Mode-Particle Interactions as Sources of Gamma-Ray Bubbles in the Milk Way Galaxy

A. Cardinali[1,2,3], B. Coppi[4]

[1] INAF-IAPS, Area di Ricerca Tor Vergata, Roma, Italy
[2] CNR, Istituto Sistemi Complessi, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[3]ENEA FSN, C.R. Frascati, Via E. Fermi, 45, 00044 Frascati (Roma), Italy
[4] MIT Cambridge Massachussets, USA

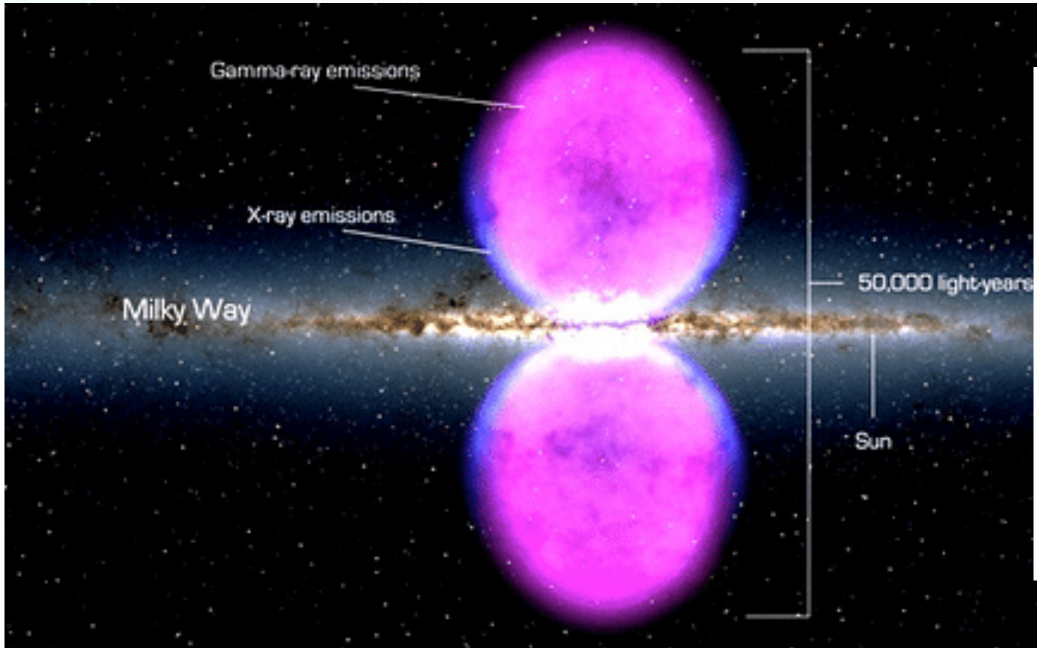
Observations

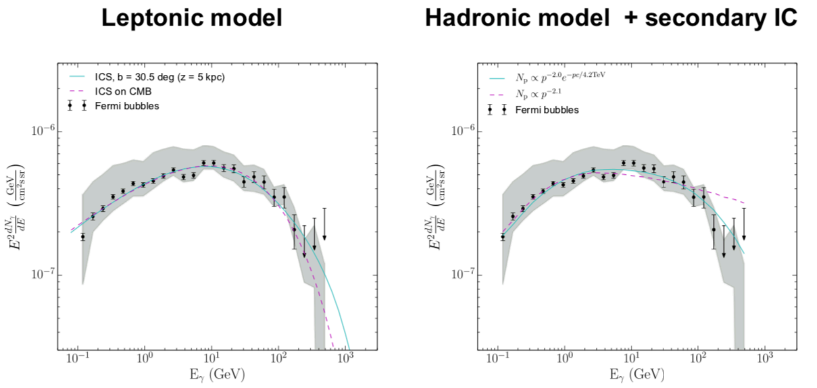
- ✓ The Fermi Gamma-Ray Space Telescope discovered in 2010 the “Fermi Bubbles” an energetic gamma-ray glow extending far above and below the plane of our galaxy (**25.000 light-years**). (*M. Su, T.R. Slatyer, D.P. Finkbeiner, ApJ 724 1044 (2010)*)

- ✓ The gamma-ray bubbles are observed by Fermi between **1-100 GeV** with a spectral index of approximately -2 (*Ackermann et al., ApJ 793 (2014)*).

- ✓ The total gamma-ray power for both bubbles is **≈4.0 × 10^{37} erg s^{-1}**.

- ✓ The gamma-ray bubbles have many unique characteristics
  - ✓ smooth surface,
  - ✓ sharp edges,
  - ✓ almost flat intensity distribution




Leptonic model

Hadronic model + secondary IC

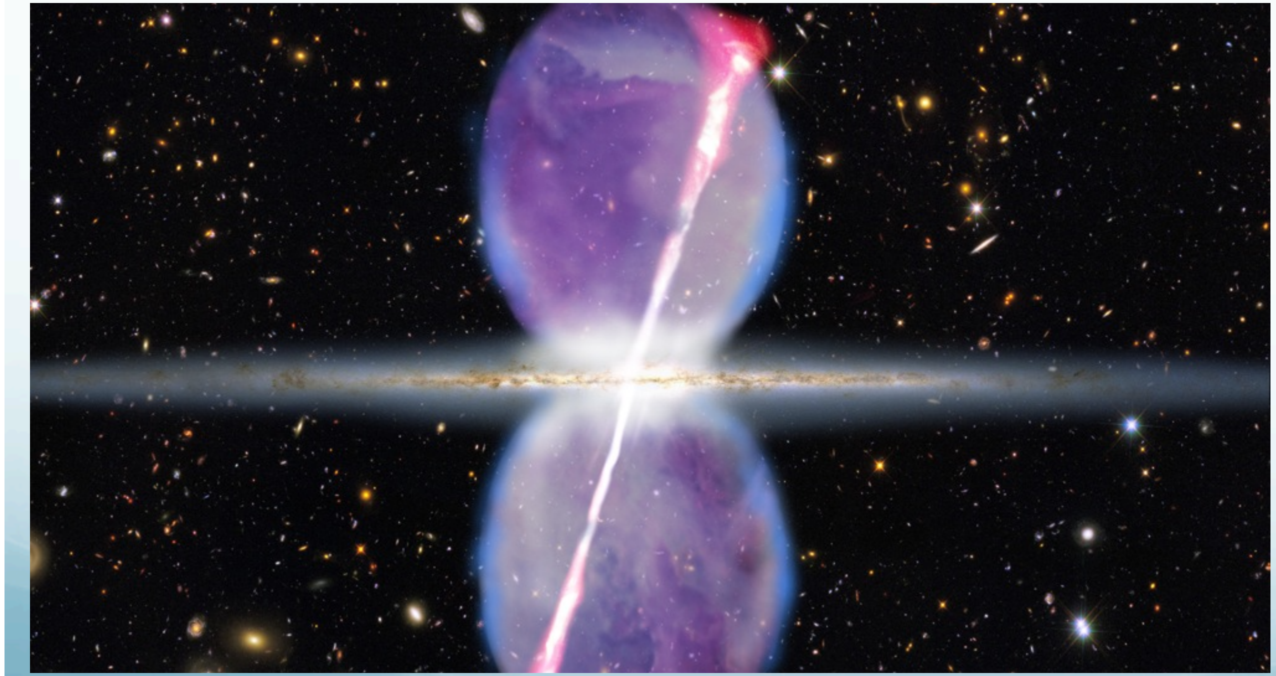
Ackermann et al (Fermi LAT), ApJ 793 (2014)

- **Cutoff or softening above ~ 100 GeV**
- **Both leptonic and hadrnoic models fit the spectrum**

Observations

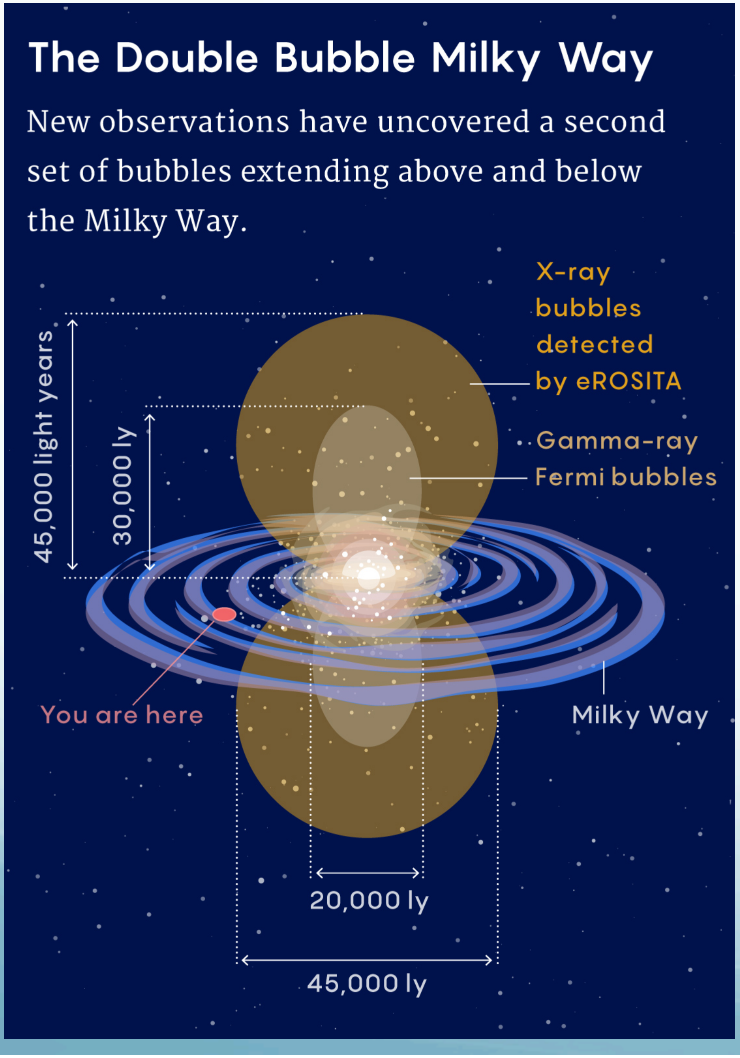
- ✓ In 2012, astronomers at the Harvard-Smithsonian Center for Astrophysics discovered jets (shown in pink) extending through the Fermi Bubbles for 27,000 light-years (*Meng Su, D. P. Finkbeiner, Evidence for Gamma-Ray Jets in the Milky Way, ApJ 753:61 (2012)*).

- ✓ Essentially the black hole at the center of Milk Way Galaxy (Sagittarius A*) fired off jets of matter that escapes along the black hole's spin axis, creating an outflow that extends far above and below the plane of the galaxy. The velocity of the flow is around ≈1000 Km/s (*E. Caretti et al., Giant magnetized outflows from the centre of the Milky Way, Nature 493, 66 (2013)*)



Observations

More recently observations by e-Rosita has extended the Fermi bubbles volume up to a distance of 45000 light/years but in the energy range of X-ray *(P. Predehl et al., Nature 588 227 (2020))*



The Double Bubble Milky Way

New observations have uncovered a second set of bubbles extending above and below the Milky Way.

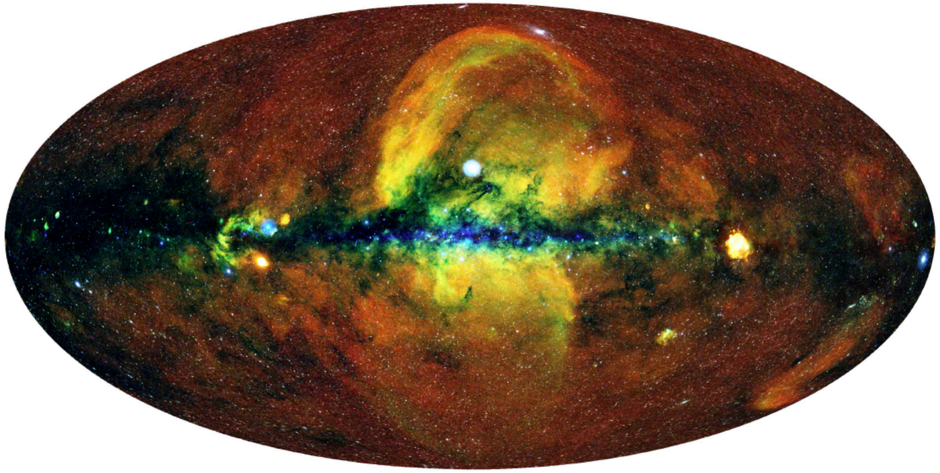
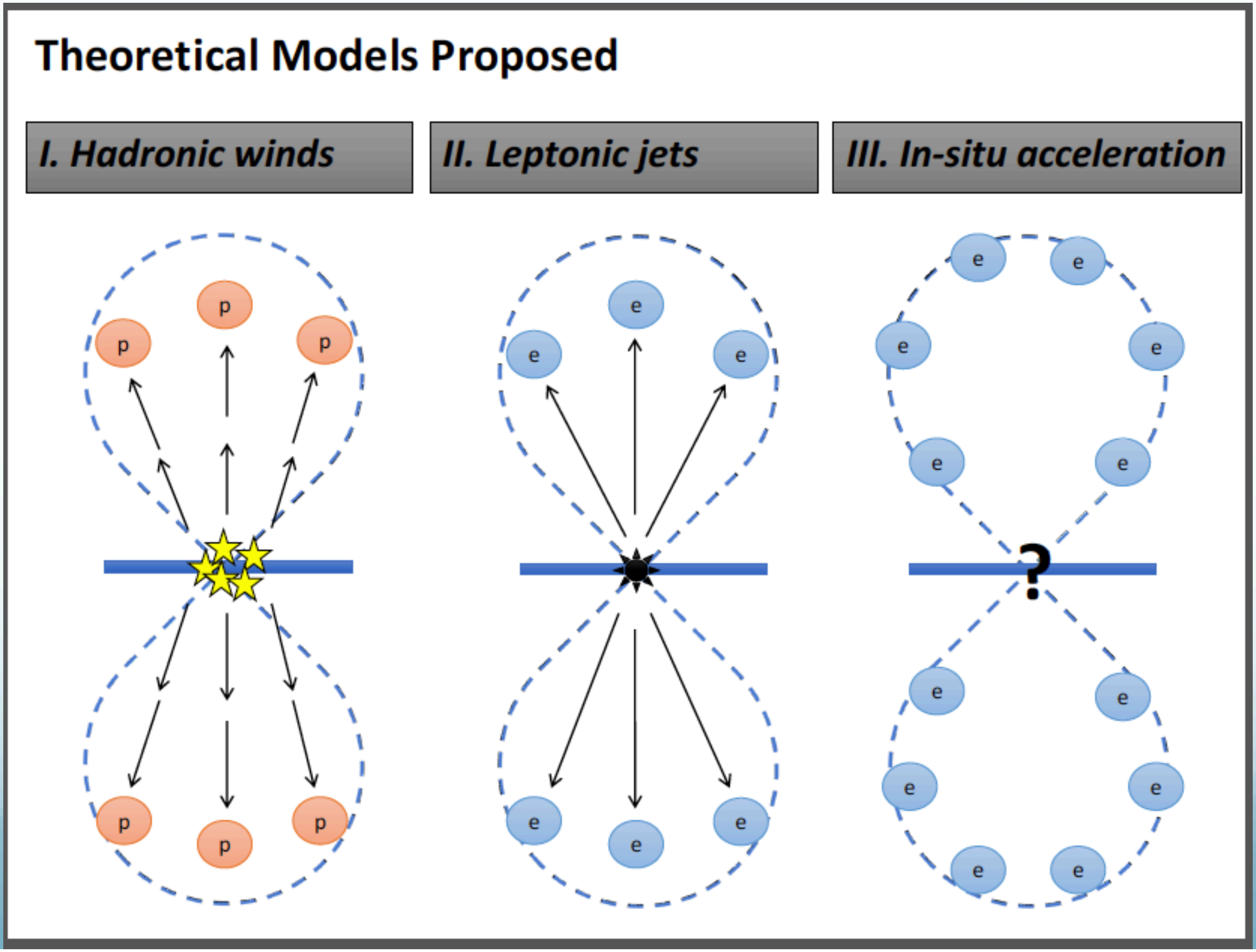


Fig. 1 | The Spektr-RG–eROSITA all-sky map. An RGB map of the first Spektr-RG–eROSITA all-sky survey (red for 0.3–0.6 keV, green for 0.6–1.0 keV, blue for 1.0–2.3 keV) is shown in Galactic coordinates, using a Hammer–Aitoff projection. The original image, with a resolution of about 12″, was smoothed (with a Gaussian with a full-width at half-maximum (FWHM) of 10′) to generate this one. Image adapted from ref. [34]. Credit: Jeremy Sanders, Hermann Brunner, Andrea Merloni and the eSASS team (MPE); Eugene Churazov, Marat Gilfanov (on behalf of IKI).

Proposed Explanations

The theory to explain these experimental observations is not still completely assessed, and relies essentially on three type of models:

H.-Y. K. Yang and M. Ruszkowski ApJ 850 2 (2017)
H.-Y. Karen Yang, M. Ruszkowski, Ellen Zweibel, Unveiling the Origin of the Fermi Bubbles, Galaxies 6 29 (2018)



Our Conjecture

- **Cooperation between "***Hadronic winds"* **and** *in "situ acceleration"*

  - ✓ Our Milk Way is surrounded by a cloud of hot thin plasma whose density and temperature were established to be (*Miller and Bregman, The Astrophysical Journal 770:118 (2013)*)
    - ✓ ($n \approx 10^{-4}$-10^{-6}cm^{-3}, T≈1-2 MK, 80-160eV)

  - ✓ Moreover the galaxy halo is permeated by a magnetic field (the topology is not yet fully understood) with an intensity in the range 5-30μG (*E.G. Zweibel and C. Heiles, Magnetic fields in galaxies and beyond, Nature 385 131 (1997)*)

  - ✓ In Laboratory Plasmas, it is theoretically known and experimentally measured that an ion/electron beam perpendicular/parallel to a static magnetic field can induce an *electromagnetic instability* in the range of Lower Hybrid Frequencies ($\omega \approx \omega_{pi}$) (*B. Chang, B. Coppi, Geophys. Res. Lett. 8 1253 (1981)*)

Our Conjecture

- On the basis of these considerations our conjecture can be summarized as

  - ✓ The jets (hadronic and/or leptonic matter) coming from the galactic center acts like charged beams moving in the galactic hot and tenuous halo plasma

  - ✓ The jet feels the large scale magnetic field of the galaxy in the galaxy halo, and induces *an electromagnetic instability in* the Lower Hybrid Frequency range which is fed by the jet energy

  - ✓ The Lower Hybrid Wave propagates in the galaxy halo by following the magnetic field lines and transfers its energy to the electron of the mantle by accelerating them at very high energy

  - ✓ The accelerated electrons in magnetic field emits synchrotron radiation or/and Inverse Compton Scattering

Quantitative Models to prove this Conjecture (first step)

Fluid non linear model

$$\frac{\partial \rho_{e/i}}{\partial t} + \nabla \cdot \left(\rho_{e/i} \vec{v}_{e/i}\right) \Rightarrow \text{charge conservation}$$

$$\frac{\partial \vec{v}_{e/i}}{\partial t} + \vec{v}_{e/i} \cdot \nabla \vec{v}_{e/i} + \left[\frac{\nabla p_{e/i}}{m_{e/i} \rho_{e/i}}\right] = \frac{q_{e/i}}{m_{e/i}} \left(\vec{E} + \frac{\vec{v}_{e/i} \wedge \vec{B}_0}{c}\right) \Rightarrow \text{momentum conservation}$$

$$\nabla \cdot \vec{E} = 4\pi \rho_{e/i} \Rightarrow \text{Poisson's Equation}$$

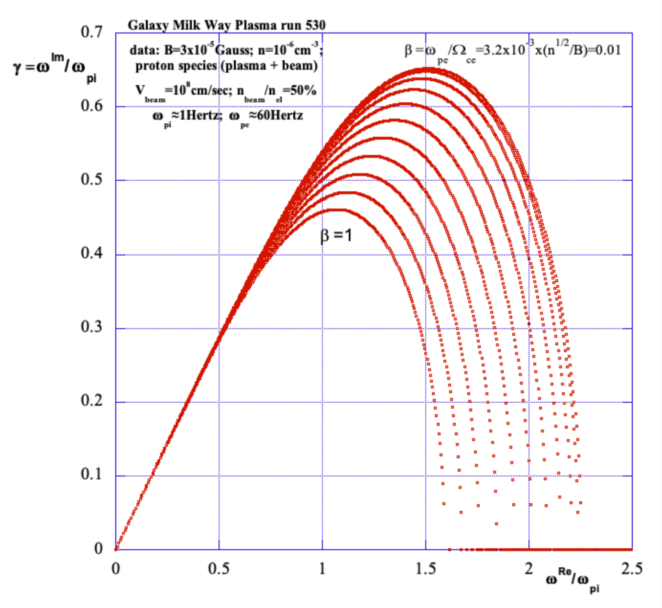
$$p_{e/i} = \kappa T_{e/i} \rho_{e/i} \Rightarrow \text{Equation of state (isothermal compression)}$$

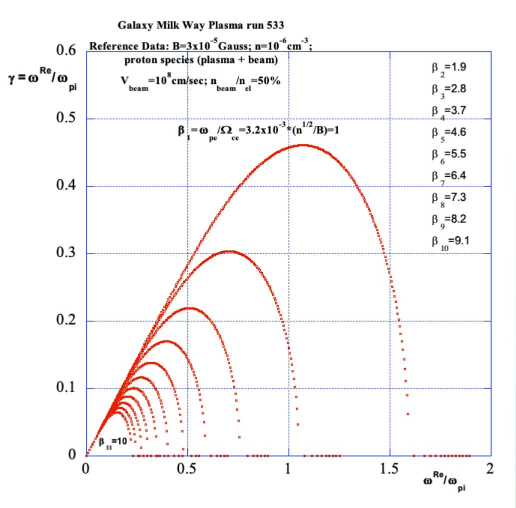
Linearization and polynomial dispersion relation in the complex domain of frequency

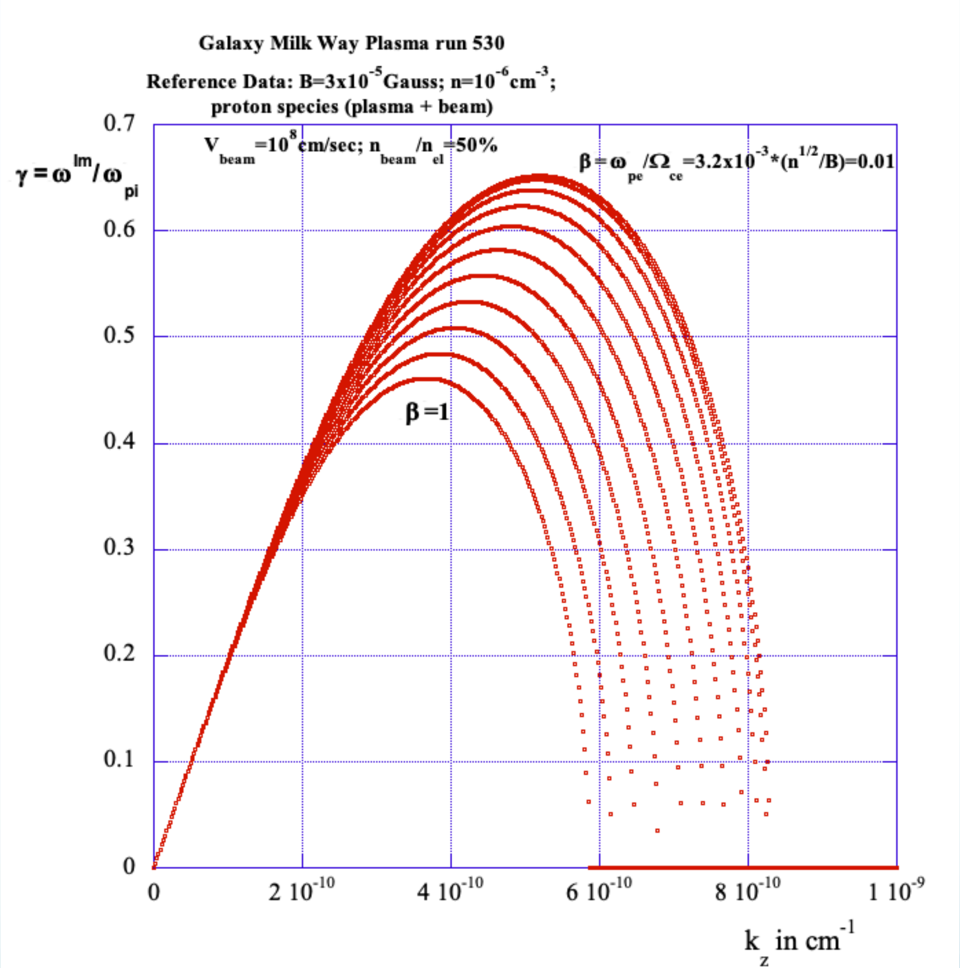
$$A_{10}\hat{\omega}^{10} + A_9\hat{\omega}^9 + A_8\hat{\omega}^8 + A_7\hat{\omega}^7 + A_6\hat{\omega}^6 + A_5\hat{\omega}^5 + A_4\hat{\omega}^4 + A_3\hat{\omega}^3 + A_2\hat{\omega}^2 + A_1\hat{\omega} + A_0 = 0$$

The A_n coefficients depend on the wavector k (parallel and perpendicular to the magnetic field, plasma density, plasma temperature and large scale magnetic field)

Numerical solution and determination of the growth rate (γ) spectrum in frequency ω and wavevector k_z (parallel to the magnetic field)







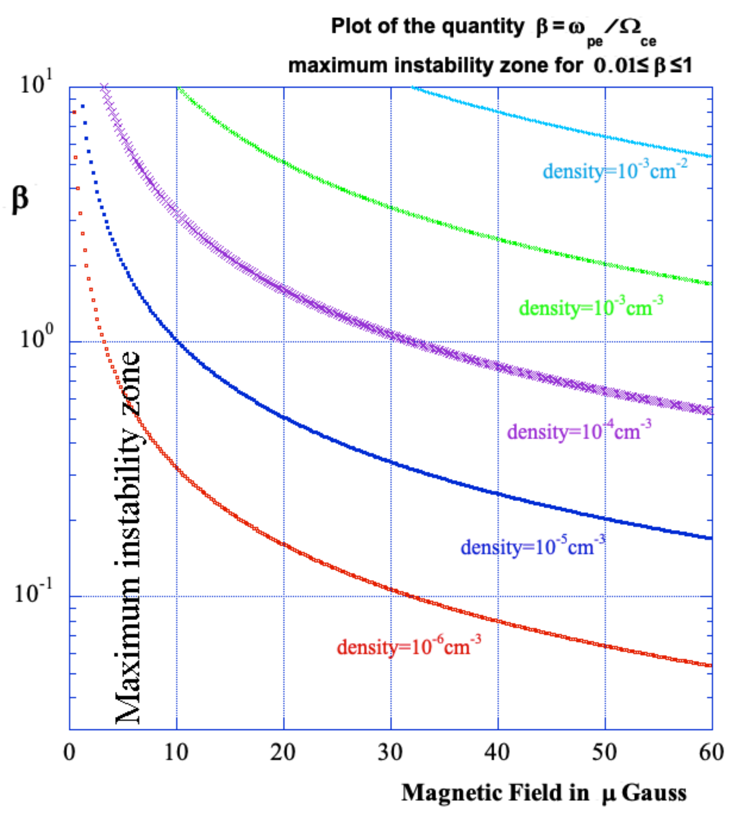
Recall: energy density of the unstable wave $E^2\left(\omega,k_z\right)=E_{thermal}^2 e^{2\gamma\left(\omega,k_z\right)t}$

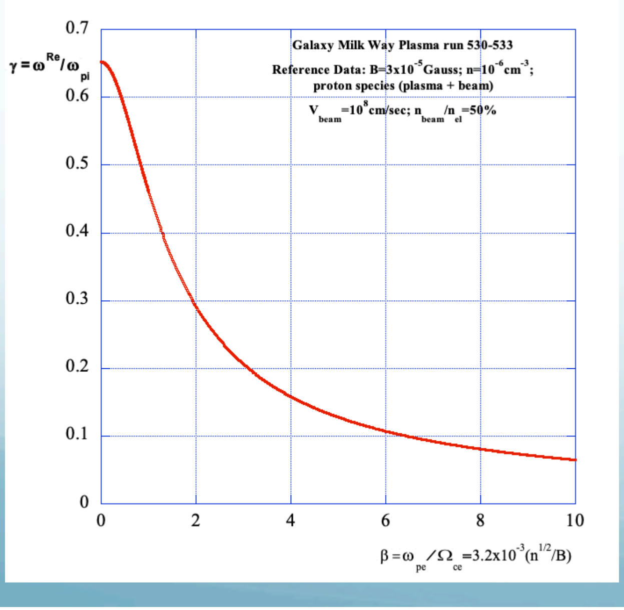
Summary of the Numerical Analysis I

- From this result we can deduce the following features:
  - ✓ The electromagnetic instability is confirmed.
  - ✓ The growing rate scales with the *noticeable parameter*

$$\beta_e = C\frac{\sqrt{n_e}}{B}$$

(*the ratio between the square root of density over the magnetic filed*). The more the β_e value decreases, the more the γ increases





Incidentally

- This noticeable parameter β_e which characterizes the plasma in milk way galaxy is very close to the β_e of the “IGNITOR” lab experiment proposed several years ago by Bruno Coppi (partially funded by the italian government but never realized) and *devoted not only to study the ignition of thermonuclear plasma but also high energy physics processes in astrophysics*

$$\beta_e\left(Ignitor\right)=0.24-0.55$$

Summary of the Numerical Analysis II

- ✓ The electromagnetic instability is confirmed to lay in the range of the LH frequencies $\omega \approx \omega_{pi}$
- ✓ The instability extends over a wide range (around the LH) of frequencies $0.1 < \frac{\omega^{\mathrm{Re}}}{\omega_{pi}} < 2.5$ and parallel wave-vector $10^{-12} cm^{-1} < k_z < 10^{-9} cm^{-1}$
- ✓ The characteristic time of the instability is t=0.1-1sec
- ✓ The saturation level (preliminary evaluation) is around γ t=50

Characteristics of the Lower Hybrid Wave I

- The Lower Hybrid Wave is an electromagnetic perturbation which propagates in a plasma medium, and it is strongly affected by the structure of the magnetic field

  - The dispersion relation is very simple $k_\perp = k_\parallel \frac{\omega_{pe}}{\omega\sqrt{\left(1+\frac{\omega_{pe}^2}{\Omega_{ce}^2}-\frac{\omega_{pi}^2}{\omega^2}\right)}}$
  - The perturbation is quasi longitudinal $\frac{E_\perp}{E_\parallel} = \frac{k_\perp}{k_\parallel} = O\left(\sqrt{\frac{m_i}{m_e}}\right)$
  - The LH frequency is in the range $\omega_{LH} \sim \omega_{pi}$
  - The wave suffers a cold resonance when $\omega = \frac{\omega_{pi}}{\sqrt{1+\frac{\omega_{pe}^2}{\Omega_{ce}^2}}}$

Characteristics of the Lower Hybrid Wave II

- Near the resonance the wave interacts with the ions, far from the resonance with the electrons
  - ✓ The interaction with electrons is a Resonant Landau Damping (in the direction parallel to the magnetic field) when the resonance condition is satisfied

$$\frac{\omega}{k_{\parallel}} \sim v_{the}$$

  - ✓ The group velocity and the energy flow is, essentially, in the parallel direction

$$\frac{v_{g\perp}}{v_{g\parallel}} = \frac{\partial\omega / \partial k_{\perp}}{\partial\omega / \partial k_{\parallel}} = O\left(\sqrt{\frac{m_e}{m_i}}\right)$$

$$\vec{S}_{Poynting} = W\vec{v}_{group} \Rightarrow W_{\text{energy-density}} = \frac{\omega}{16\pi}\frac{\partial\varepsilon_{\text{dielectric-function}}}{\partial\omega}E^2_{\text{fluctuation}}e^{2\gamma t}$$

$$\varepsilon_{\text{dielectric-function}} \approx k_{\perp}^2\left(1-\frac{\omega_{pi}^2}{\omega^2}+\frac{\omega_{pe}^2}{\Omega_{ce}^2}\right)+k_{\parallel}^2\left(1-\frac{\omega_{pe}^2}{\omega^2}-\frac{\omega_{pi}^2}{\omega^2}\right)$$

Quantitative Models to prove this Conjecture (second step)

- Fokker-Planck calculation
- The interaction between the LH wave and the thermal electrons of the Galaxy Halo is ruled by the relativistic 2D (in velocity space) Fokker-Planck equation

$$\frac{\partial f_e}{\partial t} - \sum_{species} C\left(f_e, f_{species}\right) + \nabla \cdot \vec{S}_{wave} = 0$$

$C\left(f_e, f_{species}\right)$ is the relativistic collisional operator (S.T. Beliaev and G.I. Budker, Sov. Phys. Doklady 1 (1956) 218)

Quantitative Models to prove this Conjecture (second step)

$\vec{S}_{wave}$ is the flux of electrons in velocity space due to the LH wave

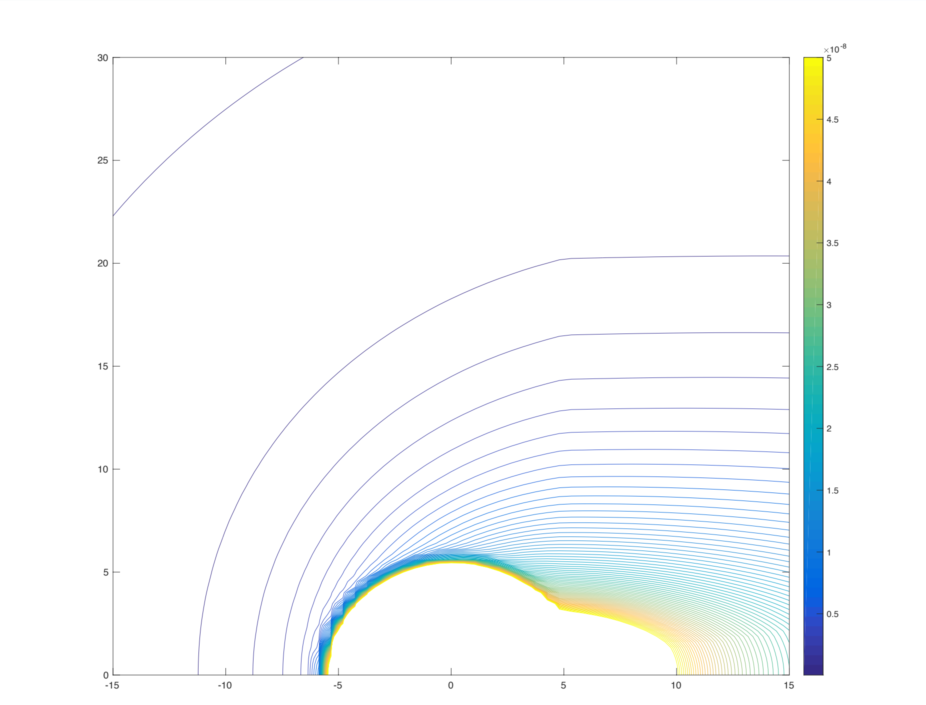
$$\vec{S}_{wave} = -\underline{\underline{D}}_{ql} \cdot \nabla f_e$$

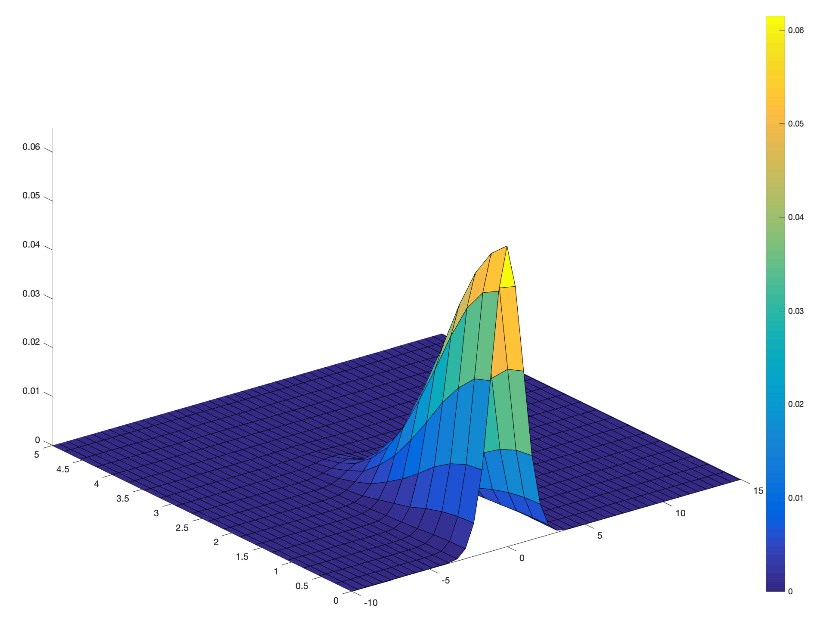
$\underline{\underline{D}}_{ql}$ is the quasilinear diffusion tensor which depends of the LH wave in plasma

$$\underline{\underline{D}}_{ql} = \frac{e^2}{m_e^2} \int \frac{d\vec{k}}{(2\pi)^3} \pi\delta\left(\omega - k_{\|}v_{\|} - n\frac{\Omega_{ce}}{\gamma_e}\right)\left(\frac{v_{\|}k_{\|}}{\omega}\right)^2 E_{\|}^2(k,\omega)\hat{v}_{\|}\hat{v}_{\|} = D\hat{v}_{\|}\hat{v}_{\|}$$

Summary of the Numerical Solution of the Fokker-Planck equation I

- The solution of the FP equation (at the steady state) can be summarized in the following plots



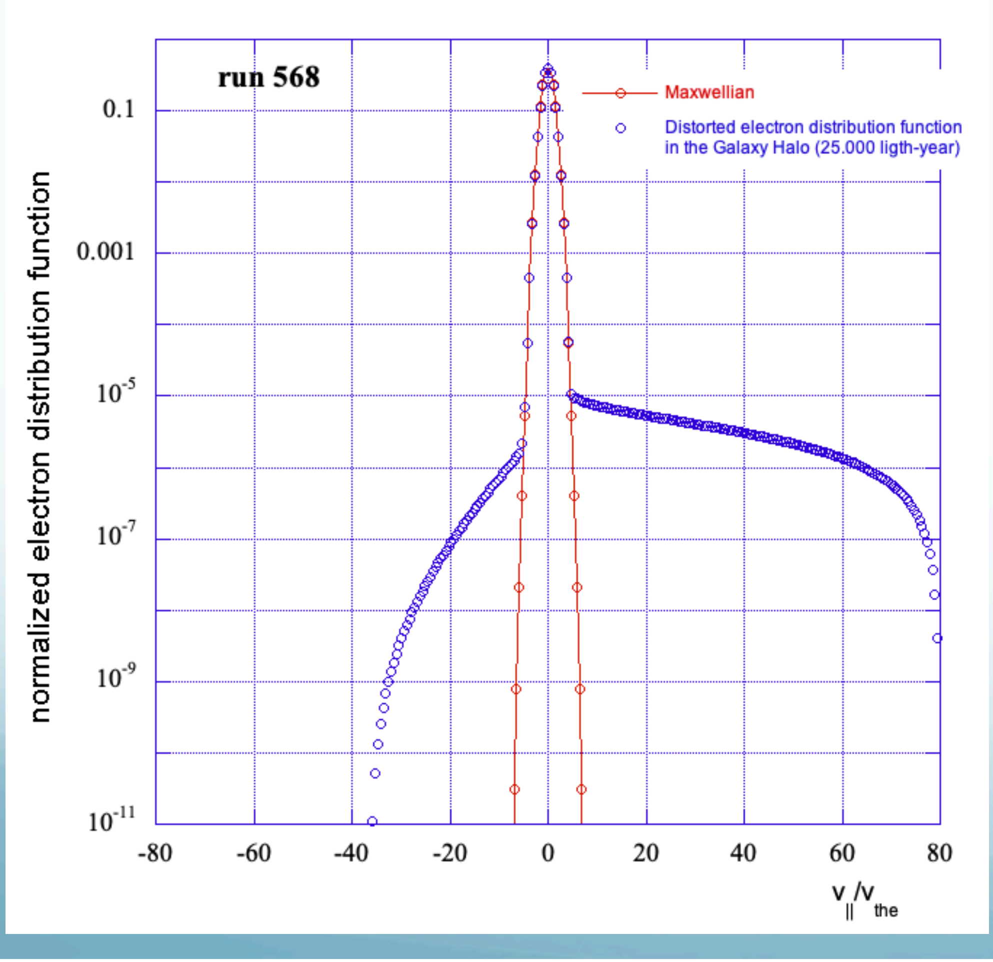


3D plot of the electron distribution function

Contour Plot of $f_e(v_{||},v_{perp})=C$

Summary of the Numerical Solution of the Fokker-Planck equation II

- An interesting plot is the distribution function f_e along the parallel phase velocity normalized to electron the thermal velocity

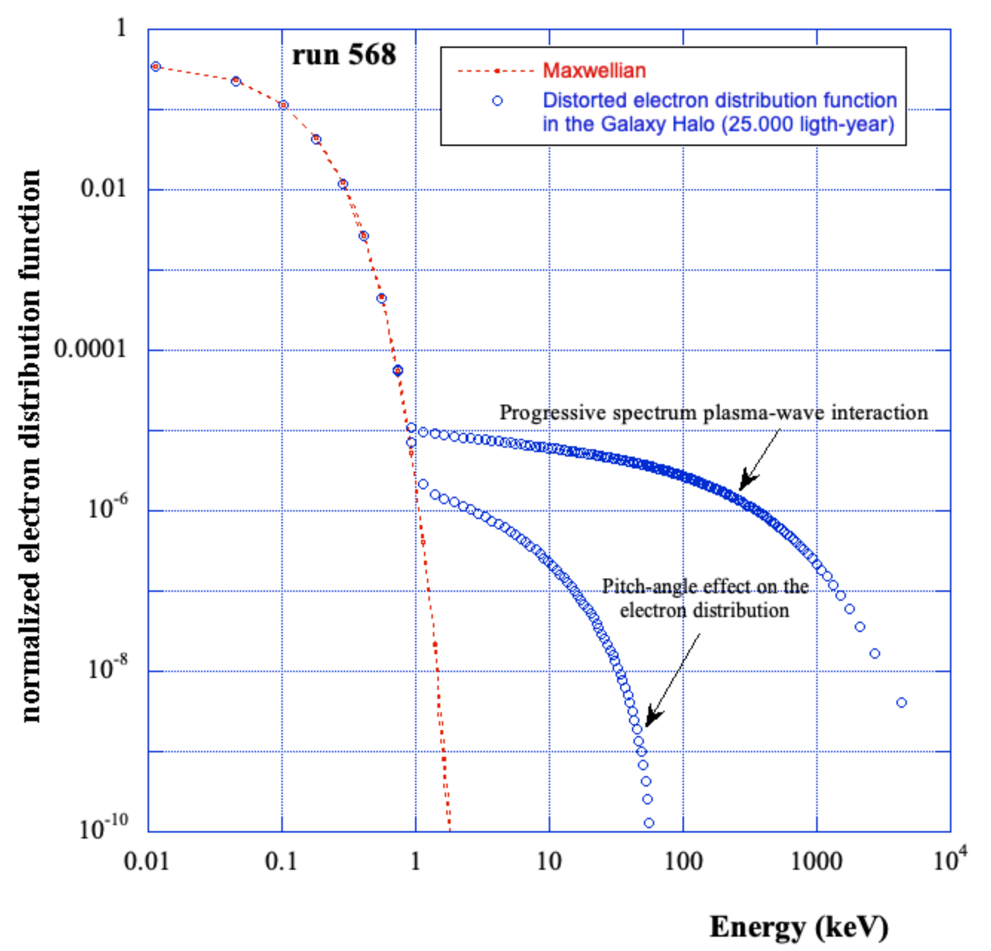


$$f_e\left(v_{\parallel}\right)=2\pi\int_0^{\infty}dv_{\perp}v_{\perp}f_e\left(v_{\parallel},v_{\perp}\right)$$

It is possible to recognize on the plot (in red) the relativistic Maxwellian

$$f_{eMax}=\frac{n_e}{4\pi m_e^2 c T_e K_2\left(\frac{m_e c^2}{T_e}\right)}e^{-\frac{m_e c^2\gamma_e}{T_e}}$$

Summary of the Numerical Solution of the Fokker-Planck equation III



A large number of the bulk electrons are accelerated at very high energy ≈10MeV and beyond up to tents of GeV

The global power density transferred from the wave to the electron is

$$P_{abs} = -2\pi \int_{-1}^{+1} d\mu \int_{-\infty}^{+\infty} \mu D \frac{\partial f_e}{\partial p_{\parallel}} \frac{p^3}{\gamma} dp$$

The global power in erg/sec is

$$P_{tot} = 4\pi \int_{0}^{R} P_{abs} e^{-\left(\frac{R-R_c}{\sigma}\right)^2} R^2 \, dR \sim 2.7\times 10^{35} \frac{erg}{s}$$

Very close to the power carried by the jets (4x10^37 erg/s)

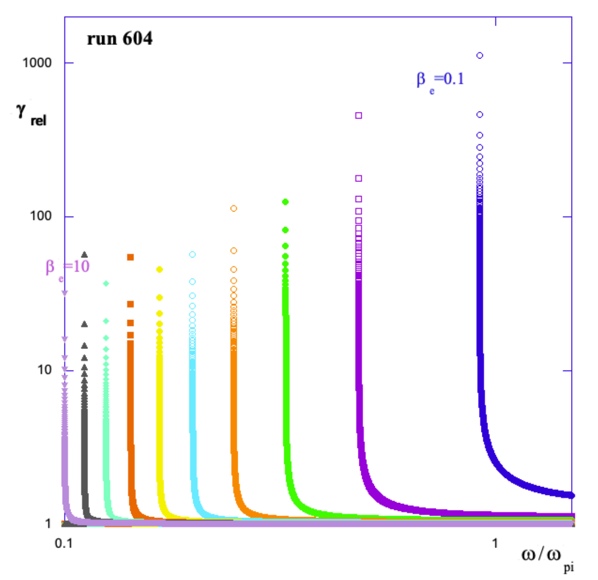
This model could explain the cutoff in the energy spectrum above 100GeV?

- The Lower Hybrid Wave interaction with the bulk electrons, in fact, has a cutoff for

$$k_z\left(cutoff\right)=\frac{\omega_{pi}}{c}\sqrt{\left(1+\beta_e^2\right)\hat{\omega}^2-1}$$

In terms of energy we have, the relativistic gamma is

$$E_{cutoff}=m_{0e}c^2\left[\frac{1}{\sqrt{1-\frac{\hat{\omega}^2}{\left(1+\beta_e^2\right)\hat{\omega}^2-1}}}-1\right]$$



Preliminary evaluation of the emission

- Electrons with energy

$$E = 51 \times \gamma_{rel} MeV$$

- Emits most of their synchrotron power near the critical frequency

$$\upsilon_{crit} \approx \frac{\gamma_{rel}^{2} \Omega_{ce}}{2\pi} \sim 84 \times \gamma_{rel}^{2}$$

- The calculated γ_{rel} are of the order 10^3
- *The critical frequency is too low for gamma emitters!! Via Synchrotron radiation*
- *Evaluation of the inverse Compton scattering (V. Vittorini INAF) under investigation*

Conclusions

- On the basis of astrophysical observation we have proposed the following explanation for the “Fermi Bubbles” in the Milk Way Galaxy

  - Jets of plasma (hadronic and leptonic matter from the center of the galaxy acts like a beam in presence of low density plasma surrounding the Milk Way Galaxy, permeated by a very low static magnetic field

  - These beams can induce in the halo galaxy plasma an electromagnetic instability, which triggers waves in the Lower Hybrid Frequency domain.
    - To this end a Fluid model of the plasma has been proposed that leads to establish the characteristic of the wave triggered by the instability and to prove that in the halo of the galaxy plasma can be really excited a Lower hybrid wave with a spectral distribution of the growth rate.

  - The waves can interacts efficiently with the electrons of the plasma by accelerating them at energies of the order of GeV
    - To this end a study based on the Kinetic Relativistic Fokker-Planck equation with a diffusion quasi-linear term and a relativistic collision operator has been successfully applied and an evaluation of the accelerated population can be accounted.

  - An evaluation of the emission mechanism which can rely on the synchrotron emission or on the inverse Compton scattering is under consideration

Bibliography

- A. Cardinali, B. Coppi, 60th Annual Meeting of the APS Division of Plasma Physics, 63, 11 2018, Portland, Oregon, USA.
- A. Cardinali, B. Coppi, 61st Annual Meeting of the APS Division of Plasma Physics, 64, 11 2019, Fort Lauderdale, Florida, USA.
- V. Ricci, A. Cardinali, B. Coppi, Sherwood Theory Fusion Conference, Princeton (USA), 2019.
- A. Cardinali, Seminario INAF-IAPS 5th Feb. 2021

Collision frequency electron-ion and electron-electron

$$\nu_{e/e} = 2.9\times10^{-6}\frac{n_e}{T_e^{3/2}}\ln\Lambda = 2.9\times10^{-12}\frac{35,3}{(80)^{3/2}} = 1.4\times10^{-13}\,Hz$$

$$\tau_{e/e} = 0.7\times10^{13}s \approx 222.000 anni$$

$$\ln\Lambda = 24 - \ln\left(\frac{\sqrt{n}}{T_e}\right) = 24 - \ln\left(\frac{10^{-4}}{8}\right) = 24 + 11,3 = 35,3$$

$$\nu_{e/i} = 4.8\times10^{-8}\frac{n_e}{T_i^{3/2}}\ln\Lambda = 4.8\times10^{-14}\frac{35,3}{(80)^{3/2}} = 0.24\times10^{-14}\,Hz$$

$$\tau_{e/i} = 4.1\times10^{14}s \approx 12.700.000 anni$$