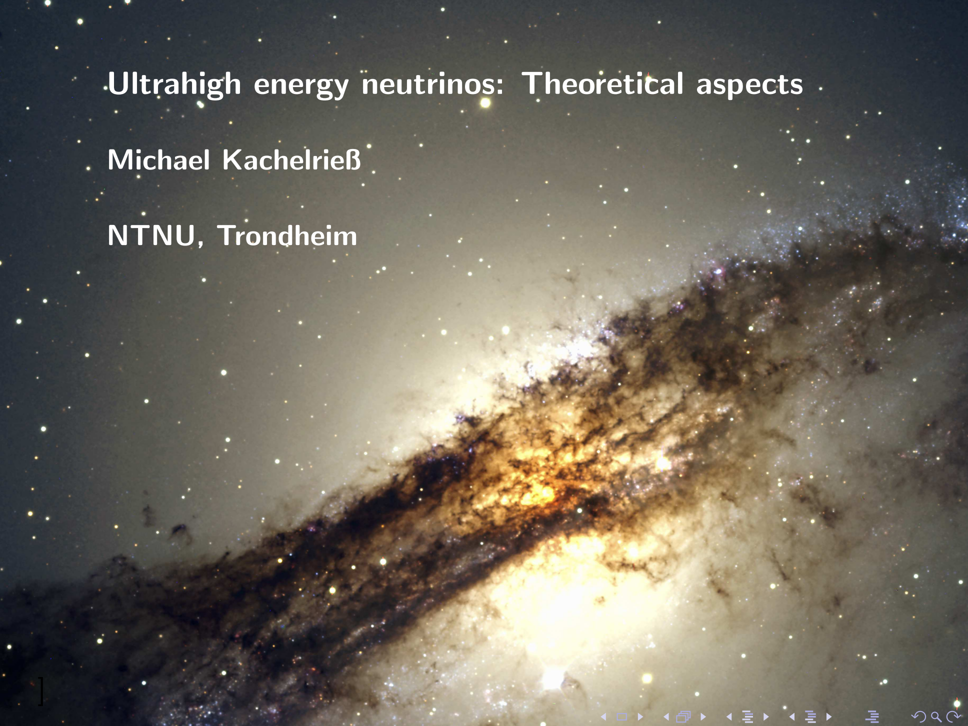

Ultrahigh energy neutrinos: Theoretical aspects

Michael Kachelrieß

NTNU, Trondheim

Outline of the talk

1. Introduction
2. Cosmogenic neutrino flux
   - best estimate
   - lower and upper limits
3. Astrophysical sources
   - point sources
   - Cen A motivated by Auger
   - diffuse flux
4. Top-down models
5. Summary

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UHE neutrinos and HE photons are unavoidable byproducts of UHECRs

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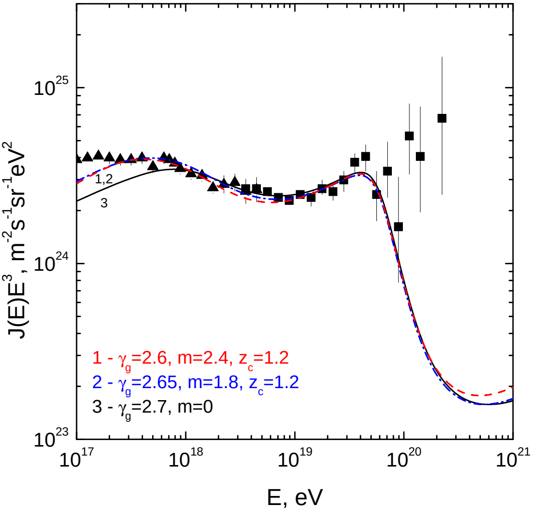
- prizes to win:
  - astronomy above 100 TeV
  - identification of CR sources
  - determine galactic–extragalactic transition of CRs
  - test/discover new particle physics

Estimates for the cosmogenic neutrino flux

- choose dip model as most economic description of data



[Berezinsky, Gazizov, Grigorieva '02]

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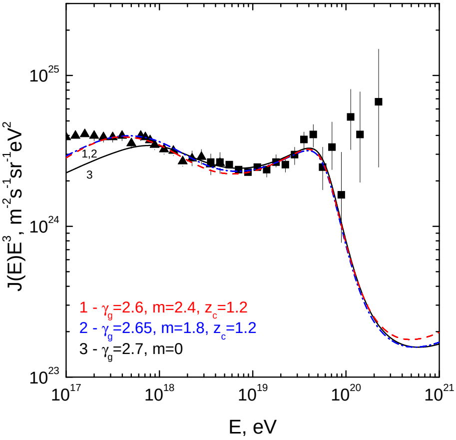

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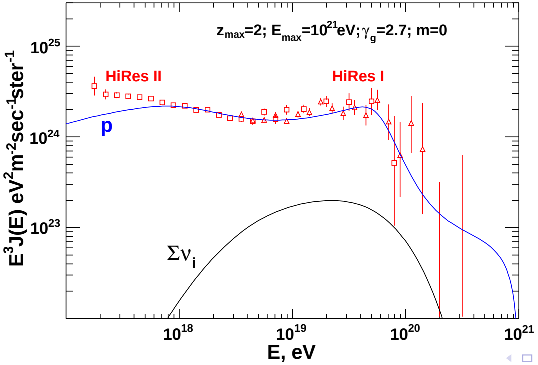

[Berezinsky, Gazizov '09]

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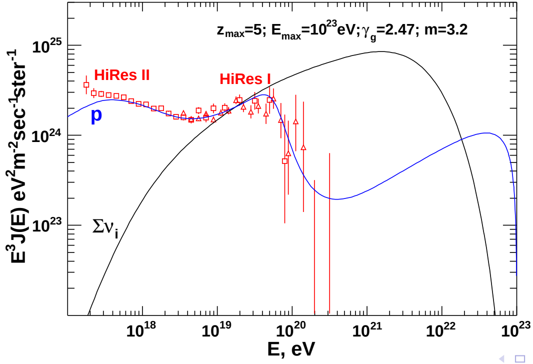
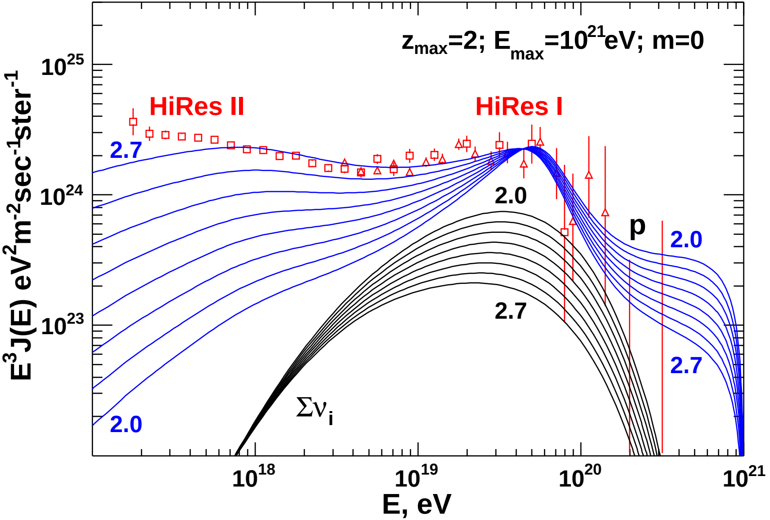


[*Berezinsky, Gazizov '09*]

Lower limit in the dip model



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General upper limit

- exists a number of “neutrino bounds” à la WB, MPR: derived using special assumptions ⇒ status of best guesses

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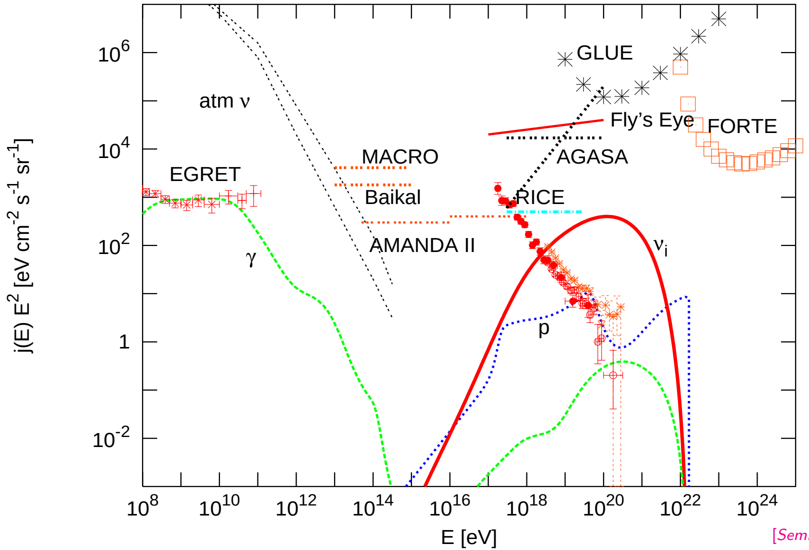
  derived using special assumptions ⇒ status of best guesses

- cascade limit: [*Berezinsky, Smirnov '75*]
  all energy in γ and $e^\pm$ cascades down to GeV–TeV range, bounded by observations:

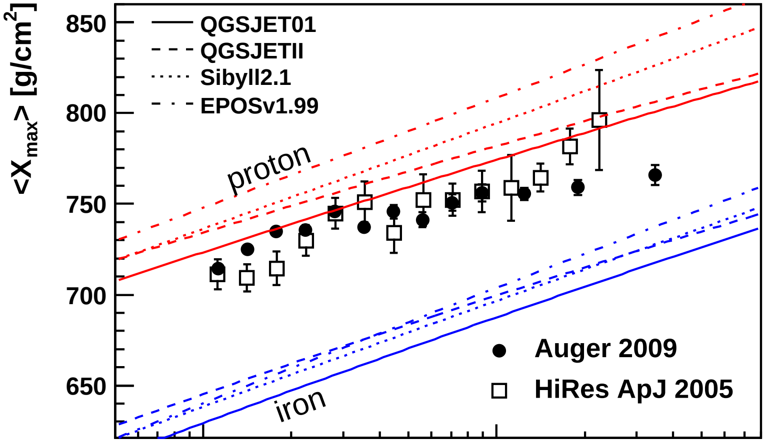
$$\begin{aligned}\omega_{\rm cas} &> \frac{4\pi}{c}\int_{E_0}^{\infty} dE\, E I_\nu(E) \geq \frac{4\pi}{c} E_0 I_\nu(>E_0) \\ &\lesssim 2\cdot 10^{-6}\,{\rm eV/cm^3}\end{aligned}$$

Elmag. cascades and EGRET limit:

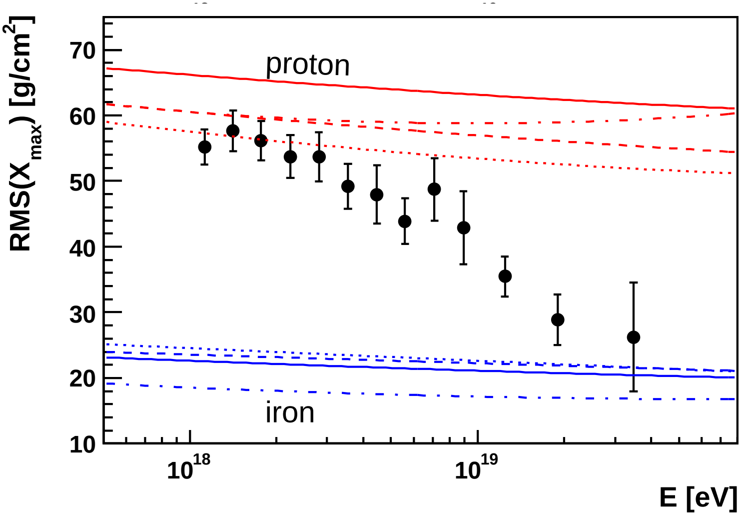


[Semikoz, Sigl '03]

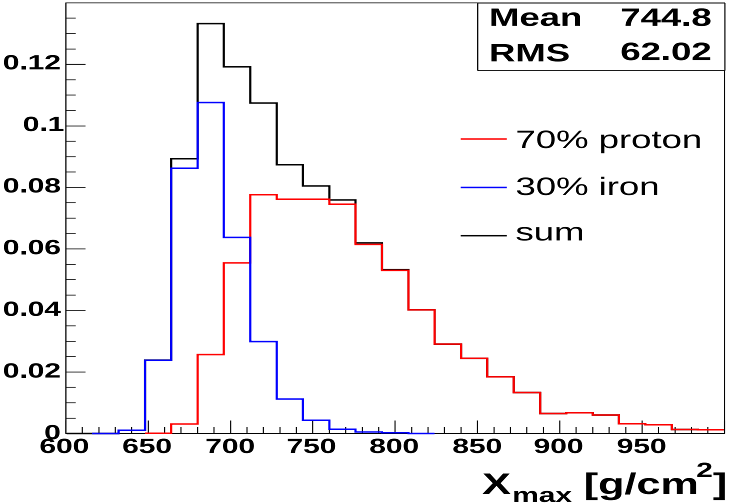
Chemical composition via $X_{\max}$:



Chemical composition via $\sigma(X_{\max})$ from Auger:

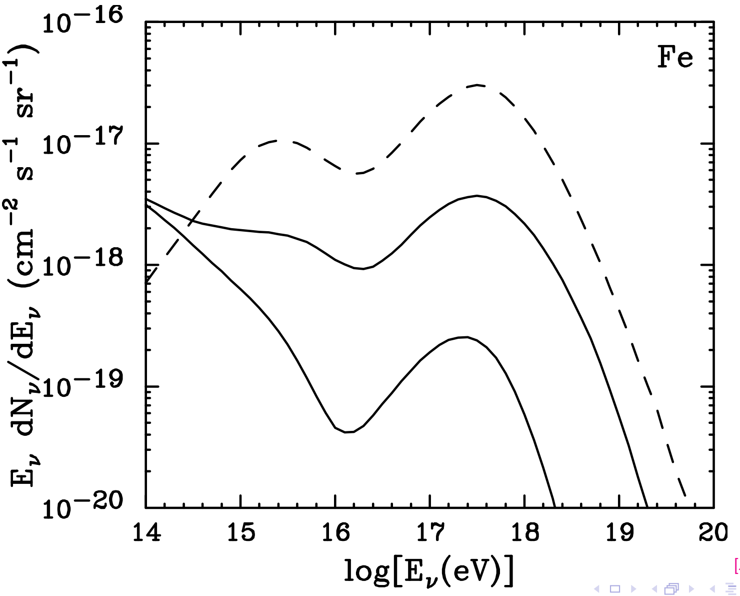


Mixed composition:



$$\sigma^2 = \sum_i f_i \sigma_i^2 + \sum_{i<j} f_i f_j (X_{\max,i} - X_{\max,j})^2$$

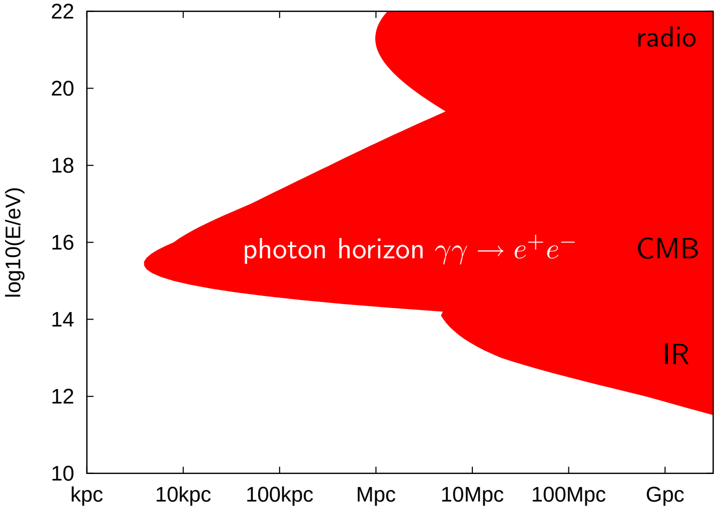
Cosmogenic neutrino flux: p versus Fe



[*Anchordoqui et al. '07*]

What is the bonus of UHE neutrino astronomy?

- astronomy with VHE photons restricted to few Mpc:



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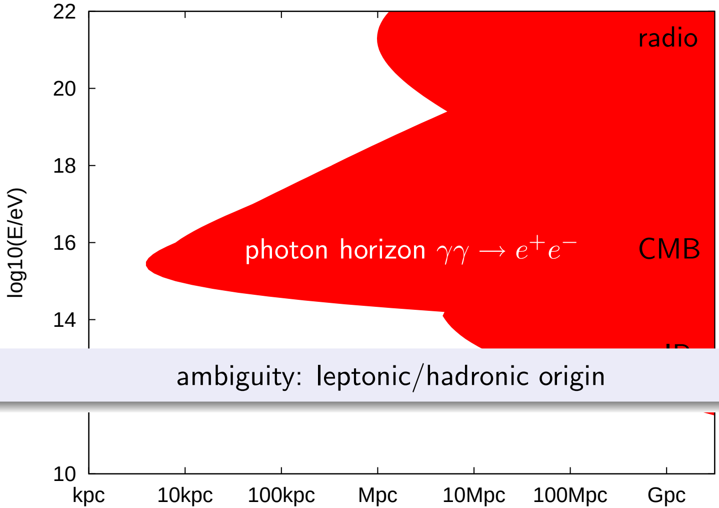
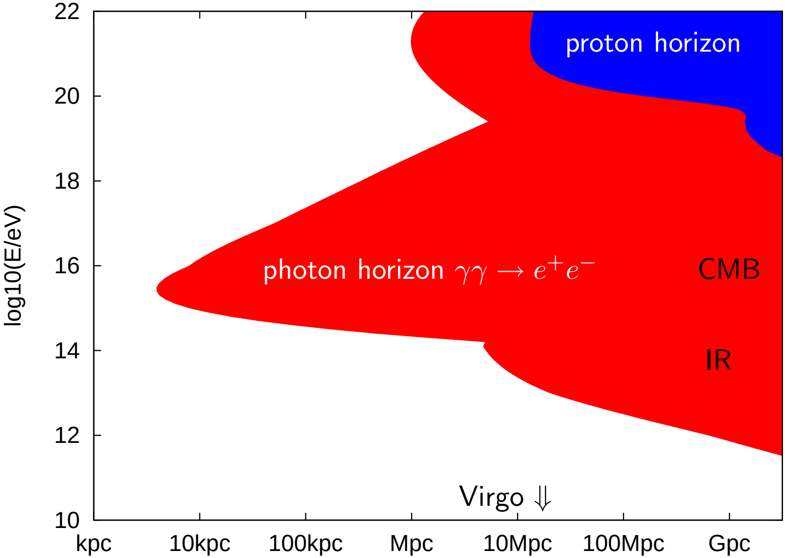


ambiguity: leptonic/hadronic origin

UHE neutrino astronomy vs UHECRs?



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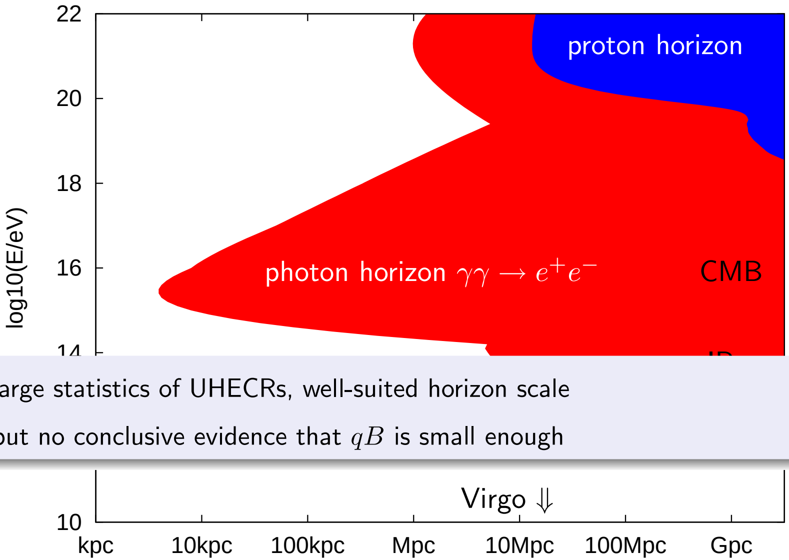

- large statistics of UHECRs, well-suited horizon scale
- but no conclusive evidence that qB is small enough

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Neutrino astronomy:

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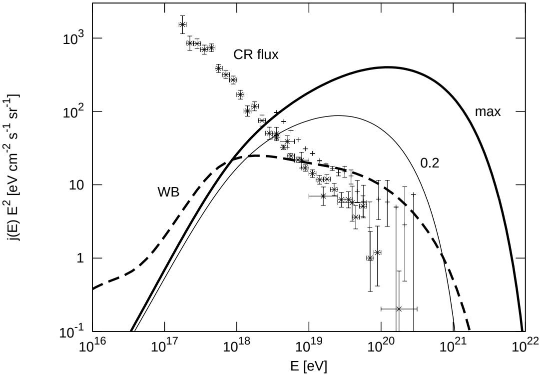

$\Rightarrow$ identification of steady sources challenging

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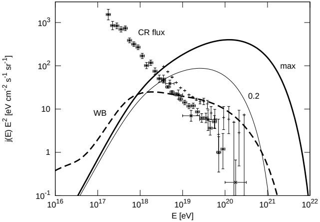
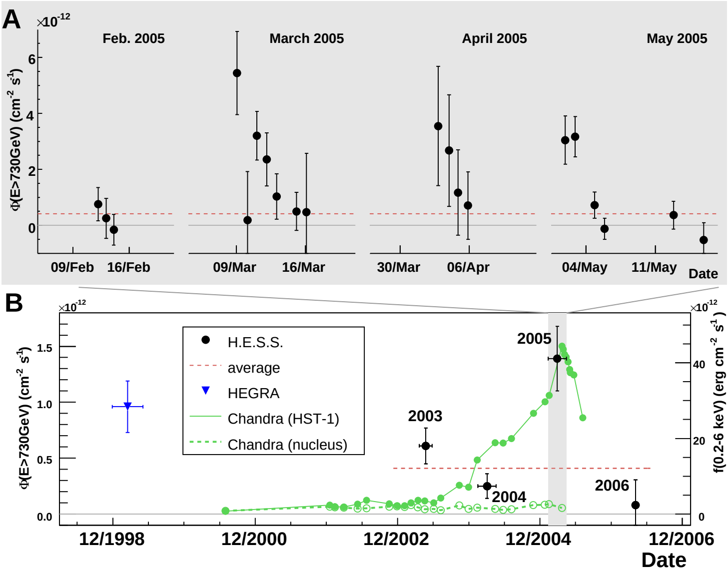


$\Rightarrow$ identification of steady sources challenging

- correlation with AGN flares, GRBs
- which AGNs? GeV/TeV photon sources?

HESS observations of M87:



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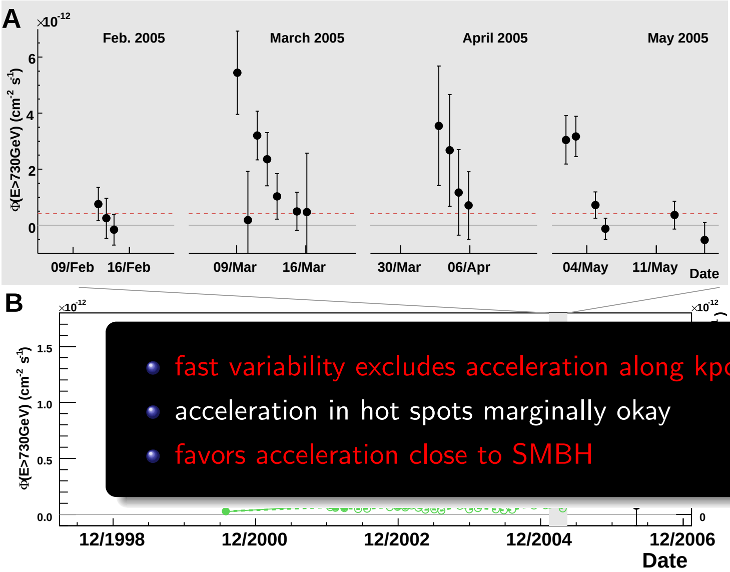
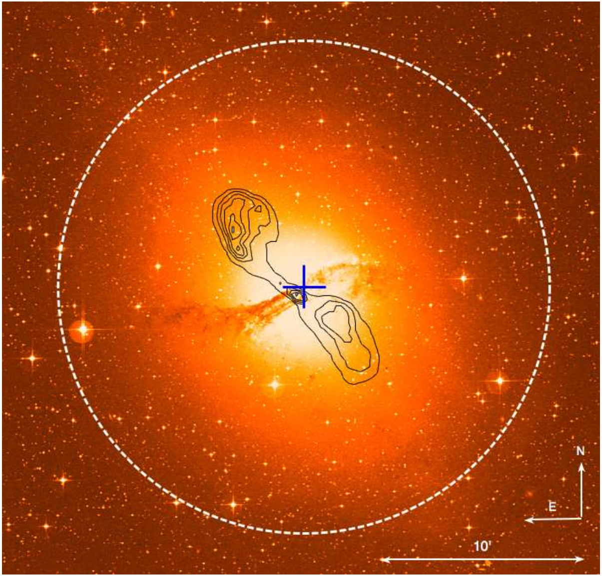


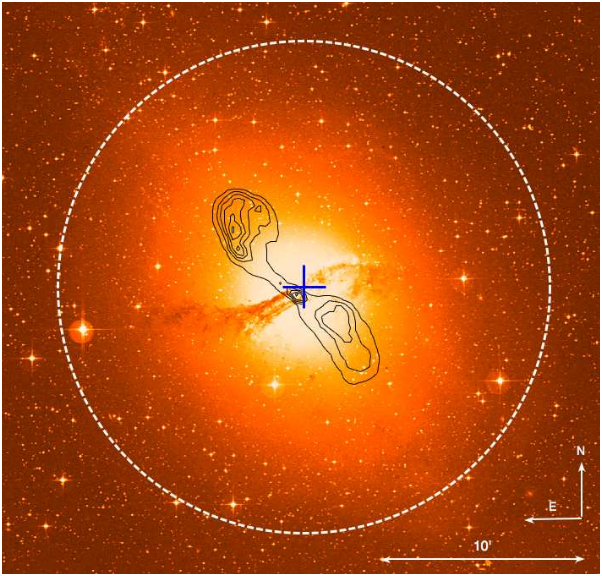
- fast variability excludes acceleration along kpc jet
- acceleration in hot spots marginally okay
- favors acceleration close to SMBH

HESS observations of Cen A



- no variability

HESS observations of Cen A



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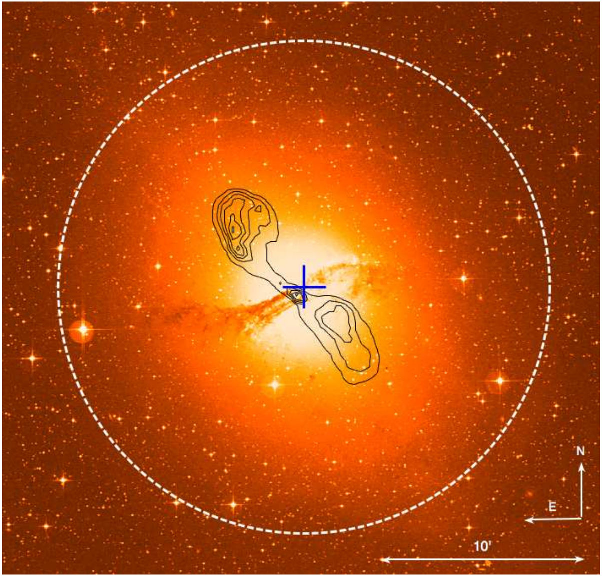

- no variability
- consistent with point source
- HE emission from central region (1'$\simeq$ 1.1 kpc)

Multi-messenger astronomy with Cen A?

- 2 events correlated with Cen A within 3.1°
- more events close-by [*Gorbunov et al. '07, Fargione '08, Rachen '08*]
- general correlation with AGN

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– tension to PAO chemical composition
– $E_{\max}$ for most AGN (incl. Cen A) high enough?

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correlations with AGN:

- independent/additional evidence?

- Cen A closest AGN

⇒ good test case for multi-messenger astronomy: accompanying γ-ray and neutrino fluxes?

Study two base models

[MK, Ostapchenko, Tomas '08]

- neglect details of acceleration
- fix 2 basic scenarios: "core" and "jet"

acceleration close to the core

acceleration in accretion shock/regular fields

pγ interactions

$\tau_{\gamma\gamma} \gg 1$, synchrotron losses for $e^{\pm}$

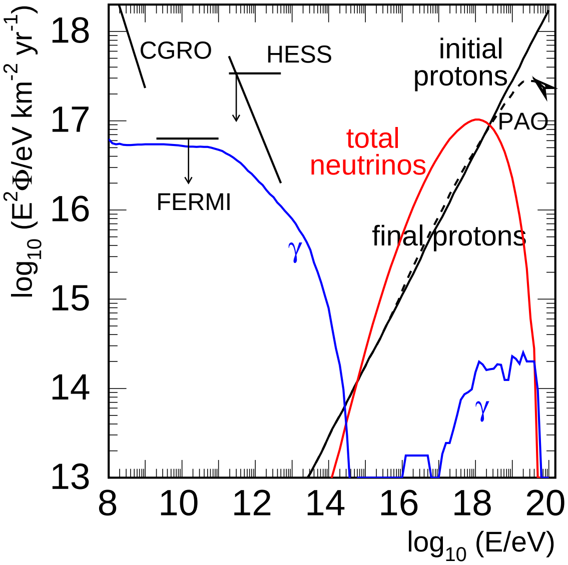
acceleration in jet

shock acceleration

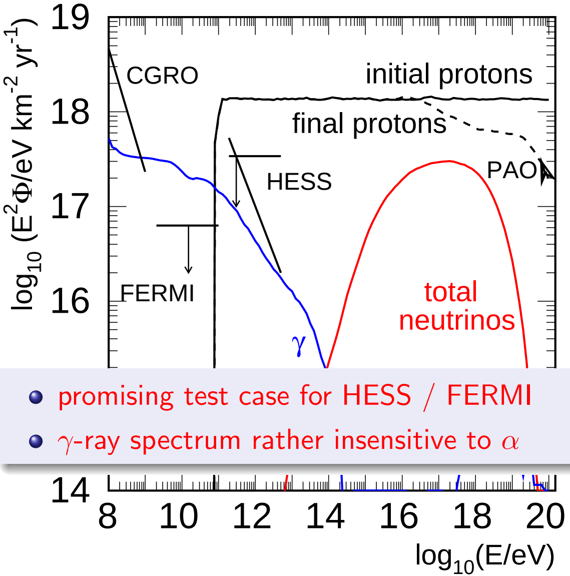
pp interactions

$\tau_{\gamma\gamma} \ll 1$, synchrotron losses for $e^{\pm}$

Results for acceleration close to the core: $\alpha = 1.2$

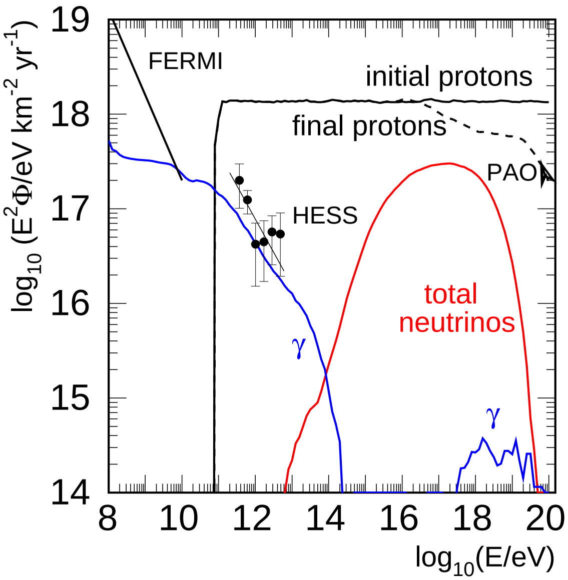


Results for acceleration close to the core: $\alpha = 2$



- promising test case for HESS / FERMI
- γ-ray spectrum rather insensitive to α

Comparison to recent HESS and FERMI observations



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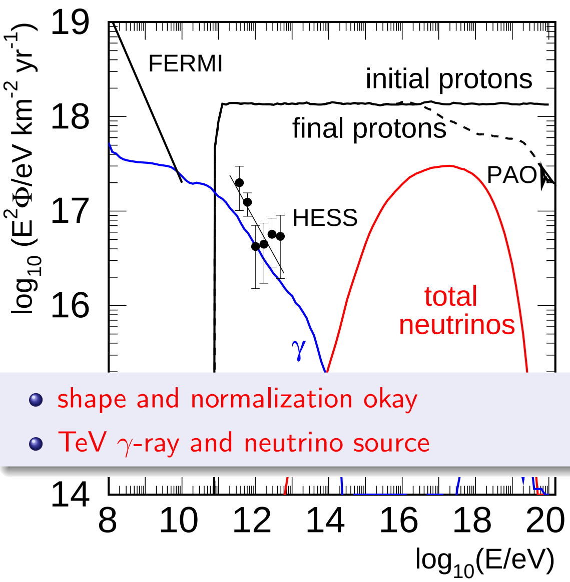
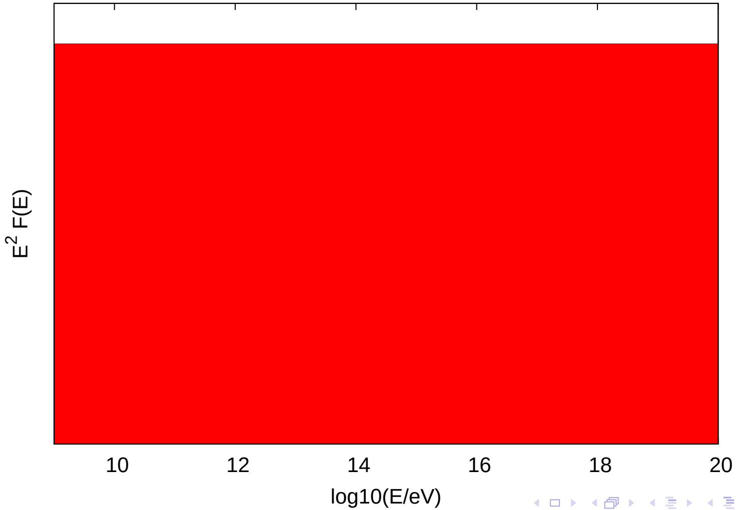


- shape and normalization okay
- TeV γ-ray and neutrino source

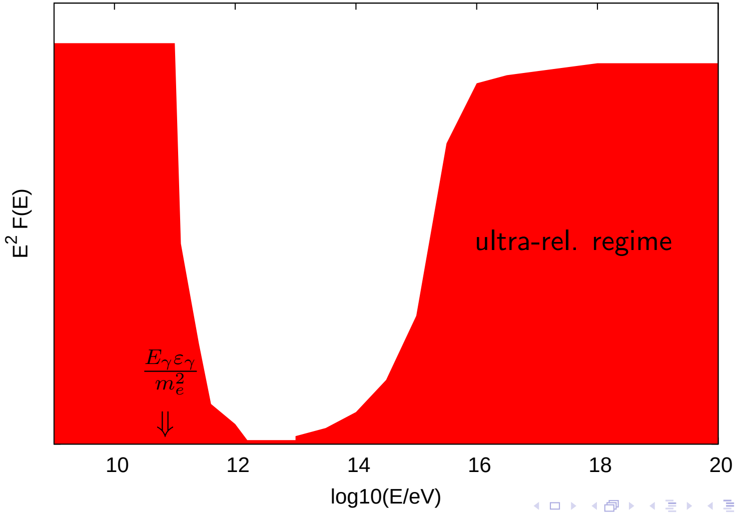
Regenerating TeV photons: a) in the source

- injection spectrum $F_\gamma(E) \propto 1/E^2$



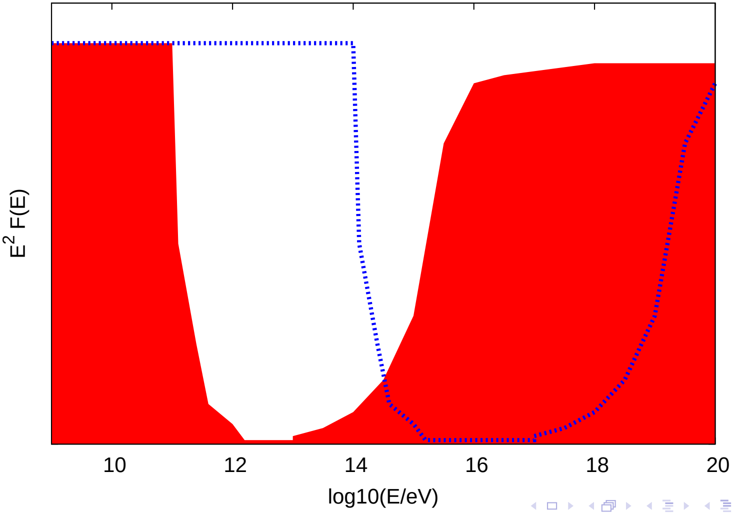
Regenerating TeV photons: a) in the source

- : thin above 10^{16}eV, ultra-rel. regime



Regenerating TeV photons: b) on CMB

- photons above 10^{16}eV cascade on CMB



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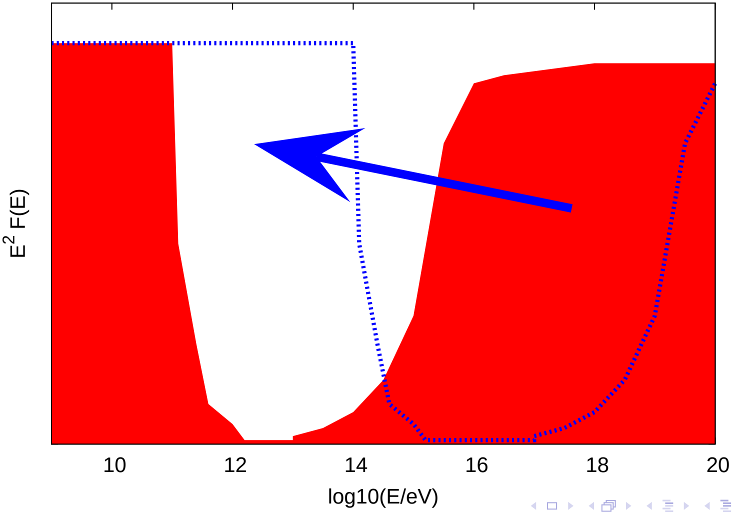

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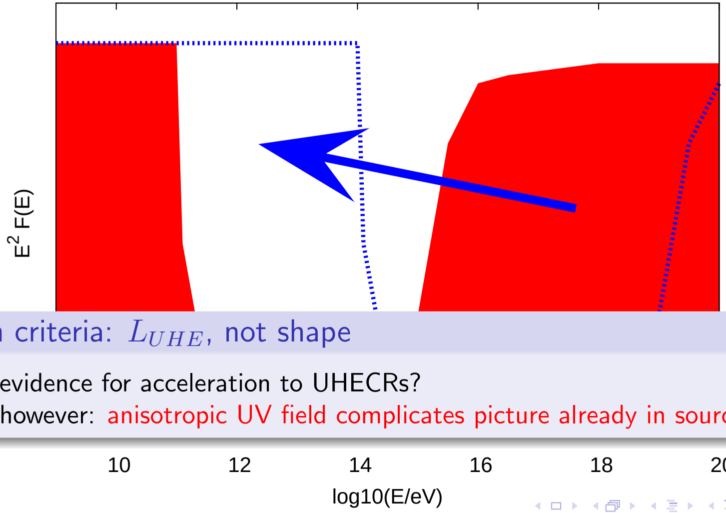

main criteria: L_{UHE}, not shape

- evidence for acceleration to UHECRs?
  however: anisotropic UV field complicates picture already in source

Neutrino event rates per km^3 per year

acceleration in the jet ($\alpha = 2$ or broken power-law)

spectral break E_b/eV	-	10^{18}	10^{17}
contained ν-events	0.02	0.4	2.0
muon events	0.01	0.2	0.7

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- "good" neutrino cases excluded by HESS/Fermi
- diffuse flux more promising

Diffuse flux from AGN - normalized to Cen A

- assume Cen A is a "typical source" with injection spectrum $j(E)$
- diffuse flux from all Cen A-like sources

$$\varphi^{\rm diff}(E) = \frac{cn_0}{4\pi} \int_0^\infty dz \left| \frac{dt}{dz} \right| \frac{dE_0(E,z)}{dE} \varepsilon(z) j^0(E_0) \,,$$

- enhancement between $\mathcal{O}(10)$ (no evolution) and $\mathcal{O}(100)$ (strong evolution) [Koers, Tinyakov ('08)]
- Halzen, O'Murchadha ('08): all FR-I radio galaxies: 5 events/yr

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Top-Down Models

UHECR primaries are produced by decays of supermassive particle X with $M_X \gtrsim 10^{12}$ GeV.

- topological defects: monopoles, strings, super-strings. ...

  [Hill '83; Ostriker, Thompson, Witten '86]

- superheavy metastable particles

  [Berezinsky, MK, Vilenkin '97; Kuzmin, Rubakov '97]

Main properties:

- theoretically well-motivated; testable predictions
- no acceleration problem
- no visible sources
- if $X \in$ CDM, no GZK-cutoff

Raison d'être for top-down models

- AGASA excess as original motivation for top-down models is gone
- Photon and anisotropy limit allow only subdominant contribution to UHECRs
- allows still search for inflationary/GUT/string scale physics
- can still give largest neutrino fluxes, especially at UHE

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- Small fluctuations of field Φ obey

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- In inflationary cosmology

$$\Omega_X h^2 \sim \left(\frac{M_X}{10^{12}\mathrm{GeV}}\right)^2 \frac{T_{RH}}{10^9\mathrm{GeV}}$$

dependent only on cosmology, for $M_X \lesssim H_I$

[Kuzmin, Tkachev '98; Chung, Kolb, Riotto '98]

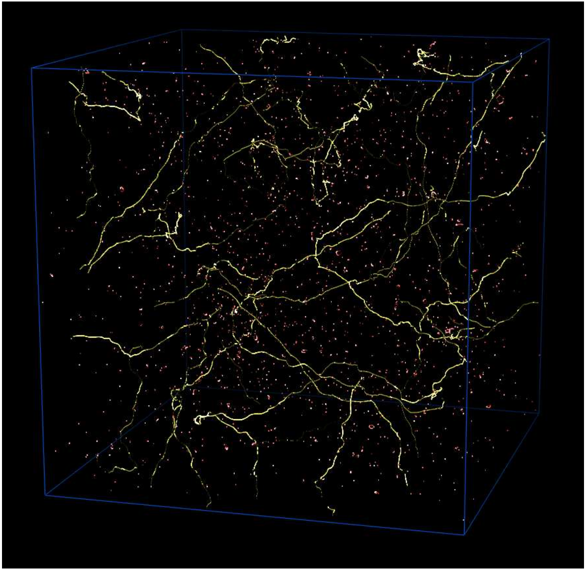
Topological defect models

+ "generic" in SUSY-GUTs
+ produced during reheating

- typical density: one per horizon/correlation length
- main energy loss low-energy radiation?

Topological defect models

[*Allen, Shellard '06*]



- box $2ct$
- matter epoch
- scaling regime

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favourable models for UHECRs:

- monopole-antimonopole pairs
- hybrid defects: cosmic necklaces

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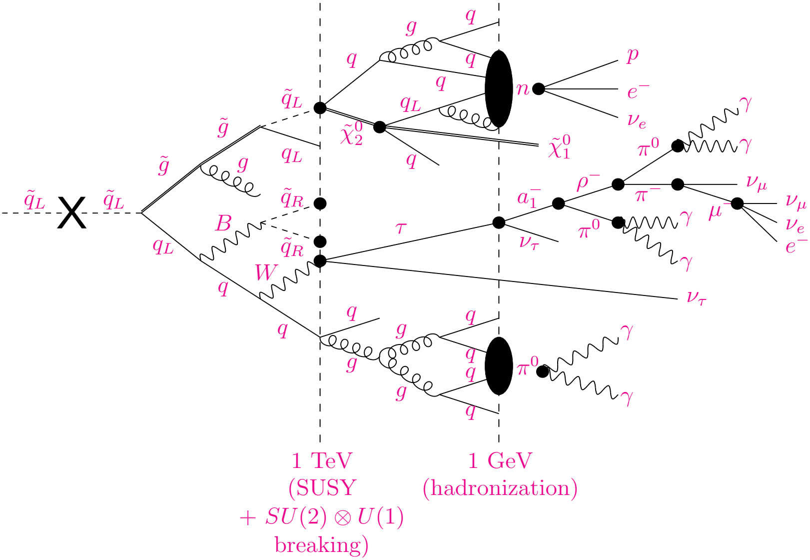
- typical density: one per horizon/correlation length
- main energy loss low-energy radiation?

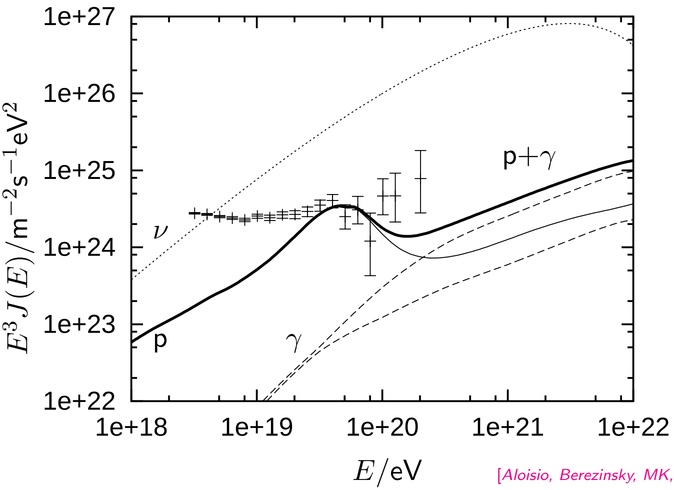
favourable models for UHECRs:

- monopole-antimonopole pairs
- hybrid defects: cosmic necklaces
  - $G \to H \otimes U(1) \to H \otimes Z_2$
  - monopoles $M \sim \eta_m/e$ connected by strings $\mu_s \sim \eta_s^2$
  - parameter $r = M/(\mu d)$:
  - $r \ll 1$ normal string dynamics
  - $r \gg 1$ non-rel. string network

Fragmentation of heavy particles

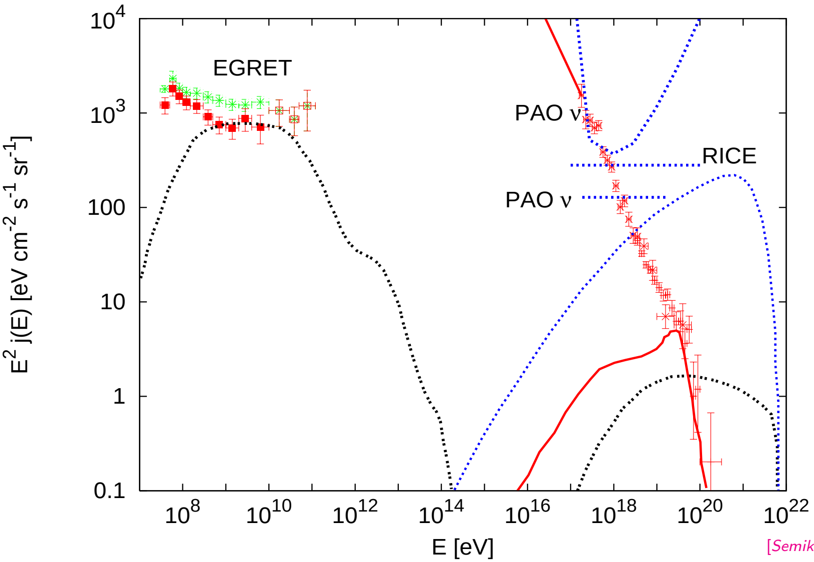


Neutrino fluxes from necklaces:



[*Aloisio, Berezinsky, MK, '03*]

EGRET versus ν_τ limit:



[Semikoz, Sigl '03]

Summary

1. astrophysical origin of main component of UHECRs is established

$\Rightarrow$ exists cosmogenic neutrino flux

2. size and energy range uncertain, mainly because of unknown chemical composition
3. ICECUBE is coming close to predicted levels of ("direct") diffuse neutrino flux
4. detection of point sources requires correlations
5. top-down models may still be dominant neutrino source at UHE

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Which sources?

- Use the auto-correlation function,

$$w(\vartheta) = \frac{DD(\vartheta)}{RR(\vartheta)} - 1\,,$$

 where
  - DD: number of pairs in catalogue
  - RR: number of pairs in random sets

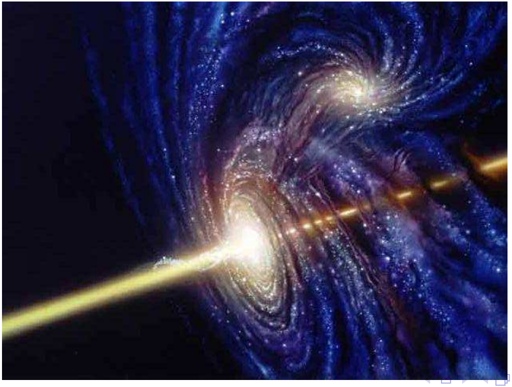
 for most popular sources of UHECRs:

Which sources?

- Use the auto-correlation function,

$$w(\vartheta) = \frac{DD(\vartheta)}{RR(\vartheta)} - 1\,,$$

for most popular sources of UHECRs: AGN



Which sources?

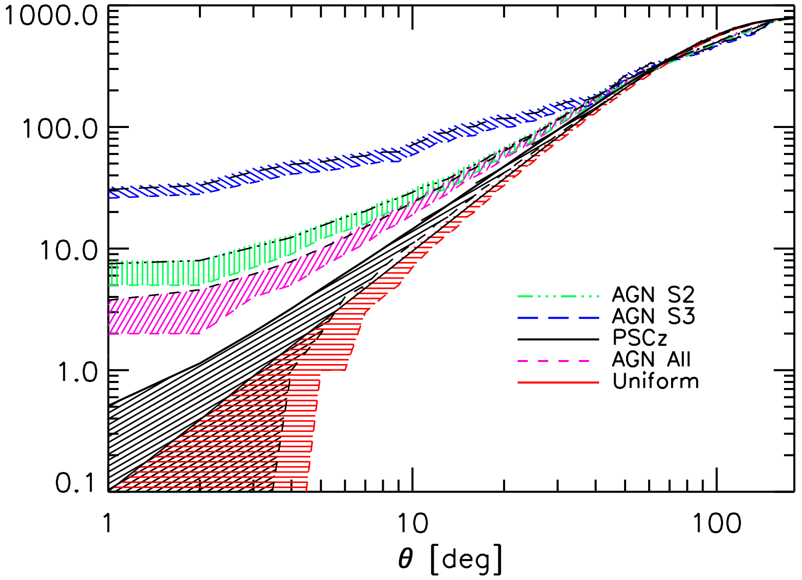
- Use the auto-correlation function,

$$w(\vartheta) = \frac{DD(\vartheta)}{RR(\vartheta)} - 1\,,$$

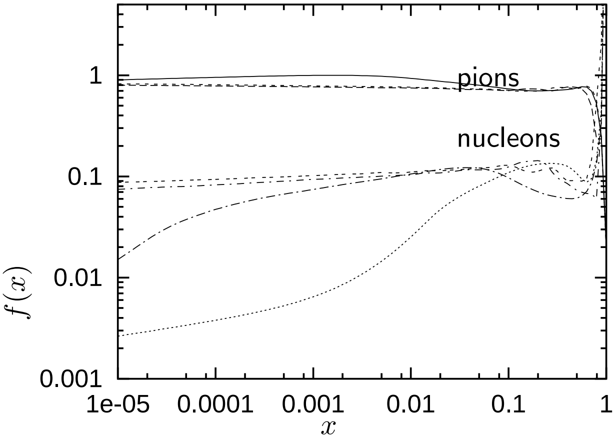
for most popular sources of UHECRs: AGN and GRB

Clustering signal of PAO for $N = 40$

[A. Cuoco et al. '07]

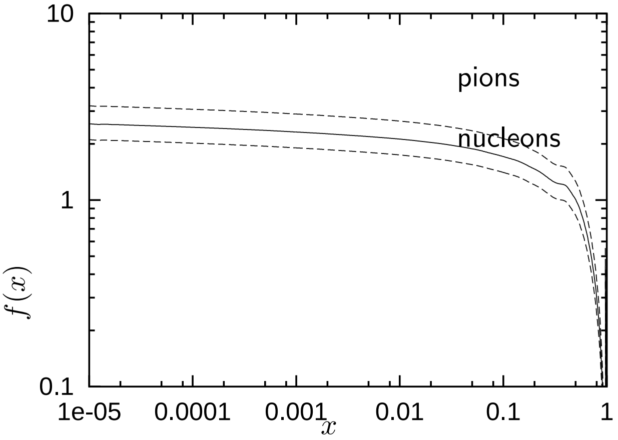


Pion-nucleon ratio:



[*Aloisio, Berezinsky, MK, '03*]

Photon-nucleon ratio:



[*Aloisio, Berezinsky, MK, '03*]

Summary

- AGASA excess as main motivation for top-down models is gone
- no positive evidence for superheavy dark matter from its two key signatures:
  - photons
  - galactic anisotropy
- SHDM remains an interesting DM candidate
- topological defects are generic prediction of (SUSY-) GUTs
- should be searched for as subdominant sources of UHECR