$e^{\pm}$ Plasmas in Cosmic Structures: BHs, JETs, CRs, DM

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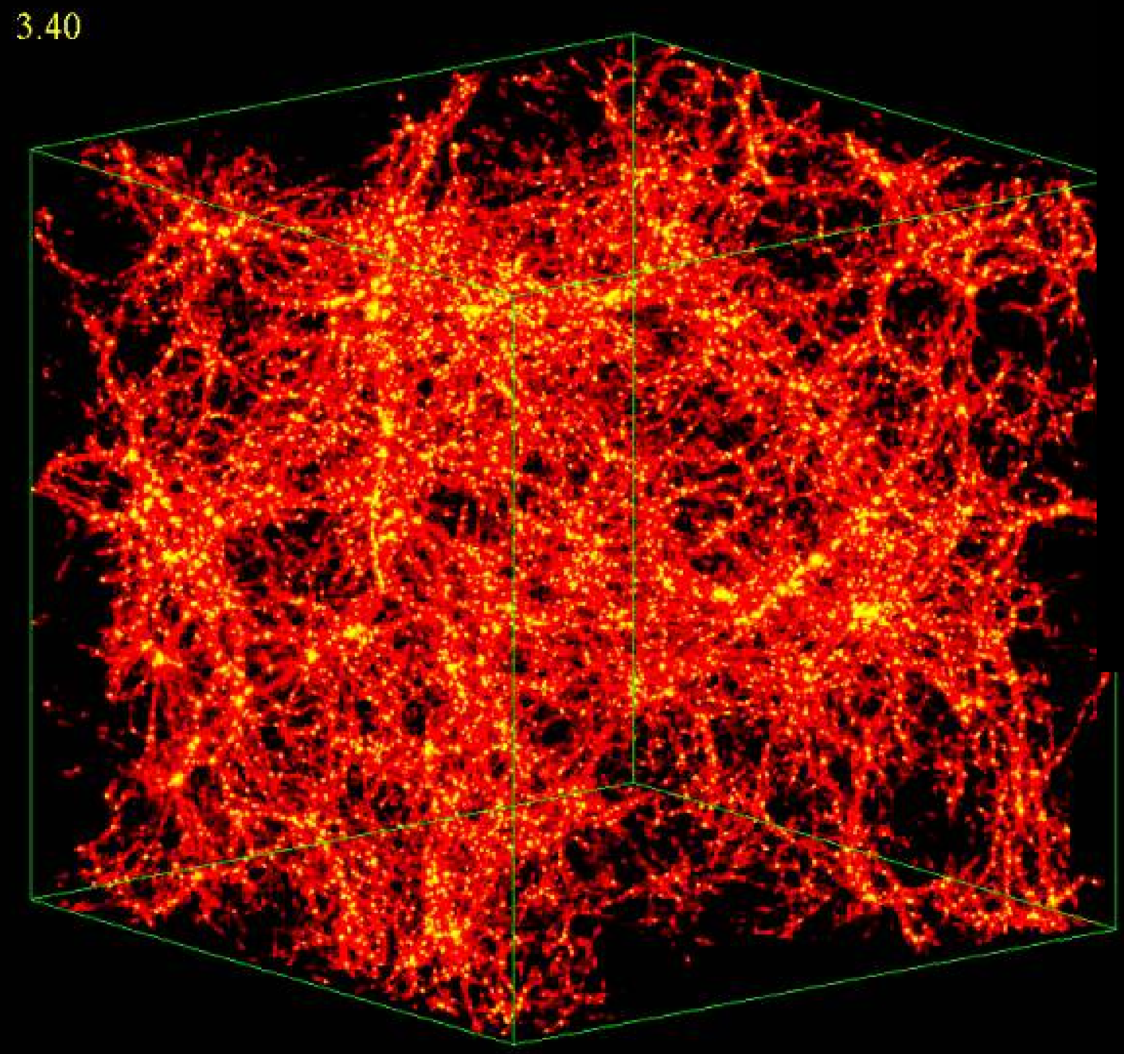
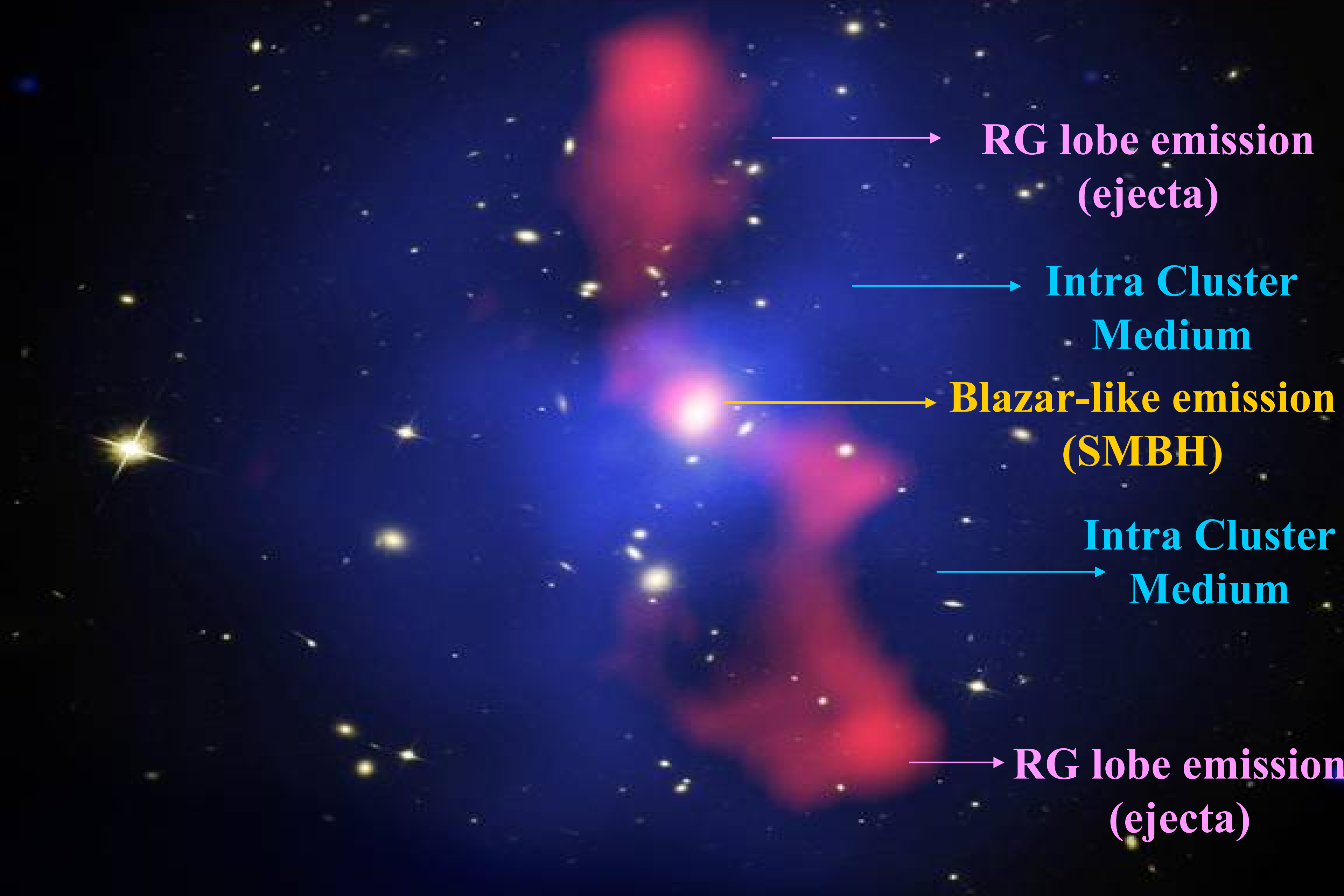
Large Scale Structures



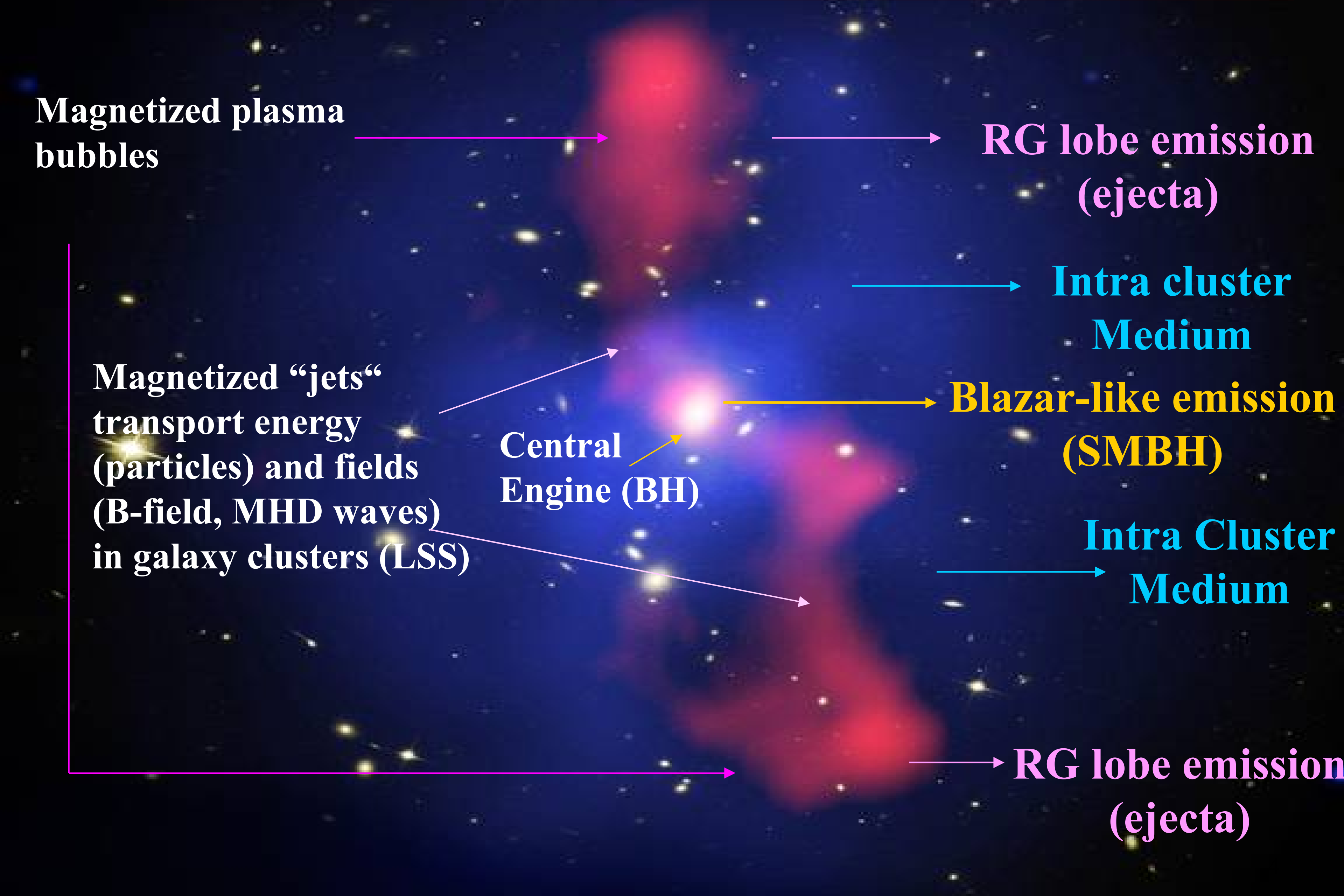
LSS: matters & fields

- Dark Matter
- Thermal plasma (ICM)
- Relativitic plasma (CRs)
- B-field
- SMBHs + Jets
- CMB + other rad. fields

Plasma in Large Scale Structures



Plasma in Large Scale Structures



e± Plasma in Large Scale Structures

Sites

- AGN Jets
- RG Lobes
- ICM
- DM halo

Origin

- Injection
- *In-situ* CR production
- Dark Matter annihilation

Probes

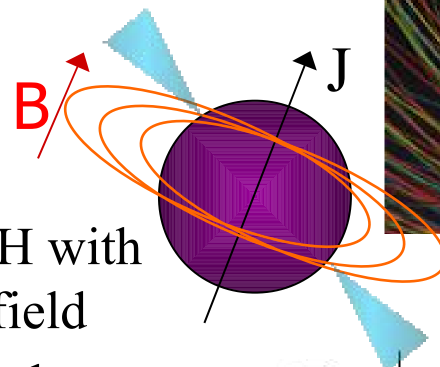
- Continuum emission
- Emission lines

The BH region

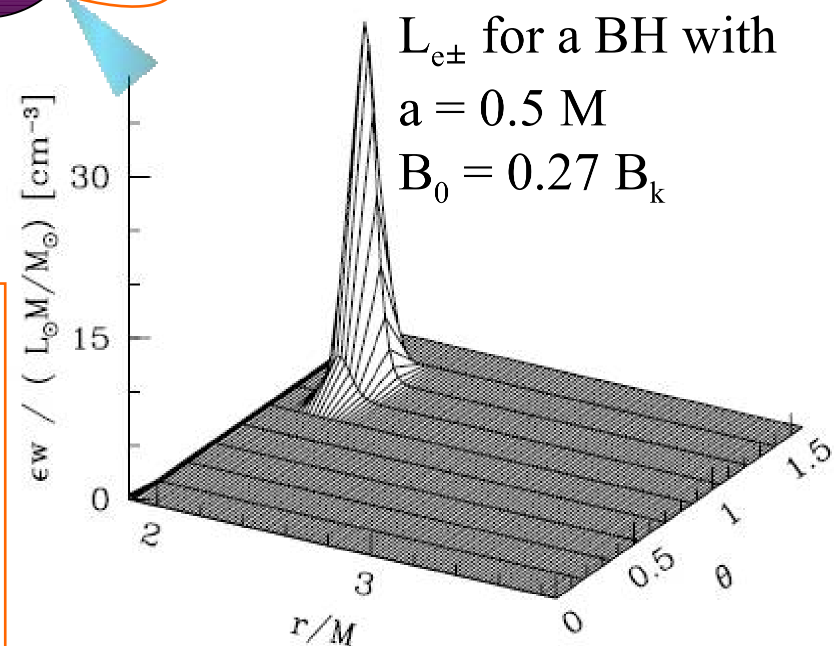
Conjecture

The curved spacetime surrounding a rotating BH dramatically alters the structure of nearby e.m. field. There is an instability of the magnetized vacuum surrounding a rotating BH immersed in a B-field ~

$B_k = m^2c^3/(e\hbar) \sim 4.4\times10^{13}$ G



Specifically, a maximally rotating BH with **$M_{BH}=3M_\odot$** immersed in a magnetic field **$B \sim 2.3\times10^{12}$ G** can be a copious producer of electron-positron pairs with a luminosity **$L_{e\pm} \sim 3\times10^{52}$ erg s^{-1}.** [Heyl 2000]



For B-field parallel (antiparallel) to J, e+ (e-) tend to escape → ∞, and the BH quickly acquires a negative (positive) charge, so that equal numbers of each charge escape → ∞.
For a maximally rotating BH, the bulk of the pair creation occurs at latitudes ~ 30° − 50°

BH region — Gravitational collapse

... **Conjectures continued**

Rotating BHs can produce e-e+ outflow when brought into contact with a strong magnetic field [Van Putten 1999].

The e-e+ outflow is produced by a coupling of the spin of the BH to the orbit of the particles.

 Analogy with Hawking radiation

For a nearly extreme Kerr BH, particle outflow from an initial state of electrostatic equilibrium has normalized isotropic emission

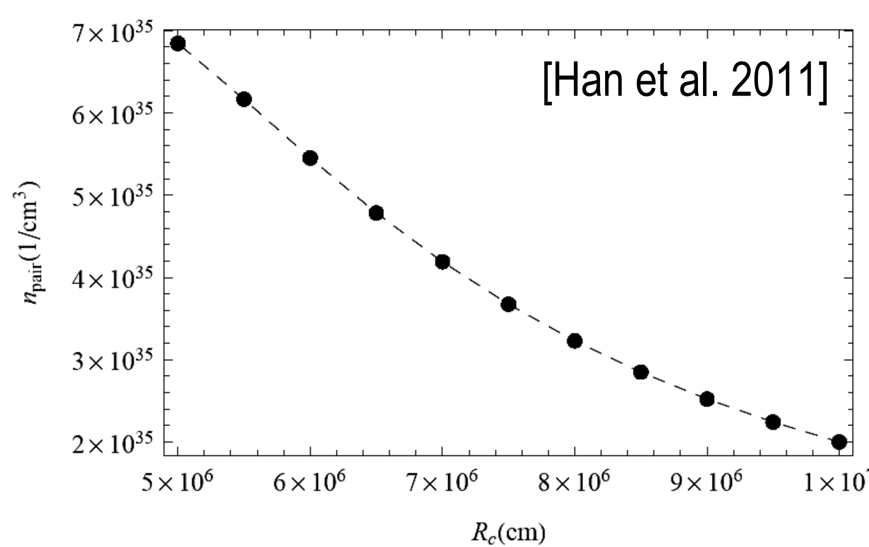
$$\sim 5 \times 10^{48} (B/B_c)^2 (M/7M_\odot)^2 \sin^2\theta \ \mathrm{erg/s}$$

$B_c = 4.4 \times 10^{13}$G
$M = M_{BH}$
$\theta \geq (B_c/3B)^{1/2}$

In gravitational collapse, e-e+ pairs are produced by strong E fields generated by charge separation: baryon core (+) and electron gas (-) [Han et al. 2011]

Gravitational energy is then converted to e-e+ energy: assuming that the energy density of the oscillating fields is totally converted to the e-e+ energy density

$$E_{pair} \equiv E_{osci} / N_{pair}$$



Seeding B-field in LSS: the beginning

Non Minimal G-EM Coupling

[Pauli 1933, Schuster 1912, Blackett 1947]

B fields of massive bodies arise from their rotation.
In other words, neutral mass currents generate B-fields implying the existence of a NMC between Gravitational & Electromagnetic fields.

$$\mathbf{m} = \left[\beta \frac{\sqrt{G_N}}{2c}\right] \mathbf{L} \qquad \mathbf{B} = \frac{3(\mathbf{m}\cdot\mathbf{r})\mathbf{r} - \mathbf{m}|\mathbf{r}|^2}{|\mathbf{r}|^5}$$

Eg: Generalized tetrad field theory

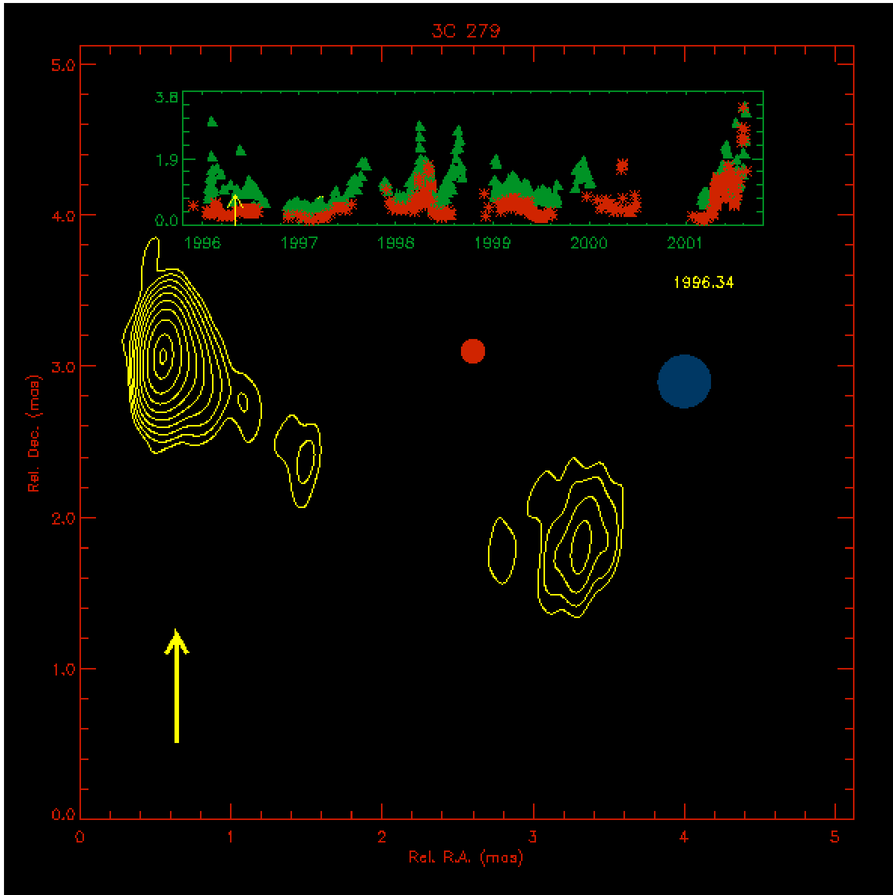
[Mikhail & Wanas 1977]

$$\left.\begin{aligned} \mathbf{B}_{\mathrm{P}} &= \frac{9}{4}\sqrt{\frac{2M}{R}}G_N \Omega\, G. \\ \mathbf{m} &= \left[\beta \frac{\sqrt{G_N}}{2c}\right] \mathbf{L} \end{aligned}\right\} \qquad \begin{aligned} \mathbf{B}_{\mathrm{P}} &= \frac{4\beta G_N^{1/2}}{5Rc} M \Omega\, G \\ \beta &\approx 2730 \left[\frac{R}{R_\odot}\frac{M_\odot}{M}\right]^{1/2} \end{aligned}$$

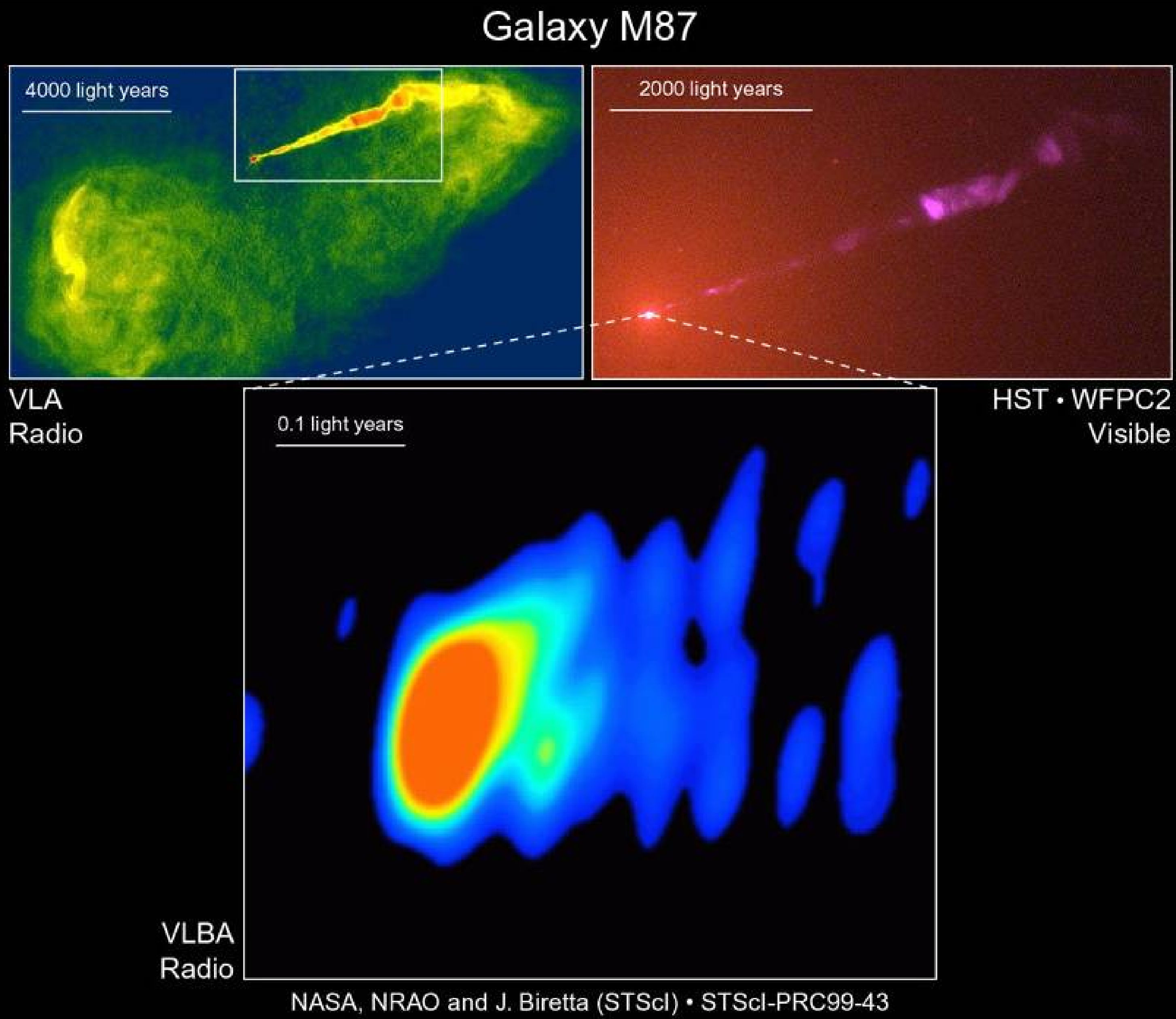
Magnetized blob launch

[S.C. et al. 2010-2011]

Magnetized plasma blob ejection
VLBA radio observation



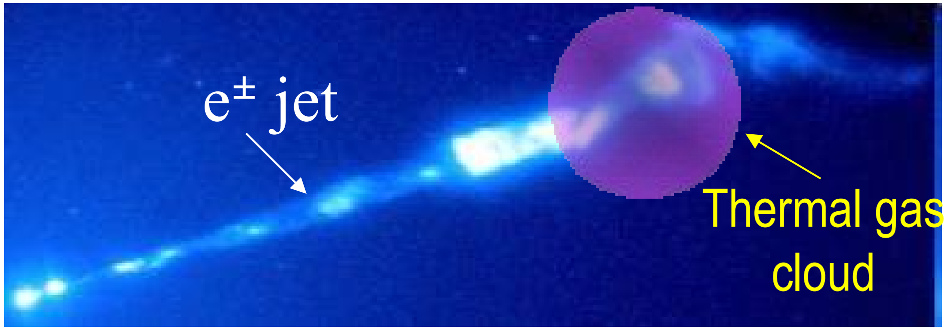
The jet region

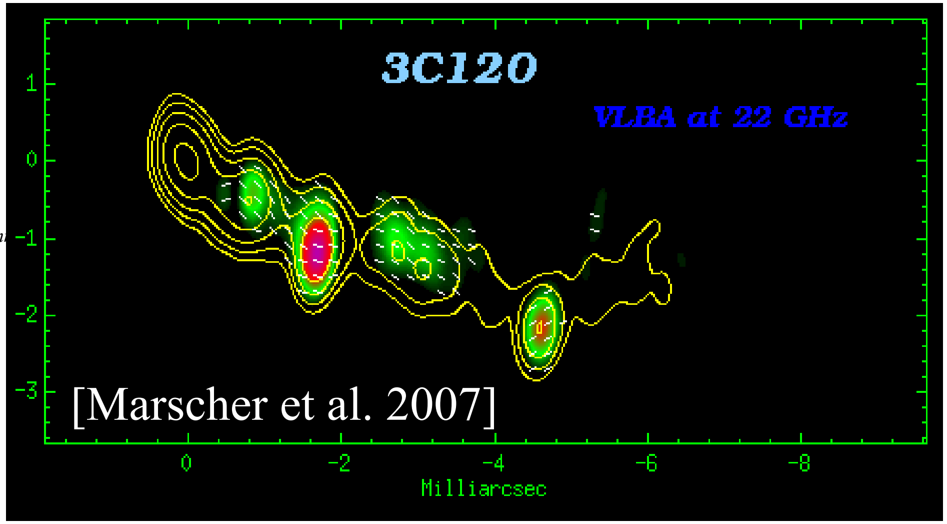


The jet region

Direct constraints

Emission line from e± annihilation
(best probe for future experiments)
[continuum need to be understood]





Inside a jet the relativistic bulk motion and internal motions decrease the annihilaton cross-section and broaden the 511 keV line.

Possible production of the 511 keV line if the jet mixes with dense thermal gas of an intervening cloud

- The case of **3C 120**
- INTEGRAL-SPI: only upper limits

$F(e+) < 2.5\ 10^{45}\ f/(1-f)^{1.5}\ [e^{+}\ s^{-1}]$

$$\tau_{ann} \approx 100 yr \cdot (5 \cdot 10^{4} cm^{-3} / n_e)$$

$$\tau_{therm} \leq 0.6 yr \cdot \gamma_e (5 \cdot 10^{4} cm^{-3} / n_e)$$

$F_{511keV} < 5.5\ 10^{-10} \times f/(1-f)^{1.5}\ [Pho/cm^{2}\ s]$

The jet region

Indirect constraints

Synchrotron self-absorption theory of jet cores constraint the magnetic field B and the relativistic particle density n.

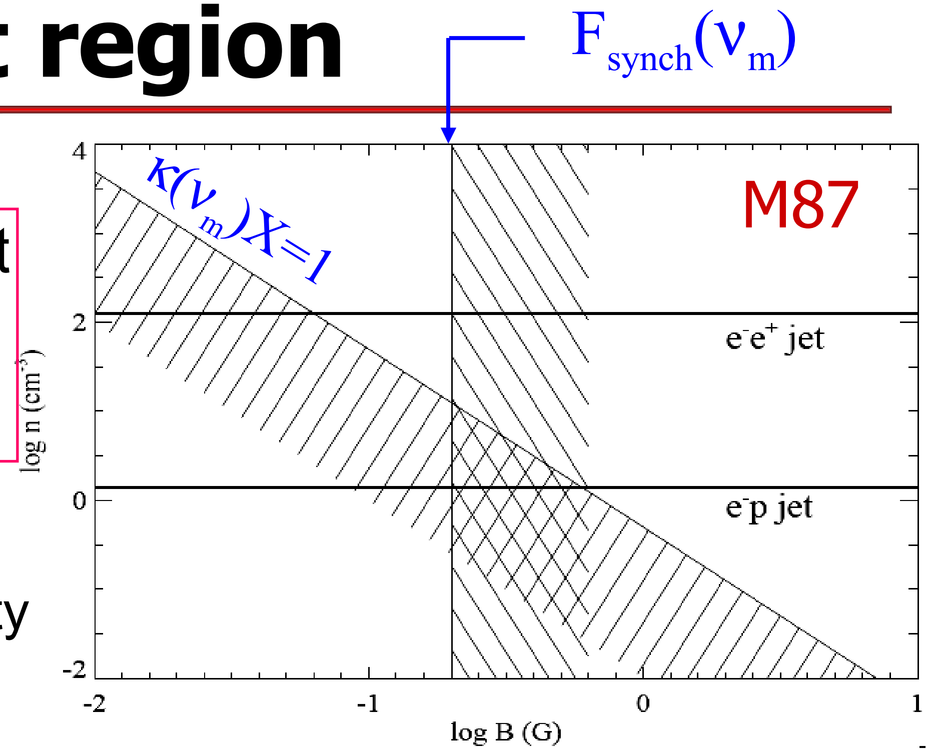
Data (5 GHz) implies $n_{min} \geq 10\ cm^{-3}$

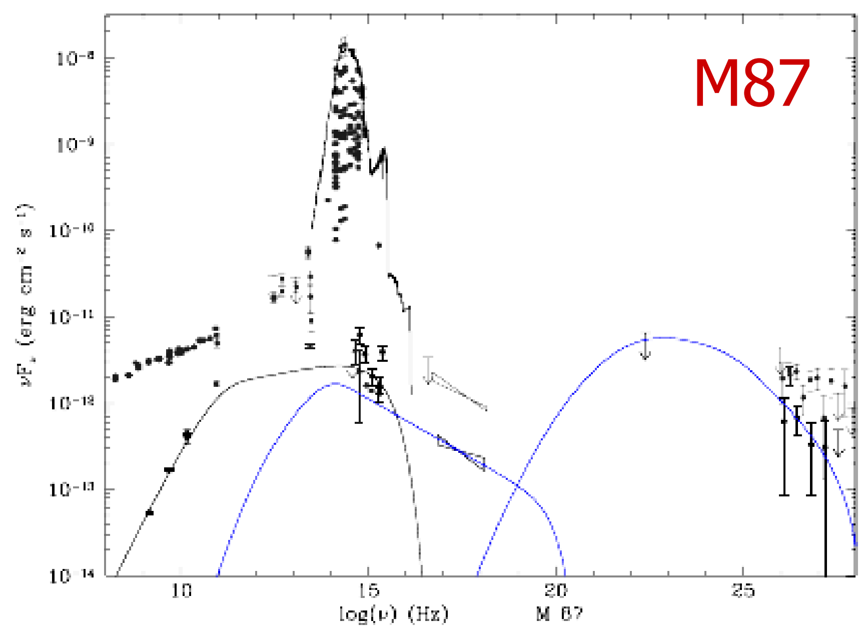
For this jet to carry the kinetic luminosity inferred from global energetic arguments, the density must be:

- $n \sim 1\ cm^{-3} \rightarrow$ (e-p jet)
- $n \sim 10^2\ cm^{-3} \rightarrow$ (e-e+ jet)

Evidence for an e-e+ dominated jet rather than an e-p dominated jet

If a jet core is still self-absorbed at ~100 GHz e-p jet are definitely ruled out.





The jet - lobe region

The jet - lobe region

Method

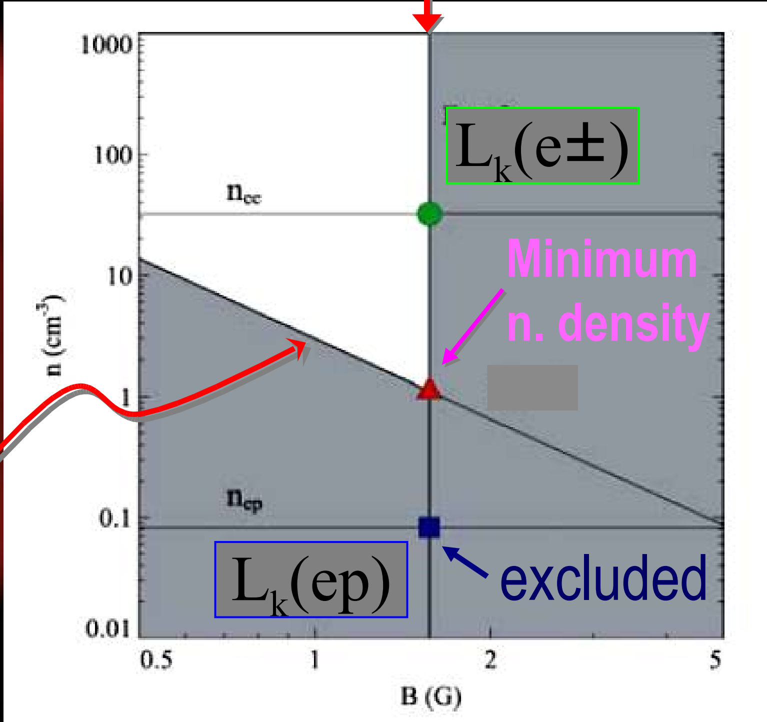
- determine the lepton content at the base of the jet from synchrotron emission & absorption
- determine the total particle energy from the power required to create the observed giant lobes (bubbles)
- the combination set constraints on the particle content in the jet/lobe

Synchrotron Flux ($\sim\nu^{-\alpha}$) in optically thick (self.-absorbed) region is independent of $n = (N_0/2\alpha)\gamma_{min}^{-2\alpha}$

$$B \lesssim 10^{-5} b(\alpha)\theta_d^4 \nu_m^5 S_m^{-2}\left(\frac{\delta}{1+z}\right) \mathrm{G},$$

Synch. radiation at frequency ν_m to be self-absorbed in the radio source

$$nB^{\left(\frac{3}{2}+\alpha\right)} \gtrsim \frac{2\delta}{3^{(\alpha+1)}\sqrt{\pi}\, g(\alpha)\alpha\gamma_{\min}^{2\alpha} e r}\left(\frac{m_e c \nu_m}{e\delta}\right)^{5/2+\alpha}.$$



Lobes in the ICM

Estimating **L_k** from lobe-ICM interaction
 all the jet energy results in the creation and expansion of radio bubbles

$$L_k = E_{bubble} / t_{bubble}$$

$$E_{bubble} = \frac{\gamma_R}{\gamma_R - 1} pV \approx (2 \div 4) pV$$

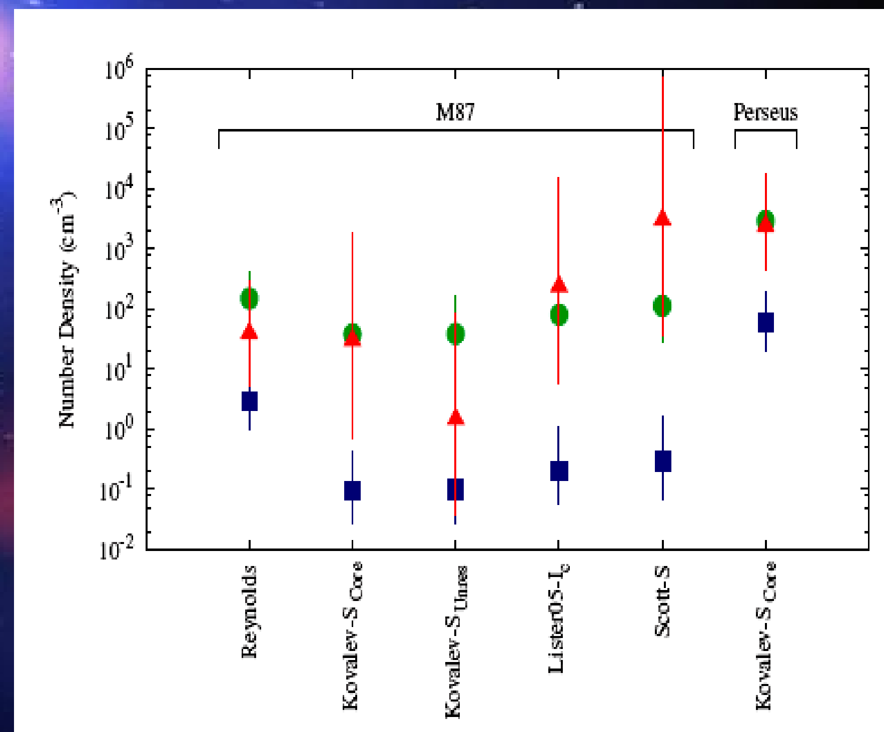
$$t_{bubble} = 2R_{bubble} / c_s$$

$$L_K \approx \Gamma^2 \beta \pi r(Z)^2 n m_e c^3 \left[\frac{4}{3}(\langle\gamma\rangle - 1) + \frac{\Gamma - 1}{\Gamma}(1 + k_a)\right]$$

[Dunn et al. 2002, Colafrancesco et al. 2012]

Constraints from radio & X-rays
(radio & SZE)

- 3C84-Perseus seems to be dominated by e$^{\pm}$ jets
- M87-Virgo case: still unclear



The jet - lobe region

General case

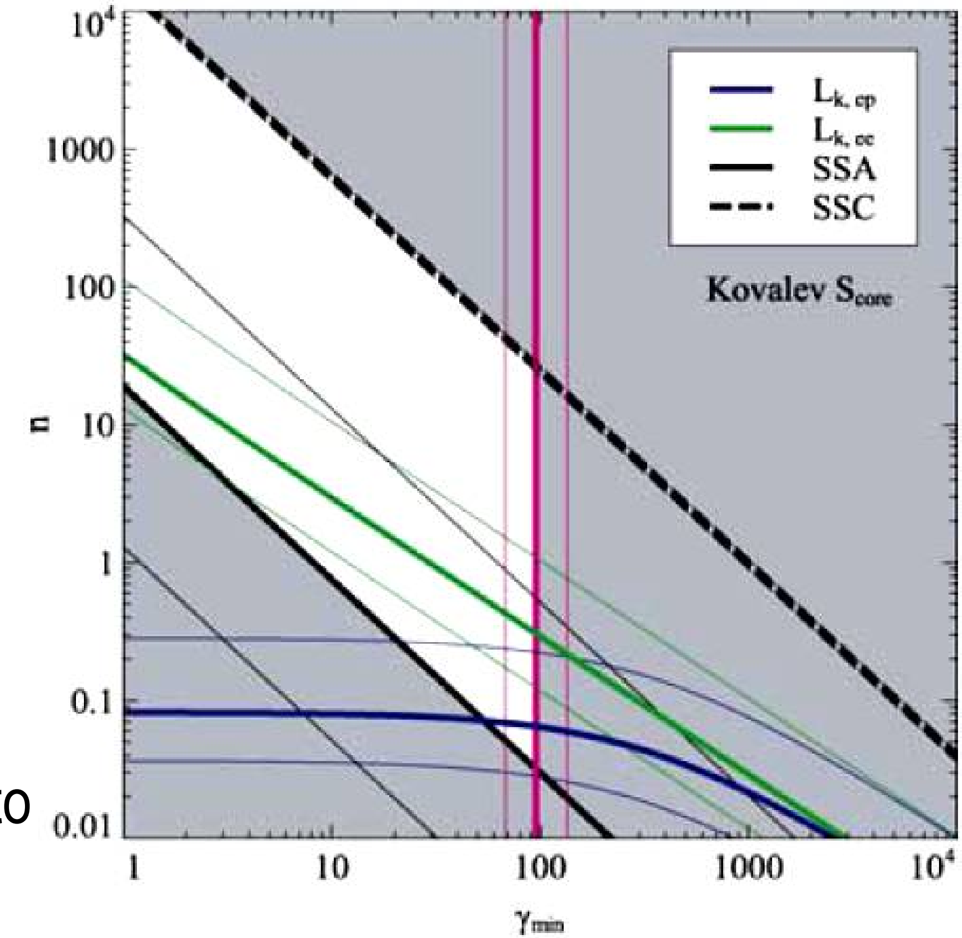
- B-field effects on jet-lobe energy

$$L_k = a \cdot n + b \cdot B^2$$

- γ_{min} effects on jet-lobe energy

$$n = \int_{\gamma_{min}}^{\gamma_{max}} N(\gamma)\mathrm{d}\gamma,$$

$$2\alpha n = -N_0 \left[\gamma^{-2\alpha}\right]_{\gamma_{min}}^{\gamma_{max}}.$$



Low γ_{min} < 50 values favour light e± jets/lobes

Large γ_{min} > 100 do not allow to distinguish e± or e-p jets

Definite probes

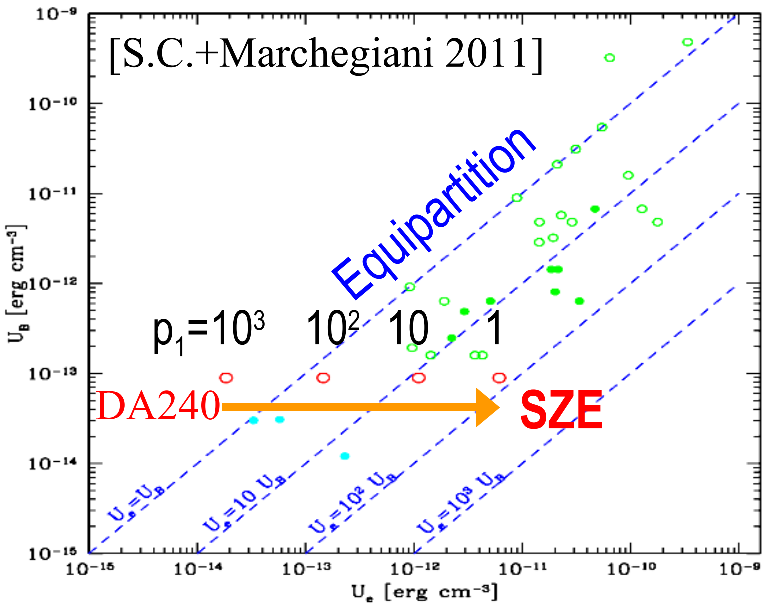
- (super)VLBI radio: probe jet base
- SZE mm: probe lobe energetic
- γ-ray: probe annihilation line

SKA RADIOASTRON

MILLIMETRON

DUAL-like

The jet - lobe energetics



$$U_e = \int_{p_1}^{\infty} dp N(p)(\sqrt{1+p^2}-1)m_e c^2$$

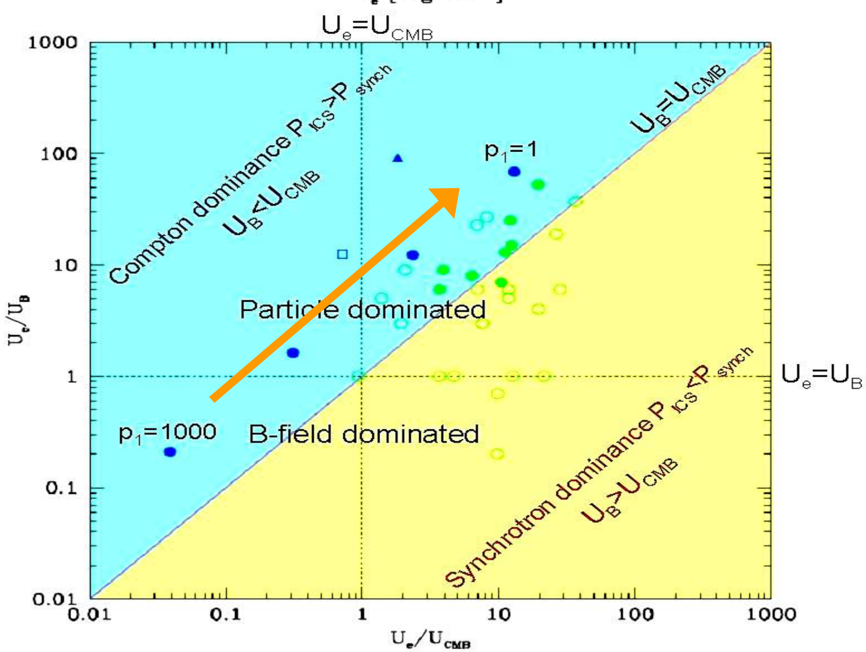
Radio ⇒ **reliable measure of U_B * Ue**

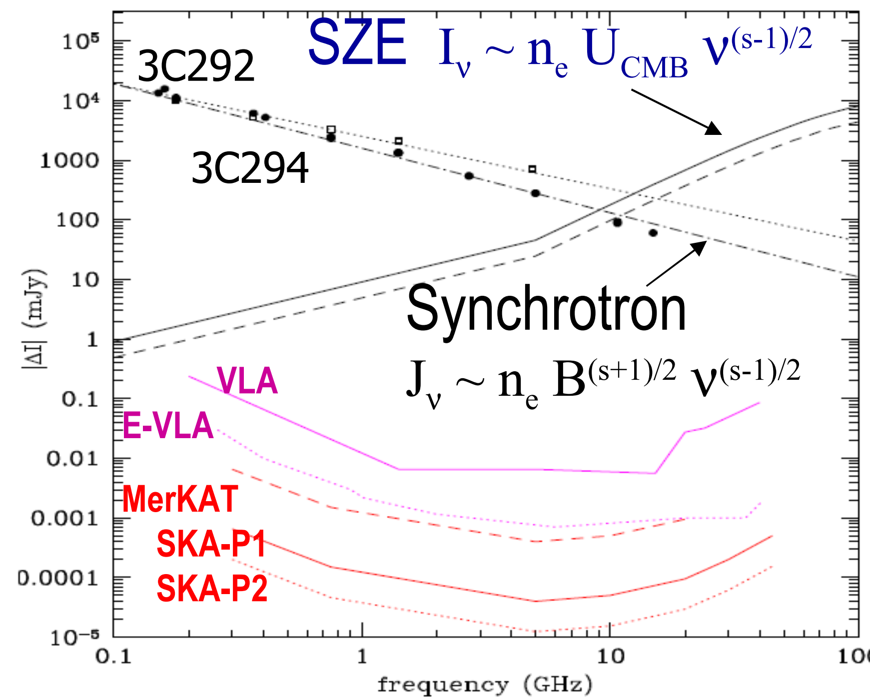
SZE ⇒ **unbiased measure of Ue**

SKA, MeerKAT

$\Delta\nu$ = 0.1 - 45 GHz

Separate Synchrotron & SZE





The Intra Cluster Medium

Clusters of galaxies are enriched with positrons
- from jets of AGNs
- from the interaction of cosmic-rays with the ICM
- from Dark Matter annihilation

The cooling of positrons and their annihilation with ICM electrons yields a narrow annihilation line

Evolution of the Positron Distribution Function

$$\frac{\partial N_+(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}[b(\gamma,t)\, N_+(\gamma,t)] + Q(\gamma) - N_+(\gamma,t)\, A(\gamma)$$

Cooling rate Production rate Annihilation rate

Thermalization

$$\tau_{\rm therm} \approx 4.8 \times 10^3\, T_{\rm keV}^{3/2} \left(\frac{10^{-3}\ {\rm cm}^{-3}}{n_e}\right)\ {\rm yr}$$

Annihilation

$$\tau_{ann} \approx 3.97 \cdot 10^9\, yr \left[\frac{n_e}{10^{-3}\, cm^{-3}}\right]^{-1}$$

$$A(\gamma_{\rm eq}) = \frac{1}{2n_+} \int dk\, \frac{dn_\gamma}{dk\, dt}\bigg|_{\rm line} \approx 8 \times 10^{-15} n_e\ {\rm s}^{-1},$$

The Intra Cluster Medium

Annihilation Line structure

Unlike annihilation in the ISM of galaxies, the line produced in clusters is not smeared by three-photon decay of positronium, because positronium formation is suppressed at the high (≥ keV) temperature of the ICM.

AGN injection

The peak emissivity in the annihilation line is

$$\dot{n}_{\rm line,\,single} \approx 2\times10^{-25} X_s^{\rm AGN} \left(\frac{n_e}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{\xi_{\rm AGN}}{0.1}\right)\left(\frac{r_{\rm mix}}{200\ {\rm kpc}}\right)^{-3} \times \left(\frac{L_K}{10^{45}\ {\rm erg\ s}^{-1}}\right)\left(\frac{\tau}{10^8\ {\rm yr}}\right)\ {\rm cm}^{-3}\ {\rm s}^{-1}, \quad \boxed{(single\ AGN\ event)}$$

$$\dot{n}_{\rm line} \approx 9\times10^{-23} X_s^{\rm AGN} \left(\frac{n_e}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{\xi_{\rm AGN}}{0.1}\right)\left(\frac{r_{\rm mix}}{200\ {\rm kpc}}\right)^{-3} \times \left(\frac{f_K}{0.1}\,\frac{\epsilon_{\rm BH}}{0.1}\,\frac{L_{B,\rm cl}}{10^{12}\ {\rm L}_{B\odot}}\right)\ {\rm cm}^{-3}\ {\rm s}^{-1}, \quad \boxed{(multiple\ simultaneous\ AGN)}$$

Cosmic Ray production

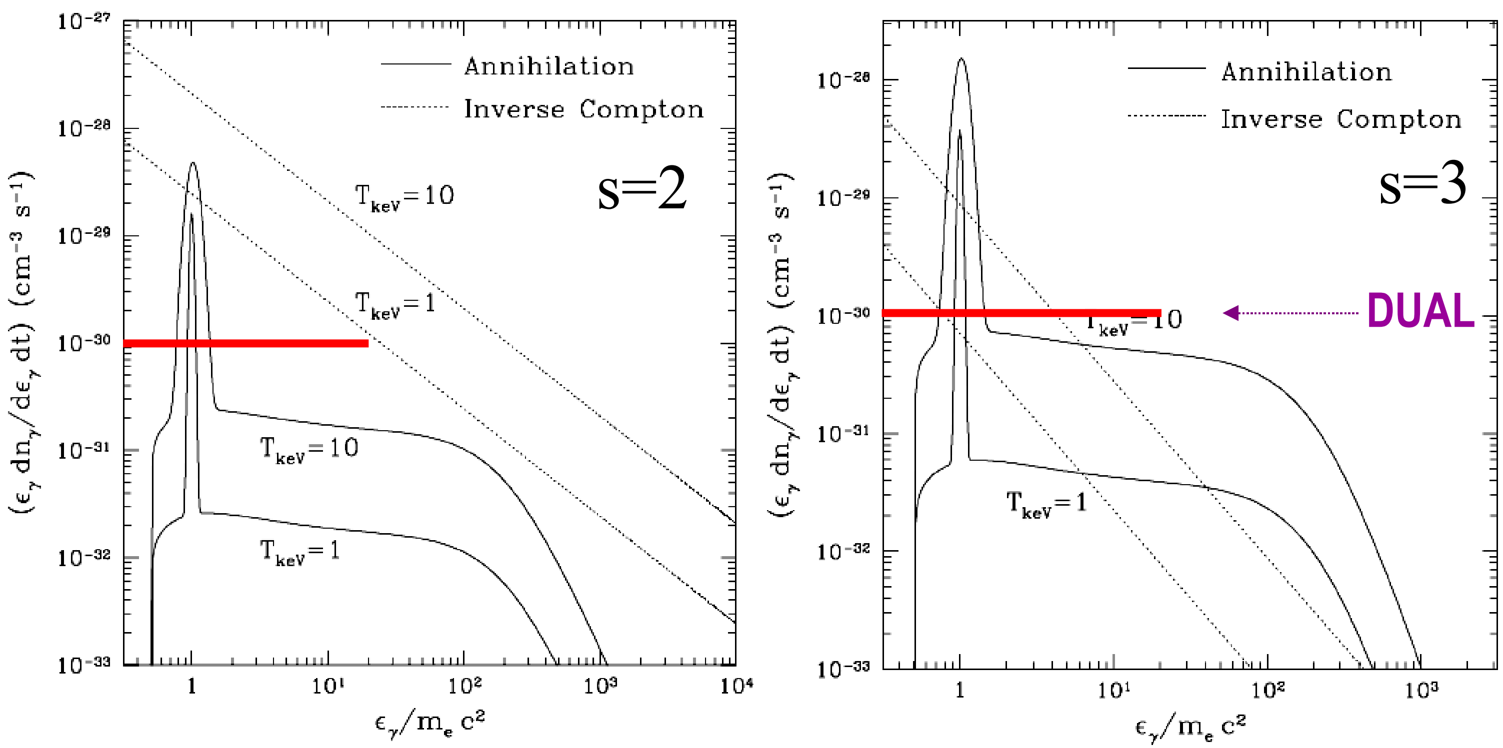
The steady-state emissivity in the annihilation line is

$$\dot{n}_{\rm line} \approx 10^{-30} X_s^{\rm CR}\, T_{\rm keV} \left(\frac{n_e}{10^{-3}\ {\rm cm}^{-3}}\right)^2 \left(\frac{\xi_{\rm CR}}{0.1}\right)\ {\rm cm}^{-3}\ {\rm s}^{-1}, \quad \boxed{(cosmic\ ray\ secondaries)}$$

The Intra Cluster Medium

Expected signals for Q ~ γ^{-s}

[Furlanetto & Loeb 2002]

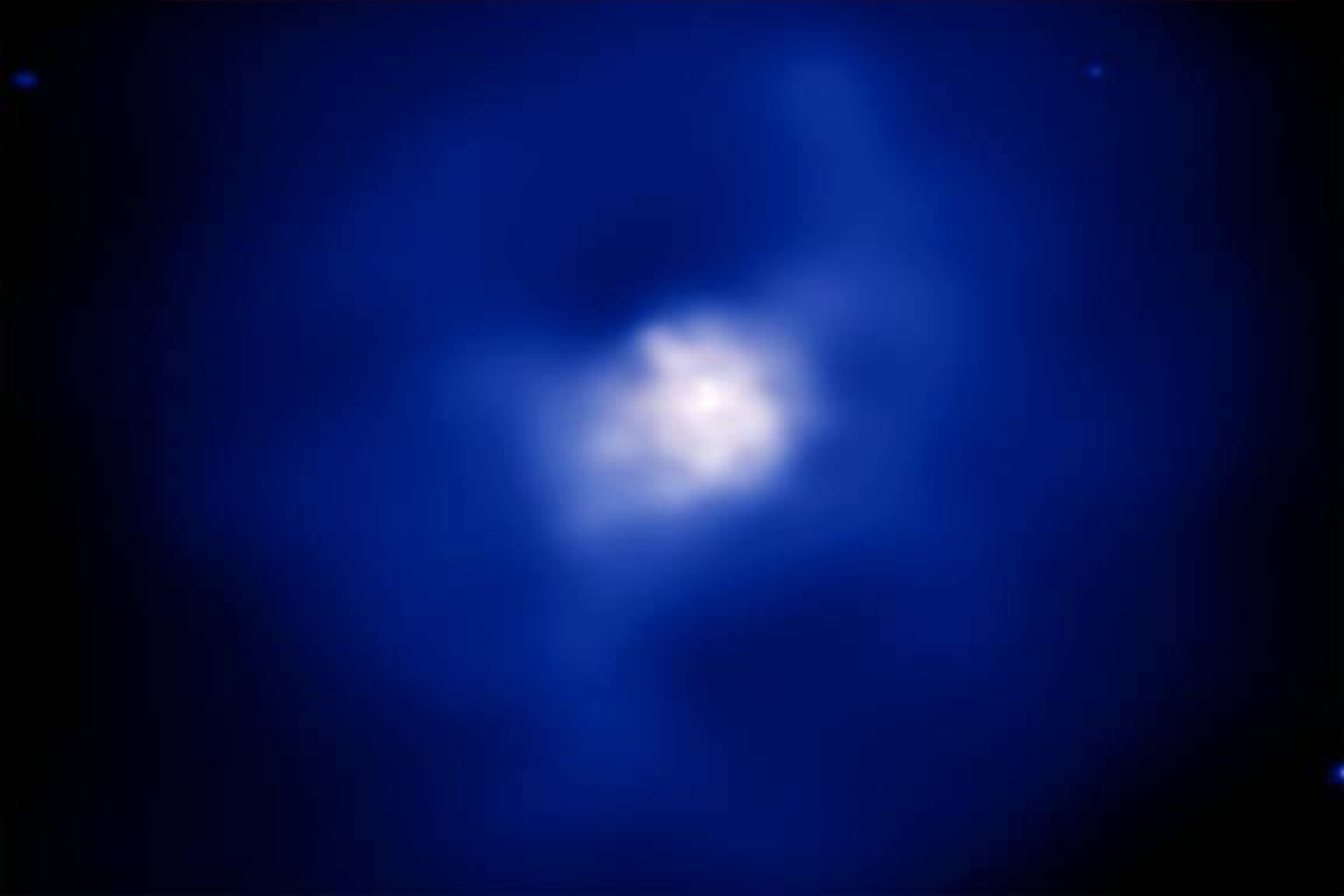


[Colafrancesco et al 2011]

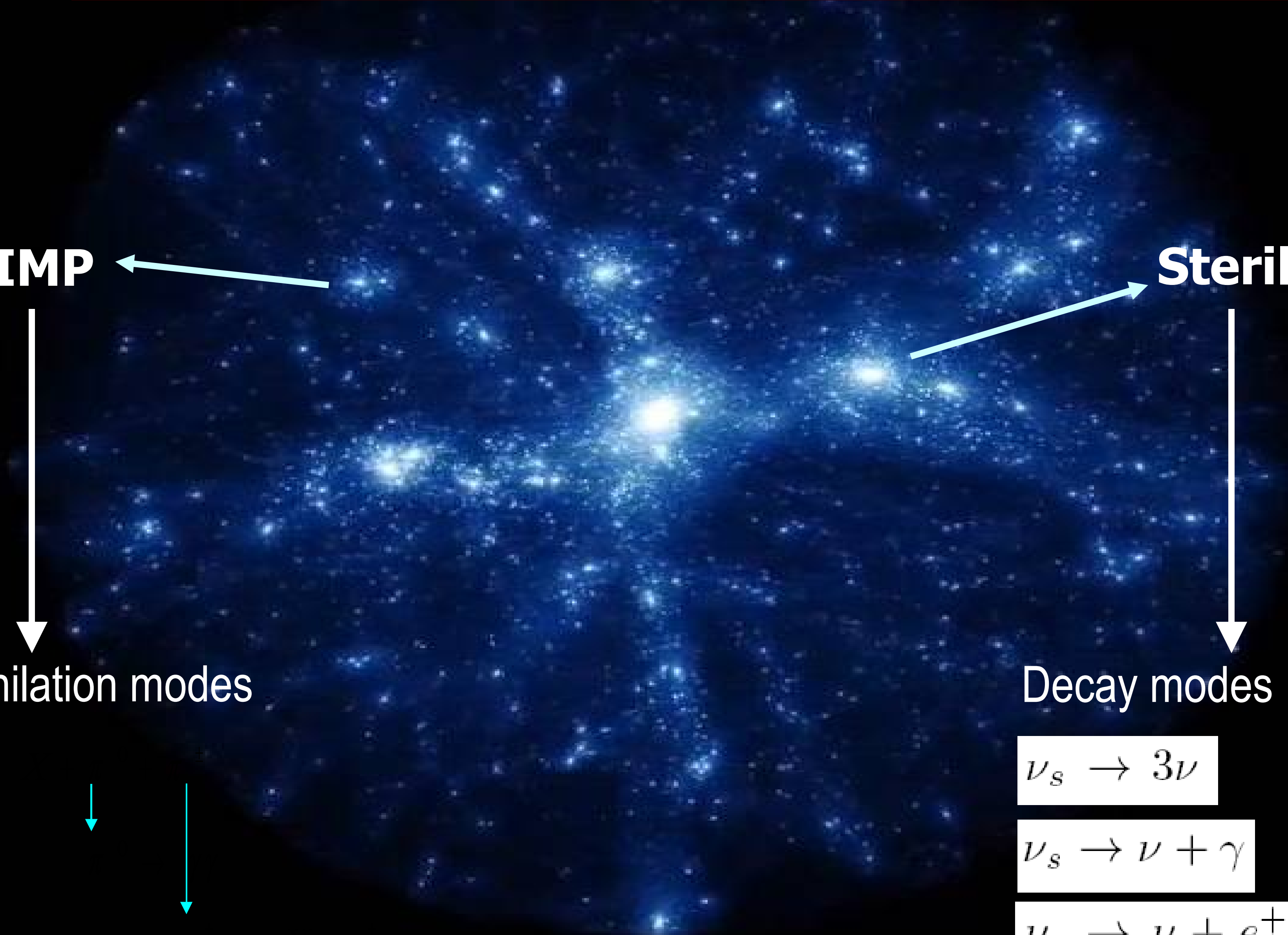
$$F_c = 8\times10^{-7}\left(\frac{r_{\rm mix}}{200\ {\rm kpc}}\right)^3\left(\frac{D}{100\ {\rm Mpc}}\right)^{-2}\left(\frac{\dot{n}_{\rm line}}{10^{-24}\ {\rm cm}^{-3}\ {\rm s}^{-1}}\right)\ {\rm photons\ cm^{-2}\ s^{-1}}, \qquad (47)$$

If AGN jets are composed of e+e− pairs, then the annihilation line from nearby galaxy clusters containing powerful radio-galaxies might be detectable with space missions with $F_{lim}=10^{-6}$ cm^{-3} s^{-1} provided that $[D^2/r^3_c]\, f^{-1}(r) < (\varepsilon\cdot{\rm Mpc})/F_{lim}$

Dark Matter halos



Dark Matter halos



WIMP

Annihilation modes

Sterile ν

Decay modes

$$\nu_s \to 3\nu$$

$$\nu_s \to \nu + \gamma$$

$$\nu_s \to \nu + e^+ + e^-$$

Dark Matter halos

WIMPs

Annihilation rate $\chi\chi \rightarrow X + \pi^{\pm} \rightarrow e^{\pm}$

$$R = n_\chi(r)\langle\sigma V\rangle_A$$

$$= 10^{-29}\ \mathrm{s}^{-1}\left(\frac{n_\chi}{10^{-3}\ \mathrm{cm}^{-3}}\right)\left(\frac{\langle\sigma V\rangle_A}{10^{-26}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}\right)$$

The positrons produced are slowed down due to thermalization processes (like CRs):

□substitute $n_{e,CR}$ with $n_{e,DM} \sim \langle\sigma V\rangle / M^2_\chi$

Thermalization is faster than annihilation in the ISM/ICM that is rich in thermal baryons

$$\dot{n}_{line} \propto \frac{<\sigma V>}{M_\chi^2} \cdot kT \cdot n_e$$

Annilation line due to WIMPs only possible in DM halos which host a co-spatial gaseous halo: □ Galaxies, Clusters.

□ Dwarf galaxies cannot thermalize e±

Sterile ν

Decay rate $\nu_s \rightarrow \nu + e^+ + e^-$

$$\Gamma_e = \frac{G_F^2}{384\pi^3}\sin^2 2\theta m_s^5\left(\frac{|V|^2}{2}+\frac{1}{8}\right) = \Gamma_{3\nu}\left(\frac{|V|^2}{2}+\frac{1}{8}\right)$$

The positrons are slowed down due to ionization losses & other thermalizations.

Larmor radius of e+ with energy Ee+

$$r = \frac{E_{e^+}}{eB} = 10^{13}\left(\frac{E_{e^+}}{10^4\ \mathrm{MeV}}\right)\left(\frac{B}{10^{-5}\ \mathrm{G}}\right)\ \mathrm{cm}.$$

The stopping distance for the random walk of an e+, the distance that the e+ is confined, is √rd ≤1 pc , much shorter than the mean free path of the e± annihilation

$$\bar{l}_{e^\pm} = \frac{1}{n\sigma_a} \sim 30\ \mathrm{kpc},$$

Therefore, the positrons will become non-relativistic before annihilation.

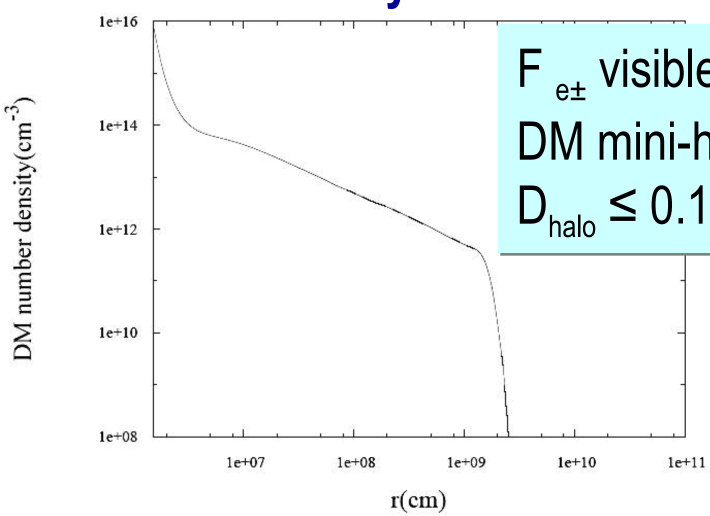
Dark Matter halos

WIMPs

DM particles captured by the stellar matter and then distributed in the core of the star. **To increase the e-e+ flux, DM particles must redistribute around the newly formed compact object formed at the end of the star lifetime** [Zhang et al. 2011]

Inelastic DM scattering

Extended dense DM mini-halo surrounding a neutron star may be formed.



$F_{e\pm}$ visible from DM mini-halos if $D_{halo} \leq 0.1$ pc

Sterile ν

The rate for a e-e+ annihilation in the diffuse region of Milky Way is [Chan & Chu 2010]

$$P \sim n\sigma_a v_e \sim 10^{-18}\ \mathrm{s}^{-1},$$

To produce 10^{43} s^{-1} e$^{\pm}$ annihilations, there must exist a large positron cloud with 10^{61} positrons in the MW, and the production rate must be much greater than the annihilation rate. For the MW buldge

$$A_{\rm bulge} \approx \int_0^{R_B} 4\pi r^2 n_s(t_0)\Gamma_e dr,$$

If $\Gamma_e = 10^{-28}$ s^{-1} and m_s =1 MeV, one can get $\sin^2(2\theta) \sim 10^{-24}$, which is consistent with the diffuse X-ray background constraint.

[e.g. Boyarsky et al.2009]

Radiative decay line $\dfrac{\Phi_\gamma}{\Phi_{e\pm}} = \dfrac{0.031}{4|V|^2+1},$

Conclusions

Electron-Positron plasma copiously produced in Large Scale Structures
by various mechanisms: SMBH jets (t-dependent), CRs, DM (steady-state)

Electron-Positron plasma are very relevant for energetics and stability of
LSS atmospheres: AGN jet composition; Cluster atmospheres; DM nature

Direct probes   511 keV annihilation line (need thermalization medium)
ICS-CMB continuum radiation (pervasive emission)

Indirect probes: radio (VLBI) + μwave + gamma
polarization (radio + soft-gamma)

Requirements: sensitivity (line + continuum) & polarization at 0.1-10 MeV
multi-frequency follow-up: radio to high-E gamma

THANKS

for your attention !