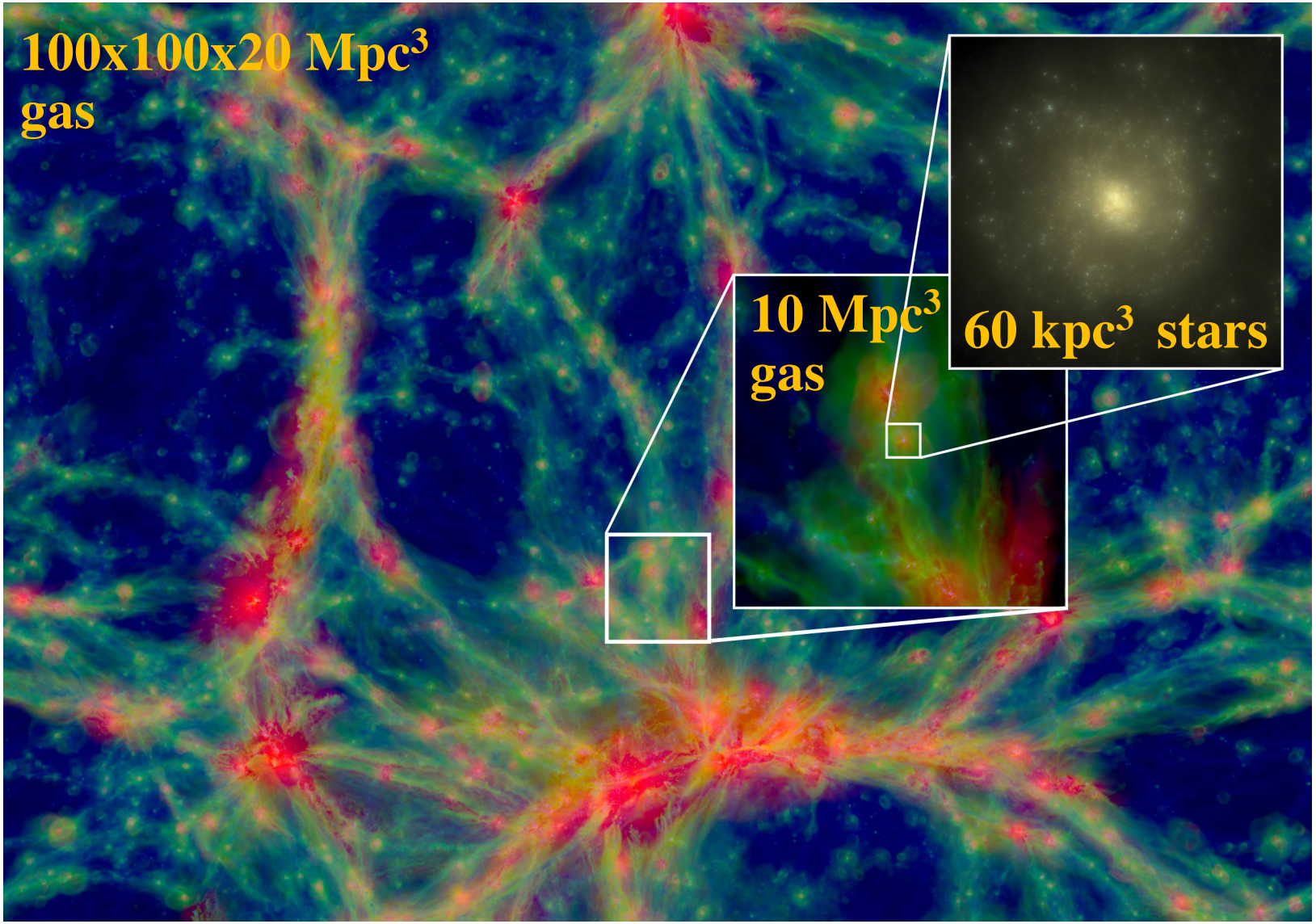
宇宙線の宇宙大規模構造における役割

井上 進（文教大／理研）
共同研究者：辻 直美（神奈川大）、川田 和正（東大宇宙線研）
水野 恒史（広島大）、長島 雅裕（文教大）ほか



EAGLE
Schaye+ 14

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

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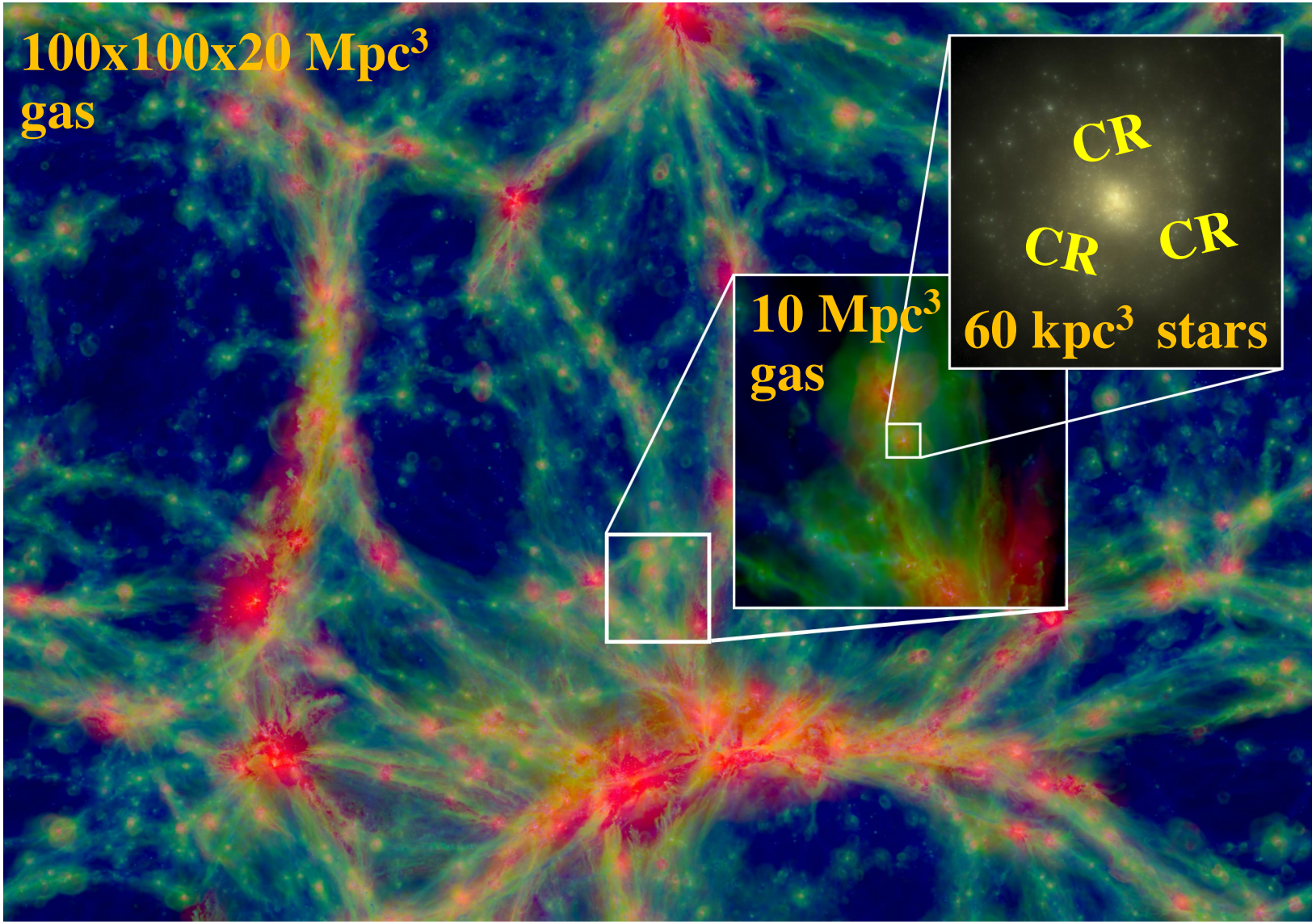

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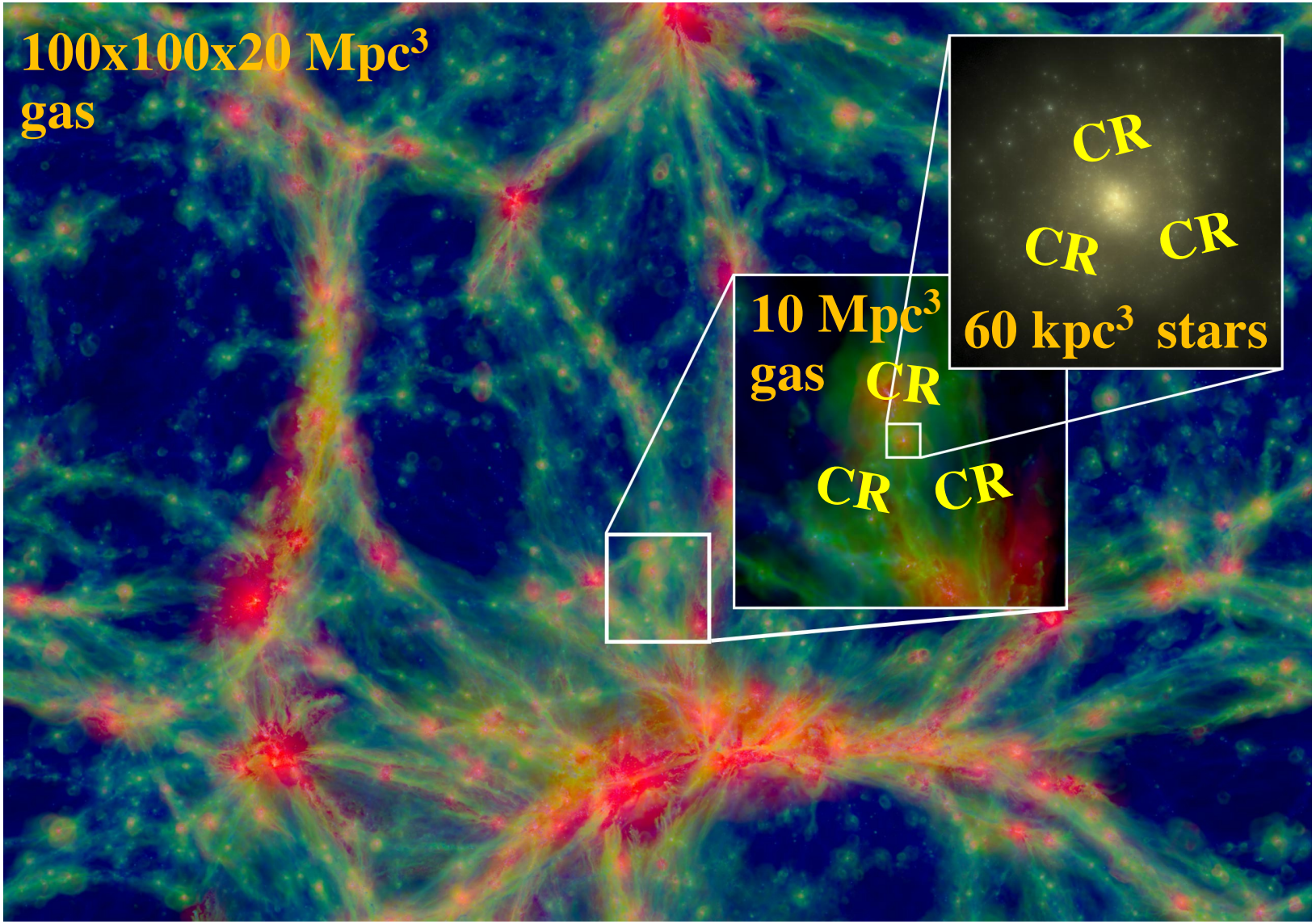

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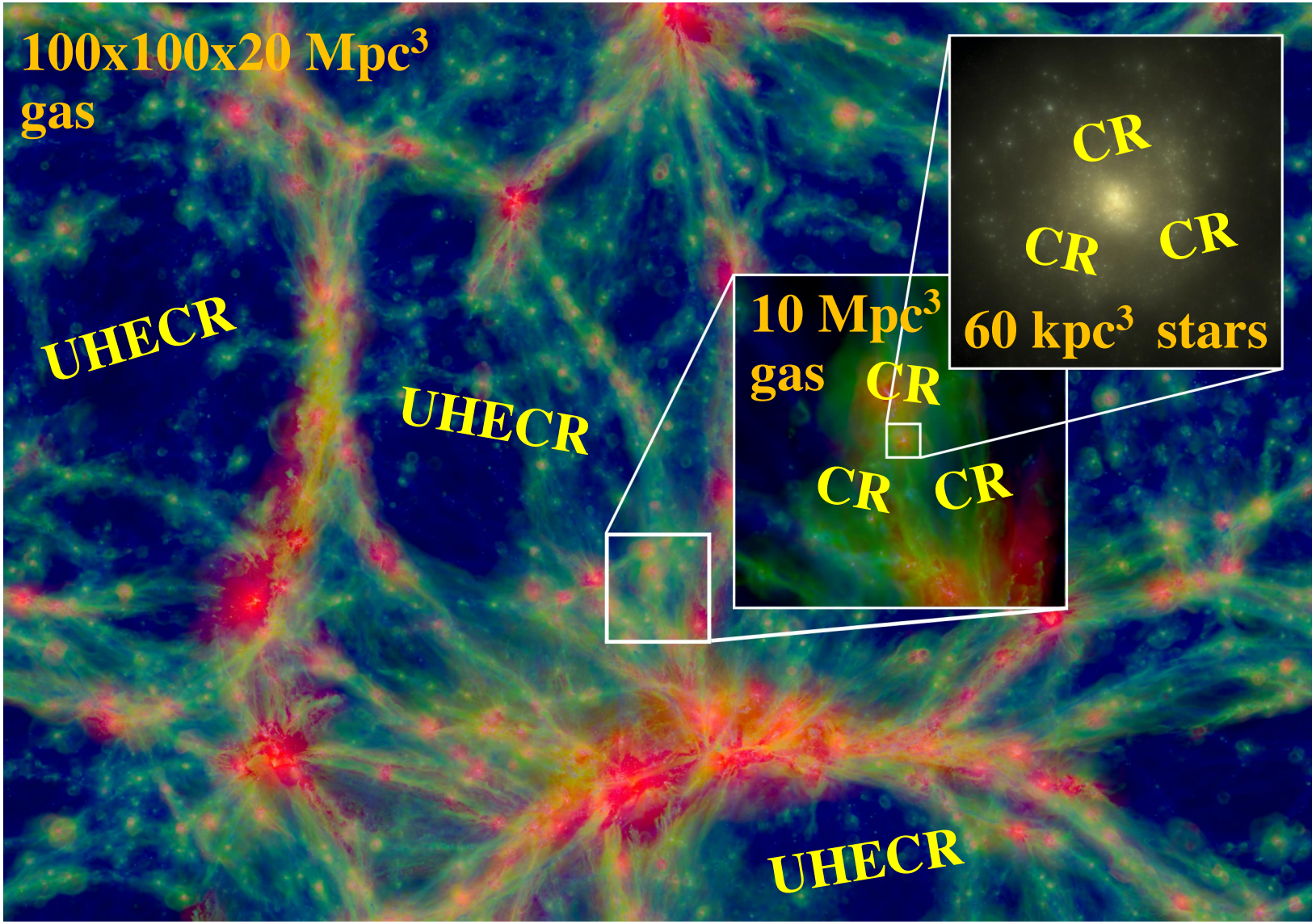

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outline

1. Introduction: large scale structure (galaxy) formation and CR feedback
2. PeV gamma rays and circumgalactic gas clouds: Indications of CRs in the Milky Way halo
   SI, Tsuji, Kawata, Mizuno, Nagashima, in prep.
3. (U)HECRs: potential effects on the cool, diffuse IGM (Lyα forest)
   preliminary studies (thoughts)

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宇宙線はマニア以外にとっても重要で面白いと叫ぶ研究会

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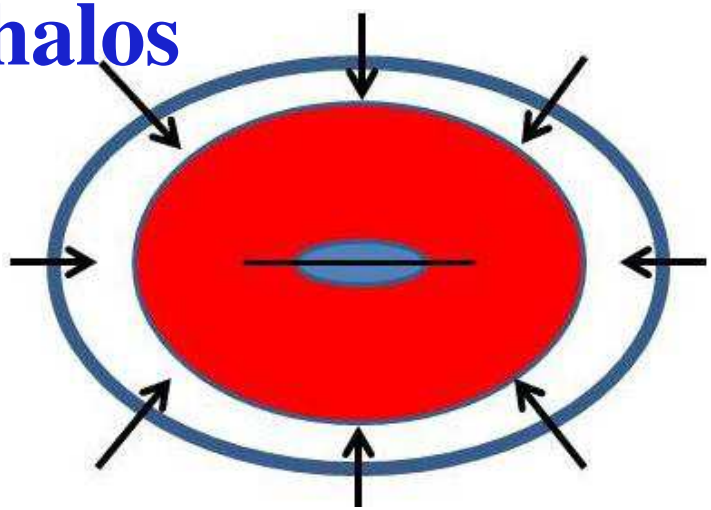
"Ask not what you can do for CRs,
ask what CRs can do for you!" (after JFK)

1. Introduction:
Large scale structure (galaxy) formation and CR feedback

galaxy formation in dark matter halos

gas in dark matter overdensity
-> collapse* + virialization
-> shock heating + fast cooling
-> star formation + stellar feedback
-> pressure-supported hot halo
-> slow cooling +
infall onto disk



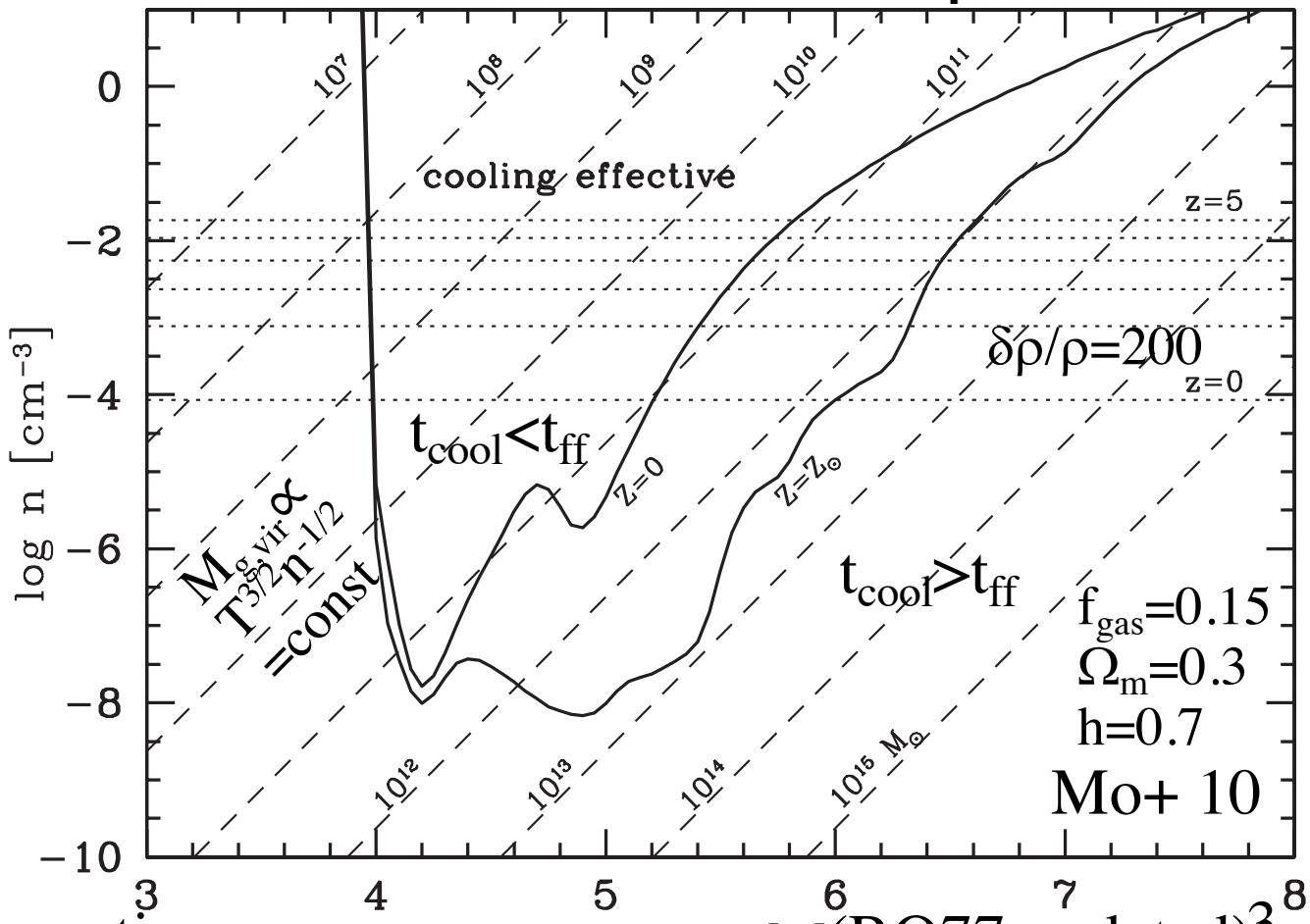
Rees & Ostriker 77
White & Rees 78
Blumenthal+ 84…

-> SMBH formation
+ AGN feedback

Silk & Rees 98…

CRs? B fields?

*final major merger in hierarchical structure formation



(RO77 updated)

cosmic ray feedback in galaxy formation

potential roles

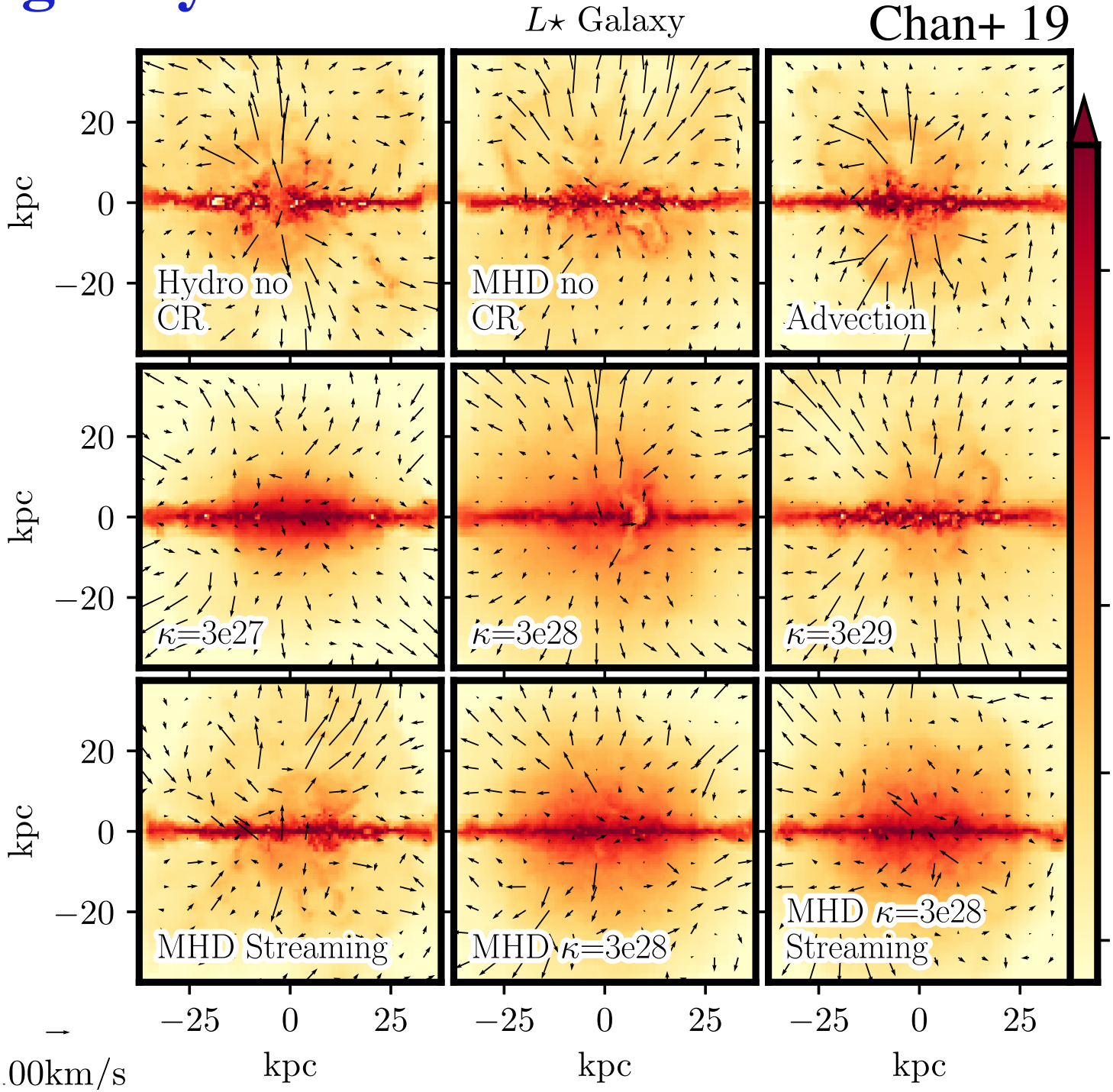
- pressure relative to gas
  - limited cooling
  - enhancement in adiabatic expansion $p_{CR}/p_{gas} \propto \rho^{-1/3}$
- heating -> ionization
  - collisional
  - MHD wave generation -> damping

potential environments

- galactic winds: drive or assist
- galaxy halos (circumgalactic medium): regulate gas infall
- group/cluster cool cores
- warm-hot intergalactic medium

…

galaxy formation simulations with CR feedback



FIRE: Hopkins+

ChaNGa: Butsky+

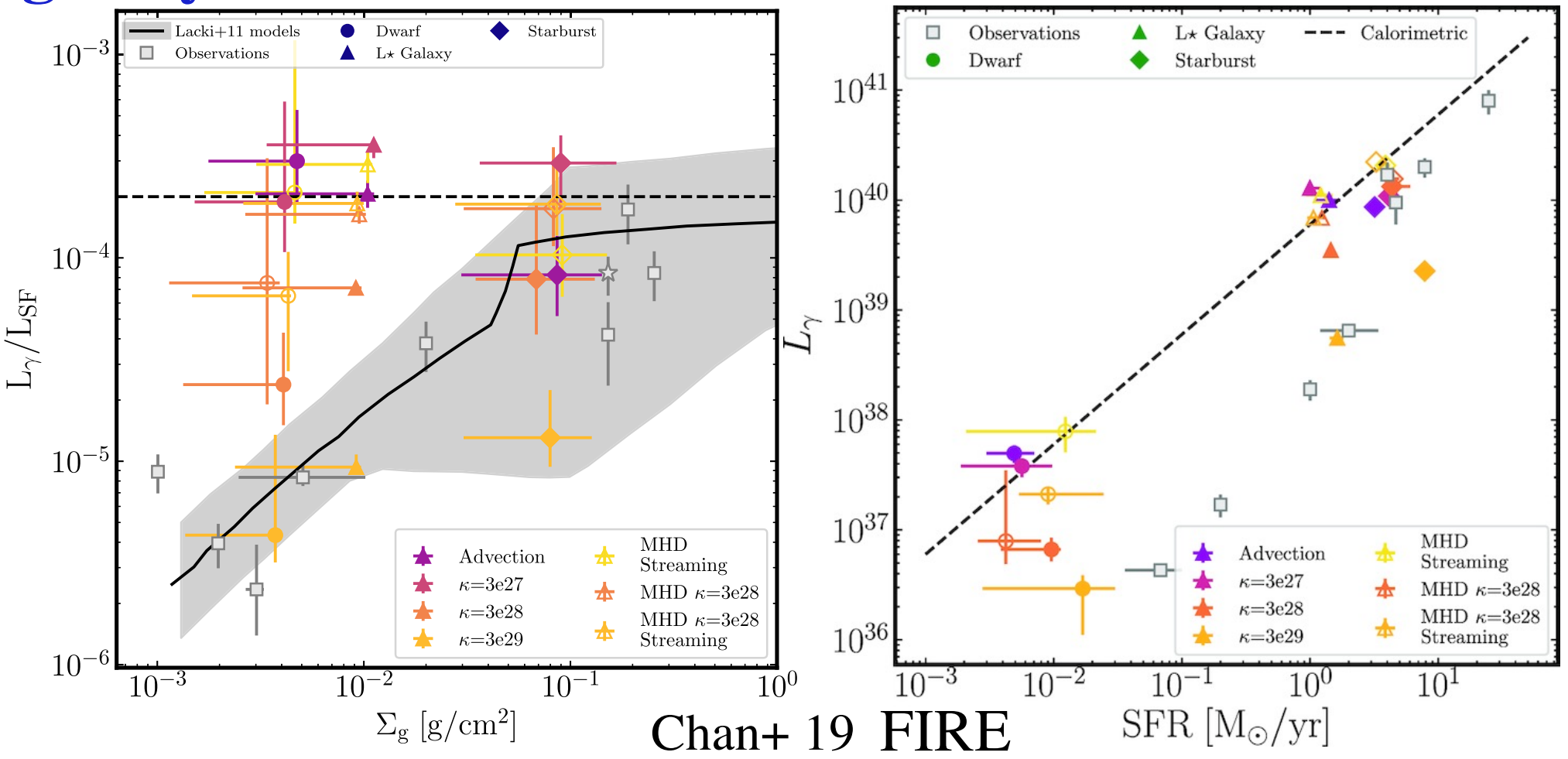
AREPO/AURIGA: Pfrommer+

RAMSES: Dubois+

...

- potentially significant impact of p_{CR} depends strongly on assumed CR transport
- caveat: single energy bin treatment

galaxy formation simulations with CR feedback



Chan+ 19 FIRE

- parameters selected to match various observations, including Fermi observations of star forming galaxies

  BUT

  observational constraints insufficient!

- more detailed results vs observations emerging e.g. Hopkins+ 22

cosmic ray feedback in galaxy formation

goals for observations

- prove existence of CRs where lacking: CGM, etc
- clarify CR spatial and spectral distribution $n_{CR}(E,r)$
- prove non-negligible p_{CR}/p_{gas} -> broadband info required

2. PeV γ rays and circumgalactic gas clouds: Indications of CRs in the Milky Way halo

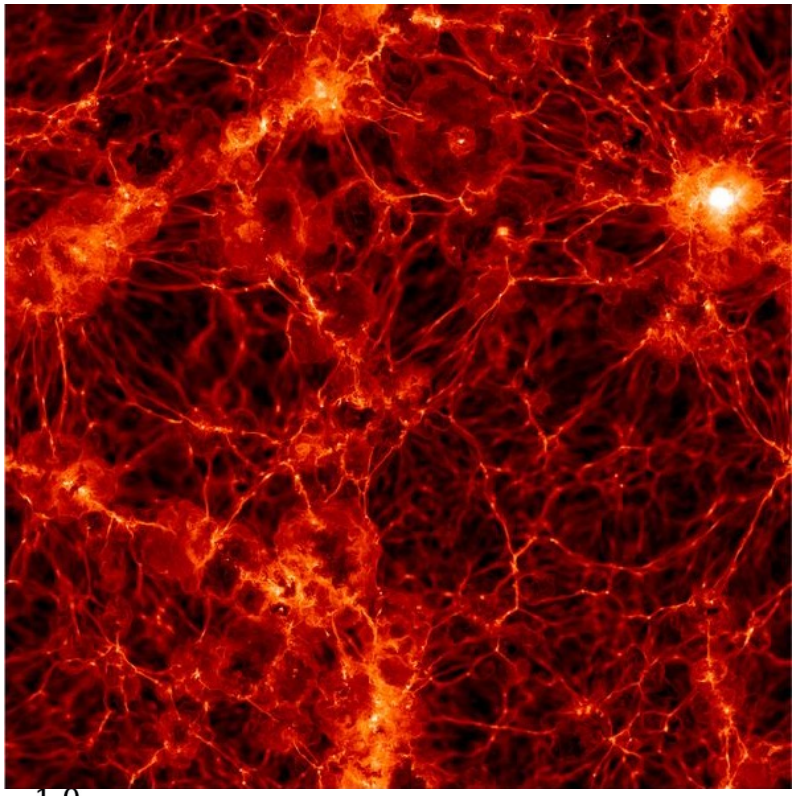
SI, Tsuji, Kawata, Mizuno, Nagashima, in prep.

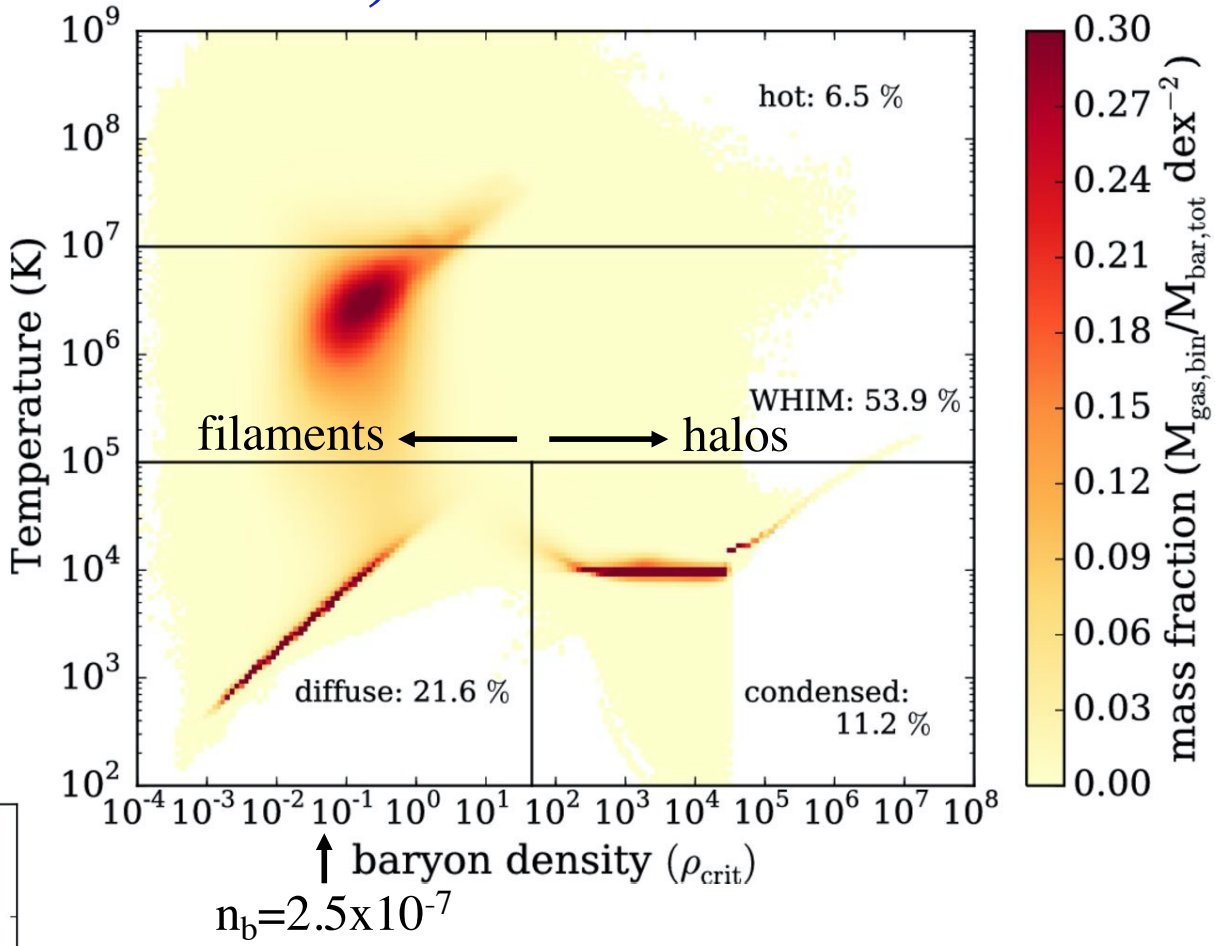
この内容は近日中に論文で公開しますので、
どうかよろしくお願いいたします。

3. Ultra-High-Energy CRs: Potential effects on the cool, diffuse IGM

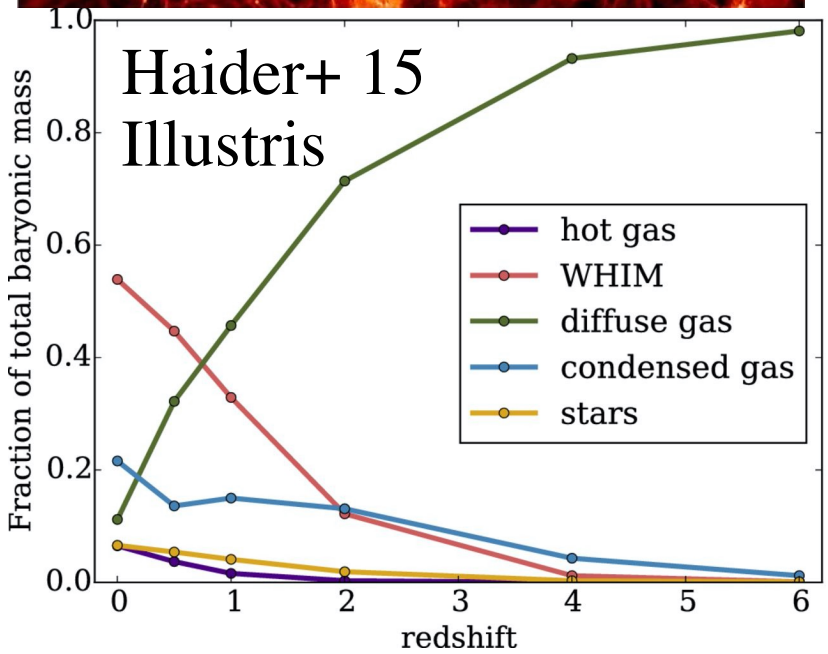
Preliminary studies (thoughts)

cosmic web: warm-hot vs cool, diffuse IGM



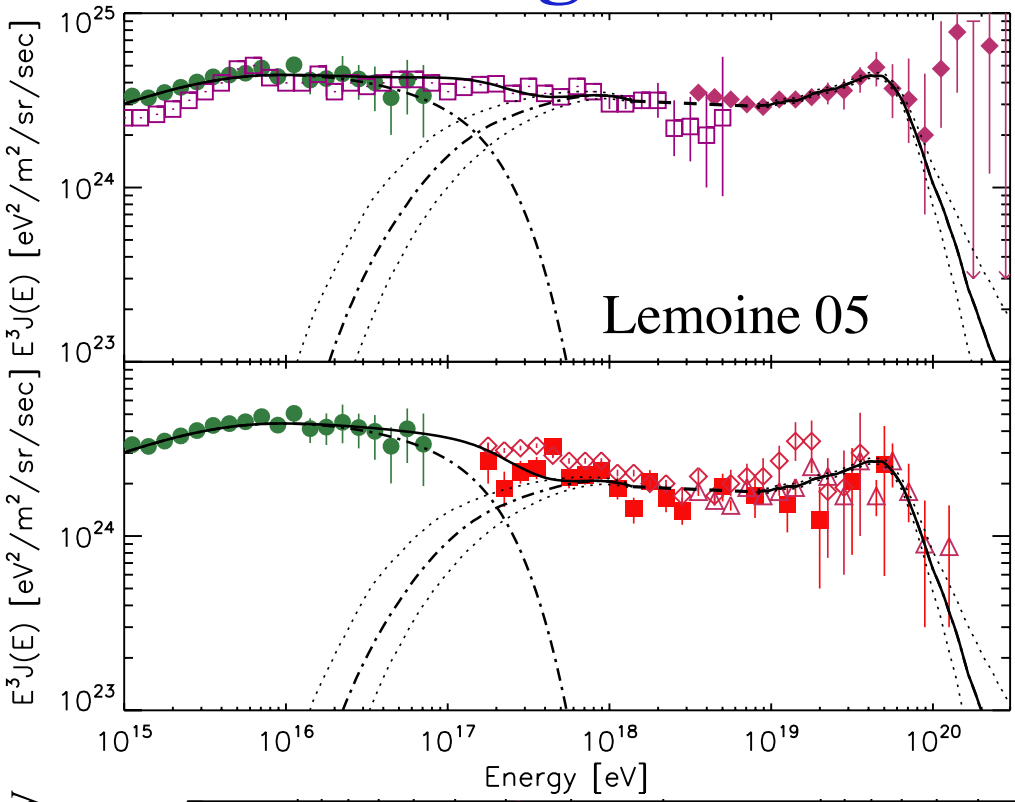


$n_b=2.5\times10^{-7}$



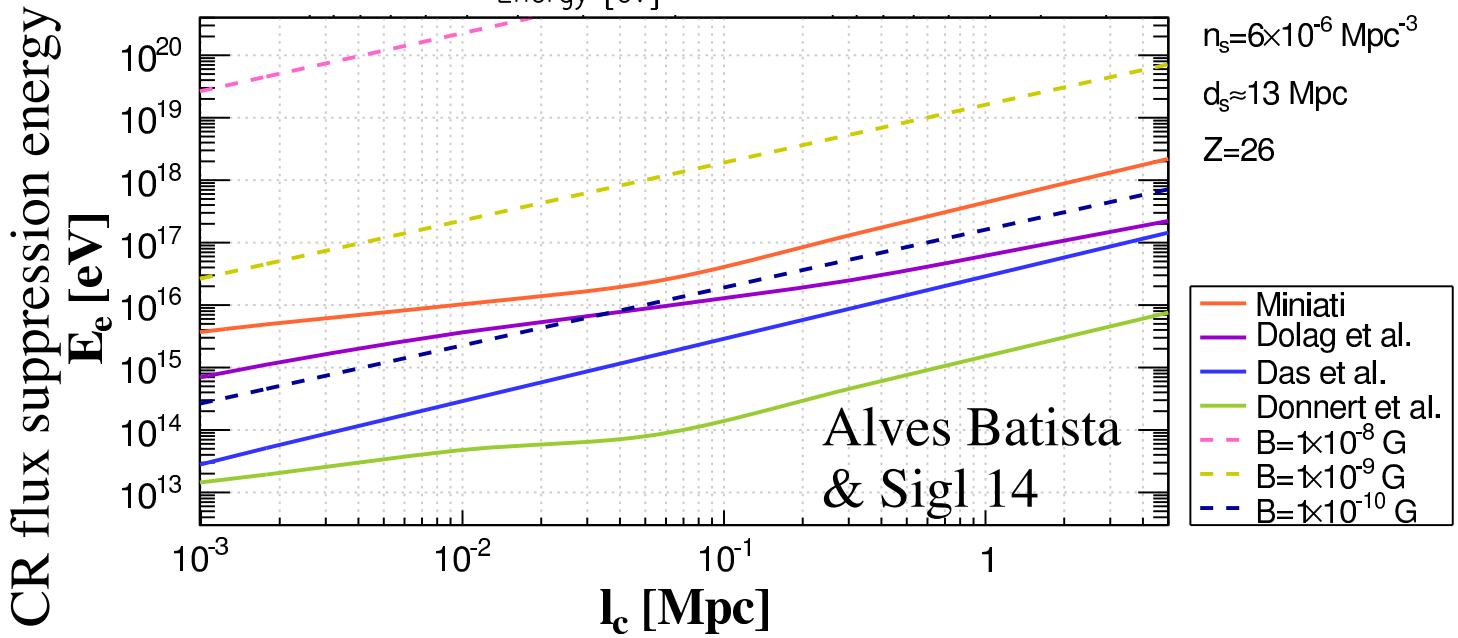
cool, diffuse IGM:
- photoionized by UV background
- observable as Lyα forest
- sizable mass fraction,
  dominant volume fraction of universe

UHECRs: magnetic horizon



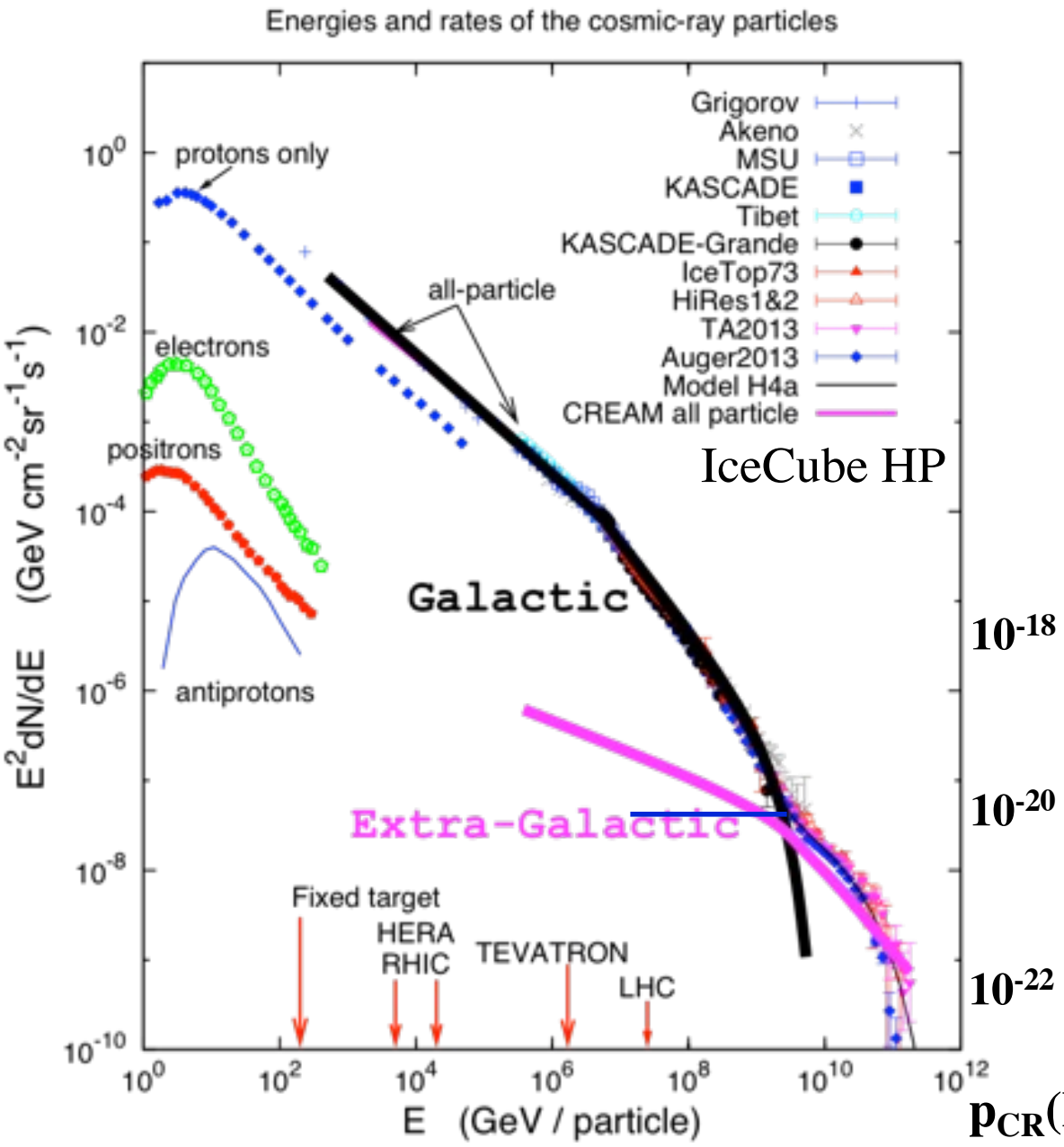
propagation (diffusion) time
in intergalactic magnetic field
(IGMF)
> age of universe

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



strongly dependent
on IGMF
(poorly constrained)

(U)HECRs vs diffuse, cool IGM



10^{-18}

10^{-20}

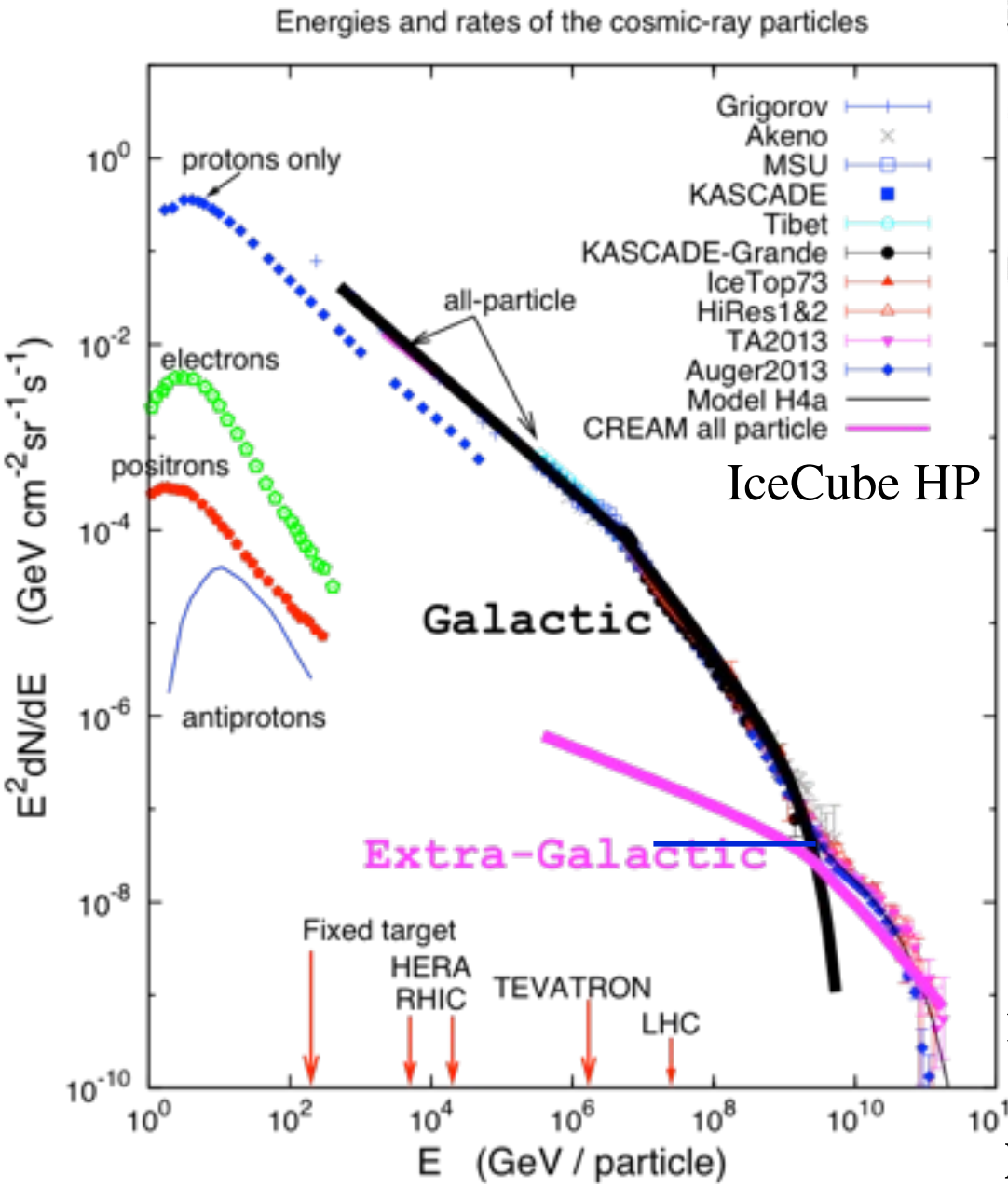
10^{-22}

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

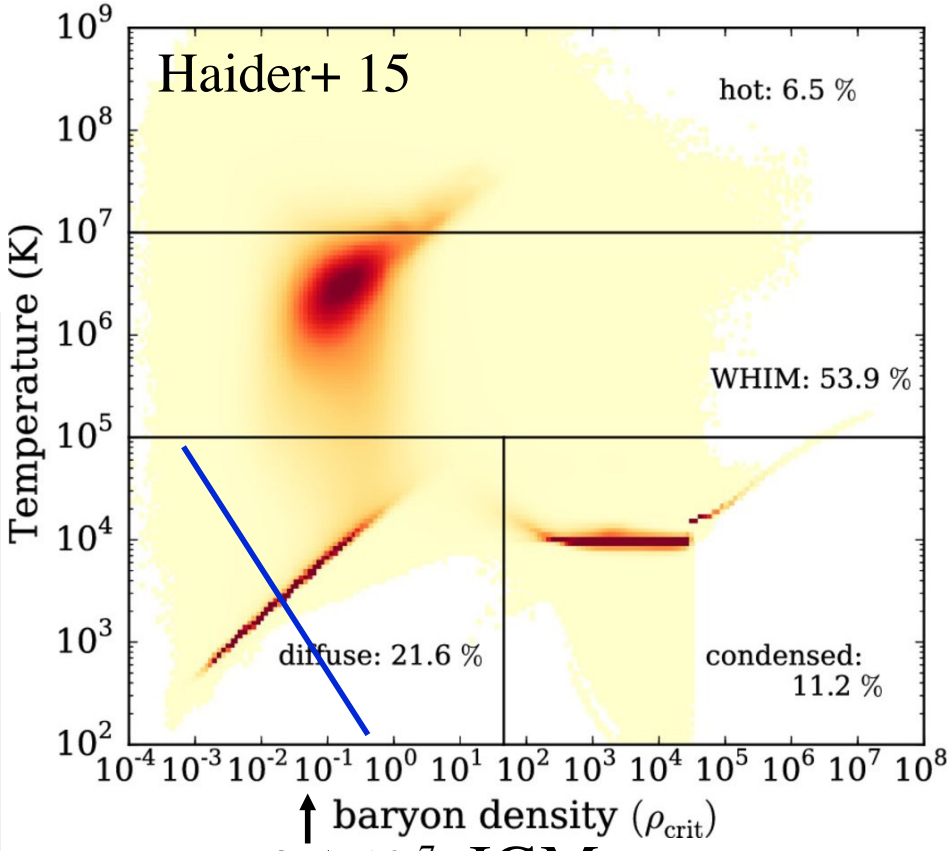
CR pressure

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

(U)HECRs vs diffuse, cool IGM



IceCube HP



$n_b=2.5\times10^{-7}$ IGM pressure

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

10^{-18}

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10^{-22} CR pressure

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

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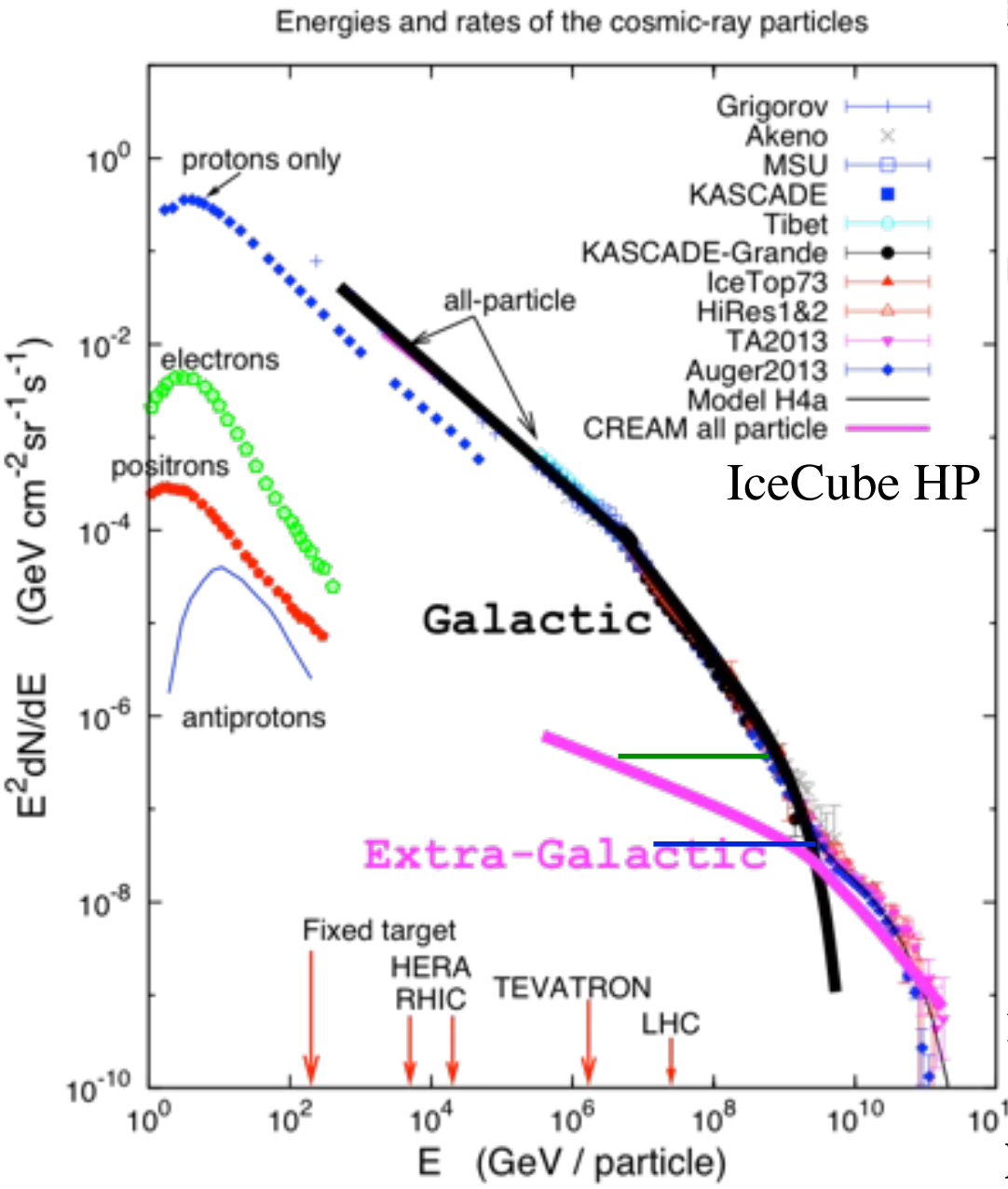
(U)HECRs vs diffuse, cool IGM



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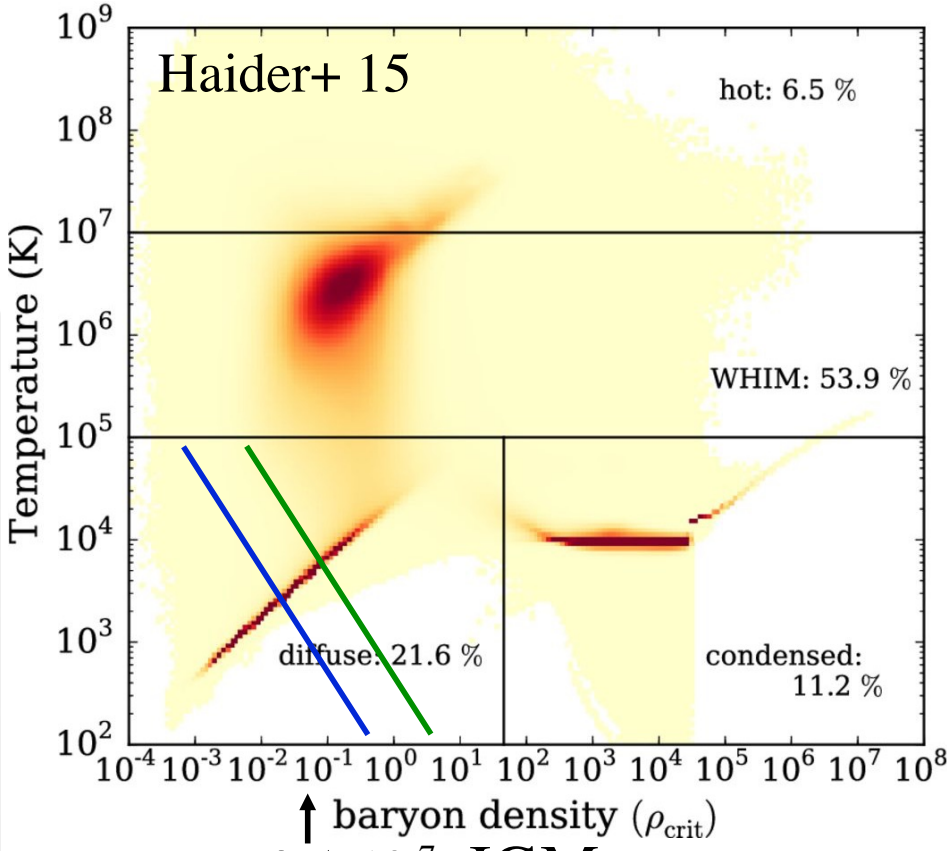

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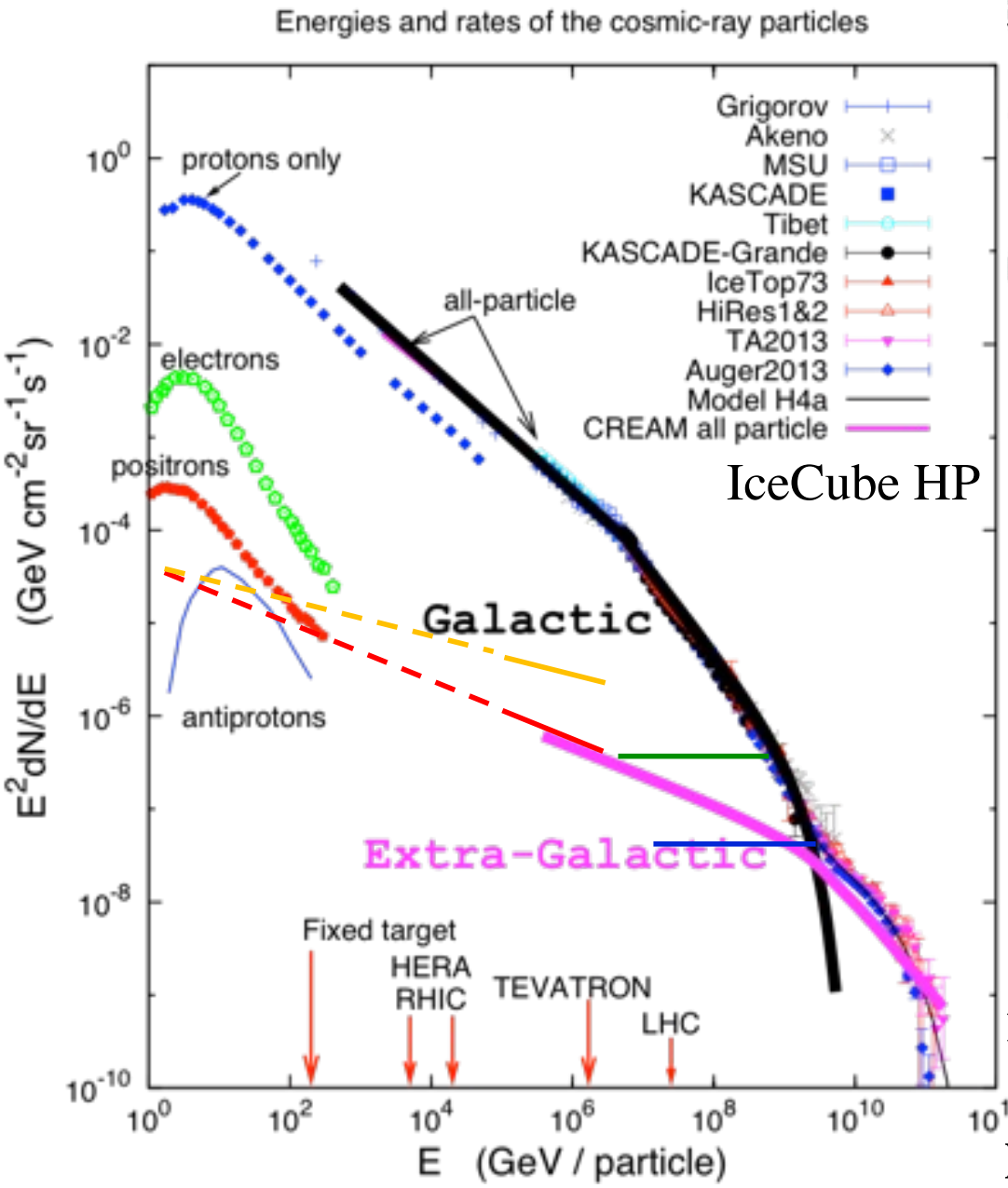

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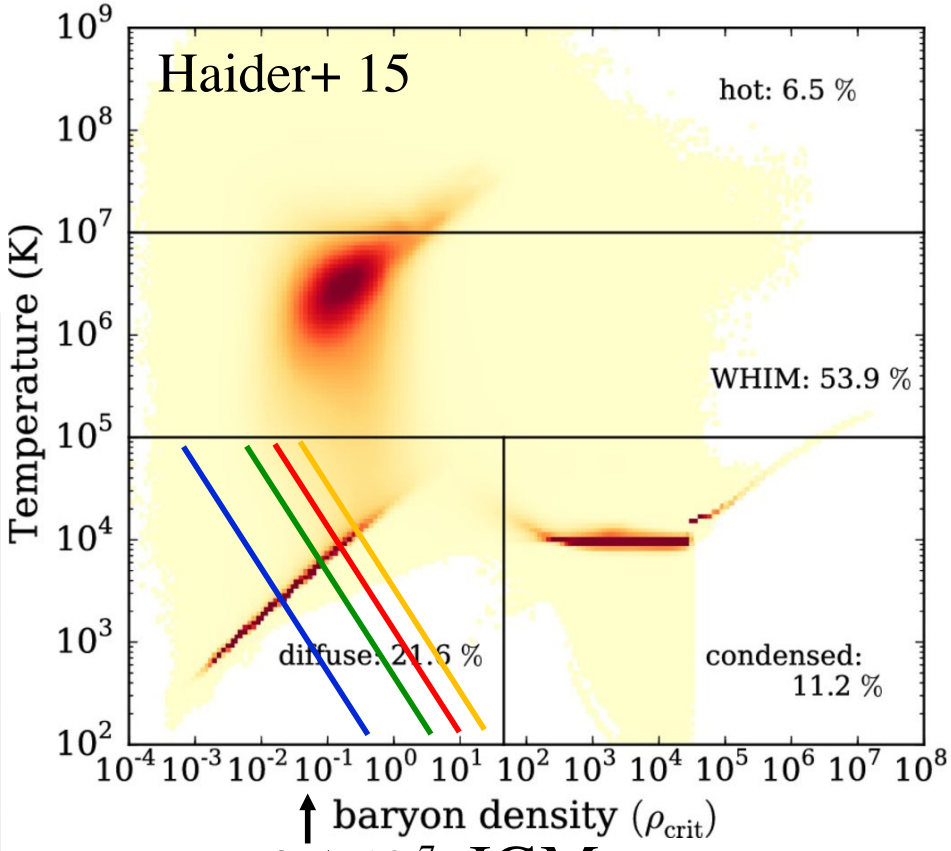

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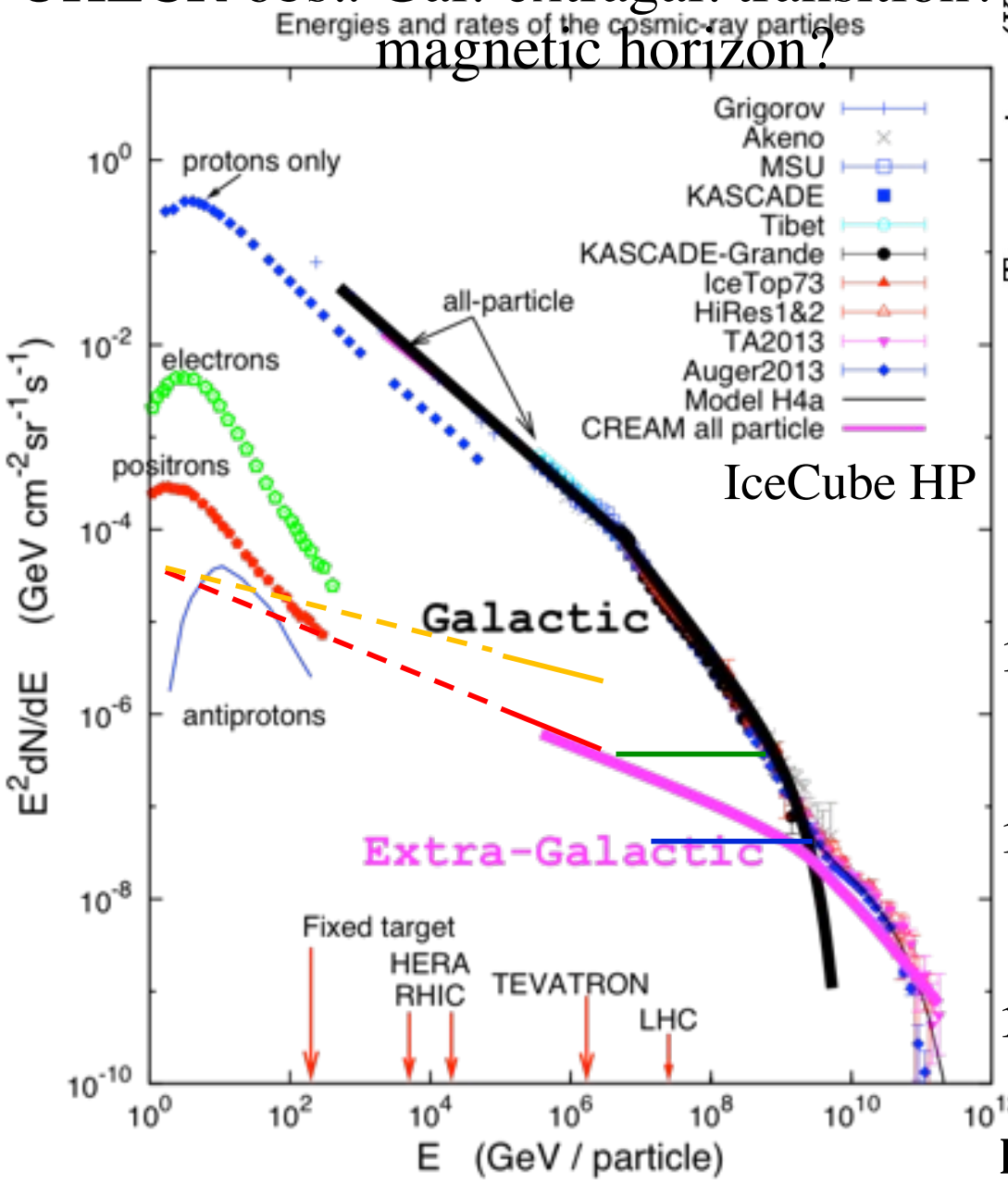
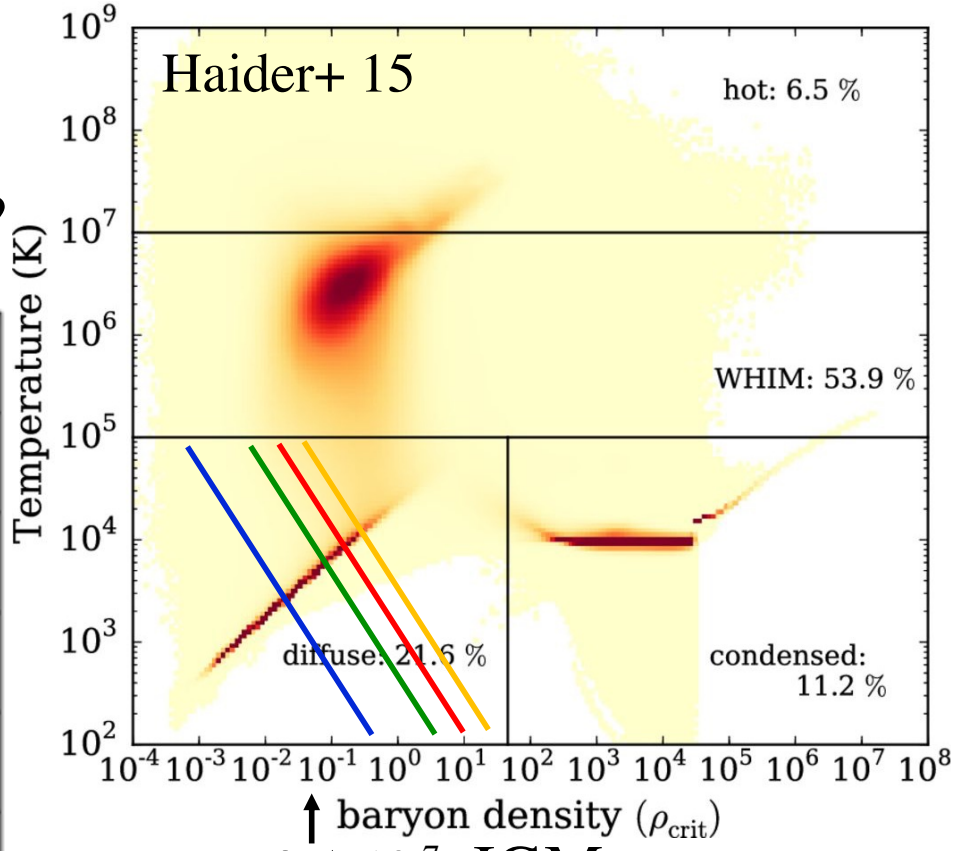
(U)HECRs vs diffuse, cool IGM

UHECR obs.: Gal.-extragal. transition? magnetic horizon?





$n_b=2.5\times10^{-7}$ IGM pressure

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non-negligible (significant) dynamical (thermal) effect on Lyα forest?

c.f. Lacki 15 for ~GeV CRs

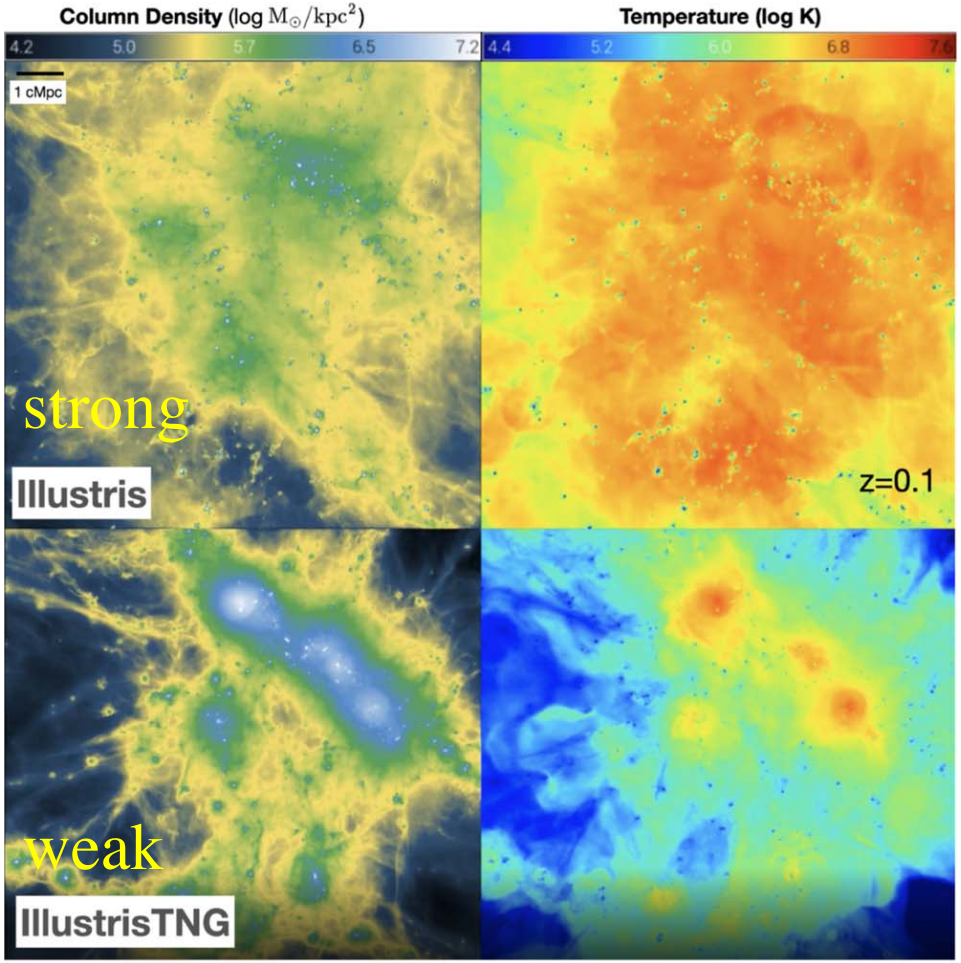
CR pressure

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

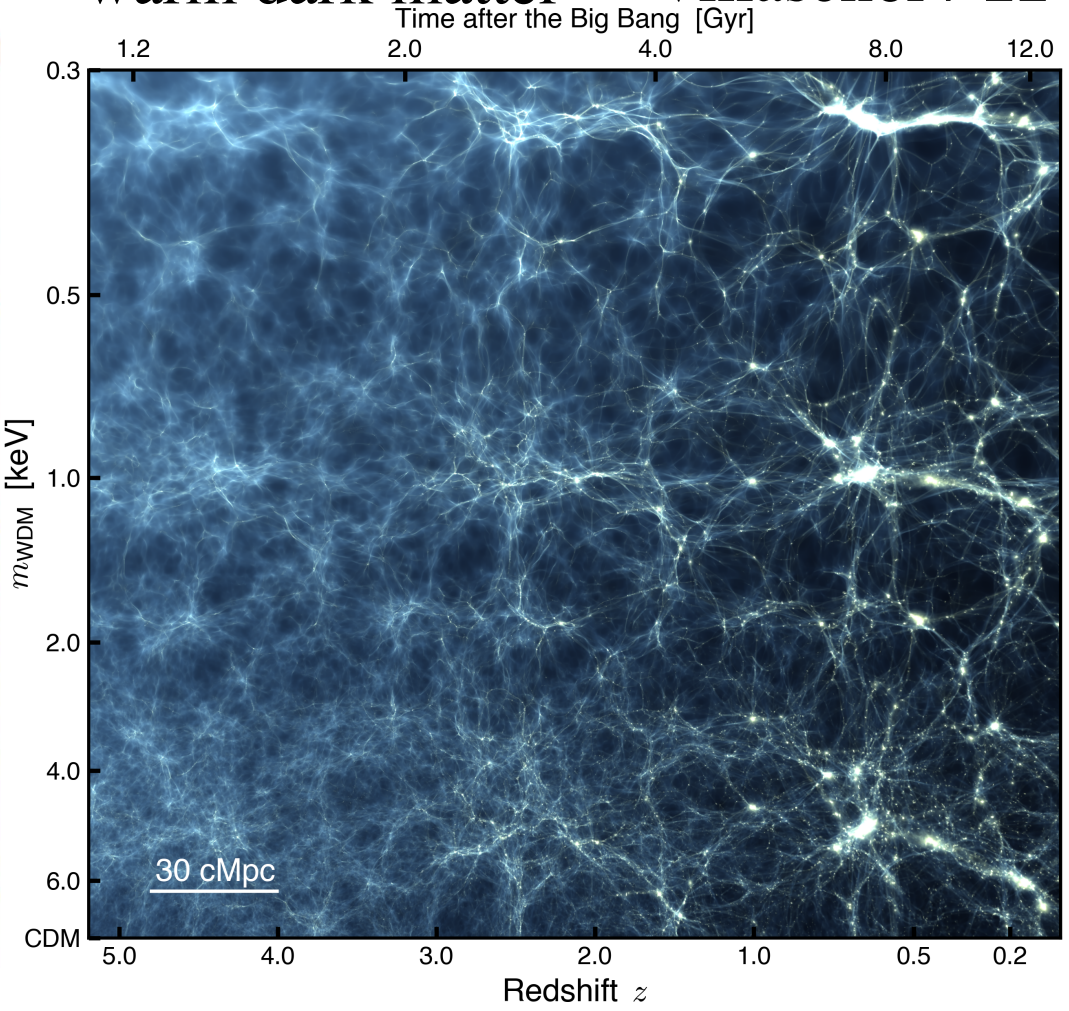
$p_{CR}(E)$(c.g.s.)

Lyα forest: probe of feedback, cosmology

AGN feedback Burkhart+ 22



warm dark matter Villaseñor+ 22



UV background e.g. Faucher-Giguere 20

c.f. evidence of extra heating? Bolton+ 22

(U)HECRs very likely exist in these regions: consideration warranted!

まとめ

- 宇宙大規模構造（銀河・銀河間物質）の形成・進化にとって
  CRの圧力・加熱は重要な役割を担っている可能性がある。
  が観測的証拠は乏しい。

- 天の川銀河ハロー内CRは必ず存在するはず。PeVγ線による探査
  はCMBγγ吸収のおかげでとても有利：系外成分が遮蔽される。
  エネルギー毎の伝搬距離がちょうどハローのスケールを網羅する。

- Tibet高銀違イベントはハローCRの兆候？
  HVCとの相関をより定量的に調査中。乞うご期待！
  LHAASO、南天からの観測 (Mega-ALPACA, SWGO)に期待。

- (U)HECR(>~PeV)の圧力は（宇宙で最大の体積を占める）
  cool diffuse IGMで重要である可能あり。
  Lyα forestへの影響を調べる。magnetic horizon等の解明も必要。