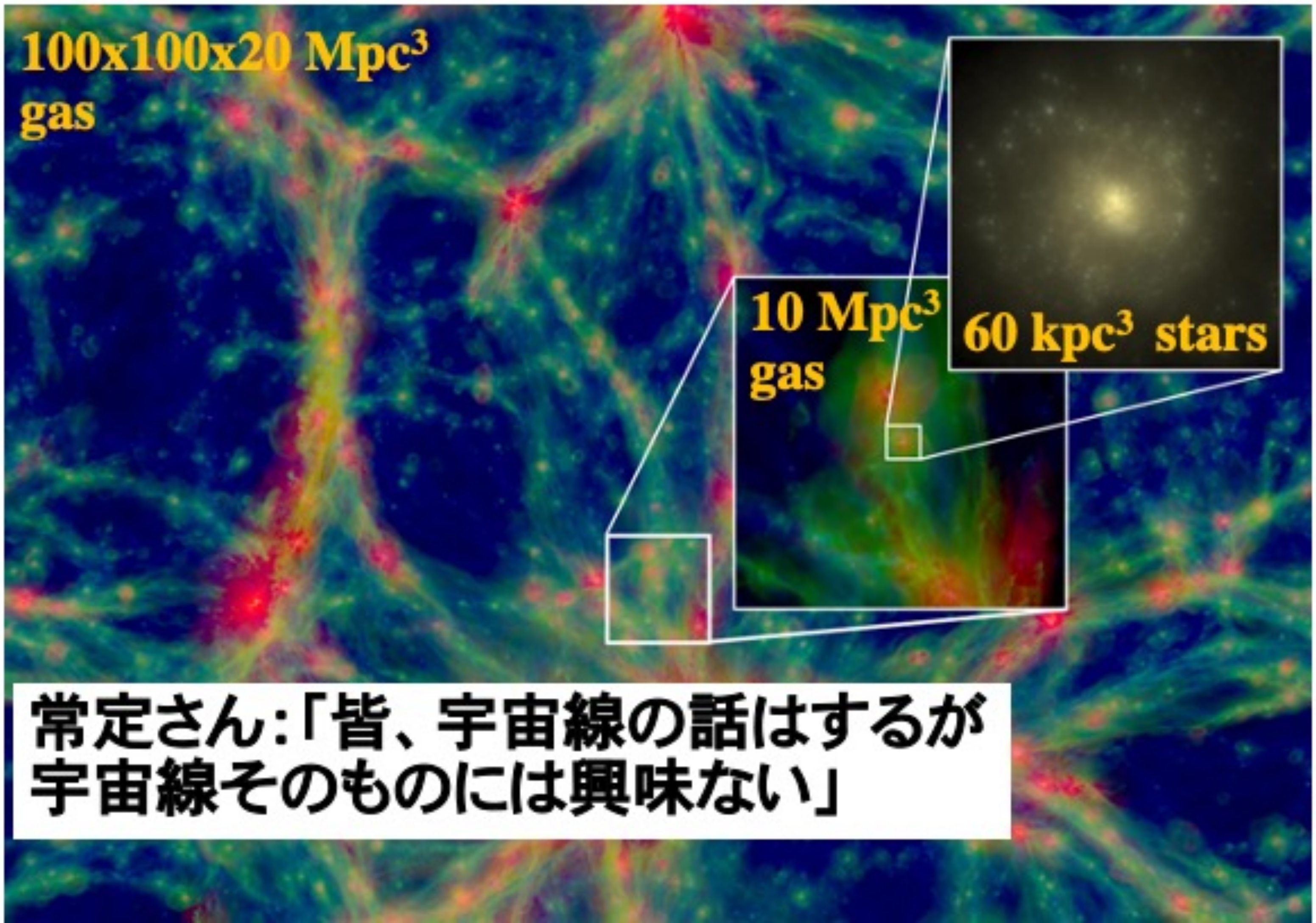
# 超高エネルギー宇宙線の宇宙論的役割とそのマルチメッセンジャー探査

井上進(千葉大/宇宙線研)

共同研究者:大平豊(東大)、藤田裕(都立大)ほか




常定さん:「皆、宇宙線の話はするが宇宙線そのものには興味ない」

EAGLE
Schaye+ 14

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

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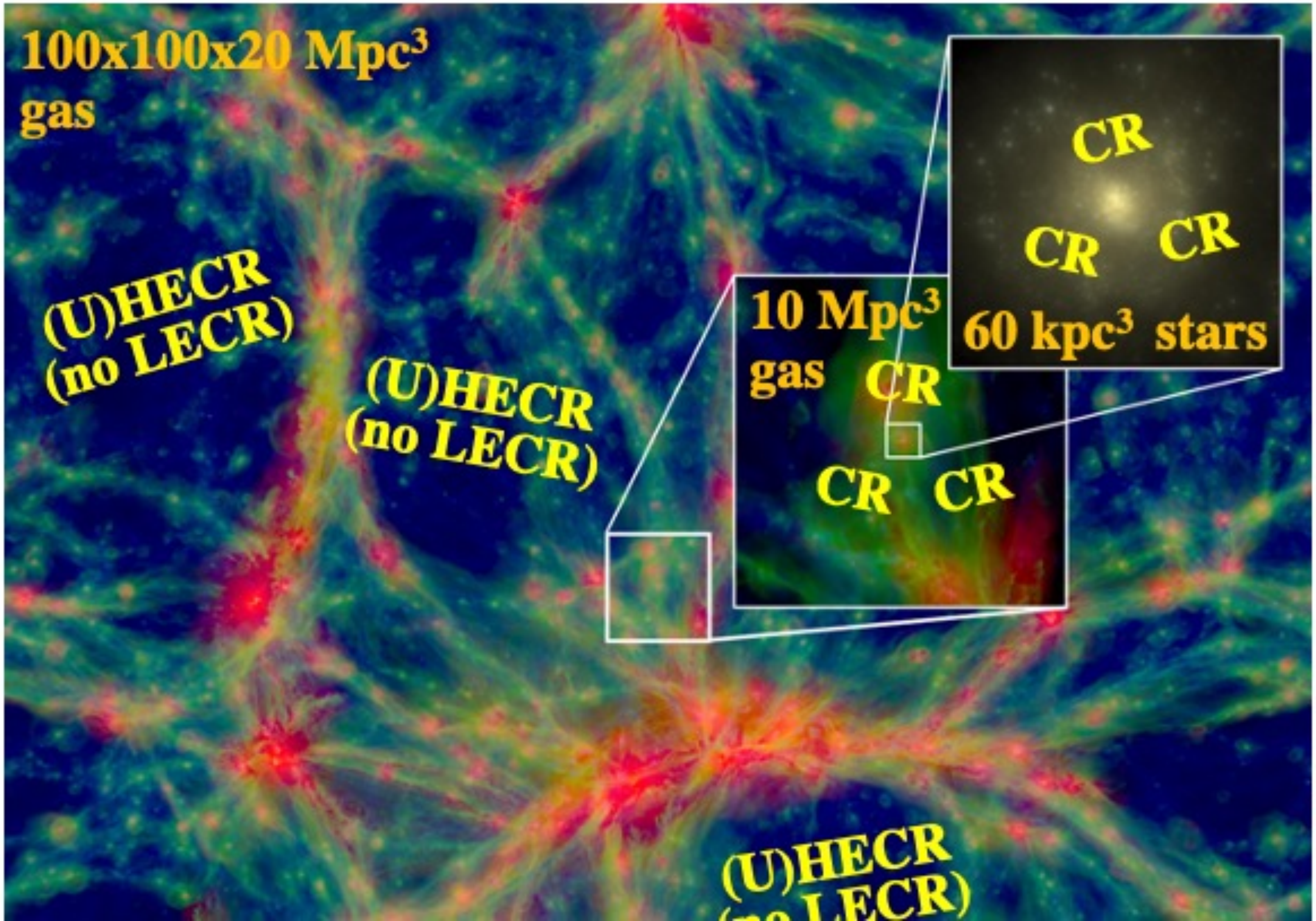


EAGLE
Schaye+ 14

B: <$10^{4.5}$ K
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## outline

1. (U)HECR pressure vs cool IGM at z=0, z~2-3

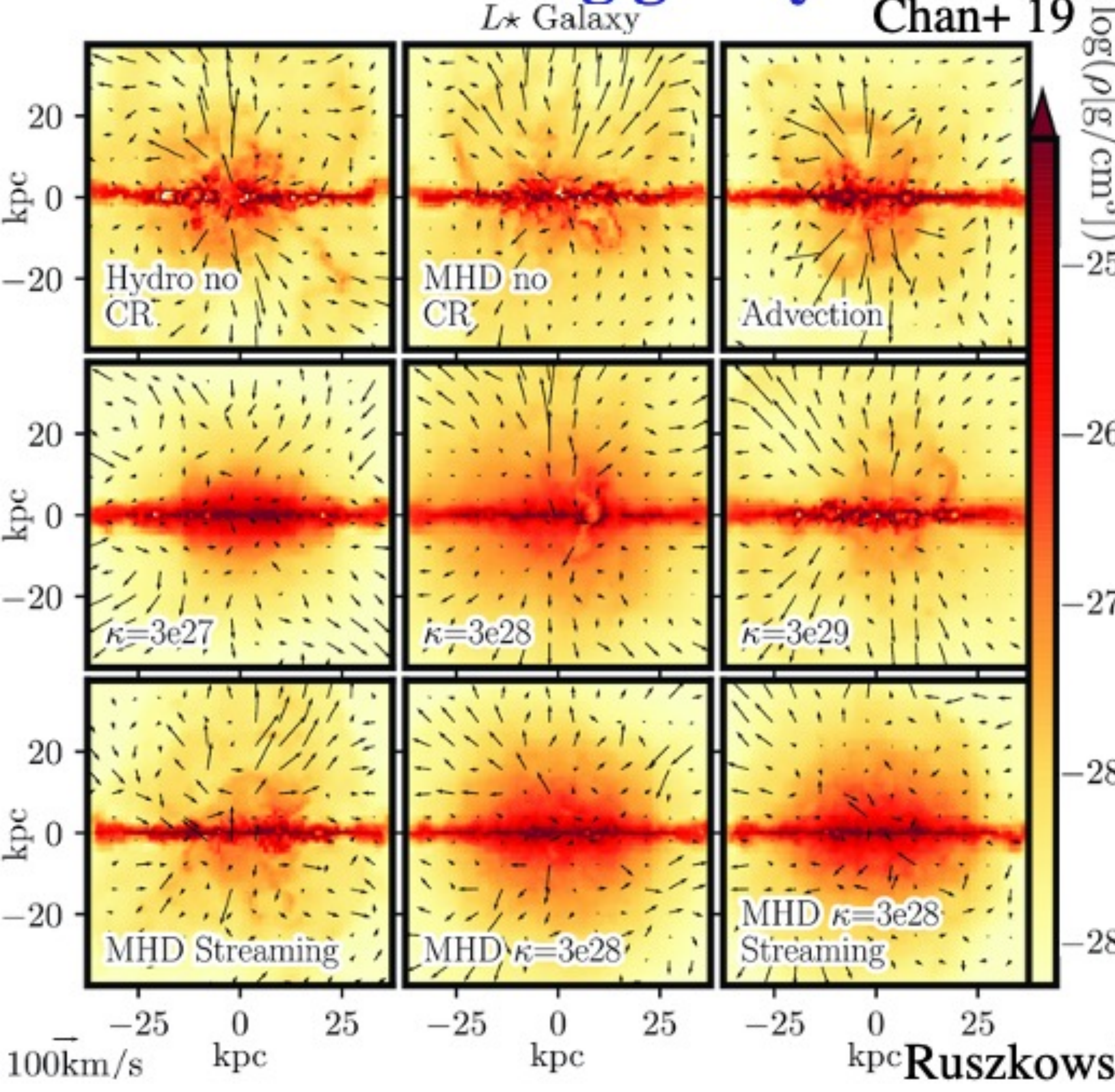
2. (U)HECR heating vs Ly$\alpha$ forest

   SI, Ohira & Fujita, in prep.

3. (U)HECR pressure near sources
   vs Ly$\alpha$ forest, $S_8$ tension

4. Relevant MWL, MM signatures

# CR feedback during galaxy formation



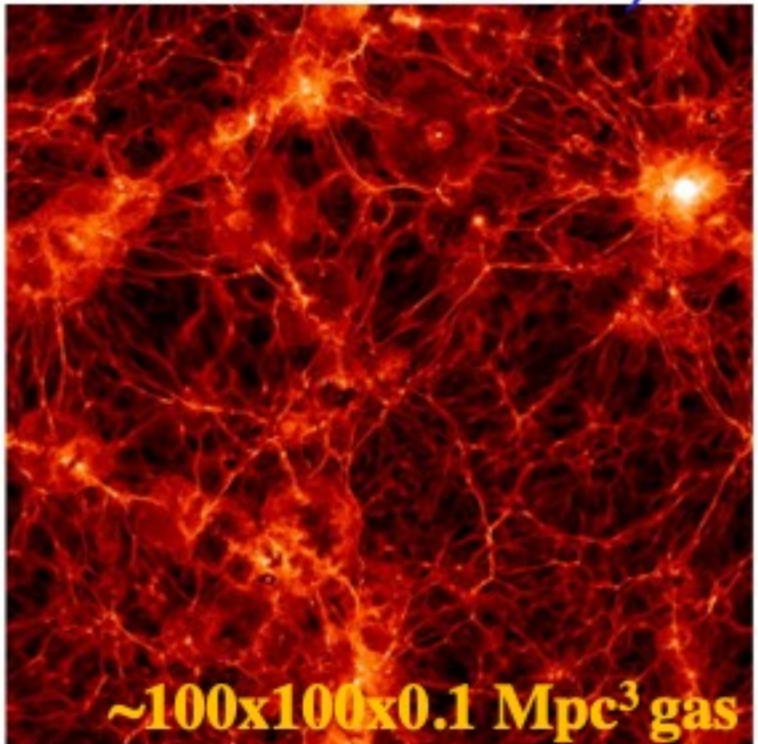

Chan+ 19

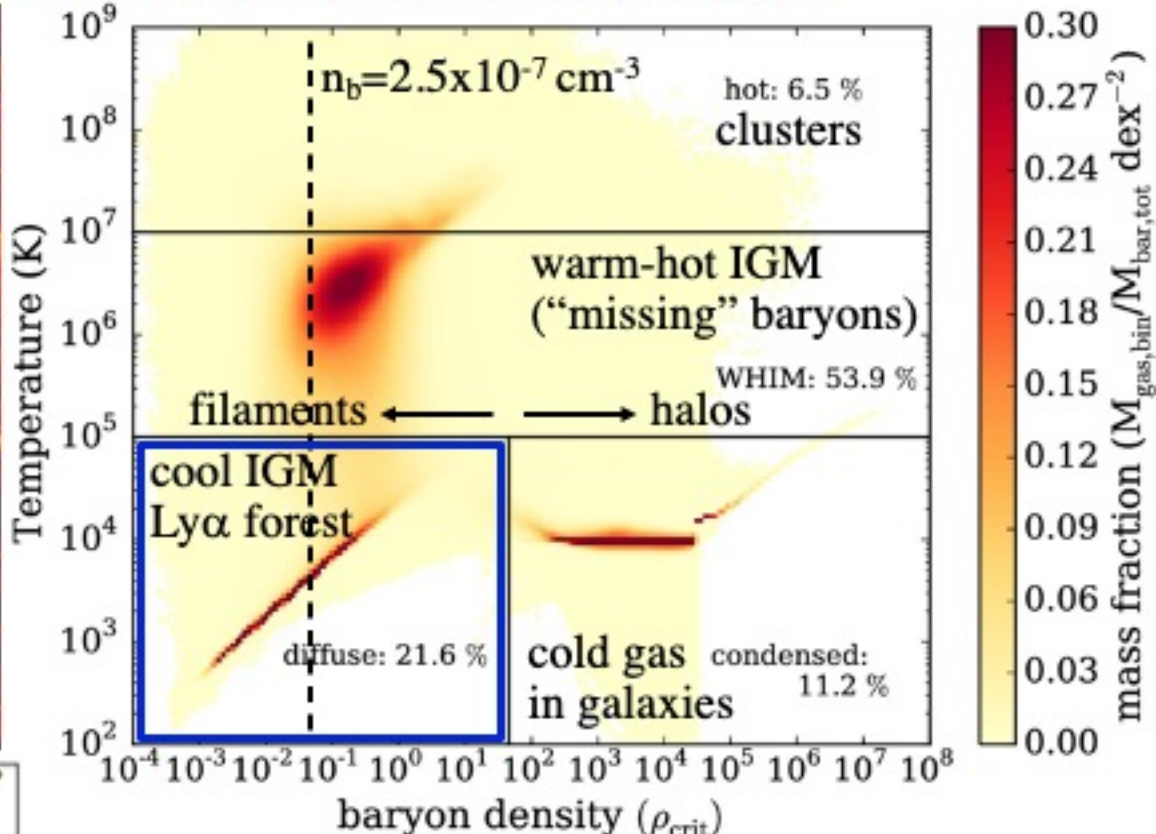
- CRs injected in disk, escape -> must exist in CGM
- Potentially large impact of $p_{CR}$, $\dot{T}_{CR}$ on CGM, gal. evol.
- Depends strongly on assumed CR transport
- Obs. constraints warranted

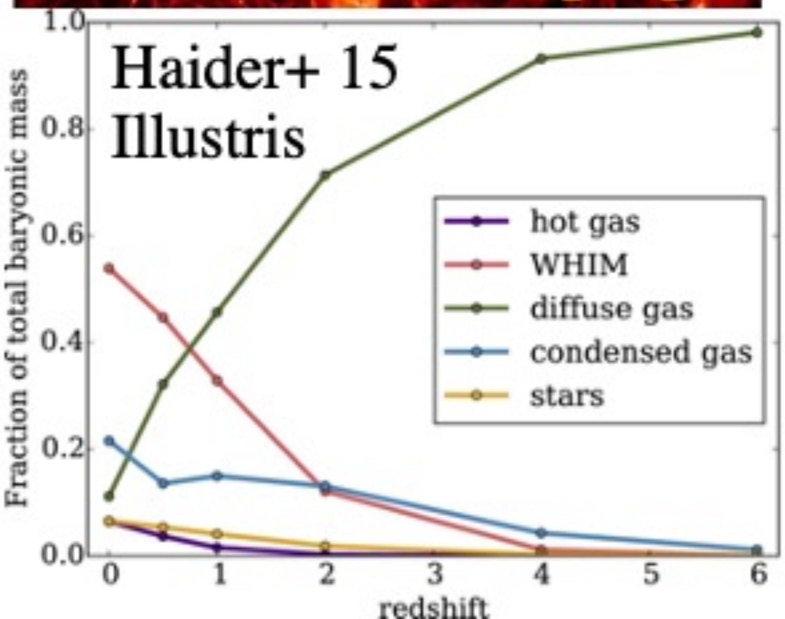
simulations
FIRE: Hopkins+
ChaNGa: Butsky+
AREPO/AURIGA: Pfrommer+
RAMSES: Dubois+
...

Ruszkowski & Pfrommer 23

# cosmic web: cool, diffuse vs warm-hot IGM



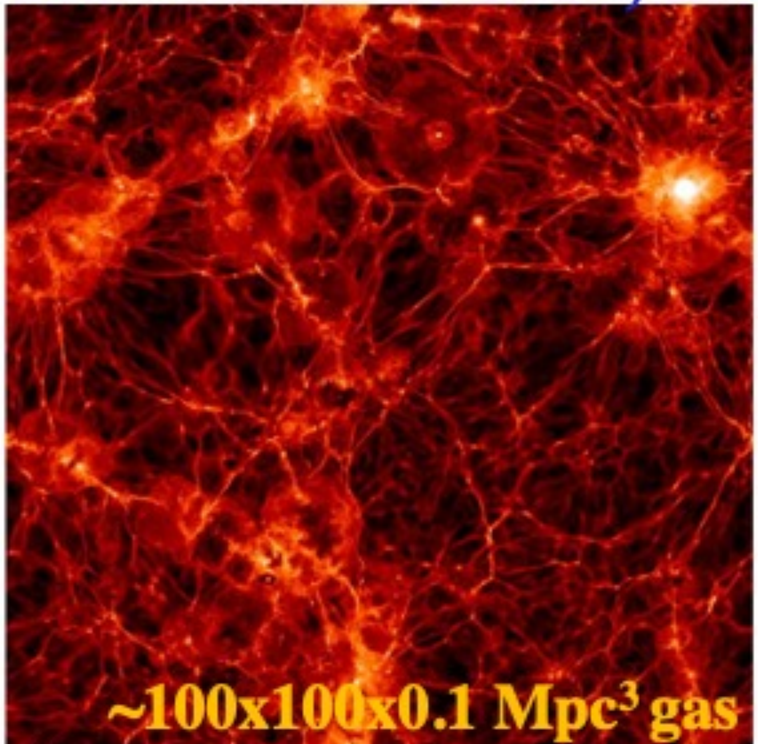



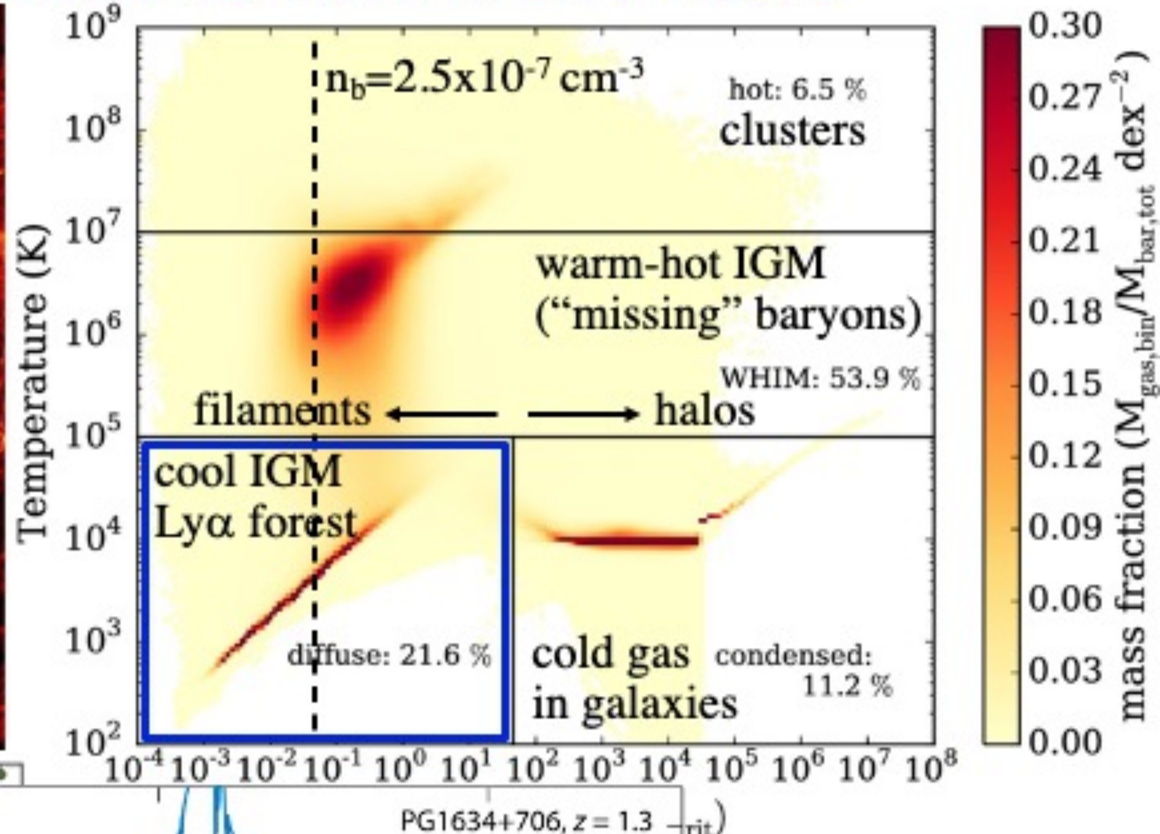



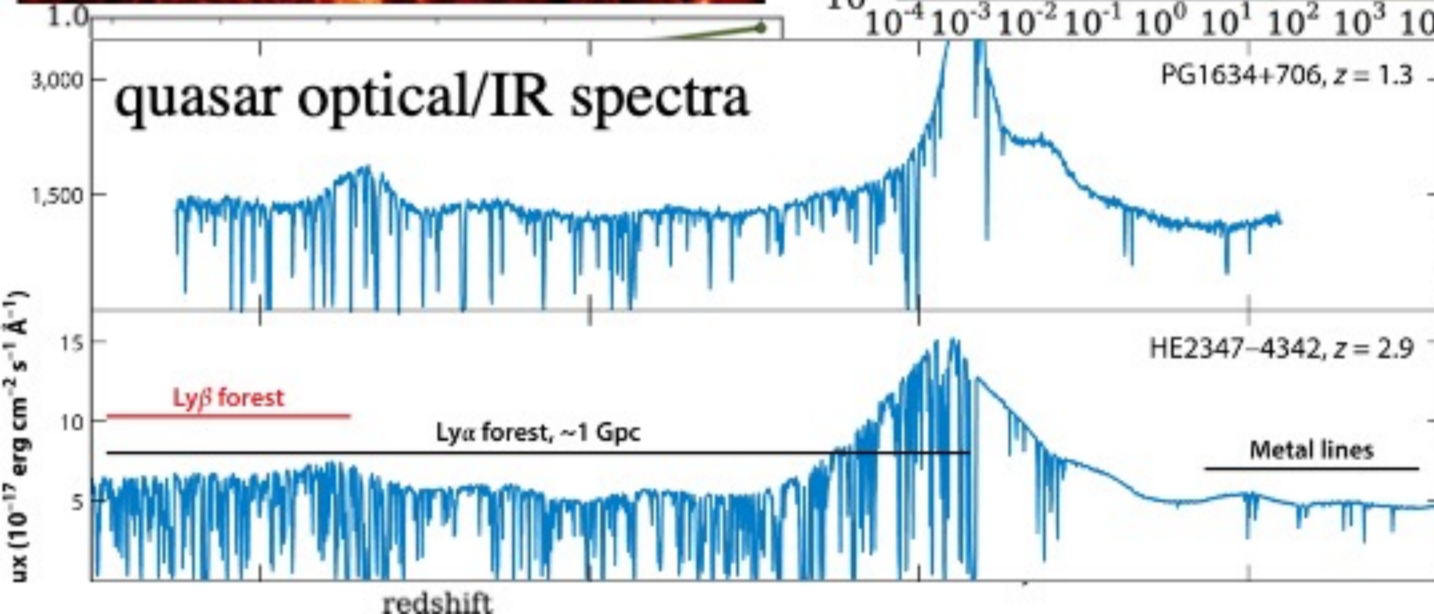

cool, diffuse IGM:

- observable as Lyα forest
- gas mainly in voids (z>~2.5), edge of filaments (z~<2.5) in CDM cosmology
- photoionized by UV background
- dominant volume fraction of universe at all z; dominant mass fraction at z>~1

# cosmic web: cool, diffuse vs warm-hot IGM

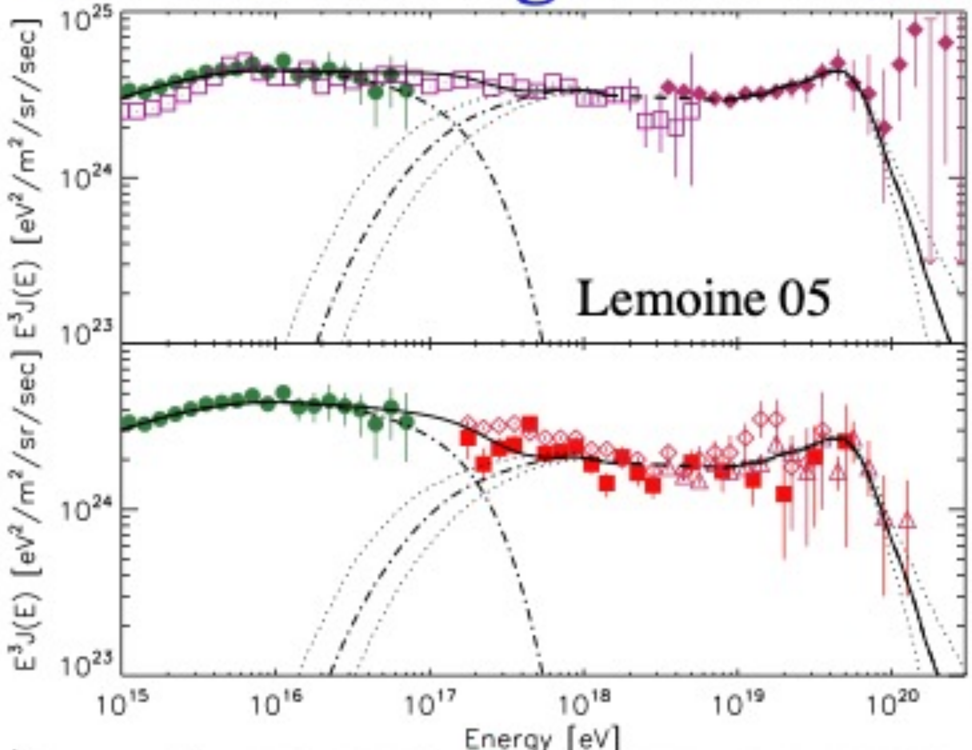



st
~2.5), edge of
DM cosmology
ckground
on of universe
fraction at z>~14

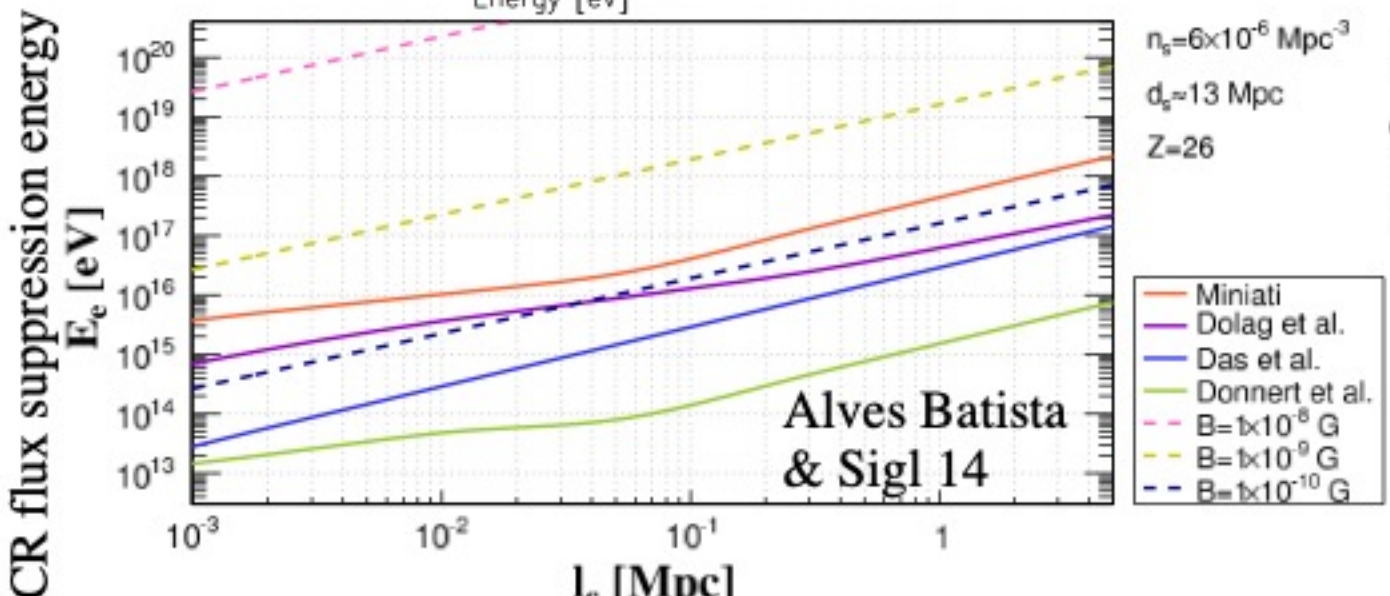
# UHECRs: magnetic horizon




propagation (diffusion) time in intergalactic magnetic field (IGMF) > age of universe

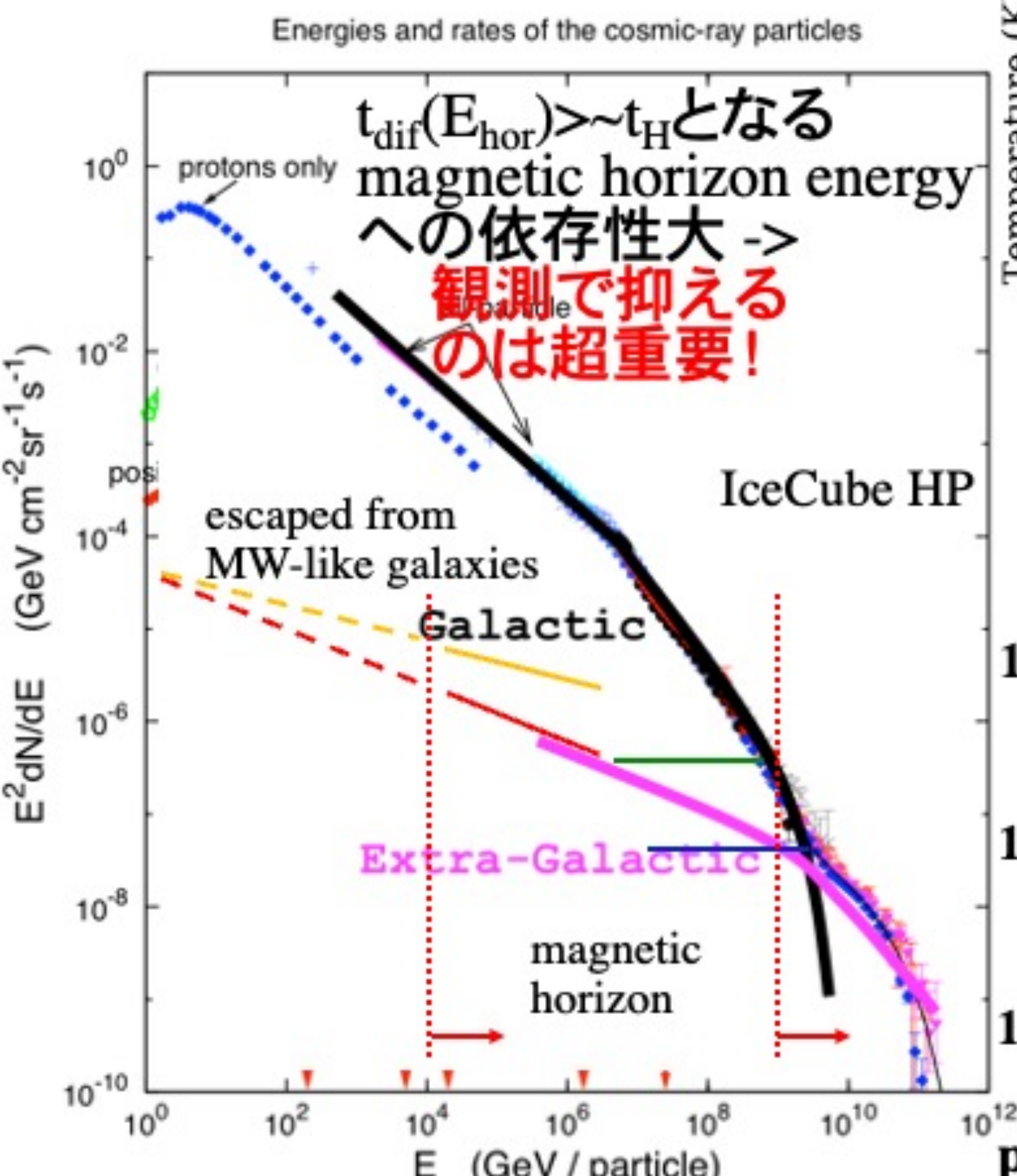
CR flux suppression at lower E
- better for explaining second knee in CR spectrum?
- (U)HECRs without LECRs in diffuse IGM

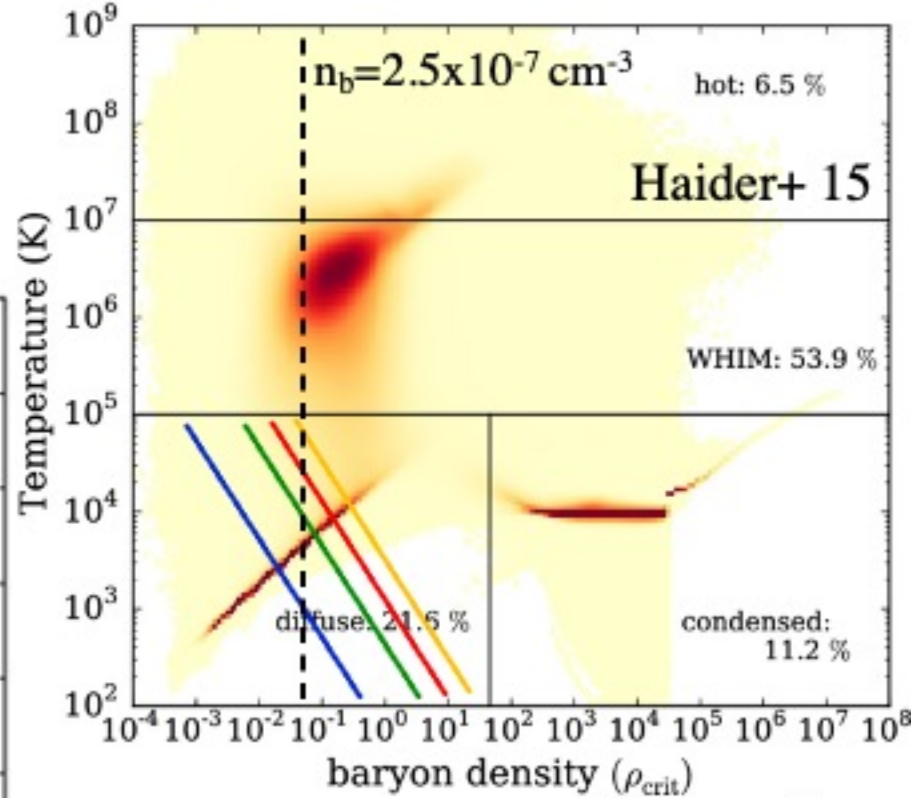
銀河間空間では(U)HECRが主役!




strongly dependent on IGMF (poorly constrained)

# pressure of (U)HECRs vs diffuse, cool IGM gas




$p_{IGM}=k_B n_{IGM} T_{IGM}$

$10^{-18}$

- cool IGM中には(U)HECRが必ず存在するはず. magnetic horizonによりLECRは無い.

$10^{-20}$

- その圧力はIGMガスと比べ無視できない. (卓越も?)

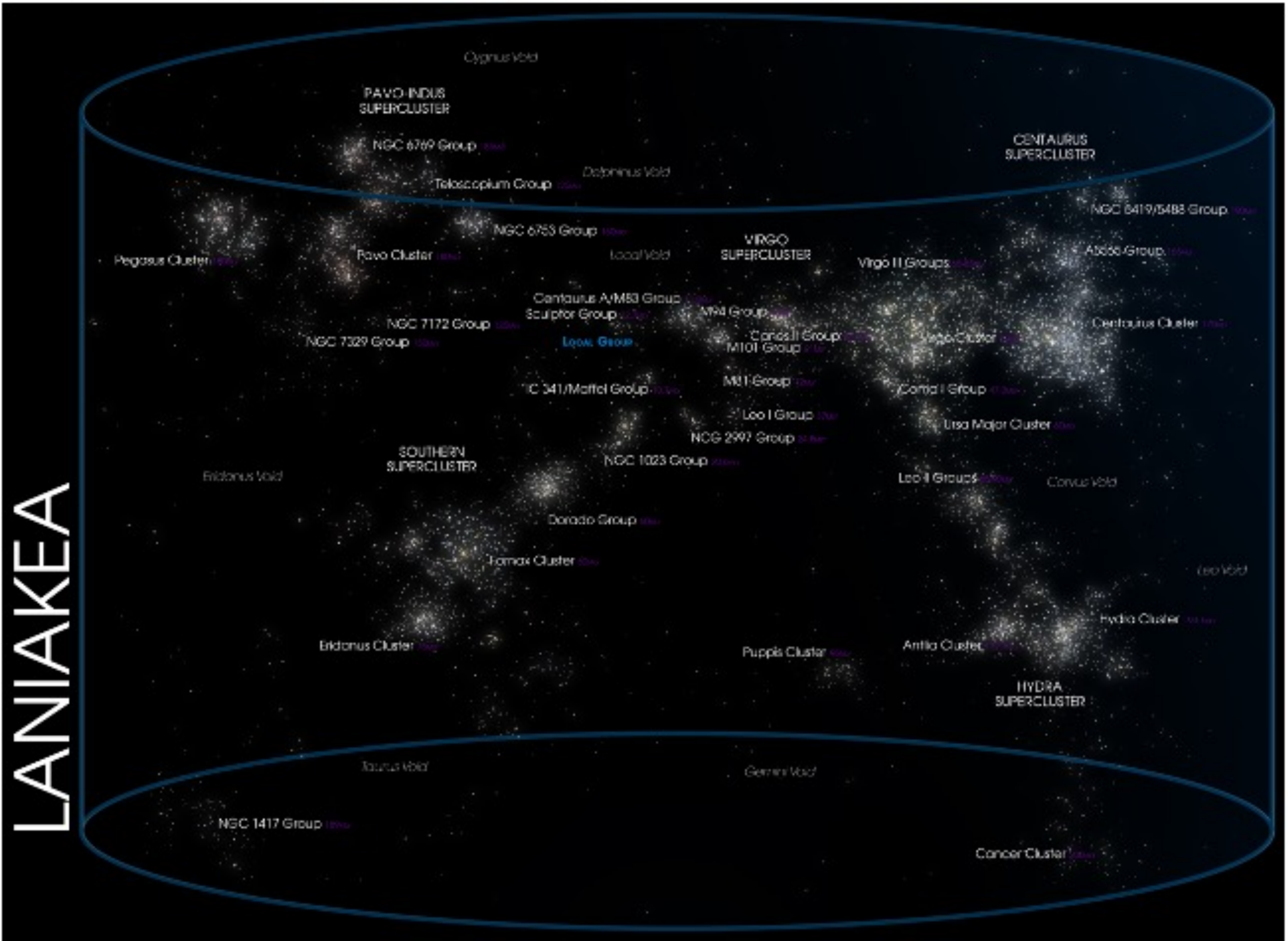
$10^{-22}$

$p_{CR}(E)$~$u_{CR}(E)/3$~$(4\pi/3c)J(E)$

**$p_{CR}(E)$(c.g.s.)**

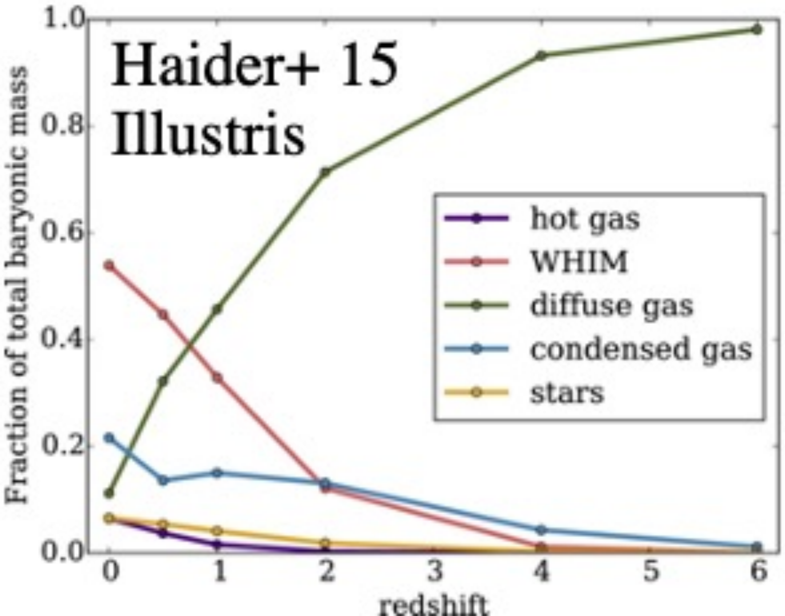
# Local Group within local large scale structure

likely consistent with periphery of filament



# cosmic web: z evolution of cool, diffuse IGM


(a) $z = 0.5$ (b) $z = 1$ (c) $z = 2$



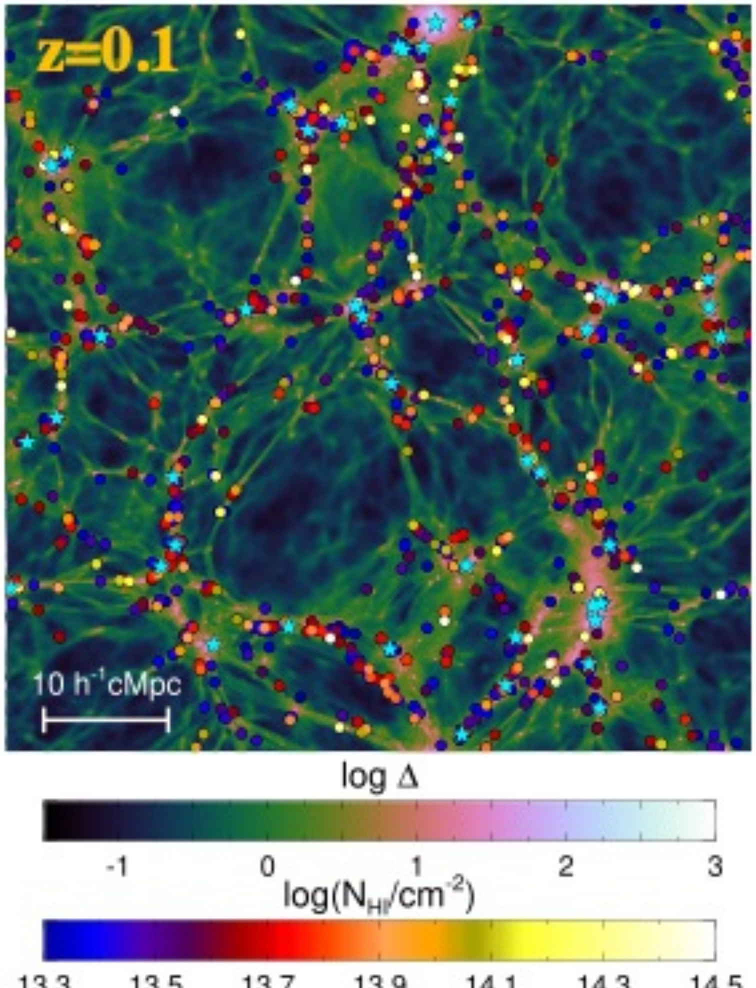

cool, diffuse IGM at z>~1

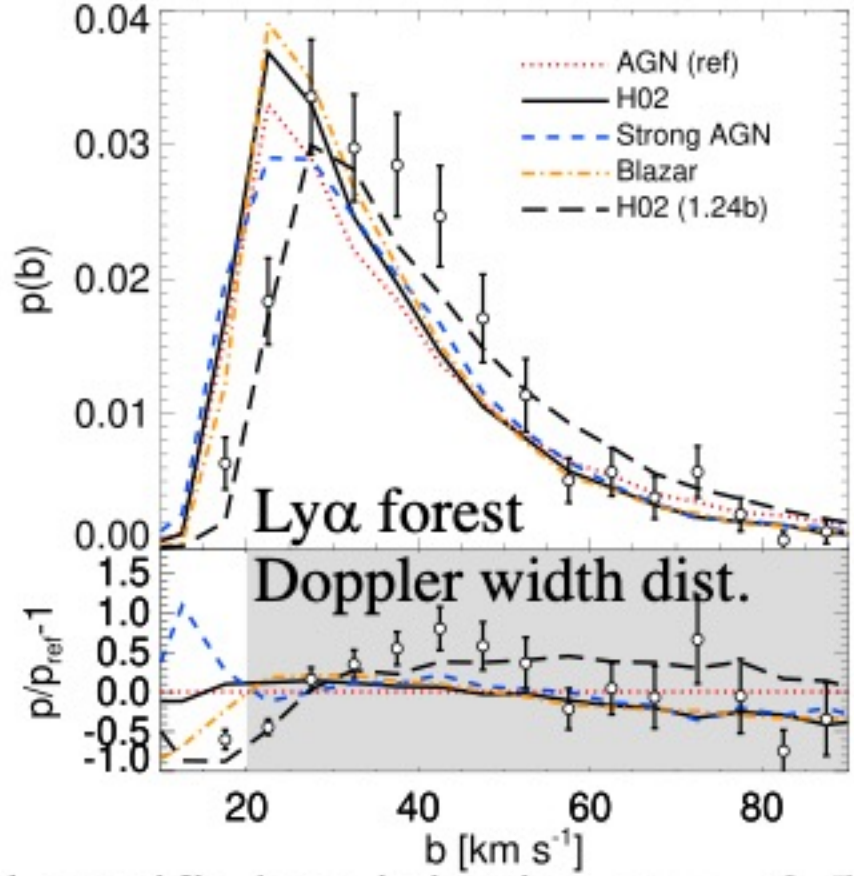
- dominant volume AND mass fraction
  -> evolve into large-scale filaments at z~0
- impact of (U)HECR pressure/heating likely max at z~2
  -> (U)HECRs (not LECRs!) potentially affect evolution of majority of baryons in the Universe?!
- depends on nature of source!
  AGN? GRB? clusters? …

# Lyα forest: evidence of missing physics? I

reproducing Doppler width distribution requires non-canonical heating (or turbulence)

Bolton+ 22




correspond to periphery of filaments at z~<2.5

potential specific heat injection at z~<2.5 of ~<6.9 eV $m_p^{-1}$ -> ~3x$10^{-18}$ erg $cm^{-3}$

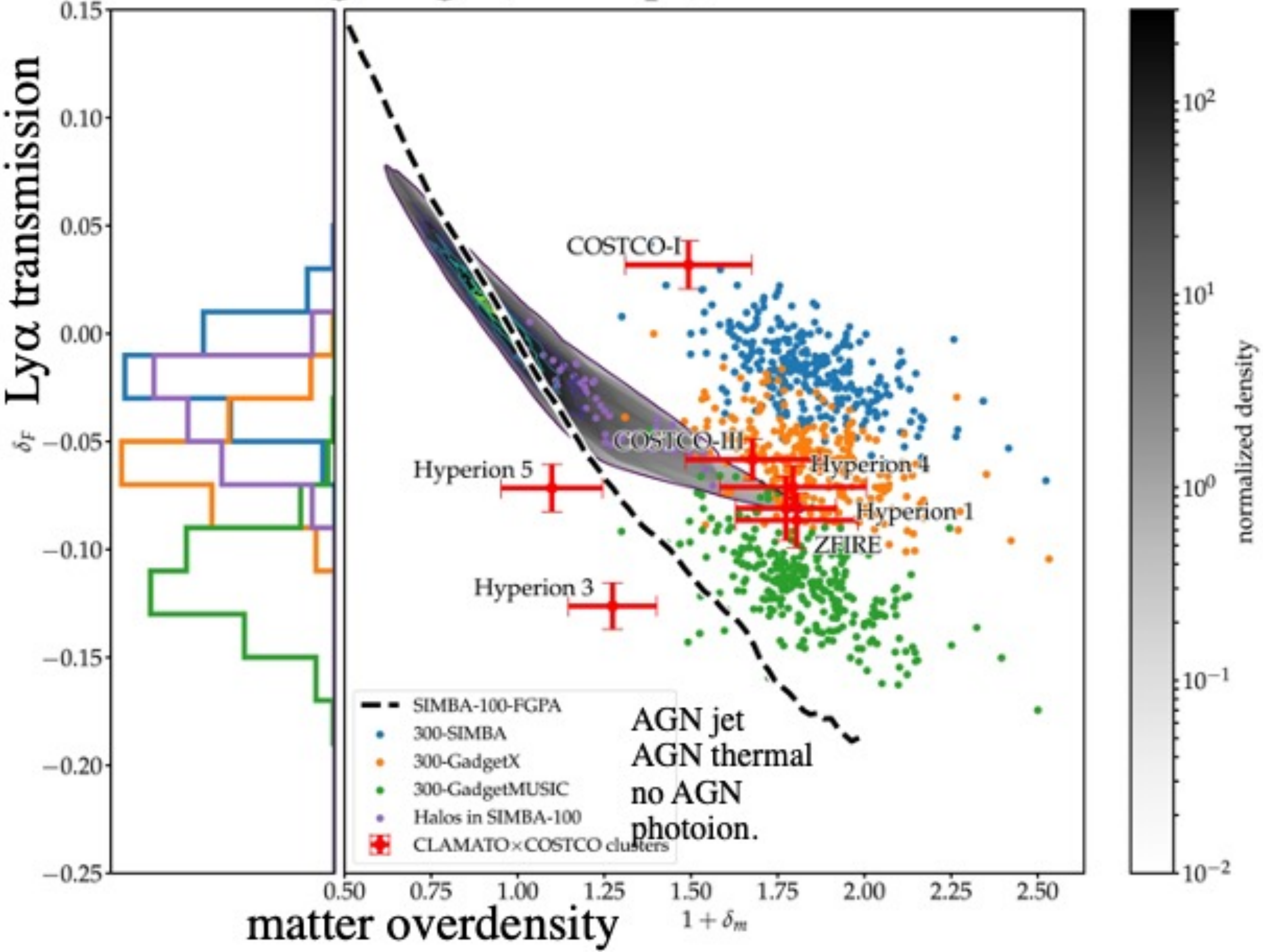
heating by dark matter? Bolton+ 22b

(U)HECRs likely exist in these regions! consequences?

# Lyα forest: evidence of missing physics? II

excess Lyα transmission around protoclusters (z~2-2.5): evidence of long-range (~10 Mpc) AGN feedback?

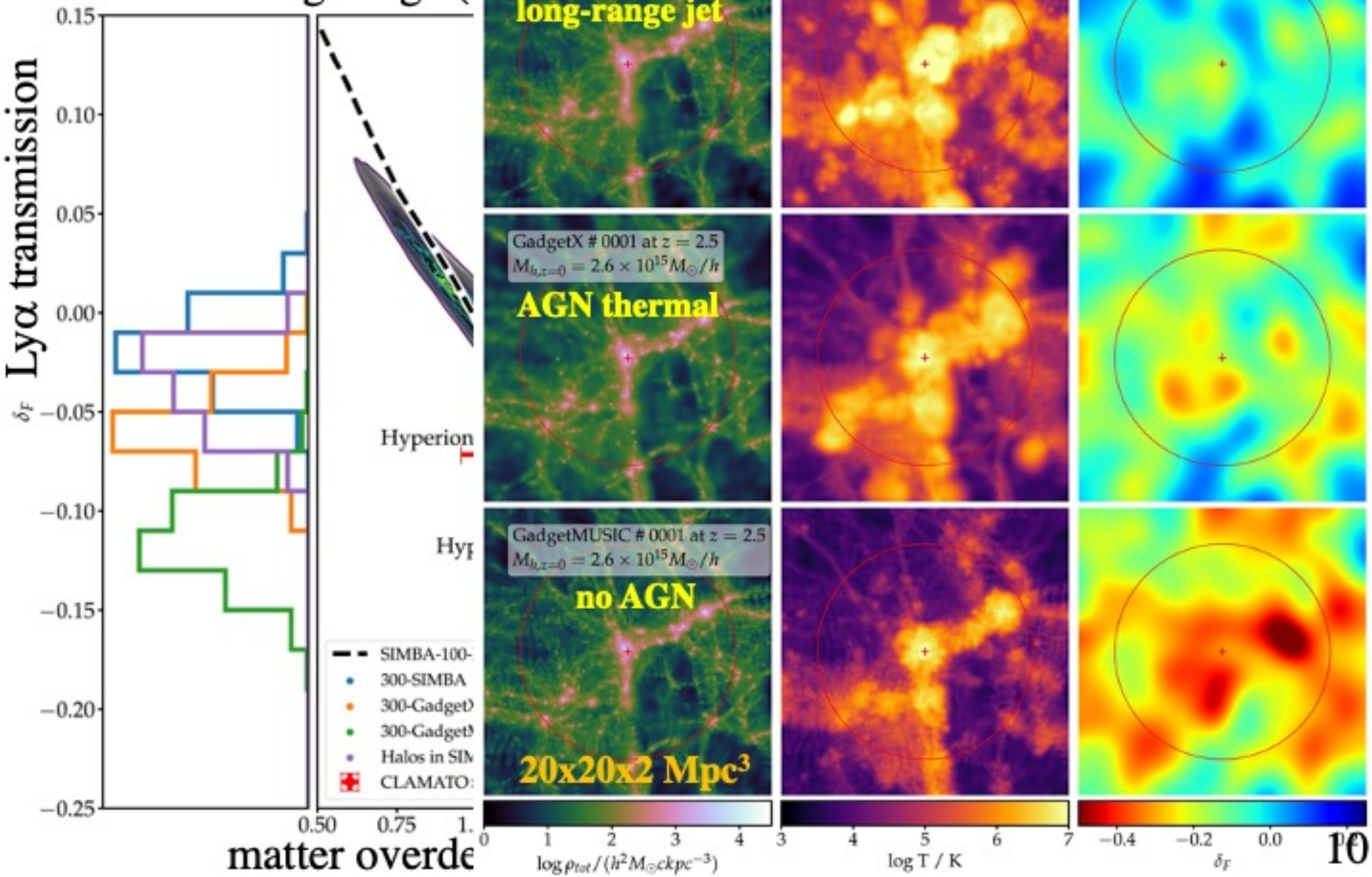
Dong+ 23,24



# Lyα forest: evidence of missing physics? II

excess Lyα transmission

evidence of long-range (

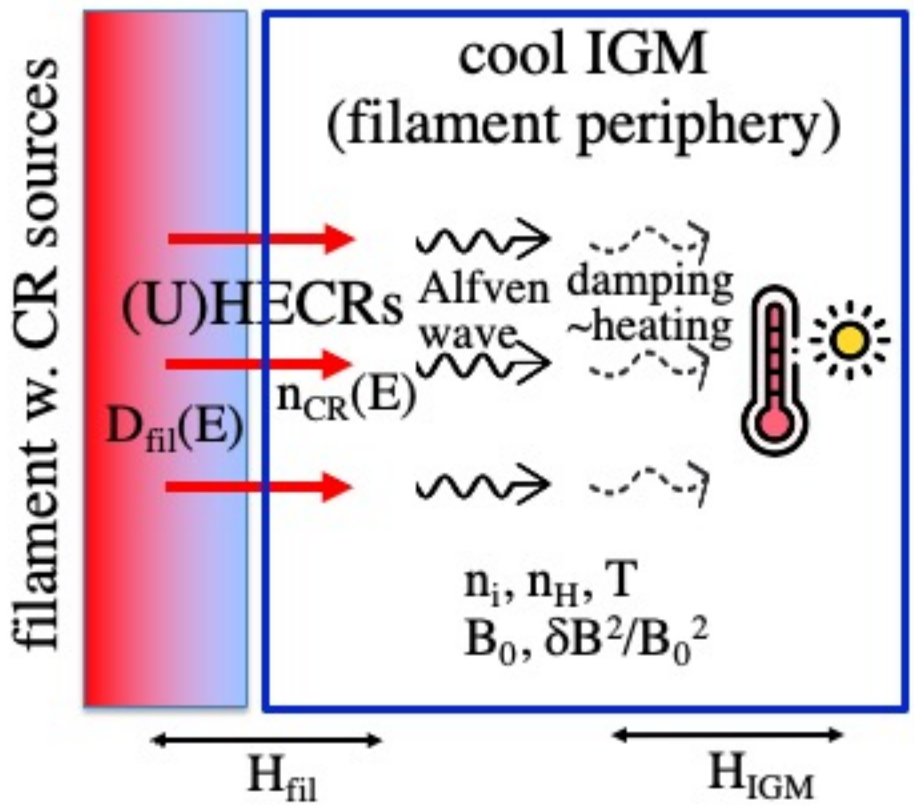


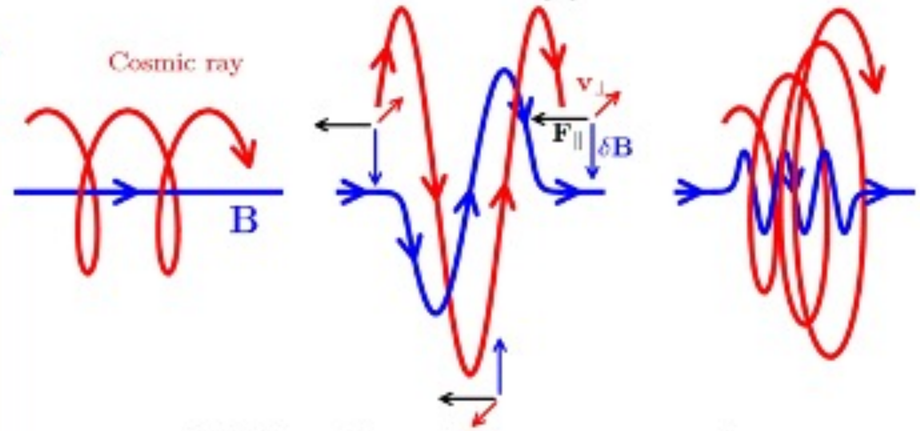
# Alfven heating by (U)HECRs in the IGM

SI, Ohira & Fujita, in prep

diffusive escape of (U)HECRs from LSS filaments into void regions ->
Alfven wave generation via resonant streaming instability induced by diffusive CR current ->
damping of Alfven waves in cool IGM (heating of gas by CRs) via:
ion-neutral collision damping or non-linear Landau damping

c.f. collisional heating? inefficient due to lack of low energy CRs




potentially also important for:
warm ionized gas in Milky Way
Wiener+ 13
cluster cool cores
Loewenstein+ 91, Fujita & Ohira 11...

# Alfven heating by (U)HECRs in the IGM

diffusion coefficient in filament $D_{fil}(E) \sim 10^{32}\ cm^2\ s^{-1} \left(\frac{E}{GeV}\right)^{1/3}$ assume $\propto (L_{max}/10\ Mpc)^{2/3}$

magnetic horizon energy $E_{mh}$ $t_{dif,fil}(E_{mh}) \sim \frac{H_{fil}^2}{D(E_{mh})} < t_H$

resonant instability growth rate for CRs escaping from filament

$$\Gamma_{CR}^{res}(k) = \frac{\pi^2}{c}\frac{v_A}{B_0} J_{CR}^{res}(k) \quad k \sim r_g(E)^{-1} \quad J_{CR}^{res}(E) = e n_{CR}(E) \frac{D_{fil}(E)}{H_{fil}}$$

CR number density averaged over universe $n_{CR}(E)$ inferred from obs.

ion-neutral damping rate

$$\Gamma_{ind}(k) = \frac{k^2}{k^2 + k_c^2} \nu_{ind} \quad \nu_{ind} = 8.4 \times 10^{-9}\ s^{-1} \left(\frac{T}{10^4\ K}\right)^{0.4} n_H \quad k_c = \frac{\nu_{ind}}{v_A}\frac{n_i}{n_H}$$

non-linear Landau damping rate (2 prescriptions)

$\Gamma_{nldLV}(k) \sim k c_s k W(k)$ $\propto c_s$ Lee & Völk 73

$\Gamma_{nldPZ}(k) \sim (2 f_k)^{-3/2} k v_A (k W(k))^{1/2}$ $\propto v_A$ Ptuskin & Zirakashvili 03

$W(k) \propto k^{-5/3}$

$$\frac{\delta B^2}{B_0^2} = \int_{k_{min}=L_{max}^{-1}}^{\infty} dk' W(k')$$

$L_{max}$=10 Mpc

Alfven heating rate $\Gamma_A = \frac{v_A \nabla p_{CR}}{u_{CR}} \sim \frac{1}{3}\frac{v_A}{H_{IGM}}$ $\propto B_0$

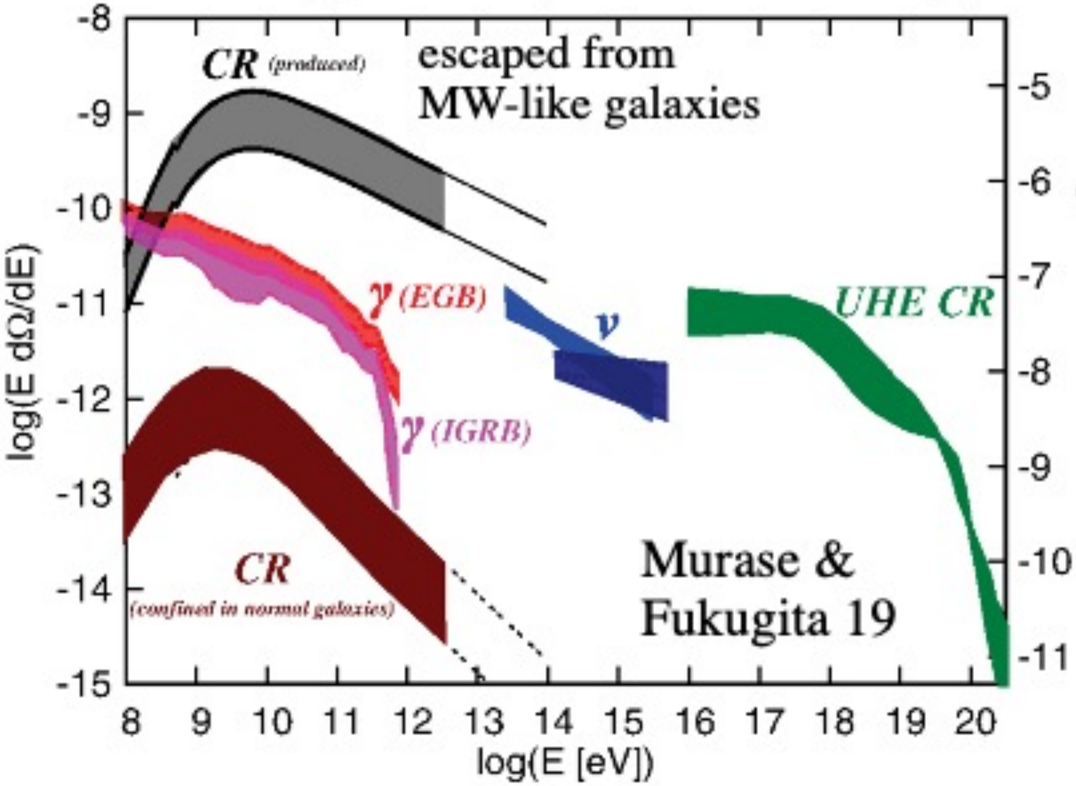
fiducial parameters at z=0

$n_i \sim 10^6 n_H \sim 10 \times 2.5 \times 10^{-7}\ cm^{-3}$, $T \sim 10^4$ K, $H_{fil} \sim H_{IGM} \sim 10$ Mpc

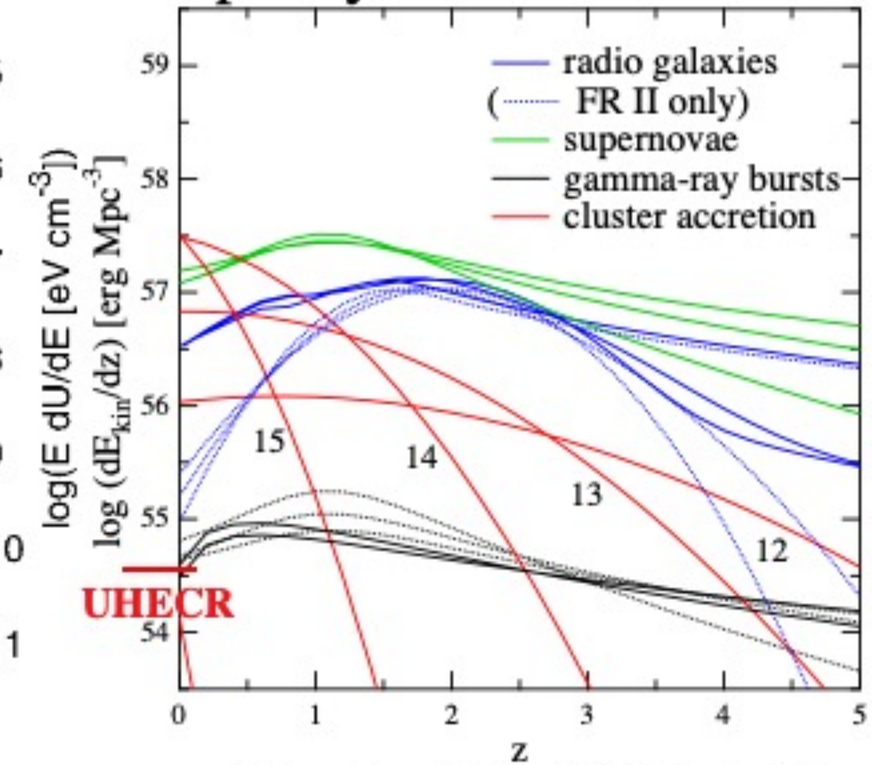
$B_0 \sim 1$ nG, $\delta B^2/B_0^2 \sim 0.1$ (plausible for filament periphery?)

# cosmic averaged CR density, z evolution

CR energy density: cosmic average




z evolution of kinetic energy
output by UHECR sources




$dE_{kin}/dz=(dt/dz)\int dL\ L\ dn/dL$

differential (per unit z)

$u_{CR}(E) \sim 7\times10^{-20}$ erg cm$^{-3}$ $(E/10^{16}\ \mathrm{eV})^{-0.33}$ $10 < \log E < 16$

~ ,, $16 < \log E < 17.5$

~ ,, $(E/10^{17.5}\ \mathrm{eV})^{-0.65}$ $17.5 < \log E < 19.5$

$n_{CR}(E) \sim 4.4\times10^{-24}$ cm$^{-3}$ $(E/10^{16}\ \mathrm{eV})^{-1.33}$ $10 < \log E < 16$

$4.4\times10^{-24}$ cm$^{-3}$ $(E/10^{16}\ \mathrm{eV})^{-1}$ $16 < \log E < 17.5$

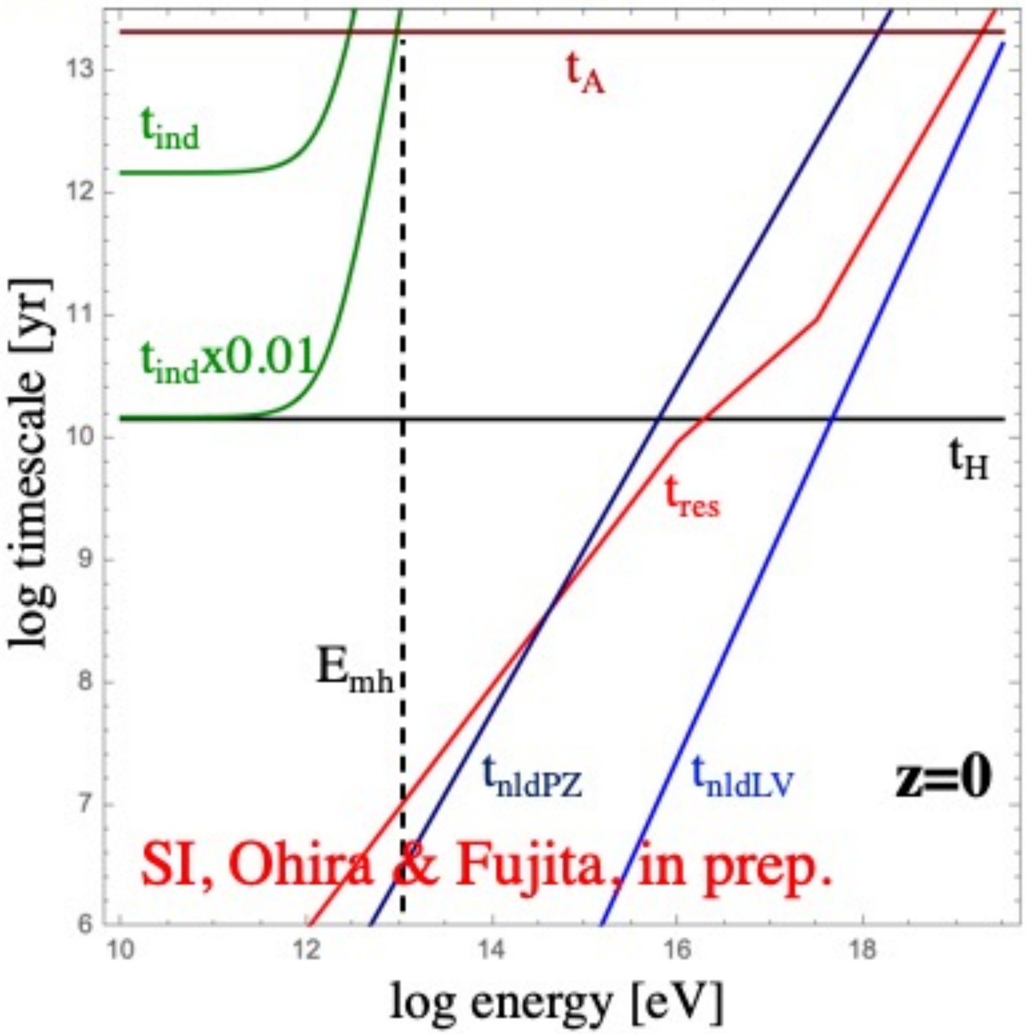
$1.4\times10^{-25}$ cm$^{-3}$ $(E/10^{17.5}\ \mathrm{eV})^{-1.65}$ $17.5 < \log E < 19.5$

z~0-2:

SF rate $\sim\propto(1+z)^2$

hi-L AGN $\sim\propto(1+z)^4$

# growth/damping/heating timescales in IGM at z=0

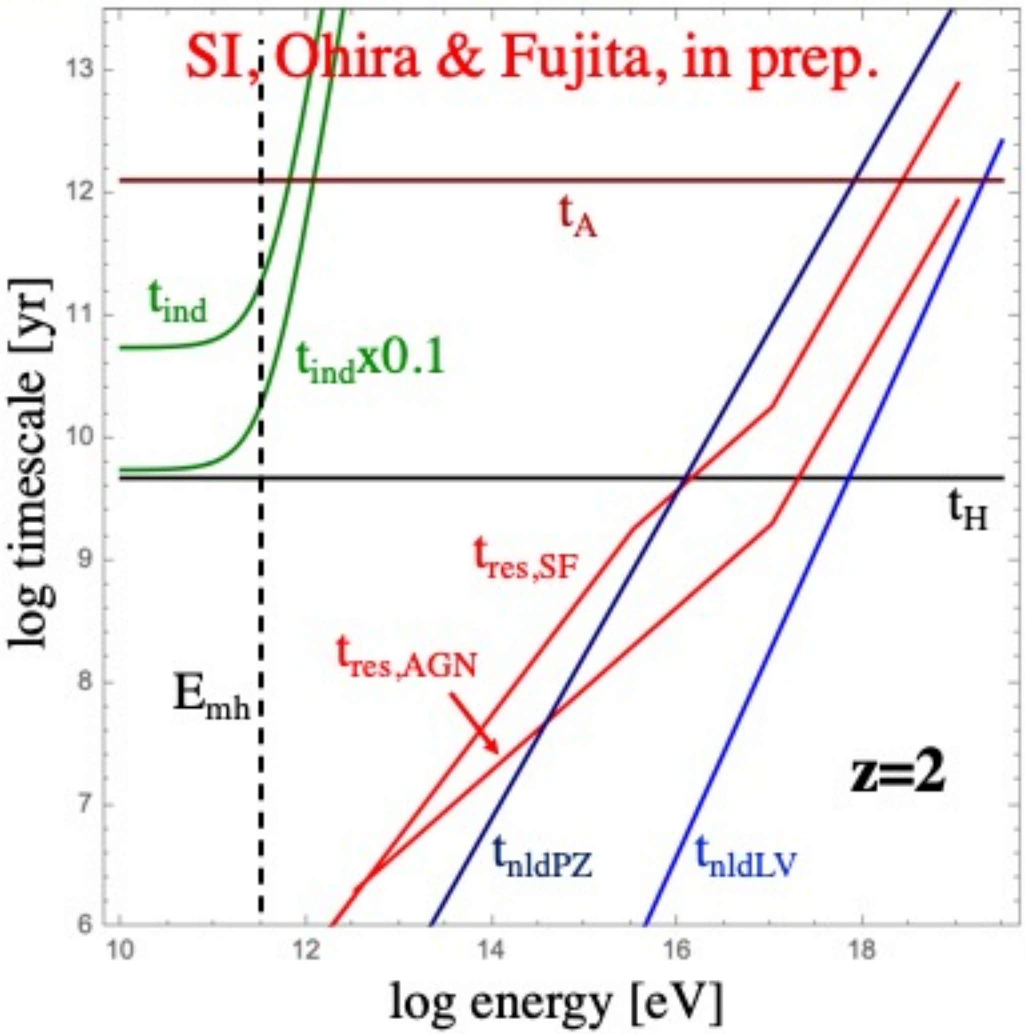



resonant instability fast enough for E~<$10^{16.5}$ eV

ion-neutral damping too slow but non-linear Landau damping potentially fast enough

(U)HECRs can potentially heat cool IGM with ~0.1% efficiency if $B_0$~1 nG, $\delta B^2/B_0^2$~0.001-1

# growth/damping/heating timescales in IGM at z=2




shorter timescales due to higher
$n_{CR}$, $n_H$, $B_0$, etc
depends on nature of UHECR source

resonant instability fast enough for $E \sim< 10^{16-17.5}$ eV, depending on z evolution of UHECR density

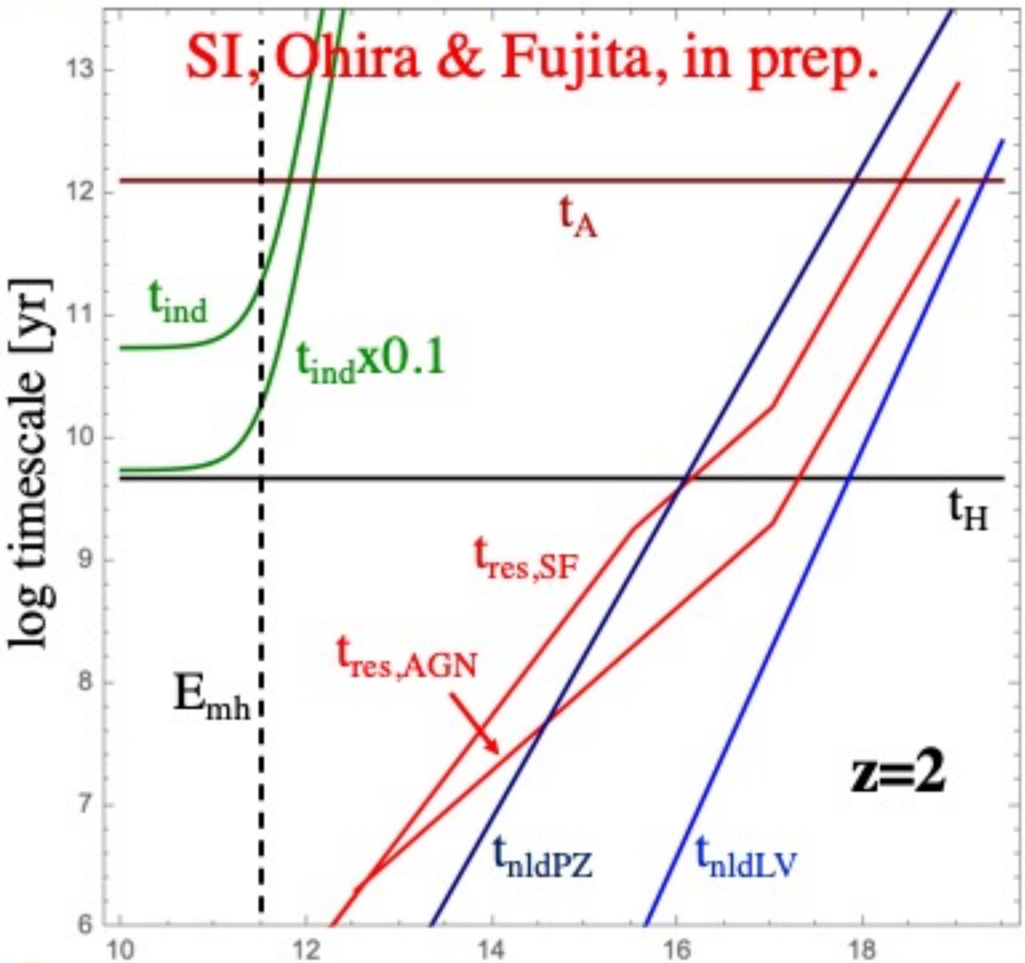
ion-neutral damping too slow but non-linear Landau damping potentially fast enough

(U)HECRs can potentially heat IGM with ~1% efficiency if $B_0 \sim 1$ nG, $\delta B^2/B_0^2 \sim 0.001$-1

non-canonical heating inferred from Lyα forest Doppler widths? -> further study warranted!

low horizon energy? ->
further study (self-confinement)
better constraints from obs.

# growth/damping/heating timescales in IGM at z=2




resonant instability fast enough for E~<$10^{16\text{-}17.5}$ eV, depending on z evolution of UHECR density

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(U)HECRs can potentially heat IGM with ~1% efficiency if $B_0$~1 nG, $\delta B^2/B_0^2$~0.001-1

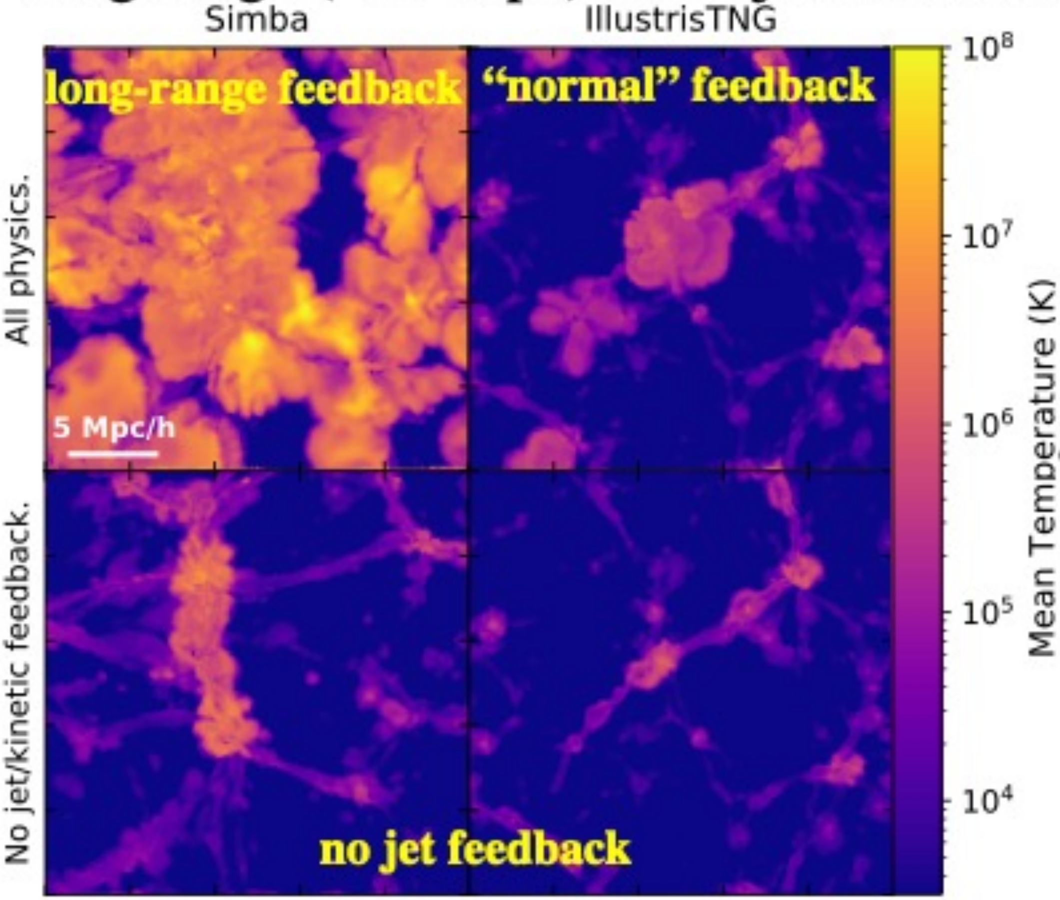
non-canonical heating inferred from Lyα forest Doppler widths?

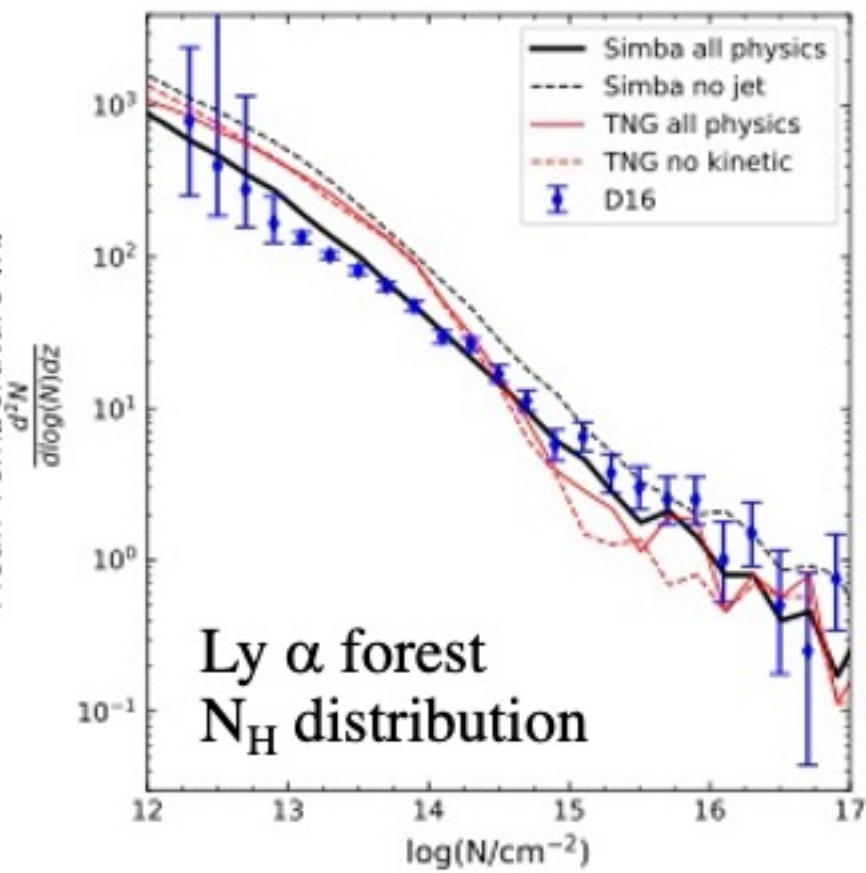
Lyα forest観測から示唆される余剰加熱を説明できる!
(銀河間磁場強度、拡散係数、Alfven波減衰過程、UHECR源z進化
などいろいろ不定性はあるが)
Lyα forest観測からUHECR源を制限?

# Lyα forest: evidence of missing physics? III

reproducing column density distribution requires long range (~10 Mpc) AGN jet feedback

Tillman+ 22
also Christensen+ 20




jet feedback without energy deposition until >~10 kpc (SIMBA simulation): physically realistic?

(U)HECRs likely exist in these regions! consequences?

# B field amplification, self-confinement, dynamical effects near (U)HECR sources
Blasi, Amato & D'Angelo 15

escape of (U)HECRs from sources into immediate environs->
non-resonant streaming (Bell) instability induced by strong CR current
-> B field amplification -> self-confinement of CRs below $E_{cut}$
-> potential displacement of ambient gas

saturation B field $\delta B(r) = 3.7 \times 10^{-9} L_{44}^{1/2} r_{\rm Mpc}^{-1}$ G.

confinement energy $E_{\rm cut} \approx 10^7$ GeV $\times L_{44}^{2/3}$.

magnetic horizon due to self-confinement

confinement radius $r_{\rm conf} \approx 3.8$ Mpc $\times L_{44}^{1/6}$.

(AGN) feedback with longer range than jet itself?

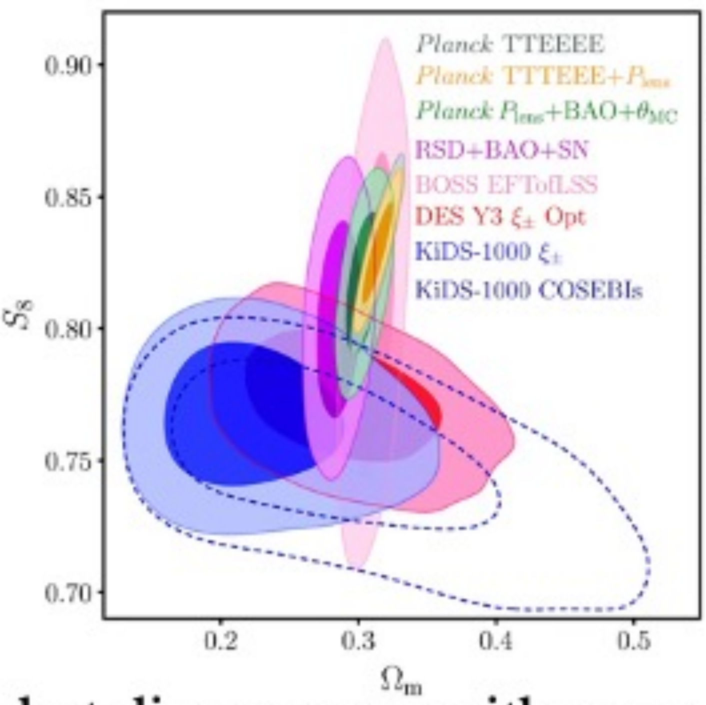
# $S_8$ tension in cosmology: AGN-> UHECR feedback?

$S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$

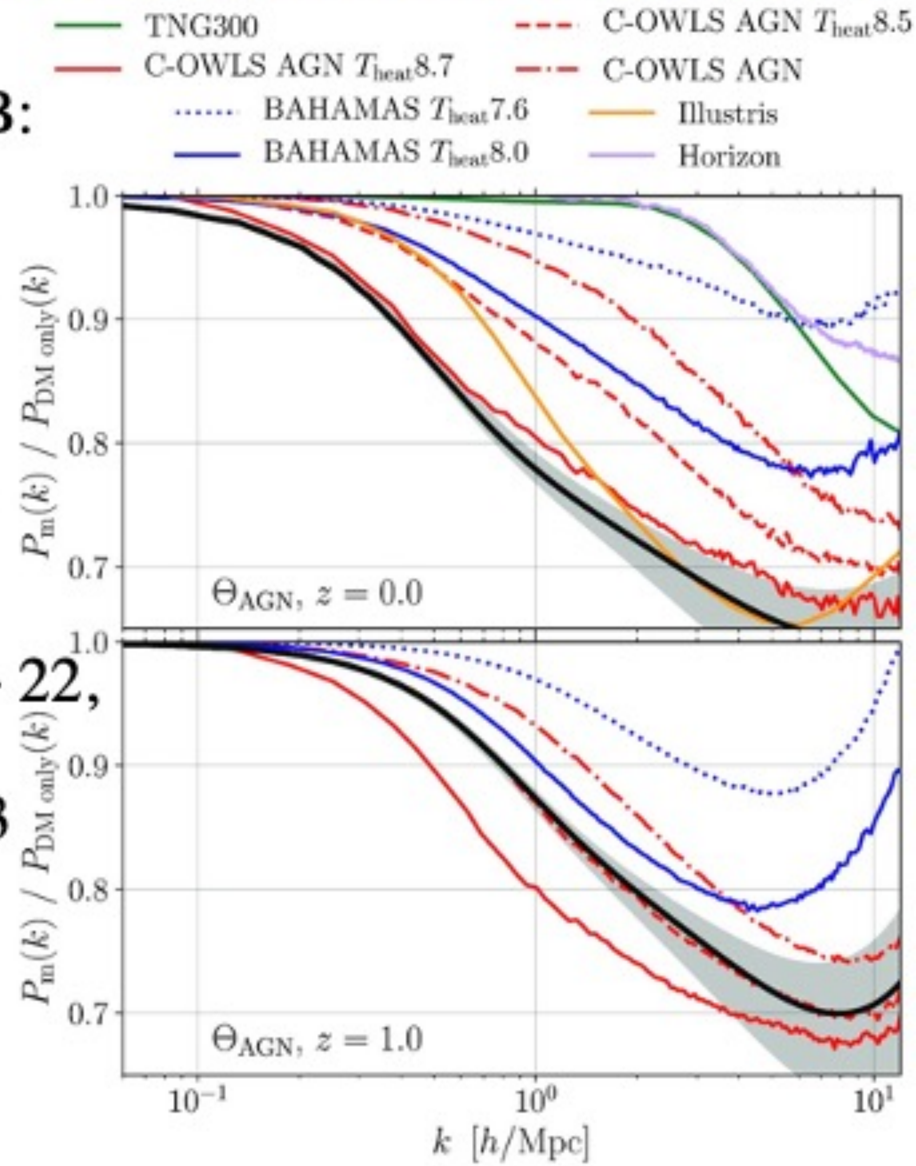
cosmic shear (galaxy lensing) vs CMB:
~9% (2.4-2.7σ) discrepancy

revision to standard cosmology?
(non-standard dark matter or
primordial spectrum?)

strong, long range AGN feedback?




Amon & Efstathiou+ 22, also Preston+ 23




**rather (U)HECR feedback??**

but discrepancy with group/cluster gas fraction?

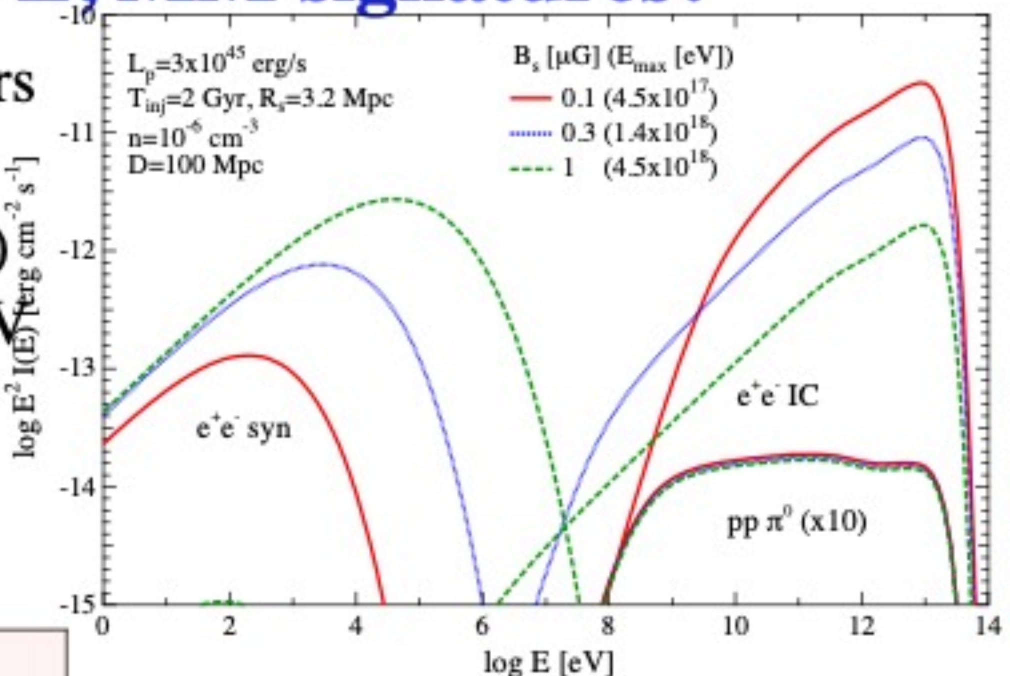
# (U)HECRs in IGM: MWL, MM signatures?

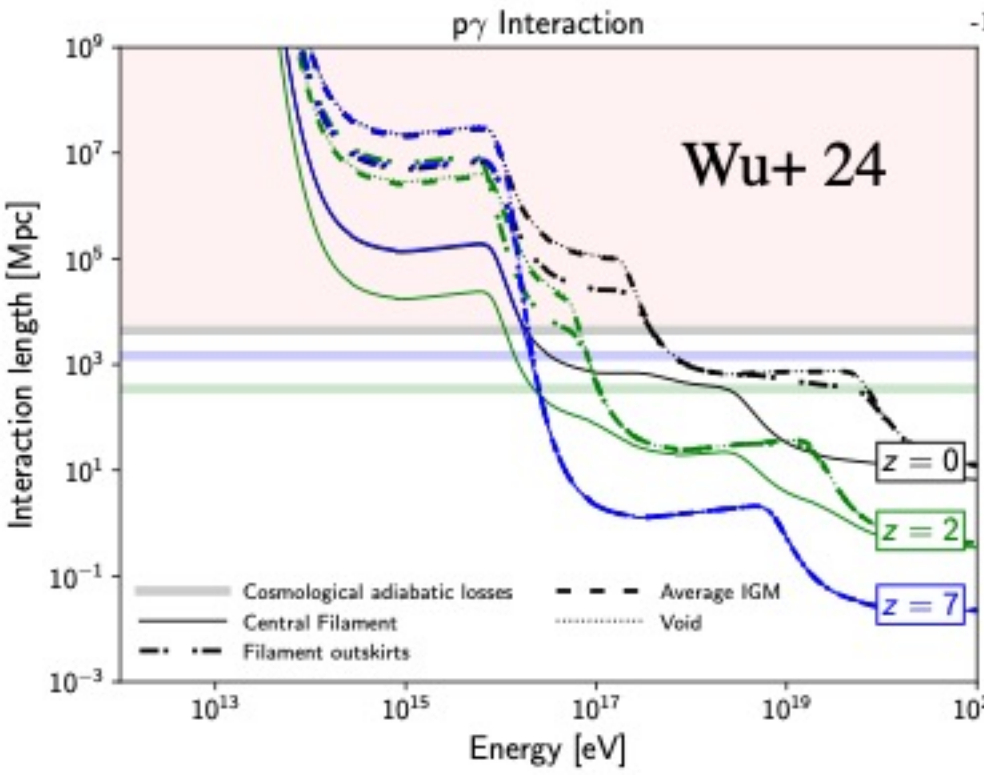
c.f. sync.+IC by Bethe-Heitler pairs in cluster accretion shocks

$p(10^{18}eV) + \gamma_{CMB} \rightarrow p + e^+e^- (10^{15}eV)$

$e^+e^- + B(\sim\mu G) \rightarrow keV, e^+e^- + \gamma_{CMB} \rightarrow TeV$

SI, Aharonian, Sugiyama 05



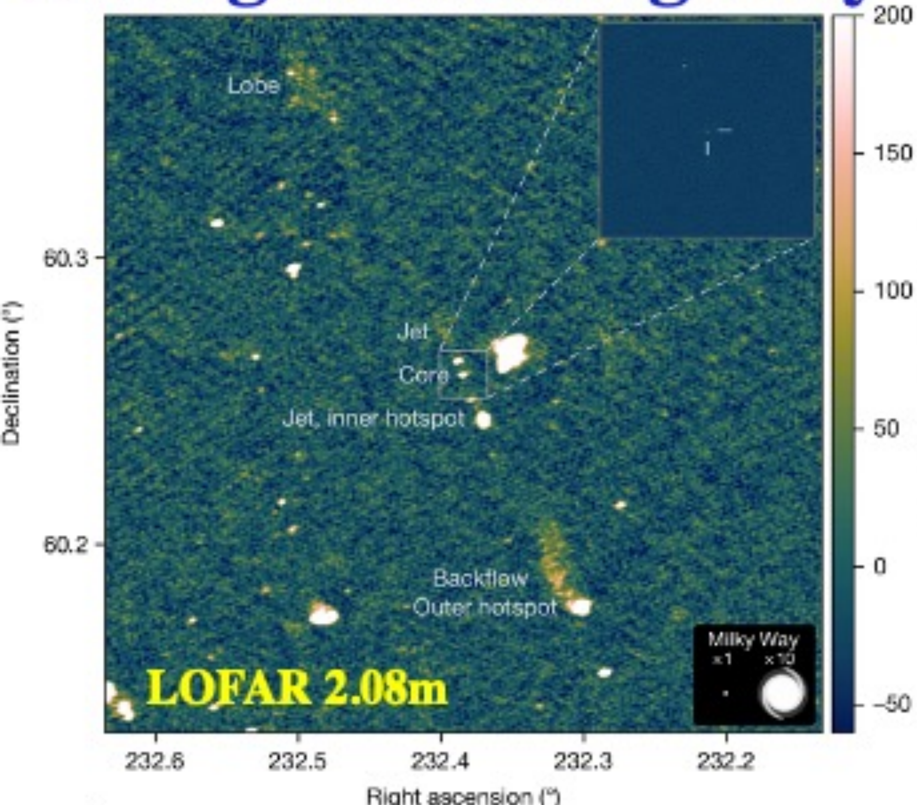



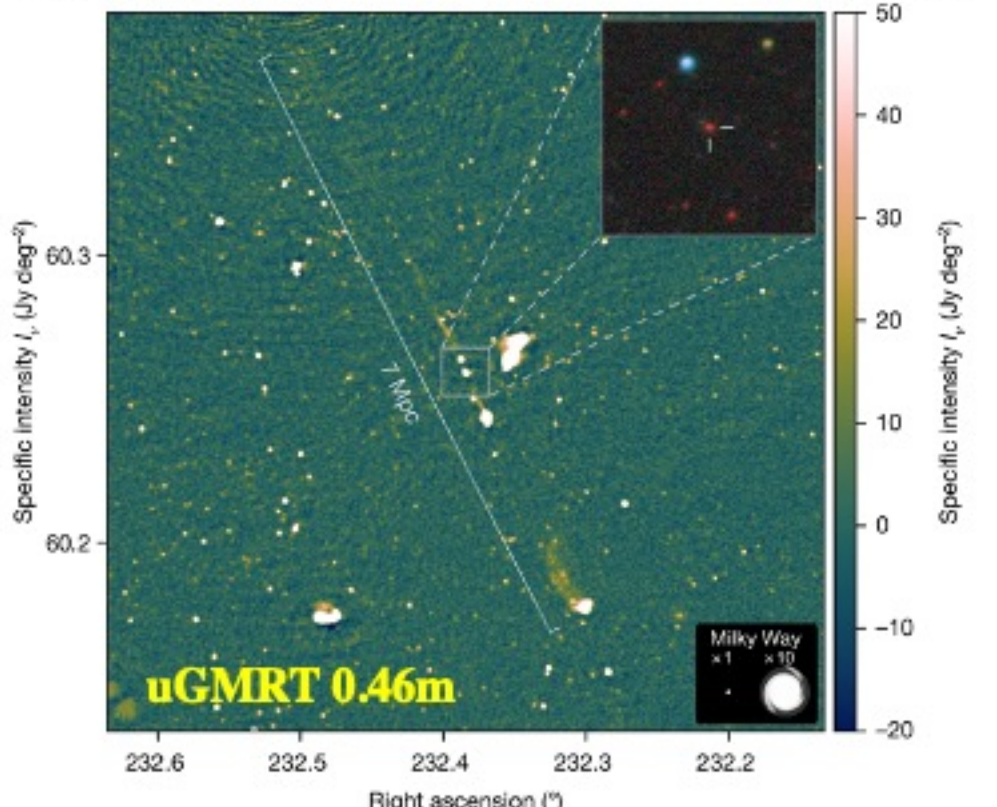

X-ray, TeV "halos" around, long-lived, self-confined (U)HECR sources?

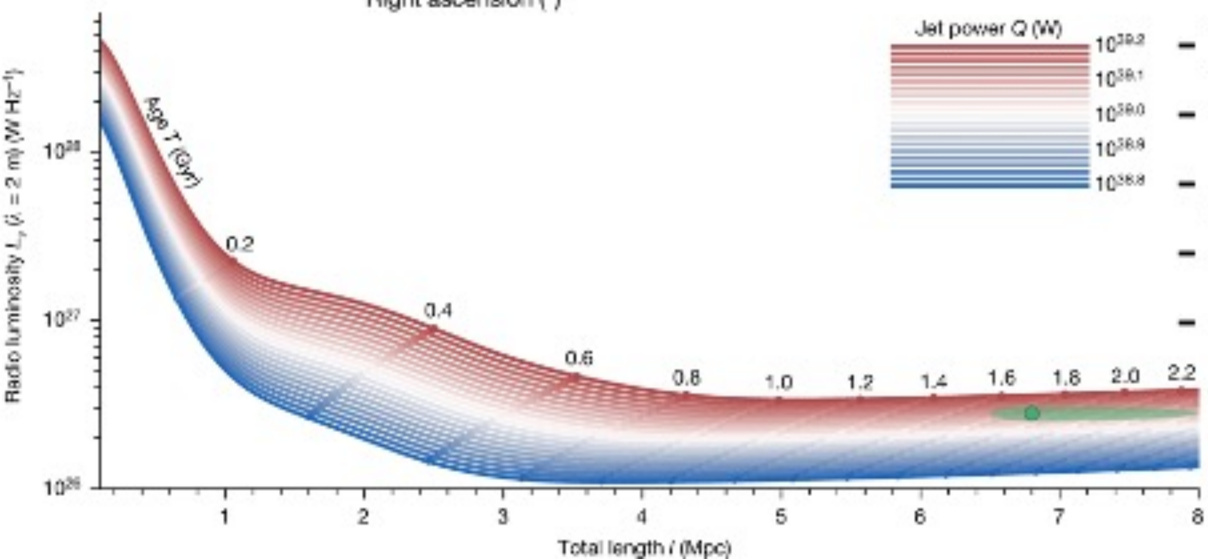
cosmogenic UHE neutrinos clustered around sources?

# ultra-giant radio galaxy "Porphyrion"

Oei+ 24




- ID with galaxy at z=0.896
- ~7 Mpc core+hotspot struc.
- group+filament environs
- $L_j$~$10^{46}$ erg/s, T~2 Gyr
- at limit of sensitivity

-> possibly common?
enhanced feedback
with (U)HECRs?

# まとめ

- Lyα forestとして観測される低温 ($T<10^5$K) IGMに(U)HECRは必ず存在するはず. (magnetic horizonでLECR無し、(U)HECRが主役!) その圧力はIGMガスと比べ無視できない (卓越する場合も?)

- z>~1で低温IGMは宇宙のbaryon質量の大半. (U)HECRの影響より大. -> (U)HECRは宇宙のbaryonの大部分に影響を及ぼしているかも

- (U)HECR: filamentからvoidへ伝搬 -> resonant streaming instabilityでAlfven波励起 -> non-linear Landau dampingで散逸 -> IGMガス加熱. Lyα forest観測から示唆される未知の加熱の正体?

- (U)HECR観測: (U)HECR源、magnetic horizon energyを抑える!

# 検討中

- (U)HECR源近傍でのBell instability -> 磁場増幅・自己閉じ込めでCR高密度領域発生.
  -> Lyα forest $N_H$分布から示唆される長距離feedbackの正体?
  -> 宇宙論パラメーターの$S_8$ tensionを解決できる?
- MWL, MM探査: X-ray, TeV γ, UHE ν
- Lyα forest 空間・時間依存性から(U)HECR起源を制限.