Cosmic Ray Airshowers and small-x QCD

Adrian Dumitru, ITP, Frankfurt University, 2005 CTEQ summer school

Collaborators: H.J. Drescher and M. Strikman

- Cosmic Rays
- Airshowers
- QCD input, small x, high gluon density

History of Cosmic Rays

(see www.auger.org)

1912 Hess discovered cosmic rays in hot air balloon

1929 Cosmic rays seen in cloud chamber

1932 Debate over cosmic rays

1933 Discovery of antiparticles (positron)

1937 Discovery of the muon

1938 Pierre Auger discovers extensive air showers

1949 Fermi's theory of cosmic ray acceleration

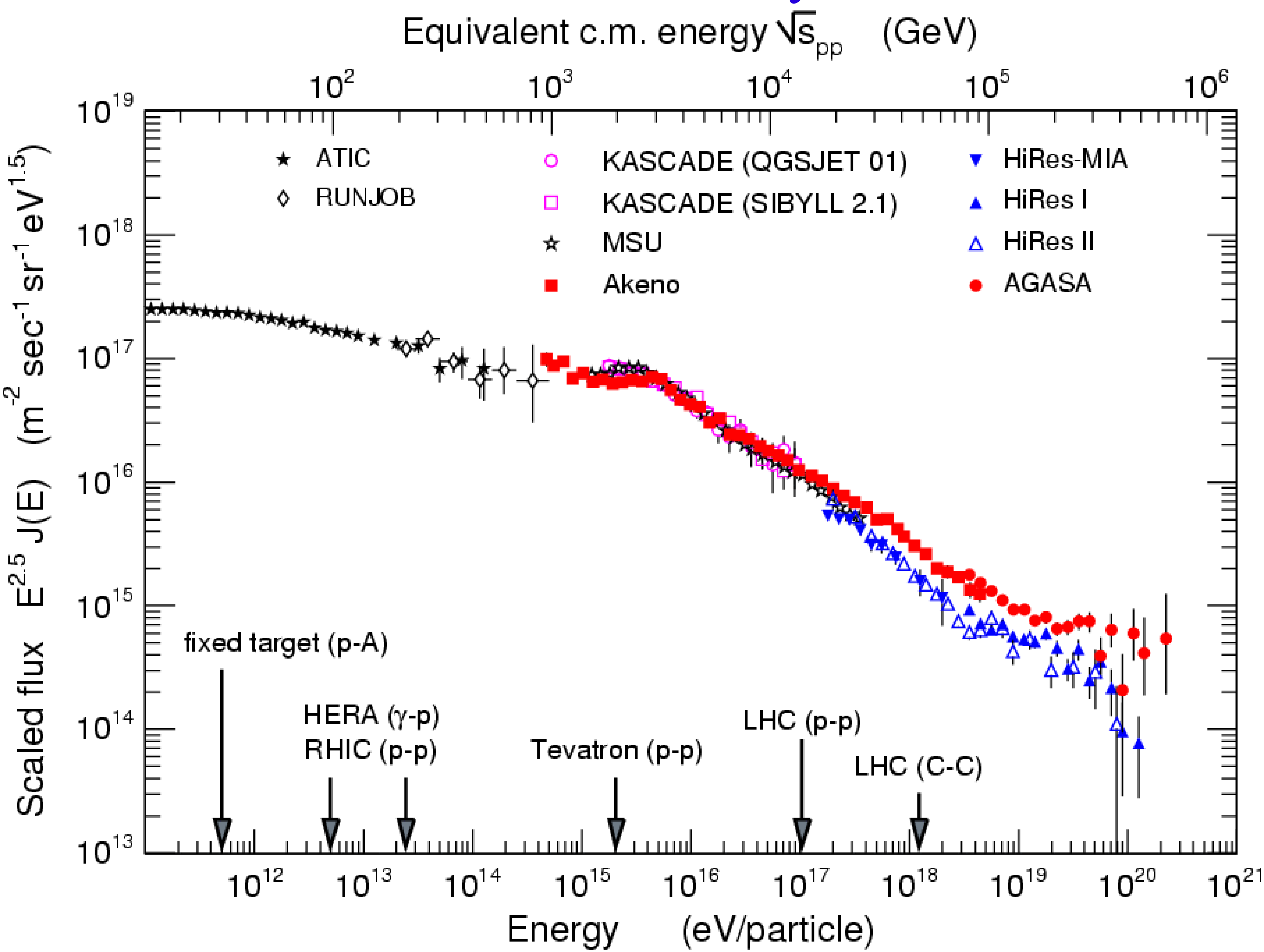
1966 GZK cutoff due to CMB

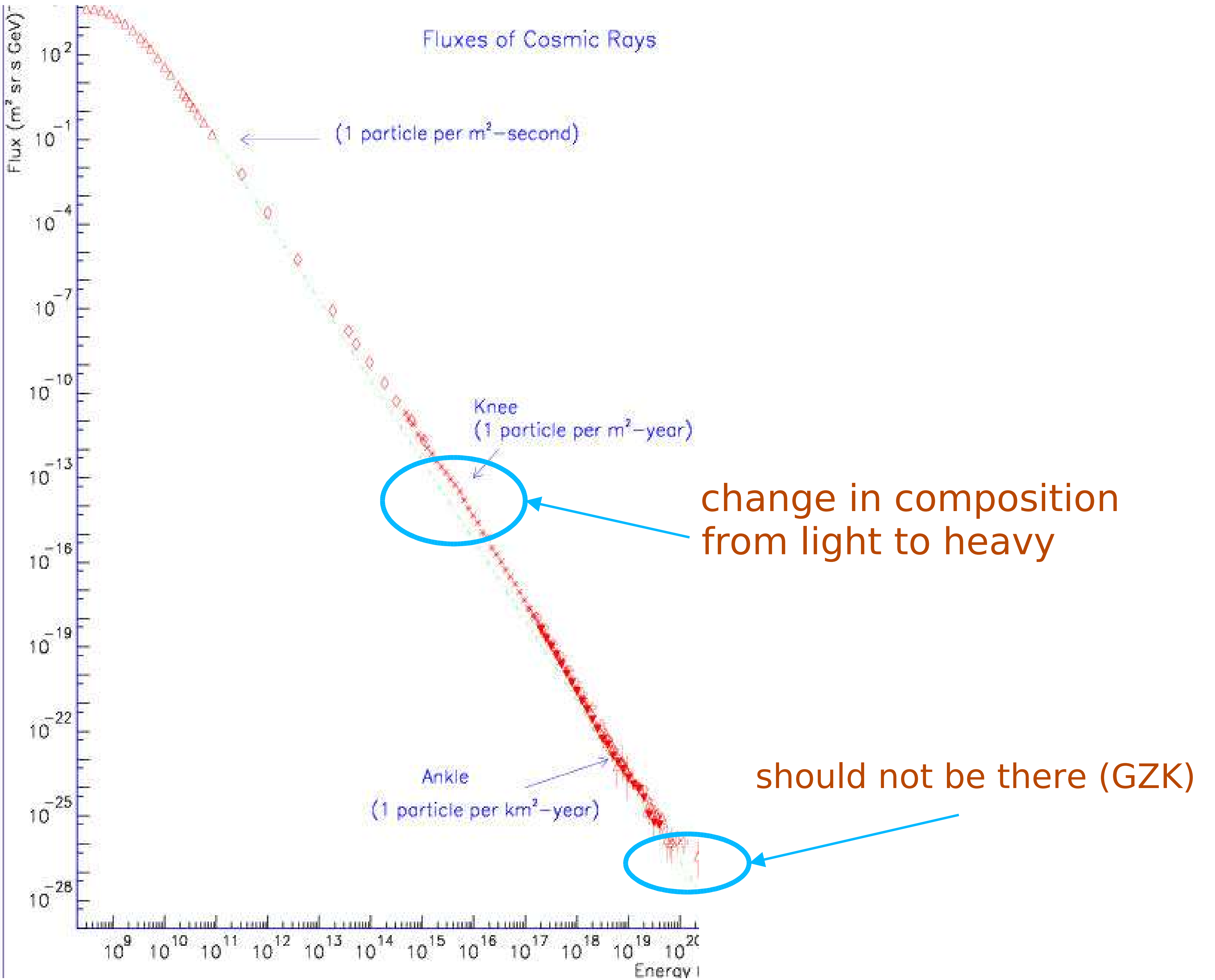
1991 Fly's Eye event $3\ 10^{20}$ eV

1994 Agasa collaboration detects $2\ 10^{20}$ eV

1995 Pierre Auger project

The flux of cosmic rays on earth




Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
Energy
change in composition
from light to heavy
should not be there (GZK)

The Highest Energy Cosmic Rays

Events above 10^20 eV may have been detected

record: $3x10^{20}$ eV: Fly's eye

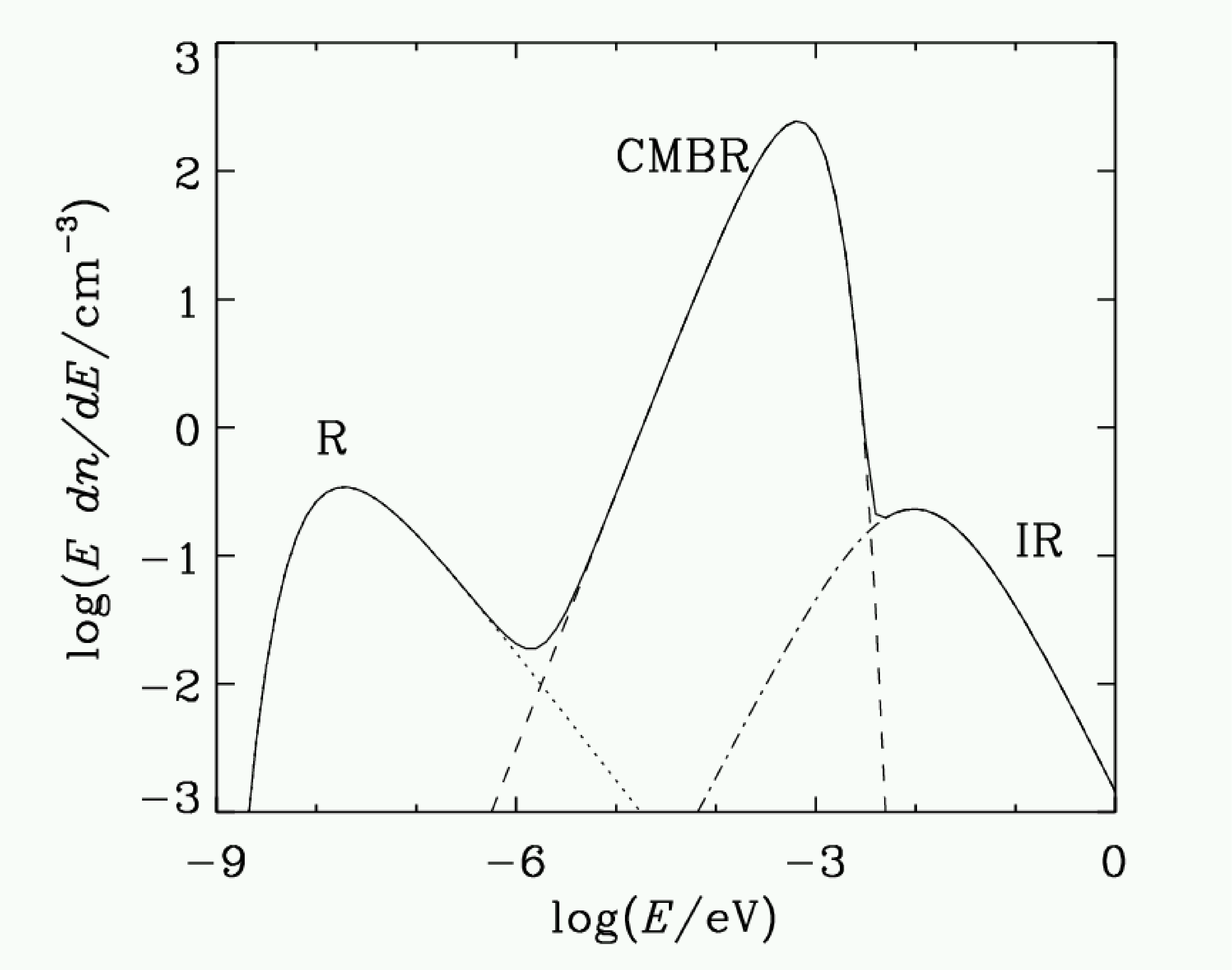
Agasa: 10 events > 10^{20} eV

- Acceleration mechanism ???

- GZK cutoff ??? (Greisen Zatsepin Kuzmin 1966)
  Protons: pion photo-production for E > $5x10^{19}$ eV
  Limits distance to < 50-100 Mpc.
  Nuclei: photo-disintegration with infrared background
  Photons: e+e- pair production with radio background

- No apparent sources (arrival directions)

R.J. Protheroe et al.
Astroparticle.Phys 4:253,1996



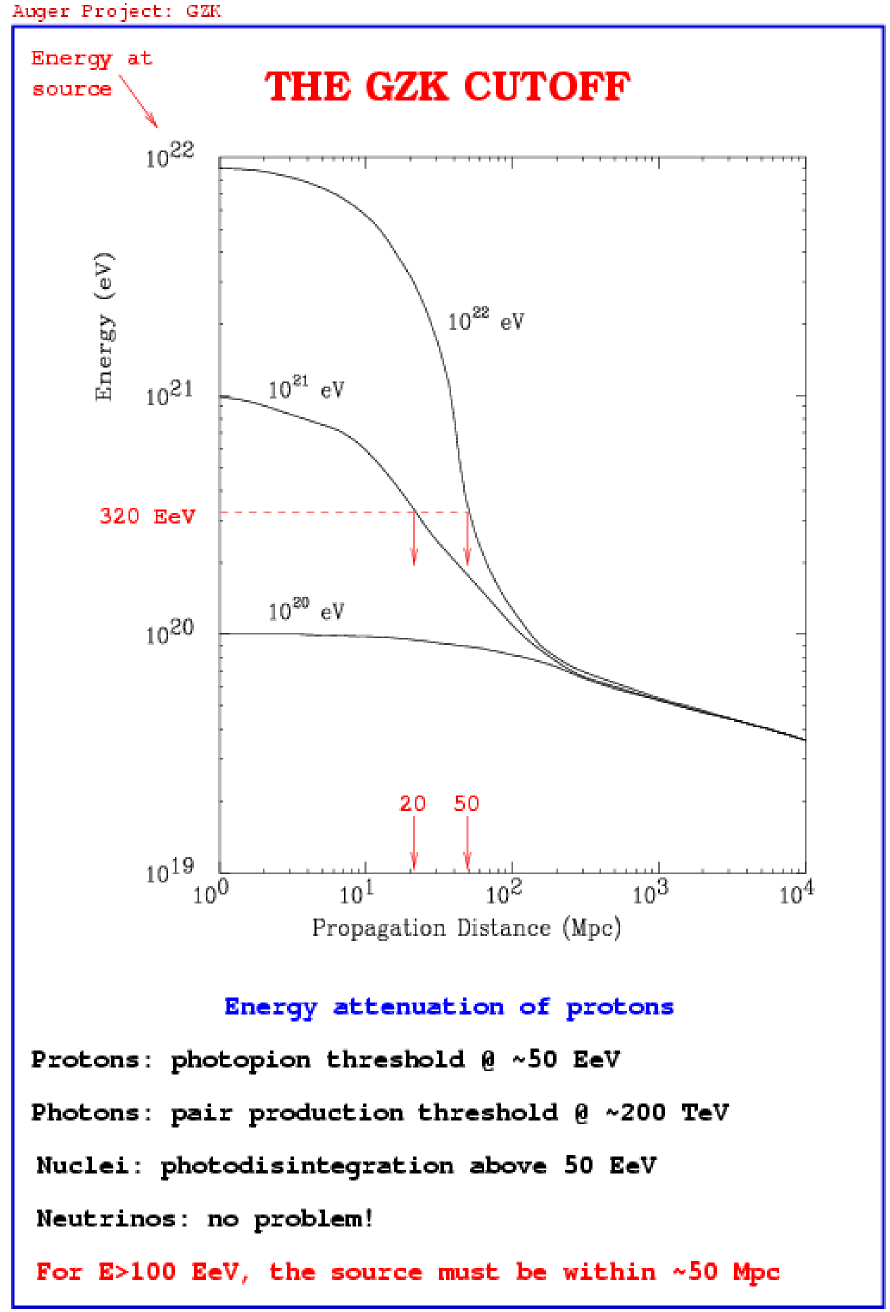
Extragalactic UHECRs

- Protons, nuclei and photons lose energy in intergalactic space due to interactions with the CMB

Problem with propagation

sources < 50 Mpc

Proton energy vs. distance
(J. Cronin)



Attempts to explain origin of UHECR

Bottom-Up models
acceleration

Neutron Stars

AGNs

Radio Lobes

Clusters

Colliding Galaxies/Clusters

Gamma Ray Bursts

Bottom-Up Signatures:

Protons/Nuclei
Power Law Spectrum
Sources (or B)

Top-down models
decay of X-particles

Super Heavy Relic particles
Topological Defects

Top-Down Signatures:

Photons
Non-Power Law Spectrum
No Sources

Detection of UHECR

Direct detection not possible:

Flux very low:

$E > 10^{20}$ eV

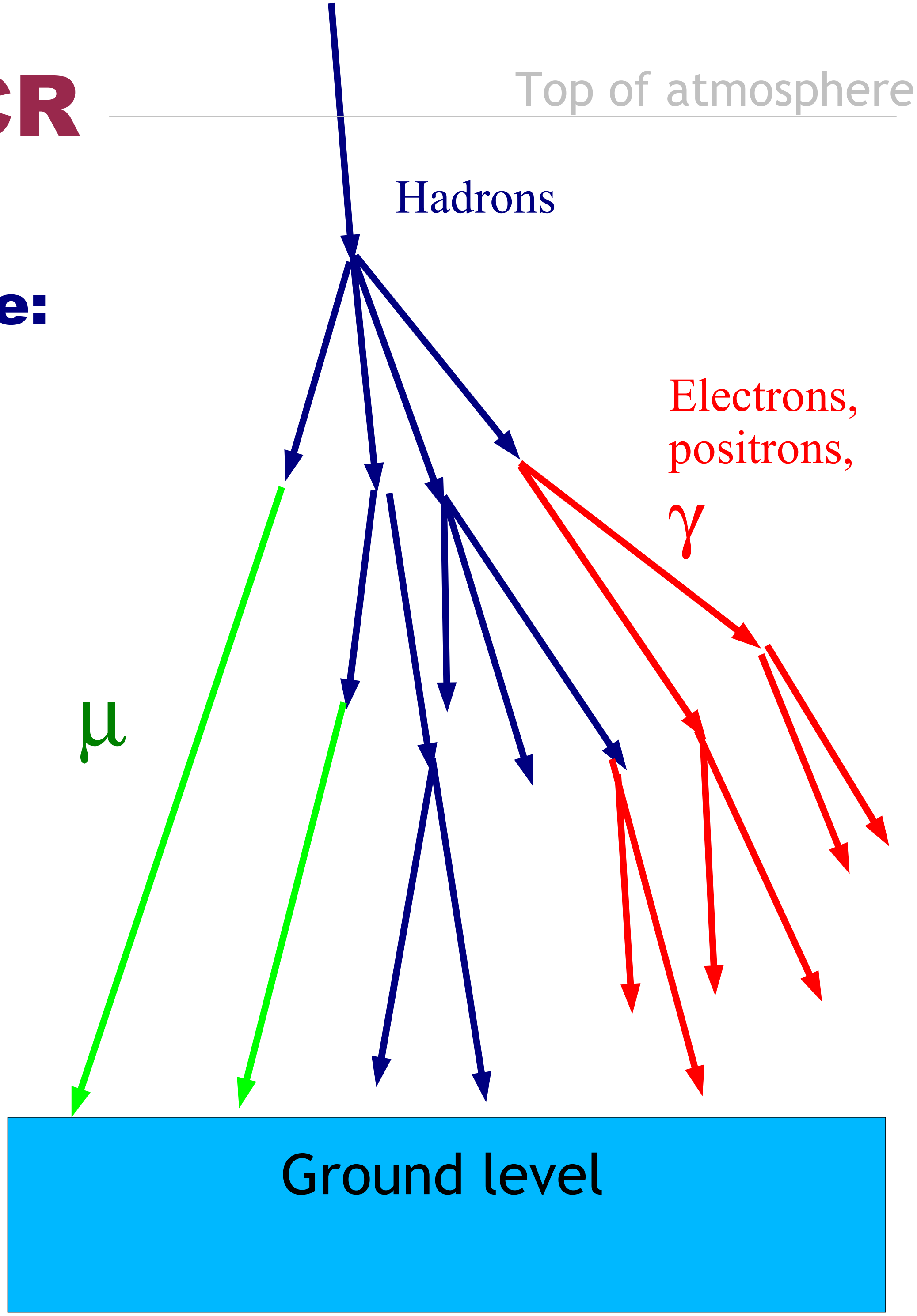
-> 1 particle/km^2/century

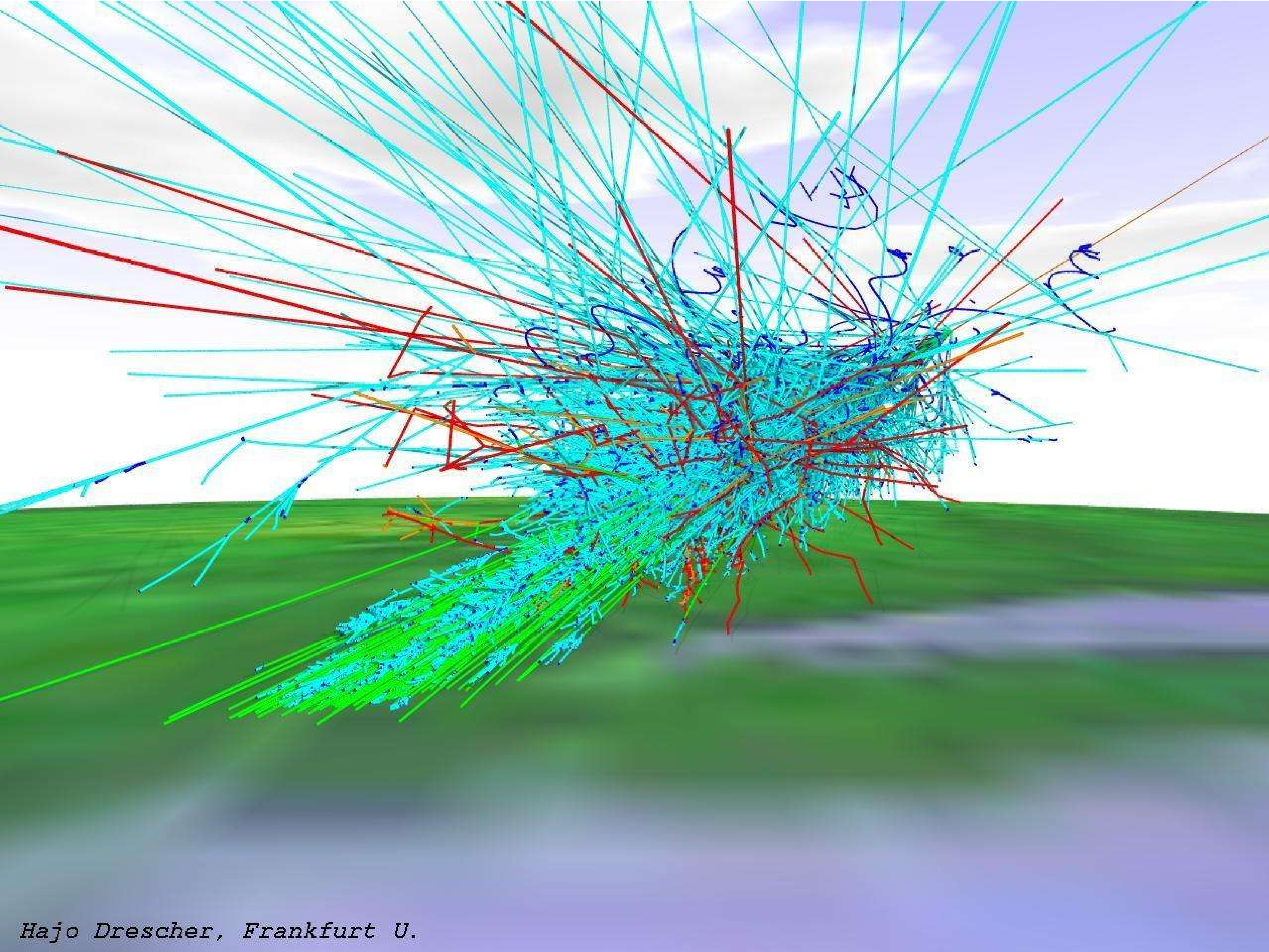
indirect detection via

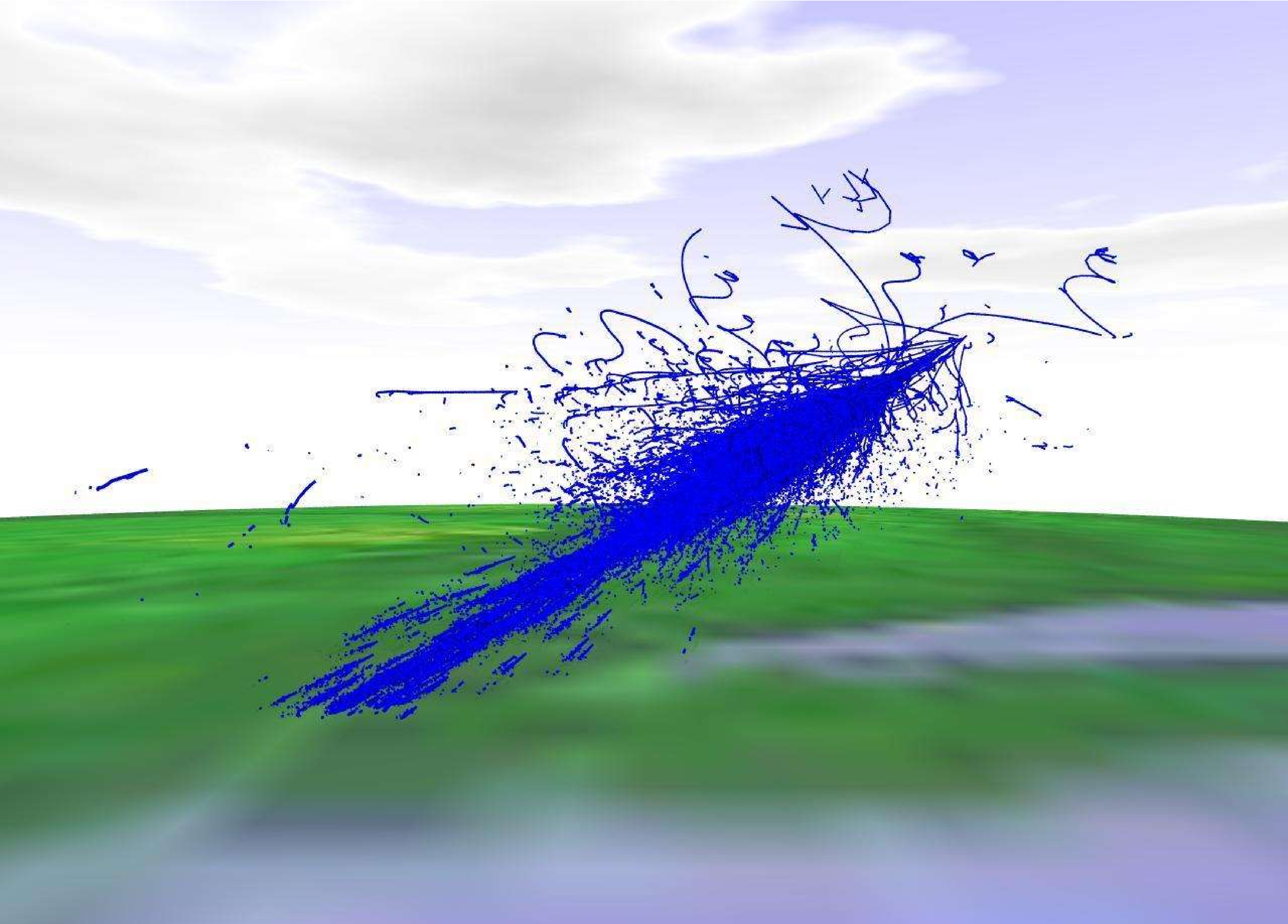
AIR SHOWERS

induced by UHECRs

Reconstruct primary from shower properties:
- Energy,
- Arrival direction,
- Particle type




Hajo Drescher, Frankfurt U.



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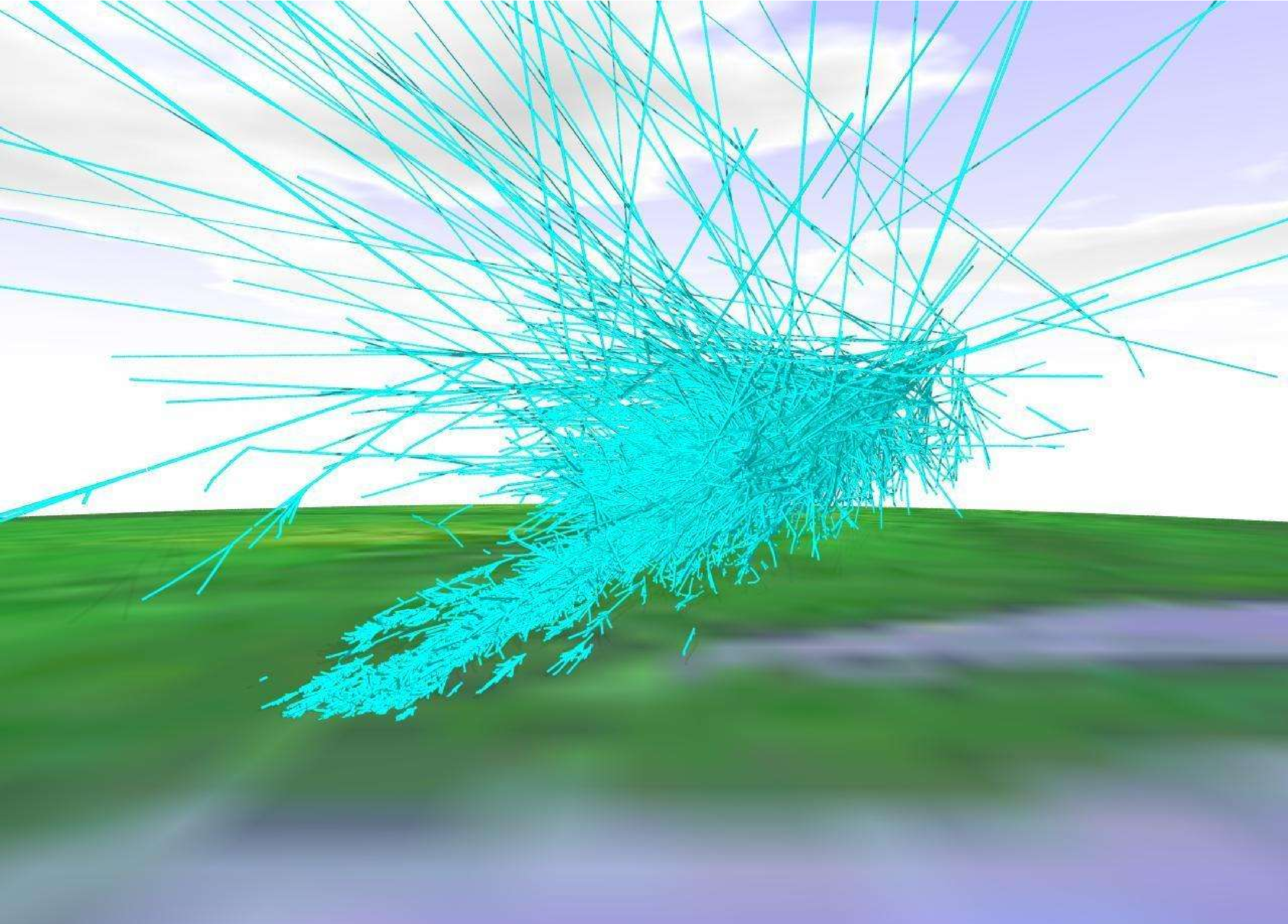

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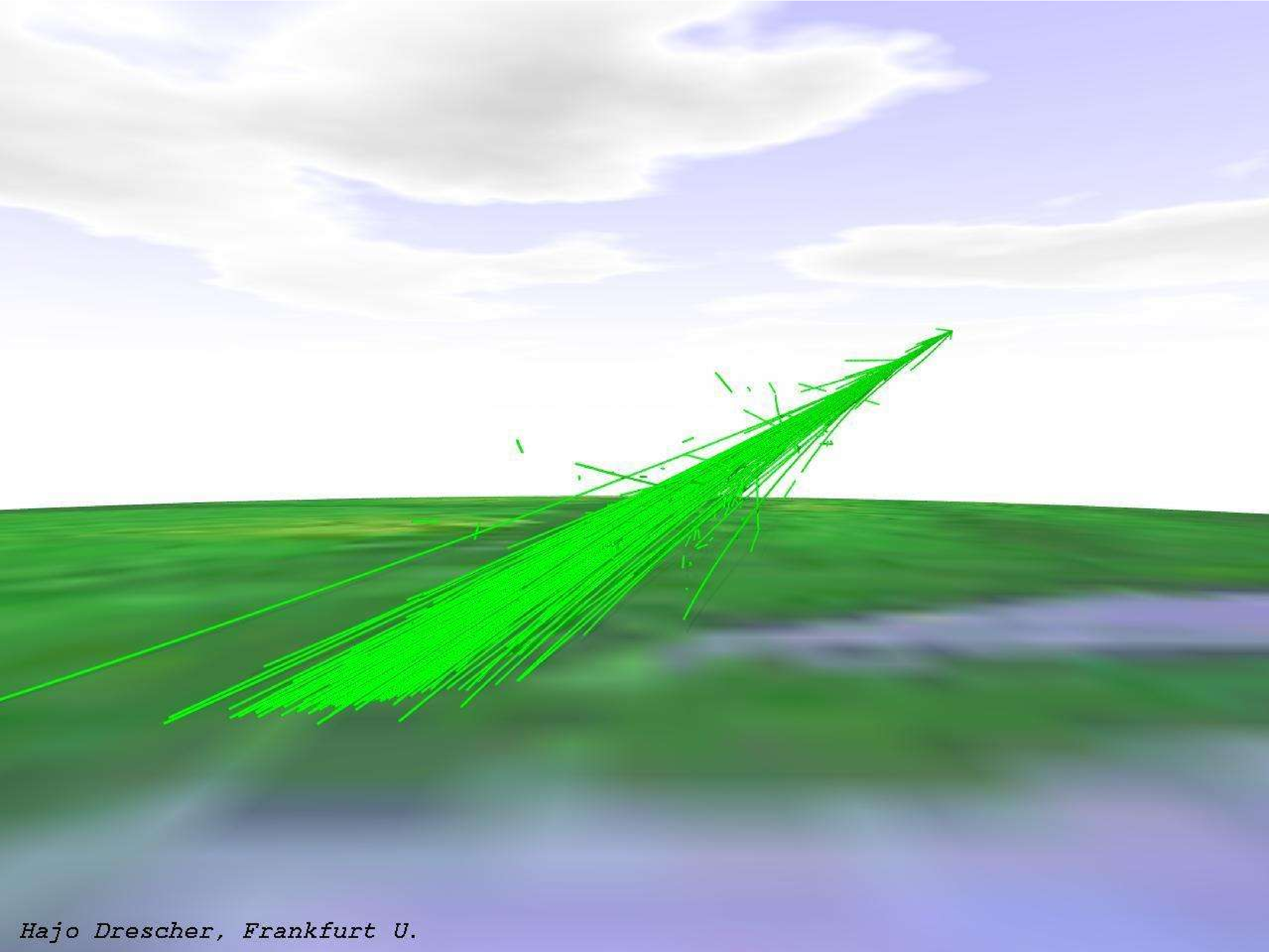
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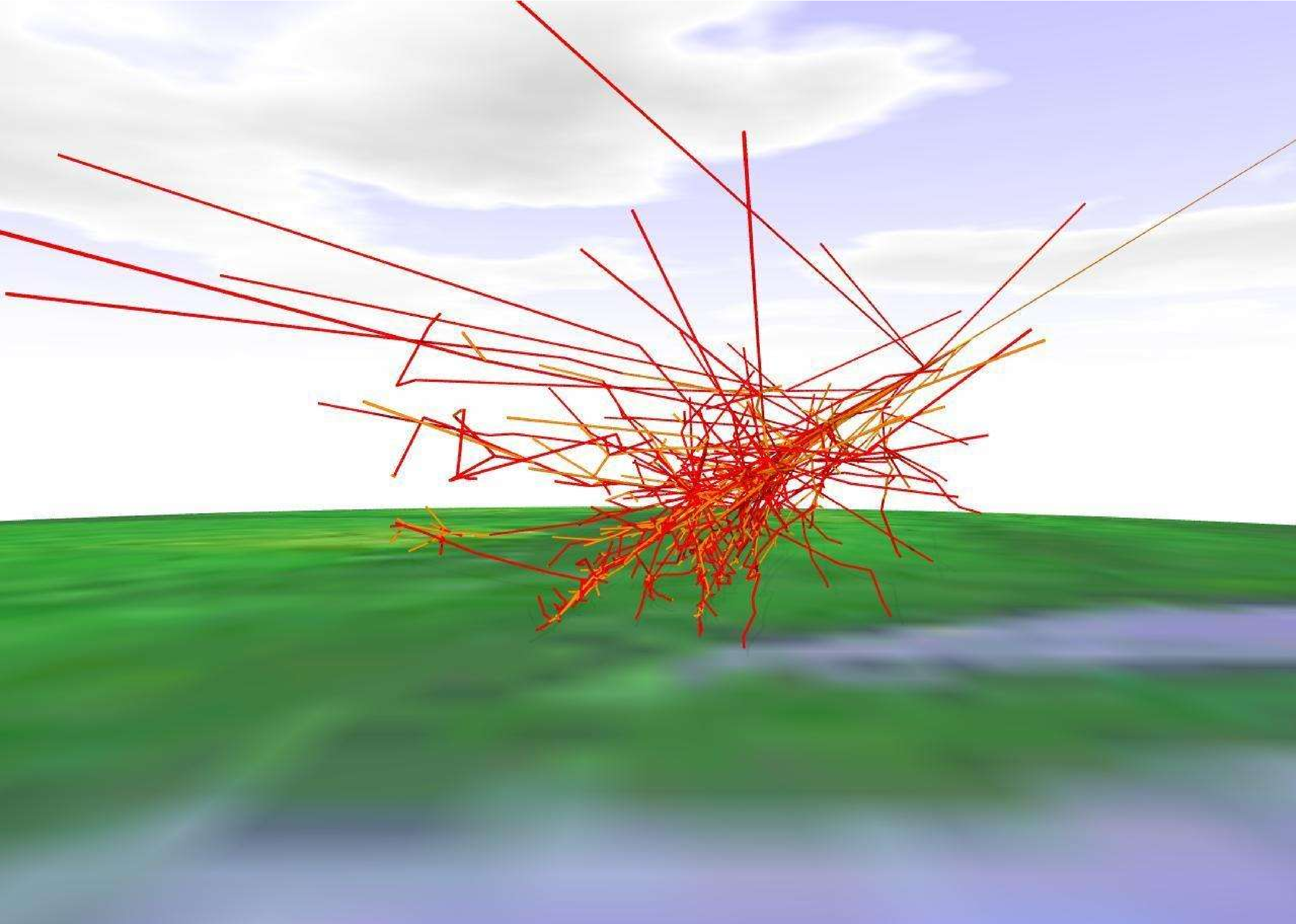
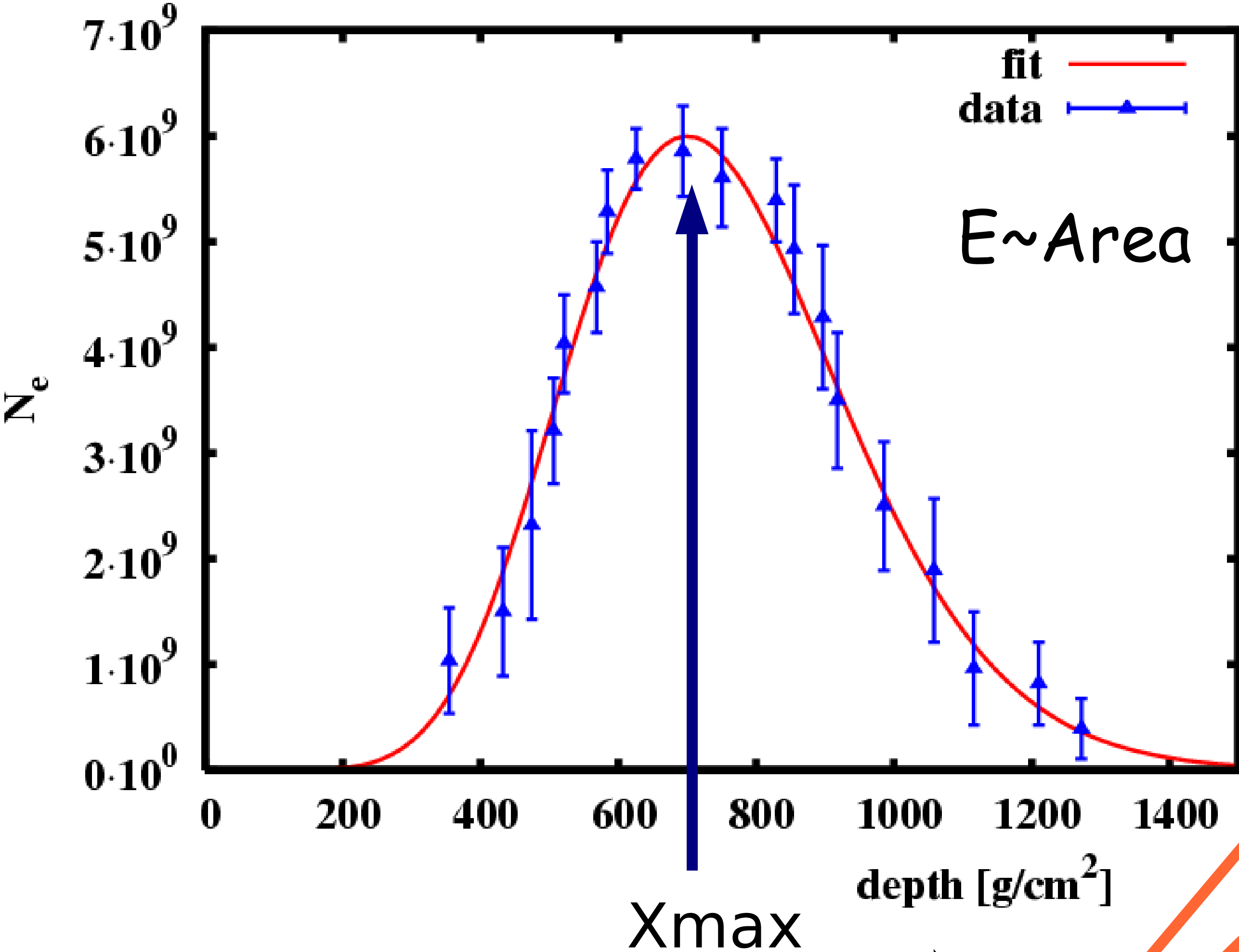


Hajo Drescher, Frankfurt U.

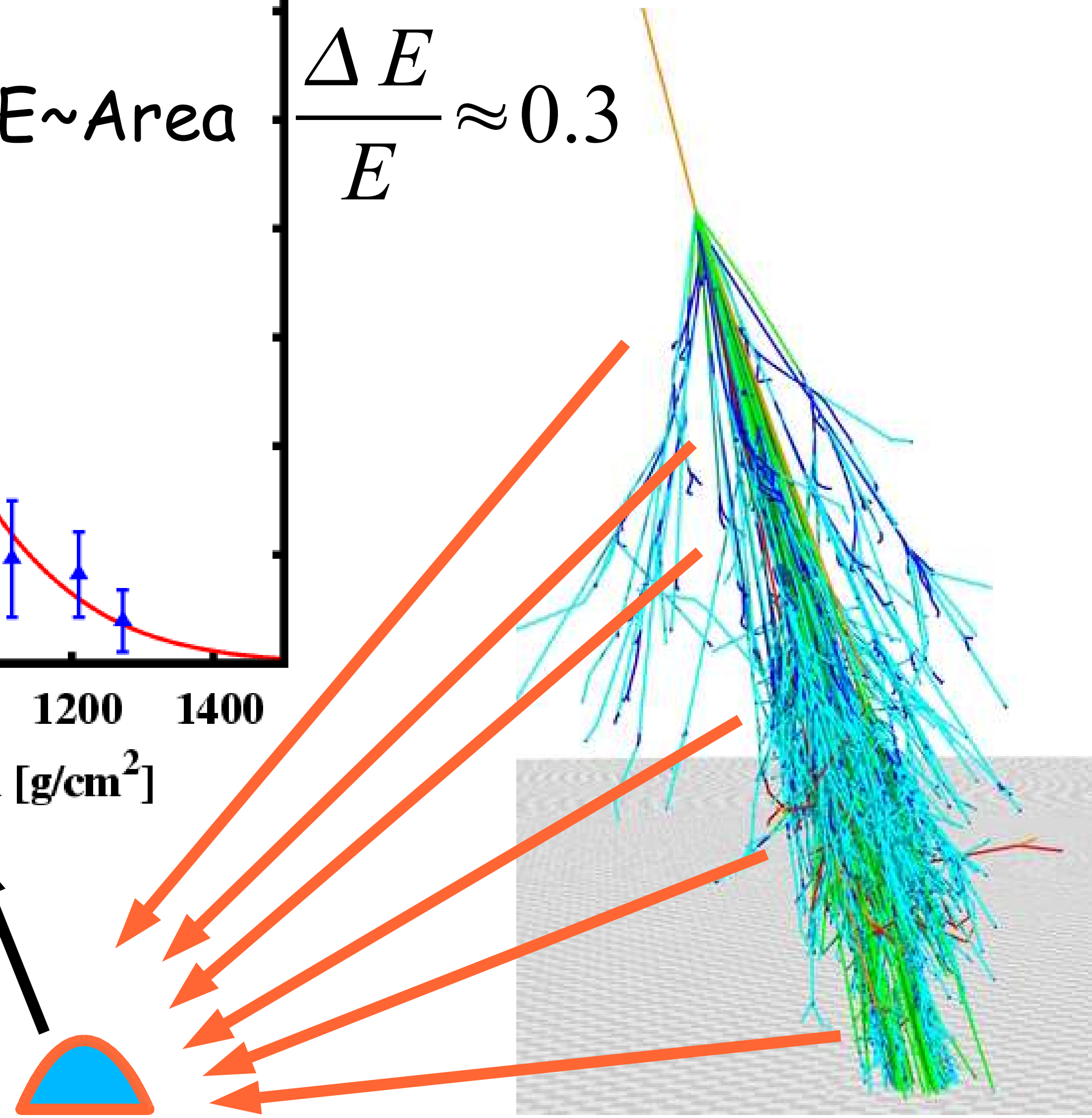
Two Types of Detectors

- Ground Shower Array (AGASA, Auger)
  - Large area because of low flux ($1/\ km^2$ / century > 10^{20} eV)
  - Collects data day and night, any weather
  - Measures direction by arrival times across array
  - Relies on modeling of shower to infer energy and primary
- Air Fluorescence (HiRes, Auger)
  - 10% duty cycle (clear, moonless nights)
  - Difficult to calibrate
  - Insensitive to atmospheric shower modeling

Longitudinal measurement with fluorescence light



E~Area $\frac{\Delta E}{E} \approx 0.3$



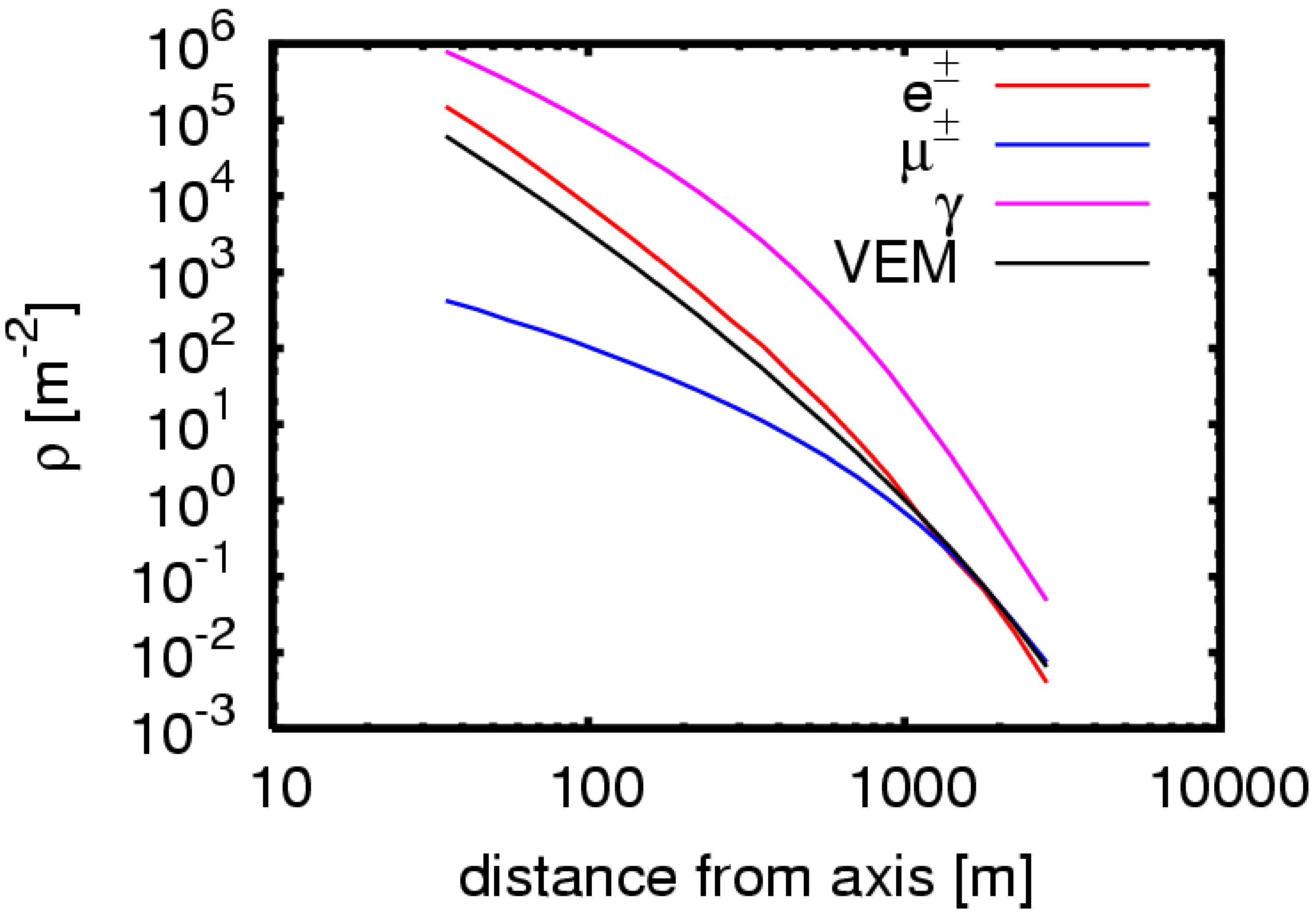
Fly's Eye detector

$$X = \int \mathrm{d}s\, \rho(s)$$

$E_0 = 10^{10}$ GeV

shower produces ~ 6 billion particles at Xmax

Lateral Distribution Function (LDF)



Density **ρ(1000)**

Slope of LDF

Also:
Arrival time in Detector

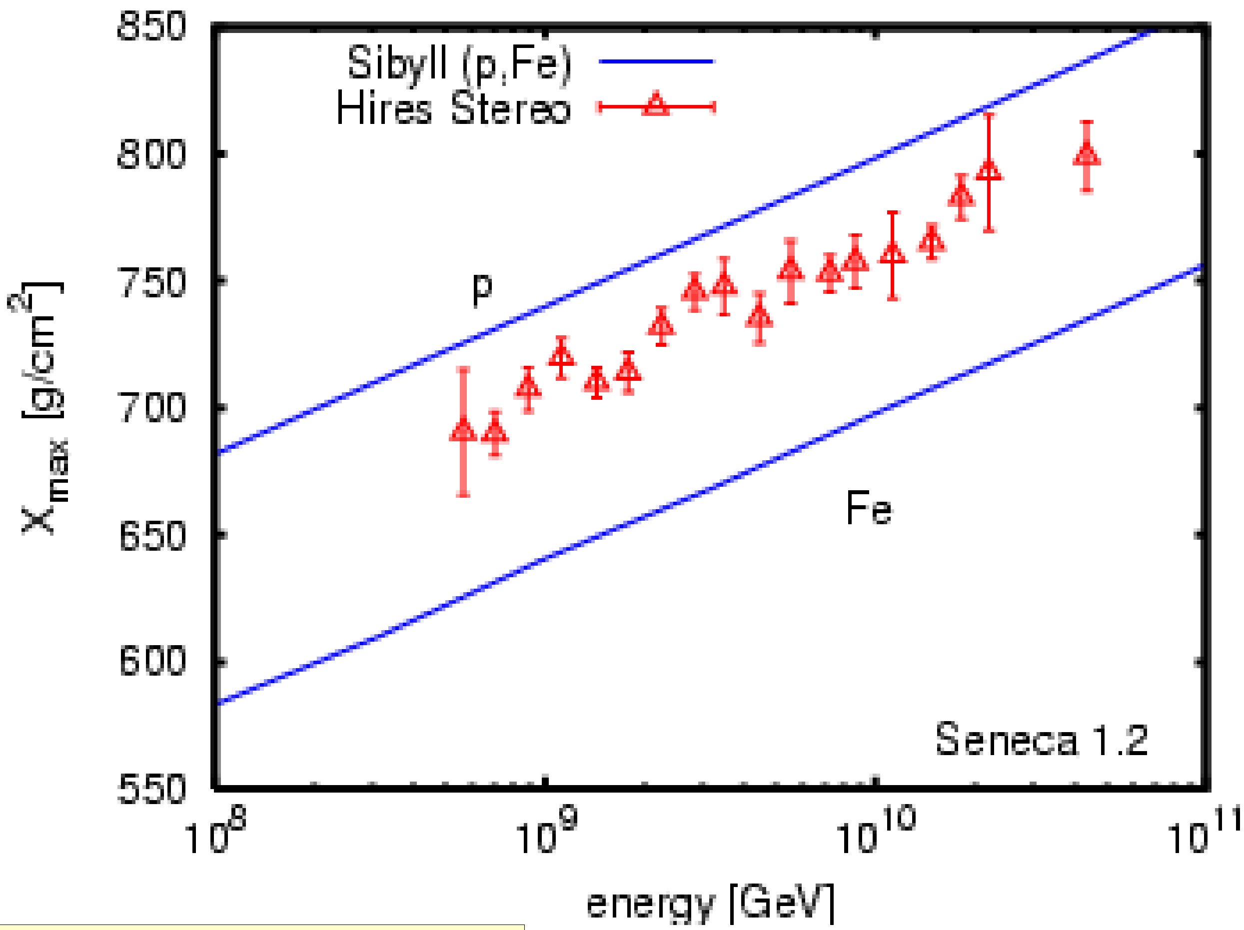
VEM: vertical equivalent muons

Energy Dependence of Xmax for p, Fe primaries

Sibyll:

- Leading Twist Hard (pt cutoff)
- Phenomenological modeling of soft

R. Engel, T. Gaisser, T. Stanev, P. Lipari, '99



X_{max} is composition estimator (but model dependent): Fe(E) ≅ 56*p(E/56)

Lesson: mixture of various nuclei... ???

Traditional Monte-Carlo method for air shower simulations

Choose some high energy and low energy hadronic model

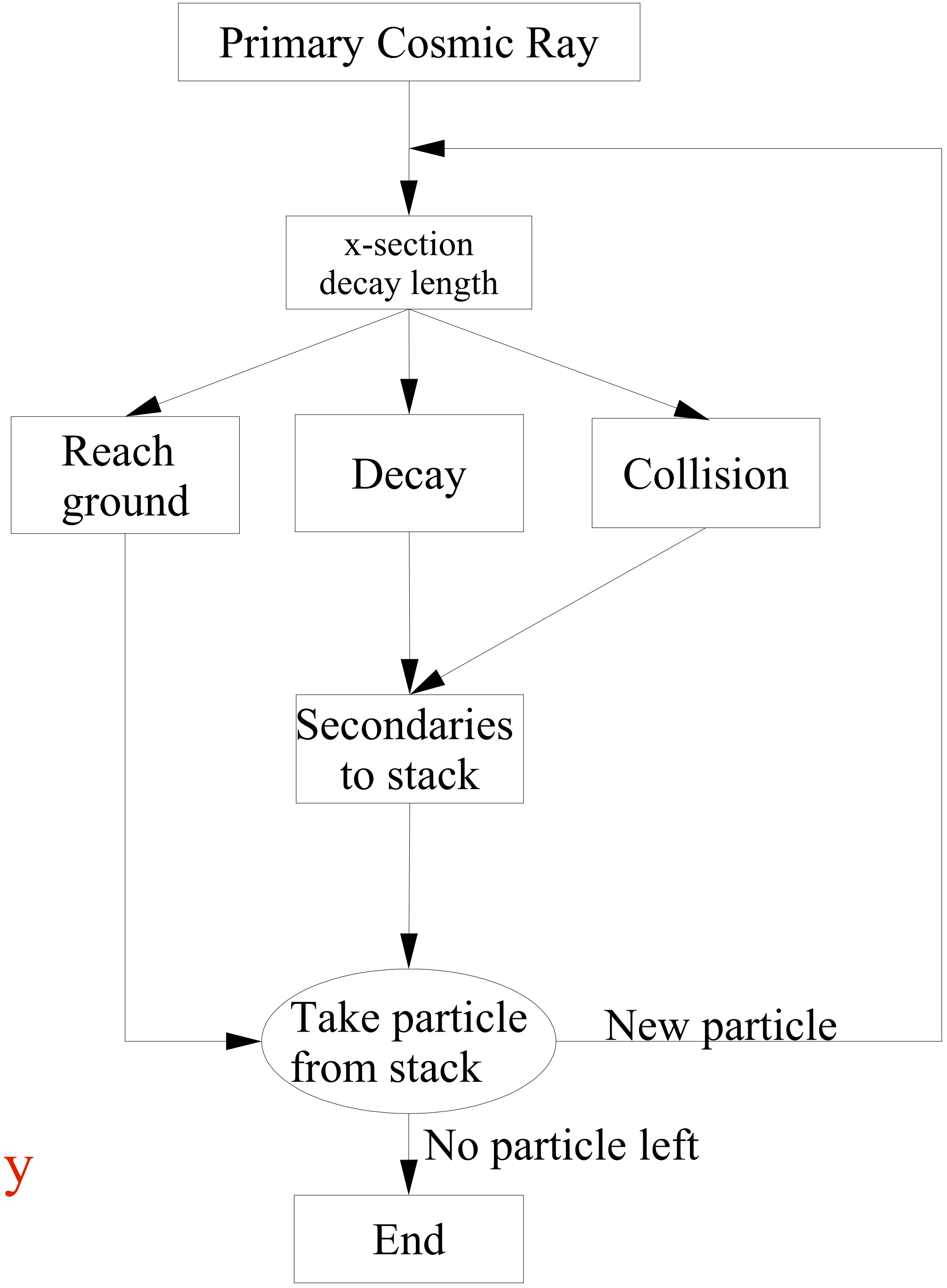
choose model for electromagnetic interactions

Interaction length dependent on thickness of material

decay length dependent on geometrical path

- MOCCA (Hillas),
- CORSIKA (Heck, Knapp et al),
- AIRES (Sciutto)

Not feasible for very high energy (large number of particles)



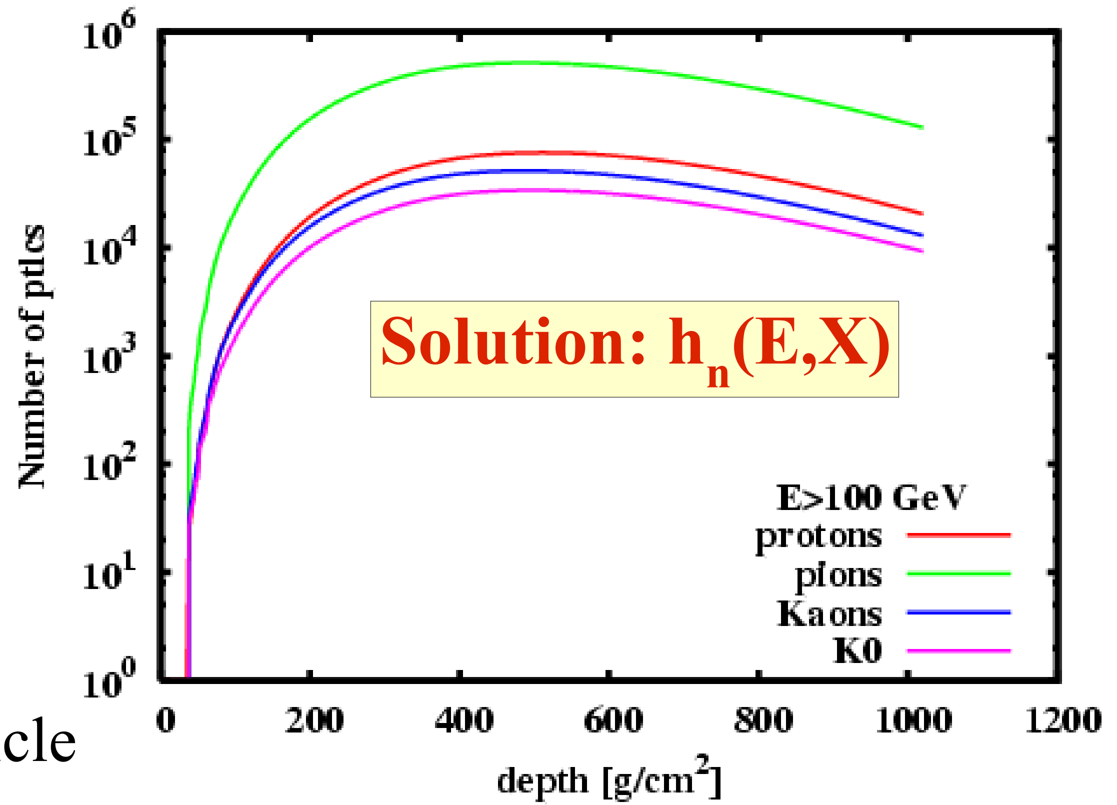
Cascade equations (1d !)

H. Drescher, G. Farrar
Phys.Rev.D67:116001,2003

$$\frac{\partial h_n(E,X)}{\partial X} = -h_n(E,X)\left(\frac{1}{\lambda_n(E)}+\frac{B_n}{E\,X}\right)$$

$$+\sum_m \int_{E_{\min}}^{E_{\max}} h_m(E',X)\left(\frac{W_{mn}(E',E)}{\lambda_m(E')}+\frac{B_m D_{mn}(E',E)}{E'\,X}\right)\mathrm{d}E$$

h_n:number of hadrons n per dE
E: Energy   X: slant depth
B_n: decay constant
λ_n:interaction length
W_{mn}: collision function
D_{mn}: decay function
initial condition:
$h_n(E,X)=\delta(E-E_0)$ for a given particle



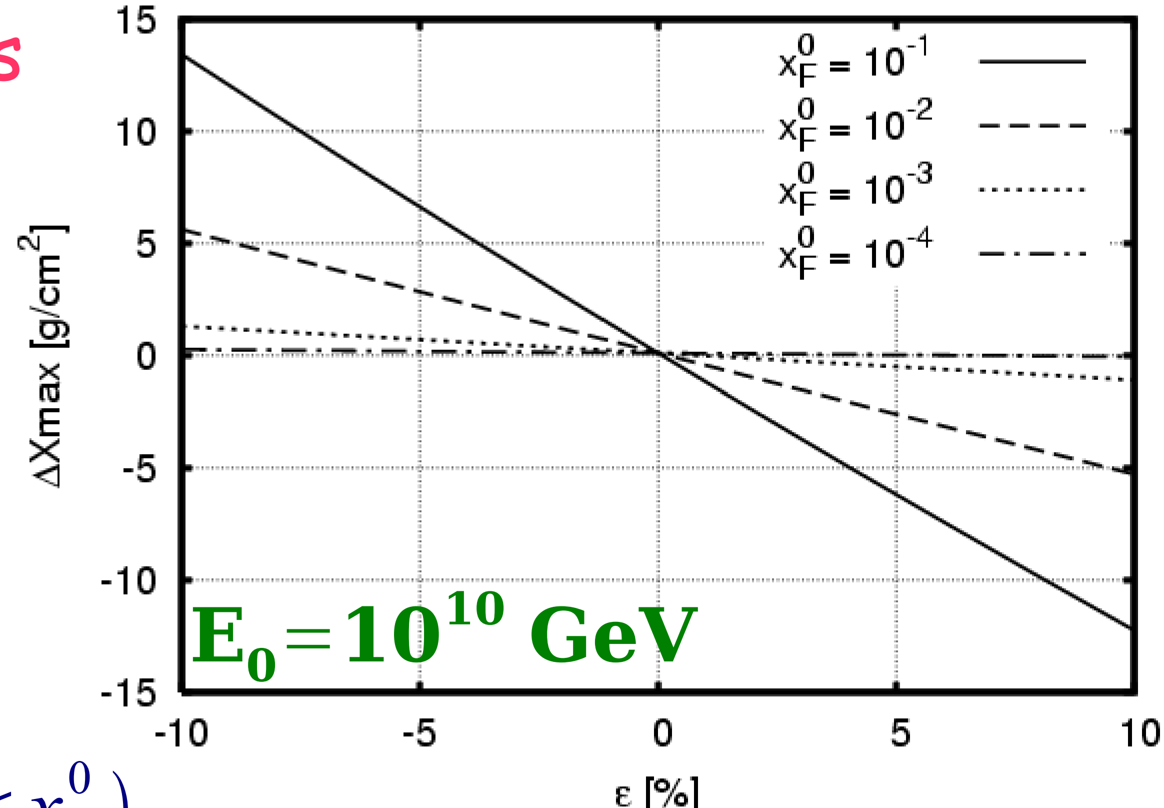
Cascade equations, identify QCD input:

$$\frac{\partial h_n(E,X)}{\partial X} = -h_n(E,X)\left(\frac{1}{\lambda_n(E)} + \frac{B_n}{E\,X}\right) + \sum_m \int_{E_{\min}}^{E_{\max}} h_m(E',X)\left(\frac{W_{mn}(E',E)}{\lambda_m(E')} + \frac{B_m D_{mn}(E',E)}{E'\,X}\right) \mathrm{d}E$$

- Mean free path $\rightarrow \sigma_{tot}(h + air \rightarrow X)$
- Energy distribution of secondaries $\rightarrow dN/dx_F$ (p_t integrated !)

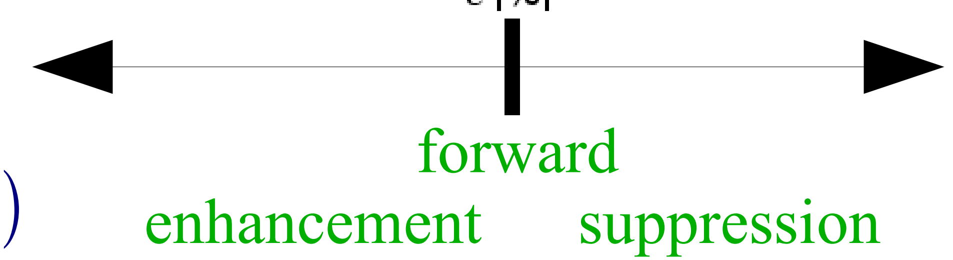
Sensitivity to forward region

- Linear sensitivity analysis of Cascade Equations to x_F distribution (at fixed σ_{tot})



$$\frac{dN}{dx_F} \Rightarrow \frac{dN}{dx_F}(1+\epsilon) \quad (for\ x_F < x_F^0)$$

$$\frac{dN}{dx_F} \Rightarrow \frac{dN}{dx_F}(1-\epsilon') \quad (for\ x_F > x_F^0)$$



=▶ Xmax mainly sensitive to forward region, $x_F > 10^{-3}$

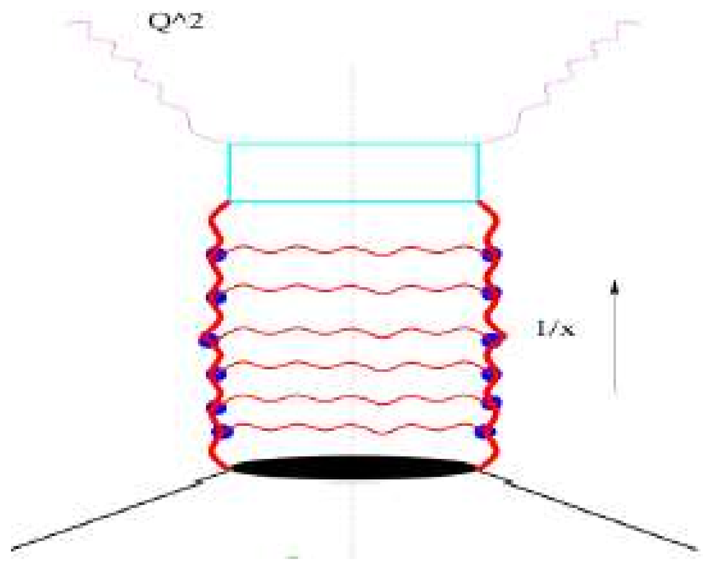
- Large-x partons from the projectile interact with small-x partons from target
- Need to understand small-x gluon fields in the target
- Relevant limit of QCD is Regge limit:

$$x \to 0 \; ; \; Q^2 = \text{fixed}$$

- Large phase space between (relevant) projectile and target partons gets filled by radiated gluons

QCD small-x evolution

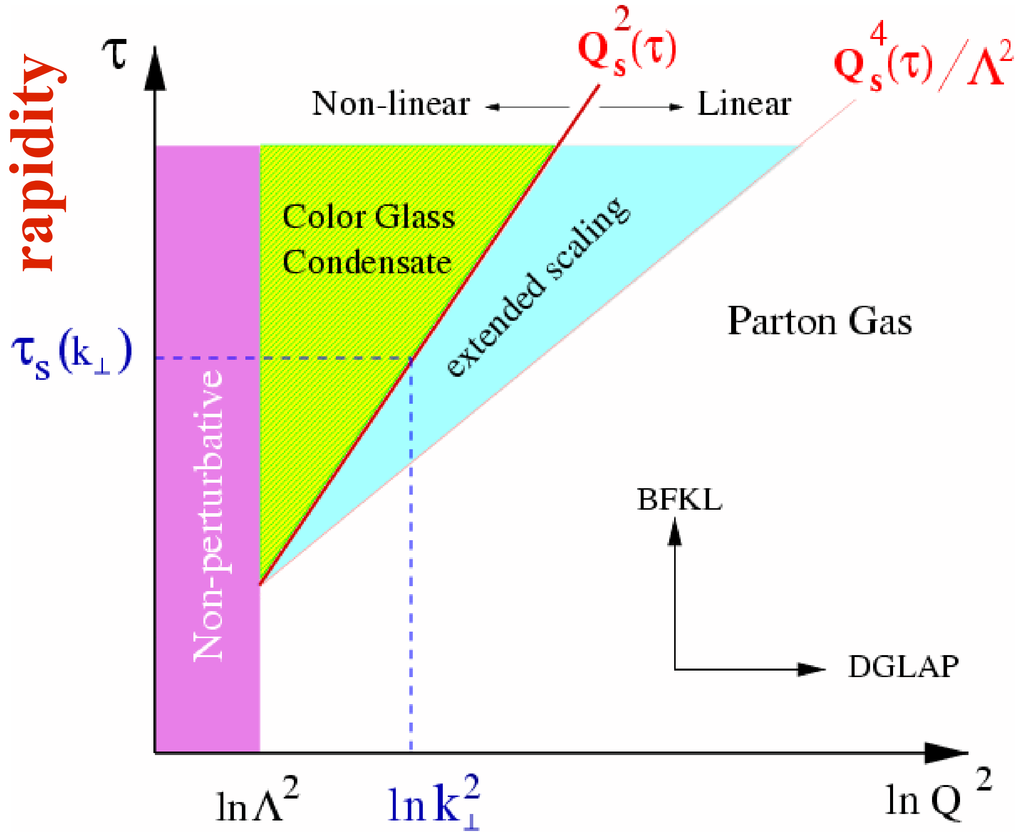
The BFKL equation (Balitsky-Fadin-Kuraev-Lipatov)



- Resums $\alpha_S \log(1/x)$ $\rightarrow$ Evolution in x, not Q^2
- # of gluons grows very rapidly, $xG(x,Q^2) \sim 1/x^{\lambda}$
- phase space density must saturate at $f \sim 1/\alpha_S$,

  when scattering amplitude $T(x,Q_S{}^2) \sim 1$.

Evolution of Qs



Iancu, Venugopalan
hep-ph/0303204

determine Qs(x) from BFKL

fixed coupl. BFKL:

$$Q_s^2(y,A) = Q_0^2 \exp c\bar{\alpha}_s y \rightarrow Q_s^2(x) = Q_0^2\,(x_0/x)^\lambda$$

GB-W: $\lambda \sim 0.28$ Initial condition : $Q_0^2 \sim A^{1/3} \log A$

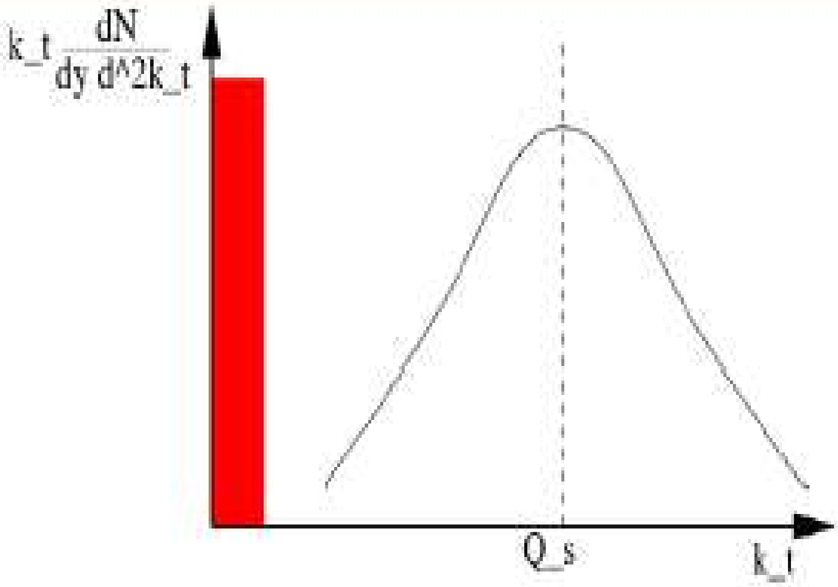
running coupl BFKL : $\bar{\alpha}_s(Q^2) = b_0/\log Q^2/\Lambda^2$

$$
\begin{aligned}
Q_s^2 &= \Lambda^2 \exp\left(\log(Q_0^2/\Lambda^2)\sqrt{1+2\,c\,\bar{\alpha}_s\,y}\right)\\
y \to 0: \quad \to &\quad Q_0^2 \exp\left(\bar{\alpha}_s\,c\,y\,\log Q_0^2/\Lambda^2\right) \overset{!}{=} Q_0^2 \exp \lambda y\\
\to Q_s^2 &= \Lambda^2 \exp\sqrt{\log(Q_0^2/\Lambda^2)\,(2\lambda y + \log Q_0^2/\Lambda^2)}\\
y \to \infty: \quad \to &\quad \Lambda^2 \exp\sqrt{2\lambda y\,\log Q_0^2/\Lambda^2}
\end{aligned}
$$

	RHIC	LHC	GZK
y_P	10.7	17.3	26.1
Qs (r.c.)	1.1 GeV	2.4 GeV	5.9 GeV
Qs (f.c.)	1.4 GeV	4.5 GeV	19.2 GeV

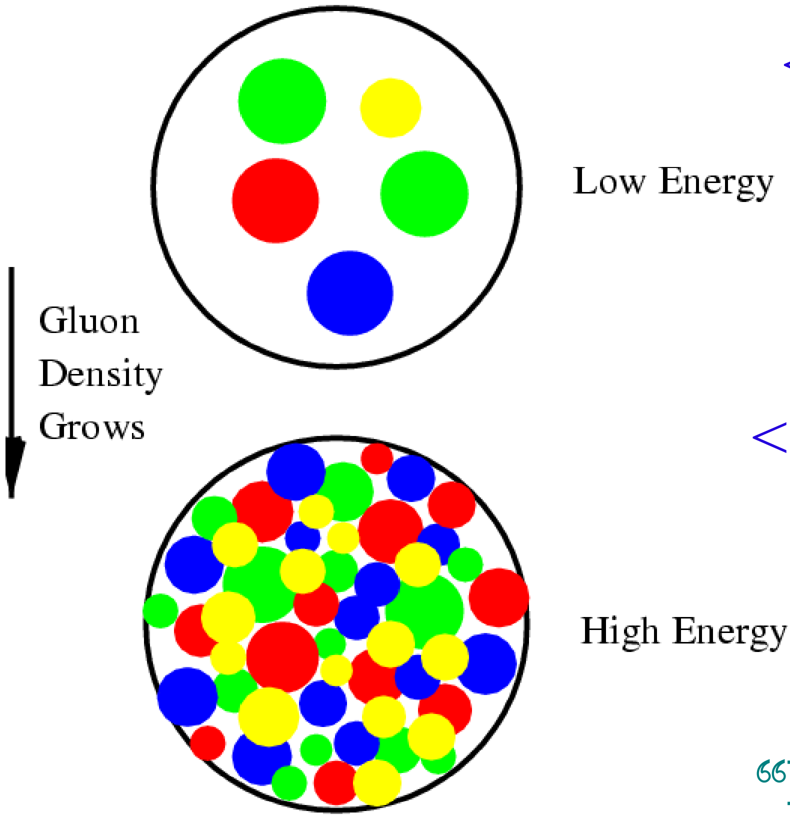
λ=**0.28;** **central** “p+N”; (Q_0/Λ)^2~Nval/3

The Color Glass Condensate



- Typical gluon momentum is Q_S
- Occupation number ~$1/\alpha_S$: Condensate
- Random small-x fields "frozen" during scattering process, slow internal dynamics is similar to spin glasses

Hadrons at small x: a "Color Glass Condensate"



<-- Dilute Parton Gas

<-- `Saturated' Classical Color Field

"McLerran-Venugopalan Model"

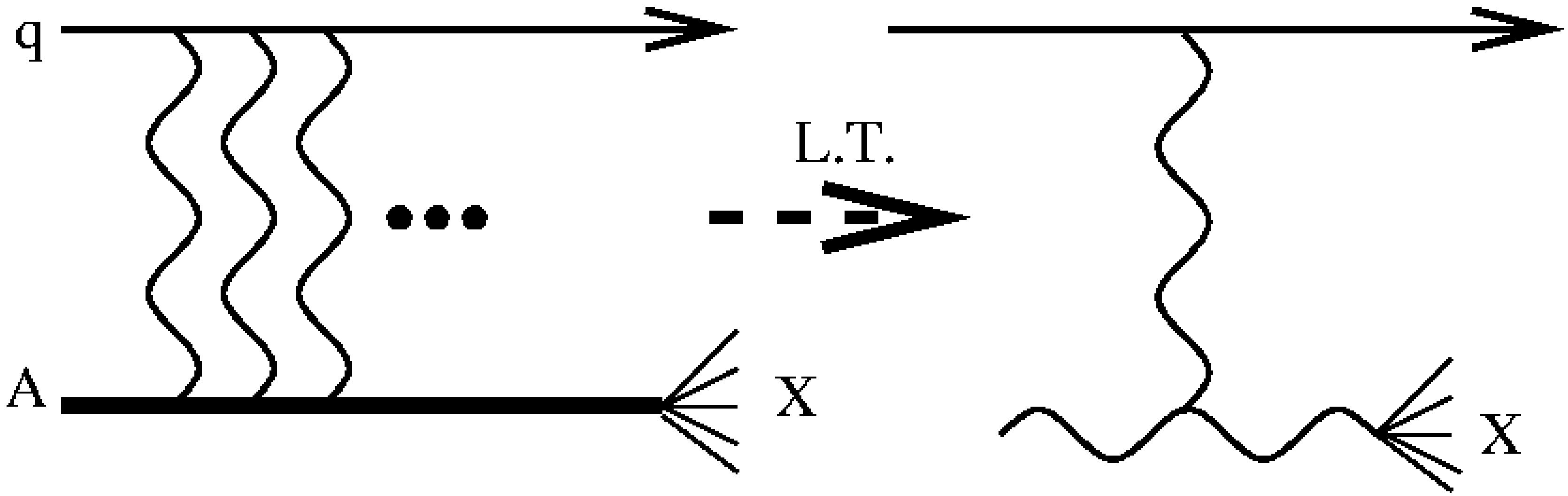
- Small-x gluons evolve slowly
- Color averaging with static random sources :

$$\langle O \rangle = \int \mathcal{D}\rho \; O[\rho] \exp\left(-\int \mathrm{d}^2 x_t \mathrm{d}x^- \; \mathrm{tr} \; \rho^2/\mu^2\right)$$

μ^2 is average color charge squared per area

- Field of nucleus : $[D_\mu, F^{\mu\nu}] = \delta(x^-)\,\delta^{\nu +}\, g\,\rho$

Quark-Nucleus Scattering



Quark Scattering Amplitude :

$$\langle q\ out \mid p\ in \rangle = \bar{u}(q)\ \tau(q,p)\ u(p)$$

with

$$\begin{aligned}
\tau(q,p) &= 2\pi\,\delta(p^- - q^-)\,\gamma^- \int \mathrm{d}^2x_t\,[V(x_t) - 1]\ e^{ix_t(q_t - p_t)} \\
V(x_t) &= \mathcal{P}\exp\left(-ig^2 \int_{-\infty}^{\infty} \mathrm{d}x^- \frac{1}{\partial_t^2}\,\rho^a(x^-, x_t)\, t^a\right)
\end{aligned}$$

Color averaging with a Gaussian leads to

$$\langle V(x_t)\rangle_\rho = \exp -g^4 C\chi \int \mathrm{d}^2 z_t\, G_0^2(x_t - z_t)$$

$$\langle V(x_t)V^\dagger(\bar{x}_t)\rangle_\rho = \exp -g^4 C\chi \int \mathrm{d}^2 z_t\, [G_0(x_t - z_t) - G_0(\bar{x}_t - z_t)]^2$$

with $C = (N_c^2 - 1)/4N_c \quad , \quad G_0(x_t) = -\int \frac{\mathrm{d}^2 k_t}{(2\pi)^2} \frac{\exp ik_t x_t}{k_t^2}$

and

$$\chi(x^-, x_t) = \int_{x^-}^{x_A^-} \mathrm{d}z^- \mu^2(z^-, x_t) \to \frac{1}{\pi R_A^2} \frac{N_c}{N_c^2-1} \int dx\, g_A(x)$$

Defining the saturation momentum

$$Q_s^2 = 4\pi^2 \alpha_s^2 \frac{N_c^2-1}{N_c}\, \chi$$

--->

$$\frac{\mathrm{d}\sigma^{qA}}{\mathrm{d}q^- \mathrm{d}^2 q_t \mathrm{d}^2 b} = \delta(q^- - p^-)\, C(q_t)$$

$$C(q_t) = \int \frac{\mathrm{d}^2 r_t}{(2\pi)^2} e^{iq_t r_t} \left\{ \exp\left[-2Q_s^2 \int_\Lambda \frac{\mathrm{d}^2 p_t}{(2\pi)^2} \frac{1}{p_t^4} \left(1 - e^{ip_t r_t}\right)\right] -2\exp\left[-Q_s^2 \int_\Lambda \frac{\mathrm{d}^2 p_t}{(2\pi)^2} \frac{1}{p_t^4}\right] + 1 \right\}$$

--->

$$\mathrm{d}\sigma^{\mathrm{el}}/\mathrm{d}^2 b = \left[1 - e^{-Q_s^2/4\pi\Lambda^2}\right]^2 \quad , \quad \mathrm{d}\sigma^{\mathrm{tot}}/\mathrm{d}^2 b = 2\left[1 - e^{-Q_s^2/4\pi\Lambda^2}\right]$$

Limits for qA cross section :

$$C(q_t) =$$

$$q_t \gg Q_s \; : \quad \frac{1}{2\pi^2} \frac{Q_s^2}{q_t^4} \left[1 + \frac{4}{\pi} \frac{Q_s^2}{q_t^2} \log \frac{q_t}{\Lambda} + \mathcal{O}\left(\frac{Q_s^2}{q_t^2}\right)\right]$$

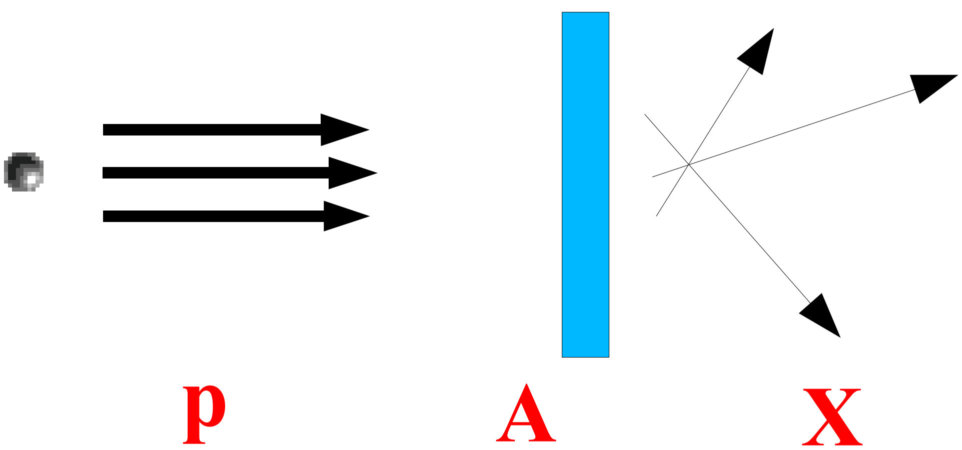
$$q_t \lesssim Q_s \; : \quad \frac{1}{Q_s^2 \log Q_s/\Lambda} \exp\left(-\frac{\pi q_t^2}{Q_s^2 \log Q_s/\Lambda}\right)$$

Shattering the projectile

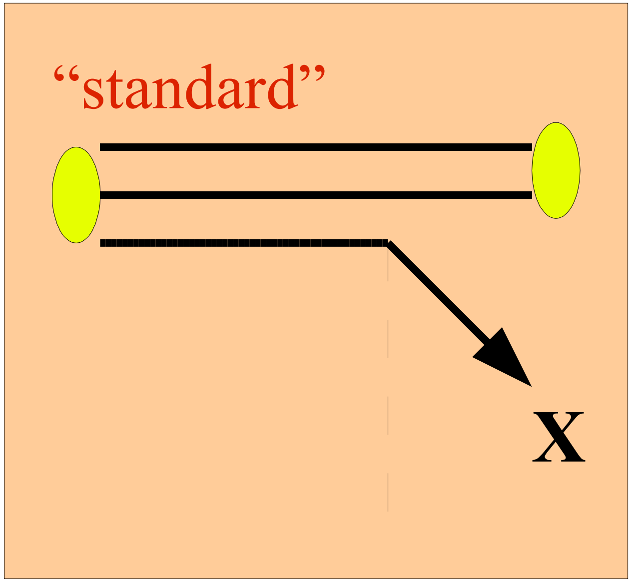
Probability for quark to be scattered to q_t~0 (<u>with</u> color exchange !) :

$$\int_0^{\Lambda} \mathrm{d}^2 q_t \frac{\mathrm{d}\sigma^{\rm in}}{\mathrm{d}^2 b \, \mathrm{d}^2 q_t} \simeq 1 - \exp\left(-\frac{\pi \Lambda^2}{Q_s^2 \log Q_s/\Lambda}\right) \simeq \frac{\pi \Lambda^2}{Q_s^2 \log Q_s/\Lambda}$$

--> suppression of "beam-jet remnants" (soft physics) in the high-density limit



$$\langle q_t \rangle \sim Q_s$$



<u>All partons resolved at scale Qs, coherence of proton destroyed.</u>

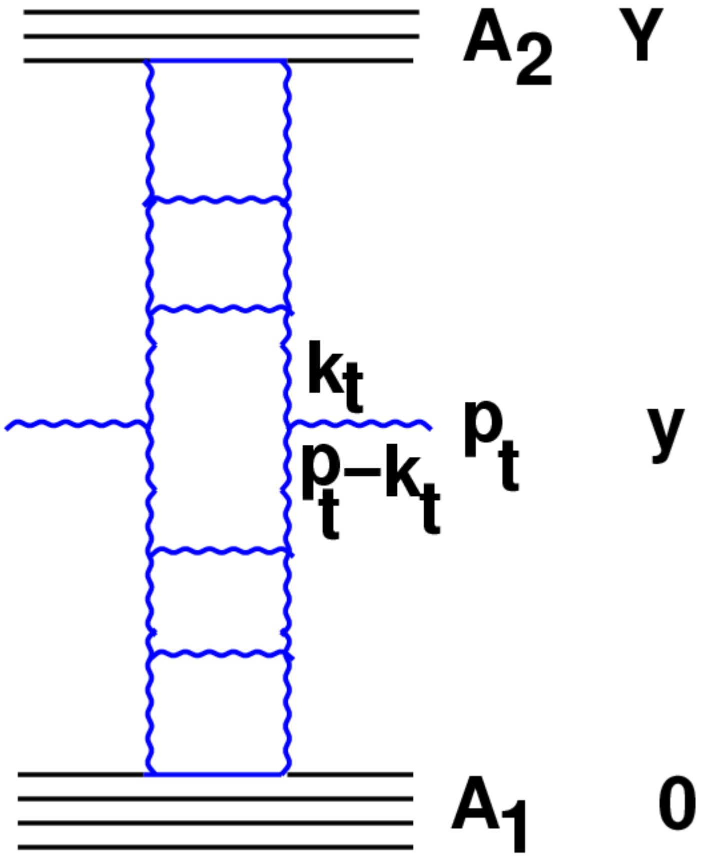
Gluon radiation

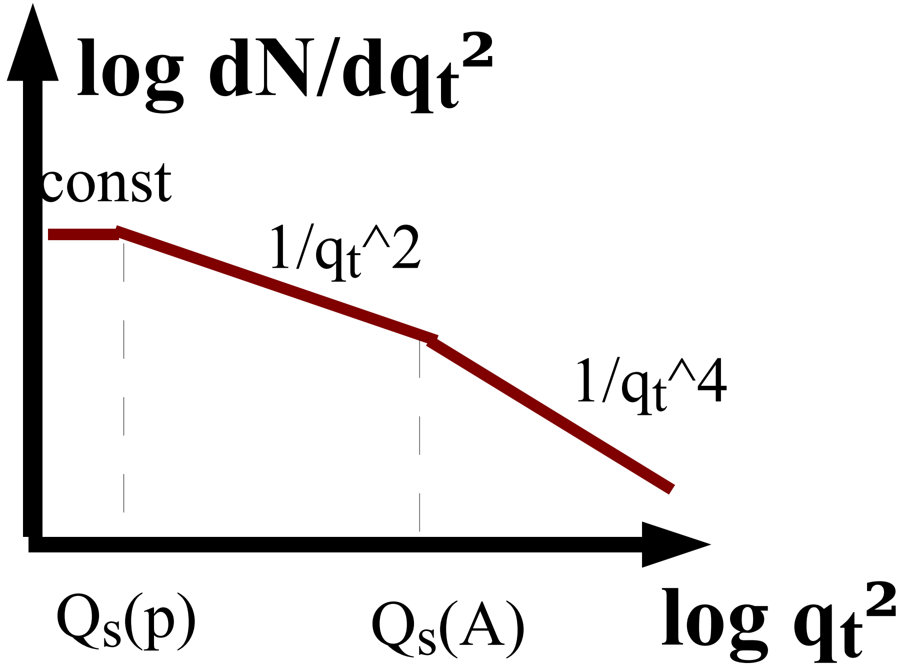
$$\frac{\mathrm{d}N^g}{\mathrm{d}y\mathrm{d}q_t^2} = 4\pi\alpha_s \frac{N_c}{N_c^2-1}\frac{1}{q_t^4}$$

$$x_2\, g_A(x_2, q_t^2)\; x_1\, g(x_1, q_t^2)$$

$$xg(x, q_t^2) \propto \frac{1}{\alpha_s}\min(q_t^2, Q_s^2(x))\;(1-x)^4$$

(Kharzeev, Levin, Nardi, NPA 2004)

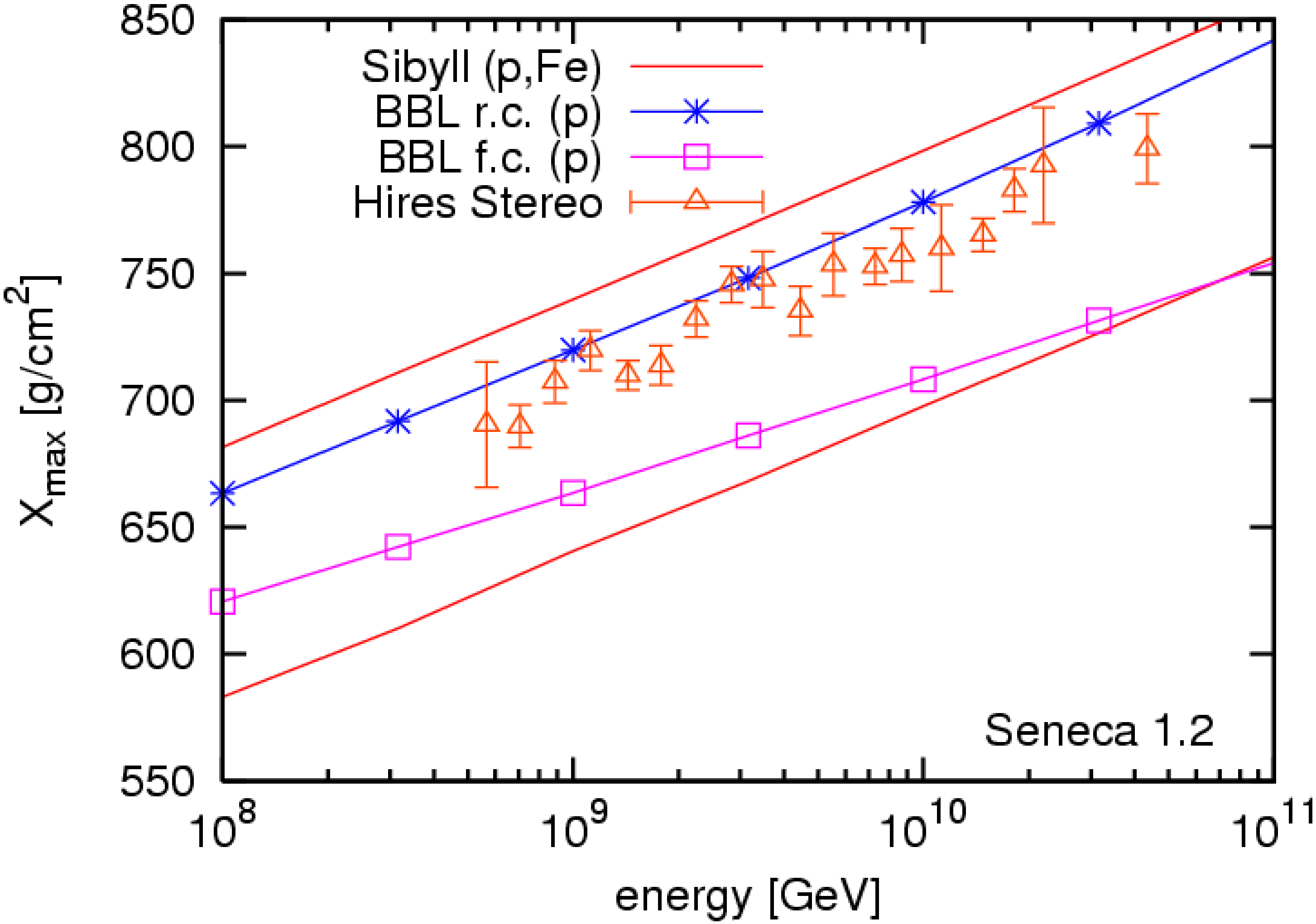




Cosmic Ray Airshowers

hep-ph/0408073

"penetration depth"



=> Sensitive to evolution of Qs !!

* $1/x^{0.3}$ yields too large Qs at GZK energies

Summary

- **QCD → CR airshowers: cross sections and x_F distrib. at extreme energies, moderate p_t (Regge limit)**
- **CR → QCD: e.g. constraints on small-x evolution**
- **SPECIFIC EXAMPLES :**
- **Indications for a less rapid growth of $Q_S(x)$ as compared to RHIC or HERA.**
- **High-density effects increase inelasticity (forward suppression) --> hadron-induced showers resemble those of “nuclei” in present models (X_{max} lower, more μ, ...)**
- **Lighter Composition predicted**