Non-Thermal Radiation from Intergalactic Shocks

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CONCEPT

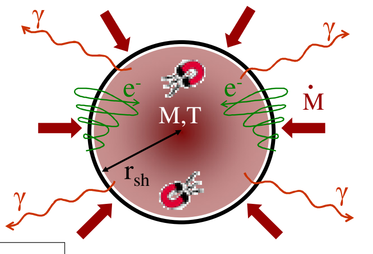
Intergalactic shocks emit radiation in the following process:

Converging flows during structure formation (SF)
➡ Collisionless shocks ➡ Electron acceleration
➡ Inverse-Compton (of CMB photons) and synchrotron emission

The emission from strong shocks dominates the radiation from the periphery of galaxy clusters and from galaxy filaments; traces LSS

ANALYTICAL MODEL

Approximations:
1) Large scale structure (LSS) composed of halos (e.g. according to the Press-Schechter halo mass function)
2) Halo mass distribution: isothermal sphere
3) Strong shocks only



Halo Parameters:

- M - mass
- T - temperature
- r_{sh} - shock radius
- $\dot{M}$ - mass accretion rate

Halo Dimensional Analysis:

isothermal sphere:

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

velocity dispersion
Hubble's coefficient
effective mass

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

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

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

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

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

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

unknown dimensionless parameters

Relativistic Electron Distribution

Strong shocks ➡ $dn_e/d\gamma\propto\gamma^{-2}$

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

$$t_{cool}=\frac{m_ec}{\frac{4}{3}\sigma_Tu_{CMB}}\gamma_e^{-1}\cong1.2\times10^{10}\gamma_{200}^{-1}\ {\rm yr}$$

energy cutoff γ_{max}: cooling limited

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

Parameterization (no complete model):

SNR observations ➡ electron energy $\xi_e\approx5\%$ (2.5%-7.5%)
$B_{cluster}\approx0.1\mu$G ➡ magnetic energy $\xi_B\approx1\%$ (0.05%-2%)
} % out of shock thermal energy

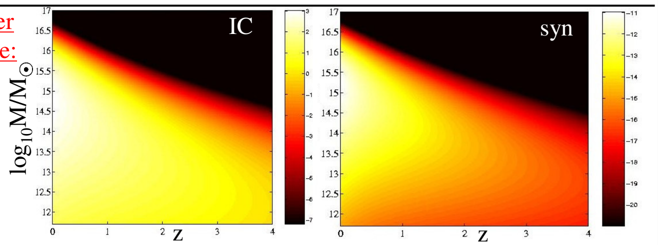
Emitted Radiation:

halo luminosity:

$$\begin{cases}\nu L_\nu^{IC}(M,z)=\left[\frac{3}{2}\dot{N}_b(M,z)k_BT(M,z)\right]\times\xi_e\times\frac{1}{2\ln\gamma_{\rm max}}\\ \nu L_\nu^{syn}(M,z)=\frac{B(M,z)^2/8\pi}{u_{cmb}}\times\nu L_\nu^{IC}(M,z)\end{cases}$$

Integration over halo abundance:

(images: the integrands in the mass-redshift plane)



$$\boxed{\begin{aligned}\langle\nu I_\nu^{iC}\rangle&=1.6\,f_{acc}\,f_T(\xi_e/0.05){\rm keV\,s^{-1}cm^{-2}sr^{-1}}\\ \langle\nu I_\nu^{syn}\rangle&=5\times10^{-12}\,f_{acc}\,f_T^2f_r^{-2}(\xi_e/0.05)(\xi_B/0.01){\rm erg\,s^{-1}cm^{-2}sr^{-1}}\end{aligned}}$$

TREE-SPH COSMOLOGICAL SIMULATION

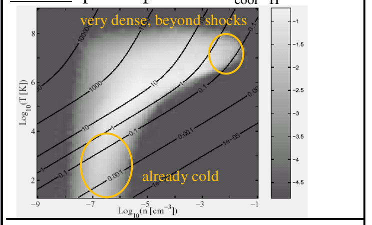
Cosmological model		
Ω_Λ	vacuum energy	0.7
Ω_{dm}	dark matter energy	0.26
Ω_b	baryon energy	0.04
h	Hubble coefficient	0.67
n	fluctuation power	1
σ_8	fluctuation normalization	0.9

Simulation parameters		
N_b	number of SPH particles	224^3
N_{dm}	# of dark matter particles	224^3
L	simulation box size	200 Mpc
M_{SPH}	SPH particle mass	3.6×10^{11}M
M_{res}	mass resolution	$\sim10^{11}M_\odot$
Z_0	initial redshift	50

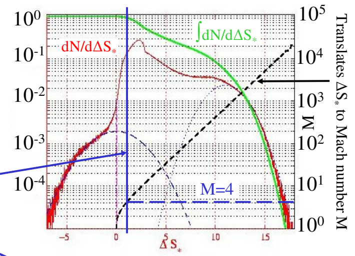
SHOCK IDENTIFICATION

Cooling is inefficient in the relevant regions (panel 1) ➡ Adiabatic simulations suffice
➡ Entropy changes (panel 2) of SPH particles trace the shocks (panel 4)

Panel 1: phase space with t_{cool}/t_H contours

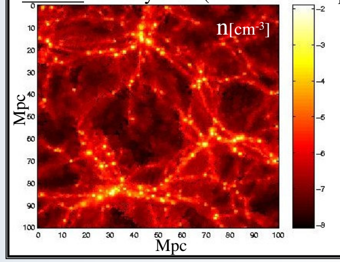


Panel 2: histogram of entropy change $\Delta S_*\equiv\Delta S/C_V$ accumulated by SPH particles in the epoch 0<z<2

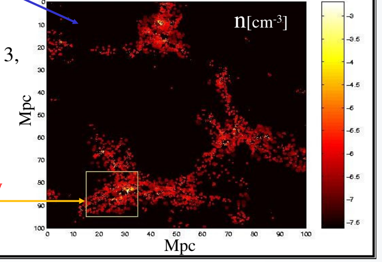


Particles with ΔS* above the cutoff trace all shocks of Mach number M>4

Panel 3: density slice (100x100x10 Mpc)



Panel 4: same density slice as shown in panel 3, but including the M>4 shocked particles only



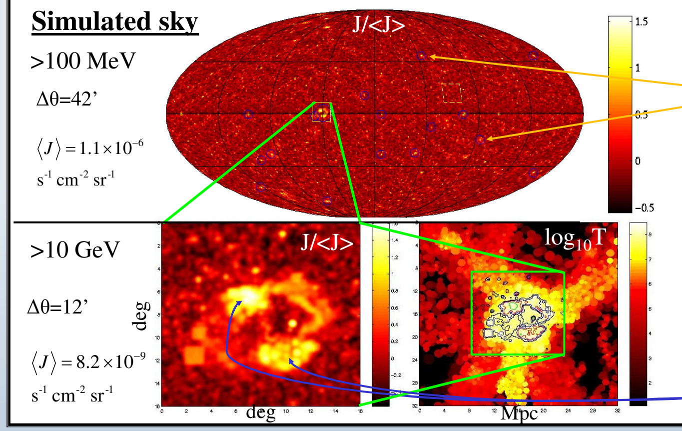
Shock fronts may be identified

INTEGRATED EMISSION

Simulated sky

>100 MeV
Δθ=42'
$\langle J\rangle=1.1\times10^{-6}$ s^{-1} cm^{-2} sr^{-1}

>10 GeV
Δθ=12'
$\langle J\rangle=8.2\times10^{-9}$ s^{-1} cm^{-2} sr^{-1}



Conclusions:

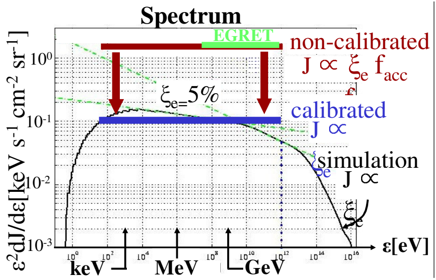
- >10 sources well resolved by GLAST (for ξe≈0.05)
- γ-ray clusters: targets for MAGIC, HESS, VERITAS
- γ-ray morphology: accretion rings with bright emission at filament intersections

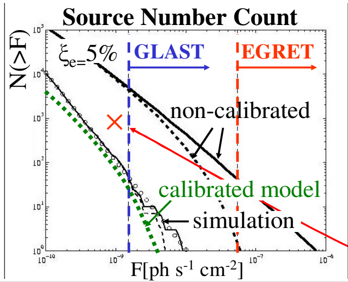
MODEL CALIBRATION

Model halo parameters (column 1) are calibrated with various features of the simulation (column 2). Agreement between the radiation fields extracted from the simulation and from the calibrated model (column 3) provides an independent check of the calibration scheme.

Param.	Calibrated using	Value (range)
f_T	Mass average temperature: $\langle T(z)\rangle_M\approx4\times10^6e^{-0.9z}$ K	0.5 (0.45-0.55)
f_{acc}	Mass fraction processed by strong shocks, e.g. f(z<2) ≈ 41%	0.12 (0.08-0.17)
f_r	Typical size of bright emitting region (e.g. 2 Mpc for $10^{15}M_\odot$)	0.1 (0.05-0.2)

GAMMA-RAY SIGNAL



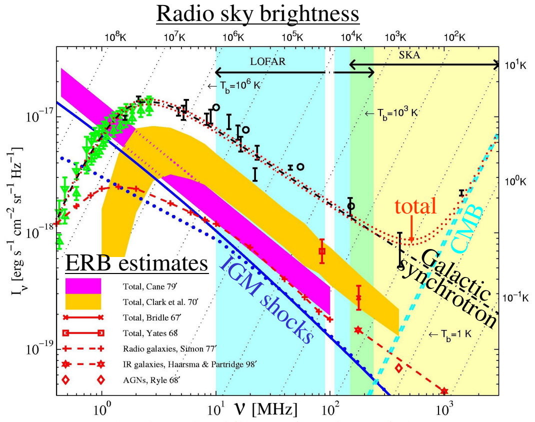


Conclusions:

- IGM ≥ 10% of EGRB flux
- > a dozen GLAST sources for ξe>0.03
- Cross-correlation with LSS (e.g. Scharf & Mukherjee 2002)

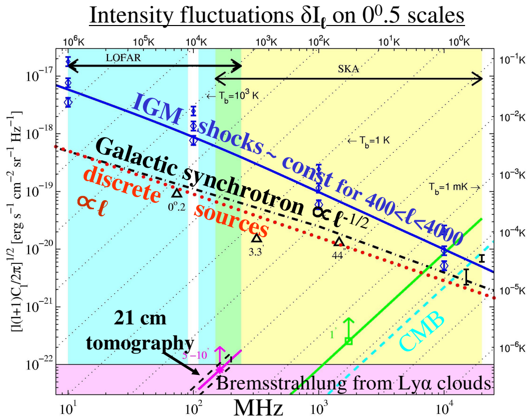
RADIO SKY

Radio sky brightness



IGM shocks: significant fraction of the ERB

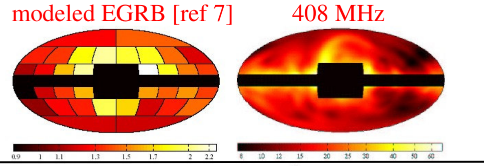
Intensity fluctuations δI_ℓ on $0^0.5$ scales



IGM fluctuation dominate on 1'-$0^0.5$ scales

EXTRAGALACTIC GAMMA-RAY BACKGROUND

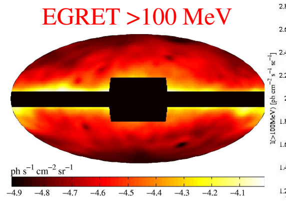
Previous estimate
$I_X=1.45\pm0.05$
(Sreekumar et al. 1998)
(>100 MeV, units: 10^{-5}ph s^{-1}cm^{-2}sr^{-1})

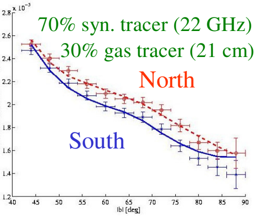


Previous EGRB estimates are:

- Non isotropic on large scale
- Correlated with Galactic tracers
- High (≈ total polar intensity)

Fit EGRET latitude profile as a sum of 2 components; one linear in a Galactic gas tracer and the other linear in a synchrotron tracer:





Results:

Robust EGRB flux upper limit

$I_X<0.5$ @99% C.L.

(~1/3 of previous estimates)

CONCLUSIONS AND IMPLICATIONS

Conclusions

- γ-ray sources detectable by GLAST and Ćerenkov detectors
- Signal fluctuations dominate the radio sky on ~1'-0.5^0 scales
- Indirect detection, e.g. cross correlations with LSS tracers
- Extragalactic backgrounds: EGRB low, ERB unknown
- Calibrated analytical model, fast shock identification in SPH

Implications of signal detection

- First identification of intergalactic shocks
- Reconstruction of large-scale flows
- Tracer of warm-hot IGM (WHIM)
- Probe of intergalactic magnetic fields

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