LOFAR family meeting 2023

Turbulent re-acceleration by solenoidal turbulence and mega halo in cluster outskirts

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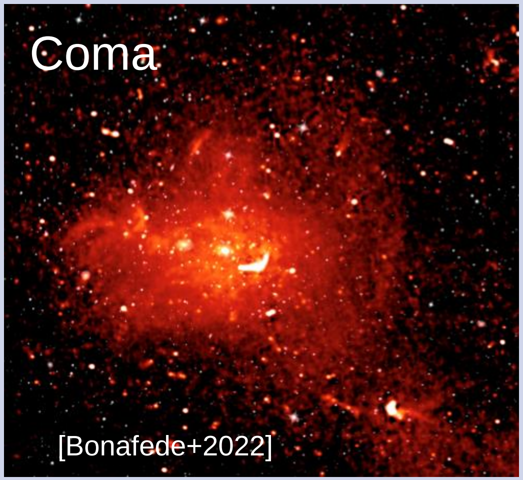
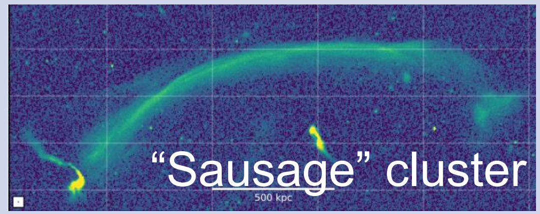
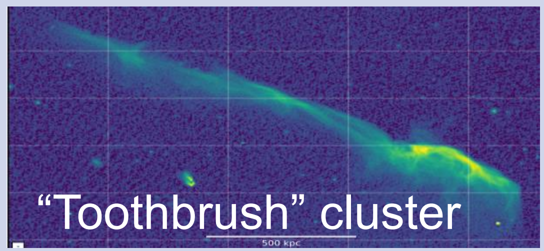
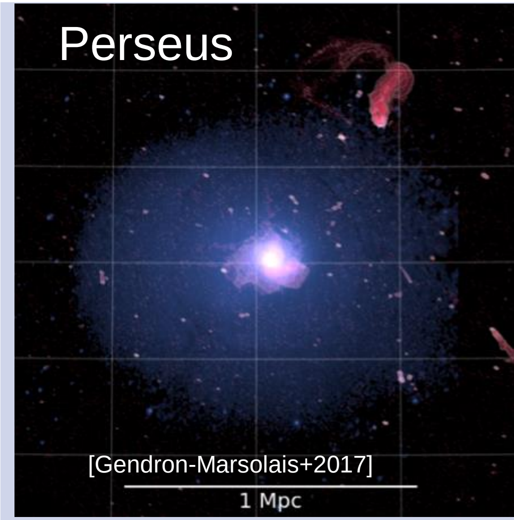
Diffuse Radio Emission in Clusters

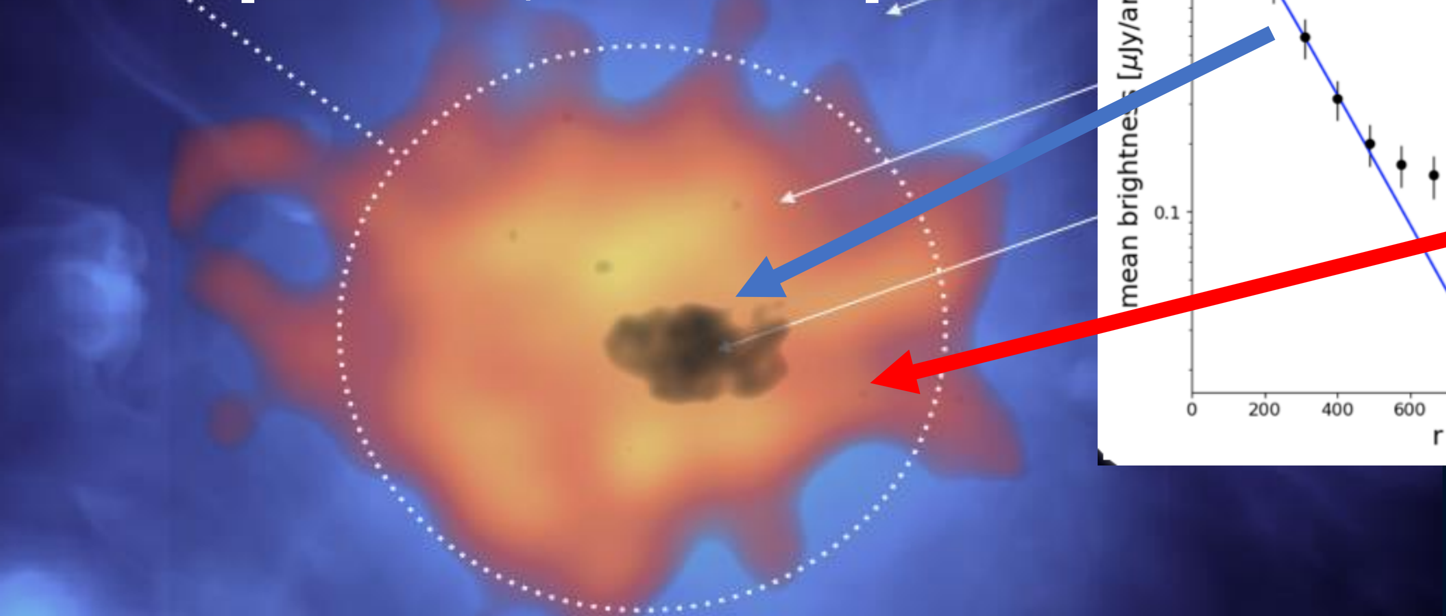
Giant Radio Halo	Radio Relic	Mini Halo
	 	
Spherical	elongated	Spherical
~ 1Mpc	~ 1Mpc	~ 300 kpc
Merging clusters	Merging clusters	Relaxed clusters

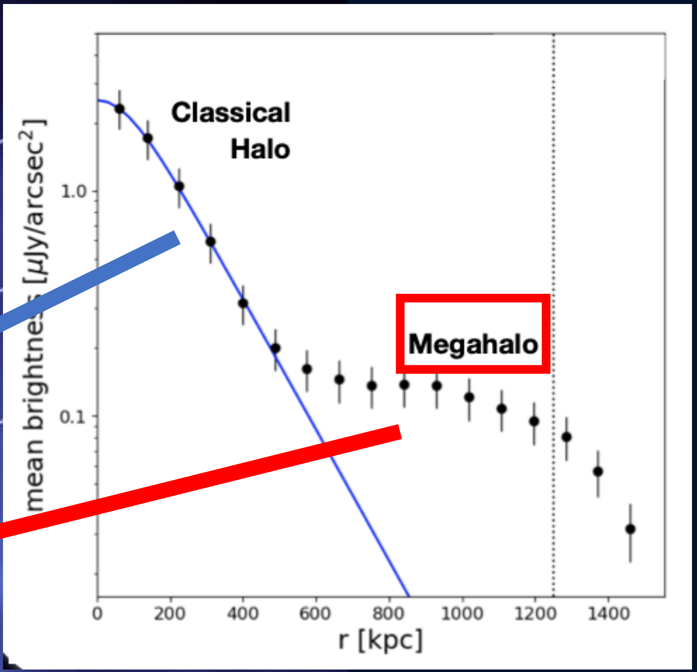
Correlate with dynamical state of clusters

mergers・mass accretion ⟷ **particle acceleration & magnetic field amplification**

“Mega” Halo

[Cuciti+2022, Botteon+2022]

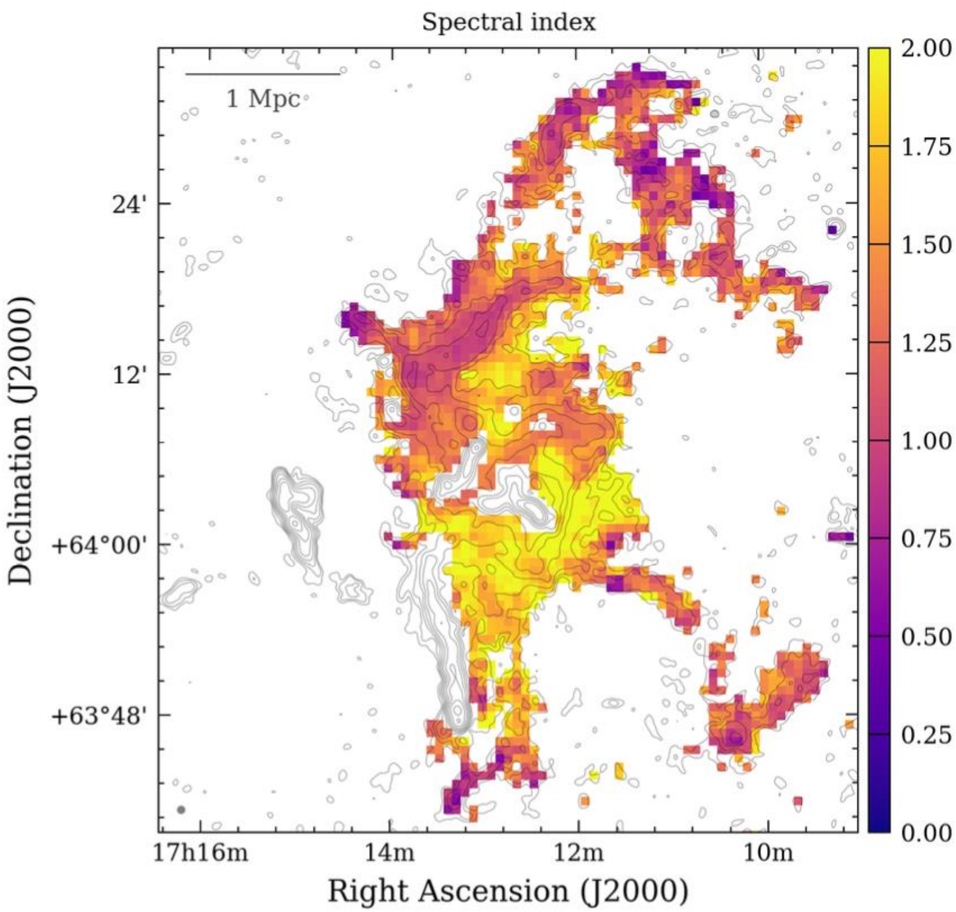




- **Bigger than classical giant halos**
  (×30 in volume)
- emissivity : ~1/30 of giant halos
- extending up to ”the edge”(=virial radius)
- steep spectral index ($\alpha_{syn} \sim 1.5$)
- not a simple extrapolation of classical RH(?)

Abell 2255, LOFAR observation

[Botteon+2022]



Talk by Andrea Botteon, yesterday

- redshift : $z = 0.08$
- a complex system including radio halo, relics, radio galaxies
- ~ 5 Mpc diffuse emission

Radio emission from the low-density outskirts!

non-thermal (CR electron and B field) energy density should not exceed ICM energy density

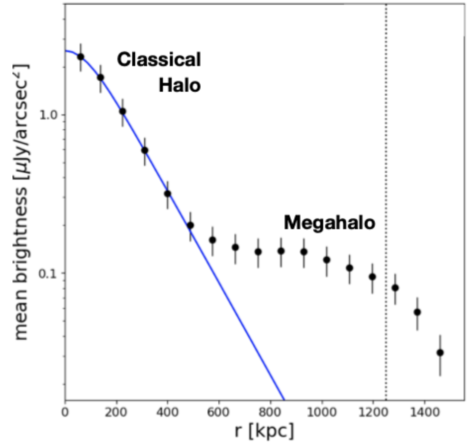
$$\epsilon_{NT} \leq \epsilon_{ICM}$$

➡ $0.1\ \mu\mathrm{G} \leq B \leq 1.7\ \mu\mathrm{G}$

(significantly larger than B field in the IGM)

Origin of Mega Halos ?

particle acceleration
+ B field amplification
in cluster outskirts



Particle acceleration

with large volume-filling factor
→ **turbulent acceleration**
(as in giant halos?)

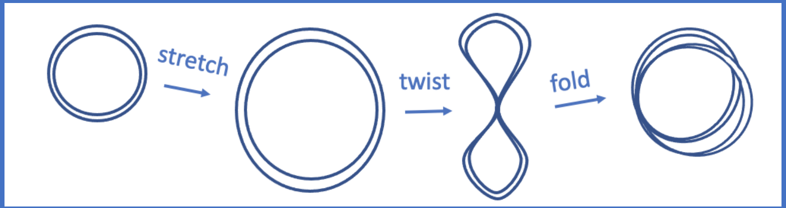
[e.g.,Brunetti & Lazarian 2007,2011,2015]

driven by
major mergers and/or mass accretion

B field amplification

turbulent dynamo by
incompressible mode

[e.g.,Kazantsev 1969,Eyink+2011,Beresnyak+2012,Miniati+2015]

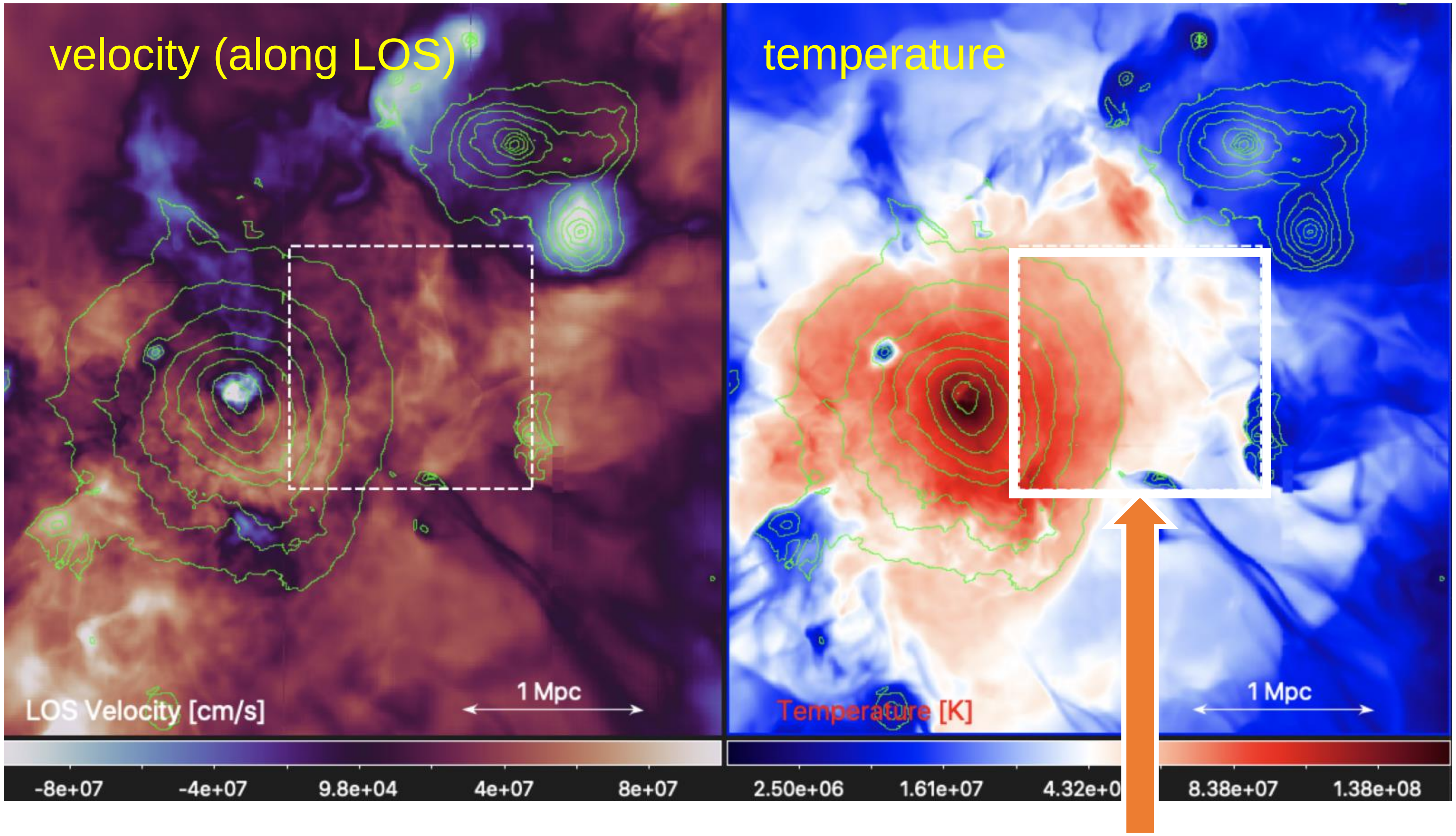


This work:

- MHD simulation → **turbulence in cluster outskirts**
- mega halo spectrum → **efficiencies of CR acceleration and dynamo**

ENZO simulation

[The Enzo Collaboration+ 2013, Vazza+ 2010,2011,2018]



- grid MHD code
- initial field ($B = 10^{-10}$ G at z = 40)
- AMR : maximum resolution
  $\Delta x = 3.95$ kpc/cell
- $z_{obs} = 0.02$

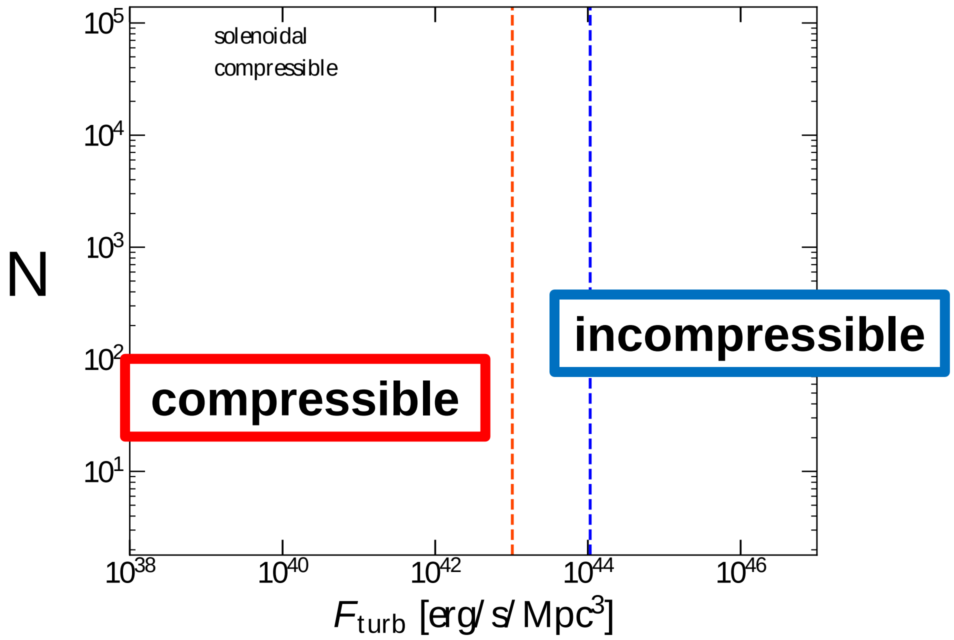
mega halo region:

1.2 Mpc from the center , volume = 1.6^3 Mpc^3

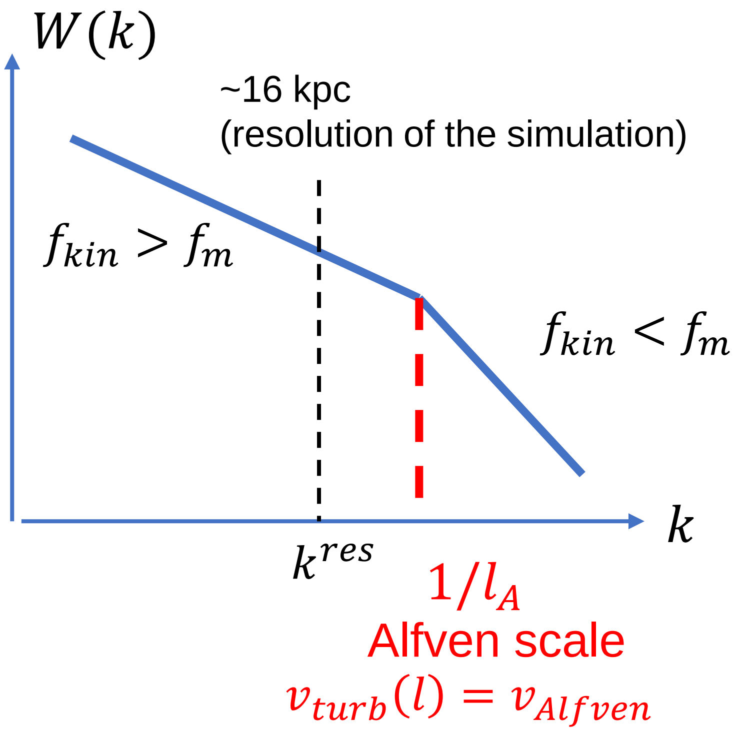
- low-density ($n_{\mathrm{ICM}} = 10^{-4}\ \mathrm{cm}^{-3}$)
- feature of mass accretion is apparent

Turbulence in cluster outskirts

distribution of turbulent energy flux



spectrum of turbulence



dominated by the solenoidal mode

[e.g., Vazza+2011, Miniati+2014]

incompressible : $\sim 10^{44}$ erg/s/Mpc^3

compressible : $\sim 10^{43}$ erg/s/Mpc^3

$$l_A \sim 0.5\ \mathrm{kpc} \left(\frac{L}{500\mathrm{kpc}}\right)\left(\frac{M_A}{10}\right)^{-3}$$

※ B in simulation may be underestimated, because dynamo is not fully resolved

[e.g., Vazza+2018]

Re-acceleration with solenoidal turbulence

[Brunetti & Lazarian 2016, Brunetti & Vazza 2020]

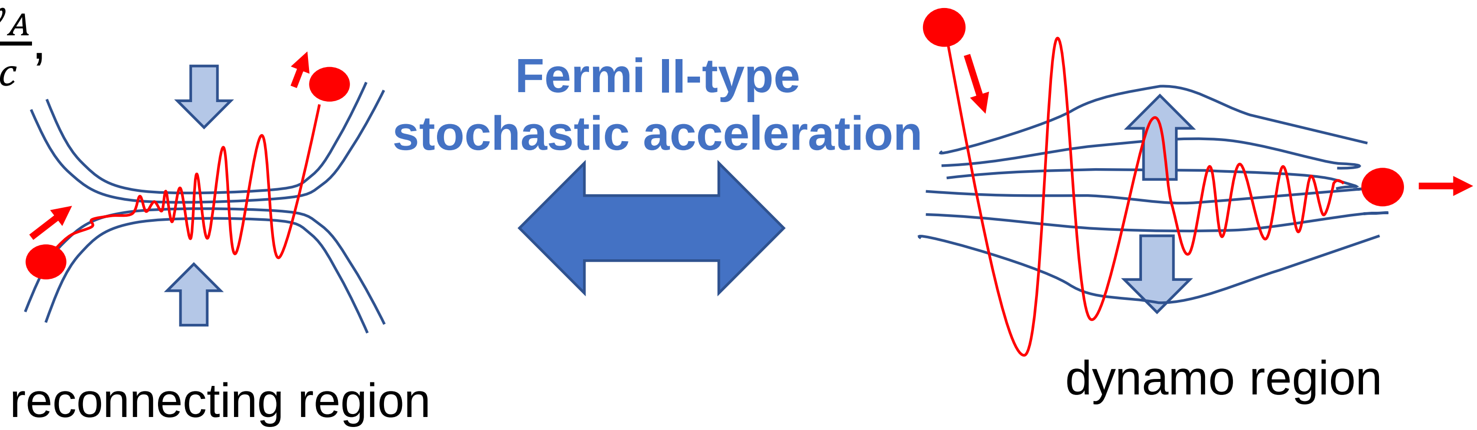
Fermi II acceleration associated with the turbulent reconnection

[Lazarian&Vishniac 1999]

incompressible … no divergence in fluid motion

instead, **diffusion(dynamo and reconnection) of magnetic field line**

$\frac{\Delta p}{p} \sim \frac{v_A}{c}$,



$$D_{pp} = \left\langle \frac{\Delta p \Delta p}{\Delta t} \right\rangle \sim 3 \left(\frac{l_A}{\lambda_{mfp}} \right)^2 \frac{v_A^2}{c \lambda_{mfp}} p^2$$

parameter : **mean free path** $\boldsymbol{\psi \equiv \lambda_{mfp}/l_A}$

$\boldsymbol{l_A}$**: Alfven scale (~0.1-1 kpc)**

Fokker-Planck equation

$$\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial p}(\dot{p}_{cool} N_e) + \frac{\partial}{\partial p}\left[D_{pp}\frac{\partial N_e}{\partial p} - \frac{2}{p}D_{pp}\right] + Q_e$$

- radiative + Coulomb cooling: $\dot{p}(\rho, B, z)$
- re-acceleration: $D_{pp}(\psi, B, \rho, \delta v_{turb}, L)$

- magnetic field: B ($\eta_B, \rho, \delta v_{turb}$)
- injection of seed electrons: Q_e

(※ neglect secondary electrons from *pp* collisions)

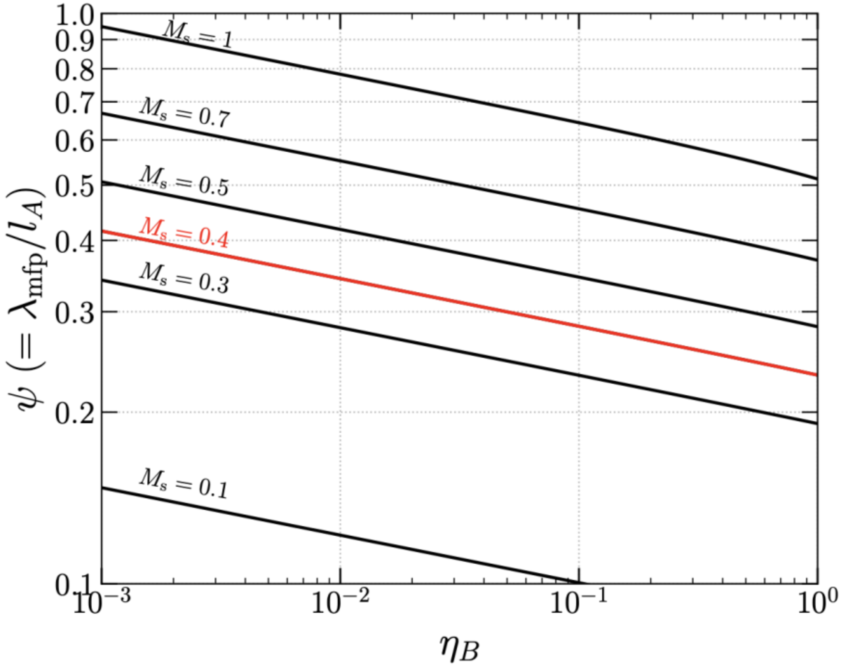
a snapshot of MHD simulation (10^6 cells)

parameters : ψ, η_B

dynamo: $\frac{B_{dyn}^2}{8\pi} \sim \frac{1}{2}\eta_B \rho_{ICM} \delta v_{turb}^2$

acceleration: $D_{pp} = 3\sqrt{\frac{5}{6}}\frac{c_s^2}{c}\frac{\sqrt{\beta_{pl}}}{L}M_s^3 \psi^{-3} p^2$

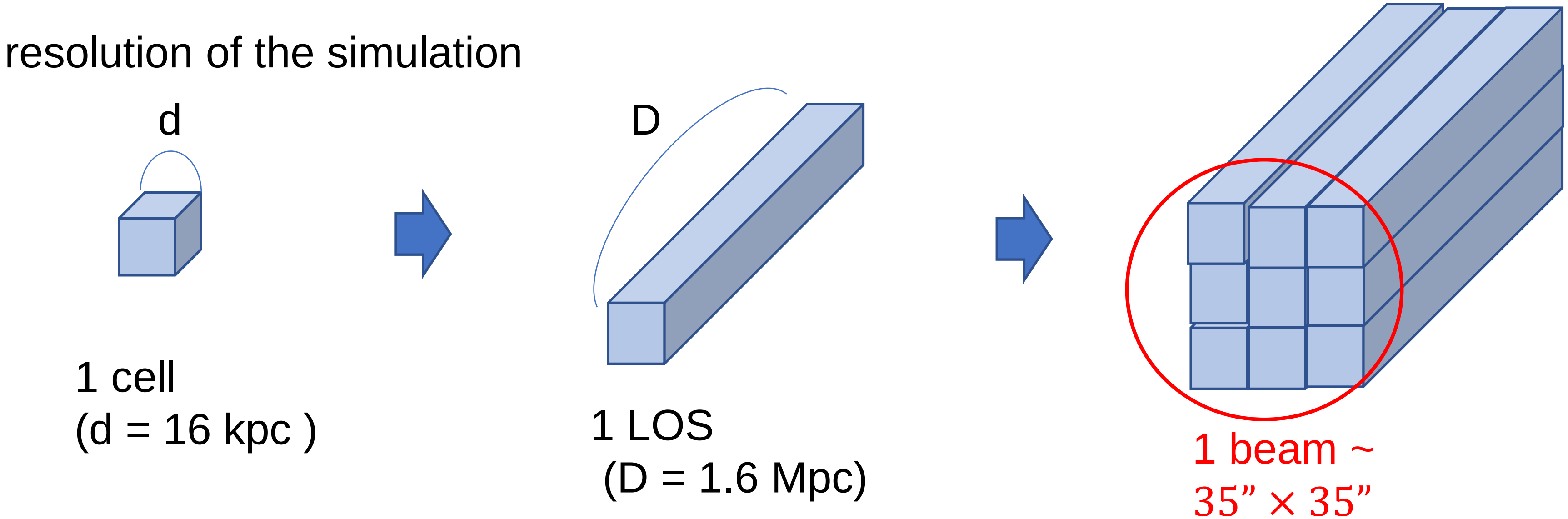
at ~100 MHz
the acceleration balances the cooling



$10^{-3} < \eta_B < 10^{-1}$
[e.g., Cho+2009, Beresnyak 2012, Xu &Lazarian 2016]

➡ $\mathbf{0.3 < \psi < 0.5}$

LOS integration and the beam size



LOFAR HBA sensitivity

$$\sigma_{rms} = 0.2\ mJy/beam$$

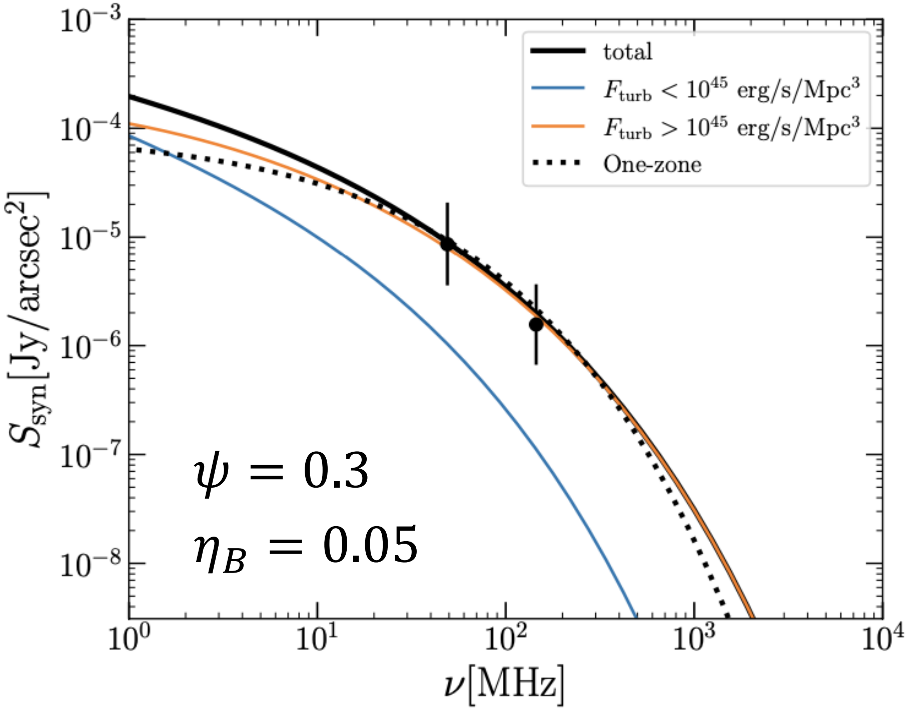
brightness larger than 2σ → detection

30% of the area can be covered with LOFAR sensitivity

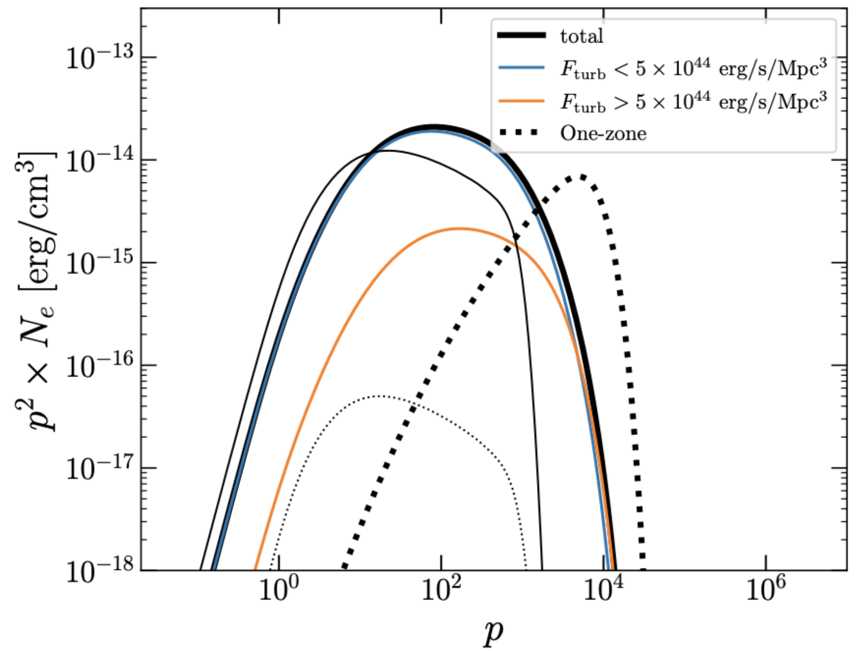
can explain the large extension of the mega halo

Result: mega halo spectrum

spectrum of the beams
detectable with LOFAR sensitivity



energy spectrum of CR electrons



turbulent cells with $F_{turb} > 10^{45}$ erg/s/Mpc^3
dominates the emission (~3% of the cells)

$p \sim 10^4$ electrons are responsible for the emission (small fraction)

most of electrons have $p \sim 10^2$

Discussion

1. mean free path and diffusion

$\psi \sim 0.5 \;\rightarrow\; \lambda_{mfp} \sim 0.5 l_A \sim 0.1\mathrm{kpc}$

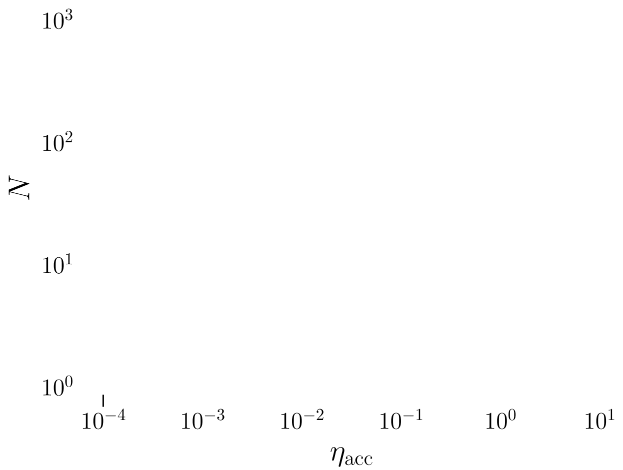
spatial diffusion coefficient

$$D = \frac{1}{3} c\lambda_{mfp} \sim 1.5 \times 10^{31}\ \mathrm{cm^2/s}$$

diffuse over 300 kpc in 0.5 Gyr (~ acceleraation timescale)

- diffusion length is much larger than then beam size of LOFAR
- but we have neglected the effect of diffusion
- the filling factor may be underestimated

distribution of η_{acc}



2. efficiency of turbulent acceleration

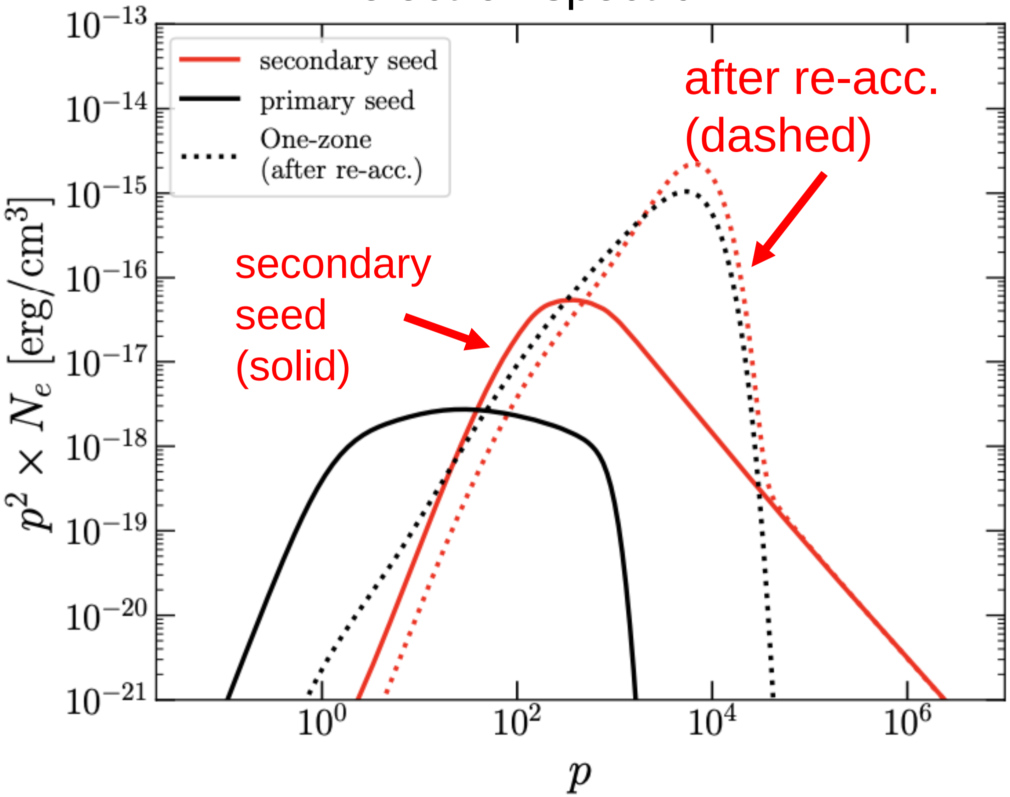
$$\eta_{acc} \equiv \frac{\text{(Energy gain rate of CRs)}}{\text{(Energy flux of turbulence)}}$$

$$\eta_{acc} \sim 0.1 \longleftarrow$$

mega halo flux can be explained,
when 10% of the turbulent energy channels into CR acceleration

Appendix: secondary electrons

electron spectrum



from hadronic pp collision

- **without re-acceleration (solid line)**
  … electron density at $p \sim 10^4$ is not sufficient
  (pure-hadronic model is excluded)
- **with re-acceleration (dashed line)**
  … comparable to primary model when

$$\epsilon_{CR_p} \sim \epsilon_{ICM}$$

ϵ_{CR_p} : CR energy density

ϵ_{ICM} : ICM energy density

seed electrons can be originated from hadronic (pp) process

But, **CR energy density need to be as large as ICM energy density**

Summary

the "mega halo" in A2255
& turbulent re-acceleration model

◆ mega halos [Cuciti+2022, Botteon+2022]

- extending up to the virial radius of clusters
- **CR acceleration and dynamo in cluster outskirts**

◆ *ENZO* simulation [Vazza+, Dominguez-Fernandez+2019 , Beduzzi+2023]

- a certain level of large-scale turbulence in cluster outskirts
- **dominated by solenoidal (incompressible) mode**

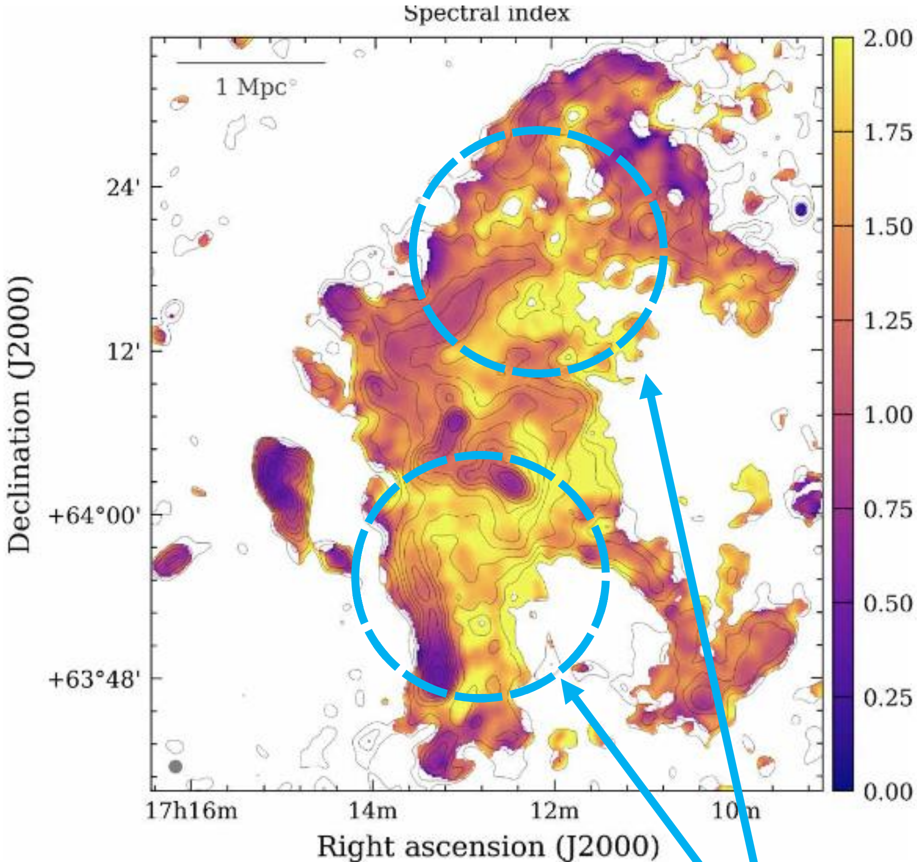
◆ turbulent re-acceleration model [Brunetti & Lazarian 2016]

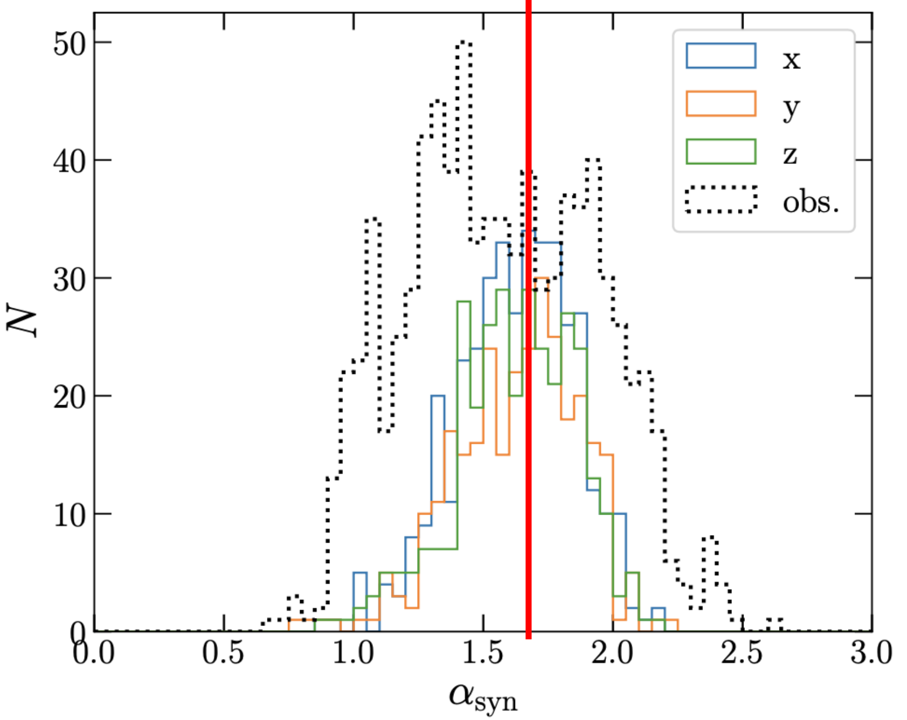
- 2^{nd} order Fermi acceleration in turbulent reconnection/dynamo
- **mean free path of CR electrons ~ Alfven scale**
- **η ~ 10%** of the energy of turbulence consumed by CR acceleration
- pp collision may provide the seed electrons, but $\epsilon_{CR_p} \sim \epsilon_{ICM}$ is required

Spectral index

[Botteon+2022]

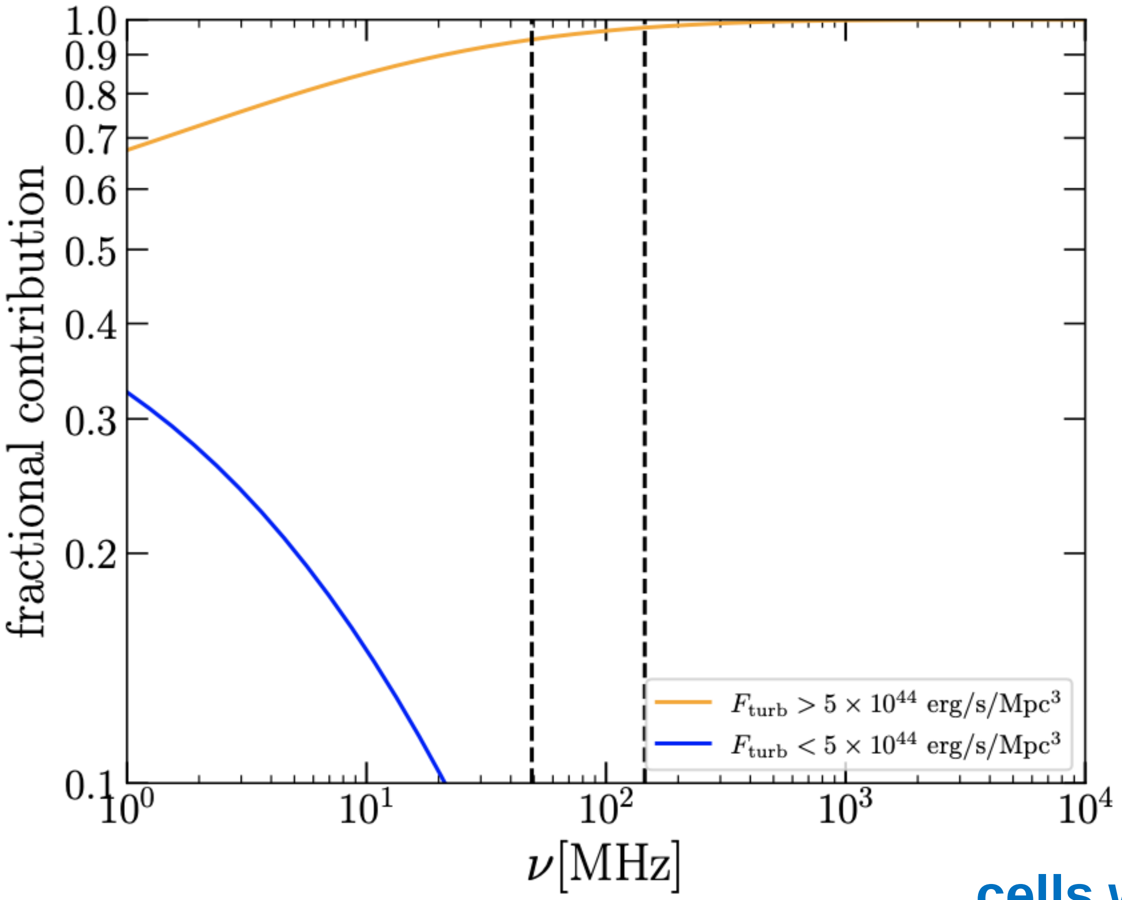
$\alpha_{syn} \sim 1.6$ in our calculation





$\alpha_{syn} \sim 1.2 - 1.6$

Turbulent cells



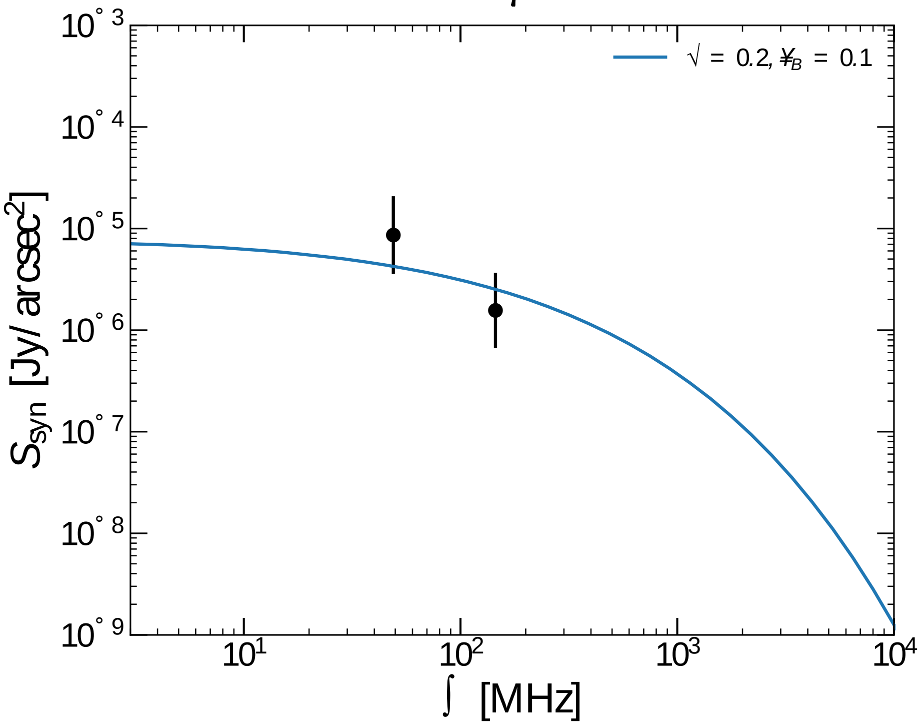
cells with large F_{turb}
→ higher frequency

cells with moderate F_{turb}
→ lower frequency

Onezone: parameter study

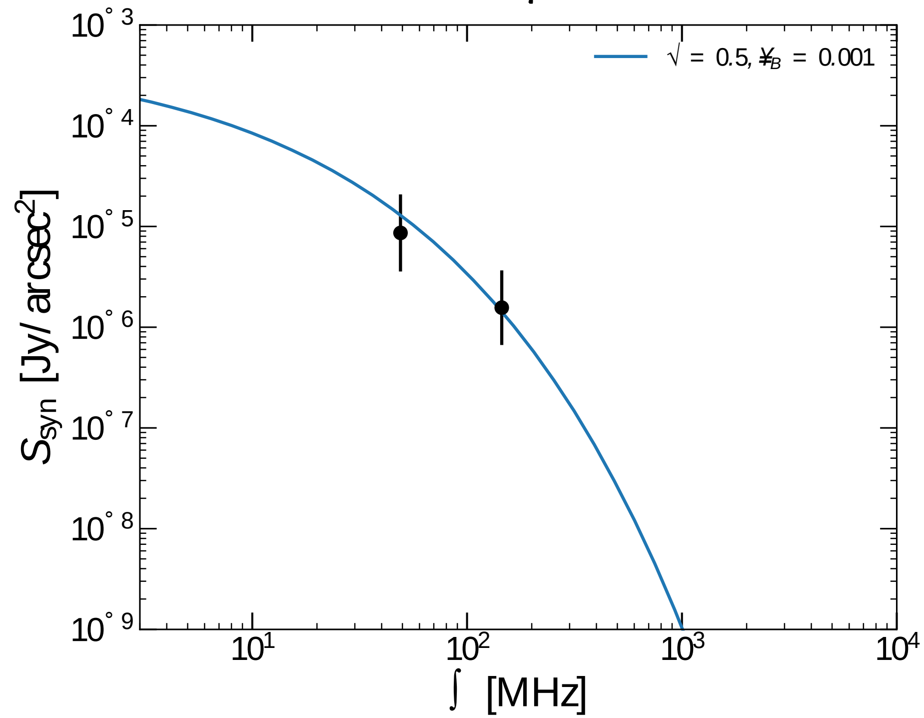
$\eta_B = 10^{-1}, \psi = 0.2$

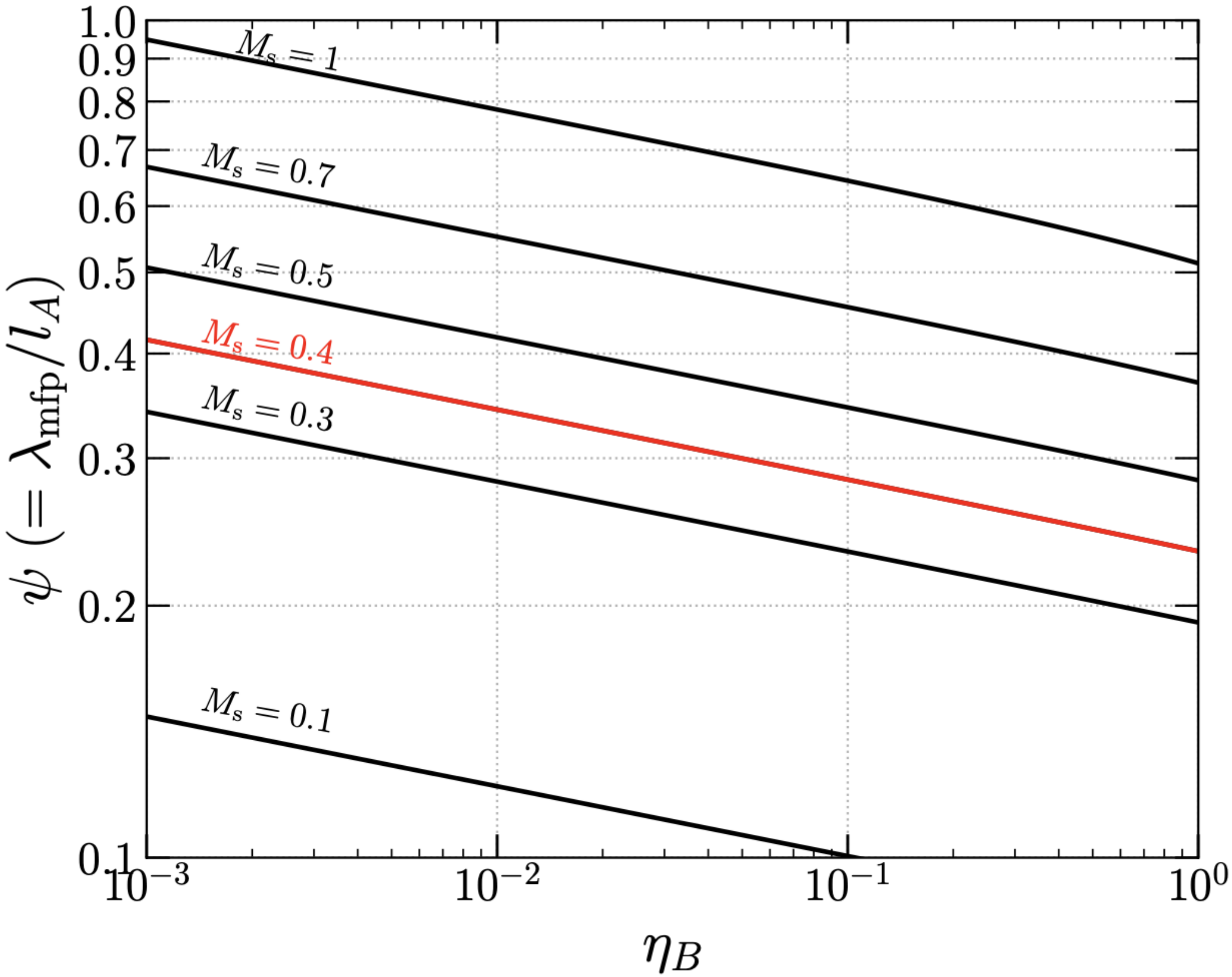
$B \sim \mu G$



$\eta_B = 10^{-3}, \psi = 0.5$

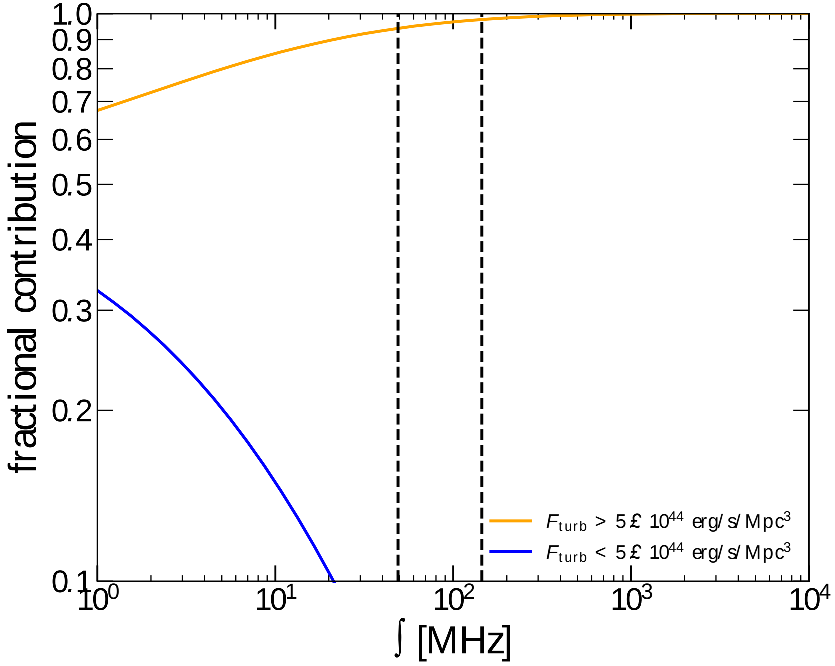
$B \sim \mu G$



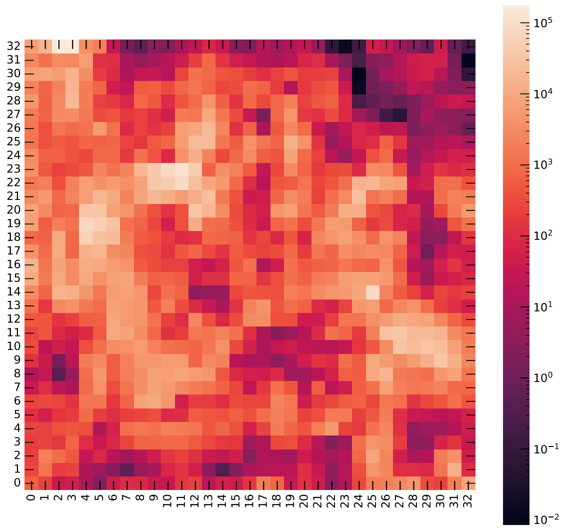


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
ψ $(= \lambda_{\rm mfp}/l_A)$
$M_{\rm s} = 1$
$M_{\rm s} = 0.7$
$M_{\rm s} = 0.5$
$M_{\rm s} = 0.4$
$M_{\rm s} = 0.3$
$M_{\rm s} = 0.1$
10^{-3}
10^{-2}
10^{-1}
10^{0}
η_B

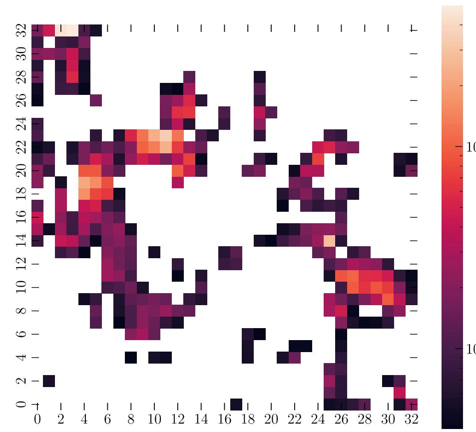
Filling factor



LOS integrated brightness

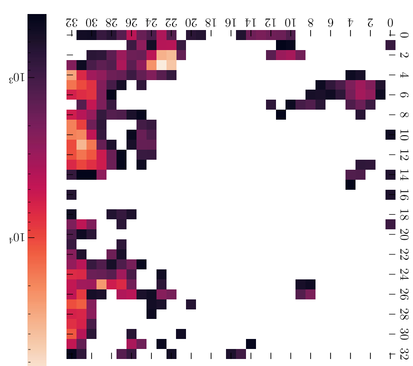


observable beam
(along-x)

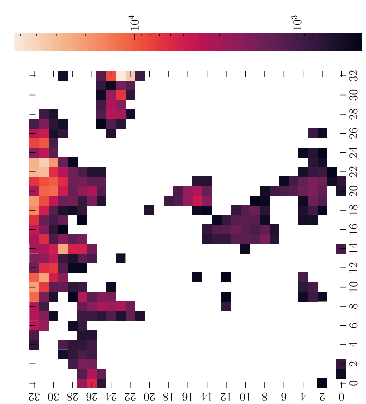


beam coverage
~25 - 30%

(along-y)

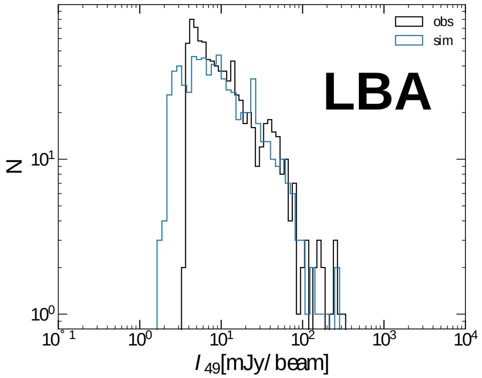


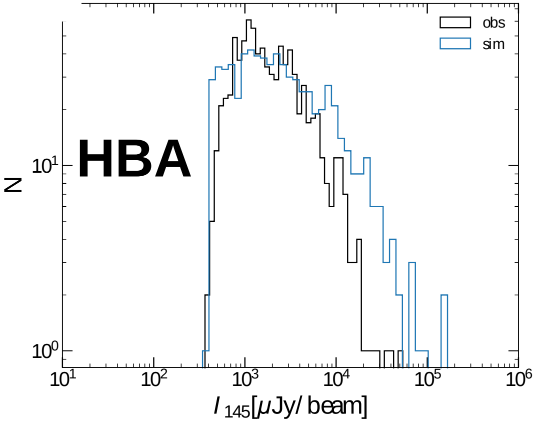
(along-z)



Cell-wise calculation with $(\eta_B = 0.05, \boldsymbol{\psi = 0.4})$

Normalized at LBA intensity → $\boldsymbol{\epsilon_{seed} = 5 \times 10^{-15}}$
$\boldsymbol{T_{dur} = 1.5 t_{eddy}}$

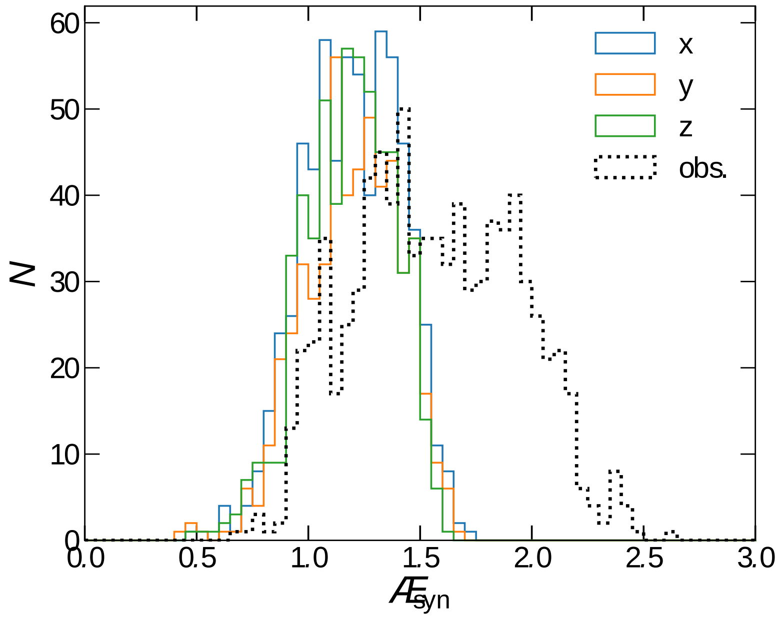




typical value of spix.

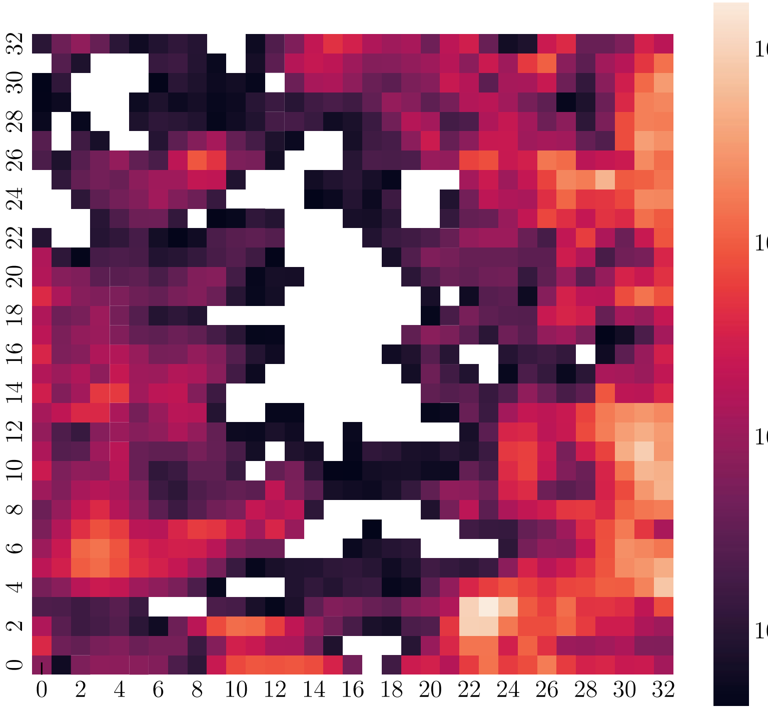
$\alpha_{syn} \approx -1.2$

(a smaller η_B is preferred?)



Cell-wise calculation with $(\eta_B = 0.05, \boldsymbol{\psi = 0.4})$

beam coverage ~70%



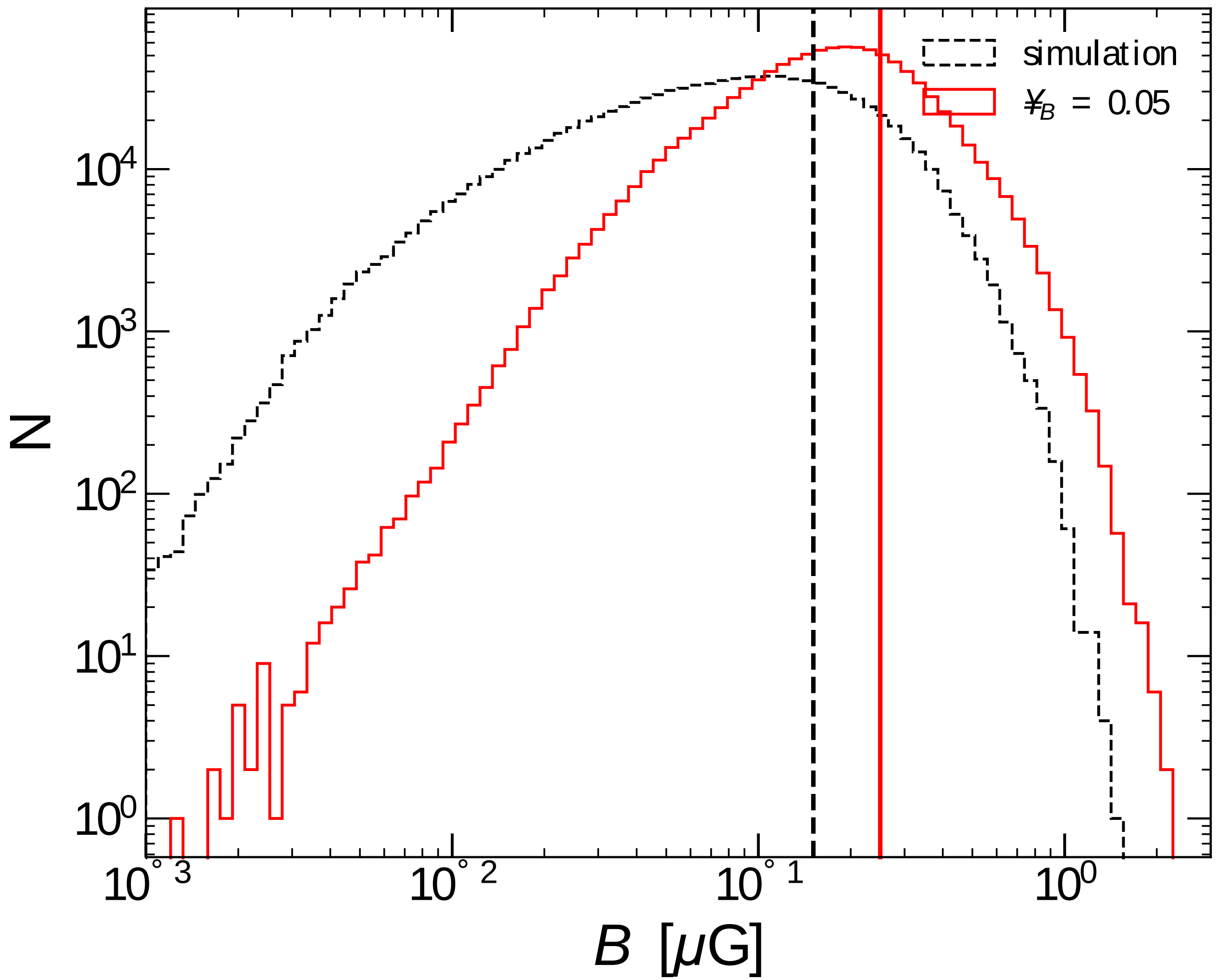
Cell-wise calculation with $(\eta_B = 0.05, \boldsymbol{\psi = 0.4})$

	ϵ_{seed}	$\langle \alpha_{syn} \rangle$	beam		
$T_{dur} = 1.0t\_eddy$	1.2e-14	1.3	62%		
$T_{dur} = 1.5t\_eddy$	5e-15	1.2	70%		

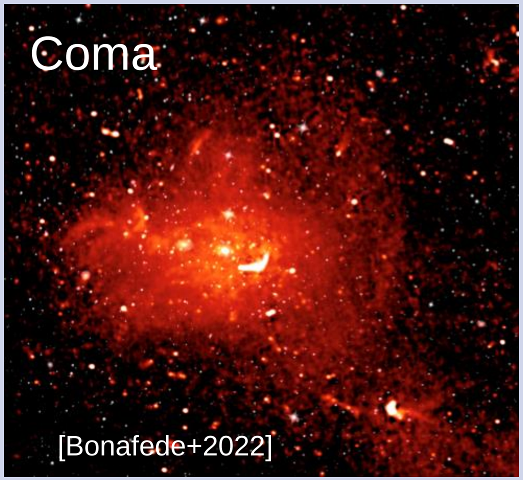
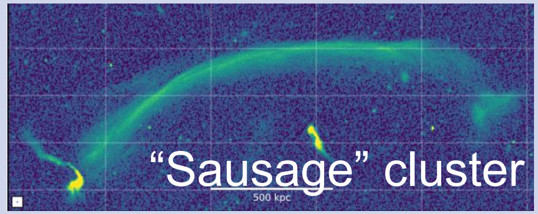
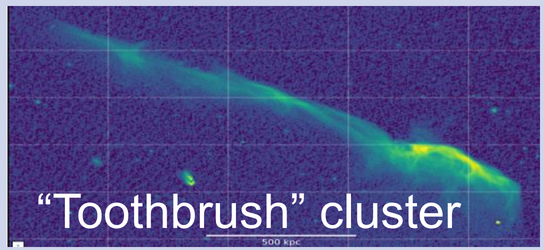
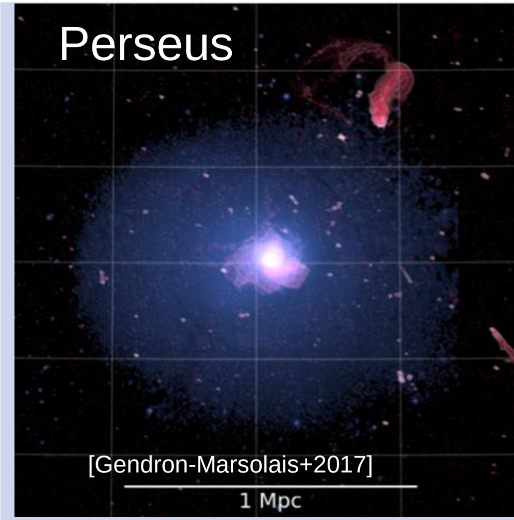
$\eta_B = 0.05, \boldsymbol{\psi = 0.5}$

$T_{dur} = 1.5t\_eddy$	**5e-14**	**1.6**	**30%**

For a better match to the spectral index,
a smaller η_B would be preferred for $\boldsymbol{\psi = 0.4}$

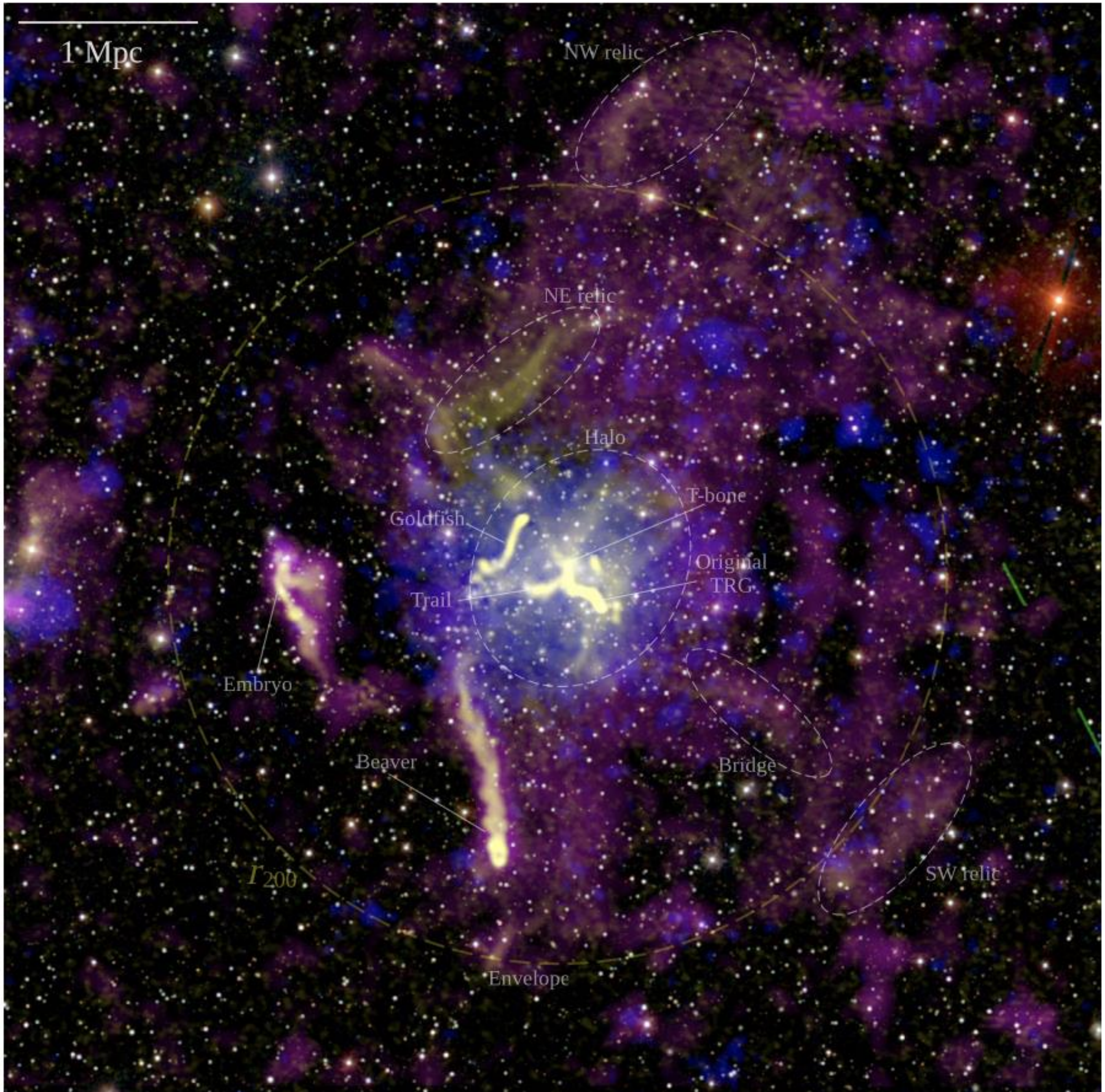

simulation
¥B = 0.05
N
10^4
10^3
10^2
10^1
10^0
10° 3
10° 2
10° 1
10^0
B [μG]

銀河団の電波放射

Giant Radio Halo	Radio Relic	Mini Halo
	 	
球状	弧状	球状
~ 1Mpc	~ 1Mpc	~ 300 kpc
衝突銀河団	衝突銀河団	緩和した銀河団

銀河団の動的な状態と密接に関係

銀河団衝突・質量降着 ⟷ 粒子加速・磁場増幅


1 Mpc
NW relic
NE relic
Halo
T-bone
Goldfish
Original
TRG
Trail
Embryo
Beaver
Bridge
SW relic
r_{200}
Envelope

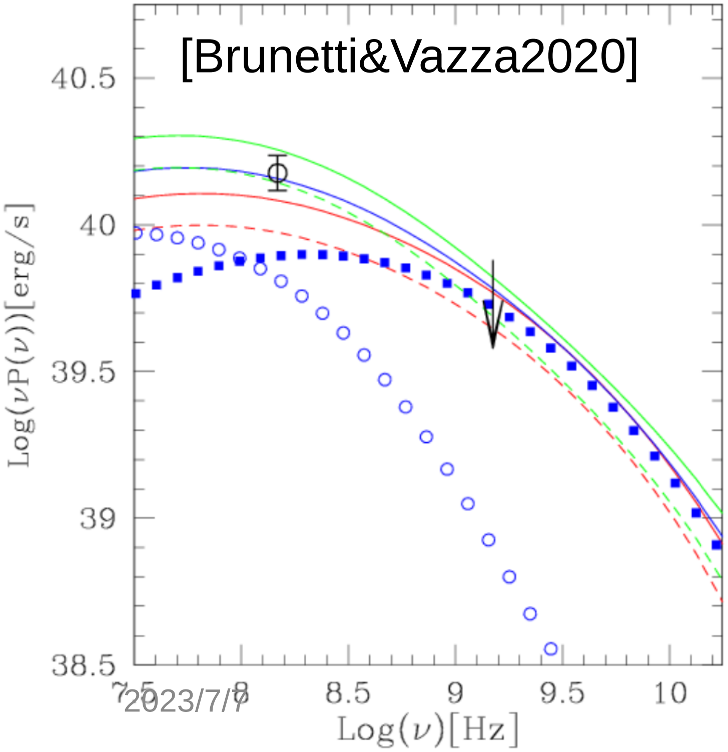
Fokker-Planck方程式

2. 全cell($N = 10^6$)で計算

各cellでの乱流強度,温度, ガス密度, etc… を用いて計算

注意すべき点 … 視線方向積分！

スペクトル形状は少数のhardな放射に強く影響される



← 電波スペクトルを成分分解

■: 乱流強度が上位15%のcellからの放射

○: 残りの85%からの放射

スペクトルの足し算

→ cut-offの形状は簡単に隠されてしまう

Ultra-steep haloやmega haloなど、

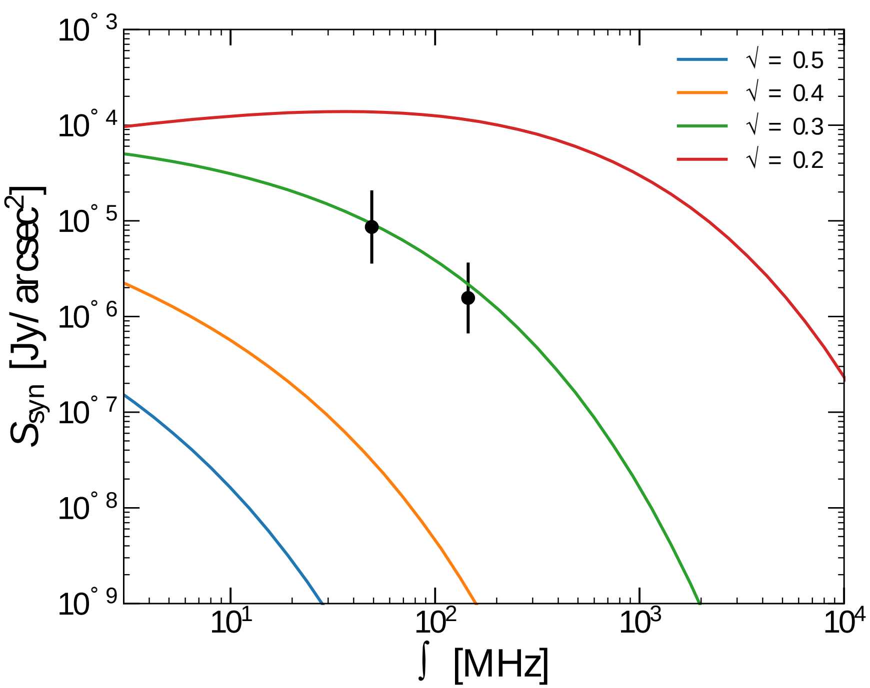
べきが急な放射の場合には特に注意！

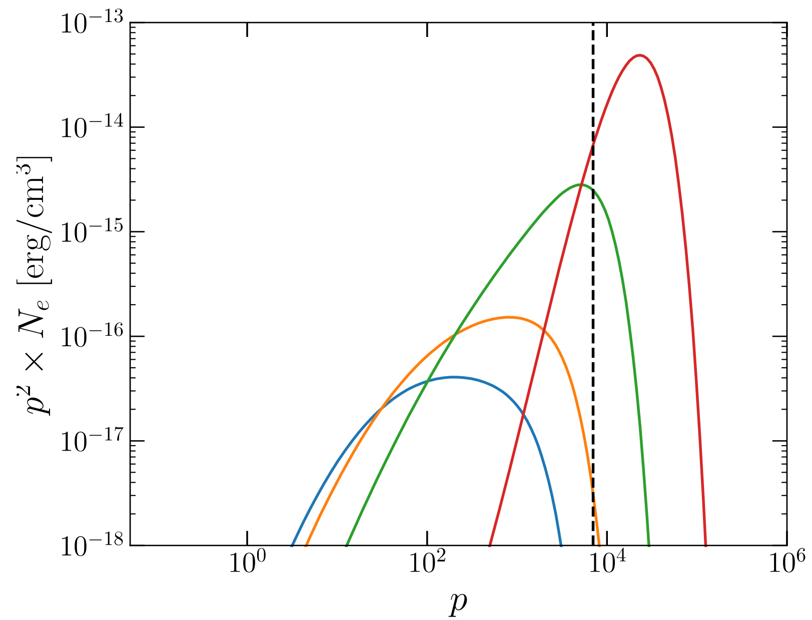
Fokker-Planck を解いてみる

1. One-zone モデル

$\psi = 0.3, \eta_B = 0.05$

$t_{acc} \approx 0.24$ Gyr



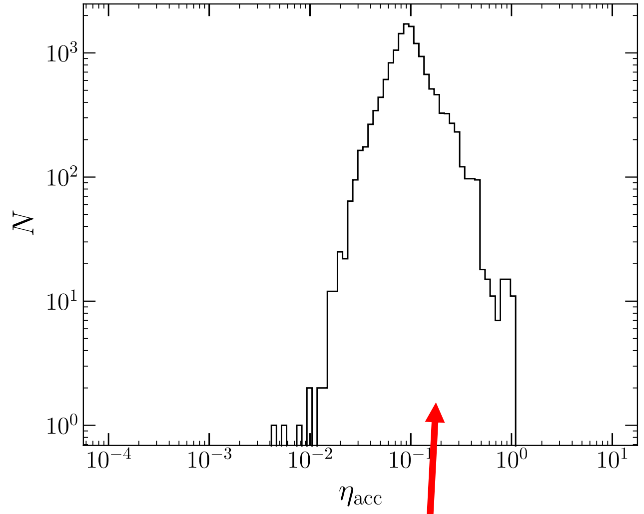


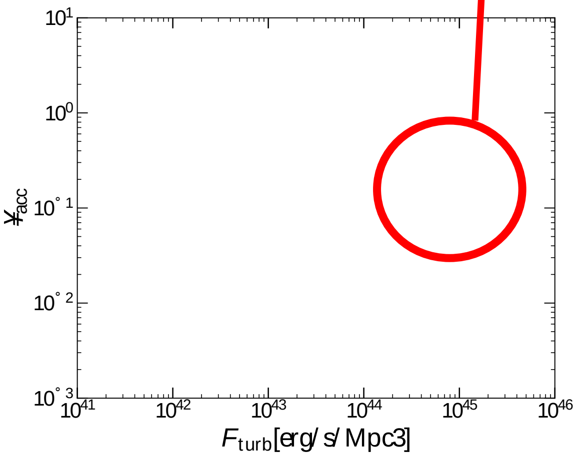
$\eta_{acc} \equiv \frac{\Delta\epsilon_e}{\epsilon_{turb}} \approx 0.05$

乱流エネルギーの~5%が宇宙線へ
“効率の良い”再加速が必要!

Energetics

加速効率 η_{acc}の分布





$$\eta_{acc} \equiv \frac{(\text{CRエネルギー増加率})}{(\text{乱流kinetic energy flux})}$$

*one zoneモデル: $\eta_{acc} = 0.09$

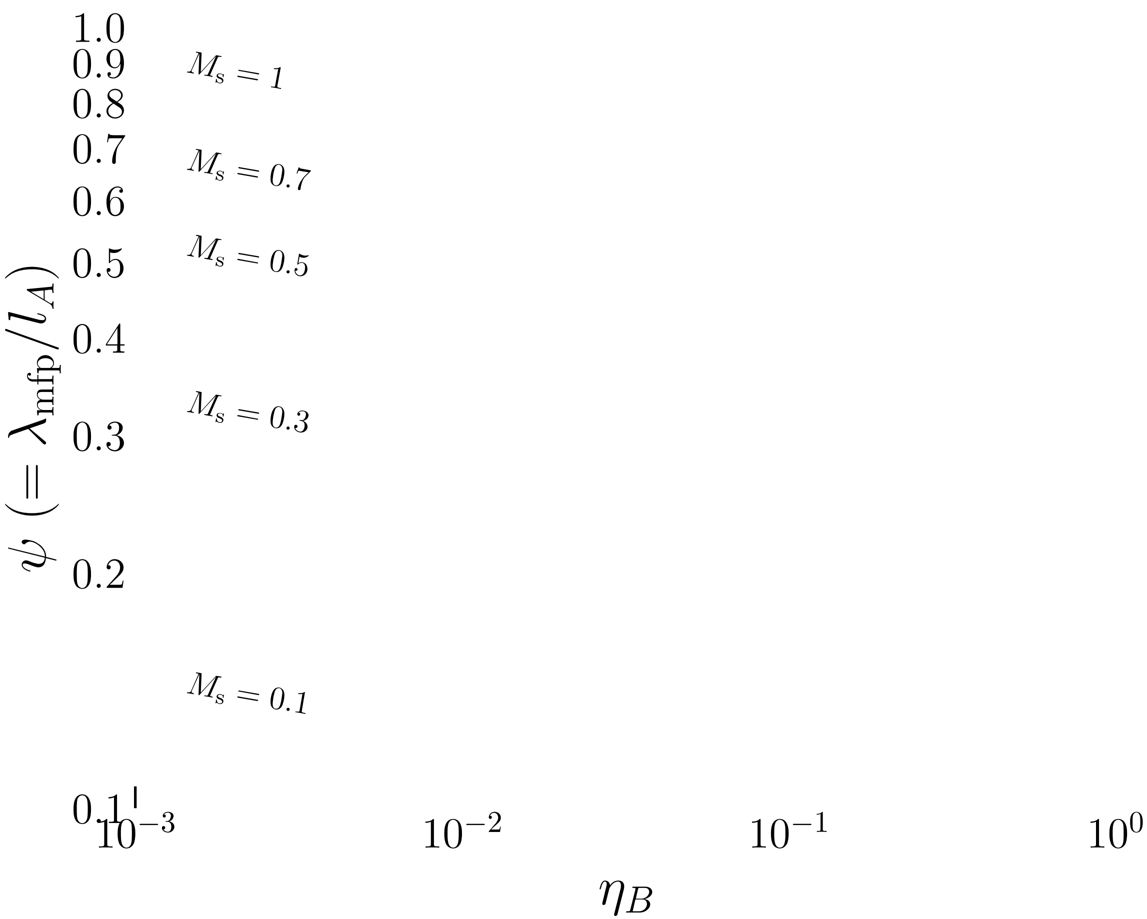
cellごとに計算すれば、一部の乱流が強い(ϵ_{turb}が大きい)領域で放射を稼ぐため、全体のηは小さくなると期待していた。

しかし、実際はone-zoneとあまり変わらなかった

乱流エネルギーの約10%が粒子加速に使われたら、放射を説明できる！
(圧縮性乱流では~100%が必要？)

ψ v.s. η_B

$\xi = 7$, $\nu_{obs} \approx 100$ MHz



MHD simulationで見られるsolenoidal乱流のMach数

$M_s \sim 0.3 - 0.5$

$\eta_B = 0.05$, $\psi \approx 0.3 - 0.5$

Alfven scale

~ (guiding center) mfp

Radio Halo(Brunetti&Lazarian2016)

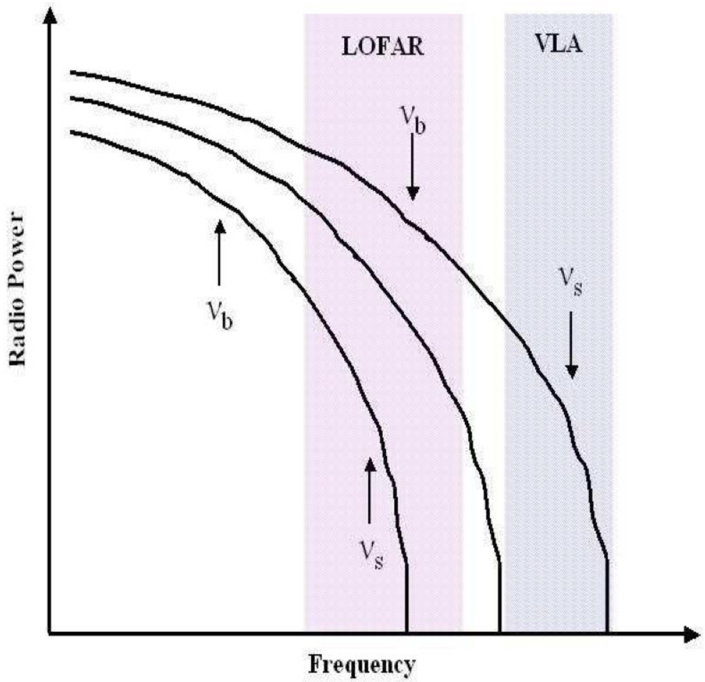
$\psi = 0.5$

Radio bridge (Brunetti&Vazza2020)

$\psi = 0.5$

Steepなべき指数とbreak frequency

Fokker-Planckを解かずに、**加速と冷却の釣り合い**から加速効率を議論する



[Cassano+18]

- break frequency ν_b
  加速効率 = 冷却効率

$$t_{cool}(\gamma, B) = \frac{6\pi m_e c}{\sigma_T} \frac{\gamma_b^{-1}}{B^2 + B_{cmb}^2}$$

$$t_{acc} = \frac{\sqrt{6/5}}{12} \frac{c}{c_s} \frac{L}{\sqrt{\beta_{pl}}} M_s^{-3} \psi^3$$

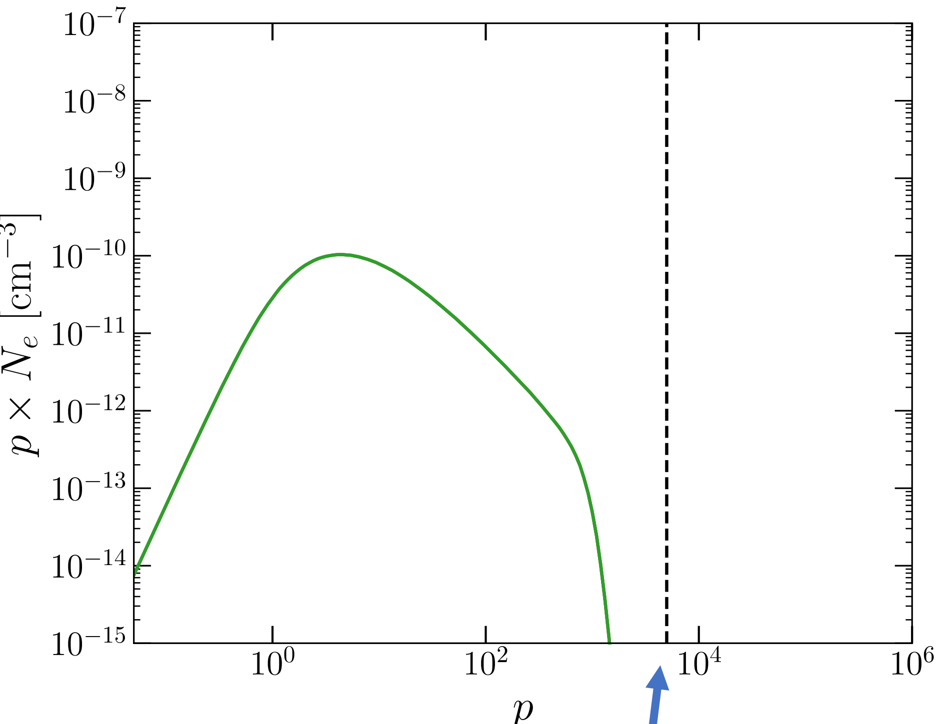
- steepening frequency ν_s
  スペクトルのべきが$\alpha \sim -1.5$ になる振動数

$$\nu_s = \xi \nu_b, \quad \xi \sim 5-7$$

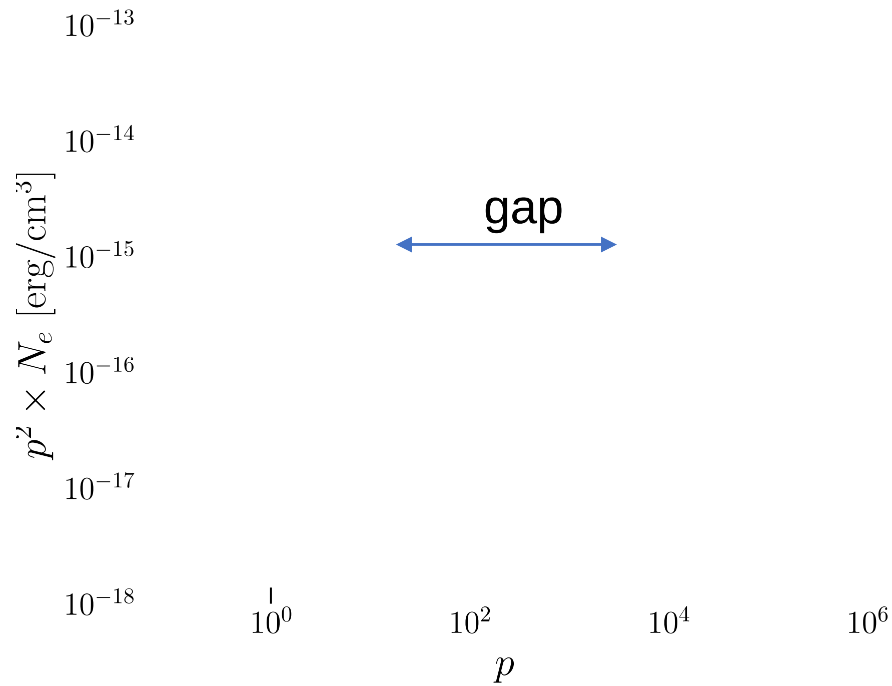
※pure-primary モデルでのみ正しい
※再加速の長さ(継続時間)に依存

End of cooling phase (2Gyr)

CR number spectrum



CR energy (“νF_ν”) spectrum

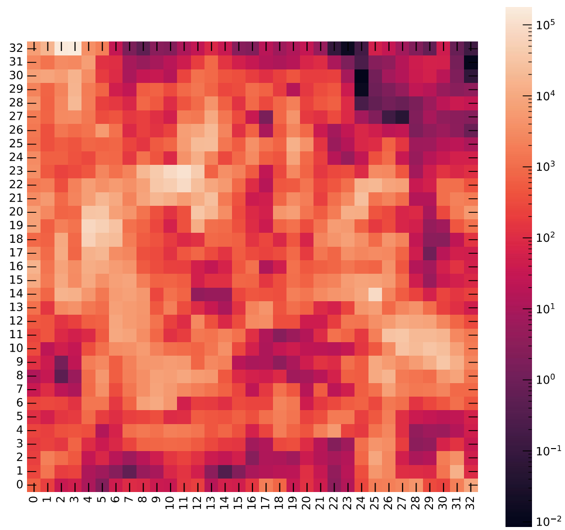


$\gamma_{min} \ll 10^3$!!!

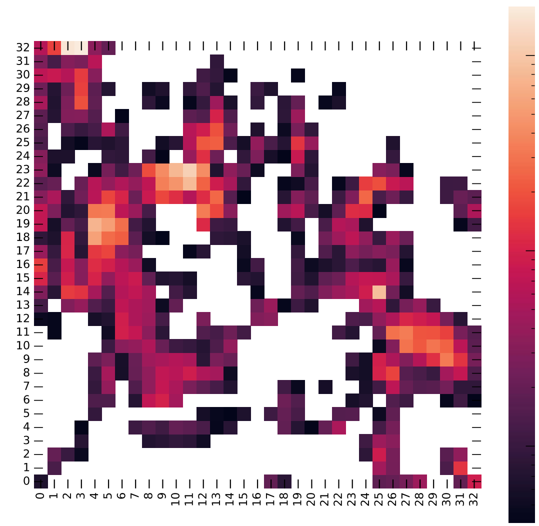
めっちゃ加速しないといけない

energy required for 100 MHz emission in $B \sim 0.2\mu\text{G}$

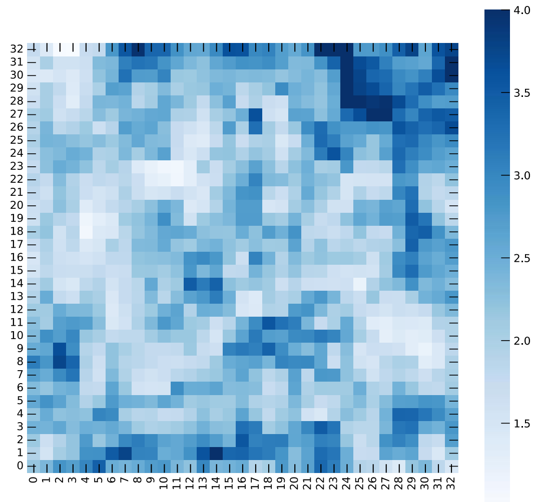
145 MHz intensity

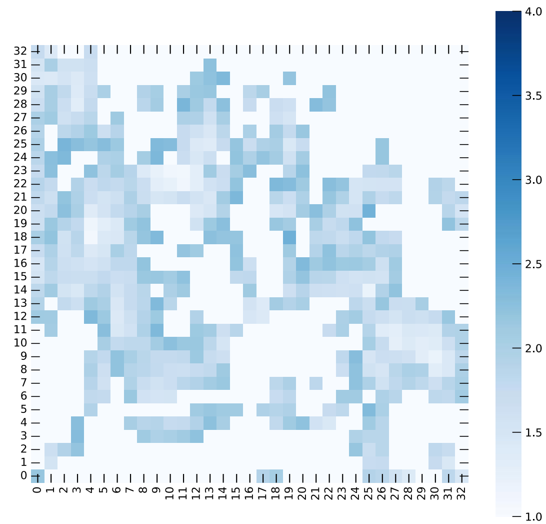


LOFAR感度を考慮



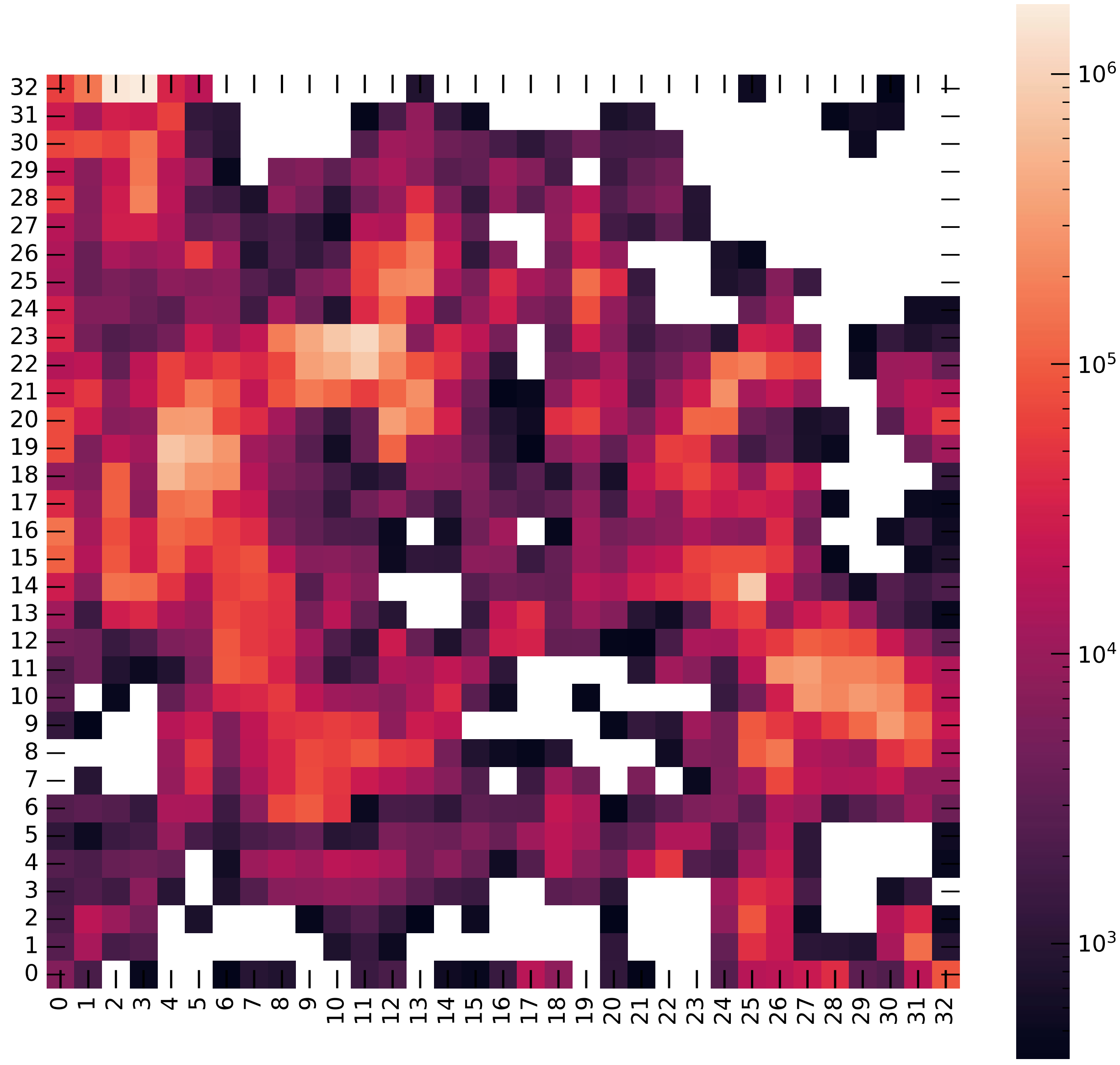
Spectral index





softで暗い放射は受からない

→ **indexの統計は感度に依存！**



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