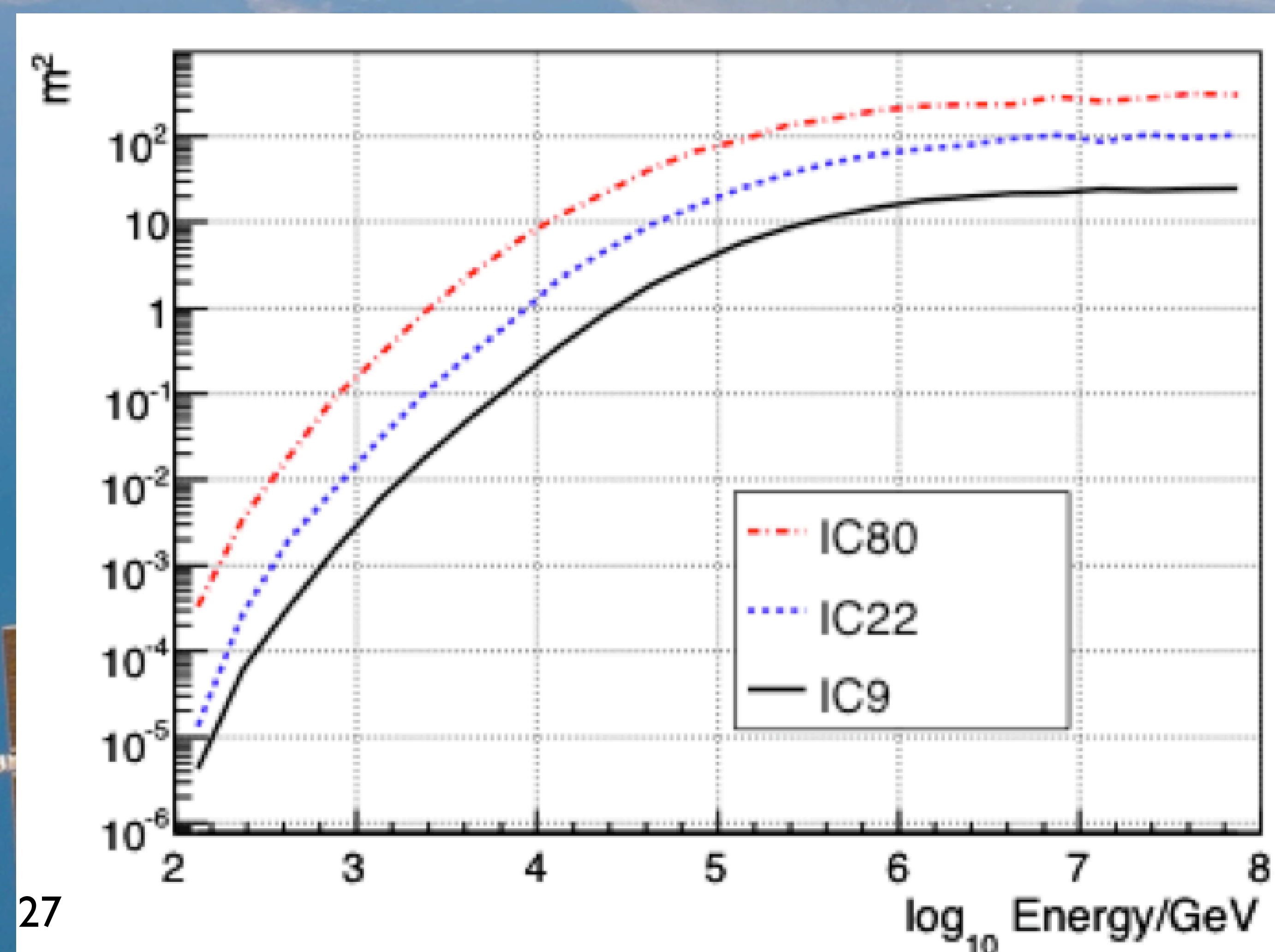
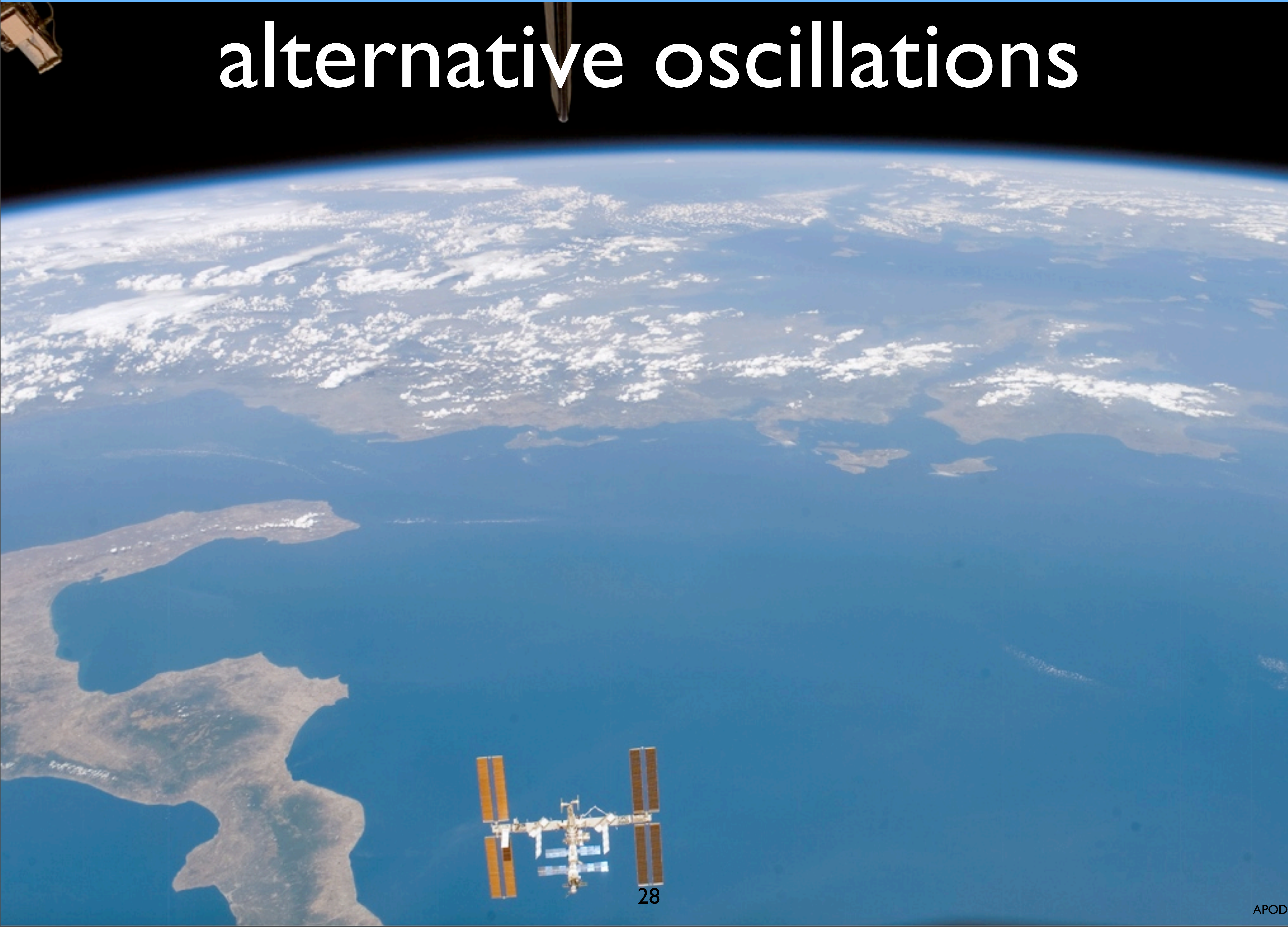
neutrino statistics

geometry	year	livetime	up muons	efficiency	purity	status
IC-9	2006	137.4 d	233 (1.7/d)	3%	~90%	final
IC-22	2007	285 d	~7,980 (~28/d)	25%	95%	preliminary
IC-40	2008	~365 d	~40,000 (110/d)			predicted
IC-80	2011	~365 d	~80,000 (220/d)			predicted



alternative oscillations



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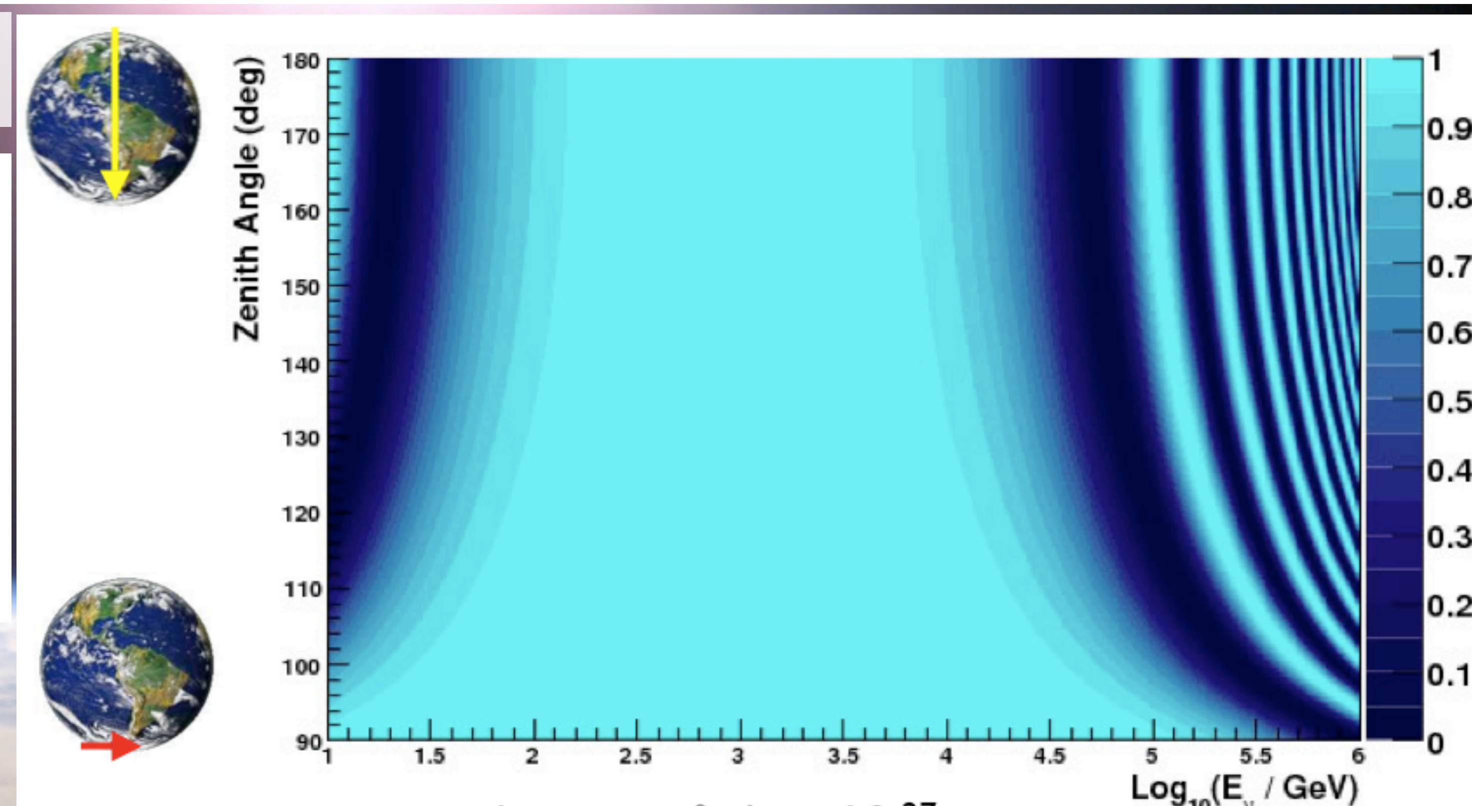
Violation of Lorentz Invariance

AMANDA -II 2000-2006

Violation of Lorentz Invariance

neutrinos have distinct maximum velocity eigenstates ≠ *c*, and difference $\delta c/c$ results in oscillations



maximal mixing, $\delta c/c = 10^{-27}$

$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\mathcal{R}\right)$$

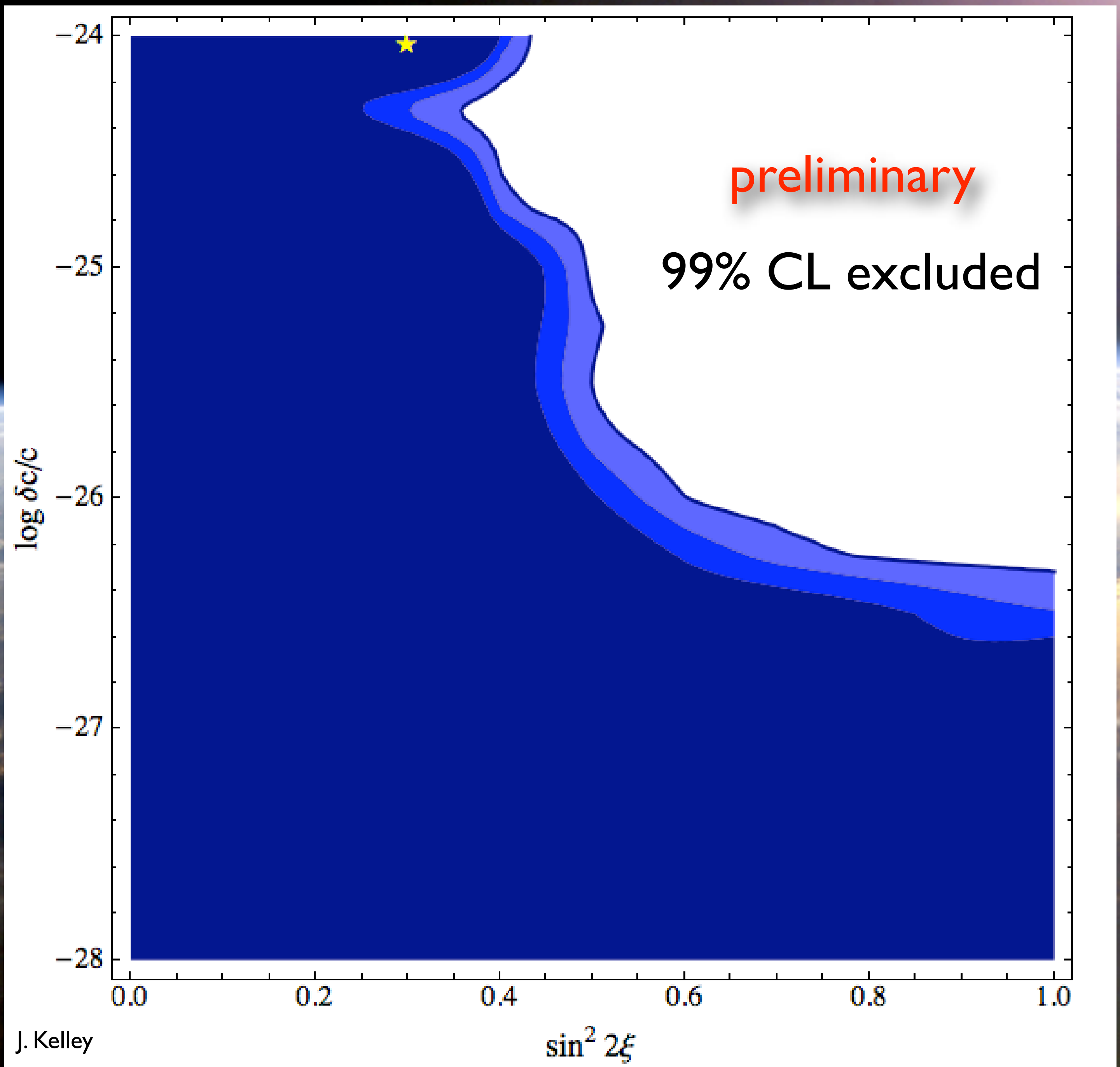
$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2}(\sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos\eta) \, ,$$

$$\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos\eta)} \, ,$$

$$R = \frac{\delta c}{c}\frac{E}{2}\frac{4E}{\Delta m^2_{23}}$$

Violation of Lorentz Invariance

AMANDA -II 2000-2006 : sensitivity



$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\mathcal{R}\right)$$

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$$\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23} \cos 2\xi + \sin 2\theta_{23} \sin 2\xi \cos\eta)} \, ,$$

$$R = \frac{\delta c}{c} \frac{E}{2} \frac{4E}{\Delta m^2_{23}}$$

- 2000-03 analysis (Ahrens):

  $\delta c/c < 5.3 \times 10^{-27}$ (90%CL)

- Median sensitivity (χ^2 approx.):

  $\delta c/c < 4.3 \times 10^{-27}$ (90%CL)

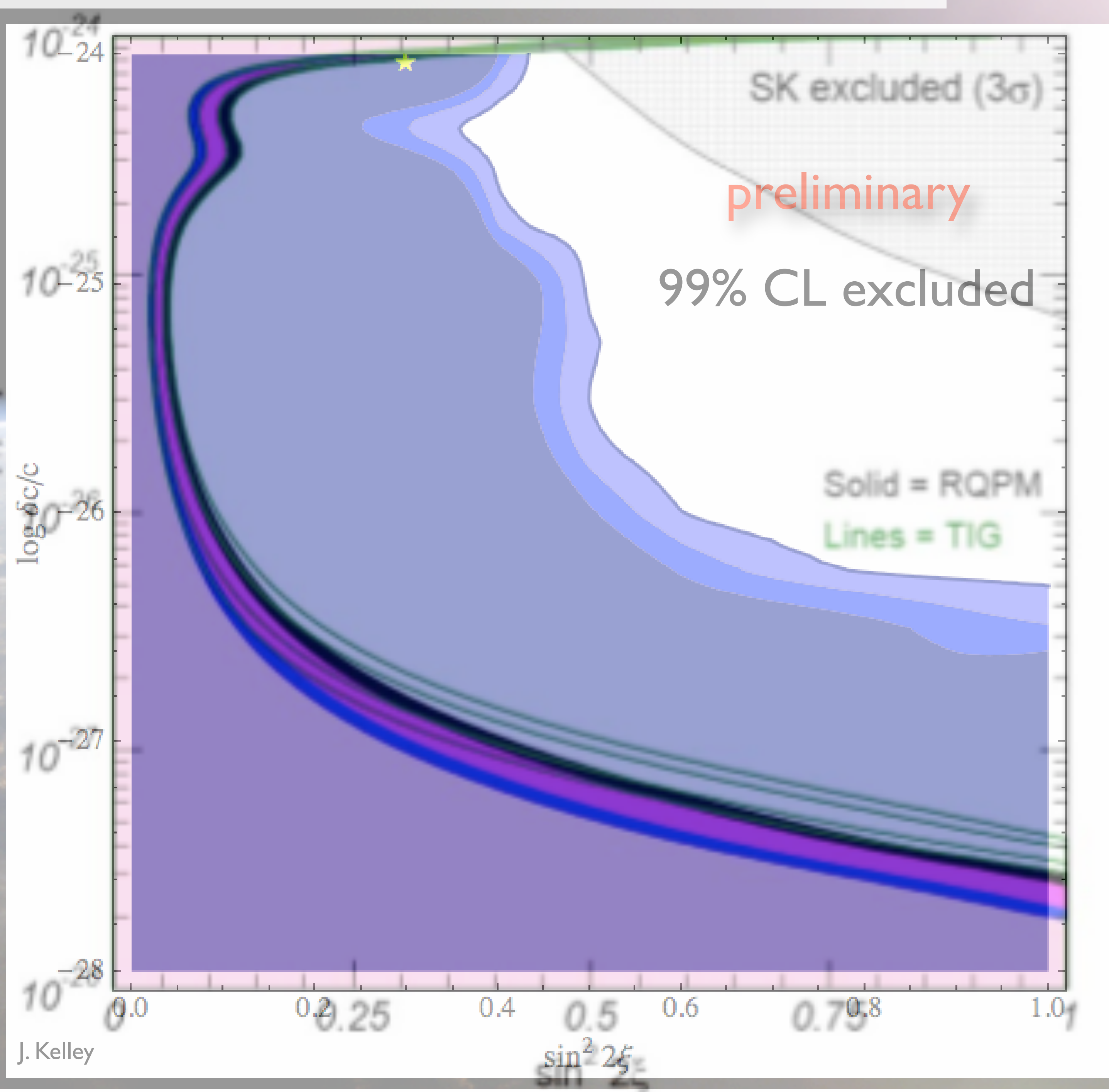
- Sample sensitivity (1 MC experiment, full construction):

  $\delta c/c < 4.5 \times 10^{-27}$ (90%CL)

(maximal mixing, $\cos\eta = 0$)

Violation of Lorentz Invariance

AMANDA -II 2000-2006 : sensitivity



$$P_{\nu_\mu \to \nu_\mu} = 1 - \sin^2 2\Theta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\,\mathcal{R}\right)$$

$$\sin^2 2\Theta = \frac{1}{\mathcal{R}^2}(\sin^2 2\theta_{23} + R^2 \sin^2 2\xi + 2R \sin 2\theta_{23} \sin 2\xi \cos\eta)\,,$$

$$\mathcal{R} = \sqrt{1 + R^2 + 2R(\cos 2\theta_{23}\cos 2\xi + \sin 2\theta_{23}\sin 2\xi\cos\eta)}\,,$$

$$R = \frac{\delta c}{c}\frac{E}{2}\frac{4E}{\Delta m^2_{23}}$$

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  $\delta c/c < 4.5 \times 10^{-27}$ (90%CL)

(maximal mixing, $\cos\eta = 0$)

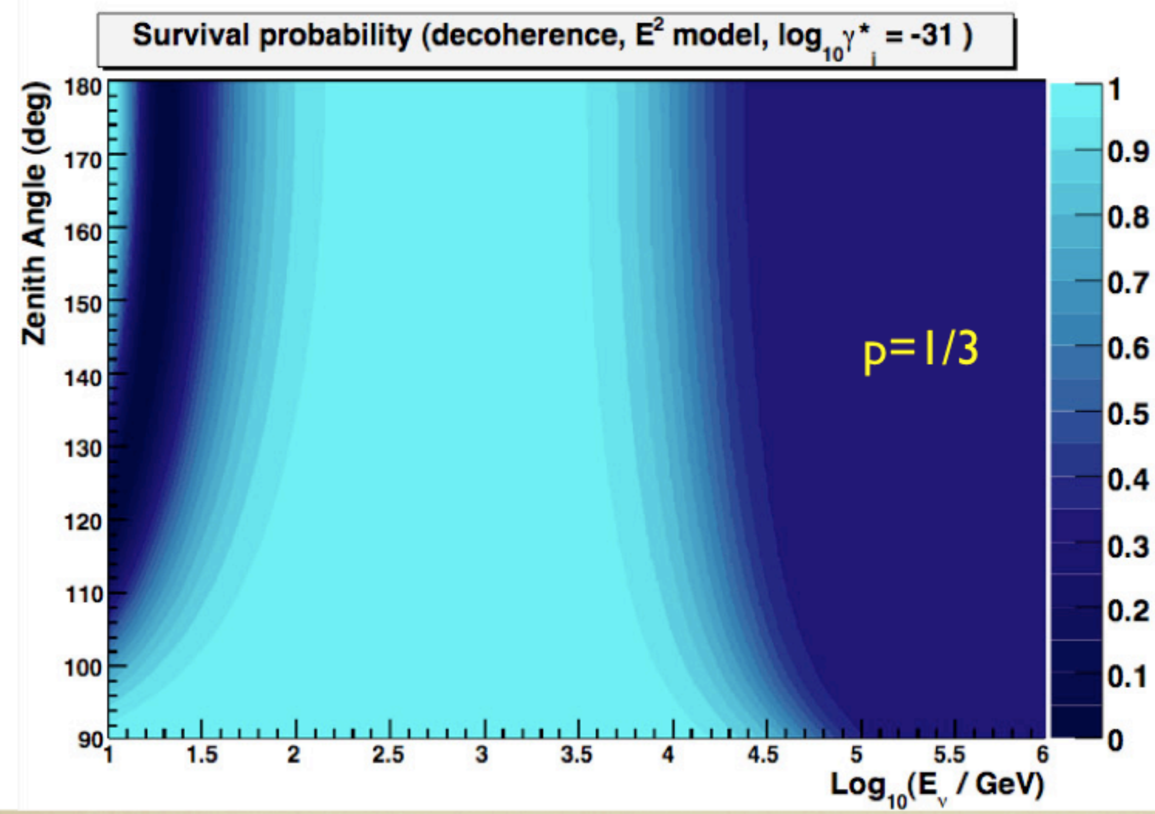
Gonzalez-Garcia, astro-ph/0701333

Quantum Decoherence

AMANDA -II 2000-2006

Quantum Decoherence

interaction with *foamy* space-tim structure may modify neutrino flavor



characteristic exponential behavior

1:1:1 ratio after decoherence

$$
\begin{aligned}
P[\nu_\mu \rightarrow \nu_\mu] = \frac{1}{3} + \frac{1}{2}\Bigg(& e^{-\gamma_3 L}\cos^4\theta_{23} + \frac{1}{12}e^{-\gamma_8 L}(1-3\cos 2\theta_{23})^2 \\
& + 4e^{-\frac{\gamma_6+\gamma_7}{2}L}\cos^2\theta_{23}\sin^2\theta_{23}\Bigg(\cos\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right] \\
& + \sin\left[\frac{L}{2}\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}\right]\frac{(\gamma_6-\gamma_7)}{\sqrt{\left|(\gamma_6-\gamma_7)^2-\left(\frac{\Delta m^2_{23}}{E}\right)^2\right|}}\Bigg)\Bigg)
\end{aligned}
$$

derived from Barenboim, Mavromatos *et al.* (hep-ph/0603028)

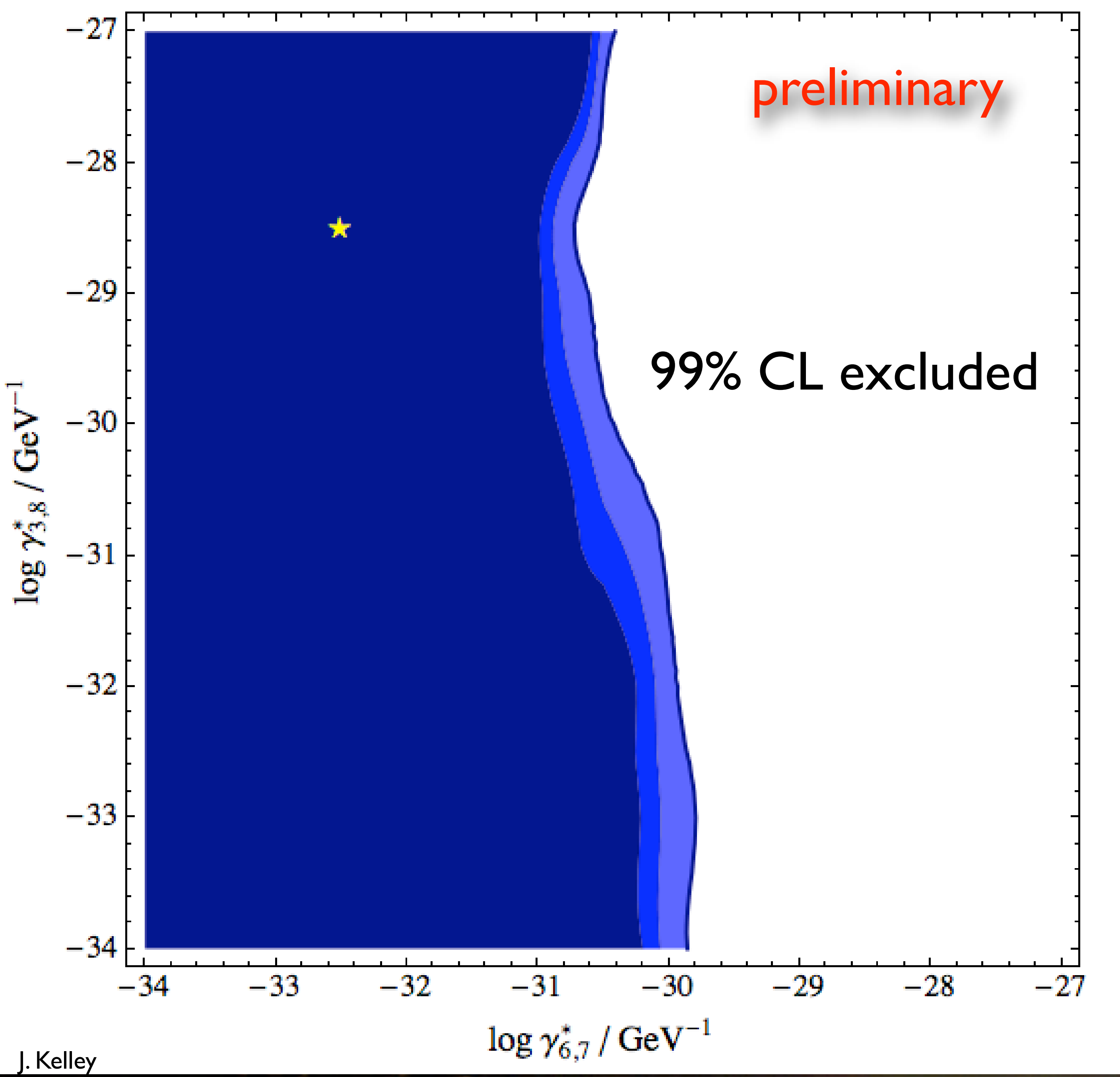
Energy dependence depends on phenomenology: $\gamma_i = \gamma_i^* \; E^n, \quad n \in \{-1, 0, 2, 3\}$

$n = -1$	$n = 0$	$n = 2$	$n = 3$
preserves Lorentz invariance	simplest	recoiling D-branes*	Planck-suppressed operators‡

*Ellis *et al.*, hep-th/9704169 ‡ Anchordoqui *et al.*, hep-ph/0506168

Quantum Decoherence

AMANDA -II 2000-2006 : sensitivity



- ANTARES sensitivity (3 years)*:

  $\gamma^* < 2 \times 10^{-30}$ GeV^{-1} (2-flavor)

- This analysis (1 MC experiment, full construction):

  $\gamma^* < 2.0 \times 10^{-31}$ GeV^{-1}

  (E^2 model, $\gamma_3 = \gamma_8 = \gamma_6 = \gamma_7$)

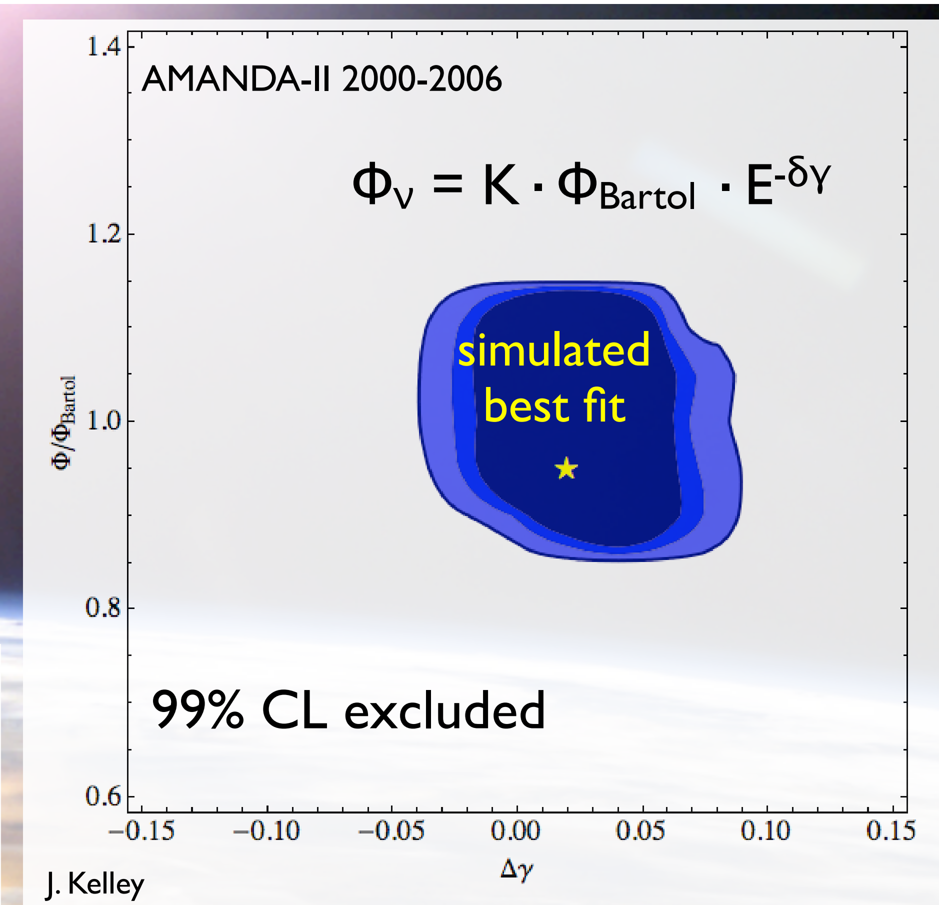
* Morgan *et al.*, astro-ph/0412618

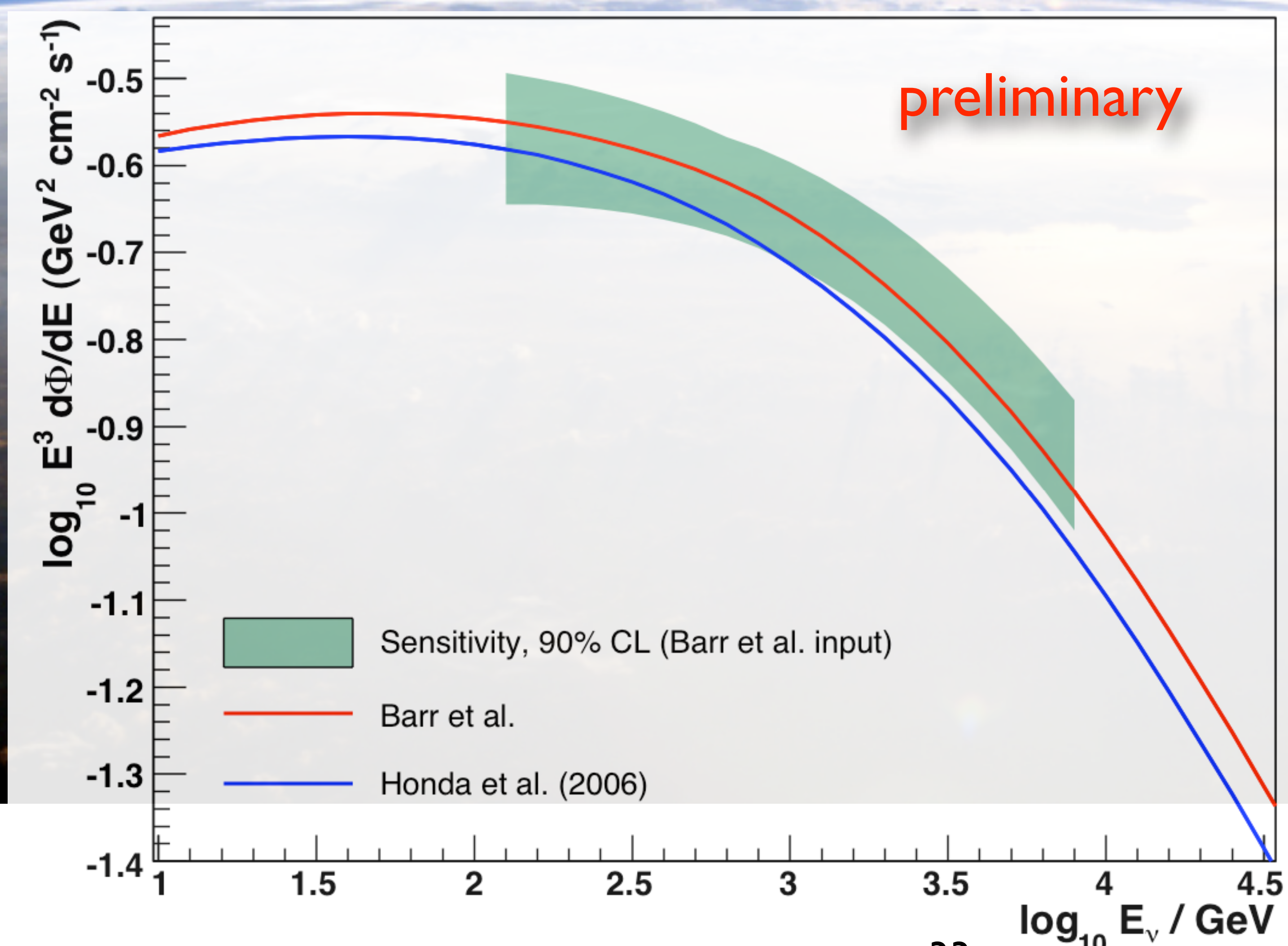
atmospheric neutrino deconvolution

AMANDA -II 2000-2006

2 parameter spectrum deconvolution

likelihood fit bases on simulated neutrino with Bartol spectrum (Barr et al., Phys.Rev.D70:023006,2004)





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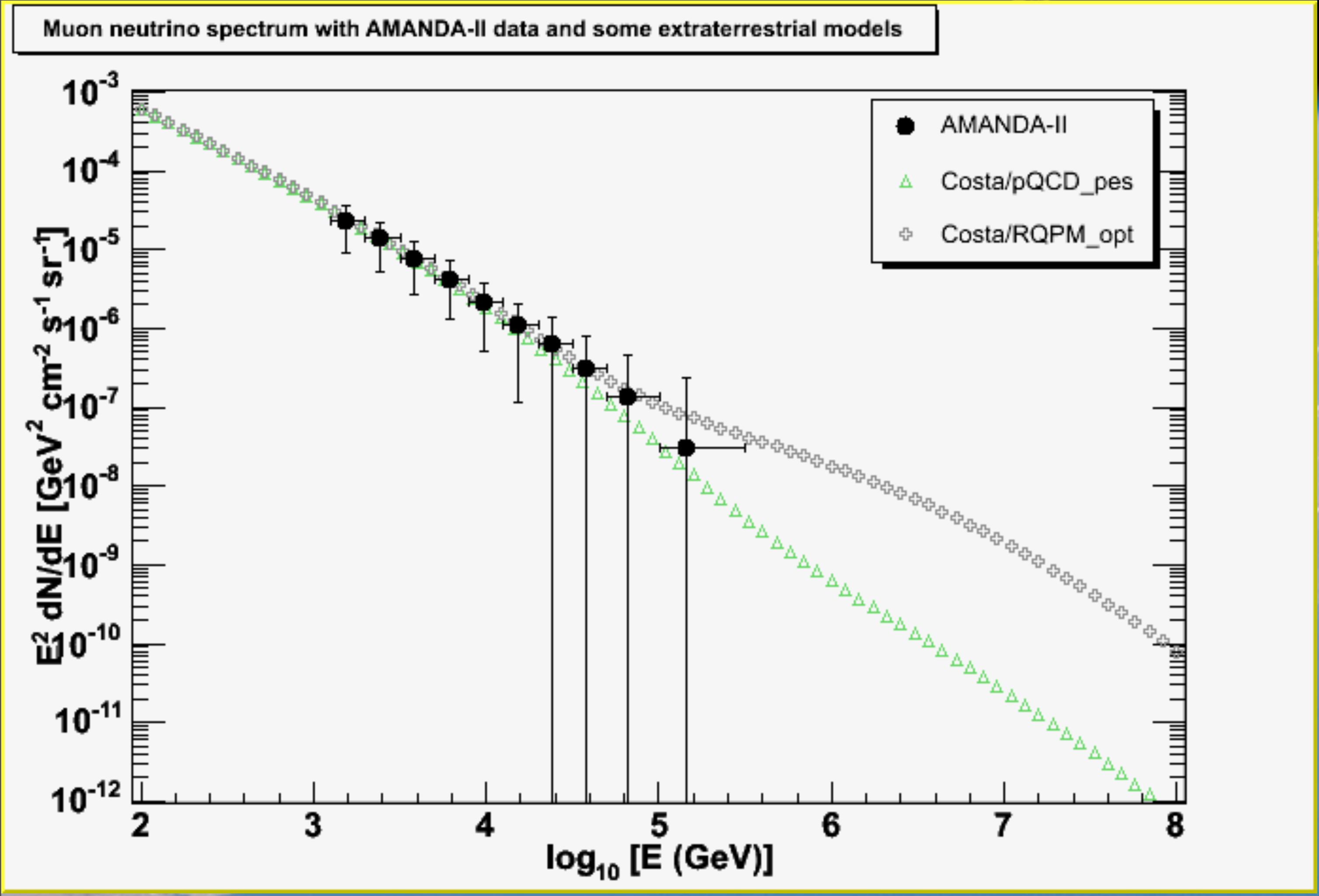
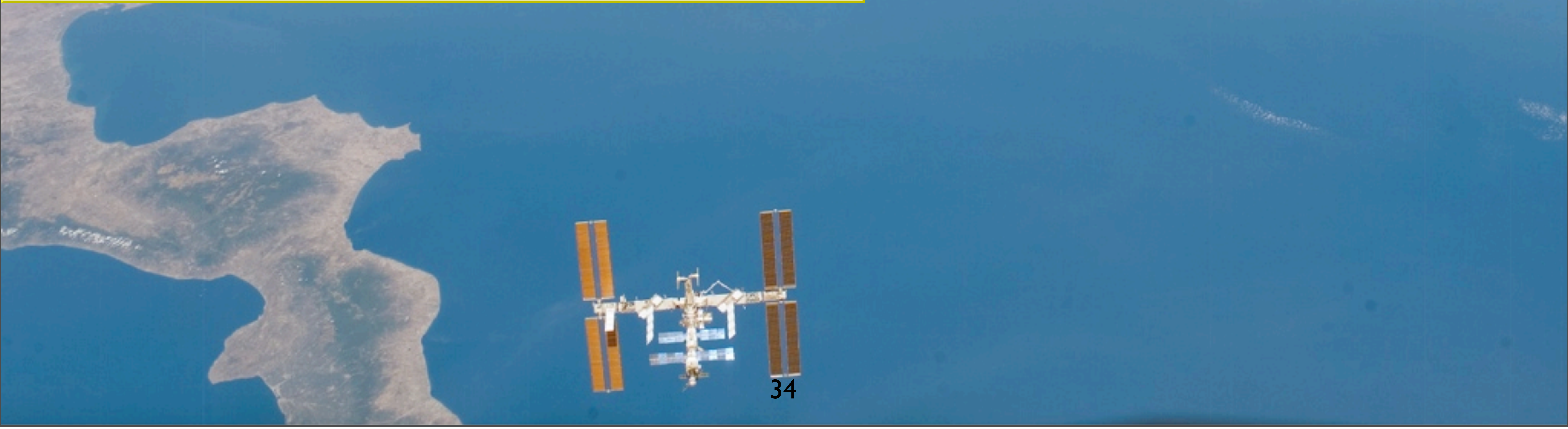
charm in the atmosphere



benchmark DPMJET-II with recent accelerator data

use charm production in CORSIKA

propagate charmed particles in CORSIKA



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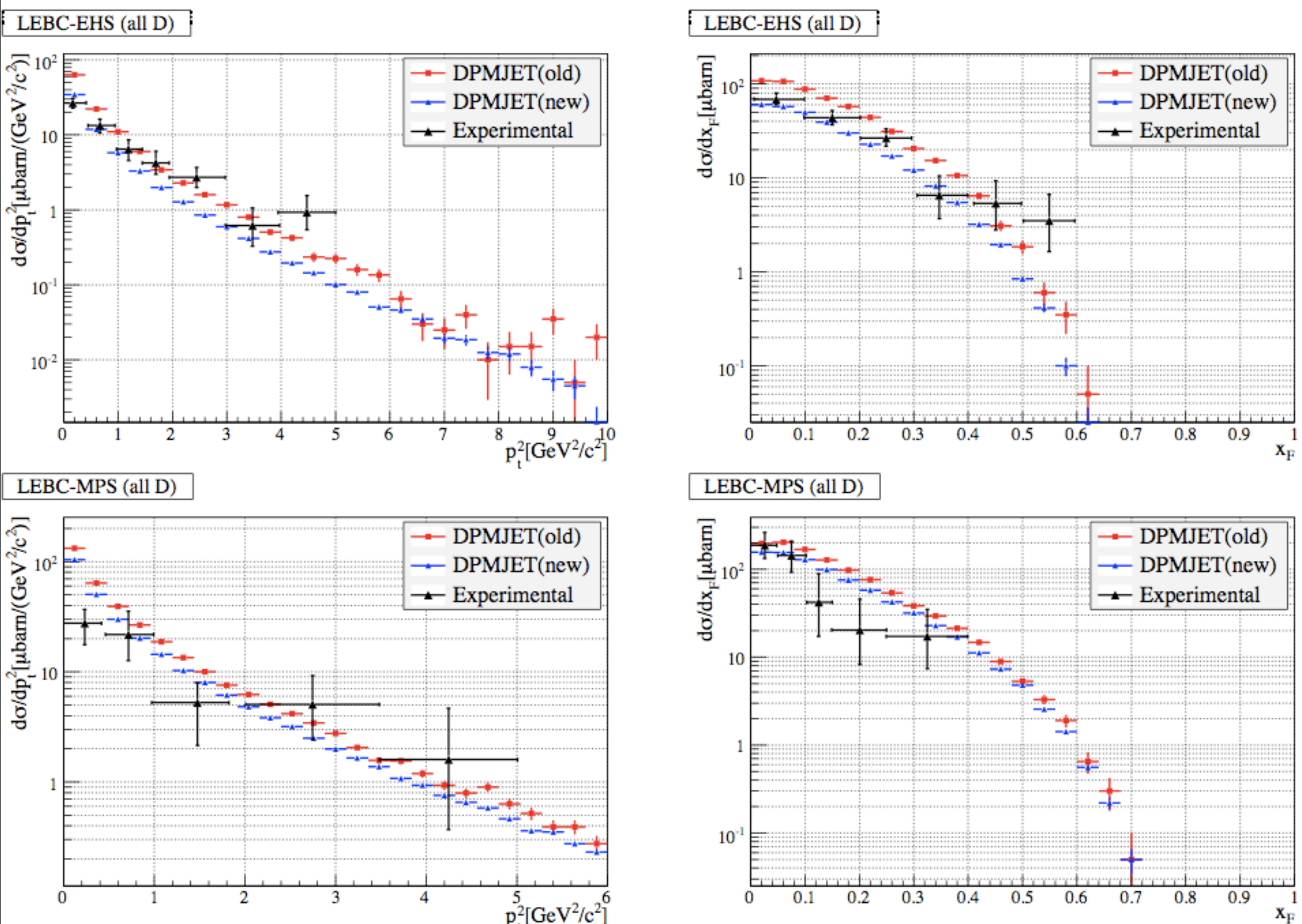
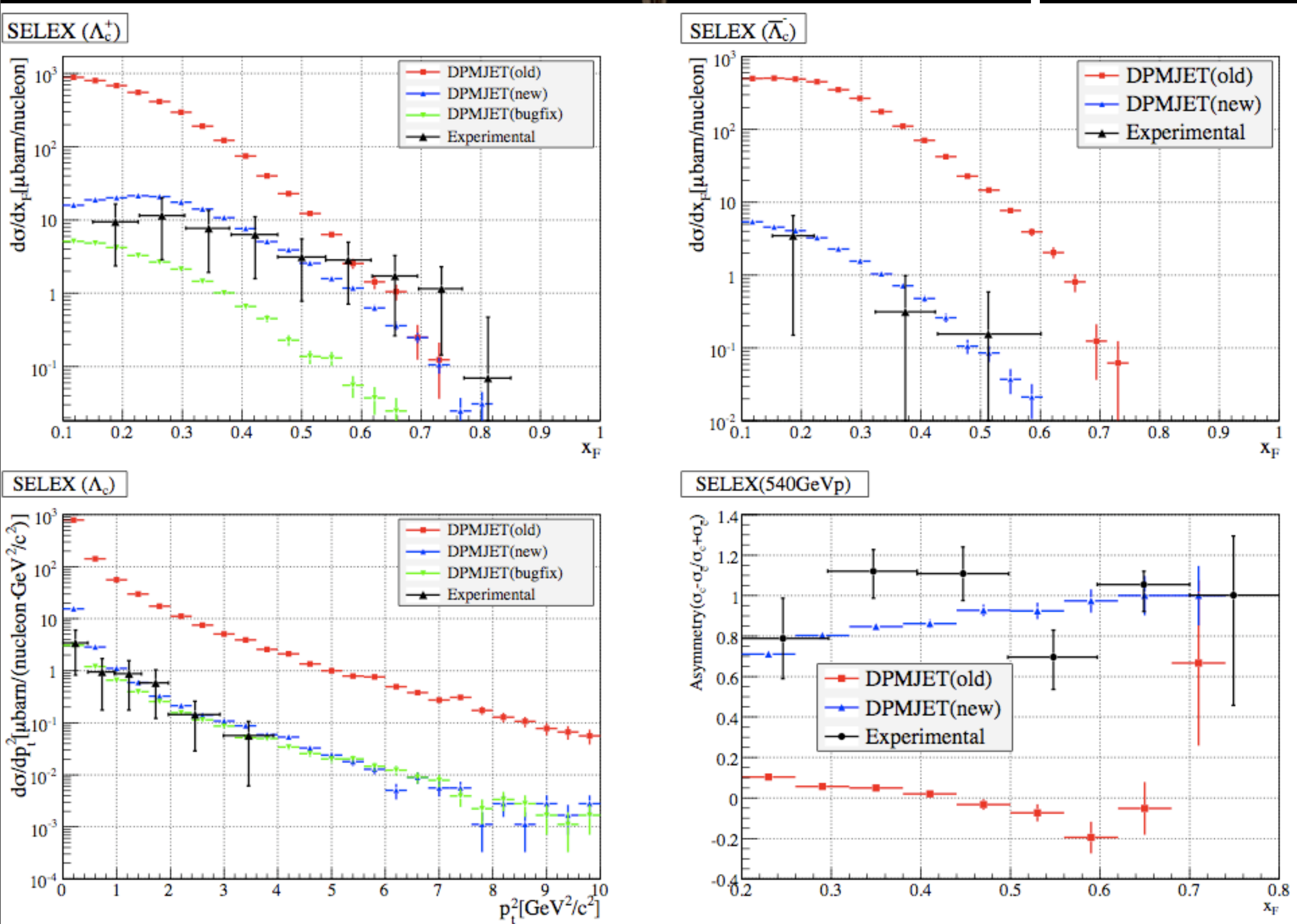
charm in the atmosphere



P.Berghaus, T.Montaruli, J.Ranft arXiv:0712.3089v2

charm in the atmosphere



P.Berghaus, T.Montaruli, J.Ranft arXiv:0712.3089v2

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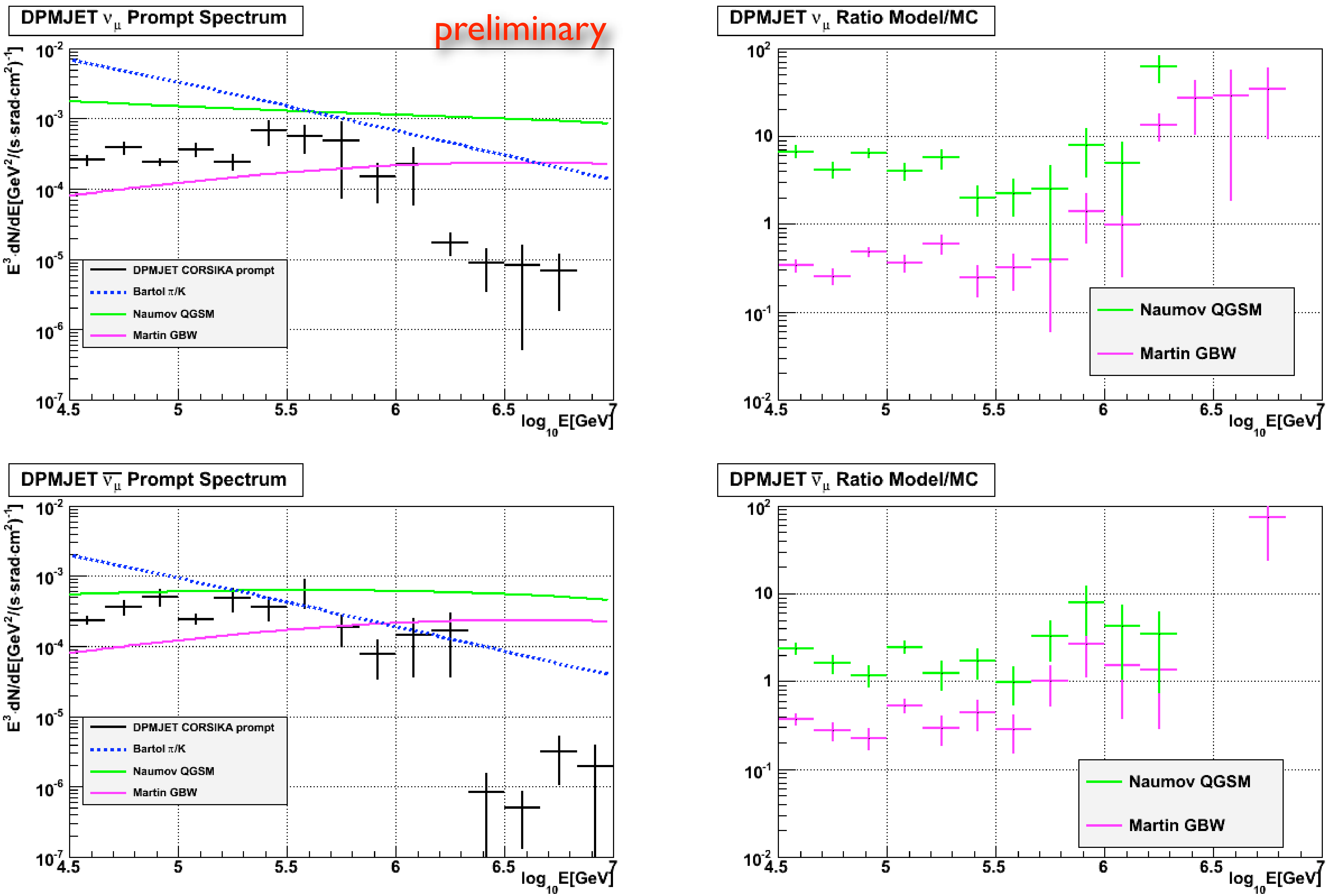
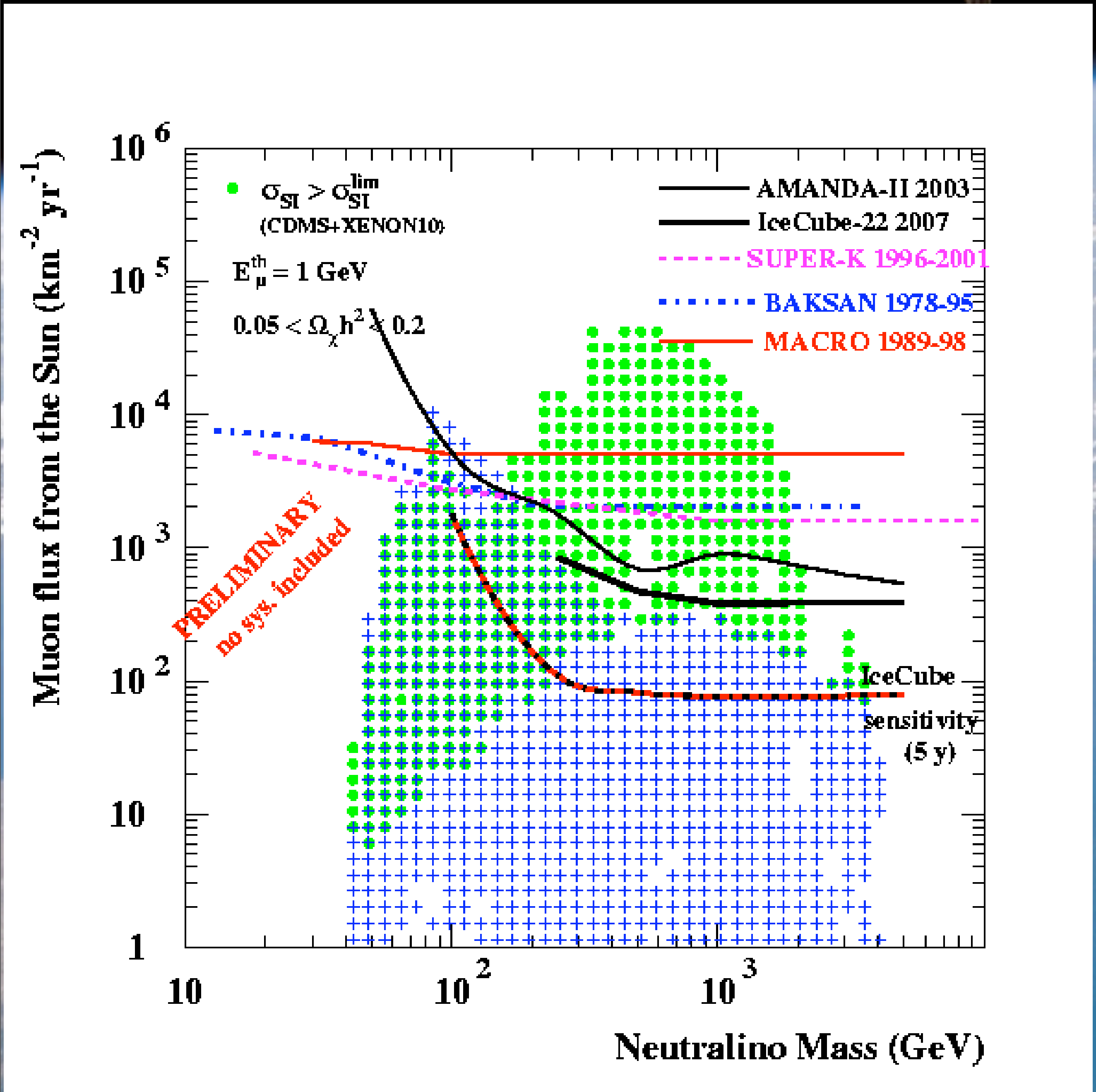
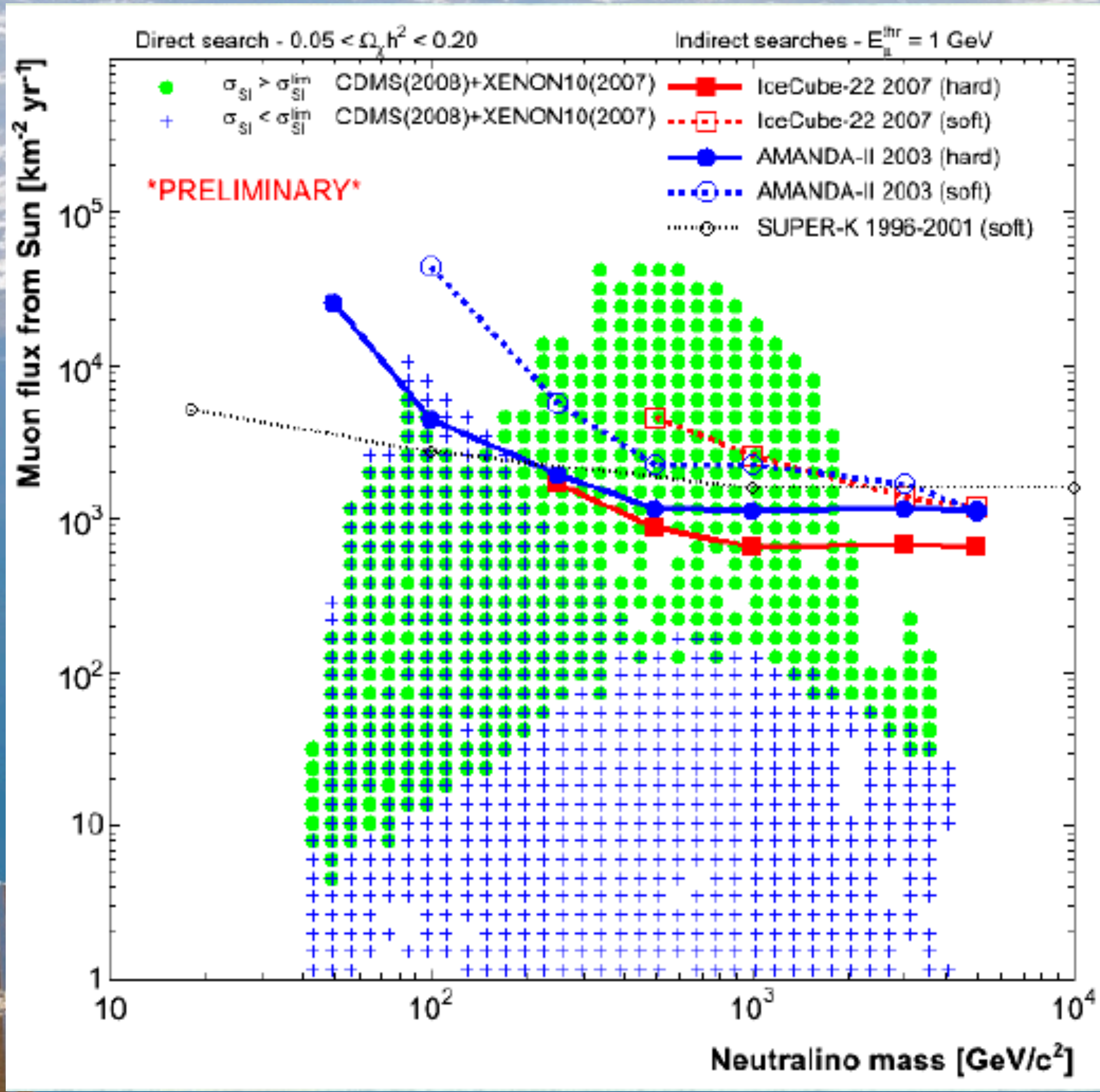
charm in the atmosphere



P.Berghaus, T.Montaruli, J.Ranft arXiv:0712.3089v2

indirect WIMP searches





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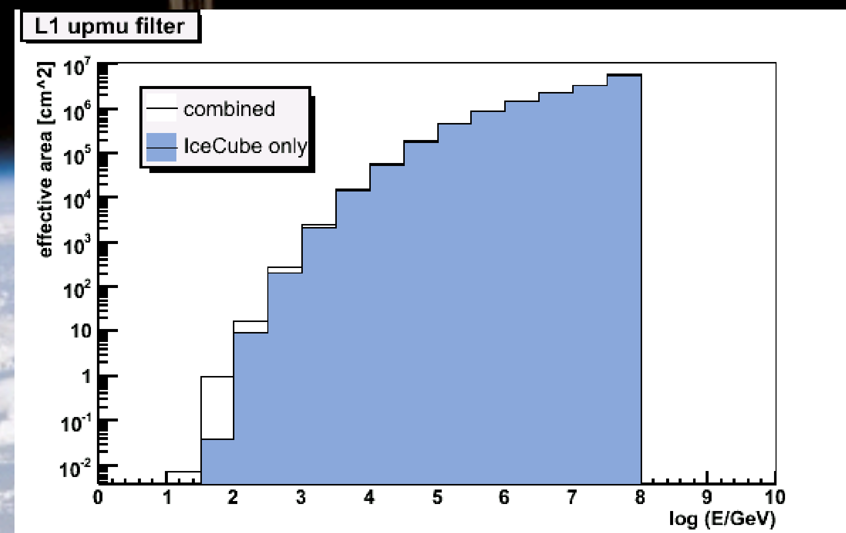
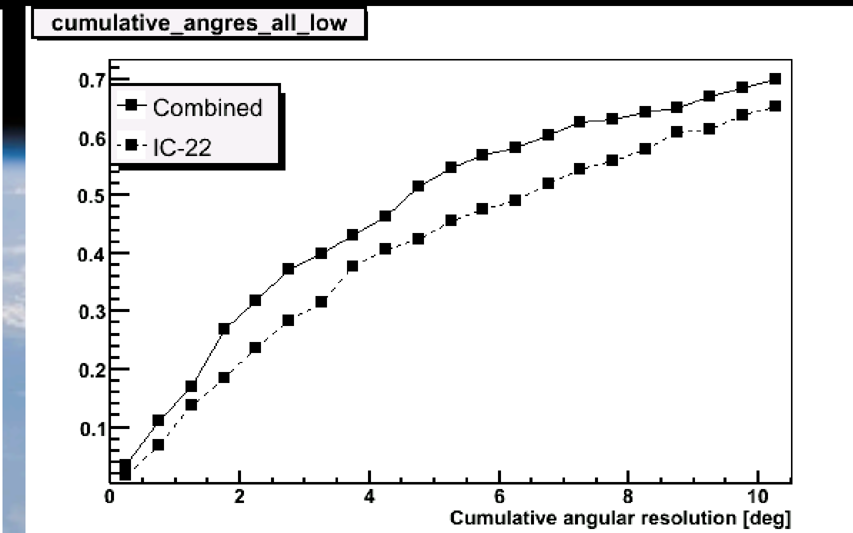
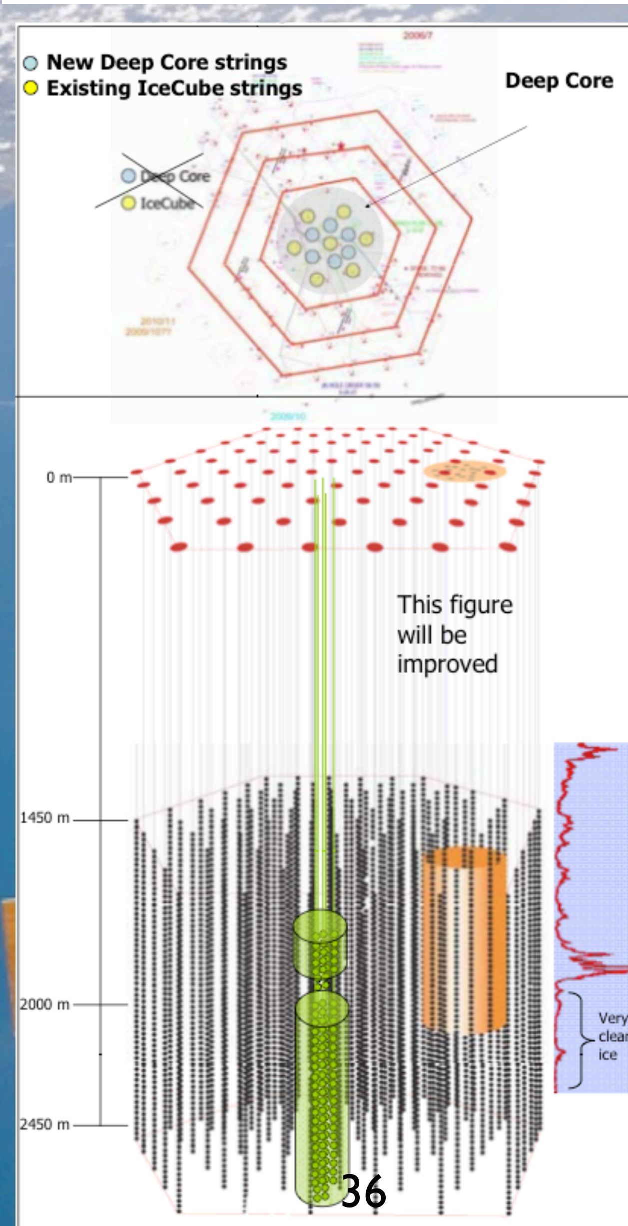
low energy extension

IceCube+AMANDA





IceCube+DeepCore



- $E_{th} \gtrsim 30$ GeV
    - atmospheric neutrinos
    - oscillations
    - galactic sources of $\lesssim$ 10 TeV
    - WIMP dark matter

use high QE PMT (+38%)

deploy first string in 08/09

other 5 strings in 09/10

APOD

hardware

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APOD

the DOM

DOM Requirements

- Fast timing: resolution < 5 ns DOM-to-DOM on LE time.
- Pulse resolution < 10 ns
- Optical sens. 330 nm to 500 nm
- Dynamic range
  - 1000 pe / 10 ns
  - 10,000 pe / 1 us.
- Low noise: < 500 Hz background
- High gain: O(10^7) PMT
- Charge resolution: P/V > 2
- Low power: 3.75 W
- Ability to self-calibrate
- Field-programmable HV generated internal to unit.
- Flasher board – capable of emitting optical pulses O(20) ns wide > 10^9 γ/pulse
- 10000 psi external

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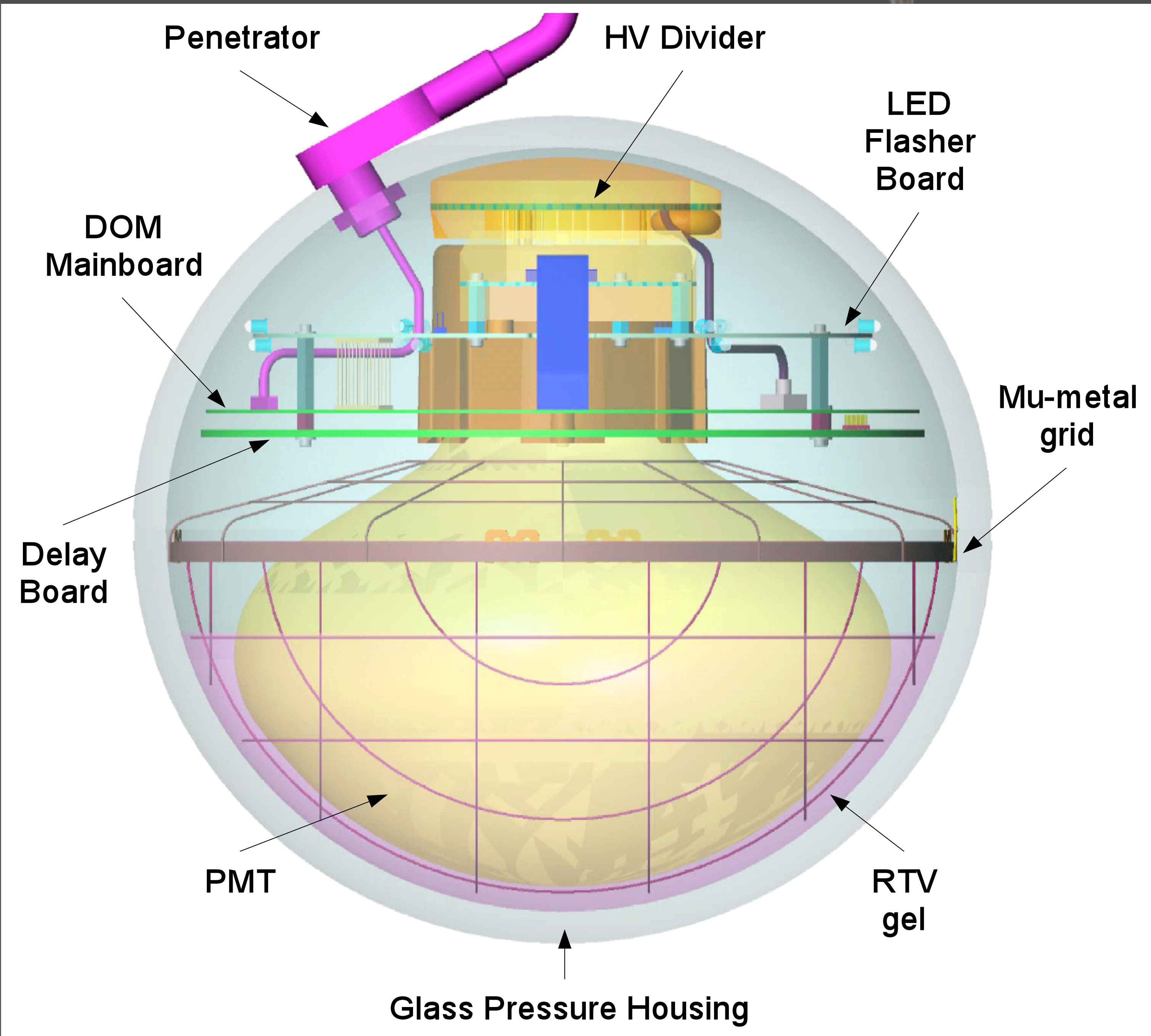
APOD

the DOM



DOM Requirements

- Fast timing: resolution < 5 ns DOM-to-DOM on LE time.
- Pulse resolution < 10 ns
- Optical sens. 330 nm to 500 nm
- Dynamic range
  - 1000 pe / 10 ns
  - 10,000 pe / 1 us.
- Low noise: < 500 Hz background
- High gain: O(10^7) PMT
- Charge resolution: P/V > 2
- Low power: 3.75 W
- Ability to self-calibrate
- Field-programmable HV generated internal to unit.
- Flasher board – capable of emitting optical pulses O(20) ns wide > 10^9 γ/pulse
- 10000 psi external

APOD

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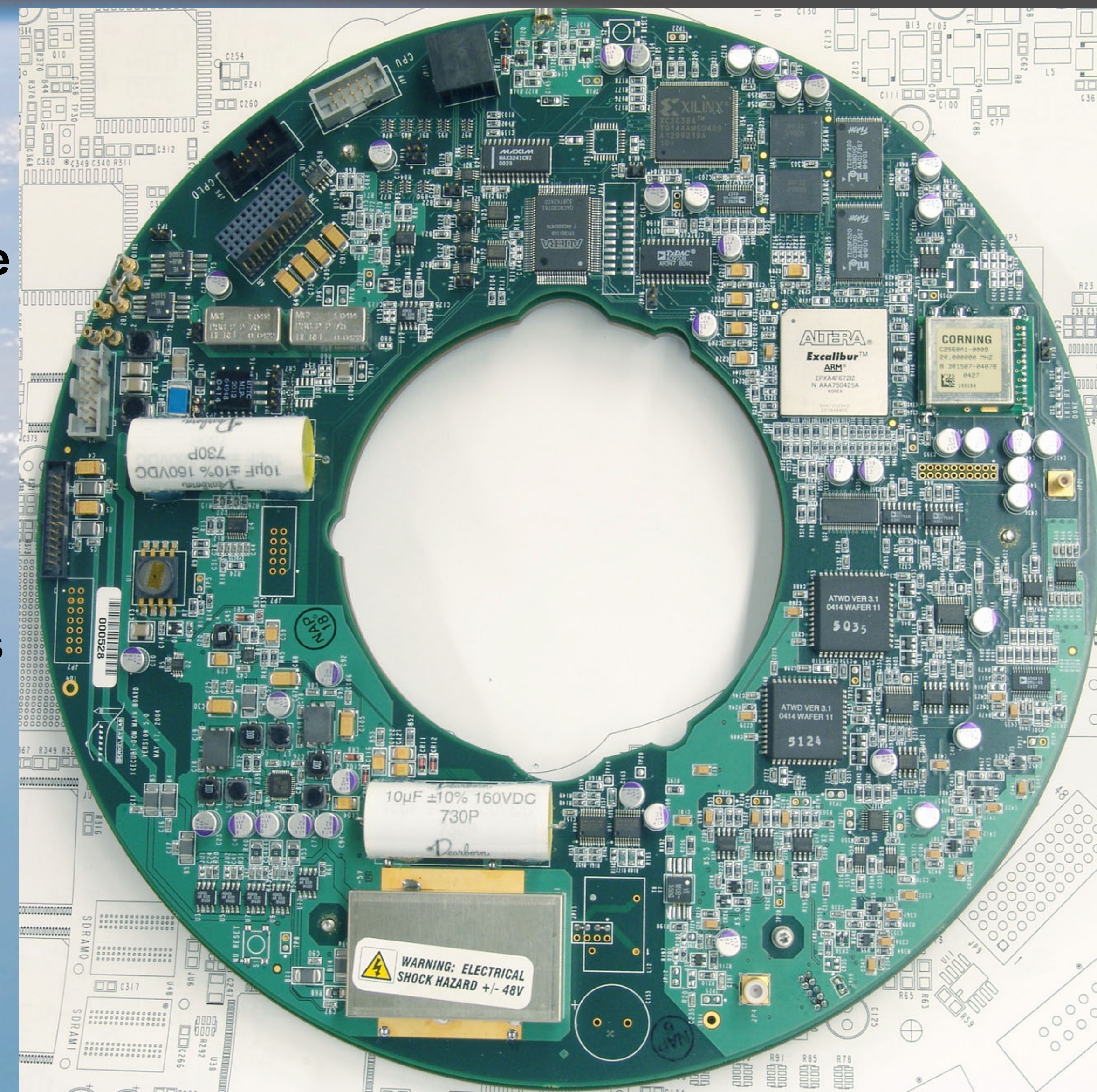
the DOM

DOM Mainboard

This is the core of the DAQ. It contains an Altera Excalibur ARM CPU / 400 k-gate FPGA which controls most aspects of the acquisition and communications with the surface. All aspects except bootloader program remotely reloadable.



Fast waveform capture via 1 of 2 ATWD ASICs which capture 4 ch at 200 MSPS – 800 MSPS, 128 samples deep and 10-bits wide. ATWDs operate in "ping-pong" mode – true deadtimeless operation possible. 3 ch are high, medium, low gain (14-bit effective dynamic range).

Slow waveform capture from 40 MHz 10-bit FADC which captures long slow pulses for 6.4 usec.

Digital communication to surface using electrical pairs – two DOMs per pair. Electrical penetrators more robust. Communication bandwidth 1 Mbit.

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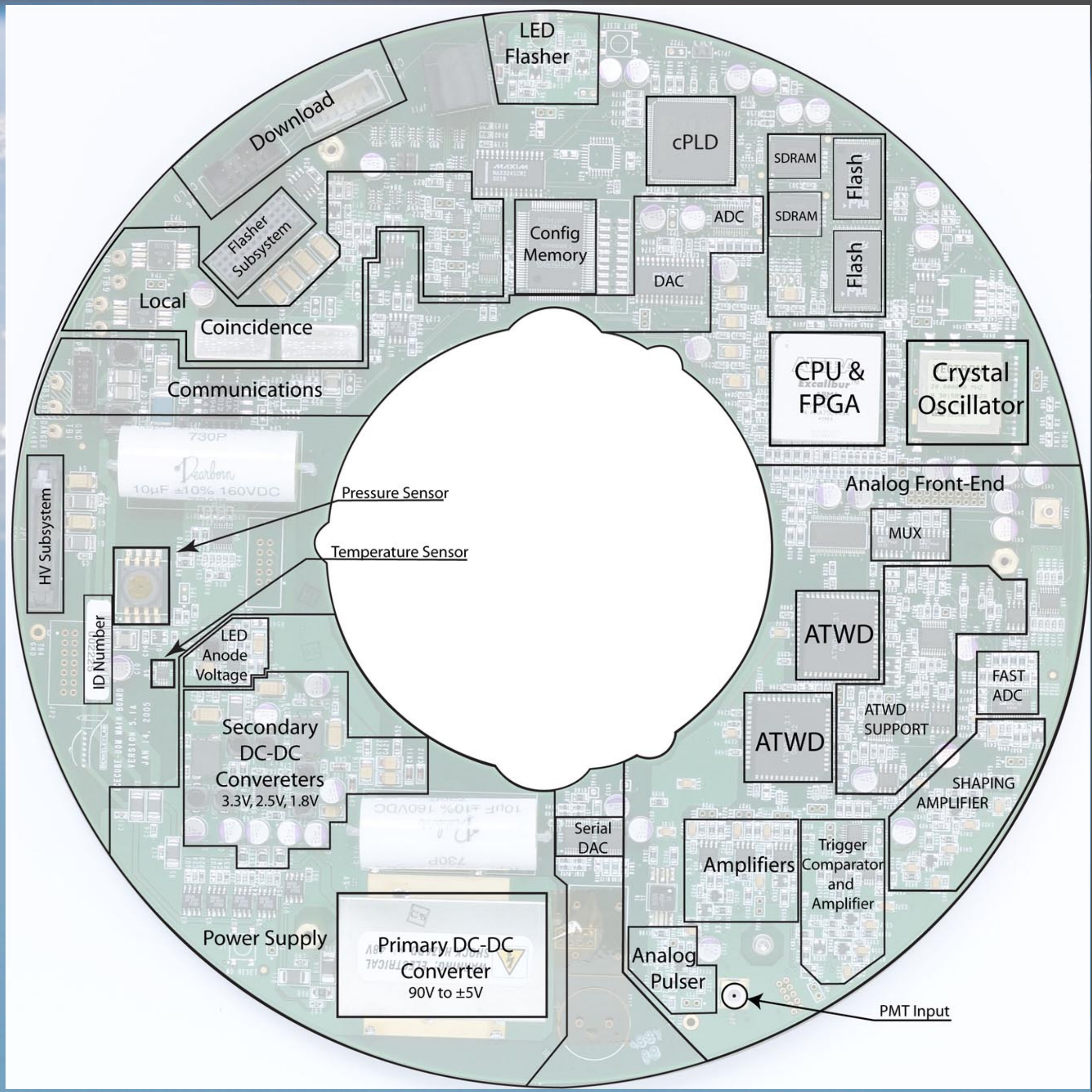

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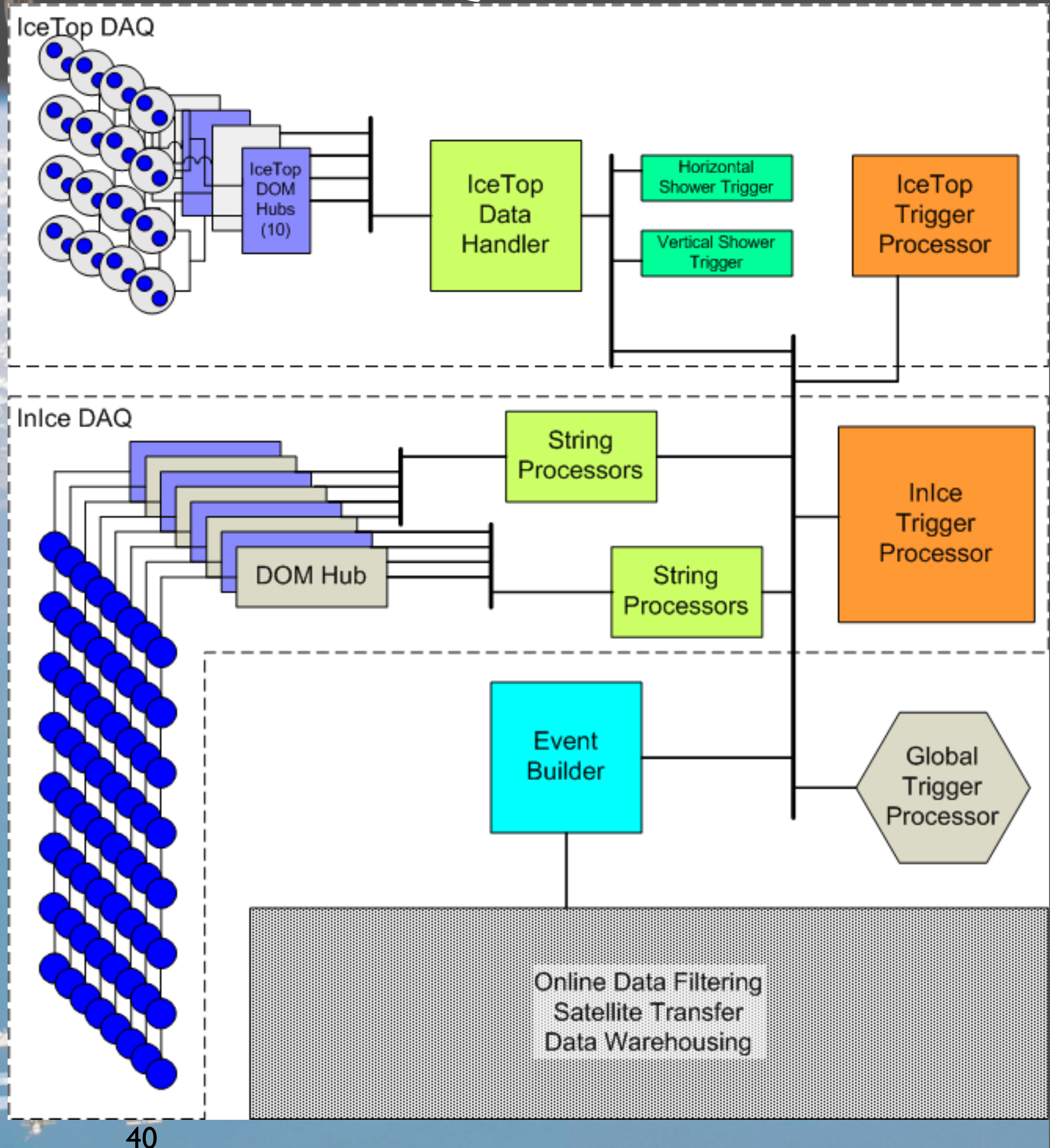
surface DAQ

- DOMs independently collect and buffer up to 8k waveforms.
- DOM communication handled at surface by DOR card – hosted by standard industrial PCs called 'DOMHub.'
- Beyond Linux driver DAQ software is a distributed set of Java applications.
- Data is time coordinated and sorted by processing nodes which may in future perform data reduction.
- Triggers take sorted streams; request to event builder to grab data from string processors and IceTop data handlers to make events.
- Note: data from deep-ice and surface arrays participate in triggers *and* are bundled together at event level.
- Online filter at pole selects 'interesting' events for transmission north over satellite (limited bandwidth).
- All data taped – raw data rate currently 70 GB / day.



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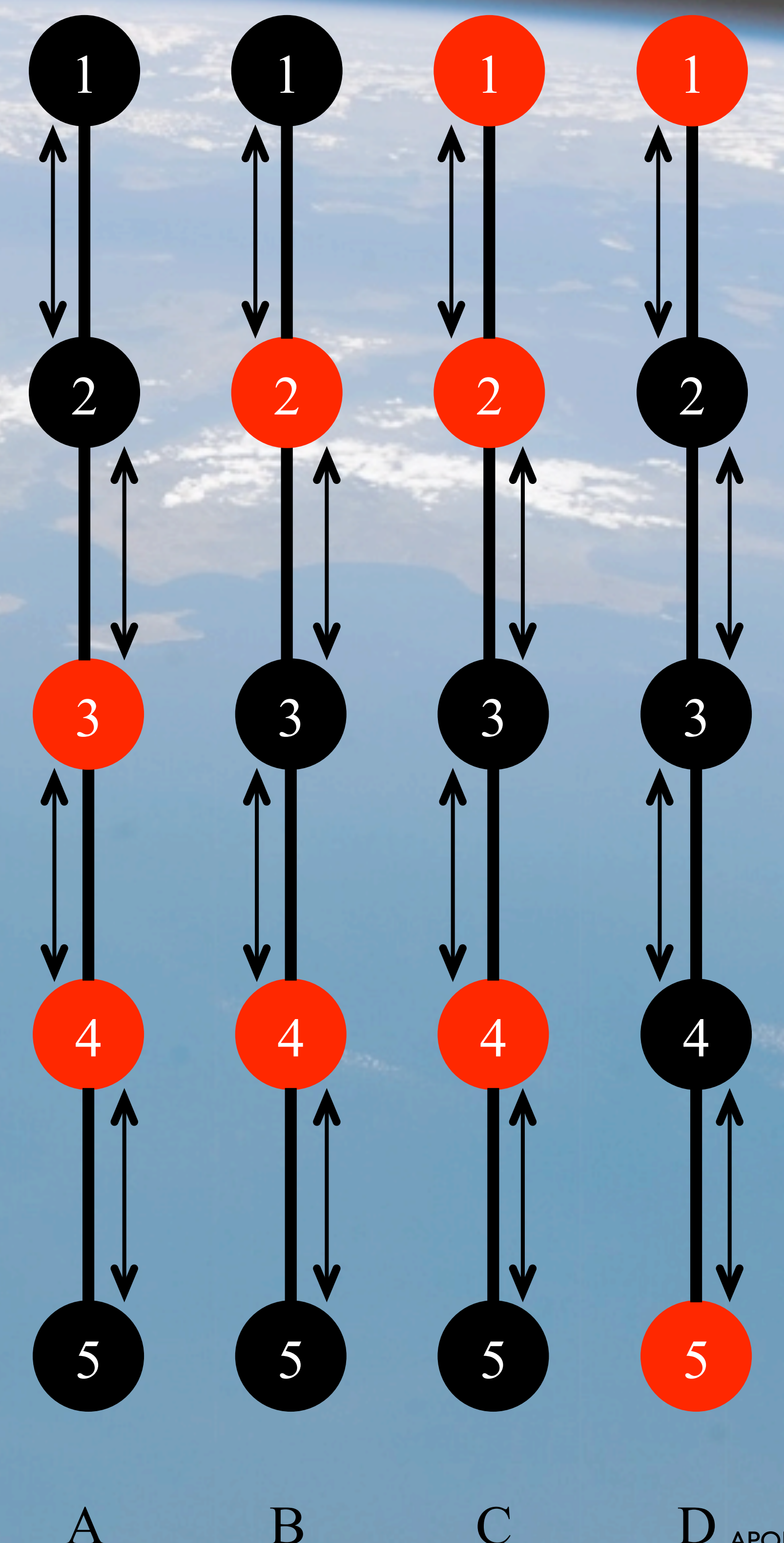
local coincidence mode

DOMs contain 2 wire pair (UP, DN) for exchanging LC signals between adjacent DOMs on string†. DOM FPGA trigger logic can abort waveform capture on absence of one or both signals. LC signals are binary-coded digital – DOMs can "relay" LC info thru; in this manner LC can span up to 4 DOMs distant in either direction.

IceCube currently running in NN mode – that is DOM trigger requires adjacent hit (red circles) – as shown in case A to right. In this mode B and D would not trigger, C would trigger only 1 and 2 and reject 4.

This has advantage of (a) *dramatically* reducing amount of data sent over 1 Mbit link to surface (see figure) and (b) makes array virtually "noiseless." Disadvantage is that real photon hits are lost in ice.

IceCube baseline – operate in "soft" LC mode: waveforms suppressed /wo/ LC requirement, all hit timestamps (12 bytes) sent to surface.



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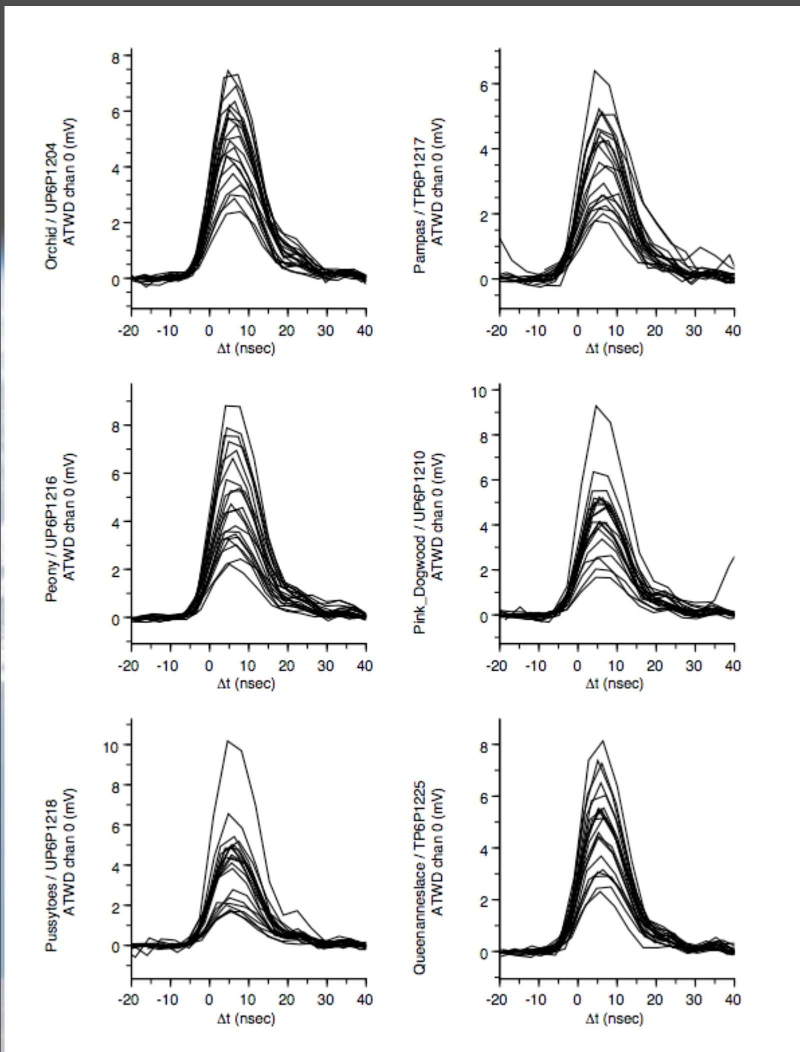
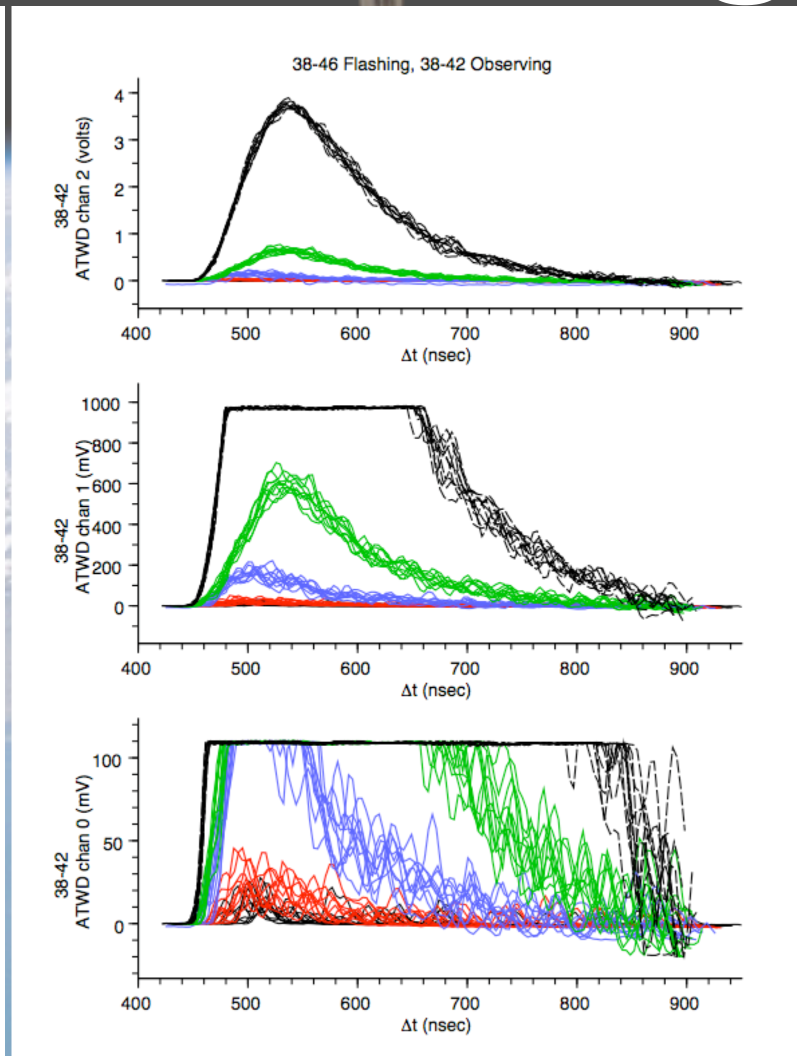
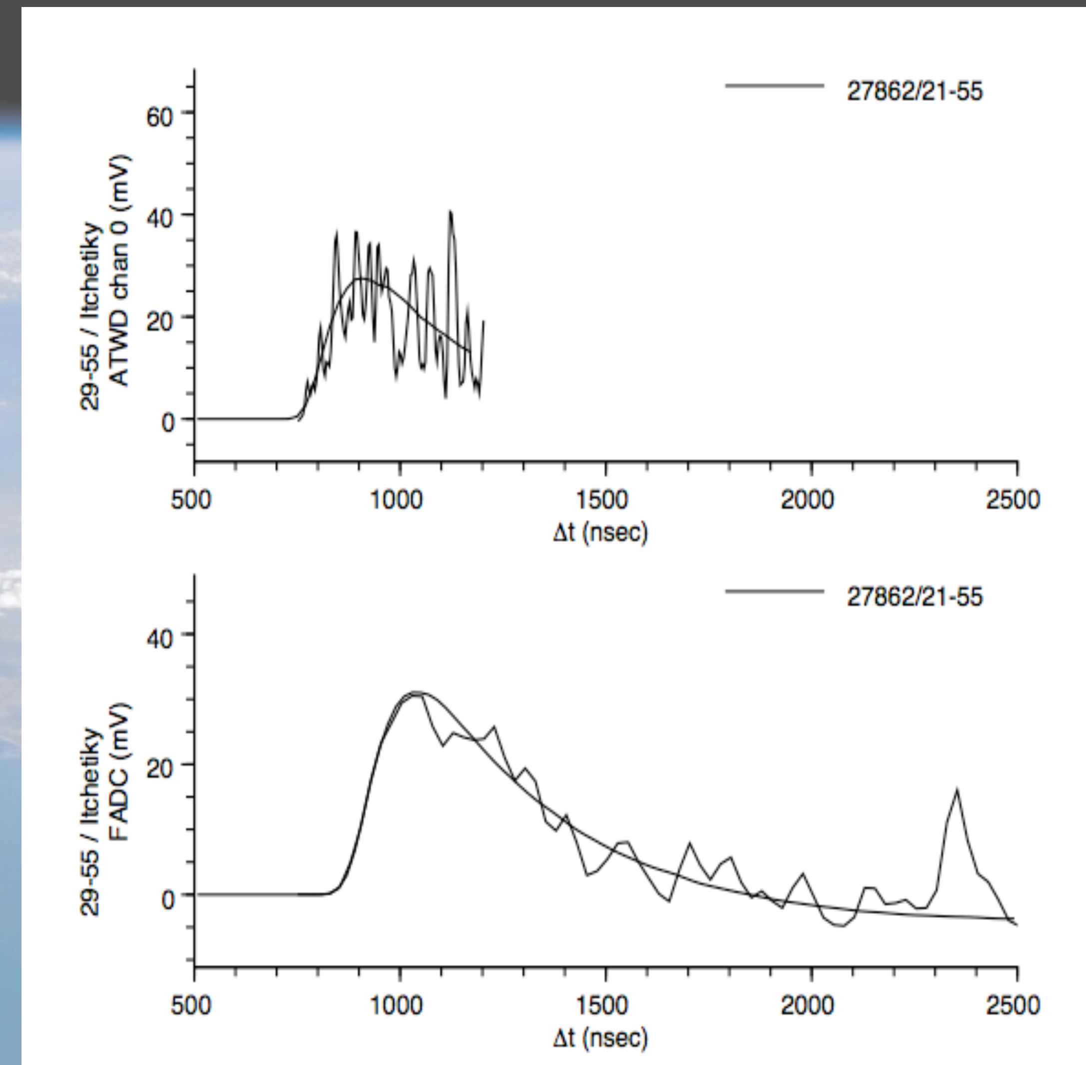
waveform digitization







ATWD digitization

- 300 MHz sampling + 128 bins = 425 ns
- 3 different amplitude gains : x1, x8, x64

fADC digitization

- 40 MHz + 255 bins = 6.4 μs

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calibration in short

- **time calibrations**
  sync DOM (20 MHz) oscillator to surface clock (every 3 sec) - RAPCal : $\sigma \sim 2$ ns
  PMT transit time correction (with flashers) : $\sigma \sim 2$ ns
  waveform sampling time calibration (every month) - DOMCal

- **amplitude calibrations**
  waveform and amplitude (every month) - DOMCal : detected p.e. with $\lesssim$ 10%

- **geometry calibrations**
  laser ranger : DOM-to-DOM on the string 17 ± 0.04 m
  relative DOM depth precision ~ 1 m (wrt to surface coordinates and cable length)

- **energy calibrations**
  calibration flashers (fully characterized blue LED)
  “standard candle” with Cherenkov-like emission of known photons
  atmospheric muon and muon-neutrino spectrum (MC-dependent)

- **pointing calibration**
  AMANDA-II / SPASE : < 0.5^o
  shadow of the moon : 3σ in 1 yr in AMANDA (on-going), in 1 month in IceCube

- **IceTop calibrations (VEM – Vertical Muon Equivalent)**

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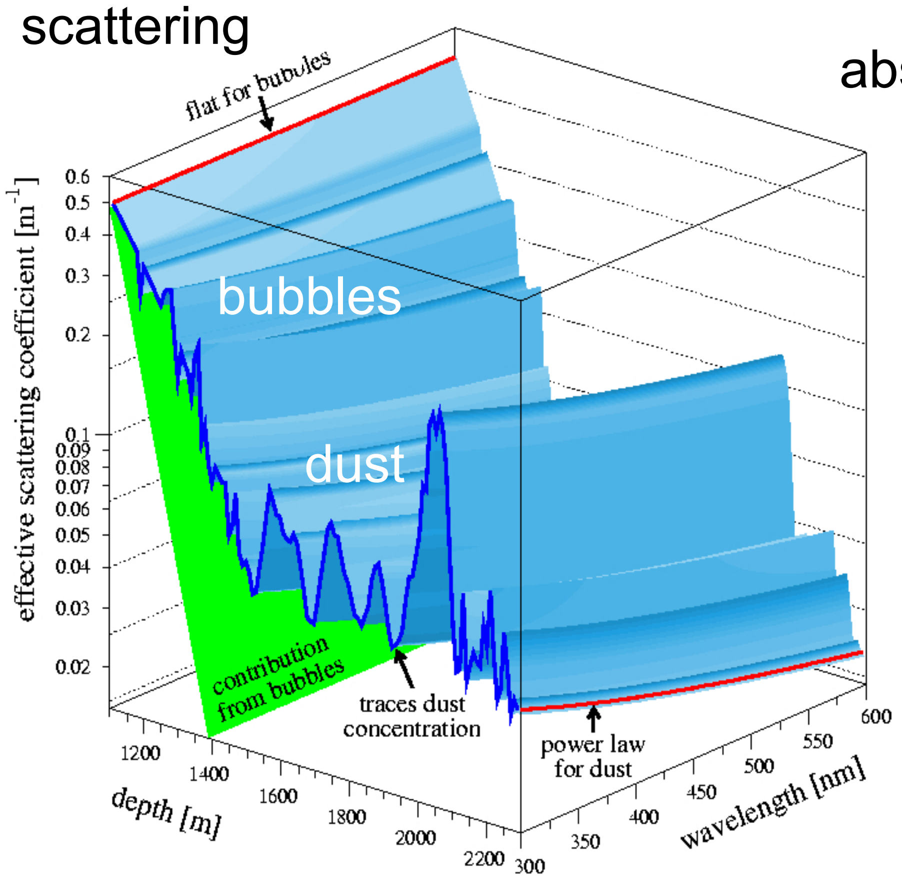
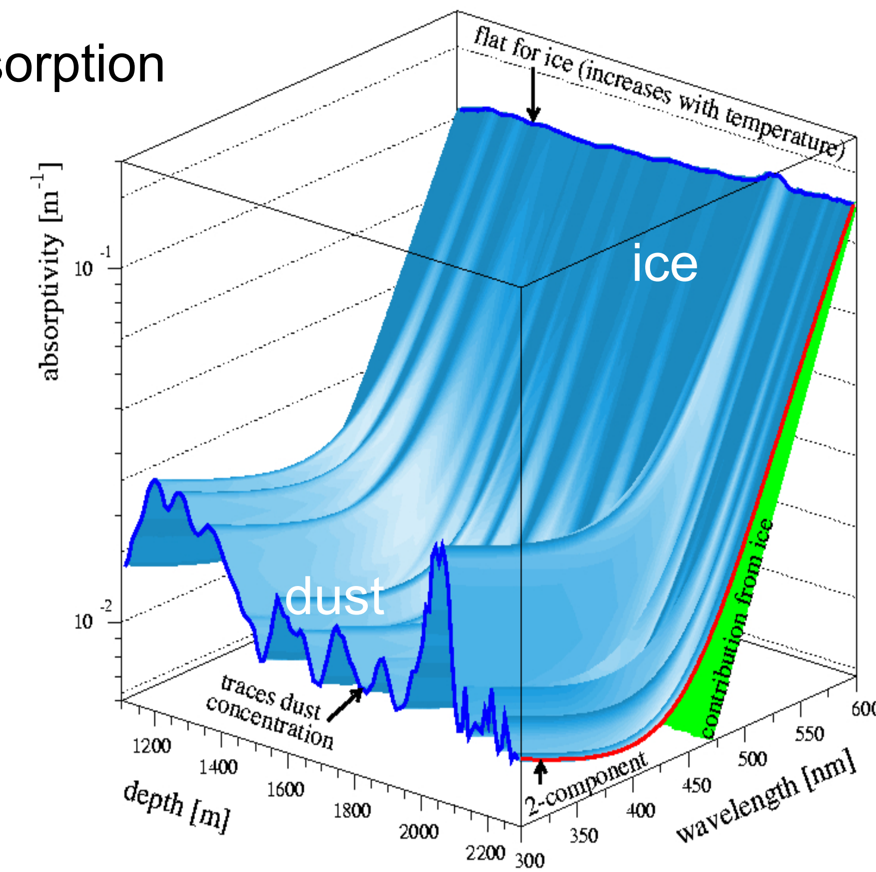
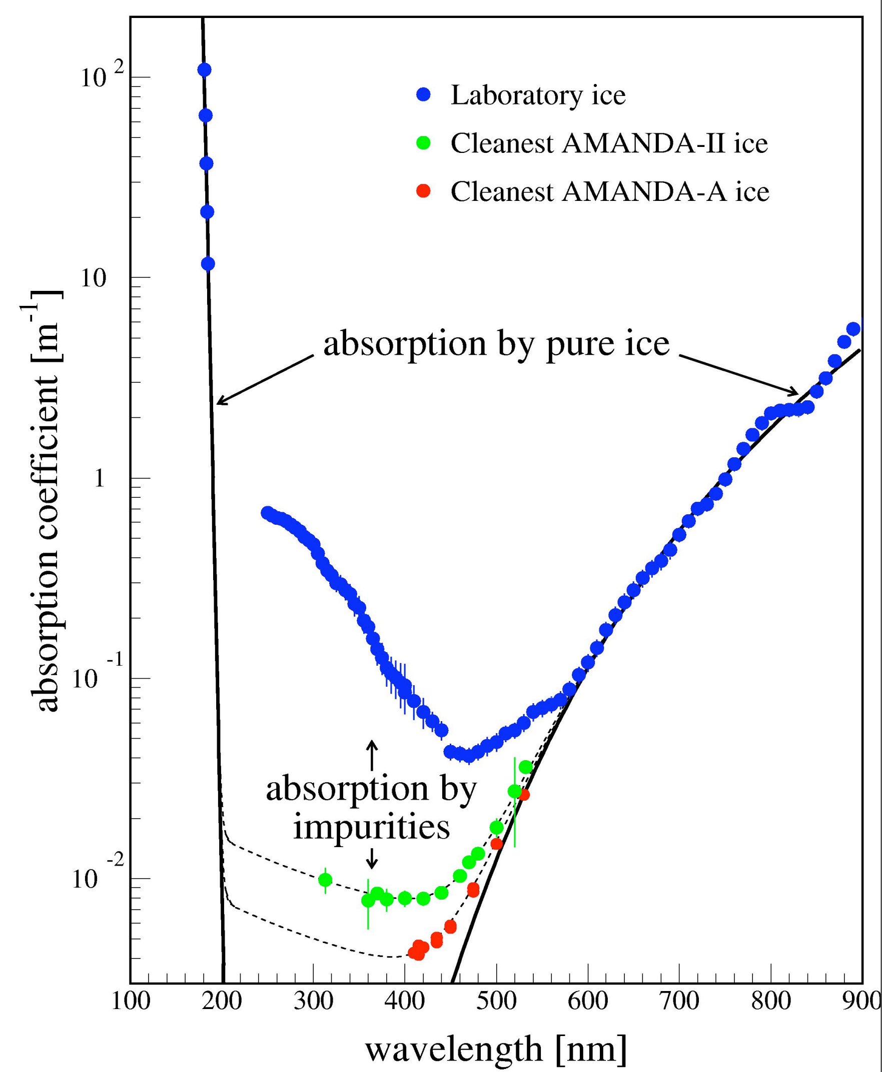
Polar ice optical properties



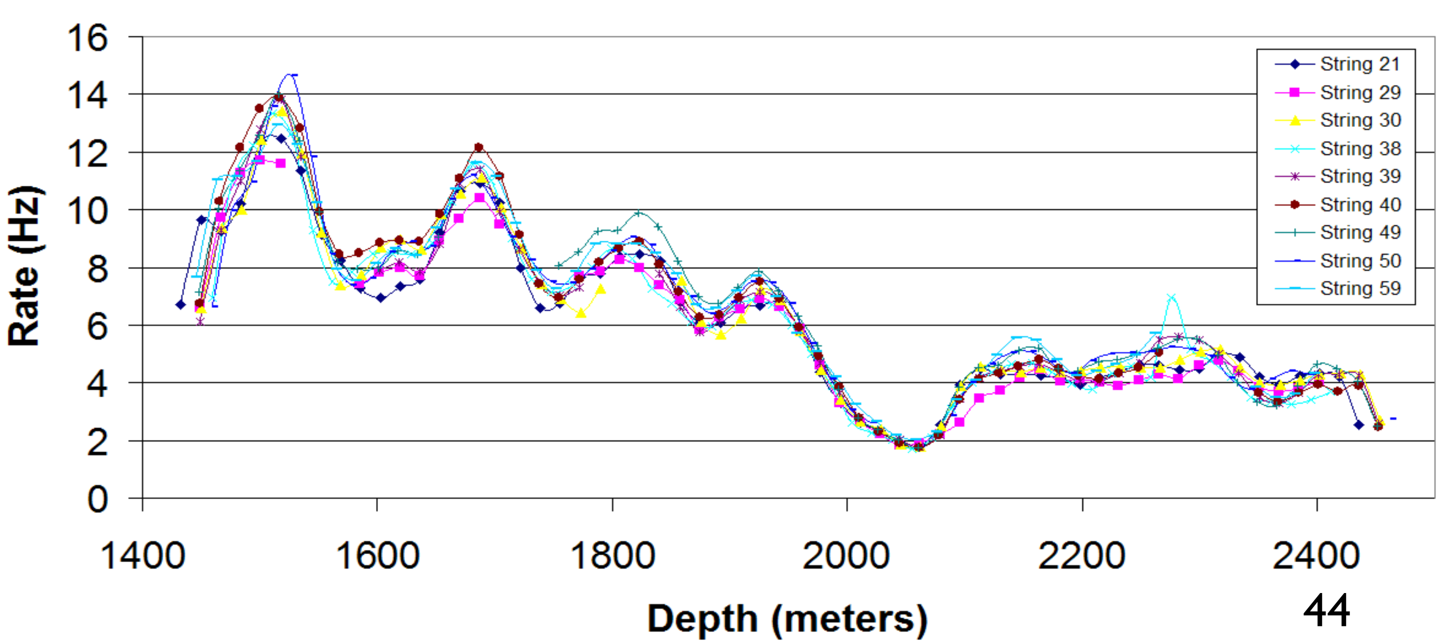


Measurements:

- in-situ light sources
- atmospheric muons



J. Geophys. Res. 111 (2006) D13203



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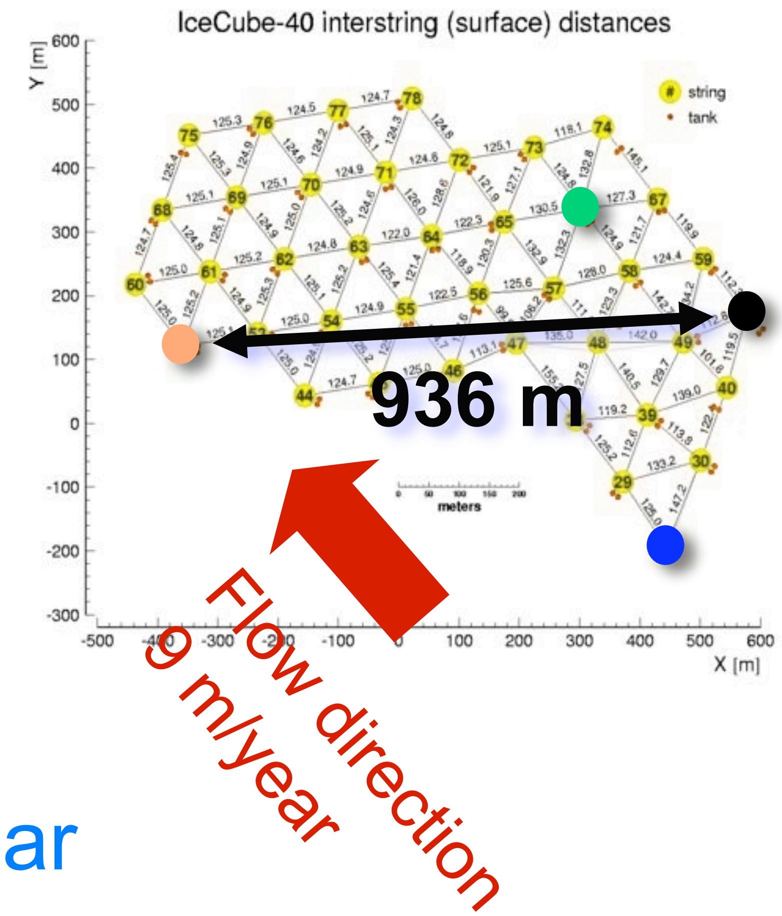
Average optical ice parameters:

λ_{abs} ~ 110 m @ 400 nm

λ_{sca} ~ 20 m @ 400 nm

Ice Properties



- Analyses are sensitive to the optical properties of the ice.
- Below 1400 m, dominated by impurities in the ice
- Measure with ‘dust logger’
  - Ice layers are not completely planar
    - Up to 70 m/km tilt