Acceleration of High-Energy Particles by Cosmic Shocks

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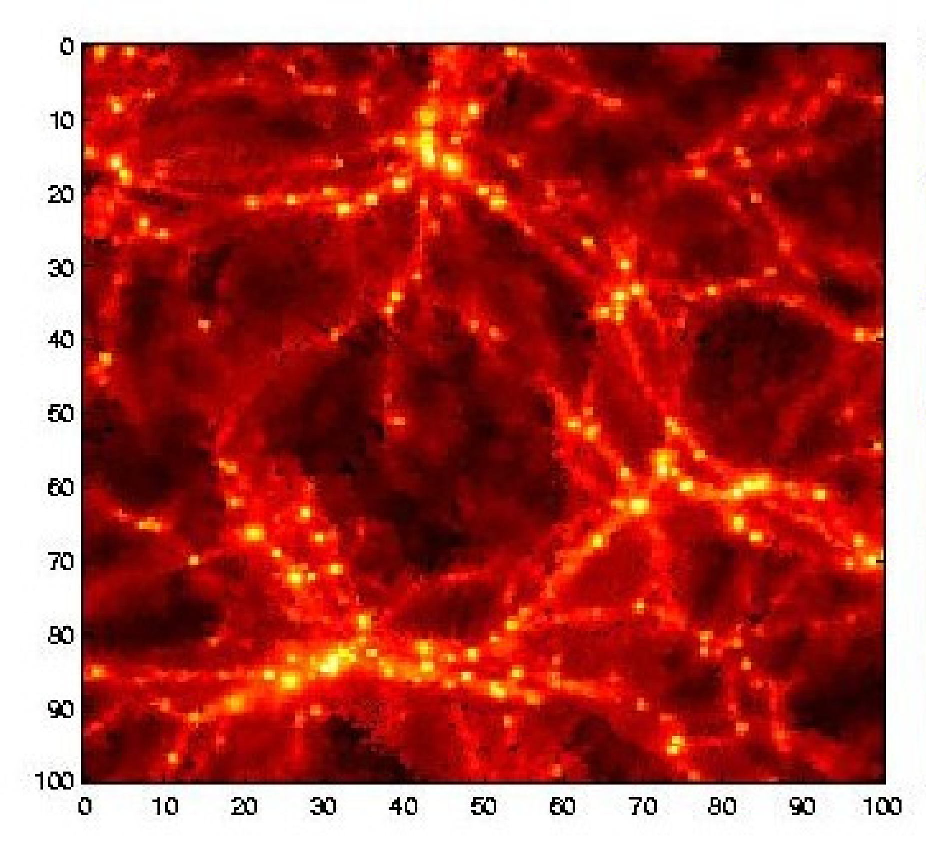
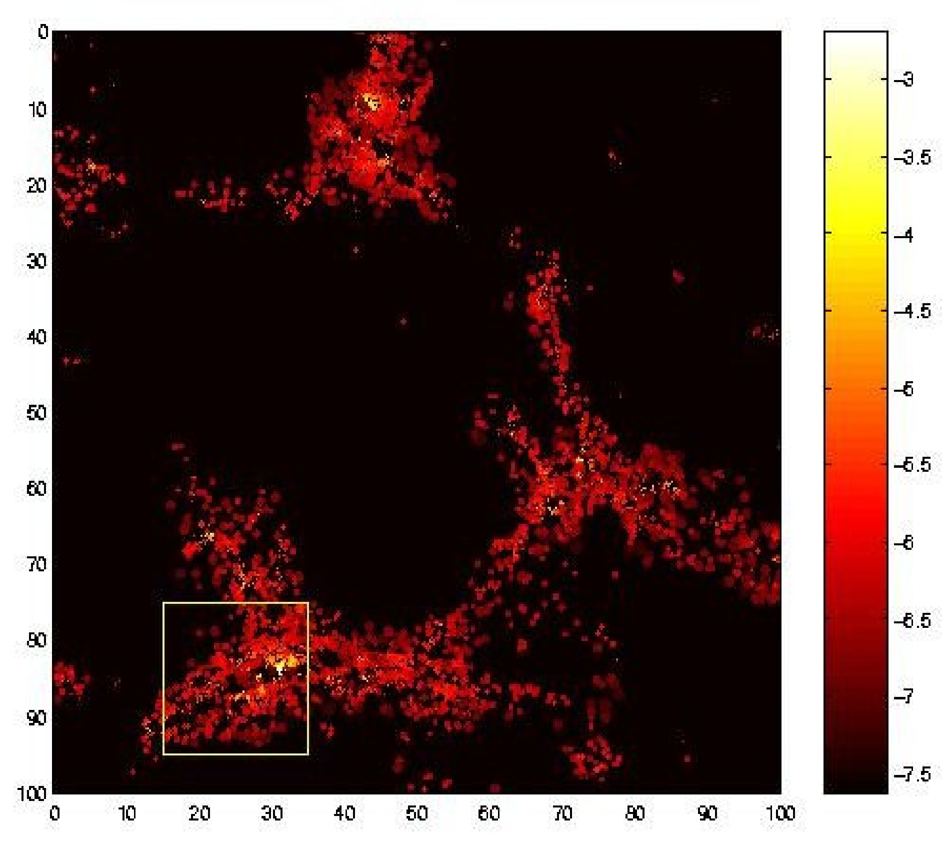
Fermilab, 7/13/2005

Structure Formation in the IGM



Density contrast of gas at z=0 for a 100x100x10 Mpc^3 slice



Density contrast of gas shocked between z=0.14-0.09

Collisionless Intergalactic Shocks

For a shock compression factor $r = \rho_{sh}/\rho_0$

$$\frac{dn_e}{dp_e} = Kp_e^{-\alpha}, \quad \alpha = \frac{r+2}{r-1}$$

For strong shocks:

$$r = (\Gamma + 1)/(\Gamma - 1) = 4 \quad \text{and} \quad \alpha = 2 \ \text{if} \ \Gamma = 5/3$$

$$\frac{dn_e}{dp_e} = Kp_e^{-2}$$

Examples: SN 1006, SN RX J1713.7-3946

E_max= 100 TeV (from X-ray and TeV observations)

v_sh ~ 1000-2000 km/s

Energy fraction in relativistic electrons: $\xi_e \sim 1 - 10\%$

IGM Acceleration Parameters

Larmor radius = $6 \times 10^{-2} (\frac{\gamma_e}{10^7}) (\frac{B}{0.1\mu\mathrm{G}})^{-1}$ pc $\ll$ Mpc

→the magnetic field could have a short coherence length.

The acceleration e-folding time:

$$t_{\mathrm{acc}} \sim (\frac{r_L}{c})(\frac{c^2}{v_{sh}^2}) = 2 \times 10^4 \mathrm{yr} (\frac{\gamma_7}{B_{-7}})$$

Cooling time: $t_{IC} = 1.2 \times 10^{10}\ \mathrm{yr}\ (\frac{\gamma_e}{200})^{-1};$

$$(t_{synch}/t_{IC}) \sim 10^2 (B/0.1\mu\mathrm{G})^{-2}$$

Maximum Lorentz factor:

$$t_{\mathrm{acc}} = t_{IC} \rightarrow \gamma_{\max} = 4 \times 10^7 (B_{-7} T_7)^{1/2}$$

Scattered CMB: $h\nu = 36 (\frac{\gamma_e}{200})^2\ \mathrm{eV} = 90 \gamma_7^2\ \mathrm{GeV}$

Spectrum of Scattered Radiation

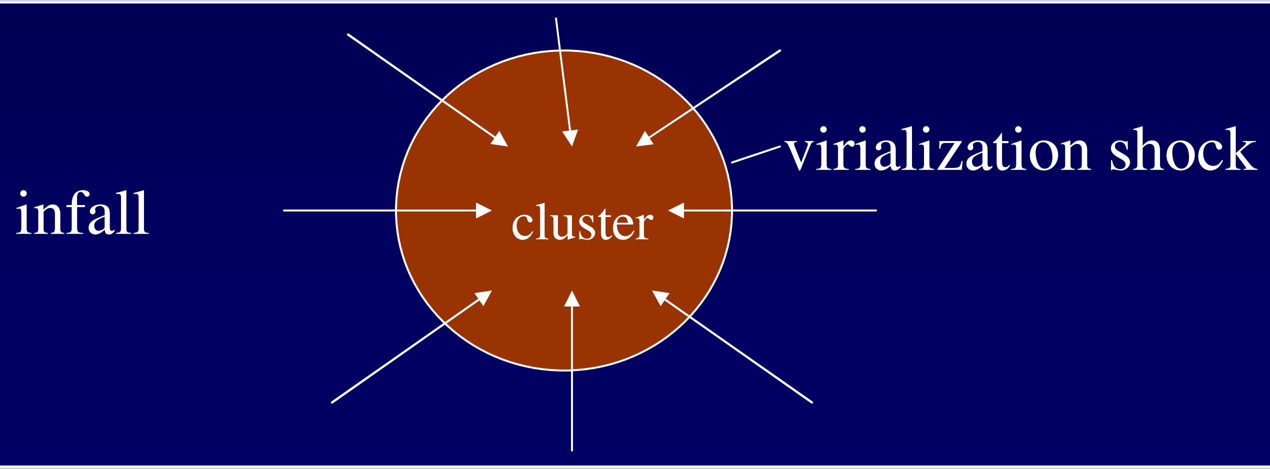
$$\nu\frac{dU}{d\nu} = \frac{U_e}{2\ln\gamma_{\max}} = const$$

$$E^2\frac{dJ}{dE} = 1.1\left(\frac{\xi_e}{0.05}\right)\left(\frac{T_{sh}}{\mathrm{keV}}\right)\ \frac{\mathrm{keV}}{\mathrm{cm}^2\ \mathrm{s}\ \mathrm{sr}}$$

$$h\nu_{\max} = 1.2B_{-7}T_7\ \mathrm{TeV};\ \ 10\text{-}15\%\ \ \mathrm{of\ soft\ XRB}$$

In young X-ray clusters:

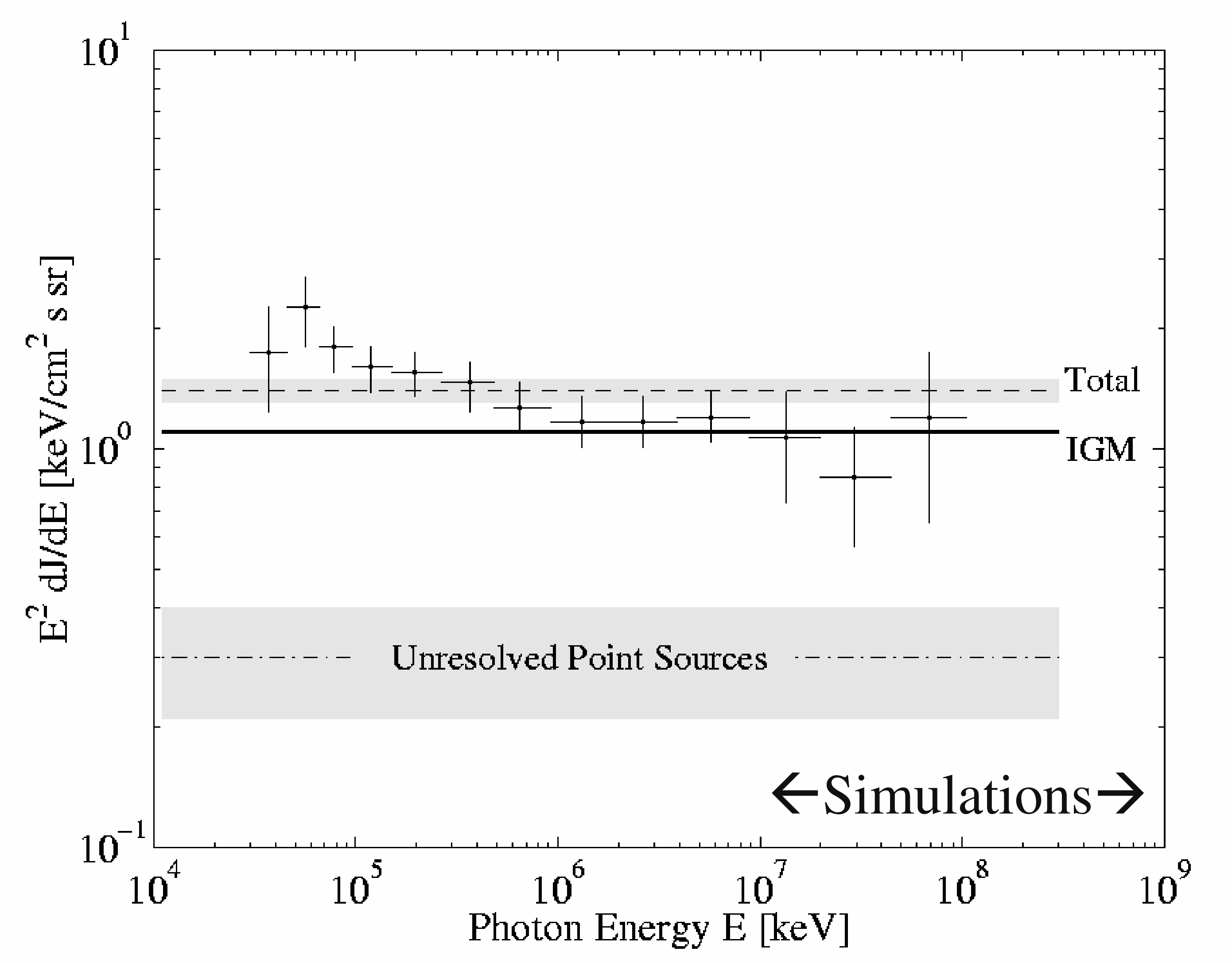
$$L_\gamma \sim 10^{45}\left(\frac{\xi_e}{0.05}\right)\left(\frac{t_{\mathrm{vir}}}{\mathrm{Gyr}}\right)^{-1}\left(\frac{M_{\mathrm{gas}}}{10^{14}M_\odot}\right)\left(\frac{T_{sh}}{5\ \mathrm{keV}}\right)\ \frac{\mathrm{ergs}}{\mathrm{sec}}$$



But note that if r~2 instead of 4:

$$\alpha \sim 4\ \ \mathrm{instead\ of}\ \ 2\ \ \mathrm{and}\ \ \nu L_\nu \propto \nu^{-1}$$

Gamma-Ray Background



T=1 keV

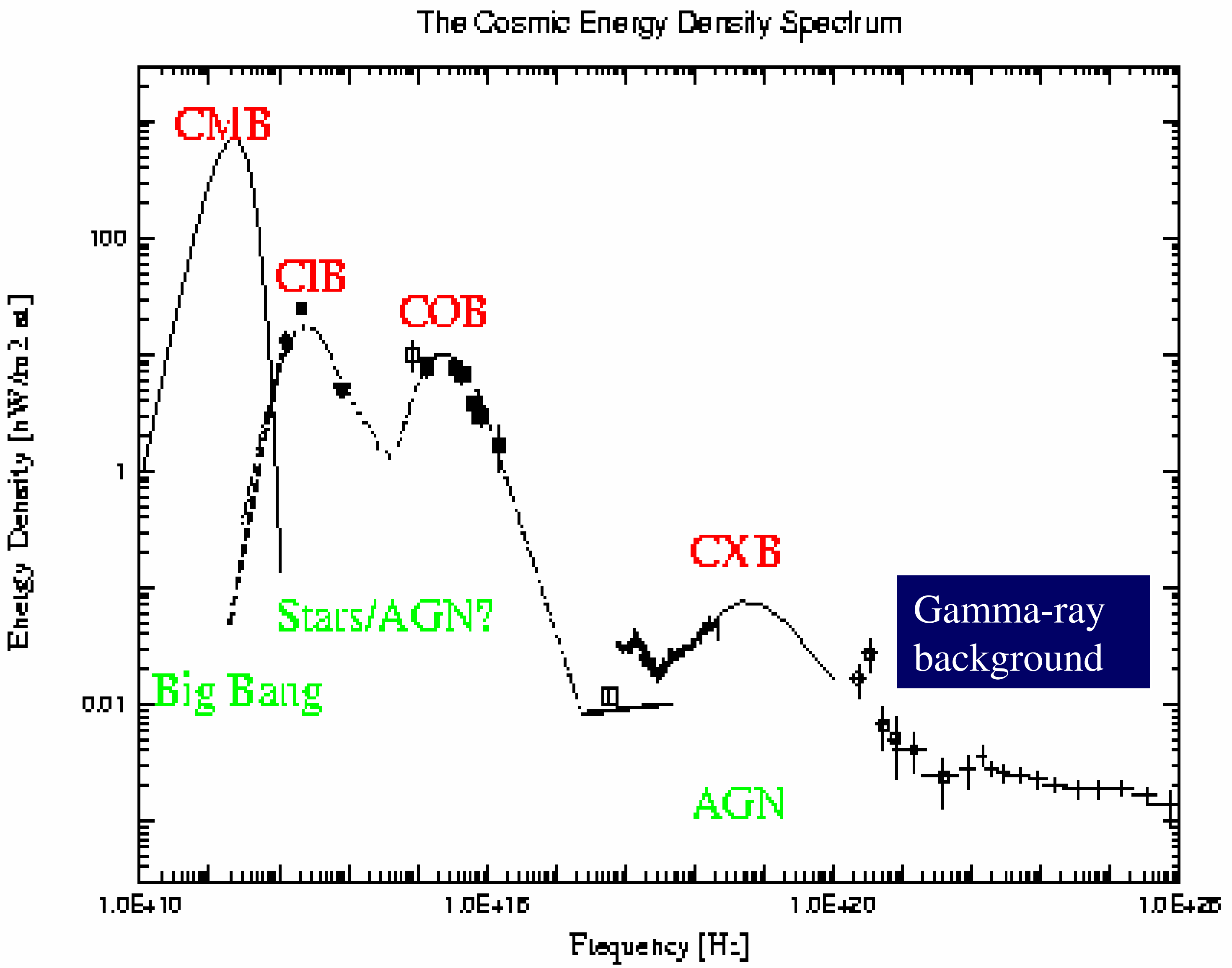
strong shocks

T=0.3 keV

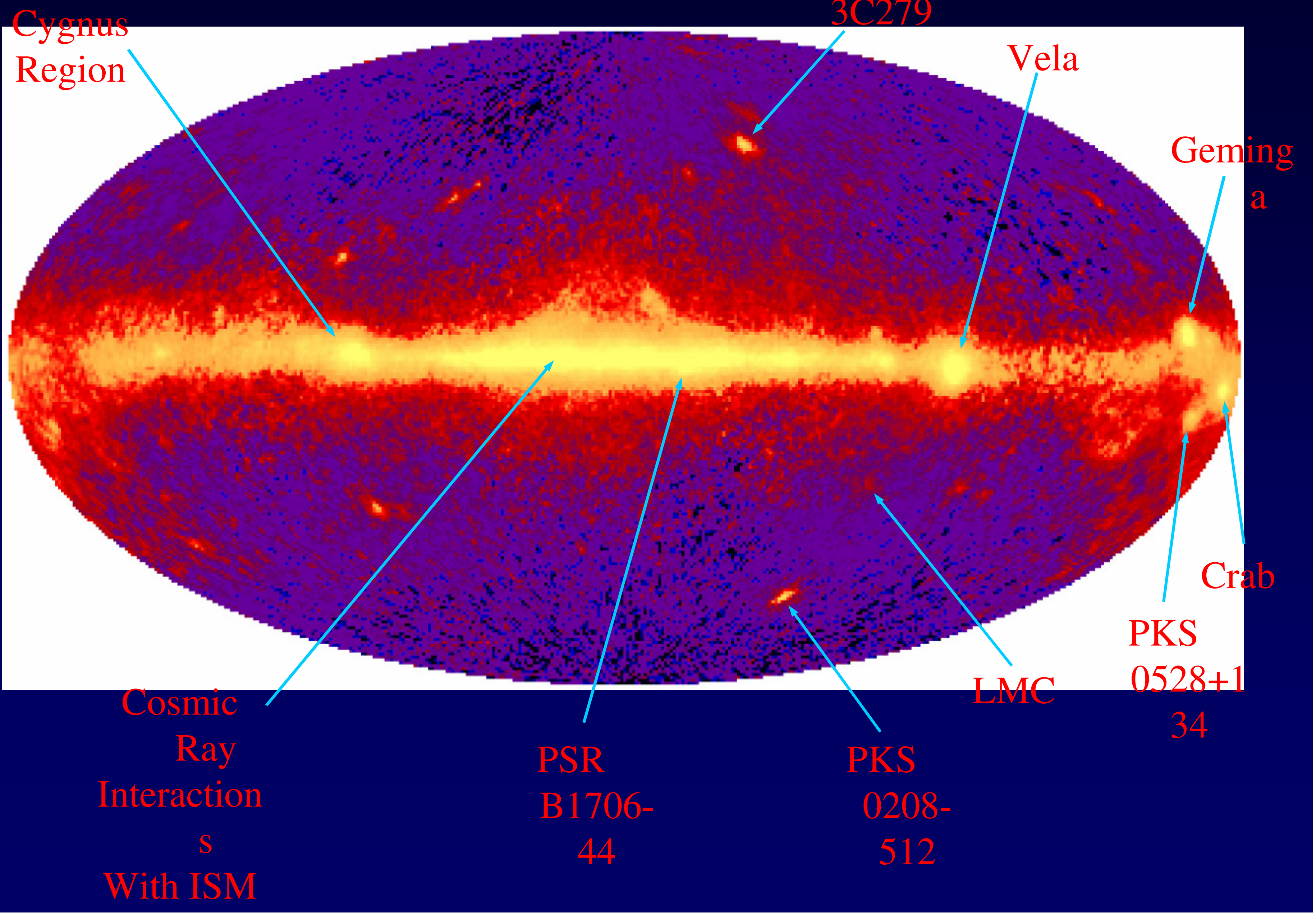
strong +weak
shocks

Loeb & Waxman, Nature, 405, 156, 2000

Cosmic Background Radiation



EGRET All Sky Map (>100 MeV)



Dimensional Analysis

Given n(M,z), $L^{IC/syn}(M,z)=?$

Halo properties:

$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

$$\bar{\rho}(M) = 200\rho_C$$

$$\rho(r_{sh}) = \frac{50}{3}\rho_C$$

$$M = \boxed{\frac{\sqrt{2}}{5}}\frac{\sigma(M,z)^3}{GH(z)}$$

$$\dot{M}(M,z) = f_{acc}\frac{\sigma(M,z)^3}{G}$$

$$k_B T(M,z) = f_T \ \mu m_p \sigma(M,z)^2$$

$$r_{sh}(M,z) = f_r \boxed{\frac{\sqrt{2}}{5}}\frac{\sigma(M,z)}{H(z)}$$

Waxman & Loeb (2000)

Electron distribution

Strong shock → $\frac{dn_e}{d\gamma} \propto \gamma^{-2}$

$$t_{acc} = \frac{r_L / c}{\beta_{sh}^2} \cong 2\times10^4 \frac{\gamma_7}{B_{-7}} T_{\rm keV}^{-1}\ {\rm yr} << t_H$$

$$\gamma_{\rm max} = 3.3\times10^7 \left(\frac{T}{10^7 K} \frac{B}{0.1 \mu G} \right)^{1/2}$$

$$t_{cool} = \frac{m_e c}{\frac{4}{3}\sigma_T u_{CMB}} \gamma_e^{-1} \cong 1.2\times10^{10} \gamma_{200}^{-1}\ {\rm yr}$$

Loeb & Waxman (2000)

Radiation

<u>Thermal</u> energy → relativistic electrons: ξ_e

<u>Thermal</u> energy → magnetic fields: ξ_B

Inverse-Compton: $$\nu L_\nu^{IC}(M,z) = \left[\frac{3}{2}\dot{N}_b(M,z)k_B T(M,z)\right]\times\xi_e\times\frac{1}{2\ln\gamma_{\max}}$$

Synchrotron: $$\nu L_\nu^{syn}(M,z)\boxed{=\frac{B(M,z)^2/8\pi}{u_{cmb}}\times\nu L_\nu^{IC}(M,z)}$$

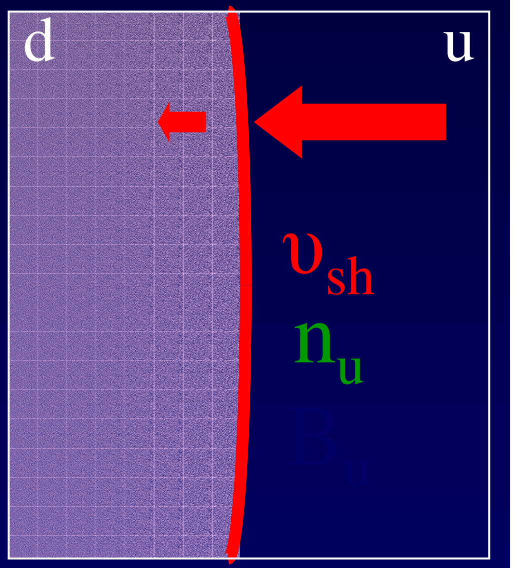
Waxman & Loeb (2000)

Estimating ξ_e and ξ_B

Cluster observations: $B \approx 0.1 \mu G$

$\Rightarrow \xi_B \approx 1\%$ Waxman & Loeb (2000)

Strong, non-relativistic shock:



- IGM and SNR, $\upsilon_{sh} \sim 10^3$ km s^{-1}
- n_u: rescale time in units of ν_p^{-1}
- B_u: not possible to rescale time by ν_c

$$\left(\nu_{c,ion} / \nu_{e.m.}\right)^2 = \frac{B_u^2 / 8\pi}{\frac{1}{2} m_p n_u \upsilon_{sh}^2} << 1$$

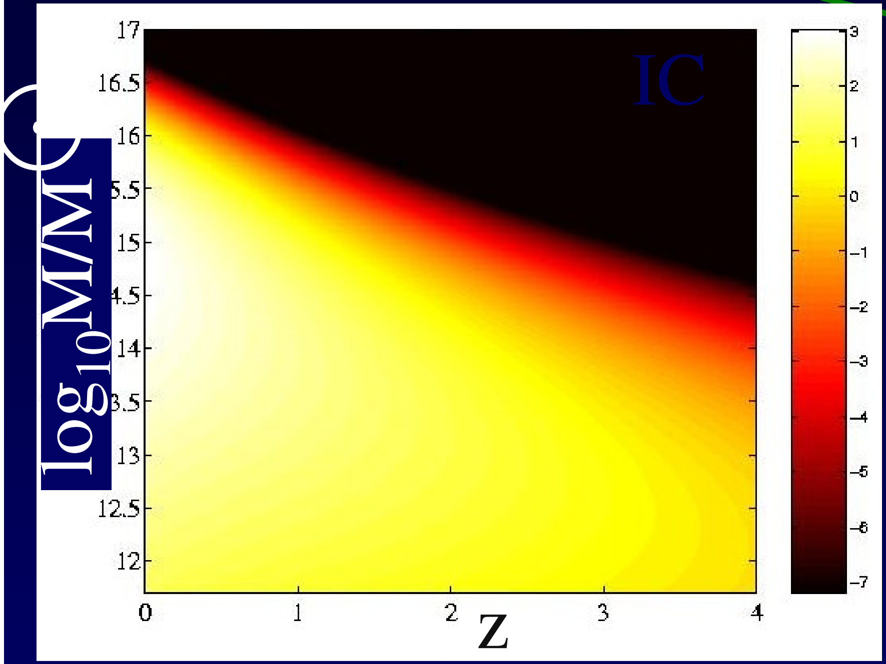
$$\nu_{e.m.} \equiv \nu_{p,ion} \beta_{sh}$$

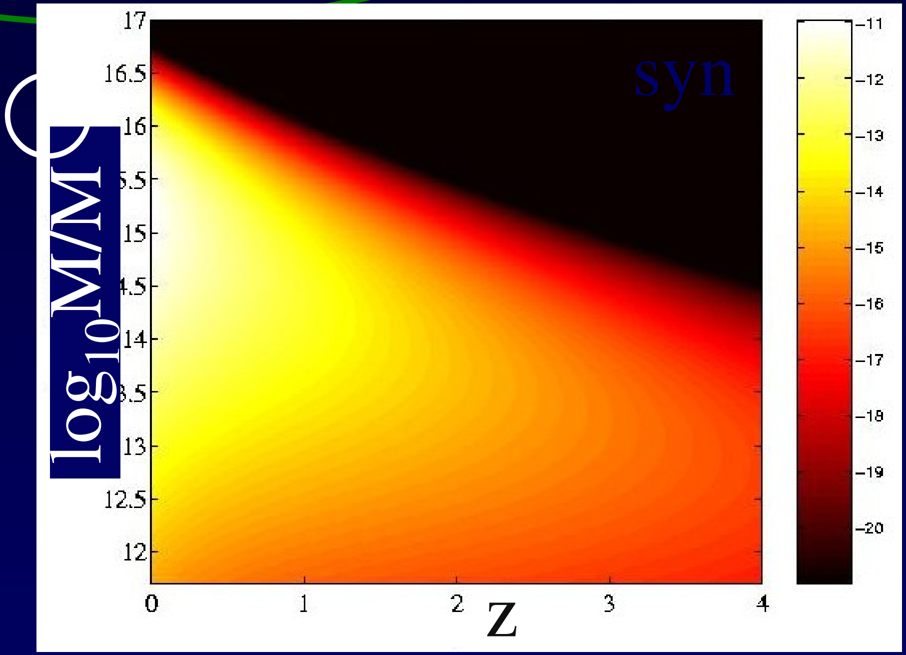
SNR observations: $\xi_e \approx 5\% \quad (2.5\% - 7.5\%)$

Keshet et al. (2003)

γ-ray and Radio Emission by Halos

$$\left\langle \nu I_\nu^{iC,syn} \right\rangle = \int dz \int dM \, \frac{c\,dt}{dz} \frac{dn(z)}{dM} \frac{\nu L_\nu^{iC,syn}(M,z)}{4\pi(1+z)^4}$$





$$\left\langle \nu I_\nu^{iC} \right\rangle = 1.6 \boxed{f_{acc} \, f_T} (\xi_e / 0.05) \mathrm{keV\,s^{-1} cm^{-2} sr^{-1}}$$

$$\left\langle \nu I_\nu^{syn} \right\rangle = 5 \times 10^{-12} \boxed{f_{acc} \, f_T^2 f_r^{-2}} (\xi_e / 0.05)(\xi_B / 0.01) \mathrm{erg\,s^{-1} cm^{-2} sr^{-1}}$$

calibration necessary

Keshet, Waxman & Loeb (2004b)

Cosmological Simulations

Motivation:

- fewer free parameters: only ξ_e and ξ_B
- Weak shocks (mergers + accretion)
- Complicated 3D geometry
- Additional physics (preheating, feedback)

SPH simulation (GADGET; Springel & Hernquist)

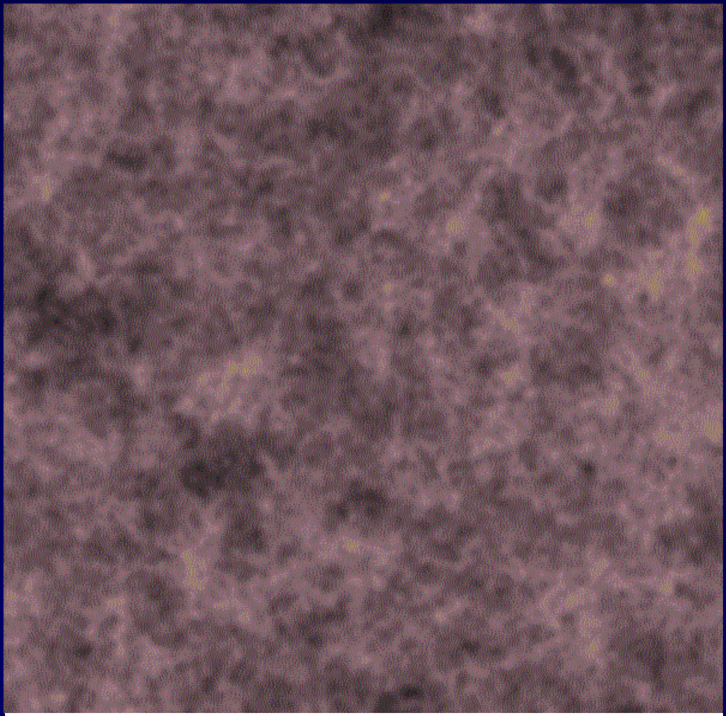
$224^3 \sim 10^7$ gas / dark matter particles

200 Mpc box, $Z_0=50$

ΛCDM cosmology

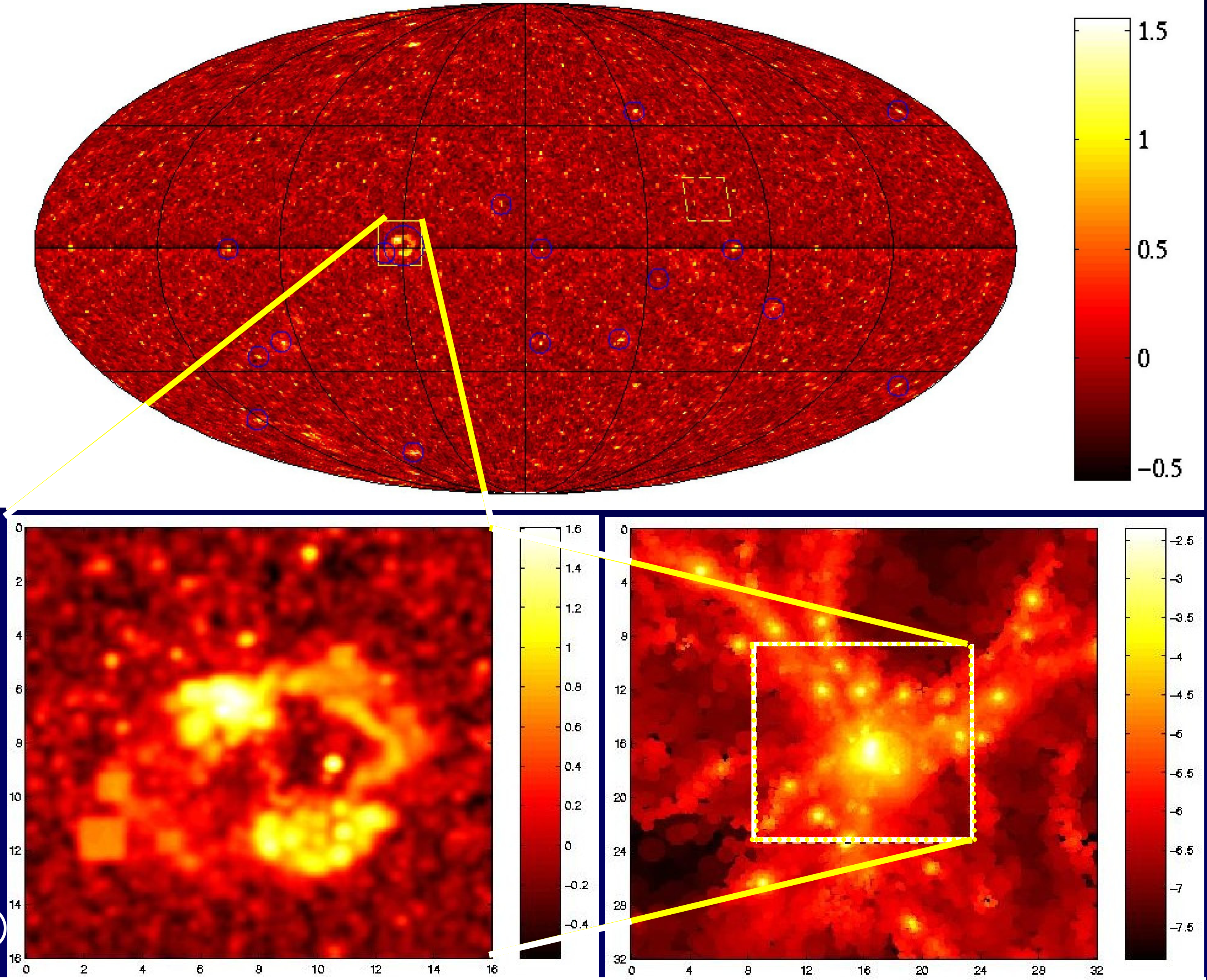
$\Omega_\Lambda=0.7$, $\Omega_{d.m.}=0.26$, $\Omega_b=0.04$

$H=0.67$, $k=0$, $n=1$, $\sigma_8=0.9$



Springel & Hernquist (2000)

$\langle J \rangle = 1.1$
$\times 10^{-6} s^{-1}$
$cm^{-2} sr^{-1}$

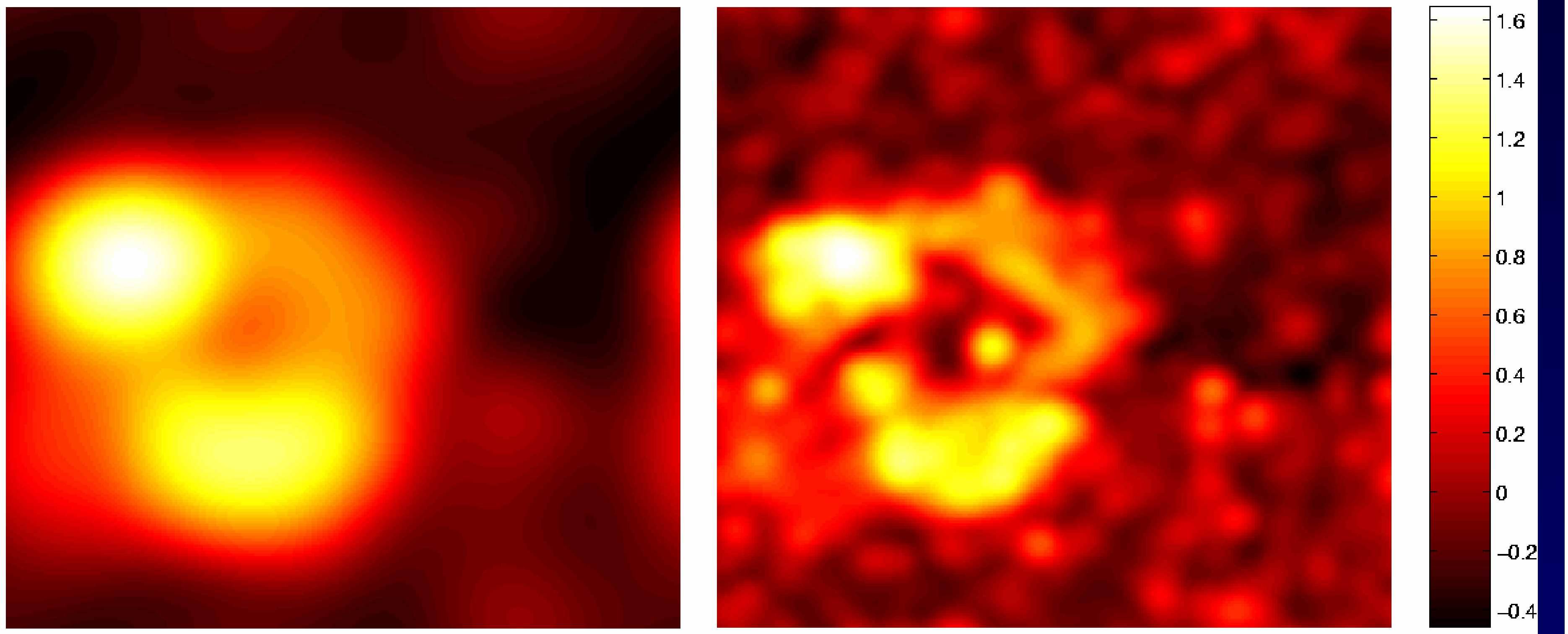


>10 GeV
$\Delta\theta = 12'$
$\langle J \rangle = 8.2$
$\times 10^{-9} s^{-1}$
$cm^{-2} sr^{-1}$
Z=0.012
$10^{15} M_\odot$

➡ Targets for MAGIC, HESS, VERITAS Keshet et al. (2003)

Gamma-Ray Clusters

Flux Above 1 GeV From a Simulated 16x16 degrees^2 Field

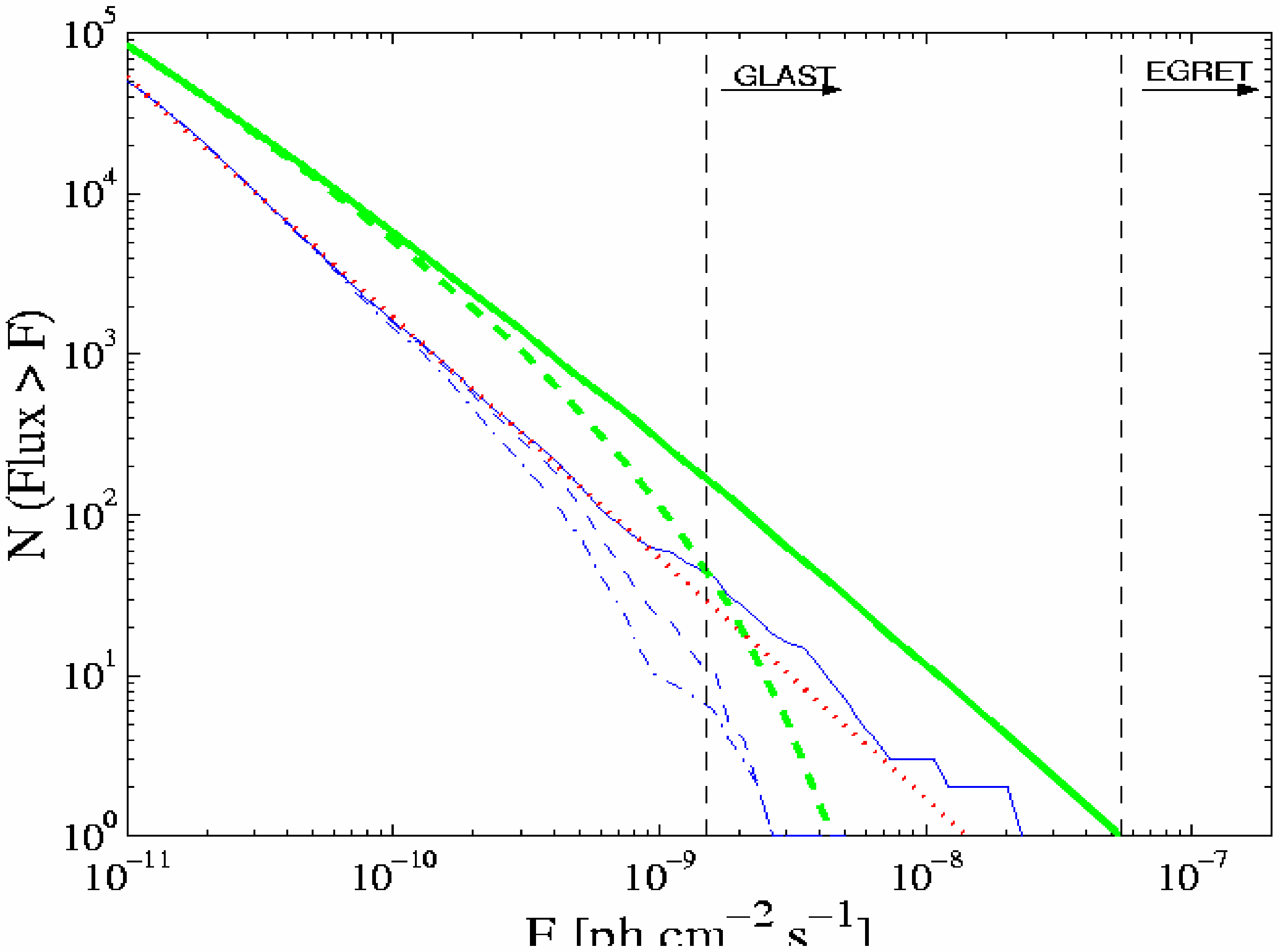


EGRET

GLAST

Keshet et al. 2001

Number Counts at 100 MeV *From Simulations*



Keshet et al. (2002)

$\xi_e = 0.05$

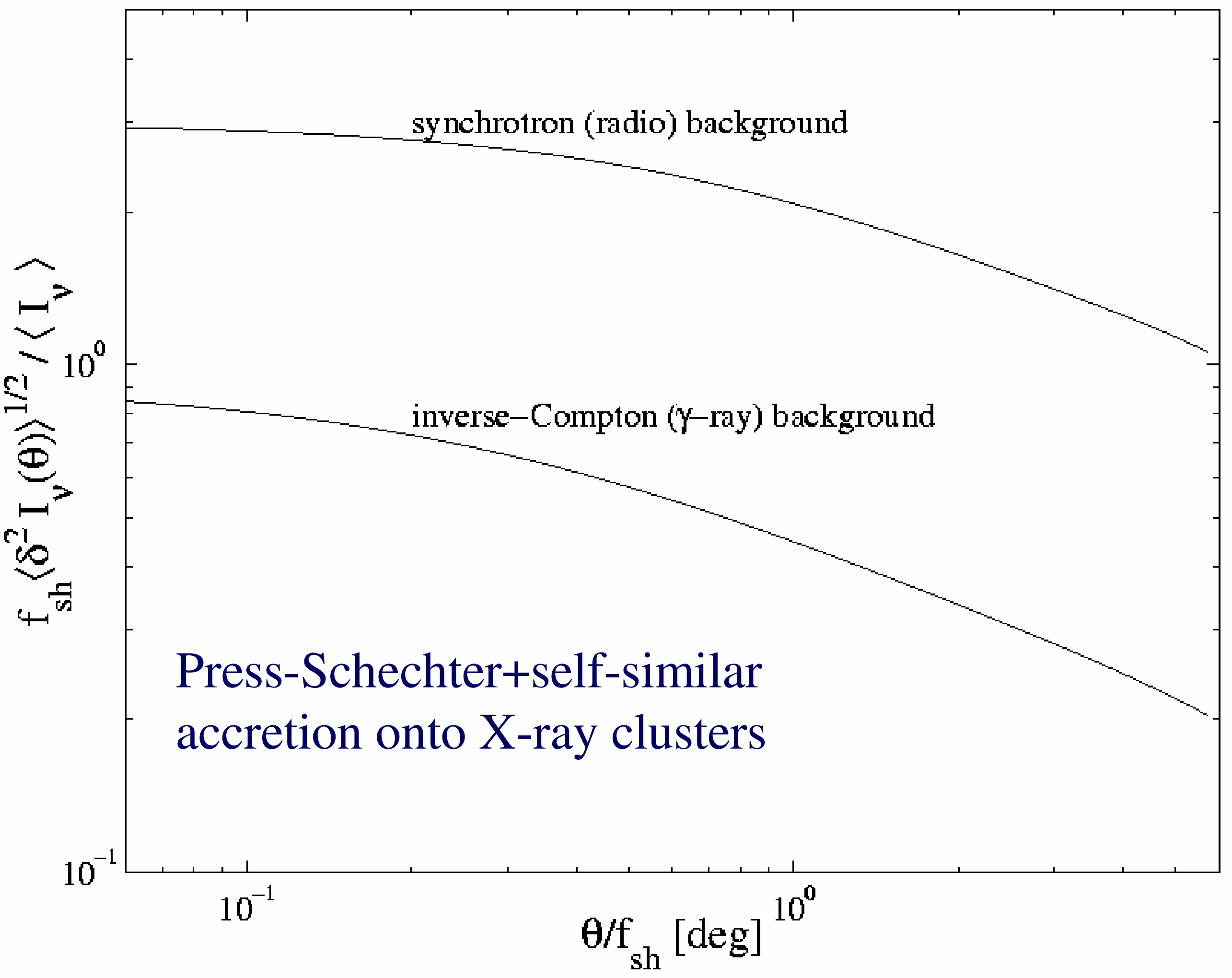
Present and future γ-ray telescopes

Planned launch: 2007

MAGIC >30 GeV, first light 2003

VERITAS 50 GeV-50 TeV, first light 2004, completion 2006

Predicted Anisotropies

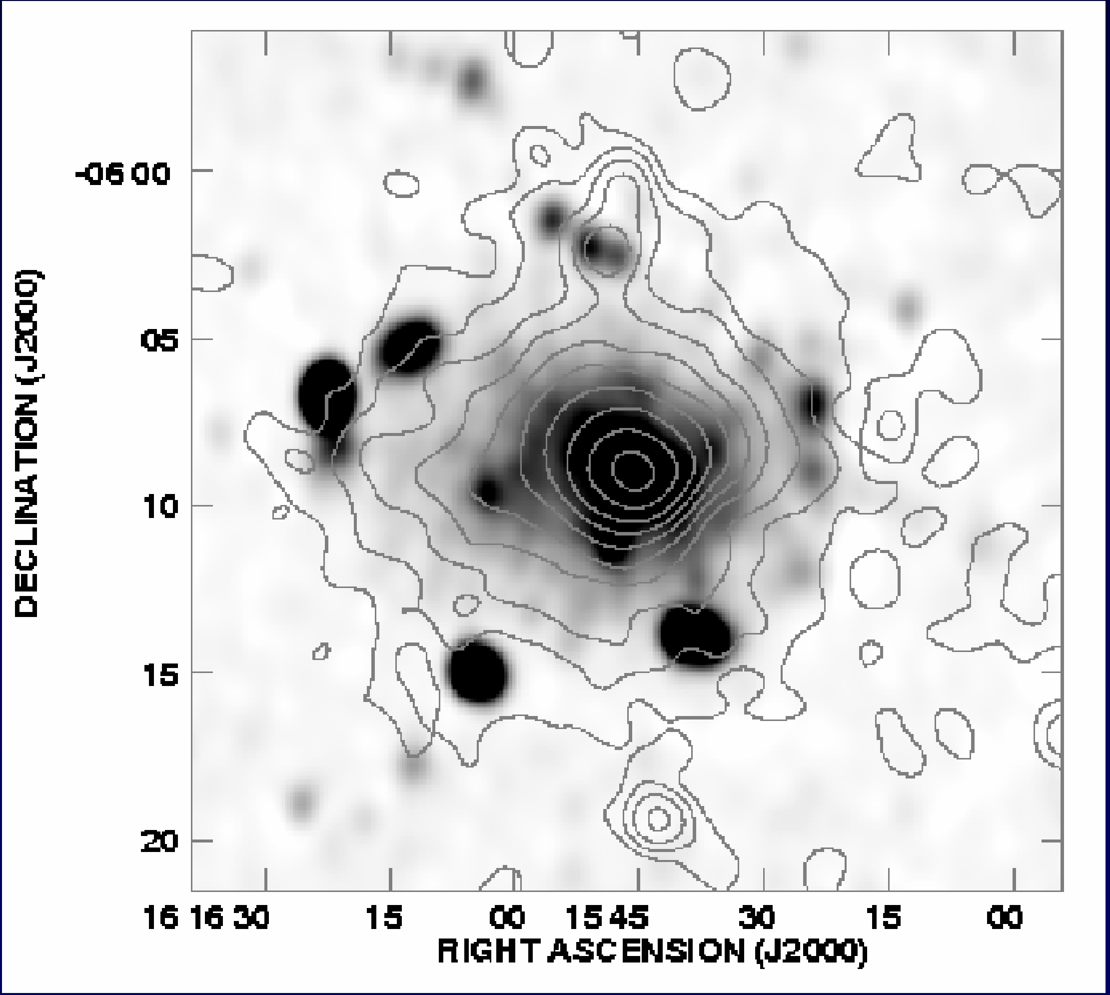


Press-Schechter+self-similar accretion onto X-ray clusters

$$\text{For } \theta < 1^\circ : \quad \Delta T \approx 40\mu\mathrm{K}\left(\frac{\xi_B}{0.01}\right)\left(\frac{\nu}{10\mathrm{GHz}}\right)^{-3}$$

Waxman & Loeb, ApJL,545, L11 (2000)

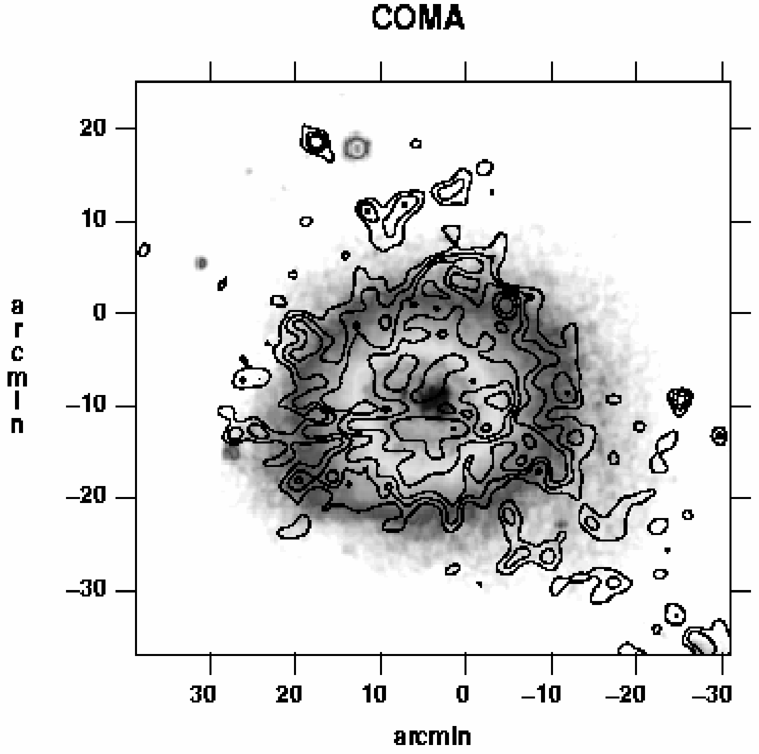
Radio Clusters



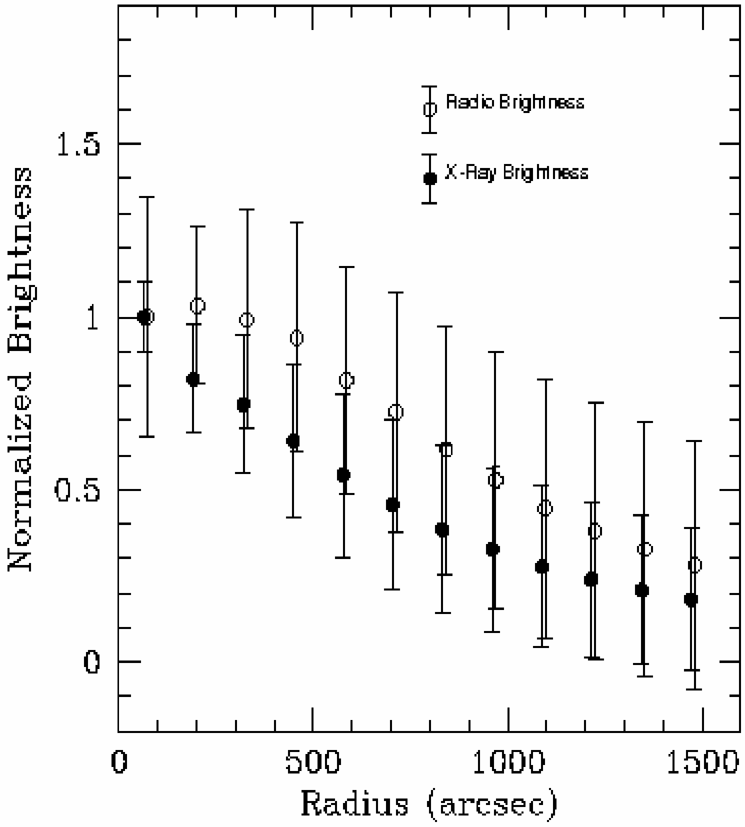
A2163

Feretti et al. 2001

Radio Surface Brightness



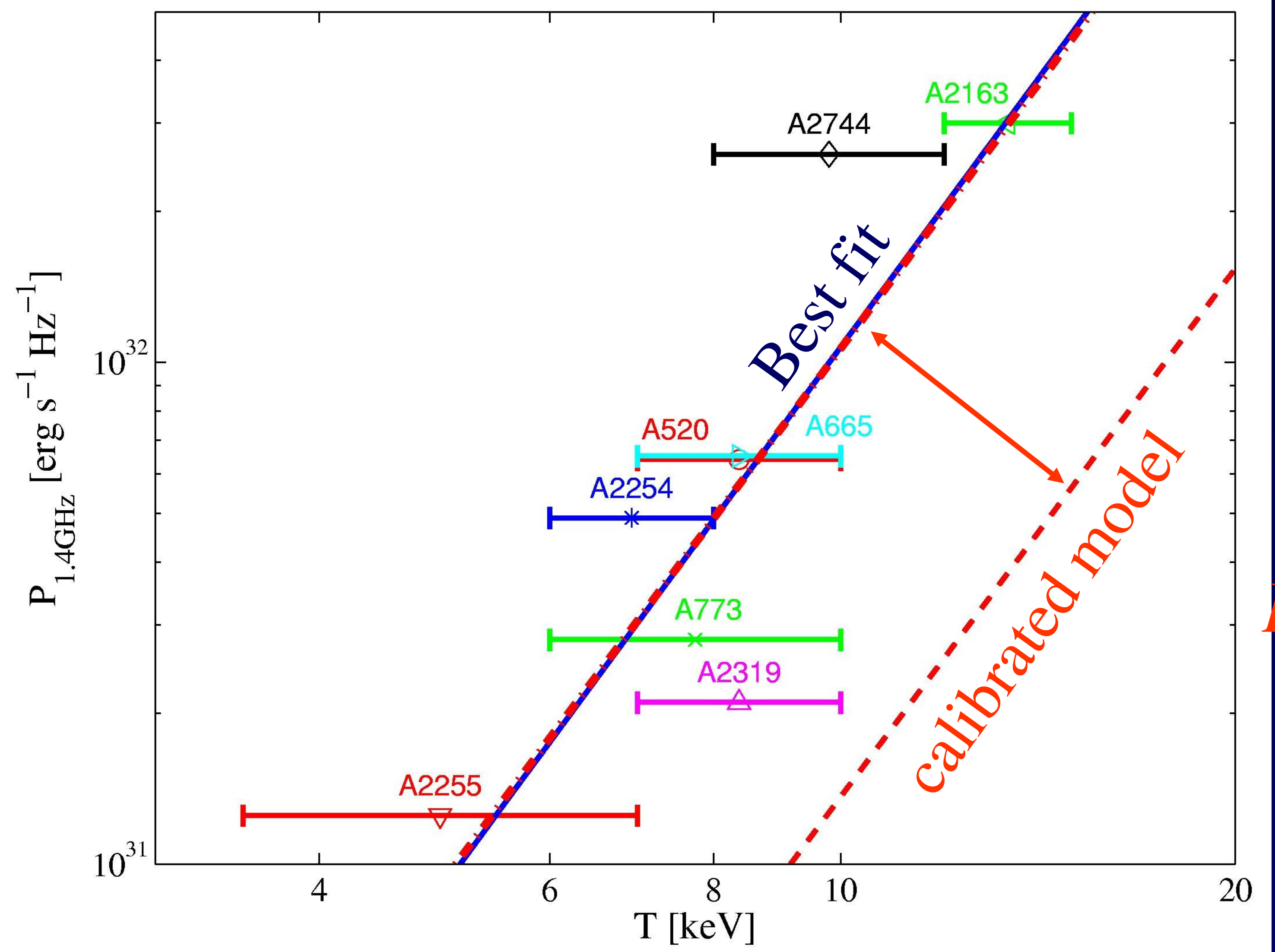
Contours of the halo image at 90 cm, after subtraction of discrete sources, superimposed on the grey-scale X-ray PSPC image of the cluster Coma. Contour levels are: 5, 8, 11, 16, 23, 32 mJy/beam. The radio image is published in Feretti (2000), while the X-ray image is from White et al. (1993).



Comparison between the normalized radio and the X-Ray brightness profiles in Coma. The radio data points are offset by 9″ for clarity.

Govoni et al. 2001

Diffuse radio sources



Best fit:

$L_\nu(T) \propto T^{\phi}$

$\phi = 3.55$

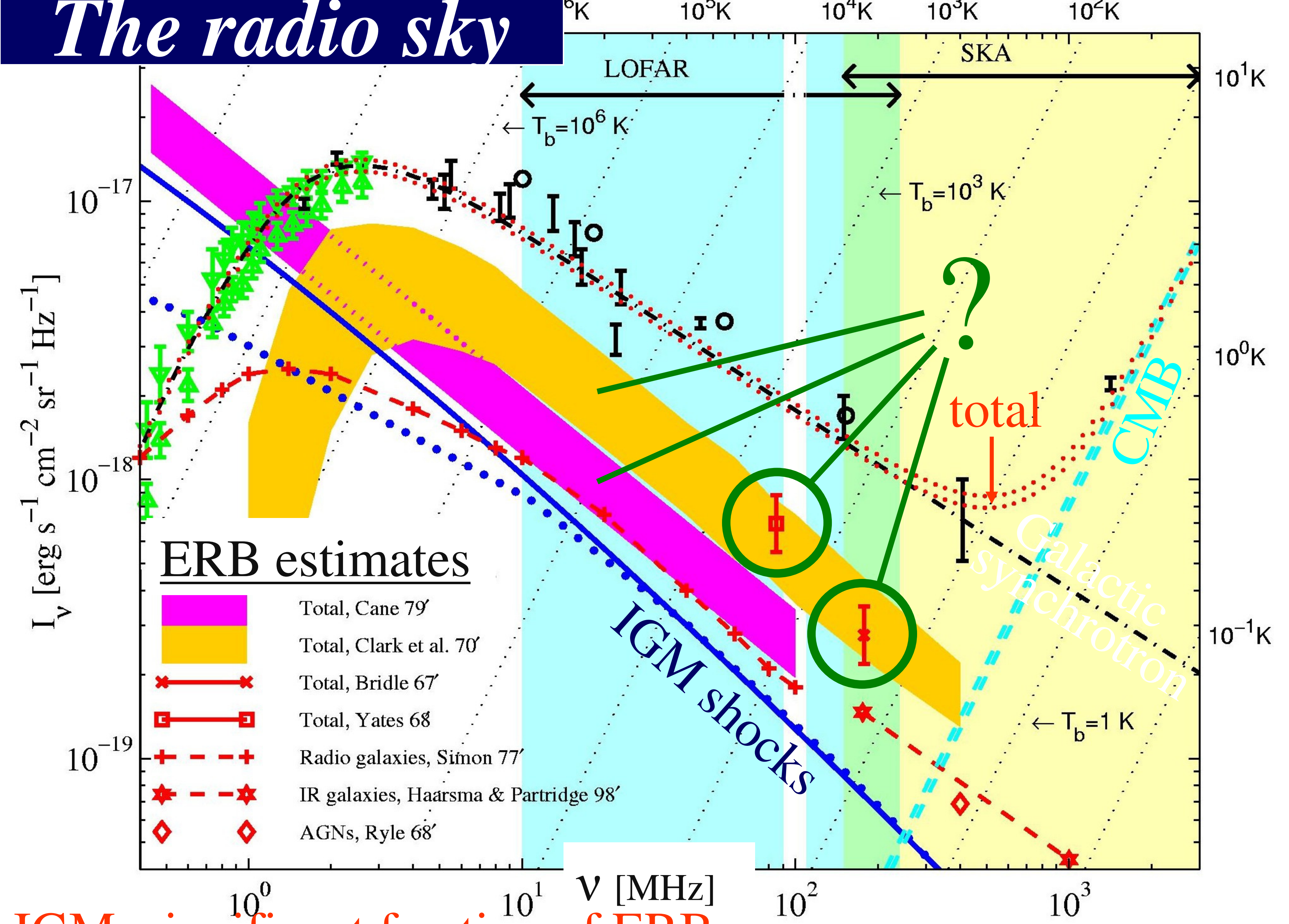
Model:

$L_\nu(T) \propto T^{7/2}$

Radio halos: association with structure formation

Keshet, Waxman & Loeb (2004b)

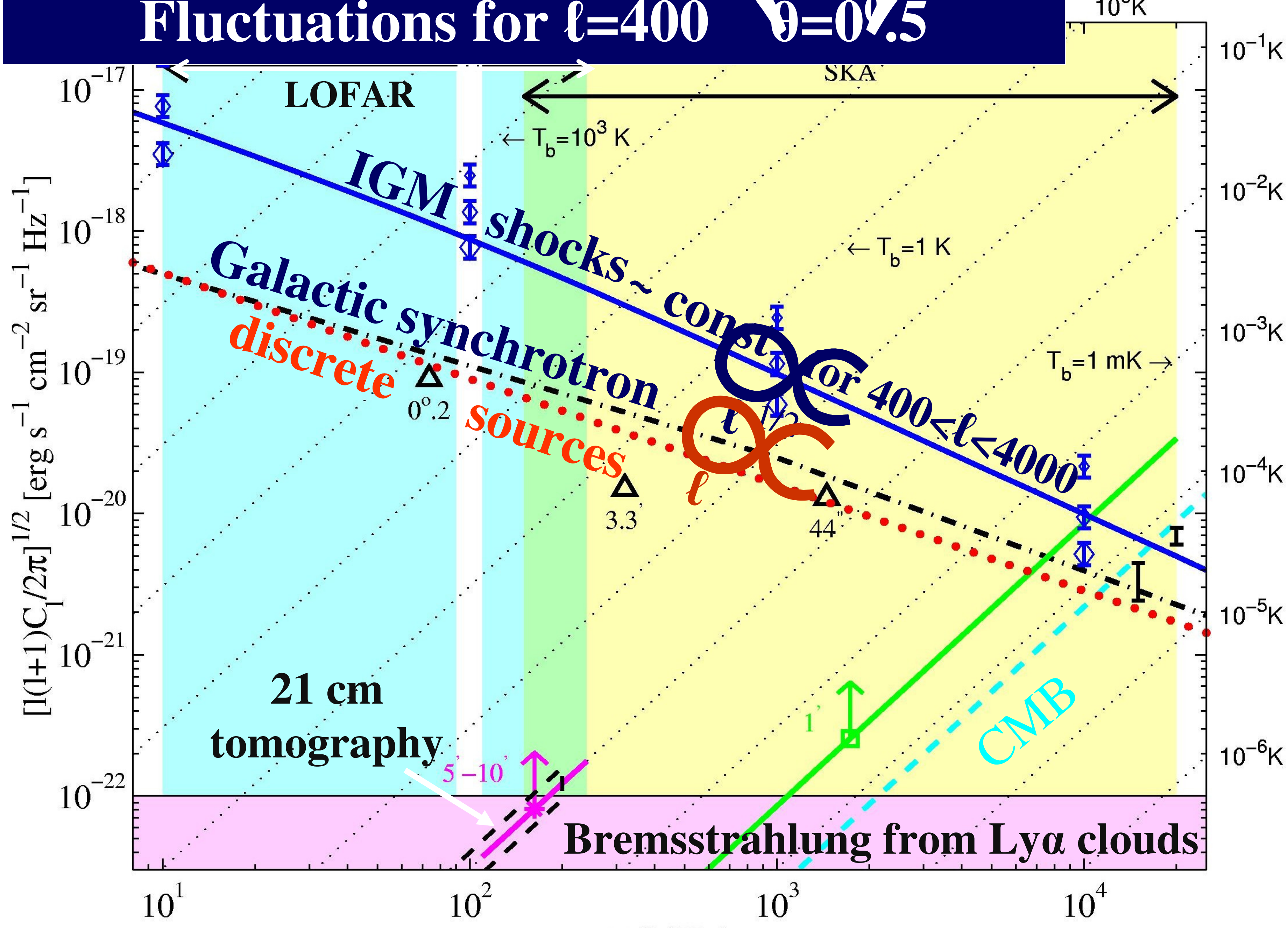
The radio sky



IGM: significant fraction of ERB

Keshet, Waxman & Loeb (2004b)

Fluctuations for ℓ=400 θ=0°.5

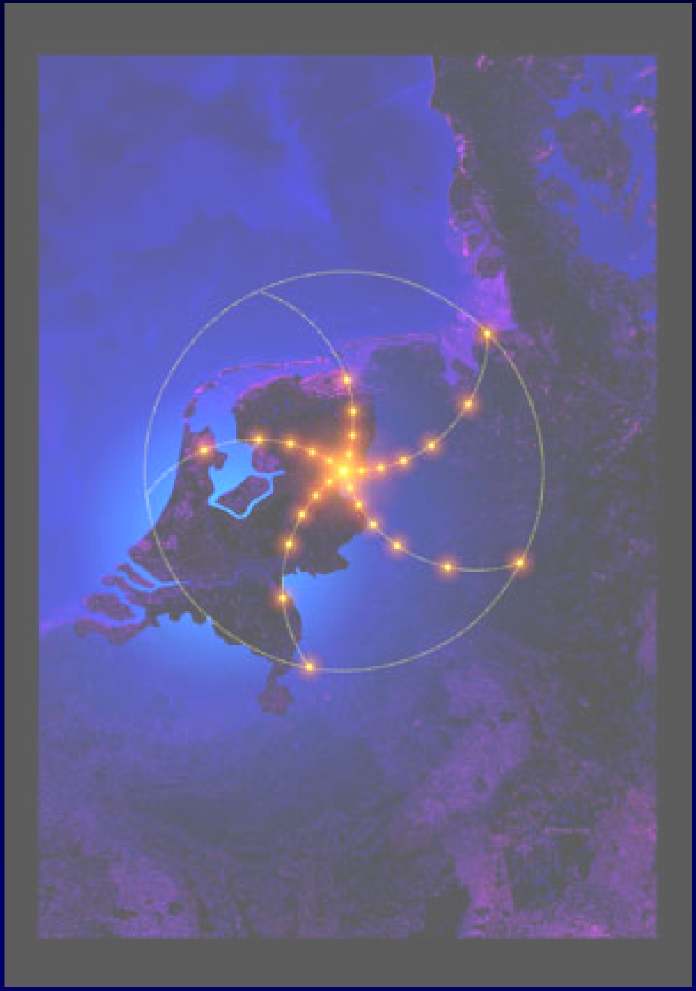


1'-0°.5: IGM fluctuations dominate

Keshet, Waxman & Loeb (2004b)

Future radio telescopes

LOFAR



Northern Netherlands shore

SKA

Conclusions

- Collisionless IGM shocks accelerate electrons and protons to relativistic energies.
- The gamma-ray (IC) and radio (synchrotron) emission by the accelerated electrons could be a substantial fraction of the fluctuations in the low-frequency (<10 GHz) and gamma-ray backgrounds.
- ***X-ray clusters*** are ***radio*** and ***gamma-ray clusters*** as well.