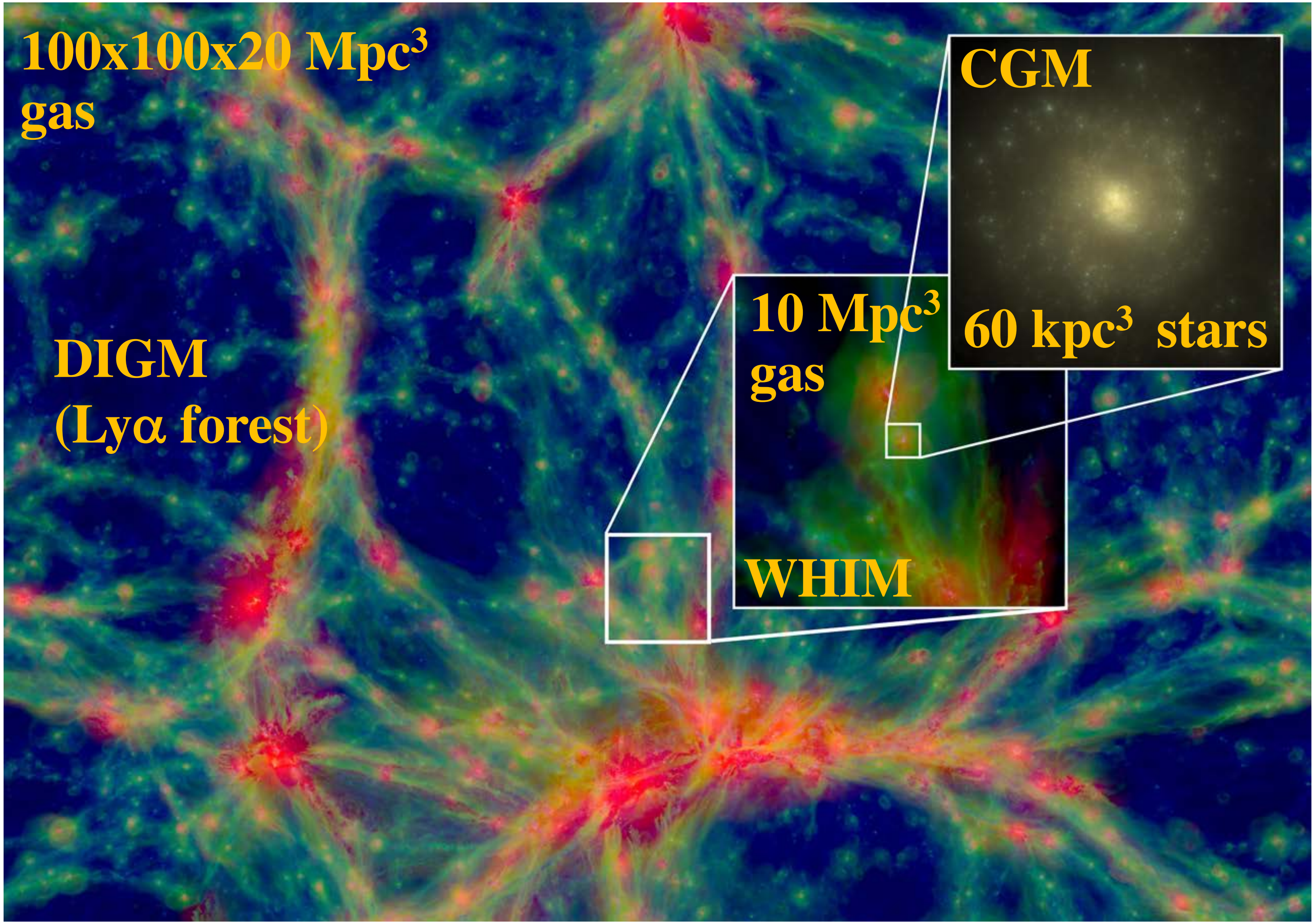
The role of TeV-PeV cosmic rays in the Milky Way and beyond

Susumu Inoue (Chiba)



EAGLE
Schaye+ 14

B: <$10^{4.5}$ K
G: $10^{4.5}$-$10^{5.5}$
R: >$10^{5.5}$ K

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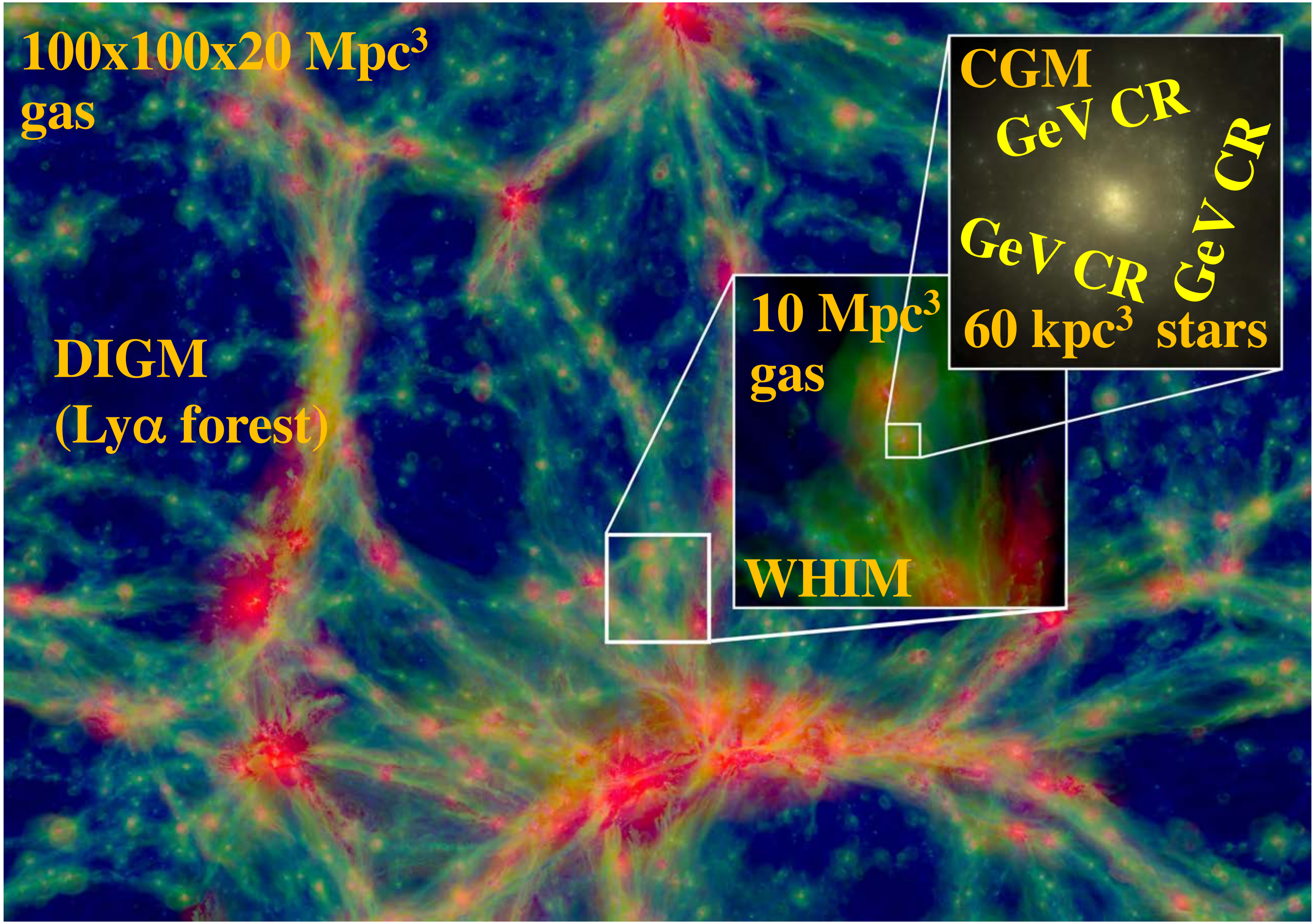

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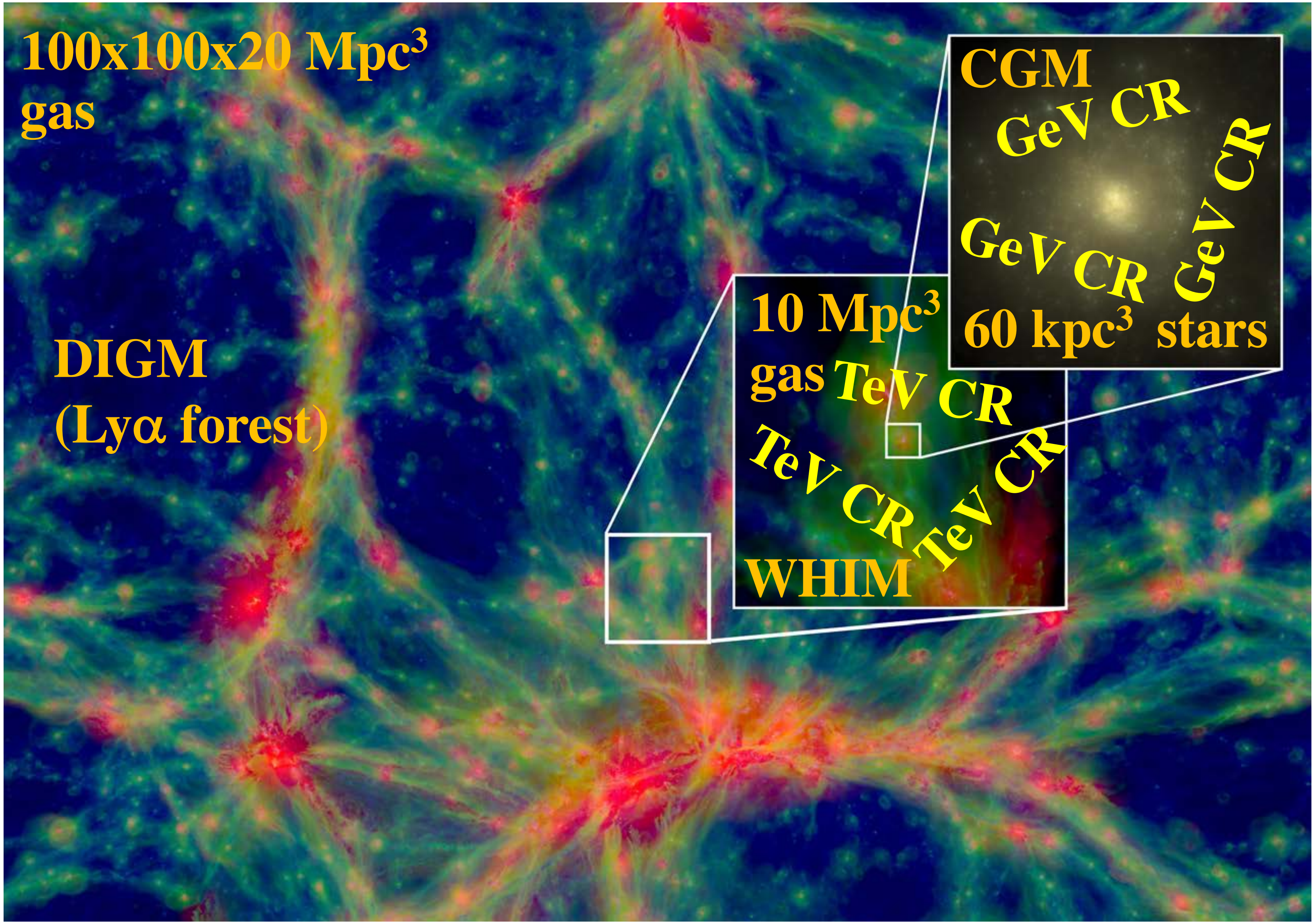

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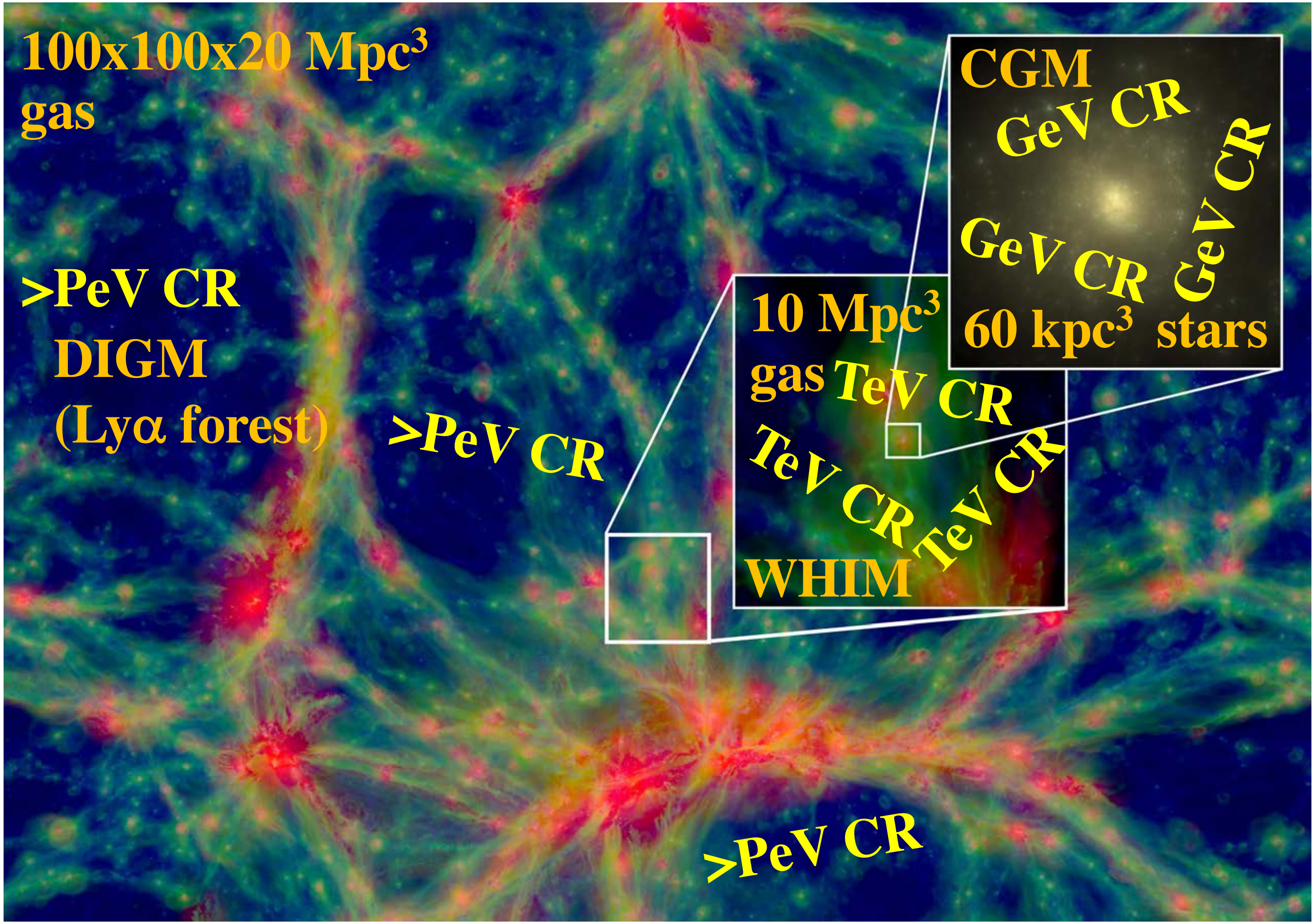

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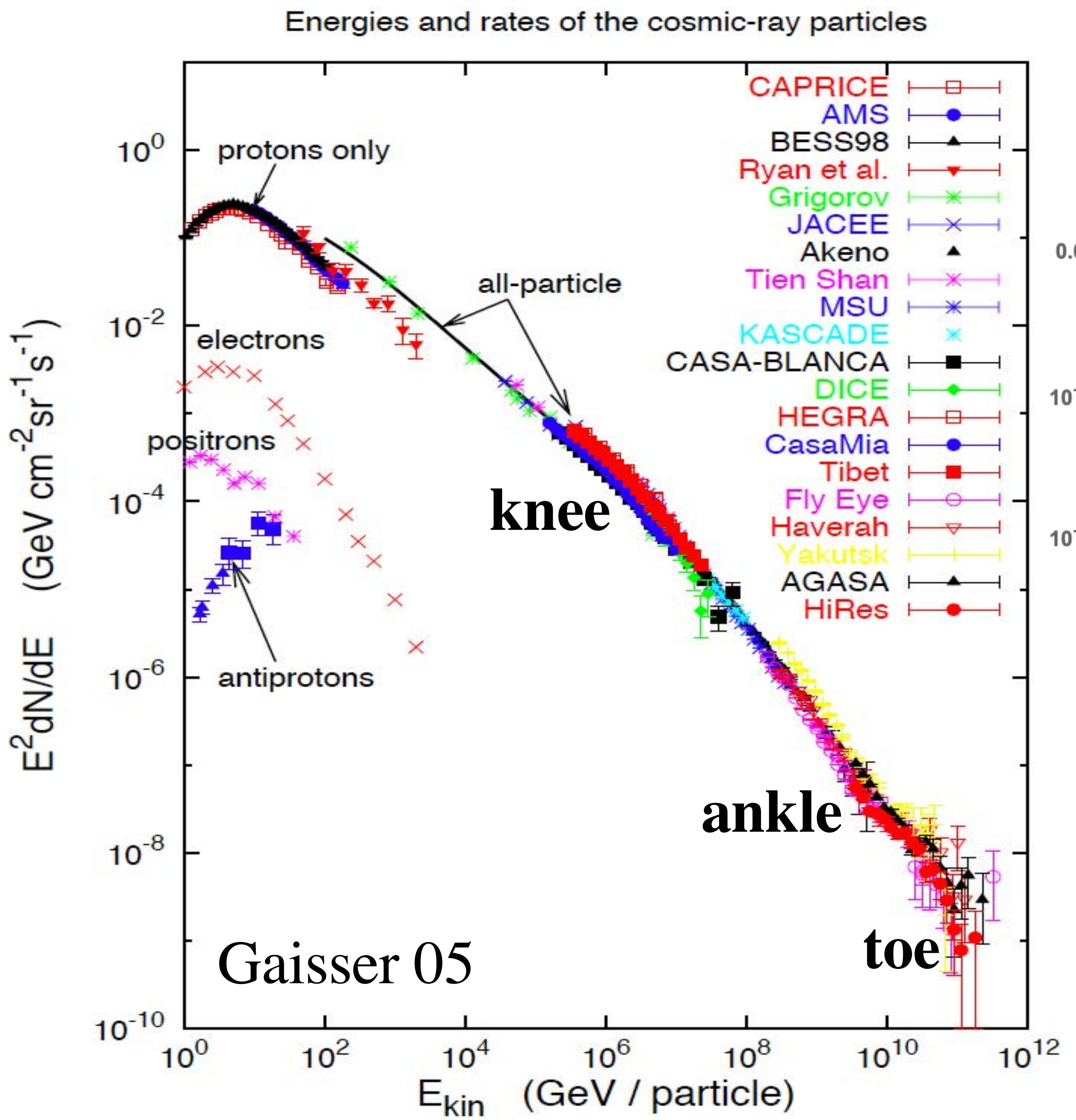
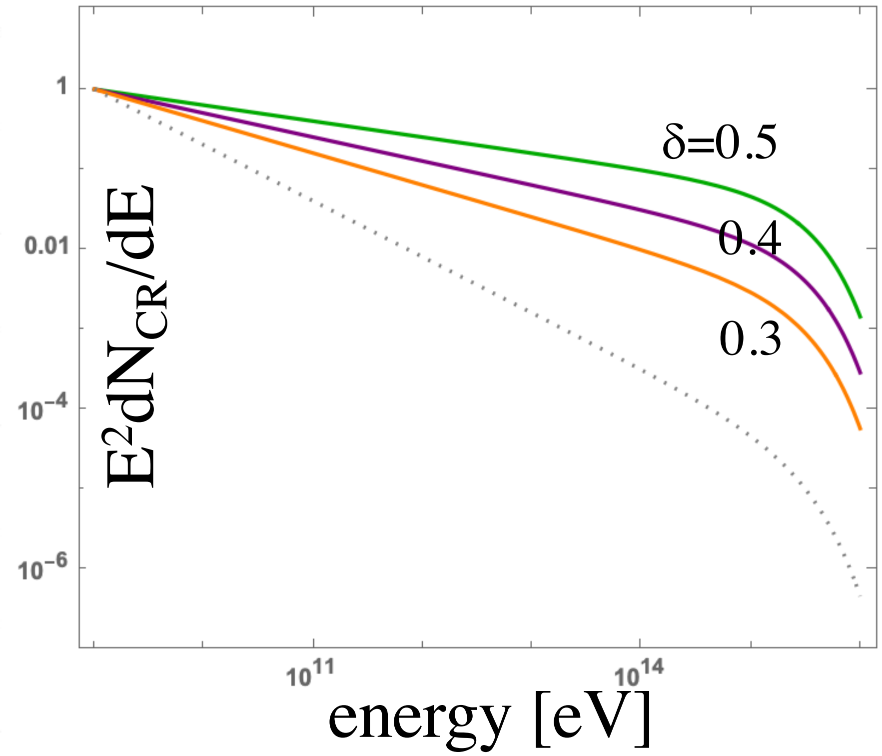
observed CR spectrum vs source energetics





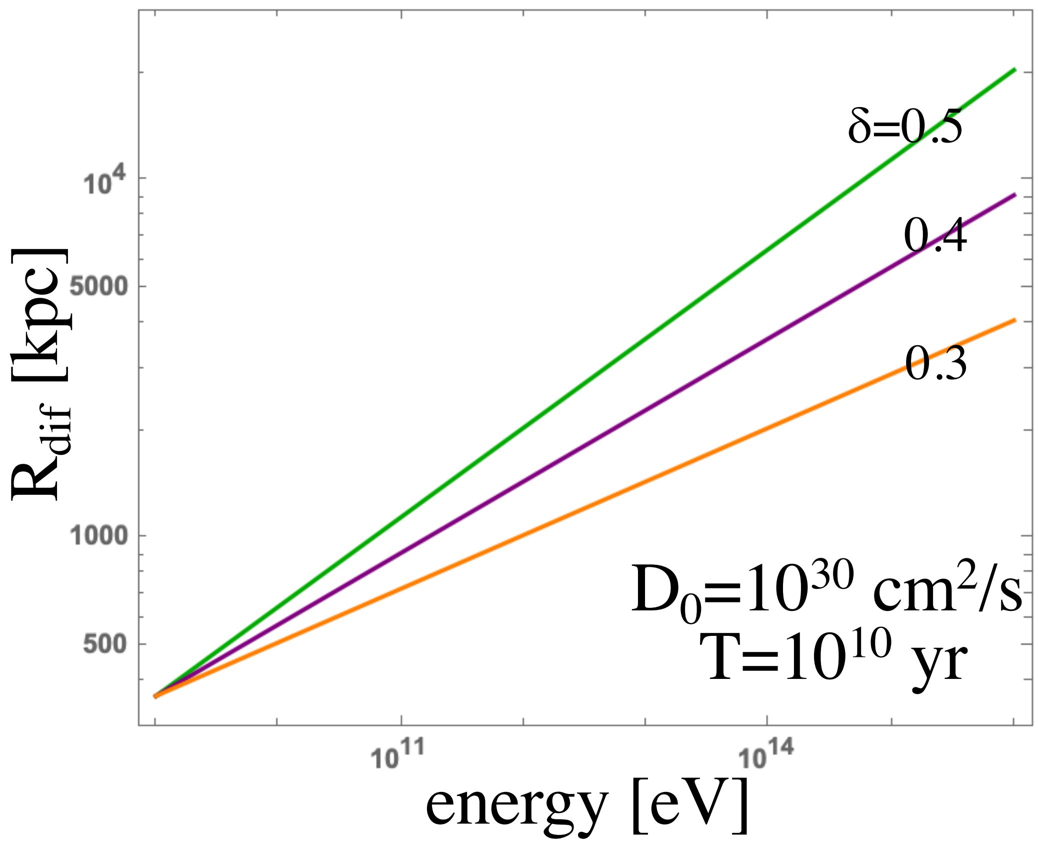
$D(E) = D_0 (E/\mathrm{GeV})^{\delta}$

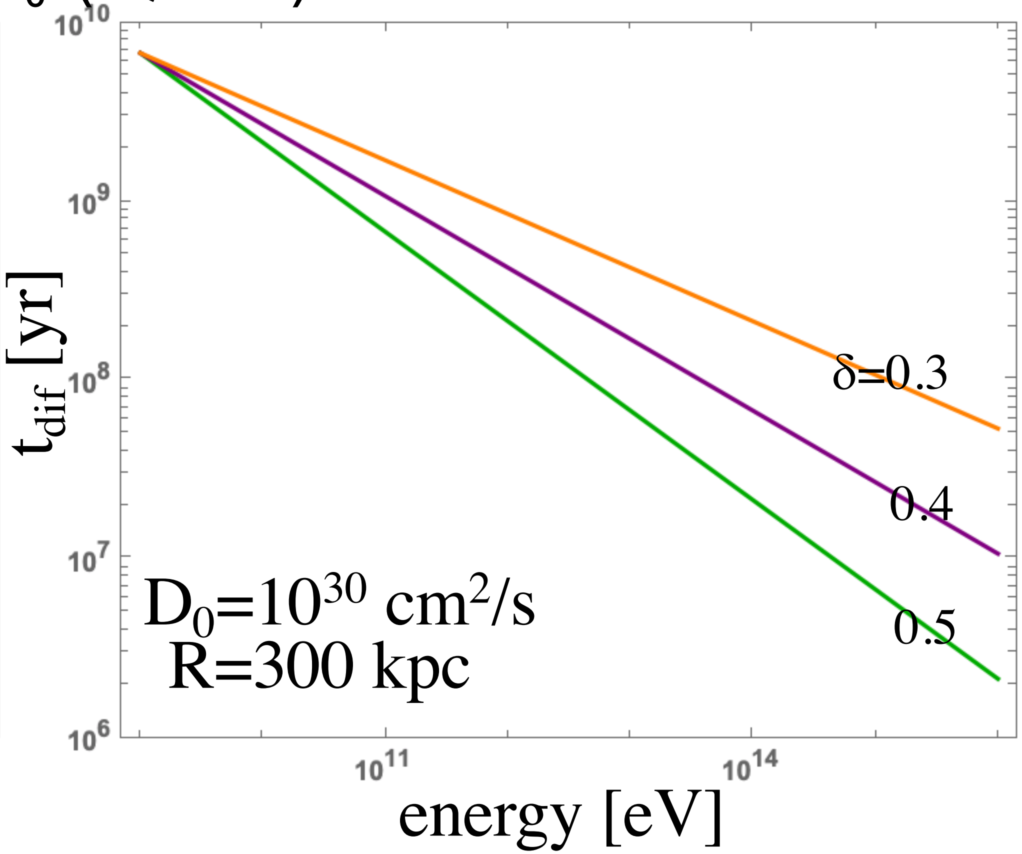
spectrum in ISM
source spectrum +
steepening by E-dep.
confinement

diffusion radius, diffusion time

$$R_{dif}(E) = (4\,D(E)\,t)^{1/2} \qquad t_{dif}(E) \sim \frac{R^2}{4\,D(E)}$$

$$D(E) = D_0\,(E/\mathrm{GeV})^{\delta}$$





consider protons only
for nuclei E->E/Z

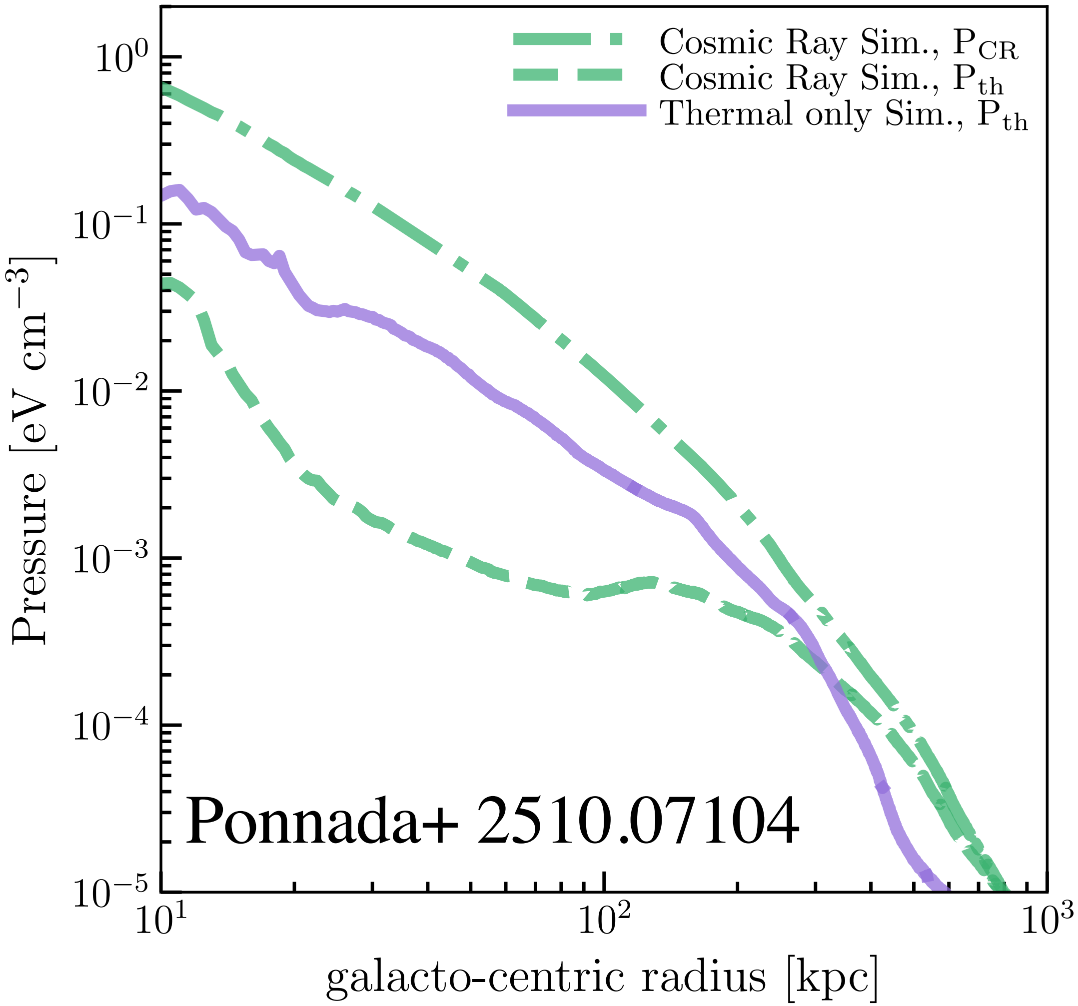
CR-dominated halos: possible evidence

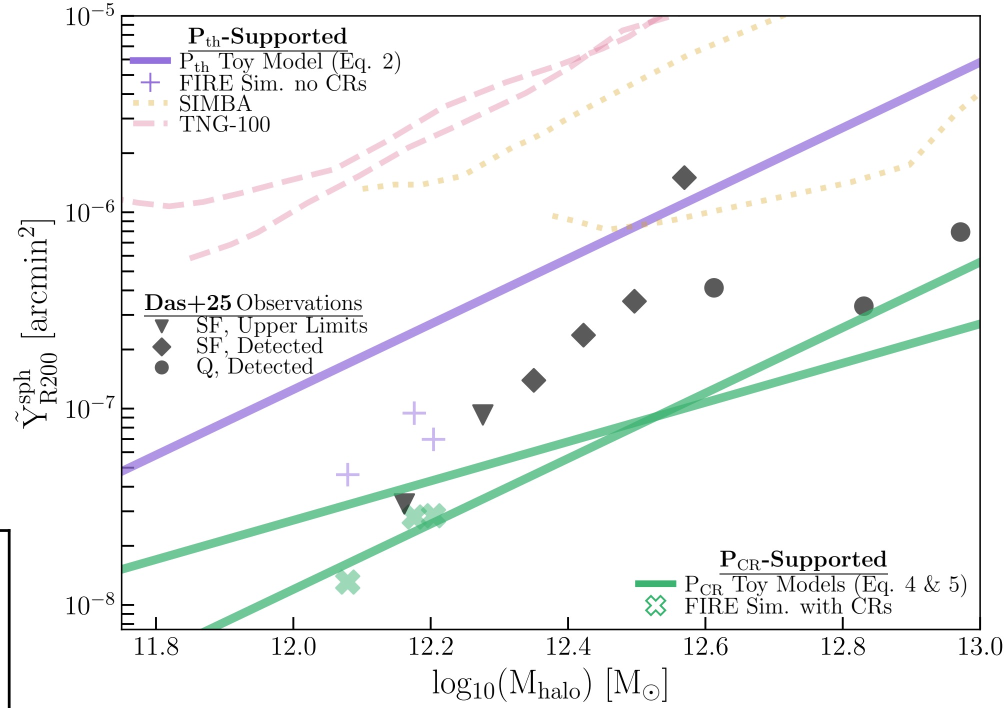
MW-like galaxies stacked sample

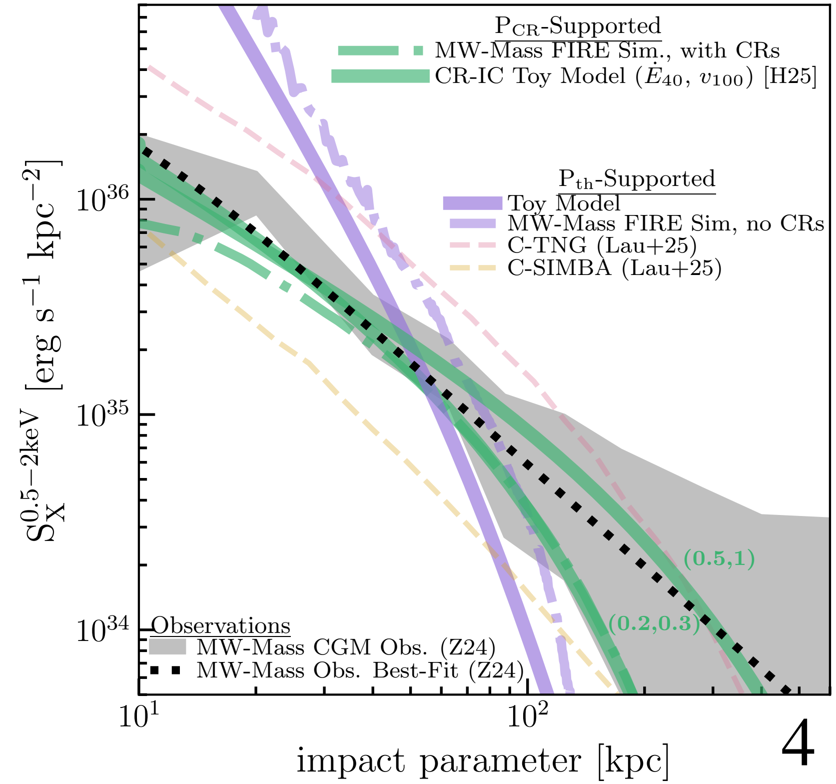
Sunyaev-Zeldovich effect Das+ 25

X-rays (eROSITA) Zhang+ 24

D(GeV, <100 kpc)~10^{30} cm^{2}s^{-1}



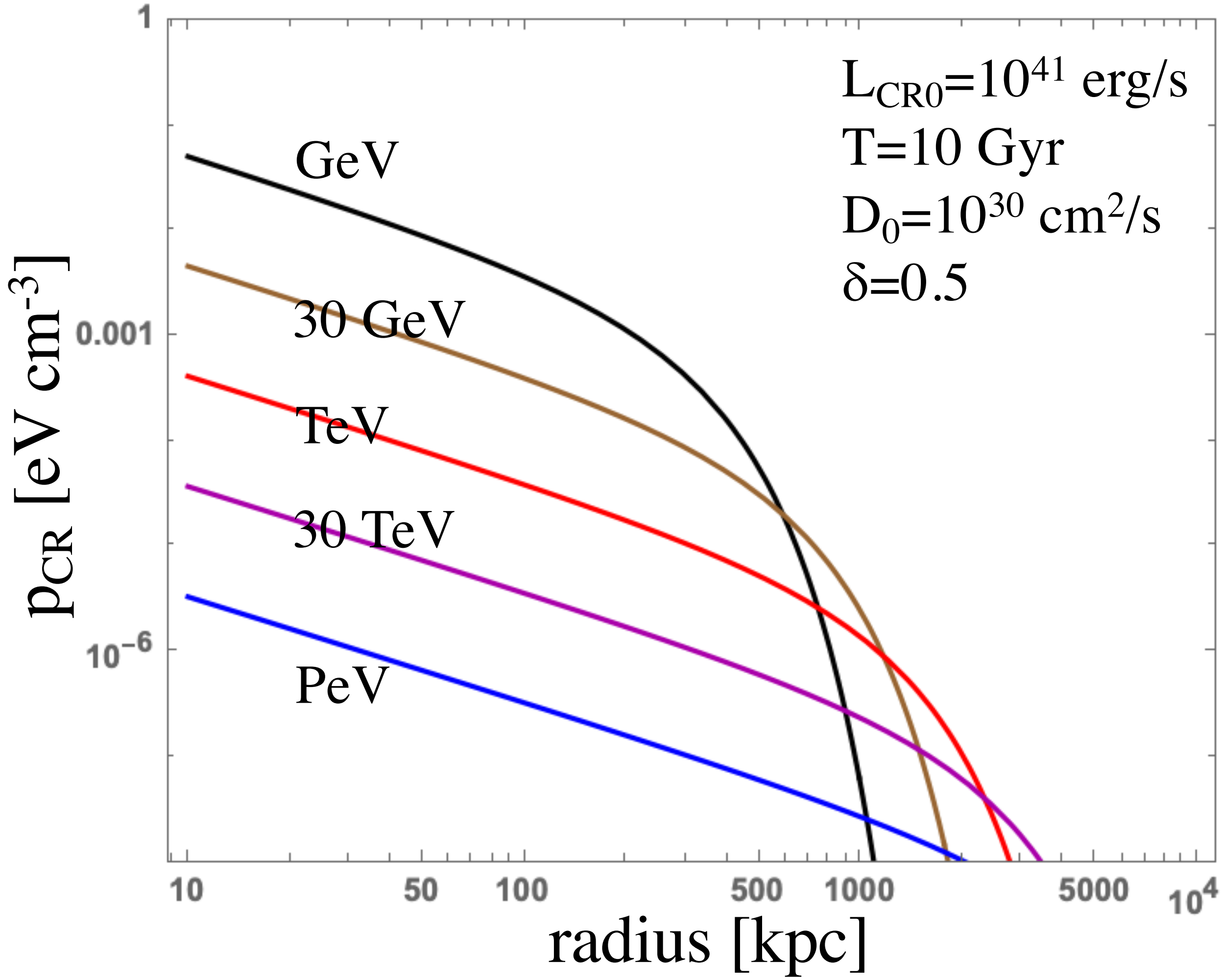




simple diffusion solution

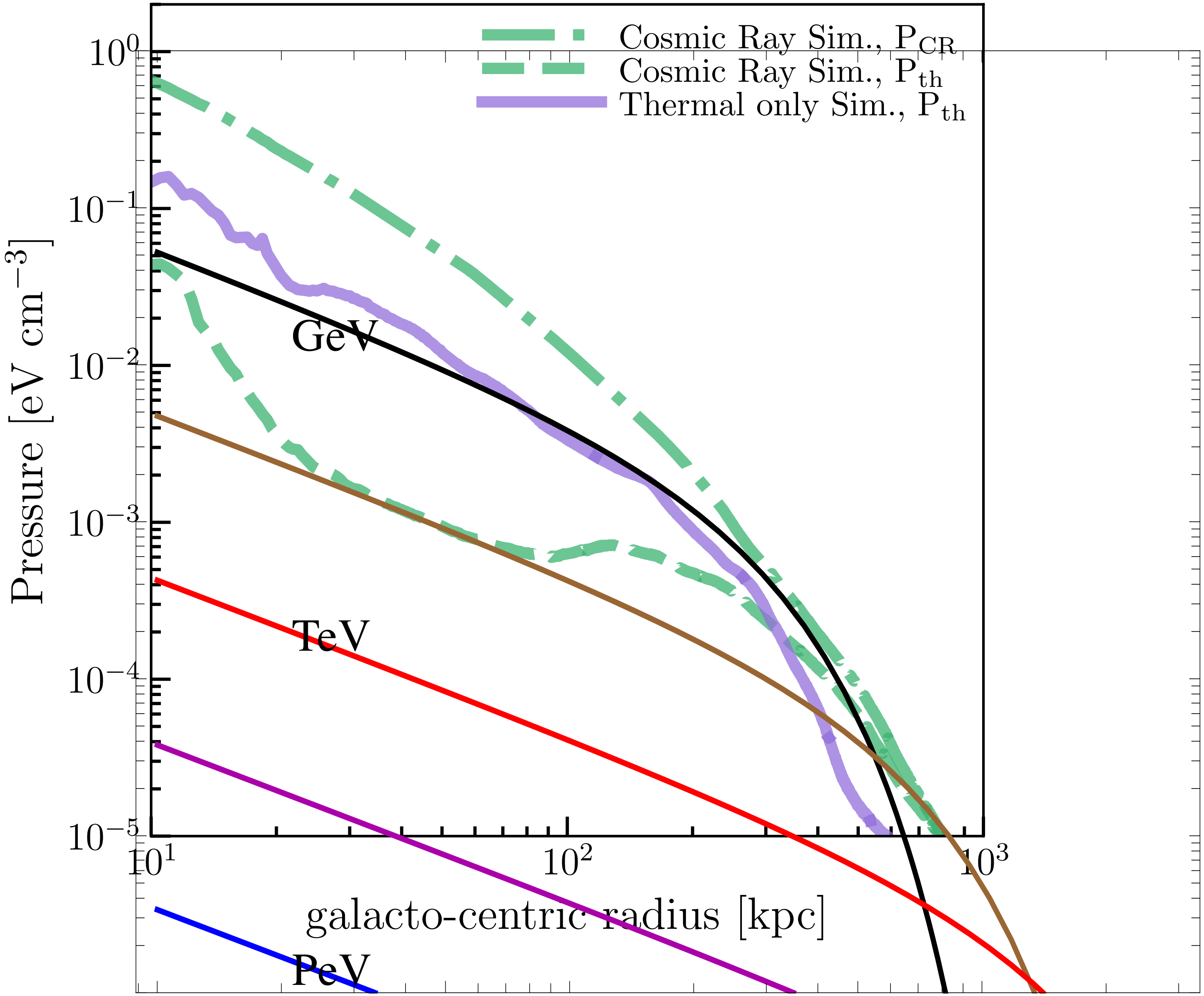
$$U_{CR}(E,r,t) = \frac{L_{CR}(E)}{4\pi D(E)\, r}\,\mathrm{erfc}\left(\frac{r}{(4\,D(E)\,t)^{1/2}}\right) \qquad \mathrm{erfc}(x) = 1 - \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}\,dt$$

$$p_{CR}(E,r,t) = \frac{1}{3}\,U_{CR}(E,r,t) \qquad D(E) = D_0\,(E/\mathrm{GeV})^{\delta} \quad L_{CR0}\,(E/\mathrm{GeV})^{-0.7+\delta}$$



c.f. Ponnada 26 and references therein

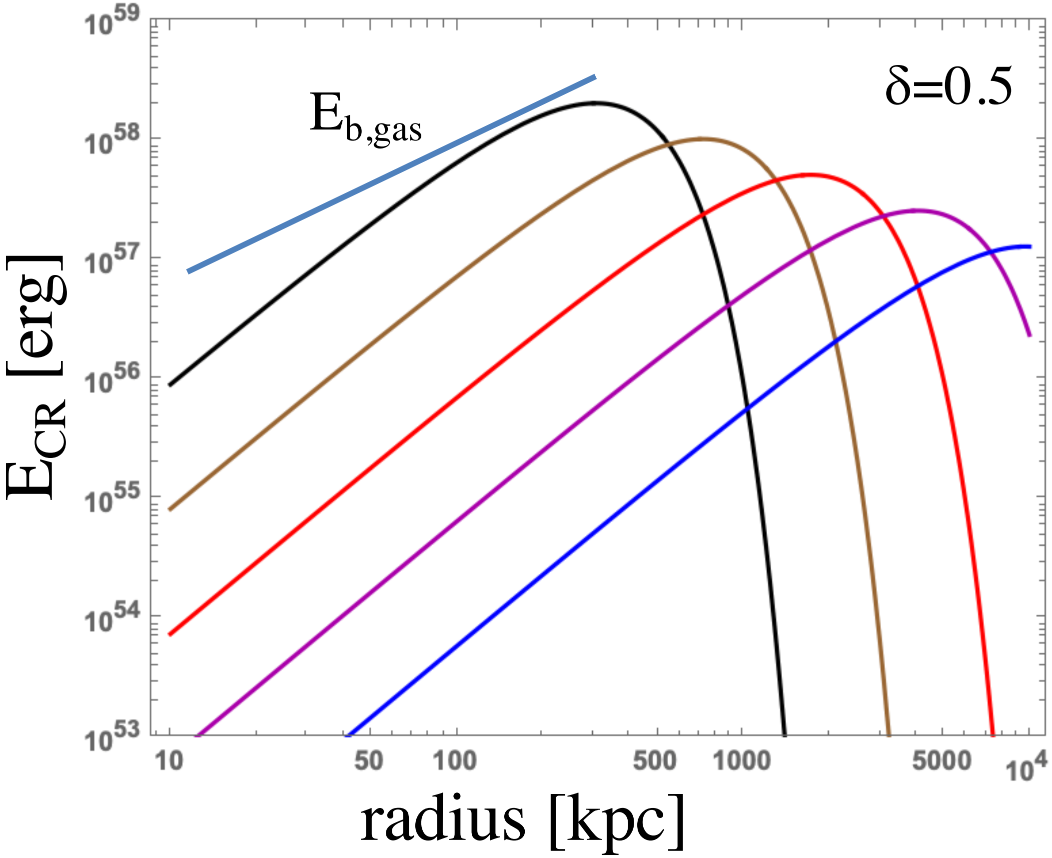
CGM vs CR pressure: Milky Way-like



$L_{CR}=10^{41}$ erg/s
T=10 Gyr
$D_0=10^{30}$ cm^2/s
$\delta=0.5$

TeV-PeV CRs compared to GeV CRs

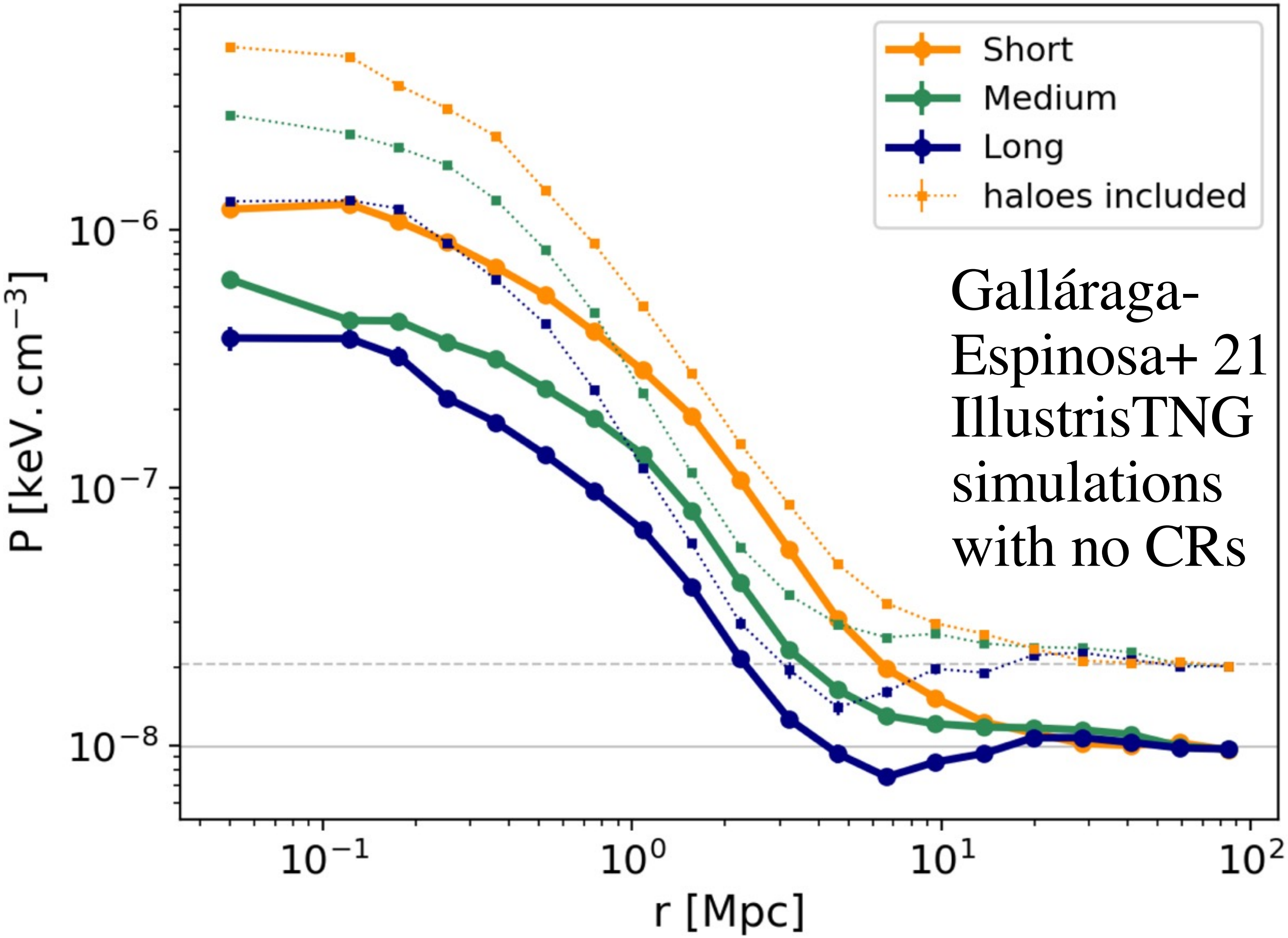
$E_{CR}(E, r, t) = 4\pi r^3 U_{CR}(E, r, t)$ total CR energy per log radius



- total energy of escaped TeV-PeV CRs ~ source energy

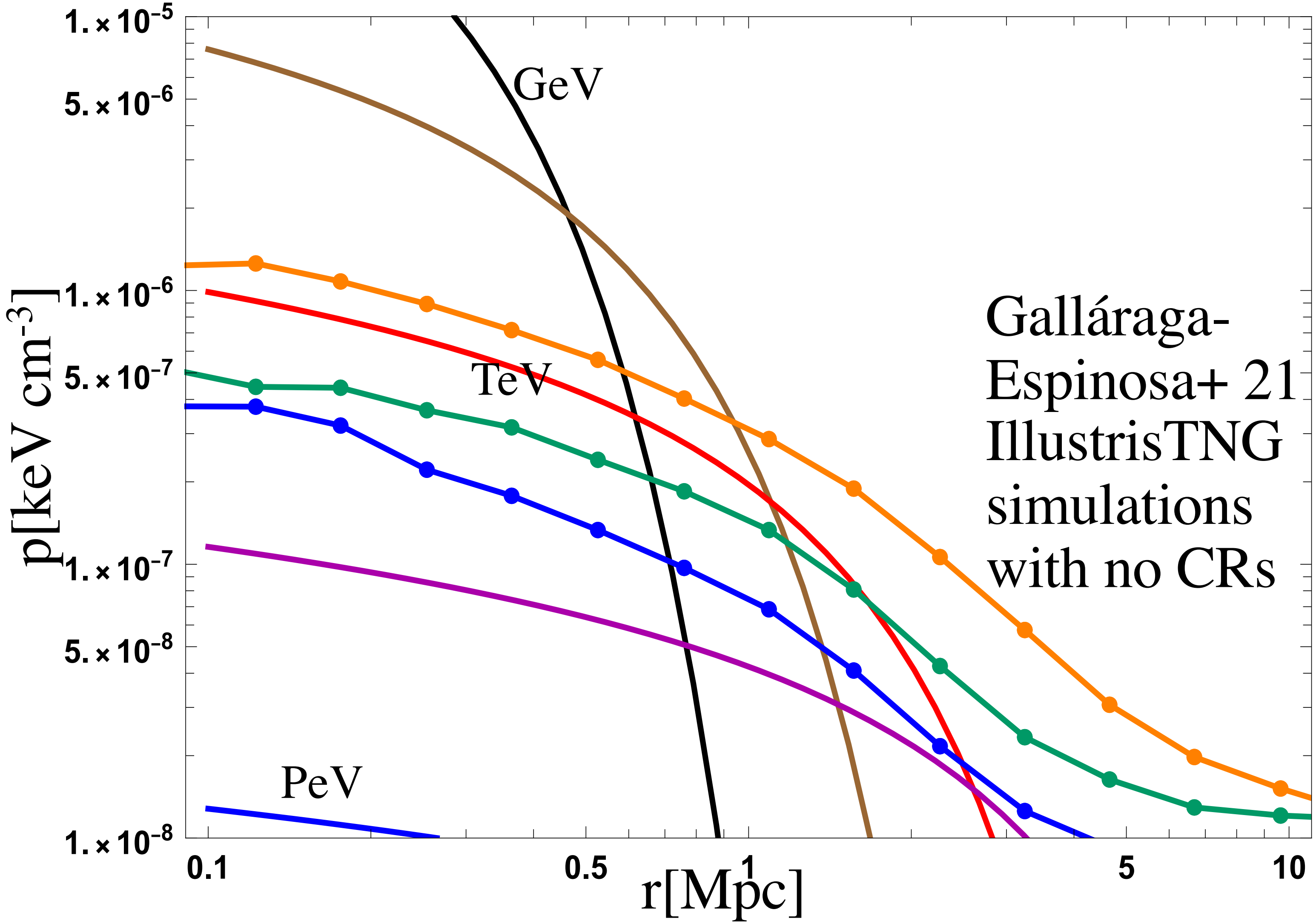
- gas inflowing from larger R
  -> TeV-PeV CRs affect earlier stages of accretion

gas pressure in filaments



short: L < 9 Mpc
medium:
9 Mpc < L< 20 Mpc
long: L > 20 Mpc

gas pressure in filaments vs CRs

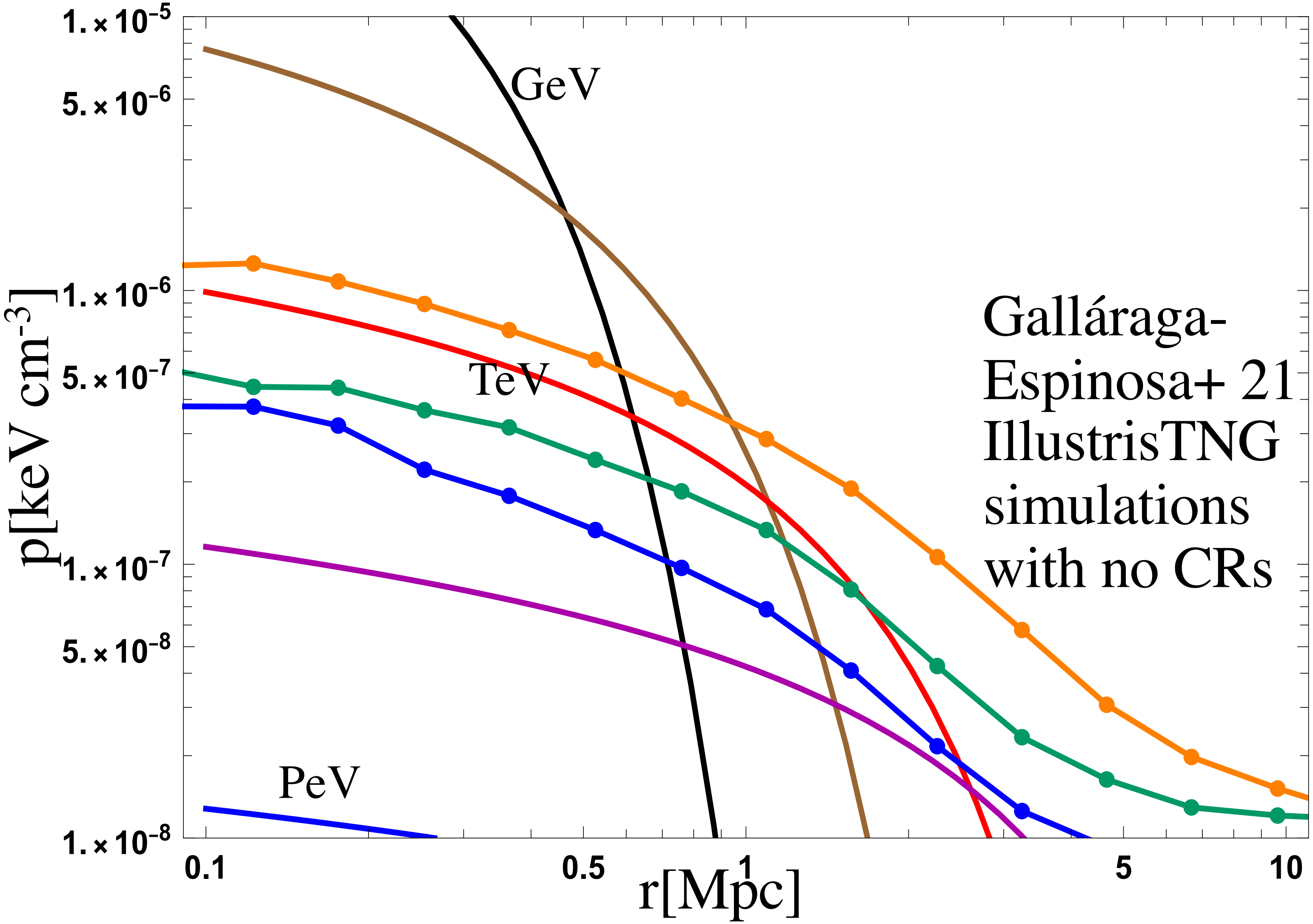


Galláraga-Espinosa+ 21 IllustrisTNG simulations with no CRs

cylindrical symmetry
MW-like galaxy population
L_{CR}=6x10^{42} erg/s
T=10 Gyr
D_0=10^{30} cm^2/s
δ=0.5

VHECRs can be energetically important vs WHIM!

gas pressure in filaments vs CRs



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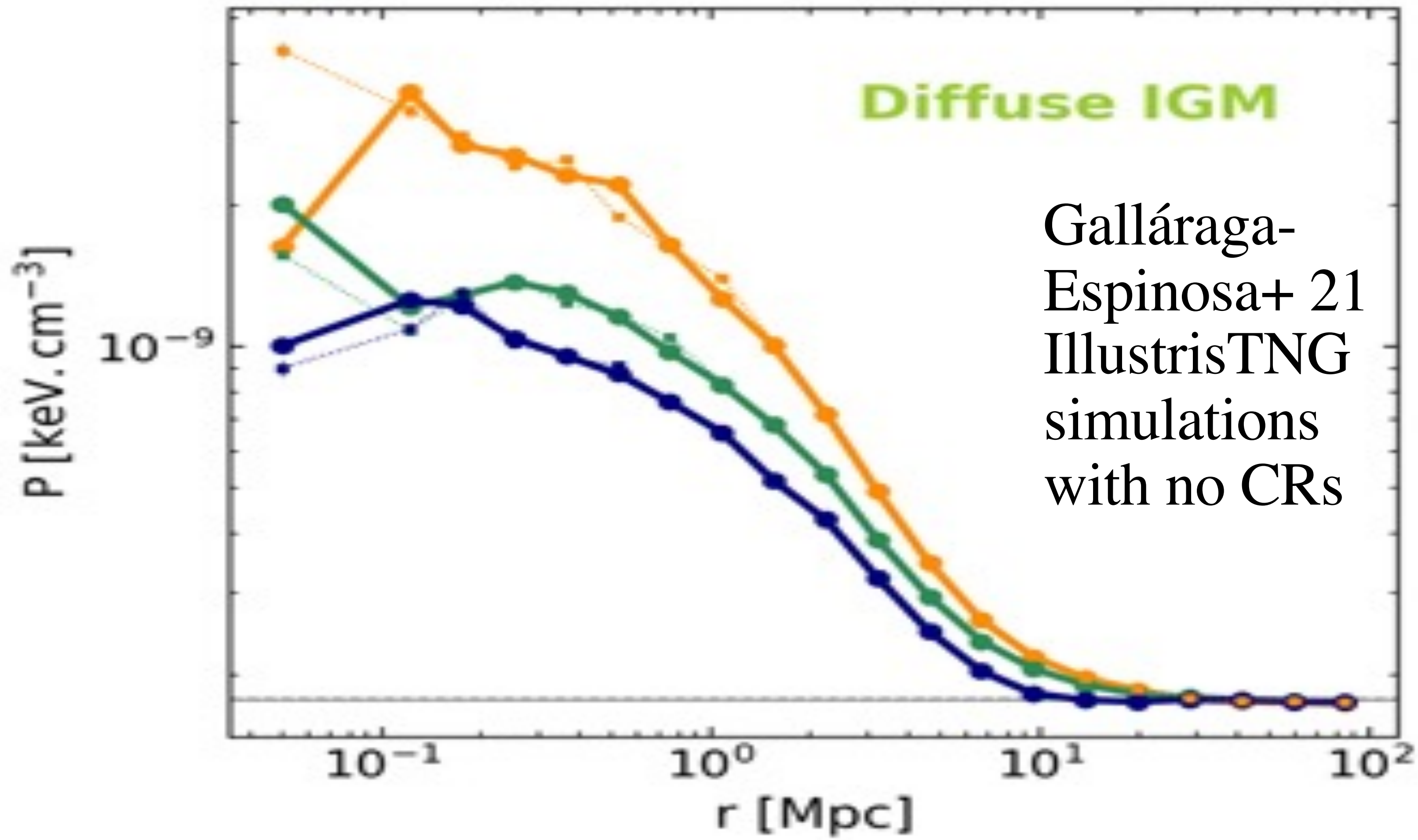
VHECRs can be energetically important vs WHIM!

- affect gas accretion onto halos, star formation rate, galaxy lum. func.
- allow cooler gas, affect observability of WHIM (missing baryons)
- affect measurements of cosmological parameter S_8

cool, diffuse IGM pressure



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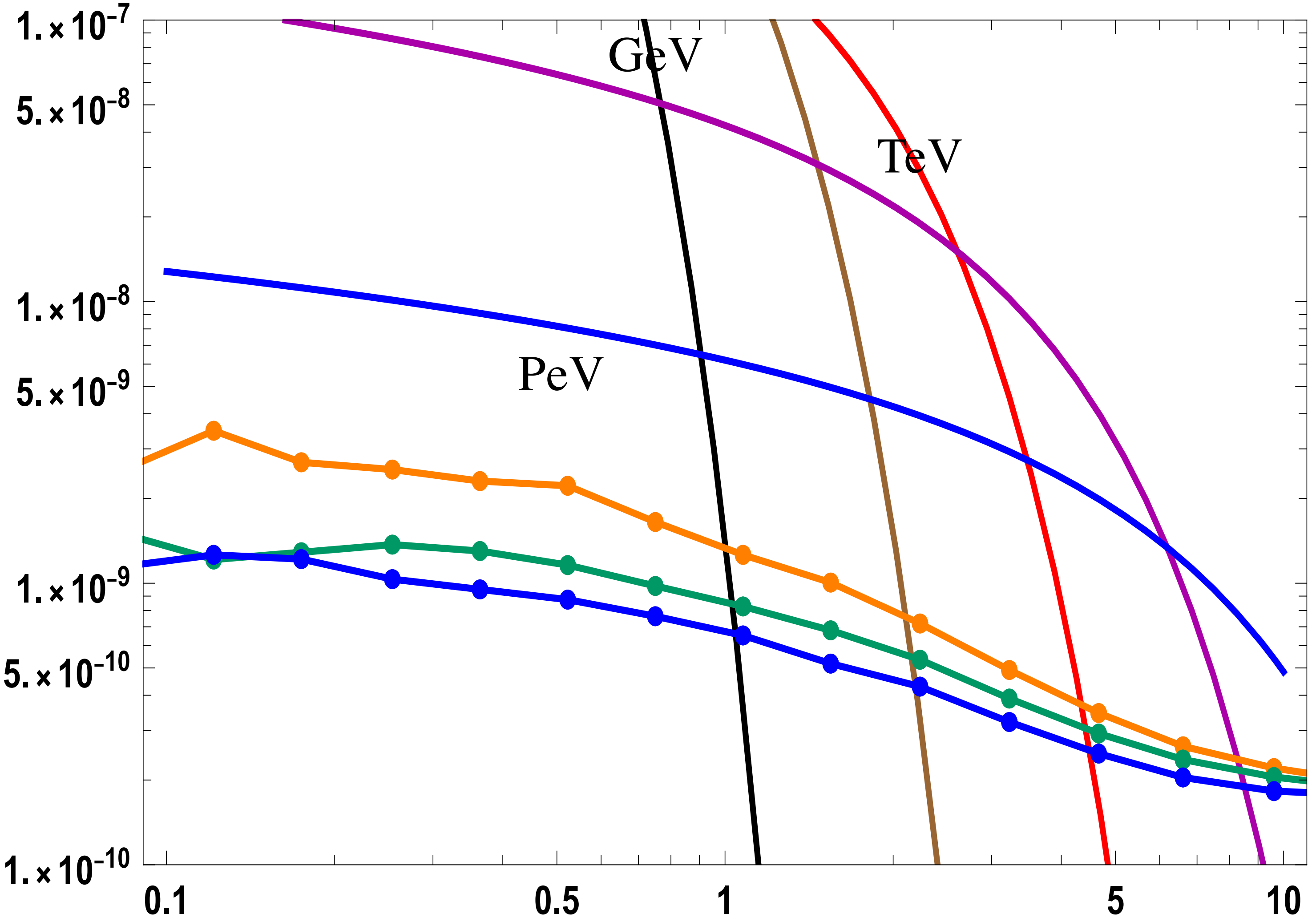

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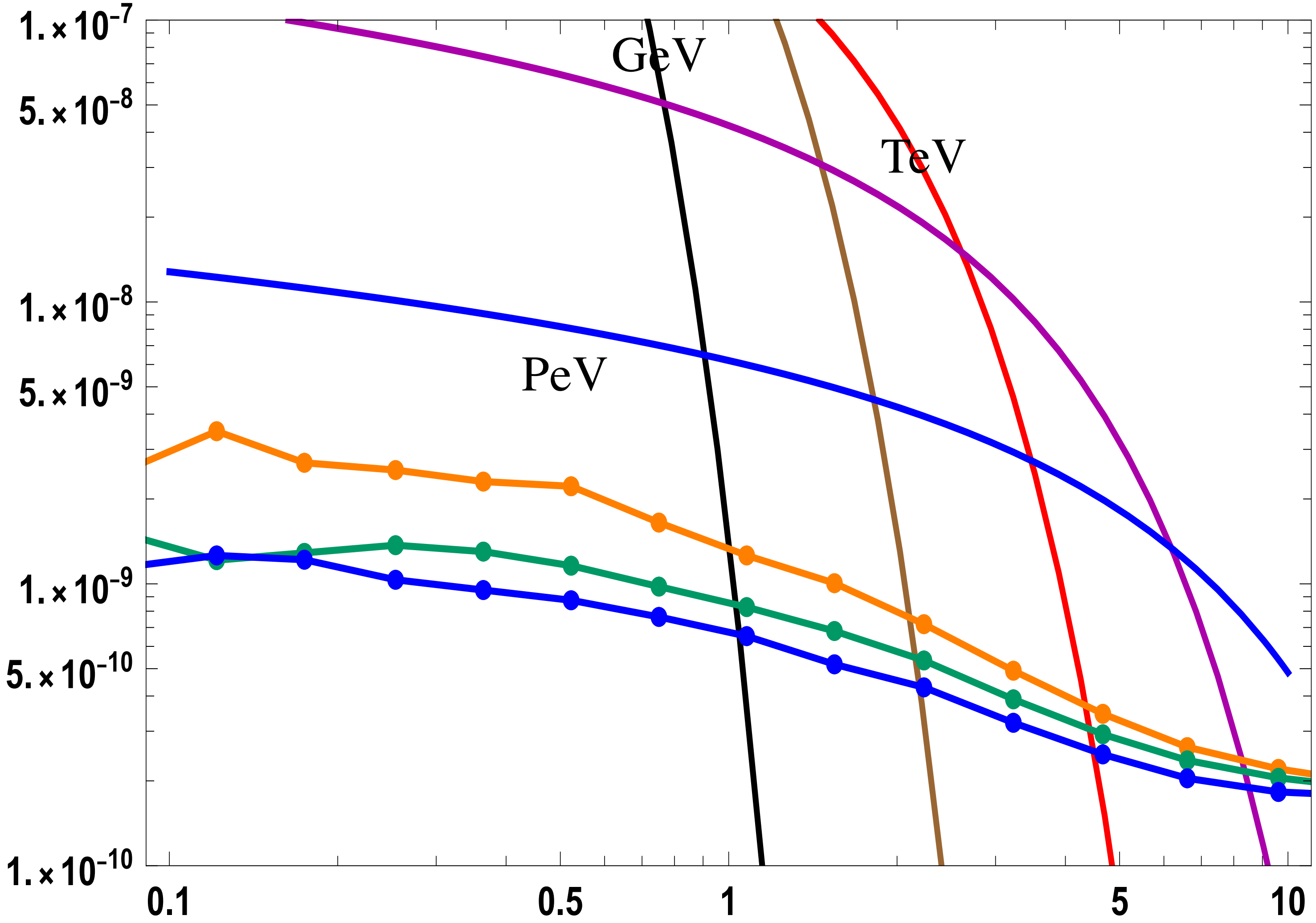
VHE-(U)HECRs can be energetically important vs cool, diffuse IGM!

cool, diffuse IGM pressure



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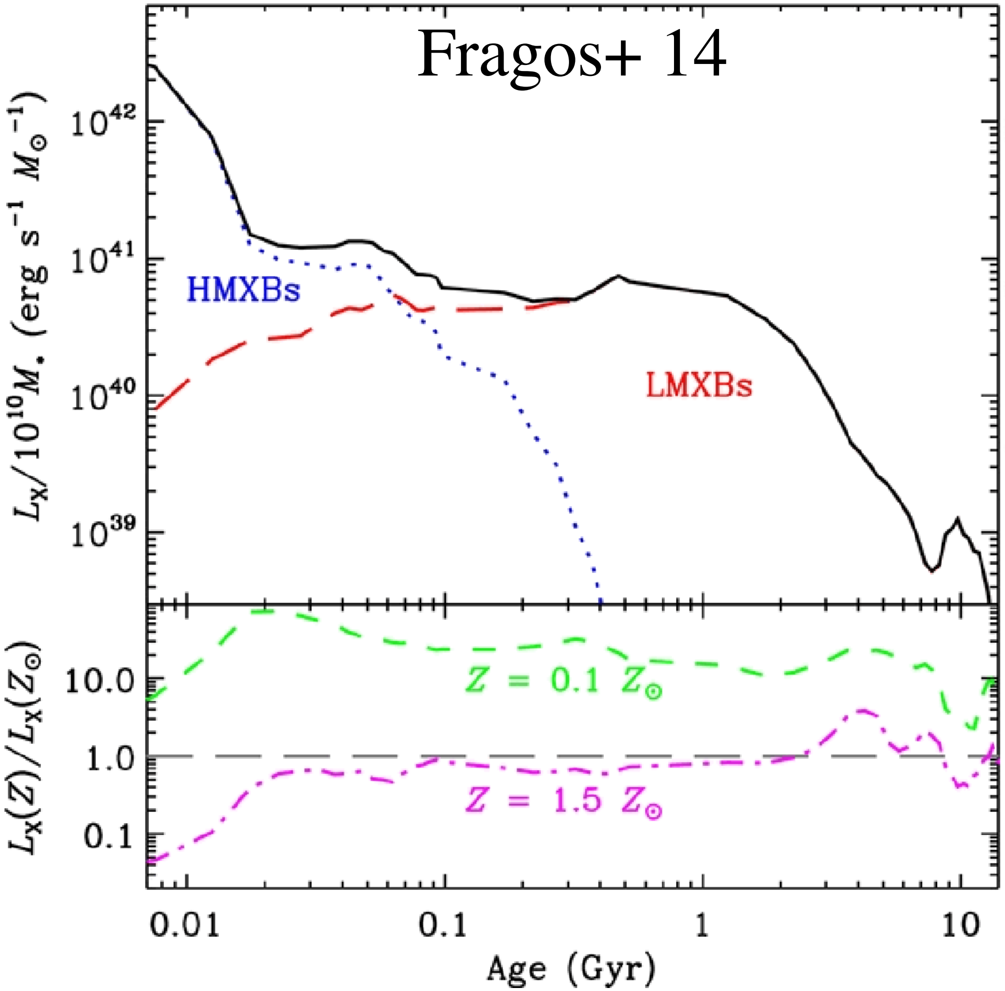
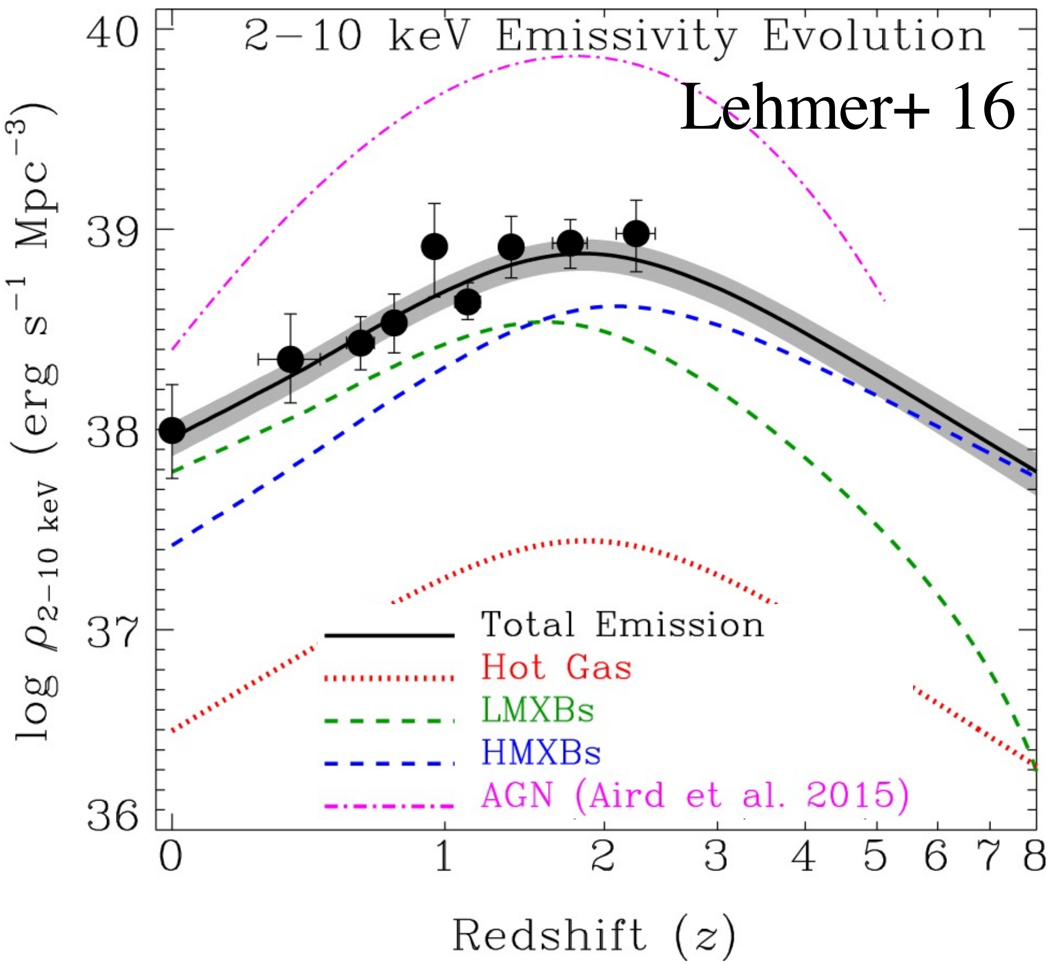
VHE-(U)HECRs can be energetically important vs cool, diffuse IGM!

- affect gas accretion onto filaments, star/structure formation
- relation to observed “anomalies” (excess heating, T inversion, etc)
  -> potential constraints from existing data

potential dependence on pevatron identity

microquasars: HMXB vs LMXB: difference in t evolution





PeV CRs in cool IGM: z-dependence of effect on Lyα forest?

“large-scale” pevatrons: Fermi bubble, Galactic wind shock, accretion shock…

summary

- TeV-PeV CRs vs GeV CRs: energetically minor in MW disk, but possibly not so minor at outer CGM and beyond
- TeV CRs can reach the WHIM and be energetically important
  -> potential effect on gas accretion onto halos,
     WHIM observability, S8 measurement
- TeV-PeV CRs can reach cool diffuse IGM and be energetically important
  -> potential effect on gas accretion onto filaments,
     relevance for observed Lyα forest anomalies
- potential dependence on nature of source
  Identifying pevatrons may also be important for understanding IGM evolution!

(- observational tests: challenging)
   c.f. PeV γ has some advantages for MW CGCRs,
   see SI et al. ICRC 2025; in prep.