Propagation of Cosmic Rays in Magnetized Protoplanetary Disks

Soonyoung Roh
UNIST (Ulsan National Institute of Science and Technology), Korea

in Collaboration with Yuri I. Fujii and Marco Padovani

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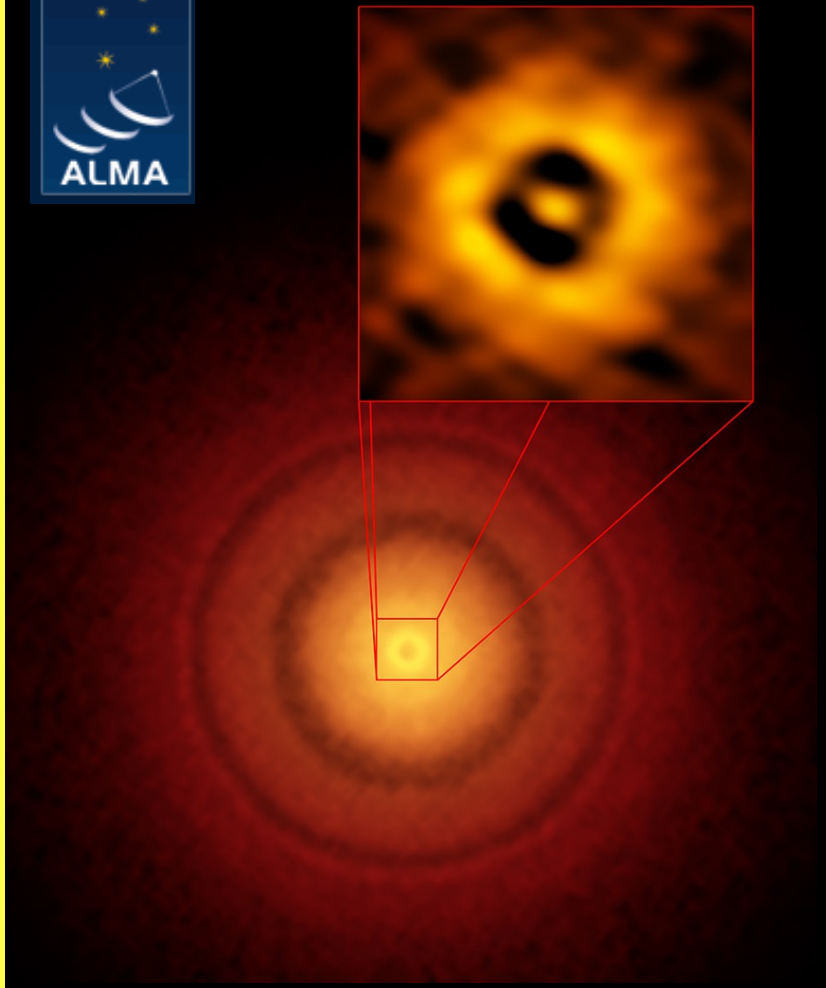
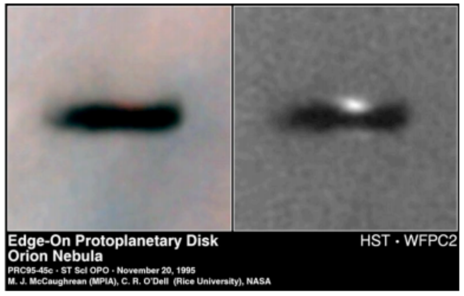
ALMA's Best Image of a Protoplanetary disk



Planets form in disks around young starts.

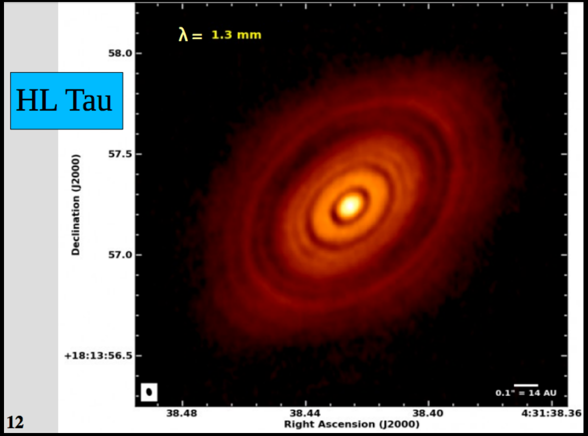
Credit: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)



Edge-On Protoplanetary Disk
Orion Nebula
PRC95-45c · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

HST · WFPC2

Egde-on PPD
Orion Nebula



New images from the ALMA reveal never-before-seen details in the planet-forming disk around Sun-like star.

Astrophysical Disk

Circular, coplanar and thin,Keplerian

Shearing, dissipative systems

- ✦ Shearing and differential rotation leading to viscous forces which cause radial motions.

- ✦ Dissipation: angular momentum transport outward, matter moves inward, energy liberated.
  => allow the accretion of gas on to the central star

- ✦ Angular momentum transport is the key to the evolution of protoplanetary disks.

The Magnetorotational instability (MRI)

Magnetorotational instability (MRI) is a promising mechanism that drives Magnetohydrodynamic (MHD) turbulence in accretion disk.

MHD turbulence is triggered and sustained in the disk by the MRI.

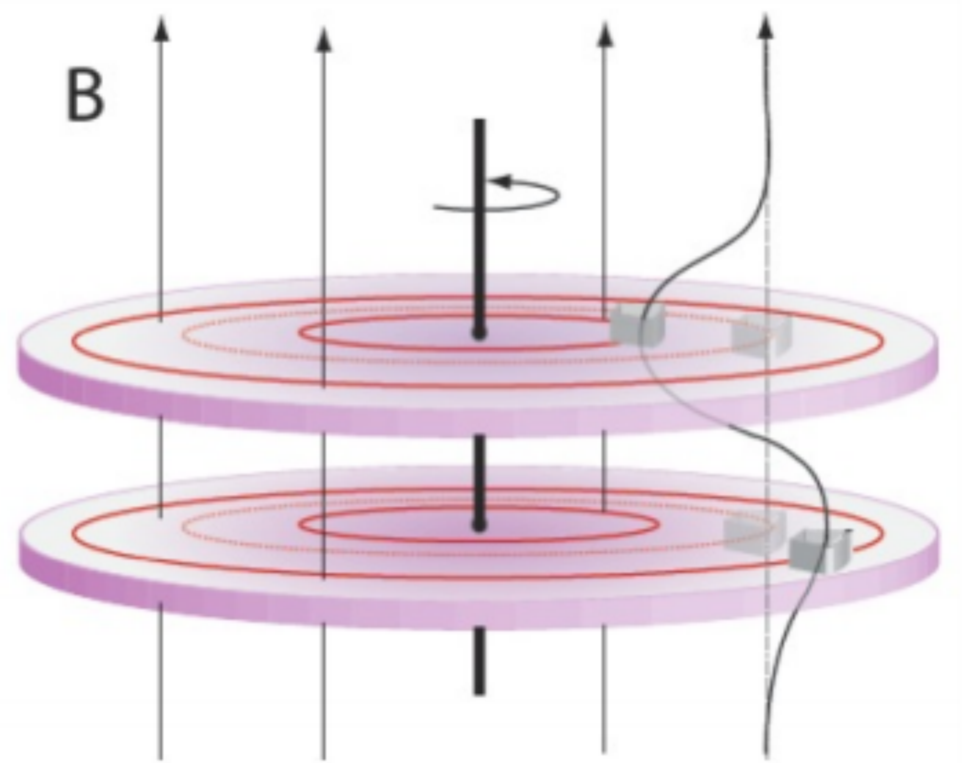


image courtesy of Nick Murphy' lecture

Balbus & Hawley 1991; Balbus & Hawley (1991)

The Magnetorotational instability (MRI)

The MRI requires good coupling between the disk gas and the magnetic field.

Sufficient ionization degree is needed.

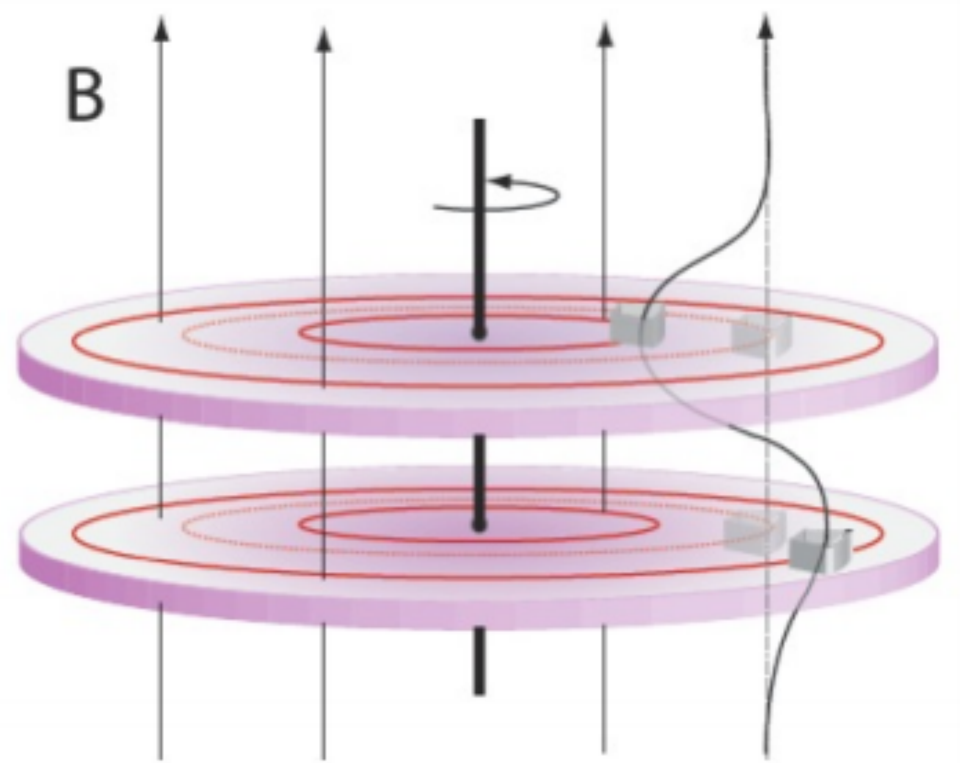


image courtesy of Nick Murphy' lecture

Umebayashi&Nakano 1981

Previous work

In many studies on ionization in PPDs, ionization rate by cosmic rays, ζ_{C}, is estimated as

$$\zeta_{\mathrm{C}} = \frac{\zeta_{\mathrm{CR}}}{2}\left\{\exp\left[-\frac{\chi(r,z)}{\chi_{\mathrm{CR}}}\right] + \exp\left[-\frac{\Sigma(r)-\chi(r,z)}{\chi_{\mathrm{CR}}}\right]\right\}$$

Umebayashi&Nakano 1981

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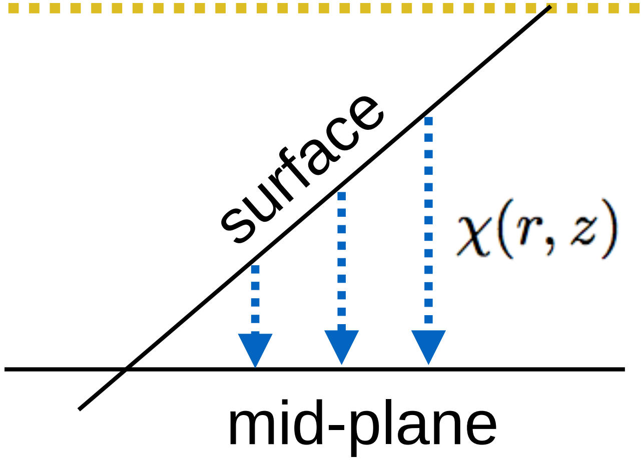

$$\chi(r,z) = \int_z^\infty \rho(r,z)dz \quad [\mathrm{g\ cm^{-2}}]$$

! : surface density

z: vertical direction

r : radius

! : density

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$$!_l = ""_z^{!}\ "(r,z)\,dl \quad [\mathrm{g\ cm^{-2}}]$$

! : surface density

r : radius

z: vertical direction

! : density

l: particle travel distance

Propagation of CRs

Solve relativistic equation of motion (4th-order Runge-Kutta Method) including energy loss equation

$$\mathbf{P} = \gamma m_i \mathbf{v} \qquad \frac{d\mathbf{P}}{dt} = q_i\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \quad + \text{ energy loss}$$

energy loss eq.

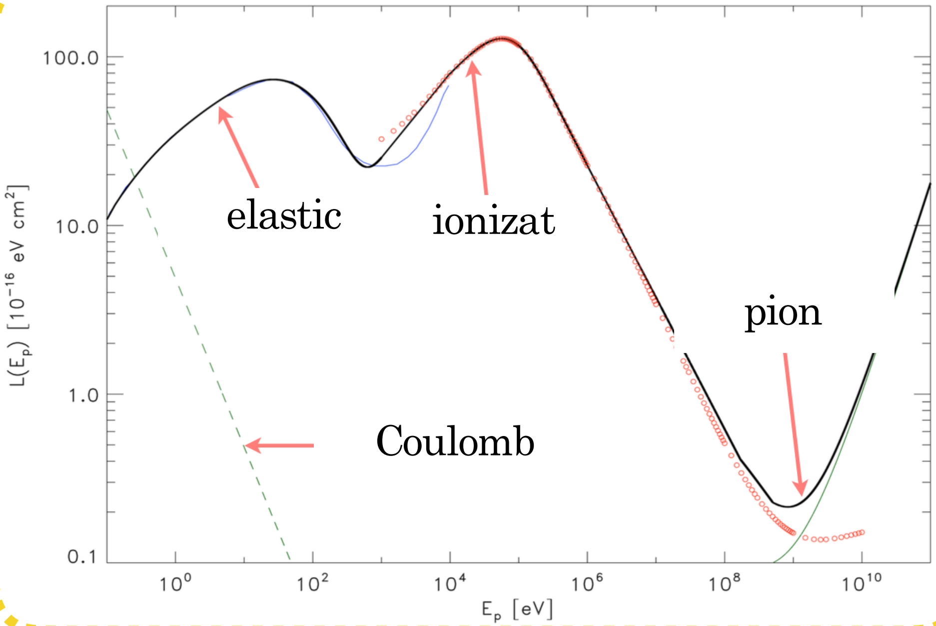
$$L_k(E_k) = -\frac{1}{n(\mathrm{H_2})}\left(\frac{\mathrm{d}E_k}{\mathrm{d}\ell}\right) = -\frac{\mathrm{d}E_k}{\mathrm{d}N(\mathrm{H_2})}$$

$$N(H_2) = \quad n(H_2)dl$$

dl [cm]: path length E_k [eV]: CR kinetic energy

$n(H_2)$ [cm^{-3}]: number density of the molecular hydrogen in the medium

$N(H_2)$ [cm^{-2}]: column number density of molecular hydrogen along a particle trajectory



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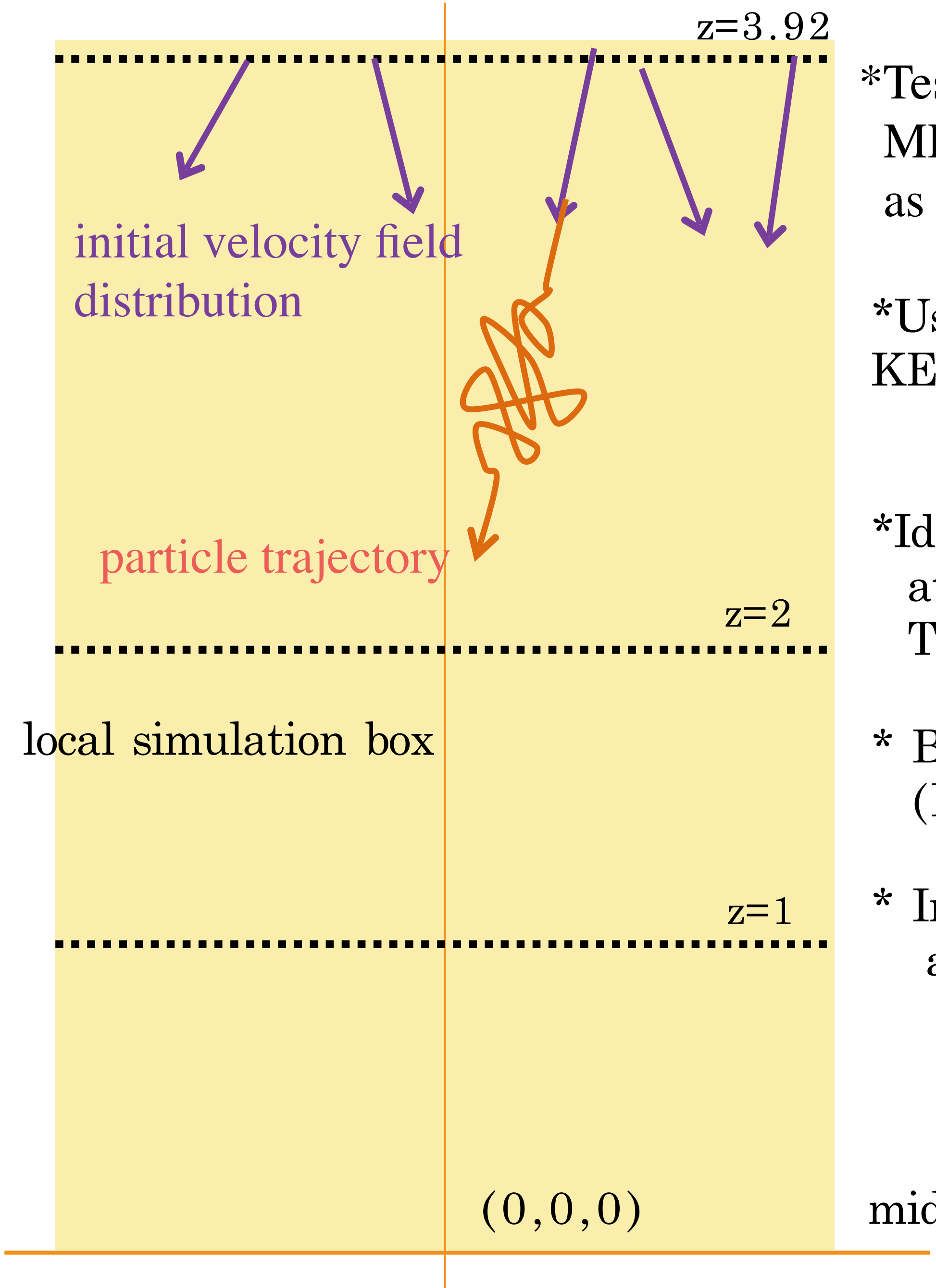
Simulation setup



*Test particle calculations of CRs using a snapshot of a MHD simulation of the MRI-active protoplanetary disk as the background.

*Used Particle energy ranges(0.5 million particles)
KE_0 = 10^6eV, 10^7eV, 10^8eV, 10^9eV, 10^{10}eV,
and 10^{11}eV

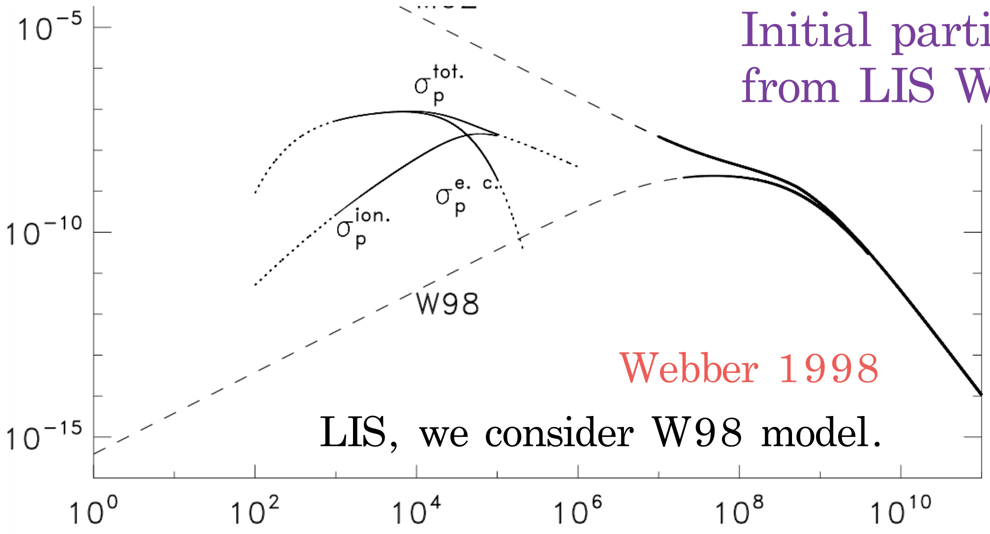
*Ideal-MHD simulation in a local box located at 1AU of a MMSN type of the disk
T~ 280K, plasma beta = 10^5 @mid-pnace

* Box size
(Lx, Ly, Lz)=(±1H, ±1H, ±4H)

* Initial position and velocity distributions are randomly generated.

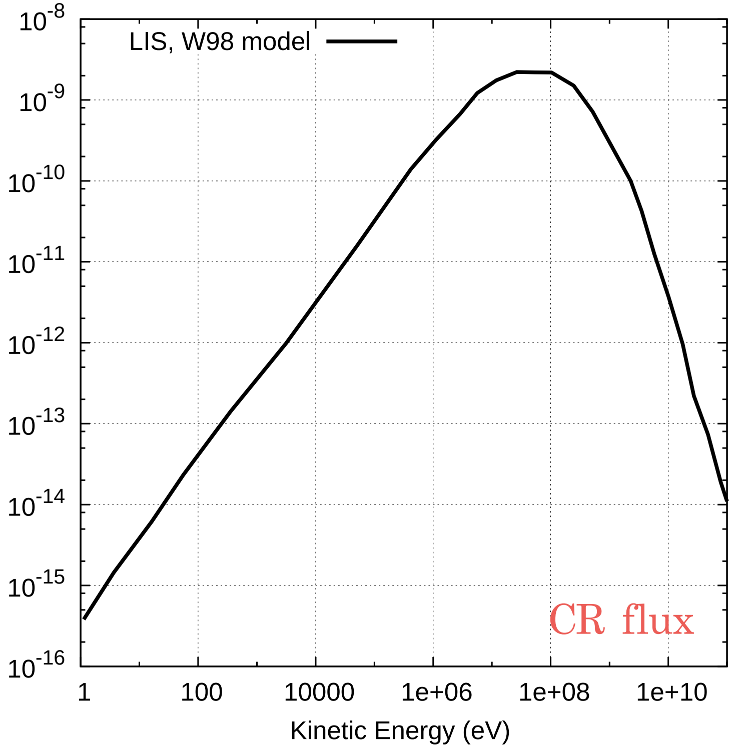
Particle distribution

Initial particle distribution is obtained from LIS W98 model.



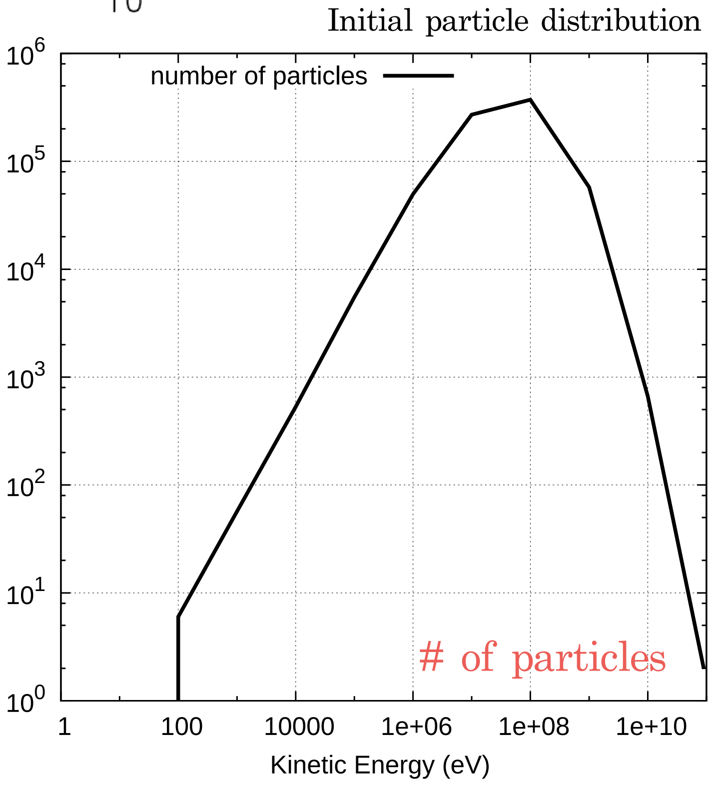
Webber 1998

LIS, we consider W98 model.



CR flux

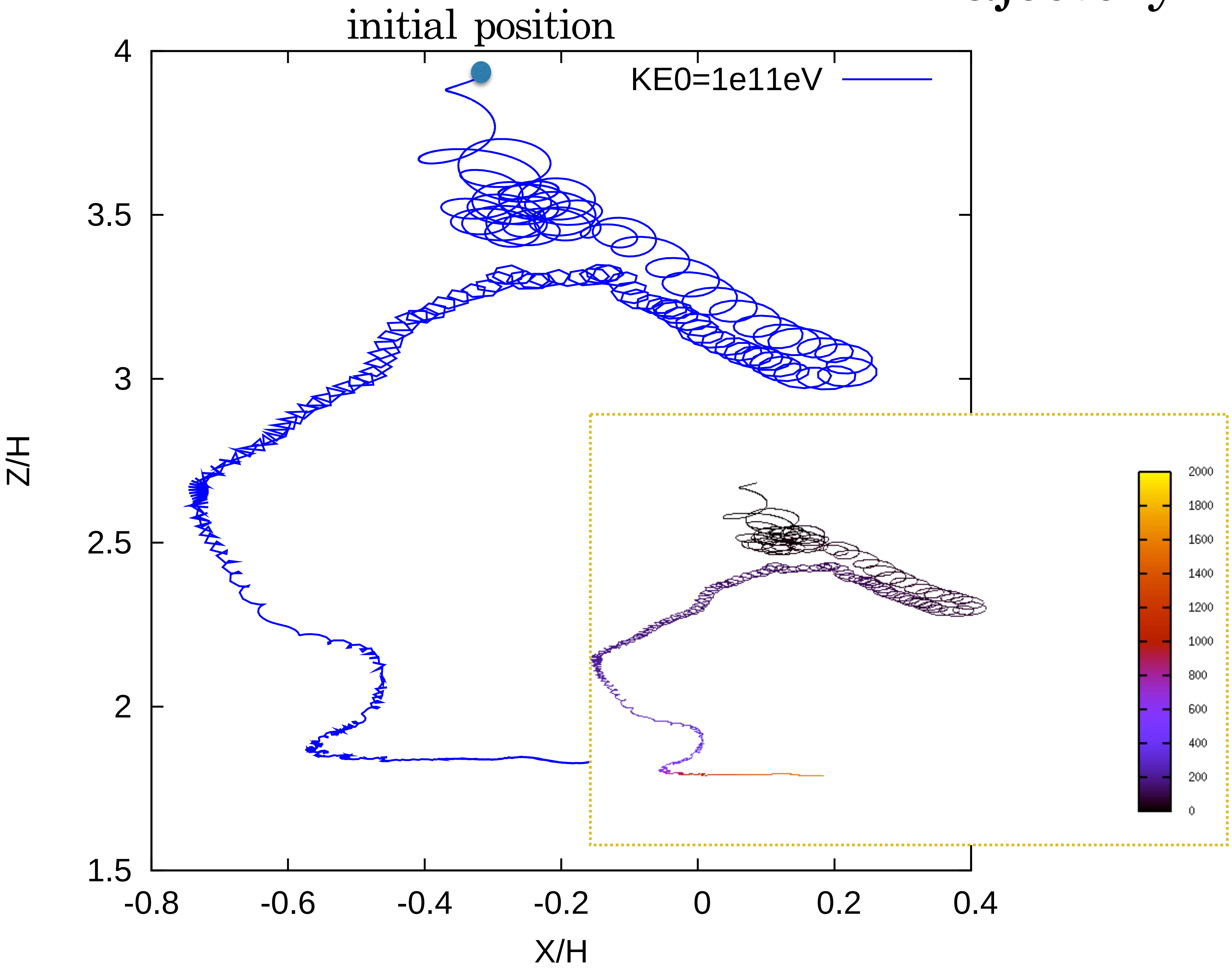
Generated
from
W98 model

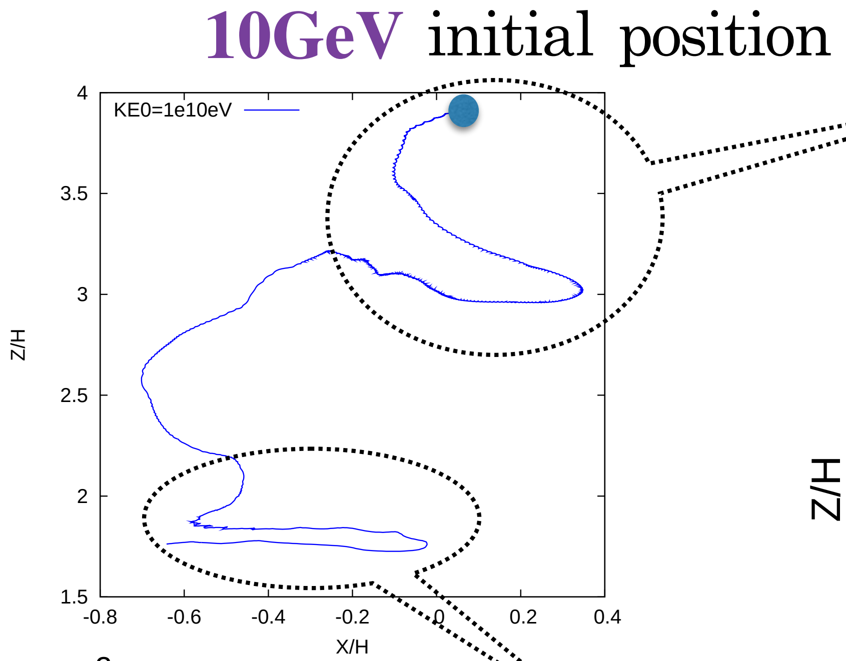


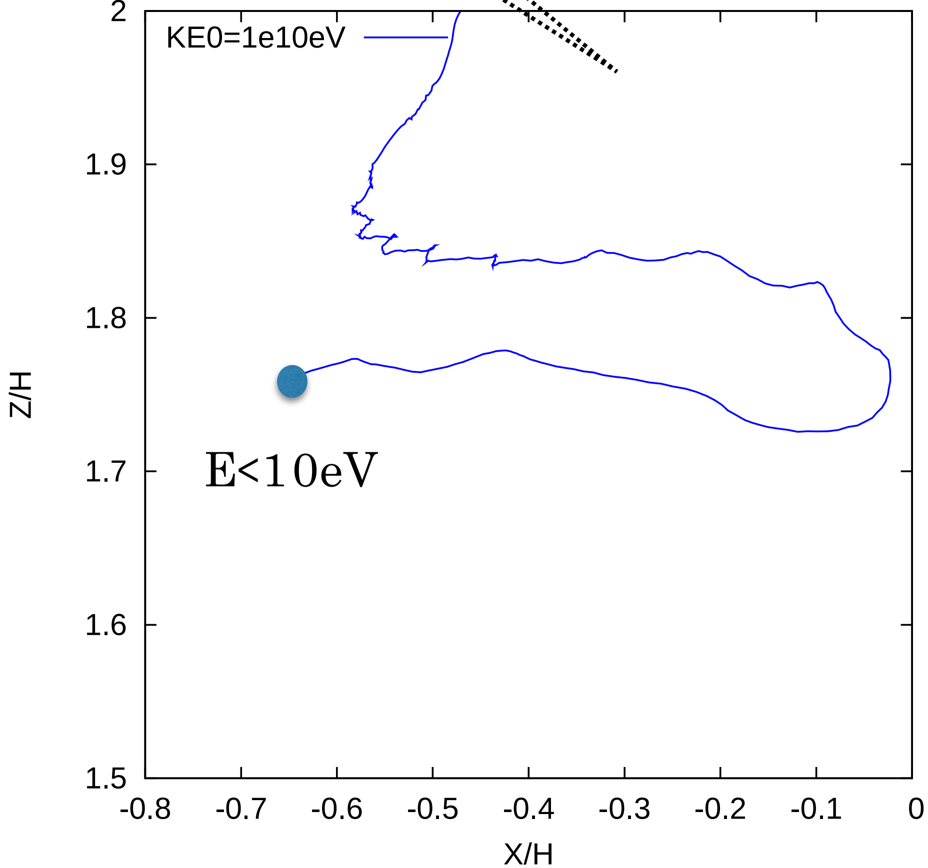
# of particles

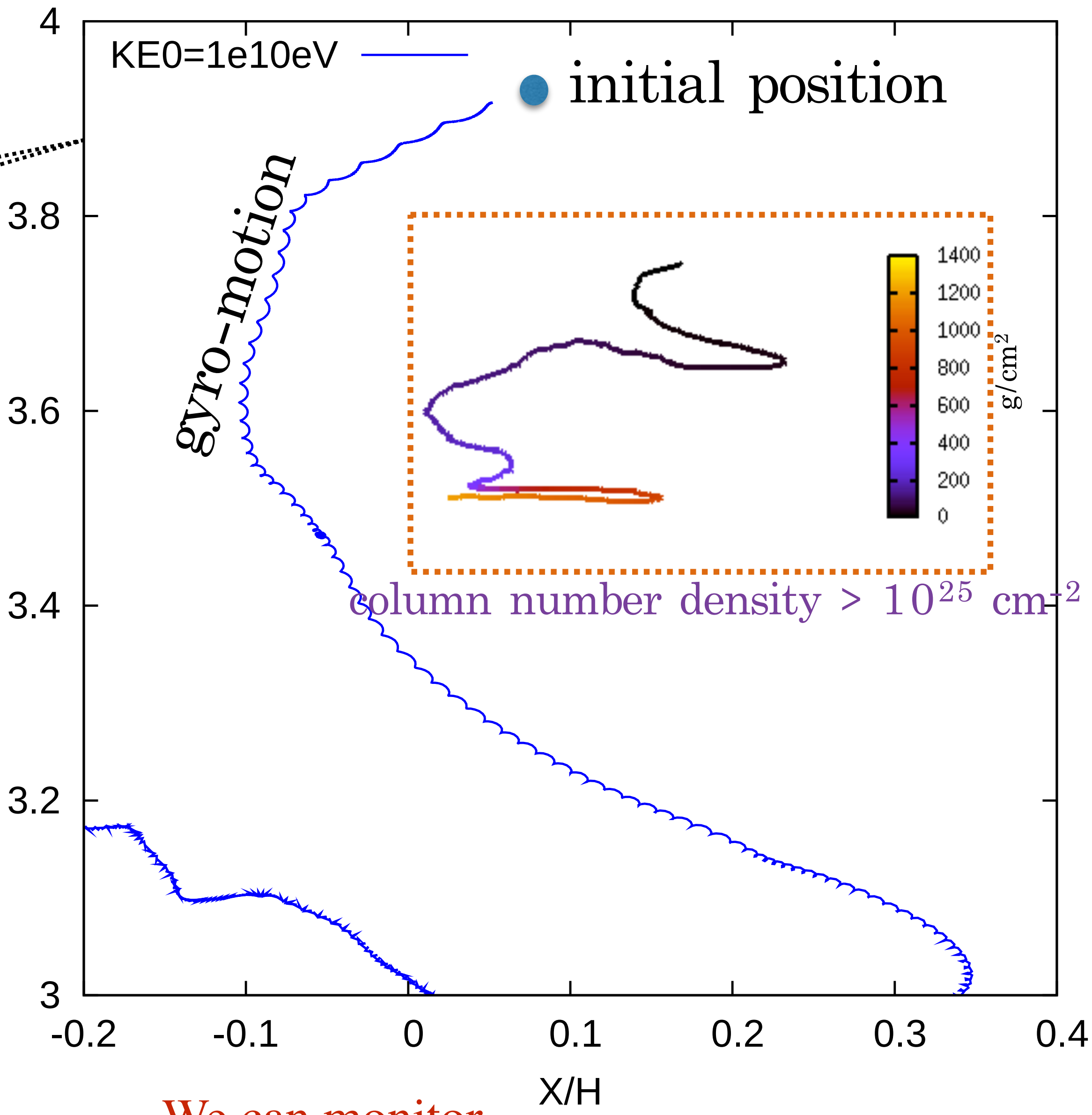
Trajectory

* particle trajectories: initial kinetic energy 100GeV









We can monitor

- -Energy (momentum)
- -B and v @ particle position
- -Column density along the path
- -Energy loss (collision + eq. of motion)
- -Pitch-angle

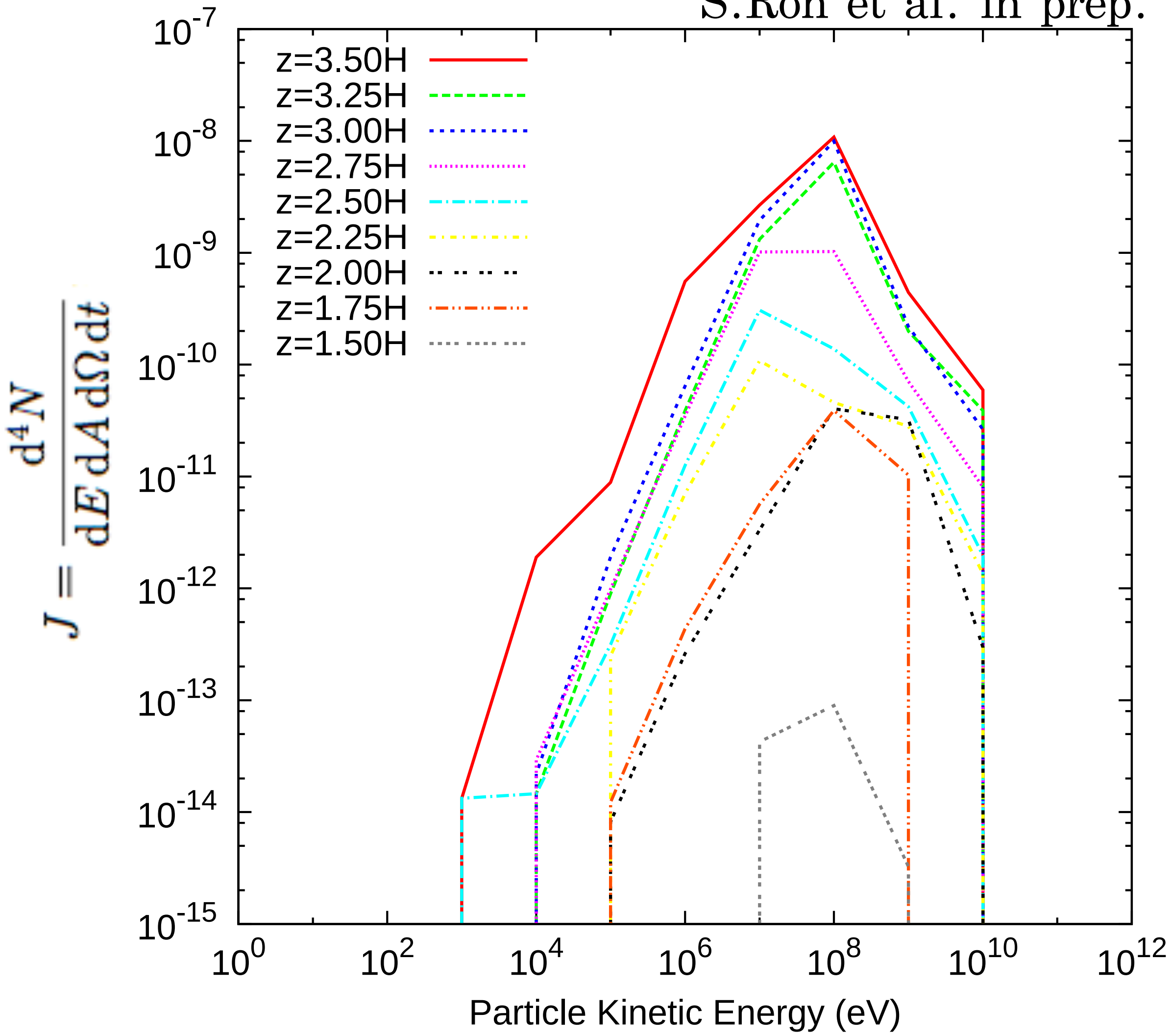
Cosmic Ray Flux

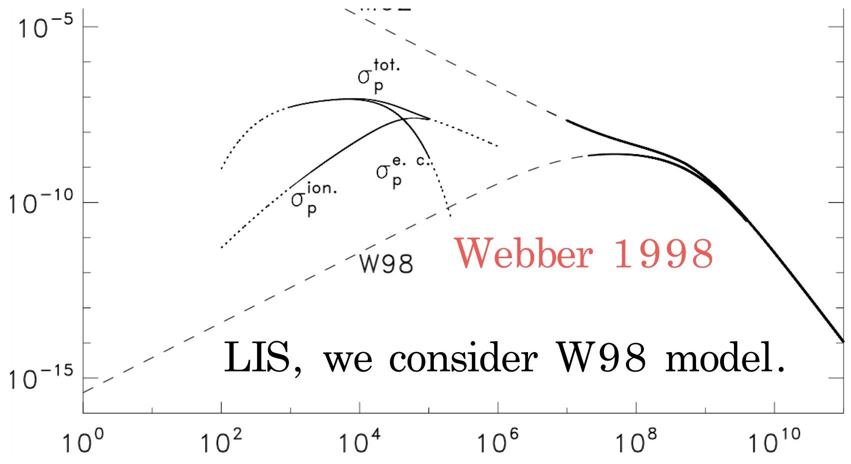
The following definition of the differential cosmic ray flux J is used:

$$J = \frac{d^4 N}{dE\, dA\, d\Omega\, dt}$$

where dN is the number of particles in the energy range dE, passing through an area and solid angle elements dA and dΩ in a time interval dt.(A. Dmitry et al. 2016)

S.Roh et al. in prep.





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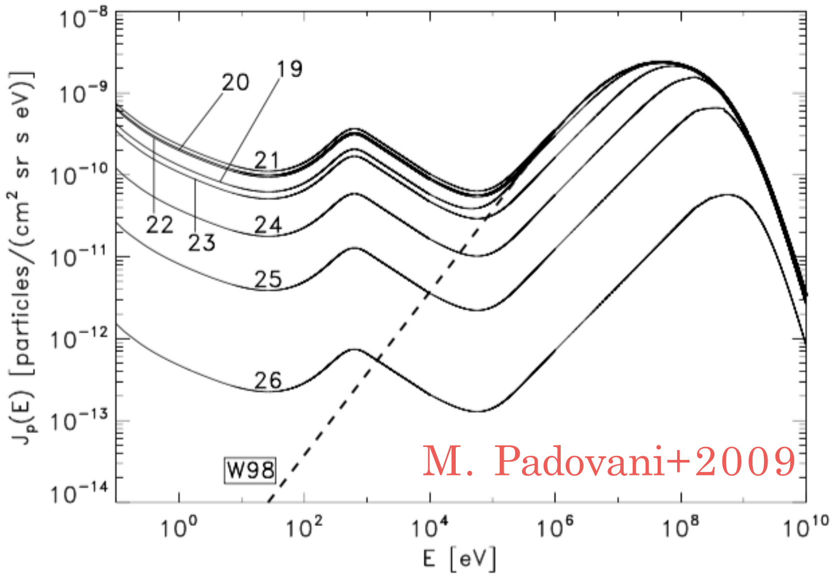

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Summary and Conclusion

- Ionization rate plays an important role in setting chemical and physical fate of disks and ultimately that of planets form there.
- CRs are believed to be a primary ionization source in deep inside of a disk (e.q., Glassgold et al. 1997; Walsh et al. 2012) due to their deep penetration.
- Actual path of cosmic ray propagation is complicated due to gyro motion along turbulent magnetic field.

-In order to quantitatively analyze the propagation of CRs considering energy loss processes in magnetized PPDs, we have performed test particle calculations of CRs .

-Consider the local interstellar spectrum of CRs and calculated their trajectories in the disk.

-Ionization Rate @ each height: r elation to the ionization rate within the disk.