DM and Baryogenesis as two sides of the same coin

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1. Two (naively unrelated) problems: DM and Baryogenesis.

- "Naive" Moral: Dark matter requires New (unknown) Fields
- New Fields must be Nonbaryonic: Arguments come from structure formation requirements, BBN, decoupling DM from radiation, etc
- This proposal: Instead of ``New Fields'' → "New phases" (colour superconductor) of ``Old Fields (quarks and gluons)''
- Instead of "Baryogenesis" → "separation of charges" of conventional fields (quarks and gluons).

- Strong CP problem has been with us for > 30 years. We still do not have a better resolution of this problem than axion.

- Therefore, I assume that the QCD axion exists.

- It does not imply that entire DM is represented by the axions (free particles of BEC). Part of the energy from the original $\theta \sim 1$ can be realized in a different form ....

- It relaxes conventional constraints on the axion mass (coupling constant)

- We propose that on the global level the Universe is symmetric. The separation of baryon charges is originated at the QCD scale. Some charges are locked in form of large dense quark matter nuggets (and anti-nuggets), similar to Witten's strangelets.

- The nuggets remain stable over cosmological timescales and serve as DM.

- Mechanisms of formation and properties of quark nuggets (in colour superconducting phase) and Witten's strangelets are very different.

- We take the advantage of strong CP violation resulting from $\theta \neq 0$ during the QCD phase transition. This source of CP violation is not available anymore today.

- Strong CP violation in QCD: from a "fundamental problem" it becomes a "fundamental key element" in resolution of "matter-antimatter asymmetry puzzle" in our universe.

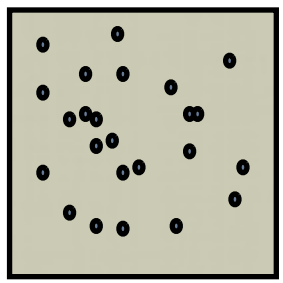
Matter in the Universe

A model which explains both the matter-antimatter asymmetry and the observed ratio of visible matter to DM

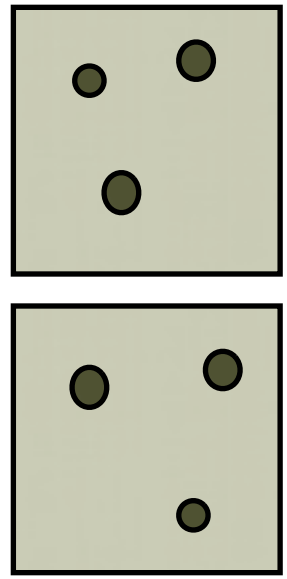
$$B_{tot} = 0 = B_{nugget} + B_{visible} - \bar{B}_{antinugget}$$

$$B_{DM} = B_{nugget} + \bar{B}_{antinugget} \simeq 5\ B_{visible}$$

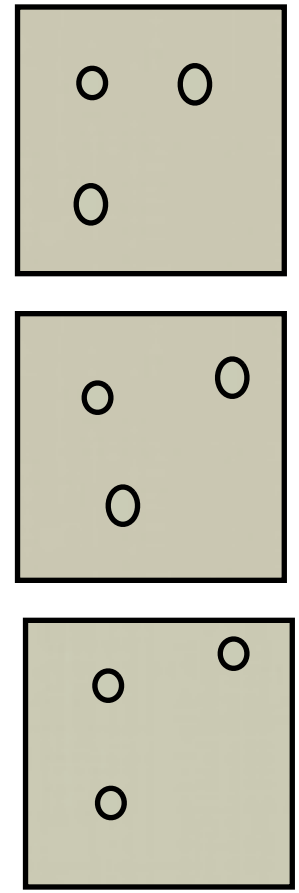
The ratio $B_{nugget}/\bar{B}_{antinaget} \simeq 2/3$ *is determined by CP violating parameter* $\theta \sim 1$



One part: visible matter



Two parts: matter nuggets



Three parts: anti-matter nuggets

- Excess of antimatter is locked away in anti-quark nuggets requiring no fundamental baryon asymmetry to explain the observed matter/antimatter asymmetry.

- The nuggets have a large binding energy (~100 MeV) such that large baryon charge in the nuggets is not available to participate in BBN at T~MeV.

- If the nuggets are sufficiently massive the observational consequences of these objects will be suppressed by small number density

- A small geometrical factor replaces a weak coupling constant for large nuggets

$$\epsilon \sim S/V \sim B^{-1/3} << 1$$

$$B \sim 10^{25}, \quad R \sim 10^{-5}\ cm, \quad M \sim 10\ g$$

(to be compared with the axion correlation length $m_a^{-1} \sim 10^{-5} cm$)

2. Observational Cosmological Puzzles

(naively unrelated story)

- Several independent observations of the galactic core suggest unexplained sources of energy:

- The most known case is the 511 keV line (INTEGRAL) which has proven very difficult to explain with conventional astrophysical positron sources.

- A similar, but less known mystery is the excess of gamma-ray photons detected by COMPTEL across a broad energy range 1-20 MeV. Such photons have been found to be very difficult to produce via known astrophysical sources

- Detection by the CHANDRA satellite of diffuse X-ray emission from across the galactic bulge provides a puzzling picture: after subtracting known X-ray sources one finds a residual diffuse thermal X-ray emission consistent with very hot plasma (T= 10 keV). Source of energy fuelling this plasma is a mystery.

- The WMAP experiment has revealed an excess of microwave emission, $23 < w < 61$ GHz from the center of our Galaxy. This excess, which is uncorrelated to the known foregrounds, is known as the ``WMAP haze".

- Recent measurements by the arcade2 experiment unambiguously show an excess in the isotropic radio background at frequencies below the GHz scale.

- Origin of these excesses remains a mystery as all conventional sources for these diffuse emissions are not capable to describe the observations.

3. Immediate (generic) consequences:

- If DM is originated from the QCD scale the relation $\Omega_{DM} \sim \Omega_B$ may come naturally as both contributions are originated from the same QCD physics.

- The DM nuggets made of quarks/antiquarks do interact with visible matter. However, the interaction is strongly suppressed: a small geometrical factor $\sigma/M \simeq 10^{-10}\mathrm{cm}^2/\mathrm{g}$ replaces the standard requirement for the coupling constant to be weak. It is well below typical cosmological limits

$$\sigma/M \leq 1\mathrm{cm}^2/\mathrm{g}$$

- All effects are proportional to a single unknown parameter computed along the line of sight

$$B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$$

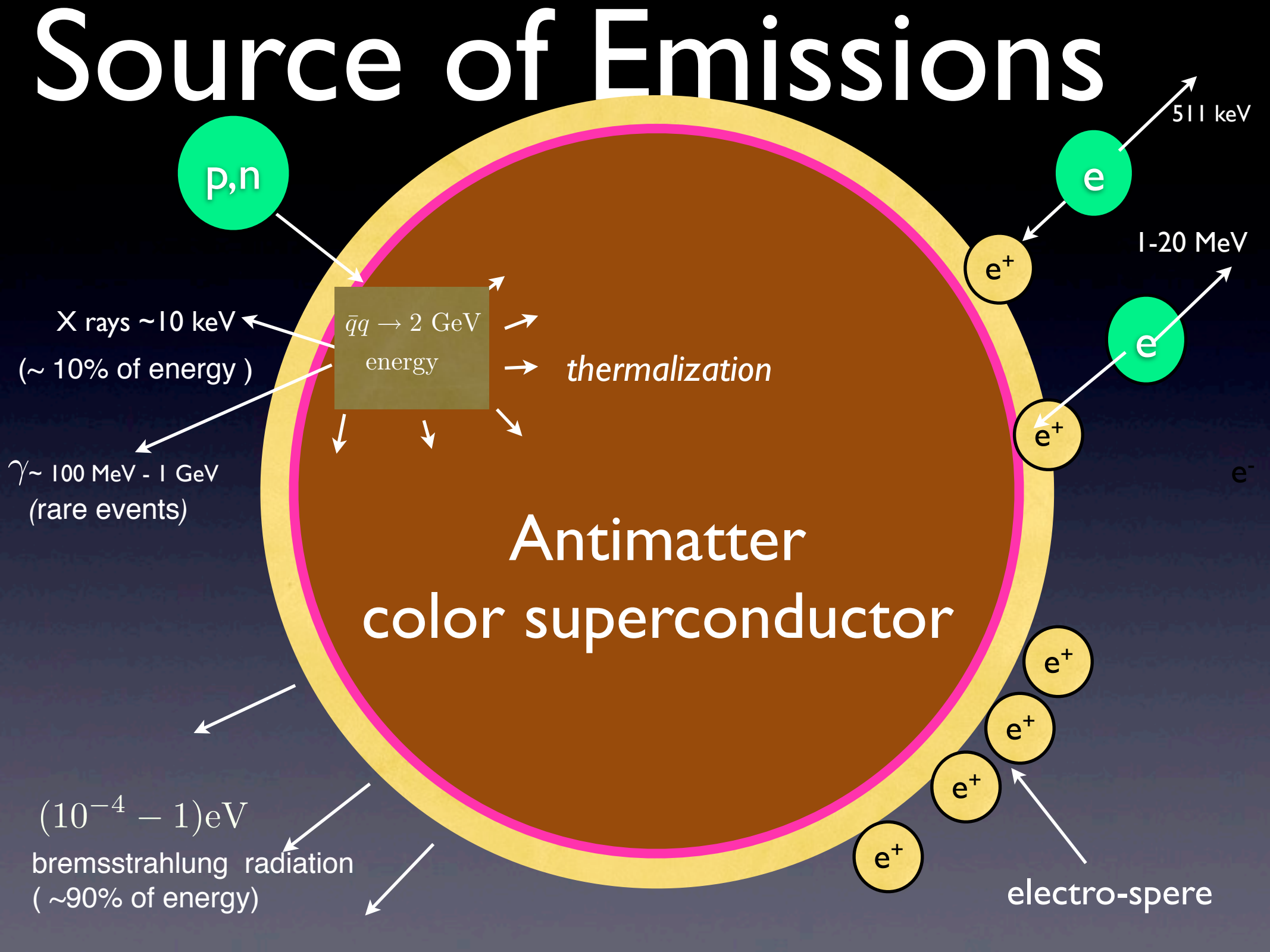
- Standard tight constraint on antimatter presence in our universe does not apply here as it does not radiate/ annihilate as conventional matter.

- Rare events of annihilation of the visible matter with antimatter nuggets provide an excess of radiation which apparently have been observed in different frequency bands: 511 keV, 1-20 MeV, X -rays, microwaves (WMAP haze),....

- on large scales, the nuggets behave as standard collisionless cold dark matter. However: some modifications are expected in dense regions (galaxies), where DM does interact strongly with visible matter.

- The idea of the charge separation during the QCD phase transition at $\theta \neq 0$ (the key element of the proposal) can be tested at RHIC and LHC. Recent Experimental results (STAR, ALICE collaborations) support charge separation effect (local P, CP violation in heavy ion collisions has been observed).

Source of Emissions



Relevant Literature
(galactic / cosmological excess emissions)

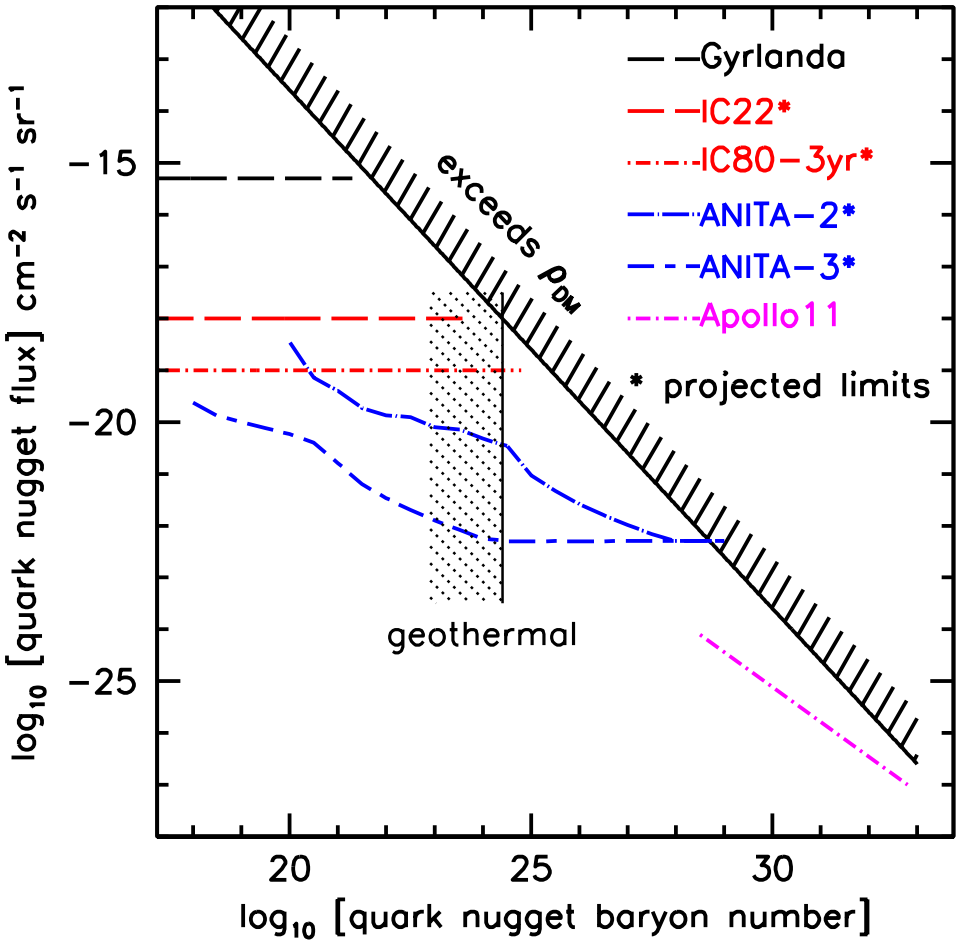
- DM-Baryogenesis — JCAP 2003; PRD. 2005
- 511 keV line (INTEGRAL) — PRL. 2005
- 1-20 MeV excess (COMPTEL) — JCAP 2008; PRD. 2010
- X-ray emission (CHANDRA) — JCAP 2008
- 23 < w < 61 GHz (WMAP haze) — PRD. 2008
- w< 1 GHz (ARCADE 2) — arXiv 1210.2400

Recent development. Prospects for ground based (suborbital) detection.

- K.Lawson, PRD 83 (2011), 103520
- P. Gorham, PRD 86 (2012), 123005
- K.Lawson, arxiv 1208.0042
- Expected flux at the earth's surface

$$\frac{dN}{dA\,dt} = nv \approx \left(\frac{10^{25}}{B}\right) km^{-2} yr^{-1}$$

- This flux is well below the sensitivity of any conventional WIMP DM searches. The flux of nuggets is similar to that of cosmic rays near GZK limit (see Lawson's talk on Auger for the details).



Plot from P. Gorham, PRD 86 (2012) 123005

Existing and projected limits on anti-quark nugget fluxes

CONCLUSION (detection prospects):

1. *Radio emission of anti-quark nuggets with* $B = 10^{24} - 10^{28}$ *can be studied by balloon -borne instruments such as ANITA.*
2. *Analysis of existing ANITA-2 data for these event signatures has begun, and results may be expected within the next year.*

Conclusion

- " Non- baryonic Dark matter" could be ordinary baryonic matter which is not in the ``normal hadronic phase", but rather, in the exotic colour superconducting phase.

- In this phase the baryon charge is not available for BB Nucleosynthesis

- A small geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces a weak coupling const.

- Conventional killing problem (for most models) of insufficient CP violation is automatically resolved here: CP violation is large at the QCD phase transition; it diminishes by now as a result of the axion dynamics.

- All effects are proportional to one and the same asymmetric normalization factor (which is a single unknown parameter in the entire framework).

$$B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$$

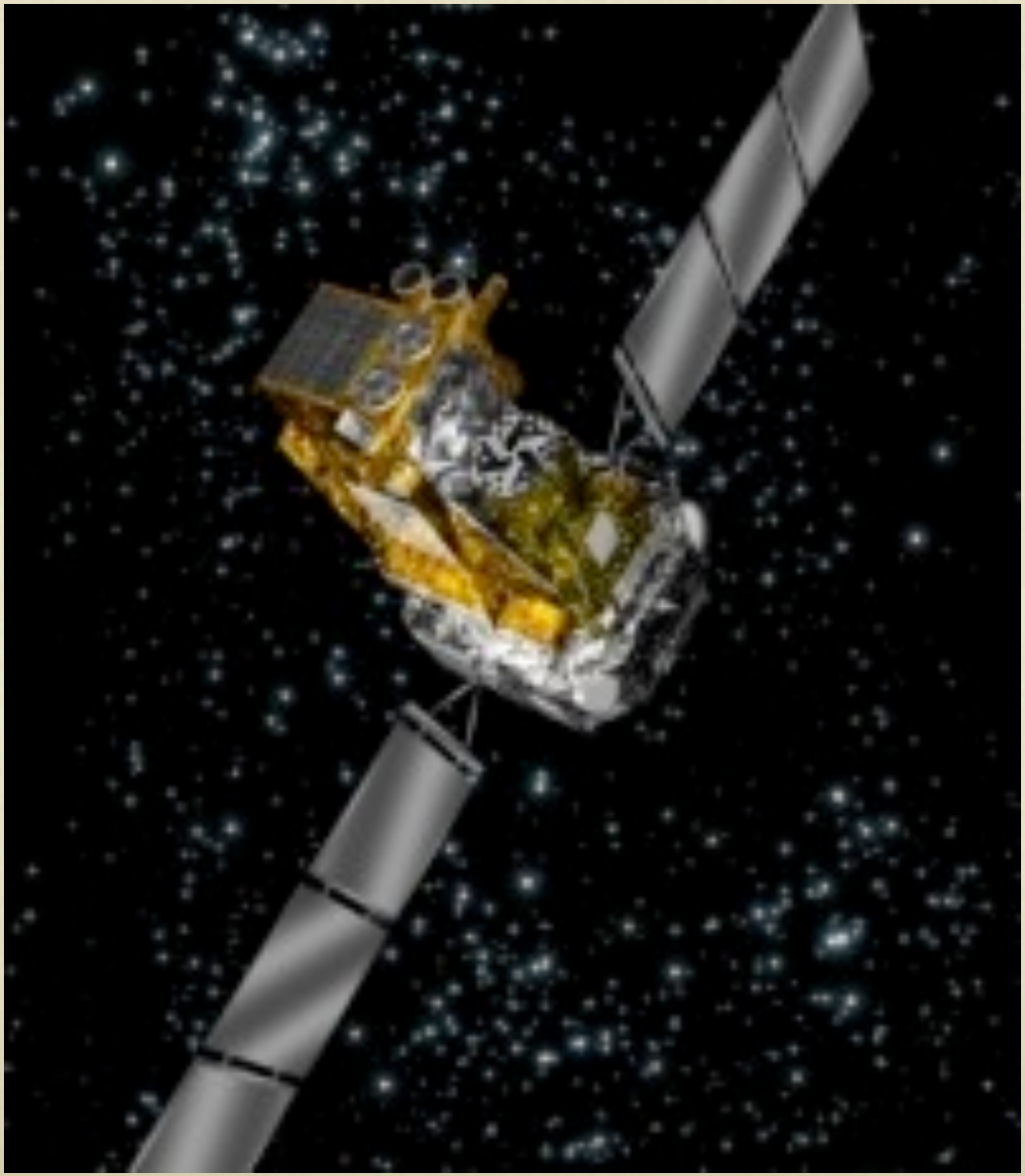
- This is very different (e.g. morphologically) from conventional DM models where effect is proportional to

$$\int dr \rho_{DM}^2(r) \text{ (annihilating DM) } \textit{ or } \int dr \rho_{DM}(r) \text{ (decaying DM)}$$

- All relative intensities are fixed by conventional physics. It covers 11 orders of magnitude:

$\omega \sim 10^{-4}$ eV for WMAP haze *to* $\omega \sim 10$ MeV for COMPTEL

4. SPI / INTEGRAL
the 511 keV line from Galactic Center



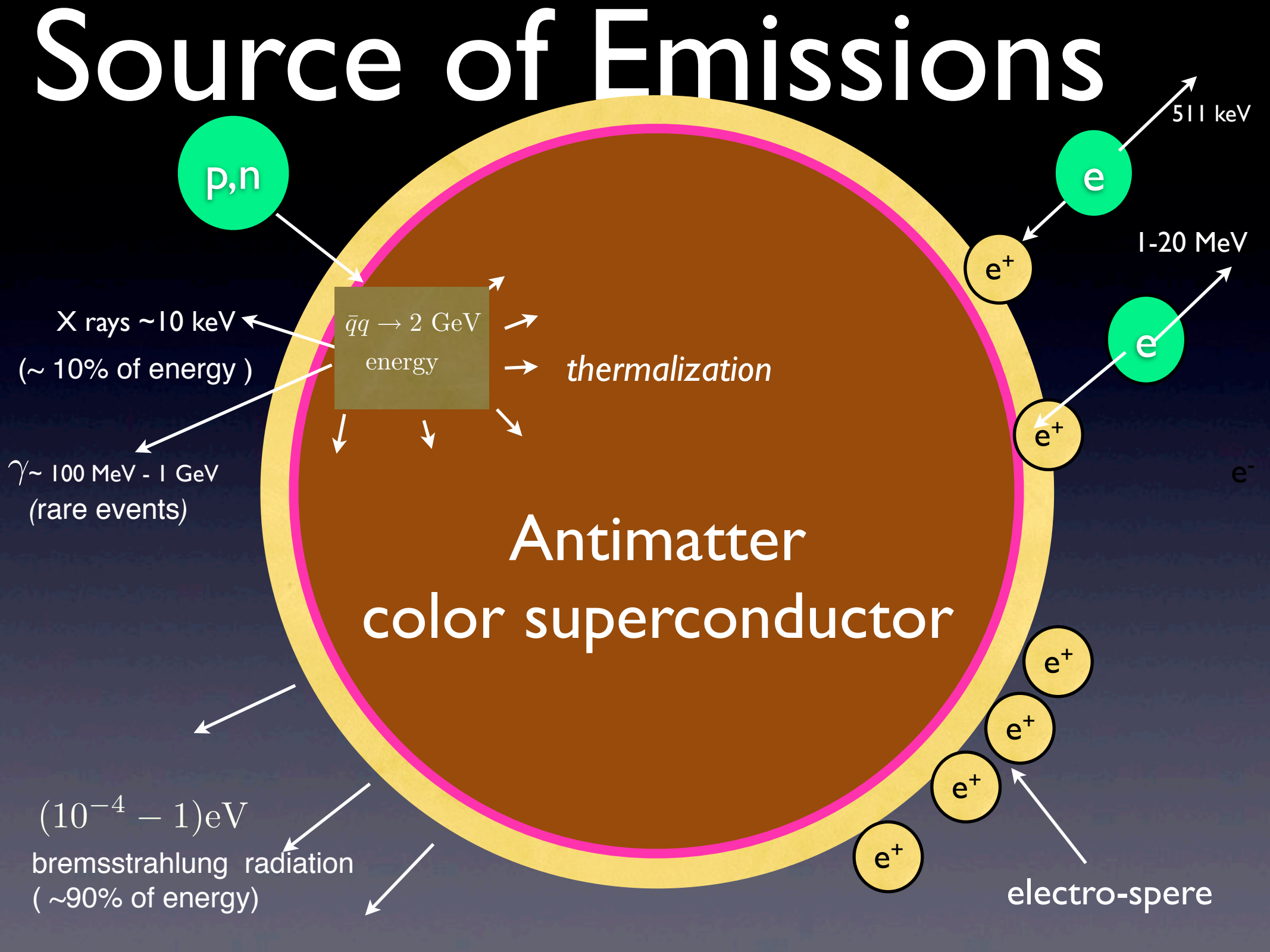
THE 511 KEV LINE FROM GC.

- SPI/INTEGRAL OBSERVES 511~KEV PHOTONS FROM POSITRONIUM DECAY FROM THE GALACTIC CENTER WHICH IS DIFFICULT TO EXPLAIN WITH CONVENTIONAL ASTROPHYSICAL POSITRON SOURCES.

- WE PROPOSE THAT THE 511KEV LINE WITH $\Gamma \sim 3\ keV$ CAN BE NATURALLY EXPLAINED BY THE NUGGETS OF DARK ANTIMATTER.

- ALL INGREDIENTS ARE PRESENT IN THIS SCENARIO: THE DM DROPLETS CARRY POSITRONS IN THE BULK; THE RELEVANT CROSS SECTION FOR THE ELECTRON FALLING TO THE DM DROPLET IS THE GEOMETRICAL SIZE OF THE OBJECT; A QUARTER OF THE POSITRONIUM RELEASE BACK-TO-BACK 511 PHOTONS.

Source of Emissions



- The probability per unit time that collision happens in the presence of a single nugget is given by $\frac{dW}{dt} = 4\pi R^2 n_{e^-} v$
- The probability of such events per unit volume per unit time is

$$\frac{dW}{dV\,dt} \simeq 4\pi R^2 n_{e^-}(r) \cdot v \cdot \overline{n}_{DM}(r) \simeq \frac{4\pi R^2}{B} \cdot v \cdot (\frac{\rho_{visible}}{1GeV}) \cdot (\frac{3/5\rho_{DM}}{1GeV})$$

- The total flux of photons resulting from annihilation is obtained by integrating over the line of sight and over the whole solid angle of observation , $\Phi = \int dr \int_{\Delta\Omega} d\Omega \frac{dW}{dV\,dt} \sim B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$
- The prediction is sensitive to the product of dark and visible matter distribution along the line of sight (it is not symmetric as predicted by all conventional DM models. Intensity in this proposal is proportional to the visible component as well) $\int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$
- The observed width $\Gamma \sim m_e \alpha \sim 3\ KeV$ is determined by known atomic physics (resonance positronium formation at $v/c \sim \alpha$)

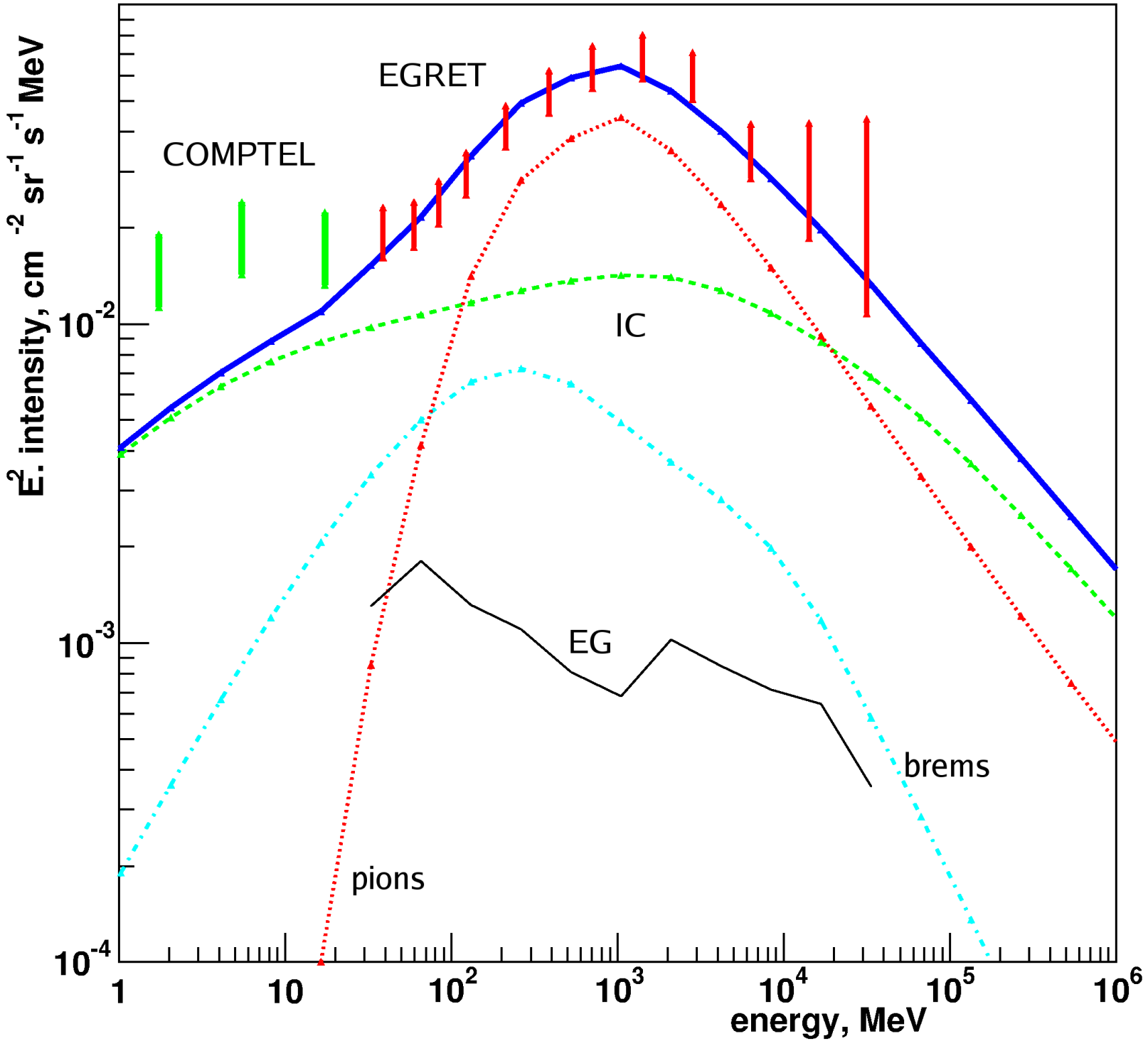
5. Excess of diffuse gamma-rays in 1-20 MeV band. Observations.

- The flux of gamma rays in the 1-20~ MeV range measured by COMPTEL represents yet another mystery.

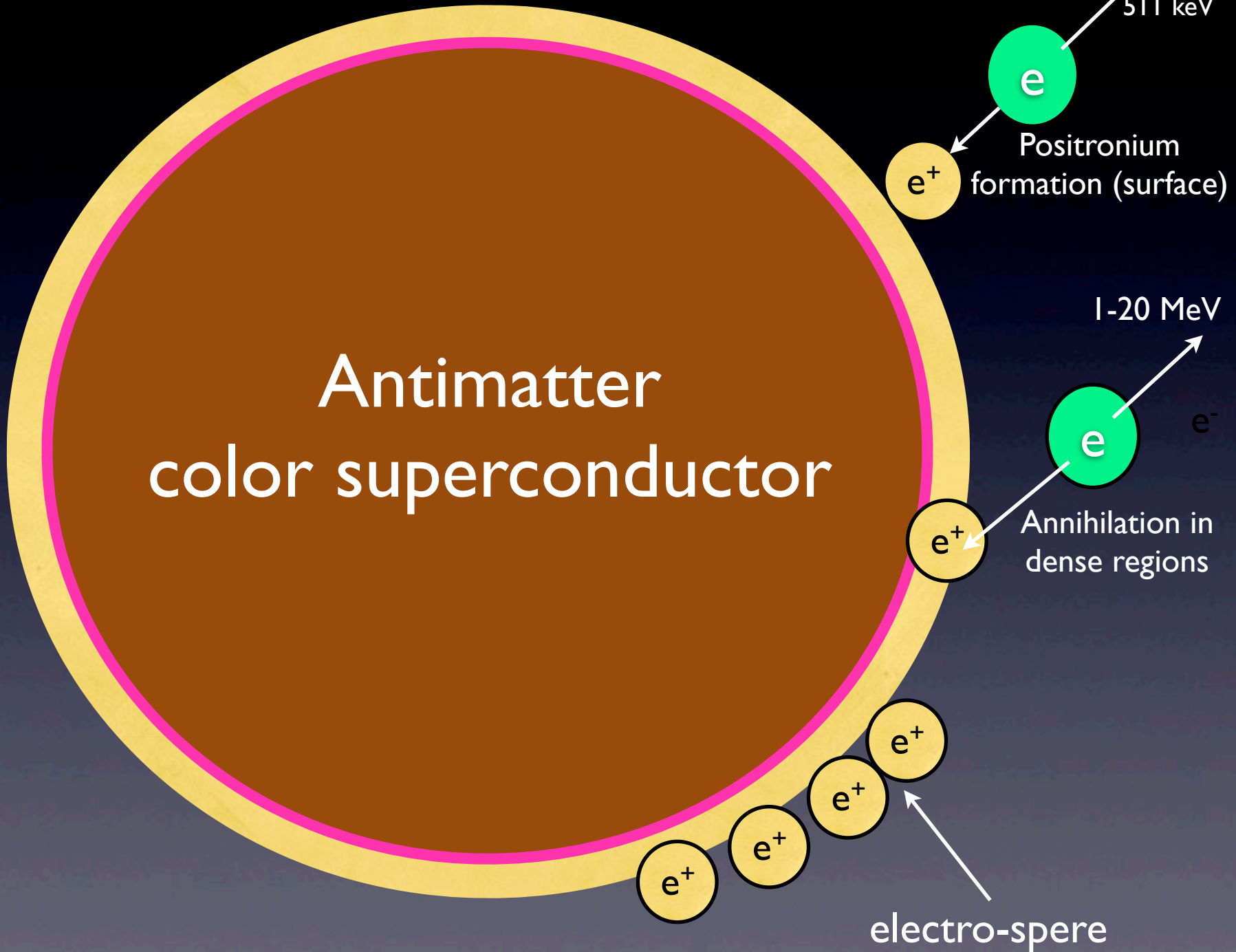
- The models (of cosmic rays) for diffuse galactic gamma rays fit the observed spectrum well for a very broad range of energies, 20 MeV- 100 GeV. The models typically also give a good representation of the latitude and the longitudinal distributions. However, the models fail to explain the excess in the 1-20 MeV range observed by COMPTEL.

- Some additional gamma ray sources are required to explain this excess in the 1-20 MeV range (Strong et al, 2004). These data suggest the existence of an energy source beyond currently established astrophysical phenomenon.

- The observed spectrum is extremely difficult to explain by known astrophysical mechanisms.


EGRET
COMPTEL
IC
EG
brems
pions
E^2. intensity, cm $^{-2}$ sr $^{-1}$ s $^{-1}$ MeV
10^{-2}
10^{-3}
10^{-4}
1
10
10^2
10^3
10^4
10^5
10^6
energy, MeV

Source of Emissions



6. Excess of diffuse gamma-rays in 1-20 MeV band. Proposal.

- Non-resonance direct annihilation would produce a broad spectrum at 1~20 MeV which we identify with the excess observed by COMPTEL.This continuum emission must always accompany the 511 keV line and the two must be spatially correlated (prediction).

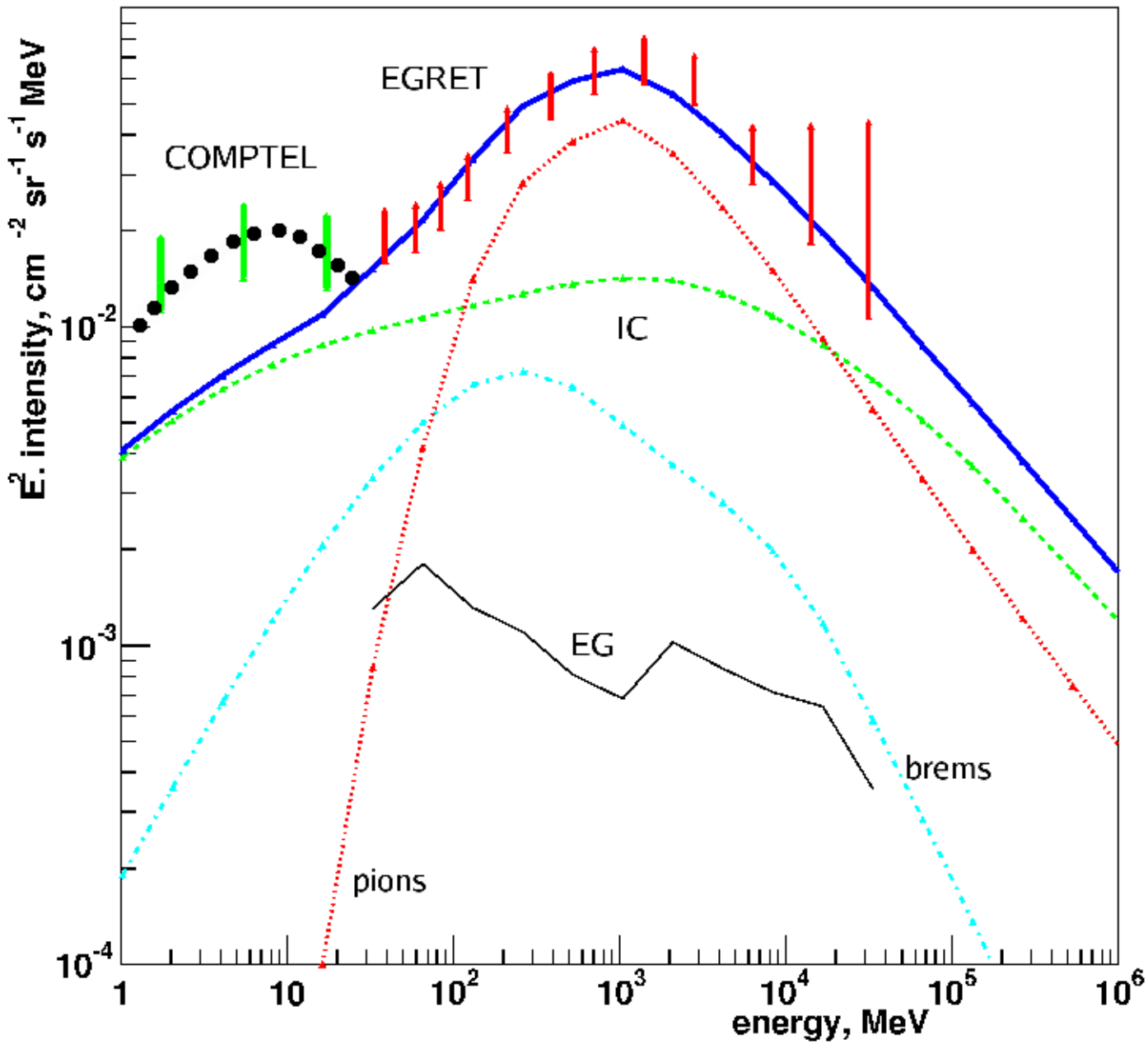
- The typical energy scale is not introduced as a free parameter but fixed by the value of the lepton chemical potential ~20 MeV (was calculated long ago for the quark matter). It is precisely where an excess of diffuse gamma rays is observed by COMPTEL.

- No new parameters are required to explain the excess in the 1-20~ MeV range -- the normalization and spectrum are fixed by 511 keV flux and known QED physics.

Excess of diffuse gamma-rays in 1-20 MeV band. Continuation.

- If spatial correlations between 511 keV line and excess of the diffuse gamma -ray emission in 1-20 MeV range is confirmed, this would unambiguously imply that the positrons are hidden in some form of antimatter nuggets as both emissions are originated from $e^+e^- \to 2\gamma$ annihilation but there is very tight constraints on free energetic few MeV positrons.

- The relative ratio of 1-20~ MeV photons and 511 keV line is very sensitive to the profile function of electro-sphere. It was computed using a Thomas-Fermi approximation. There are NO free parameters in computations.


EGRET
COMPTEL
IC
EG
brems
pions
E². intensity, cm ⁻² sr⁻¹ s⁻¹ MeV
energy, MeV
10⁻²
10⁻³
10⁻⁴
1
10
10²
10³
10⁴
10⁵
10⁶

7. X-rays from the Core of our Galaxy. Observations by CHANDRA

- A recent analysis of the CHANDRA image of the galactic center finds that the intensity of the diffuse X ray emission (after subtracting known X-ray sources)well described by a hot 8~ keV plasma with surface brightness [Muno et al 2004]:

$$\Phi_T = (1.8 - 3.1) \times 10^{-6} \frac{\mathrm{erg}}{\mathrm{cm}^2 \ \mathrm{s} \ \mathrm{sr}}$$

- The energy required to sustain such plasma corresponds to the entire kinetic energy of one supernova every 3000 yr, which is unreasonably high. Also: it would be too hot to be bound to the Galactic center.

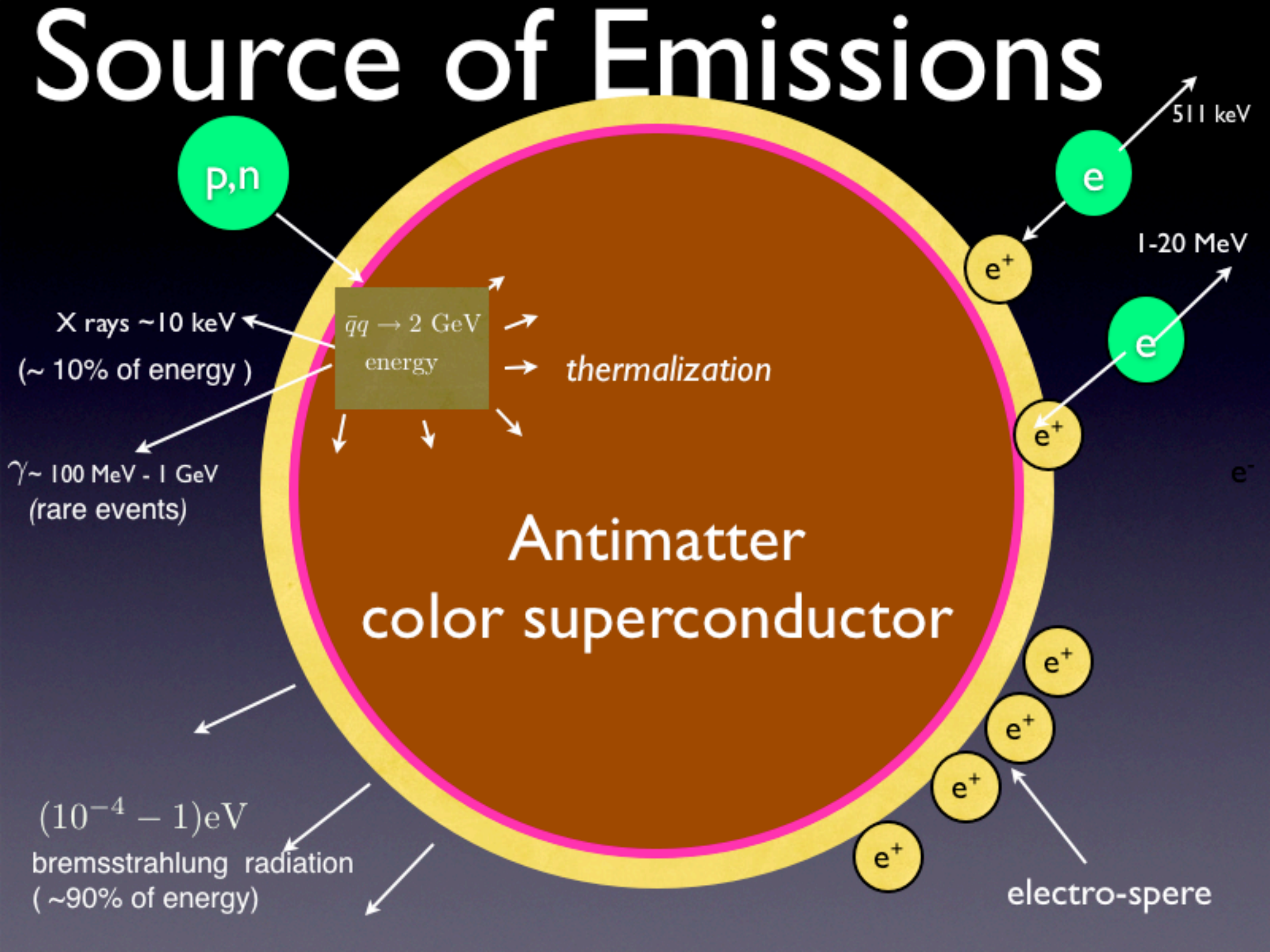
- Source of energy fuelling this plasma is a mystery.

- Could the Missing Energy be due to annihilation with ``Dark Antimatter''?

- Proposal.
  antimatter nuggets provide a single annihilation target for both: electrons and protons/neutrons.
  As a result, both the 511~keV emission from electron annihilation and the thermal X-ray emission from proton annihilation should originate from the same regions of space with the same normalization factor

$$B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$$

Source of Emissions



8. X-rays . Proposal. Details.

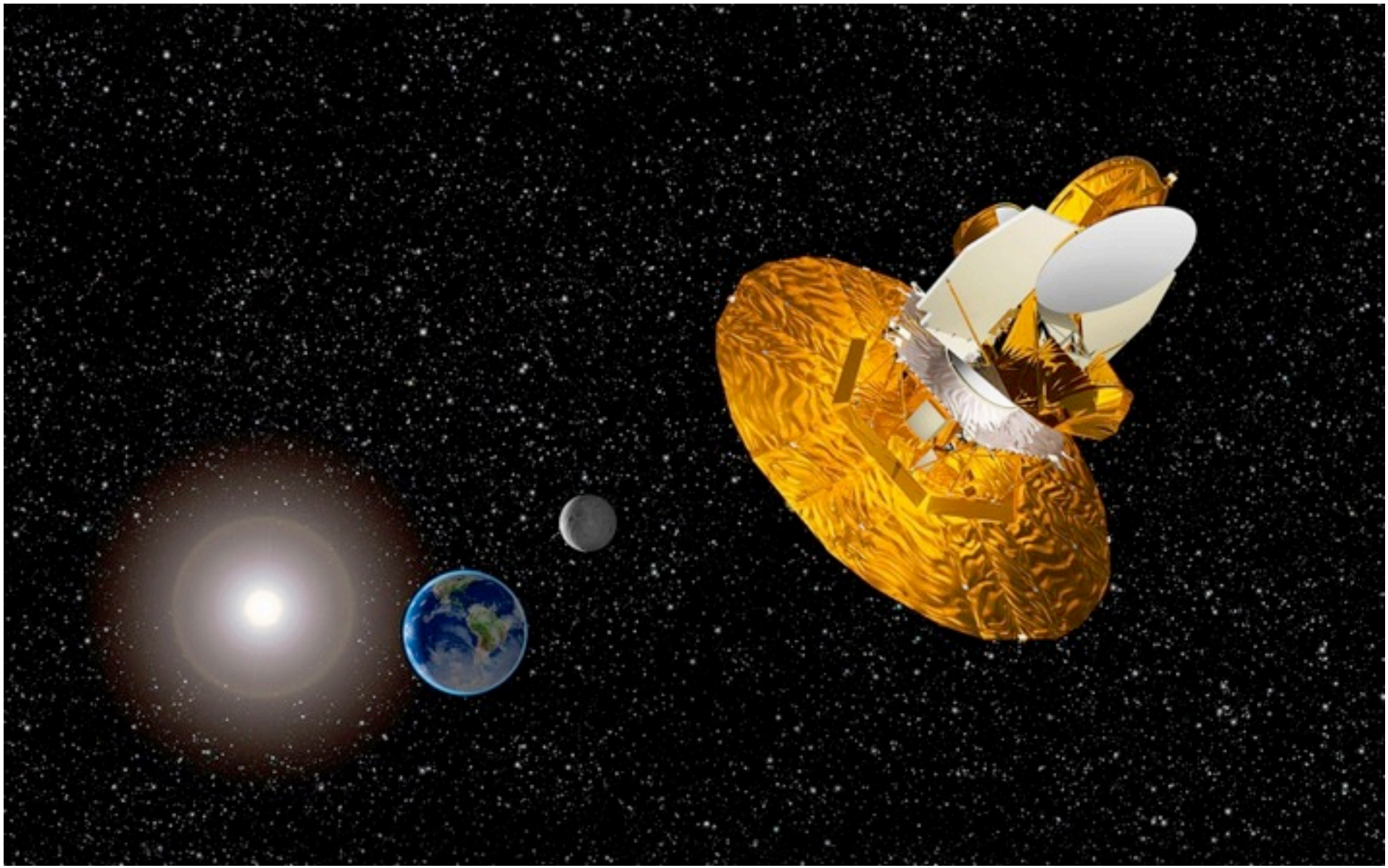
- Proton annihilation rate is directly related to that of electrons. It gives a testable prediction between 511 KeV line and diffuse hot 8 KeV X ray emission.

- Our proposal naturally accommodate the observed flux with normalization to 511 KeV line.

- Proton annihilation events will release about 2 GeV of energy per event. This occurs inside the nuggets, and the energy will be quickly transfered to leptons (positrons).

- The nuggets will radiate the energy in form of X-rays and thermal (eV) radiation. These two very different emissions must be correlated.

9. WMAP haze. Observations.



- WMAP has detected an excess of GHz microwave radiation -- dubbed the ``WMAP- haze'' -- from the inner (20 degrees) core of our galaxy from the following bands: 22 GHz, 33GHz, 41 GHz, 61 GHz, 93 GHz [Finkbeiner:2003].

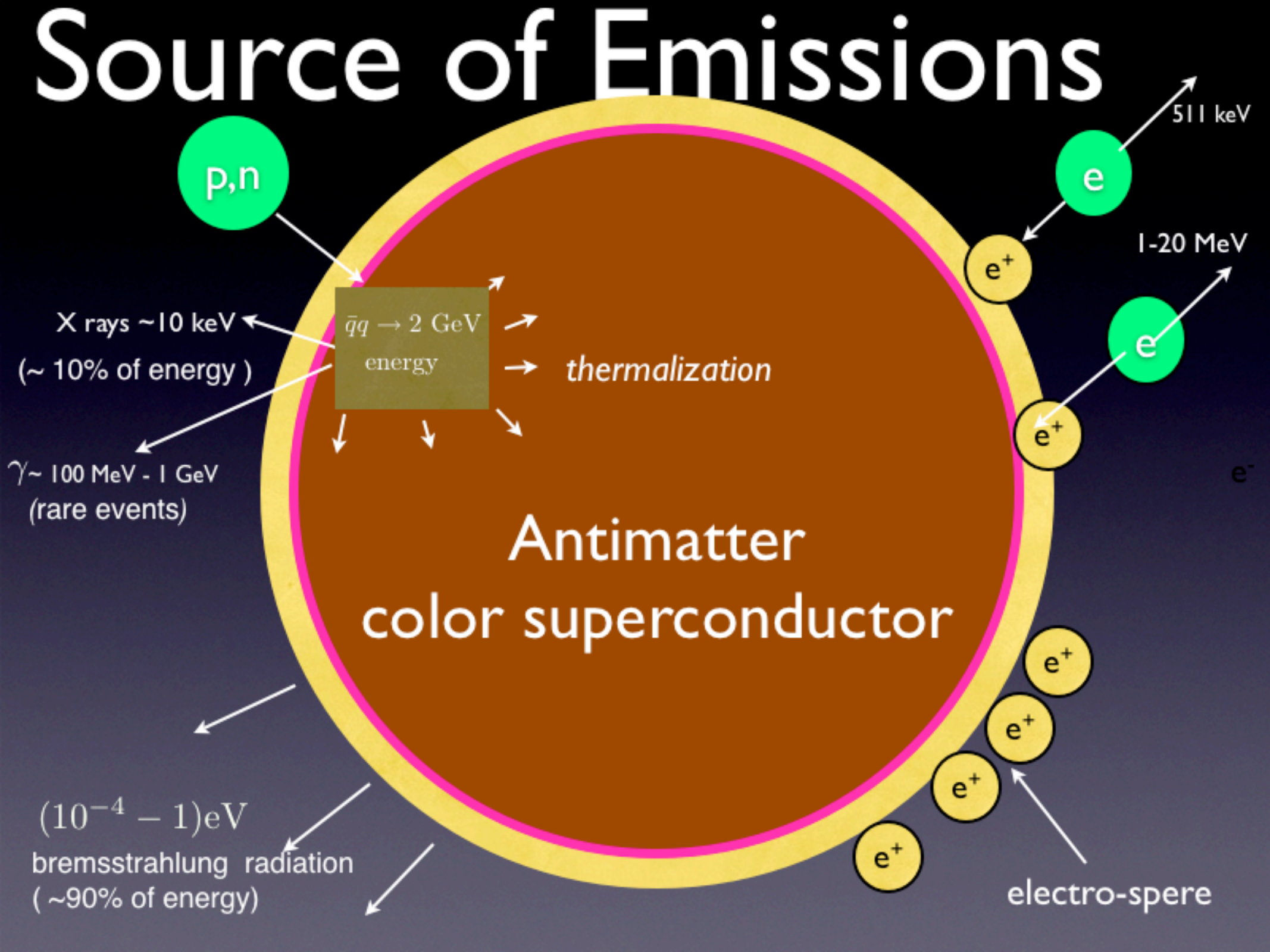
$$\frac{\mathrm{d}\Phi_{\mathrm{WMAP}}}{\mathrm{d}\omega} \approx \frac{(3-6)\times 10^{-20}\mathrm{erg}}{\mathrm{cm}^2\cdot \mathrm{s}\cdot \mathrm{sr}\cdot \mathrm{Hz}}, \quad \text{Total power} \approx 10^{36}\,\frac{\mathrm{erg}}{\mathrm{s}}$$

- This excess (diffuse microwave emission) is uncorrelated to the known foregrounds.

- Source of this emission is a mystery: the spectrum is consistent with free-free emission from hot gas $10^4 K \leq T \leq 10^6 K$ but Hα recombination line is absent where the haze is the most robust. Also: the haze is uncorrelated with the Hα map.

- Could the WMAP haze be related to annihilation of visible matter with `` Dark Antimatter'' nuggets?

Source of Emissions



10."WMAP haze"- possible resolution

- Proton annihilation events will release about 2GeV of energy per event and will occur close to the surface of the nugget creating a hot spot that will mainly radiate X-ray photons with keV energies rather than GeV gamma-rays.

- Considerable portion of this energy will be thermalized inside the bulk of the nuggets and will be emitted as bremsstrahlung radiation from the entire surface of the nugget with long tail at small $\omega \sim 10^{-4}$ eV which provides a natural explanation for ``WMAP haze" intensity.

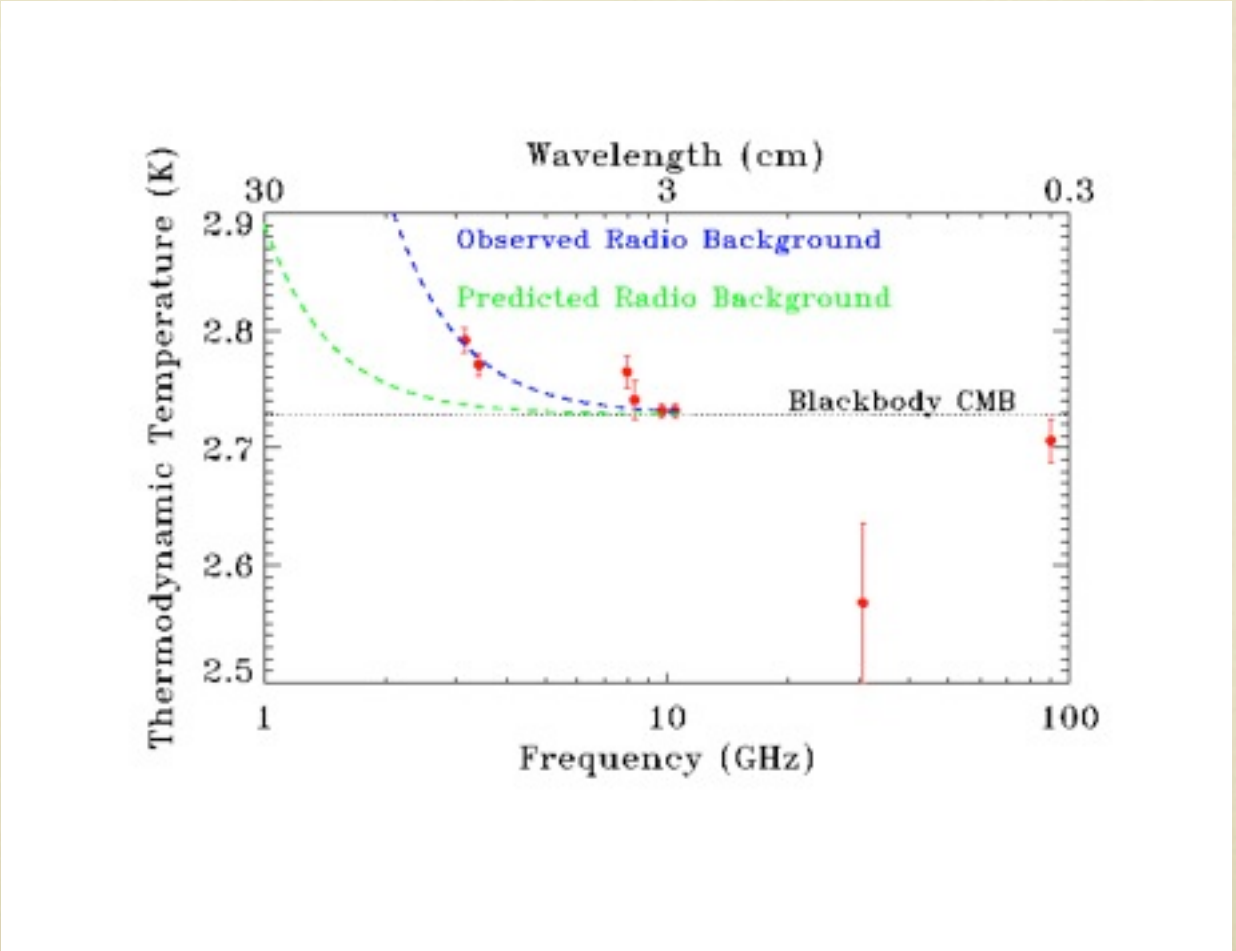
- $$\frac{dQ}{d\omega dt} \sim \frac{T^3\alpha^{5/2}}{\pi}\sqrt[4]{\frac{T}{m}}(1+\frac{\omega}{T})\exp(-\frac{\omega}{T})\ln\frac{T}{\omega}, \quad T \simeq 1eV$$

- the spectrum is indeed free free emission (without H α recombination line) as originally fitted

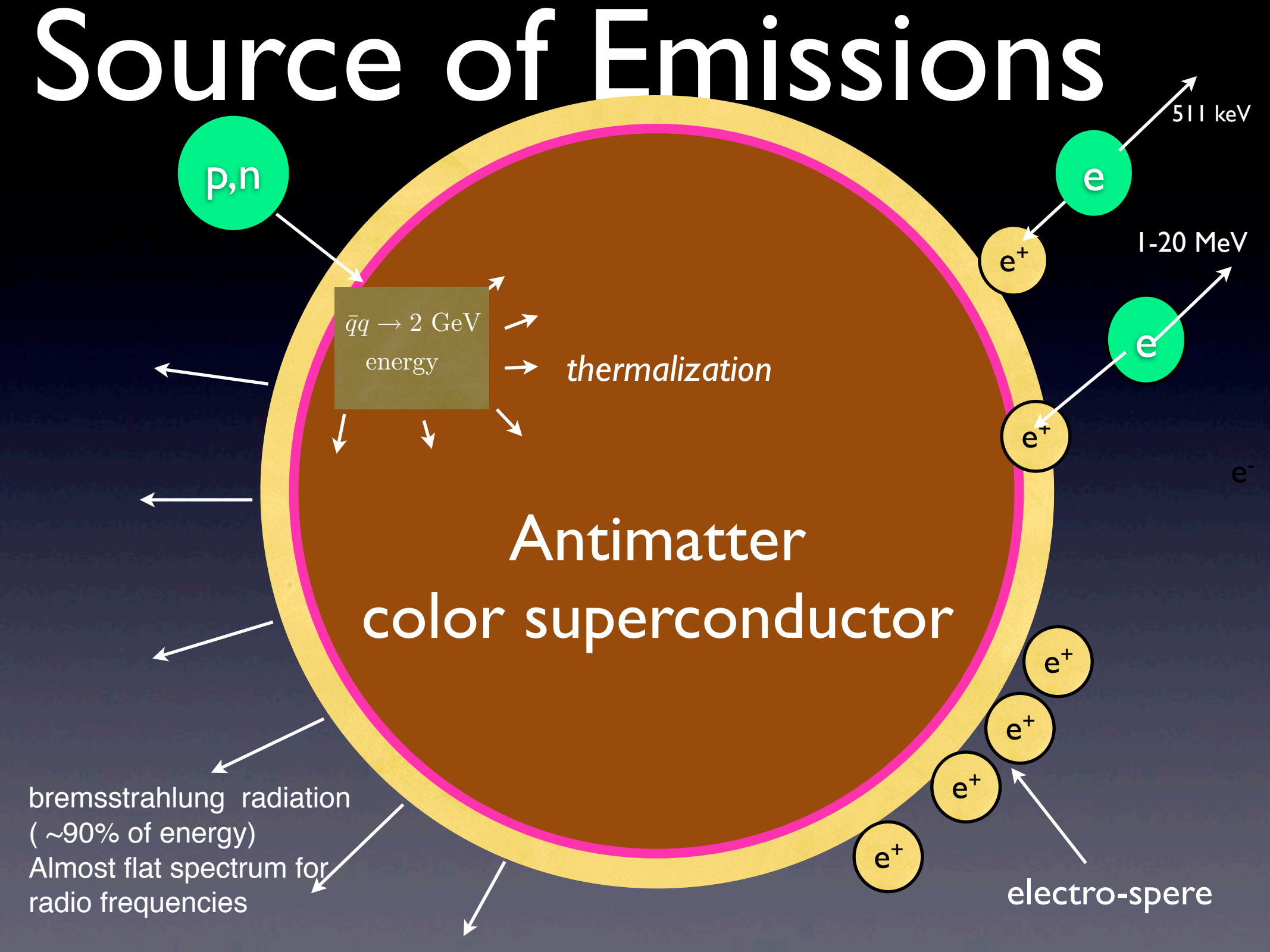
- there are no free parameters in this calculation (intensities and spectrum) as all of the scales are set by well-established physics: QED and Thomas-Fermi approximation.

11. Isotropic Radio Background from ARCADE 2

- Measurements by the ARCADE 2 experiment unambiguously show an excess in the isotropic radio background at frequencies below GHz scale. This radio excess seems impossible to fit through reasonable modifications to the spectra of known background radio sources



Source of Emissions



- The basic proposal: the nuggets normally make small contribution to the isotropic CMB background. However, the thermal spectrum of the CMB falls as ω^3 below peak while the nugget contribution remains essentially constant

$$\frac{dQ}{d\omega dt} \sim \frac{T^3\alpha^{5/2}}{\pi}\sqrt[4]{\frac{T}{m}}(1+\frac{\omega}{T})\exp(-\frac{\omega}{T})\ln\frac{T}{\omega}, \quad T \simeq 1\mathrm{eV}$$

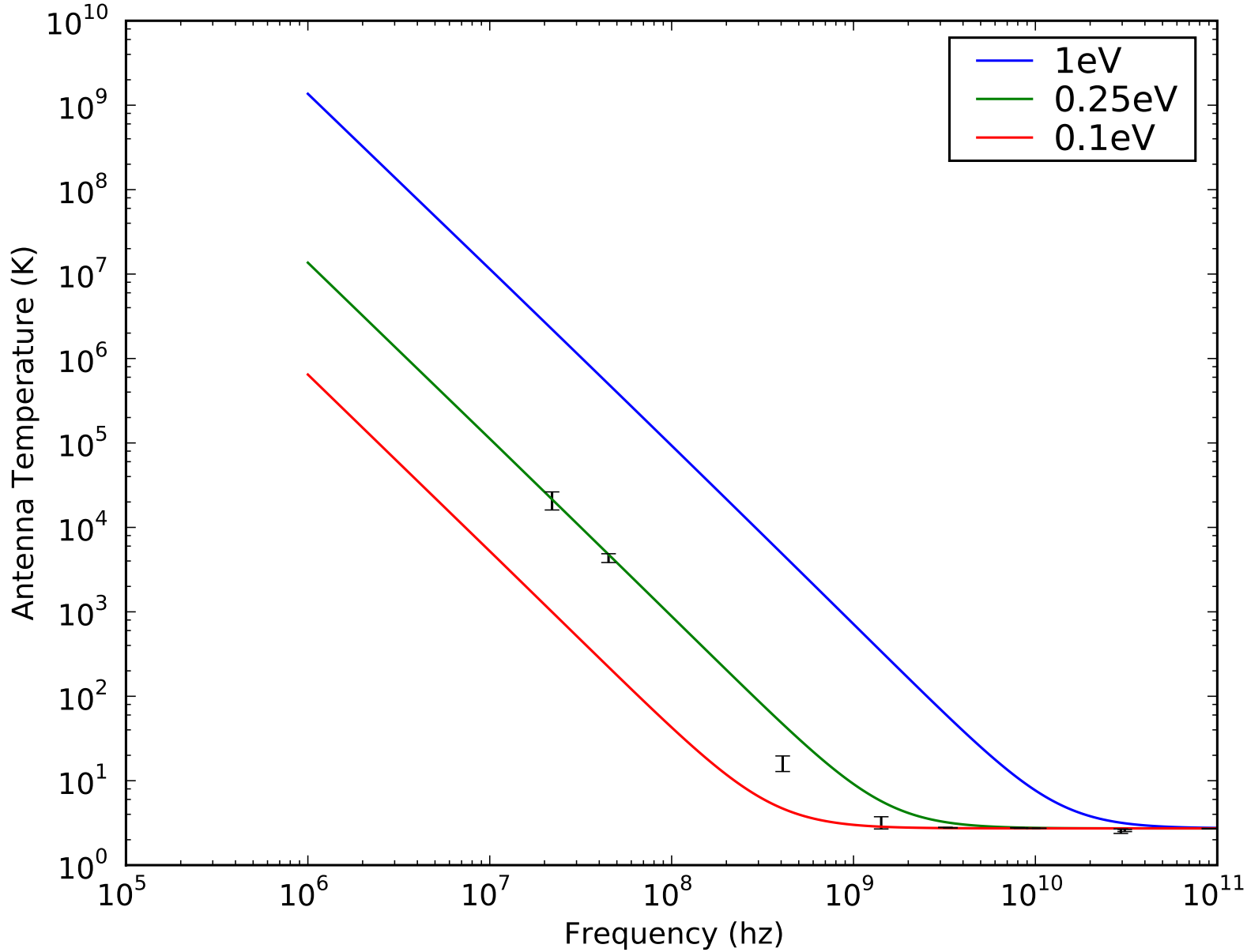
- Thermal emission spectrum of a nugget is <u>almost flat</u> at energies below the nugget temperature $\omega \ll T$

- This feature of "flatness" of the spectrum results in an observed isotropic background "antenna temperature" that seems to grow with the third power of frequency (in comparison with CMB which should stay constant).

- With computed spectrum we can now determine the present day radio background due to the presence of quark matter (anti) nuggets. This is accomplished by integrating the source density over all redshifts "z" correcting for the redshifting of photon frequency after emission.

- The integral is saturated by z~10^3 and is not sensitive to late time complications (such as reheating, structure formation, etc)

- Uncertainty is parametrized by the initial temperature of the nuggets T_{LS} at the time of last scattering (during CMB formation). This parameter is calculable in principle as it is determined by conventional physics. Our estimates are consistent with $T_{LS} \sim 0.25\ \mathrm{eV}$ shown on the plot.



$$I(\nu) = \frac{c}{H_0} \int \frac{dz}{(1+z)h(z)} \frac{\rho_{DM}}{M_N} \frac{dE}{d\nu\ dt} [\nu(1+z), T(z)]$$

Conclusion

- " Non- baryonic Dark matter" could be ordinary baryonic matter which is not in the ``normal hadronic phase", but rather, in the exotic color superconducting phase.

- In this phase the baryon charge is not available for BB Nucleosynthesis

- A small geometrical factor $\epsilon \sim S/V \sim B^{-1/3} << 1$ replaces a weak coupling const.

- The antimatter nuggets provide a single annihilation target for both: electrons and protons/neutrons. As a result, all the emissions:

- THE 511~KEV LINE,
- EXCESS OF THE SOFT GAMMA-RAY SPECTRUM IN 1 -20 MEV REGION
- THE DIFFUSE X-RAY EMISSION FROM PROTON ANNIHILATION (HOT SPOTS IN NUGGETS)
- THE DIFFUSE EV AND WMAP-HAZE (10^{-4} EV) THERMO - EMISSION **SHOULD ORIGINATE FROM THE SAME REGIONS OF SPACE WITH THE SAME NORMALIZATION FACTOR**
- $$B^{-1/3} \int dr \rho_{visible}(r) \cdot \rho_{DM}(r)$$
- THIS IS THE ONLY ELEMENT FROM UNKNOWN PHYSICS

- All relatives intensities of gamma diffuse emissions with frequencies ranging over 11 orders of magnitude are fixed by known, well-established physics.

- On large scales, the nuggets behave as standard collisionless cold dark matter. However: some modifications are expected in dense regions (galaxies), where DM does interact strongly with visible matter.

- The idea of the charge separation during QCD phase transition can be tested at RHIC, Brookhaven. Preliminary analysis of data apparently supports the idea of charge separation (and strong CP violation) at RHIC. These conditions at RHIC and LHC may mimic the early universe during the QCD phase transition.

- The main question to the astro community: is it possible to study/analyze the correlations between different (naively unrelated) emissions ?