The Universal Prior to Extragalactic Cosmic Ray Production

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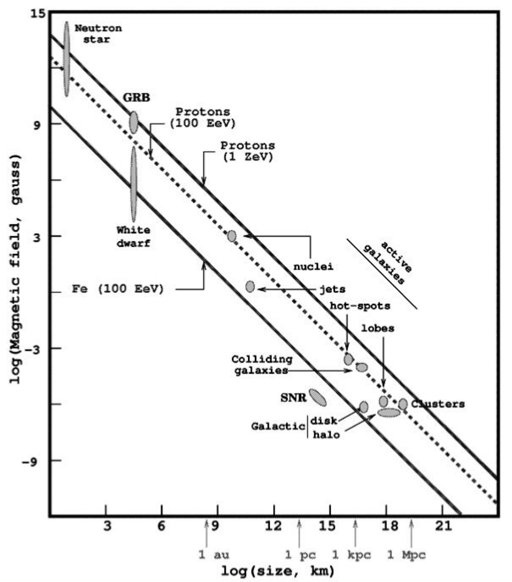
28$^{\text{th}}$ Texas Symposium on Relativistic Astrophysics
Geneva, 13-18 December 2015

The Hillas Plot: 10^{20} eV everywhere! Why?

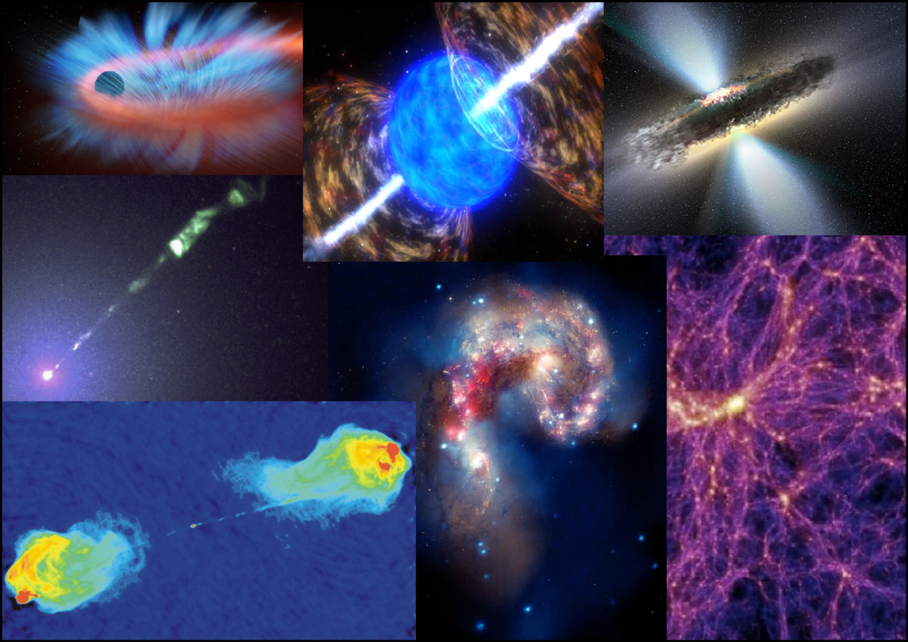


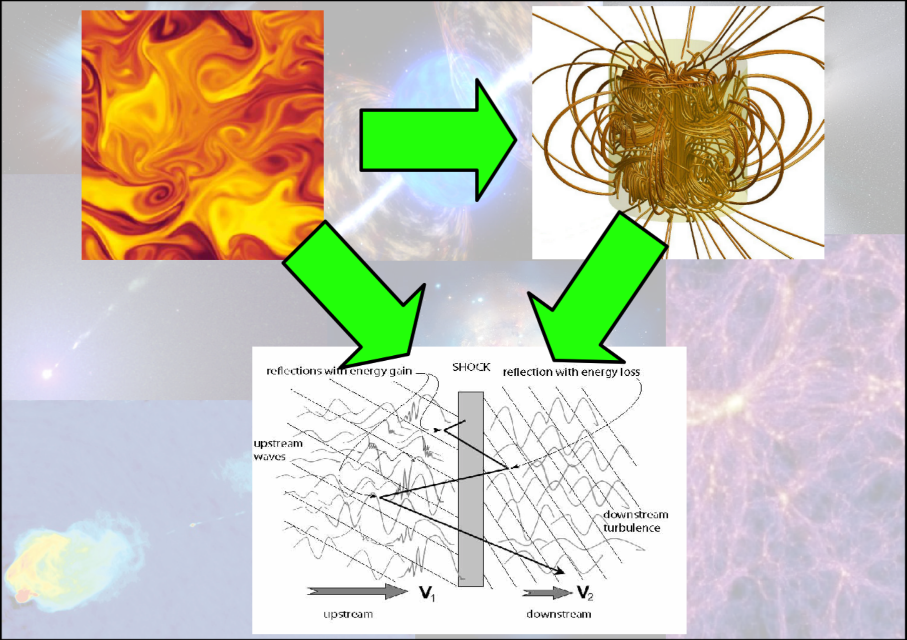
Over almost 20 orders of magnitude:

$$E_{\mathrm{H}} \equiv \left[ZeBR\right]_{\mathrm{objects}} \sim (10\text{--}100)\, Z\, \mathrm{EeV}$$

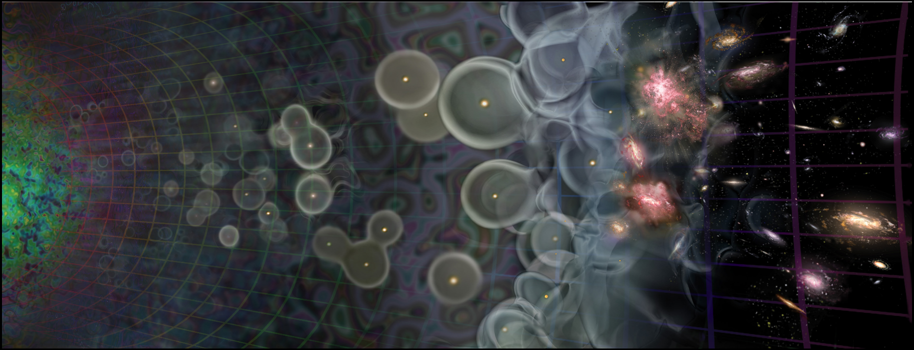
$$\Psi_{\mathrm{W}} \sim 3\times10^{45}\,\frac{\mathrm{erg}}{\mathrm{Mpc}^3\,\mathrm{Yr}}$$

Why?




reflections with energy gain
SHOCK
reflection with energy loss
upstream waves
downstream turbulence
V_1
V_2
upstream
downstream

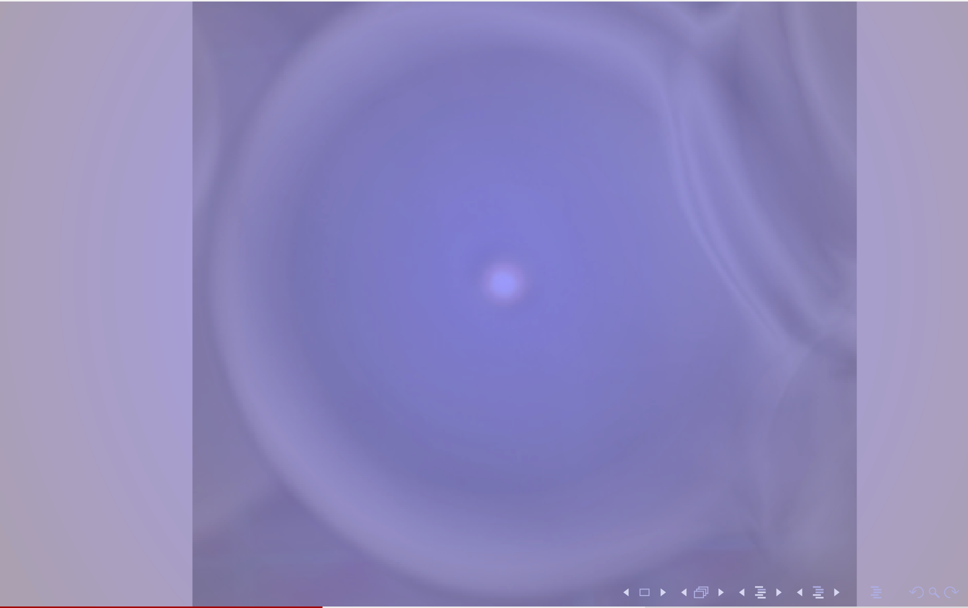
Scale-free processes: Gravity grooves!



$$\left[\frac{dn(M)}{dM}\right]_{\rm PSt} = \frac{\rho_c \Omega_m}{M^2\sqrt{\pi}}\sqrt{\frac{M}{M_*}} \qquad \text{for} \quad M < M_*$$

Press & Schechter, 1974

Energetics of the Universe



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$$\rho_{m/b} = \frac{M_{m/b}}{V} = \frac{3H_0^2\Omega_{m/b}}{8\pi G}$$

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$$E_{\mathrm{G}} = \frac{3}{10} M_m c^2$$

$$E_{\mathrm{nuc}} \approx \frac{\langle b \rangle}{m_p} M_b$$

$\Uparrow$ $\Uparrow$

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$\Downarrow$ **5% in stars**

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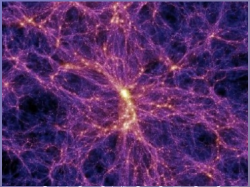
$\Leftarrow$



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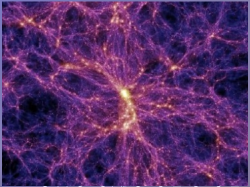

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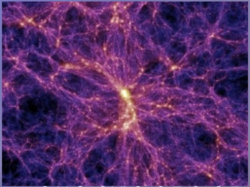
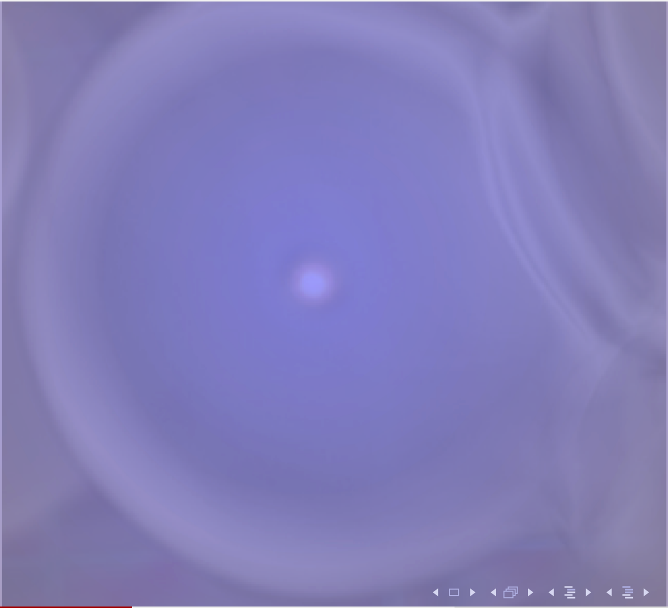


Scale-free production of non-thermal energy



Scale-free production of non-thermal energy

Gravitational potential energy density converted to magnetic energy density

$$\frac{B_r^2}{8\pi} = \xi \left[r \frac{d}{dr} \frac{3 U_\mathrm{G}}{4\pi r^3} \right]_{r=\sigma R_\mathrm{S}} = \frac{9c^4}{400\pi G} \frac{\xi}{\sigma^2} \frac{1}{r^2}$$

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Total nonthermal energy integrated over hirachical clustering

$$\Psi_{\rm nth} \gtrsim H_0 \int_0^{M_*} dM \left[\frac{3c^2}{50}\,\frac{\xi}{\sigma}\,M\right]\left[\frac{dn(M)}{dM}\right]_{\rm PSt} \simeq 4\times10^{-3}\,\frac{\xi}{\sigma}\,\frac{H_0^3 c^2 \Omega_m}{G}$$

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Efficiency

$$\xi = \xi_\mathrm{nth}\, f_\mathrm{gas}\,\frac{\Omega_b}{\Omega_m} \lesssim 10^{-2}$$

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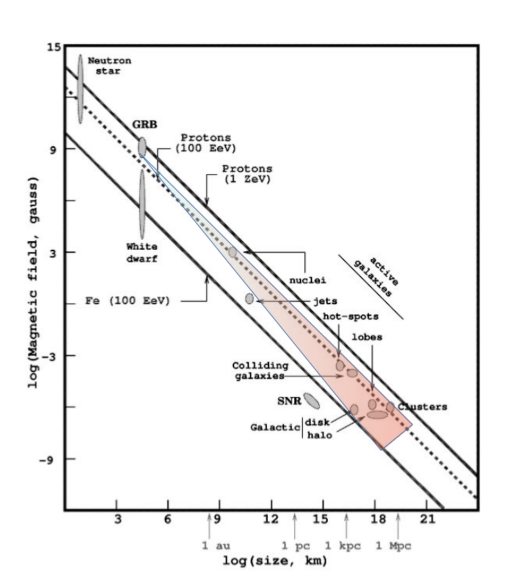
Efficiency and Scaling

$$\xi = \xi_{\rm nth}\, f_{\rm gas}\,\frac{\Omega_b}{\Omega_m} \lesssim 10^{-2} \qquad \frac{d\Psi_{\rm nth}}{d\ln r} \propto r^{1/2}$$

The Hillas Plot: Explained and understood!



$$E_{\rm H} \sim \left[ZeB_r r\right]_{\rm cosmology}$$

$$\Psi_{\rm nth} \gtrsim \Psi_{\rm W}$$

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Particle acceleration

No losses

$$\hat{E} \lesssim \beta E_{\rm H} \qquad (D = \tfrac{1}{3} r_{\rm g} c)$$

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$$\tau_{\mathrm{a}} \sim \frac{3}{\beta^2} \frac{E}{eBc} \lesssim \tau_{\mathrm{loss}}$$

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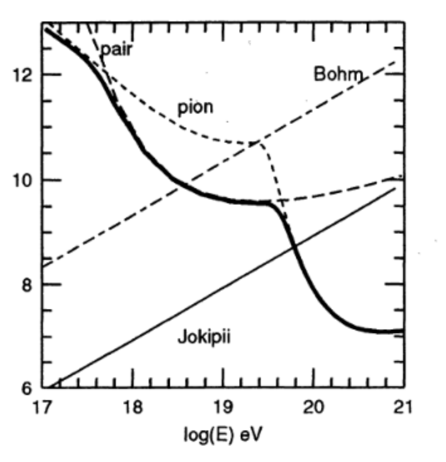
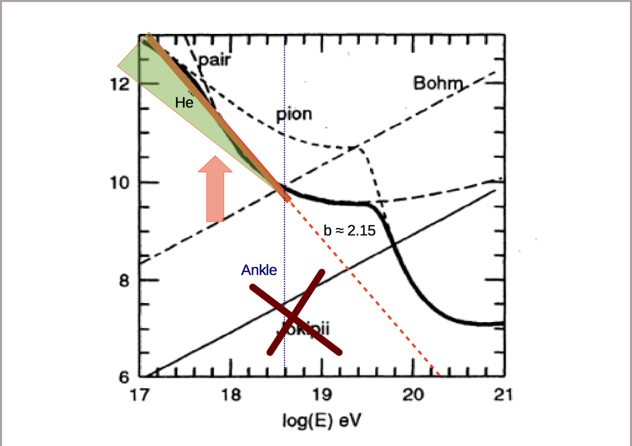
Contributions to the cosmic ray flux above the ankle: clusters of galaxies

Hyesung Kang,[1★†] Jörg P. Rachen[2★] and Peter L. Biermann[2★]
[1]Department of Earth Sciences, Pusan National University, Pusan 609-735, Korea
[2]Max-Planck-Institut für Radioastronomie, D-53010 Bonn, Germany



Contributions to the cosmic ray flux **below** the ankle: clusters of galaxies **!!**



Basic model and analytical approximation

Cosmological integral over source function

$$N_i(E) = \int_0^{\hat{z}_i(E)} dz\, \frac{\Psi_i(E[1+z])(1+z)^m}{\mathcal{E}(z)} = N_{i,0}\,(E/E_0)^{-a}\, f_\mu(E/\hat{E}_i)$$

$$\text{with} \quad \mathcal{E}(z) = \Omega_m(1+z)^3 + \Omega_\Lambda \approx \tfrac{1}{3}(1+z)^3 + \tfrac{2}{3}\,, \; \mu \equiv 1 + m - a$$

$$\text{and} \quad \hat{z}_i(E) = (E/\hat{E}_i)^{-k} - 1\,, \quad k = \tfrac{1+b}{4+2b} \approx 0.38\,, \quad m = -1, 0, 1$$

Analytical approximation for cutoff function

$$f_\mu(y_i) = \tfrac{1}{\mu\sqrt{2}} \Big[y_i^{-k\mu}\, {}_2F_1\big(\tfrac{1}{2}, \tfrac{\mu}{3};\, 1+\tfrac{\mu}{3};\, -\tfrac{1}{2} y_i^{-3k}\big) - {}_2F_1\big(\tfrac{1}{2}, \tfrac{\mu}{3};\, 1+\tfrac{\mu}{3};\, -\tfrac{1}{2}\big) \Big] \quad (y_i \equiv E/\hat{E}_i\,,\ \mu < 0)$$

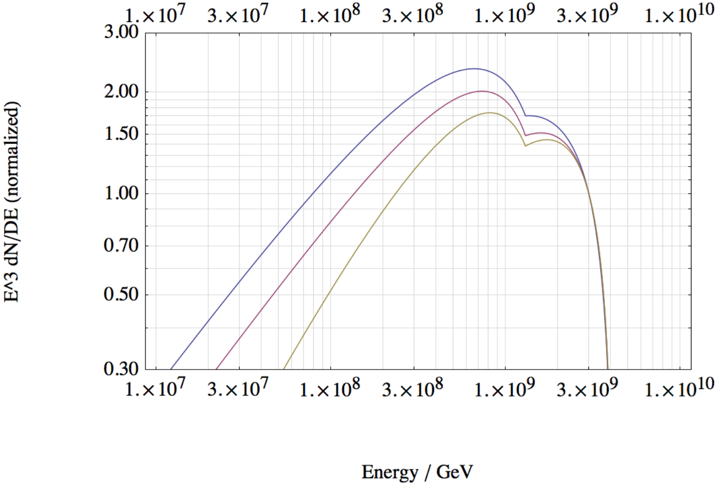
$$f_0(y_i) = \tfrac{\sqrt{2}}{3} \Big[\coth^{-1}\sqrt{\tfrac{3}{2}} - \coth^{-1}\sqrt{1 + \tfrac{1}{2} y_i^{-3k}} \Big]$$

Abundances

$$N_{i,0}/N_{p,0} = (Y_{p,i}/Y_{p,p})\, Z_i^{a-1} \rightsquigarrow \quad N_{\mathrm{He}}/N_p \approx 0.315 \times 2^{a-1}\,, \quad N_i \simeq 0 \ \text{else}$$

$$\hat{E}_i/\hat{E}_p \approx \sqrt[1+b]{Z_i^3/A_i^{1-b}} \rightsquigarrow \quad \hat{E}_{\mathrm{He}}/\hat{E}_p \approx 3.2$$

Spectrum and composition of cluster VHECR



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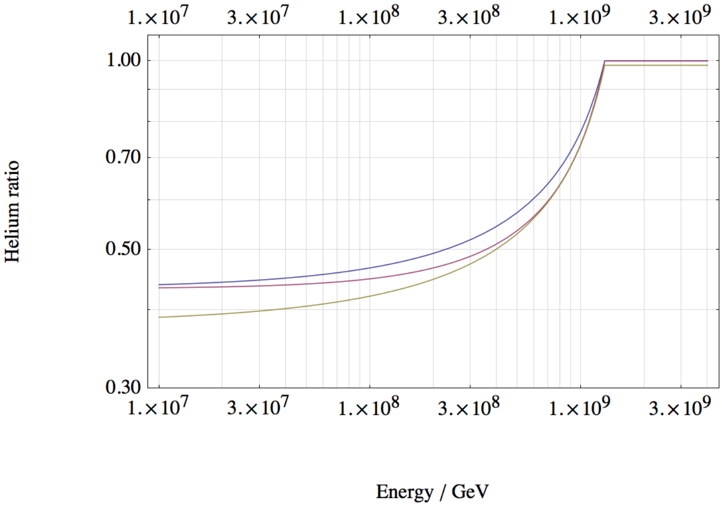

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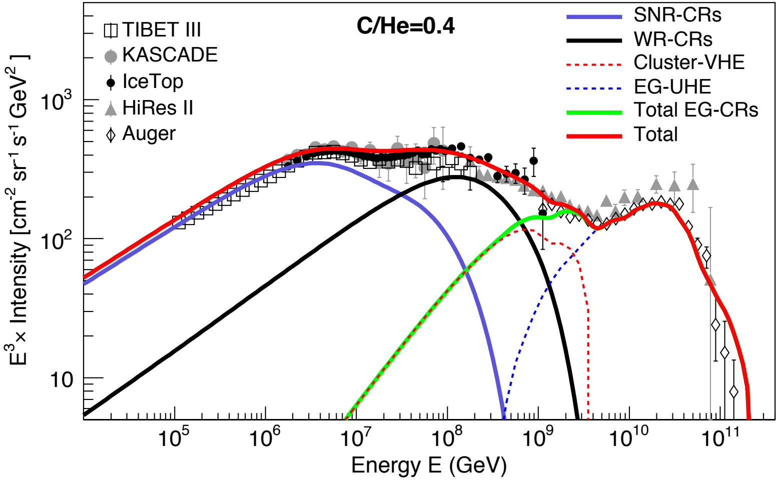

PRELIMINARY — provided by Satyendra Thoudam

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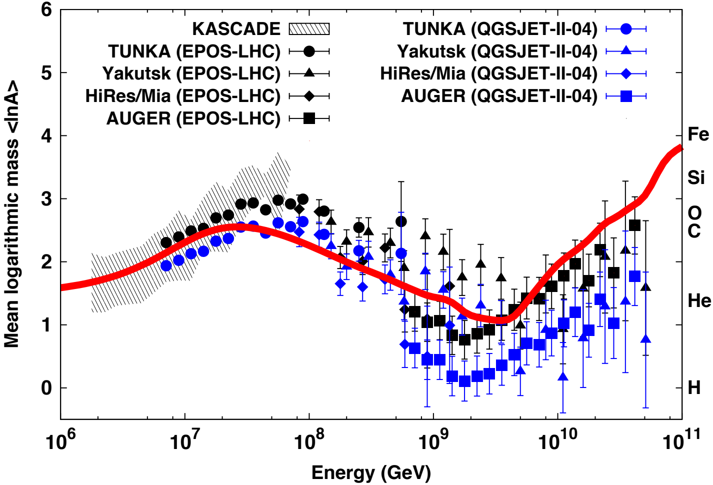

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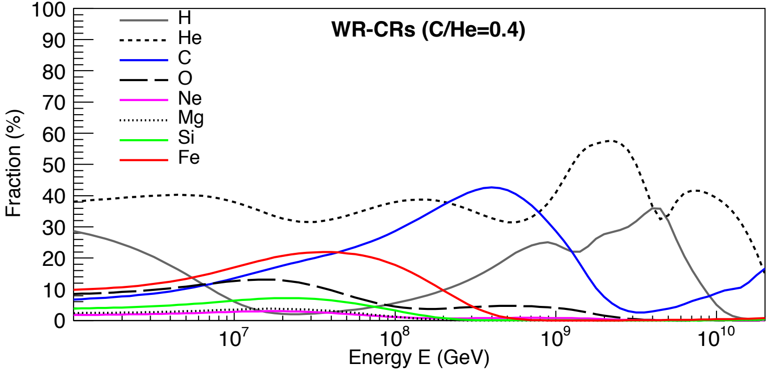

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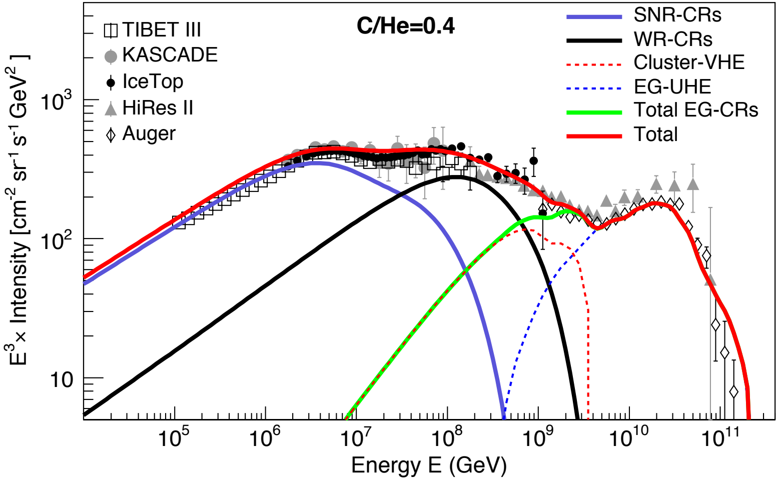
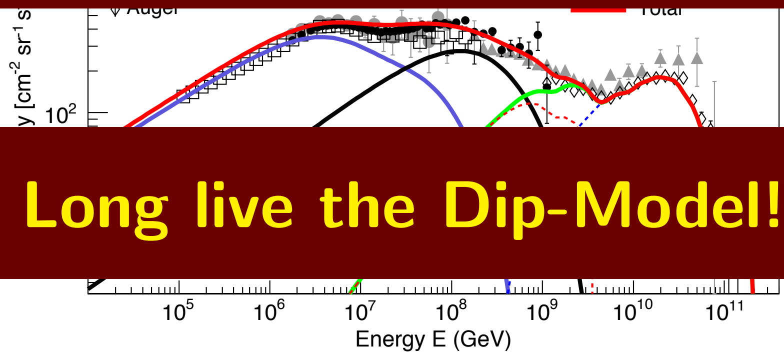


Spectrum and composition of cluster VHECR

The Dip-Model is dead!



Long live the Dip-Model!

Coming up ...

Radio detections of cosmic rays reveal a strong light mass component at 10^{17} - $10^{17.5}$ eV

S. Buitink[1,2], A. Corstanje[2], H. Falcke[2,3,4,5], J. R. Hörandel[2,4], T. Huege[6], A. Nelles[2,7], J. P. Rachen[2], L. Rossetto[2], P .Schellart[2], O. Scholten[8,9], S. ter Veen[3], S. Thoudam[2], T. N. G. Trinh[8], J. Anderson[10],

to be published in Nature, expected January 2016

Study of the energy spectrum and composition of cosmic rays up to the highest energies

S. Thoudam[1,2,⋆], A. van Vliet[1], A. Achterberg[1], S. Buitink[3], H. Falcke[1,4,5], J.R. Hörandel[1,4], J.P. Rachen[1]

[1] Department of Astrophysics, IMAPP, Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, The Netherlands
[2] Now at: Department of Physics and Electrical Engineering, Linnéuniversitetet, 35195 Växjö, Sweden
[3] Astronomical Institute, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels, Belgium
[4] NIKHEF, Science Park Amsterdam, 1098 XG Amsterdam, The Netherlands
[5] ASTRON, Postbus 2, 7990 AA Dwingeloo, The Netherlands

to be submitted January 2016

The Message of the Story

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  - **Possible explanation for PeV electron neutrinos due to photodisintegration of helium (tbd)**

Thanks!

Bayesian Modeling of the Galactic Magnetic Field using ground and space-based radio to sub-millimetre and ultra-high energy cosmic ray data

INTERNATIONAL SPACE SCIENCE INSTITUTE

Torsten Enßlin, Glennys Farrar, Diego Harari, Marijke Haverkorn, Jörg Hörandel, Tess Jaffe, Jans Jasche, Natalia Nowak, Niels Oppermann, Katarzyna Otmianowska-Mazur, Christoph Pfrommer, Jörg Paul Rachen (coordinator), **Anvar Shukurov, Theo Steininger, Xiaohui Sun, Robert Tautz, Michael Unger, Arjen van Vliet;** with contributions by **Nafiun Awal, Dieter Breitschwerdt, Günter Sigl, Todor Stanev, Andy Strong;** Bern, Switzerland, 2014-2016.