A multi-messenger approach to ultra-high energy cosmic ray sources

Ricard Tomàs

Astroparticle Physics Group

II. Institut für Theoretische Physik, Universität Hamburg

SFB676 Particles, Strings and the Early Universe
- the Structure of Matter and Space-Time -

February 15th, Desy, Zeuthen

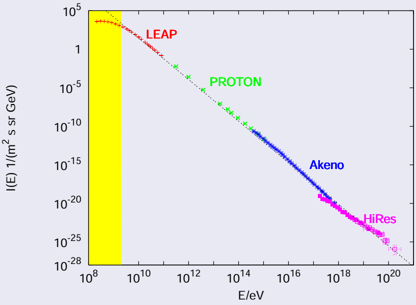
Outline

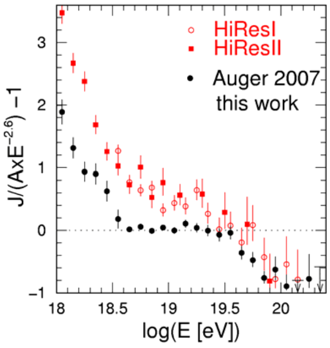
Outline

1. Introduction: Astronomy with
   - Ultra High Energy Cosmic Rays (UHECRs)
   - Gamma rays
   - Neutrinos
2. High Energy Neutrinos from Astrophysical Thick Sources
   - Neutrino yields
   - Neutrino flavor
3. Future Prospects
4. Summary

Introduction: Astronomy with UHECRs

Observation of Ultra High Energy Cosmic Rays (UHECRs)

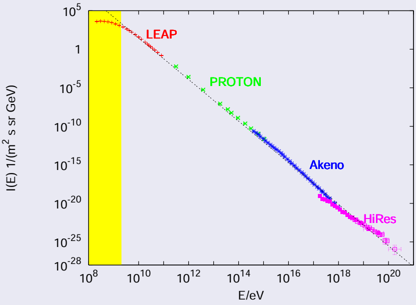


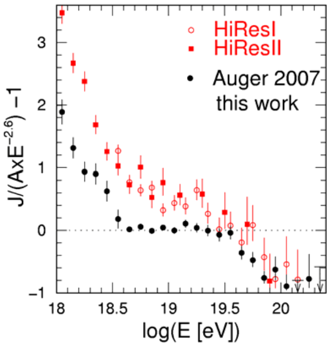


Question: where do they come from?

Introduction: Astronomy with UHECRs

Observation of Ultra High Energy Cosmic Rays (UHECRs)



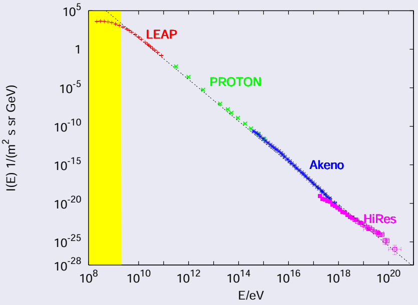


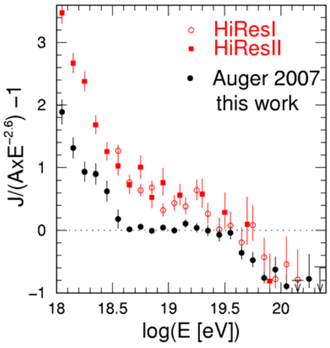
Question: where do they come from? ⇒ approaches

- top-down: decay of superheavy particles

Introduction: Astronomy with UHECRs

Observation of Ultra High Energy Cosmic Rays (UHECRs)





Question: where do they come from? ⇒ approaches

- top-down: decay of superheavy particles → disfavored
- bottom-up: accelerated in astrophysical sources → candidates?

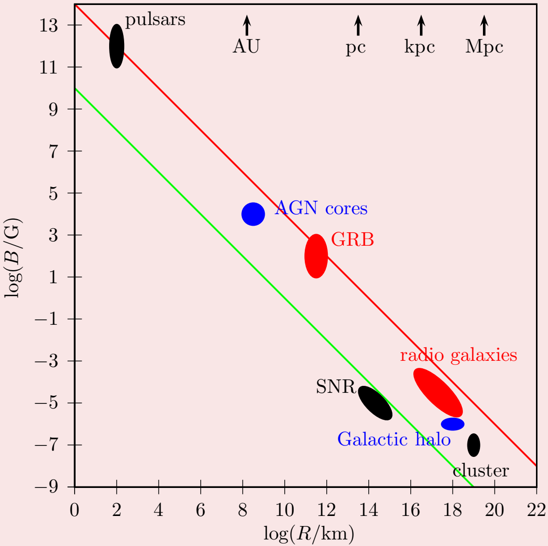
Introduction: Astronomy with UHECRs

Hillas plot

Larmor orbit inside accelerator size

$\Downarrow$

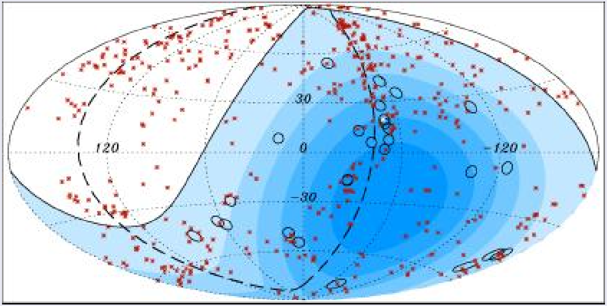
$E_{\mathrm{max}} = \Gamma Z e B R_s$



Introduction: Astronomy with UHECRs

Pierre Auger Observatory (PAO)

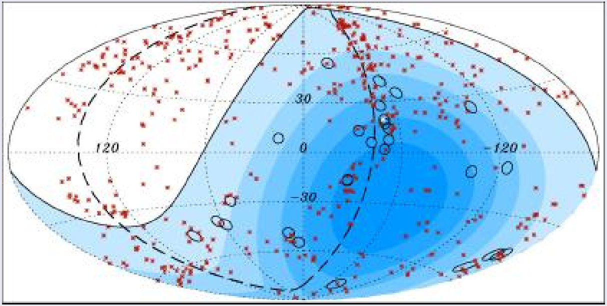
correlation: arrival UHECRs directions $\leftrightarrow$ positions of nearby AGN



Introduction: Astronomy with UHECRs

Pierre Auger Observatory (PAO)

correlation: arrival UHECRs directions ↔ positions of nearby AGN



However

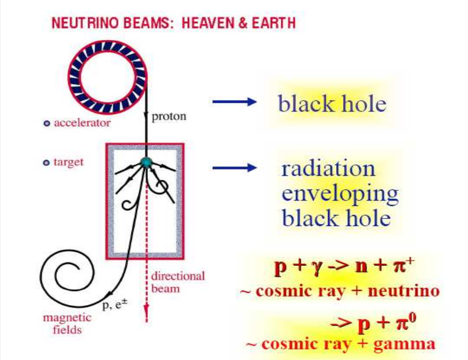
- results not confirmed
- UHECRs affected by not well-known magnetic fields

Outline

1. Introduction: Astronomy with
   - Ultra High Energy Cosmic Rays (UHECRs)
   - Gamma rays
   - Neutrinos
2. High Energy Neutrinos from Astrophysical Thick Sources
   - Neutrino yields
   - Neutrino flavor
3. Future Prospects
4. Summary

Introduction: Astronomy with Gamma rays

gamma-rays are expected together with UHECRs



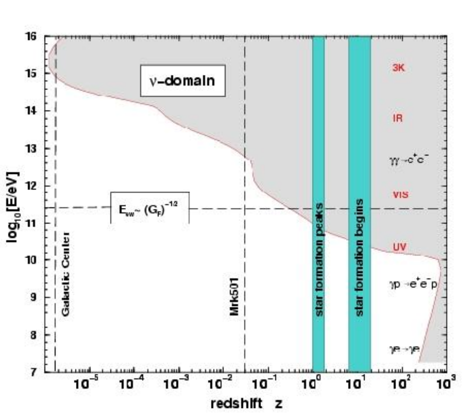
[F. Halzen]

- neutral particles ⇒ not affected by B ⇒ point back to the source

Introduction: Astronomy with Gamma rays

Problems

- universe is opaque to photons for E larger than hundreds of TeV



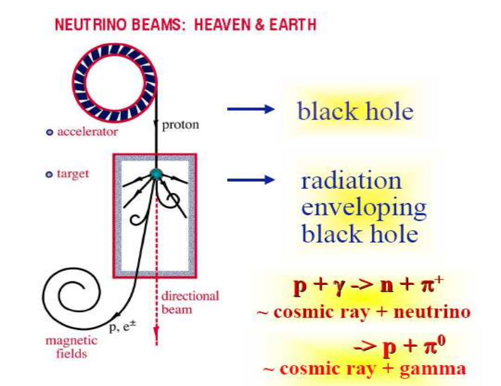
- Extragalactic Background Light can affect the measurement

Outline

1. Introduction: Astronomy with
   - Ultra High Energy Cosmic Rays (UHECRs)
   - Gamma rays
   - Neutrinos
2. High Energy Neutrinos from Astrophysical Thick Sources
   - Neutrino yields
   - Neutrino flavor
3. Future Prospects
4. Summary

Introduction: Astronomy with Neutrinos

HE neutrinos expected together with UHECRs



[F. Halzen]

Introduction: Astronomy with Neutrinos

HE neutrinos expected together with UHECRs

- neutral $\Longrightarrow$ not affected by magnetic fields $\Longrightarrow$ point directly to the source
- weakly interacting with matter $\rightarrow$: deep penetrating power
  - information from the edge of the Universe
  - information from the inner layers of astrophysical objects $\rightarrow$ internal dynamics (Sun, supernovae (SN), ...)
- *non-standard* properties: flavor mixing $\Rightarrow$ sensitive to the composition in the source

Introduction: Astronomy with Neutrinos

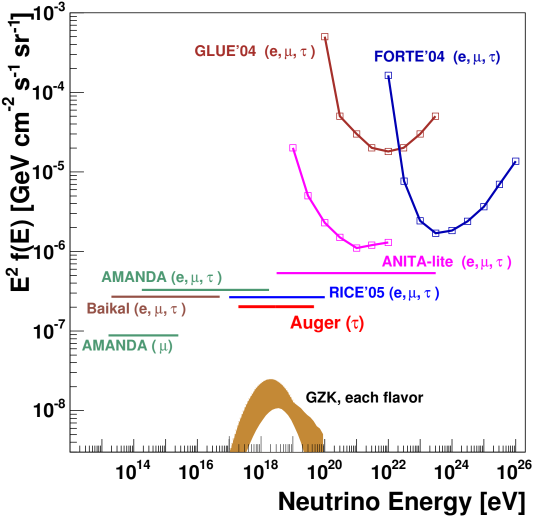
HE neutrinos expected together with UHECRs

- neutral $\Longrightarrow$ not affected by magnetic fields $\Longrightarrow$ point directly to the source
- weakly interacting with matter $\rightarrow$: deep penetrating power
  - information from the edge of the Universe
  - information from the inner layers of astrophysical objects $\rightarrow$ internal dynamics (Sun, supernovae (SN), ...)
- *non-standard* properties: flavor mixing $\Rightarrow$ sensitive to the composition in the source

Problem

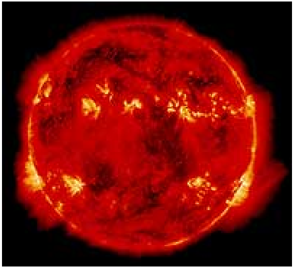
very hard to detect $\Rightarrow$ currently only upper bounds

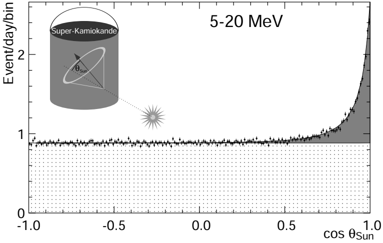
Introduction: Astronomy with Neutrinos



Examples

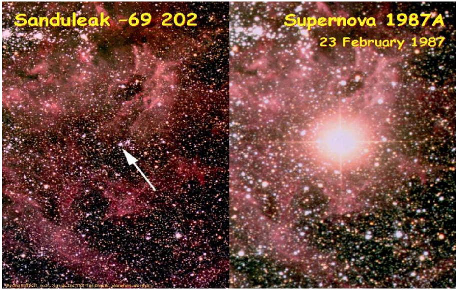
- Sun

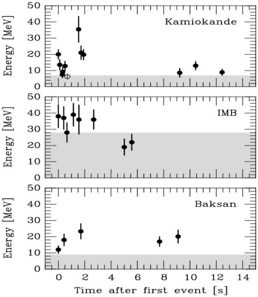




Examples

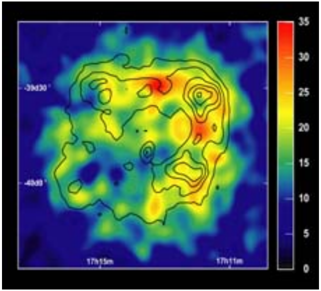
- Sun
- SN1987A





Examples

- Sun
- SN1987A
- SNR RX J1713.7-3946



Examples

- Sun
- SN1987A
- SNR RX J1713.7-3946
- cascade limit: EGRET bound on diffuse extragalactic γ-ray flux $\Rightarrow$ limit on the differential ν intensity

Examples

- Sun
- SN1987A
- SNR RX J1713.7-3946
- cascade limit: EGRET bound on diffuse extragalactic γ-ray flux $\Rightarrow$ limit on the differential ν intensity
- UHECRs limit: energy density injected by extragalactic sources $\longrightarrow$ bound on the diffuse ν flux (Waxmann, Bahcall)

Examples

- Sun
- SN1987A
- SNR RX J1713.7-3946
- cascade limit: EGRET bound on diffuse extragalactic γ-ray flux $\Rightarrow$ limit on the differential ν intensity
- UHECRs limit: energy density injected by extragalactic sources $\rightarrow$ bound on the diffuse ν flux (Waxmann, Bahcall)
- PAO observation on UHECRs from Cen A $\Rightarrow$ ν flux predicted

Astrophysical Thick Sources

Crucial point: UHECRs $\leftrightarrow$ gamma-rays $\leftrightarrow$ HE neutrinos

Assumption: transparent sources (interaction depth $\tau_0 \equiv R_s/l_{\rm int} \ll 1$)

$\downarrow$

what happens if this condition is not fulfilled?

... non-trivial relation among the different fluxes

- A) thick sources ($\tau_0 \gtrsim 1$)
- B) transparent sources with strong magnetic fields $\longrightarrow$ diffusion

  $\Rightarrow$ effective size of the source $R_{\rm eff}$ increases $\Rightarrow \tau_{\rm eff} \equiv R_{\rm eff}/l_{\rm int} \gtrsim 1$

Outline

Monte Carlo simulation

source: phenomenological characterization

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ $\longrightarrow (\alpha = 2,\ E_{\max} = 10^{24}$ eV$)$
- slab with
  - –protons
  - –thermal photons $\longrightarrow$
    - – size R_s
    - – temperature T
    - – magnetic field B

Monte Carlo simulation

source: phenomenological characterization

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ $\longrightarrow (\alpha = 2,\ E_{\max} = 10^{24}\ \mathrm{eV})$
- slab with $\begin{cases} -\text{protons} \\ -\text{thermal photons} \longrightarrow \begin{cases} -\ \text{size } R_s \\ -\ \text{temperature } T \\ -\ \text{magnetic field } B \end{cases} \end{cases}$

processes

- $p + \gamma \rightarrow$ secondary mesons $(\pi,\ K,\ \text{charm})$ $\begin{cases} -\ \text{decay} \rightarrow \text{HE } \nu's \\ \end{cases}$

Monte Carlo simulation

source: phenomenological characterization

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ $\longrightarrow (\alpha = 2,\ E_{\max} = 10^{24}$ eV$)$
- slab with $\left\{ \begin{array}{l} -\text{protons} \\ -\text{thermal photons} \longrightarrow \left\{ \begin{array}{l} -\text{ size } R_s \\ -\text{ temperature } T \\ -\text{ magnetic field } B \end{array} \right. \end{array} \right.$

processes

- $p + \gamma \rightarrow$ secondary mesons (π, K, charm) $\left\{ \begin{array}{l} -\text{ decay} \rightarrow \text{HE } \nu' s \\ -\text{ meson} + \gamma \end{array} \right.$

extended version of SOPHIA [A. Mücke *et al.*, 2000], HERWIG [G. Corcella *et al.*, 2001]

Monte Carlo simulation

source: phenomenological characterization

- injected protons $\mathrm{d}N/\mathrm{d}E \propto E^{-\alpha}$ $\longrightarrow (\alpha = 2,\ E_{\max} = 10^{24}$ eV)
- slab with
  - −protons
  - −thermal photons $\longrightarrow$
    - − size R_s
    - − temperature T
    - − magnetic field B

processes

- $p + \gamma \rightarrow$ secondary mesons (π, K, charm)
  - − decay $\rightarrow$ HE $\nu's$
  - − meson $+ \gamma$

extended version of SOPHIA [A. Mücke *et al.*, 2000], HERWIG [G. Corcella *et al.*, 2001]

- synchrotron radiation
- e^+e^- pair production
- inverse Compton scattering
- diffusion due to turbulent magnetic field

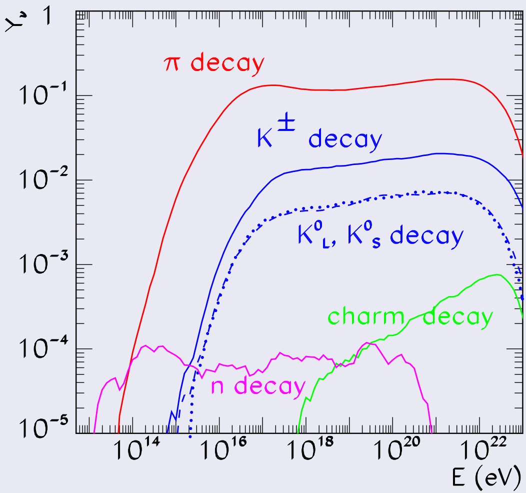
Neutrino Yields: transparent source

Neutrino Yield Y_ν

$$Y_\nu(E) = \frac{\phi_\nu(E)}{p_{\rm int}\phi_p(E)}$$

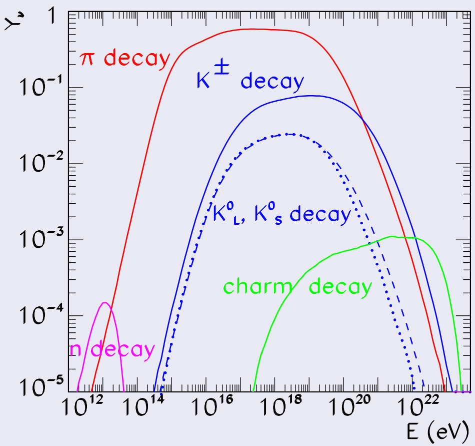
- ν's from π decay dominates
- above $E_{\rm th}$ no dependence on energy

Source at $T = 10^4$ K and $\tau_0 = 0.1$



Neutrino Yields: A) thick source

Source at $T = 10^4$ K and $\tau_0 = 10^2$



[M. Kachelrieß and R. T., 2006]

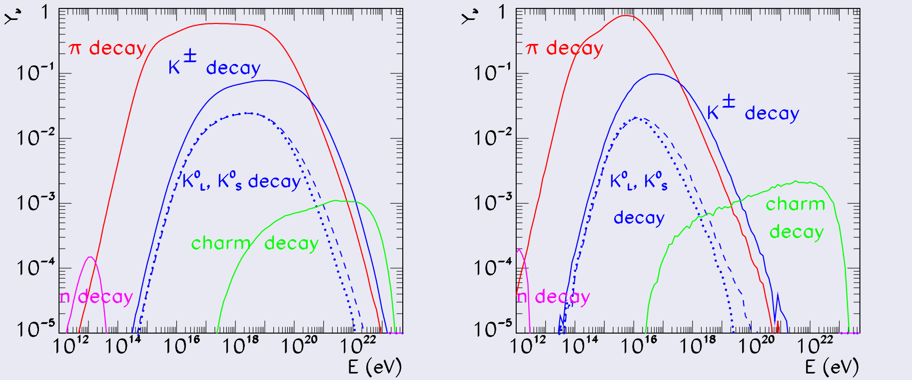
multiple scattering $\Rightarrow \nu$ flux

- Low En.: more mesons produced $\Rightarrow$ increase
- High En.: mesons scatter before decaying $\Rightarrow$ suppression
- composition depends on energy:
  - Low: π decay
  - Intermediate: K decay
  - High: charm mesons decay

Neutrino Yields: A) thick source

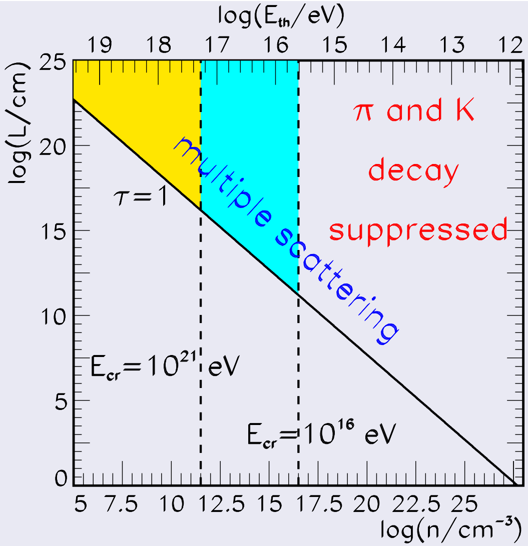
Source with $\tau_0 = 10^2$ at $T = 10^4$ K and $T = 10^5$ K

[M. Kachelrieß and R. T., 2006]

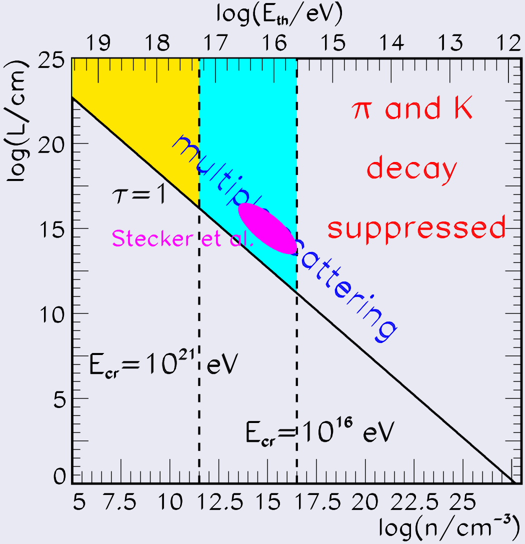


suppression at HE strongly depends on the medium density

Thick sources: conditions for large HE ν fluxes

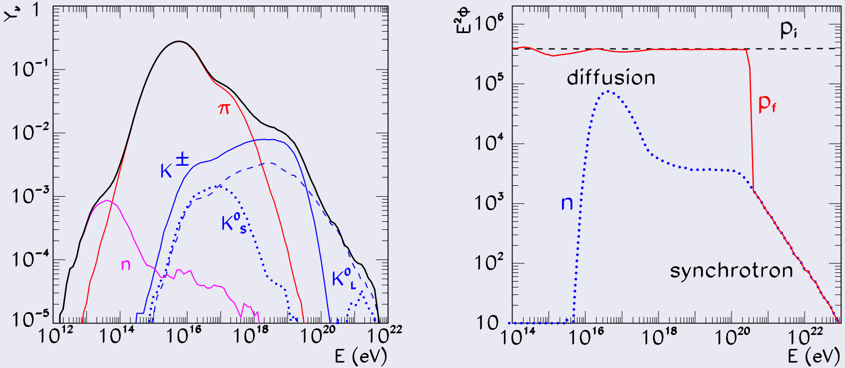


Thick sources: conditions for large HE ν fluxes



Neutrino Yields: B) transparent source with B

Source at $T = 10^4$ K, $\tau_0 = 0.1$, and $B = 10^2$ G [M. Kachelrieß, S. Ostapchenko, R. T., 2007]



magnetic field

- at HE: synchrotron losses dominate $\Rightarrow$ suppression of HE ν flux
- at LE: diffusion $\Rightarrow$ $\tau_{\rm eff}$ increases $\Rightarrow$ bump of π and n neutrinos

Outline

Flavor content $(\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$

Motivation

- *measurable* in ν telescopes and extensive air shower experiments

  [J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003, D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000]

Flavor content $(\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$

Motivation

- *measurable* in ν telescopes and extensive air shower experiments

  [J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003, D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000]
- interesting applications
  - astrophysical diagnostics: characterize sources

    [L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, 2005, T. Kashti and E. Waxman, 2005]
  - learn about ν properties [H. Athar, M. Jezabek and O. Yasuda, 2000, P. Bhattacharjee and N. Gupta, 2005, P. D. Serpico and M. Kachelrieß, 2005, J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, 2002, W. Winter, 2006, W. Rodejohann, 2007, S. Pakvasa, W. Rodejohann, and T. Weiler, 2007]

Flavor content $(\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$

Motivation

- *measurable* in ν telescopes and extensive air shower experiments

  [J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003, D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000]
- interesting applications
  - astrophysical diagnostics: characterize sources

    [L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, 2005, T. Kashti and E. Waxman, 2005]
  - learn about ν properties [H. Athar, M. Jezabek and O. Yasuda, 2000, P. Bhattacharjee and N. Gupta, 2005, P. D. Serpico and M. Kachelrieß, 2005, J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, 2002, W. Winter, 2006, W. Rodejohann, 2007, S. Pakvasa, W. Rodejohann, and T. Weiler, 2007]

Example

- pion decay $\rightarrow$ (1,2,0)
- neutron beam source $\rightarrow$ (1,0,0) [L. A. Anchordoqui *et al.*, 2003, P. D. Serpico and M. Kachelrieß, 2005]
- muon-damped ν_μ sources from π decay $\rightarrow$ (0,1,0) [T. Kashti and E. Waxman, 2005]

Flavor content $(\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$

Motivation

- *measurable* in ν telescopes and extensive air shower experiments

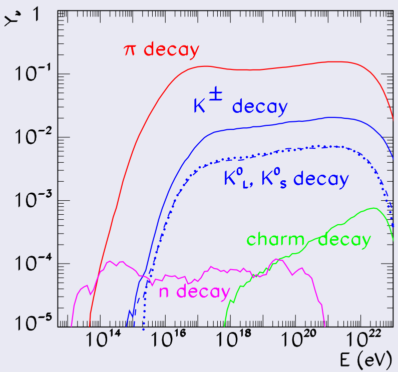
  [J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler, 2003, D. Fargion, 1997, S. I. Dutta, M. H. Reno and I. Sarcevic, 2000]
- interesting applications
  - astrophysical diagnostics: characterize sources

    [L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, 2005, T. Kashti and E. Waxman, 2005]
  - learn about ν properties [H. Athar, M. Jezabek and O. Yasuda, 2000, P. Bhattacharjee and N. Gupta, 2005, P. D. Serpico and M. Kachelrieß, 2005, J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler, 2002, W. Winter, 2006, W. Rodejohann, 2007, S. Pakvasa, W. Rodejohann, and T. Weiler, 2007]

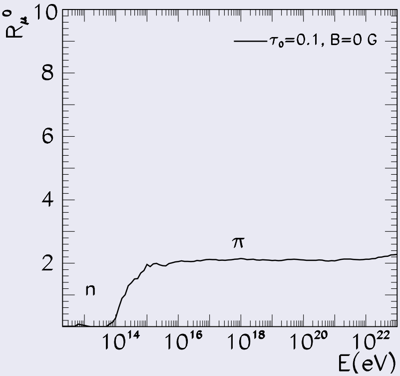
Example

- pion decay $\rightarrow$ (1,2,0)
- neutron beam source $\rightarrow$ (1,0,0) [L. A. Anchordoqui *et al.*, 2003, P. D. Serpico and M. Kachelrieß, 2005]
- muon-damped ν_μ sources from π decay $\rightarrow$ (0,1,0) [T. Kashti and E. Waxman, 2005]
- non transparent sources $\rightarrow (\phi_{\nu_e}, \phi_{\nu_\mu}, \phi_{\nu_\tau})$?

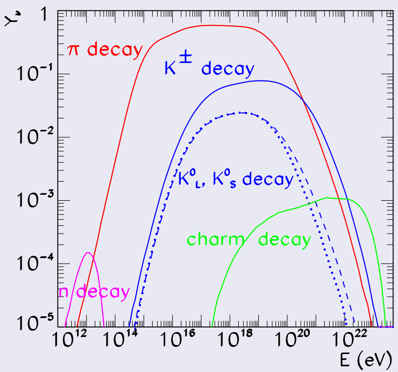
Flavor ratio $R_\mu \equiv \phi_{\nu_\mu}/(\phi_{\nu_e} + \phi_{\nu_\tau})$



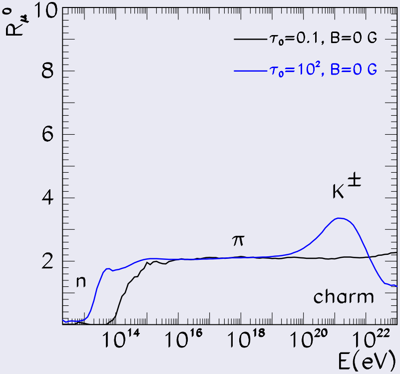
source



Flavor ratio $R_\mu \equiv \phi_{\nu_\mu}/(\phi_{\nu_e} + \phi_{\nu_\tau})$

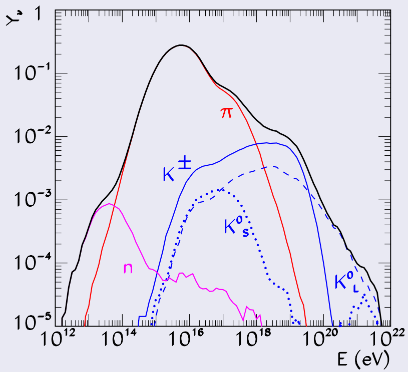


source

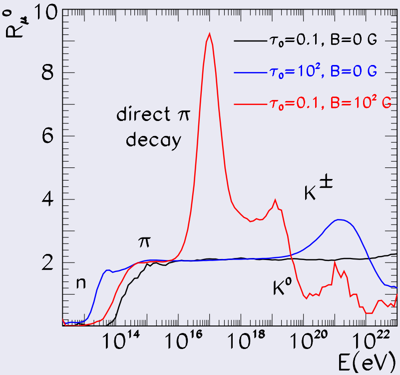


- different contributions to $\phi_\nu \Rightarrow$ strong energy dependence of R^0_μ

Flavor ratio $R_\mu \equiv \phi_{\nu_\mu}/(\phi_{\nu_e} + \phi_{\nu_\tau})$



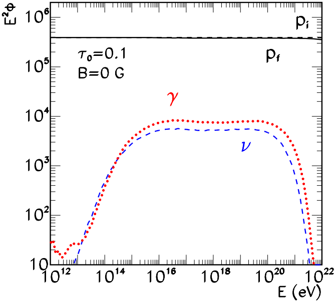
source

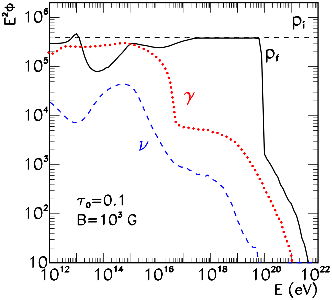


- different contributions to $\phi_\nu \Rightarrow$ strong energy dependence of R^0_μ

Future Prospects

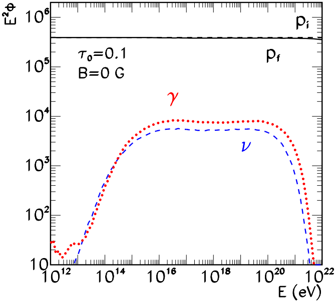
- Consider more realistic models for the sources
  - include photons into the analysis (preliminar results)

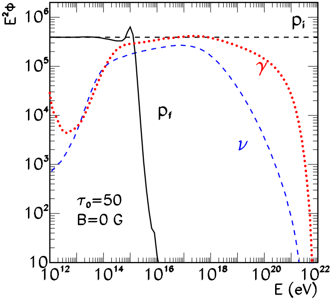




Future Prospects

- Consider more realistic models for the sources
  - include photons into the analysis (preliminar results)





Future Prospects

- Consider more realistic models for the sources
- Analyze not only the source but particle propagation after they leave
  - distribution of sources
  - extragalactic magnetic fields

  $\longrightarrow$ CRPropa code (Armengaud, Sigl, Beau, and Miniati) (http://apcauger.in2p3.fr/CRPropa/index.php)
- Include the different detectors

Final goal: constrain models + make predictions

Summary

- multimessenger approach required to identify and understand the UHECRs sources
- key ingredient: relationship between the expected fluxes of UHECRs, gamma rays and neutrinos

$$\downarrow$$

transparent sources ok, but for thick sources the connection is more involved

- we have developed a code to study the relationship between UHECRs and neutrinos for phenomenologically characterized thick sources
- future: more realistic models of sources (include photons) + propagation in the Universe + different detectors $\longrightarrow$ constrain models

P. D. Serpico and M. Kachelrieß
Phys. Rev. Lett. **94** (2005) 211102.

M. C. Gonzalez-Garcia, F. Halzen and M. Maltoni,
Phys. Rev. D **71** (2005) 093010.

B. Eberle, A. Ringwald, L. Song and T. Weiler
Phys. Rev. D **70**, 023007 (2004).

E. Waxman and J. N. Bahcall,
Phys. Rev. D **59** (1999) 023002.

F. Stecker, C. Done, M. Salamon and P. Sommers
Phys. Rev. Lett. **66**, 2697 (1991); **69**, 2738(E) (1992).

V. S. Berezinsky and V. I. Dokuchaev
Astropart. Phys. **15**, 87 (2001).

V. S. Berezinsky and V. L Ginzburg
Mon. Not. R. Astron. Soc. **194**, 3 (1987).

V. S. Berezinsky and A. Z. Gazizov,
Phys. Rev. D **47** (1993) 4206.

V. S. Berezinsky and V. V. Volynsky,
Proc. 16th Int. Cosmic Ray Conf. (Kyoto, 1979)

V. Berezinsky, A. Gazizov and S. Grigorieva,
Nucl. Phys. Proc. Suppl. **136** (2004) 147

A. Mucke, R. Engel, J. P. Rachen, R. J. Protheroe and T. Stanev,
Comput. Phys. Commun. **124** (2000) 290

G. Corcella *et al.*,
JHEP **0101** (2001) 010.

R. Aloisio, V. Berezinsky and M. Kachelrieß,
Phys. Rev. D **69** 094023 (2004).

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa and T. J. Weiler,
Phys. Rev. D **68** (2003) 093005
[Erratum-ibid. D **72** (2005) 019901].

D. Fargion,
arXiv:astro-ph/9704205.

S. I. Dutta, M. H. Reno and I. Sarcevic,
Phys. Rev. D **62** (2000) 123001.

- L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, Phys. Lett. B **621** (2005) 18 .
- T. Kashti and E. Waxman, Phys. Rev. Lett. **95** (2005) 181101.
- H. Athar, M. Jezabek and O. Yasuda, Phys. Rev. D **62** (2000) 103007.
- G. Barenboim and C. Quigg, Phys. Rev. D **67** (2003) 073024
- P. D. Serpico and M. Kachelrieß, Phys. Rev. Lett. **94** (2005) 211102.
- G. G. Raffelt, 1996.
- R. C. Schirato, G. M. Fuller, (. U. (. LANL), UCSD and LANL), arXiv:astro-ph/0205390.
- P. Bhattacharjee and N. Gupta, asXiv:hep-ph/0501191.
- P. Serpico,

Phys. Rev. D **73** (2006) 047301

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler,
Phys. Rev. Lett. **90** (2003) 181301.

J. F. Beacom, N. F. Bell, D. Hooper, S. Pakvasa, and T. J. Weiler,
Phys. Rev. Lett. **90** (2003) 181301.

G. Barenboim and C. Quigg,
Phys. Rev. D **67** (2003) 073024.

W. Winter,
hep-ph/0604191.

L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler,
Phys. Lett. B **593**, 42 (2004) .

J. P. Rachen and P. Meszaros,
Phys. Rev. D **58** (1998) 123005.

M. Ahlers, L. A. Anchordoqui, H. Goldberg, F. Halzen, A. Ringwald, and Th. J. Weiler, 2005
Phys. Rev. D **72** (2005) 023001.

A. M. Hillas,

Annual review of astronomy and astrophysics. Volume 22. Palo Alto, CA, Annual Reviews, Inc., 1984, p. 425-444.

P. Lipari,
arXiv:astro-ph/0605535.

D. Meloni and T. Ohlsson, 2006
hep-ph/0612279

W. Rodejoahnn,
JCAP01 (2007)029.

M. Kachelrieß and R. Tomàs, "High energy neutrino yields from astrophysical sources. I: Weakly magnetized sources," Phys. Rev. D **74** (2006) 063009 [arXiv:astro-ph/0606406].

:. M. Ackermann [The IceCube Collaboration], arXiv:0711.3022 [astro-ph].

M. Kachelrieß, S. Ostapchenko and R. Tomàs, “High energy neutrino yields from astrophysical sources II: Magnetized sources,” arXiv:0708.3047 [astro-ph].

O. B. Bigas and f. t. P. Collaboration, arXiv:0706.1658 [astro-ph].

L. A. Anchordoqui, H. Goldberg, F. Halzen and T. J. Weiler, Phys. Lett. B **600** (2004) 202 [arXiv:astro-ph/0404387].

A. Cuoco and S. Hannestad, arXiv:0712.1830 [astro-ph].