Title: Rewriting the Thermal History of the Universe: The Cosmological Implications of TeV Blazars

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Abstract: A recently discovered class of active galactic nuclei, TeV luminous blazars, constitute a small fraction of the power output of black holes. Nevertheless, there are suggestions that unlike the UV and X-ray luminosity of quasars, the very-high energy gamma-ray emission from the TeV blazars can be thermalized on cosmological scales with order unity efficiency, resulting in a potentially dramatic heating of the low-density intergalactic medium. The way in which this occurs, however, imparts a variety of peculiar properties to this novel heating source, resulting in a number of robust cosmological consequences. I will discuss the process by which TeV blazars heat the Universe, the strange properties that this heating has, and the variety of signatures that it has left behind, many of which have already been observed!

# Rewriting the Thermal History of the Universe:
## The Cosmological Implications of TeV Blazars

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Philip Chang

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Volker Springel

PI Cosmology Seminar, October11th, 2011

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- The extragalactic TeV Universe
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  - The Intergalactic magnetic field
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  - Heating the Universe
  - High-z Ly$\alpha$ forest
  - Galaxy cluster observations
  - Missing dwarf galaxies
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  - Galaxy [illegible]
  - Missing dwarf galaxies
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***Luminous TeV sources are critical to understanding the cosmic history of the low-density Universe!***

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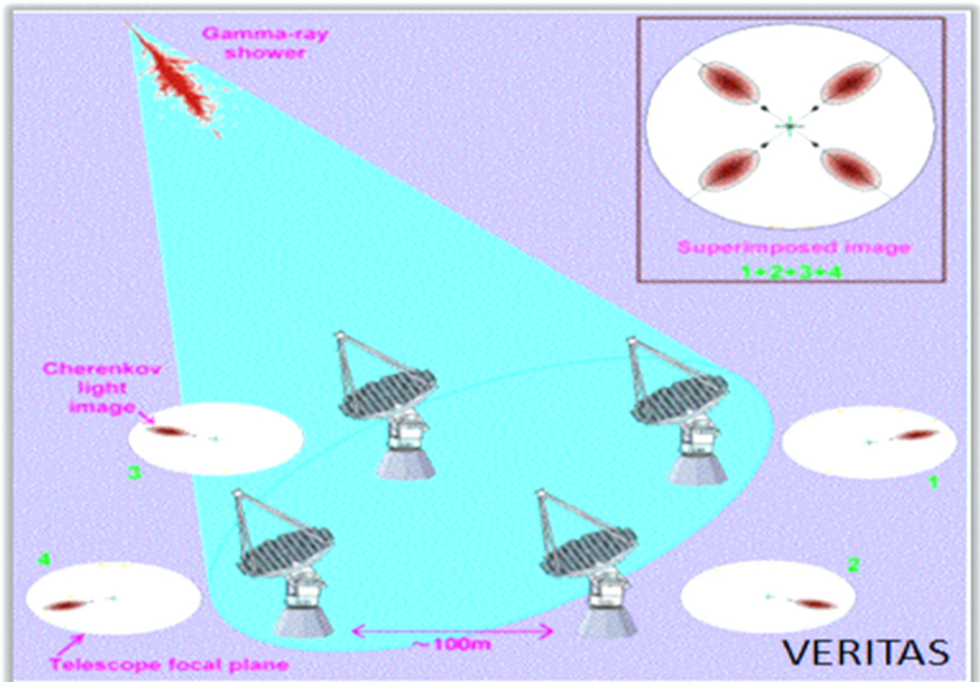
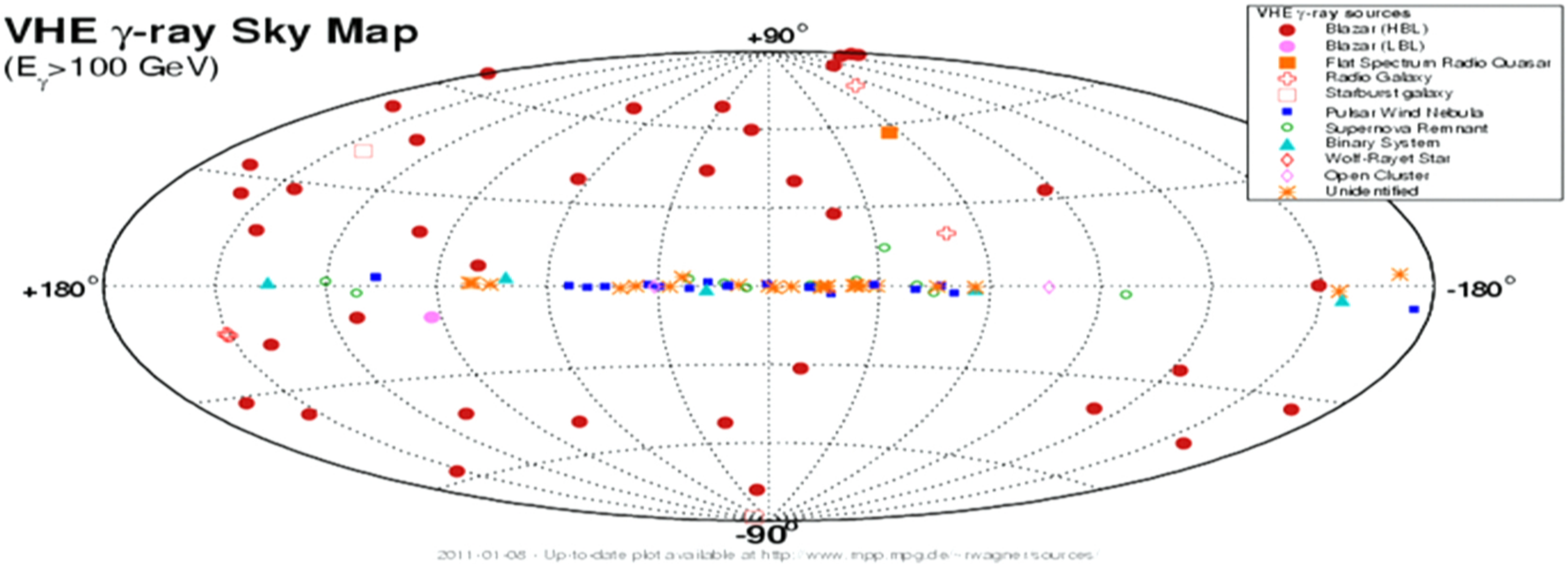
# Studying the TeV Universe

- Cerenkov Telescope Arrays (H.E.S.S., MAGIC, VERITAS)
  - VHEGRs: 100 GeV – 10 TeV
  - Low sensitivities
    → pointed observations

# The TeV Sky


VHE γ-ray Sky Map
(E$_\gamma$>100 GeV)
+90°
-90°
+180°
-180°
VHE γ-ray sources
Blazar (HBL)
Blazar (LBL)
Flat Spectrum Radio Quasar
Radio Galaxy
Starburst galaxy
Pulsar Wind Nebula
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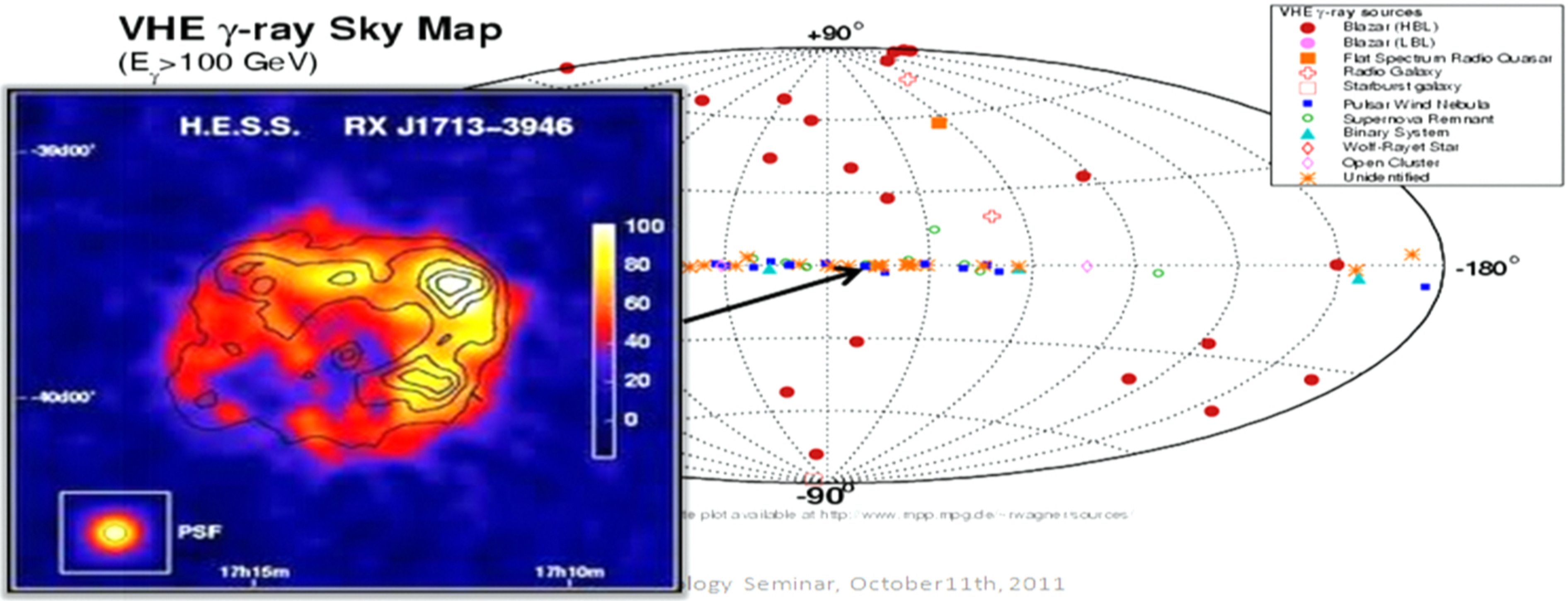


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# TeV Sources with Measured Spectra

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AEB, Chang & Pfrommer (2011)

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  - 100 MeV – 100 GeV
  - 100's of sources
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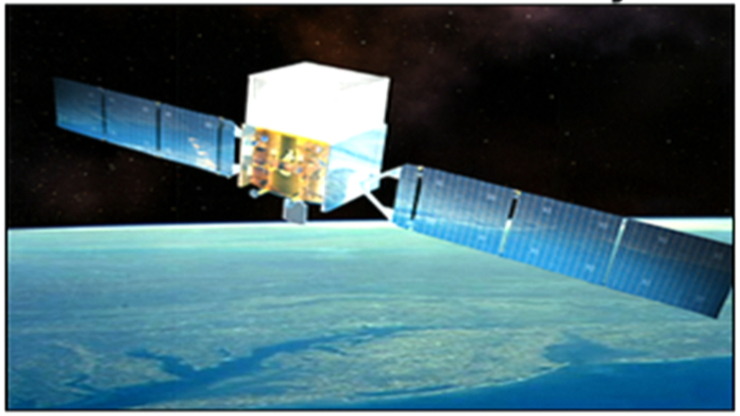

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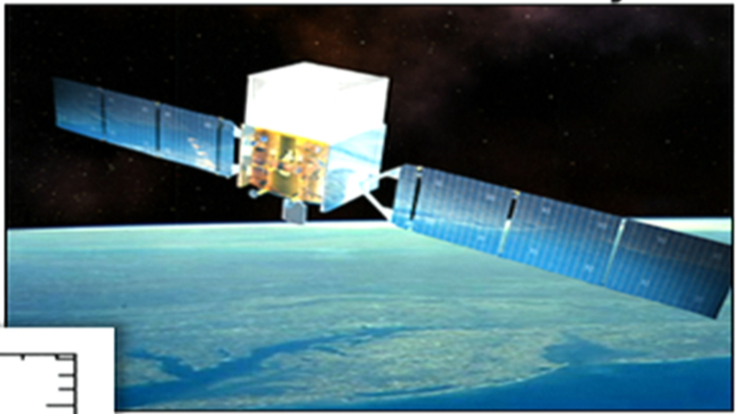

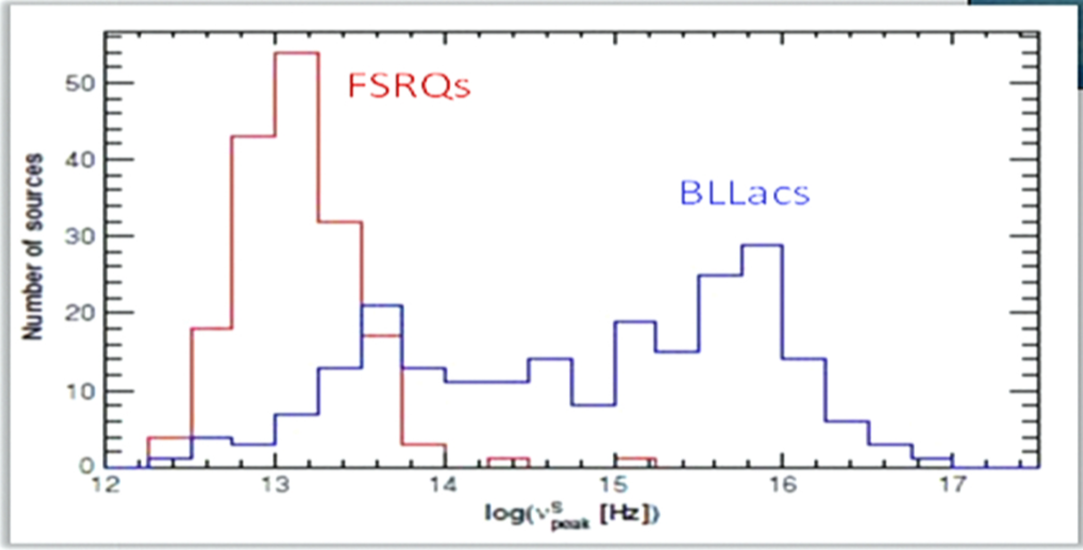


Abdo et al. 2010, ApJ, 715, 429

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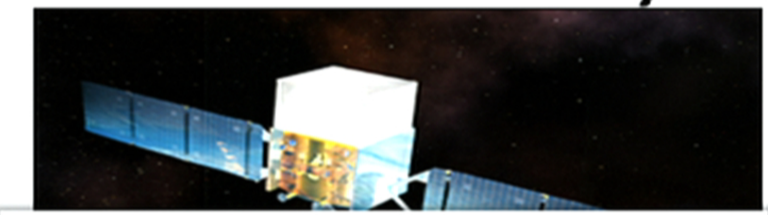

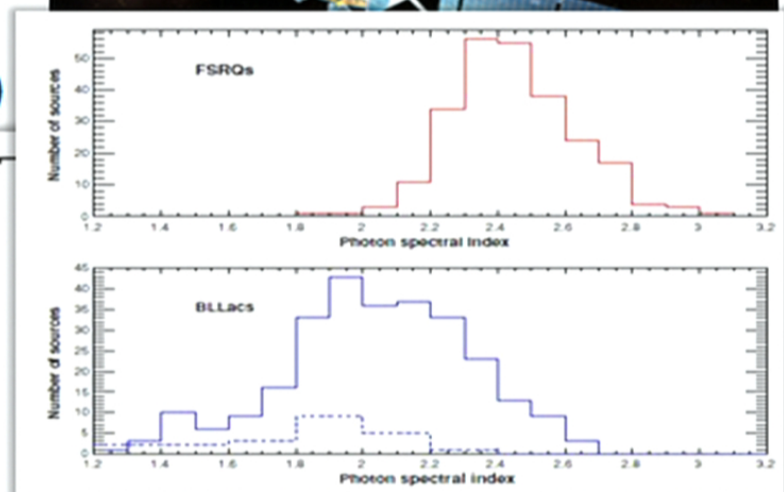


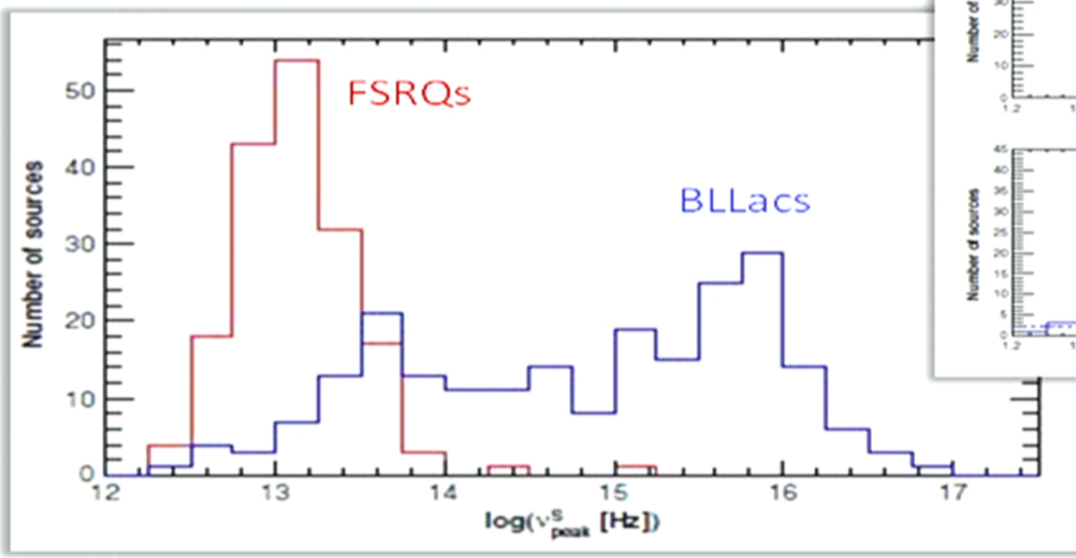


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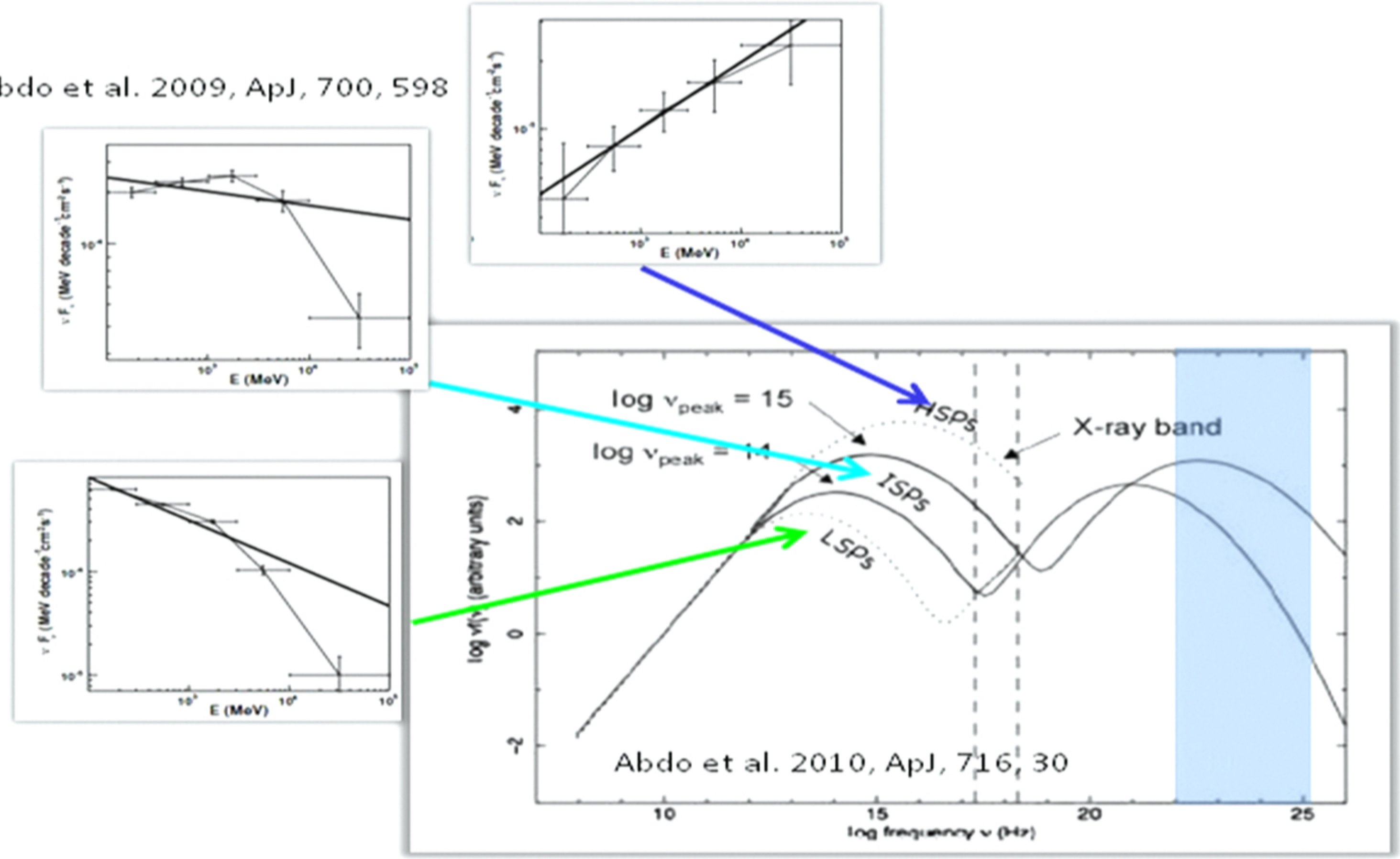
# Flavours of Fermi BL Lacs

Abdo et al. 2009, ApJ, 700, 598



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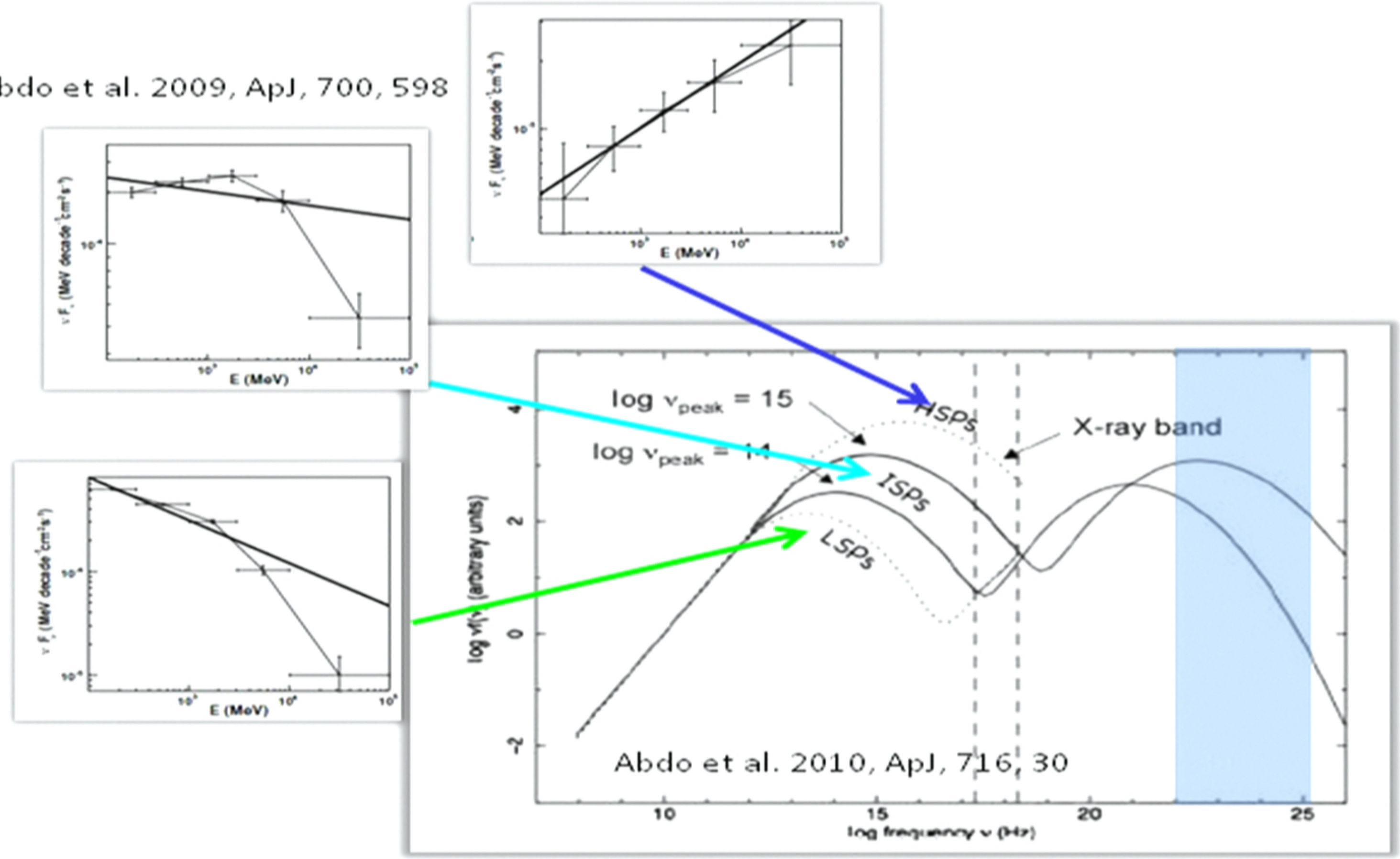

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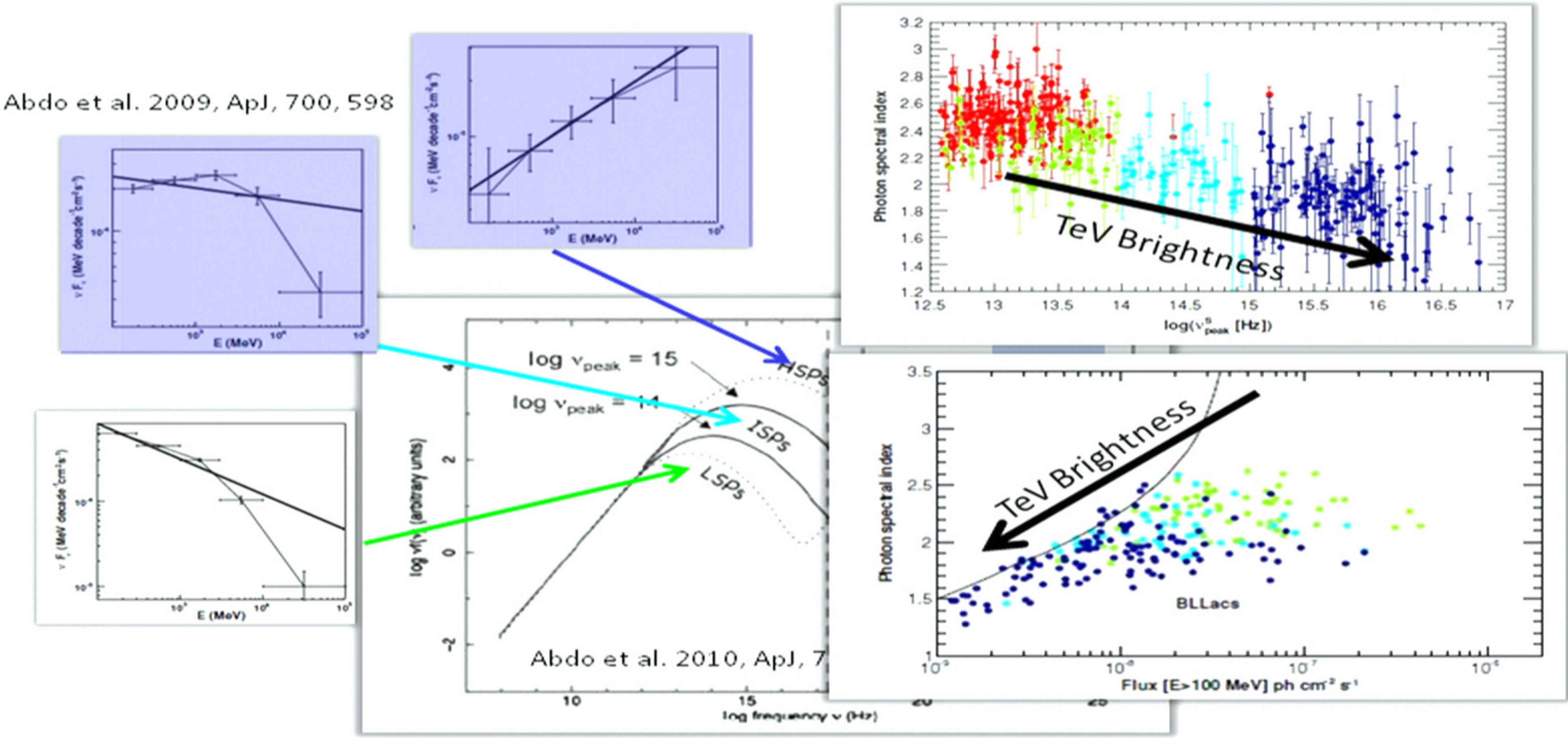

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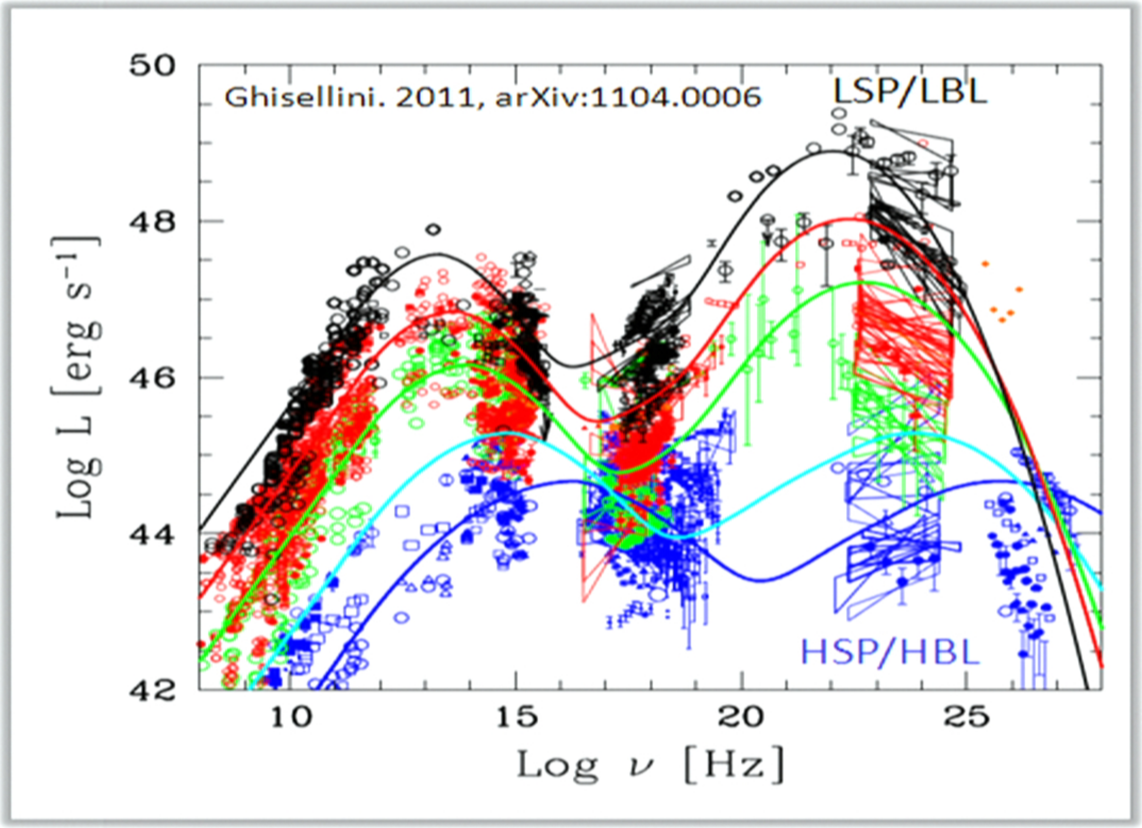


- Continuous sequence from LSP to HSP
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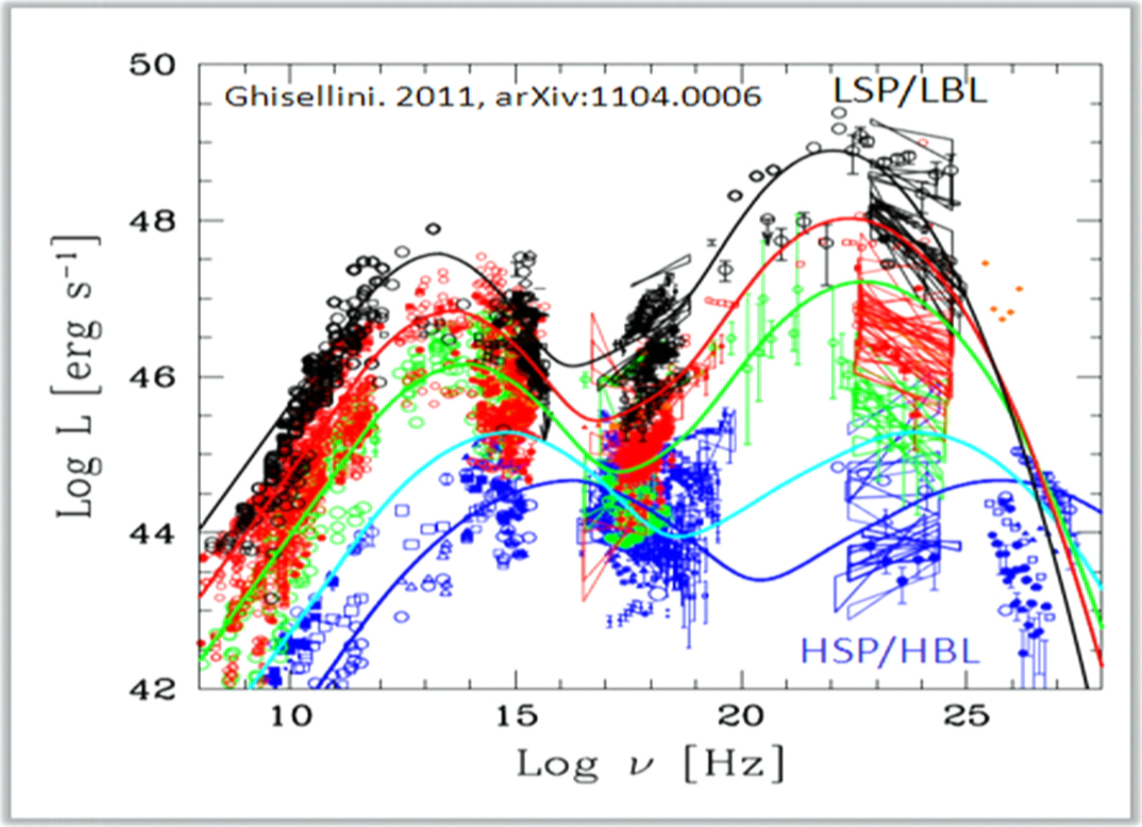


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# What are all the bright TeV sources?

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| PKS 2005-489 | 0.071 | 300 | 0.1 | 1 | 4.0 | 8.0 | 44.0 | 3.56 | $2.3 \times 10^4$ | H | Aharonian et al. (2005) |
| MAGIC J0223+430 | – | – | 17.4 | 0.3 | 3.1 | 7.6 | – | $< 3.1$ | – | R | Aliu et al. (2009) |
| 1ES 0229+200 [j] | 0.140 | 590 | 0.7 | 1 | 2.5 | 6.4 | 44.5 | 1.51 | $4.7 \times 10^2$ | H | Aharonian et al. (2007c) |
| PKS 1424+240 | $< 0.66$ | $< 2400$ | 51 | 0.2 | 3.8 | 6.3 | $< 46.1$ | $> 1.42$ | 4.0 | I | Acciari et al. (2010b) |
| M87 | 0.0044 | 19 | 0.74 | 1 | 2.31 | 5.9 | 41.4 | 2.29 | $1.5 \times 10^6$ | R | Acciari et al. (2008) |
| BL Lacertae | 0.069 | 290 | 0.3 | 1 | 3.09 | 5.4 | 43.8 | 2.67 | $8.4 \times 10^3$ | L | Albert et al. (2007a) |
| H 2356-309 | 0.165 | 690 | 0.3 | 1 | 3.09 | 5.4 | 44.6 | 1.86 | $6.5 \times 10^2$ | H | Aharonian et al. (2006) |
| PKS 0548-322 [j] | 0.069 | 290 | 0.3 | 1 | 2.86 | 4.0 | 43.7 | 2.44 | $8.4 \times 10^3$ | H | Aharonian et al. (2010) |
| Centaurus A | 0.0028 | 12 | 0.245 | 1 | 2.73 | 2.8 | 40.7 | 2.72 | $1.2 \times 10^7$ | R | Raue et al. (2010) |

[a] Comoving distance in units of Mpc
[b] Normalization of the observed photon spectrum that we assume to be of the form $dN/dE = f_0(E/E_0)^{-\alpha}$, in units of $10^{-12}$ cm$^{-2}$ s$^{-1}$ TeV$^{-1}$
[c] Energy at which we normalize the spectrum, in units of TeV
[d] Observed spectral index at $E_0$
[e] Integrated energy flux between 100 GeV and 10 TeV, in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$
[f] Inferred isotropic integrated luminosity between 100 GeV and 10 TeV, in units of erg s$^{-1}$
[g] Inferred intrinsic spectral index at $E_0$
[h] Time delay after which plasma beam instabilities dominate inverse-Compton cooling, in units of yr
[i] H, I, L, Q, and R correspond to high-energy, intermediate-energy, low-energy peaked BL Lacs, flat spectrum radio quasars, and radio galaxies of Faranoff-Riley Type I (FR I), respectively
[j] Used to place limits upon the IGMF

AEB, Chang & Pfrommer (2011)

# Where are all the bright TeV sources?

Tabl[e]
List of TeV Sources with Measured Spectral Prop[erties]

| Name | $z$ | $D_C$ [a] | $f_0$ [b] | $E_0$ [c] | $\alpha$ [d] | $F$ [e] |
|---|---|---|---|---|---|---|
| Mkn 421 | 0.030 | 129 | 68 | 1 | 3.32 | $1.7 \times 10^3$ |
| 1ES 1959+650 | 0.047 | 201 | 78 | 1 | 3.18 | $1.6 \times 10^3$ |
| 1ES 2344+514 | 0.044 | 190 | 120 | 0.5 | 2.95 | $2.3 \times 10^2$ |
| Mkn 501 [j] | 0.034 | 150 | 8.7 | 1 | 2.58 | 85 |
| 3C 279 | 0.536 | 2000 | 520 | 0.2 | 4.11 | 68 |
| PKS 2155-304 | 0.116 | 490 | 1.81 | 1 | 3.53 | 64 |
| PG 1553+113 | $> 0.09$ | $> 380$ | 46.8 | 0.3 | 4.46 | 41 |
| W Comae | 0.102 | 430 | 20 | 0.4 | 3.68 | 31 |
| 3C 66A | 0.444 | 1700 | 40 | 0.3 | 4.1 | 28 |
| 1ES 1011+496 | 0.212 | 870 | 200 | 0.2 | 4 | 26 |
| 1ES 1218+304 [j] | 0.182 | 750 | 11.5 | 0.5 | 3.07 | 24 |
| Mkn 180 | 0.045 | 190 | 45 | 0.3 | 3.25 | 20 |
| 1H 1426+428 | 0.129 | 540 | 2 | 1 | 2.6 | 20 |
| RGB J0710+591 [j] | 0.125 | 520 | 1.36 | 1 | 2.69 | 15 |
| 1ES 0806+524 | 0.138 | 580 | 6.8 | 0.4 | 3.6 | 10 |
| RGB J0152+017 [j] | 0.080 | 340 | 0.57 | 1 | 2.95 | 8.5 |
| 1ES 1101-232 [j] | 0.186 | 770 | 0.56 | 1 | 2.94 | 8.2 |
| 1ES 0347-121 [j] | 0.185 | 770 | 0.45 | 1 | 3.1 | 8.2 |
| IC 310 | 0.019 | 83 | 1.1 | 1 | 2.0 | 8.1 |
| PKS 2005-489 | 0.071 | 300 | 0.1 | 1 | 4.0 | 8.0 |
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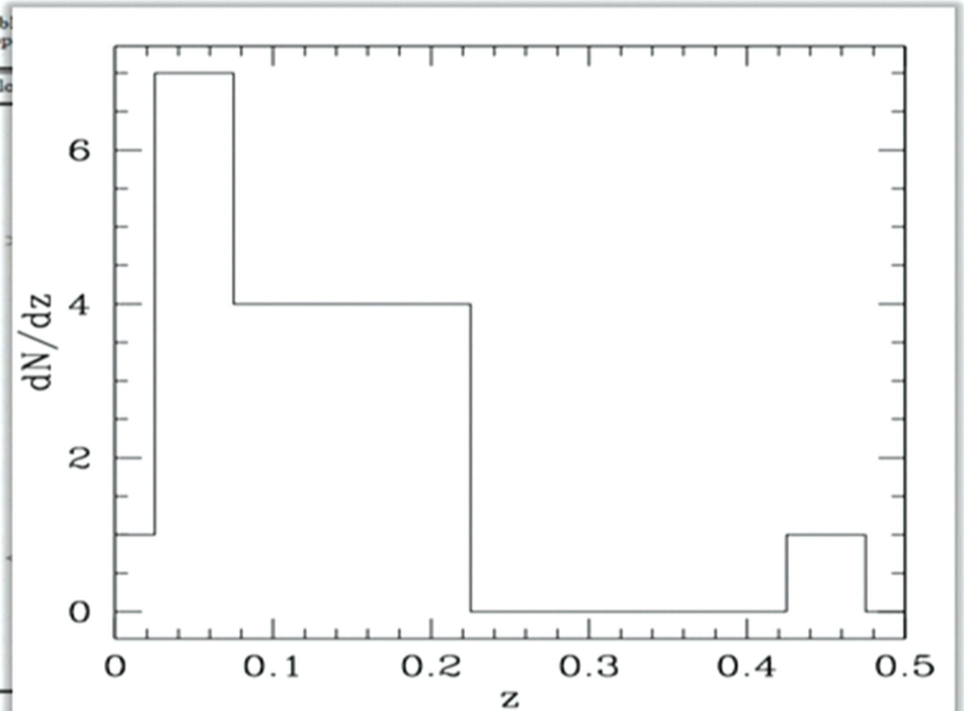
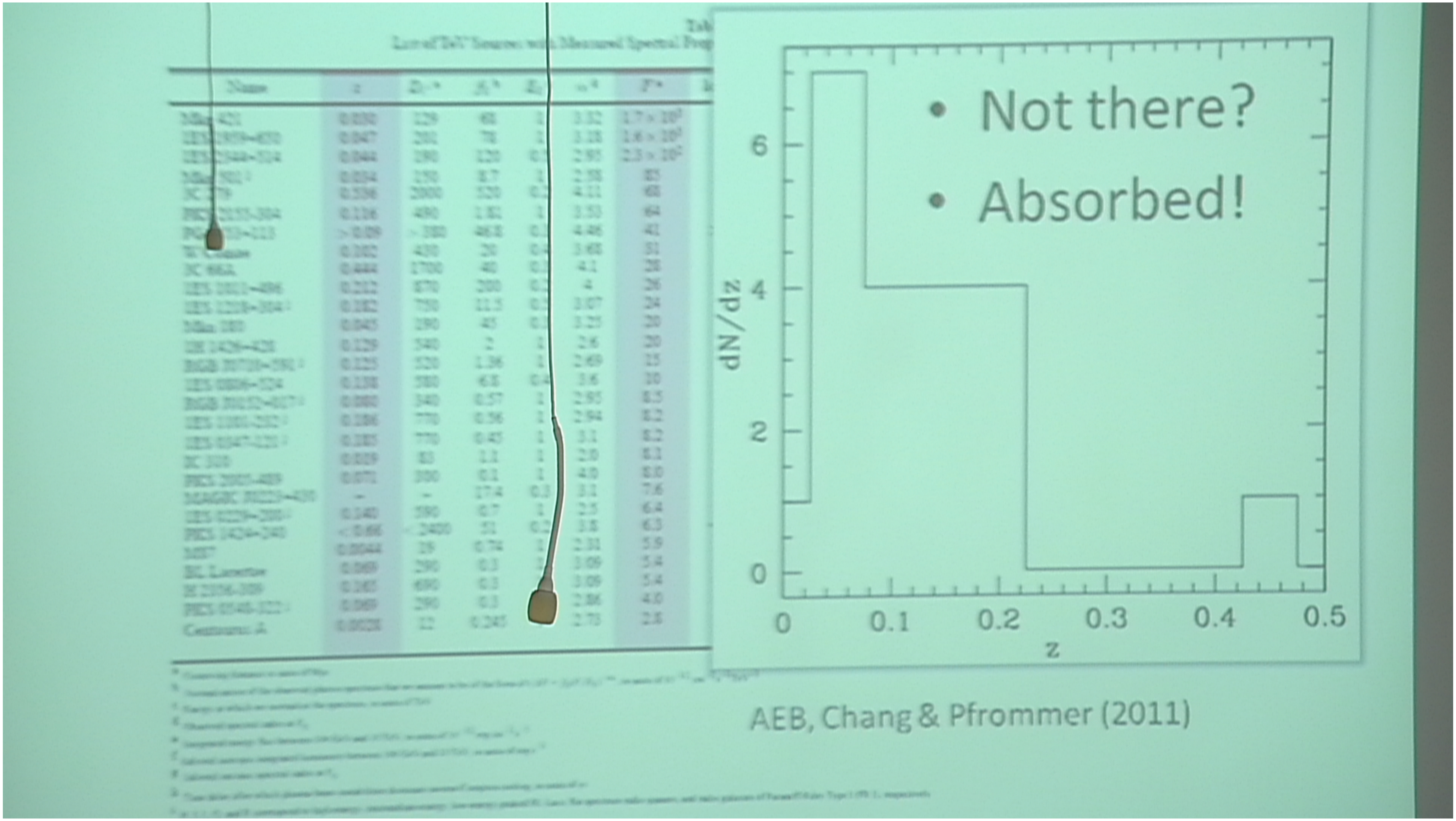


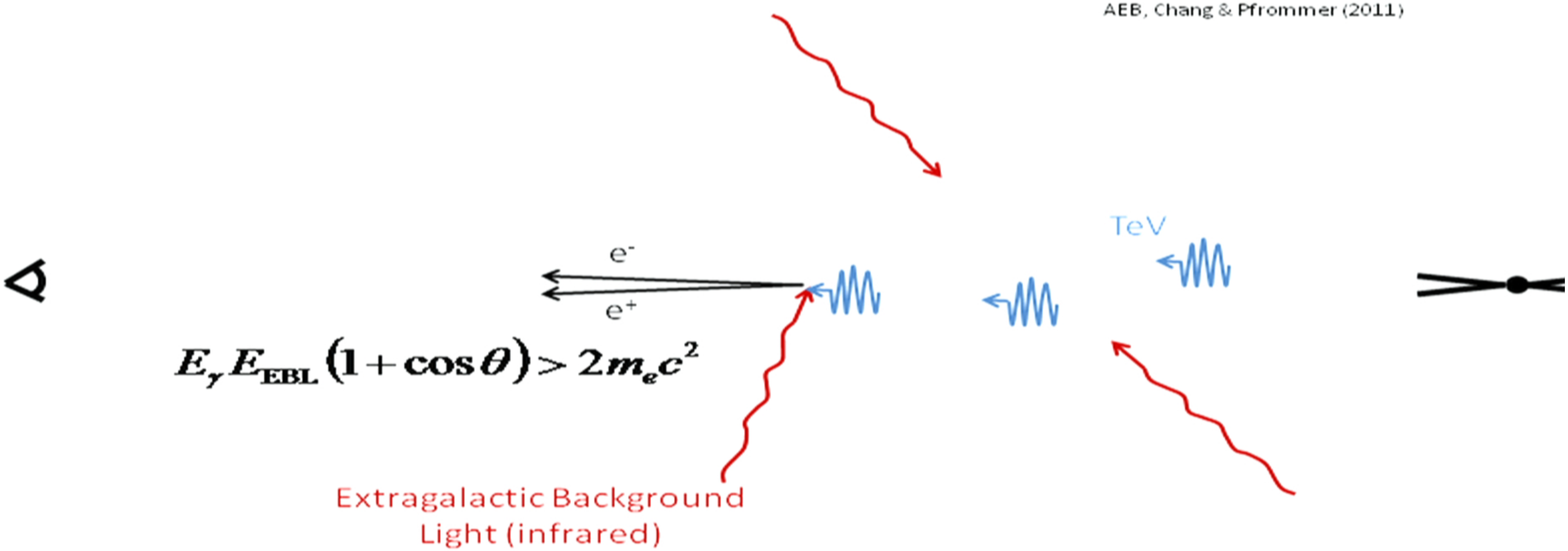

AEB, Chang & Pfrommer (2011)



• Not there?
• Absorbed!
dN/dz
0
2
4
6
0
0.1
0.2
0.3
0.4
0.5
z
AEB, Chang & Pfrommer (2011)

# Annihilation & Pair Production

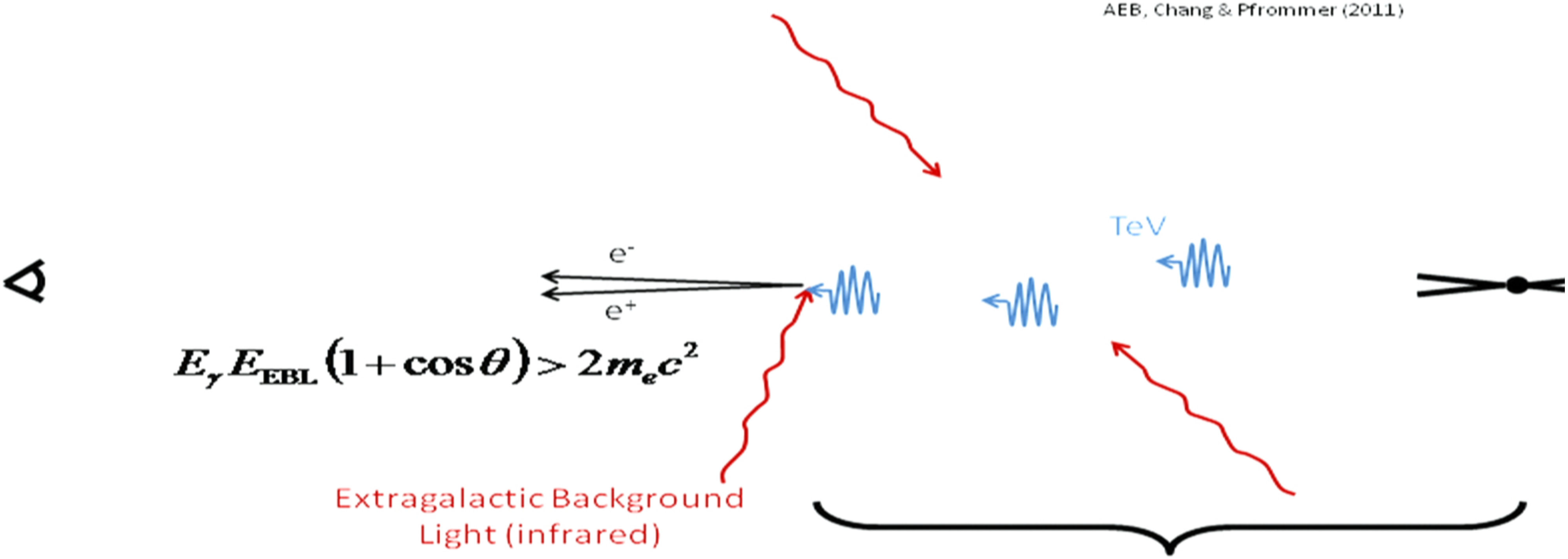
AEB, Chang & Pfrommer (2011)




$$E_\gamma E_{\mathrm{EBL}}\left(1+\cos\theta\right) > 2 m_e c^2$$

# Annihilation & Pair Production

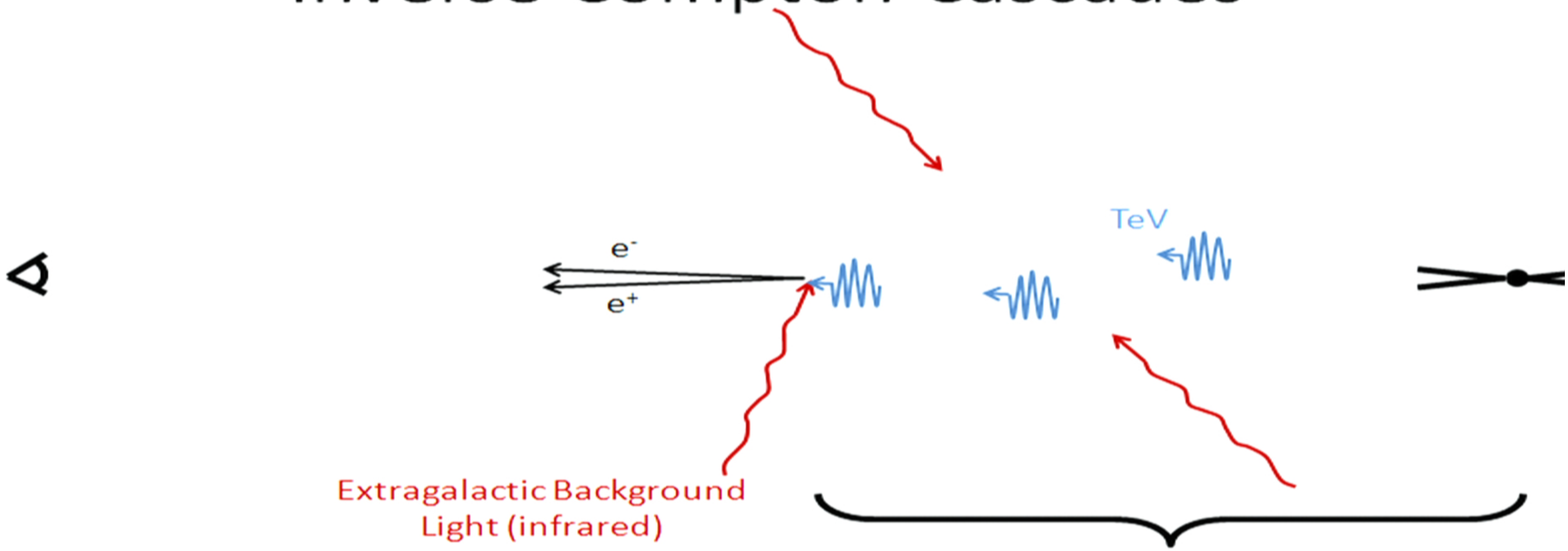
AEB, Chang & Pfrommer (2011)




$$E_\gamma E_{\rm EBL}(1+\cos\theta) > 2m_e c^2$$

$$\approx 35\left(\frac{E_\gamma}{\rm TeV}\right)^{-1} f(z)\,{\rm Mpc}$$

# What happens next?
# Inverse Compton Cascades




$$\approx 35\left(\frac{E_\gamma}{\text{TeV}}\right)^{-1} f(z)\,\text{Mpc}$$

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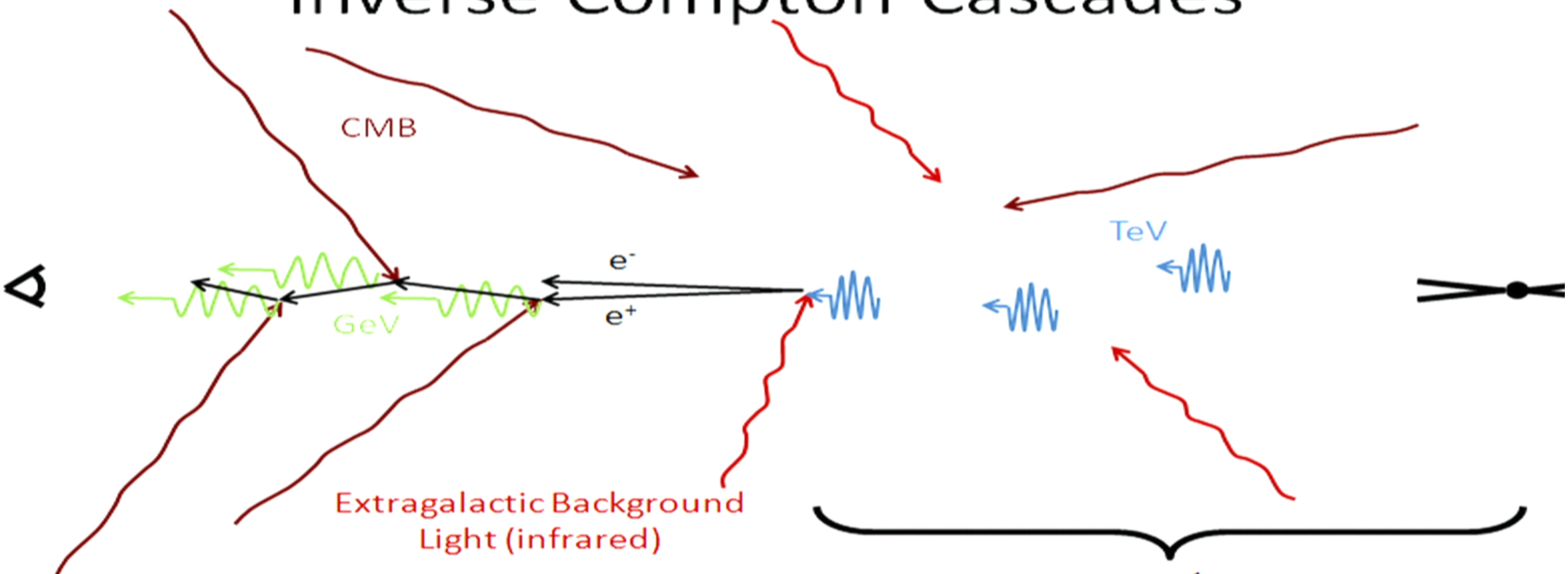
# Inverse Compton Cascades

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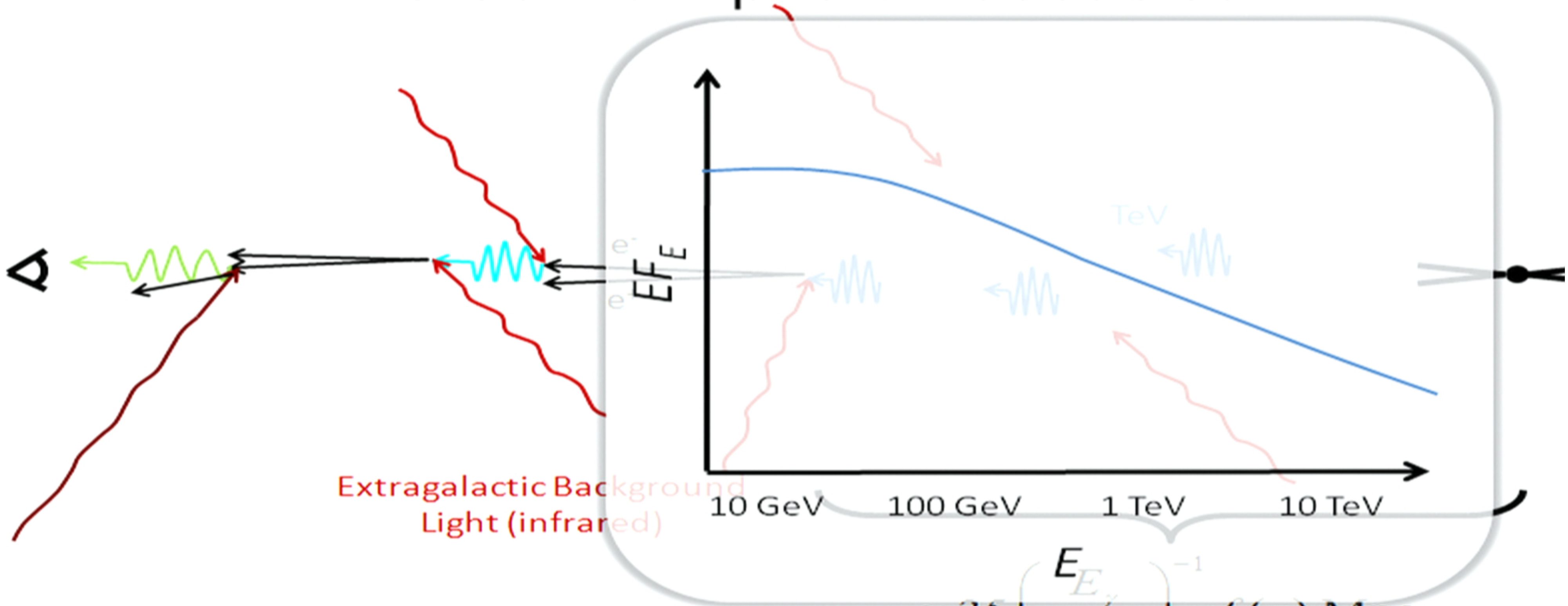
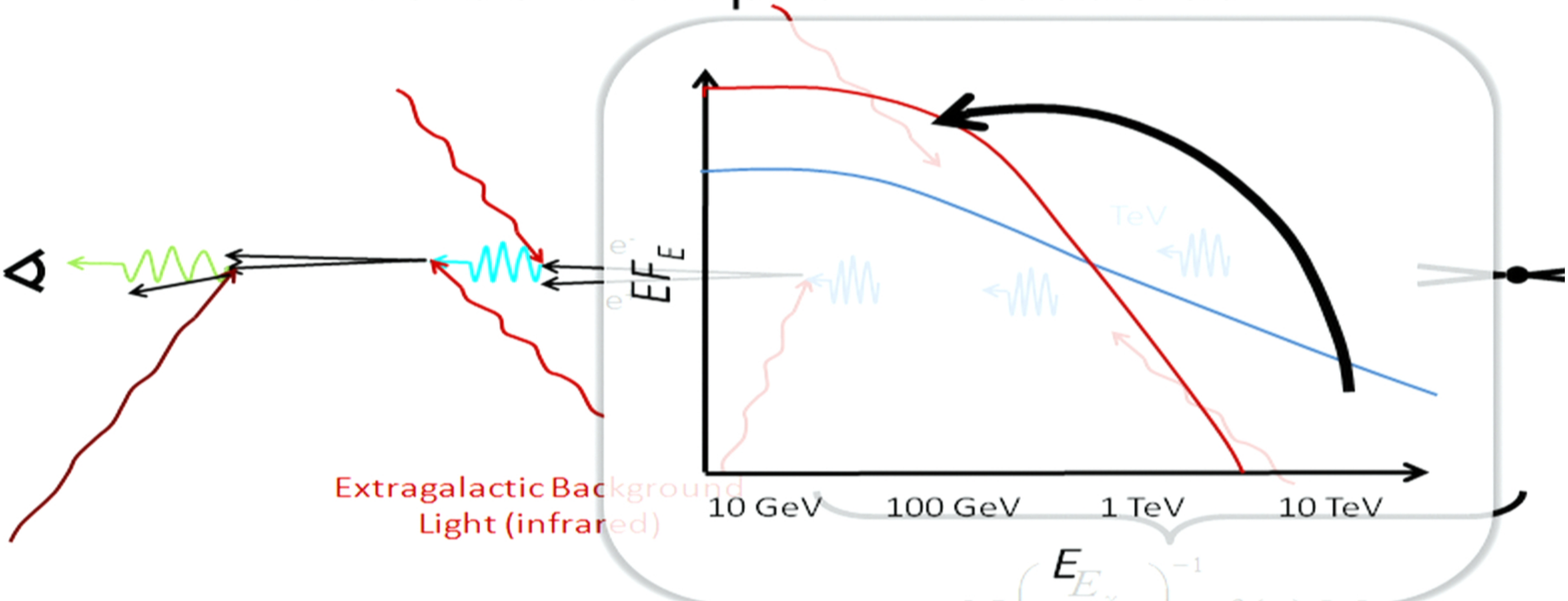
# Inverse Compton Cascades



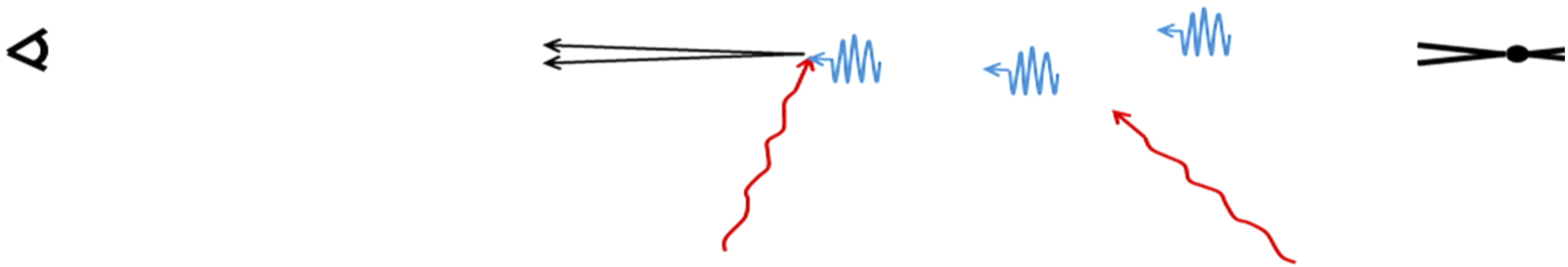

$$\approx 35 \left( \frac{E_{E_\gamma}}{\text{TeV}} \right)^{-1} f(z)\ \text{Mpc}$$

# What happens next?
# Inverse Compton Cascades




$$\approx 35 \left( \frac{E_{E_\gamma}}{\text{TeV}} \right)^{-1} f(z)\ \text{Mpc}$$

# What happens next?
# Something else ...



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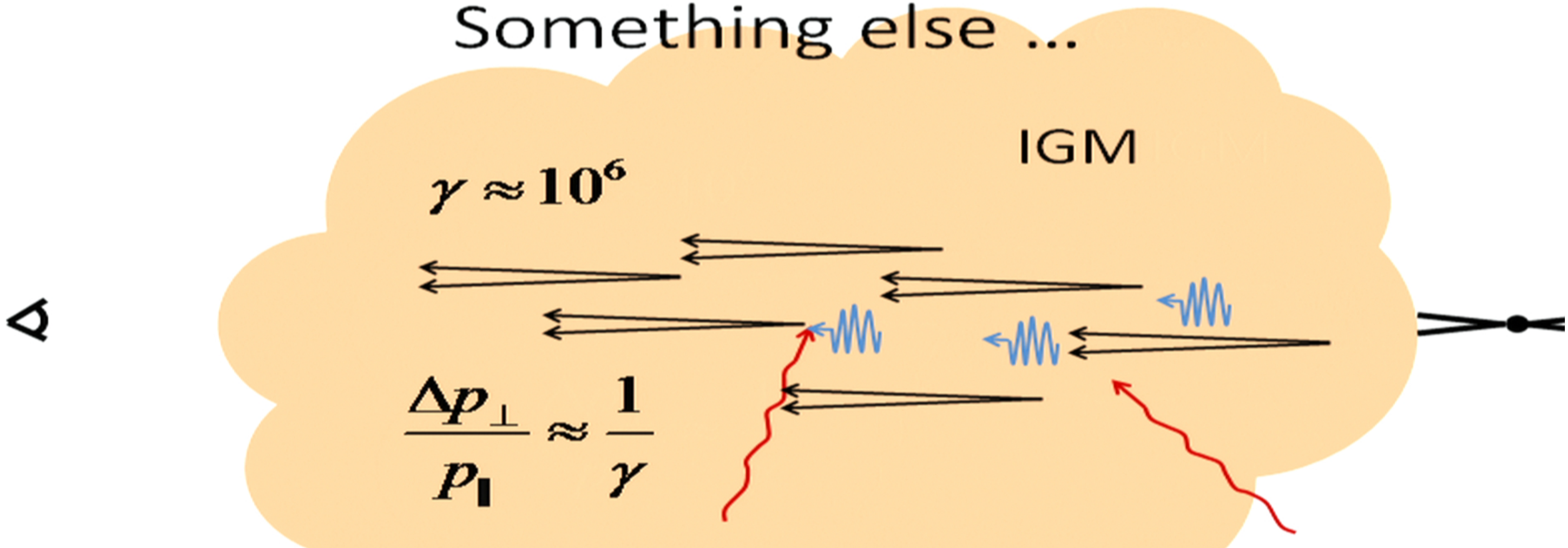
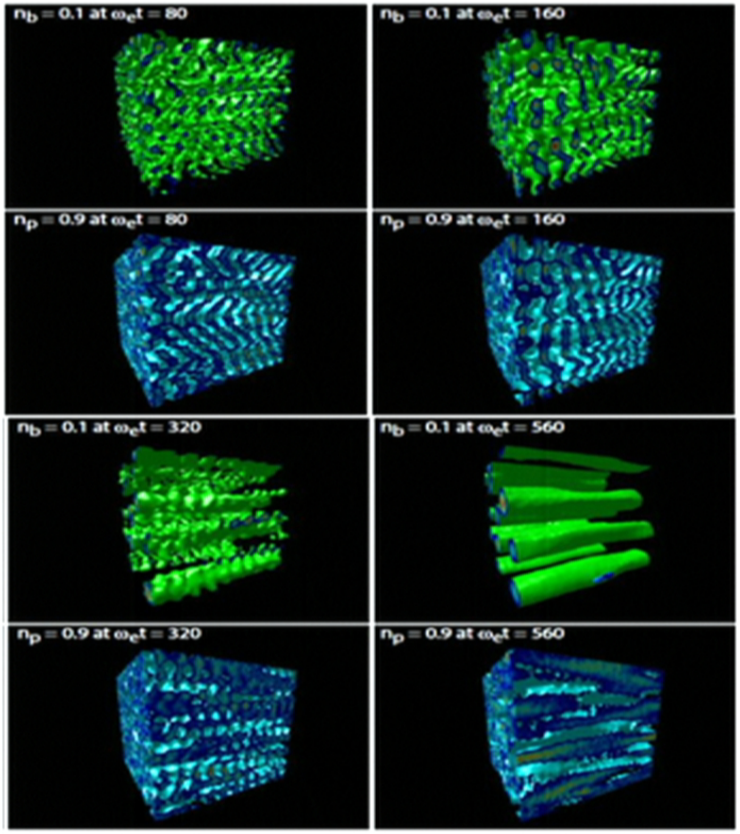
## Something else ...



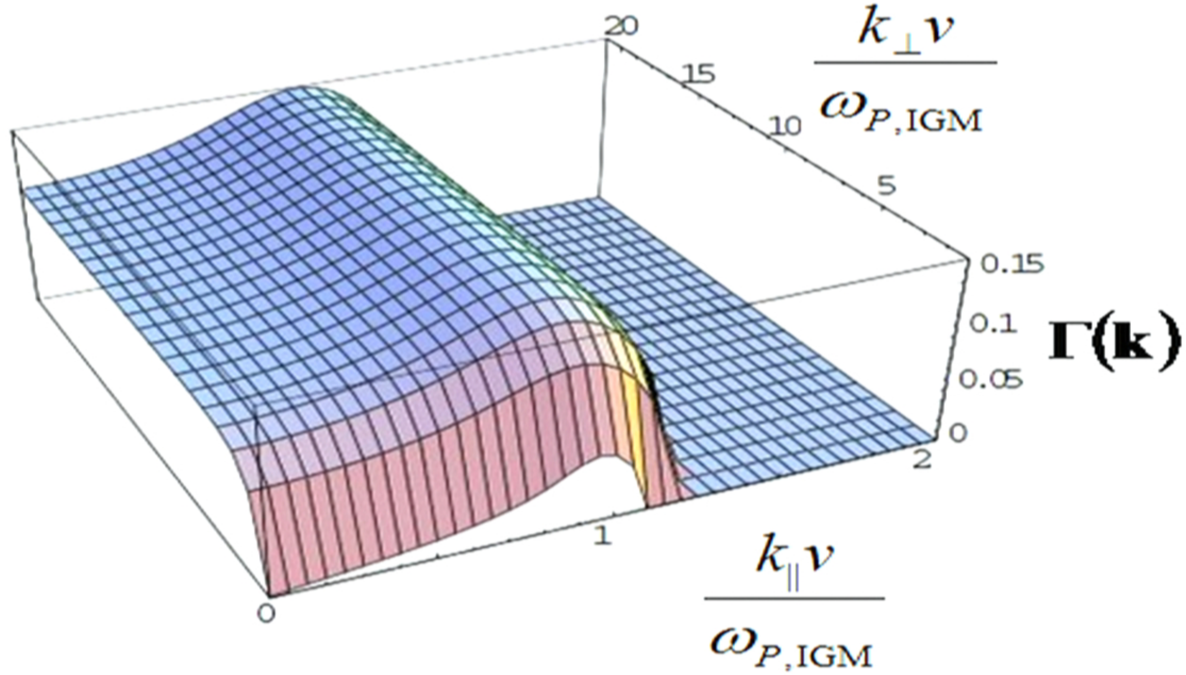

→ ***Pair plasma <u>beam</u> propagating through the IGM***

A modest hypothesis

# Plasma Beam Instabilities




Bret et al. 2010, Phys. Plasmas, 17, 120501

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A modest hypothesis

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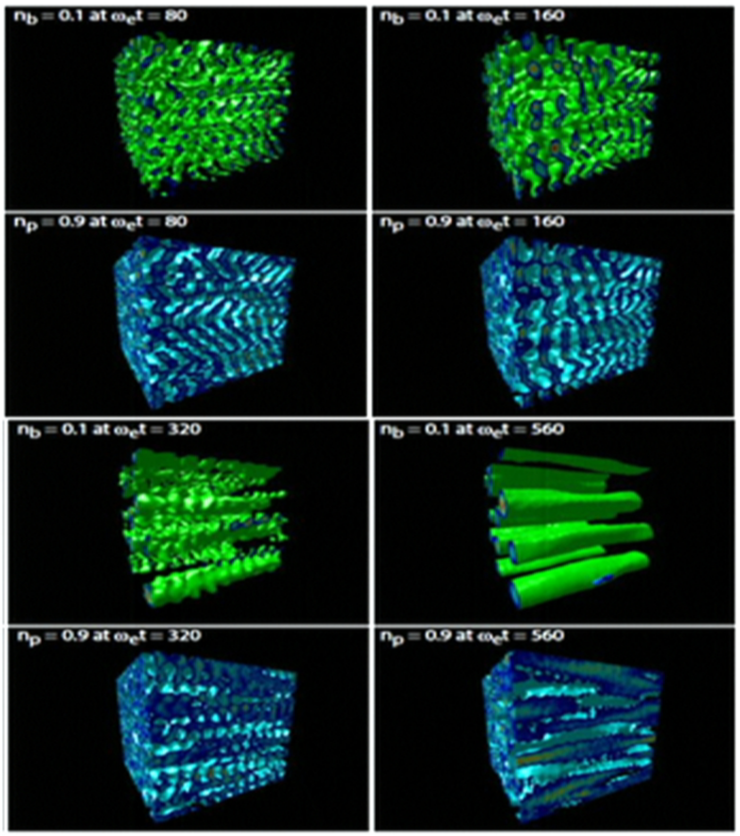


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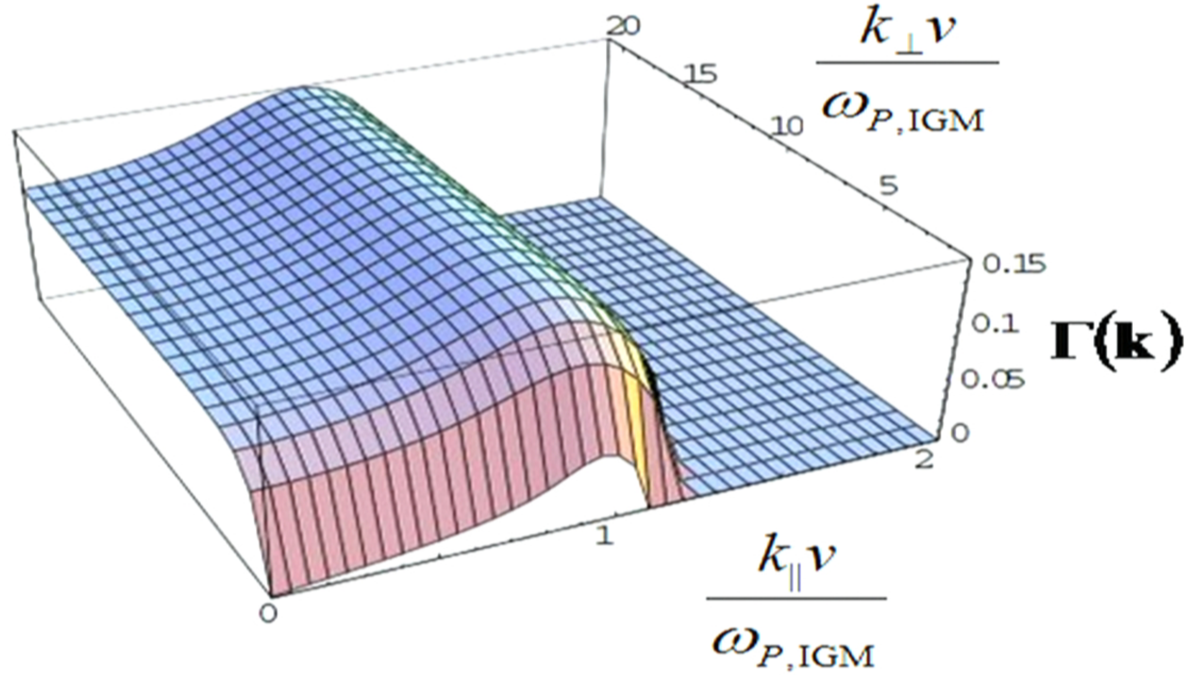


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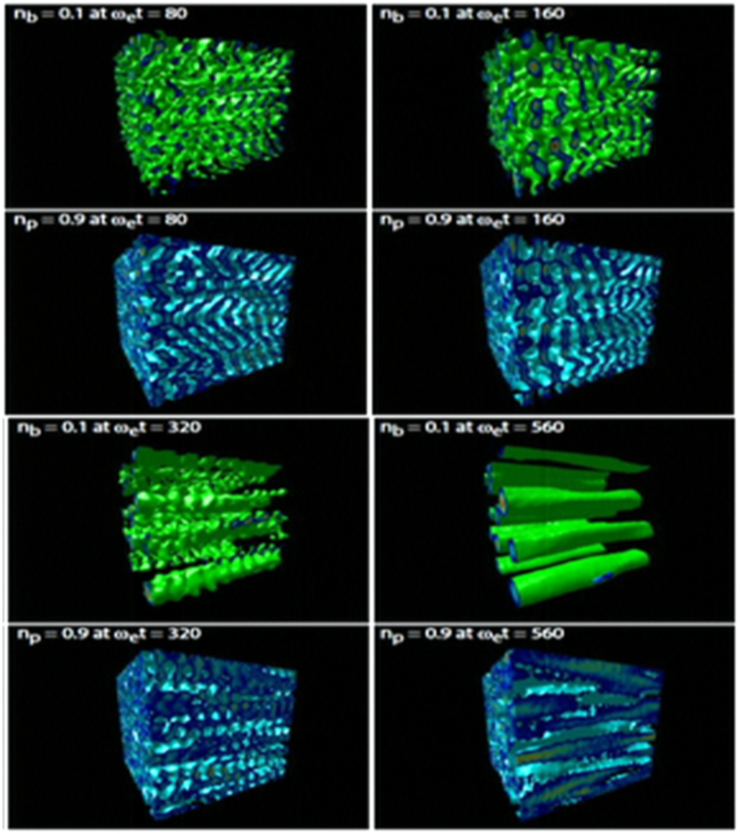


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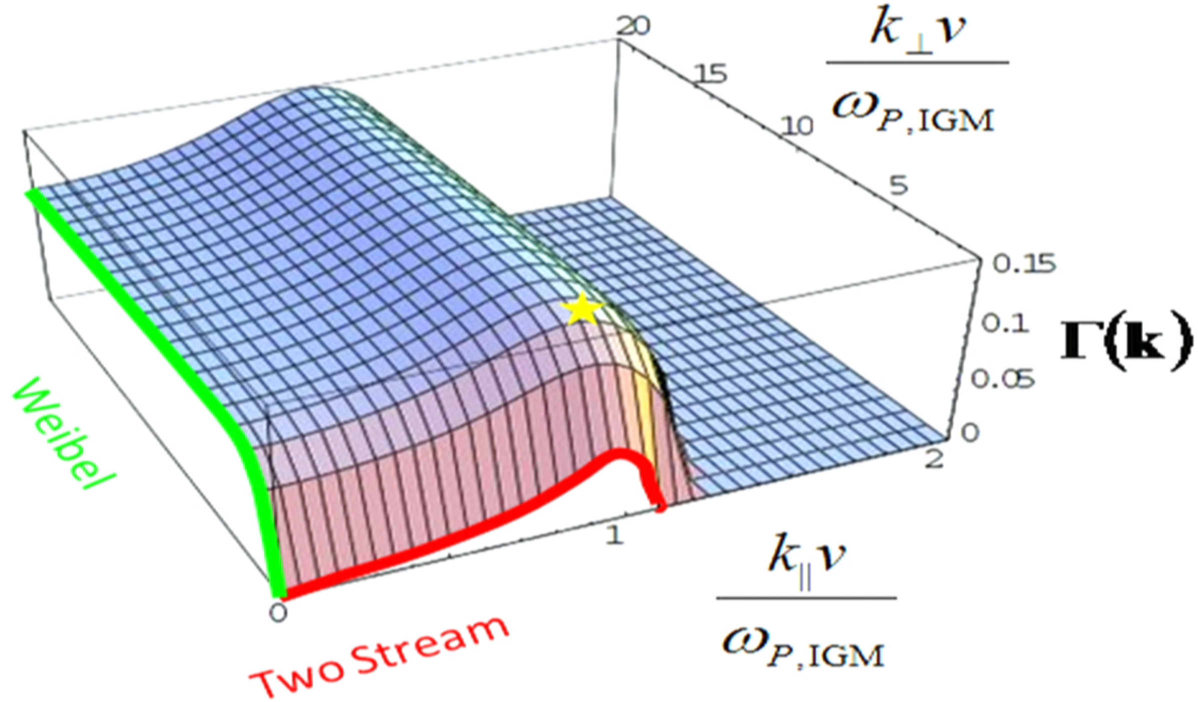


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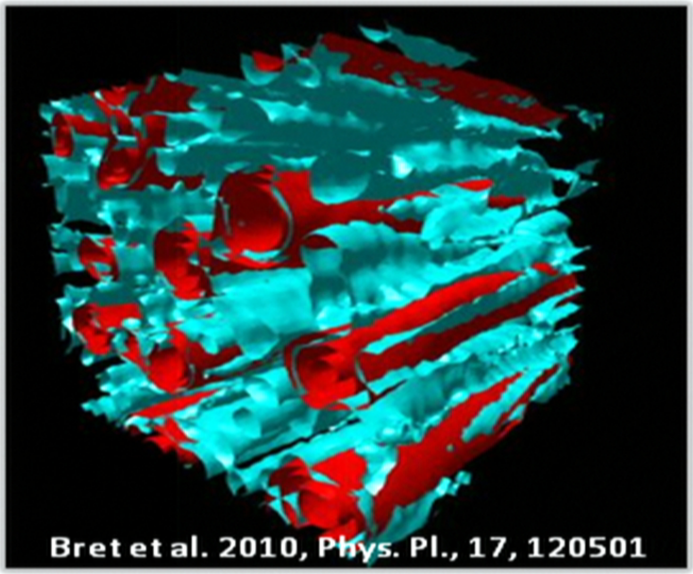
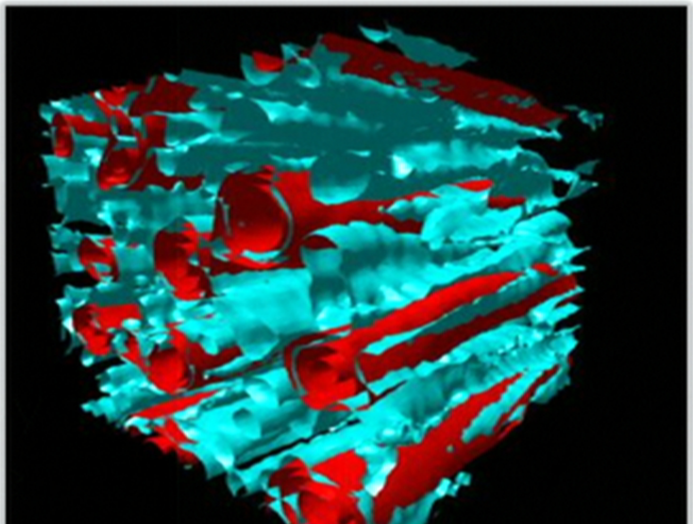
# Complications …

- Non-linear saturation:
  - Weibel well understood, saturates at equipartition
  - Where simulations done, saturate at order unity



# Complications ...

- Non-linear saturation:
  - Weibel well understood, saturates at equipartition
  - Where simulations done, saturate at order unity
  - But, maybe suppressed by non-linear parasitic mode coupling


Bret et al. 2010, Phys. Pl., 17, 120501

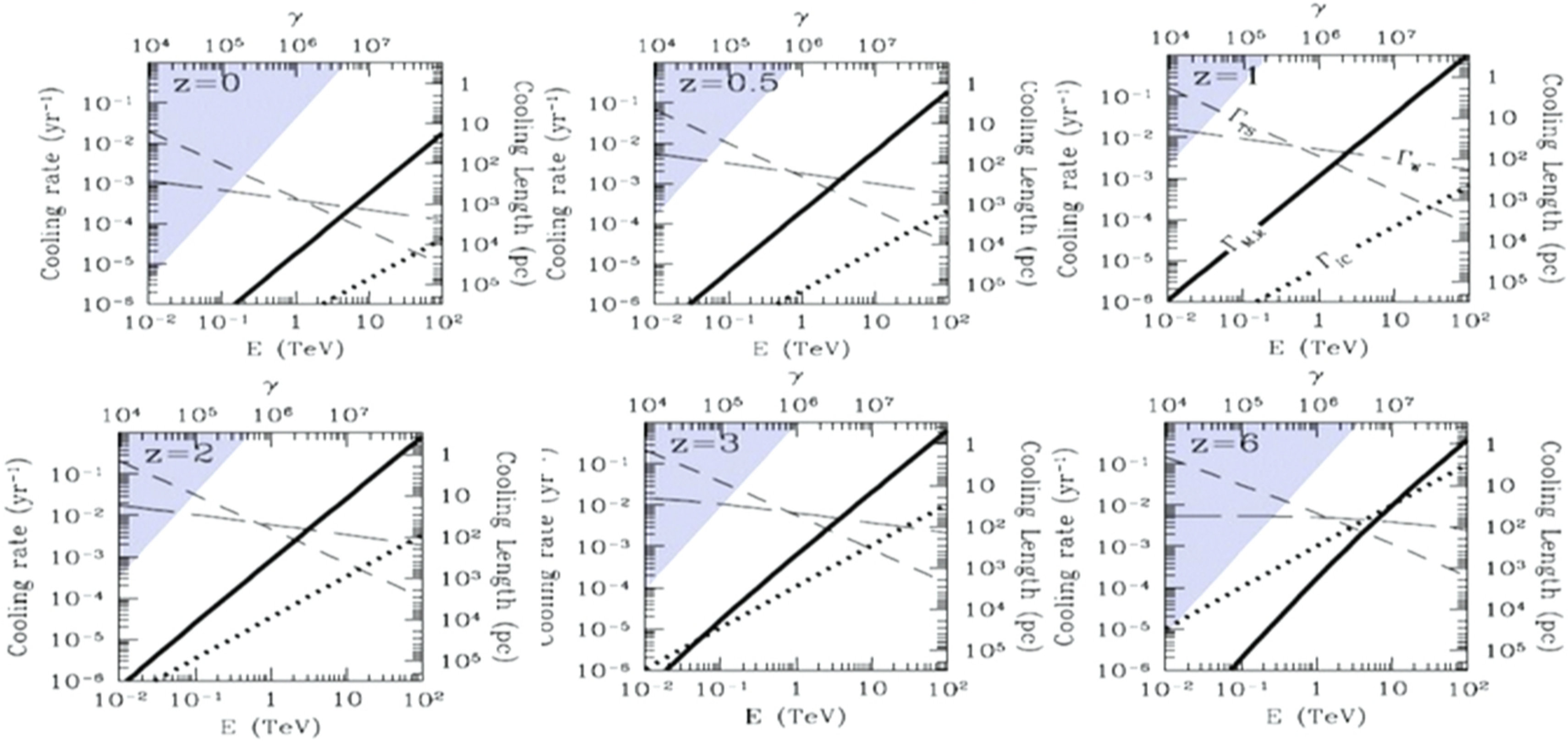
# Complications …

- Non-linear saturation:

***Assume*** *they grow at linear rate, what does that imply?*

A modest hypothesis

# Plasma Cooling Rates

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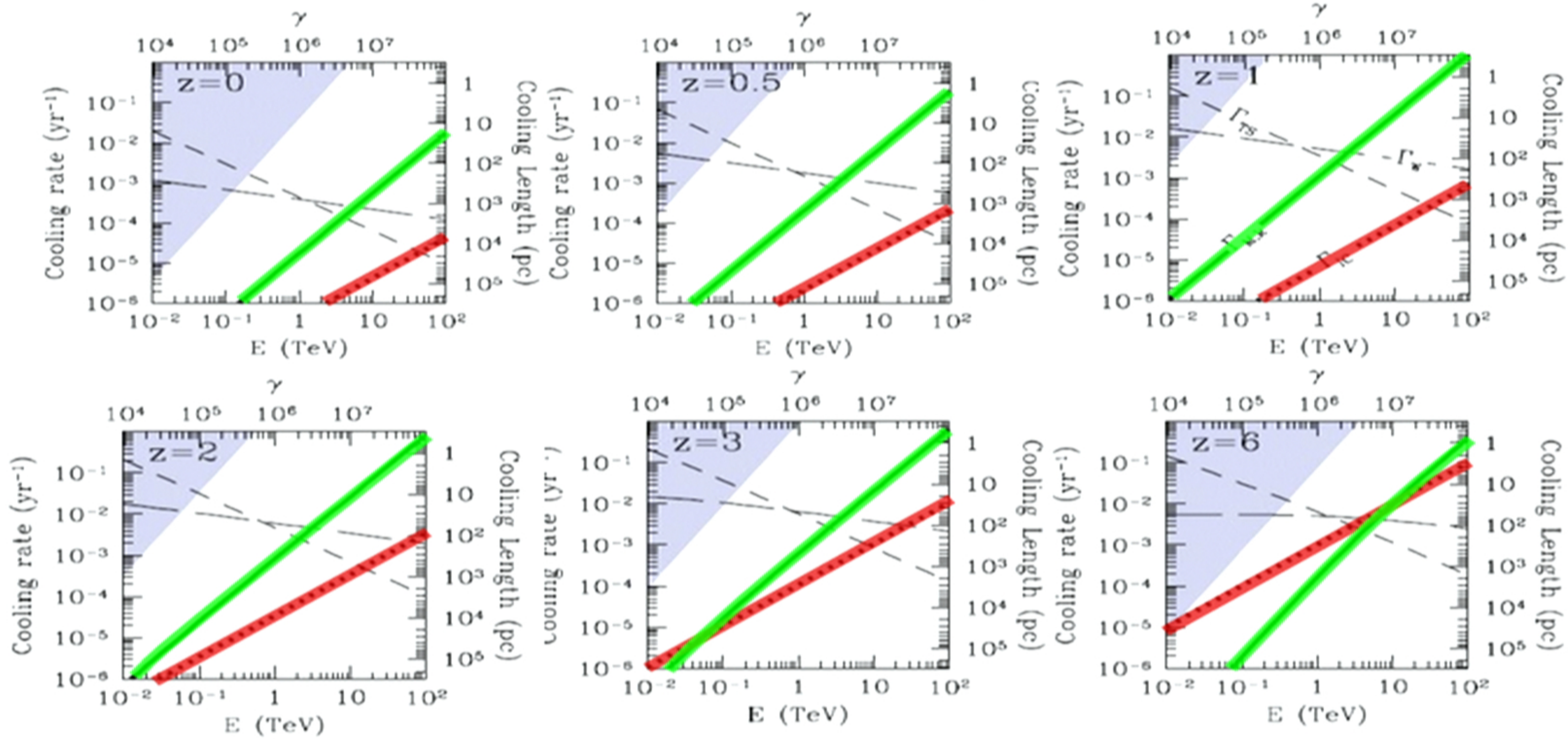


AEB, Chang & Pfrommer (2011)

# An Interesting Result

***Plasma beam instabilities, or something like them, efficiently thermalize the VHEGR emission from TeV Blazars.***

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# The Intergalactic Magnetic Field

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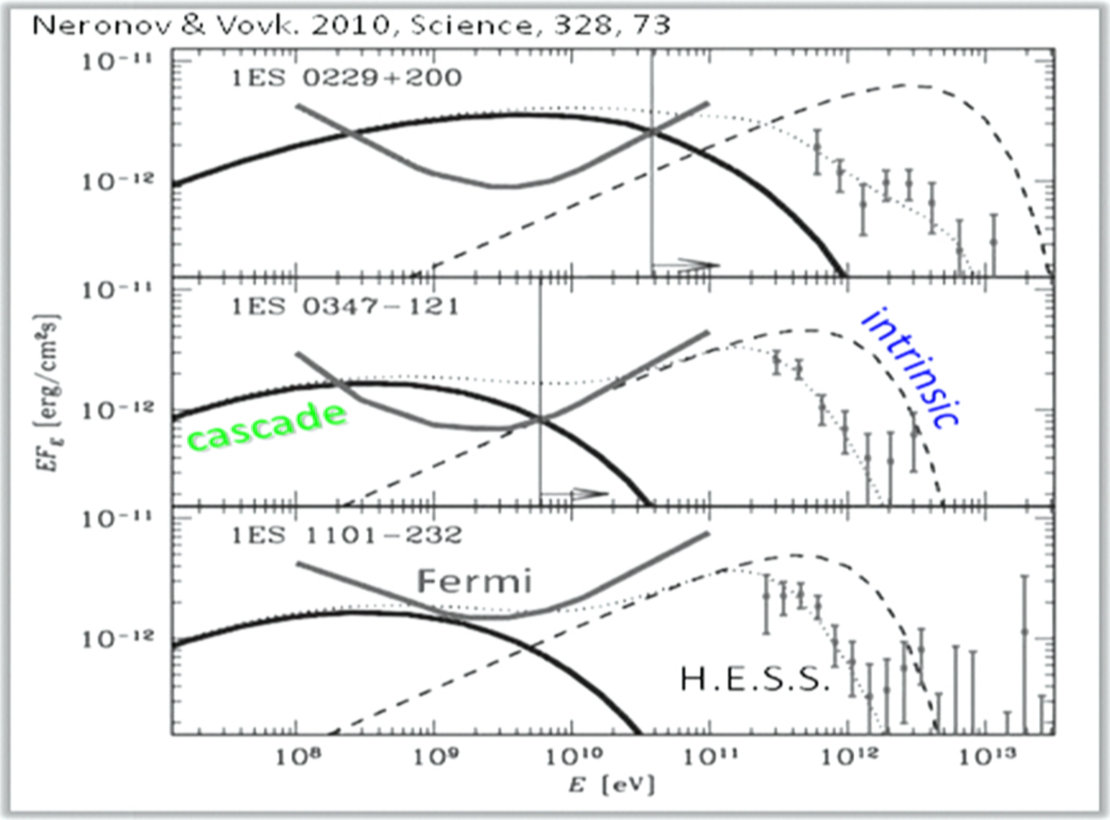
# GeV bump? What GeV bump?



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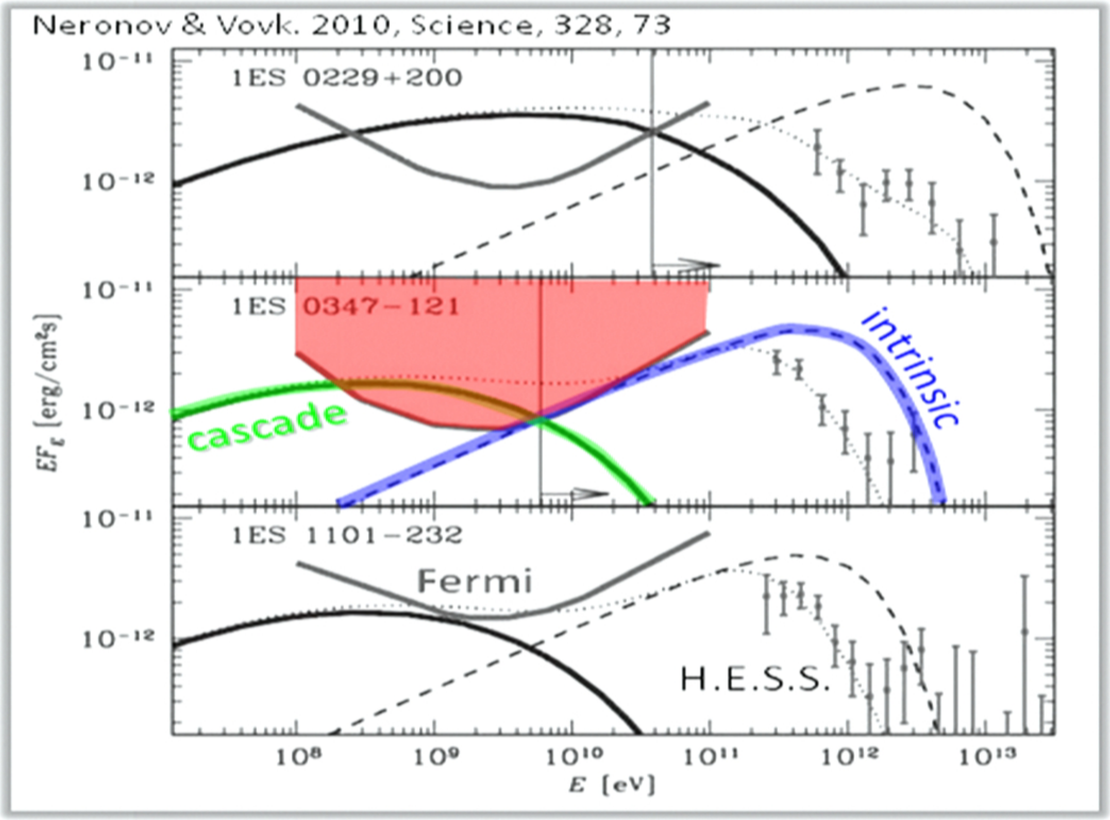

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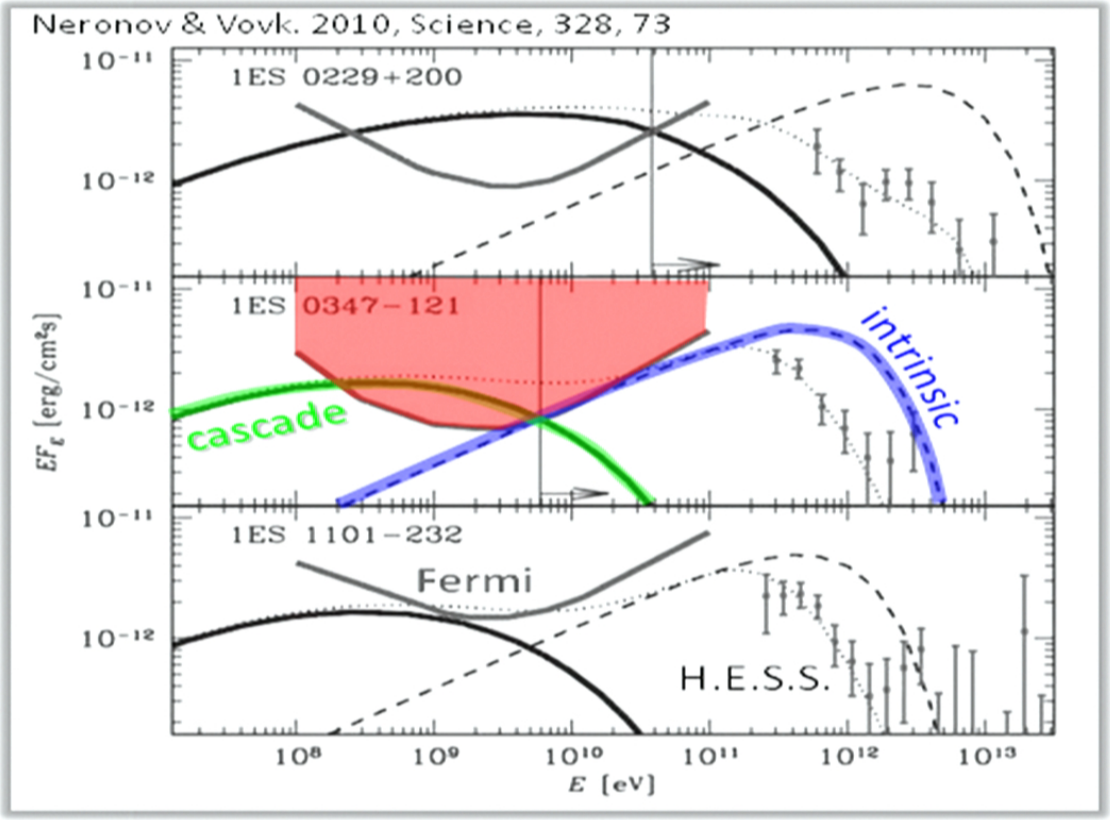

Consequences for the IGMF

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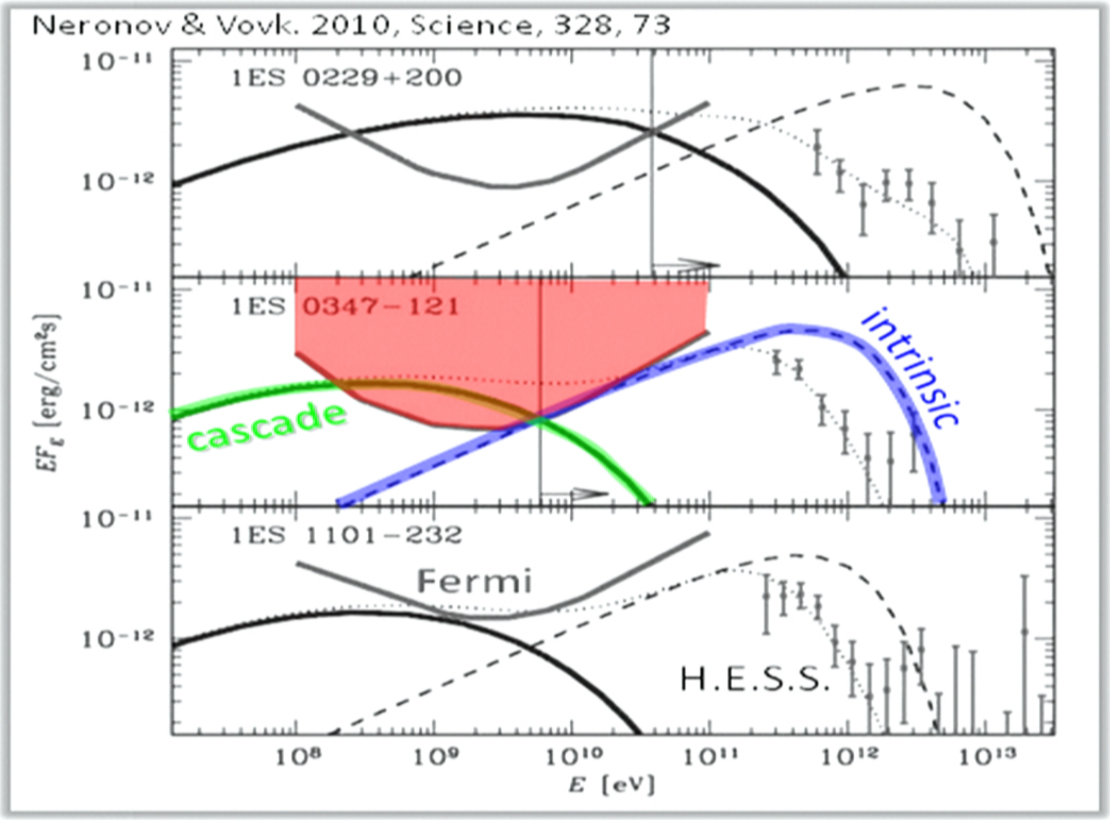
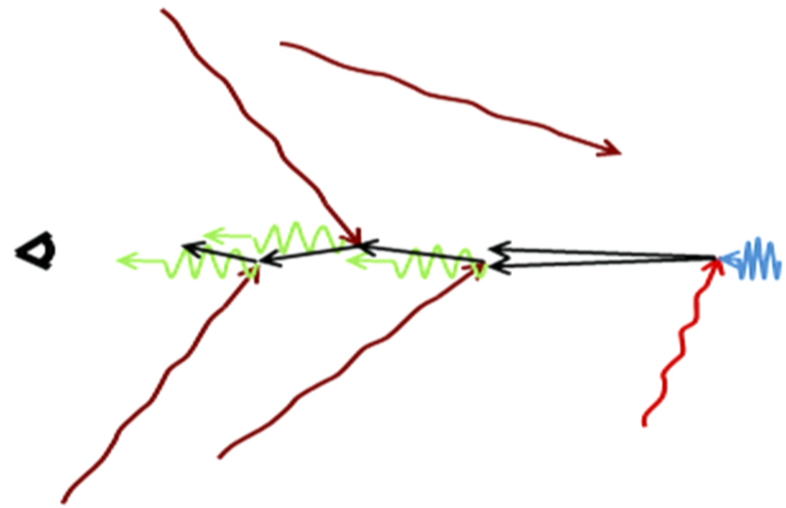



There ***must*** be a strong IGMF!



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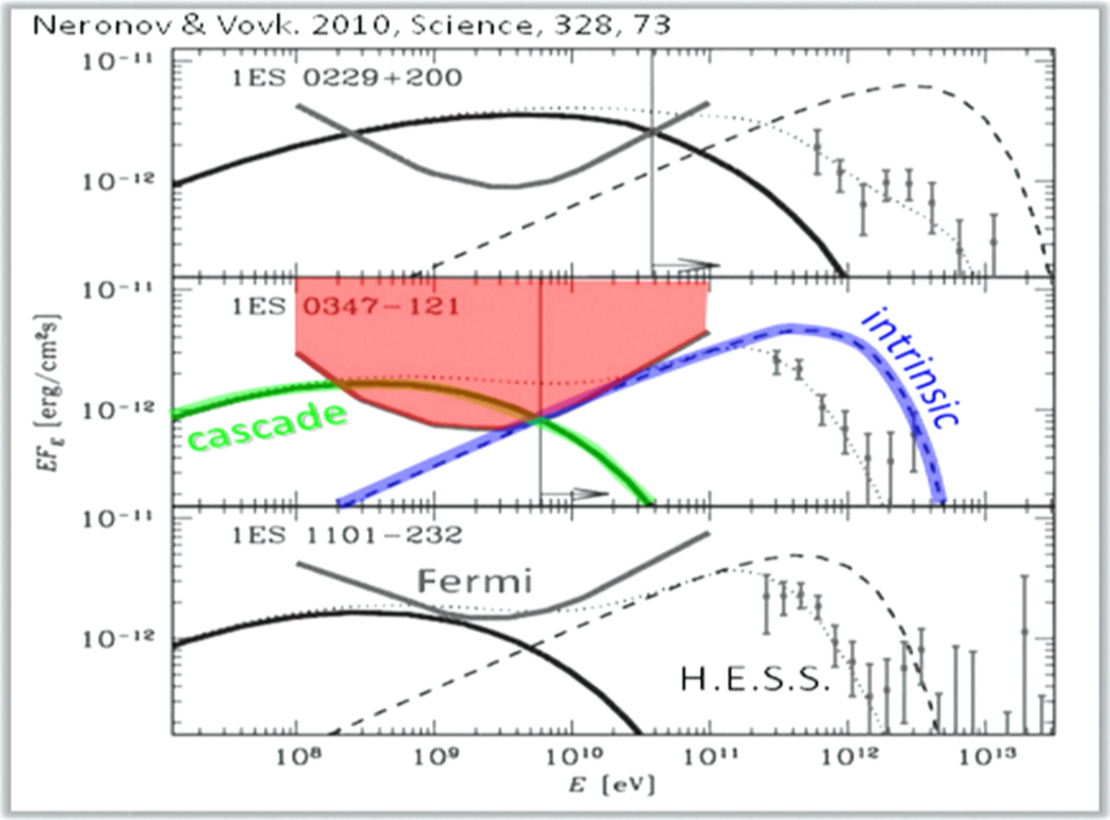


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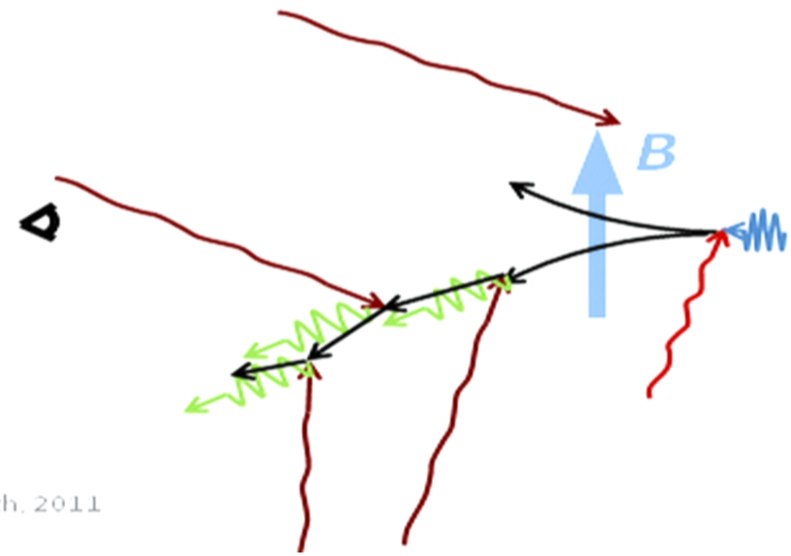
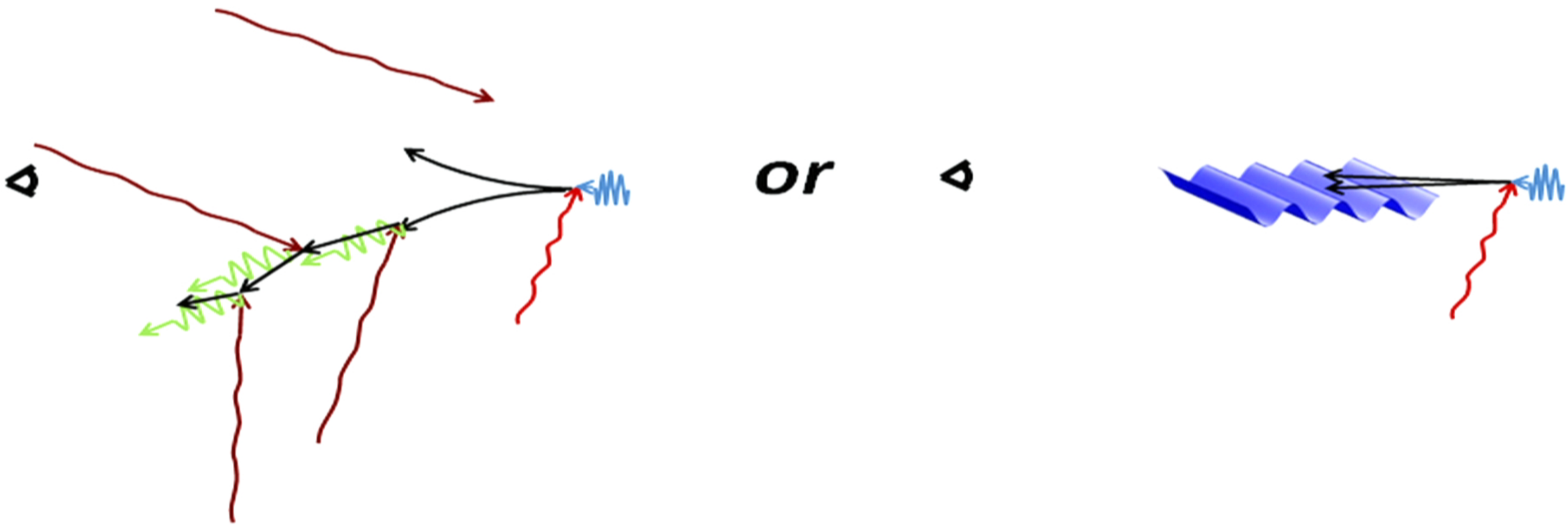


# “must” is a 4-letter word!



Consequences for the IGMF

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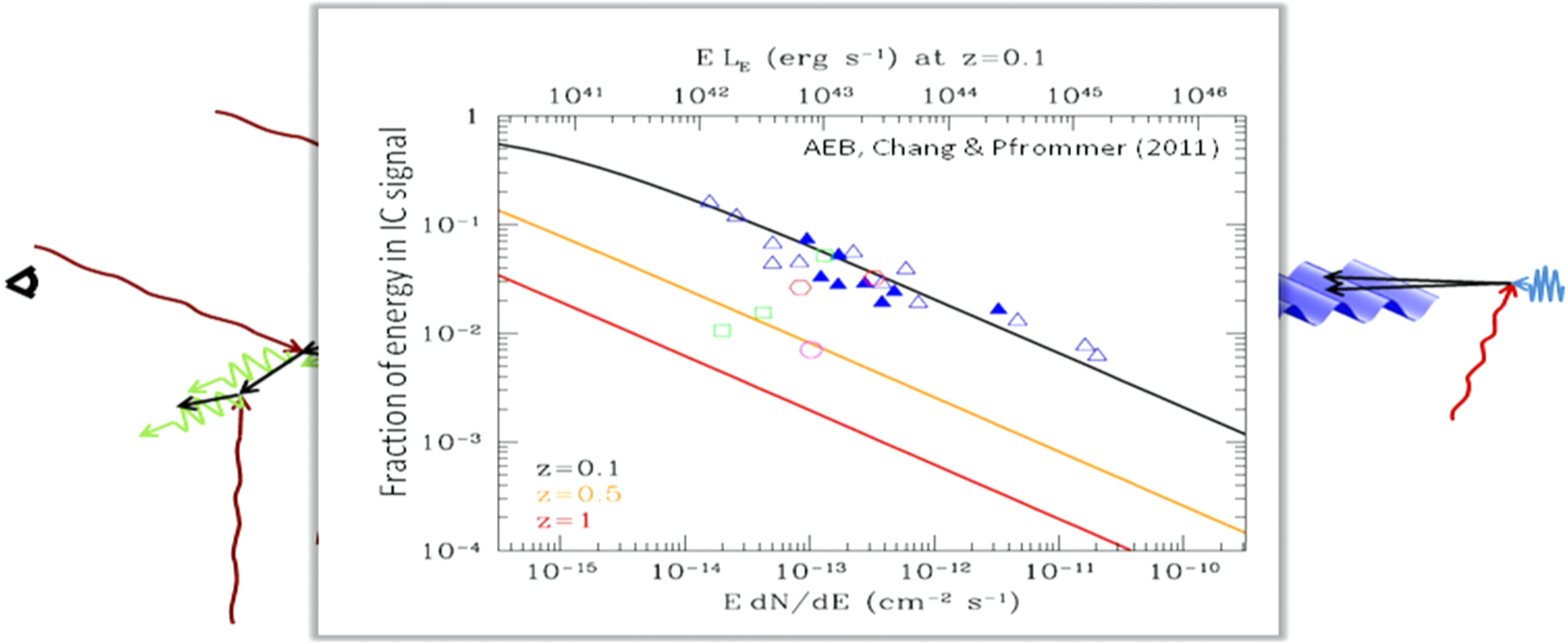


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Consequences for the IGMF

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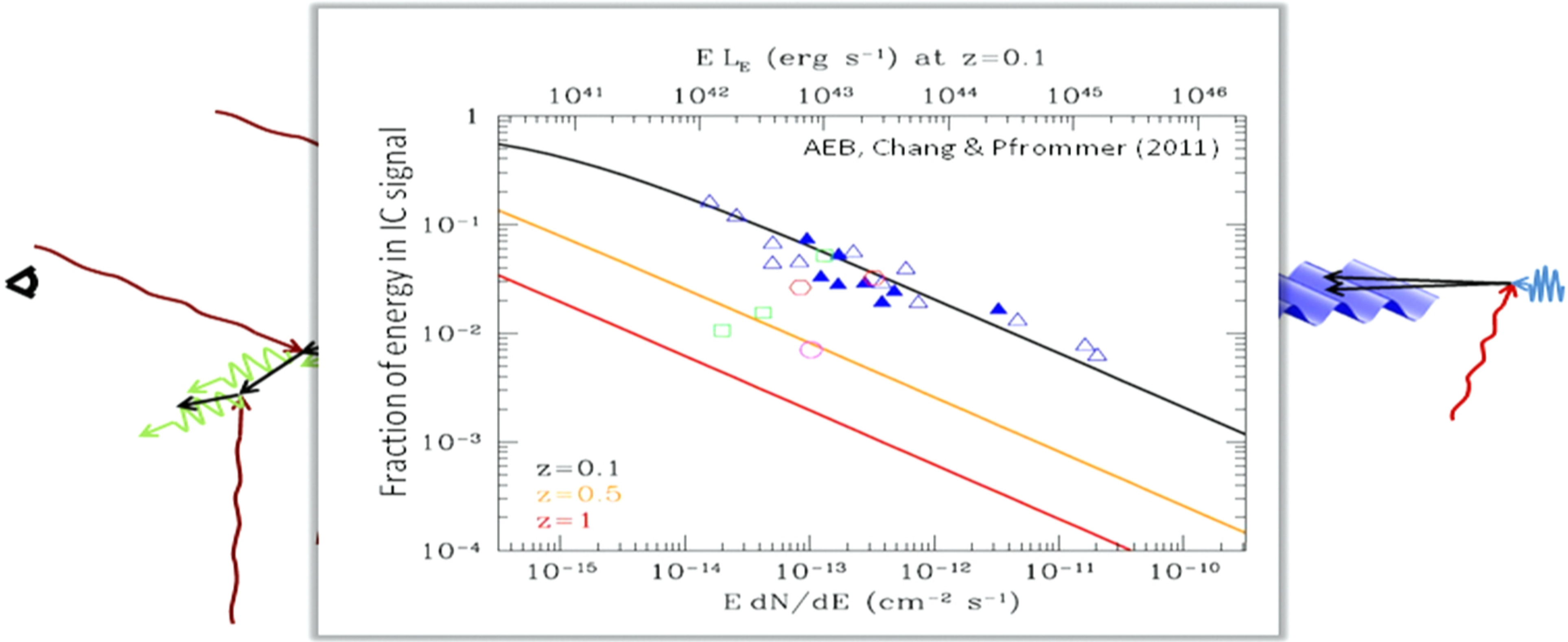


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# The TeV Blazar Luminosity Function

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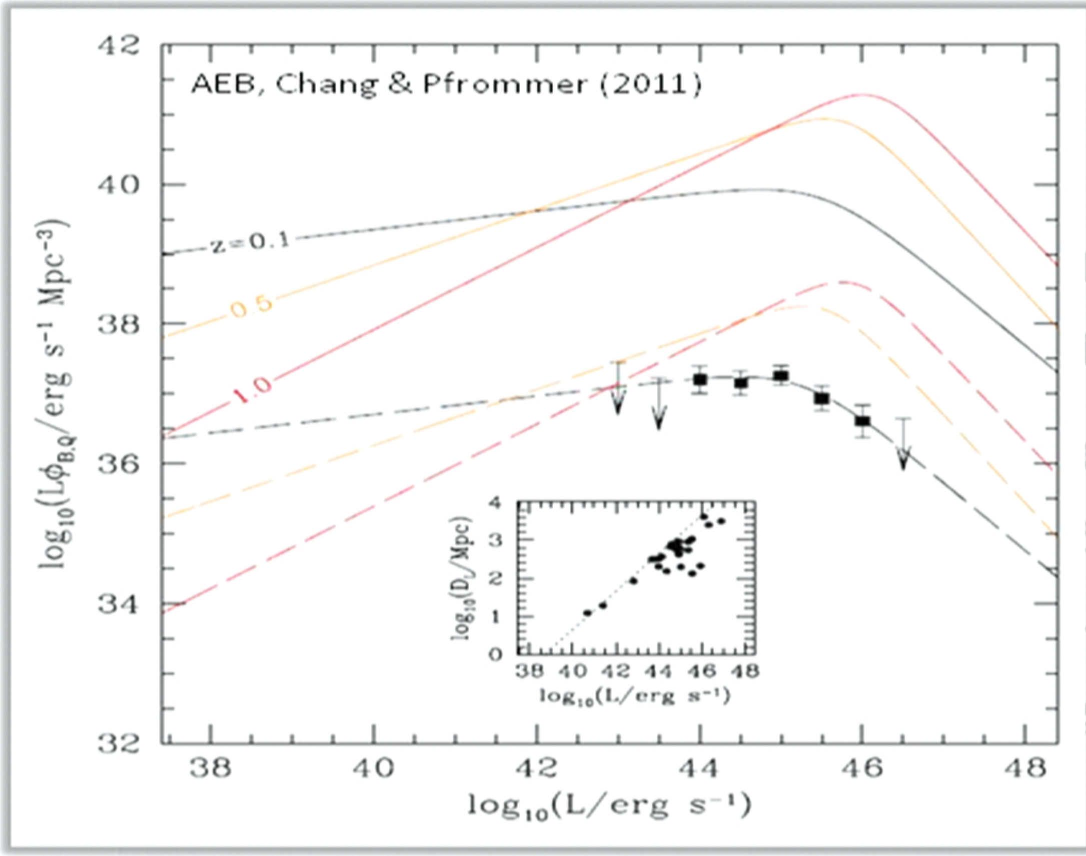
# The TeV blazar LF today

Assume:

- TeV blazars = Fermi hard gamma-ray blazars → Correct for sky coverage, observation duty cycle, galactic occultation
- TeV observations have nearly a single flux limit, $4.2\times10^{-12}$ erg/cm$^2$/s
- Ignore all of the biases in the TeV sample (e.g., target selection, scheduling, etc.)

# The TeV blazar LF today

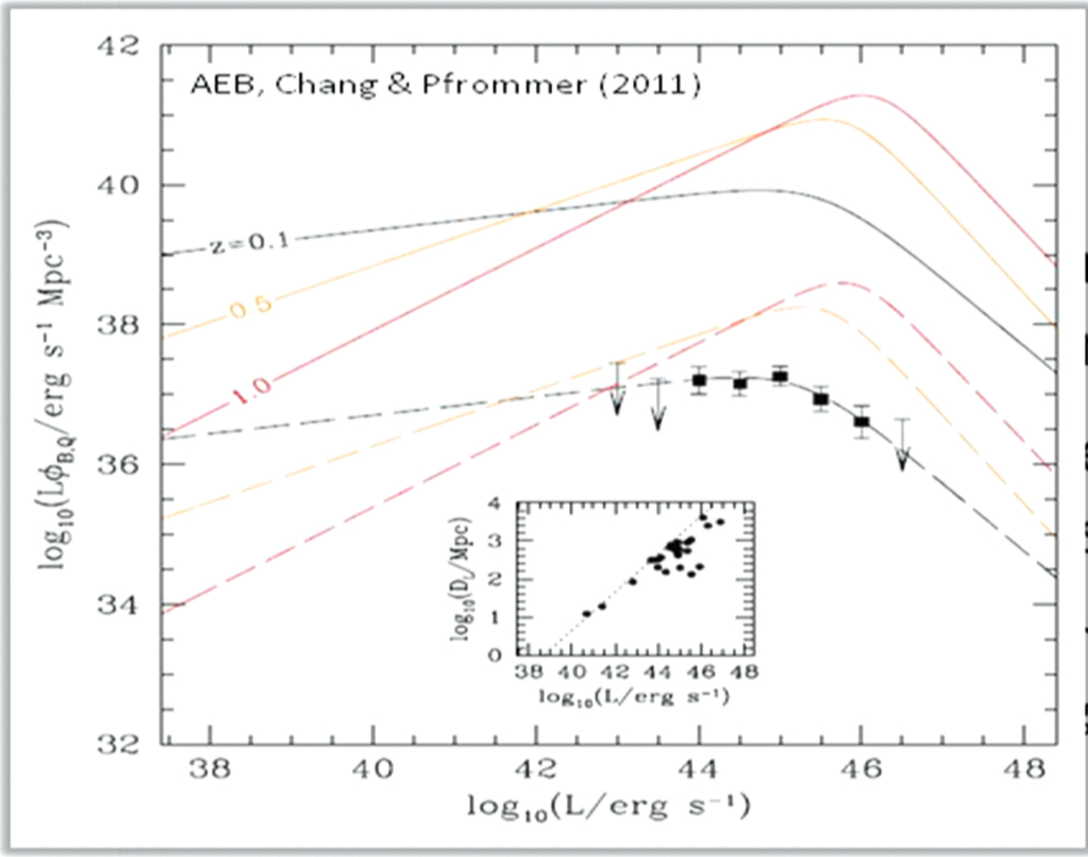



gamma-ray blazars
ge, observation duty
n

early a single flux
s

the TeV sample
, etc.)

# The TeV blazar LF today

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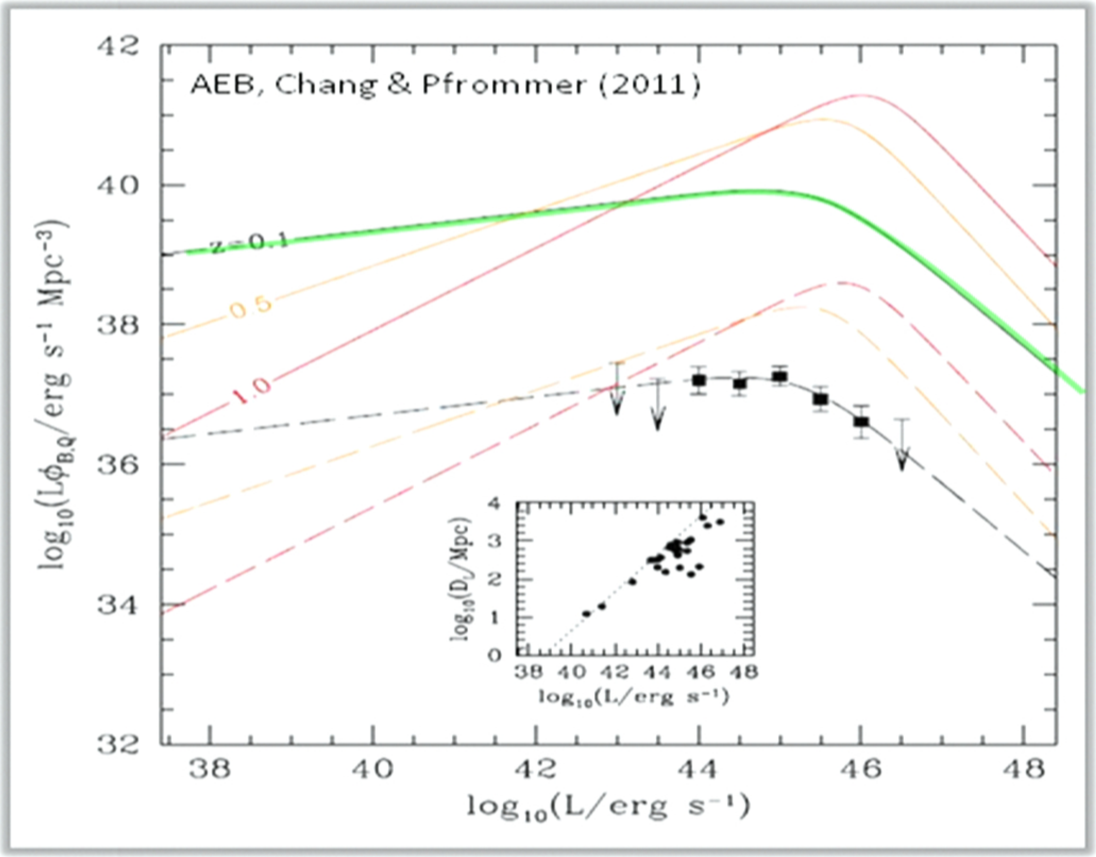
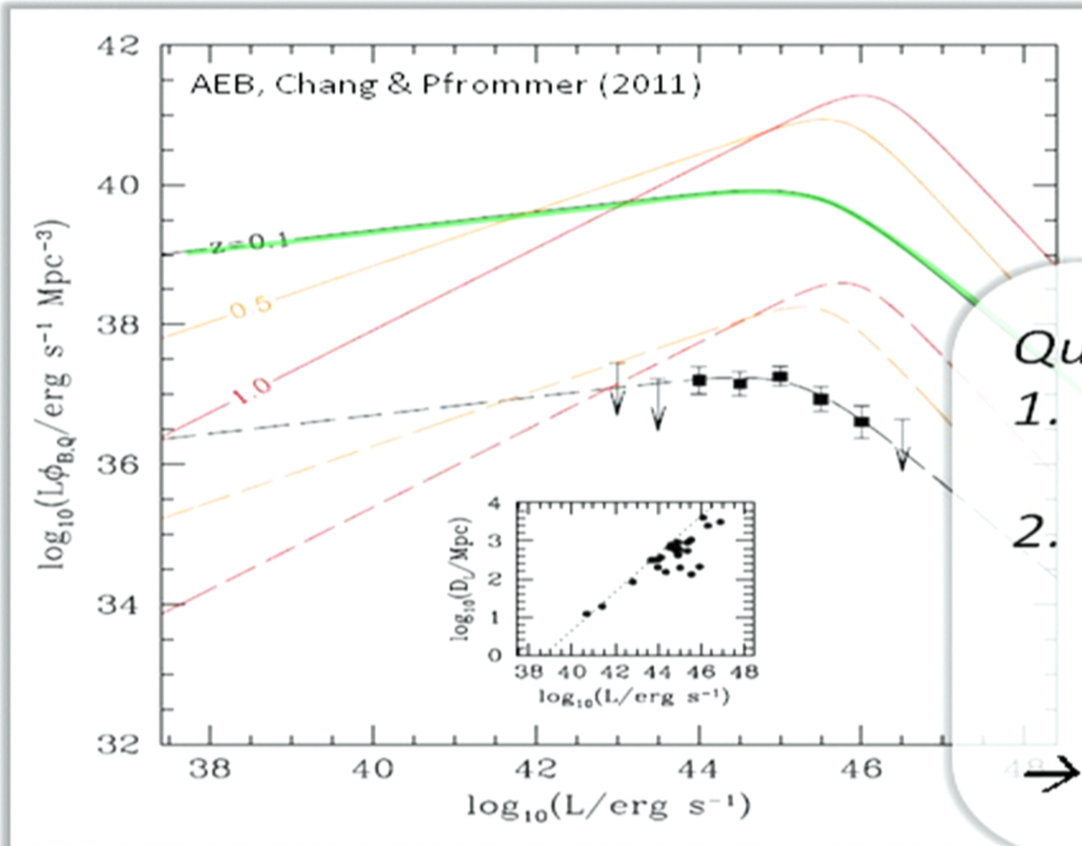



$$\phi_B(0.1, L) \simeq 3.8 \times 10^{-3} \phi_Q(0.1, 1.8L),$$

# The TeV blazar LF today



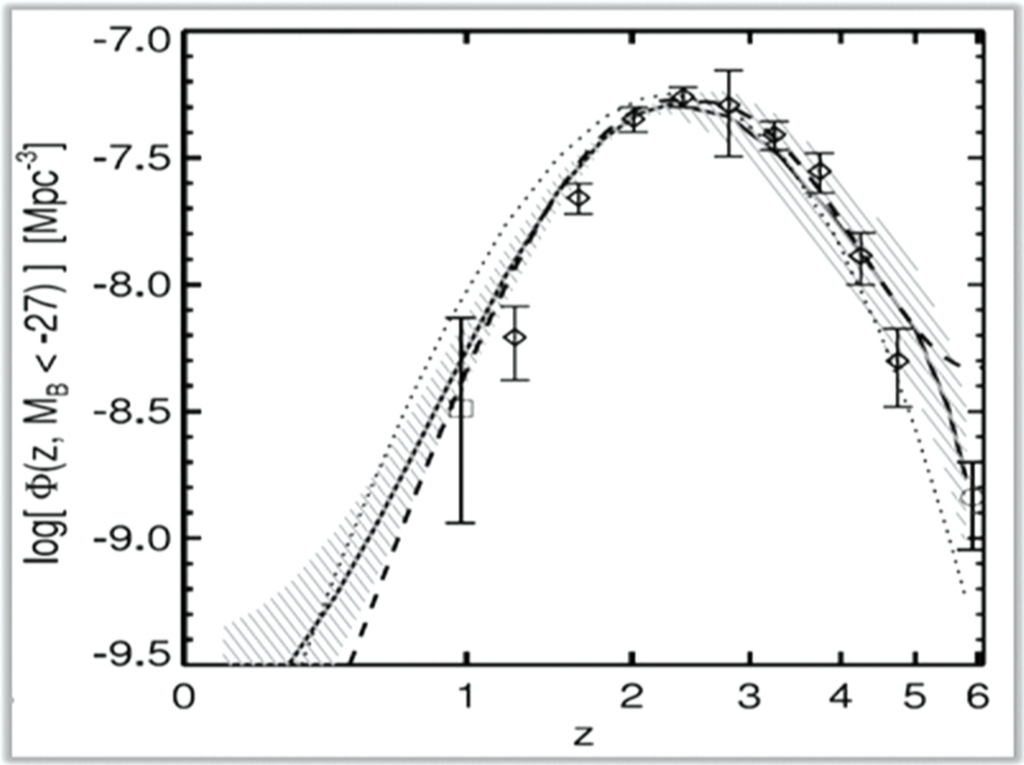

$$\phi_B(0.1, L) \simeq 3.8 \times 10^{-3} \phi_Q(0.1, 1.8L),$$

*Quasars and TeV blazars are:*

1. *Regulated by the same mechanisms*
2. *Contemporaneous parts of a single AGN population*

*→ Related in the past?*

# How many TeV blazars are there?



Consequences for the TeV blazar luminosity function

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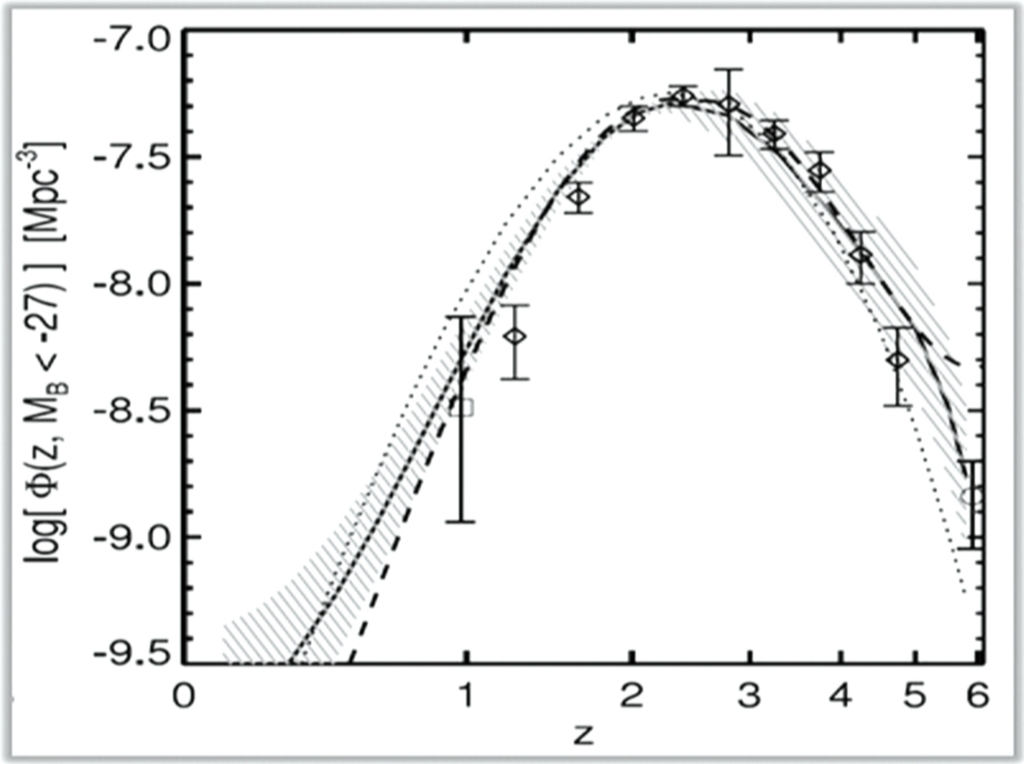


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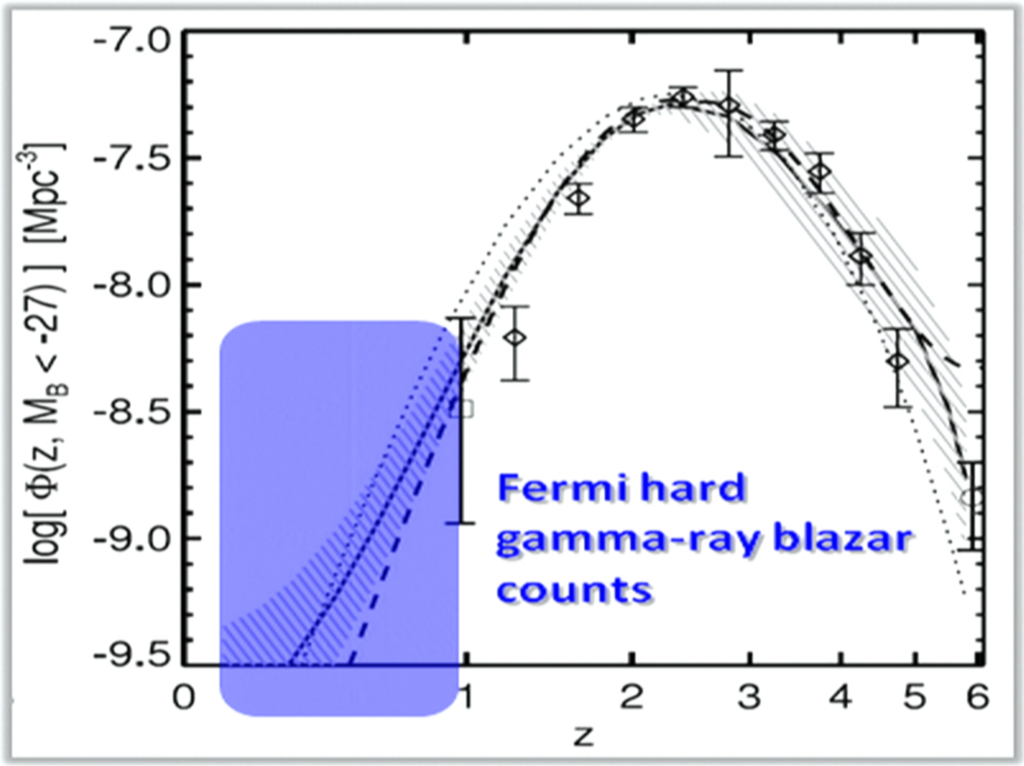

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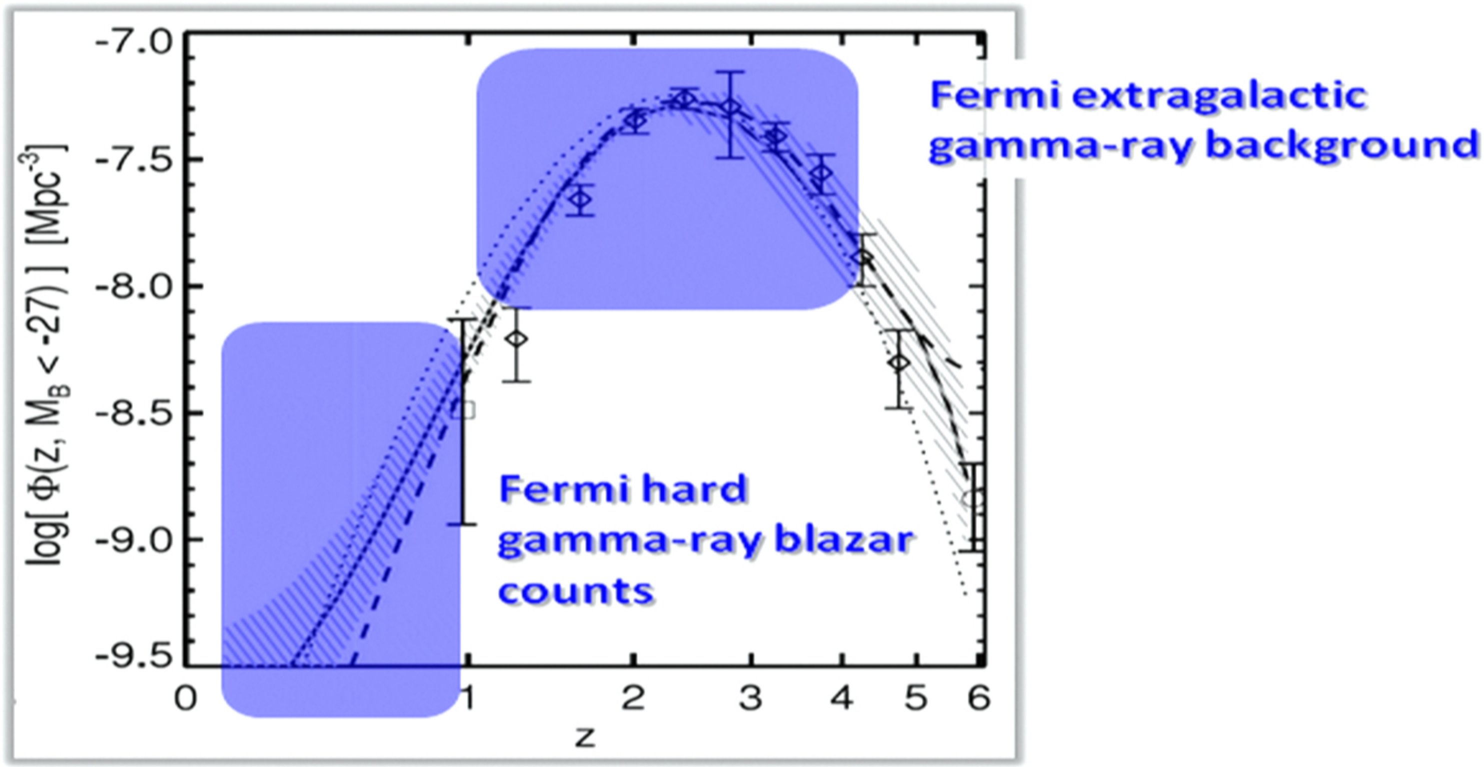
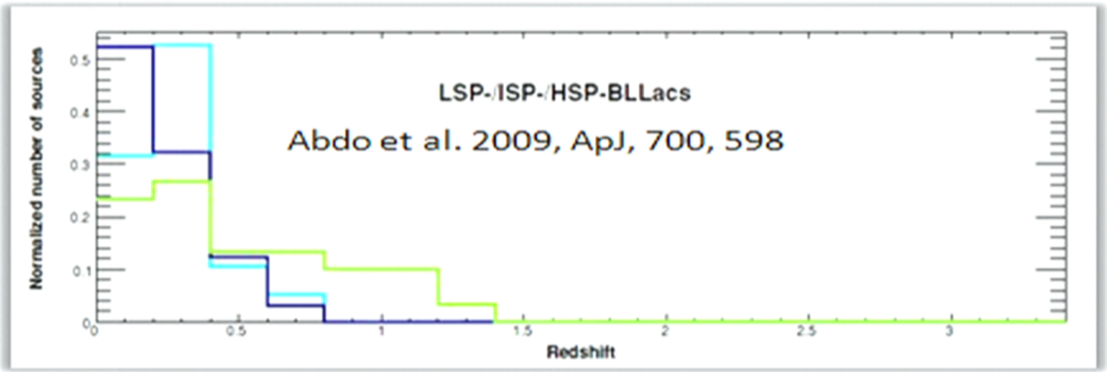


# Fermi counts and the low-z BLF



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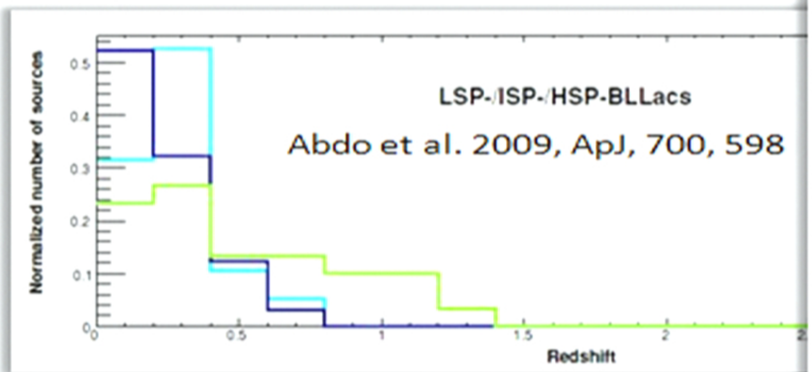
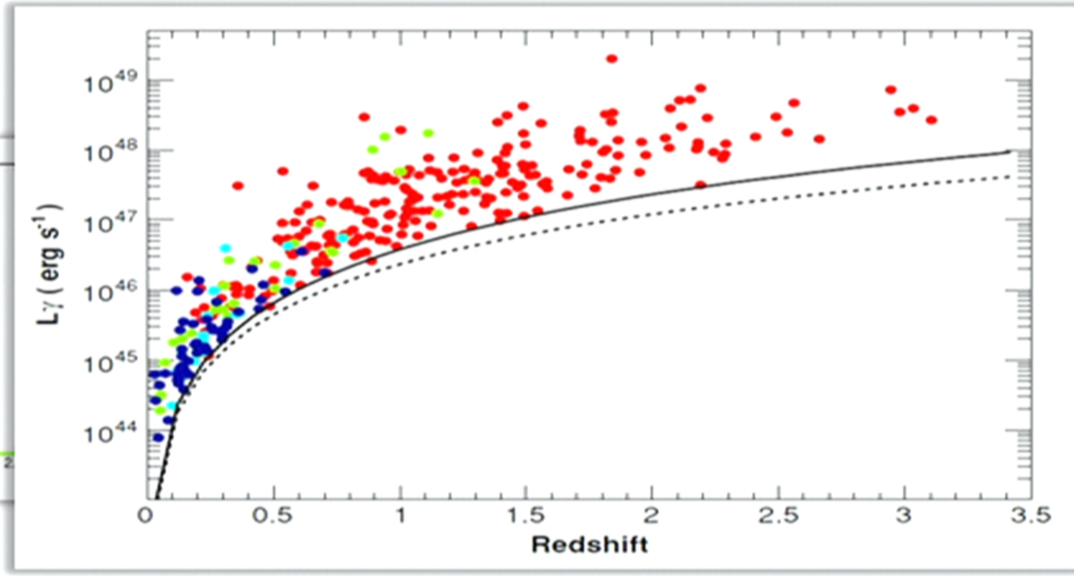
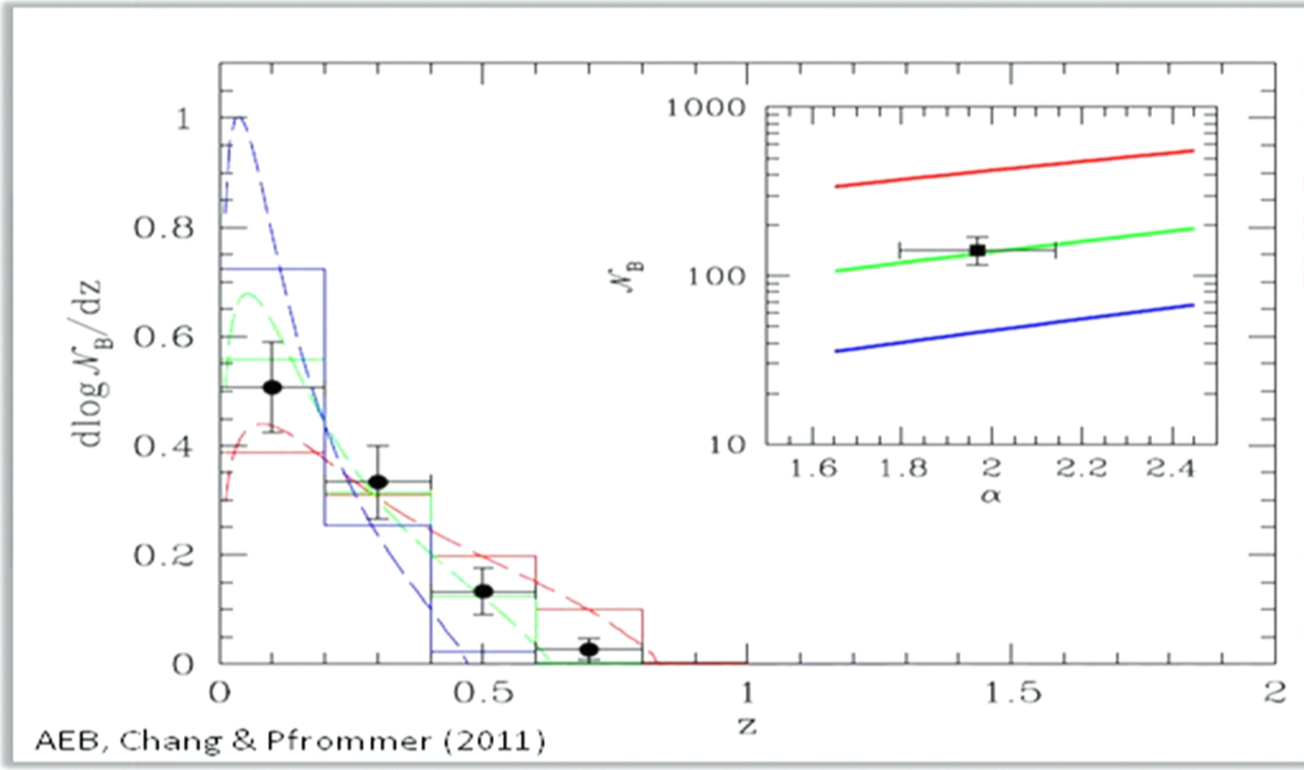
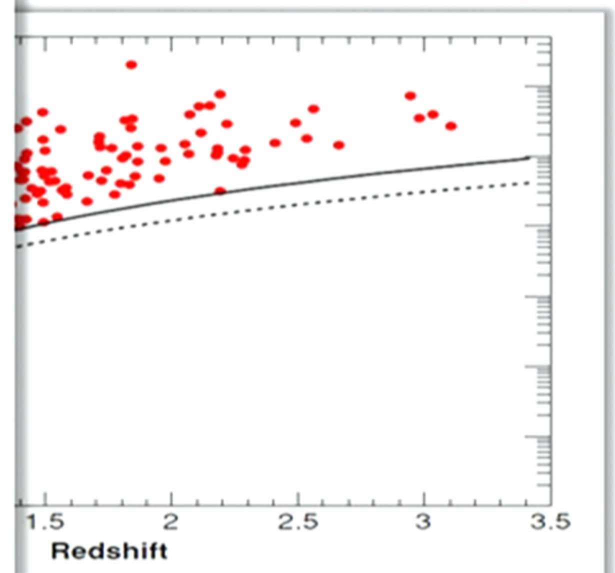


Consequences for the TeV blazar luminosity function

# Fermi counts and the low-z BLF

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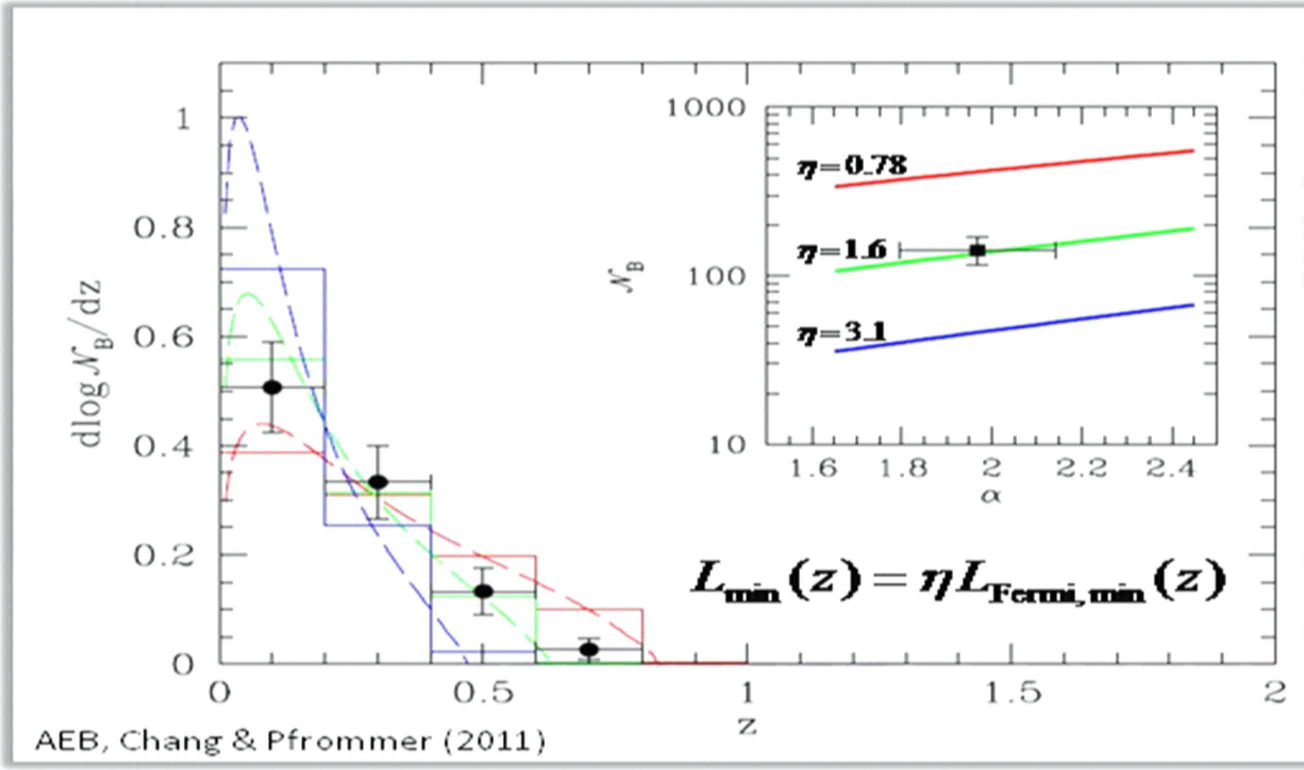


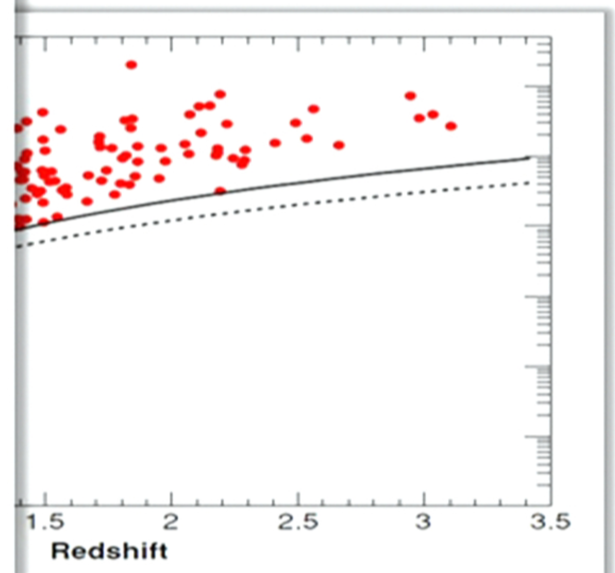

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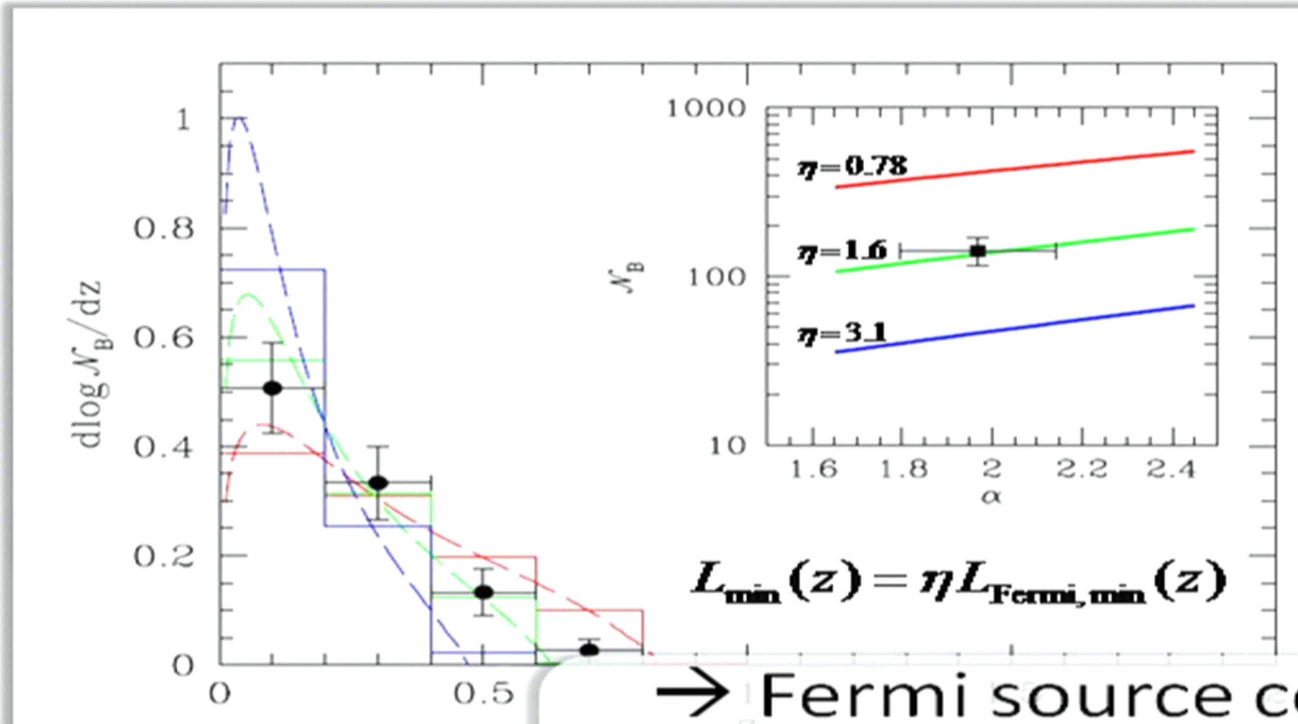
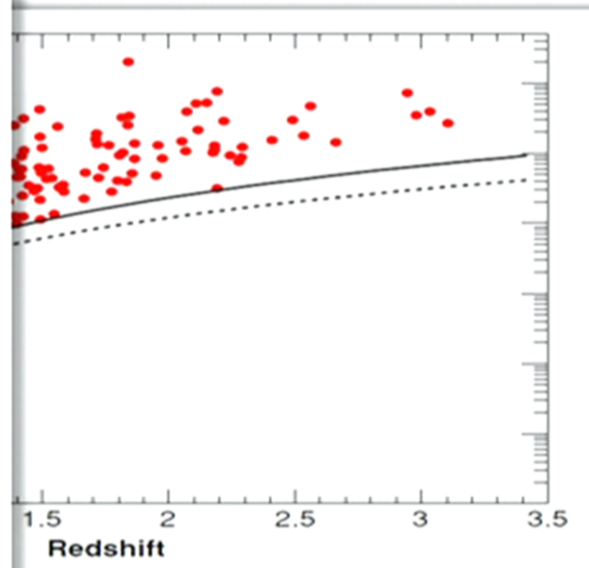
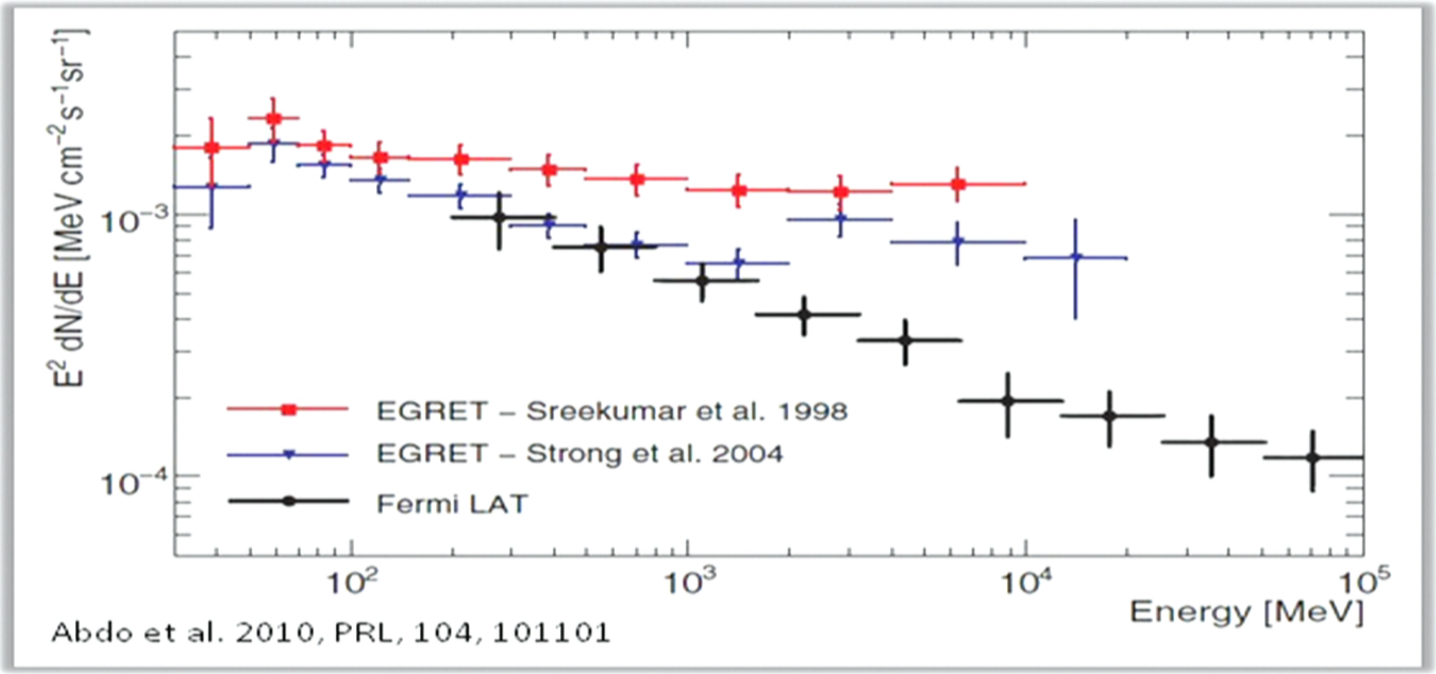



AEB, Chang & Pfrommer (2011)




→ Fermi source counts perfectly consistent with a quasar-like luminosity function for z<1

# Fermi EGRB and the high-z BLF



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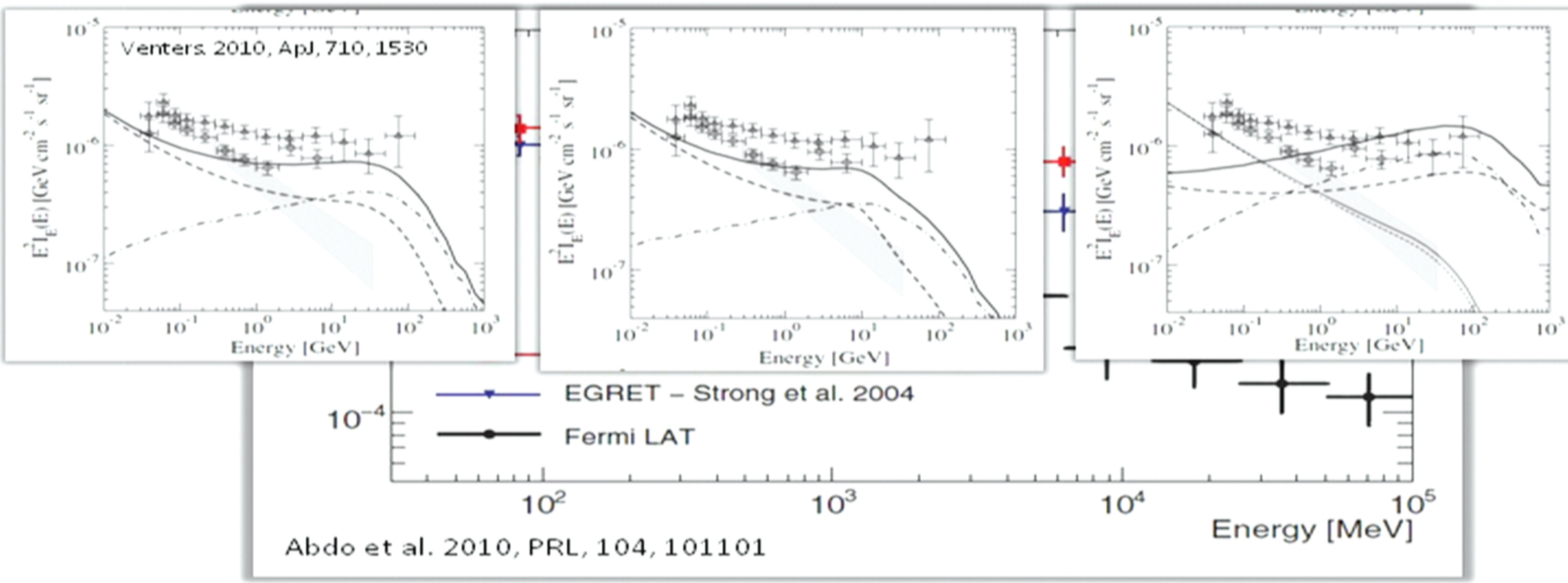

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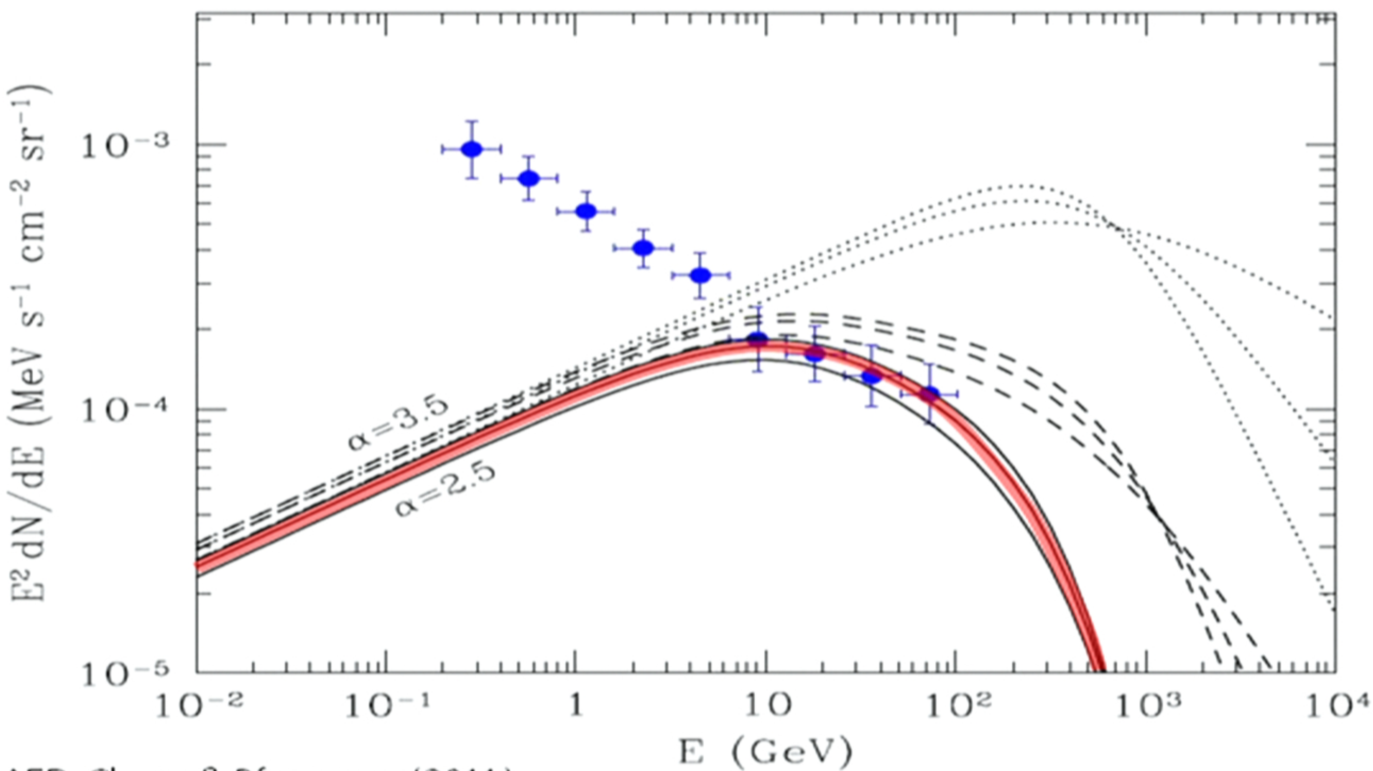


AEB, Chang & Pfrommer (2011)

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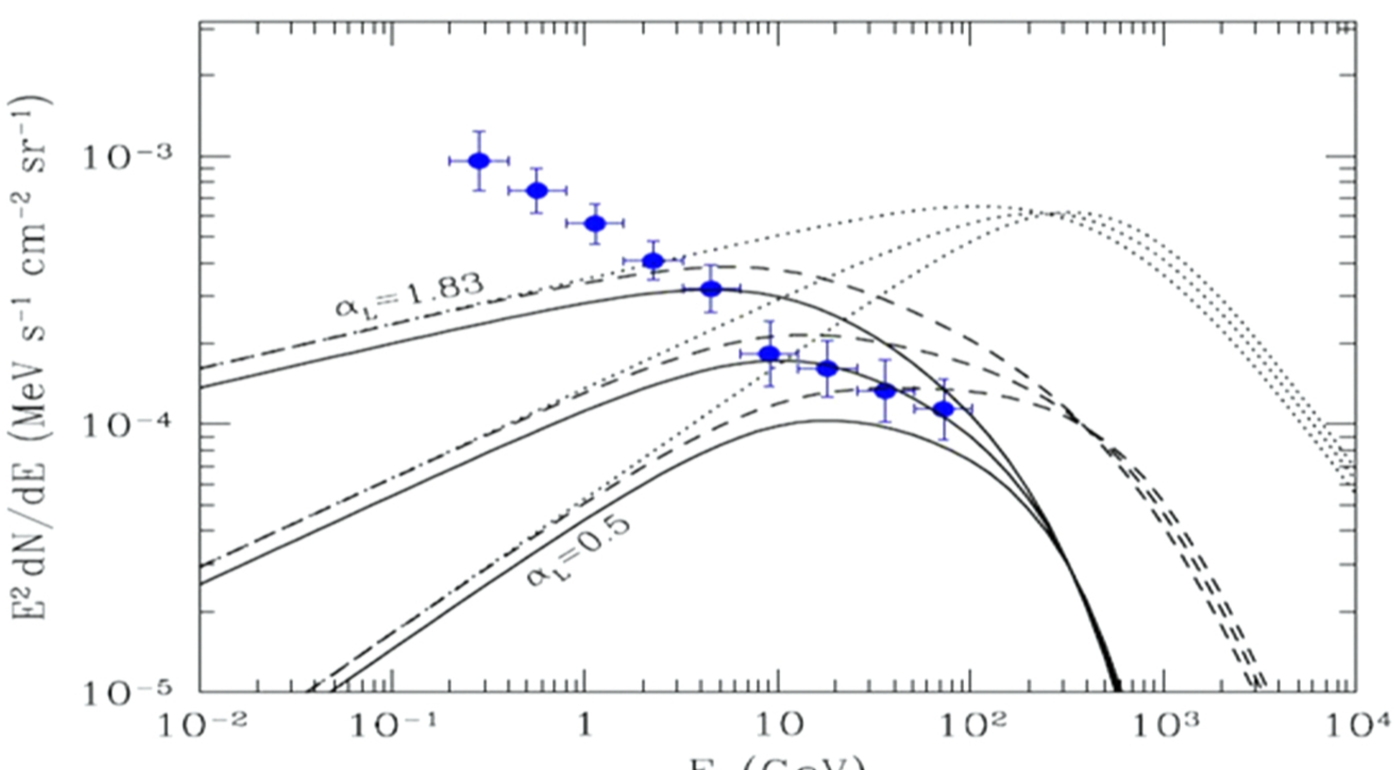


AEB, Chang & Pfrommer (2011)

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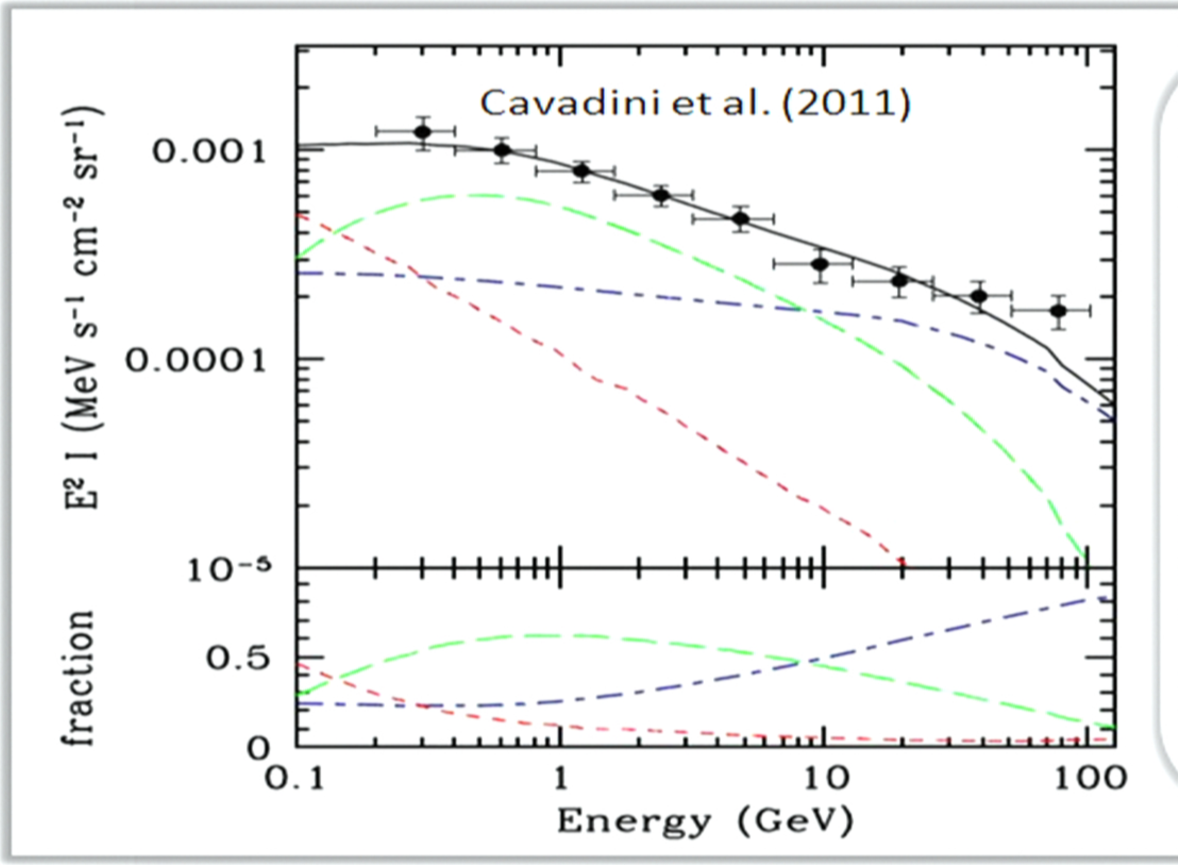


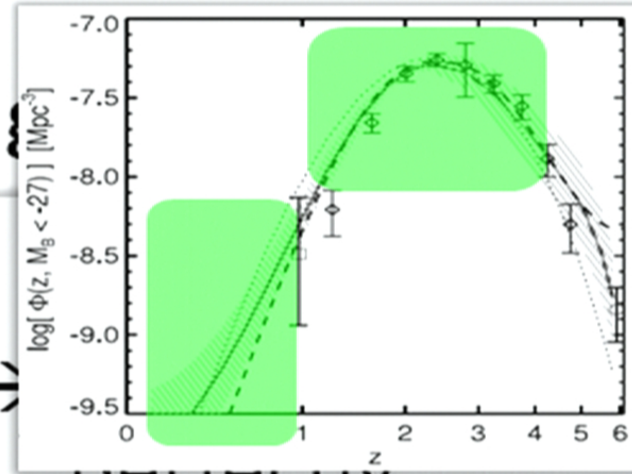


→ perfectly consistent with a quasar-like luminosity function for z>1

# Heating things up

- After reionization, photoheating is *very* inefficient:

$$f_{\rm exc} = \frac{\epsilon_{\rm exc}}{m_p c^2} \approx 4 \times 10^{-9} \left(\frac{\epsilon_{\rm exc}}{4\,{\rm eV}}\right) \quad \rightarrow \quad T \approx 15{,}000\,{\rm K}$$

$$\text{but} \quad f_{\rm BH} \approx 10^{-4} \rightarrow \varepsilon_{\rm rad,BH} \approx 10^{-5}\,!$$

- TeV blazar heating isn't, and that matters:

$$f_{\rm TeV} = \frac{\text{TeV Blazar Luminosity Density}}{\text{Quasar Luminosity Density}} \times \epsilon_{\rm rad,BH} = 2.1 \times 10^{-8}$$

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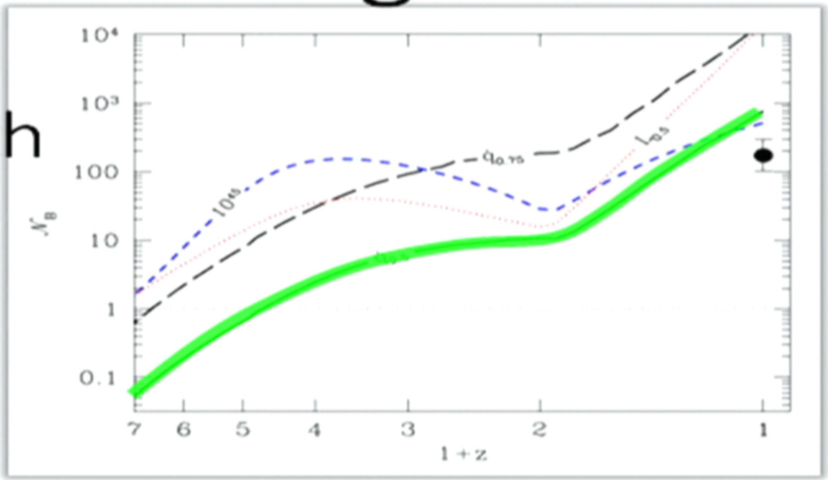
# A funny kind of heating

- Homogeneity of the EBL
- Cosmological mean free path
- High density of TeV blazars
- Weakness of the instability growth rate on $\delta$





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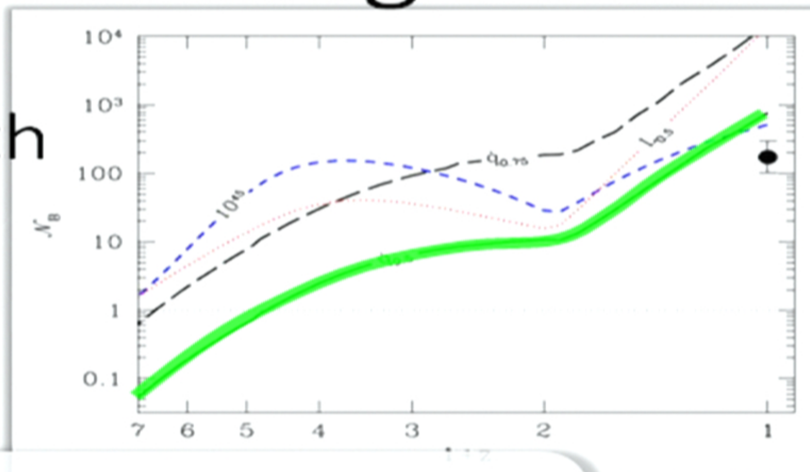


→Volumetrically constant heating rate. Makes low density regions *hot*!

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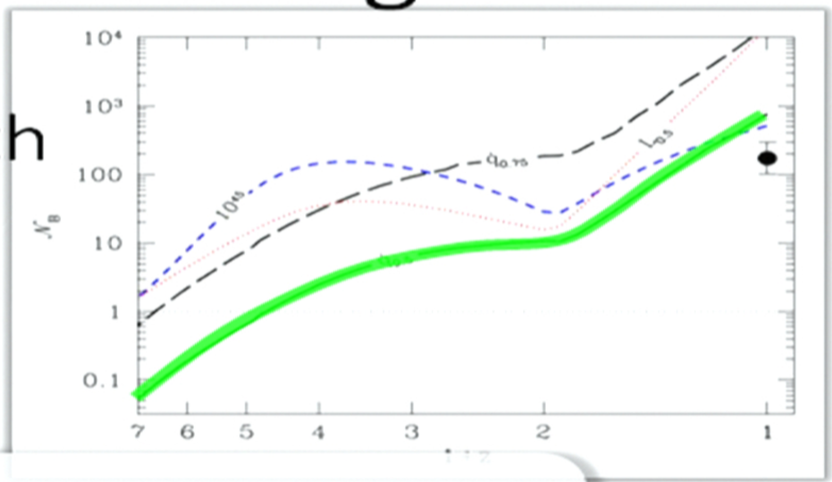

→Volumetrically constant heating rate. Makes low density regions *hot*!

- Unlike photoheating, shock heating, or AGN feedback from winds, jets, bubbles, etc.

# Rewriting the thermal history

$$\dot{Q}\Big|_{z=0} = 10^{-7}\ \text{eV cm}^{-3}\ \text{Gyr}$$

$$u\Big|_{z=0} = \frac{\dot{Q}}{H_0} \approx 10^{-6}\ \text{eV cm}^{-3}$$

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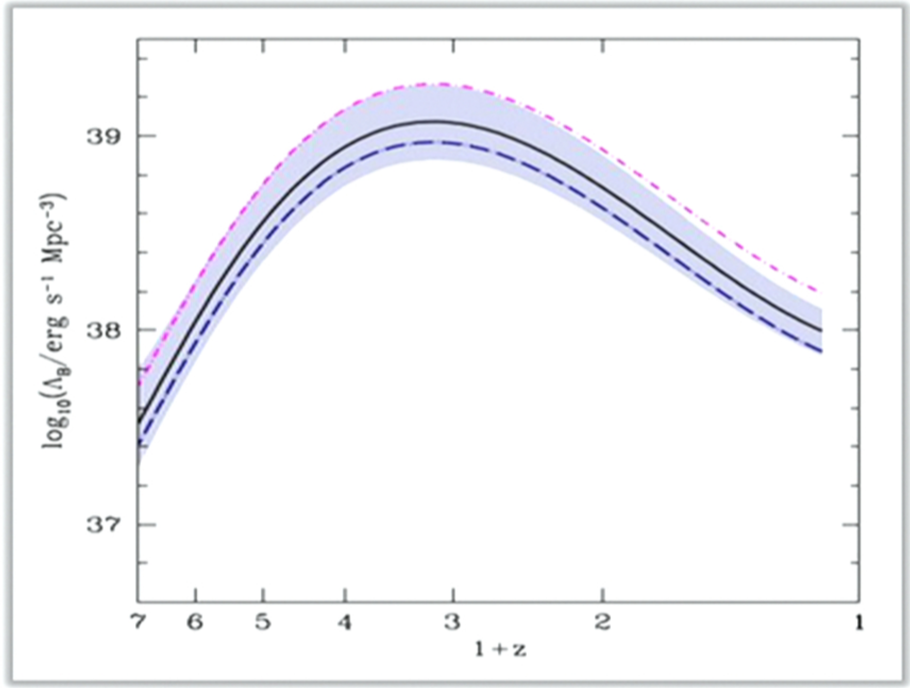
$$\dot{Q}(z) \approx \frac{\Lambda(z)}{\Lambda(0)}\dot{Q}\Big|_{z=0}$$





# Rewriting the thermal history

$$\frac{dT}{dt} = -2HT + \frac{2T}{3(1+\delta)}\frac{d\delta}{dt} - \frac{T}{\Sigma\tilde{X}_i}\frac{d\Sigma\tilde{X}_i}{dt} + \frac{2}{3k_B n_{\rm bary}}\frac{dQ}{dt}$$

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- *Photoheating*
- *Where we add TeV blazar heating!*

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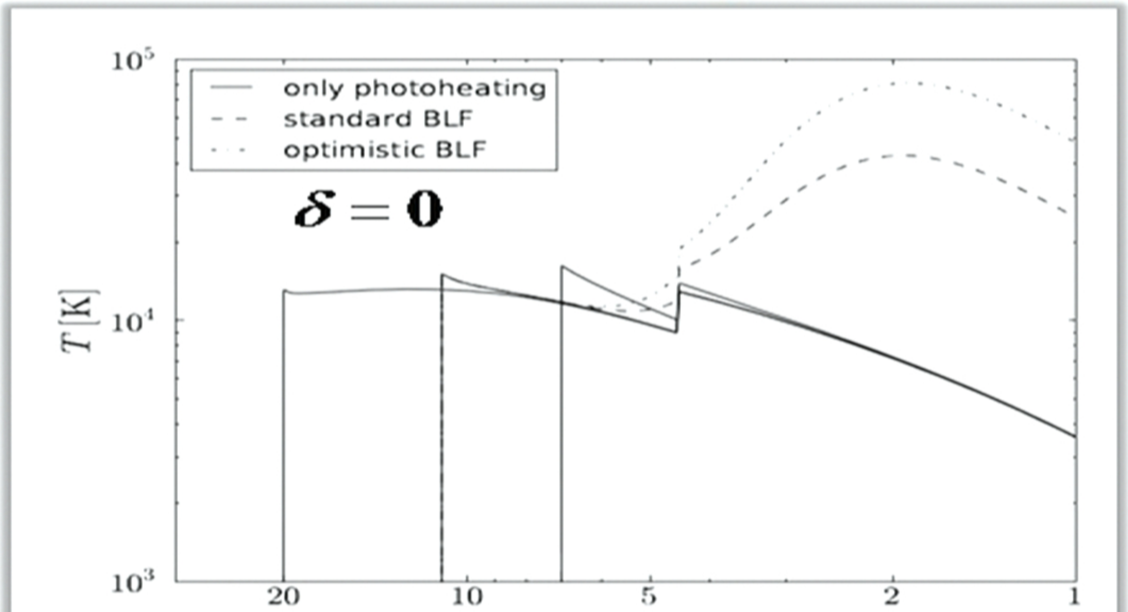

Chang, AEB & Pfrommer (2011)

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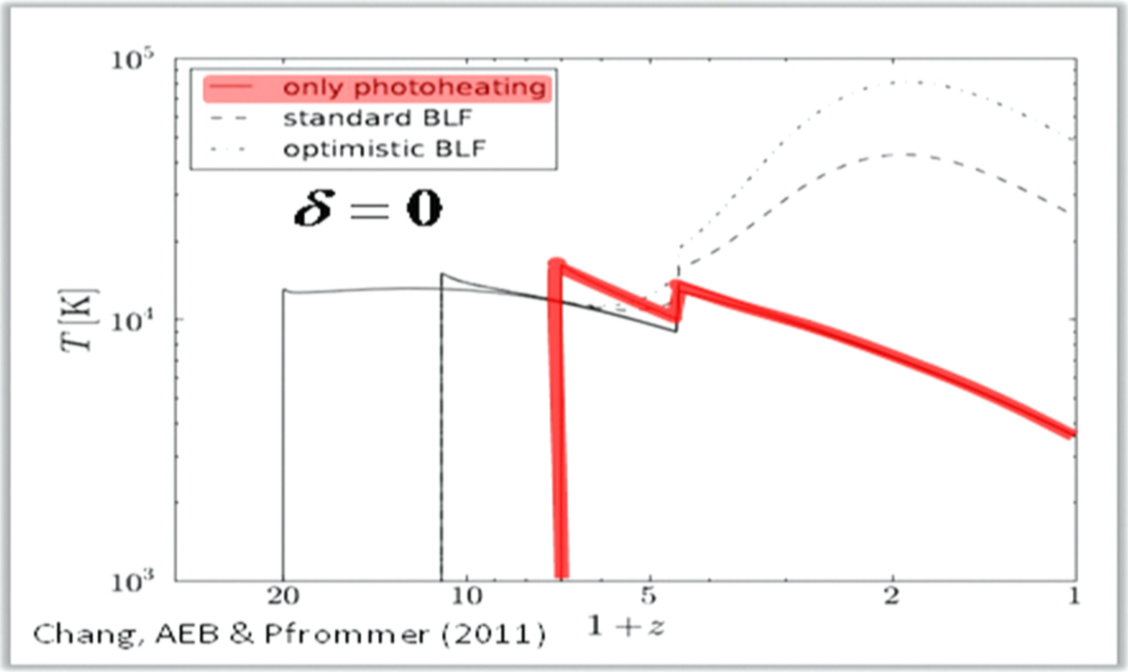

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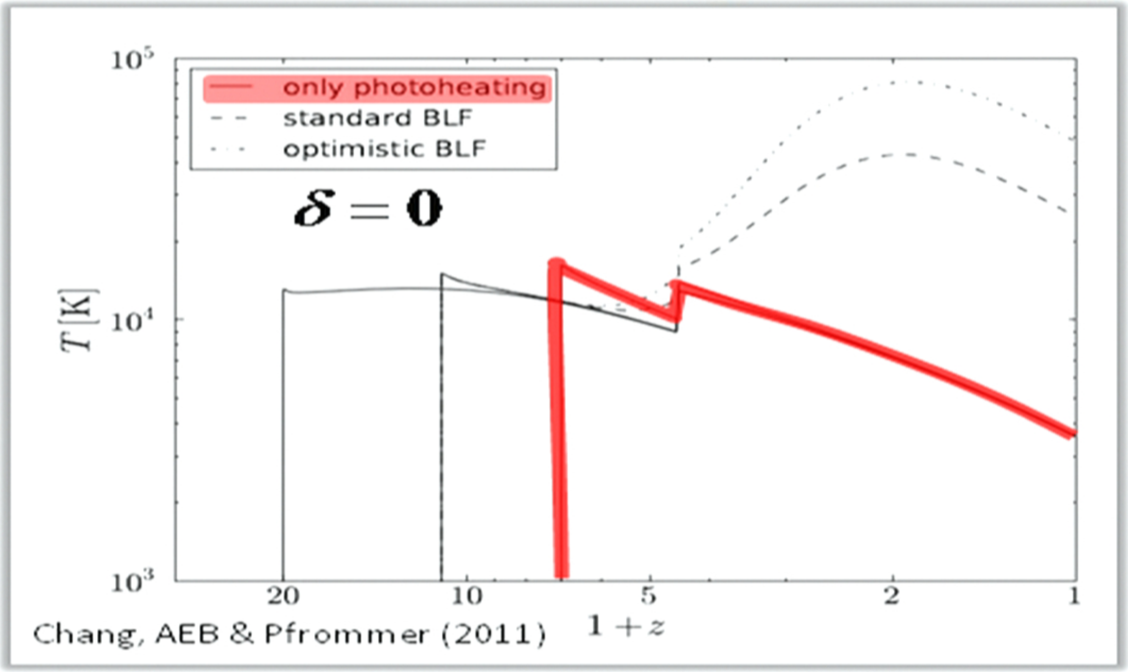

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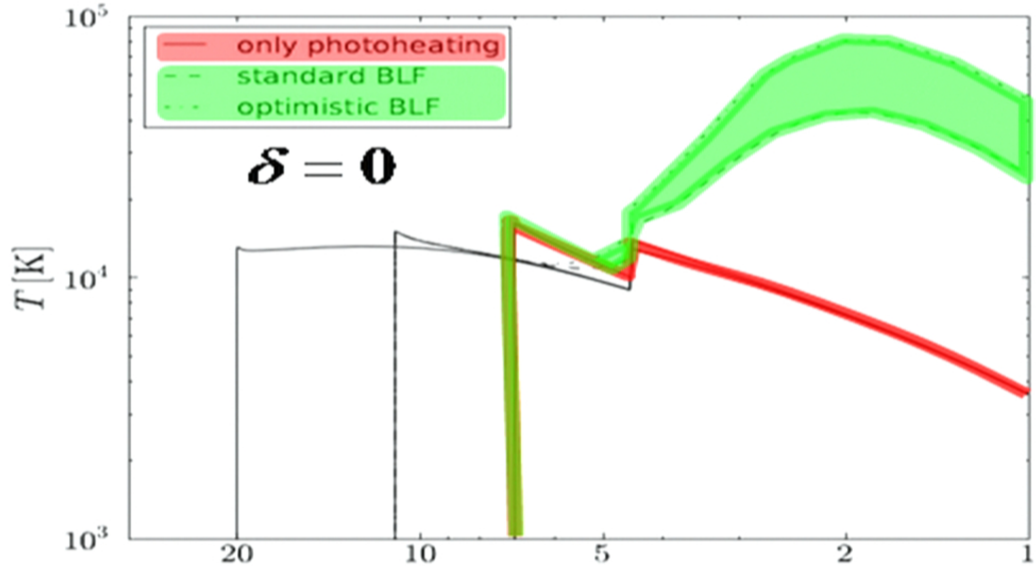
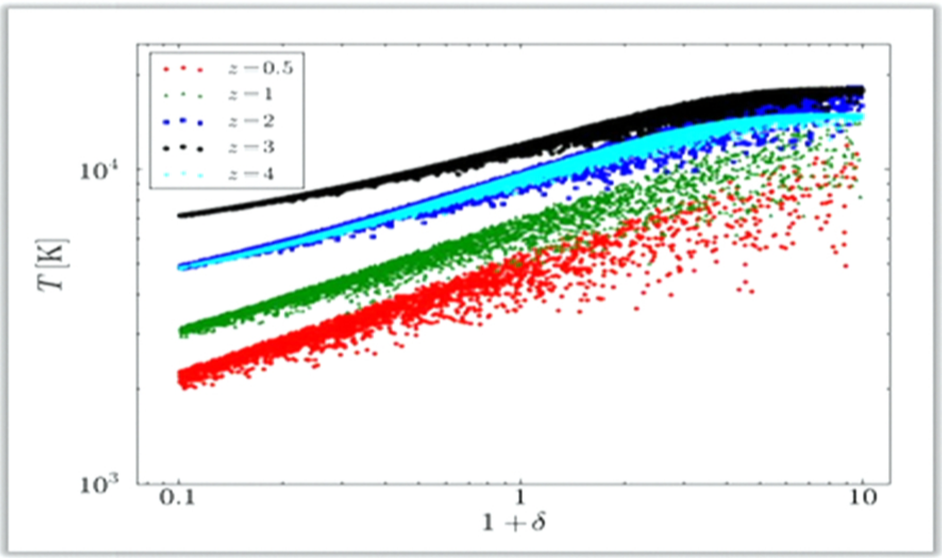



Chang, AEB & Pfrommer (2011)

# Hot voids

*Without TeV blazar heating*

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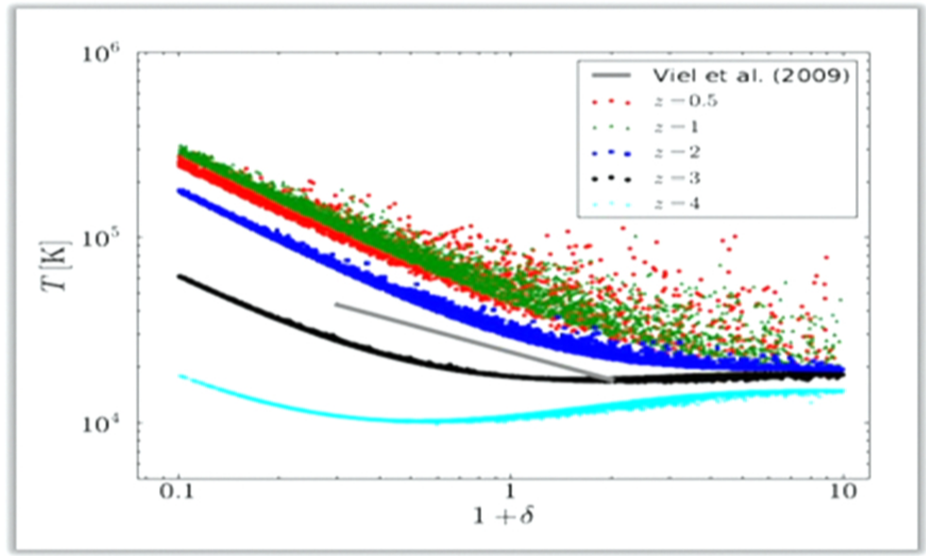


Chang, AEB & Pfrommer (2011)

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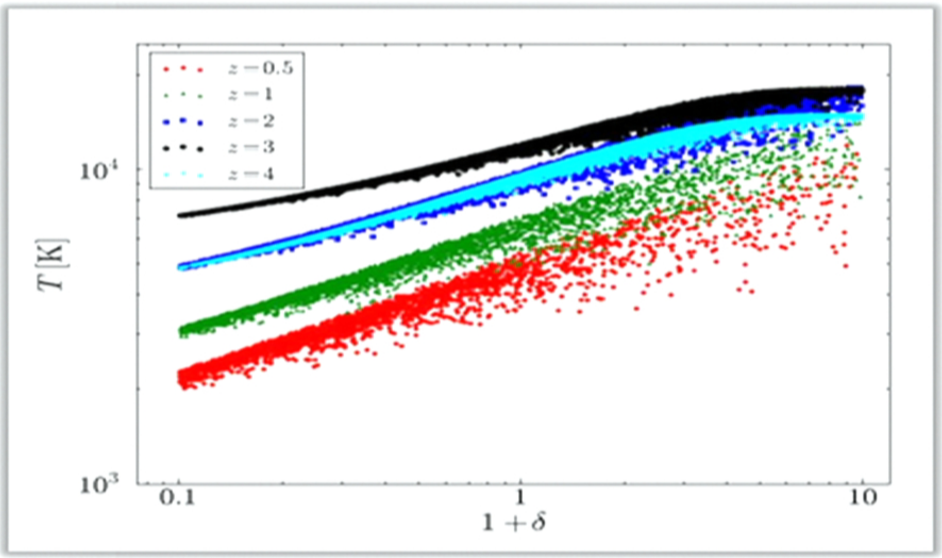


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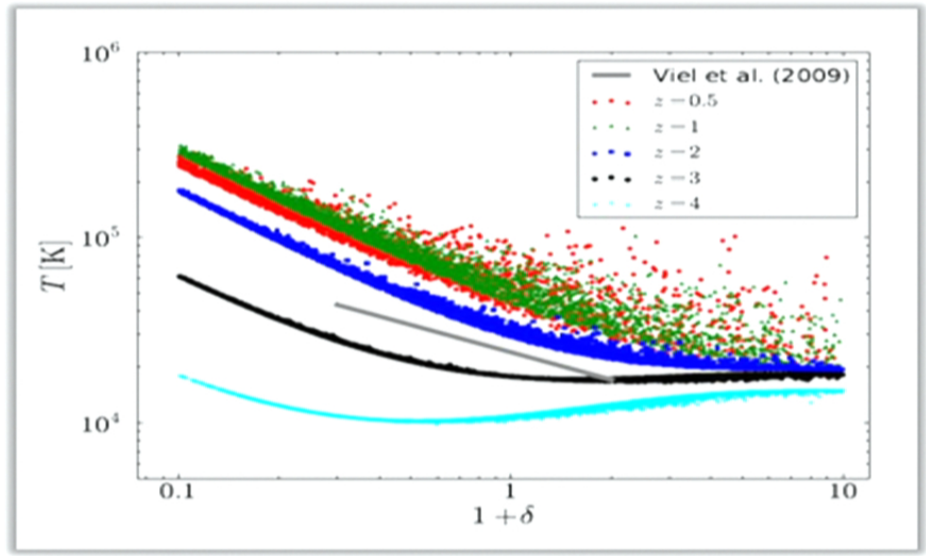


Chang, AEB & Pfrommer (2011)

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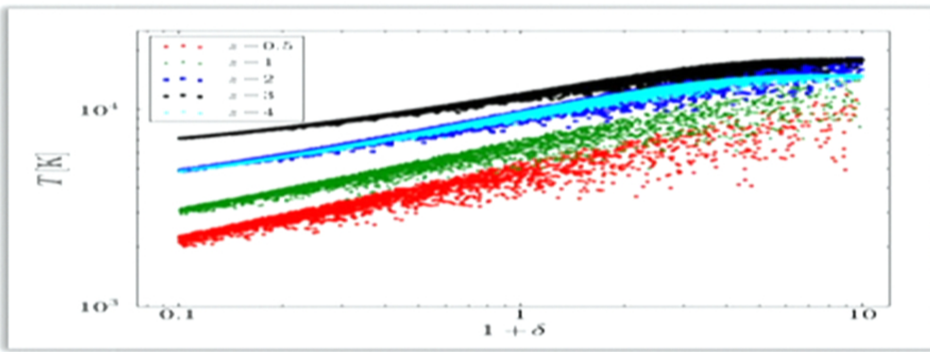


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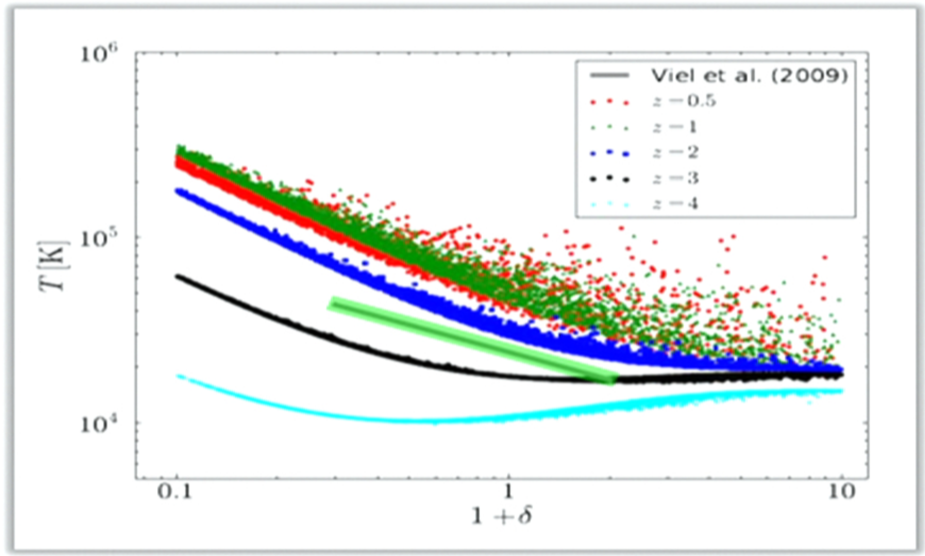
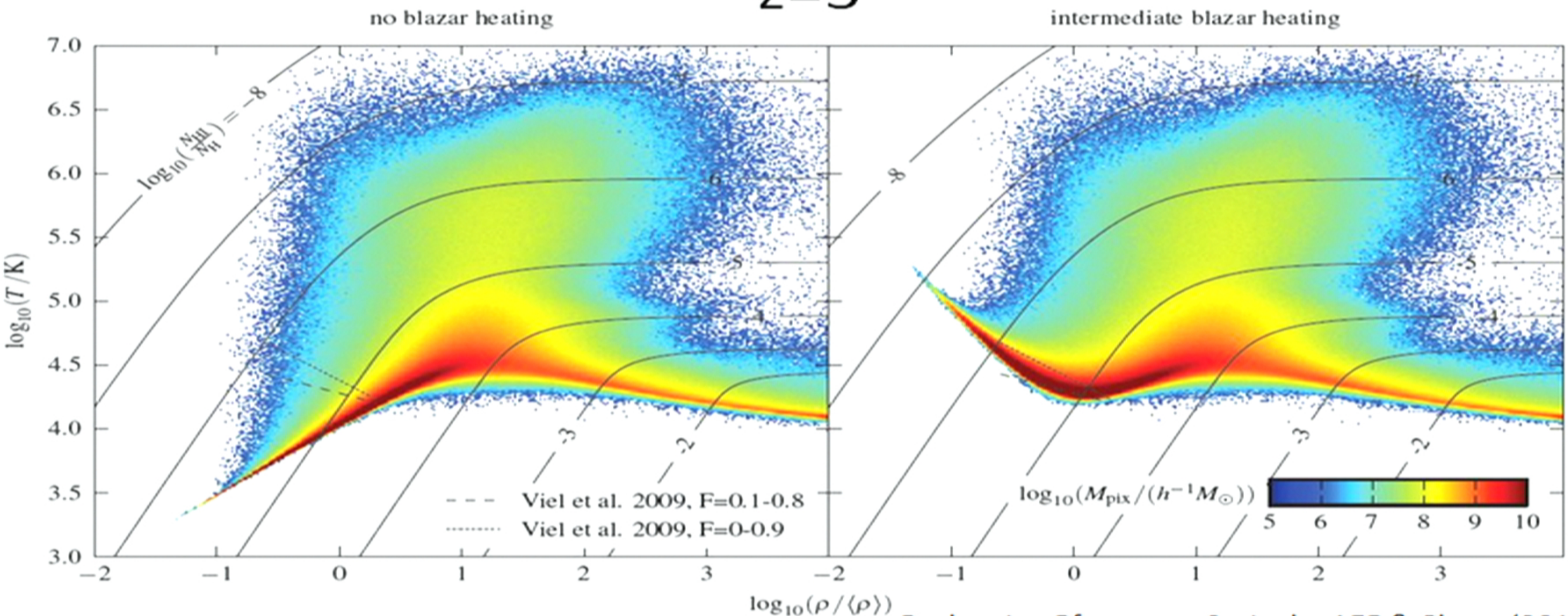



Chang, AEB & Pfrommer (2011)

Viel, Bolton & Haehnelt. 2009, MNRAS, 399, L39

# Heating cosmological simulations

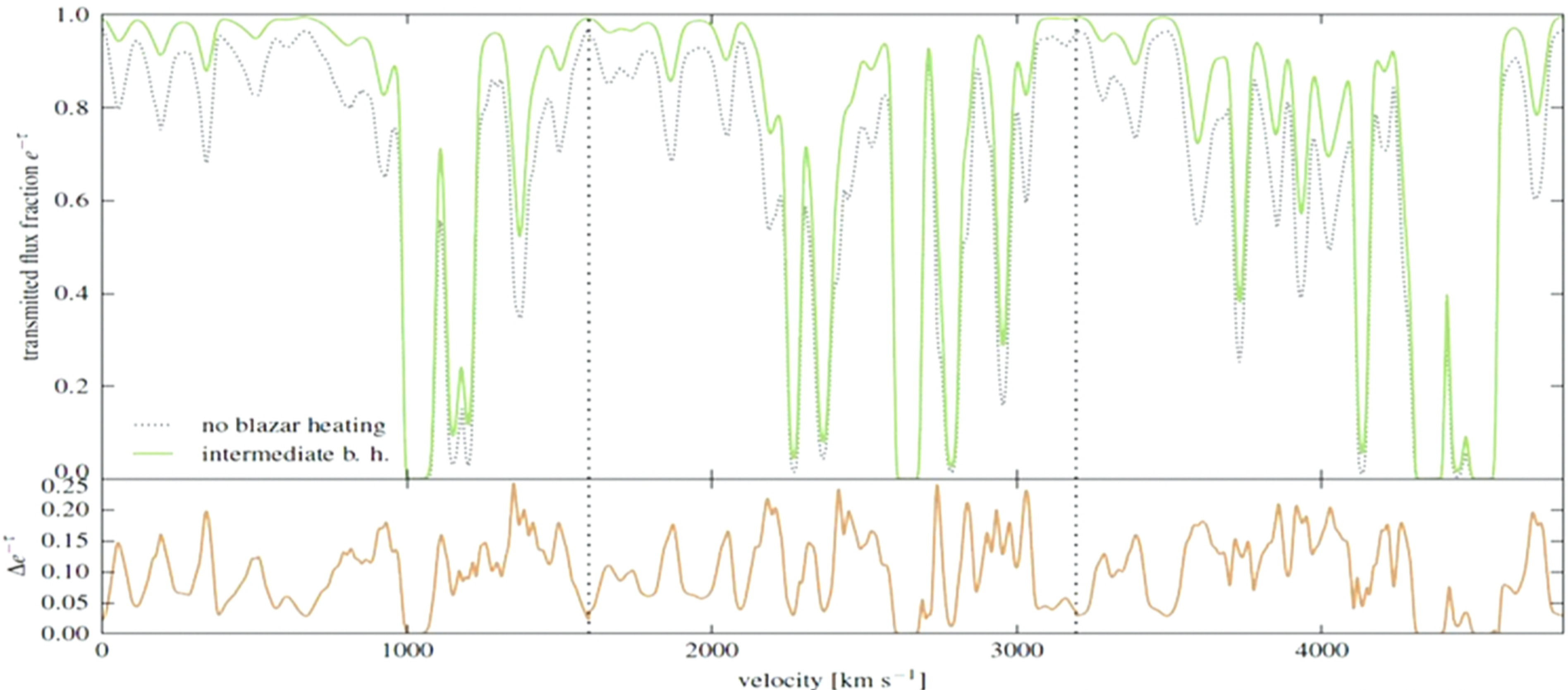
z=3




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

Consequences for the high-z Lyα forest

# Simulated Lyα forest




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

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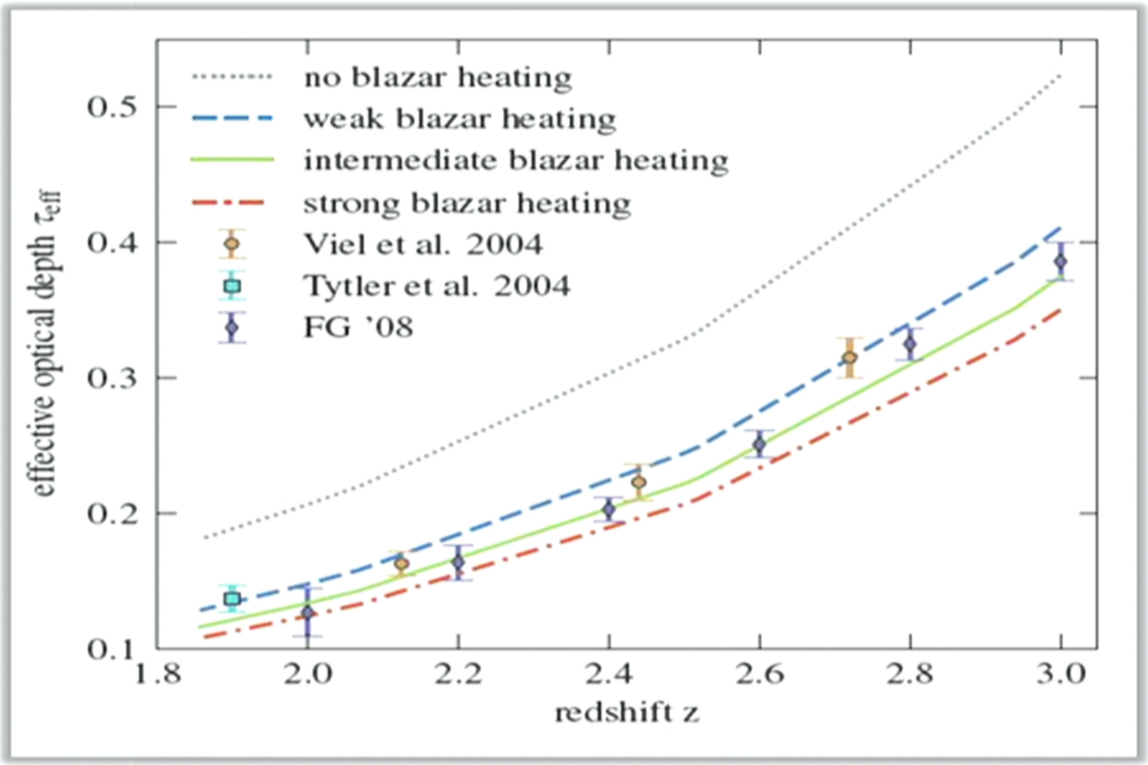
# The end of fudged Lyα calculations!




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

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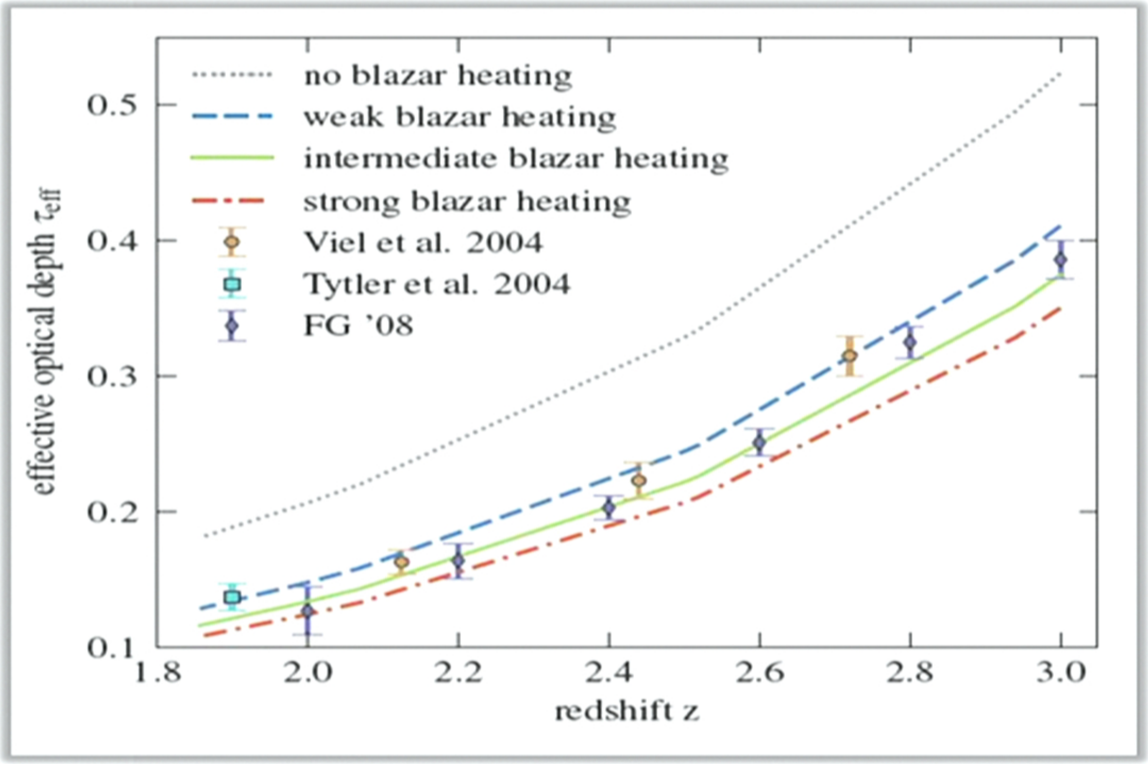
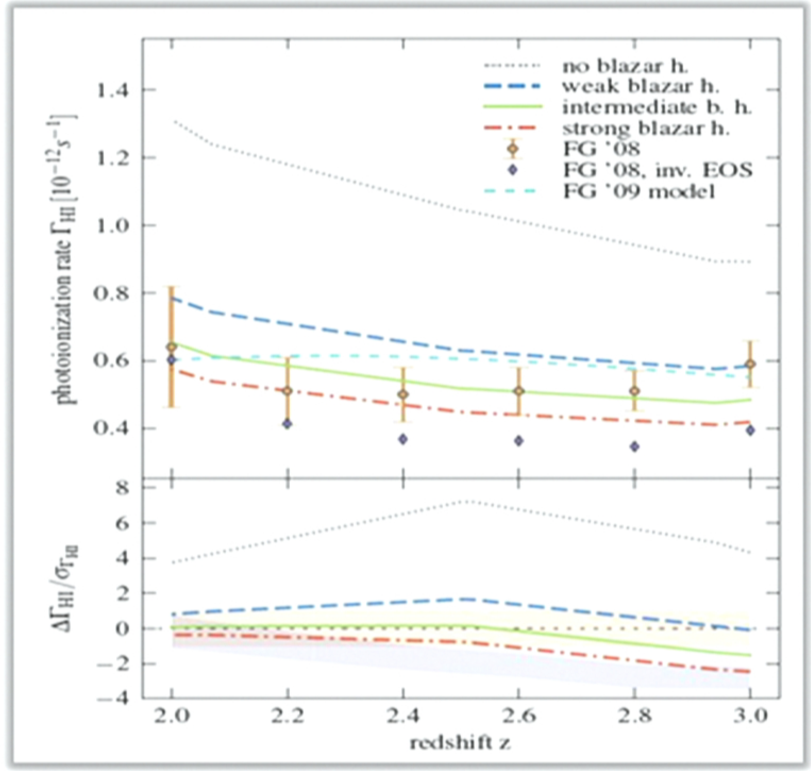
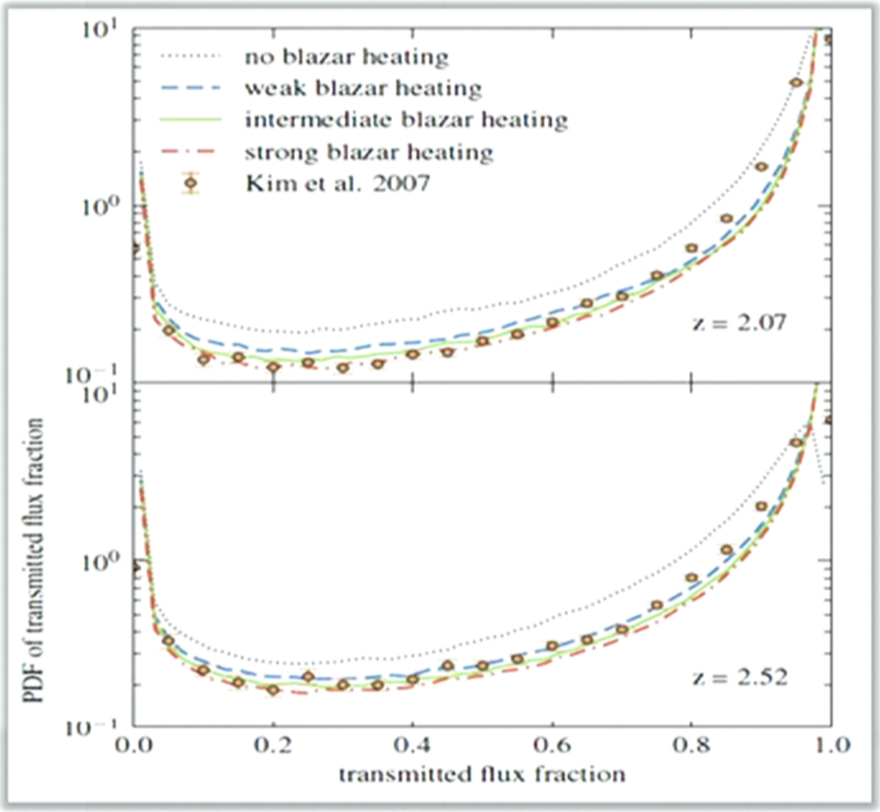


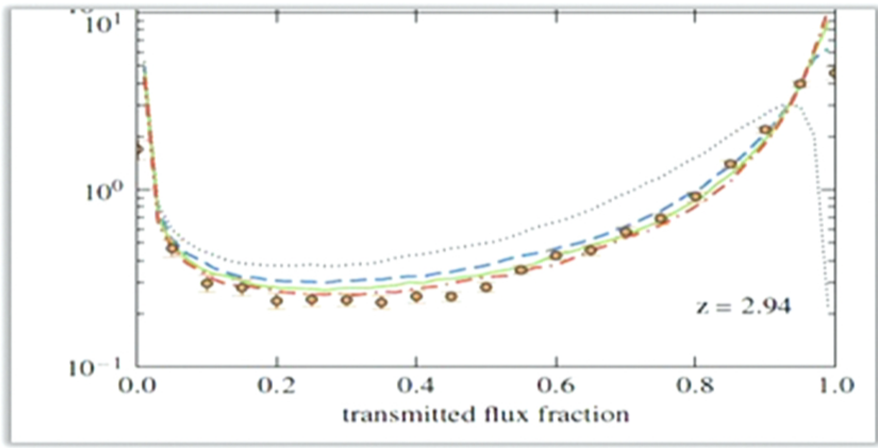




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

Consequences for the high-z Lyα forest

# Lyα Flux/absorption distributions

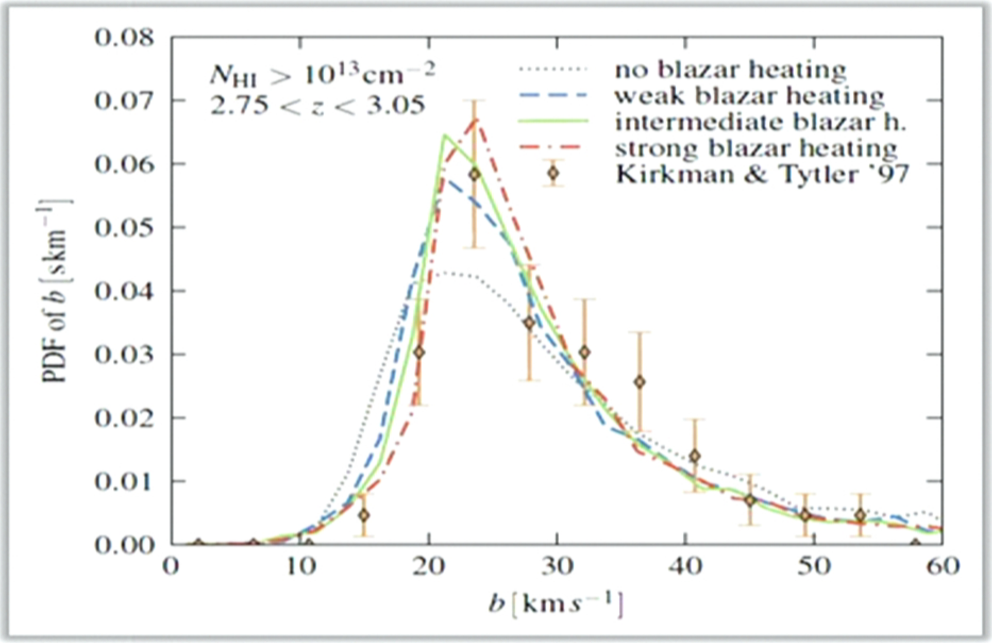


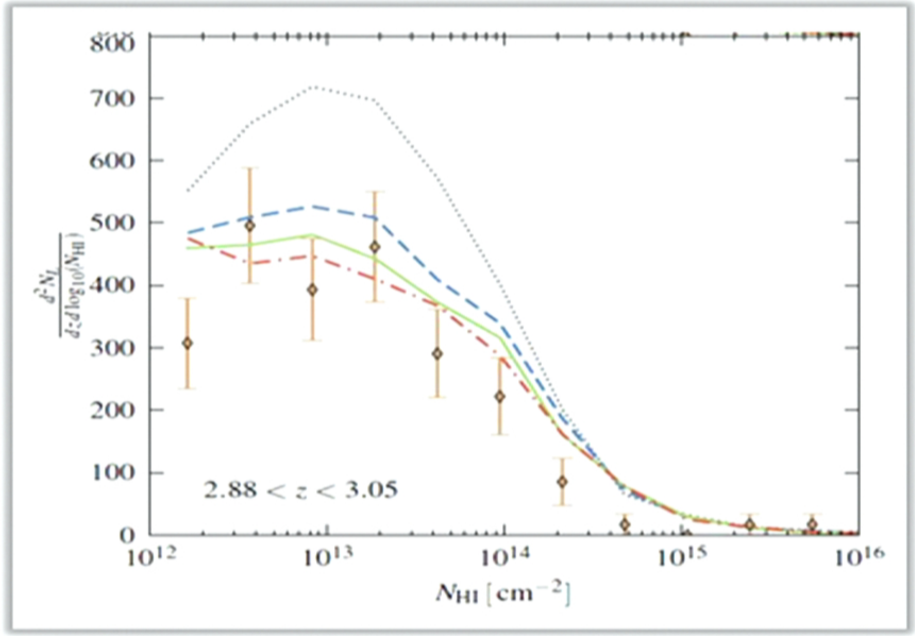




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

Consequences for the high-z Lyα forest

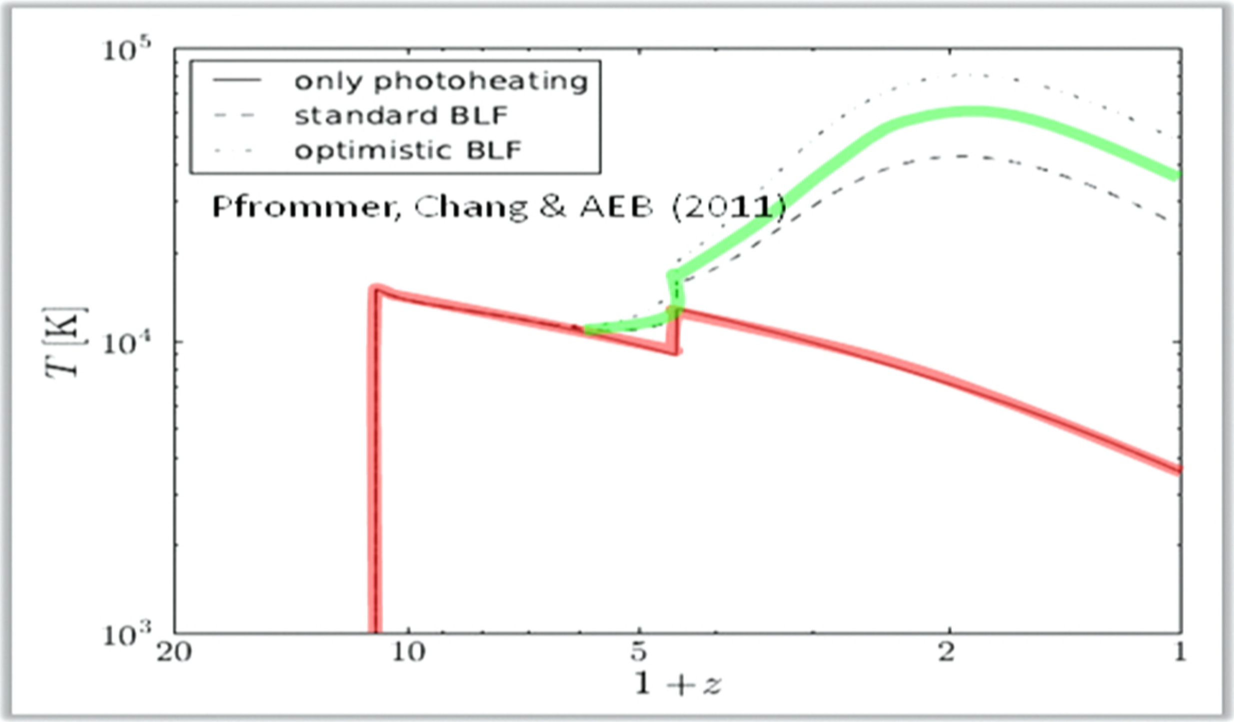
# Lyα line widths and HI columns




Puchwein, Pfrommer, Springle, AEB & Chang (2011)

# Entropy history of the Universe



Consequences for galaxy cluster observations

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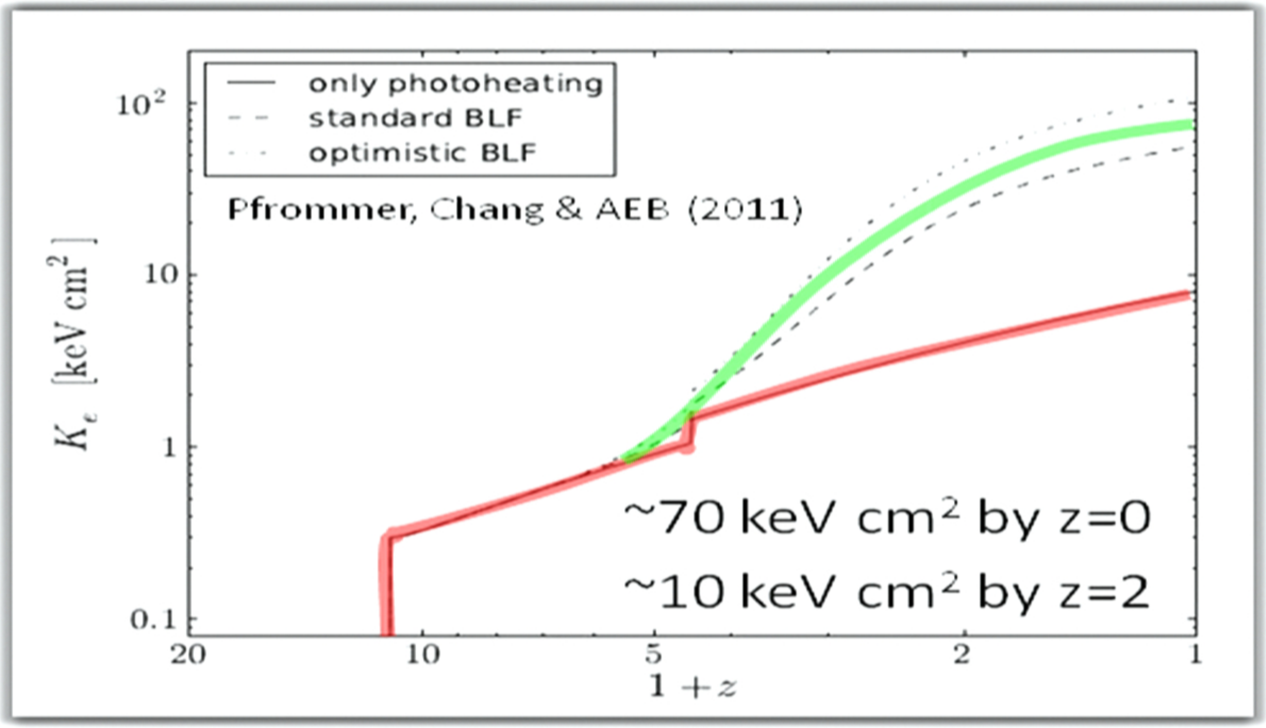


***Late time, evolving, modest preheating***

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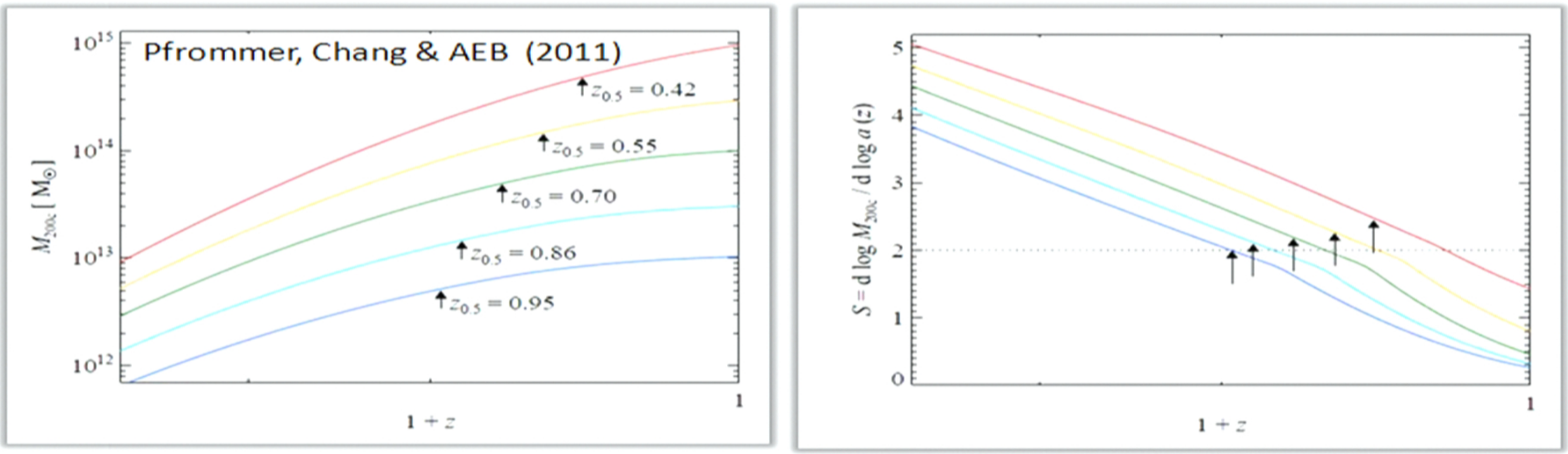
Consequences for galaxy cluster observations

# When do clusters form?




**→ *Most cluster gas accretes after z=1, when heating can have a large effect!***

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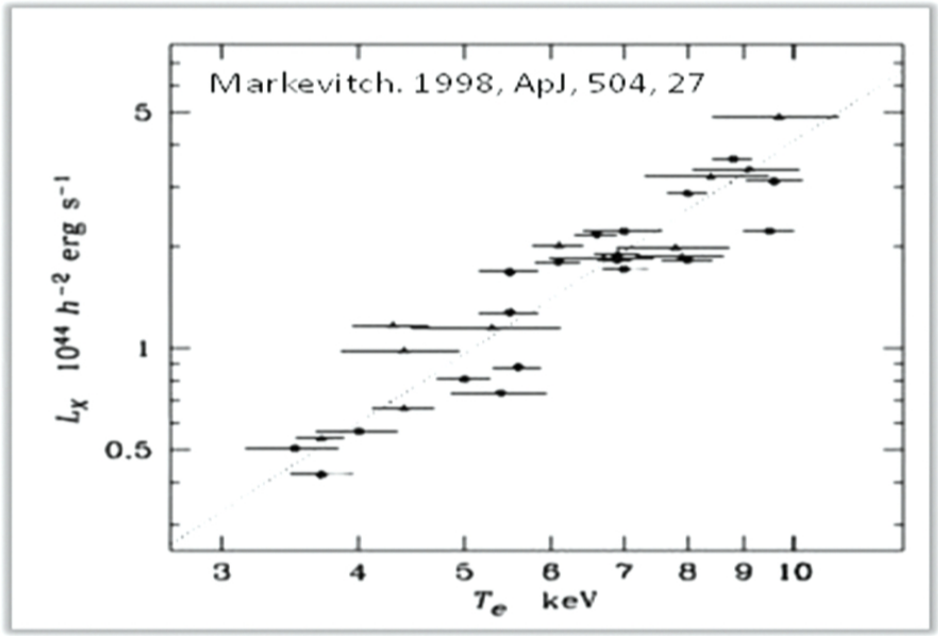
# $L_X$-T Relation, Need for a entropy floor

- For clusters $L_X \sim T^2$
- For groups $L_X \sim T^3$ to avoid violating the soft X-ray background



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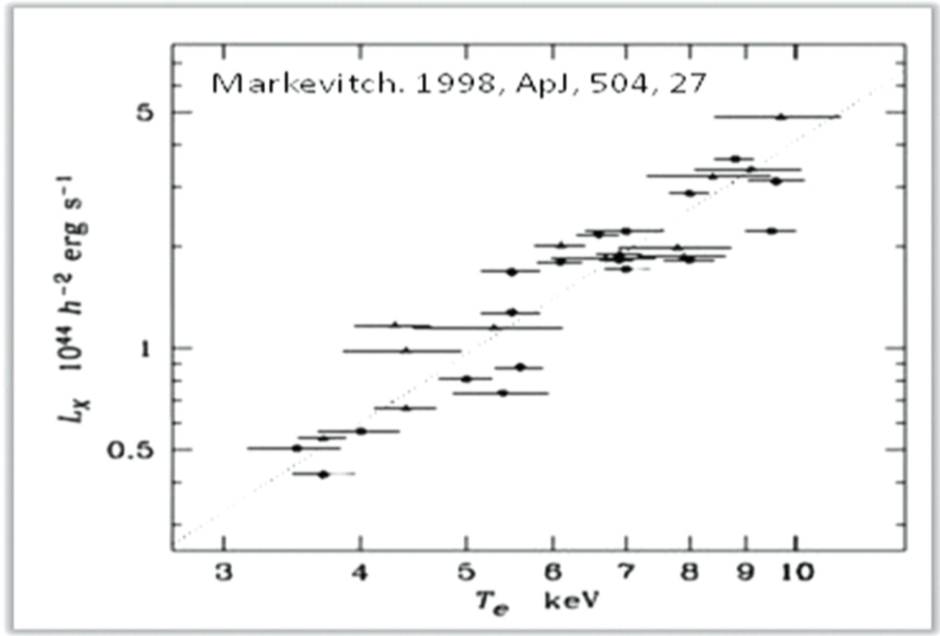

# $L_X$-T Relation, Need for a entropy floor

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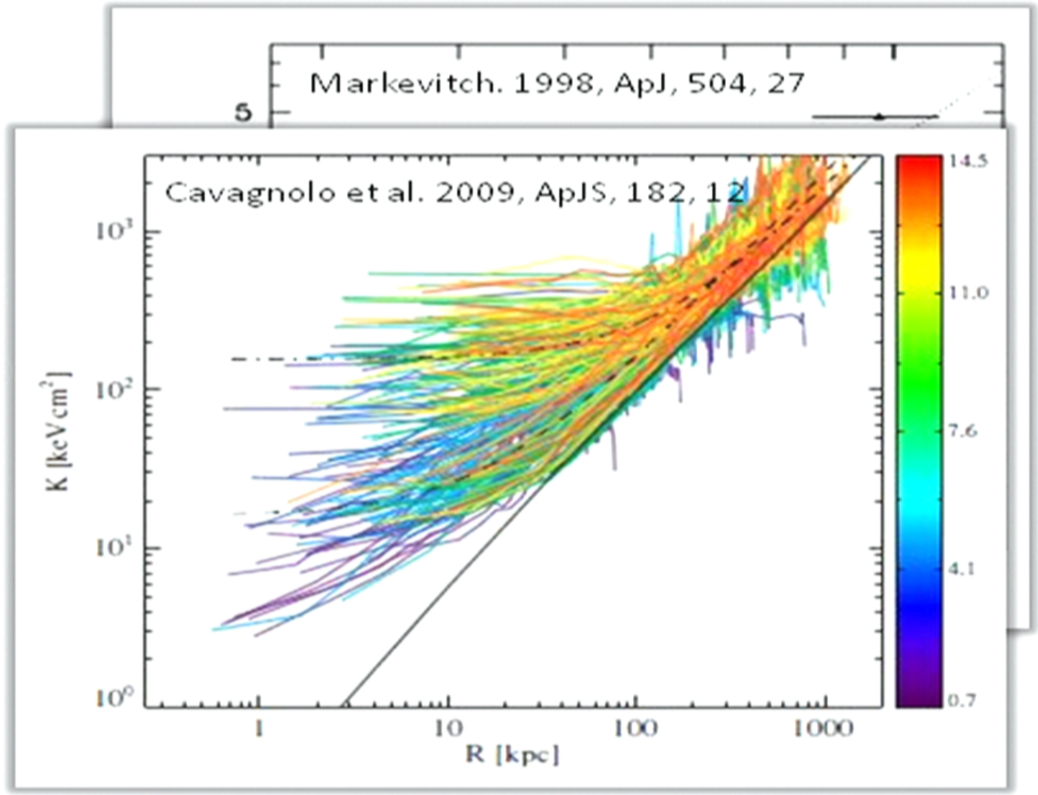
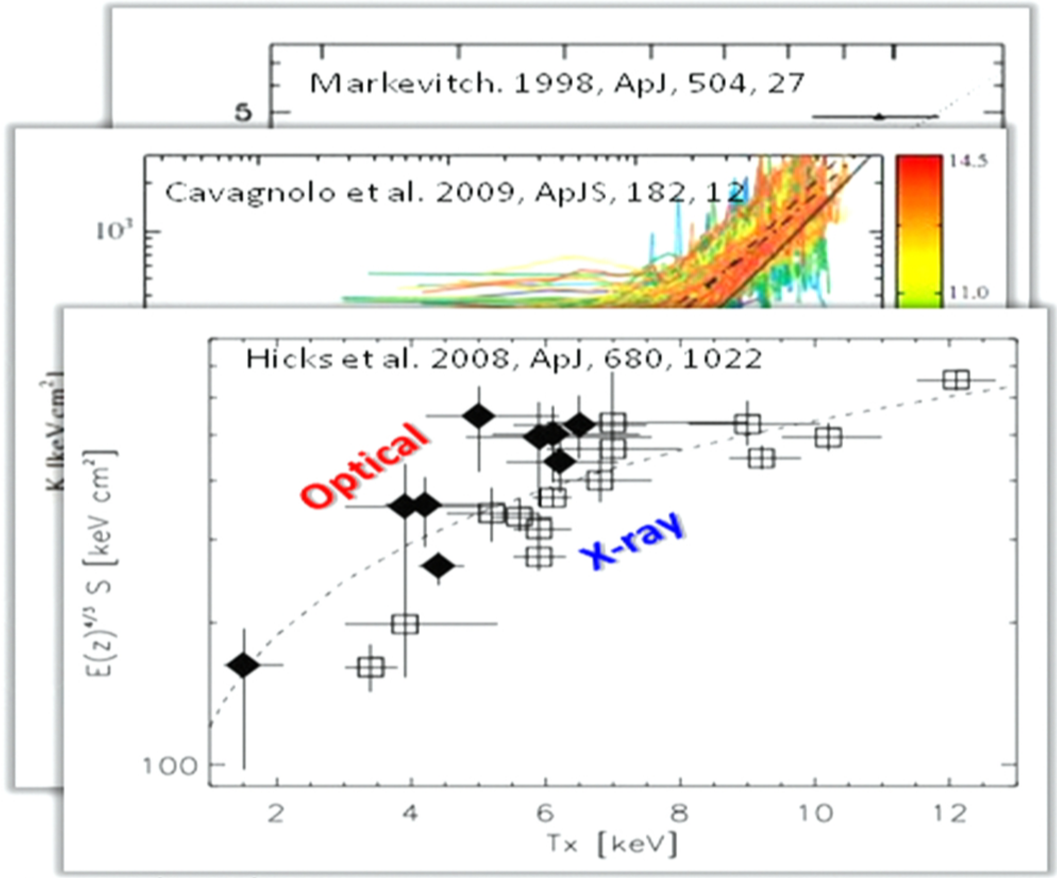
- Core entropy profiles



# $L_X$-T Relation, Need for a entropy floor

- For clusters $L_X \sim T^2$
- For groups $L_X \sim T^3$ to avoid violating the soft X-ray background
- Core entropy profiles
- Maybe different for new and old cores?

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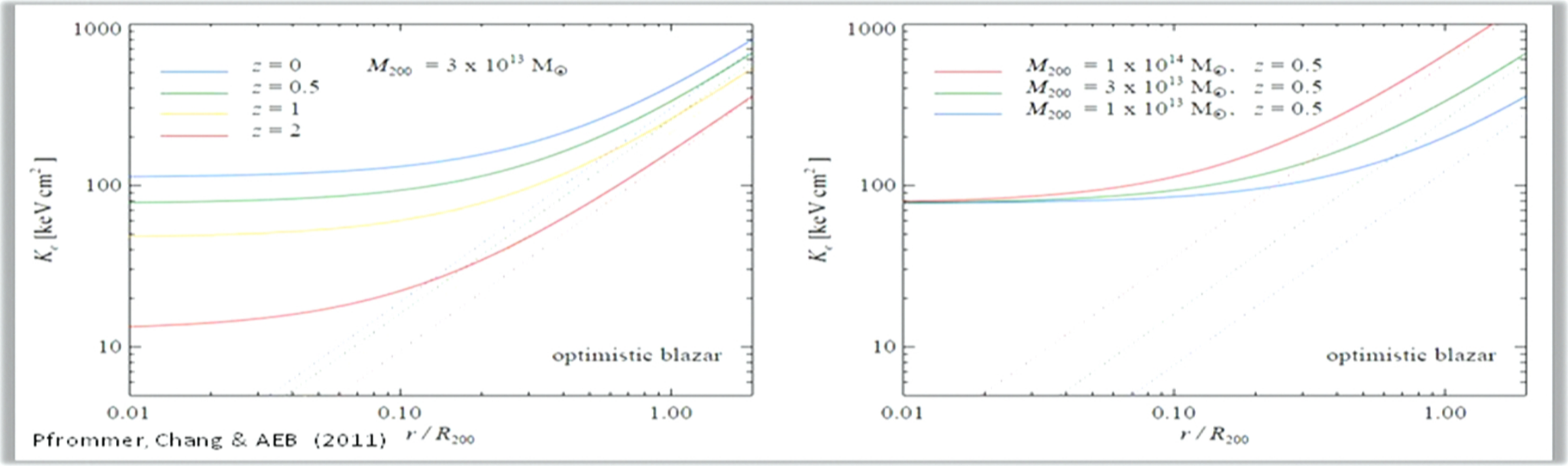
# Cluster entropy profiles with a floor

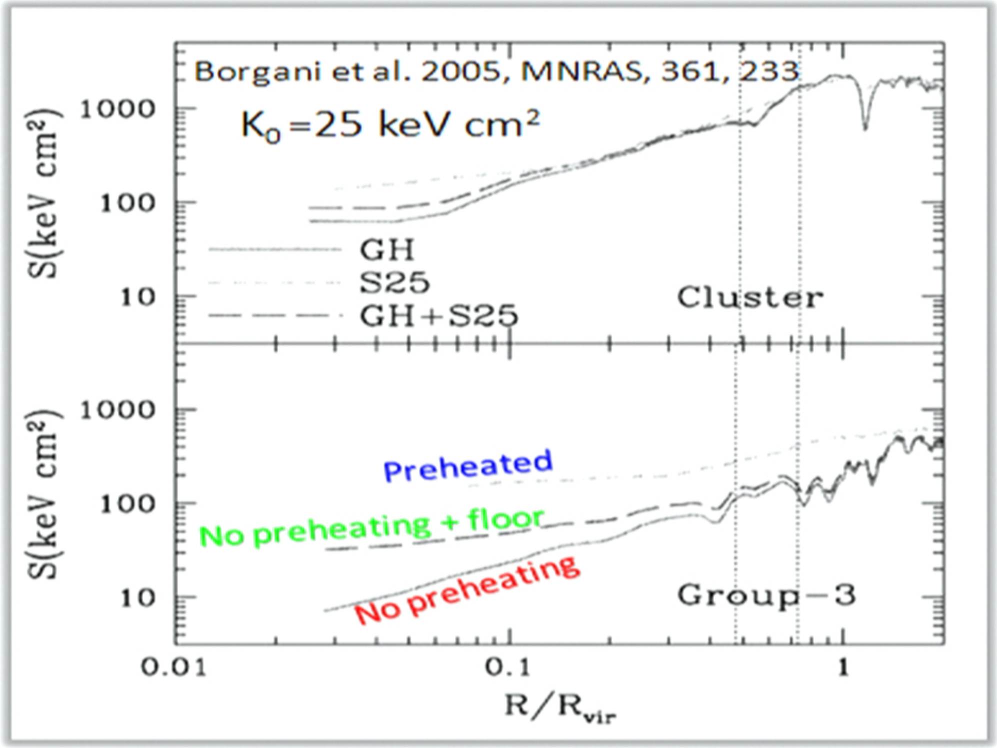



Pfrommer, Chang & AEB (2011)

- redshift-dependent core excess
- Biggest effect for groups and low-mass clusters

# Gravitational reprocessing

- Larger initial $K_0$
  → more shock heating
  → larger increase in $K_0$
- Net $K_0$ amplification of 3-5
- Expect:
  - Med. $K_0$ ~150 keV cm²
  - Max. $K_0$ ~600 keV cm²



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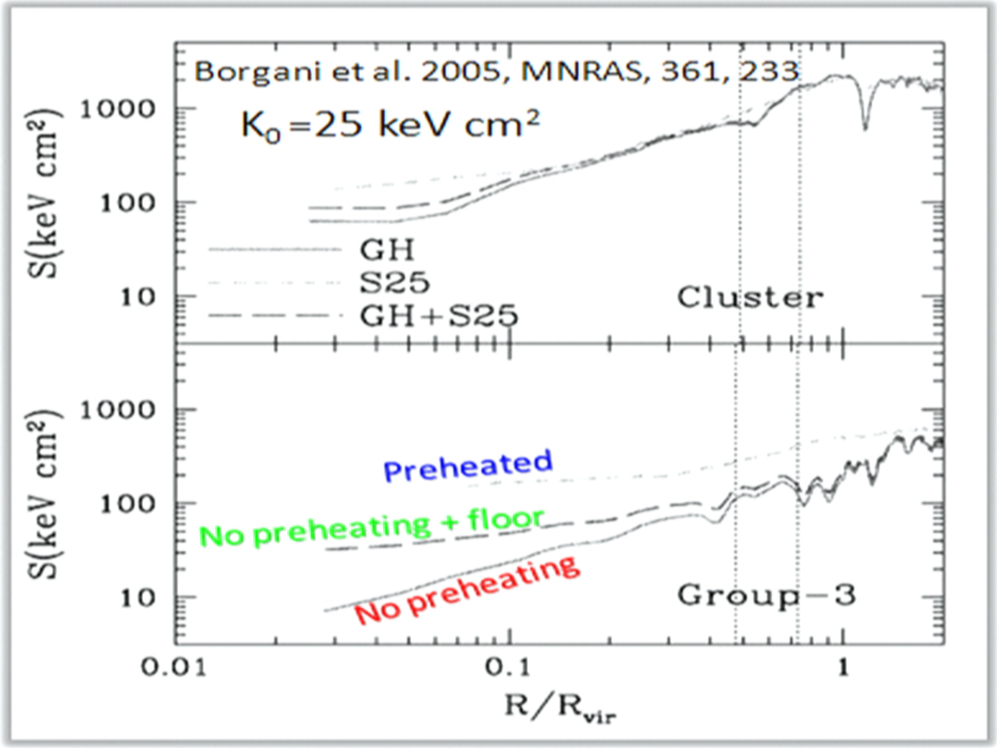
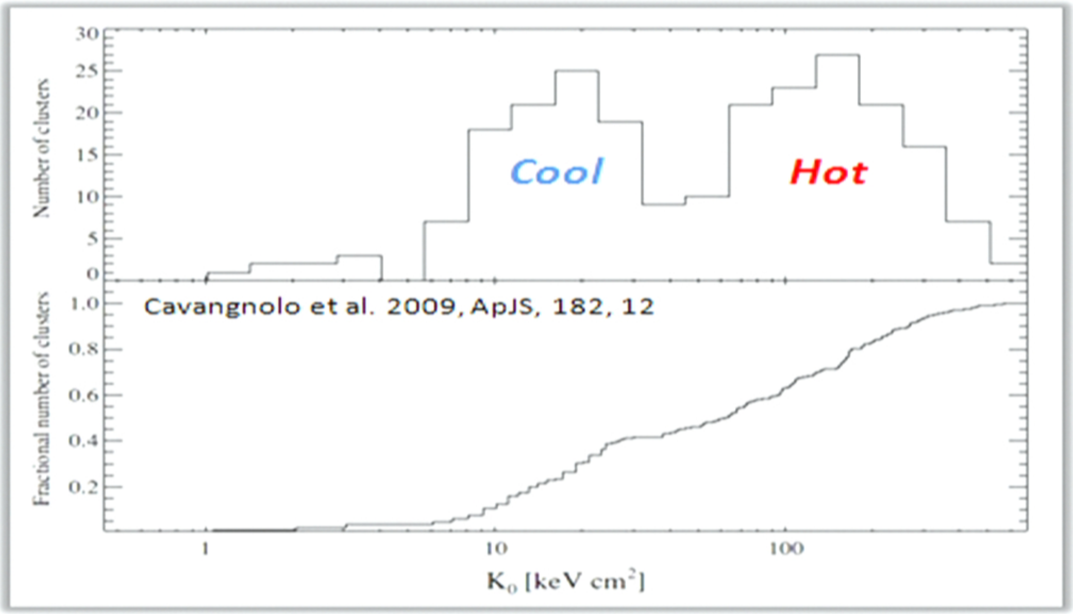


# Cool Core vs. Non-Cool Core clusters



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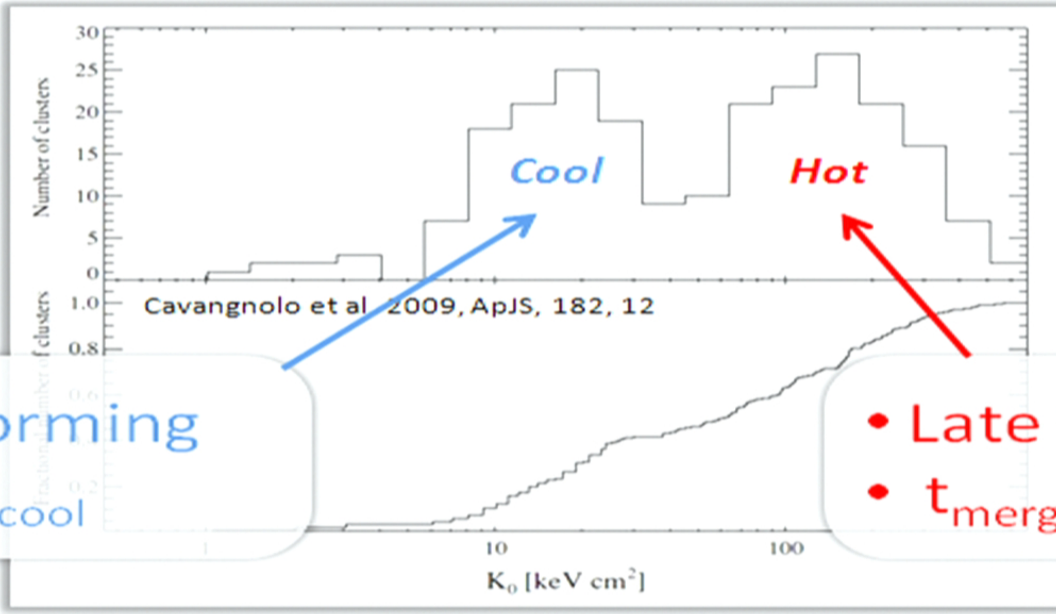
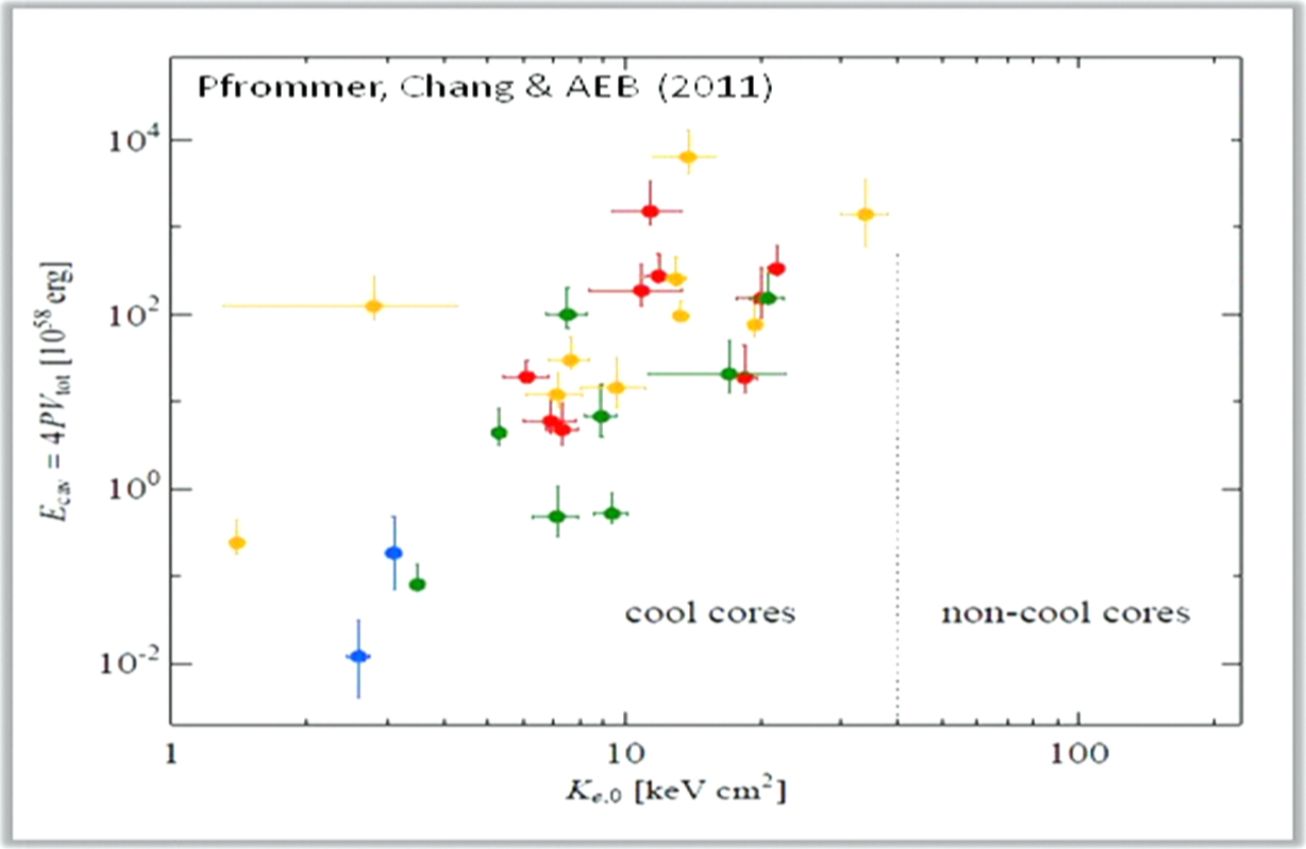



- Early forming
- $t_{merg} > t_{cool}$

- Late forming
- $t_{merg} < t_{cool}$

*Time dependent preheating + gravitational reprocessing → CC-NCC bifurcation*

# Doesn’t AGN feedback already do this?

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# Forming structures in a hot IGM

- Hotter IGM
  - → higher IGM pressure
  - → higher Jeans mass

$$M_J \propto \frac{c_s^3}{1+\delta} \propto \frac{T_{\rm IGM}^{3/2}}{1+\delta} \quad \rightarrow \quad \frac{M_{J,\rm blazar}}{M_{J,\rm photo}} \approx \left(\frac{T_{\rm blazar}}{T_{\rm photo}}\right)^{3/2} \approx 18-50$$

- In practice, use "filtering mass", which corrects for redshift evolution, and apply estimated non-linear corrections.

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  - → higher IGM pressure
  - → higher Jeans mass

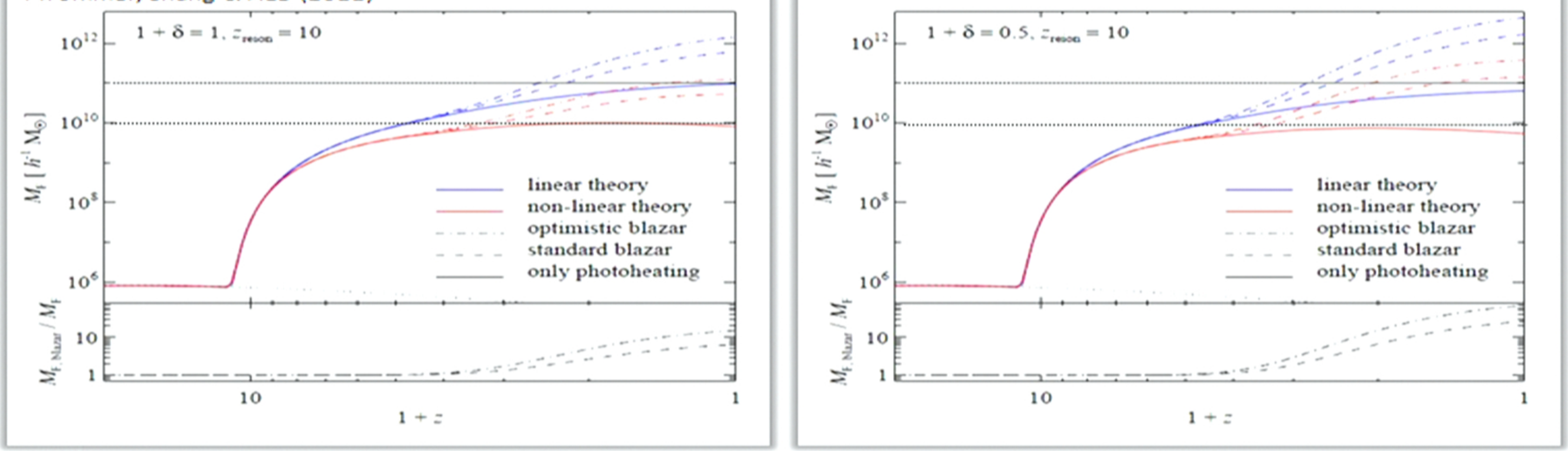
$$M_J \propto \frac{c_s^3}{1+\delta} \propto \frac{T_{\rm IGM}^{3/2}}{1+\delta} \quad \rightarrow \quad \frac{M_{J,\rm blazar}}{M_{J,\rm photo}} \approx \left(\frac{T_{\rm blazar}}{T_{\rm photo}}\right)^{3/2} \approx 18-50$$

- In practice, use "filtering mass", which corrects for redshift evolution, and apply estimated non-linear corrections.

Consequences for missing dwarf galaxies

# Blazar heated filtering masses

Pfrommer, Chang & AEB (2011)

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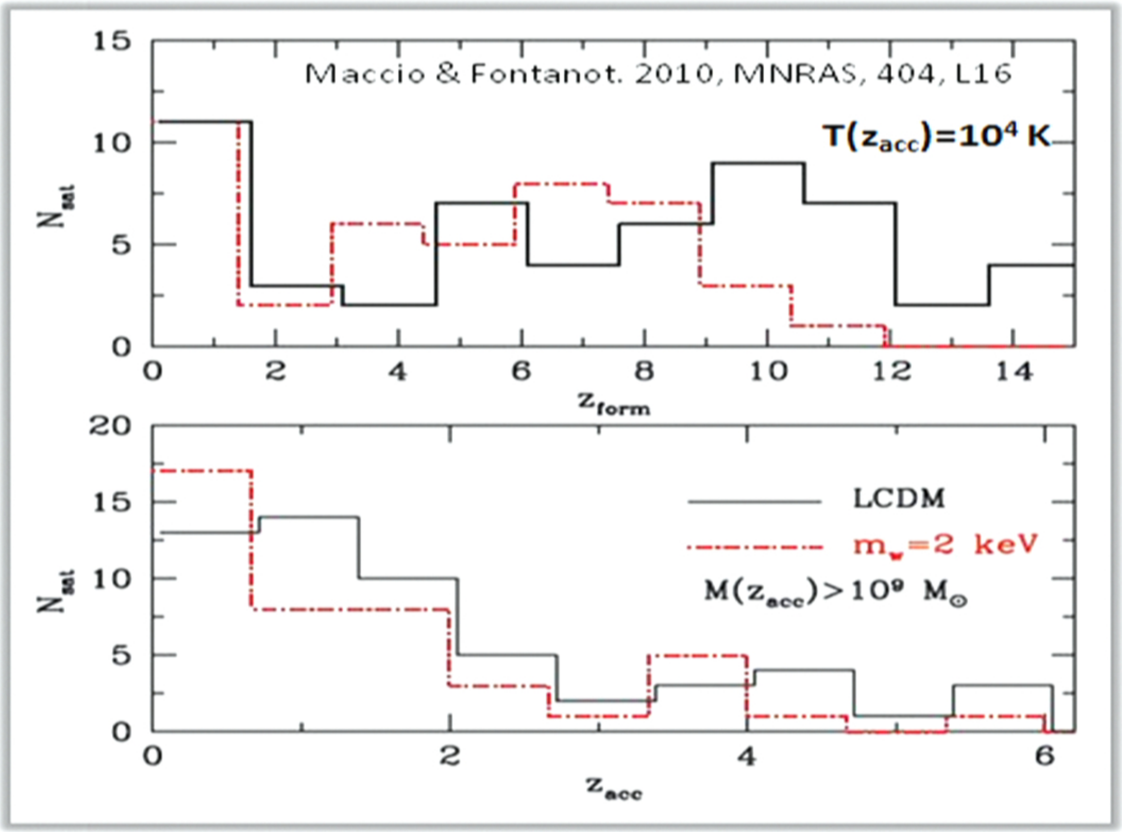
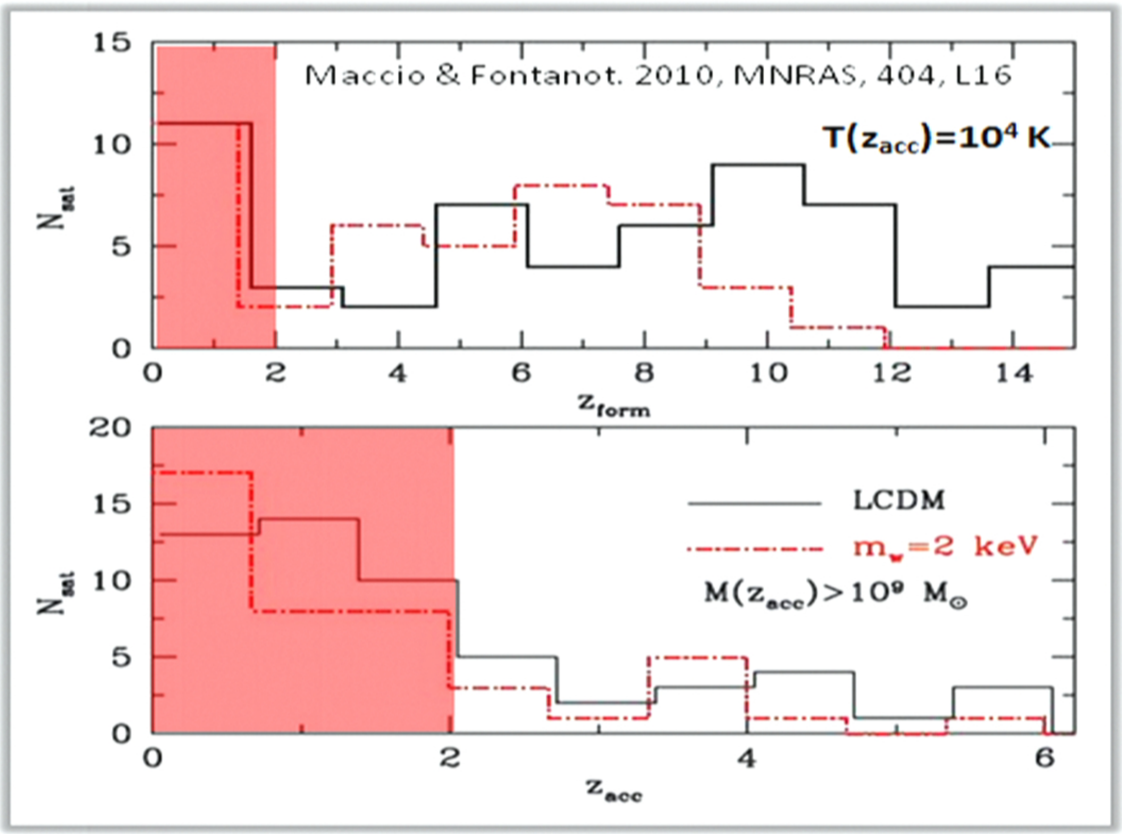
# When do dwarf galaxies form?



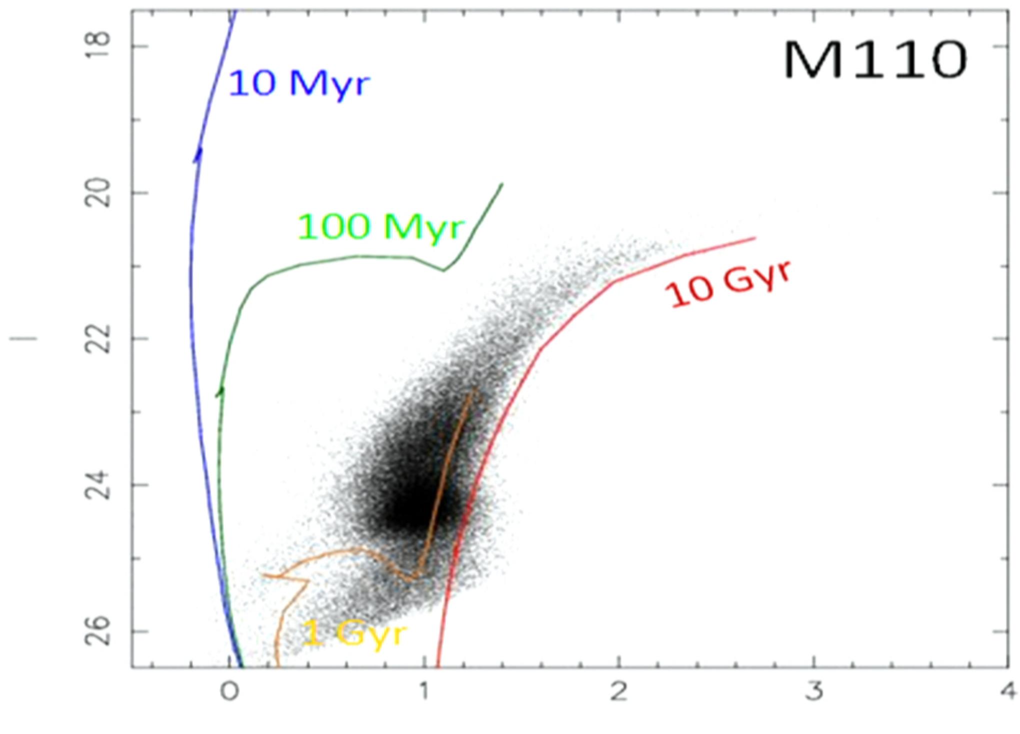

- Roughly 1/3 of dwarf *haloes* form at z<3
- When dwarf galaxies form depends upon external factors

# When do dwarf galaxies form?




- Roughly 1/3 of dwarf *haloes* form at $z<3$
- When dwarf galaxies form depends upon external factors

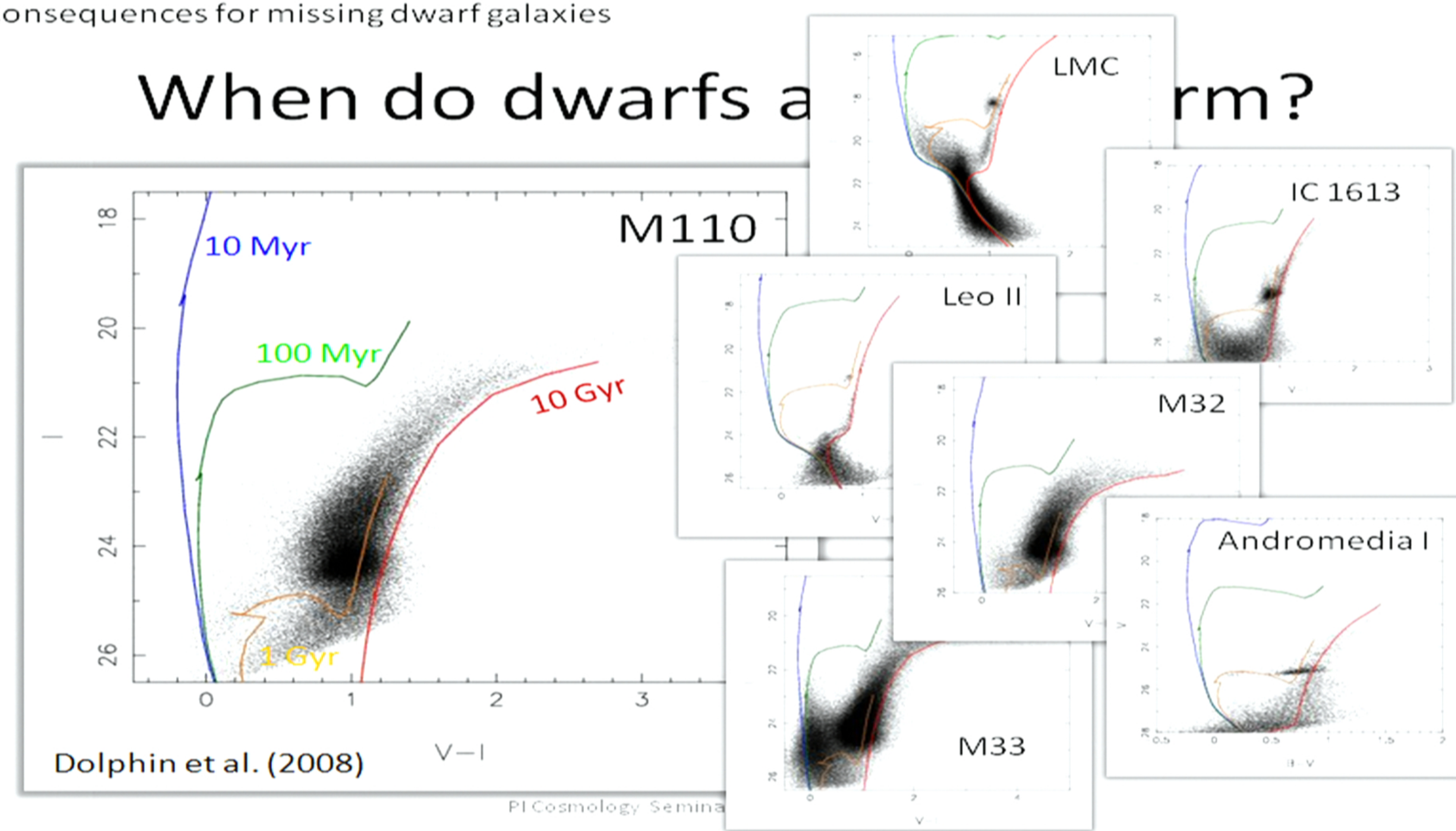
# When do dwarfs actually form?




Dolphin et al. (2008)

Consequences for missing dwarf galaxies

# When do dwarfs a… rm?

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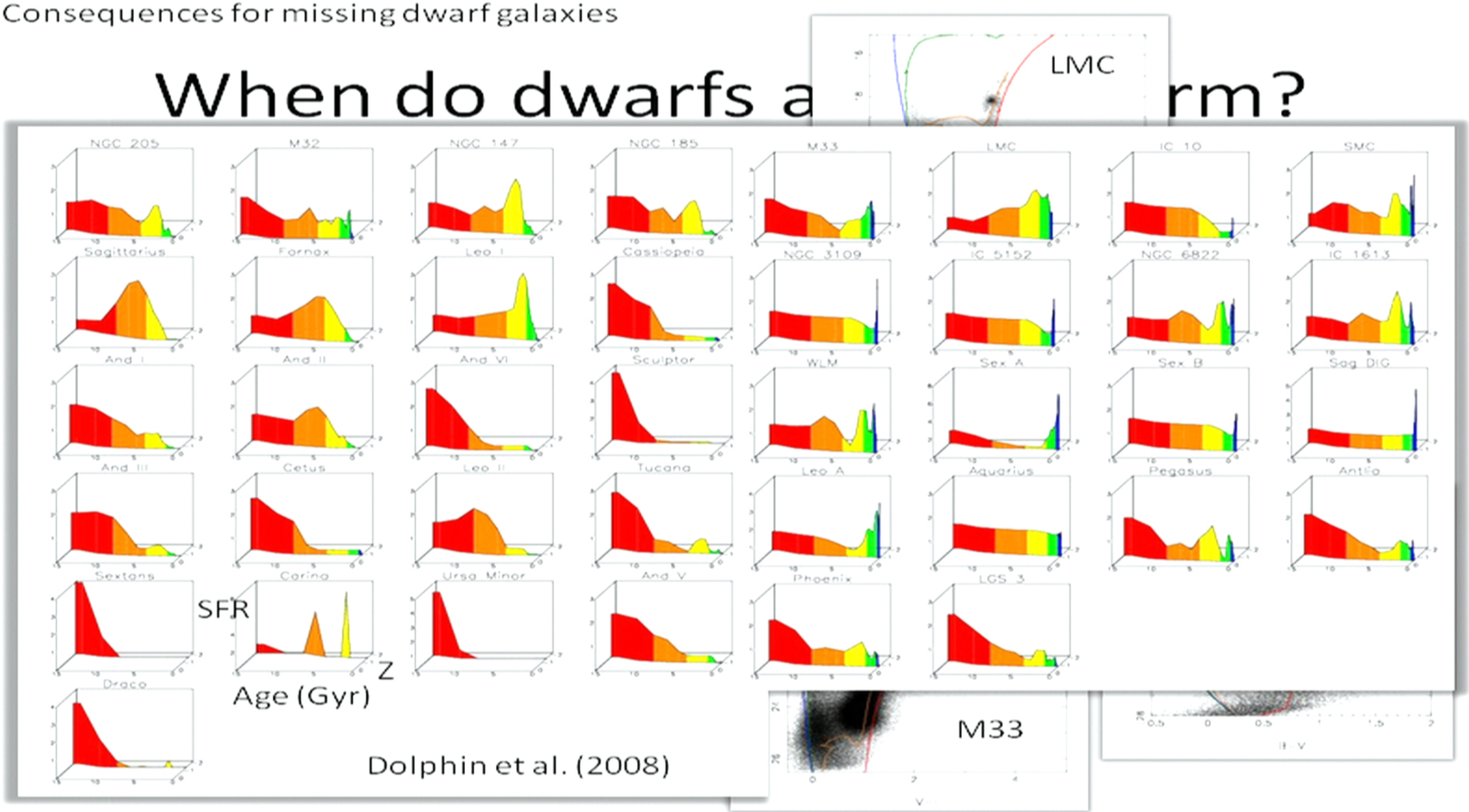
Consequences for missing dwarf galaxies

# When do dwarfs a... rm?



# Galactic HI Masses

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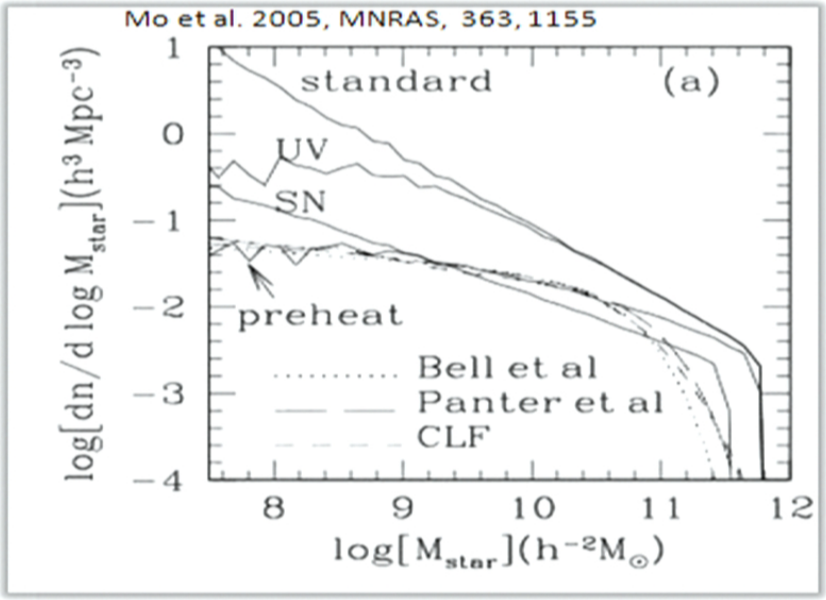
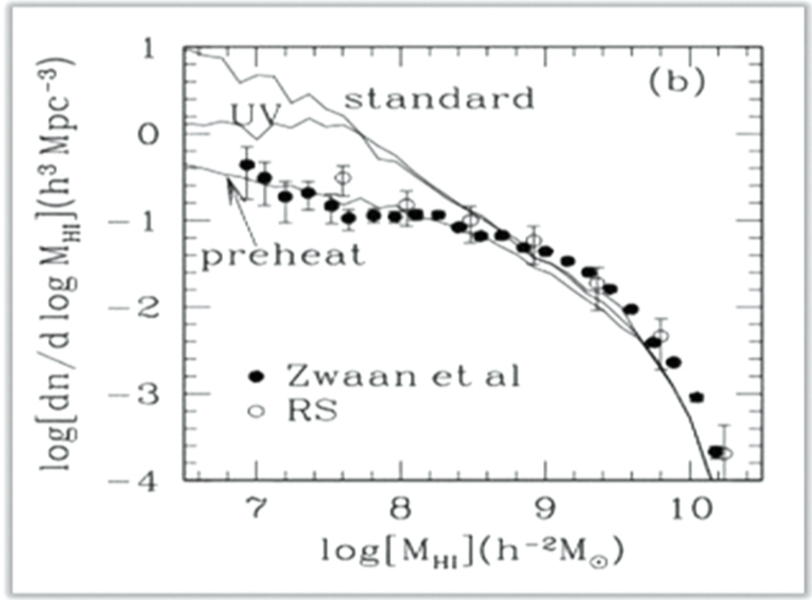
# Galactic HI Mass Function

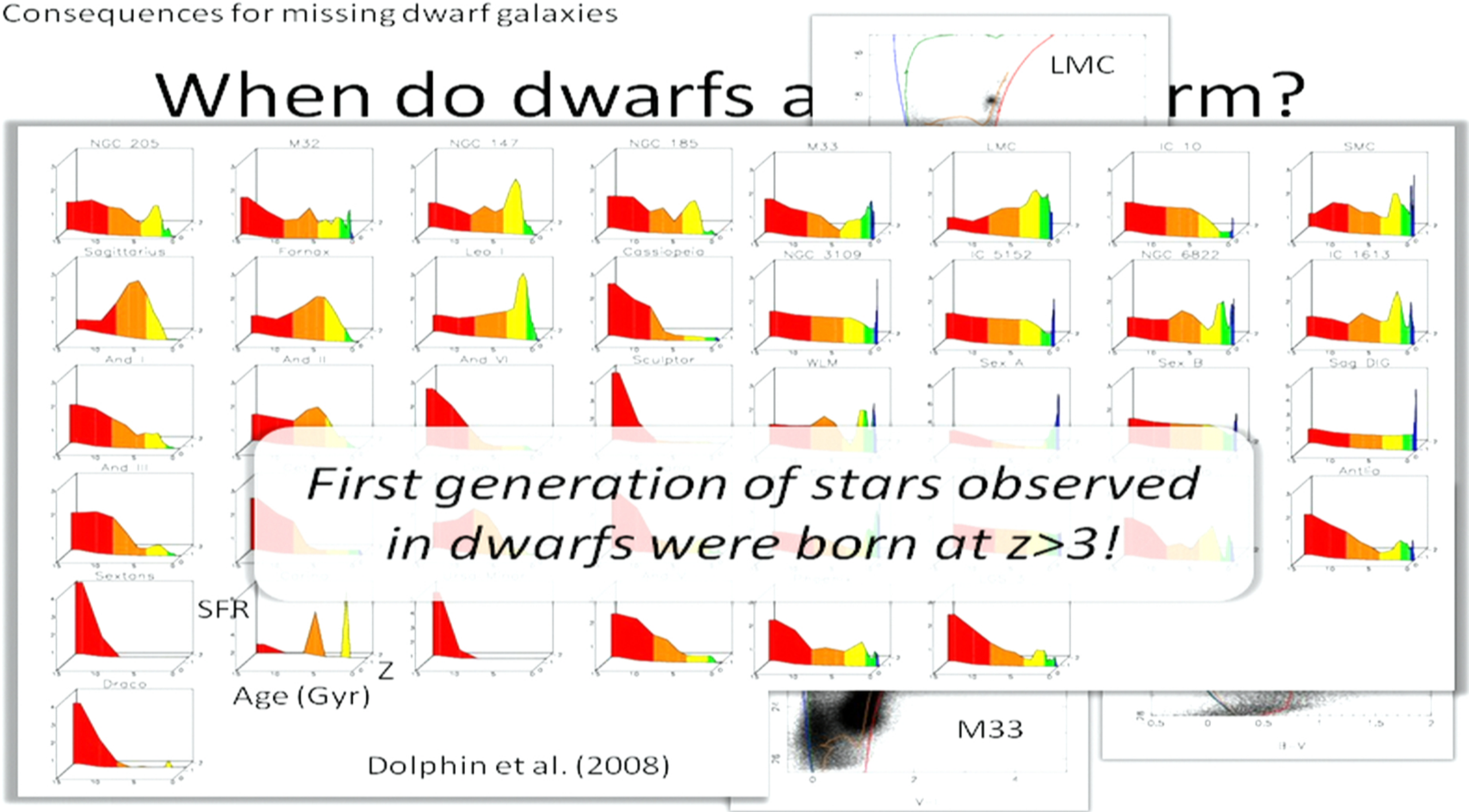



- HI mass function is too flat (i.e., gas version of missing dwarf problem!)
- Photoheating & SN feedback fail: SN ← Stars ← High HI densities!
- But, K~15 keV cm$^2$ IGM at z<2-3 works!

Consequences for missing dwarf galaxies

# When do dwarfs a… rm?




*First generation of stars observed in dwarfs were born at z>3!*

# A Trifling Investment …

- Plasma beam instabilities may dominate the fate of the VHEGR emission from blazars
- This would provide a unique, volumetrically uniform heating
- ***If this is so*** we can explain:
  - Lack of GeV bumps in nearby TeV sources
  - Fermi source counts and EGRB with a unified TeV blazar model
  - Inverted T-$\rho$ relation for voids at z~3
  - High-z Ly$\alpha$ forest statistics with the highest precision to date and no fudge factors!
  - Galaxy group/cluster entropy profiles, both magnitude and cool core – non-cool core dichotomy
  - Missing dwarf galaxies in voids and in galactic halos
  - Dwarf galaxy star formation histories
  - HI mass function