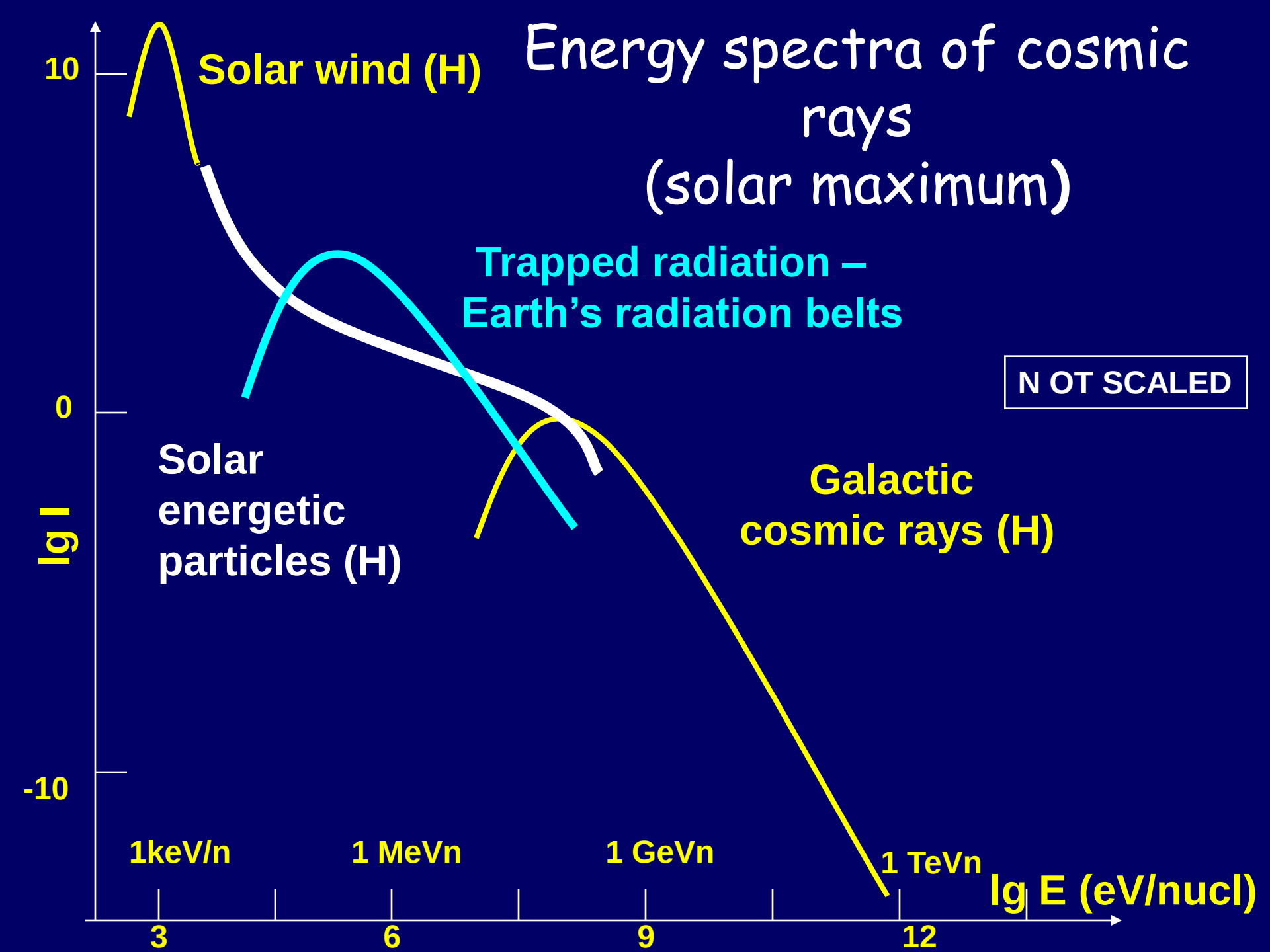
"Energetic particles acceleration in planet magnetospheres and in the Galaxy: unsolved problems"

Mikhail Panasyuk

Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University

"Plasma in Astrophysics and in the Laboratory: the Ignitor Challenge"
Round table in the Italian Embassy, 20-22 June, 2011

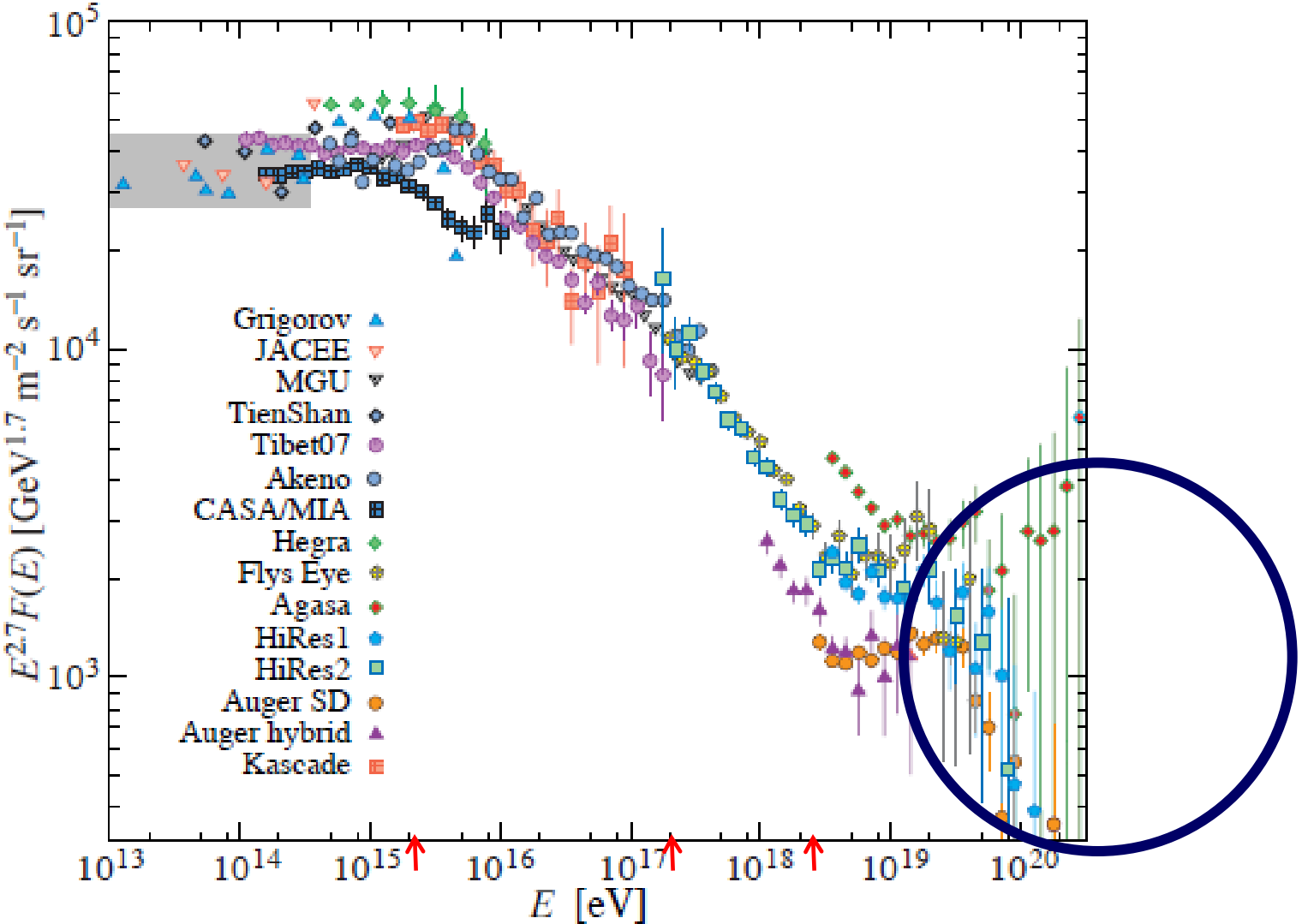

Energy spectra of cosmic rays (solar maximum)
Solar wind (H)
Trapped radiation – Earth's radiation belts
N OT SCALED
Solar energetic particles (H)
Galactic cosmic rays (H)
10
0
-10
lg I
1keV/n
1 MeVn
1 GeVn
1 TeVn
lg E (eV/nucl)
3
6
9
12

CR astrophysics main problems

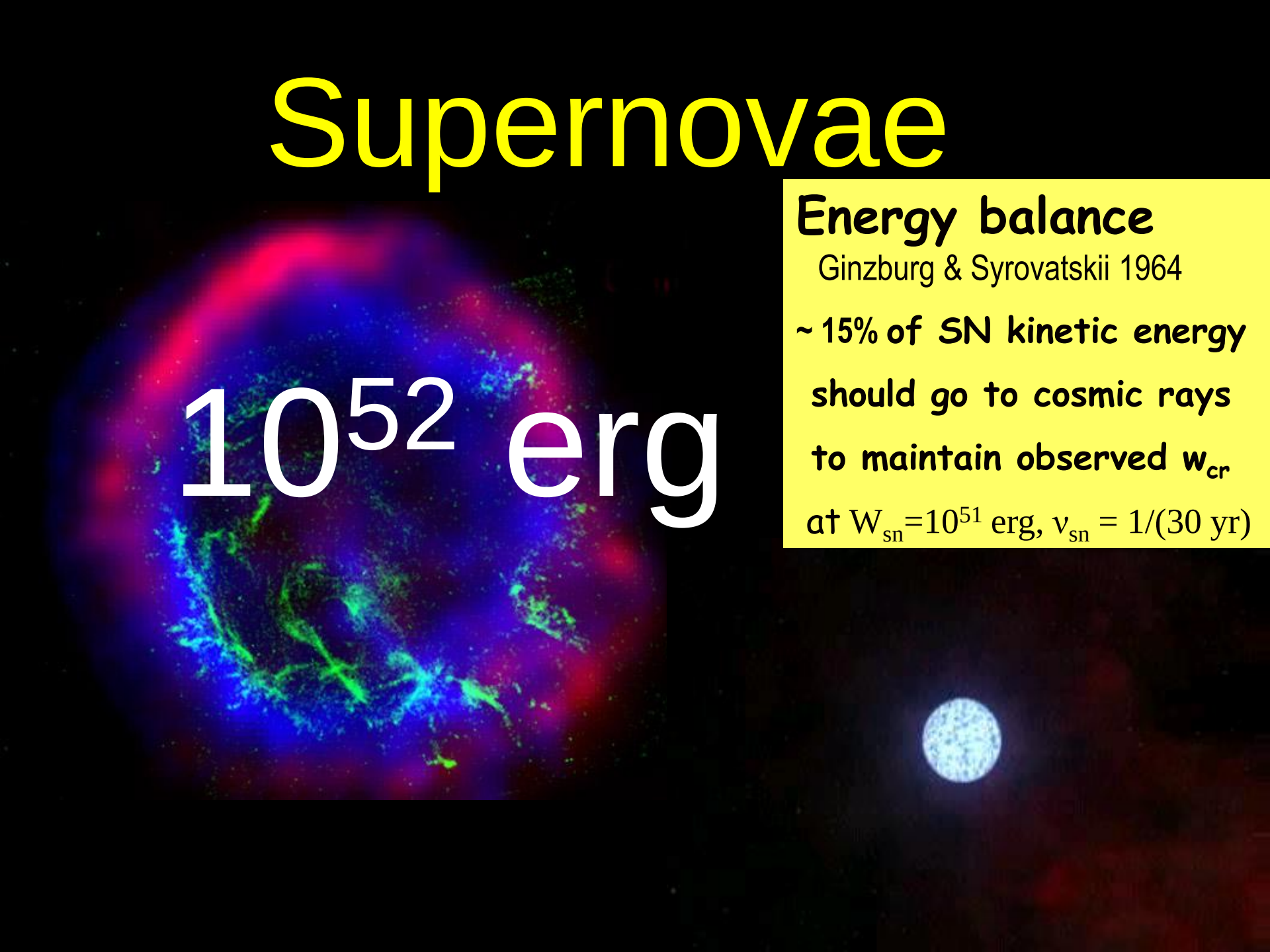
Sources ?

-Accelerators?

All particles energy spectrum of CR



Supernovae



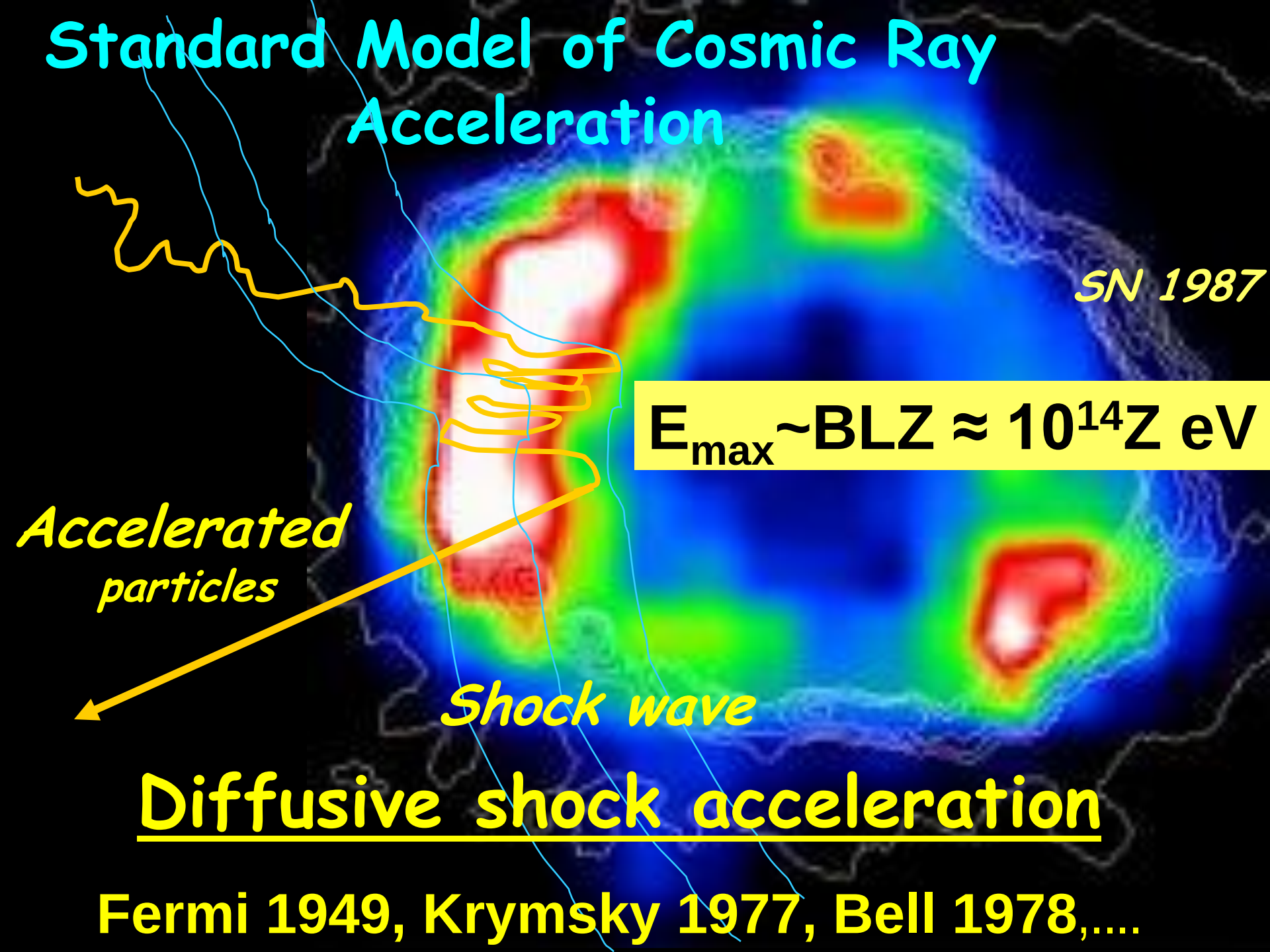
Energy balance

Ginzburg & Syrovatskii 1964

~ 15% of SN kinetic energy should go to cosmic rays to maintain observed w_{cr}

at $W_{sn}=10^{51}$ erg, ν_{sn} = 1/(30 yr)

Standard Model of Cosmic Ray Acceleration



Diffusive shock acceleration

Fermi 1949, Krymsky 1977, Bell 1978,....

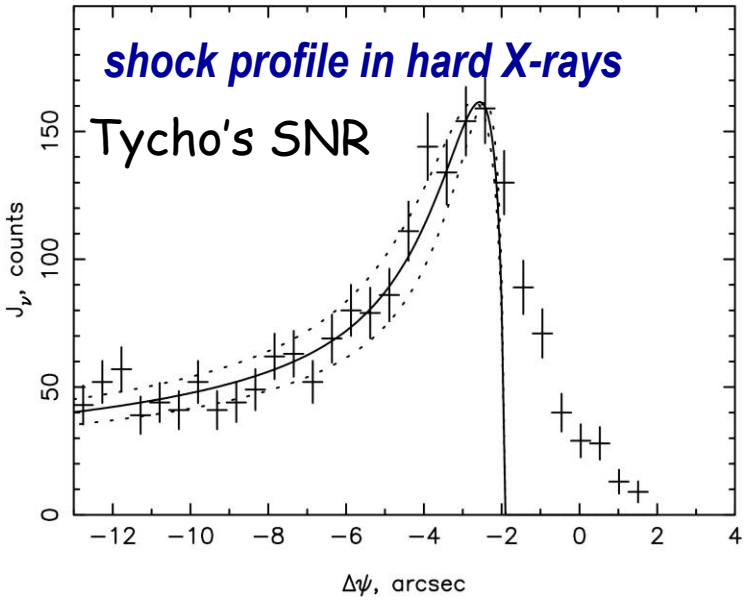
Сильные магнитные поля в остатках молодых сверхновых

Völk et al. magnetic field amplification in Tycho and other shell-type SNRs

B ~ 300 μG, for **Tycho's SNR**

consistent with synchrotron spectrum from acceleration theory

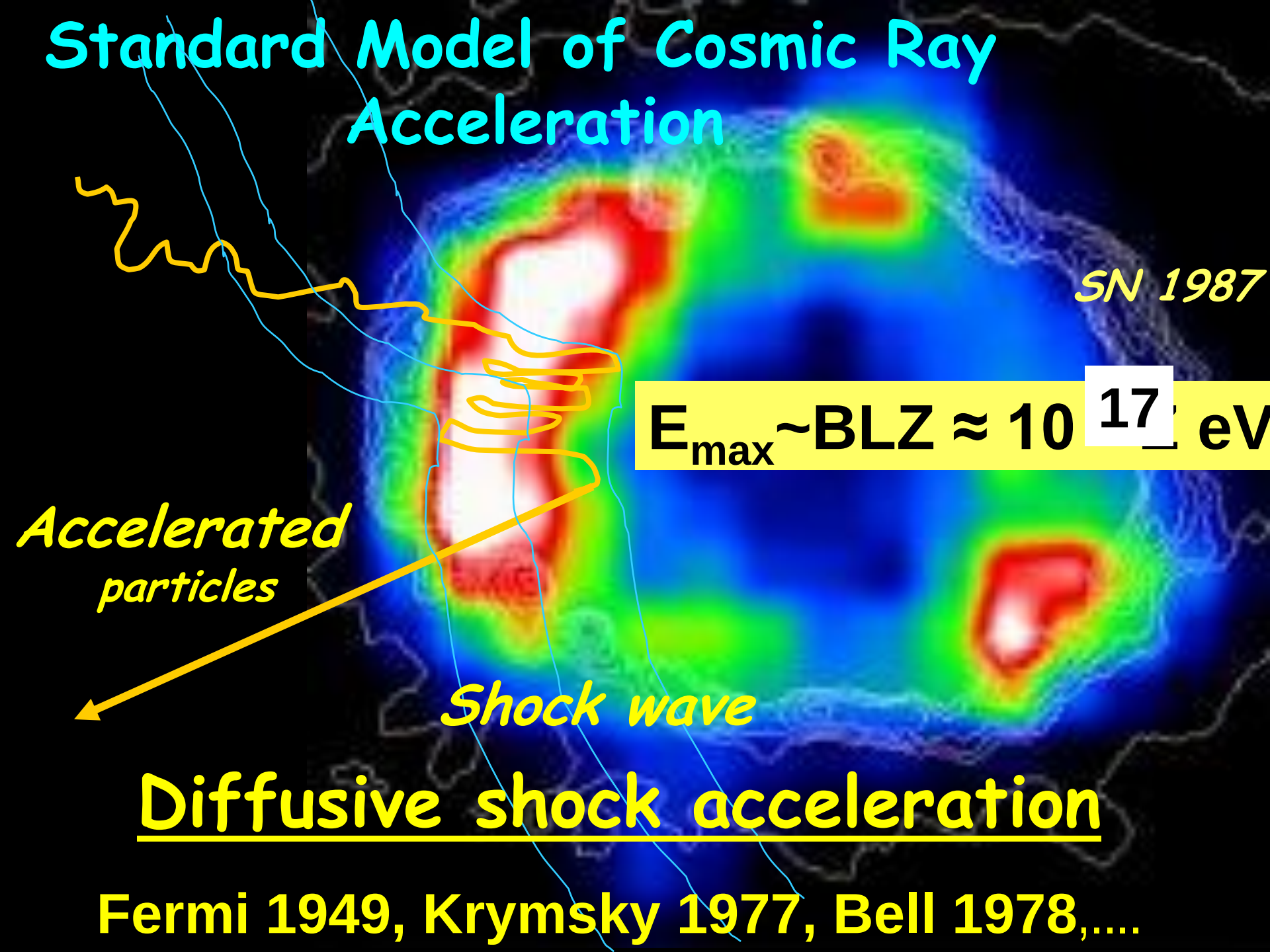
Similar amplification in all other SNRs where such data are available:
Cas A, **SN 1006**, Tycho, RCW 86, **Kepler**, RX J1713.7-3946, **Vela** Jr



diffusive shock acceleration of electrons, including synchrotron losses gives observed scale

→ very strong magnetic field in young SNRs is indirect but strong evidence of proton acceleration

Standard Model of Cosmic Ray Acceleration



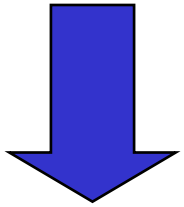
Diffusive shock acceleration

Fermi 1949, Krymsky 1977, Bell 1978,....

CR astrophysics main problems

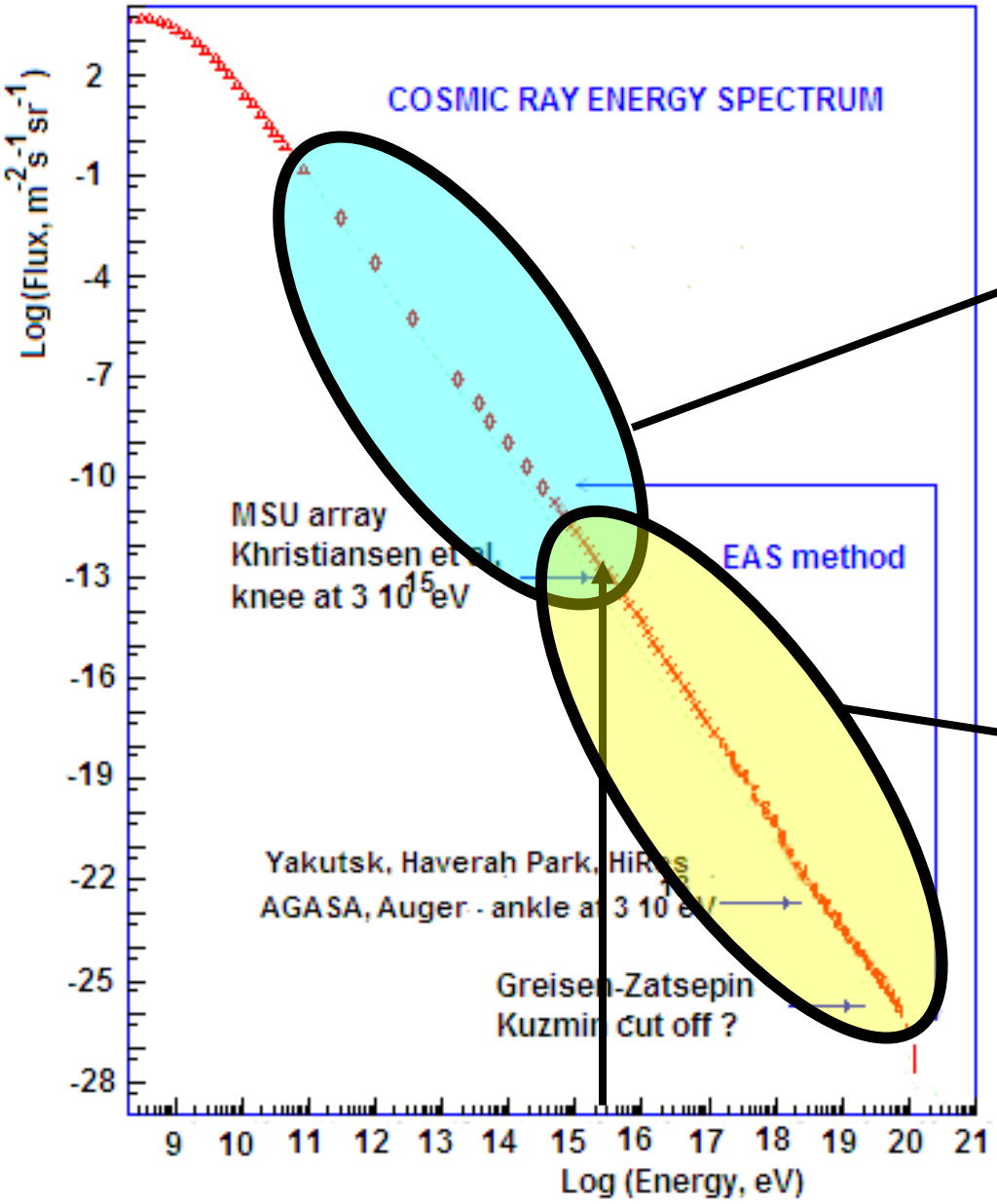
Sources ?

-Accelerators?



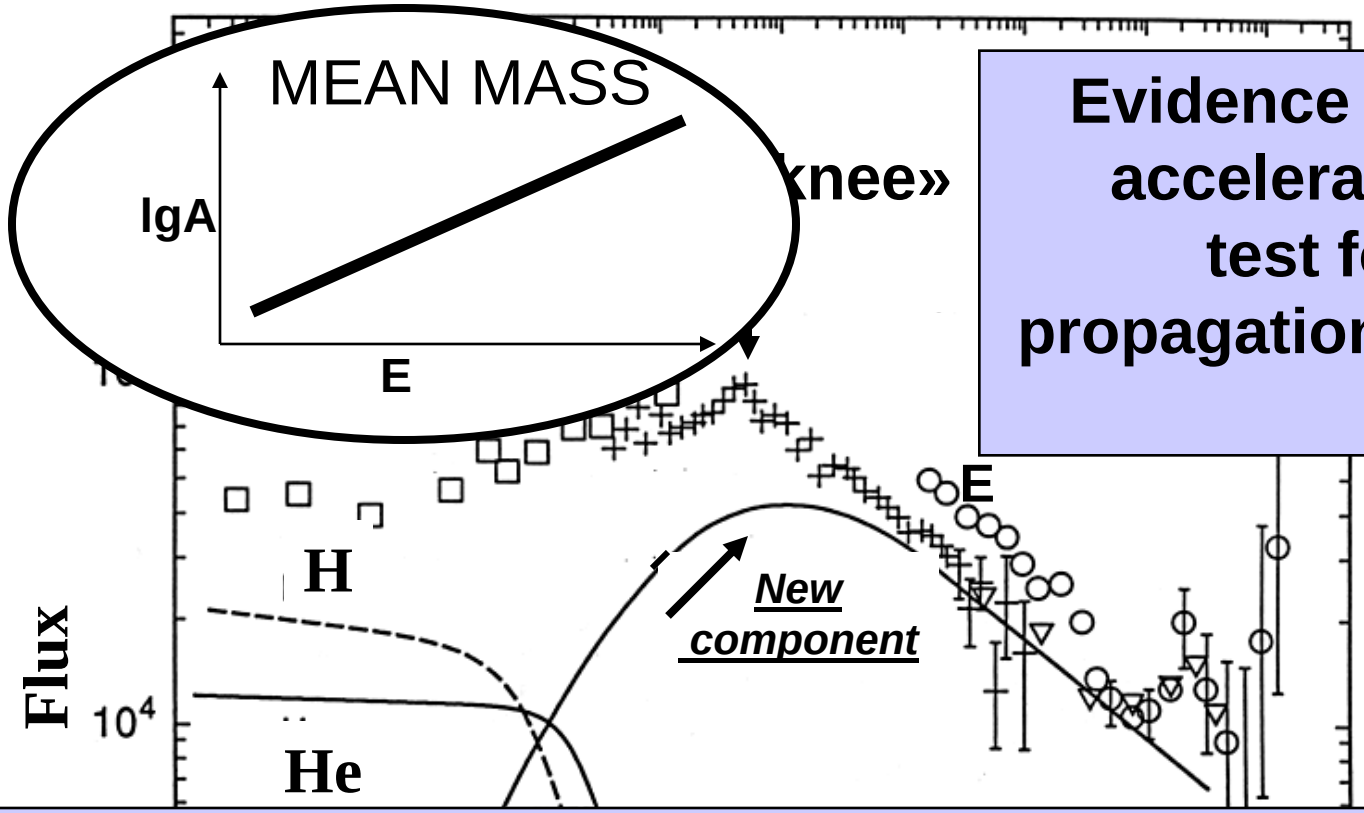
Mass composition of CR is the key for answer on this questions

CR nuclei spectra



HE CR
Balloons
Satellites

HE CR
On ground installations

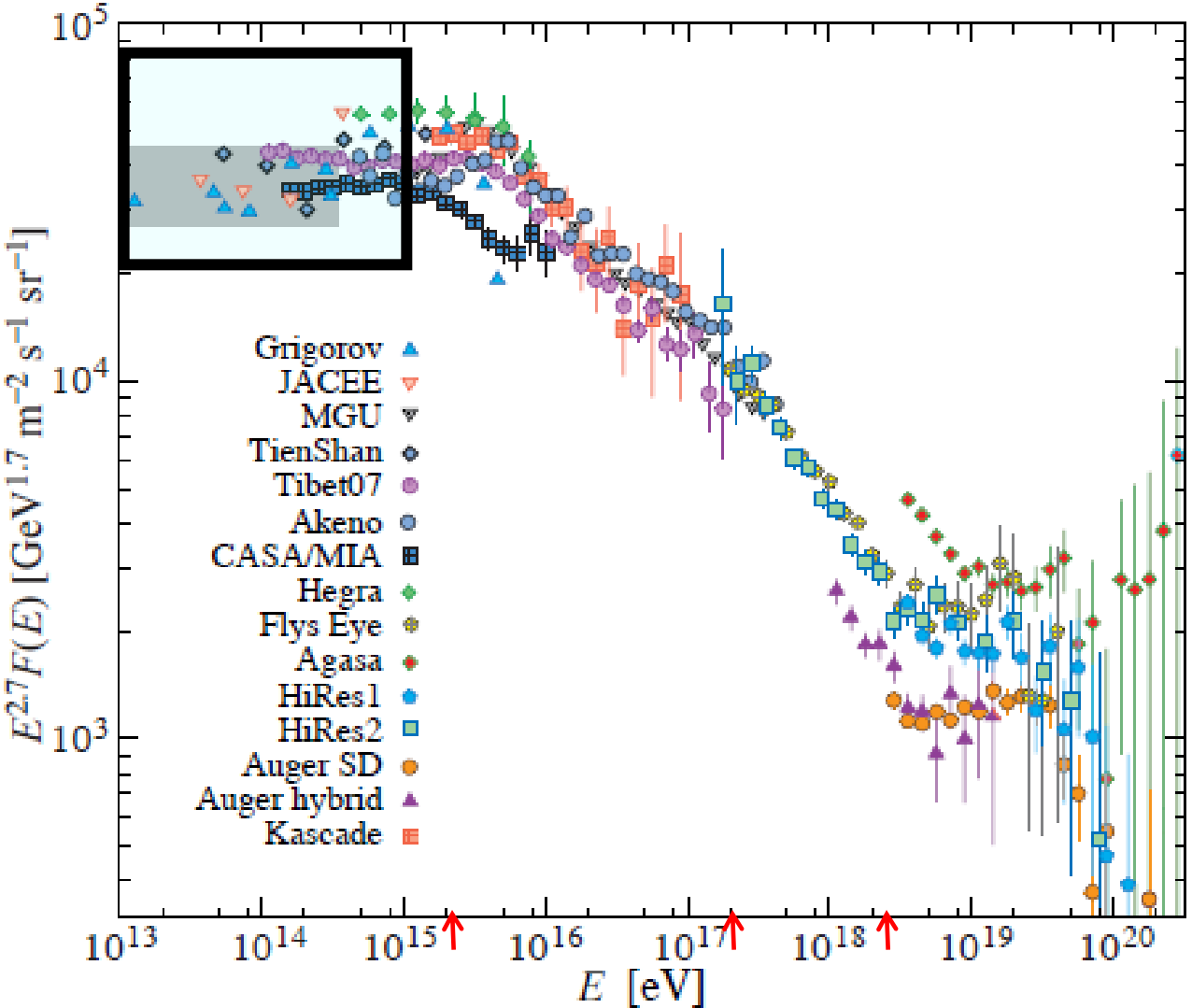


Evidence for SN acceleration, test for propagation models

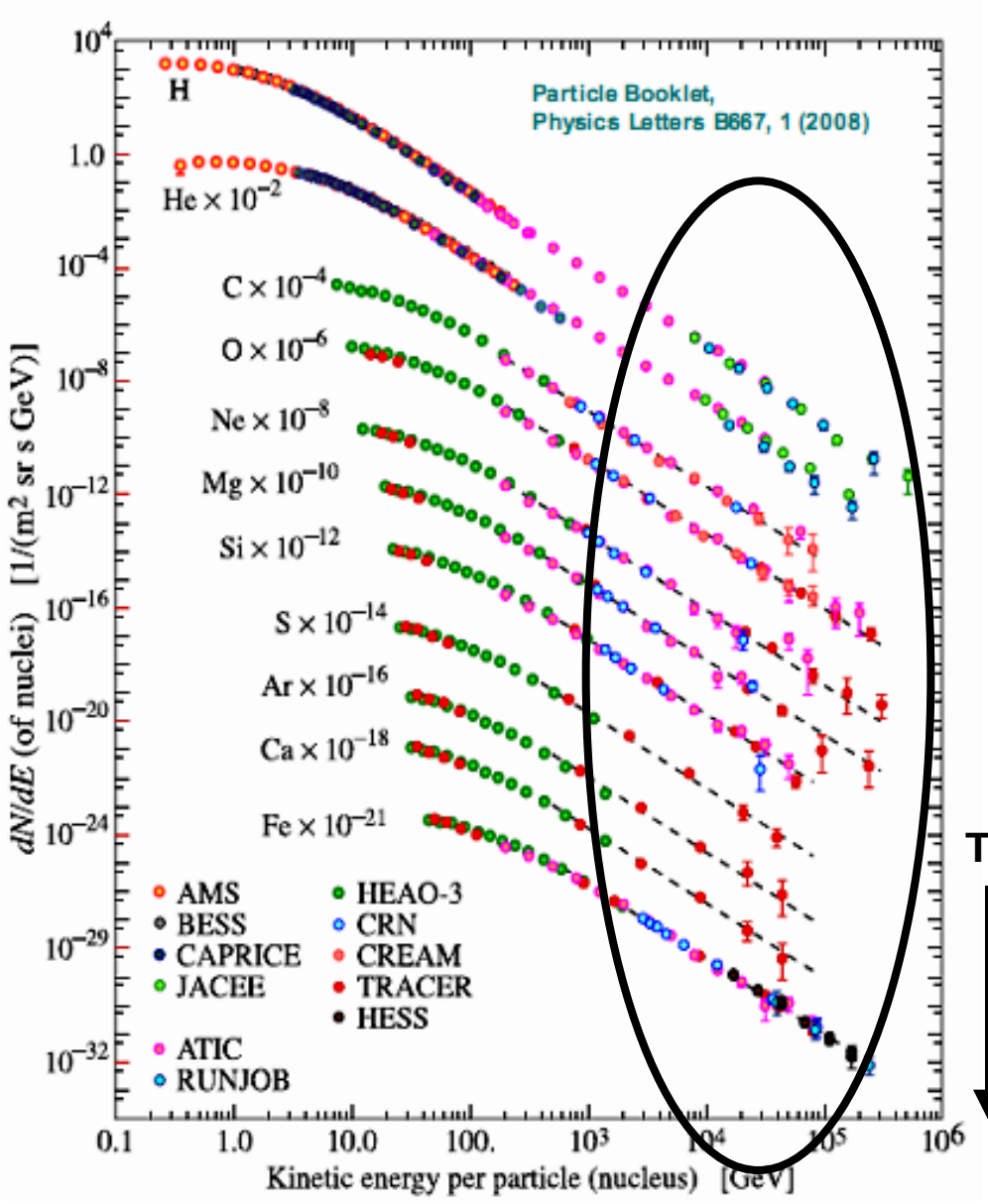
Chemical composition around 10*15 eV have to be changed because of consequences acceleration model :

E~Z

Energy spectrum of CR



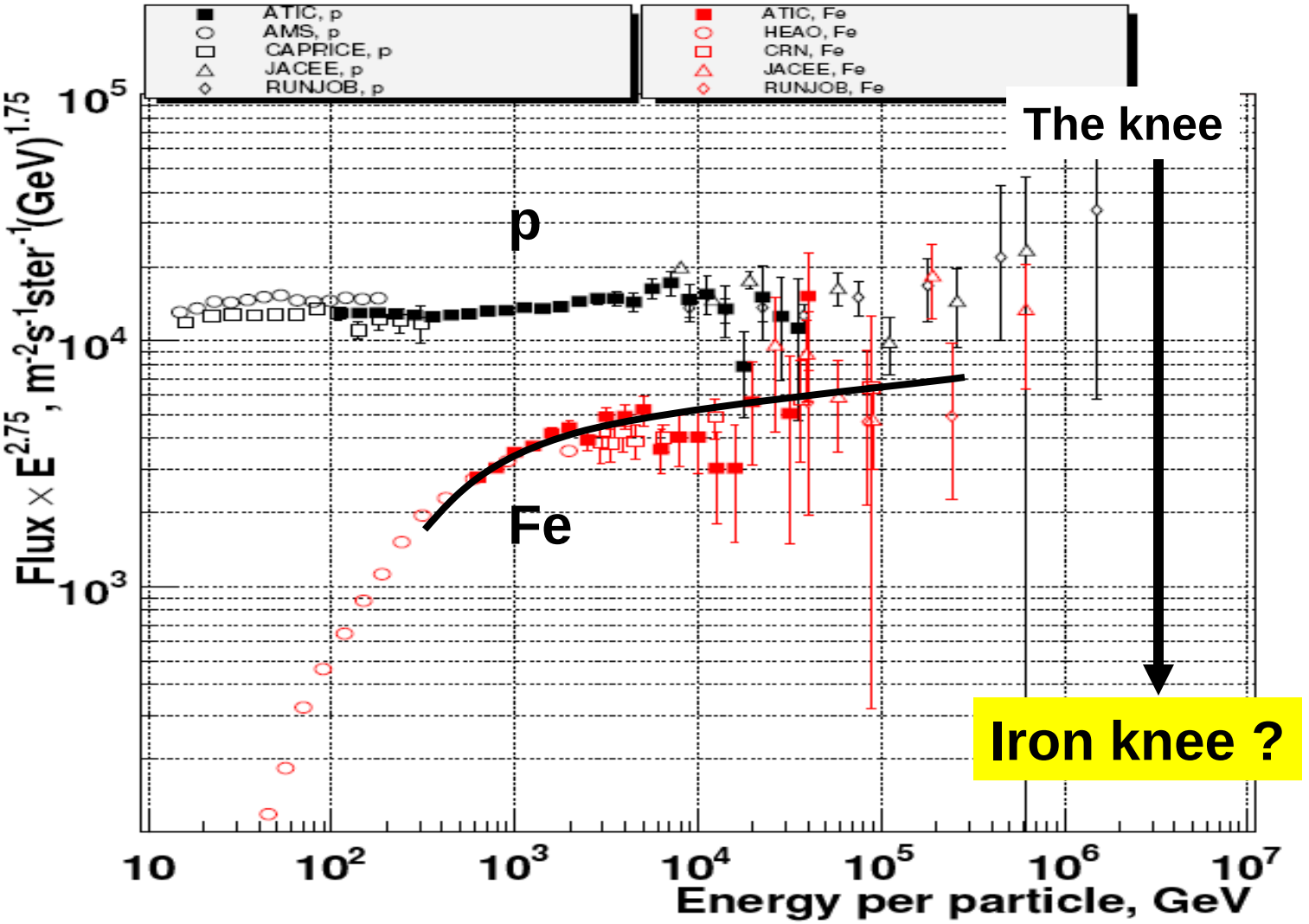
CR nuclei spectra below the knee



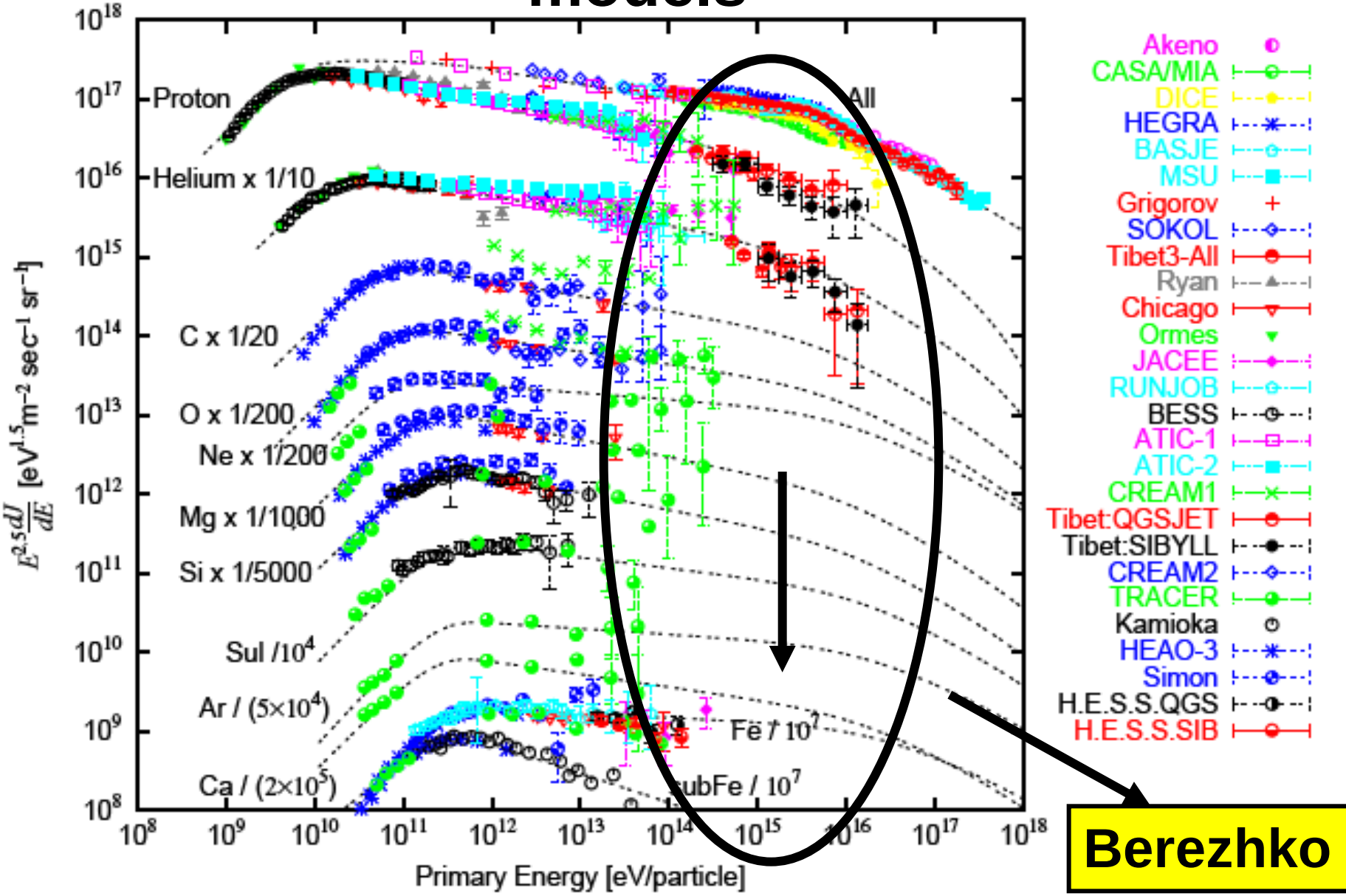
Spectra with the same slope?

The knee

Average mass definition below “the knee” – the real test for current models

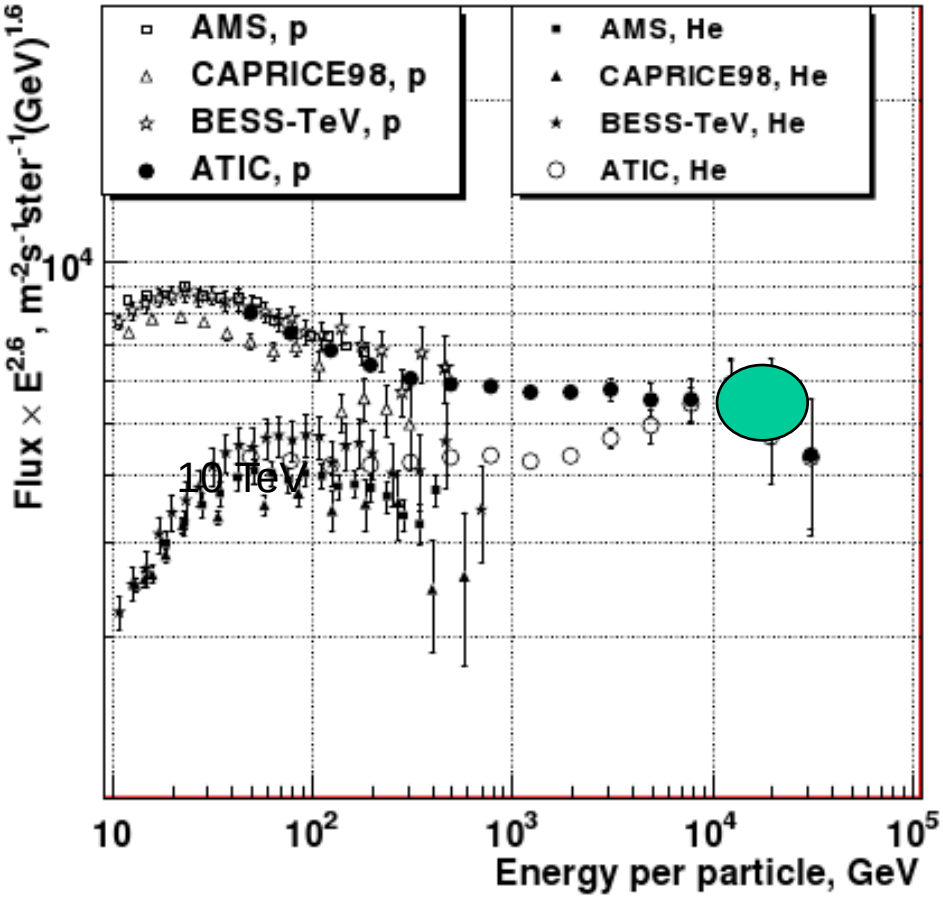


CR chemical composition & SN acceleration models



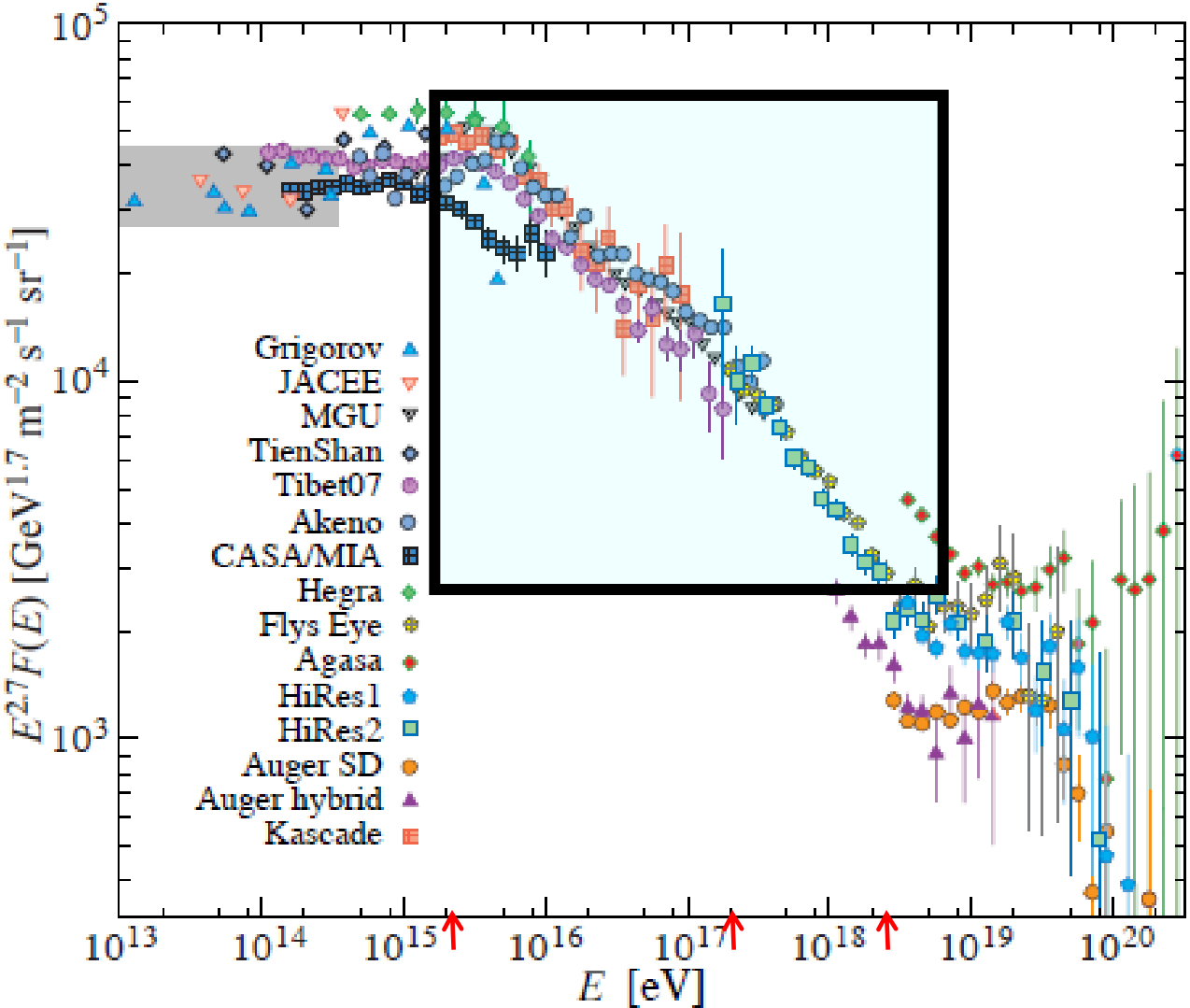
Proton and helium spectra and the multiplicity of types of cosmic ray sources

Spectra for energy per particle

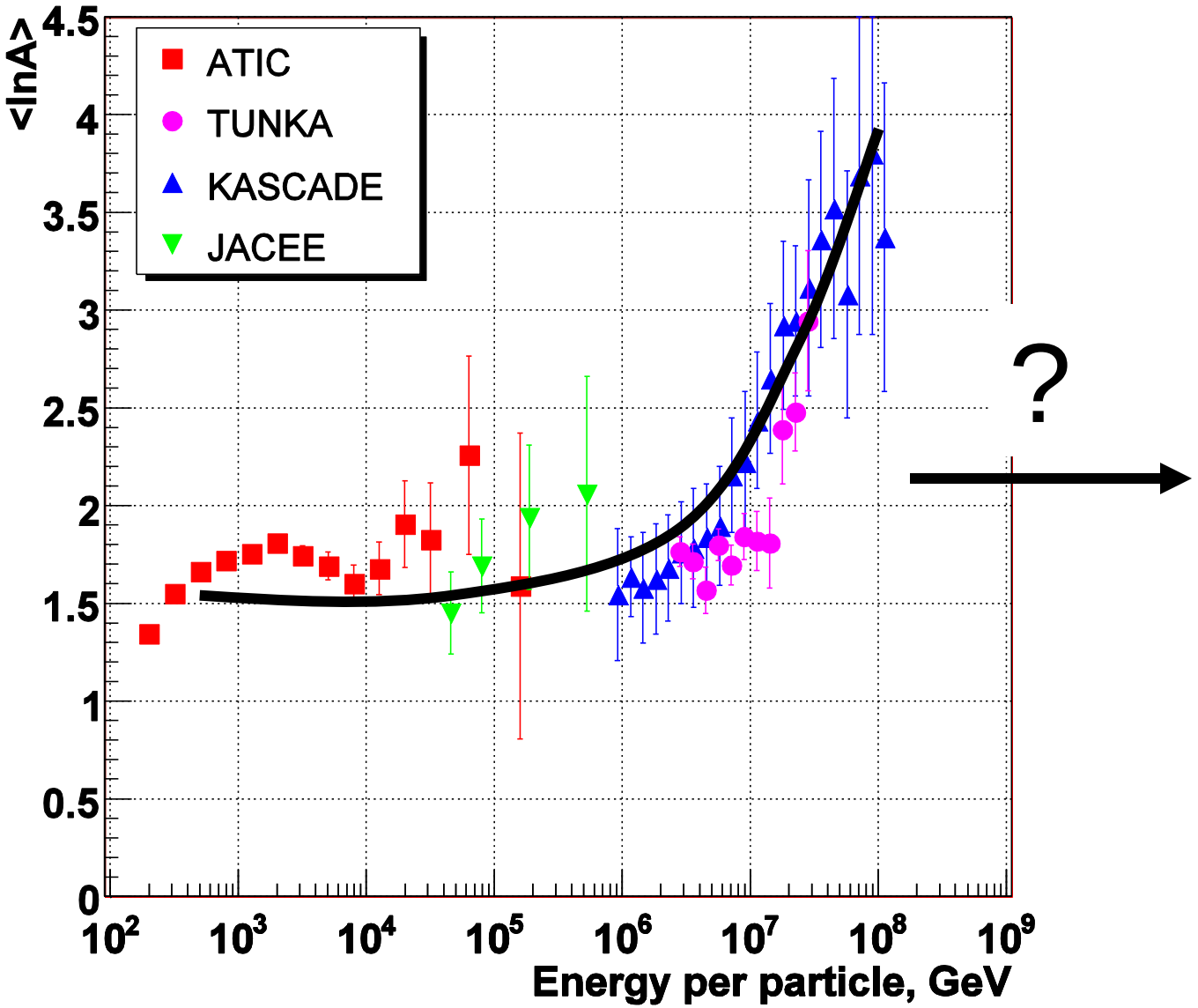


Beyond the 10*15 eV

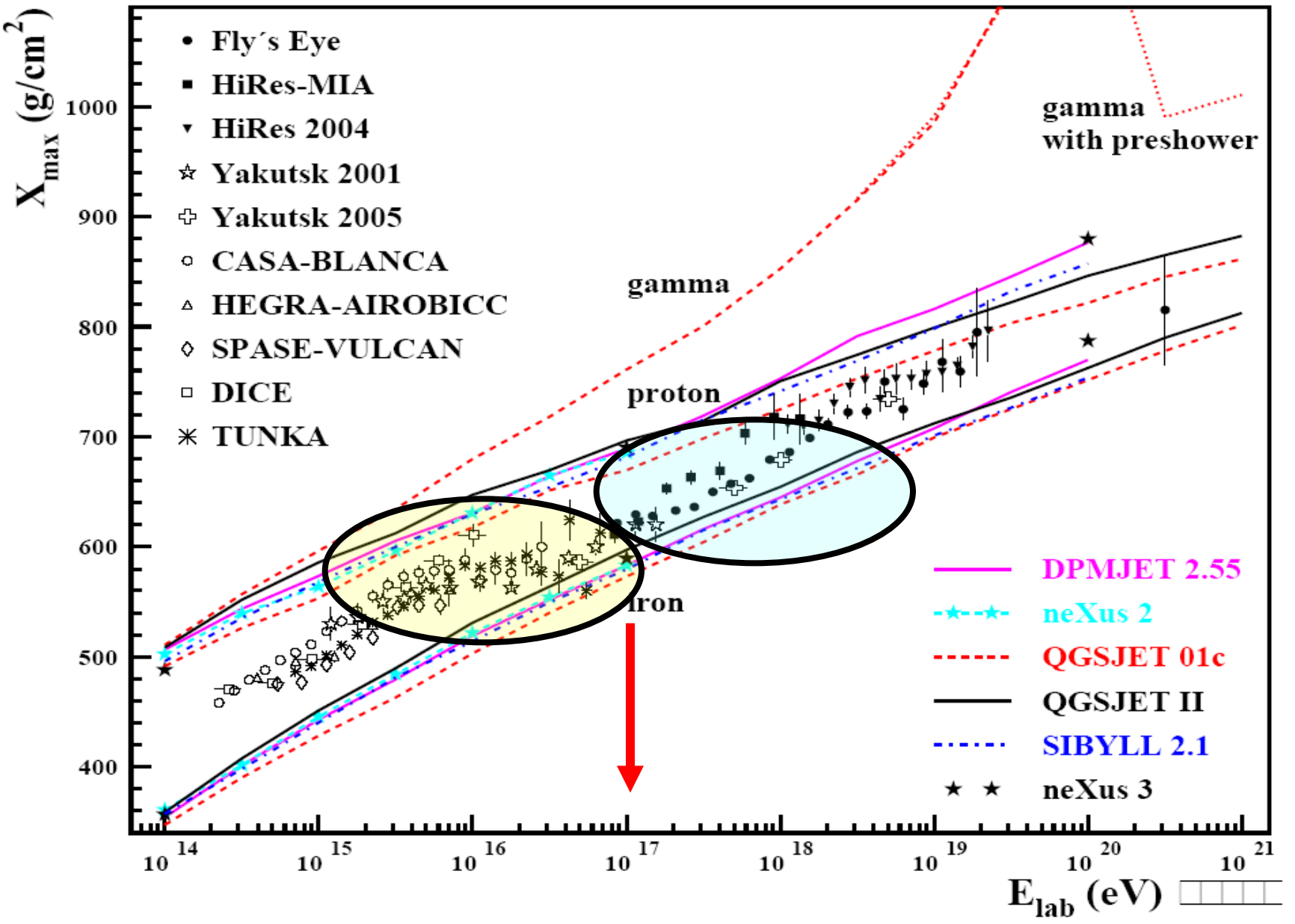
Energy spectrum of CR



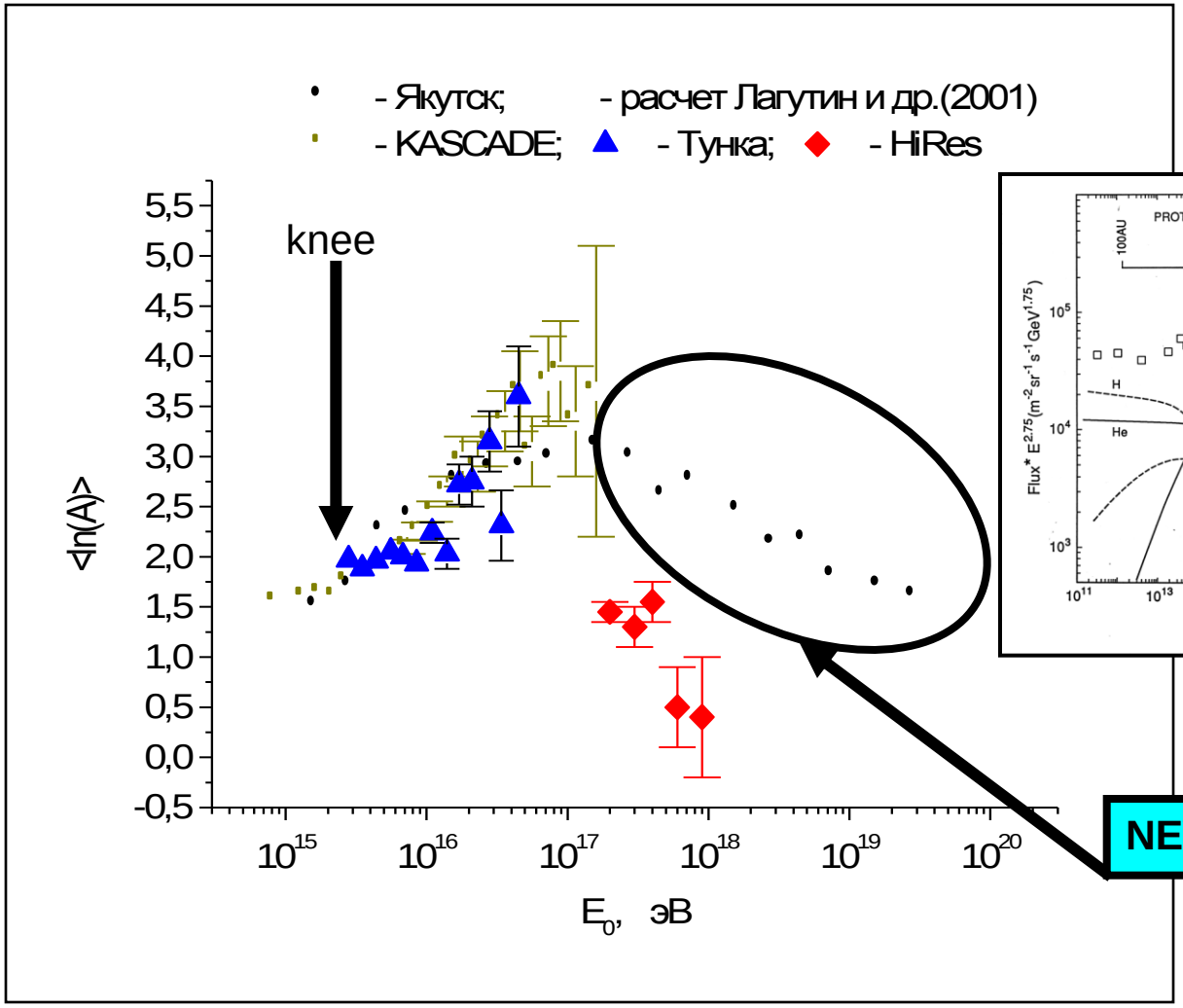
Mean mass composition dependence show enrichment by heavy ions



Beyond the 10*17 eV

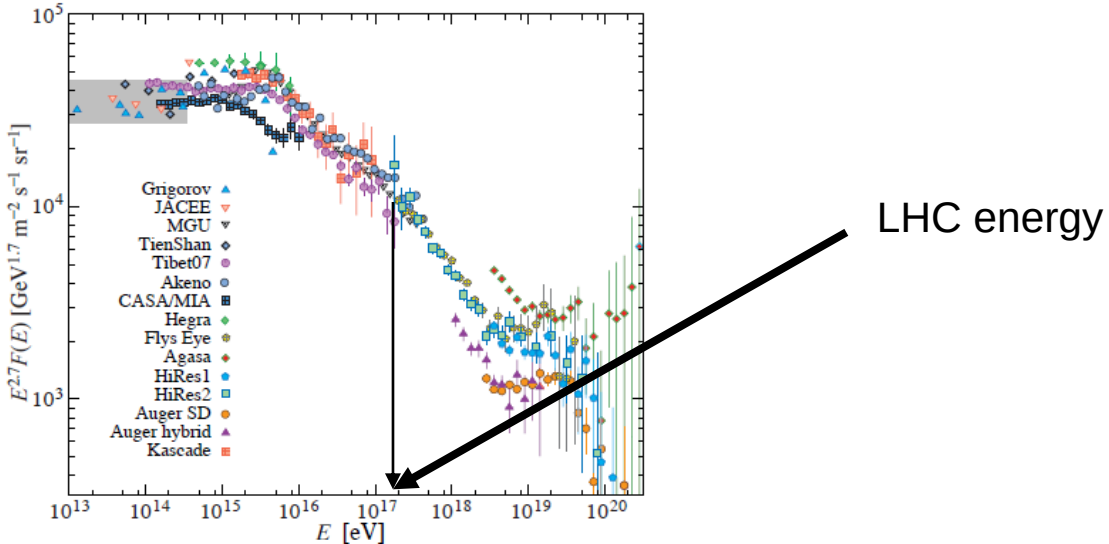

X_{max} (g/cm^2)
1000
900
800
700
600
500
400
Fly´s Eye
HiRes-MIA
HiRes 2004
Yakutsk 2001
Yakutsk 2005
CASA-BLANCA
HEGRA-AIROBICC
SPASE-VULCAN
DICE
TUNKA
gamma
with preshower
gamma
proton
Iron
DPMJET 2.55
neXus 2
QGSJET 01c
QGSJET II
SIBYLL 2.1
neXus 3
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}
10^{21}
E_{lab} (eV)

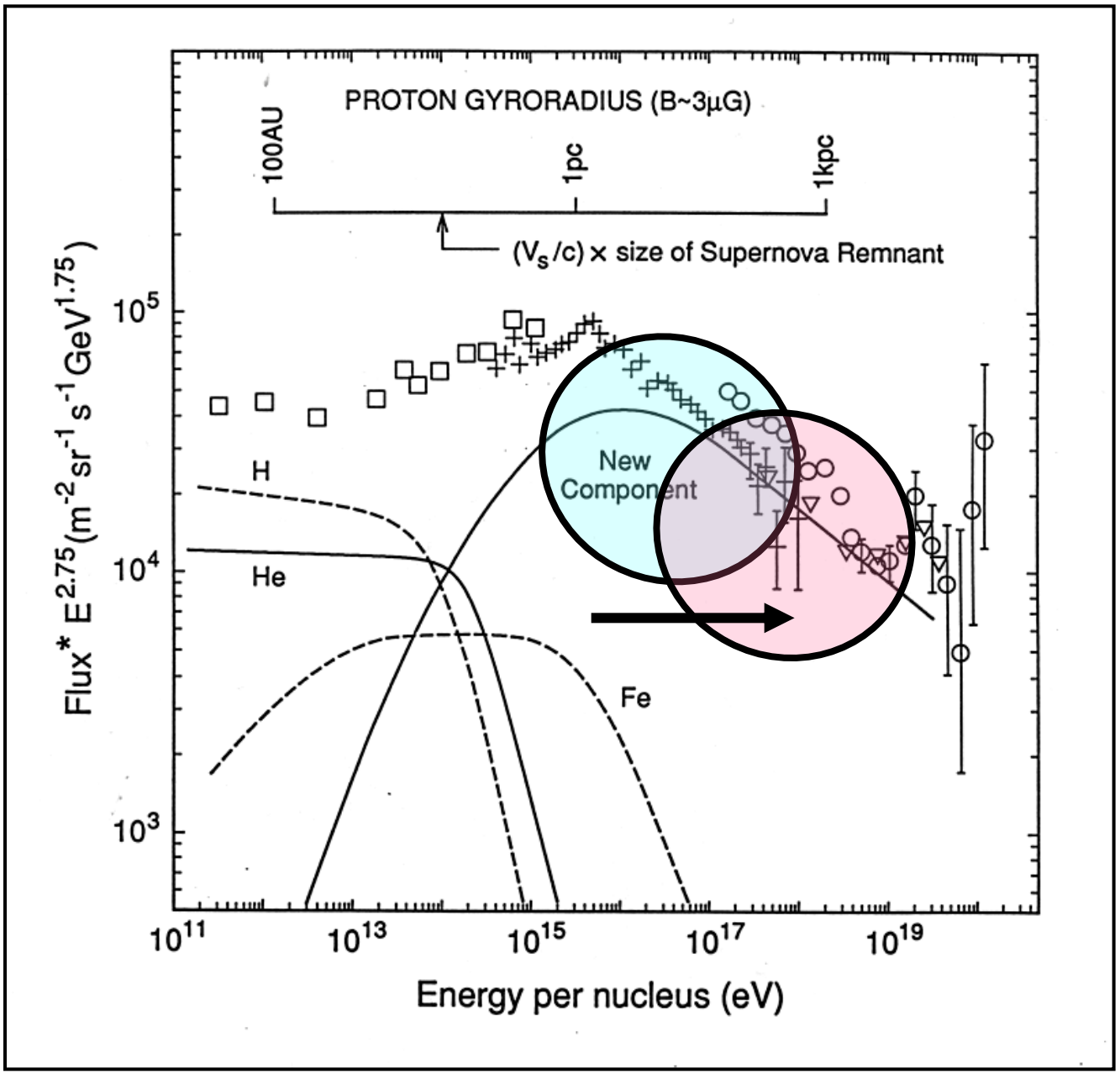
Chemical composition become more lighter beyond 10^17 eV?



So,

- Up to 10*17 eV– the transition region from light elements to heavier ones
- Beyond 10*17 eV - the transition from heavier elements to light ones, or from **galactic sources to extragalactic ones…**




PROTON GYRORADIUS (B~3μG)
100AU
1pc
1kpc
(Vs/c) × size of Supernova Remnant
New Component
H
He
Fe
Flux* E2.75(m-2sr-1s-1GeV1.75)
Energy per nucleus (eV)
10^5
10^4
10^3
10^11
10^13
10^15
10^17
10^19

Instead of conclusions -

- Have we found the transition region between galactic and extragalactic sources already?

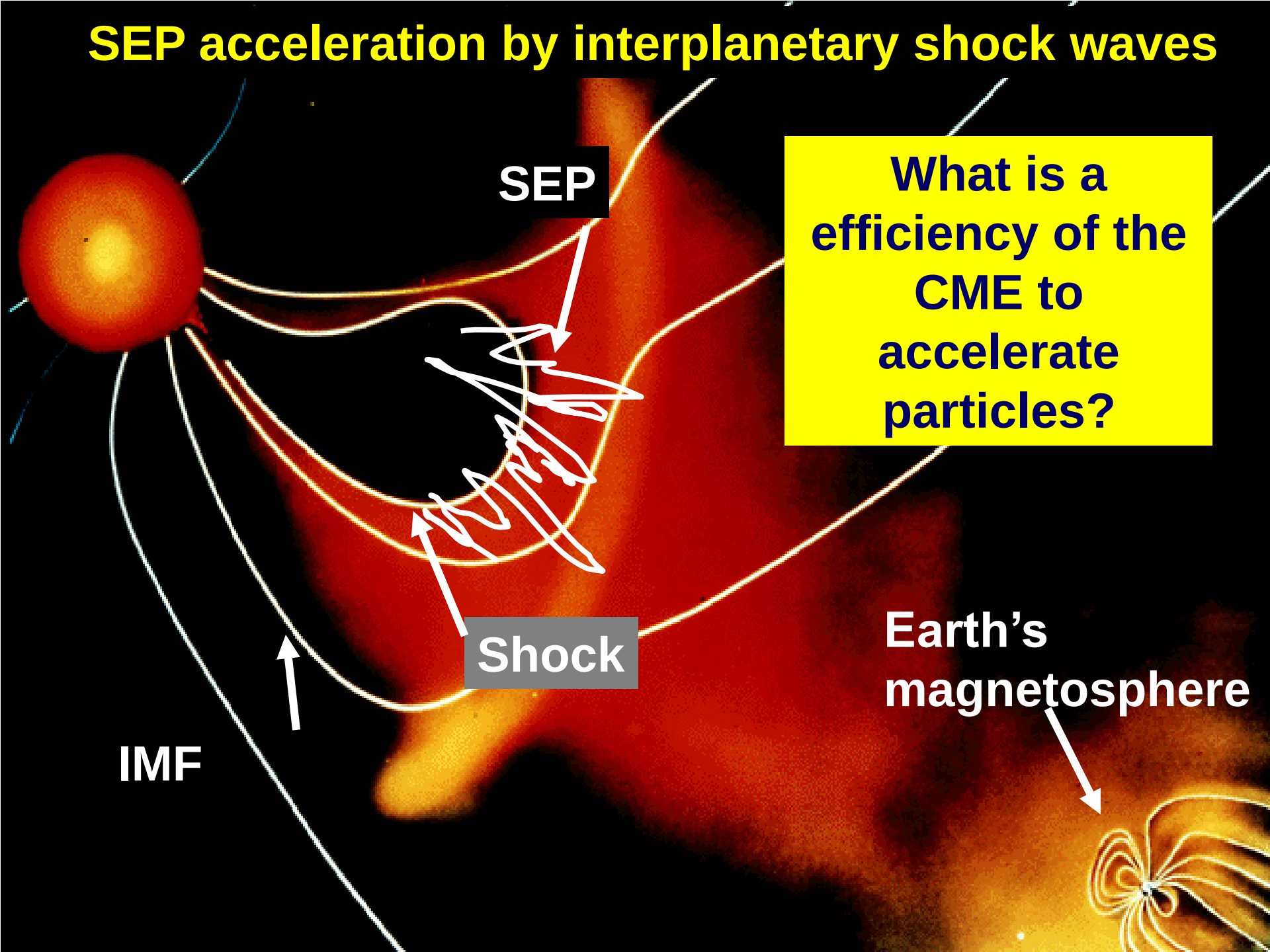
- Have we observed the LIMIT OF POWER of Galactic Accelerator egual to ~ $10^{15}Z$?

- What kind of accelerators are responsible for the origin of particles at 10*17 eV???

Do we know other shocks in the Universe?

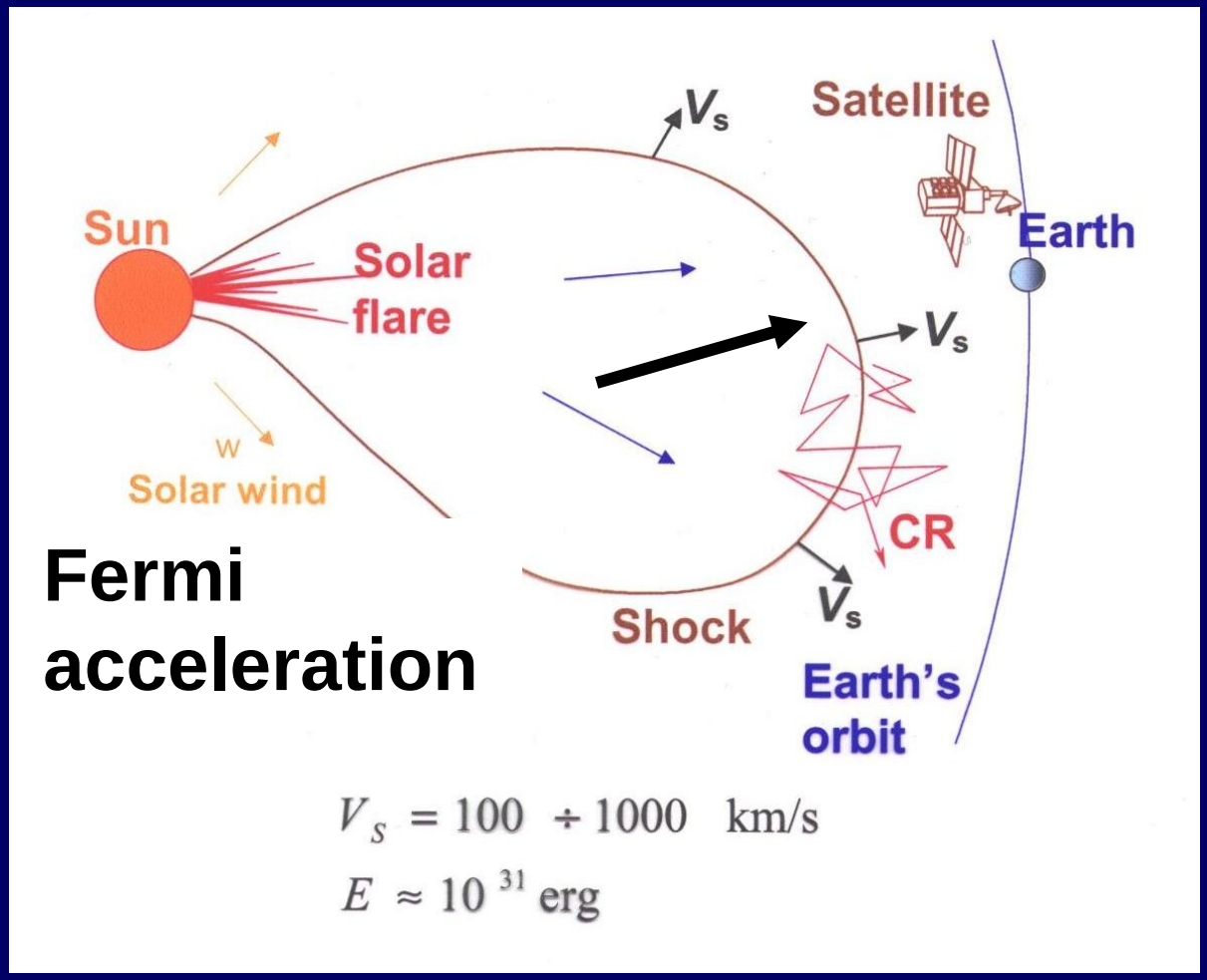
SEP's acceleration by interplanetary shock waves

SEP acceleration by interplanetary shock waves



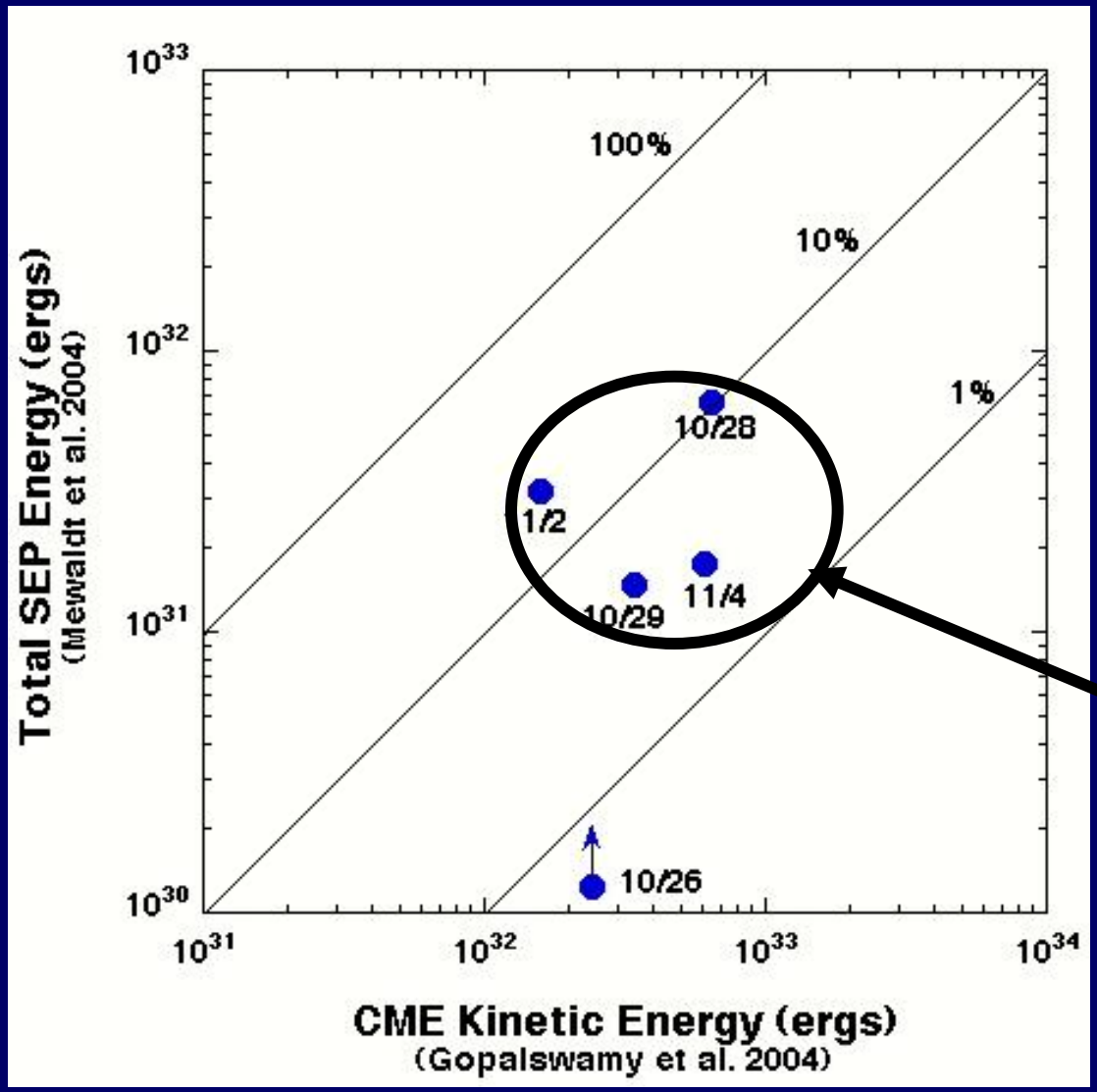
Acceleration of SEP during propagation

CME acceleration



Berezhko (1999) :*ions energy up GeV*

CME shock acceleration



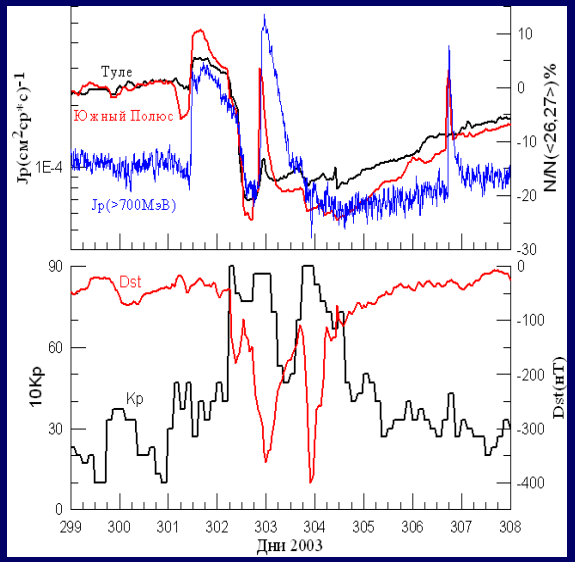
If these SEPs are accelerated by CME-driven shocks, they use *a significant fraction of the shock kinetic energy (~3% to 20%)*

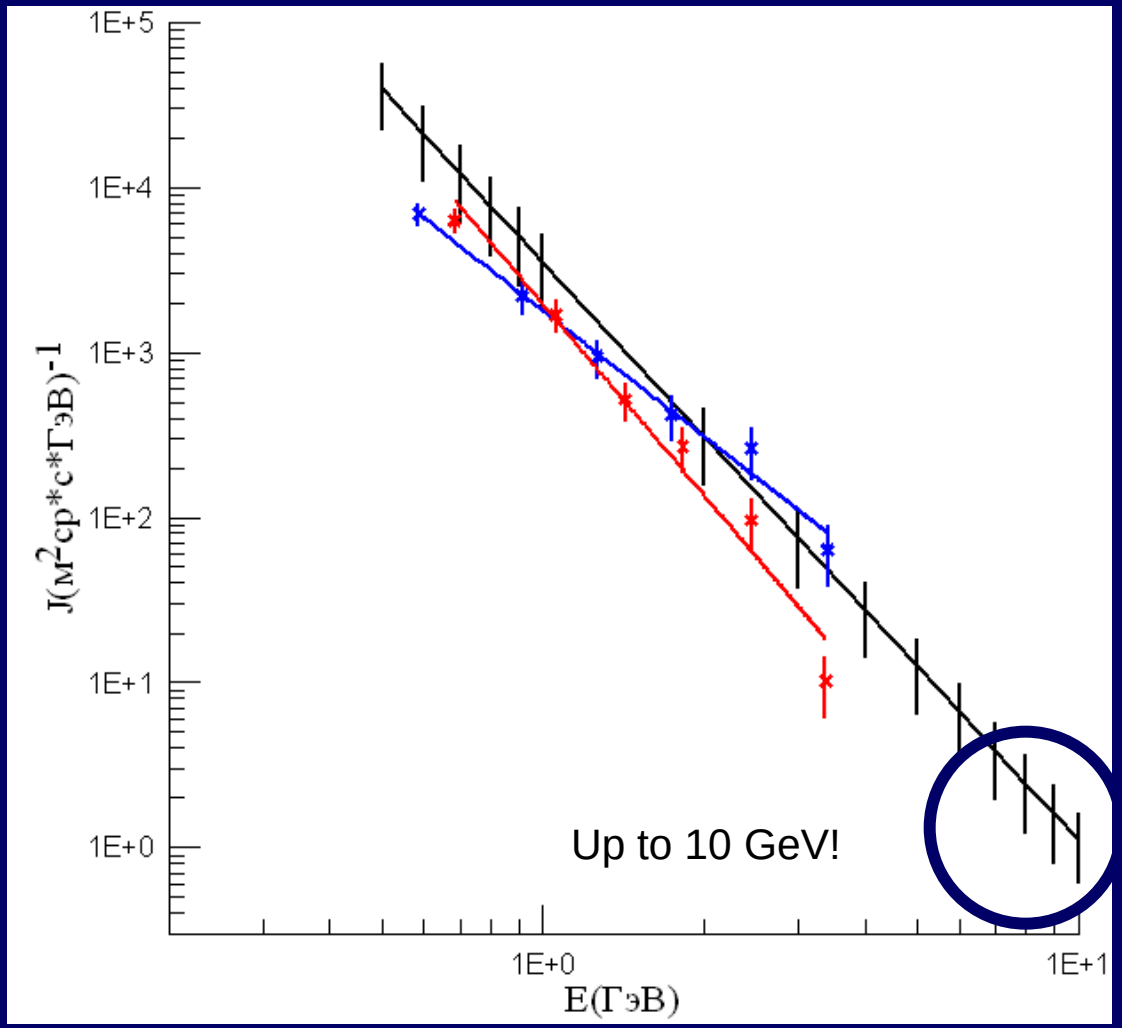
Energy range of SEP: spectra

- direct measurements from space
- indirect measurements using geomagnetic cutoff
- NM and EAS arrays measurements on ground during GLE

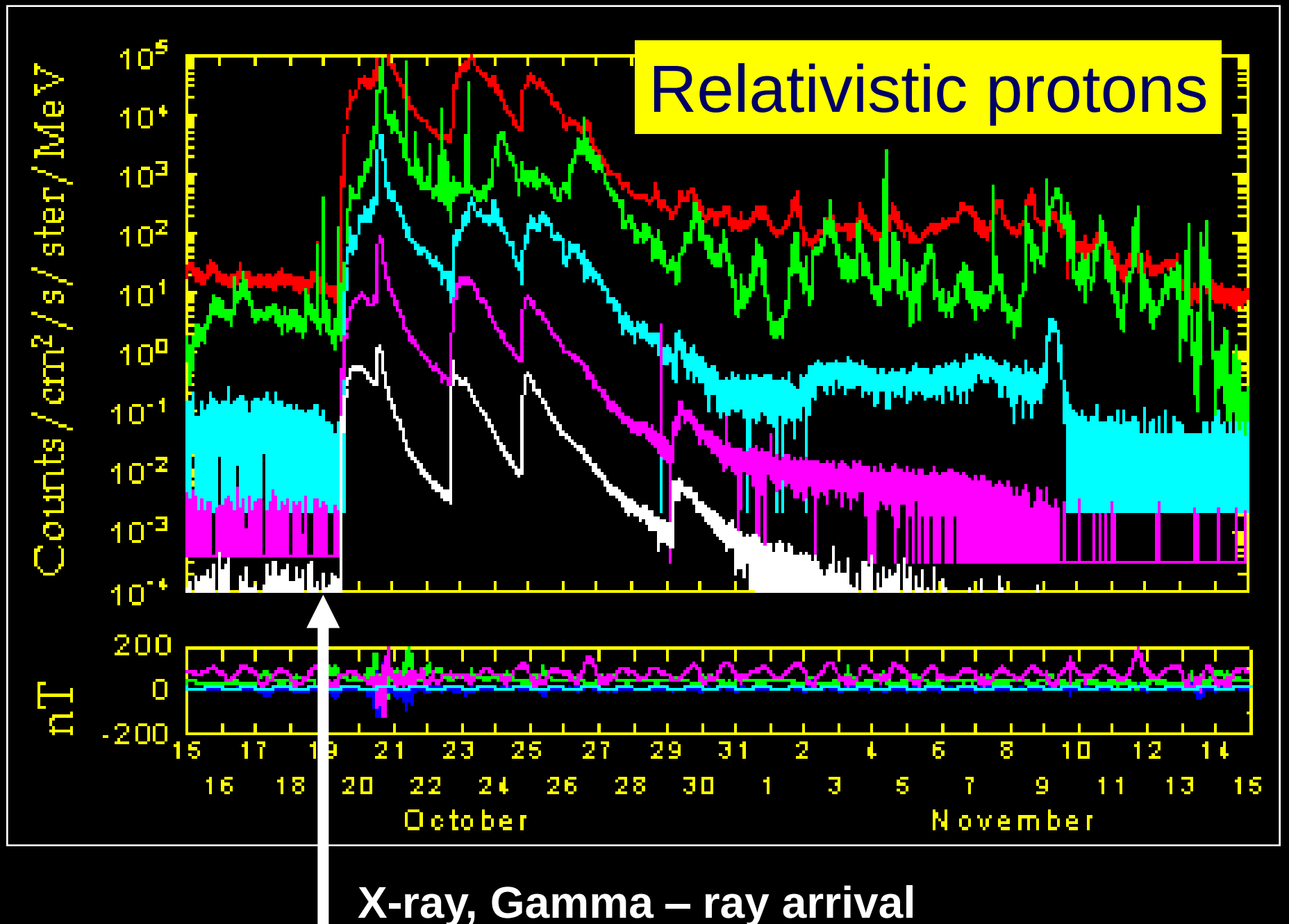
SEP spectra from cutoff (sat. data)

Coronas –F data





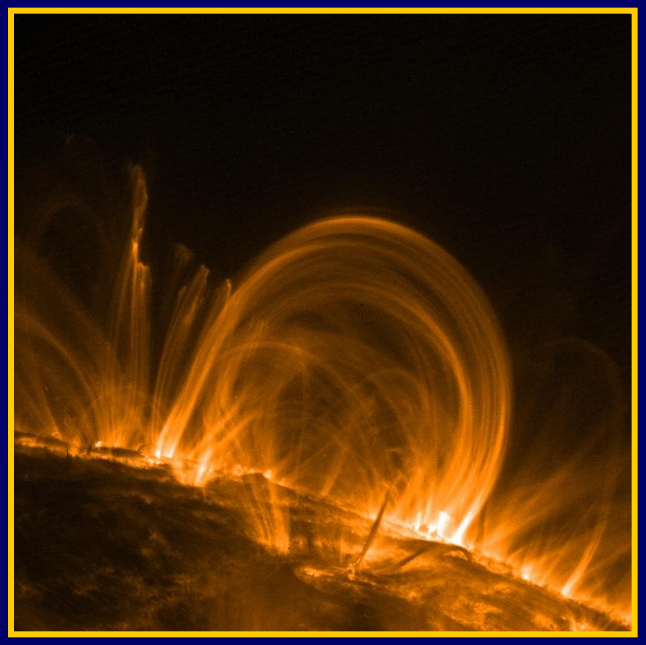
The question “does a shock wave propagating in the Corona accelerate particles up to ultra-relativistic energies “ is being discussed



X-ray, Gamma – ray arrival

- **Another acceleration mechanism have to be found…**

SEP's acceleration by interplanetary shock waves



Magnetic reconnection as a main force for solar flare particle acceleration

↓

Solar flare standard model

Particle Acceleration in Flares

- Acceleration by DC electric field in Reconnecting Current Layer

plus...

- Collapsing trap dynamics
- Stochastic dynamics (waves, shocks)

Scenario of acceleration process

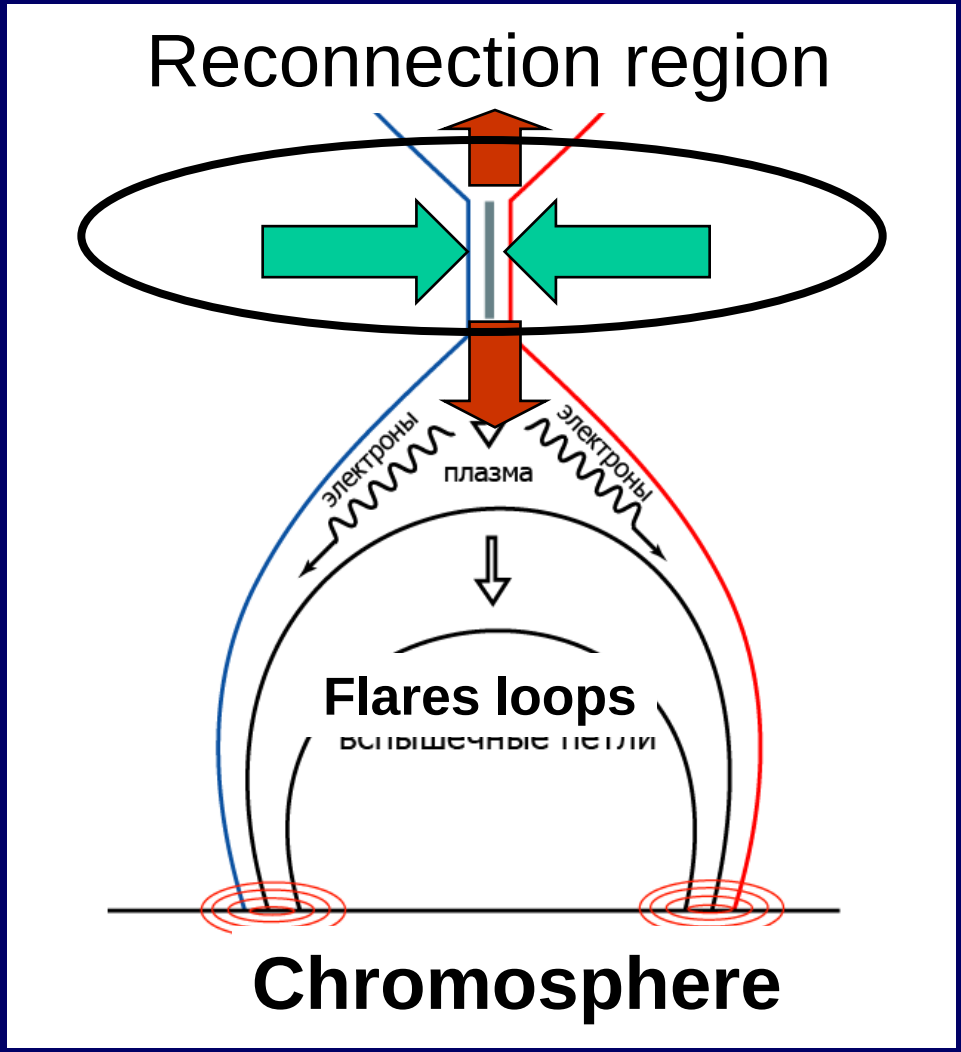
After Somov & Bogachev

- Magnetic field lines move to the X-type neutral point

-The electric field is induced and accelerates particles

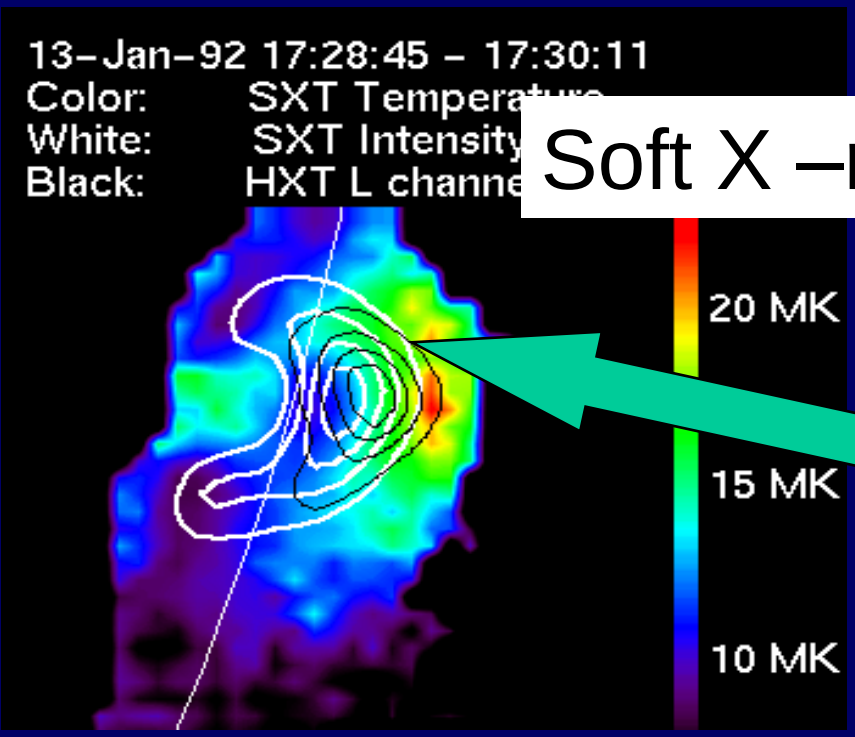
$$\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t},$$

Magnetic reconnection as an injector

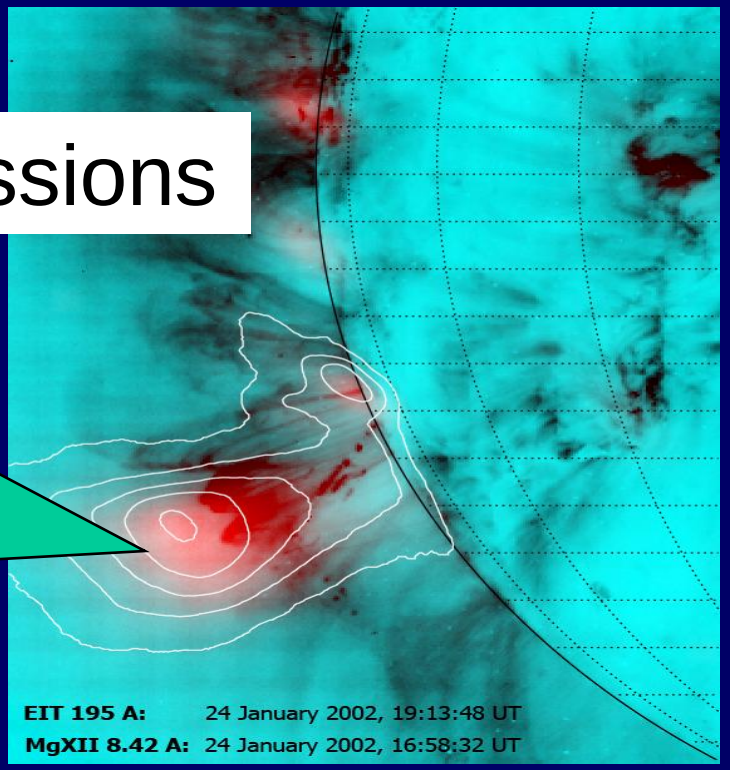


Evidences from observations

•Thermal and non-thermal HXR emission from the corona, can be interpreted as reconnecting super-hot turbulent-current layer (SHTCL)



Soft X –ray emissions



1991-2001
Yohkoh data
Tsuneta S., Kosugi T.

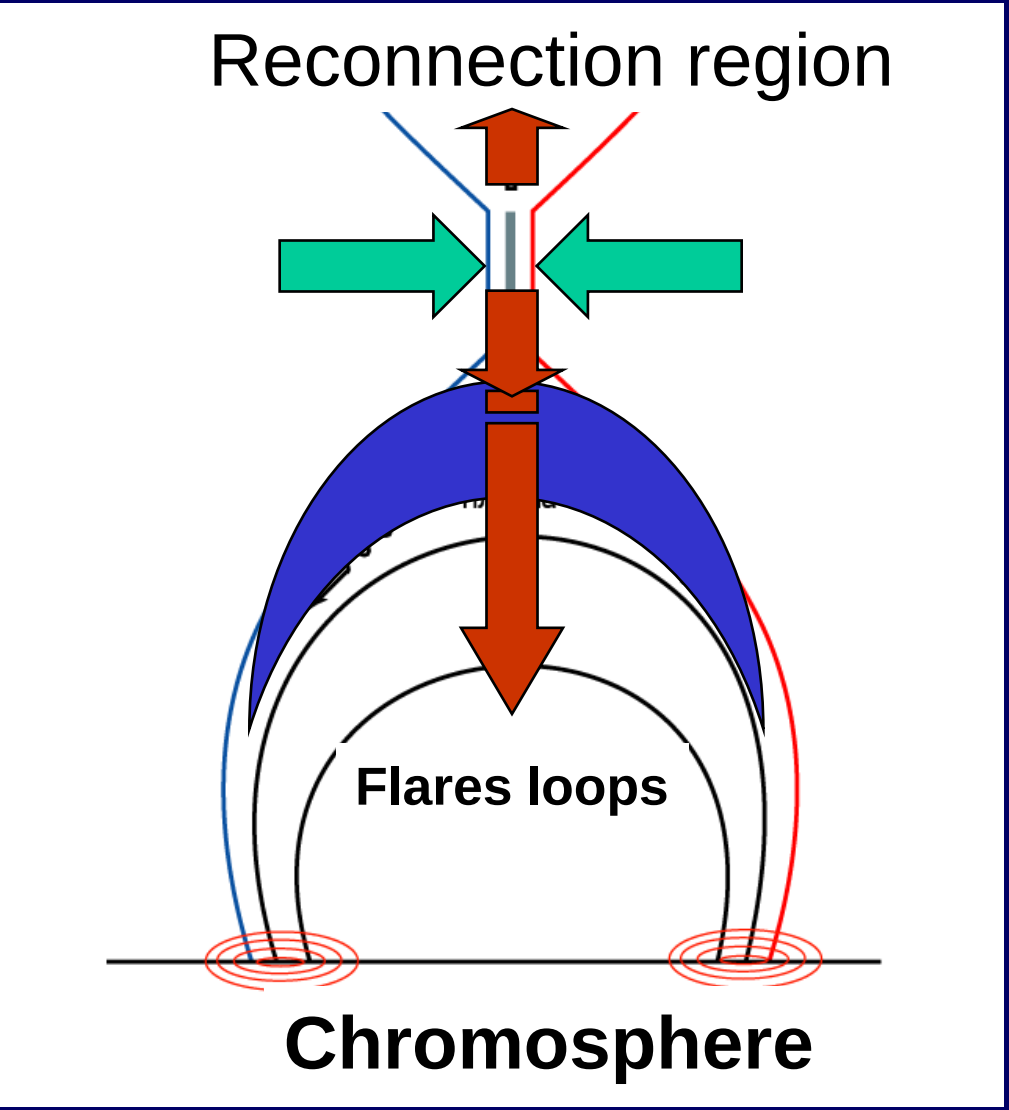
2001-2006 **SPIRIT/CORONAS-F I**. Zhitnik, C.Kuzin

Scenario of acceleration process

1.Magnetic reconnection
as an injector

2.Electron capture
and collaps of magnetic
trapping region

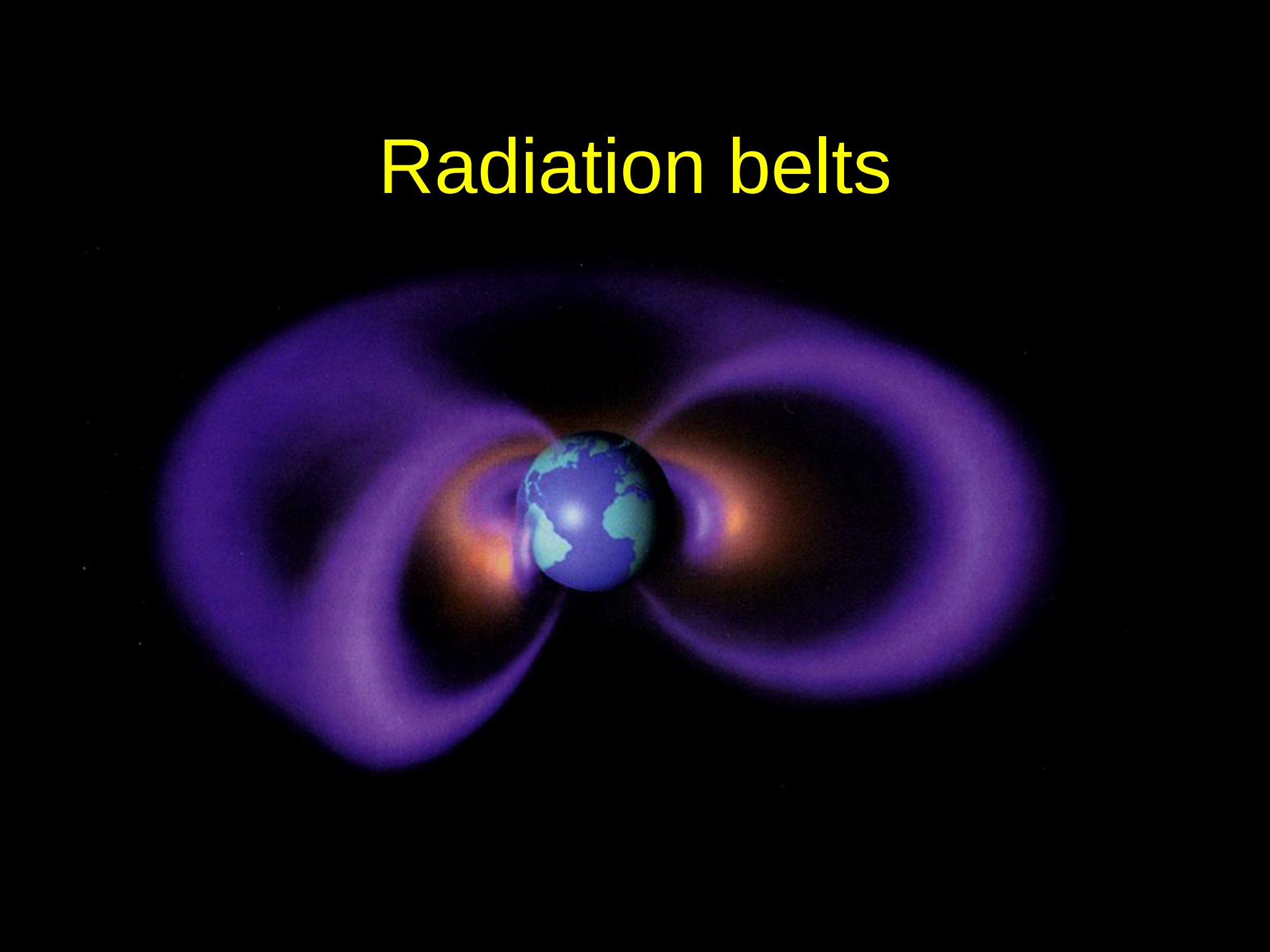
Bethatron acceleration
connected with collapse
of magnetic loops
with simultaneous
Fermi acceleration
(stochastic acceleration)



Do we have bethatron acceleration some where else?

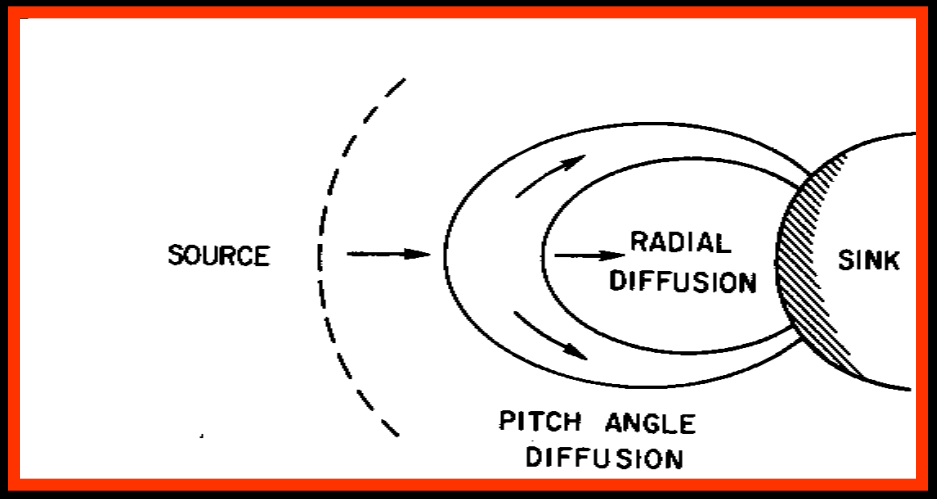
- Yes, nearby

Radiation belts



Radial diffusion -the main transport process of RB particles

Magnetic diffusion example



Solar wind fluctuations

Fluctuation of geomagnetic field

Induced electric field

Particle's drift in crossing over ExB fields

Diffusion across L-shells

D - diffusion coefficient as a critical parameter of radiation belts dynamics

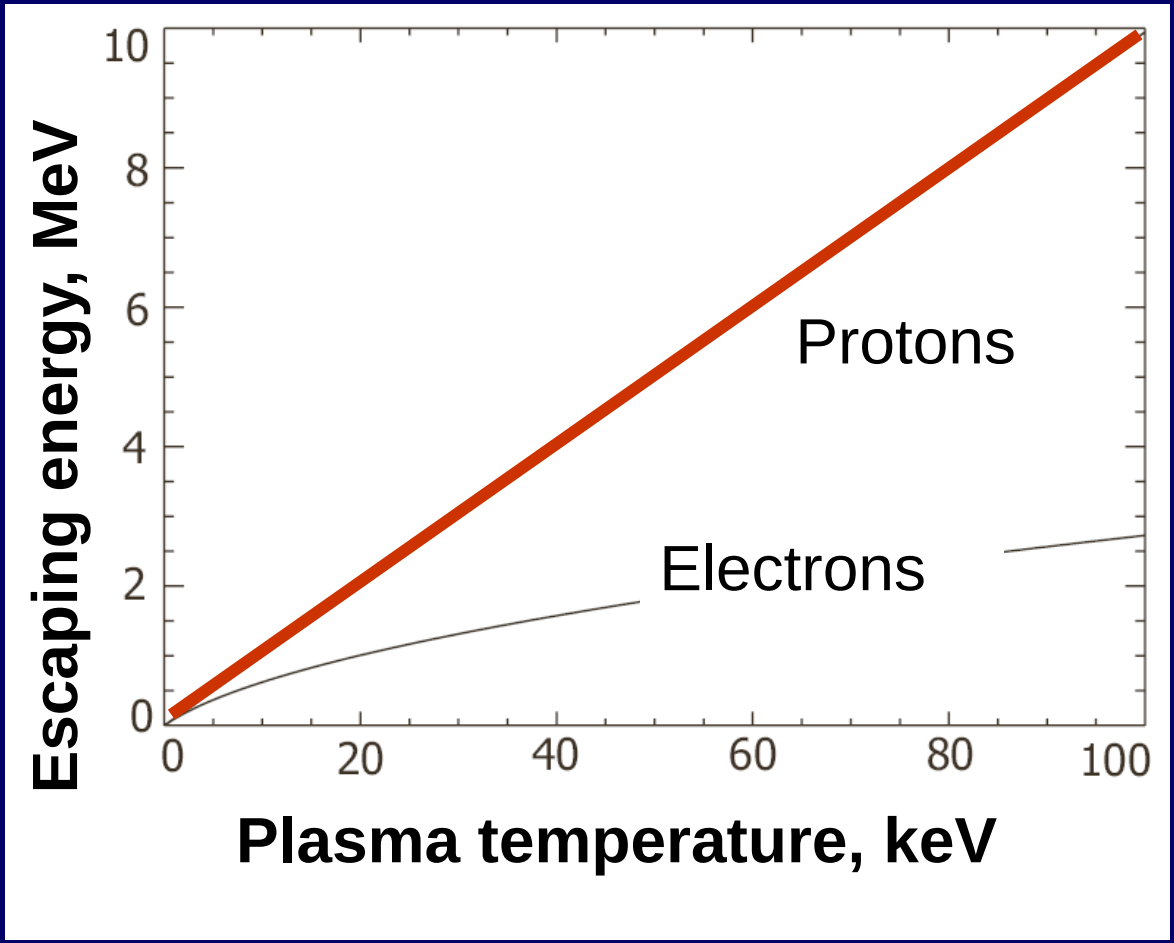
SEP acceleration mechanism should explain experimental data:

Acceleration of

- *Protons up to 1-10s 300MeV- ~several GeV*
- *Electrons up to ≈0.5s 60-100MeV*

SM gives 

Acceleration of protons and electrons



Dependent on the plasma parameters

Protons can be accelerated up to GeV, but electrons **only** up to several MeV

Bogachev, et al

SEP acceleration mechanisms

A: Electric Fields: **Parallel to B Field**

B: Fermi Acceleration

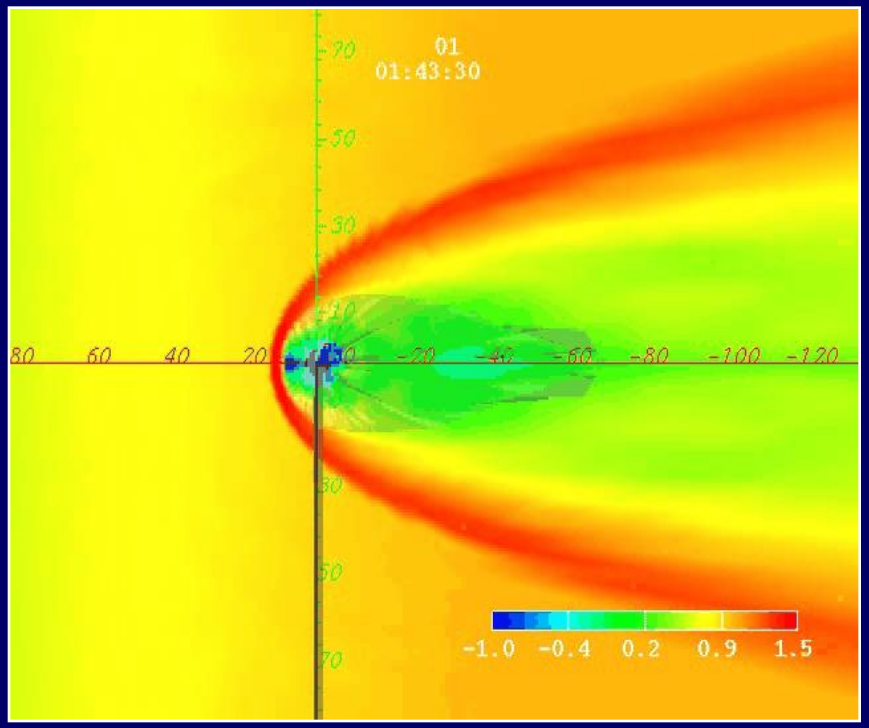
1. Shocks: **First Order Fermi**

2. Stochastic Acceleration: **Second Order Fermi**

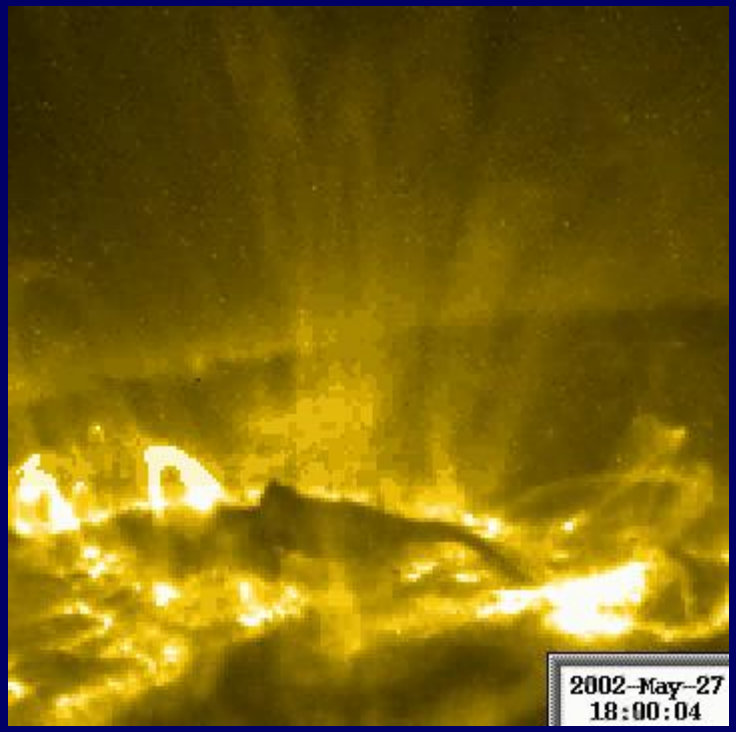
- **Do we have reconnection somewhere else?**

Reconnection is everywhere

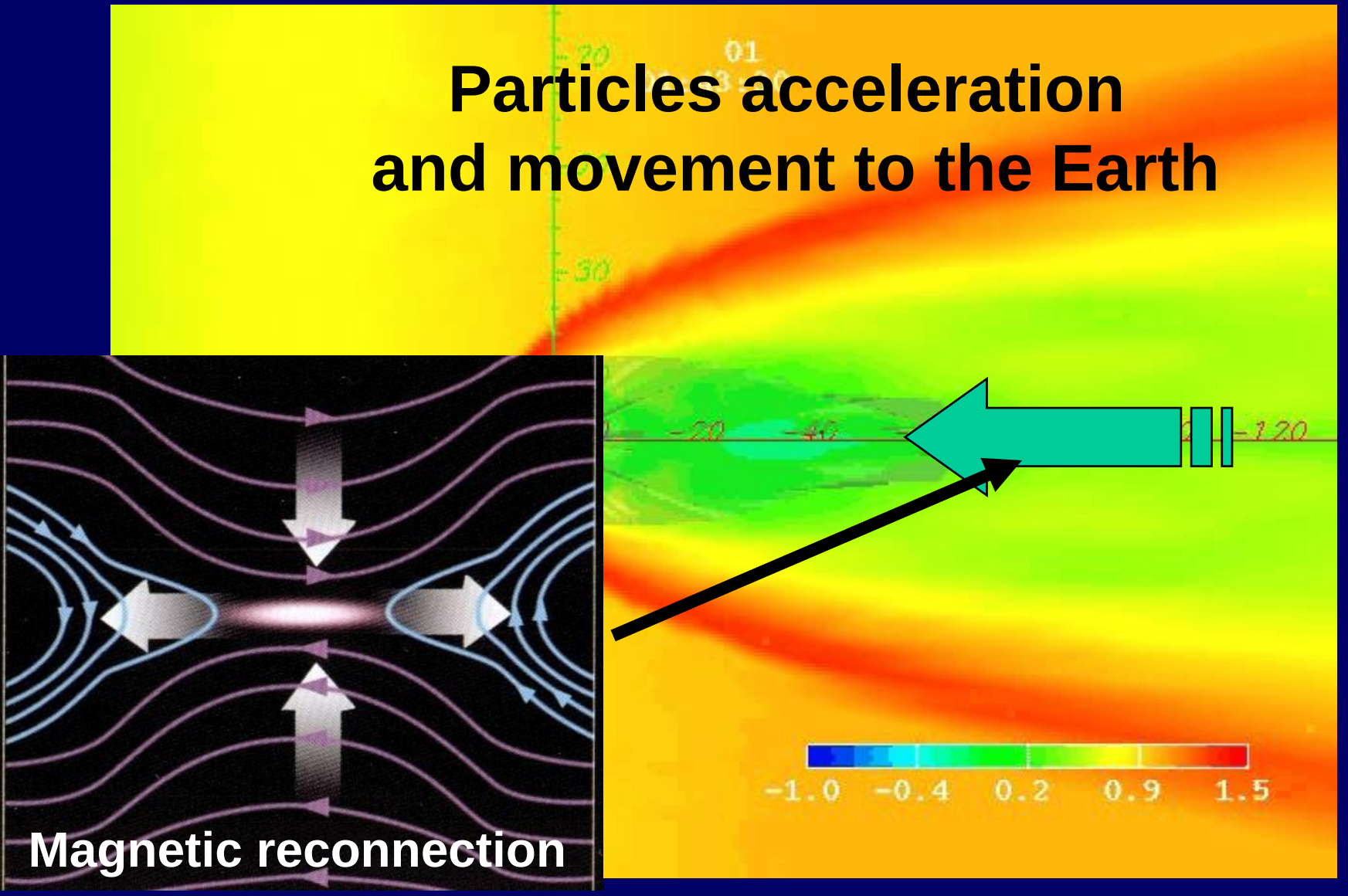
In the magnetospheres



At the Sun

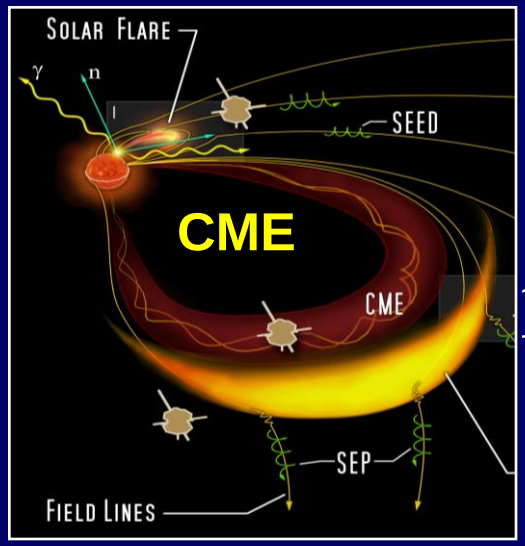


Magnetic substorms/storms reconnection

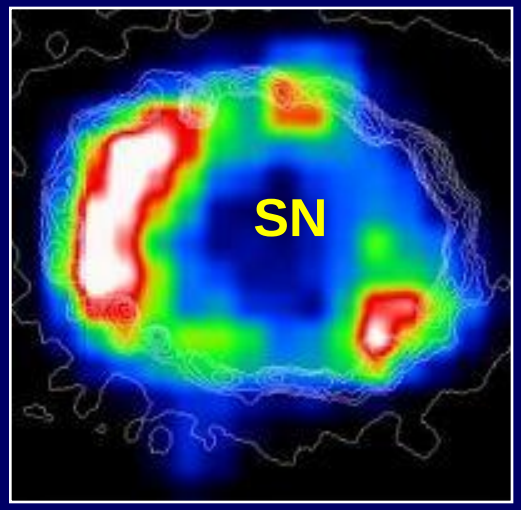


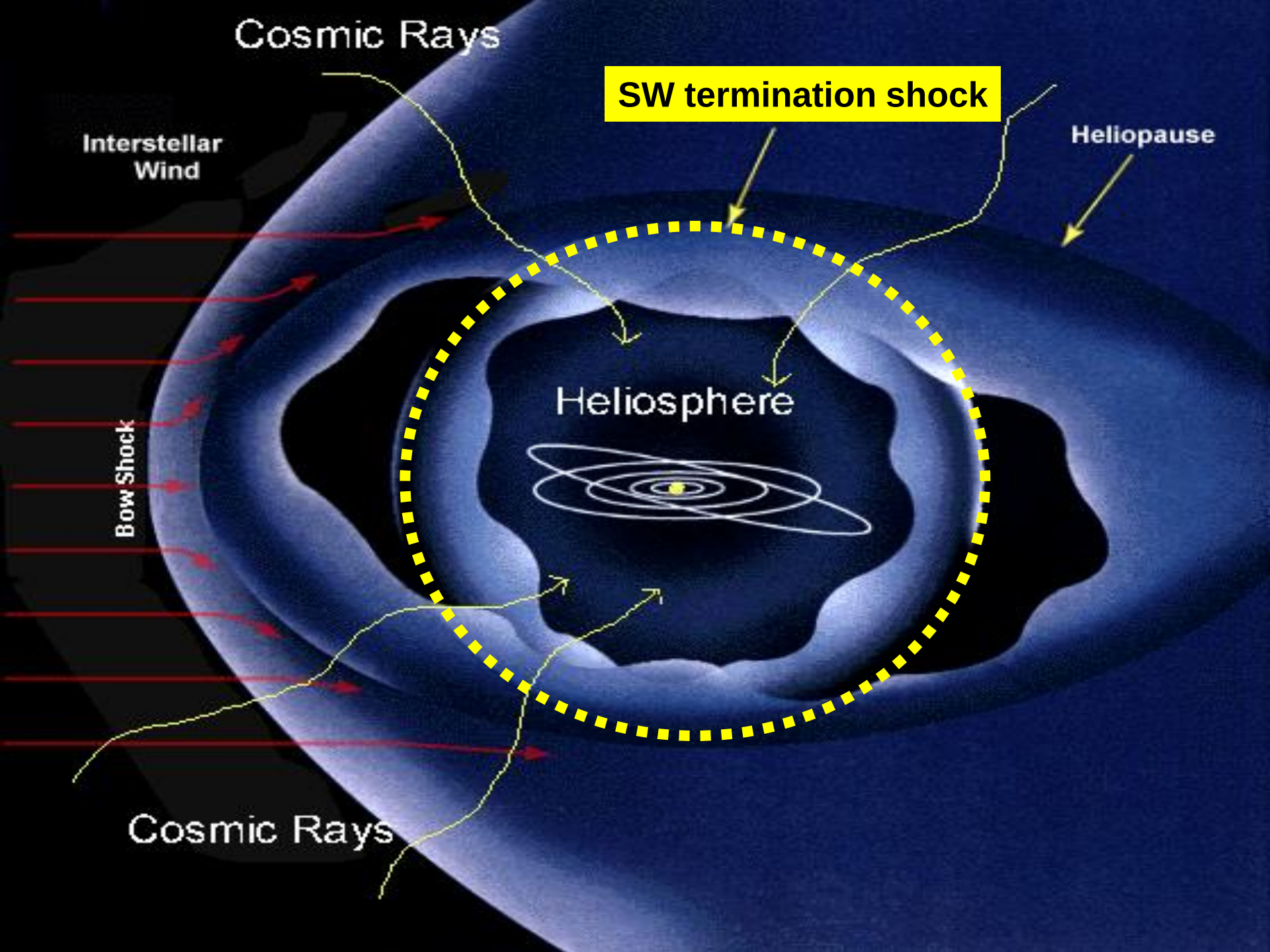
- Shock's acceleration is everywhere as well!

Shock's acceleration is everywhere as well!



	SW	GCR
N	~ $1cm^{-3}$	10^{-3} cm-3
B	~ 1nT	10^{-2} nT
T ion	~ 10 eV	10^{3} eV
Mach	~ 5	100
T	~ hours	minutes



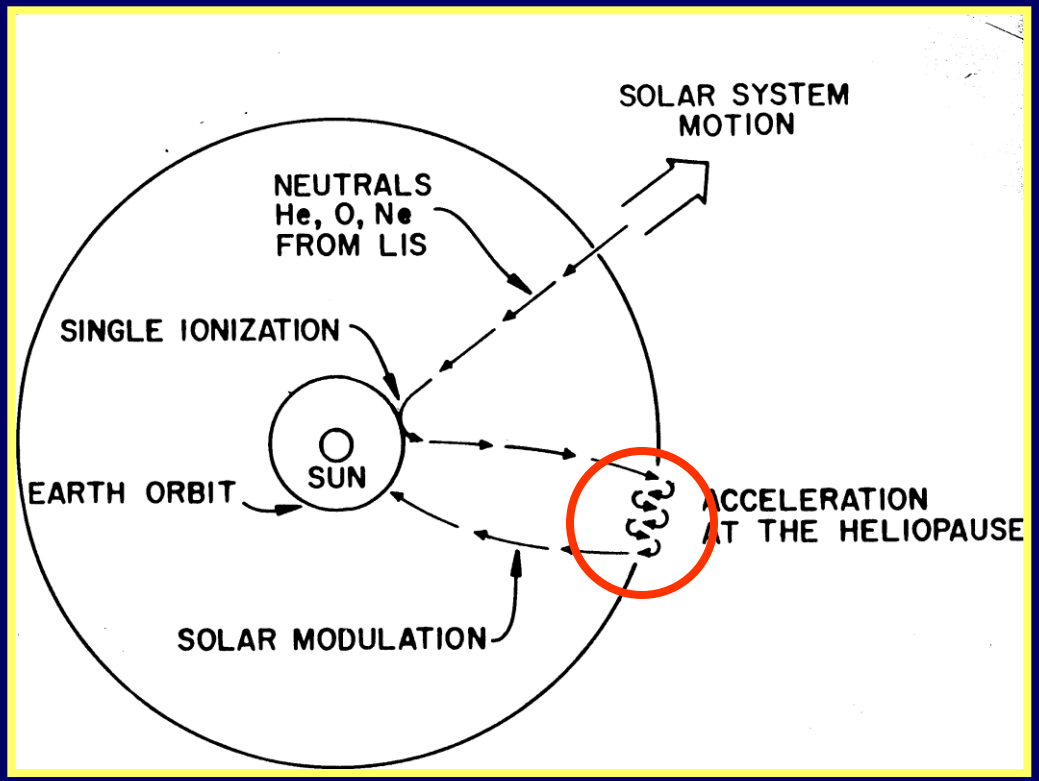

Cosmic Rays
SW termination shock
Interstellar Wind
Heliopause
Heliosphere
Bow Shock
Cosmic Rays

The anomalous cosmic ray component

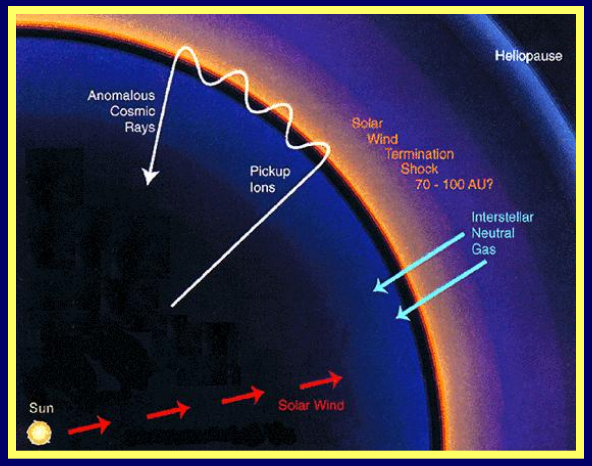
The main statements of the Fisk, Kozlovski Ramaty theory

Then…

- Acceleration of ionized neutrals, 'picked-up' by the solar wind from ~4 keV/nucleon to >10 MeV/nucleon at the heliopause (termination shock);



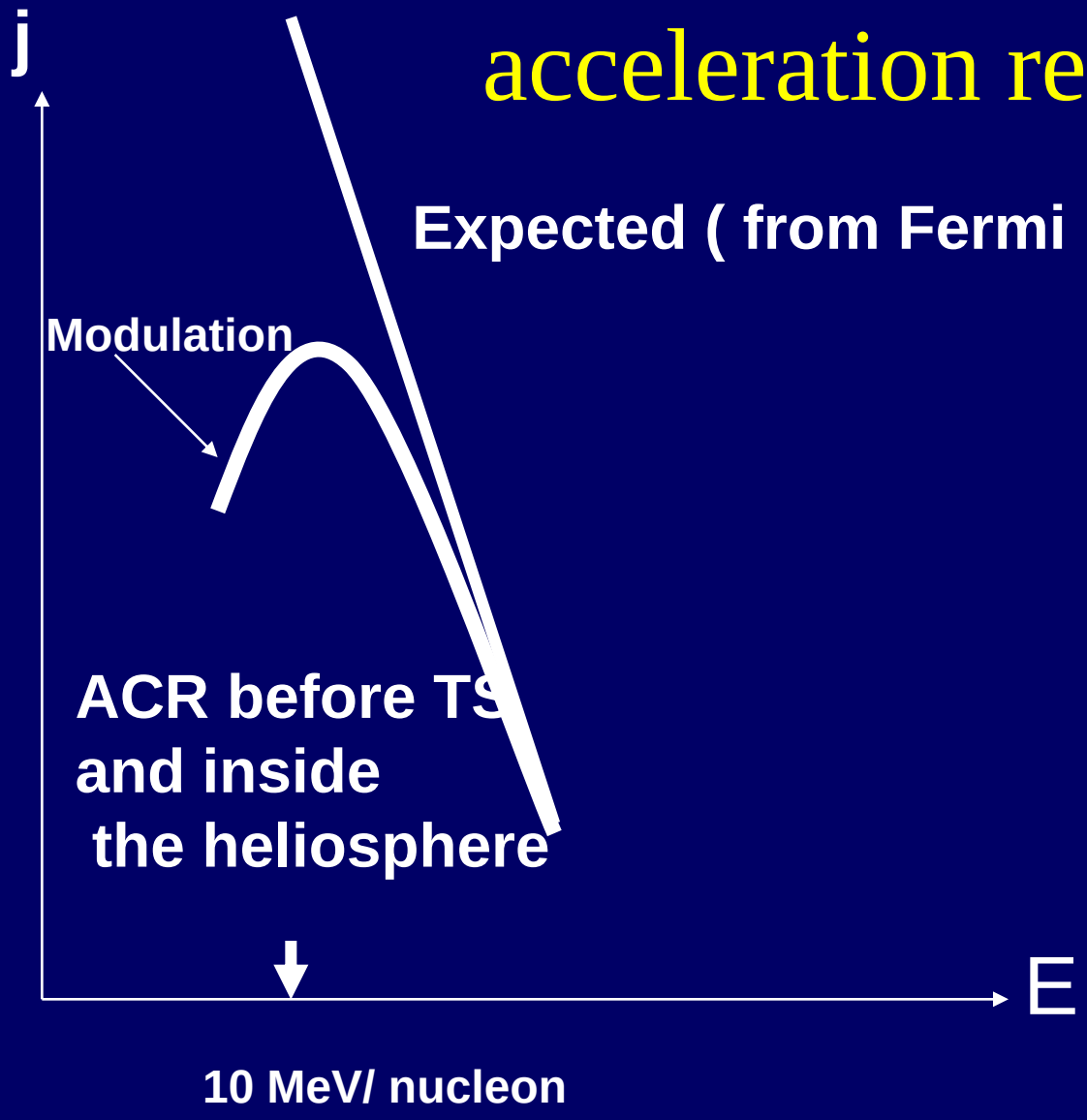
The anomalous cosmic ray acceleration



Krymski (1977), Axford *et al.* (1977) and Blandford and Ostriker (1978):

FIRST ORDER FERMI
OR COMPRESSIVE SHOCK ACCELERATION

ACR spectra near an outer acceleration region

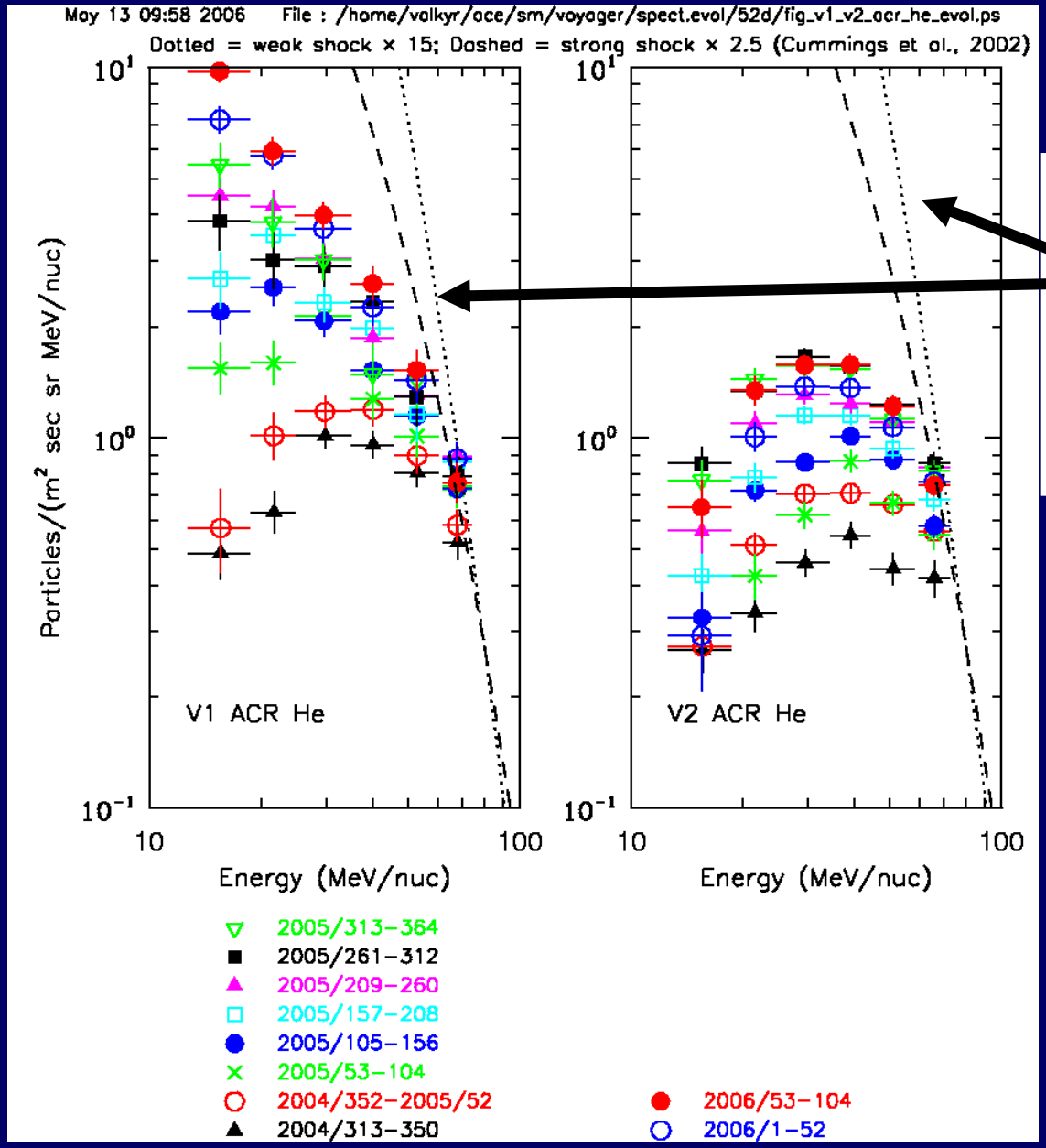


Expected (from Fermi acceleration)

Direct observation of ACR acceleration:

Voyager data

ACR He Spectral Evolution



V1 crossed shock on 2004/351

Expected source spectrum was not observed at time of shock crossing

Where is the ACR source?
Near the ecliptic?
Along the flanks?
In the heliosheath?

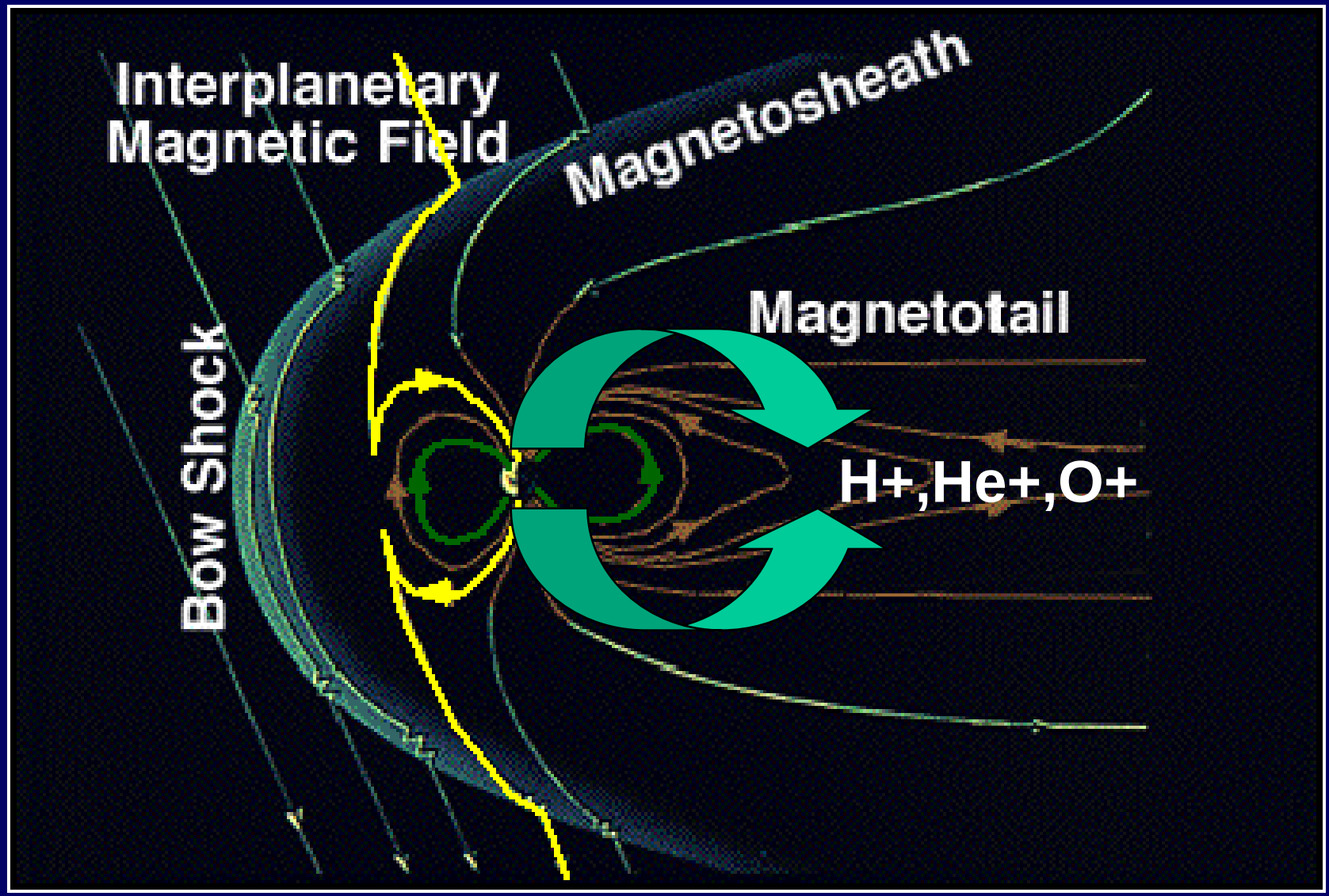
Stone et al. Science 2005 Cummings & Stone COSPAR 2006

ACR source(s)

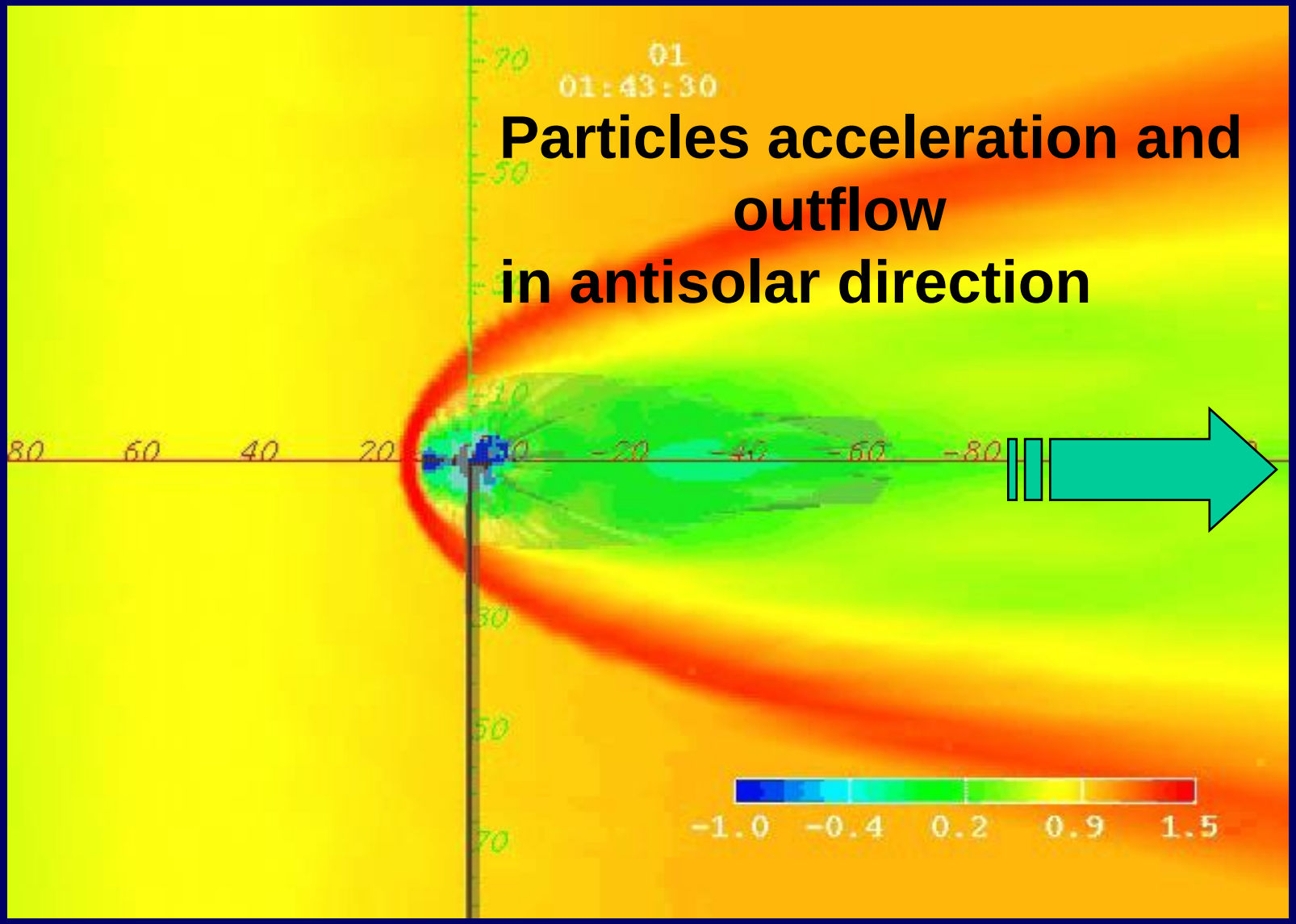
Alternative (or complementary) approach:

Ionosphere plasma of "magnetic" planets enriched by O+ can be a source for ACR

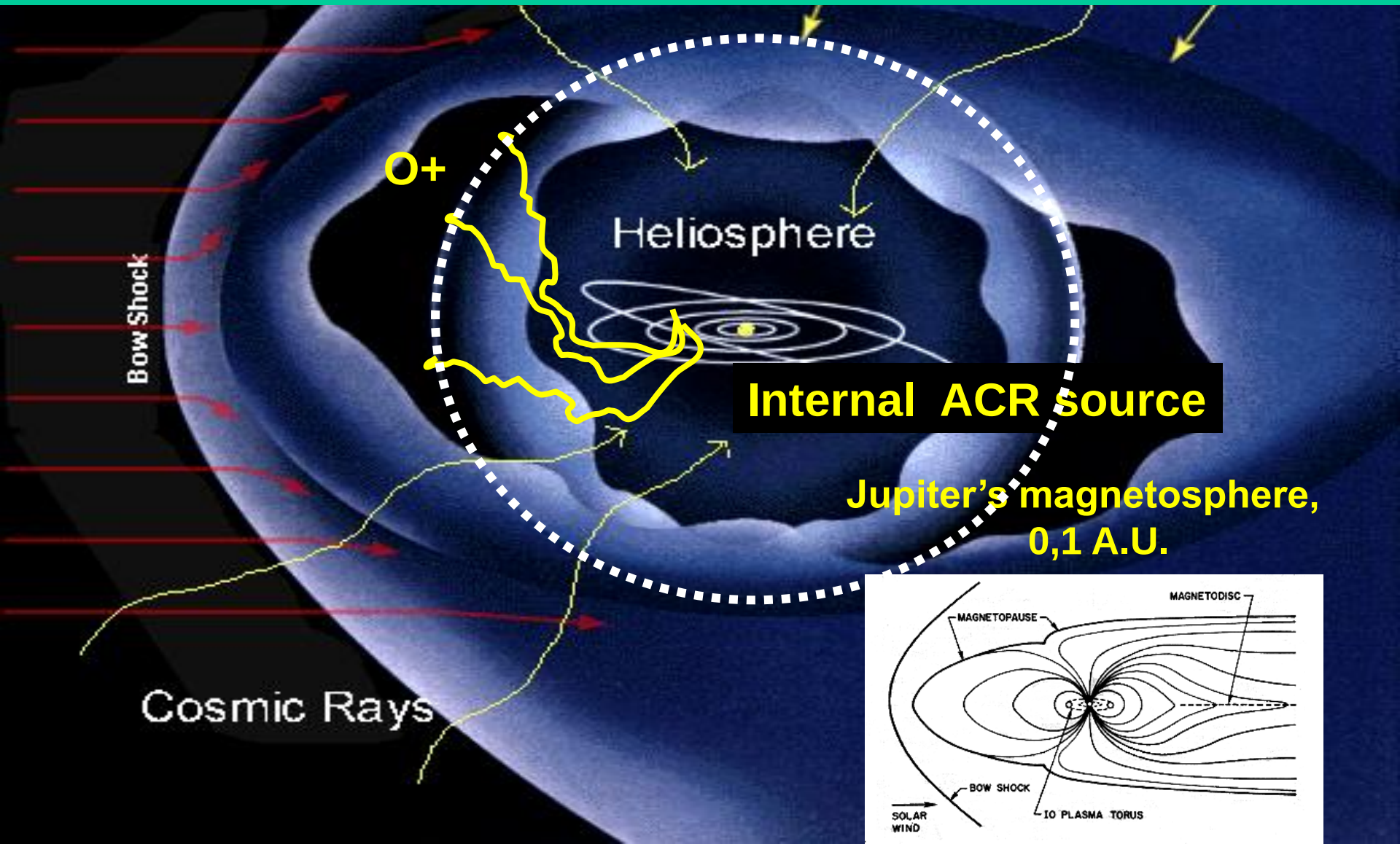
Ionosphere as a source of plasma in the Earth's magnetotail



Magnetic substorms/storms reconnection



Double acceleration of ACR: during reconnection process in the magnetospheres of the giant planets plus acceleration at heliospheric TS

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Thank you