TIM LINDEN

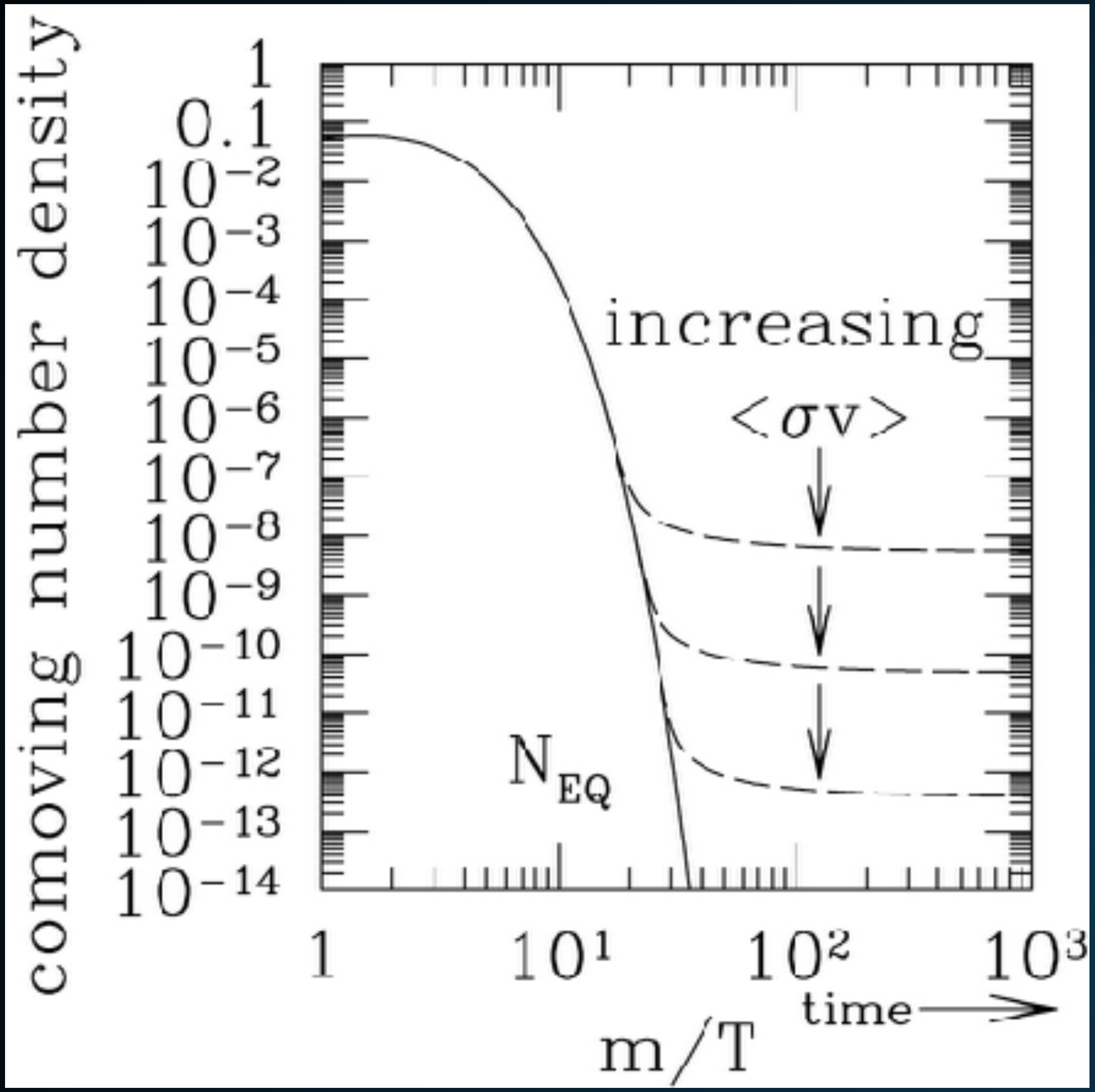
DARK MATTER, ALFVEN REACCELERATION AND THE ARCADE-II EXCESS

Radio Synchrotron Background Workshop

July 19, 2017

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

DARK MATTER ANNIHILATION AS A SOURCE



- **A dark matter particle with:**
  - **Weak Mass scale (~100 GeV)**
  - **Weak interactions**

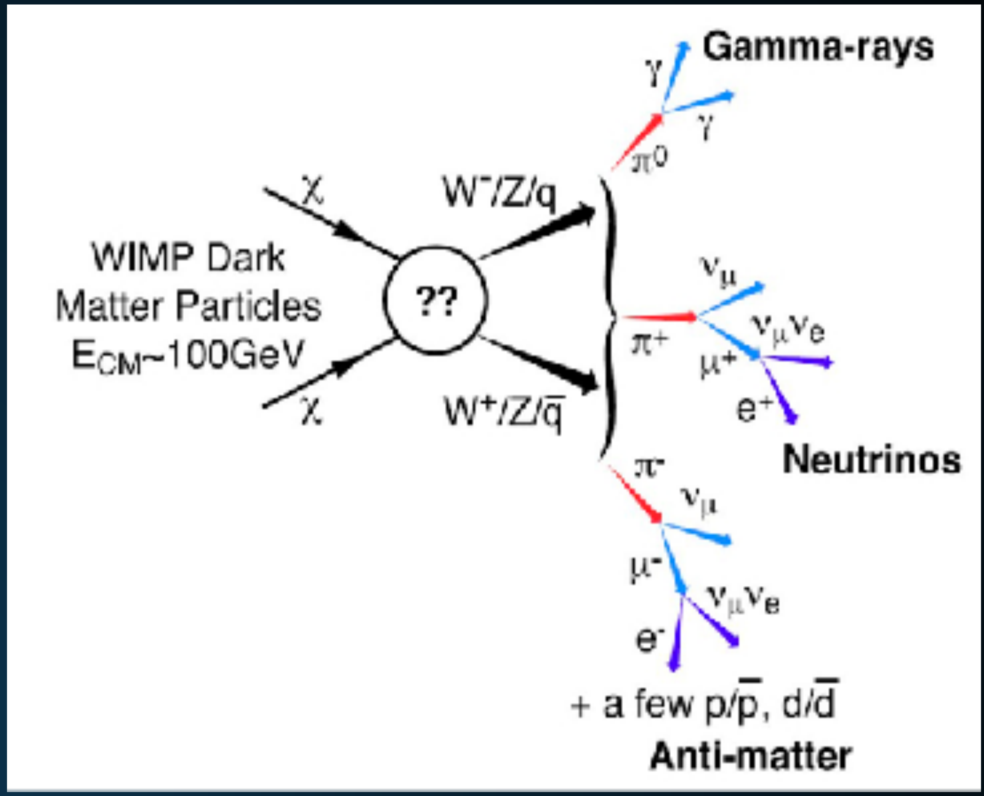
Will naturally achieve the observed relic abundance in the universe today.

$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{\text{f.o.}}}{20}\left(\frac{10^{-8}\ \text{GeV}^{-2}}{\sigma}\right)$$

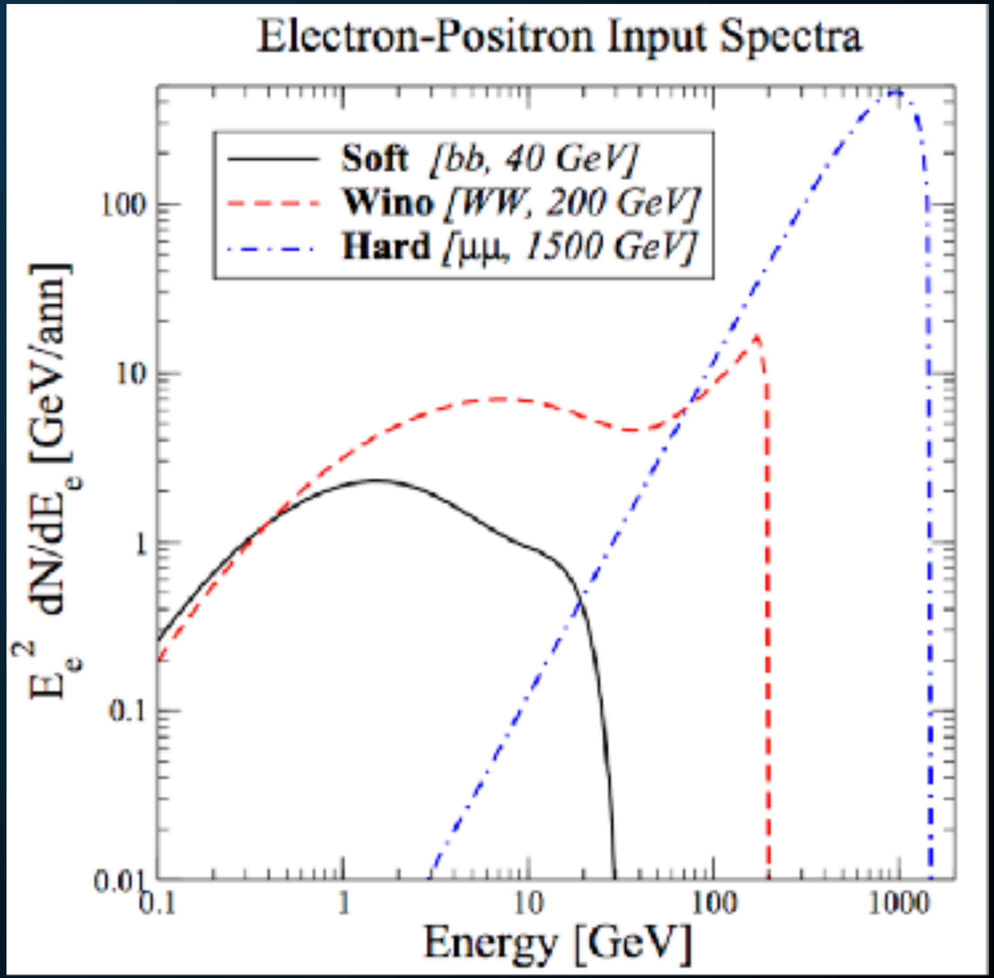
$$\langle\sigma v\rangle \sim 10^{-8}\ \text{GeV}^{-2}\left(3\times10^{-28}\ \text{GeV}^2\ \text{cm}^2\right)\ 10^{10}\ \frac{\text{cm}}{\text{s}} = 3\times10^{-26}\ \frac{\text{cm}^3}{\text{s}}$$

DARK MATTER ANNIHILATION AS A SOURCE

- These interactions don't stop entirely when dark matter freezes out.



- Annihilations of WIMP dark matter would still produce standard model particles at GeV energies today.

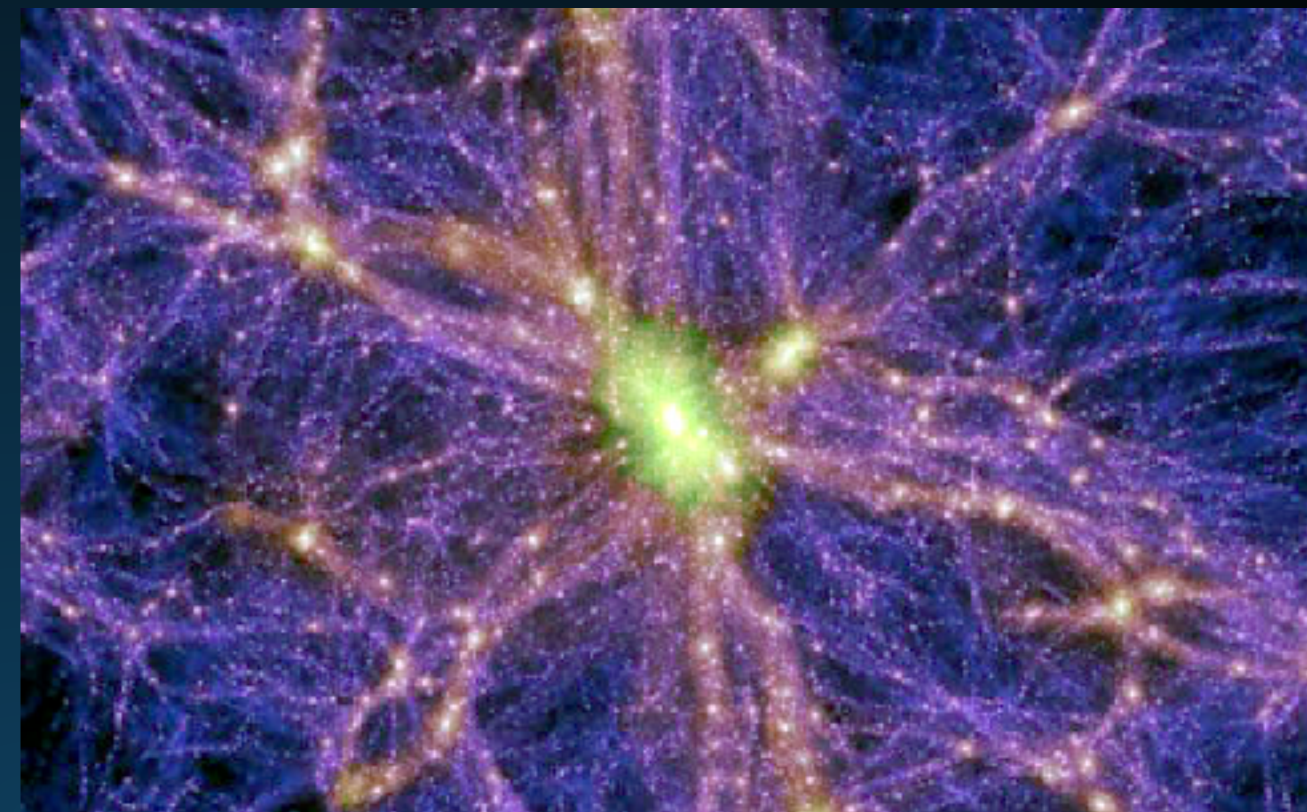


- Some electrons are produced for almost every dark matter annihilation channel.

DARK MATTER ANNIHILATION AS A SOURCE

Neto (2005)

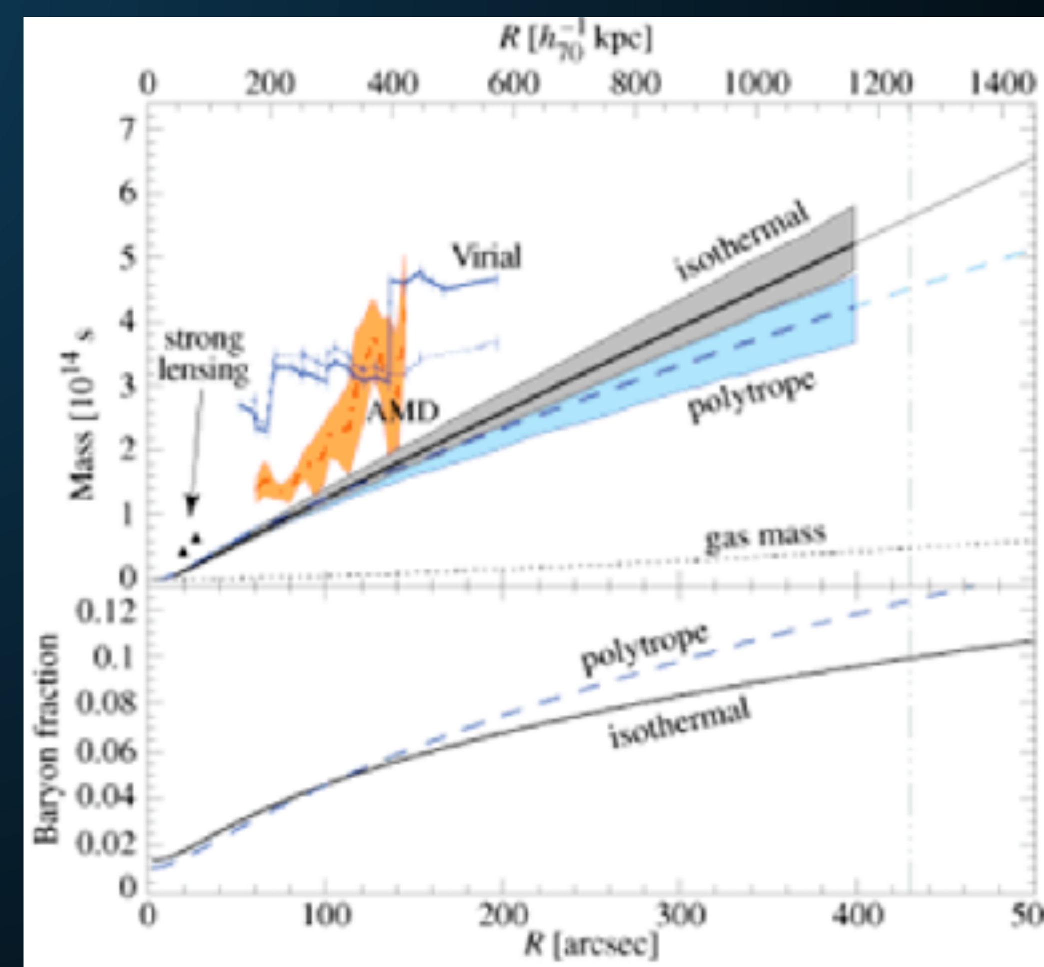
- The "source" of dark matter annihilation on the sky corresponds to the integral of the dark matter density over the line of sight squared.

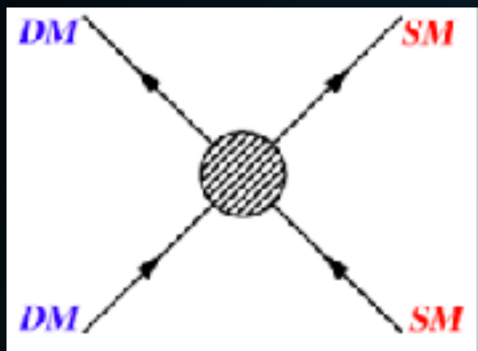


$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\mathrm{DM}}^2}\int_{E_{\min}}^{E_{\max}}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\Phi_{\mathrm{PP}}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\mathrm{l.o.s.}}\rho^2(\boldsymbol{r})\mathrm{d}l\right\}\mathrm{d}\Omega'}_{\text{J-factor}}$$

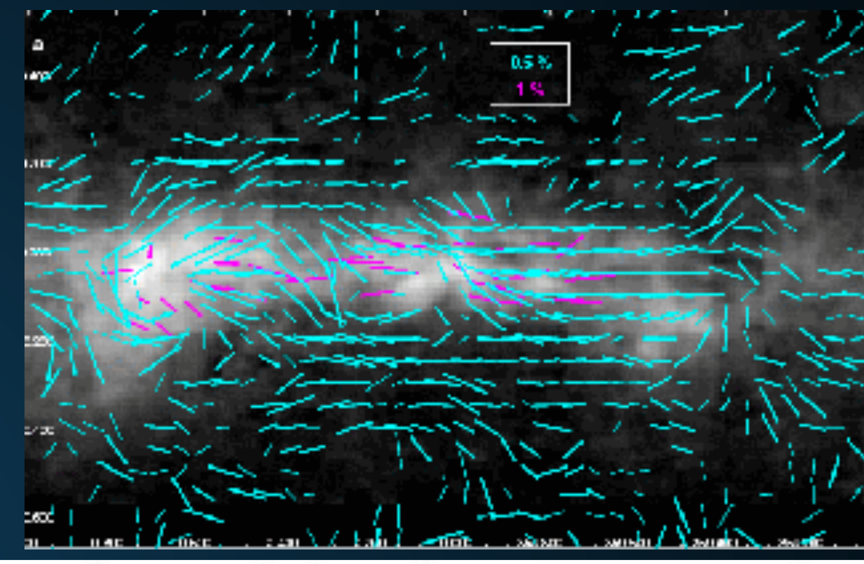
Particle Physics   Astrophysics

- Dark matter halos from large objects (e.g. clusters) can extend for Mpc.





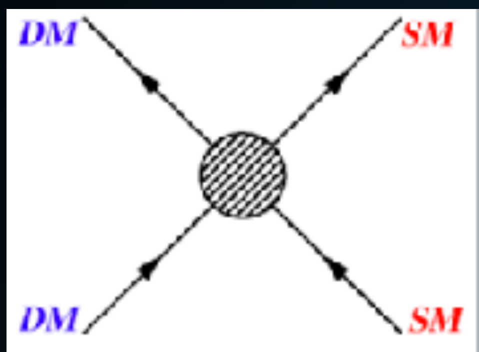
Electrons produced in the dark matter annihilation event



electrons propagate

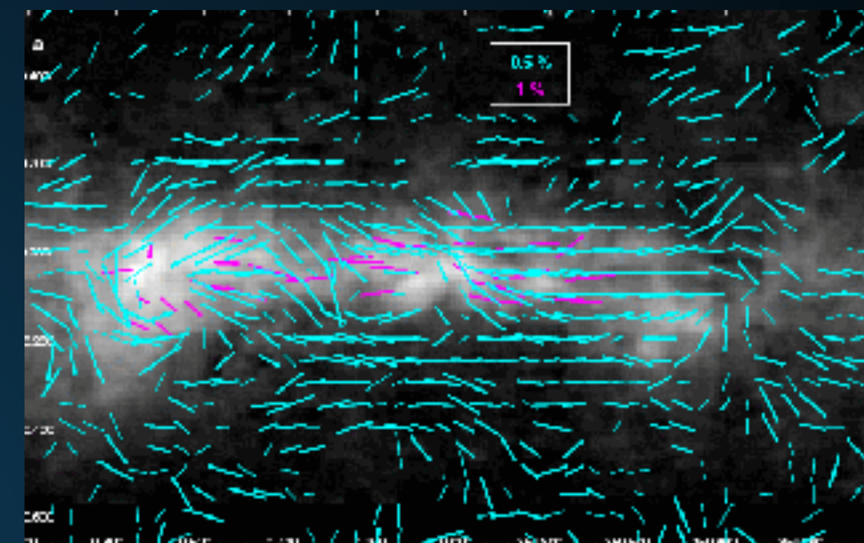
$$\frac{\partial\psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Solved Numerically:
e.g. Galprop



Electrons produced in the dark matter annihilation event

electrons propagate



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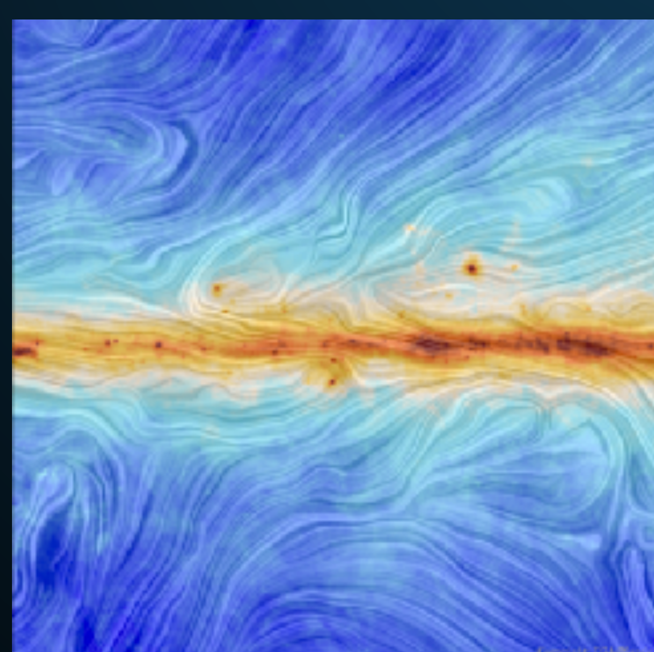
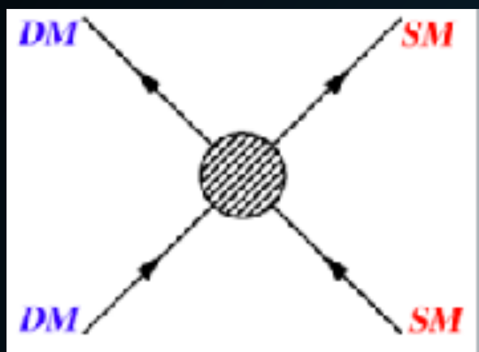
Solved Numerically:
e.g. Galprop

Magnetic field

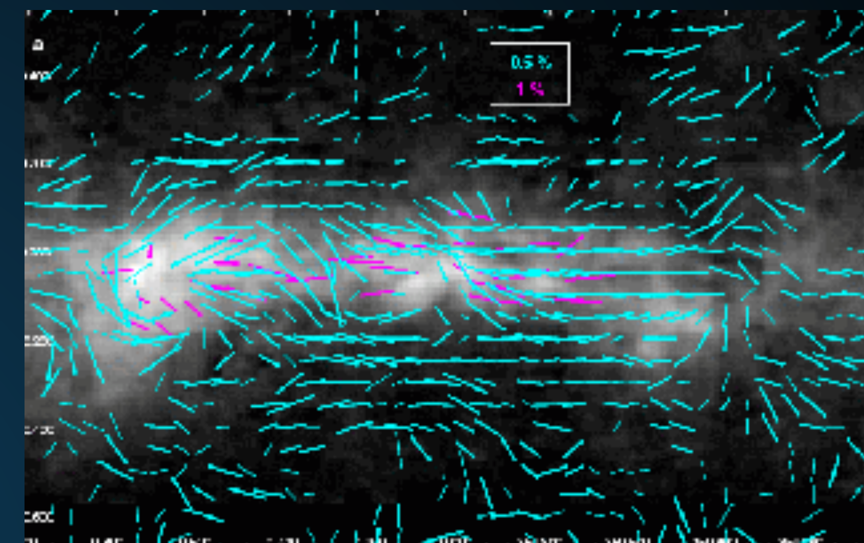


- **Electrons can interact with gas, ISRF, or magnetic fields, producing gamma-rays or radio emission.**

ELECTRON PRODUCTION AND PROPAGATION



Electrons produced in the dark matter annihilation event

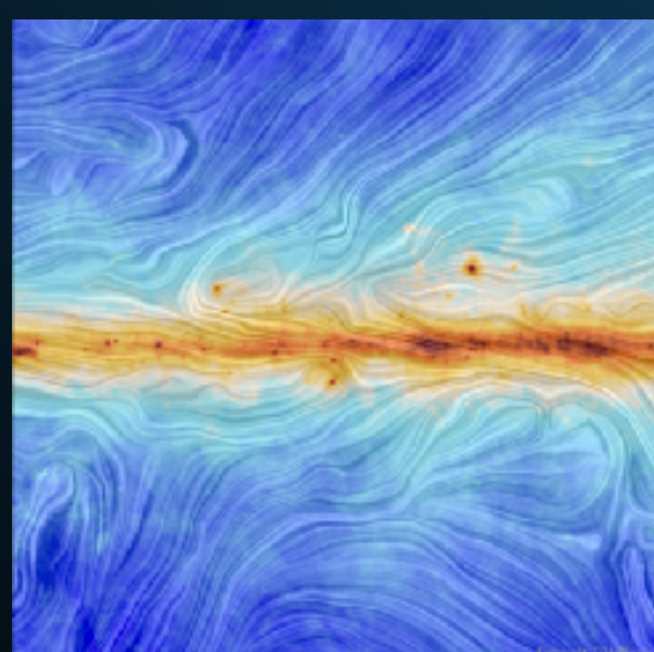


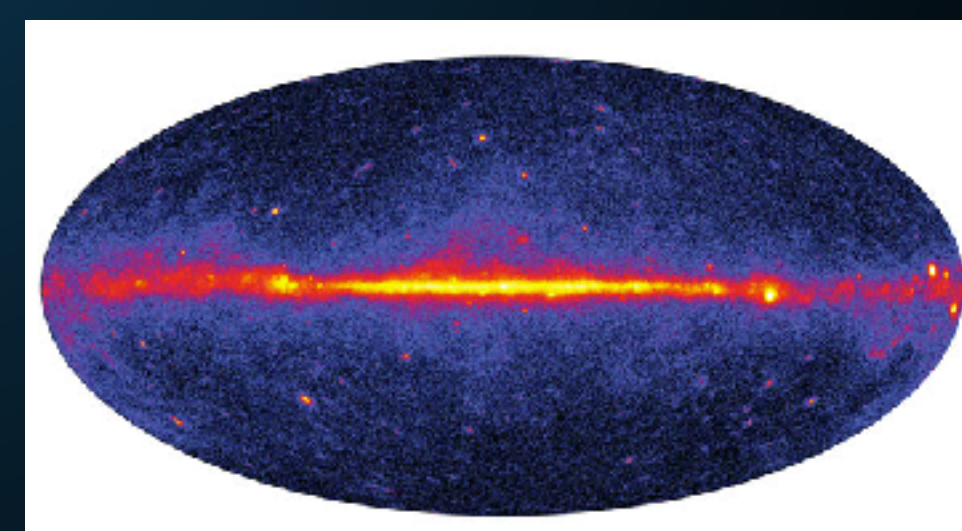
electrons propagate

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

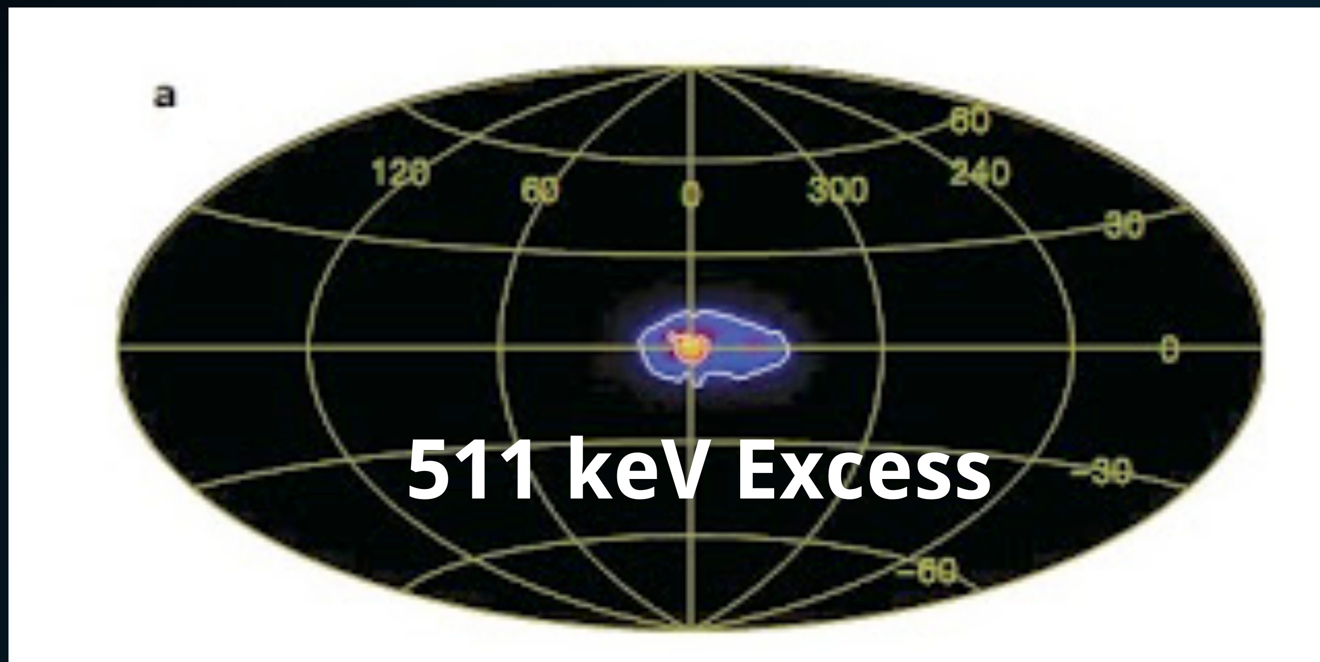
Solved Numerically:
e.g. Galprop

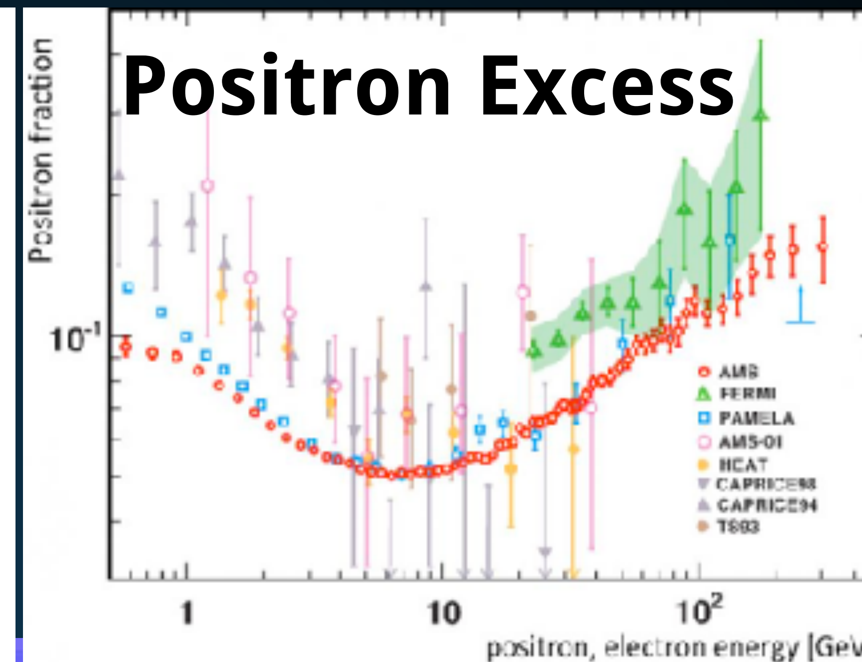
Magnetic field

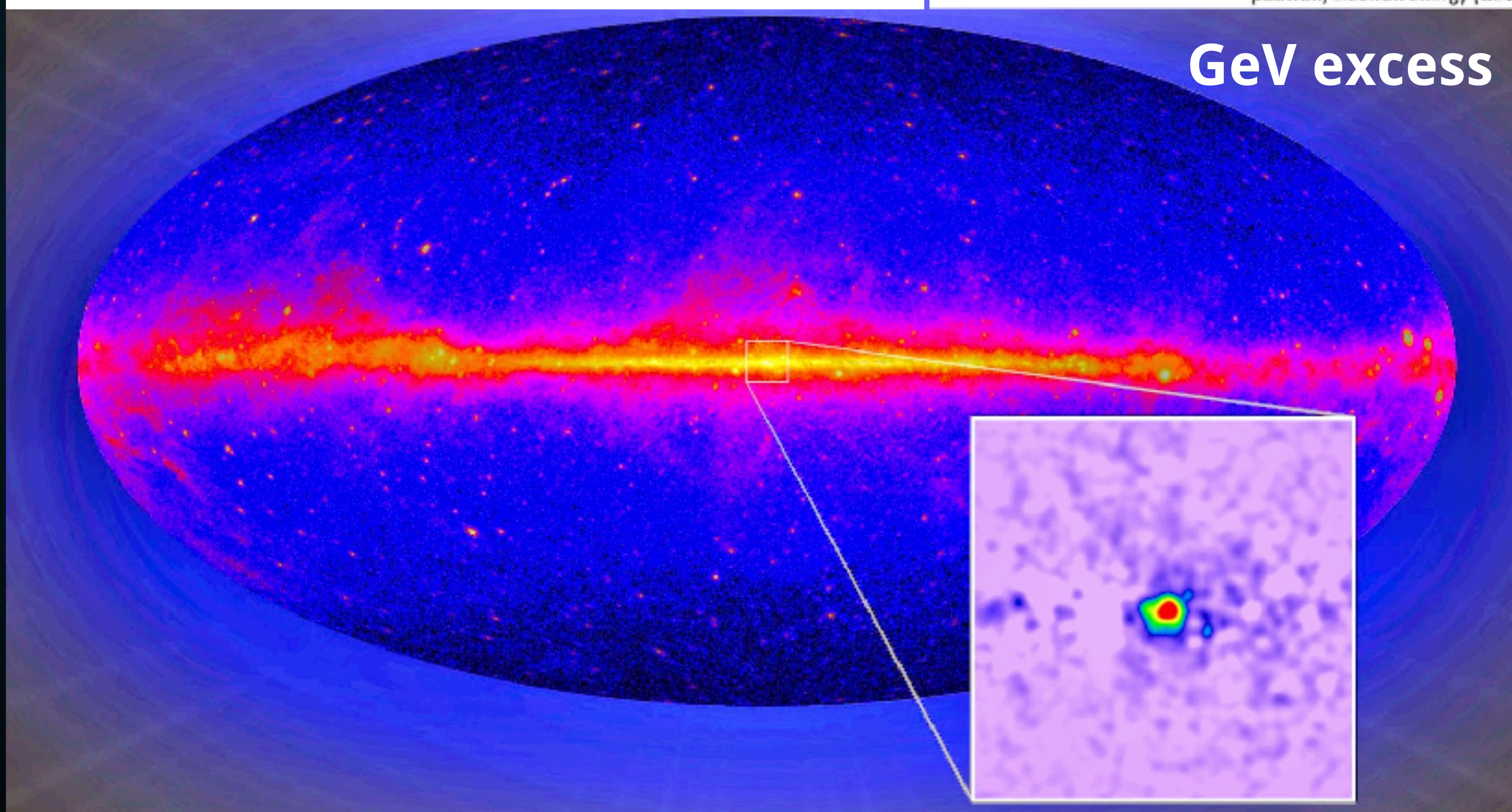




DARK MATTER ANNIHILATION AS A SOURCE







INTEGRATING DARK MATTER ANNIHILATION OVER COSMOLOGICAL DISTANCES

- As mentioned, we want total annihilation rate over line of sight:

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r}){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}}$$

  - Over cosmological redshifts, the total dark matter density changes:

$$R(z) = \int \frac{dn}{dM}(M,z)(1+z)^3 dM \frac{\sigma v}{2m_{\rm DM}^2}\int \rho^2(\vec{x},M,z)dV, \quad (1)$$

  - The morphology is set by the (z-dependent) DM density and B-field models:

$$\rho(r) \propto \frac{1}{(r/R_s)^\gamma(1+r/R_s)^{3-\gamma}},$$

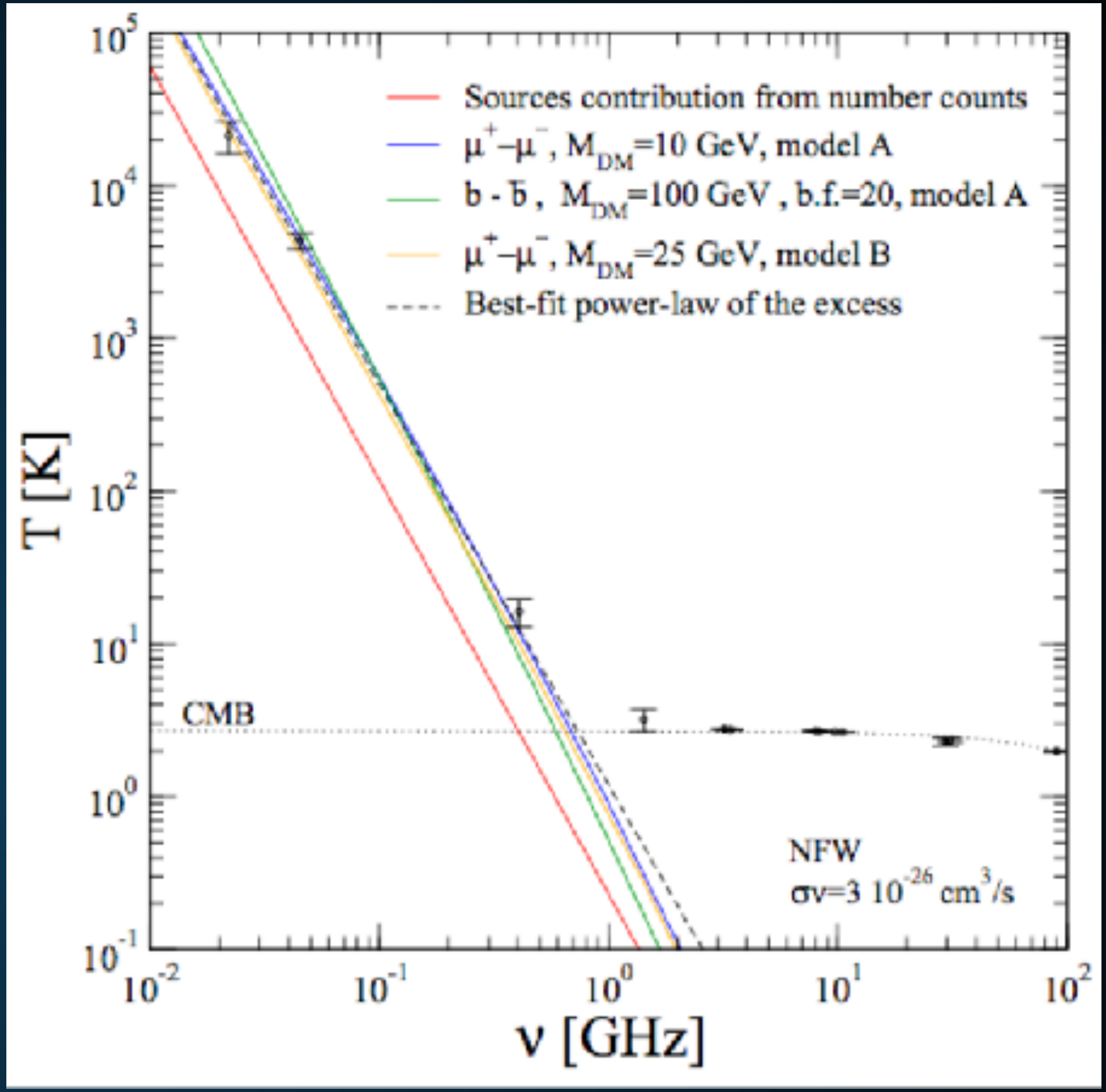
$$B(r) = B_0\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-3\beta\eta/2},$$

- This makes the total synchrotron contribution over redshift:

$$\frac{d\phi_{\rm syn}}{dE_{\rm syn}} = \frac{\sigma v}{8\pi}\frac{c}{H_0}\frac{\bar{\rho}_{\rm DM}^2}{m_{\rm DM}^2}\int dz(1+z)^3\frac{\Delta^2(z)}{h(z)}\frac{dN_{\rm syn}}{dE_{\rm syn}}(E_{\rm syn,0}(1+z)), \quad (5)$$

Fornengo et al. (2012; 1108.0569)

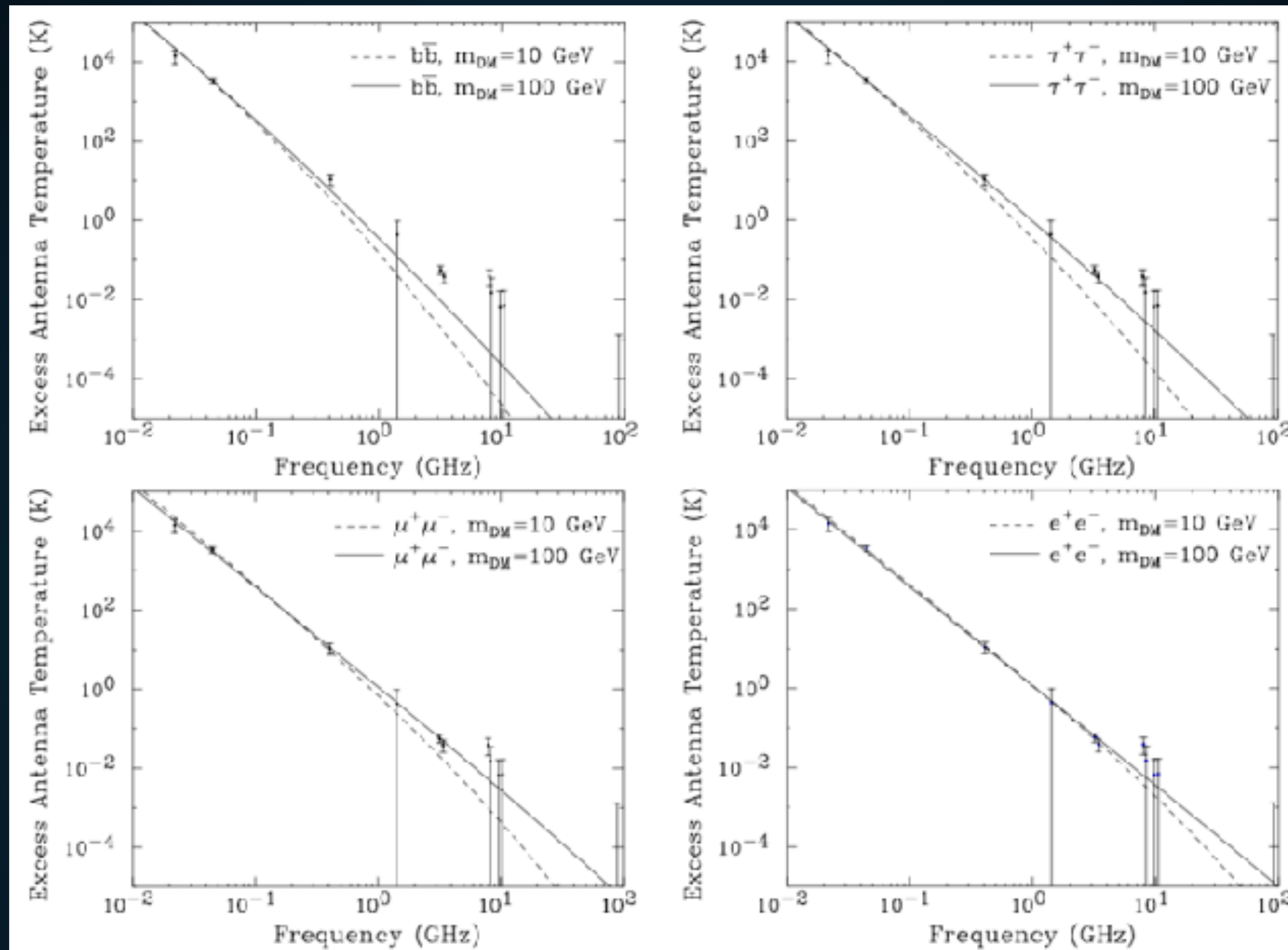
- The total sum of all of these contributions can reasonably produce the ARCADE-II excess.
- Spectrum is governed primarily by DM mass and annihilation channel.



- Amplitude governed by DM annihilation rate, magnetic field energy density, DM substructure model, etc.
- However, DM models are generally in the right ballpark.

DARK MATTER ANNIHILATION AS A SOURCE

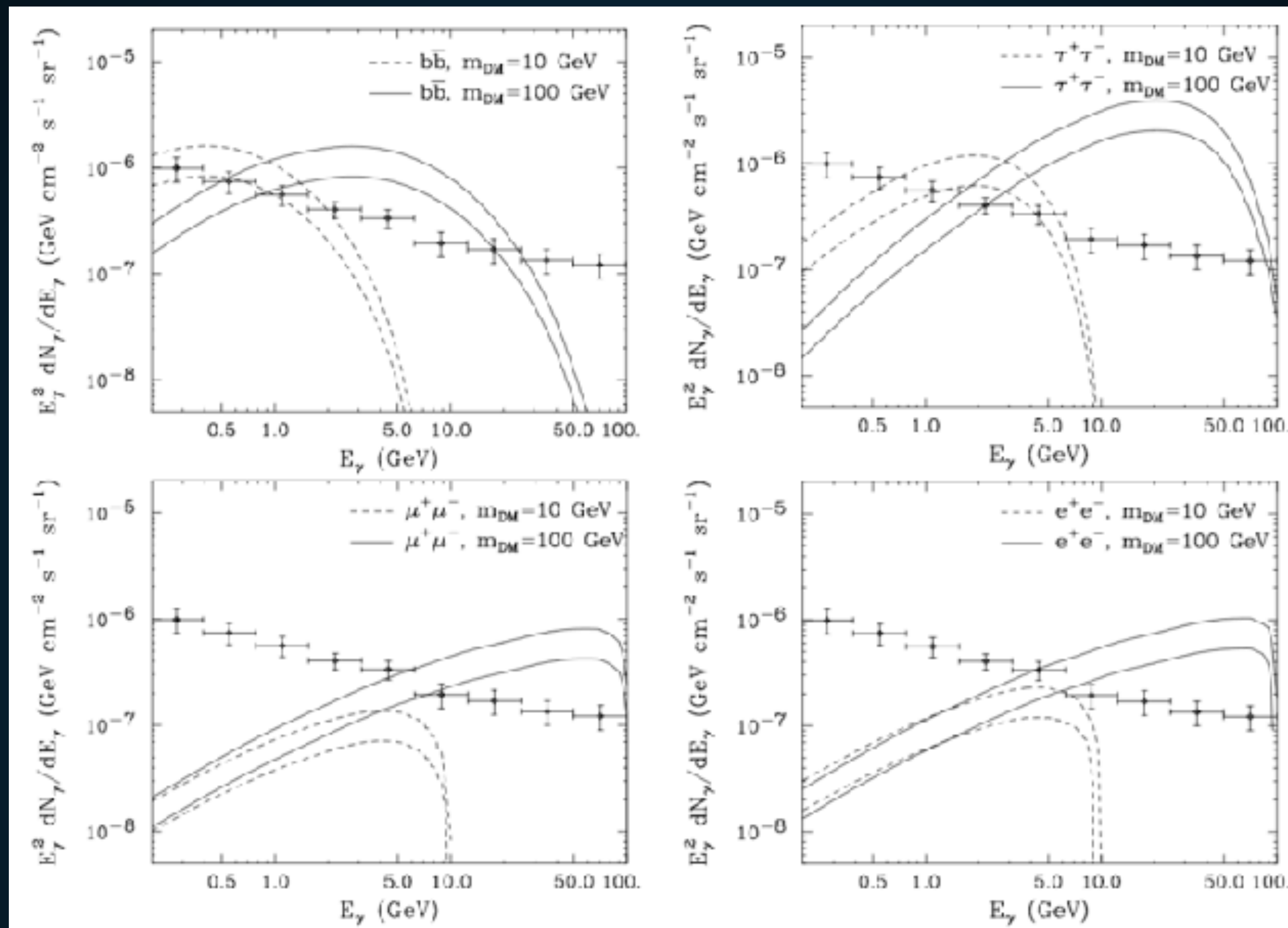
Hooper et al. (2012; 1203.3547)



- **Models with harder initial electron spectra (e.g. direct annihilation to e^+e^-) produce a better spectral fit to the data.**
- **Similar to models motivated by the positron excess.**

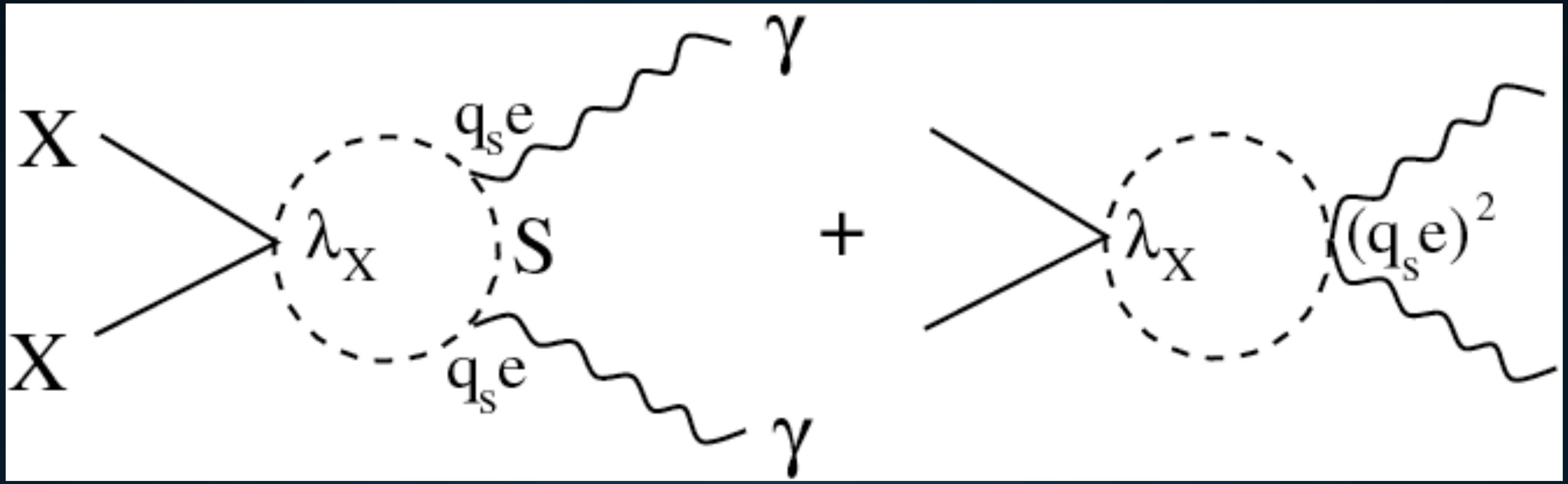
PROBLEM I: GAMMA-RAYS

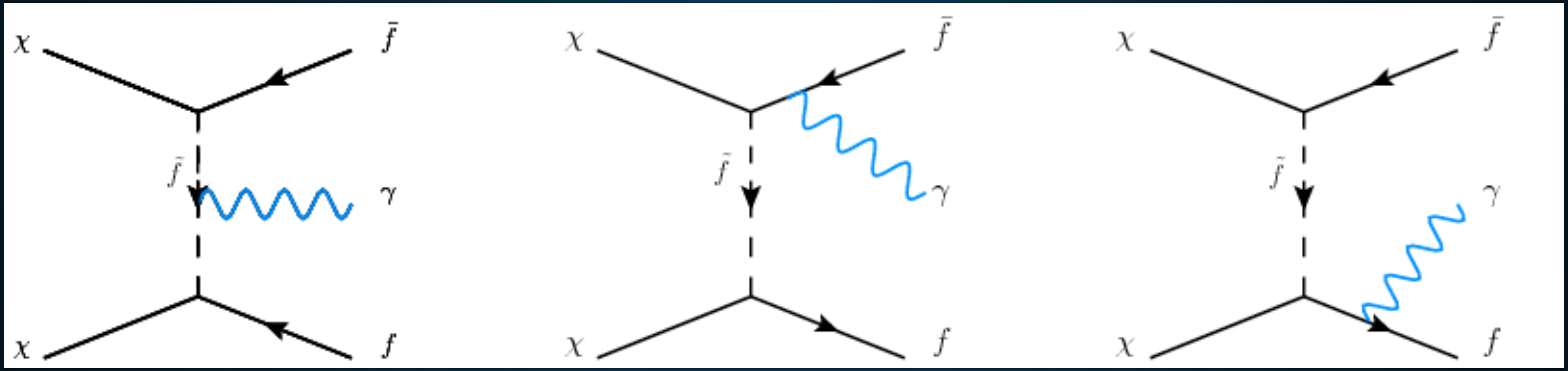
Hooper et al. (2012; 1203.3547)



- However, this emission also produces ICS in the gamma-ray band.
- This tends to exceed limits from the Fermi-LAT isotropic gamma-ray background.

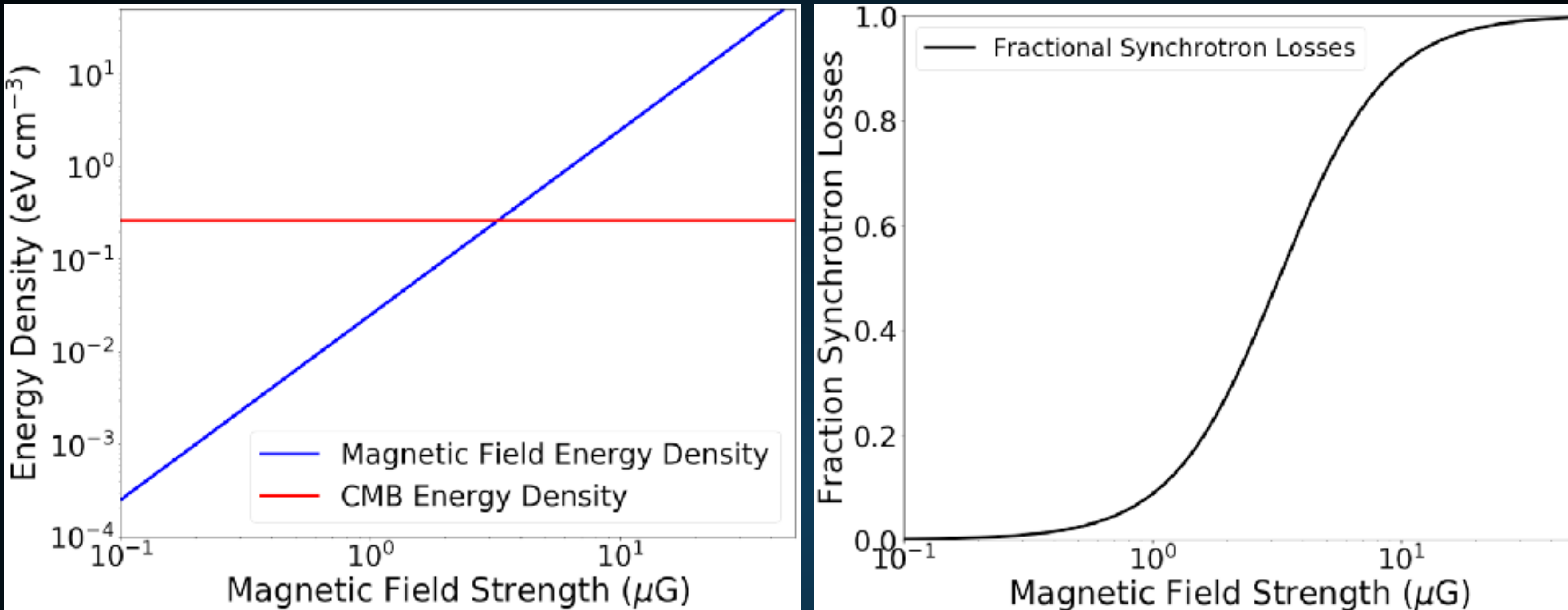
PROBLEM I: GAMMA-RAYS





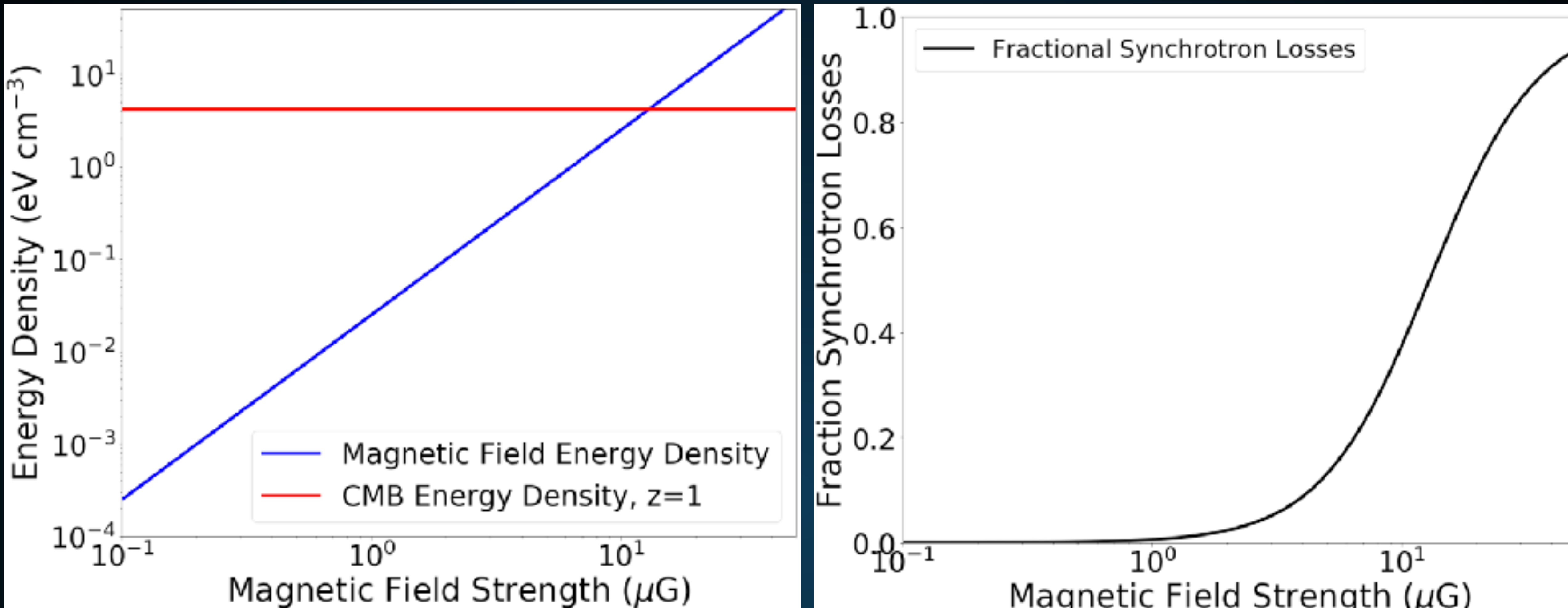
- **Part of this is inevitable from particle physics - any dark matter particle that annihilates to e^+e^-, can produce gamma-rays via loop diagrams or final state radiation.**

PROBLEM I: GAMMA-RAYS



- **More importantly, there is an inevitable contribution from the inverse-Compton scattering of the CMB.**
- **Far from galaxies, the CMB energy density should dominate the magnetic field energy density.**

SOURCES SHOULD BE SMALL AND CLUMPY



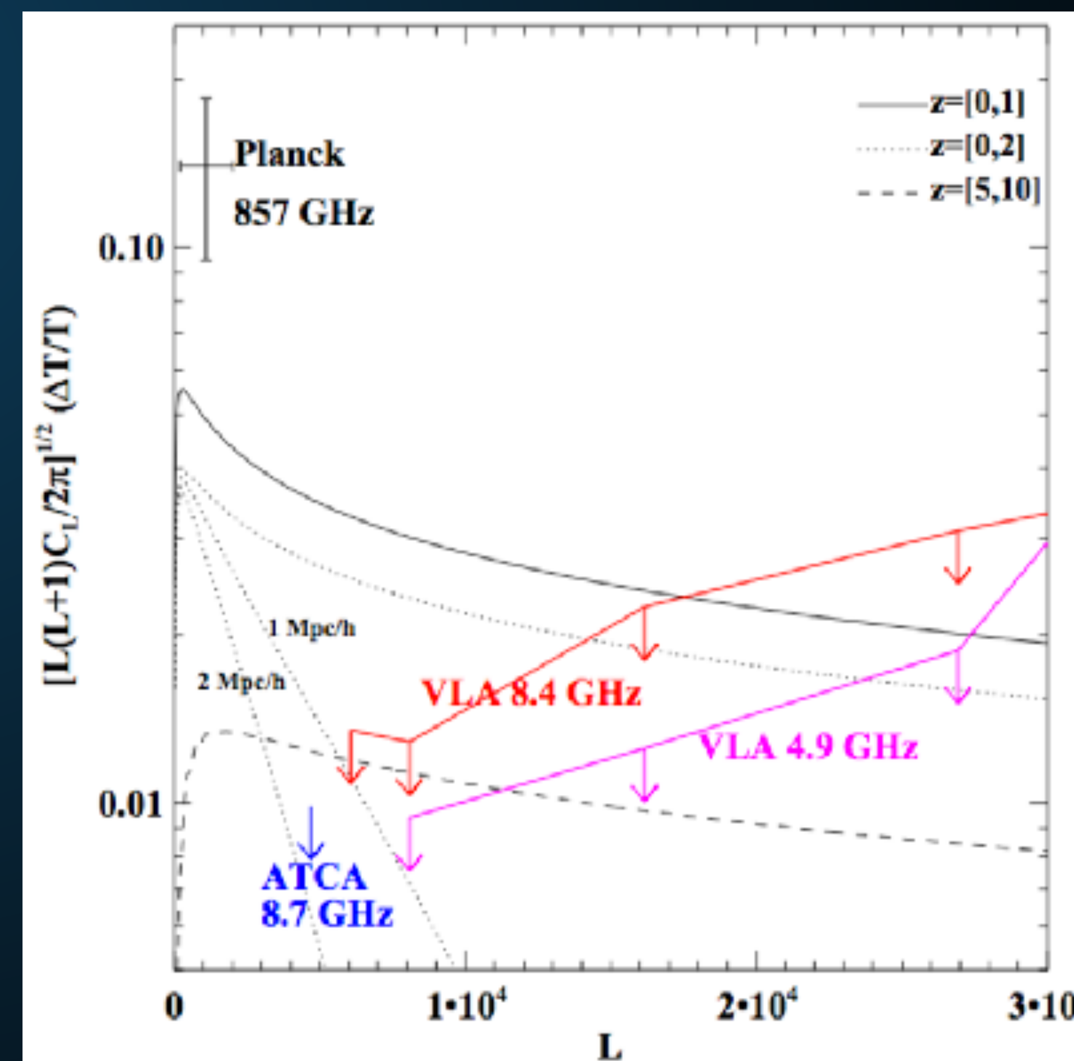
- **This is more true at high-redshift: $(1+z)^4$.**
- **<u>This is a generic problem for any model of the ARCADE-II excess. The synchrotron emission should be generated inside the cores of dense sources.</u>**

PROBLEM II: SOURCES CAN'T BE CLUMPY

Holder (2012; 1207.0856)

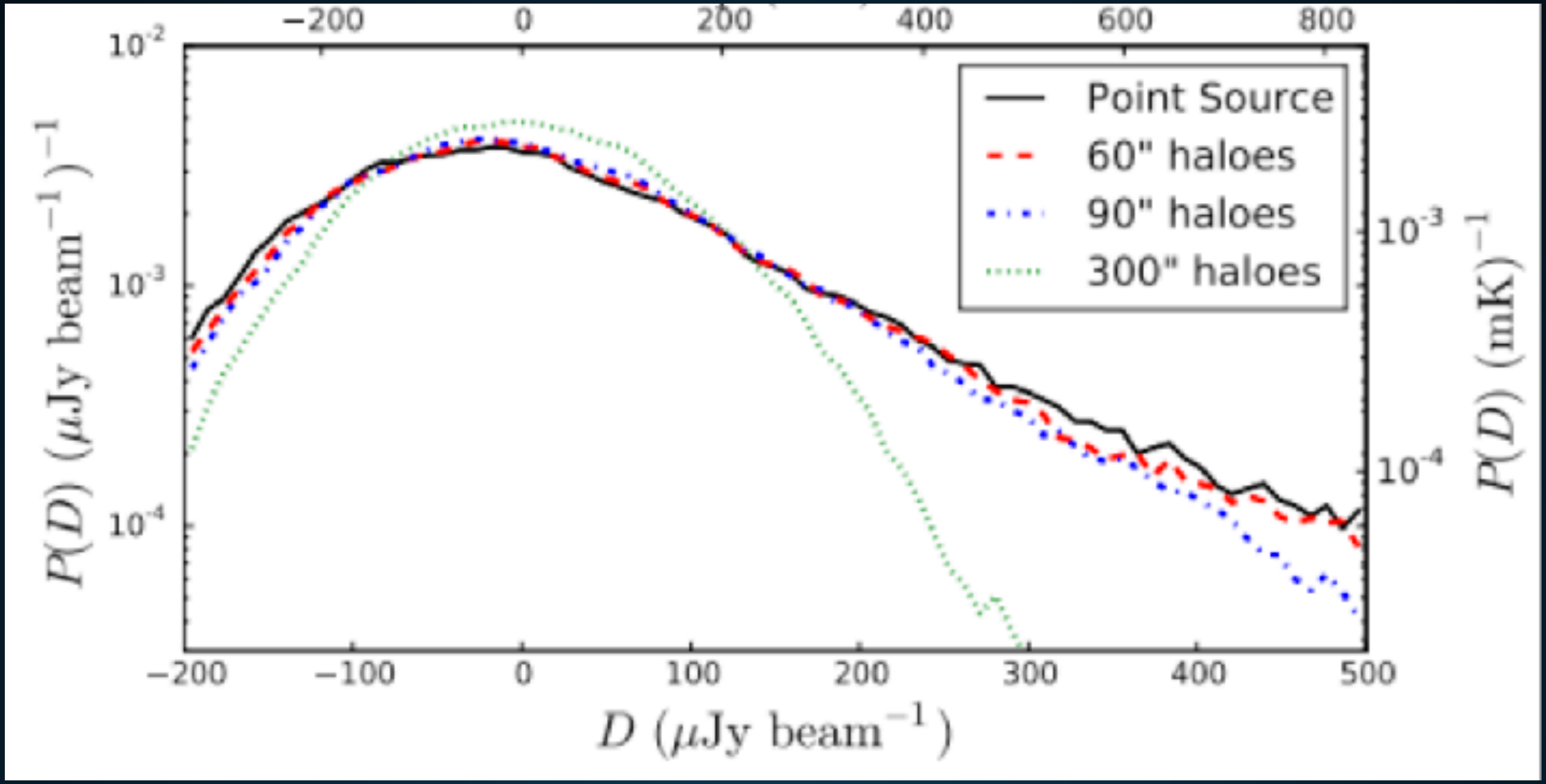
- **Observations of radio anisotropies (primarily at higher frequencies) tell us the ARCADE-II excess component is incredibly smooth.**
- **Even smoother than large-scale structure.**
- **<u>This challenges most models of the ARCADE-II excess.</u>**

Frequency	$\theta('')$	95% confidence upper limits		
		dT/T_{cmb}	dT/T_{arcade}	dT/T_{excess}
4.86 GHz Fomalont et al (1988)	12	8.5×10^{-4}	0.11	0.13
	18	1.2×10^{-4}	0.016	0.019
	30	8×10^{-5}	0.011	0.013
	60	6×10^{-5}	0.008	0.009
8.4 GHz Partridge et al (1997)	6	1.3×10^{-4}	0.070	0.082
	10	7.9×10^{-5}	0.043	0.051
	18	4.8×10^{-5}	0.026	0.031
	30	3.5×10^{-5}	0.019	0.023
	60	2.0×10^{-5}	0.011	0.013
	80	2.1×10^{-5}	0.011	0.014
8.7 GHz Subrahmanyan et al (2000)	120	1.4×10^{-5}	0.0084	0.0099



PROBLEM II: SOURCES CAN'T BE CLUMPY

Vernstrom et al. (2014; 1408.4160)



- Additionally, most of the emission can't be from individual sources smaller than 2′ on the sky.
- This observation again challenges most models where the ARCADE-II excess correlates to sources.

GO EARLY OR GO BIG

Holder (2012; 1207.0856)

- Two ways around this constraint:
  - Produce the excess in the early universe, where density perturbations are small.
  - Produce the excess from objects larger than the (~2′) sensitivity of radio observations.
- Both solutions are possible in dark matter model building.

Frequency	$\theta('')$	95% confidence upper limits		
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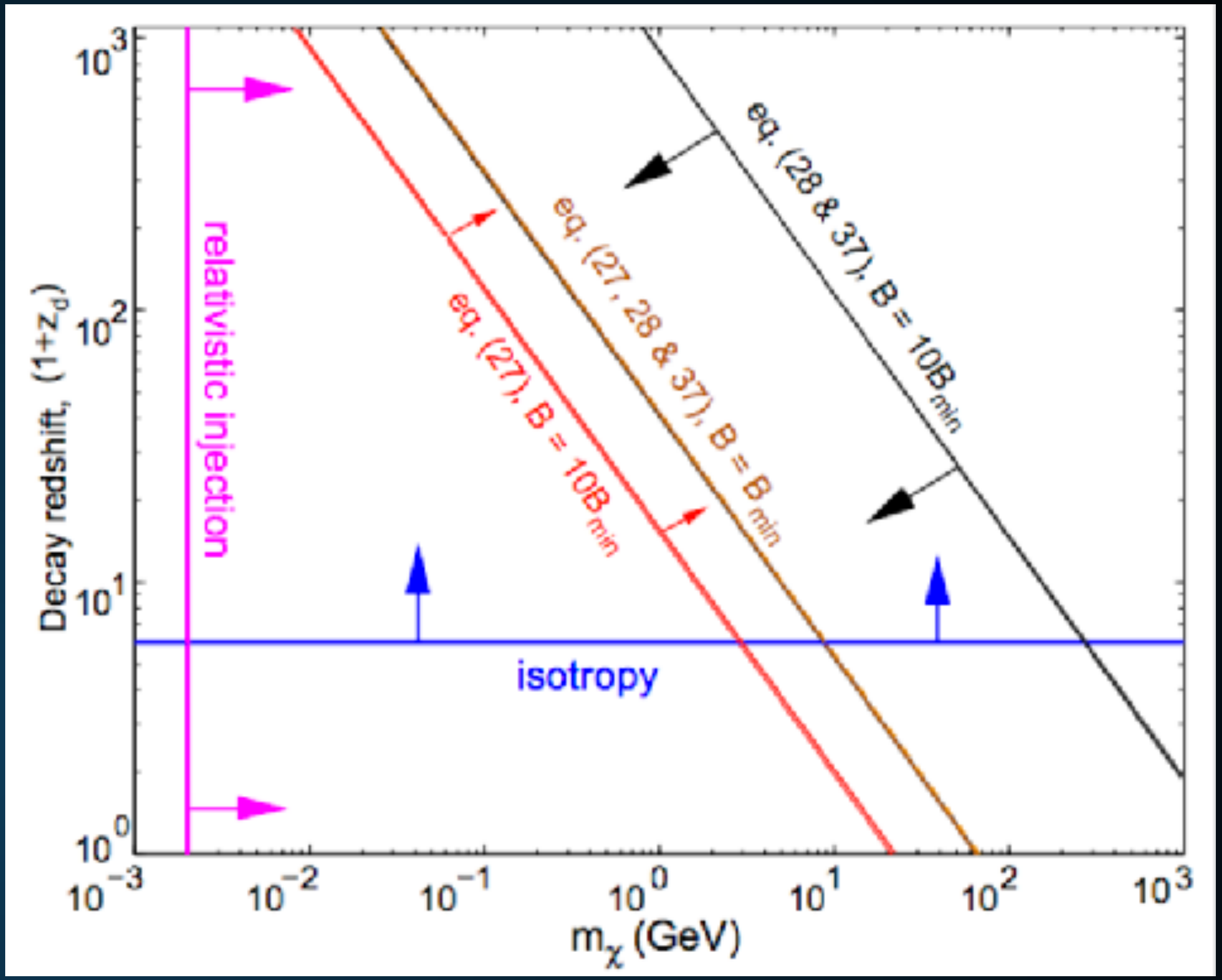
Cline & Vincent (2013; 1210.2717)

- Can consider the possibility of dark matter decays.
  - Can preferentially occur in the early universe (z > 5).
  - Occur with even lower anisotropy, because they trace the DM density.



- Personal Opinion: Models such as this are somewhat finely tuned - e.g. the decay rates are not predicted by any WIMP miracle.

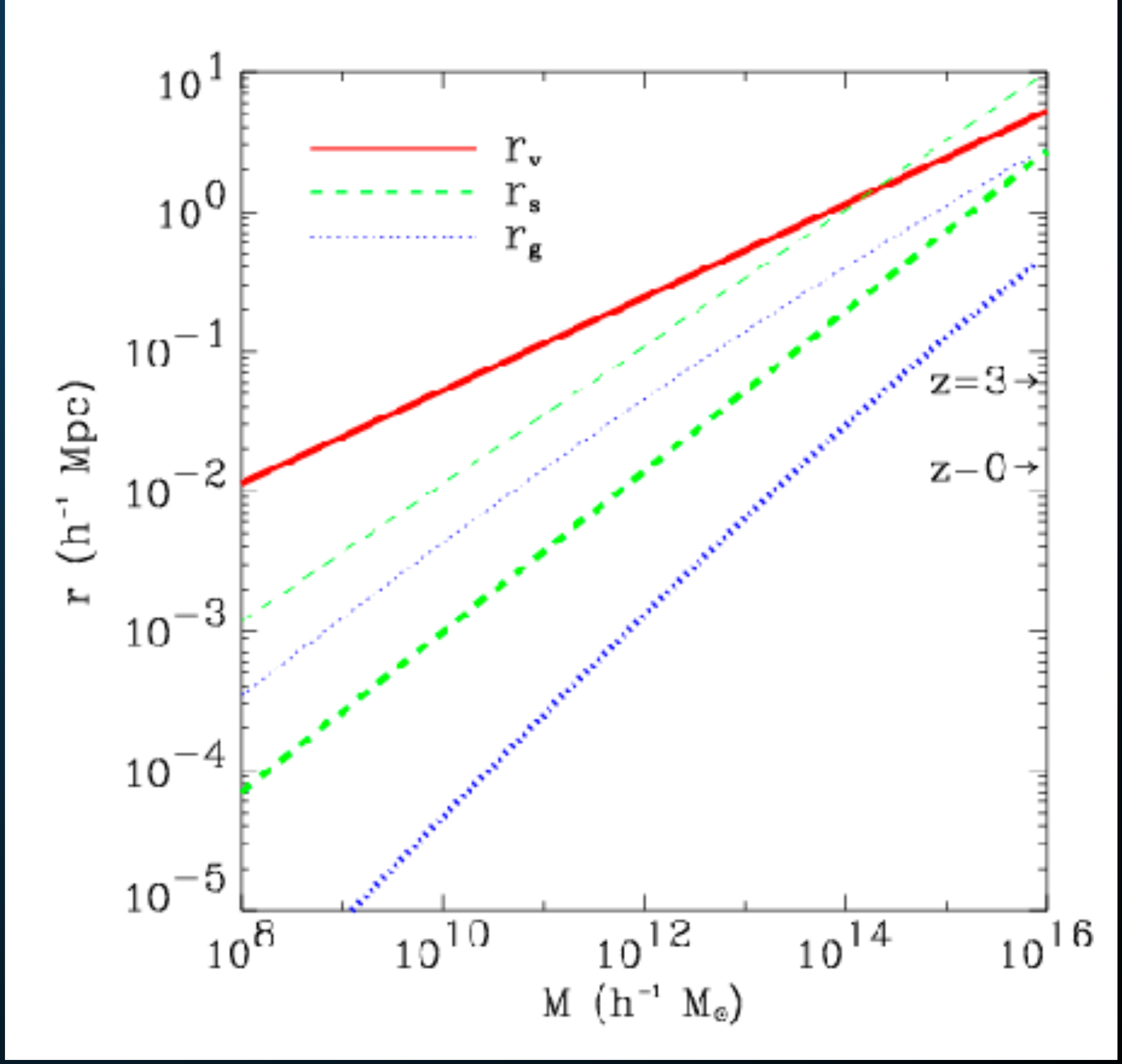
GOING BIG

The rest of the talk will focus on methods to make the emission sources larger than the ROI of radio constraints.

CAN DARK MATTER FIT THE EXCESS BETTER THAN BARYONS?

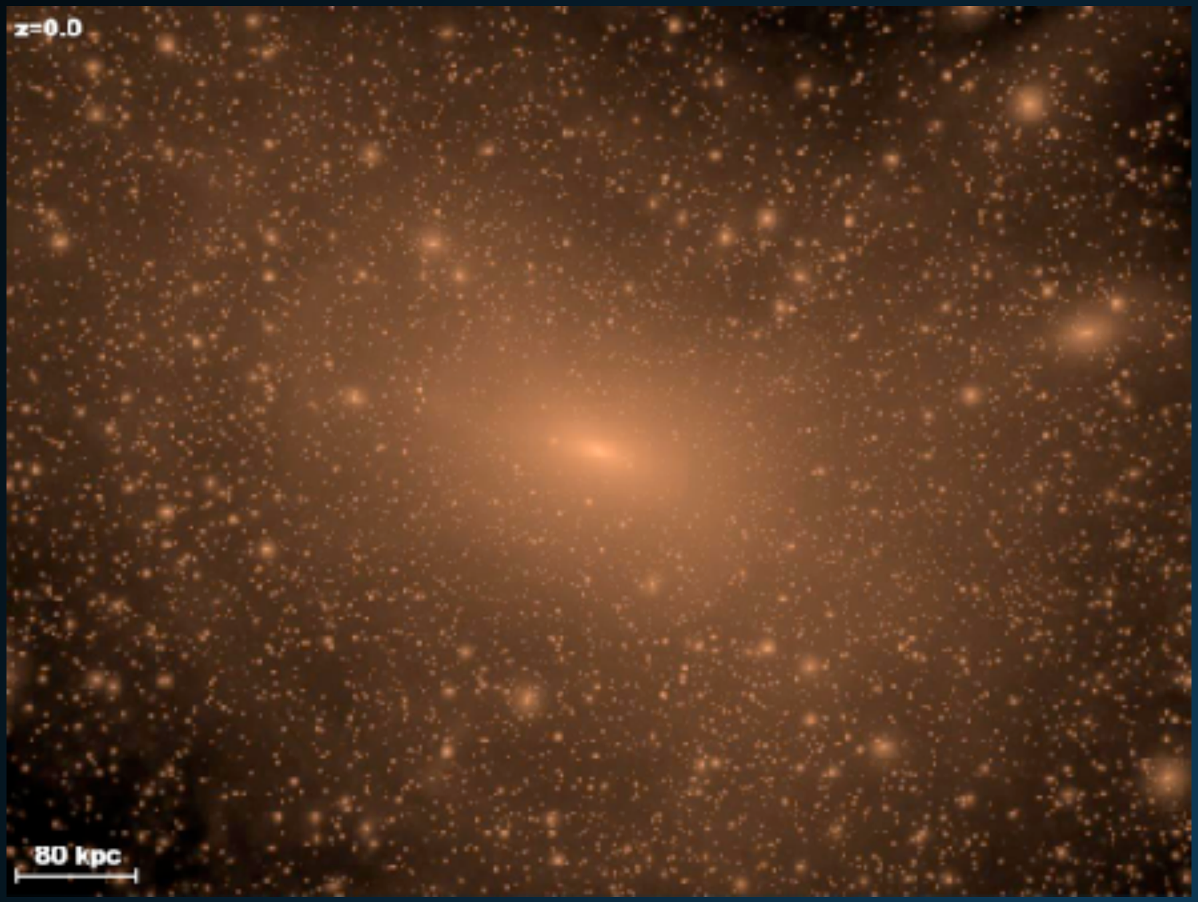
- **The 2′ constraint on the size of dark matter halo objects translates to ~0.6 - 1.3 Mpc.**
- **However, the largest clusters do have dark matter halos of this size.**
- **This is not true for baryonic emission, which is significantly clumpier.**

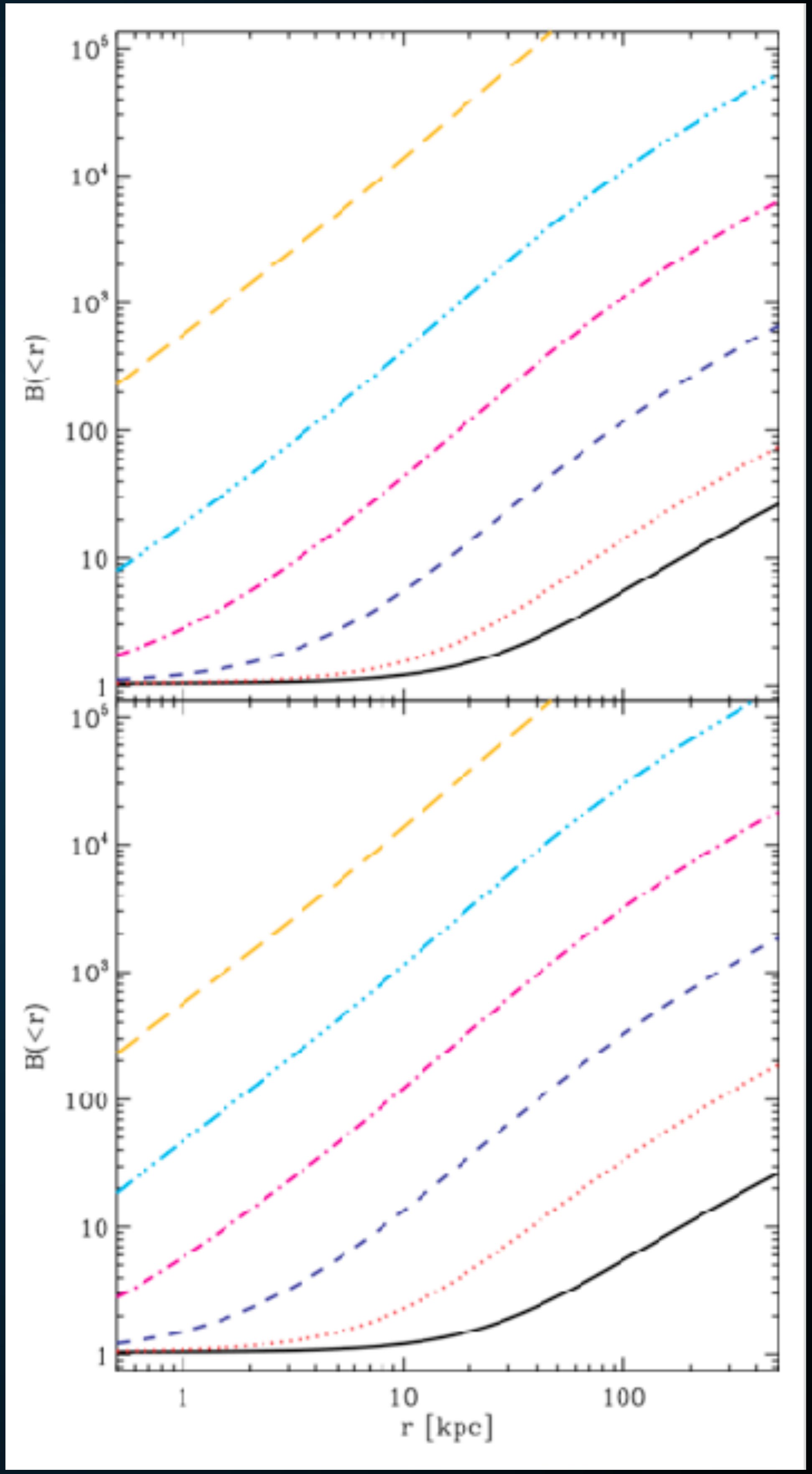
Angular Size	Physical Size			
	$z = 0.25$	$z = 0.5$	$z = 1$	$z = 2$
(arcsec)	(Mpc)	(Mpc)	(Mpc)	(Mpc)
30	0.12	0.19	0.25	0.26
60	0.24	0.38	0.49	0.51
100	0.40	0.63	0.82	0.86
150	0.60	0.94	1.23	1.29



SUBSTRUCTURE MODELING

Kamionkowski et al. (2010; 1001.3144)



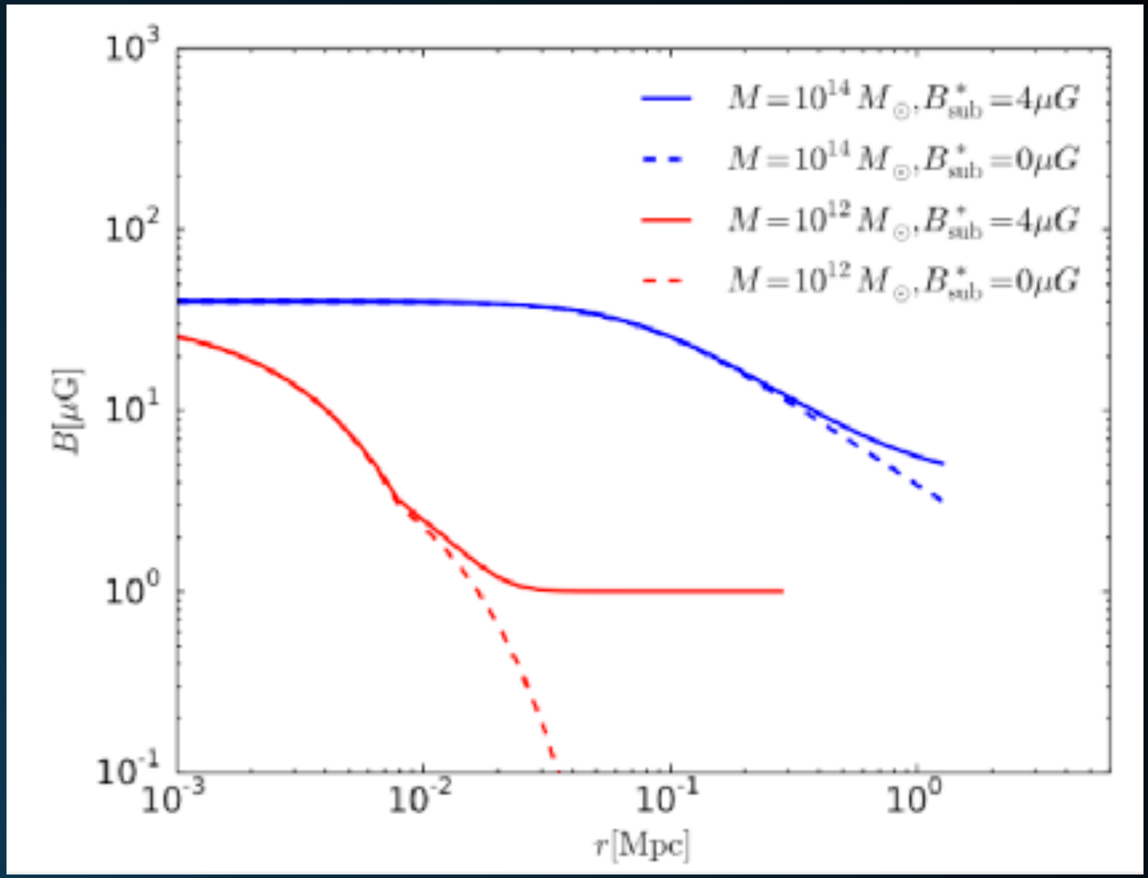


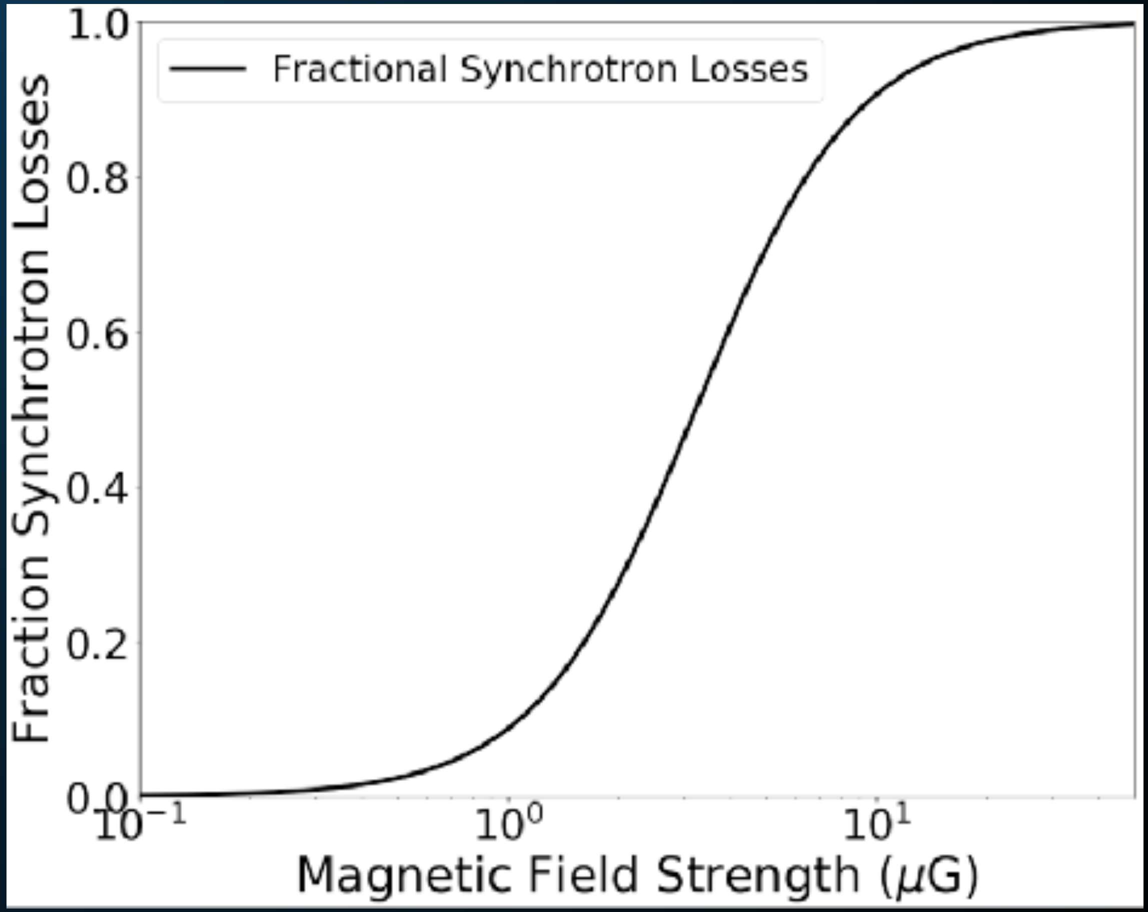
- **Dark matter contribution gets even bigger if substructure is considered.**
- **Leads to large boost factors far from the cluster center.**

MAGNETIC FIELDS SHOULD NOT BE BIG

Fang & Linden (2015; 1412.7545)

- **The major problem is the magnetic field strengths.**
- **Magnetic fields should be sourced by the baryonic component.**
- **Even if dark matter annihilates at Mpc distances - should mostly produce ICS in this region.**





MAGNETIC FIELD MODELING

Fang & Linden (2015; 1412.7545)

- **Possible Solution: Produce a model where enhanced magnetic fields trace cluster substructure:**

$$B(M,r) = B_0 \left(\frac{M}{M_0}\right)^{\alpha} \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-3\beta\eta/2}$$

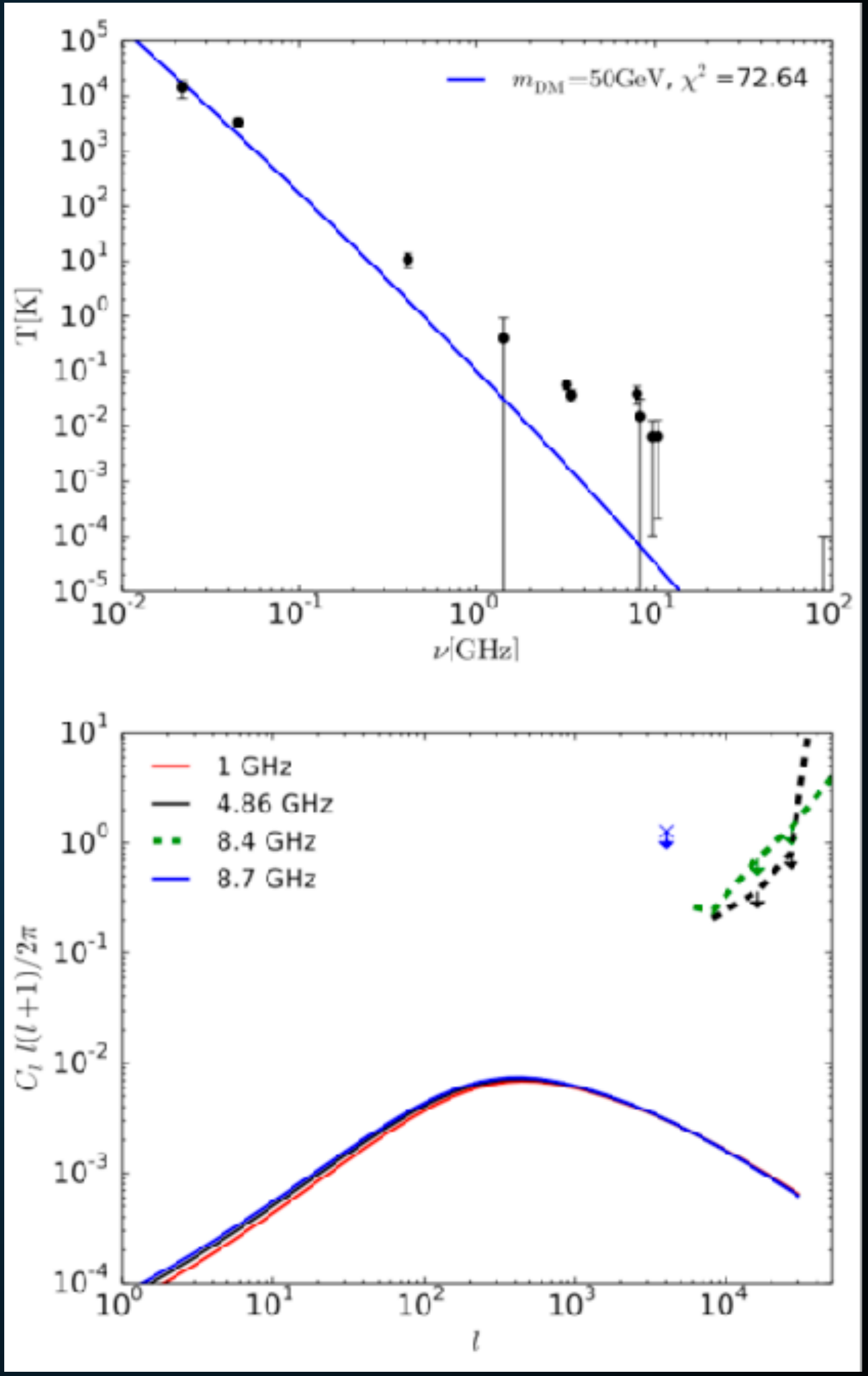
- **This magnetic field strength is either 35 μG with an core at 0.008 R_{vir}, or 7.6 μG with a core at 0.025 R_{vir}.**

- **This magnetic field is then supplemented, by a substructure magnetic field, which persists out to the end-of the simulation (often 2-4 R_{vir}). We adopt α=0.3, an test values of B_{sub}^*.**

$$B_{\rm sub} = B^*_{\rm sub} \left(\frac{M}{10^{14}\, M_\odot}\right)^{\alpha}$$

Fang & Linden (2015; 1412.7545)

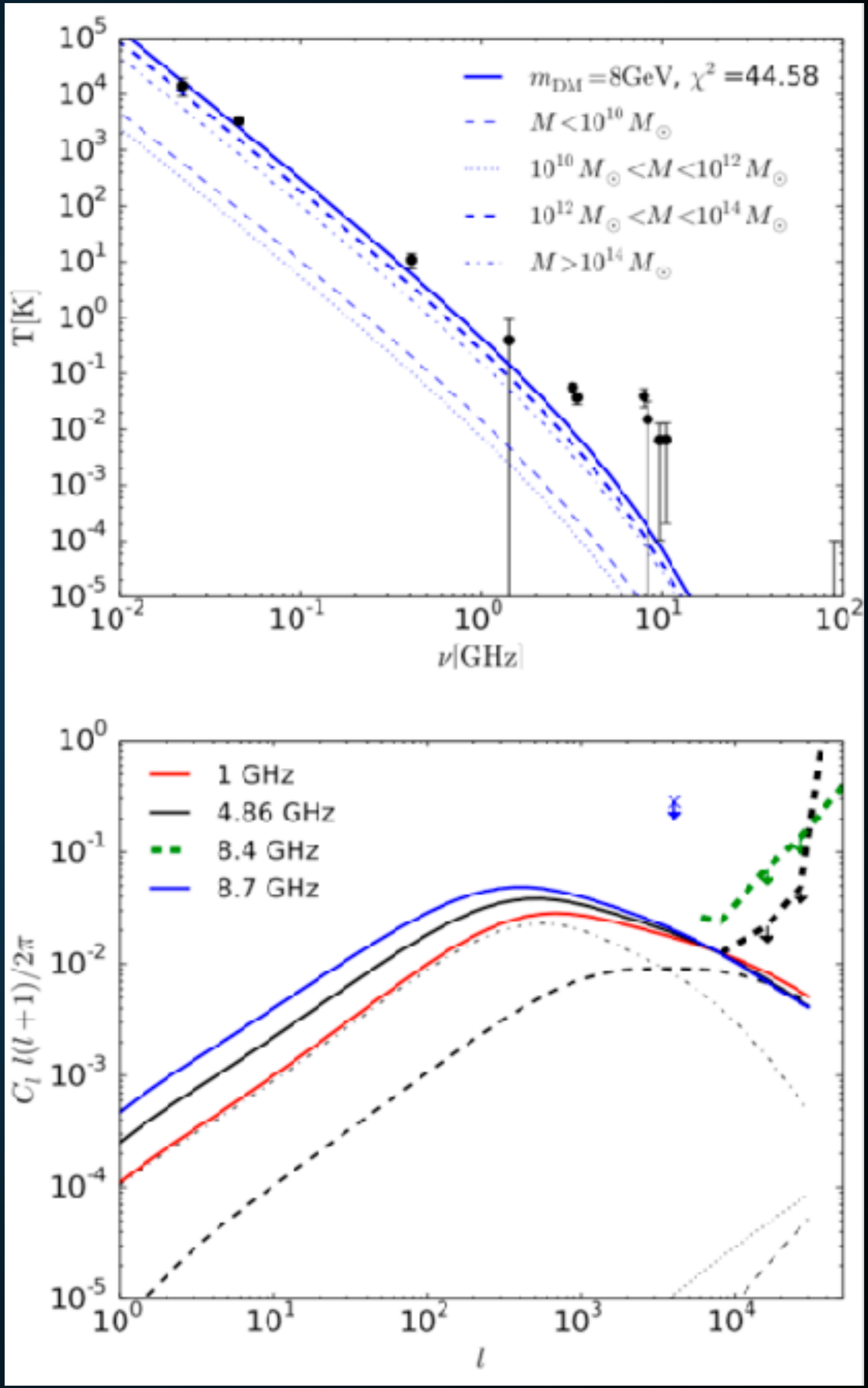
- **Models with annihilations primarily to hadronic quarks still have too soft of a spectrum to explain the emission.**
- **The anisotropies in this case can fall far below constraints.**



DARK MATTER FITS

Fang & Linden (2015; 1412.7545)

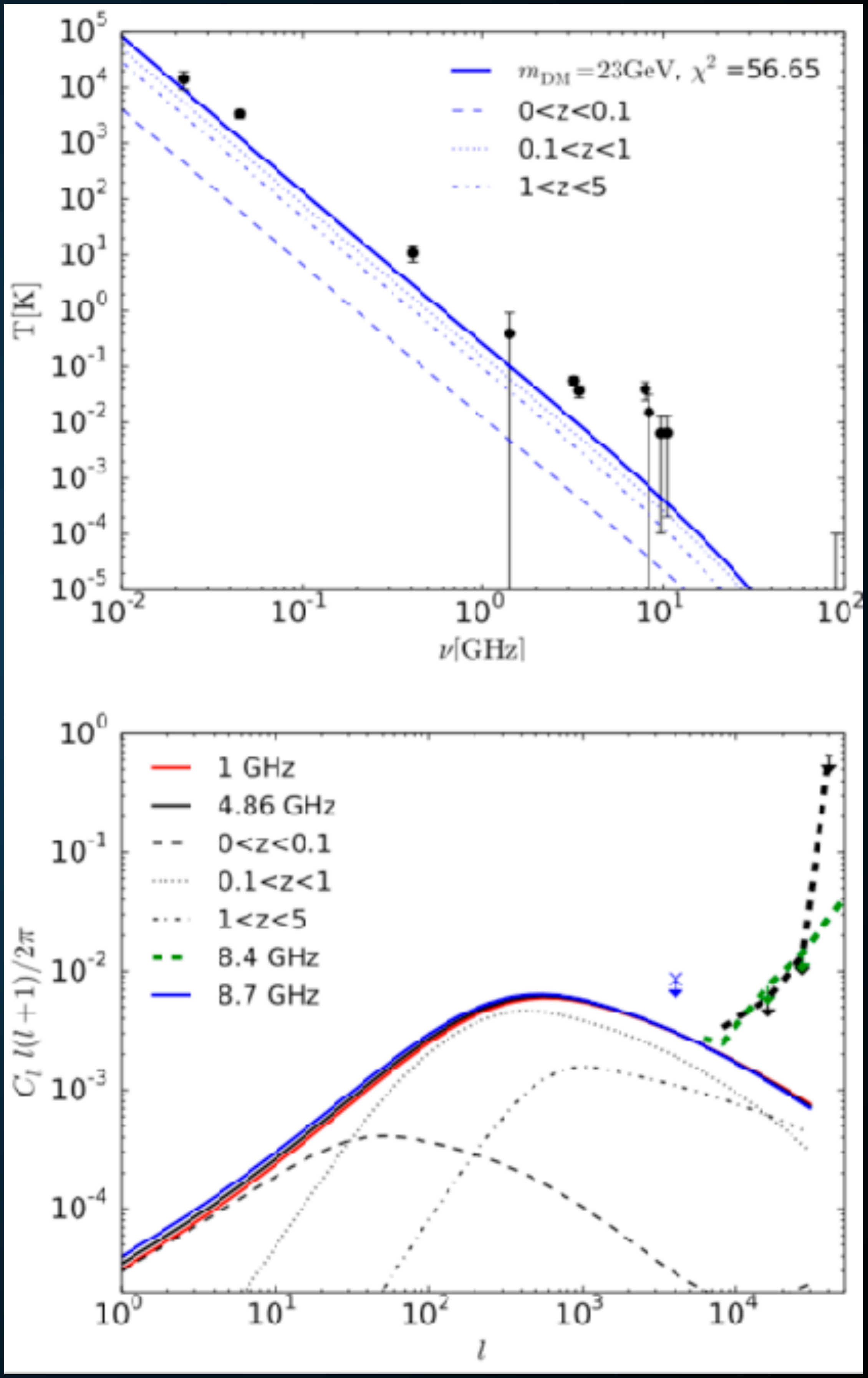
- **Models of light dark matter with annihilation to leptonic pairs produces a significantly harder spectrum.**
- **Note that about 50% of the emission is provided by clusters, and 50% by high-mass galaxies.**
- **Total anisotropy falls below constraints.**



Fang & Linden (2015; 1412.7545)

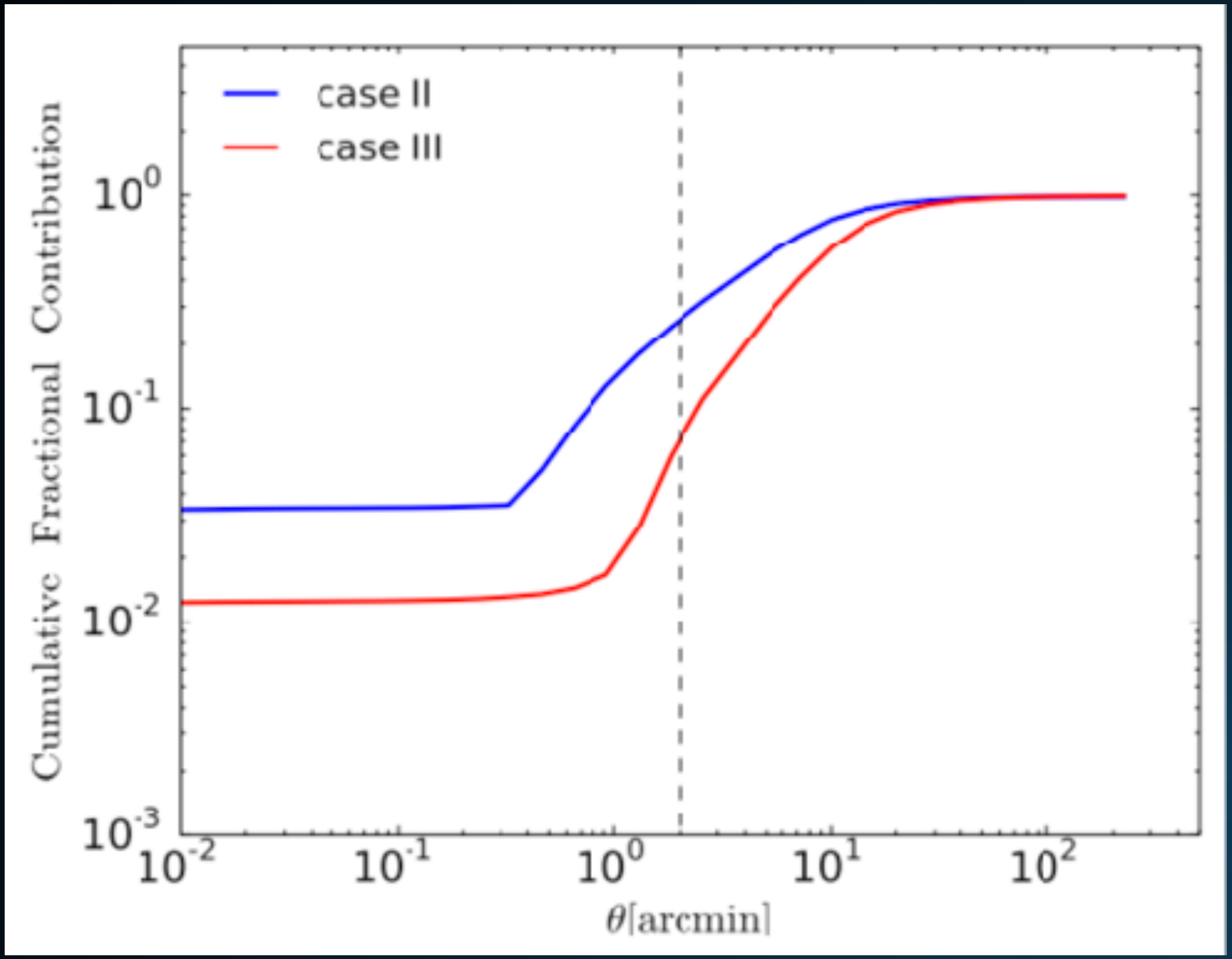
- **Charge-coupled models provide an intermediate constraint (but are easier to square with other observables).**

- **Note that the signal is dominated by emission from 0.1 < z < 1.0**



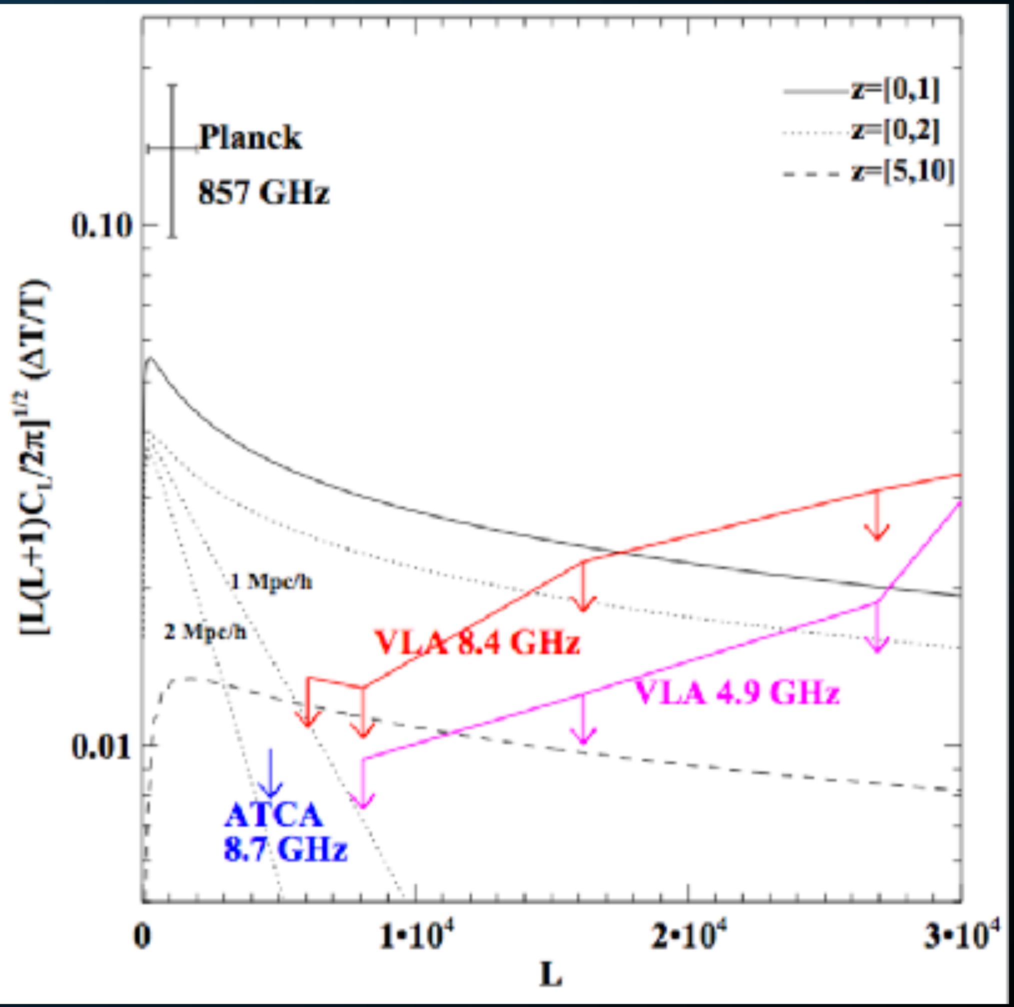
GO EARLY OR GO BIG

Fang & Linden (2015; 1412.7545)



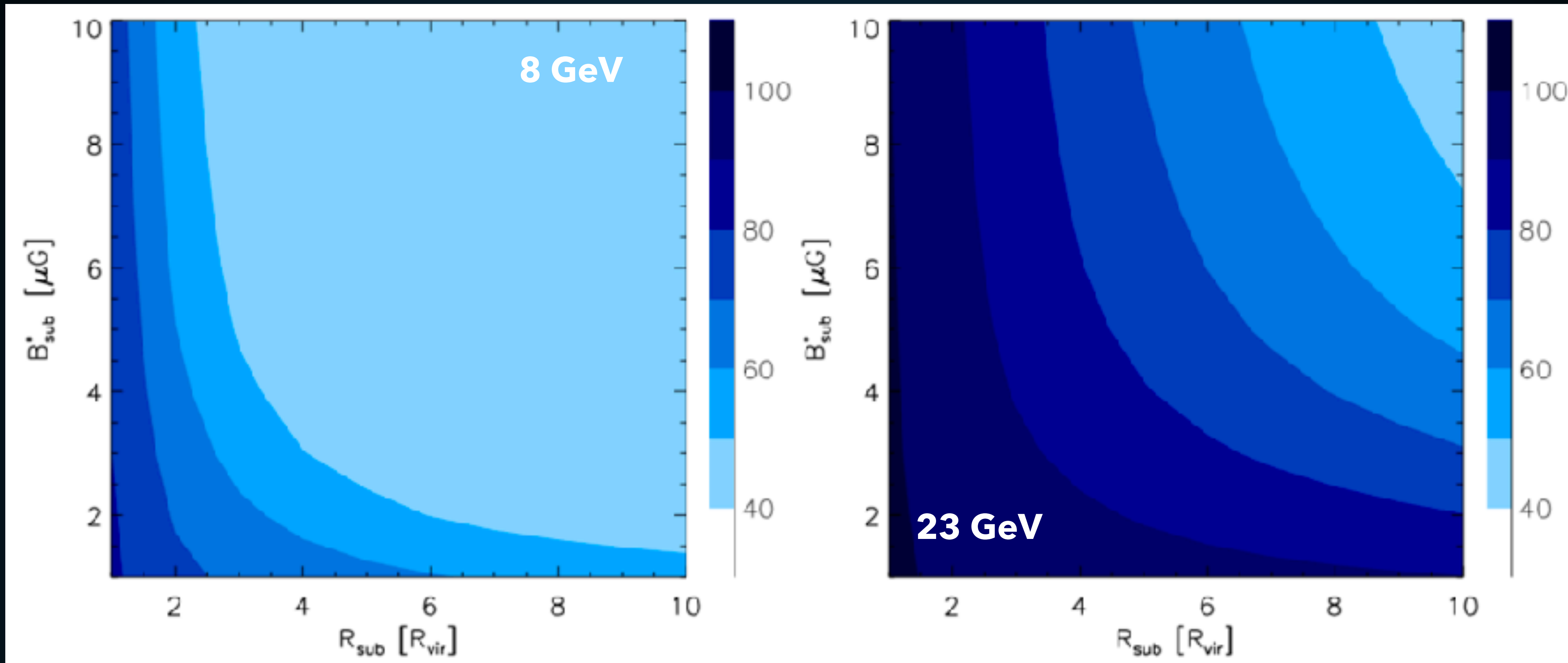
- In these cases, the majority of the emission is produced by structures larger than 2′.

Holder (2012; 1207.0856)



- In general, this allows us to produce models that fit the intensity, without overproducing the constraints from isotropy.

Fang & Linden (2015; 1412.7545)

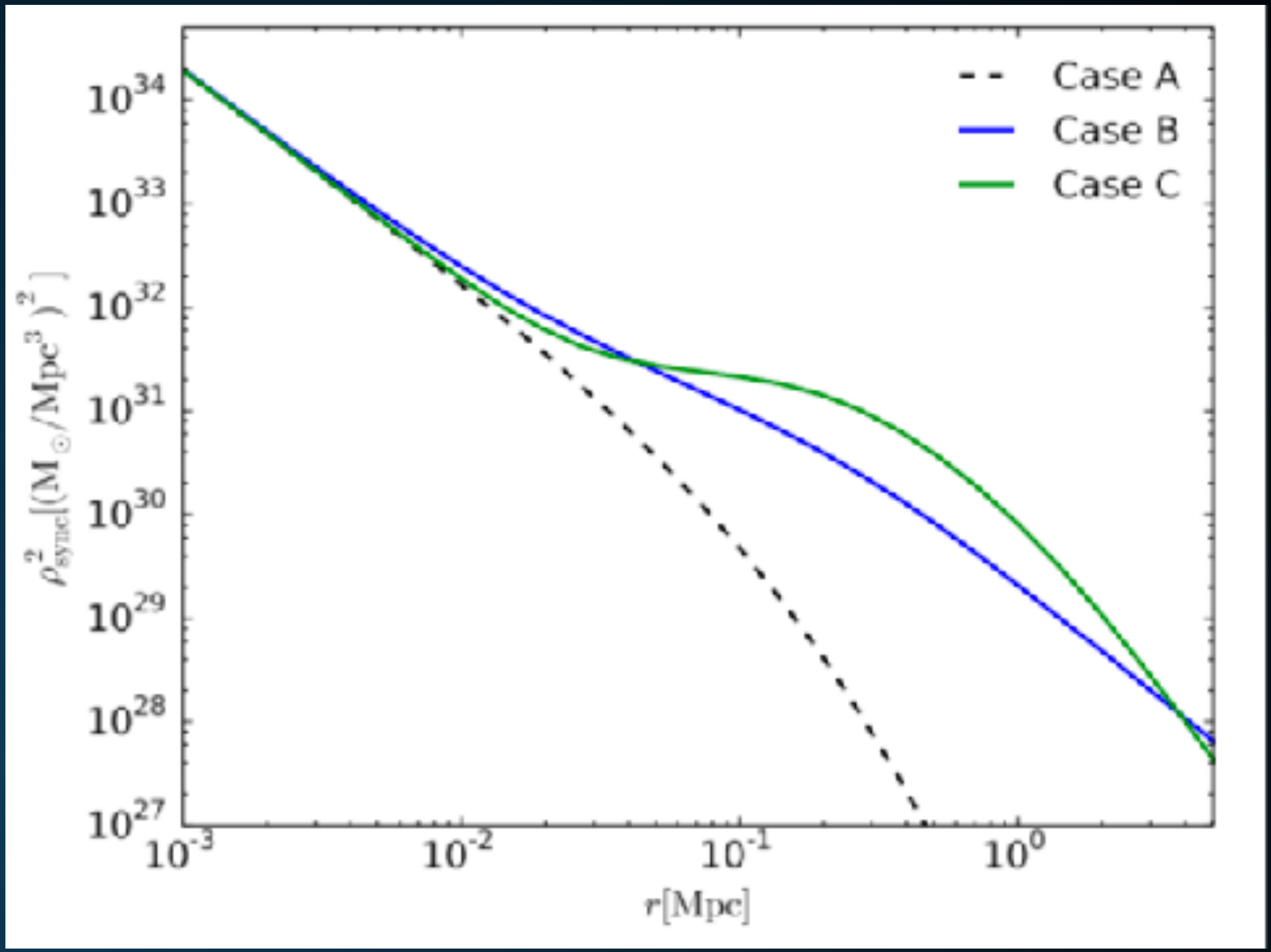


- Unfortunately, the necessary choices for the extension of the magnetic field – and the termination of substructure – are rather extreme.
- How do we generate large signal far from cluster centers?

ALFVEN REACCELERATION?

Fang & Linden (2015; 1412.7545)

- What if electrons far from the cluster center were re-accelerated by magnetic turbulence?



- Can multiply the effective synchrotron emission at large radial distances.

- Because electrons are accelerated in regions with high magnetic turbulence (field strength), ICS can be avoided.

ALFVEN REACCELERATION?

- Why appeal to two miracles when one will do?
  - i.e. Can we just accelerate ambient electrons, rather than dark matter produced electrons?

ALFVEN REACCELERATION?

Alfvénic reacceleration of relativistic particles in galaxy clusters: MHD waves, leptons and hadrons

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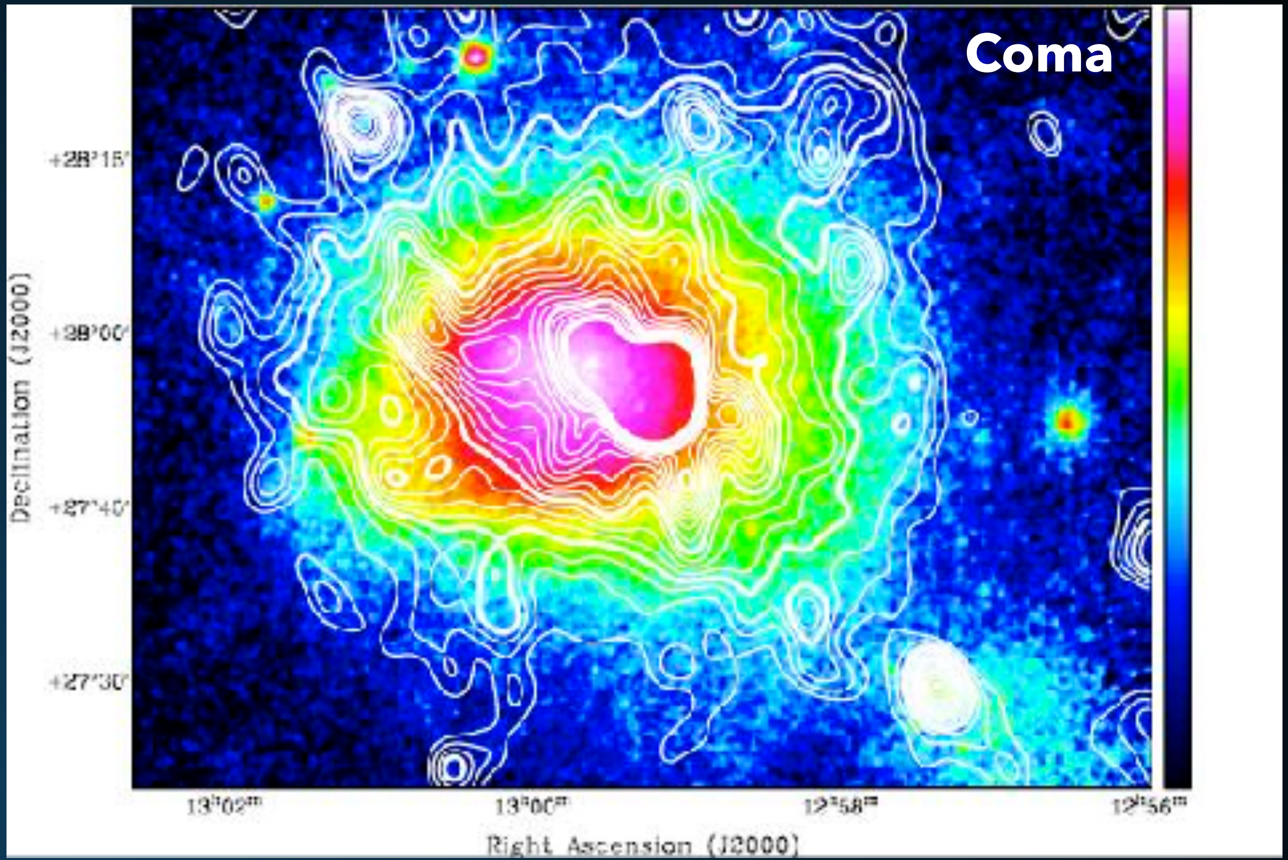
ABSTRACT

There is a growing evidence that extended radio halos are most likely generated by electrons reaccelerated via some kind of turbulence generated in the cluster volume during major mergers. It is well known that Alfvén waves channel most of their energy flux in the acceleration of relativistic particles. Much work has been done recently to study this phenomenon and its consequences for the explanation of the observed non-thermal phenomena in clusters of galaxies. We investigate here the problem of particle-wave interactions in the most general situation in which relativistic electrons, thermal protons and relativistic protons exist within the cluster volume. The interaction of all these components with the waves, as well as the turbulent cascading and damping processes of Alfvén waves, are treated in a fully time-dependent way. This allows us to calculate the spectra of electrons, protons and waves at any fixed time. The *Lighthill* mechanism is invoked to couple the fluid turbulence, supposedly injected during cluster mergers, to MHD turbulence. We find that present observations of non-thermal radiation from clusters of galaxies are well described within this approach, provided the fraction of relativistic hadrons in the intracluster medium (ICM) is smaller than 5 – 10%.

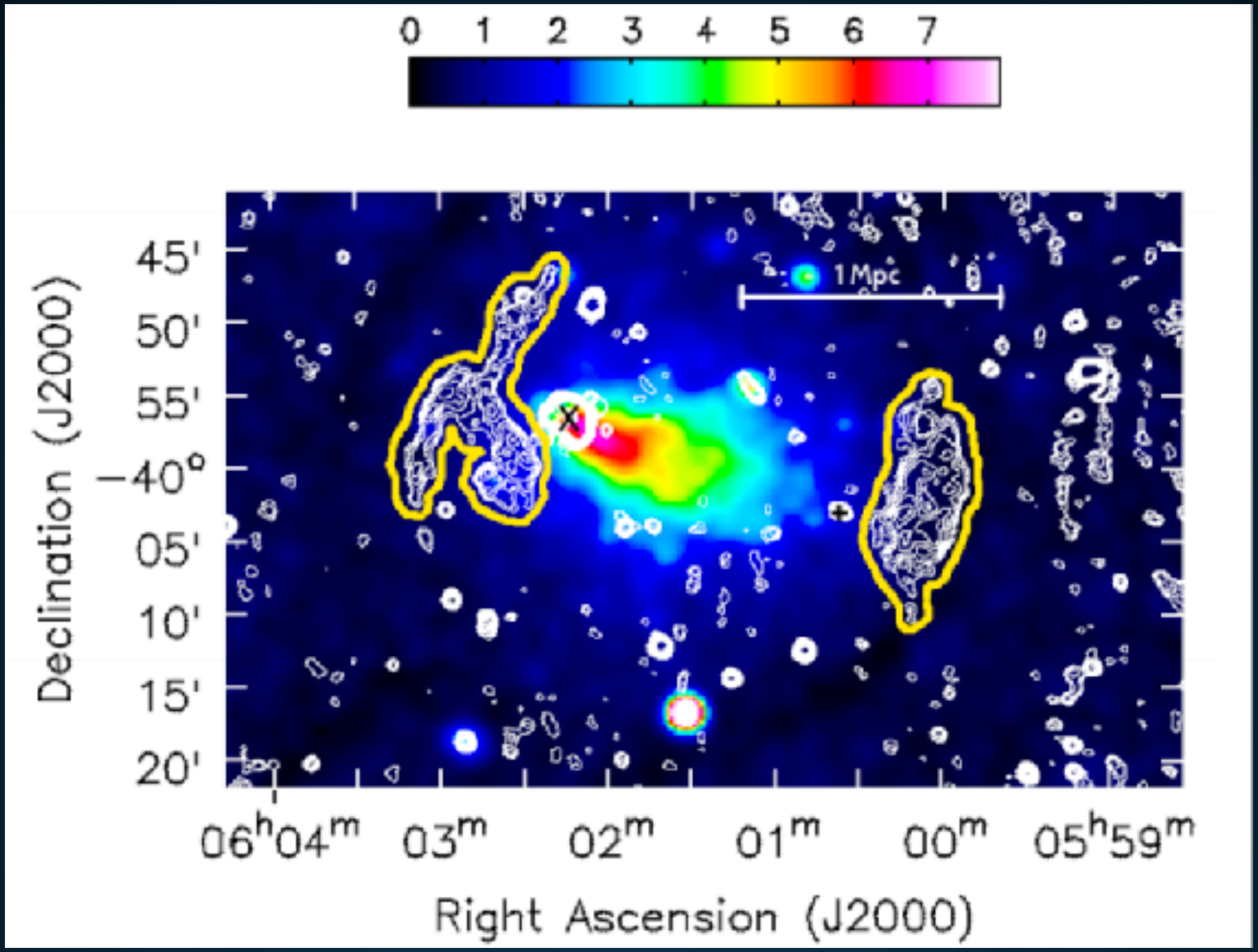
Brown & Rudnick (2011 412 2)



- **Large scale radio emission from galaxy clusters is actually detected.**
- **The source of radio emission from clusters is unknown.**
- **Can solving this problem tell us about the radio excess?**

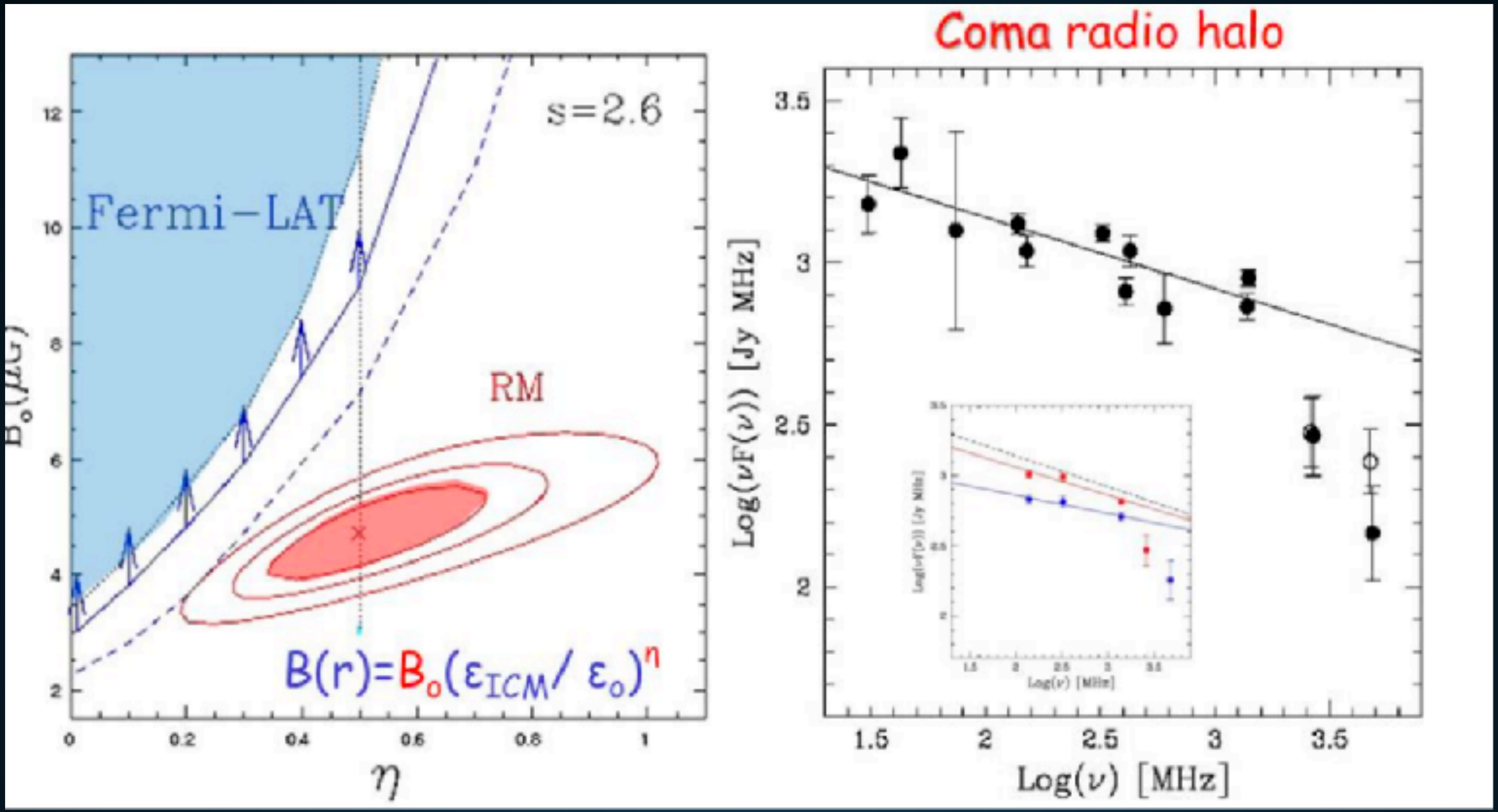
ABEL 3376 RADIO RELIC

George et al. (2015; 1506.00451)



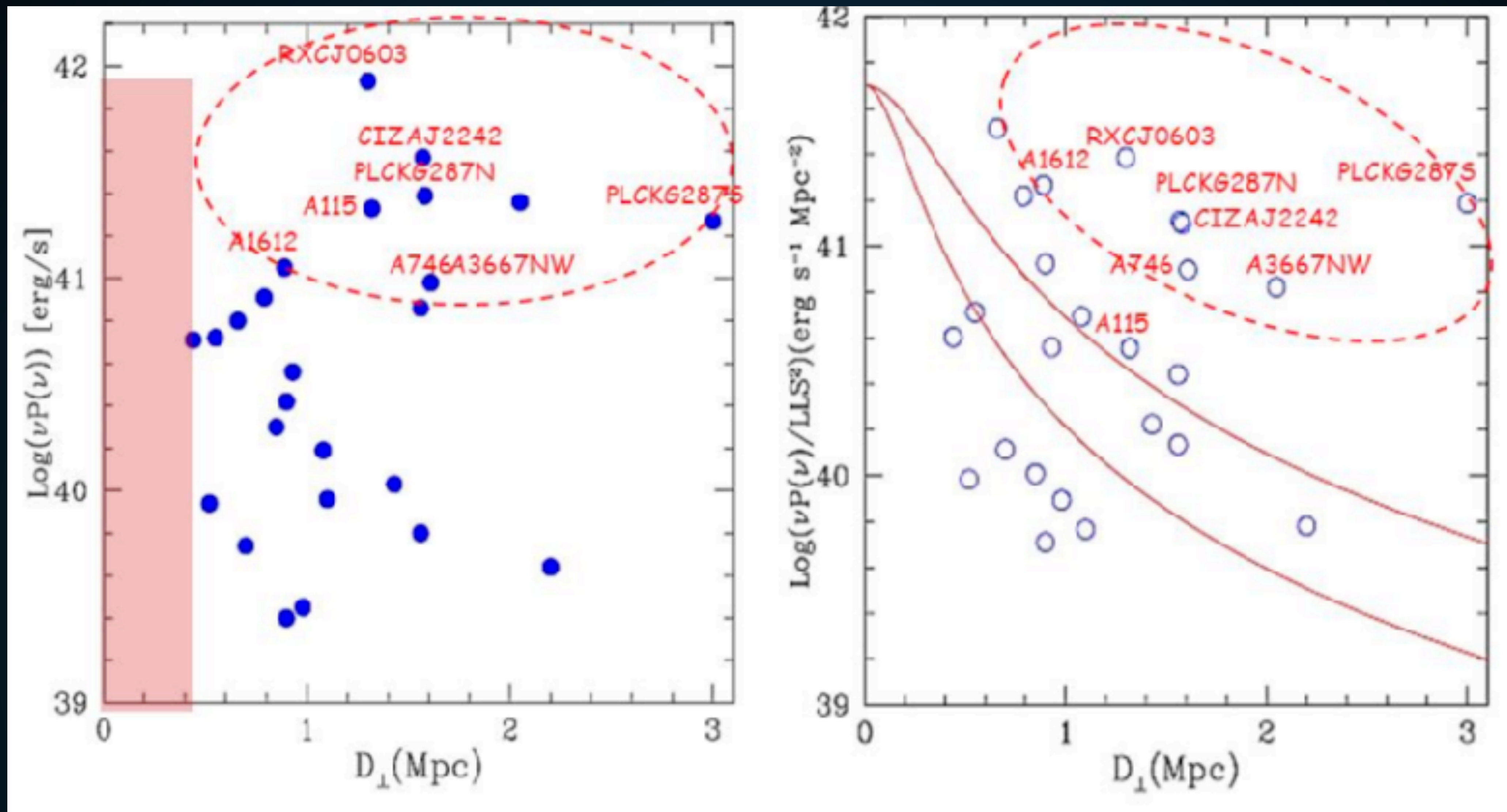
- Additionally, radio relics are observed far from cluster centers - with almost no X-Ray emission!
- This provides an explanation for the ICS problem.

Brunetti & Jones (2014; 1401.7519)



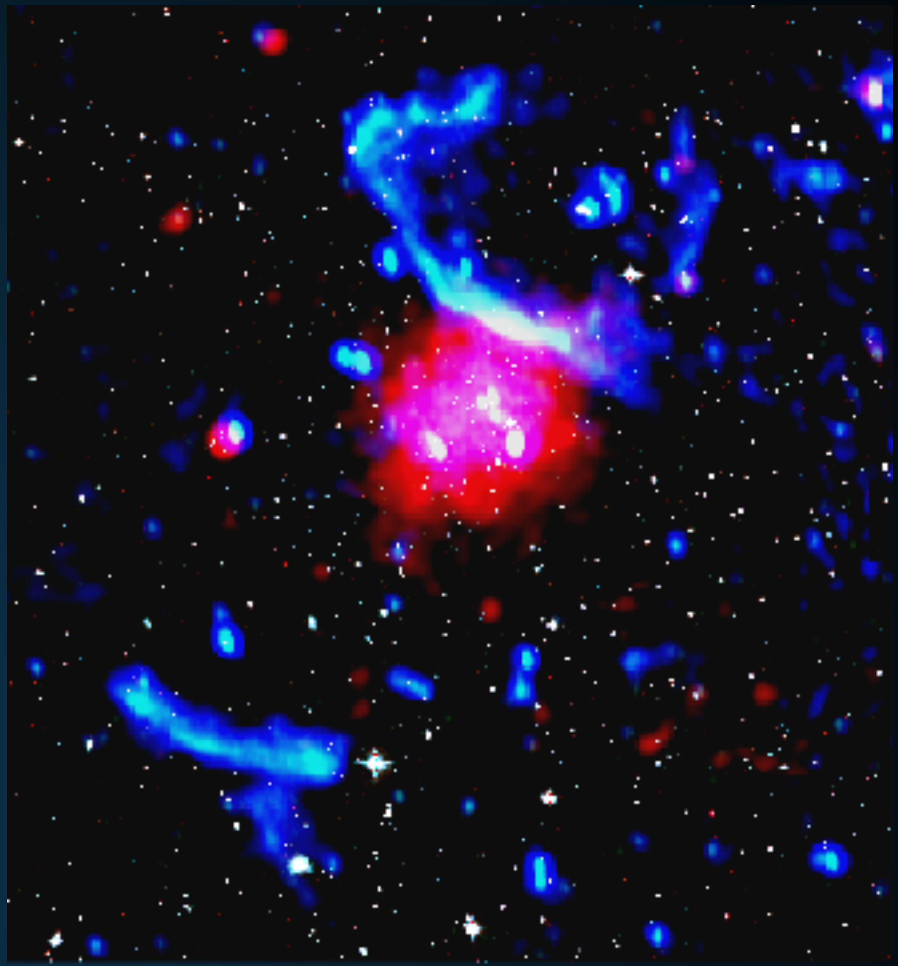
- **In fact, observations of the Coma halo require the existence of strong magnetic fields that extend to far from the cluster center.**

Brunetti & Jones (2014; 1401.7519)



- **A number of such sources exist - with bright, powerful radio emission that occurs far from the cluster center.**

RADIO EMISSION FROM CLUSTER MERGERS



- Magnetic turbulence can be produced during both major and minor merger events.
- Has been posited as an explanation for radio relics and halos.
- Collisional shocks during this merger can also accelerate an electron population.

- **Start with a turbulence spectrum and Reynolds number for the hydrodynamic cluster merger.**

$$W_f(\kappa) = W_f^0 \left(\frac{\kappa}{\kappa_0}\right)^{-m}$$

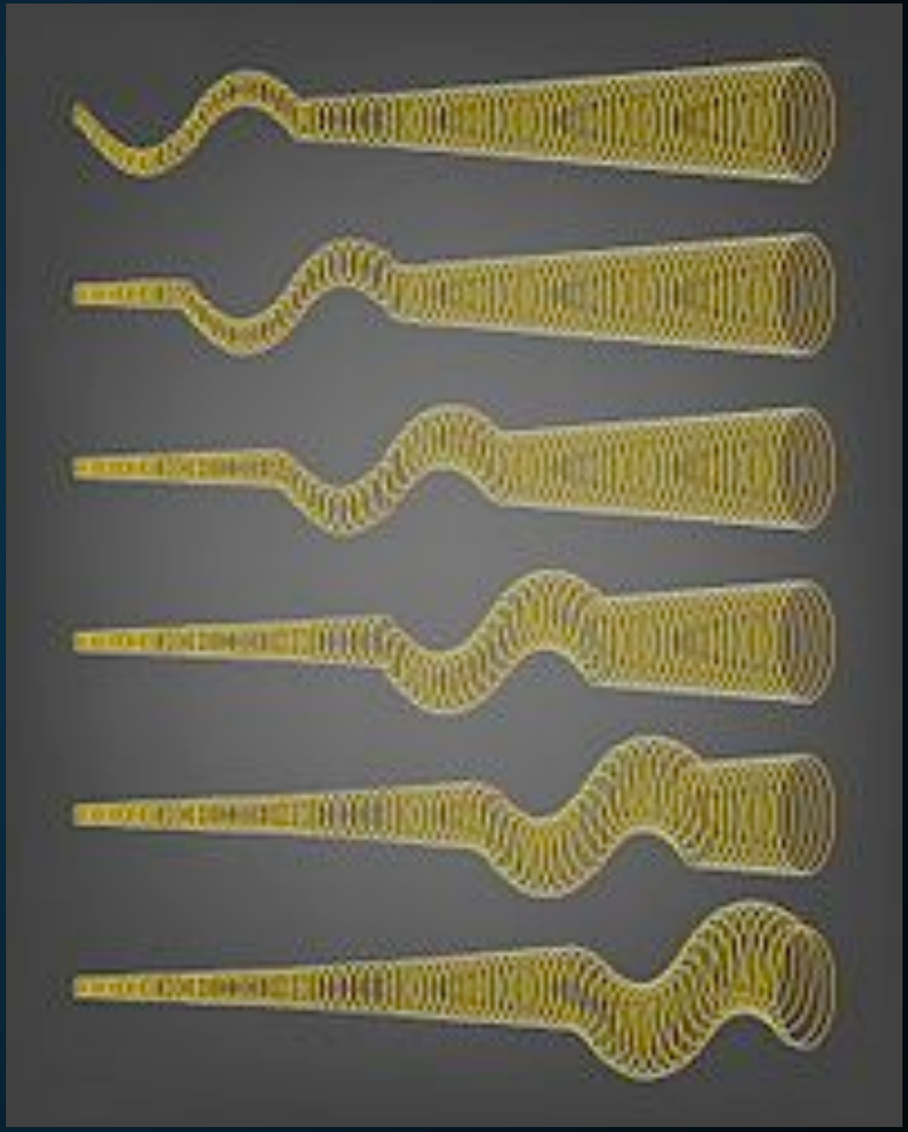
$$\mathrm{Re} = 10^{26} \left(\frac{l_0}{300\,\mathrm{kpc}}\right) \left(\frac{v_t}{300\,\mathrm{km\,s^{-1}}}\right) \left(\frac{40}{\ln \Lambda}\right) \times \left(\frac{n_p}{10^{-3}\,\mathrm{cm^{-3}}}\right)^{-1} \left(\frac{T}{2\,\mathrm{keV}}\right)^{1/2} \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{2}$$

- **From this you can calculate a total power in the Alfven wave of a post-merger cluster.**

$$P_A = 4.2 \times 10^{-32} \left(\frac{v_t}{300\,\mathrm{km\,s^{-1}}}\right)^{23/6} \times \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{-4/3} \left(\frac{n_p}{10^{-3}\,\mathrm{cm^{-3}}}\right)^{5/3} \left(\frac{T}{2\,\mathrm{keV}}\right)^{-1/12} \times \left(\frac{l_0}{300\,\mathrm{kpc}}\right)^{-7/6} \mathrm{erg\,cm^{-3}\,s^{-1}}$$

- **Particles can now be accelerated (or de-accelerated) through resonant damping with this wave, which propagates at a velocity:**

$$v_A = \frac{B}{(4\pi\rho)^{1/2}} = 70 \left(\frac{B}{1\,\mu\mathrm{G}}\right) \left(\frac{n_p}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{km\,s^{-1}}$$

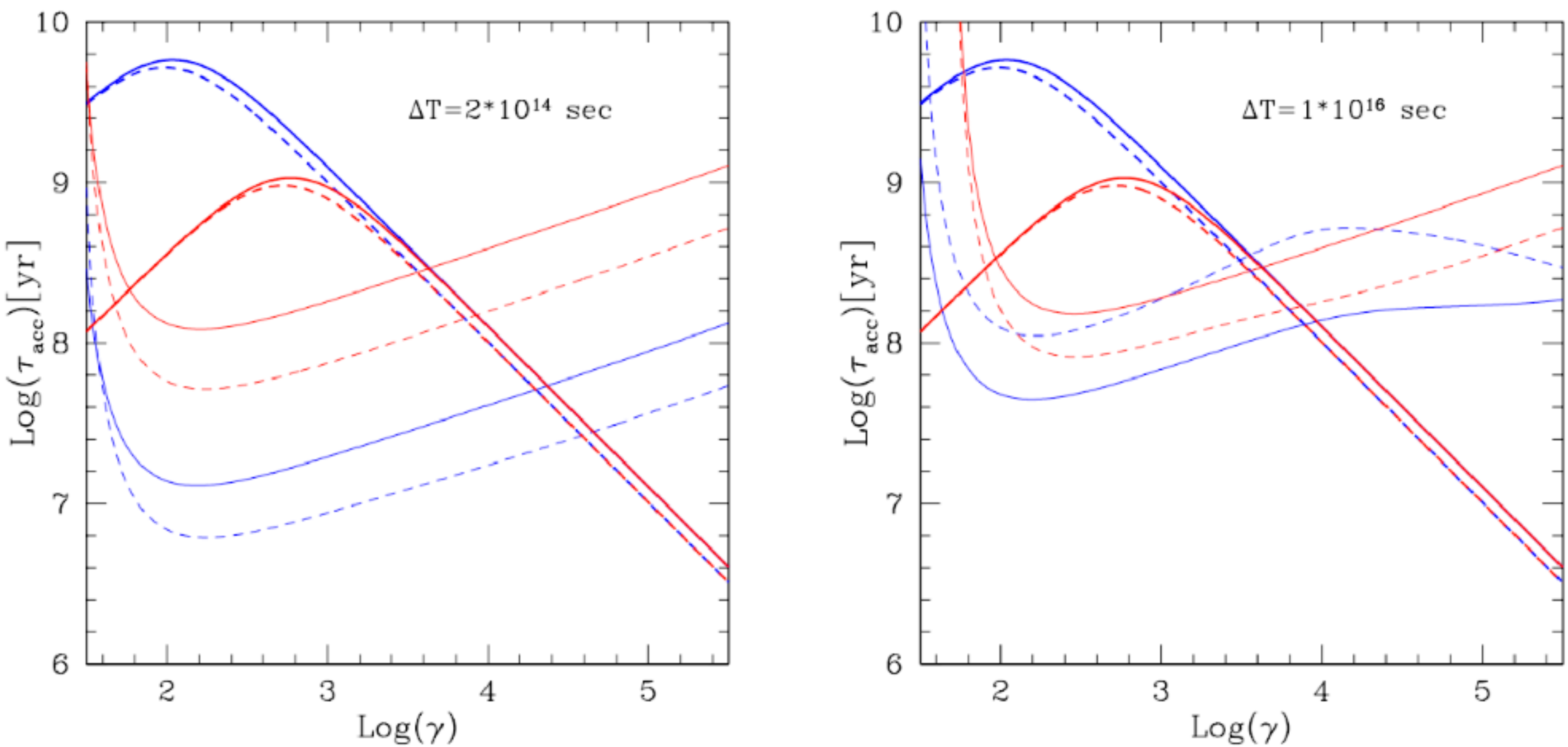


- **Because the particles must be in resonance with the wave, this indicates a maximum electron energy:**

$$E_{\rm max} = 53 \left(\frac{B}{1\,\mu\mathrm{G}}\right)^{4/3} \left(\frac{l_0}{300\,\mathrm{kpc}}\right)^{2/3} \left(\frac{T}{2\,\mathrm{keV}}\right)^{-1/6} \times \left(\frac{v_t}{300\,\mathrm{km\,s^{-1}}}\right)^{-4/3} \left(\frac{n_p}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1/6} \mathrm{GeV}$$

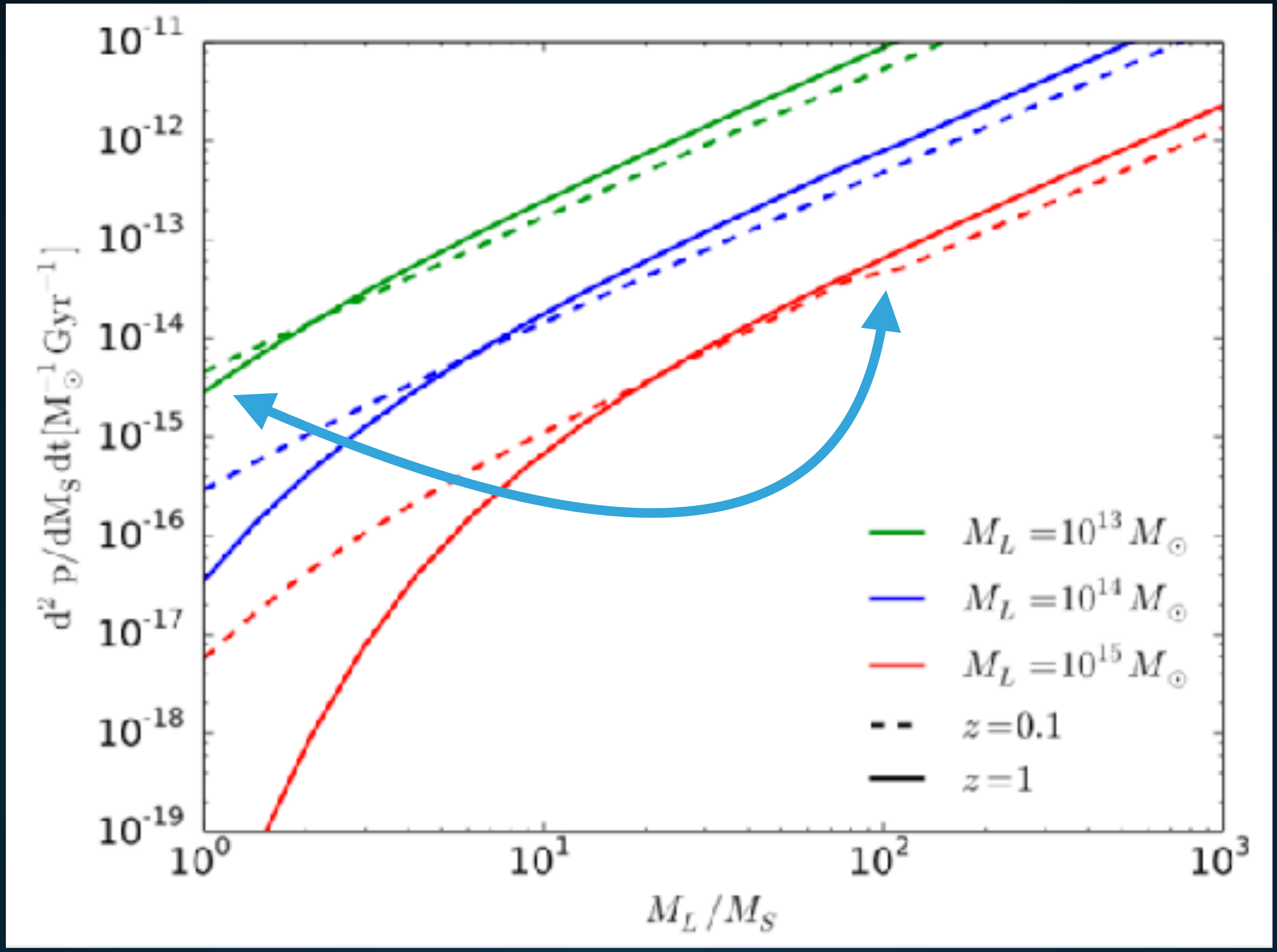
ALFVEN ACCELERATION

Brunetti et al. (2003; 0312482)



- The spectrum can become quite hard - due to the "pinching" between particle acceleration timescales and energy loss timescales

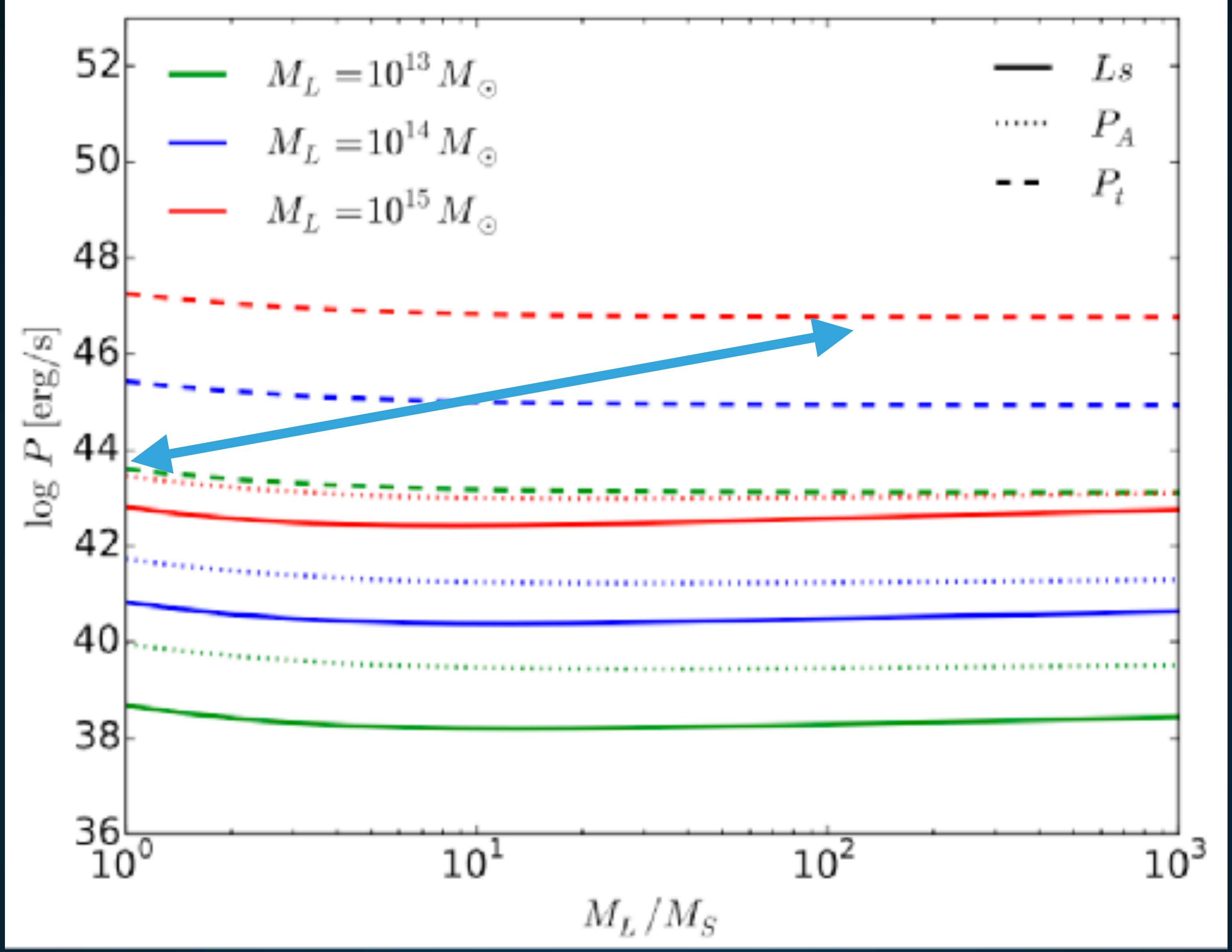
Fang & Linden (2016; 1506.05807)



- There are several appealing features of this model:
  - 1.) The cluster merger rate is dominates by the most massive clusters. Most power is generated at large spatial scales.

ALFVEN ACCELERATION IN CLUSTERS

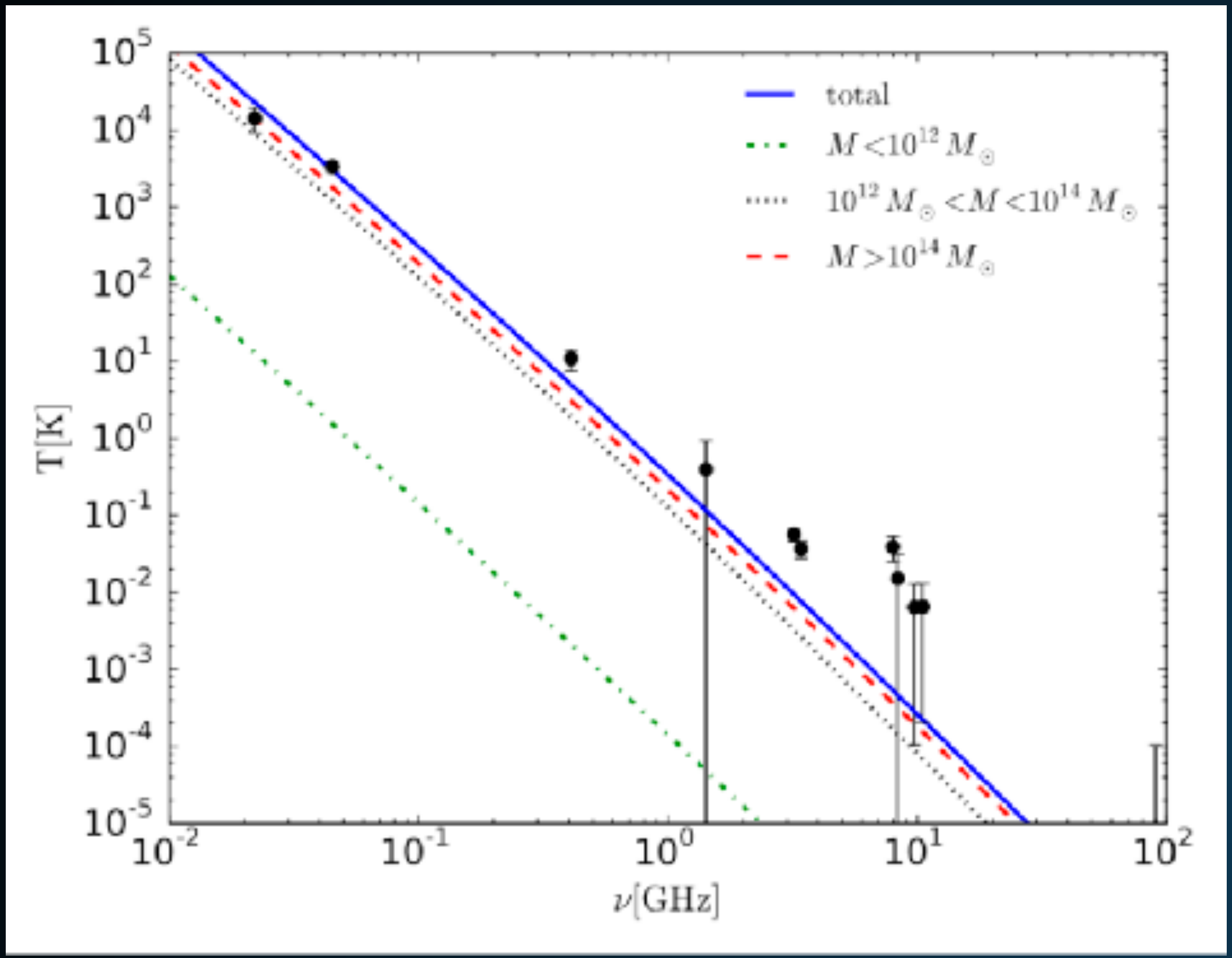
Fang & Linden (2016; 1506.05807)

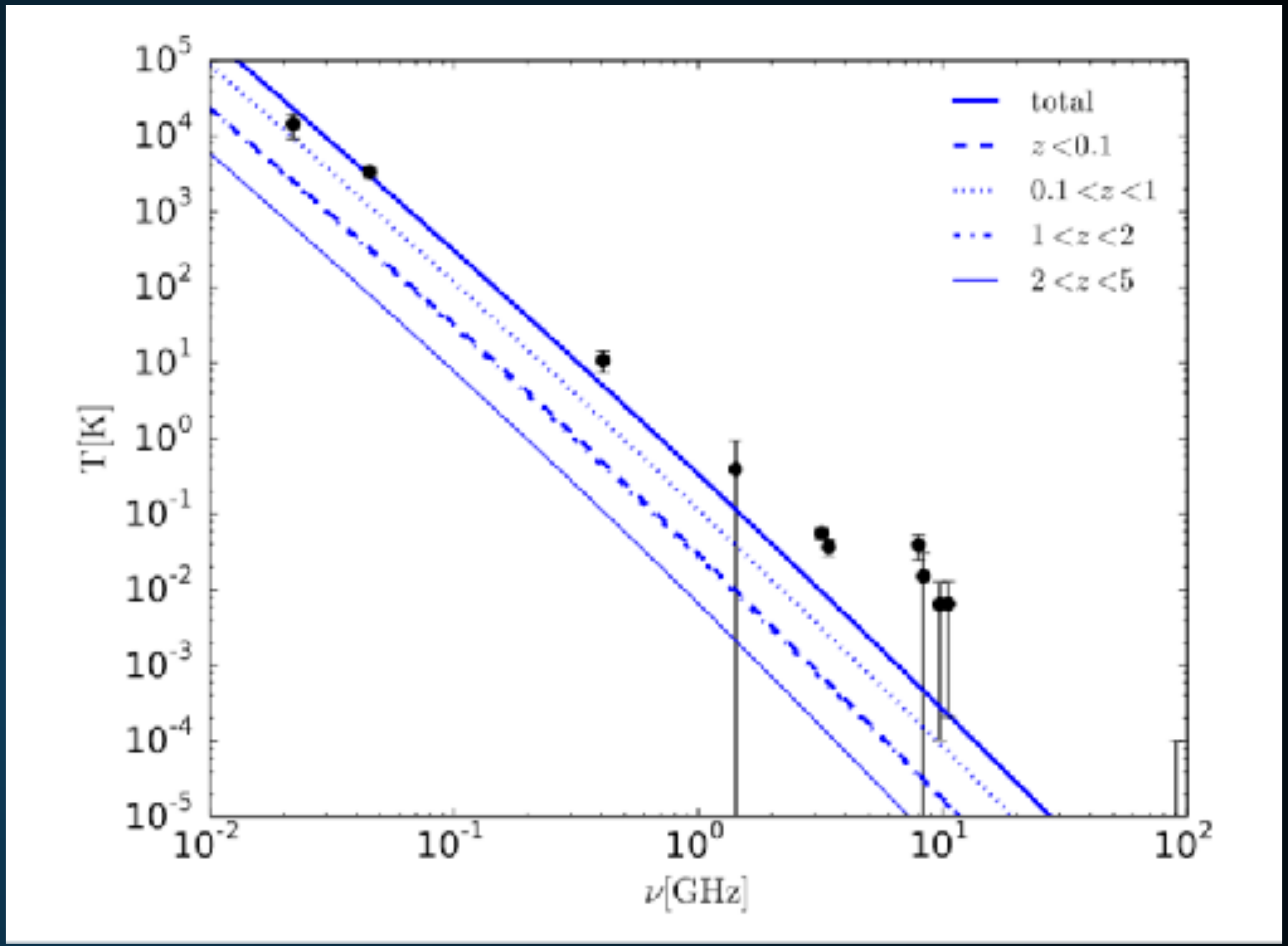


- **There are several appealing features of this model:**
  - **2.) The largest clusters also generate significantly more power than smaller cluster mergers.**

ALFVEN ACCELERATION IN CLUSTERS

Fang & Linden (2016; 1506.05807)

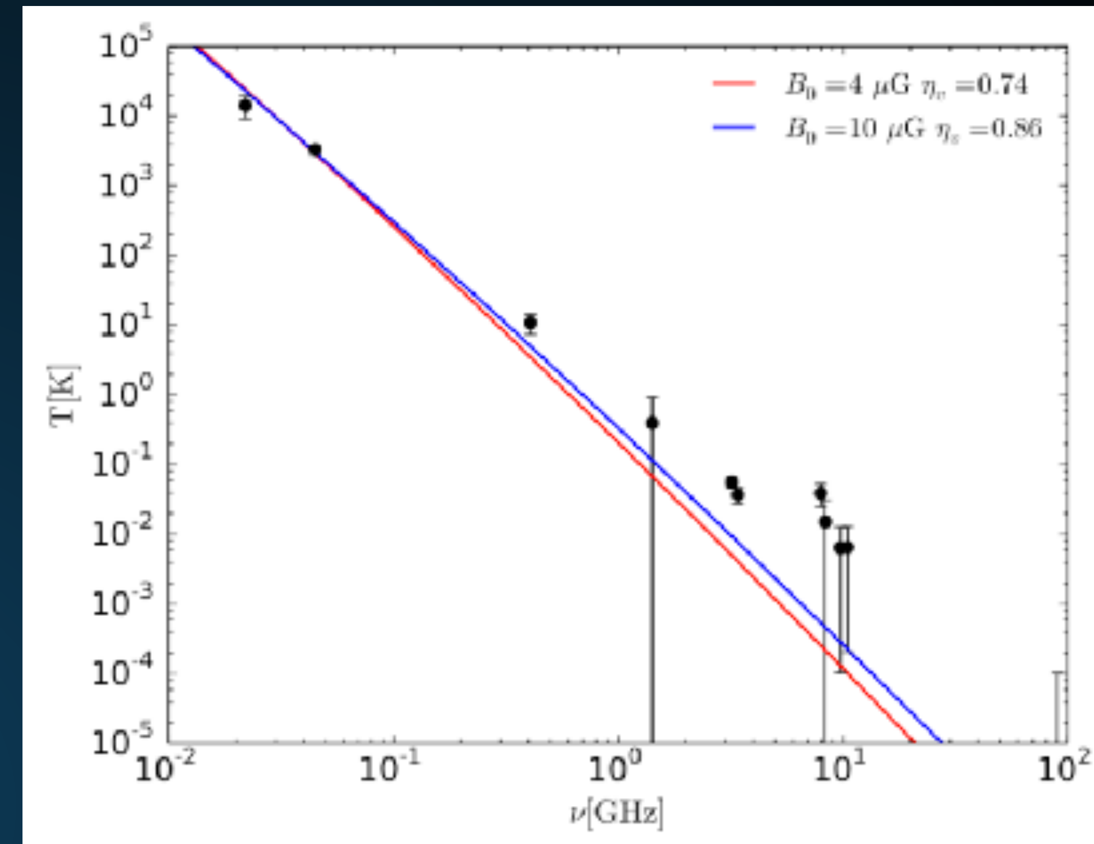


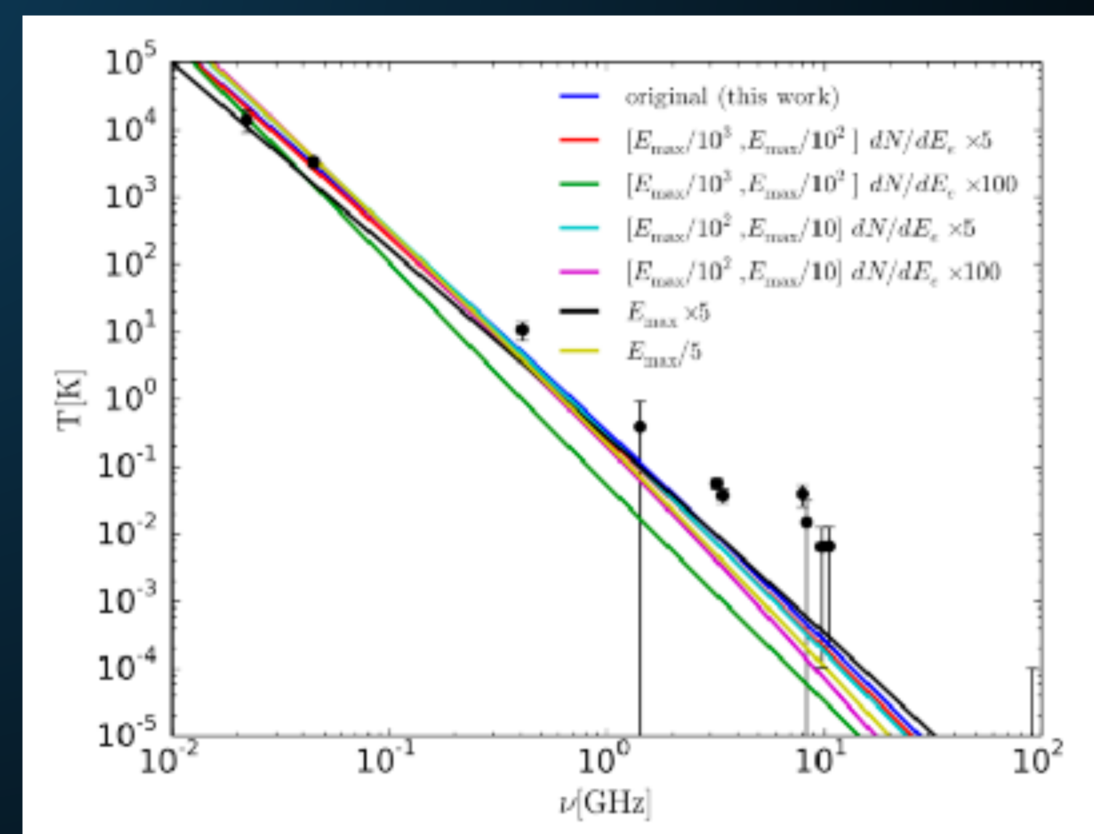


- **This emission is totally dominated by the most massive clusters.**
- **And is dominated by nearby emission sources.**
- **Anisotropy is minimal.**

Fang & Linden (2016; 1506.05807)

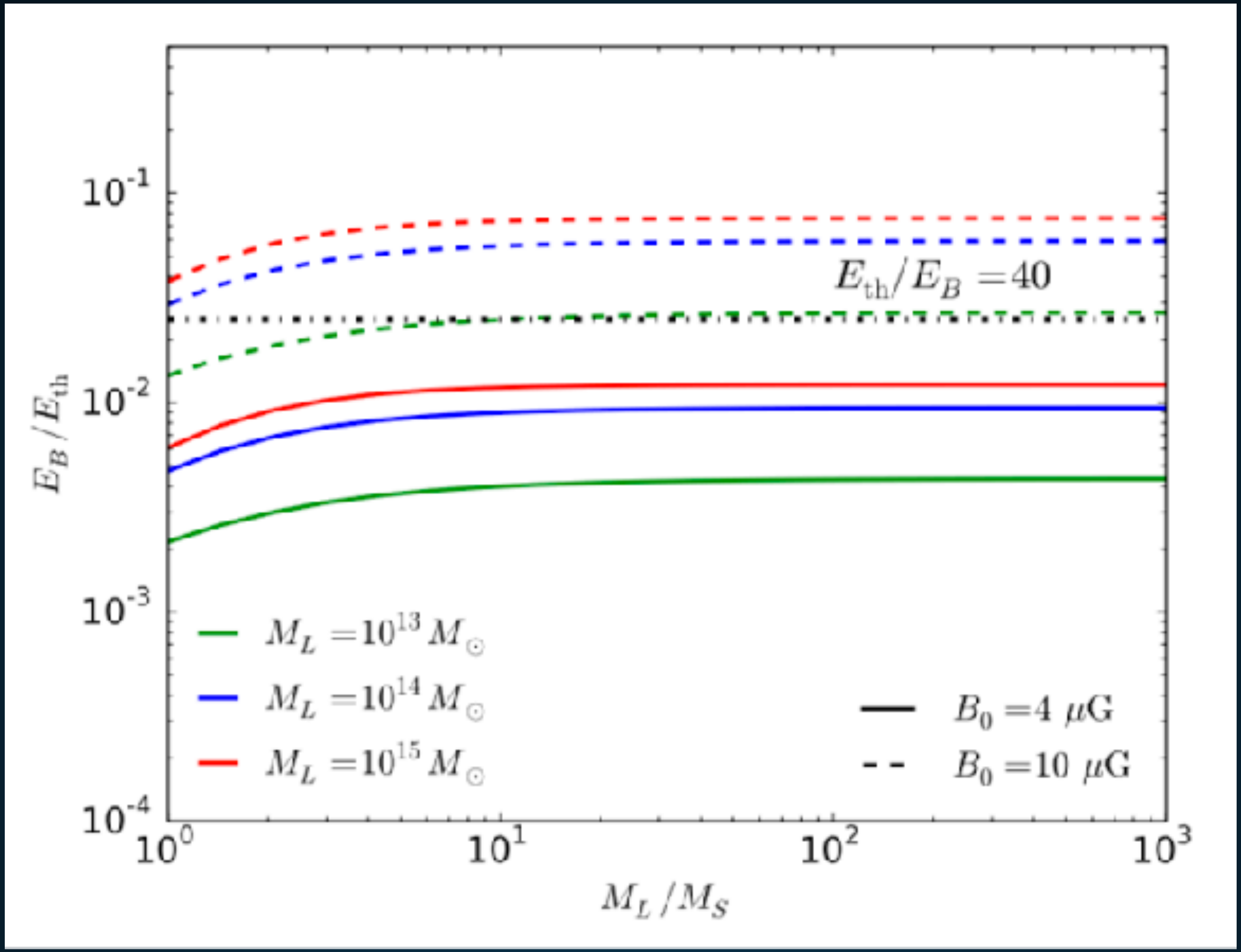
- **This emission roughly matches the ARCADE-II excess, though the spectrum is soft.**
- **Unlike DM annihilation, we do not have many choices in the steady state electron spectrum.**
- **This can be fixed by hardening the injection in some energy range (e.g. produced as secondaries through hadronic interactions)**





GO EARLY OR GO BIG

Fang & Linden (2016; 1506.05807)



- The power requirement is reasonable:
  - Need 0.5-5% of the total thermal power of the cluster in magnetic turbulence.

TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Registration and abstract submission are open
- Pre-meeting mini-workshops on Sunday, August 7

DISCUSSION AND CONCLUSIONS

- Nearly all explanations for the radio excess are difficult:
  - Why is the X-Ray emission so dim?
  - Why is the signal so diffuse?
- The most straightforward method to explain this emission is to produce the radio excess in the most largest objects.
  - Dark Matter annihilation can be dominated by clusters.
  - Alfven Reacceleration from merger shocks occur primarily in clusters.
- We have seen a number of radio halos with the intensity and spectrum necessary to explain the excess.