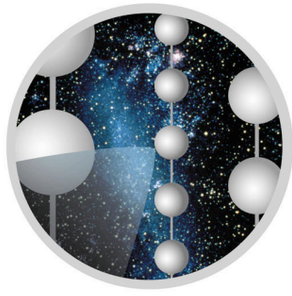
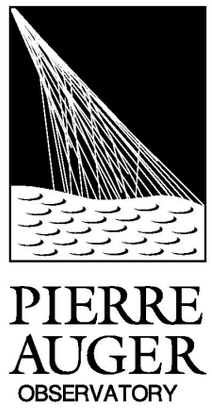
UHECR 2014 Conference,
12-16 October 2014, Springdale, Utah

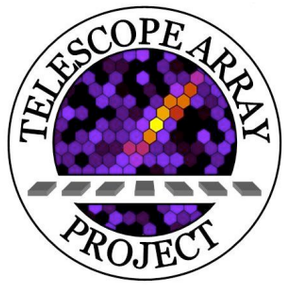
Report from the "Multi-Messenger" working group

Jaime Alvarez Muniz, Timo Karg, Daniel Kuempel,
Grigory Rubtsov, Mariangela Settimo, Sergey Troitsky

FOR THE ICECUBE, PIERRE AUGER AND TELESCOPE ARRAY COLLABORATIONS







Working Group members

IceCube:

Timo Karg[1] for the IceCube Collaboration

[1)] DESY, Zeuthen, Germany

Pierre Auger Observatory:

Jaime Alvarez-Muniz[2], Daniel Kuempel[3], Mariangela Settimo[4] for the Pierre Auger Collaboration

[2)] Universitad de Santiago de Compostela, Spain

[3)] RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

[4)] Laboratoire de Physique Nucl´eaire et de Hautes Energies (LPNHE), CNRS-IN2P3, Paris, France

Telescope Array:

Grigory Rubtsov[5], Sergey Troitsky[5] for the Telescope Array Collaboration

[5)] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

Outline

- Close relation between UHECRs, photons and neutrinos

- Status of photon/neutrino and neutron search with IceCube, Pierre Auger and Telescope Array
  - *Compared to UHECR2012 symposium:*
    - updates of the diffuse photon and neutrino flux limits,
    - directional search for UHE neutral particles for Auger and TA
    - neutrino observations at PeV with IceCube

- First combined analyses

- Future perspectives

"Multi-messenger" complementarity

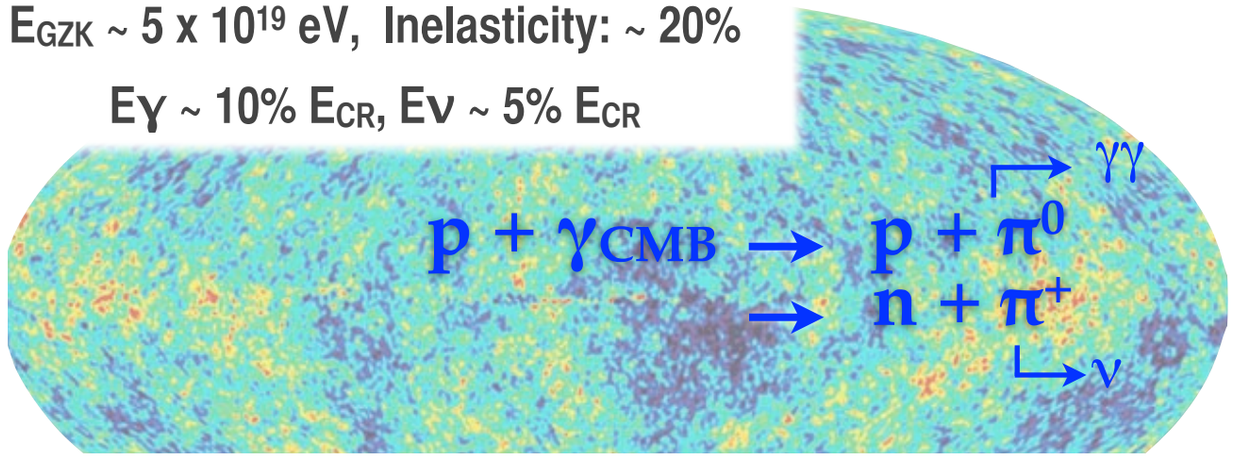
Production sites

- **Same production sites:**
  - photons/neutrons/neutrinos produced at or nearby the source
  - UHE photons/neutrinos produced during propagation
    - **GZK ν/γ: HINTS ON NATURE OF FLUX SUPPRESSION AT UHE**

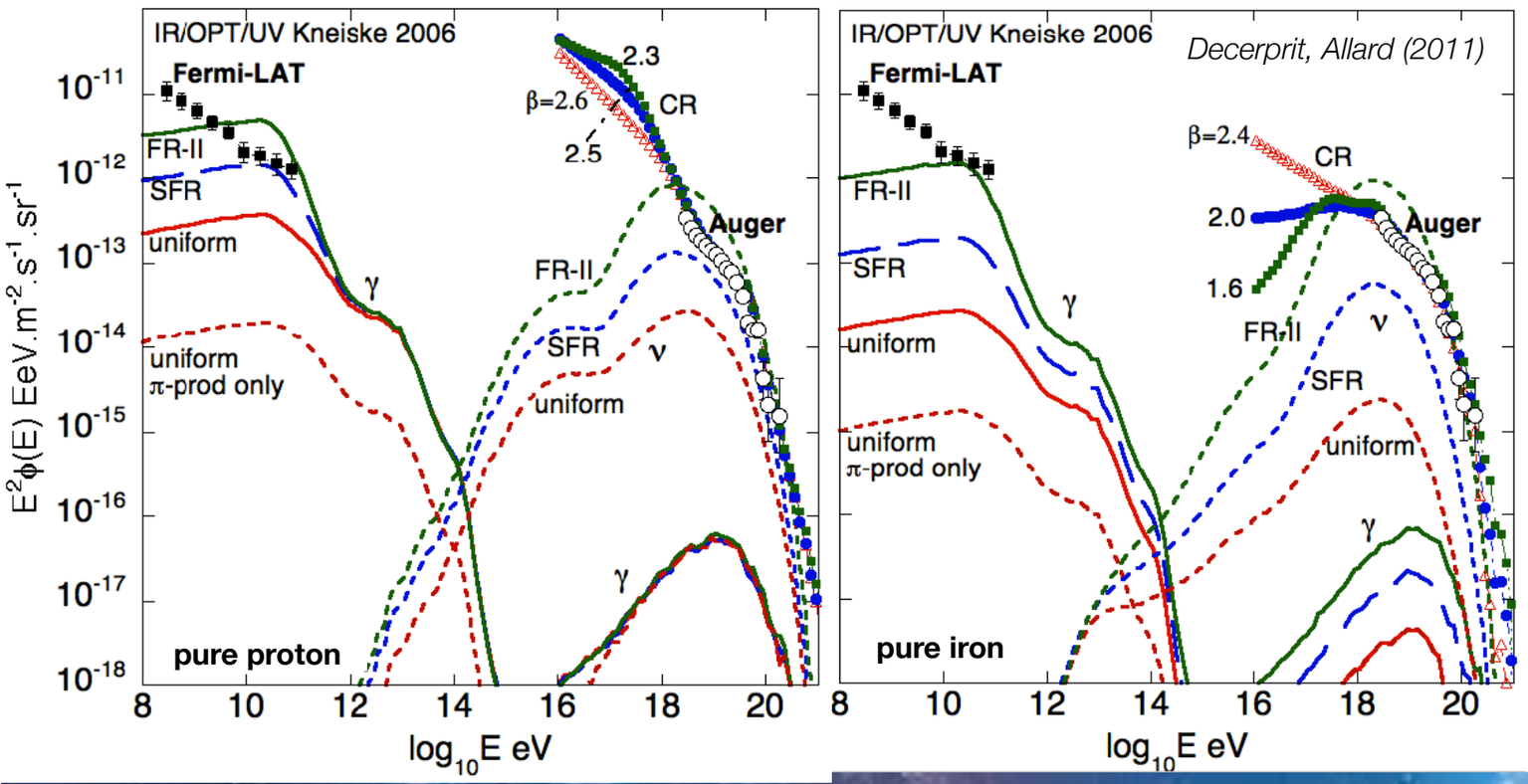
e.g., photo-pion production (GZK)

E_{GZK} ~ 5 x 10^{19} eV, Inelasticity: ~ 20%

E_γ ~ 10% E_{CR}, E_ν ~ 5% E_{CR}



- **Photon and neutrino fluxes closely related to the sources and nature of UHECRs**



photon/neutrino fluxes sensitive to:
- maximum energy at the source,
- spectral index, primary type
- source distribution and evolution,
- extragalactic background radiation
- magnetic fields

complementary informations!

“Multi-messenger” complementarity

Detection/Identification techniques

General detection challenges

extremely low fluxes (large exposure needed)

and/or only weakly interacting

- **UHE neutrons:**

✘ Neutron decay (Mean travel distance ~ 9.2 E/[EeV] kpc): only galactic region accessible

✘ EAS-induced shower impossible to be distinguished from proton case

✓ detection based on EAS-like,

✓ no magnetic deflection: point-like excess expected

(Auger/Telescope Array)

- **UHE photons:**

✓ Maximum source distance: tens/hundred of kpc (@ PeV) and tens of Mpc (@ EeV)

✓ EAS features

✘ low fluxes, hadronic (mostly proton) background rejection

(Auger /Telescope Array @ EeV)

- **neutrinos (from PeV to EeV)**:

✓ Observation of distant Universe

✓ easy signal/background separation

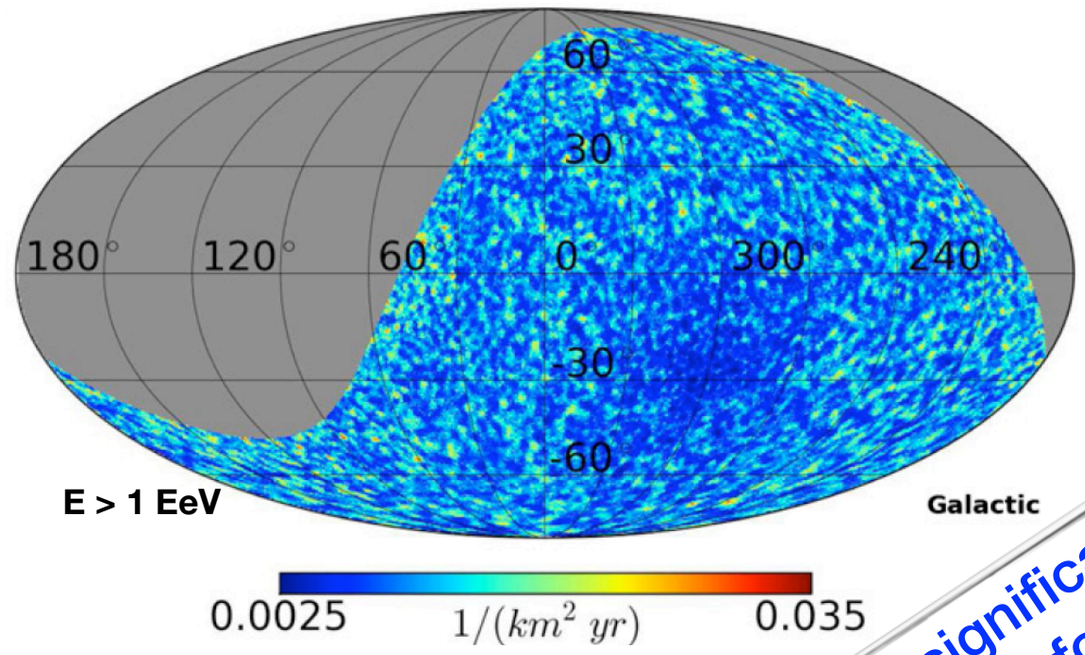
✘ low detection probability

(Auger @ E > EeV/IceCube @ E >TeV)

Neutrons

Neutron search with Auger and Telescope Array

Search for excess of CR events (proton-like) from discrete sources within the angular resolution.
Only galactic region accessible (Mean travel distance ~ 9.2 E/[EeV] kpc)



Southern Sky (dec. [-90º, +15º])
The Pierre Auger Coll., ApJ, 760 (2012) 148

Auger-SD data, Jan 2004 - Sept 2011
energy ranges: 1-2 EeV, 2-3 EeV, ≥ 1 EeV, ≥ 3 EeV
upper limits on flux and constrains on astrophysical source models

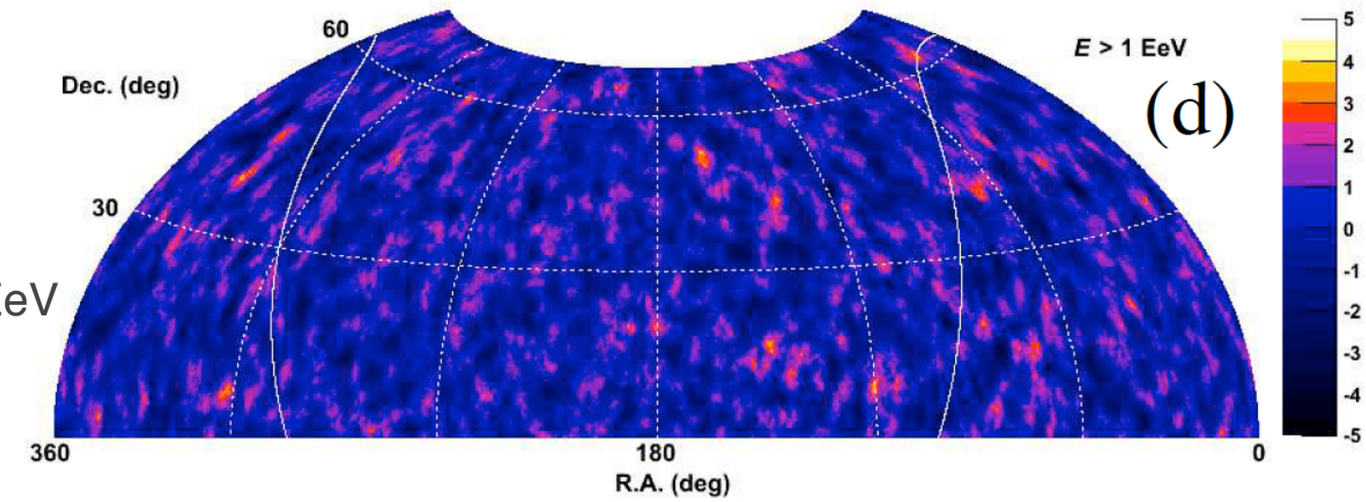
Target search performed
The Pierre Auger Coll., ApJ, 789 (2014) L34

No significant excess found

Northern Sky (dec. [0, 70º])

TA-SD, May 2008 - May 2013
energy ranges: 0.5-1 EeV, 1-2 EeV, ≥ 1 EeV, ≥ 2 EeV
mean upper limits on neutron flux: ~ 0.07/(km^2 yr) @ 1EeV
coincidence with 29 Fermi bright Galactic sources

The Telescope Array Coll., 1407.6145

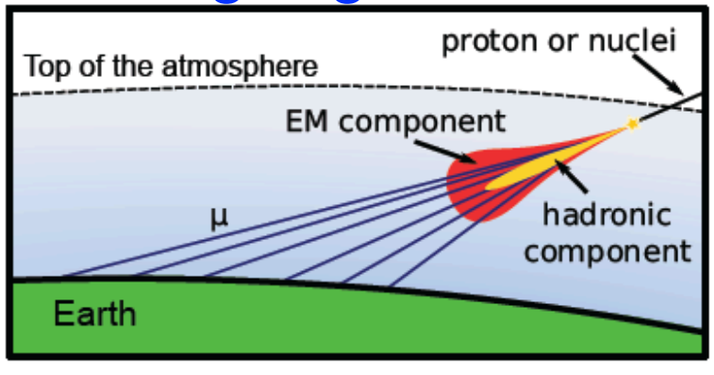


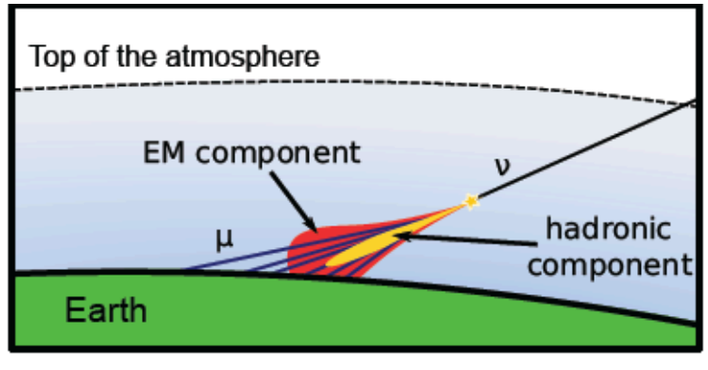
Neutrino search

ν detection with the Pierre Auger Observatory

ν selected as inclined showers with large em component (time spread of SD signals)

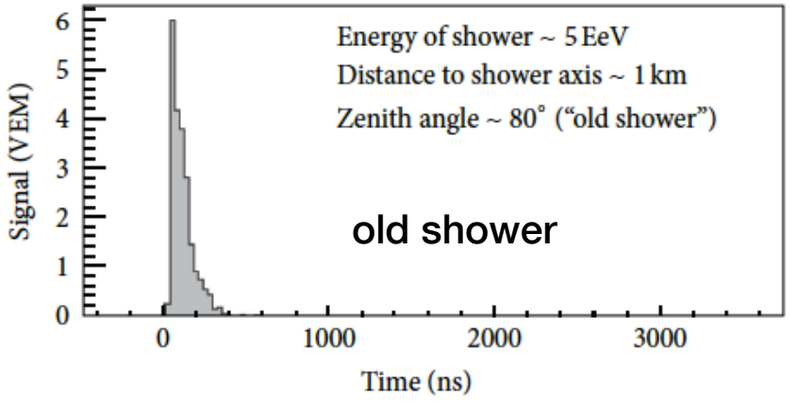
- **down-going**

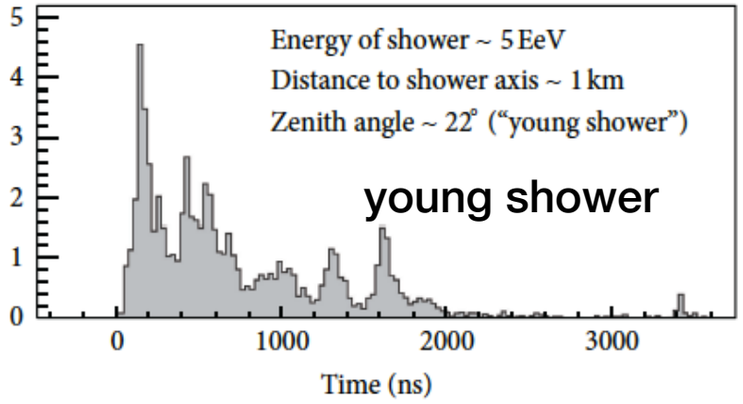




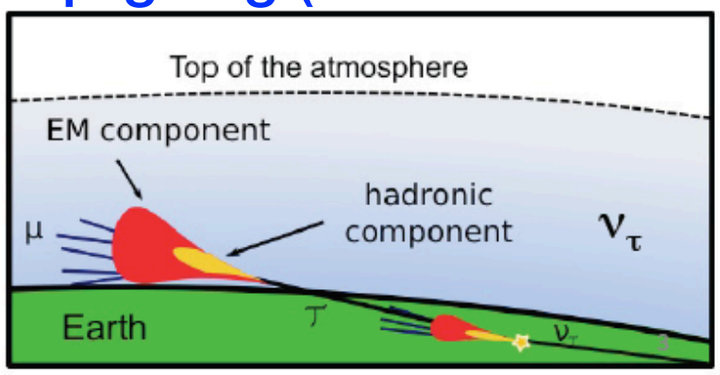
all ν flavor

Low zenith (65°,75°)
contrib. to total evt rate: **23%**
High zenith (75°,90°):
contrib. to total evt rate: 4%





- **up-going (Earth-Skimming)**



ν_τ flavor
Earth-Skimming (90°, 95°)
contrib. to total evt rate **73%**

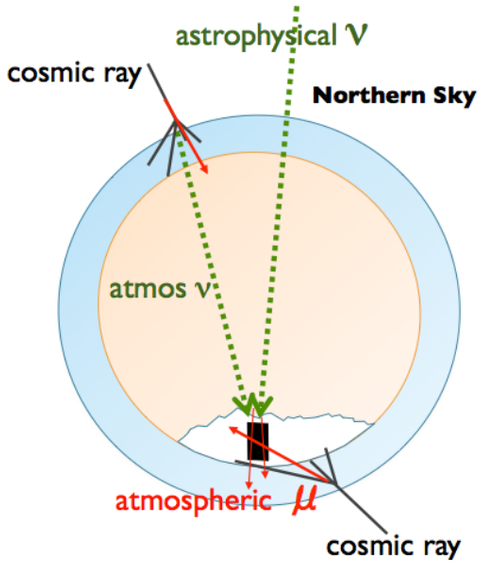
ν identification applied "blindly" to data: 01/2004 - 12/2012

No candidates found!

Neutrino search with IceCube

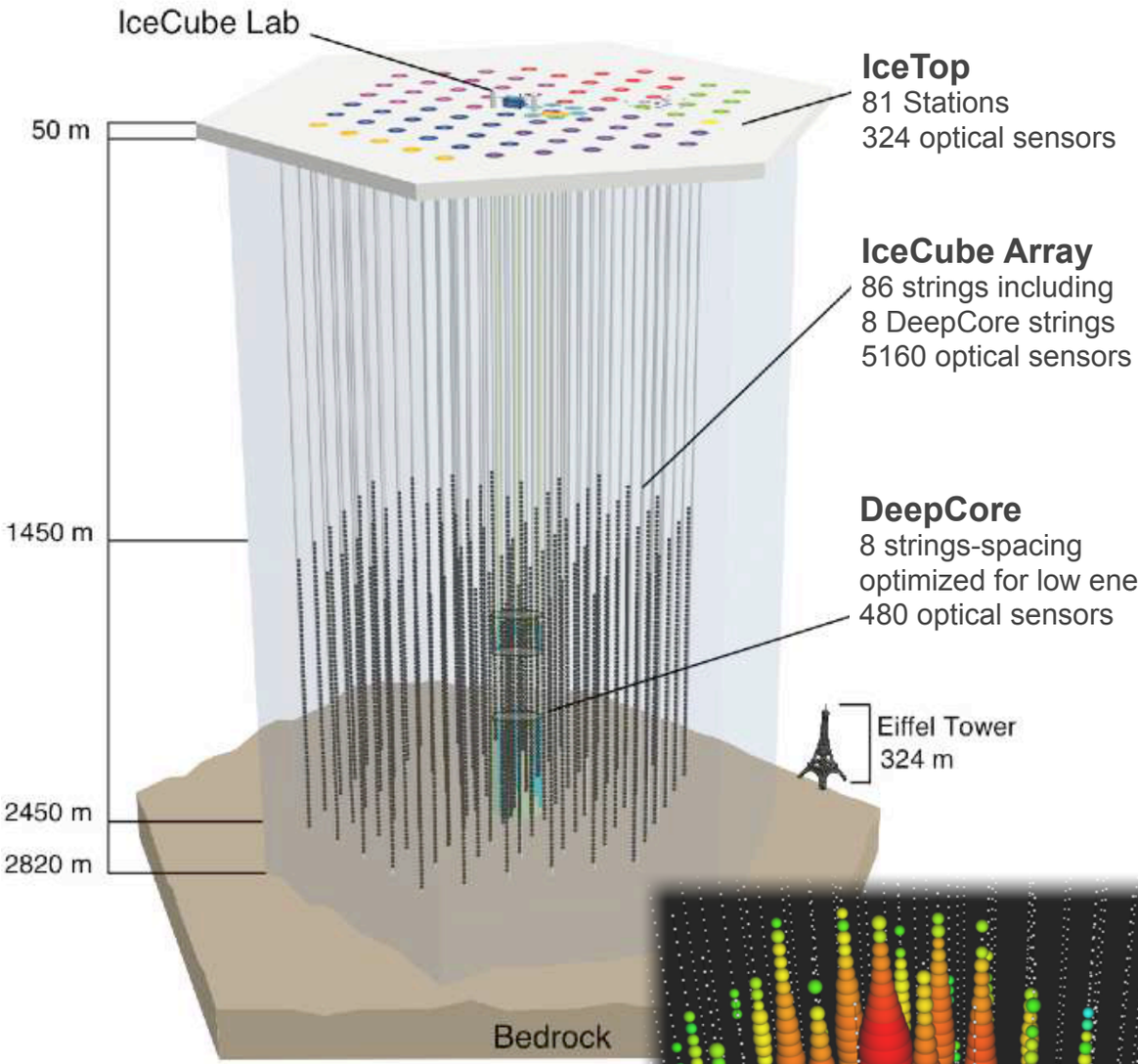
Neutrinos detected through Cherenkov light in ice
by secondary charged particles.

muons tracks, showers-like events



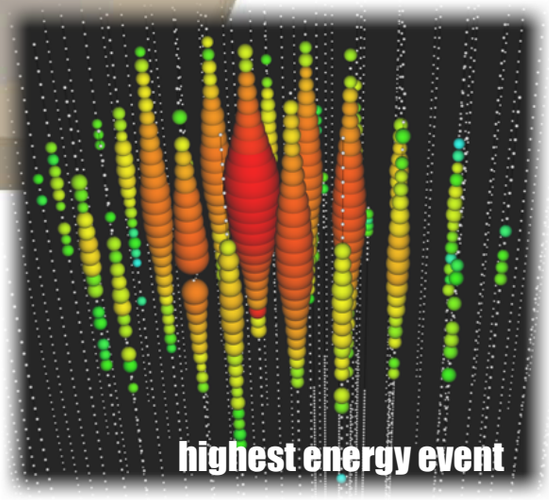
astrophysical/
atmospheric ν

Northern & Southern sky



1st evidence of astrophysical ν !!
(PeV energy range)

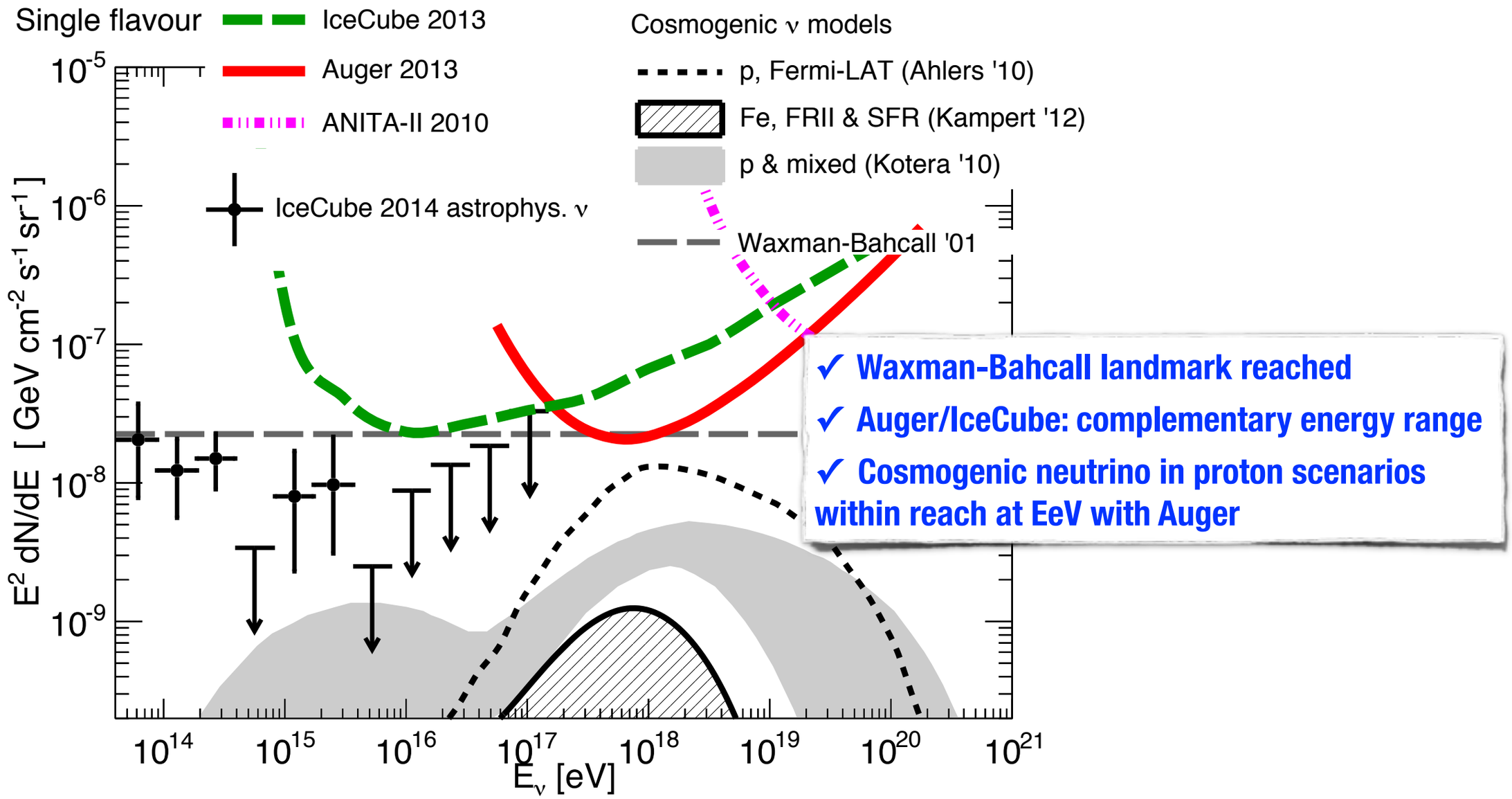
Diffuse flux of high-energy astrophysical ν
at higher energies



IceCube Coll., Phys.Rev.Lett. 113 (2014) 101101
IceCube Coll., Phys.Rev. D 88 (2013), 112008

IceCube & Pierre Auger results

Diffuse Limits: status and perspectives



- ✓ **Waxman-Bahcall landmark reached**
- ✓ **Auger/IceCube: complementary energy range**
- ✓ **Cosmogenic neutrino in proton scenarios within reach at EeV with Auger**

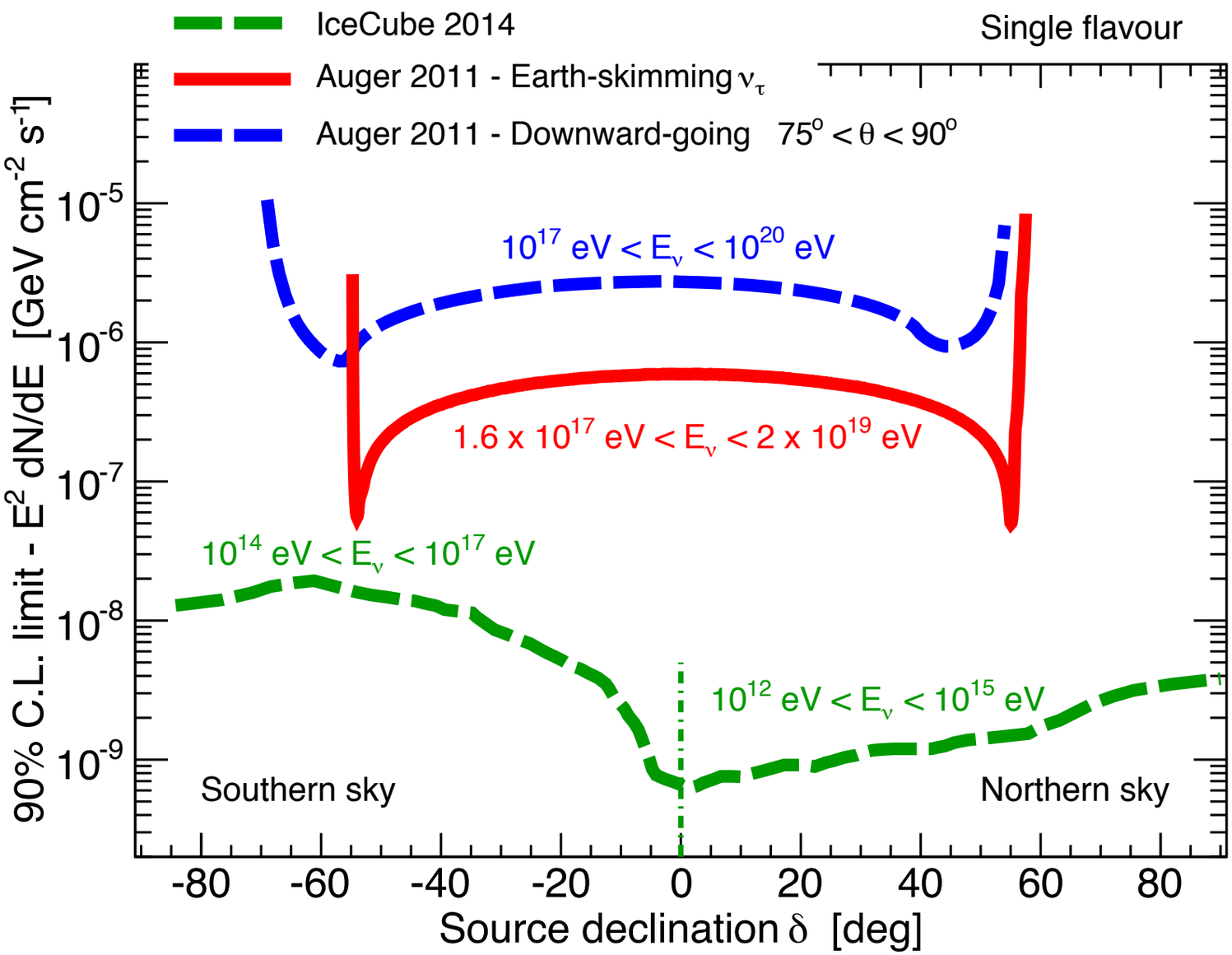
ANITA/Auger/RICE: 90% C.L. differential upper limits in bins of 0.5 in $\log_{10}(E)$
IceCube arrows: 68% C.L. differential upper limits

IceCube Coll., Phys.Rev. D 88 (2013), 112008
IceCube Coll., PRL 113 (2014) 101101

ANITA Coll., Phys. Rev. D 85 (2012) 049901(E)
Pierre Auger Coll. ICRC 2013

IceCube & Pierre Auger results

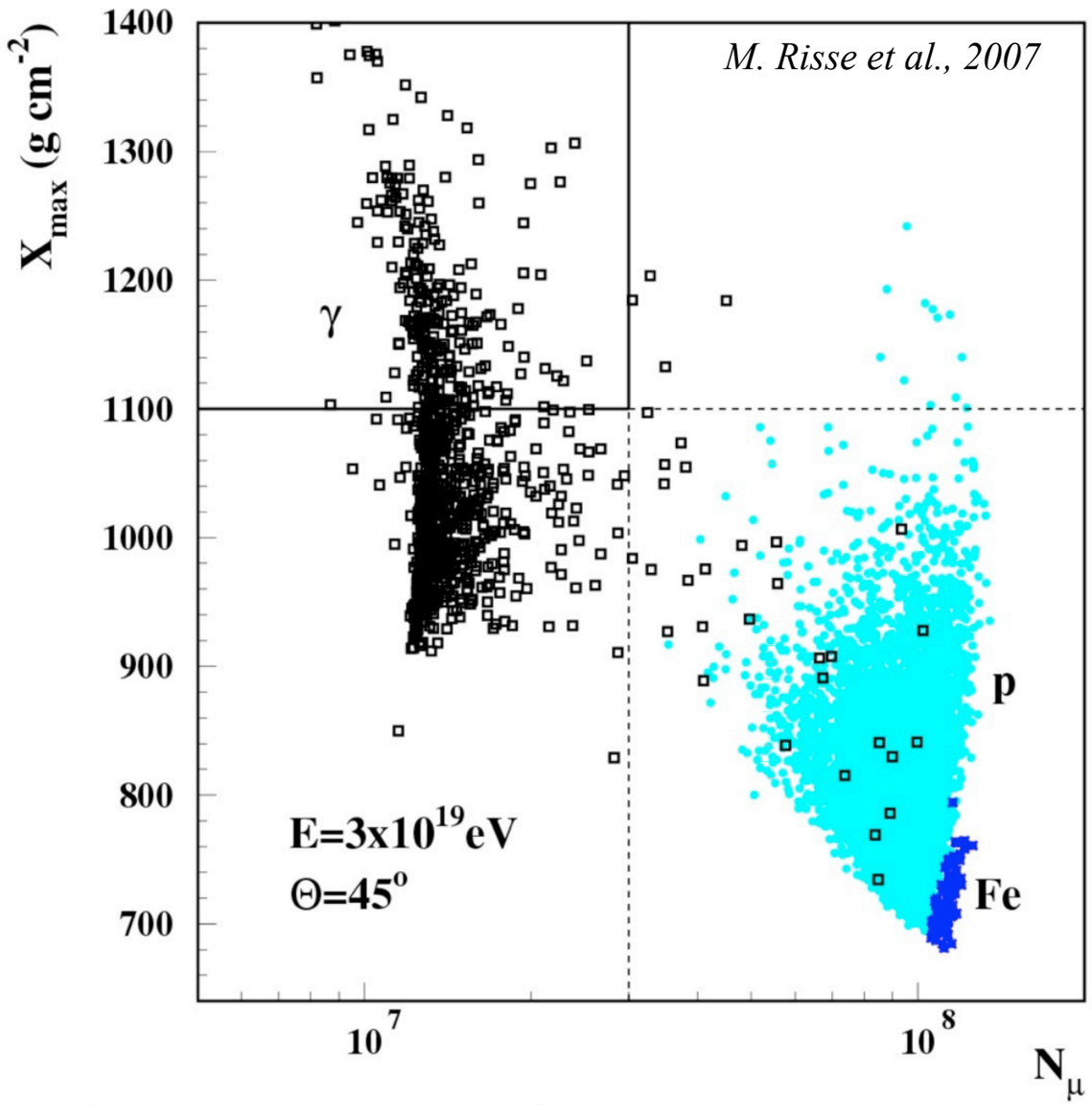
Point-like sources: status and perspectives

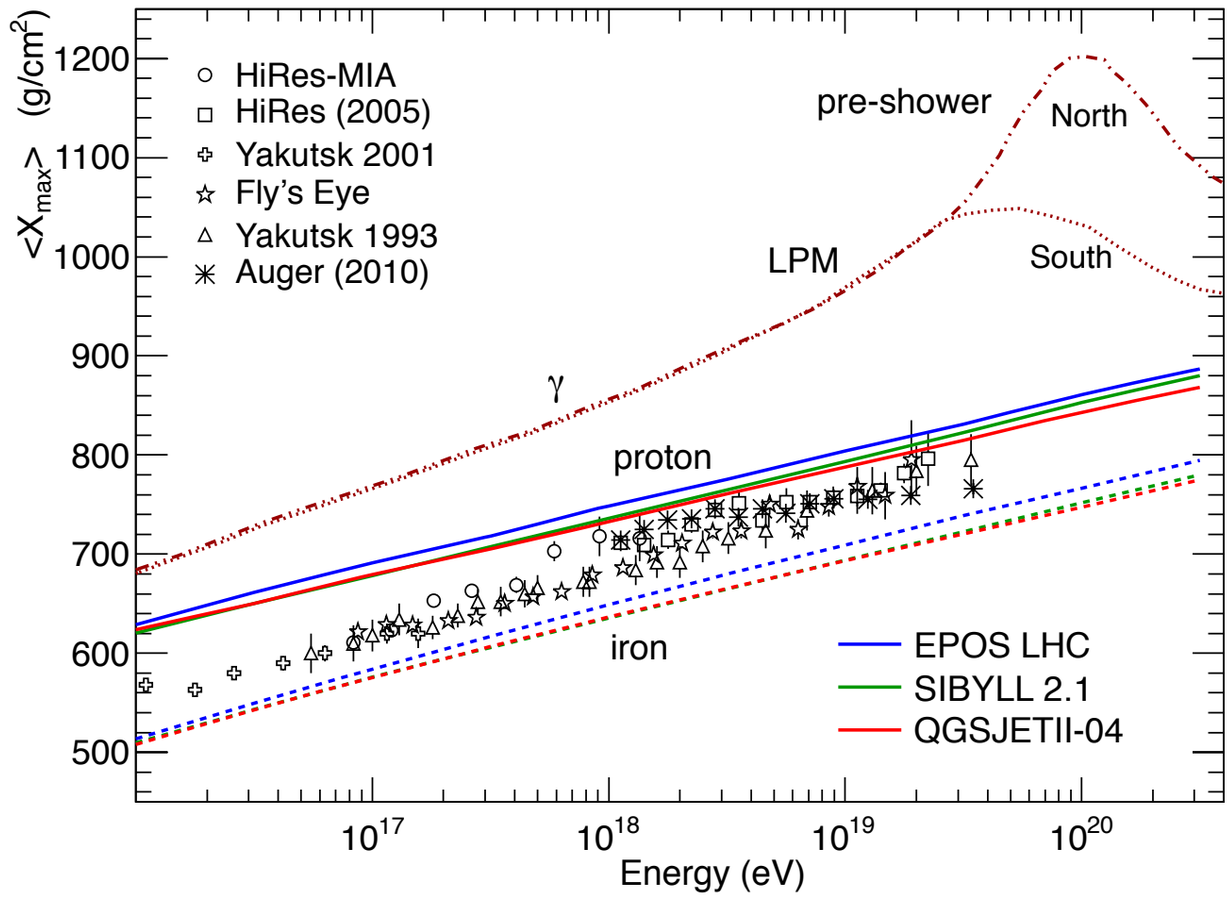


Note: Auger data until May 2010

Photons

Photon identification with EAS





- **Deep shower development**
  (i.e.large X_{max})
- **Poor muon content**

OTHER CONNECTED OBSERVABLES:

- radius of curvature
- time spread of particles at ground

Search for photons with the Pierre Auger Observatory

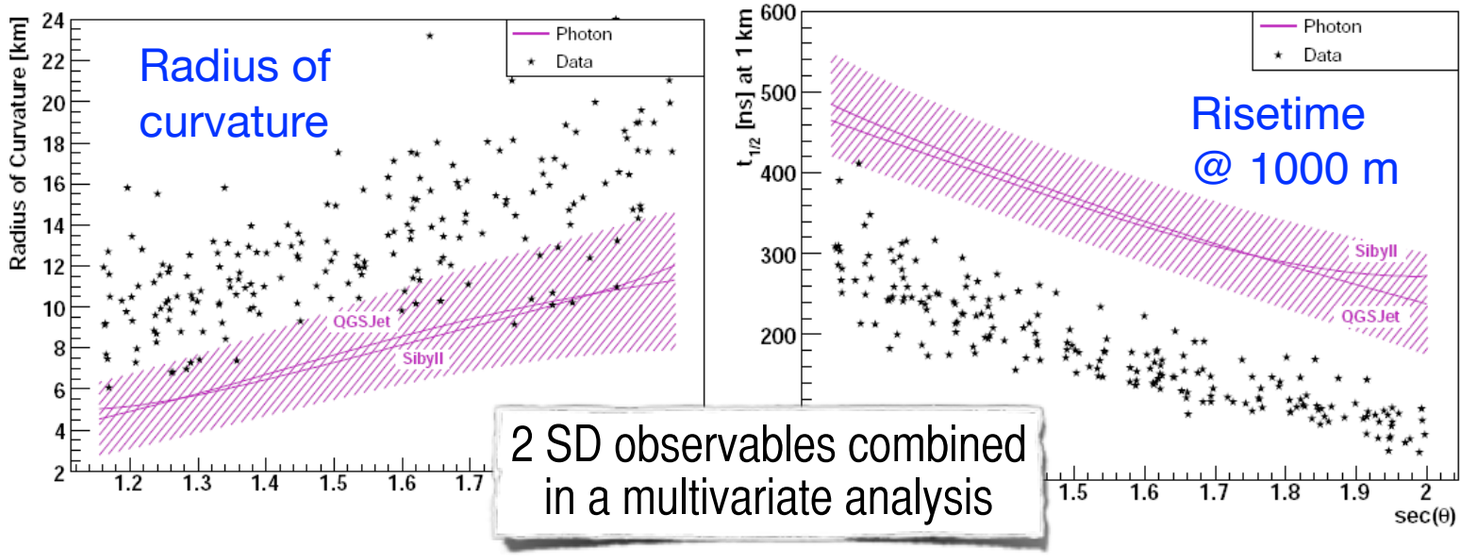
DIFFUSE LIMITS

SD events: RADIUS OF CURVATURE AND RISE TIME OF THE SIGNAL IN THE SD

- E_{thr}: 10, 20, 40 EeV
- Zenith: 30 - 60º (full efficiency range)
- Principal component analysis
- "a-priori" cut at 50% of photon selection efficiency

▸ **no candidates found**

The Pierre Auger Coll., Astrop. Phys. 29 (2008) 243



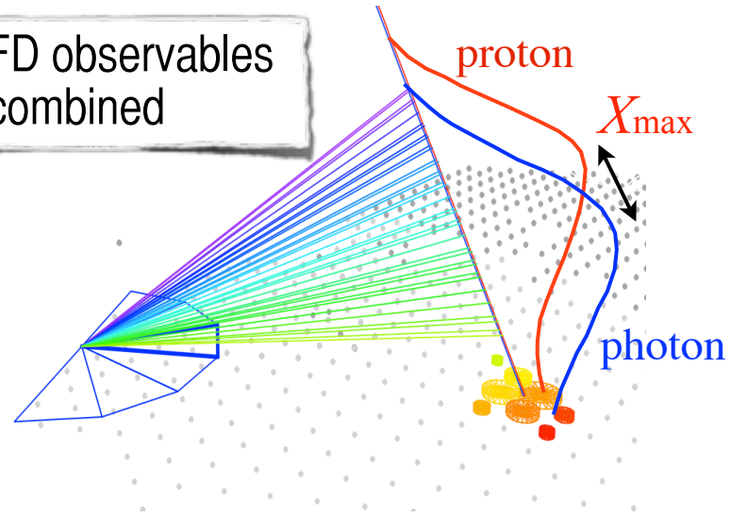
2 SD observables combined in a multivariate analysis

Hybrid events:

- E_{thr}: 1, 2, 3, 5, 10 EeV
- Zenith: 0 - 60º
- Fisher analysis combining SD and FD information
- a-priori cut at 50% photon efficiency, > 99% bkg rejection (depending on energy)
- FD duty cycle of ~ 10-15%

▸ **6, 0, 0, 0, 0 candidates (compatible with bkg)**

SD & FD observables combined



M.S. for the Pierre Auger Coll, ICRC 2011

Search for photons with the Pierre Auger Observatory

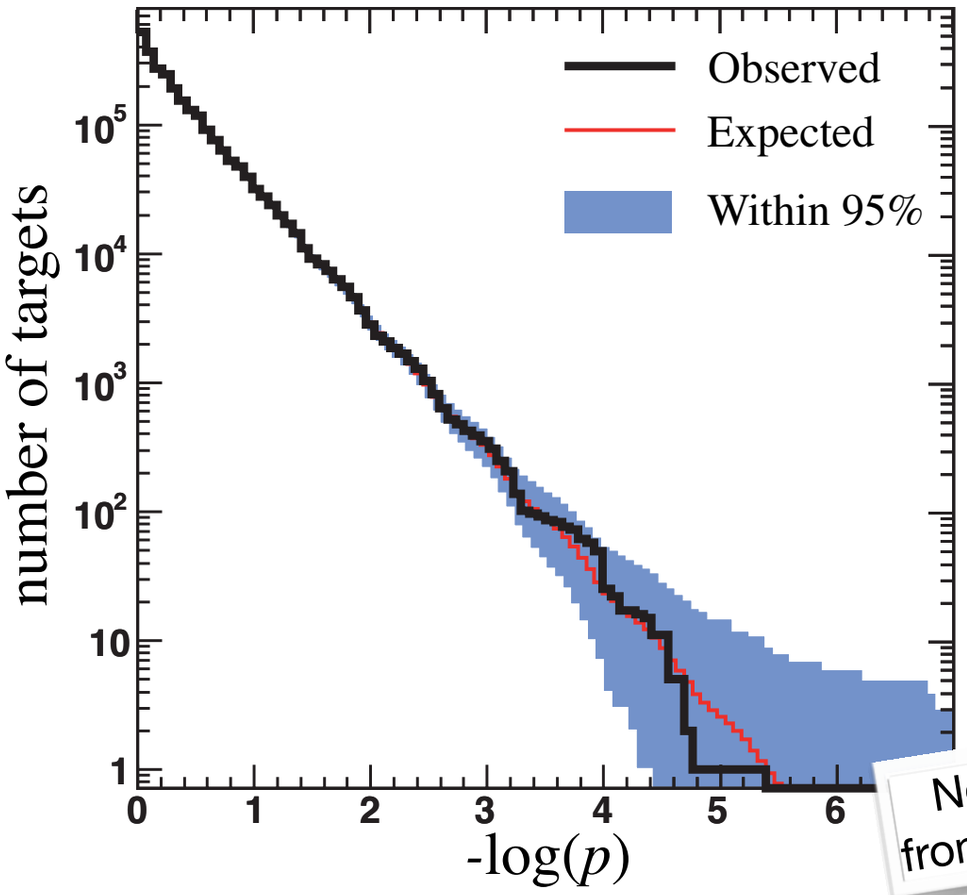
Directional Search

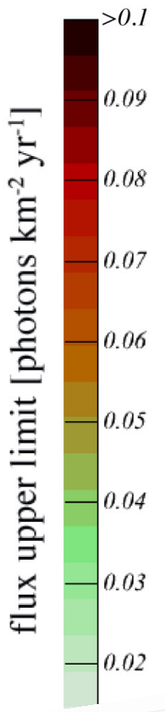
Hybrid events: multivariate analysis using several FD + SD observables

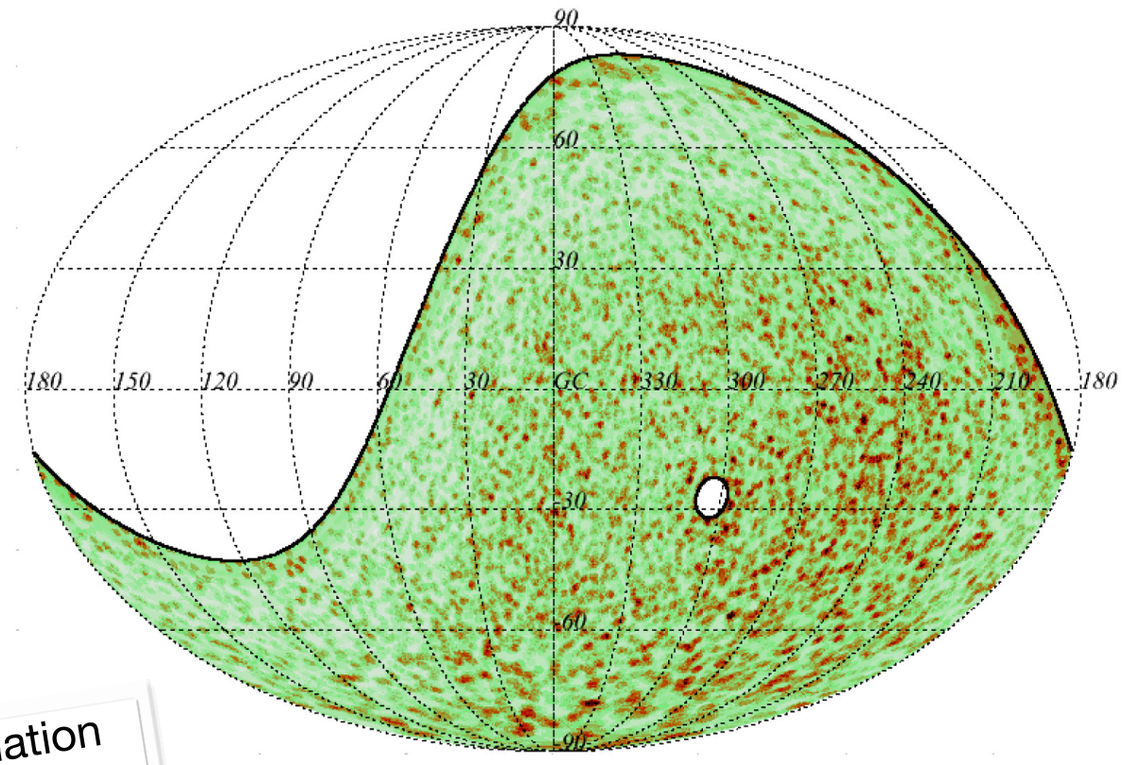
- Declination Range: -85°, +20°
- Targets separations of ~ 0.3°
- 1° Top-Hat radius for each direction

Energy range: $10^{17.3}$ - $10^{18.5}$ eV

Data Set: 01/2005 - 09/2011







No significant deviation from isotropic expectations

chance probability that pmin is observed anywhere in the sky: 36%

- Average particle flux upper limit: 0.035 photons/km²/yr
- Average energy flux limit: 0.06 eV/cm²/s (spectral index -2)
- An energy flux of 1 eV/cm²/s (expected from TeV extrapolations in the EeV range) would have been detected with > 5 σ

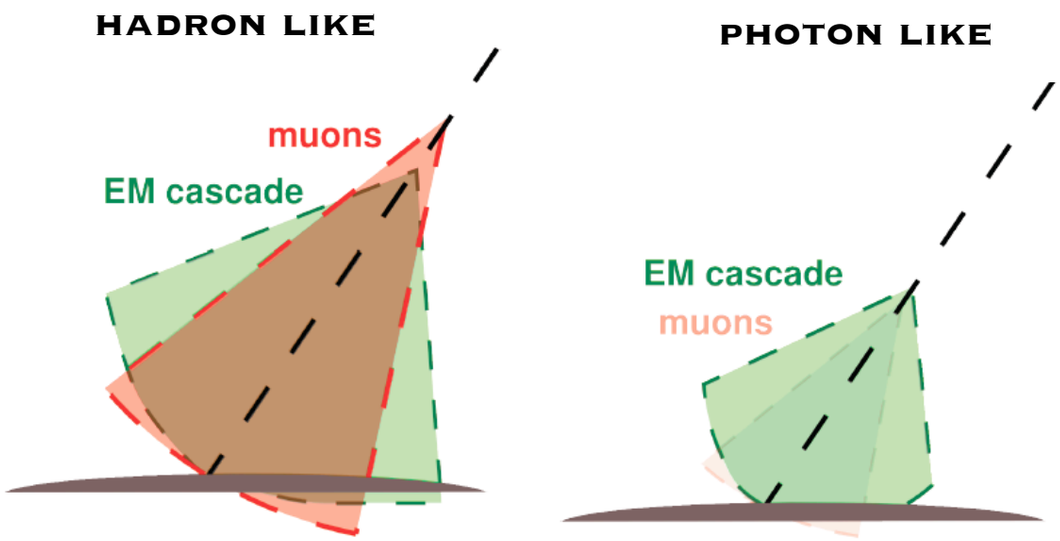
The Pierre Auger Coll., Astrophysical Journal, 789 (2014)

Search for photons with Telescope Array

Diffuse Limits

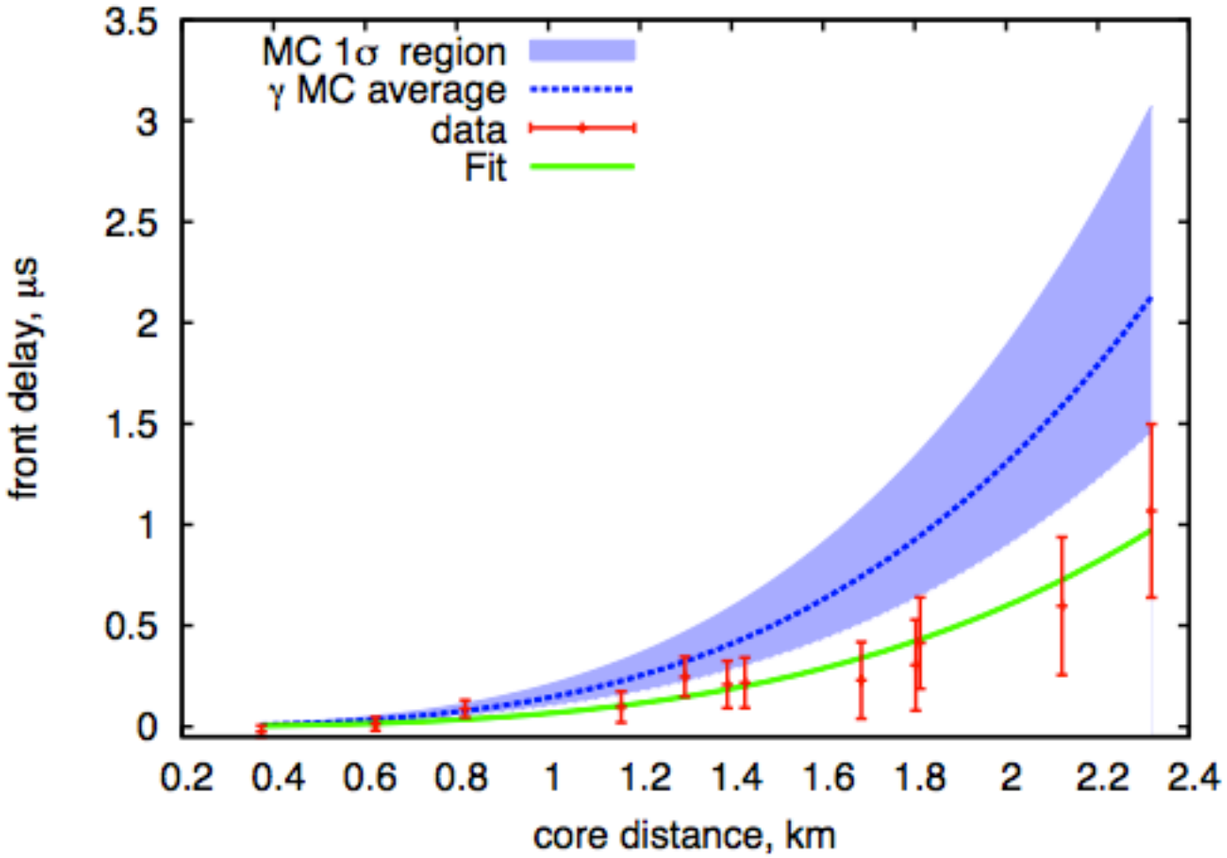
SD events:

- **Data Sample:** May 2008 - May 2013
- **Energy:** > 10 EeV
- **zenith:** 45°-60°



Deep shower maximum and shortage of muons

➡ Curved front



Combined Auger & TA analysis (next slides):

9 SD + 8 Hybrid(*) photon candidates in δ in [-20°, 20°] (compatible with background)

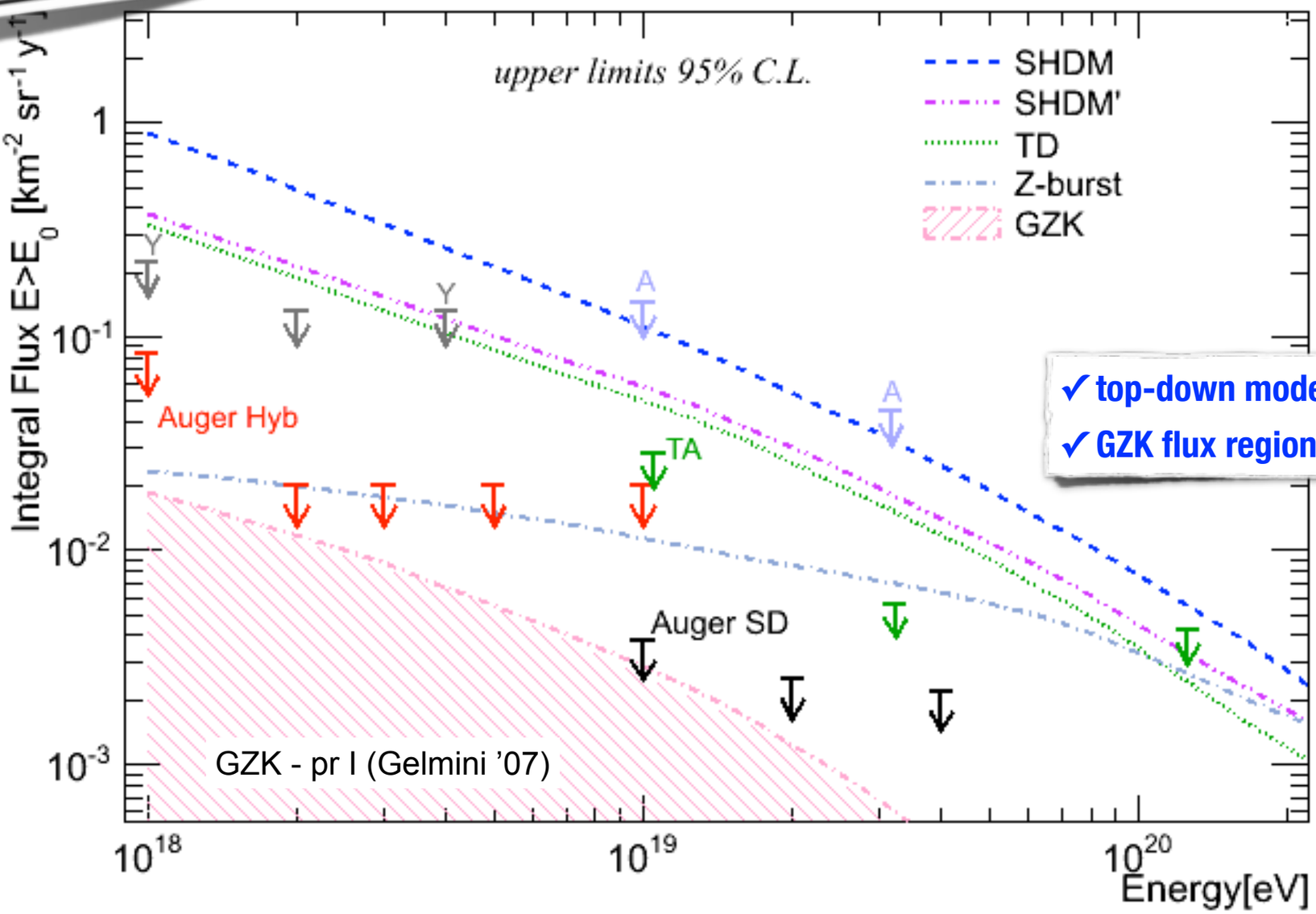
PRELIMINARY

(*) TA-Hybrid analysis (using X_{max}) in progress

G.Rubtsov for the Telescope Array Coll, ICRC 2013

Photon diffuse limits (E > 1 EeV): current status

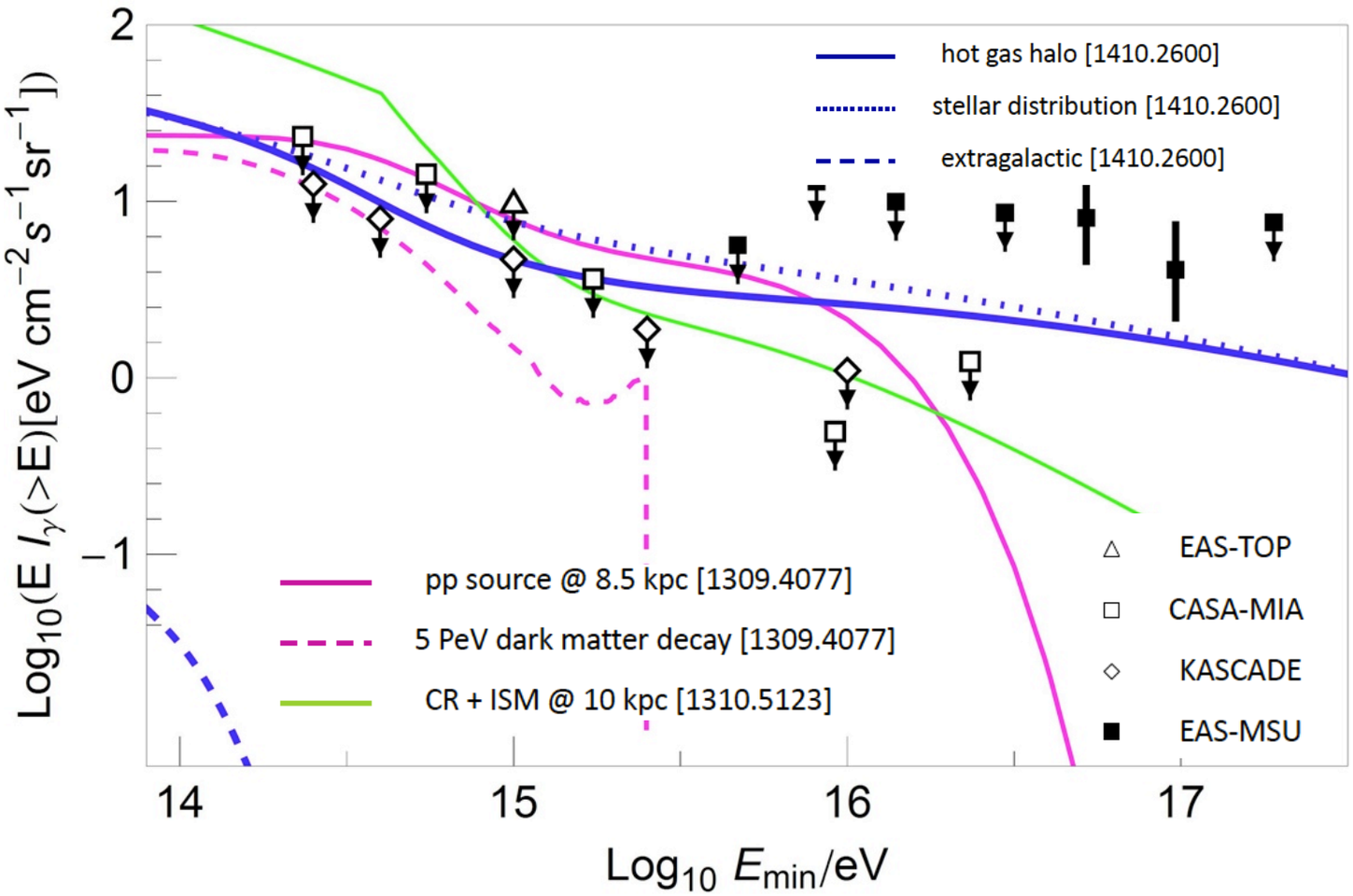
No UHE photons identified so far!!



- ✓ top-down models disfavored
- ✓ GZK flux region within reach

TA vs Auger: efficiency + geometrical exposure

Photon diffuse limits (E > 100 TeV): current status



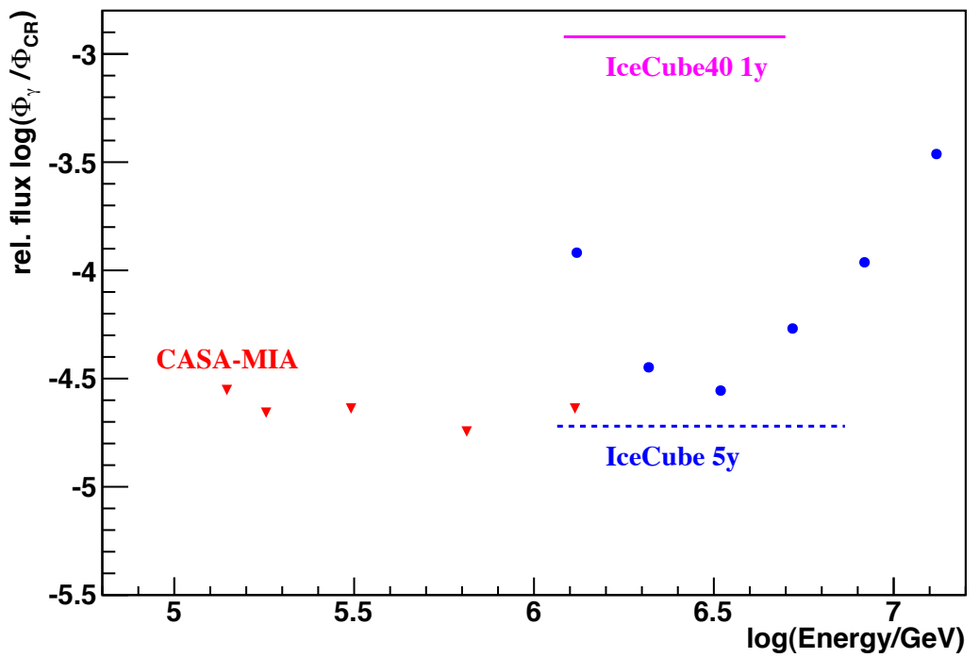
models @ PeV using constraints from IceCube measured neutrino flux

Diffuse flux limits: search for muon-less events in 1year of IceTop+IceCube IC40 and 1.2 < E < 6 PeV

sensitivity IC79 5 years in 1-10 PeV and in bins of energy

IceCube Coll., Phys. Rev. D 87 (2013) 062002

10° around the Galactic Plane



Auger & TA: a cross-correlation analysis

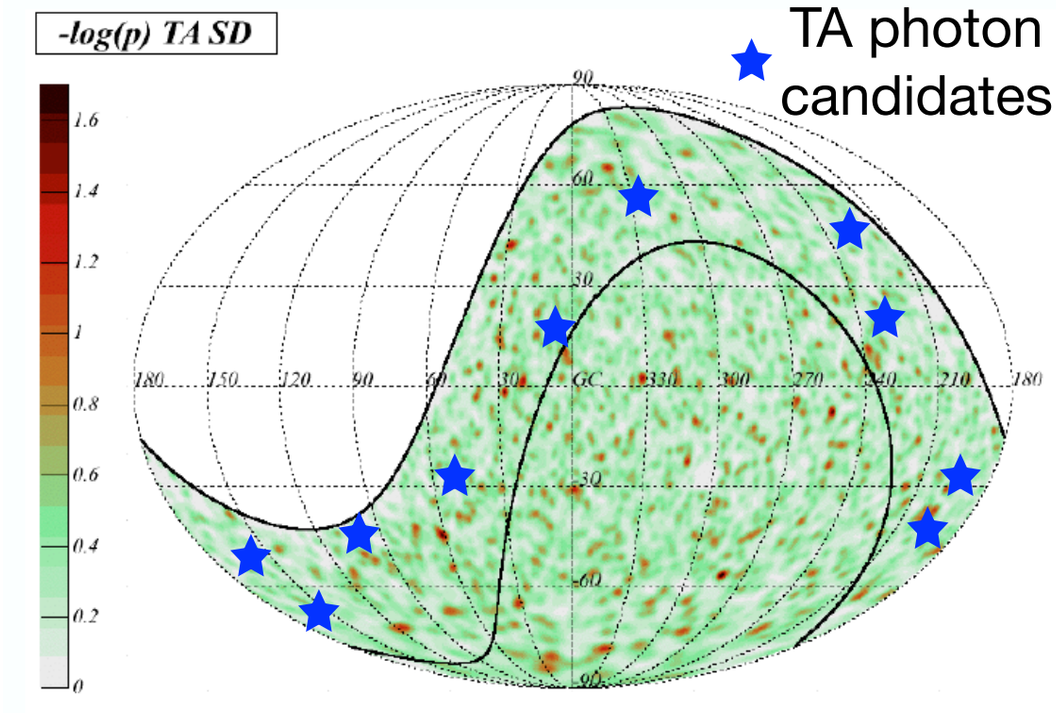
Common sky region: δ in [-20, + 20]

1. Calculate a representative Auger combined p-value from vicinity of TA photon directions (α_n, δ_n)

$$P^{\text{combined}} = \prod_n p^{\text{Auger}}(\alpha_n, \delta_n)$$

p^{Auger} = weighted average

(w according to a Von Mises - Fisher distribution) to take into account the angular resolutions of TA directions



Auger & TA: a cross-correlation analysis

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$$P^{\text{combined}} = \prod_n p^{\text{Auger}}(\alpha_n, \delta_n)$$

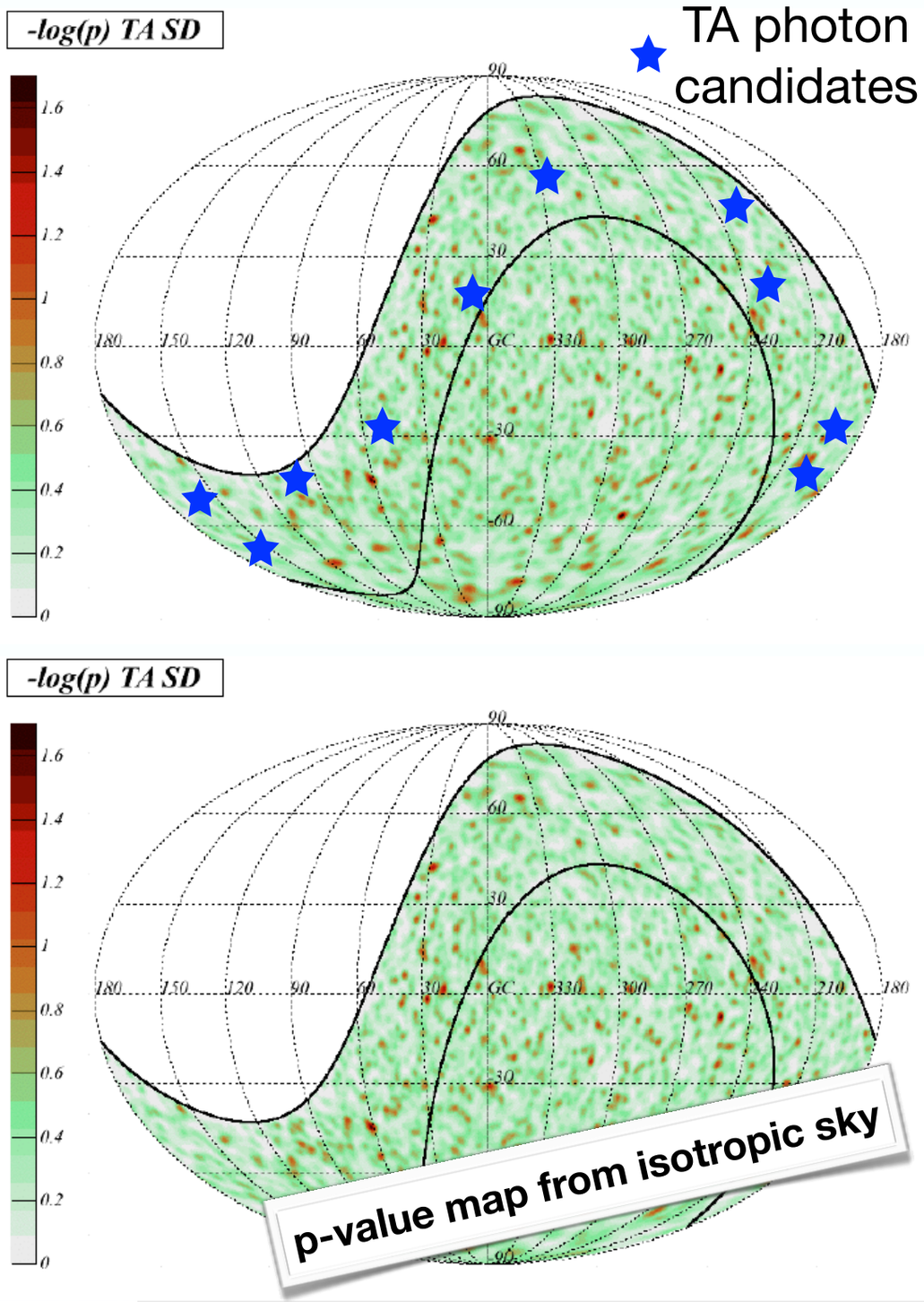
p^{Auger} = weighted average

2. Calculate the probability

$$p^{\text{chance}}(P^{\text{random}} \leq P^{\text{combined}})$$

from *k* generations of mock maps

- isotropic distributions of *n* sources according to SD/Hybrid TA exposure

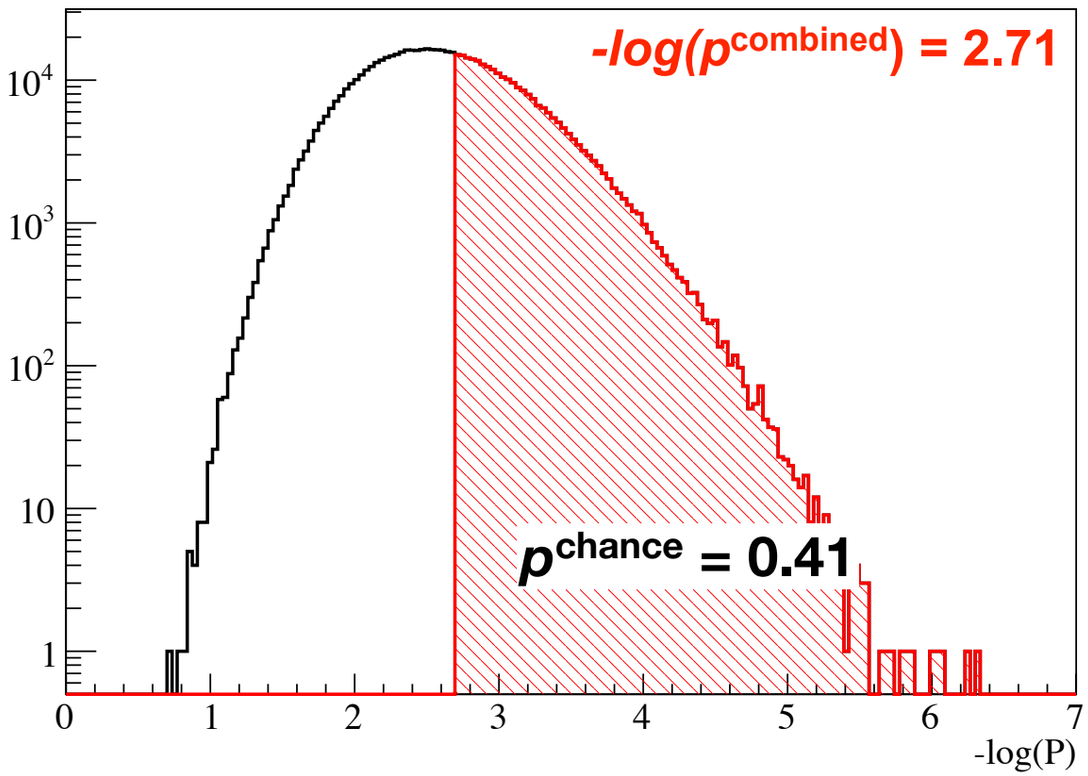


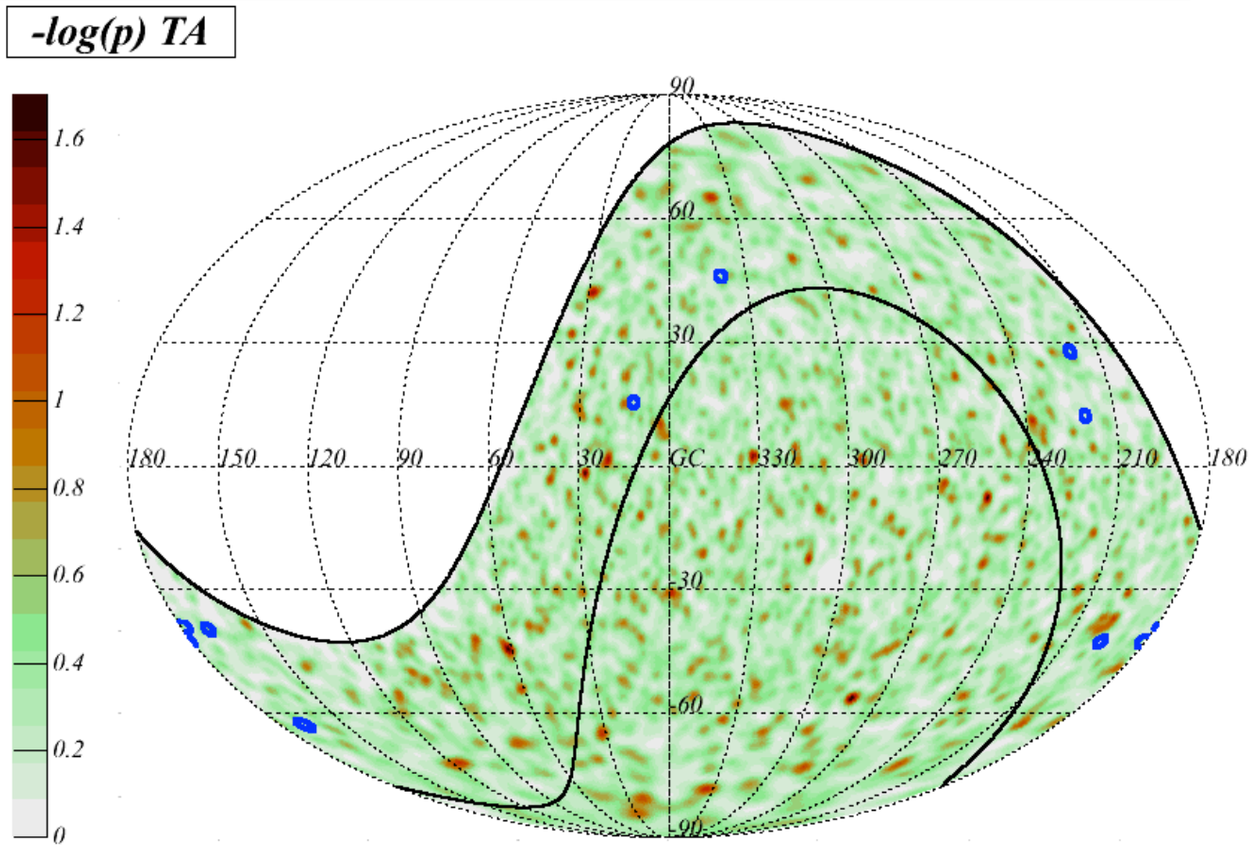
Auger & TA: a cross-correlation analysis

Representative Auger combined *p*-value from vicinity of the *9* TA-SD photon candidates directions

$$P^{\text{combined}} = \prod_n p^{\text{Auger}}(\alpha_n, \delta_n)$$

$$p^{\text{chance}}(P^{\text{random}} \leq P^{\text{combined}})$$





PRELIMINARY

Using directions of 9 SD TA photon candidates

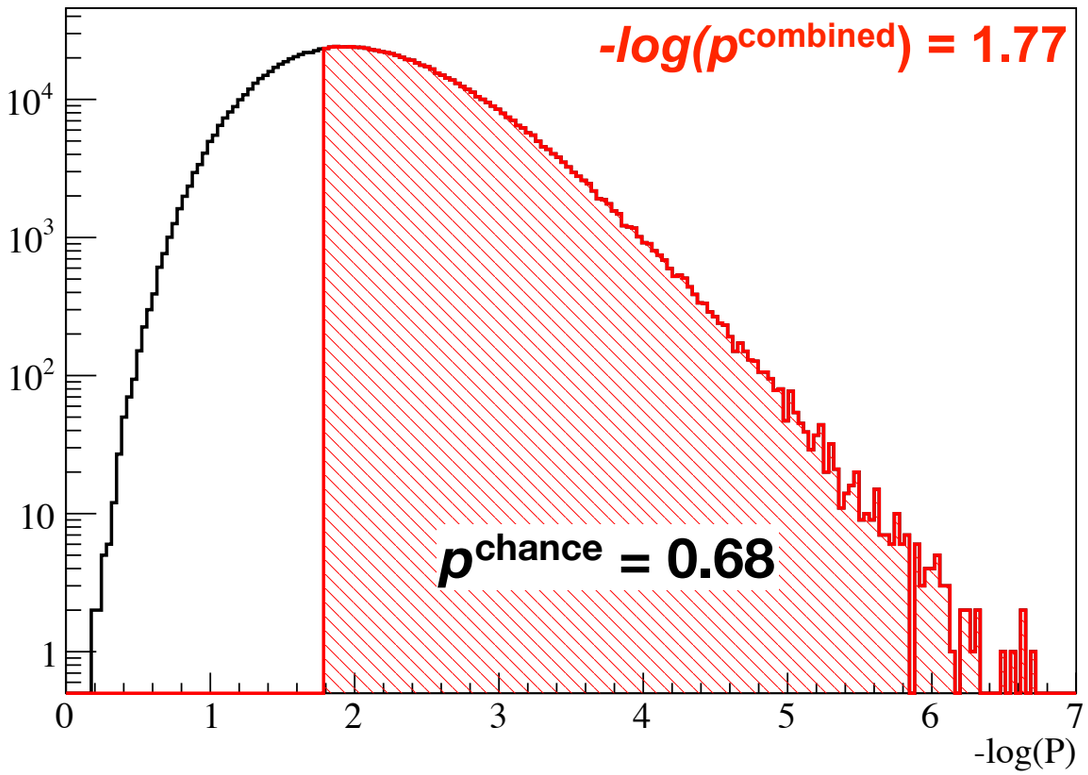
No significant excess !!!

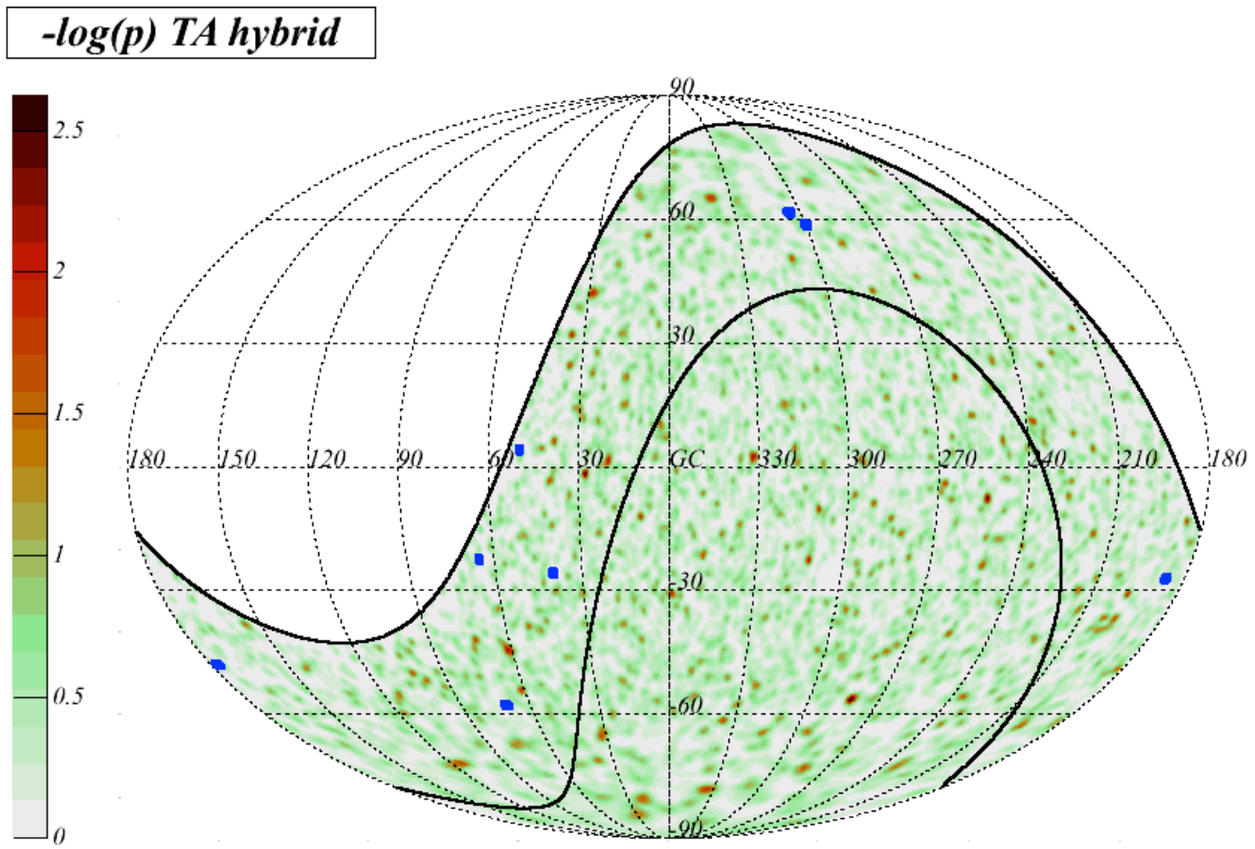
Auger & TA: a cross-correlation analysis

Representative Auger combined p-value from vicinity of the *8* TA-Hybrid photon candidates directions

$$P^{\text{combined}} = \prod_n p^{\text{Auger}}(\alpha_n, \delta_n)$$

$$p^{\text{chance}}(P^{\text{random}} \leq P^{\text{combined}})$$





Using directions of 8 Hybrid TA photon candidates

PRELIMINARY

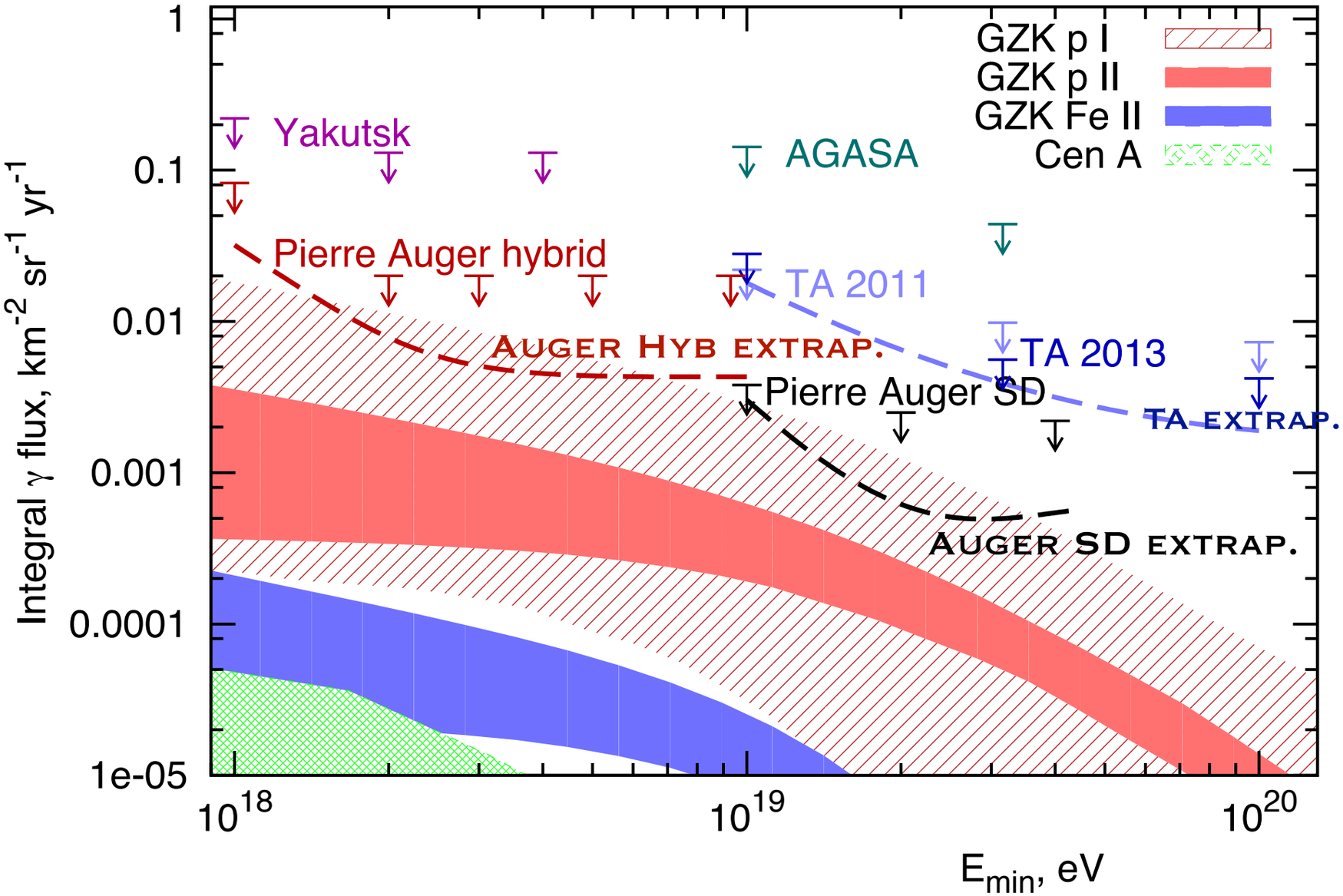
No significant excess !!!

Photon search: perspectives for 2020

(EXTRAPOLATION OF THE CURRENT ANALYSES)

"REALISTIC" SCENARIOS!

Photon selection efficiencies and background fractions as in the current analyses

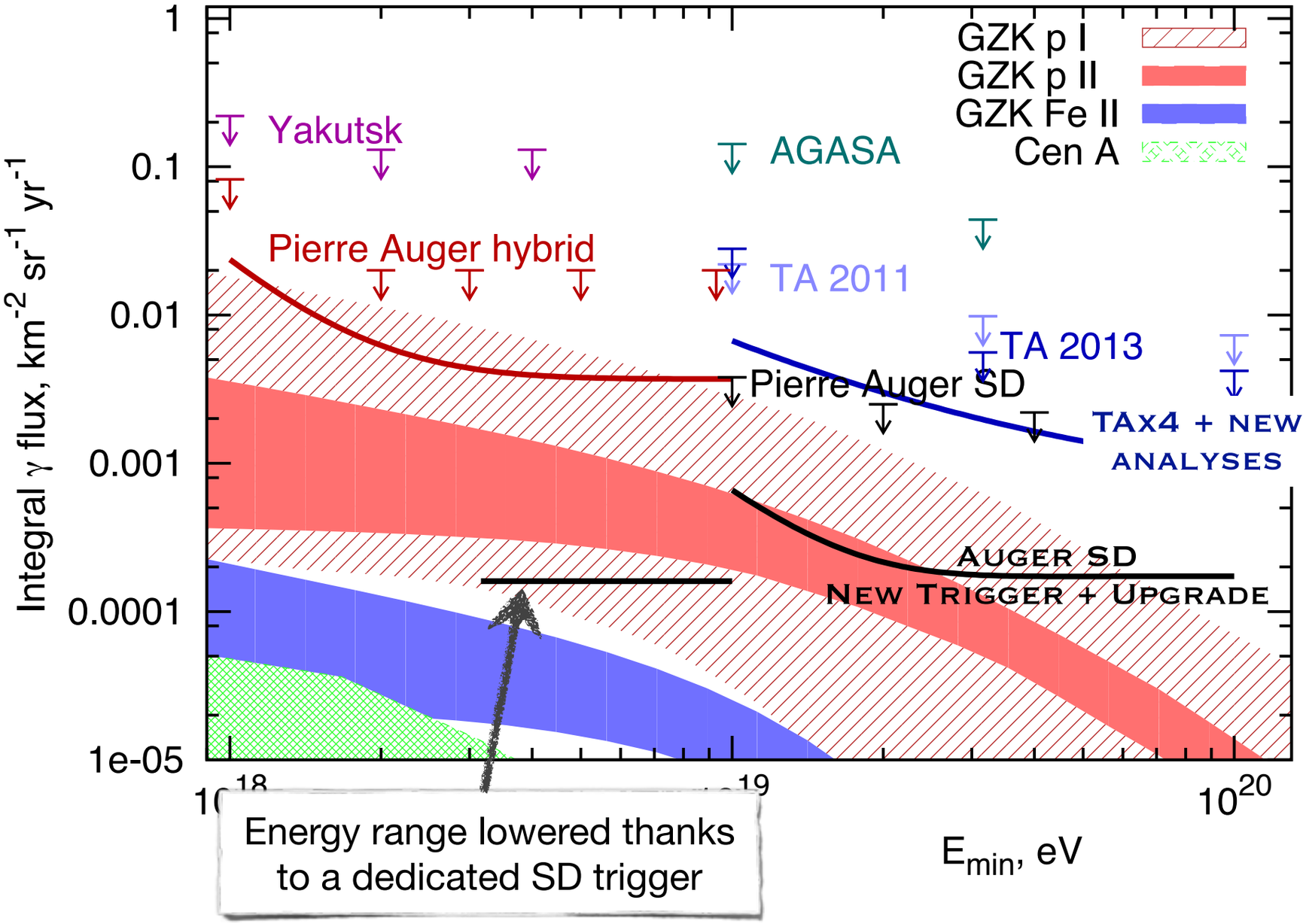


Photon search: perspectives for 2020

(Detector Upgrades and Improved analyses)

Pierre Auger: realistic until 2014 + **7 years optimistic scenario (no candidates, no bkg)**: from new triggers/ analyses and upgrades

Telescope Array: including 3 years of SD expansion (TAx4) and bkg fraction from improved analysis



Summary & Outlook

Depending on the analysis and the messenger, complementary energy ranges and/or sky regions can be exploited with IceCube, Auger and Telescope Array

- **No point-like excess found for neutrons** by Auger and TA in the Northern and Southern sky
- **No UHE photons and neutrinos identified so far.**
  - upper limits on directional and diffuse flux placed
  - Auger-TA combined analysis in a common sky region (δ in [-20,20]). *No significant excess!*
- **First astrophysical neutrino observations at PeV reported by IceCube (constrain on gamma-ray flux)**

Predicted fluxes of cosmogenic neutrinos and photons reachable in the next years (especially with upgraded detectors)

note that, based on the current predictions, only the proton scenarios can be investigated

If observed

✓ pointing to the source

✓ GZK messengers & hints on relevant parameters of the sources

in any case (even if not observed)

✓ constraints on astrophysical models

✓ hints on fundamental physics (e.g. LIV)

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