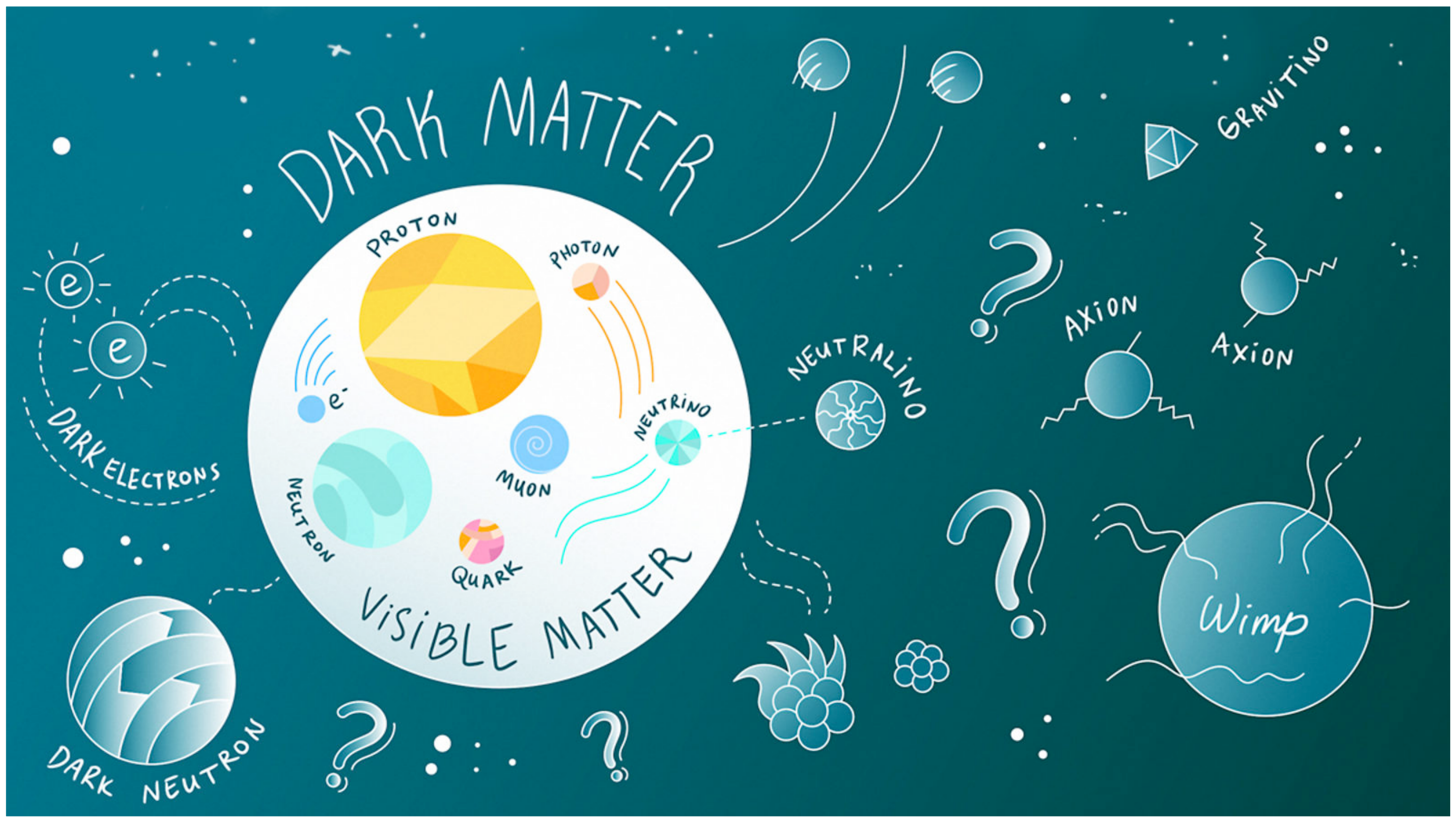
Axion Quark Nuggets: a candidate for baryonic, cold and strongly interacting dark matter



Ludovic Van Waerbeke
CEA Saclay DAp, April 16th 2019

In addition to the nature of dark energy and dark matter, the standard big-bang has a hard time to explain these:

Why is it that $\Omega_{DM} \sim \Omega_{baryons}$? The Weakly Interacting Massive Particle (WIMPS) 'miracle' does not seem to be happening.

Why is the baryon to photon ratio η~1e-10?

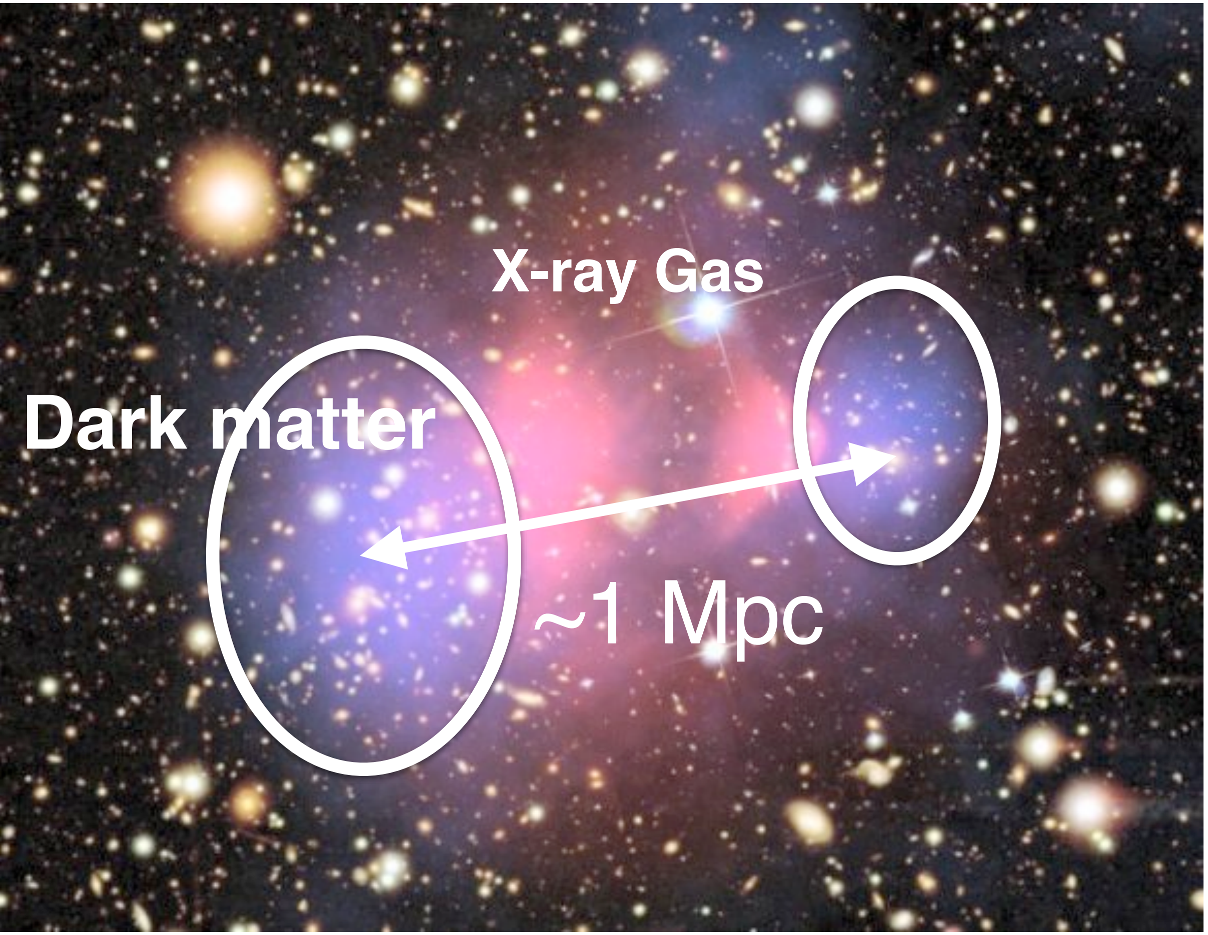
How does baryogenesis work?

The current paradigm for dark matter is:

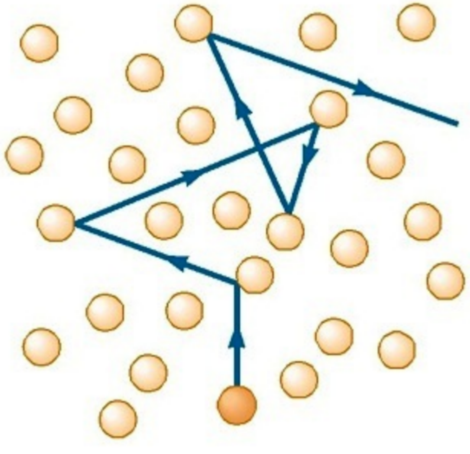
-Dark matter is cold, non baryonic and not (or VERY weakly) interacting with baryons.
-It must be a new type of matter outside the standard model of particles (there is no sign of interaction between dark matter and baryonic matter, cross-section must be extremely small)

- cosmic microwave background
- large scale structures
- baryon acoustic oscillations
- big bang nucleosynthesis)

WIMPS fulfills all the above criteria



The bullet cluster



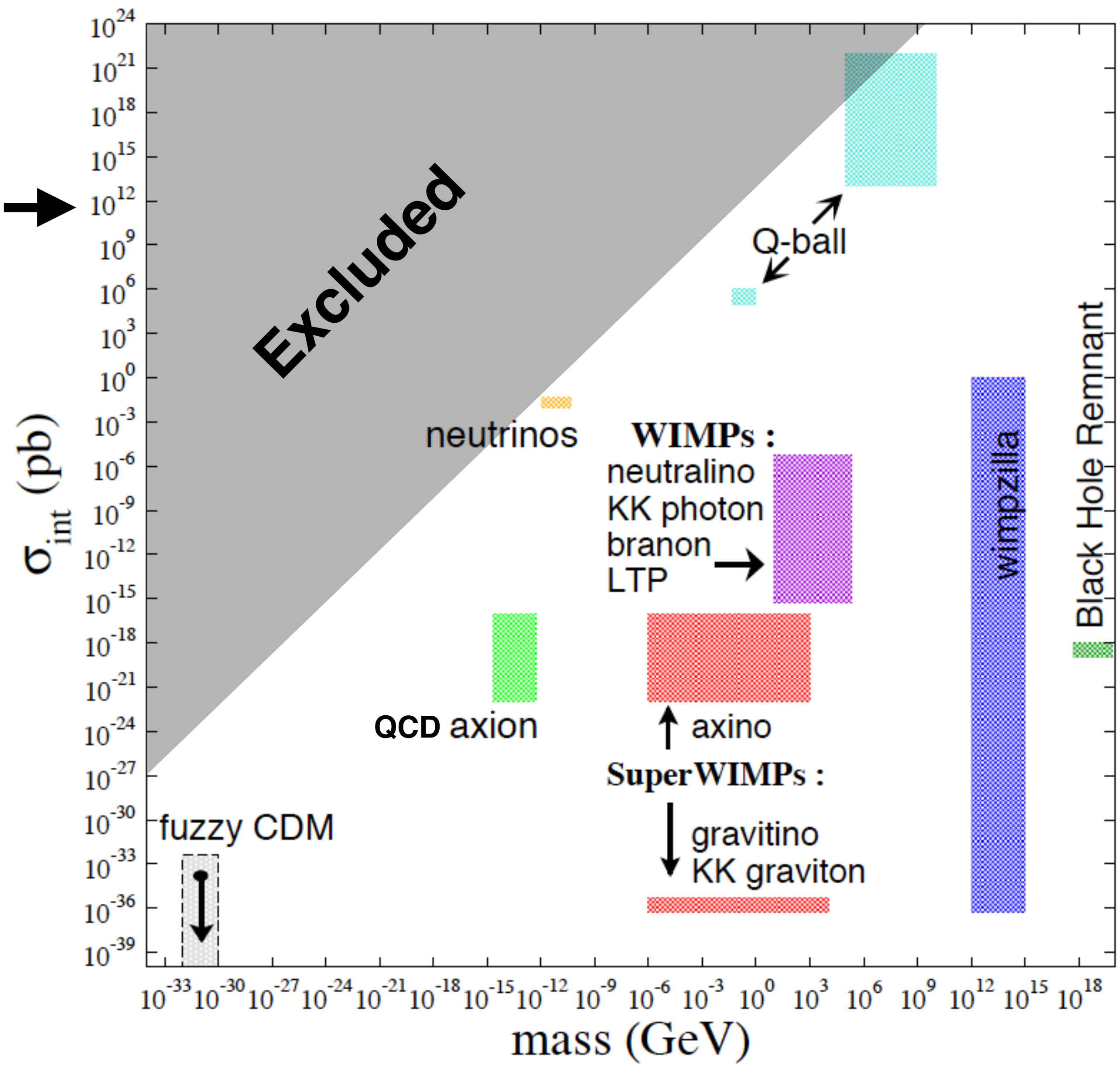
$\sigma_{xx}\, n\, \ell = 1$ Defines the dark matter

mean free path ℓ

$$\boxed{\sigma_{xx} / m_x < 1\ \mathrm{cm}^2/\mathrm{g}}$$

Self-Interacting Dark Matter Spergel & Steinhardt 2000

Dark Matter parameter space and some candidates

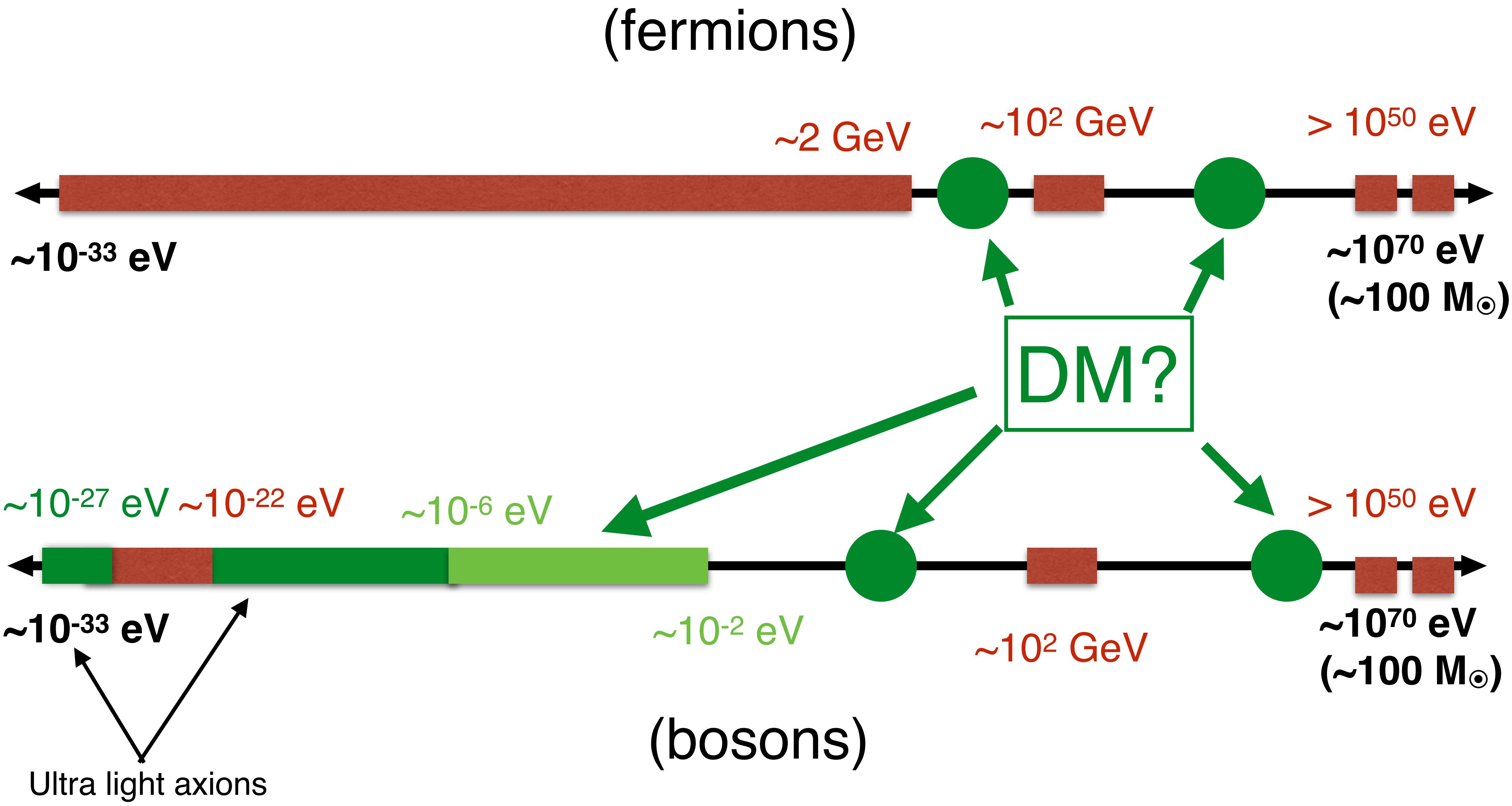


Thomson σ_e →

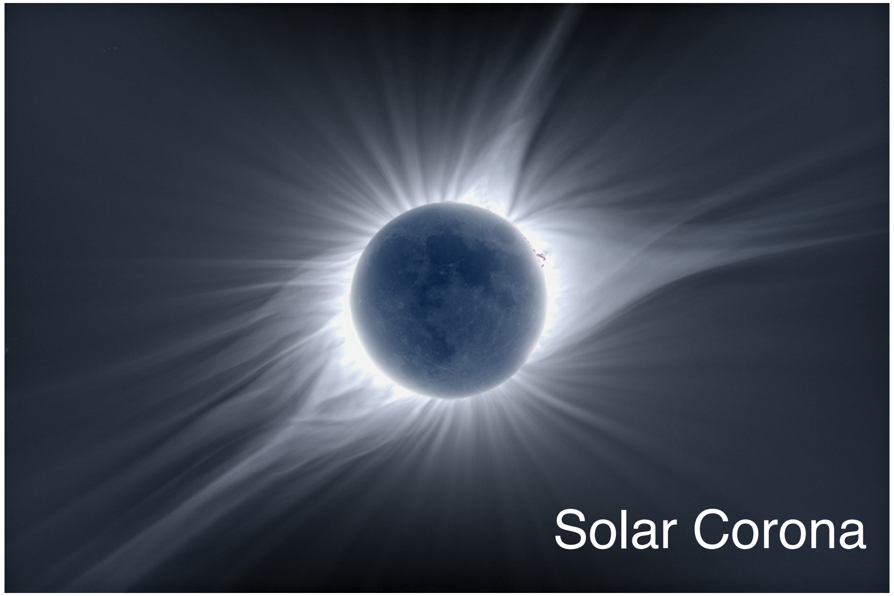
Baer arXiv:0901.4732

Current constraints on dark matter does not exclude heavy composite nuclear-density objects consisting of bound quarks or antiquarks over a significant range of masses.

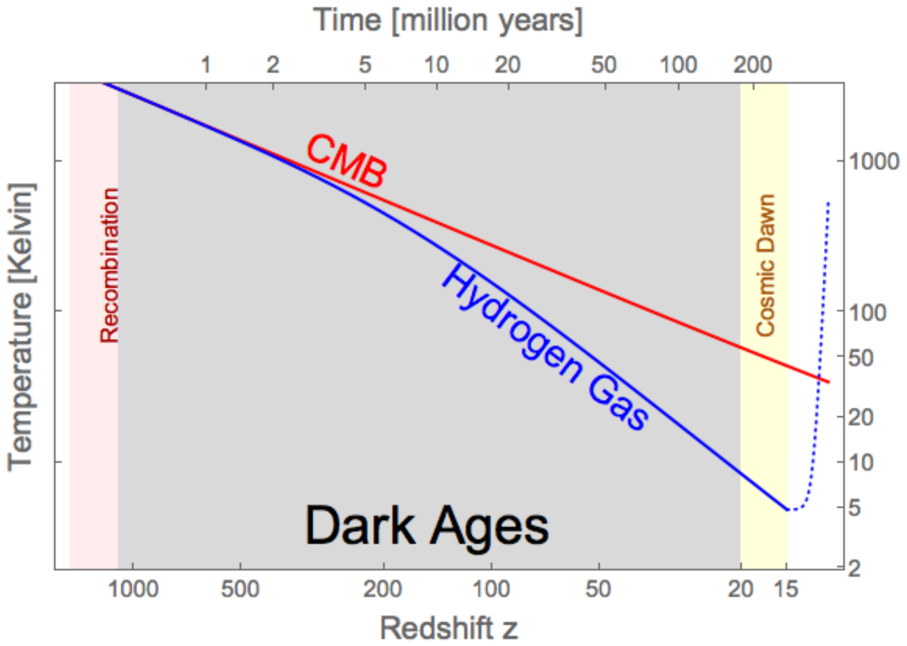
Dark Matter energy landscape
(independent of cross-section)

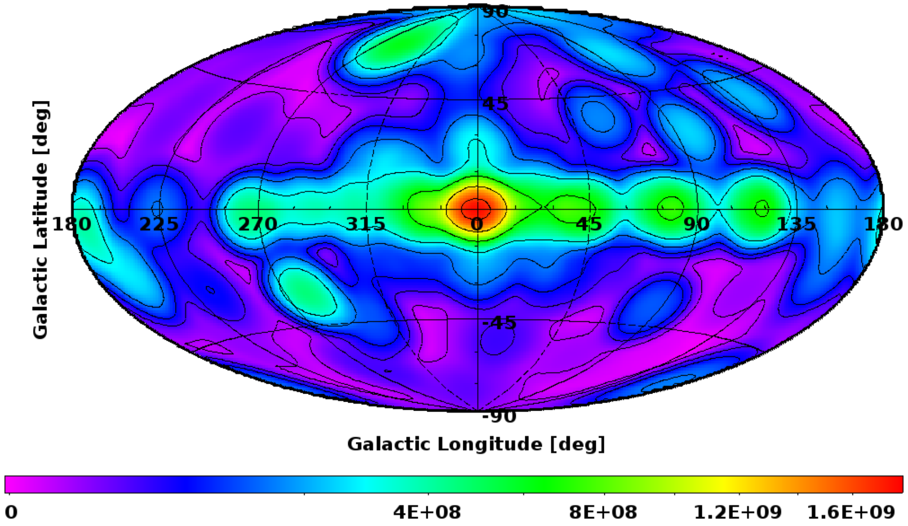


Is there anything in common between these -not fully understood- phenomena?

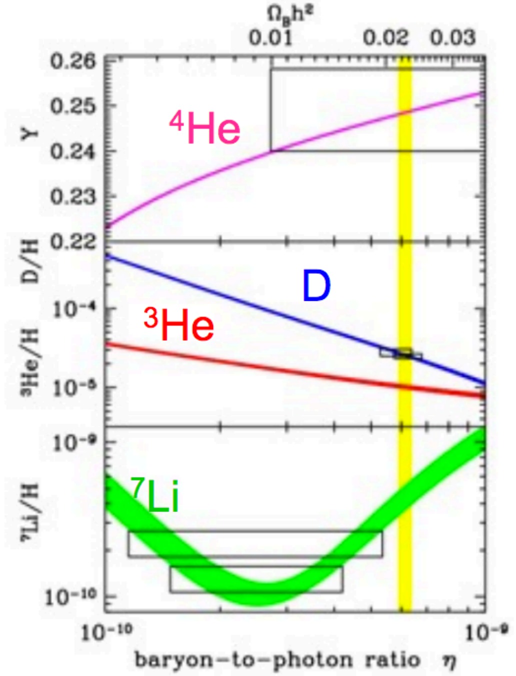


Solar Corona





511 keV line



Primordial Lithium-7

The Strong CP problem in Quantum Chromo Dynamics (QCD)

-The lagrangian of QCD, the theory describing the strong force, if one of the quarks has non zero mass, contains a term that violates the CP (Charge+Parity) symmetry.

-If CP symmetry is violated, the neutron electric dipole should be of order 10^{-18} e·m

-Experimentally, neutron dipole is ~10 orders of magnitude less, this implies that, experimentally, QCD does not violate CP symmetry. This is the **strong CP problem**.

-To resolve this issue one need to, either extremely fine tune QCD ($\theta \sim 10^{-10}$), or **promote θ to a physical field**, with a potential $V(\theta)$, that goes through a phase transition at some temperature T_c, that can naturally absorb the QCD CP violating term at $T < T_c$, when the symmetry is broken (anthropic solution too…).

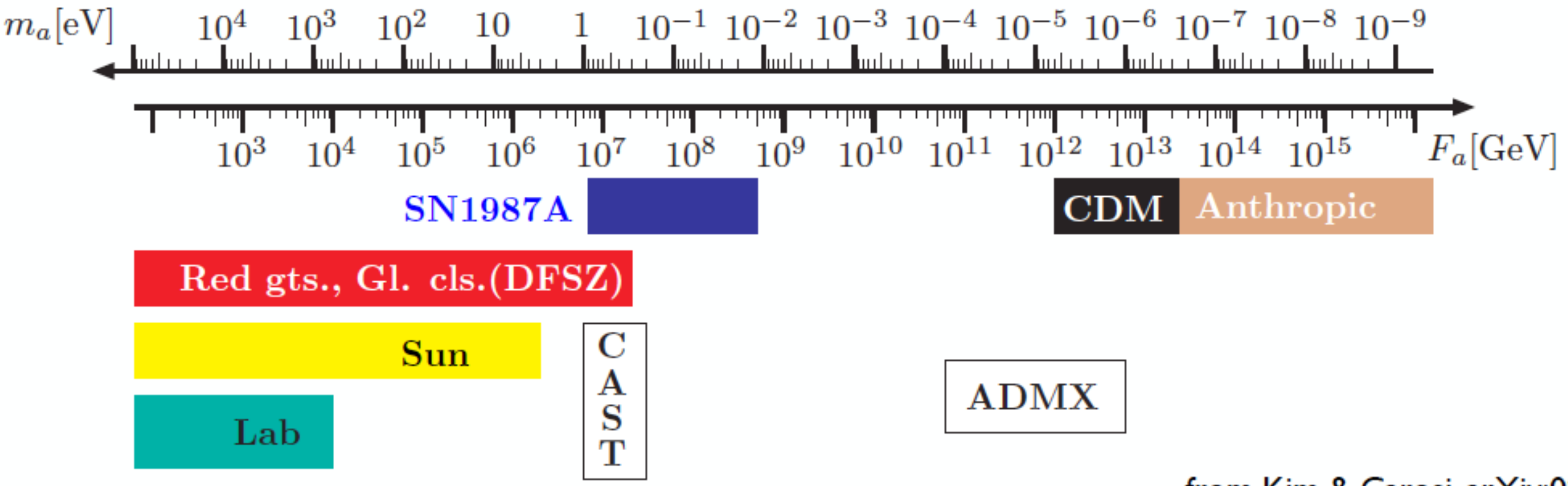
- θ as a field is called the QCD axion. $\theta=[0,2\pi]$ has a U(1) symmetry.

- At $T \sim \Lambda_{QCD}$ we have $\theta_{eff} \rightarrow 0$ (solves CP problem) and the axion field gets a mass

- The axion field interacts with photons (which enables direct detection and astrophysical effects)

QCD Axion mass constraints

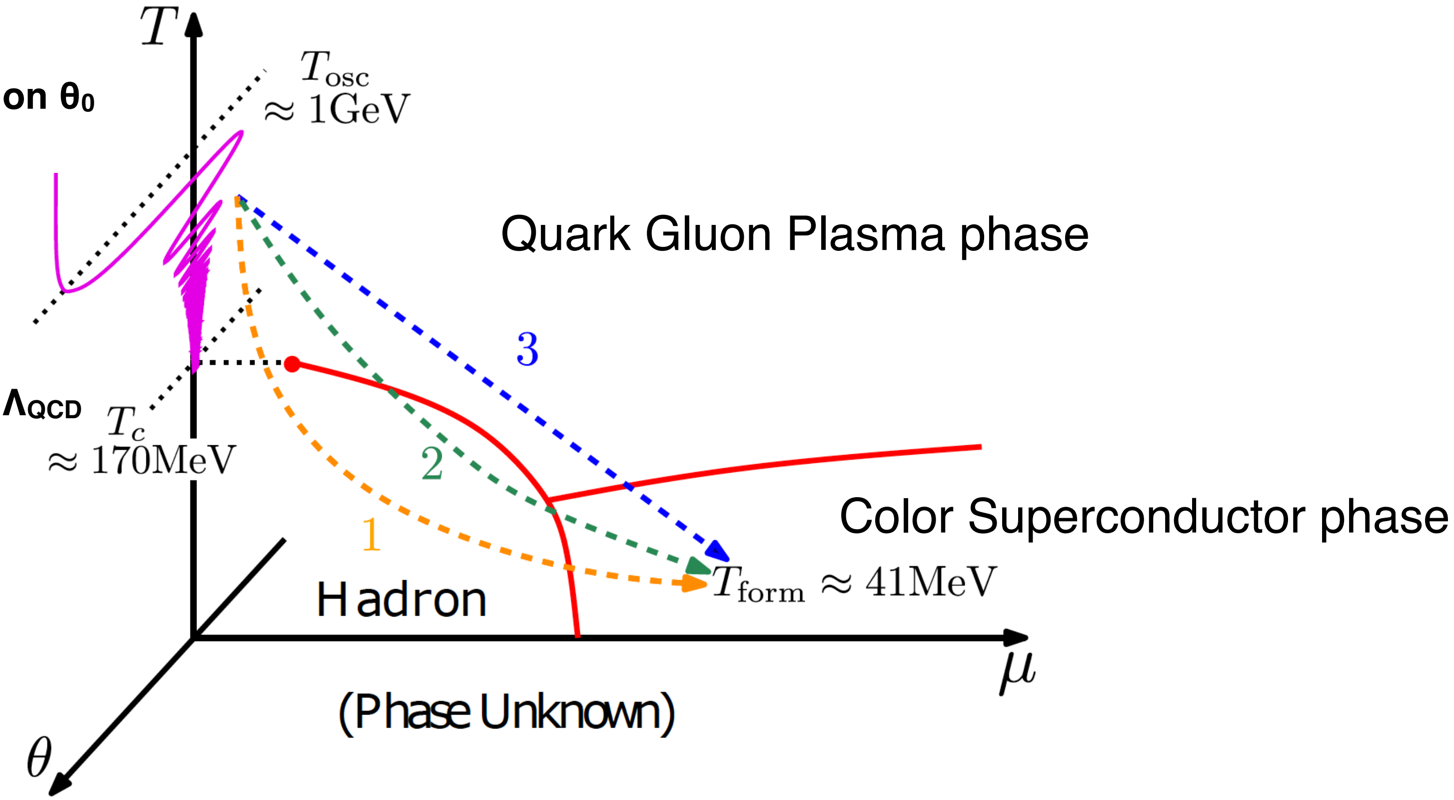
$f_a \lesssim 10^9\mathrm{GeV}$ is excluded by stellar and supernova 1987A physics



from Kim & Carosi, arXiv:0807.3125

The Axion Quark Nugget model

"Non-baryonic dark matter as baryonic colour superconductor", E. Zhitnitsky, JCAP, 2003, 10, 010



Initial axion value after inflation θ_0 of order 1: $\theta_0 \sim [0,2\pi]$

QCD phase transition scale Λ_{QCD}

Phase diagram of nuclear matter: From arXiv:1903.05090
Different paths (unknown) for quark nuggets formation (1, 2, 3)

Post big bang sequence of the axion quark nugget generation

-Inflation is over

-As θ oscillates before the QCD phase transition at T_c ~170 MeV, the vacuum energy remains the same everywhere, but the phase can vary and form topological defects because there must be continuity in the [0,2π]. Axion domain wall topological defects $N_{DW}=1$ start forming.

-Quarks and anti-quarks are trapped inside the domain walls that will form nuggets and anti nuggets

-Effective θ is very small when QCD phase transition begins (so QCD does not violate CP), this results in a slight over production (of order one) of anti-nuggets over nuggets.

-Matter and anti matter annihilate in the plasma leaving an excess of order one of baryons compared to nuggets and anti-nuggets.

-Domain wall formation stops at some temperature T_{form}. Various arguments suggest T_{form} ~ 40 MeV

-Domain walls shrink until they are stopped by nuclear fermi pressure of the CS phase

The densities $\Omega_{\text{anti-nuggets}}$; Ω_{nuggets}; Ω_{visible} can differ by order ~one, which avoids fine tuning.

Assume that the total baryonic charge of the Universe is zero (**no baryogenesis is needed**):

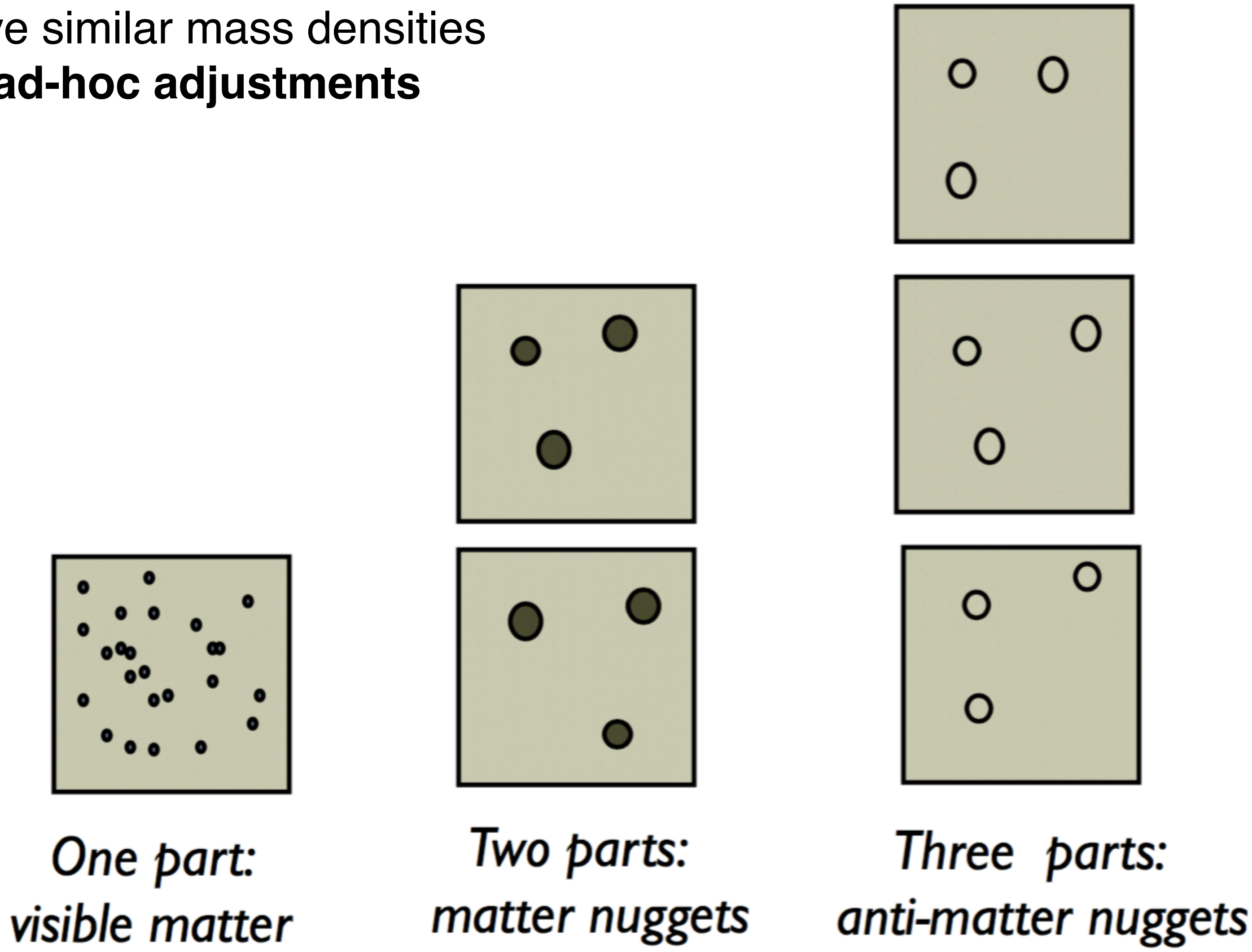
$$B_{\text{universe}} = 0 = B_{\text{visible}} + B_{\text{nugget}} - B_{\text{anti-nugget}}$$

Observation suggest that $\Omega_{\text{DM}} = \Omega_{\text{anti-nuggets}} + \Omega_{\text{nuggets}} \sim 5\ \Omega_{\text{visible}}$

$$\boxed{\text{This leads to } \Omega_{\text{visible}}\ ;\ \Omega_{\text{nuggets}}\ ;\ \Omega_{\text{anti-nuggets}} \sim 1;\ 2;\ 3}$$

Conjectured mass density budget at the end of nuggets formation

This model naturally explains why dark matter and baryonic matter have similar mass densities
without ad-hoc adjustments



Baryogenesis

The baryon to photon ratio scales like $\eta=\exp[-m_p/T_B]$
(m_p is ~5 Λ_{QCD})

In conventional cosmology $T_B \sim 22$ MeV, which leads to $\eta \sim 10^{-20}$

In AQN model $T_B \sim T_{form} \sim 40$ MeV which leads to $\eta \sim 10^{-10}$
which provides a **solution to baryon to photon ratio**

Primordial nucleosynthesis

Nuggets binding energy per nucleon is of the order of Λ_{QCD} ~170 MeV, therefore primordial nucleosynthesis (~1 MeV) cannot destroy nuggets

In the AQN model, **dark matter is composed of regular matter** trapped in the unconventional **color superconducting phase.**

Free parameter of the model: the axion mass m_a

Wall tension $\sigma_a \sim m_a^{-1}$

Nugget size $R \sim \sigma_a$

Nugget baryonic charge $B \sim \sigma_a^3$

Axion mass window: 10^{-6} eV $< m_a < 10^{-3}$ eV

Nugget size window: 10^{-6} cm $< R < 10^{-3}$ cm

Nugget baryonic charge: $10^{23} < B < 10^{32}$

Nugget mass: 0.1 g $< M_{AQN} < 10^8$ g

Observational properties

Dark matter mass density in solar system $\rho_{DM} \sim 0.3$ GeV/cm^3

Nugget number density: $(10^6 \text{ km})^{-3} < n_{AQN} < (1000 \text{ km})^{-3}$

Flux on Earth: $$\Phi = n_N v_N \approx \frac{\rho_{DM} v_N}{M_N} \approx 1 \text{ km}^{-2}\text{yr}^{-1} \left(\frac{10^{24}}{\langle B \rangle}\right)$$

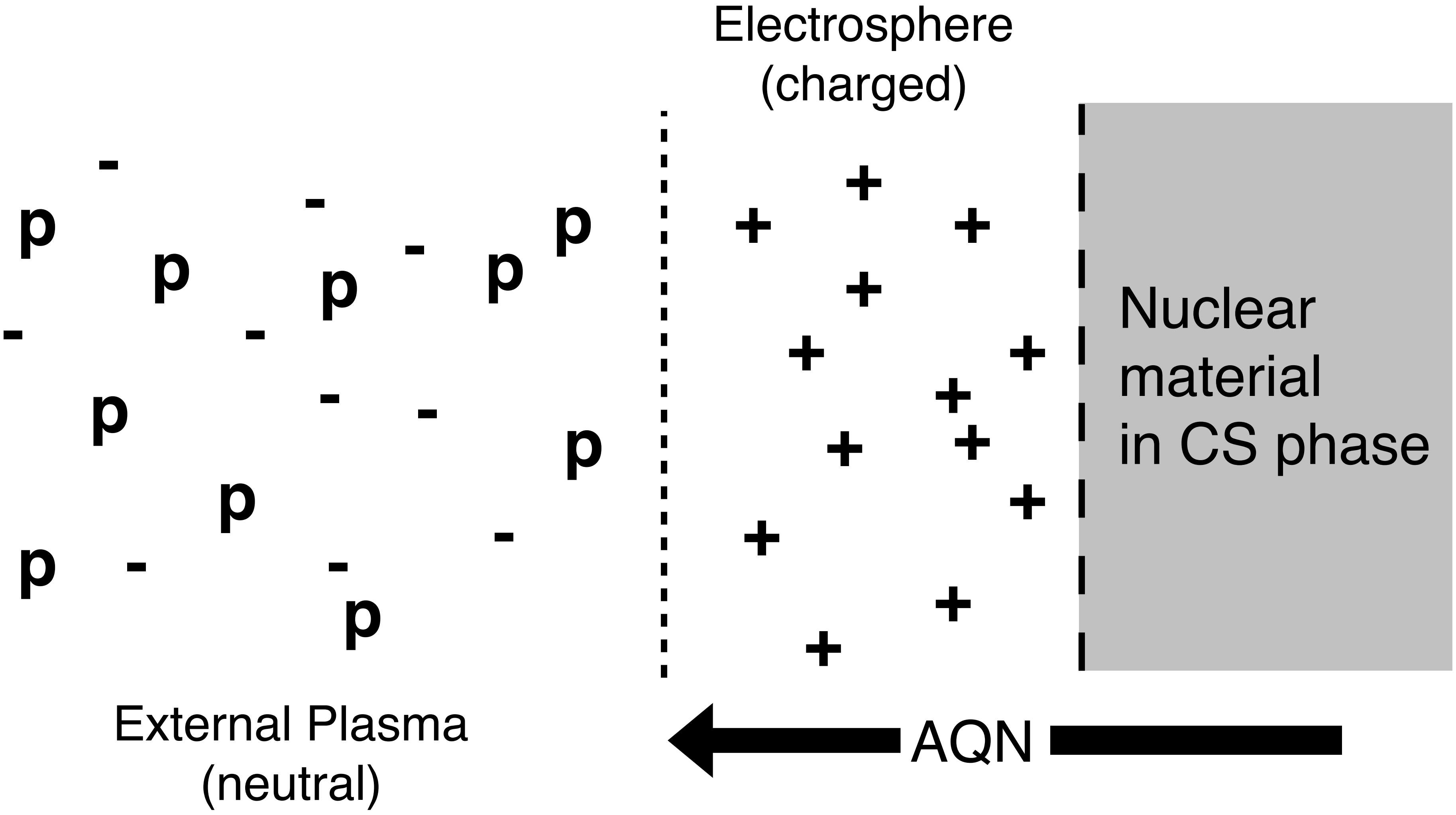
Cannot be seen by high-sensitivity dark matter detectors (Icecube, ANITA better suited)

$$\boxed{\sigma_{AQN\text{-}AQN} / M_{AQN} \sim 10^{-10} \text{ cm}^2/\text{g} \ll \sigma_{xx} / m_x}$$

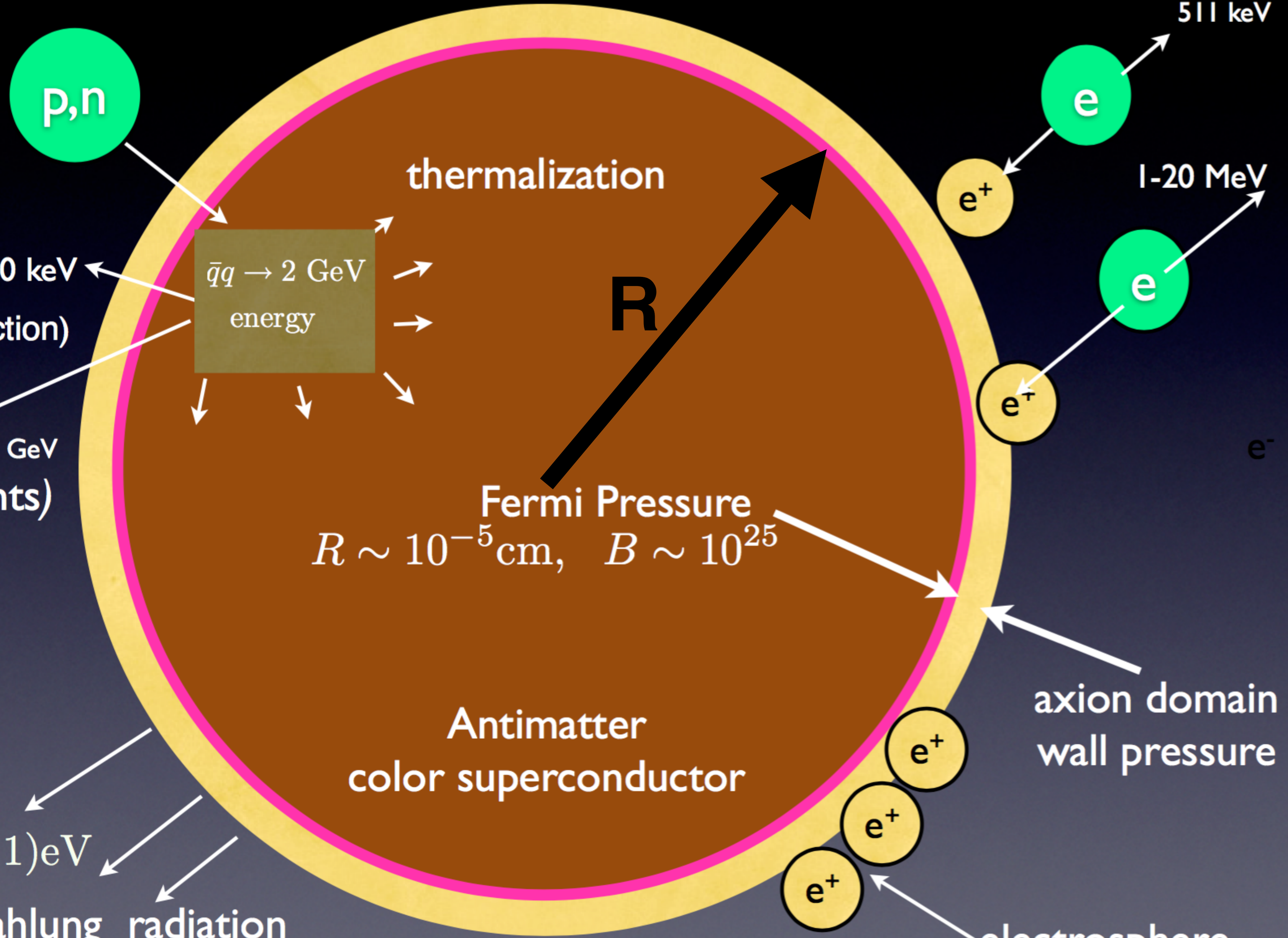
AQN nuggets behave as cold dark matter CDM

AQN nuggets behave as cold dark matter CDM

They interact extremely rarely with baryonic matter because of their n_a very low. But when they do, they interact very strongly with surrounding plasma



Antiquark nugget structure. Source of emission



thermalization

$\bar{q}q \rightarrow 2$ GeV energy

X rays ~10 keV (finite fraction)

γ~ 100 MeV - 1 GeV (rare events)

511 keV

1-20 MeV

Fermi Pressure

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

axion domain wall pressure

Antimatter color superconductor

electrosphere

$(10^{-4} - 1)\mathrm{eV}$

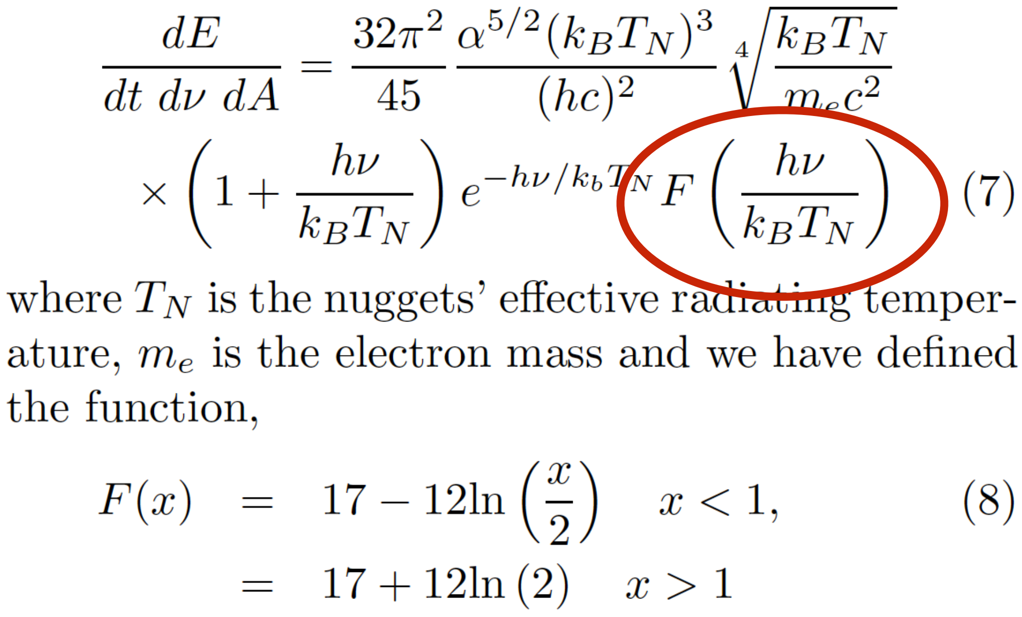
bremsstrahlung radiation (largest fraction)

Generic AQN physics

The AQN model has **one** free parameter, the Axion mass m_a,
but the interaction of the AQN with its environment is characterized by complicated physics:

-Surounding plasma temperature T_P and densities n_p, n_{e-}, n_{e+}
-Electrosphere statistics ("internal, charged, plasma")
-Nugget internal temperature T_I
-Efficiency κ of the annihilation with the Color Superconducting phase.

Very hard spectrum at low frequency compared to black body:



$$\frac{dE}{dt\ d\nu\ dA} = \frac{32\pi^2}{45}\frac{\alpha^{5/2}(k_B T_N)^3}{(hc)^2}\sqrt[4]{\frac{k_B T_N}{m_e c^2}}$$
$$\times\left(1+\frac{h\nu}{k_B T_N}\right)e^{-h\nu/k_b T_N}\boxed{F\left(\frac{h\nu}{k_B T_N}\right)} \quad (7)$$

where T_N is the nuggets' effective radiating temperature, m_e is the electron mass and we have defined the function,

$$\begin{aligned} F(x) &= 17 - 12\ln\left(\frac{x}{2}\right) \quad x < 1, && (8)\\ &= 17 + 12\ln(2) \quad x > 1 \end{aligned}$$

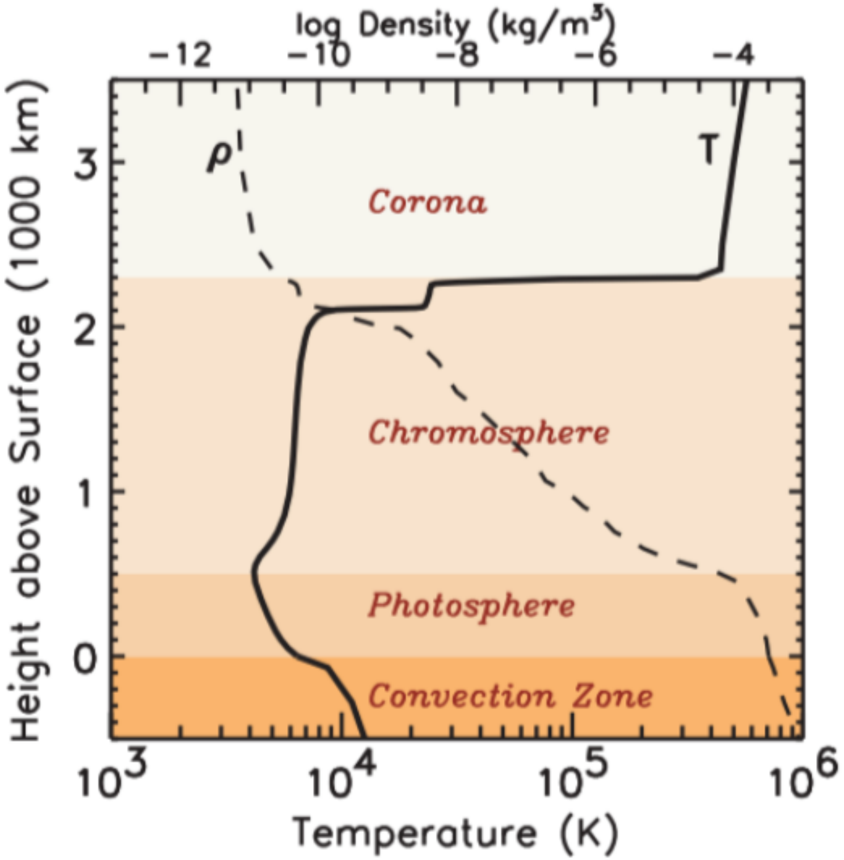
From Lawson & Zhitnitsky 2018

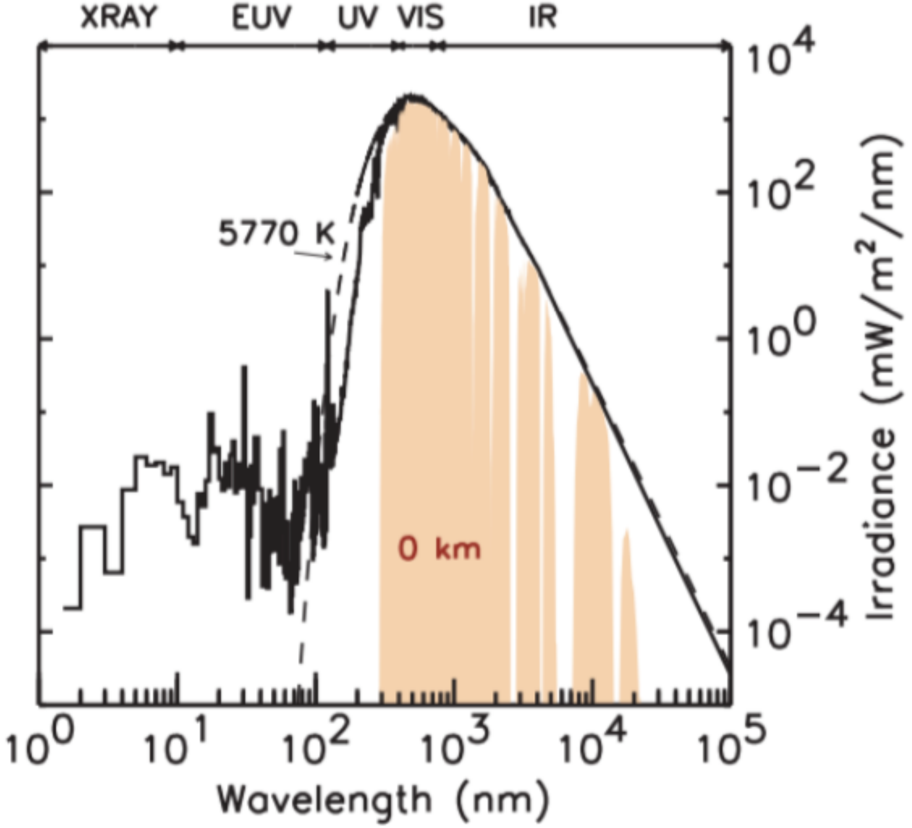
Low frequency photons cannot penetrate the nugget if their frequency is less than the plasma frequency ω_p of the electrosphere (described as a Thomas-Fermi gas theory).

Heating of the solar corona

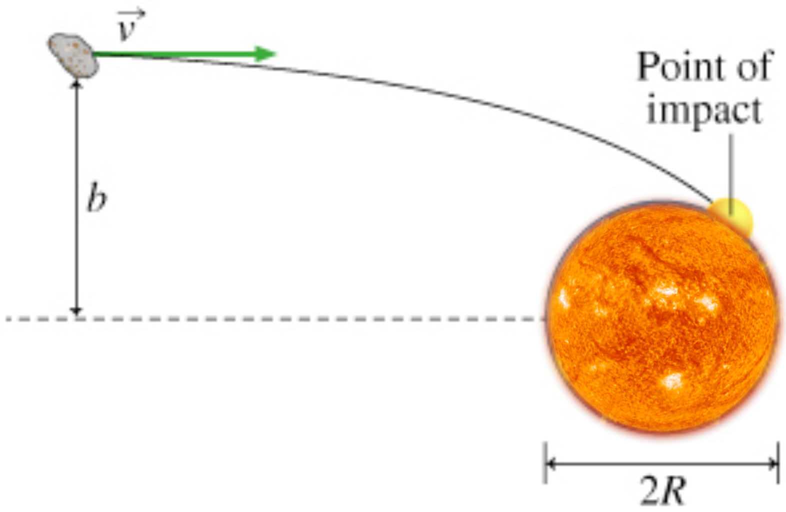
Raza, LVW, Zhitnitsky 2018

The solar corona problem: EUV/soft Xray from corona emits ~10^{27} erg/s not accounted for.





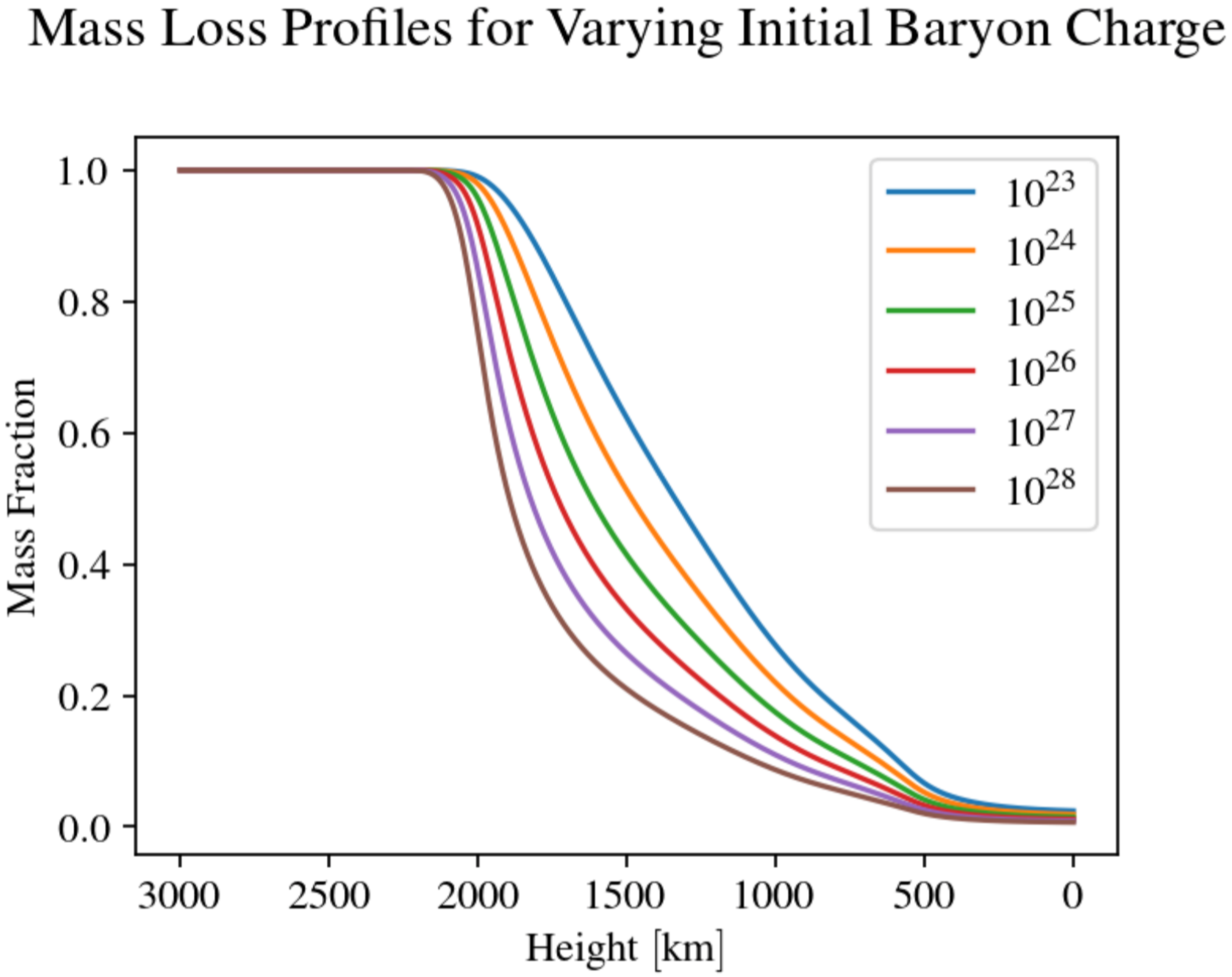
Solar corona: the basic picture

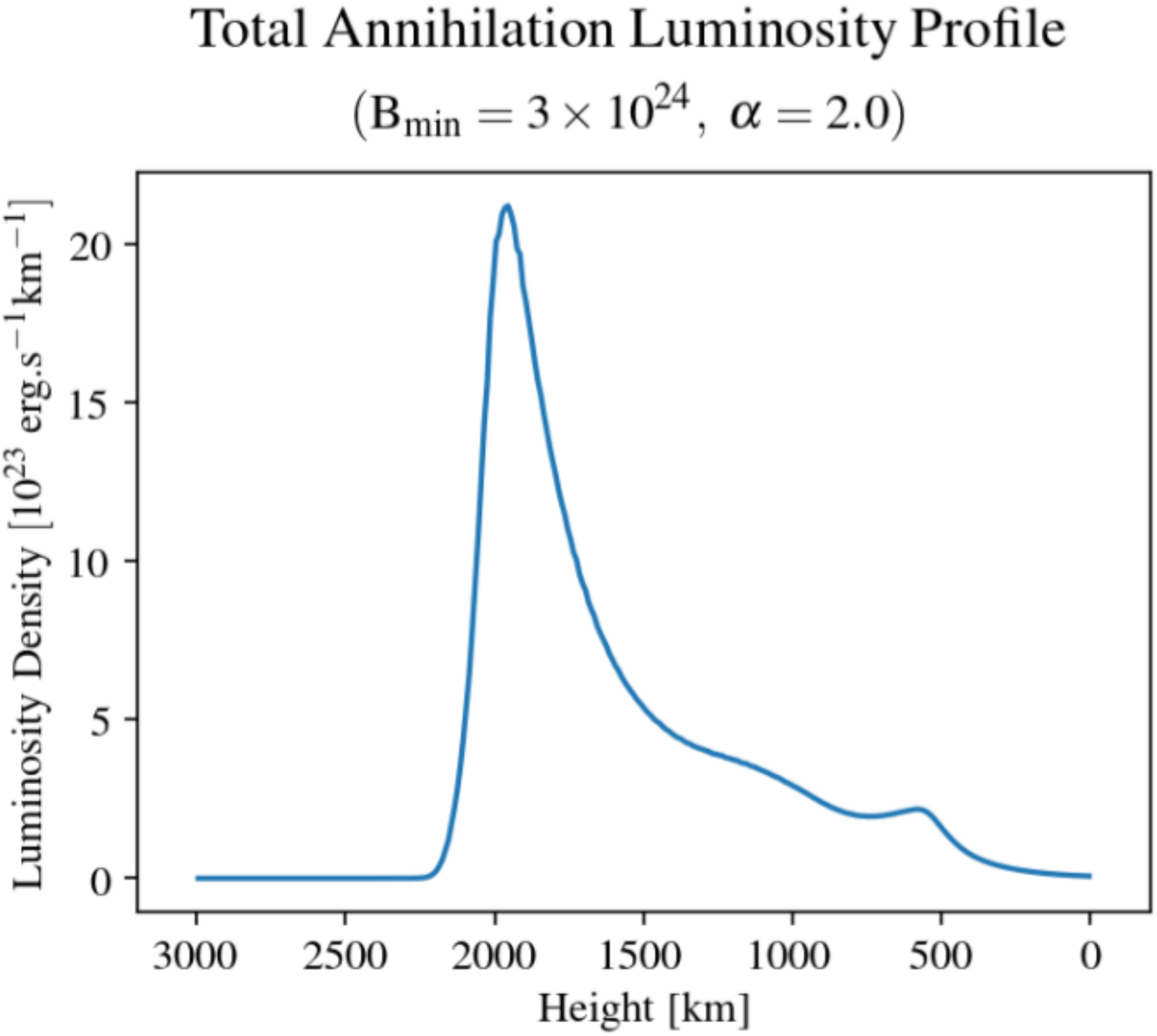


$$b_{\rm cap} \simeq R_\odot\sqrt{1+\gamma_\odot}, \qquad \gamma_\odot \equiv \frac{2GM_\odot}{R_\odot v^2}$$

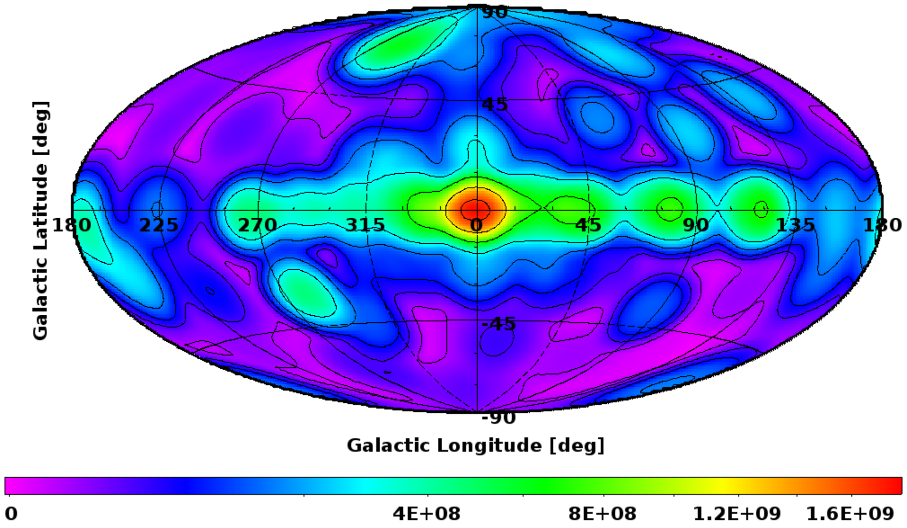
Energy budget from Dark Matter environment:

$$L_{\odot\,({\rm AQN})} \sim 4\pi b^2_{\rm cap}\cdot v\cdot \rho_{\rm DM} \simeq 3\cdot 10^{30}\cdot\frac{\rm GeV}{\rm s} \simeq 4.8\cdot 10^{27}\cdot\frac{\rm erg}{\rm s}$$


Mass Loss Profiles for Varying Initial Baryon Charge
1.0
0.8
0.6
0.4
0.2
0.0
Mass Fraction
3000
2500
2000
1500
1000
500
0
Height [km]
10^{23}
10^{24}
10^{25}
10^{26}
10^{27}
10^{28}


Total Annihilation Luminosity Profile
$(\mathrm{B}_{\mathrm{min}} = 3 \times 10^{24},\ \alpha = 2.0)$
Luminosity Density $[10^{23}\ \mathrm{erg.s^{-1}km^{-1}}]$
0
5
10
15
20
3000
2500
2000
1500
1000
500
0
Height [km]

The 511 keV line, γ-ray, X-ray, and the WMAP haze



511 keV line (INTEGRAL)

This signal has been ruled out as a signature of dark matter (WIMPS) annihilation because it correlates spatially with the galactic disk.

$$\Phi \propto \rho_{\rm DM}^2$$

In the AQN model, the DM-baryons cross-section is given by:

$$\Phi \sim R^2 \int d\Omega dl [n_{\rm visible}(l) \cdot n_{DM}(l)] \sim \frac{1}{\langle B \rangle^{1/3}}$$

The DM should follow the baryon distribution

$$\Phi \propto \rho_{\rm visible} \rho_{\rm DM}$$

511 keV line over COMPTEL 1-20 MeV excess **ratio** agrees with the emission processes from the AQN electrosphere

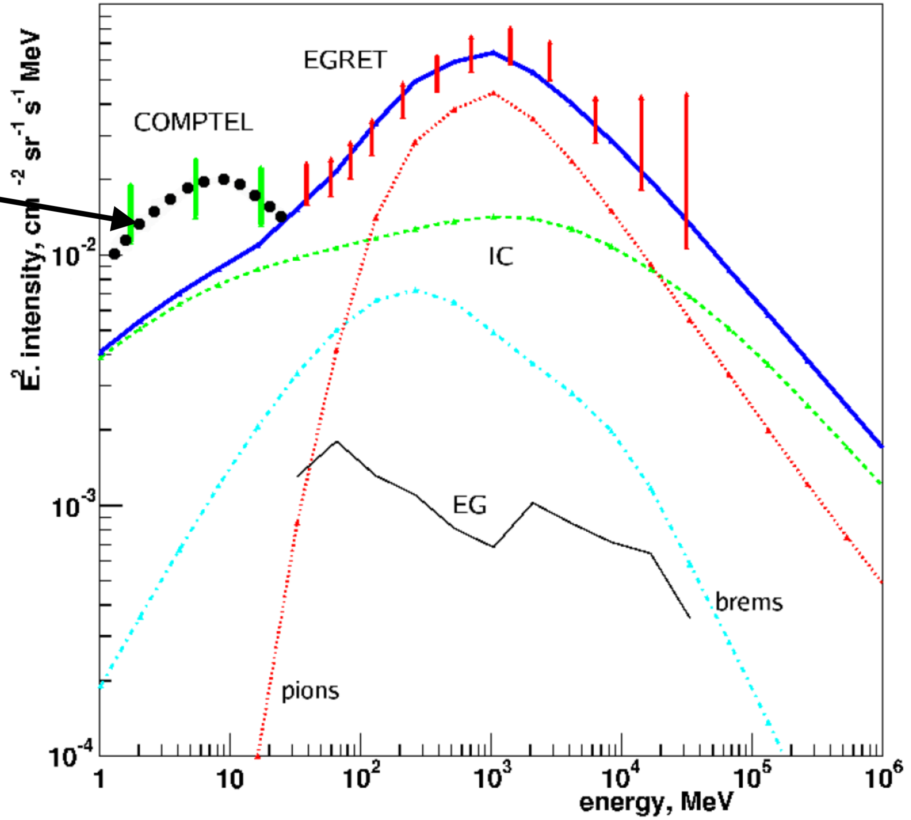
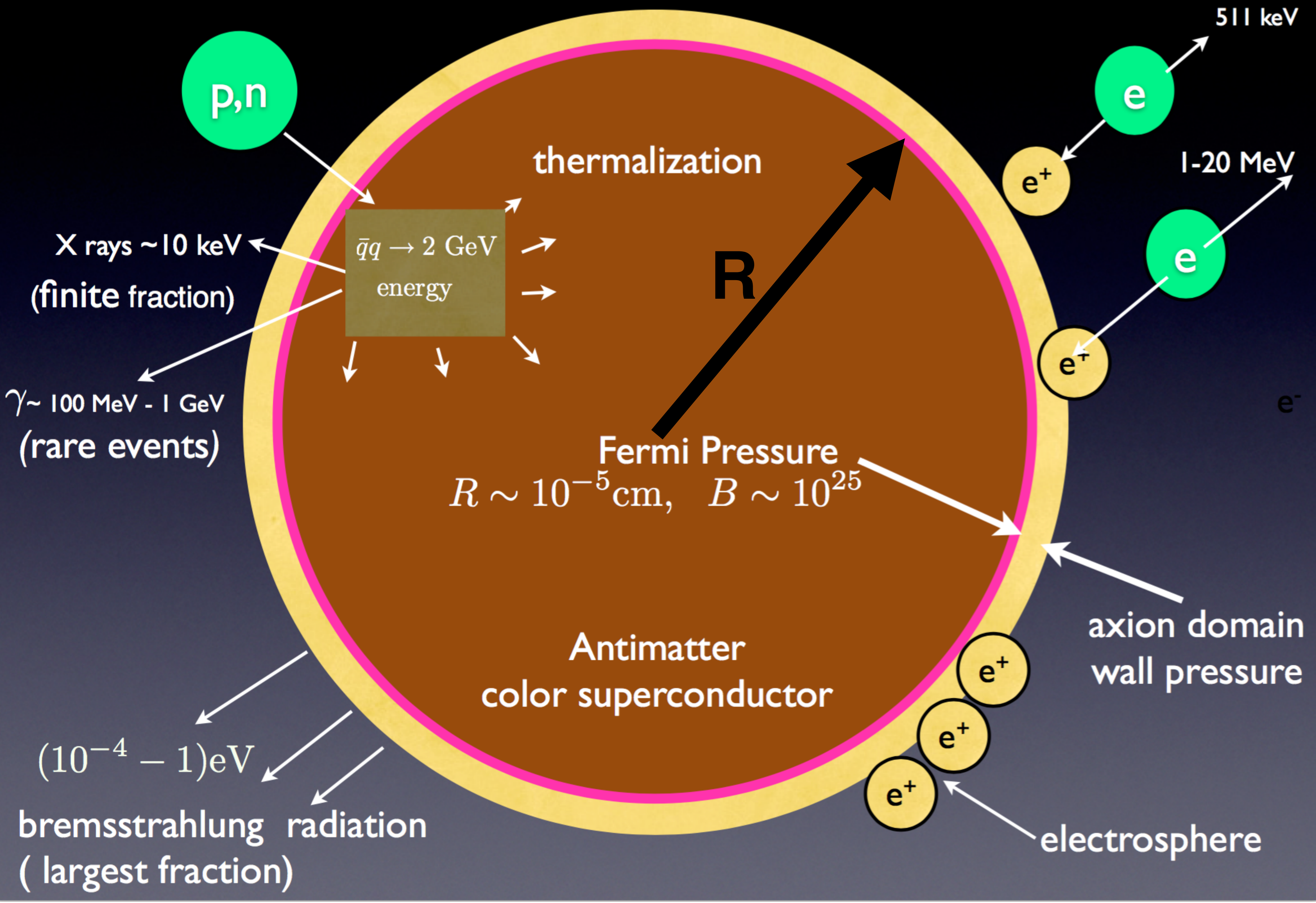


Figure 1. γ ray spectrum of inner galaxy for optimized model[24]. Green vertical bars: COMPTEL data. Heavy solid line: total calculated flux for optimized model. Heavy black dots: Combination of calculated emission spectrum from electron-nugget annihilation processes with the optimized model of [24].

CHANDRA observes 1-10 keV excess that is very difficult to explain by astrophysical sources.
AQN: proton annihilation produces x-ray emission in keV from hot spots.

Proton annihilation in **AQN** produces rarely Gev photons which are consistent with EGRET

Antiquark nugget structure. Source of emission



p,n

thermalization

$\bar{q}q \rightarrow 2$ GeV energy

R

511 keV

e

e^+

1-20 MeV

e

e^+

e^-

X rays ~10 keV (finite fraction)

γ~ 100 MeV - 1 GeV (rare events)

Fermi Pressure

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

axion domain wall pressure

Antimatter color superconductor

e^+

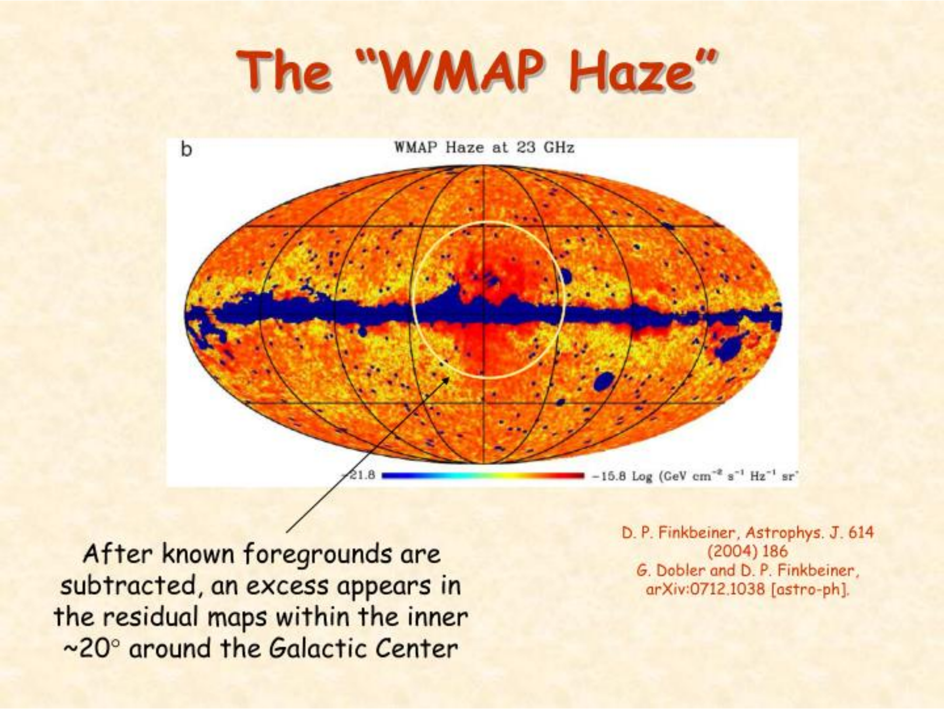
e^+

e^+

electrosphere

$(10^{-4} - 1)\mathrm{eV}$

bremsstrahlung radiation (largest fraction)



The "WMAP Haze"

After known foregrounds are subtracted, an excess appears in the residual maps within the inner ~20° around the Galactic Center

D. P. Finkbeiner, Astrophys. J. 614 (2004) 186
G. Dobler and D. P. Finkbeiner, arXiv:0712.1038 [astro-ph].

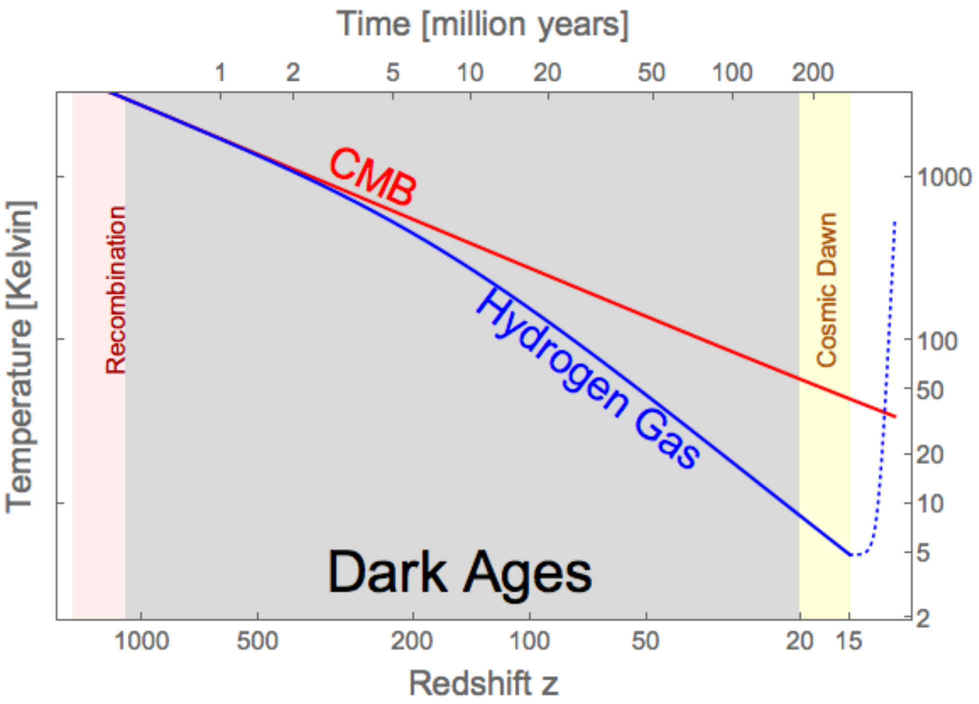
In the AQN model, there is a fraction 1-g of the annihilation energy that can't escape as keV and GeV and thermalize the electrosphere, which emits Bremsstrahlung in the 10^{-4} -1 eV range this is GHz range

$$F_{\mathrm{tot}} = (1-g)F_{\mathrm{ann}} = (1-g)\frac{\mathrm{d}E_{\mathrm{ann}}}{\mathrm{d}t\,\mathrm{d}A}$$

g ~ 1/10 match the data, this is 12 orders of magnitude difference in frequency that seem connected.

Forbes & Zhitnitsky 2008

Experiment to Detect the Global Epoch of reionization Signature (EDGES)

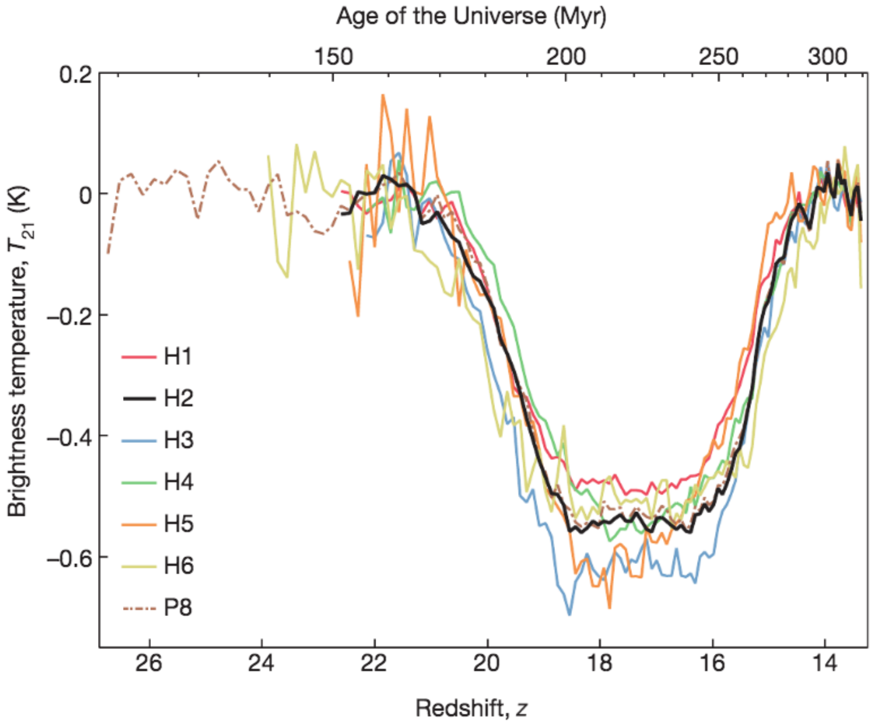


$$\delta T \sim x_{HI}\left(1 - \frac{T_r}{T_s}\right)$$

Fraction of neutral hydrogen

Wouthuysen–Field coupling between Lyα and spin temperature

Bowman et al. 2018



Feng and Holder show that a small excess of background radiation (T_R) at early time can explain the EDGES results:

$$T(\nu) = T_{\text{CMB}} + \xi T_R \left(\frac{\nu}{\nu_0}\right)^{\beta}$$

$\xi \sim 0.01$ (one percent of ARCADE2 excess) can explains EDGES result

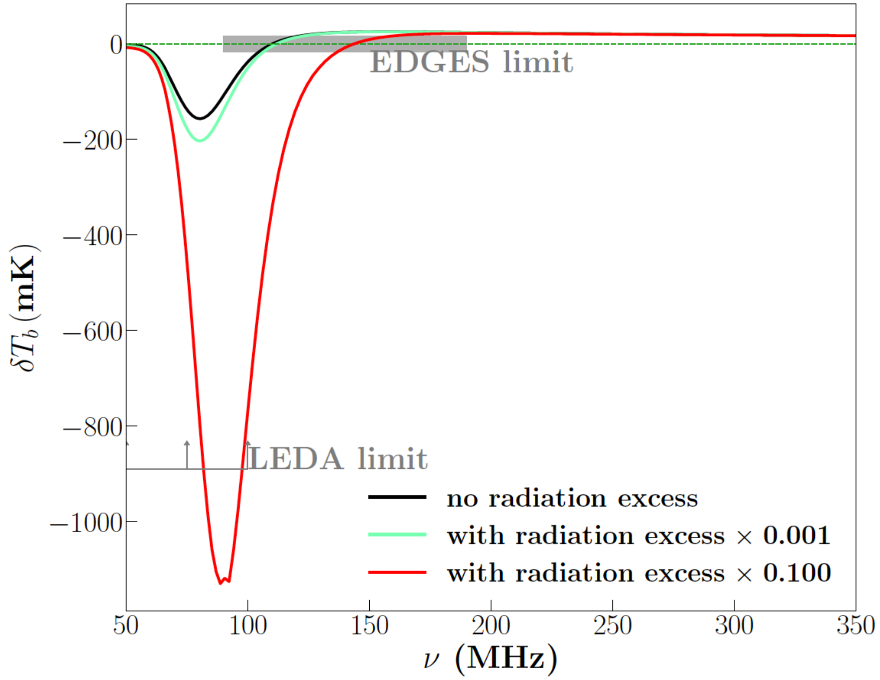


Figure 3. The enhanced global 21cm signal as a function of redshift z (top) or frequency ν (bottom). The trough located at $\nu \sim 100$ MHz will trace physical signatures in the cosmic dawn epoch at $z > 12$.

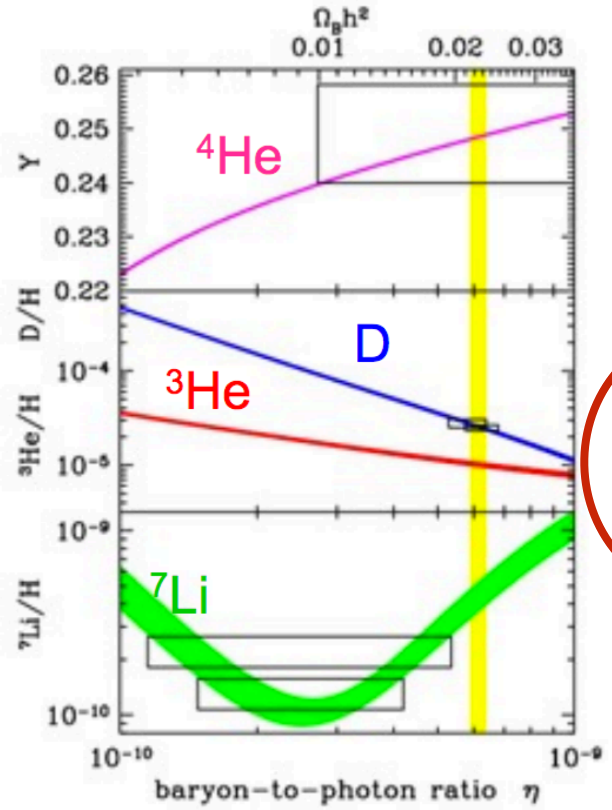
Feng & Holder 2018

From the AQN model:
Hadron annihilation efficiency $\kappa \sim 0.03$ leads to $\xi \sim 0.01$

Lawson & Zhitnitsky 2012

The Li^7 problem

Flambaum & Zhitnitsky 2019



Primordial Lithium-7

Enhancement factor due to ion charge Z and AQN charge Q at distance r.

$$\frac{\delta n_Z}{n_Z} \simeq \frac{4\pi R_{\rm cap}^3}{3} \cdot n_{AQN} \cdot \exp\left[\frac{(Z-1)\alpha Q(r)}{rT}\right]$$

Geometrical capture volume due to the presence of AQN

Relative number of trapped and captured ions with atomic number Z

For Z=1, 2; $\frac{\delta n_{\rm D}}{n_{\rm D}}; \frac{\delta n_{\rm He}}{n_{\rm He}} \ll 1$

For Z=3 $\frac{\delta n_{\rm Li^7}}{n_{\rm Li^7}} \sim 1$

Conclusion

-Dark matter can be made of regular baryonic matter, but in an unconventional phase

-Under this condition, dark matter can be baryonic and not violate primordial nucleosynthesis

-It can behave like CDM and yet strongly interact with the baryonic sector, as long as it does it *VERY* rarely (consequence of very low AQN number density).

-The AQN model leaves predictable, clean, electromagnetic signatures which can be calculated and searched for

-There are already some very troubling coincidences, over 13 orders of magnitude in frequency, for very different physical environments, but no predictions yet: work in progress

-Future directions:
Lensing-baryons cross-correlations is one of the tools that can help.
QCD axion direct search, polarization signal, other direct astrophysical signatures (e.g. CMB, baryonic-DM correlations in galaxies, Fast Radio Bursts)