# (H)ALPing the 511 keV line: A thermal DM interpretation of the 511-keV emission in the Galactic Centre

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*in collaboration with*

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IN SUPREMÆ DIGNITATIS
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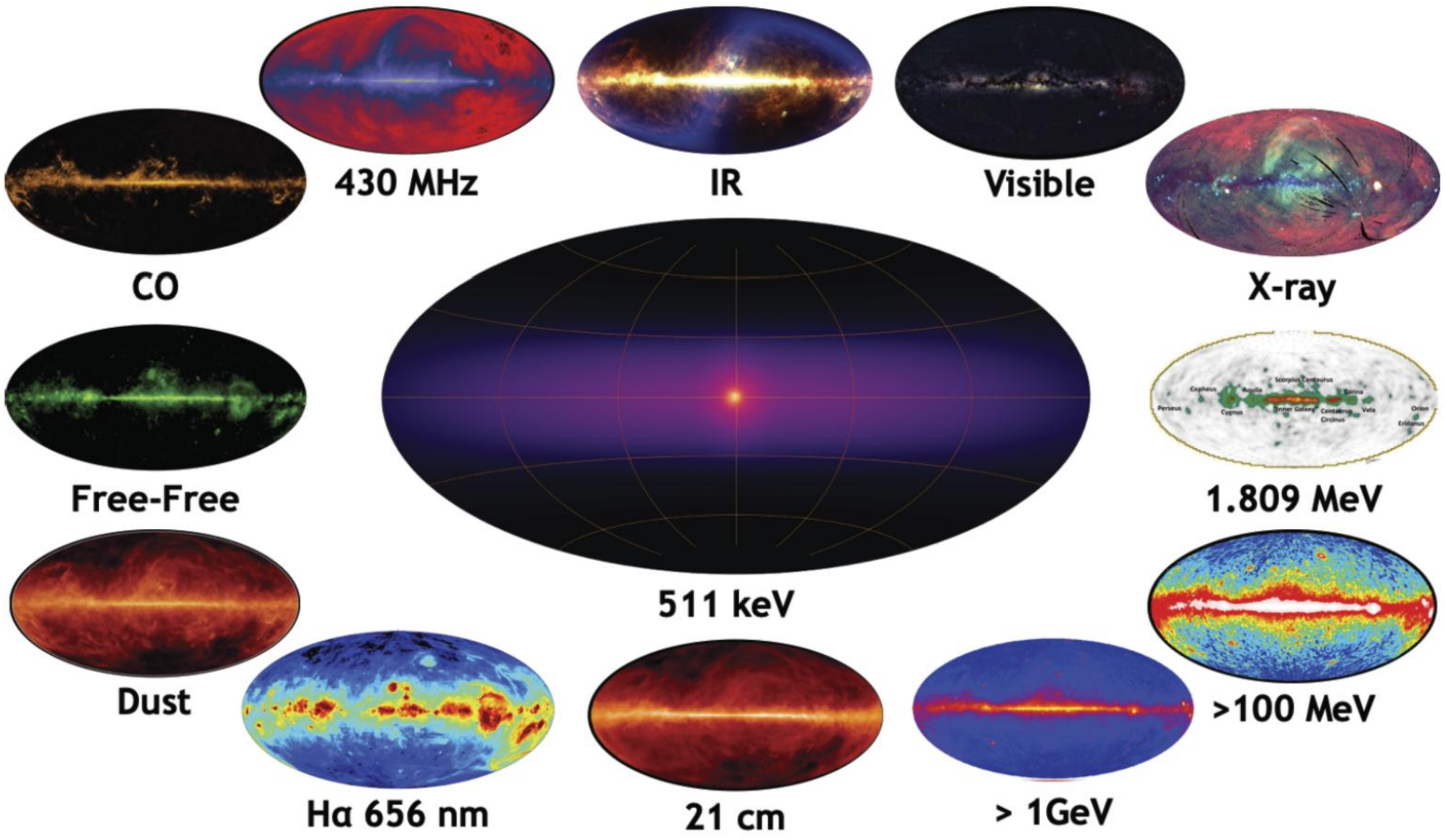
# Outlook

- Understanding the background: Origin of the diffuse gamma-ray background in the MeV band.

- The 511 KeV line
  - History
  - Properties

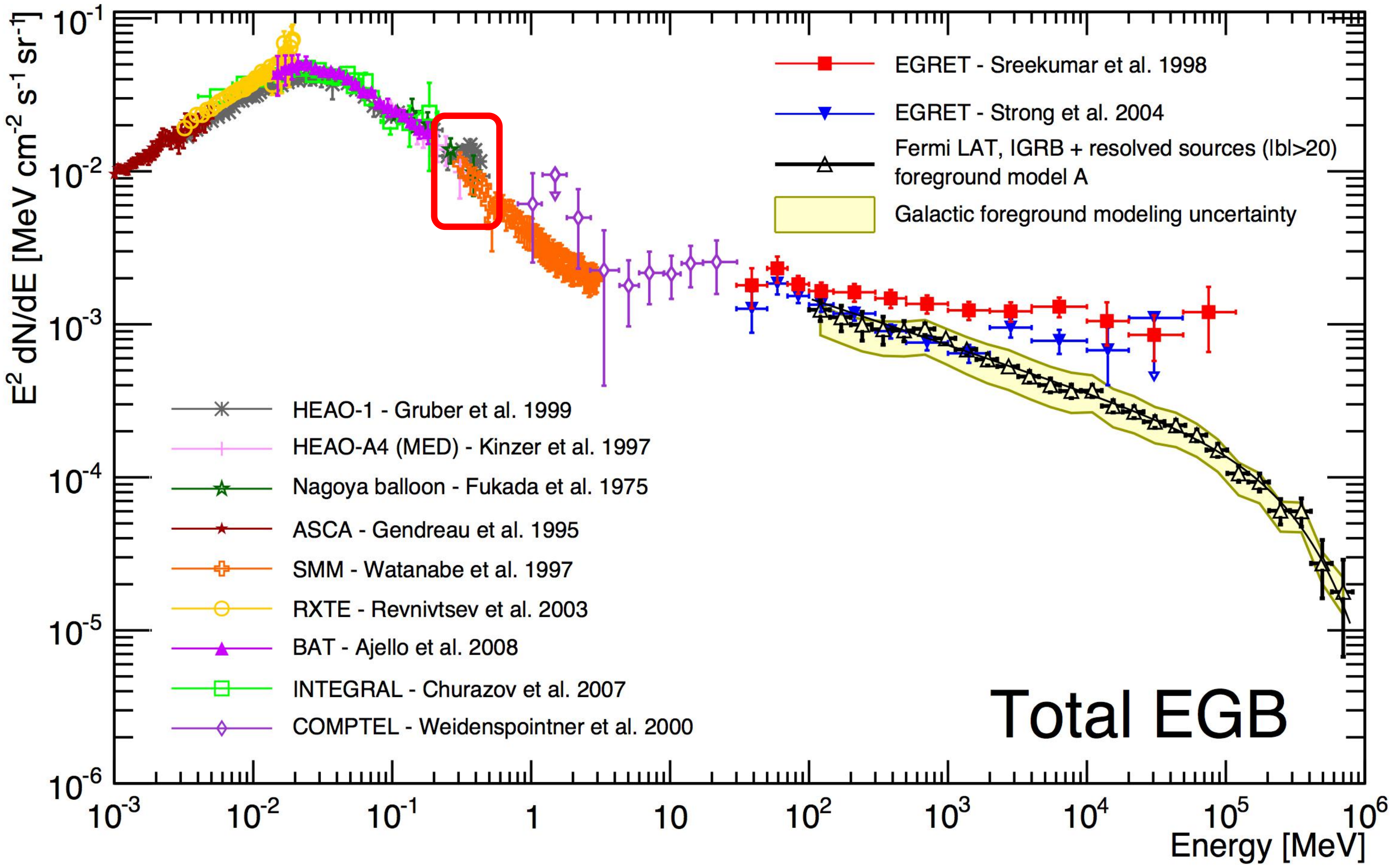
- Dark Matter as an interpretation of the 511 KeV line.
- Summary

# The Universe across colors




credit: Thomas Siegert

# Same picture



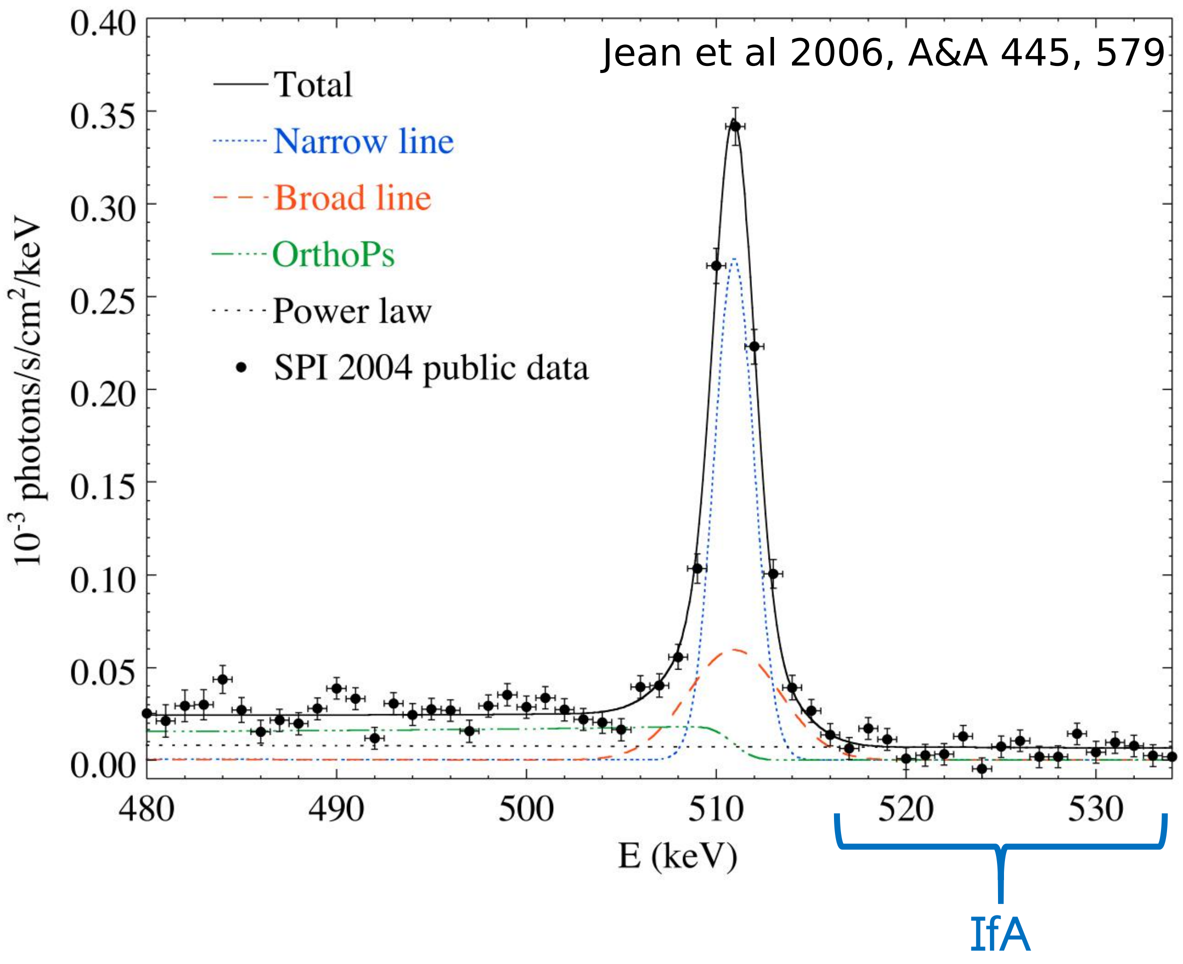

credit: Fermi-LAT Collaboration

# The origin of diffuse gamma-rays in MeV band

We know that the origin of gamma-rays in the MeV range in Electron- Positron annihilation.

- Direct Electron-Positron Annihilation

  i.e In-flight Annihilation (IfA)



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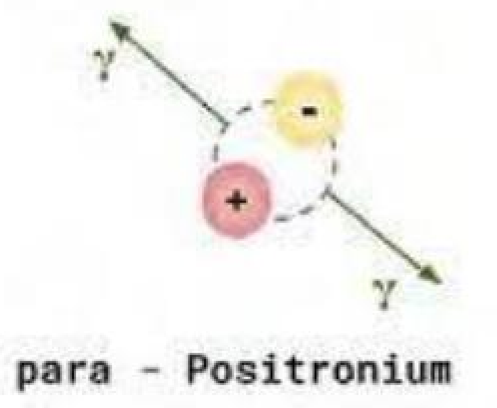
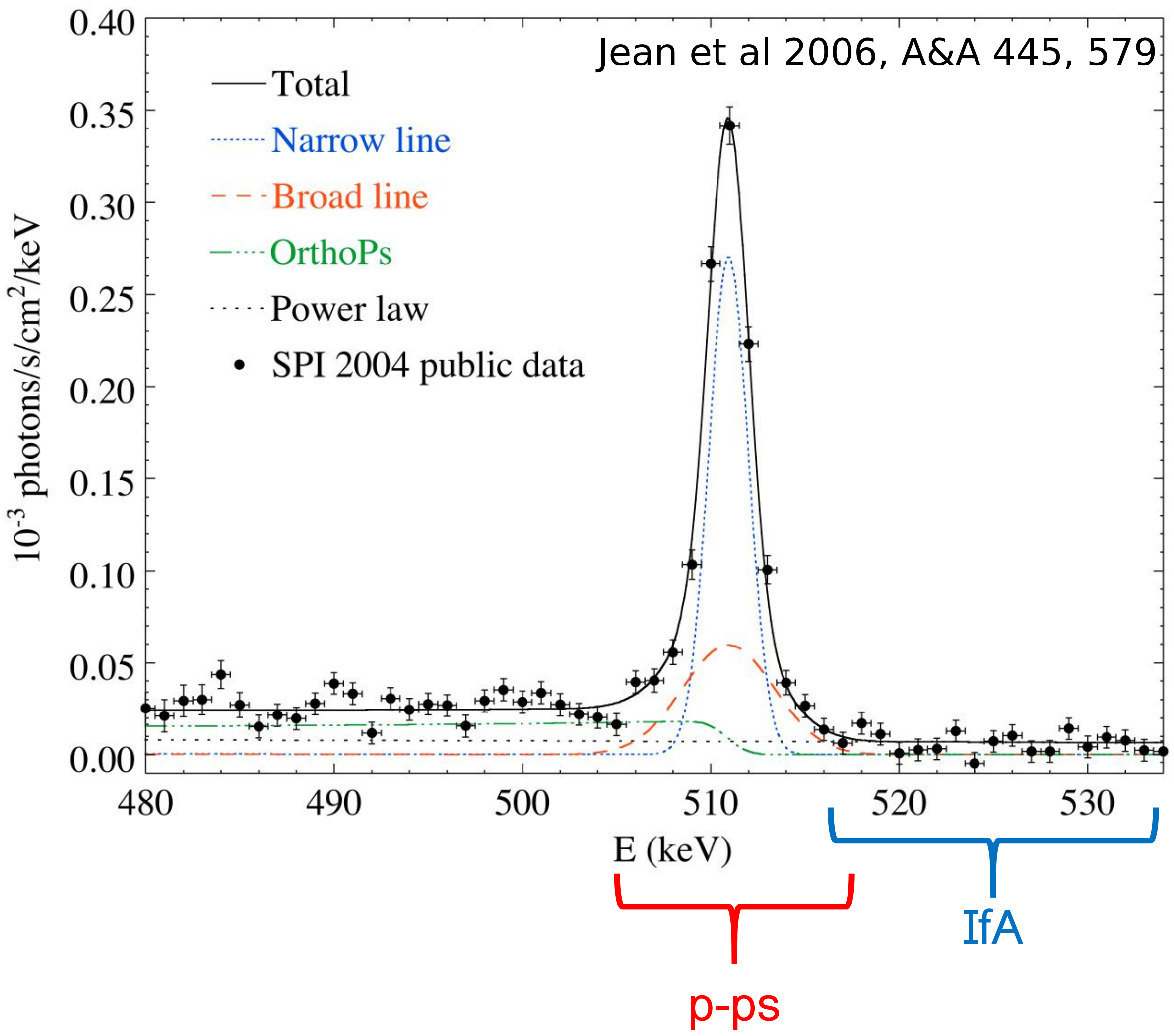
  - Para-Positronium (p-ps)



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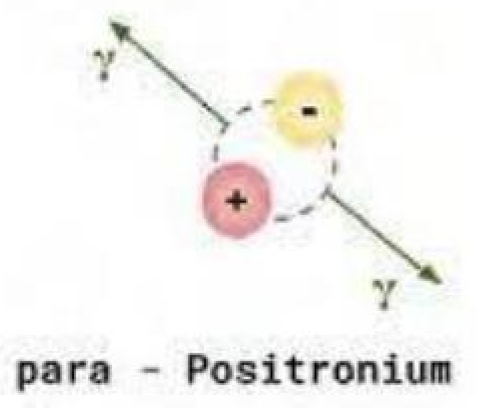


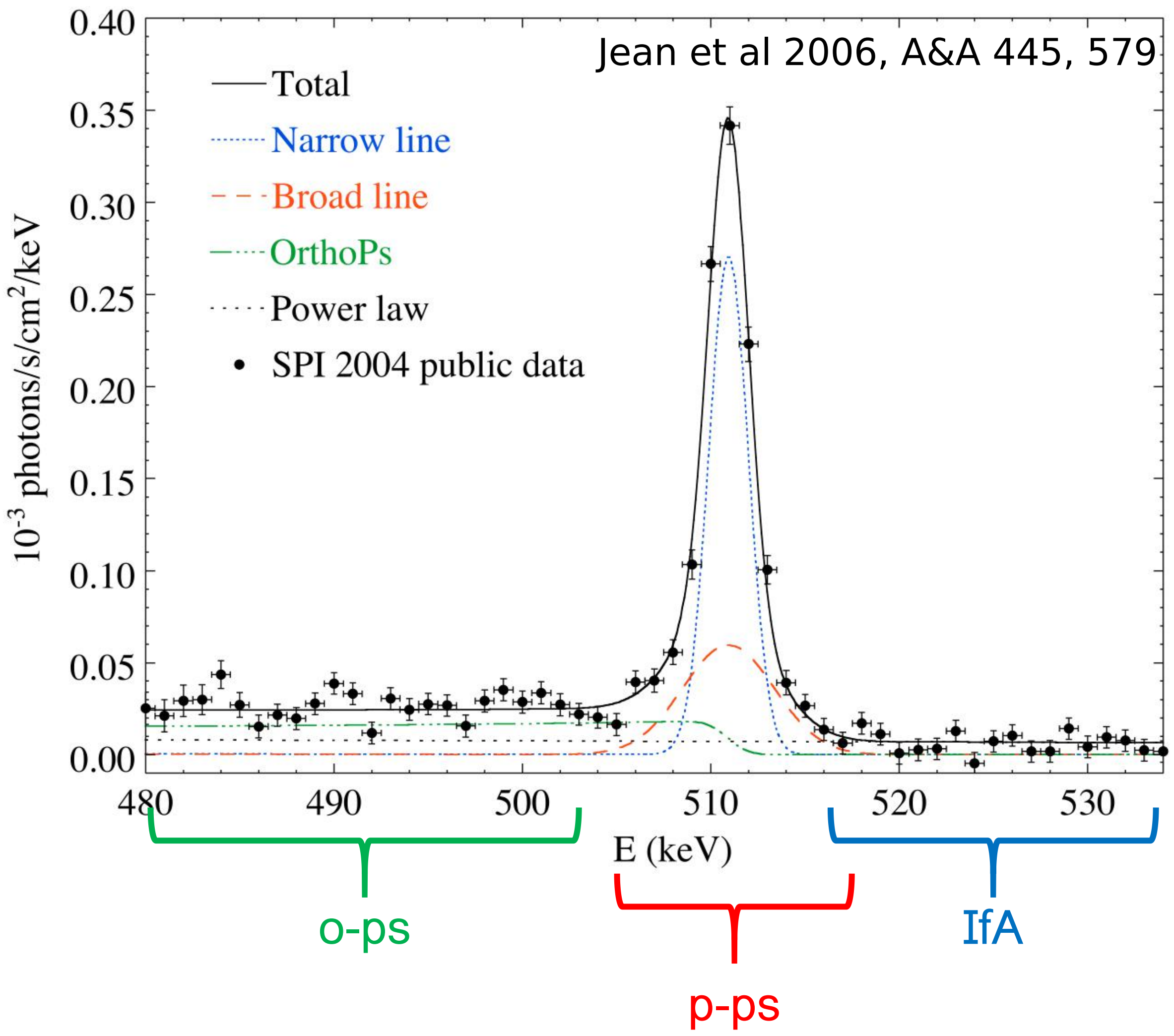

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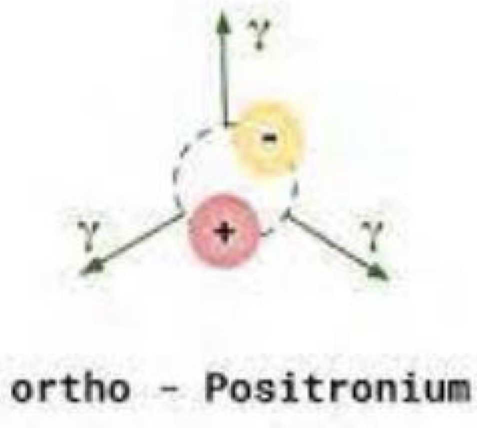


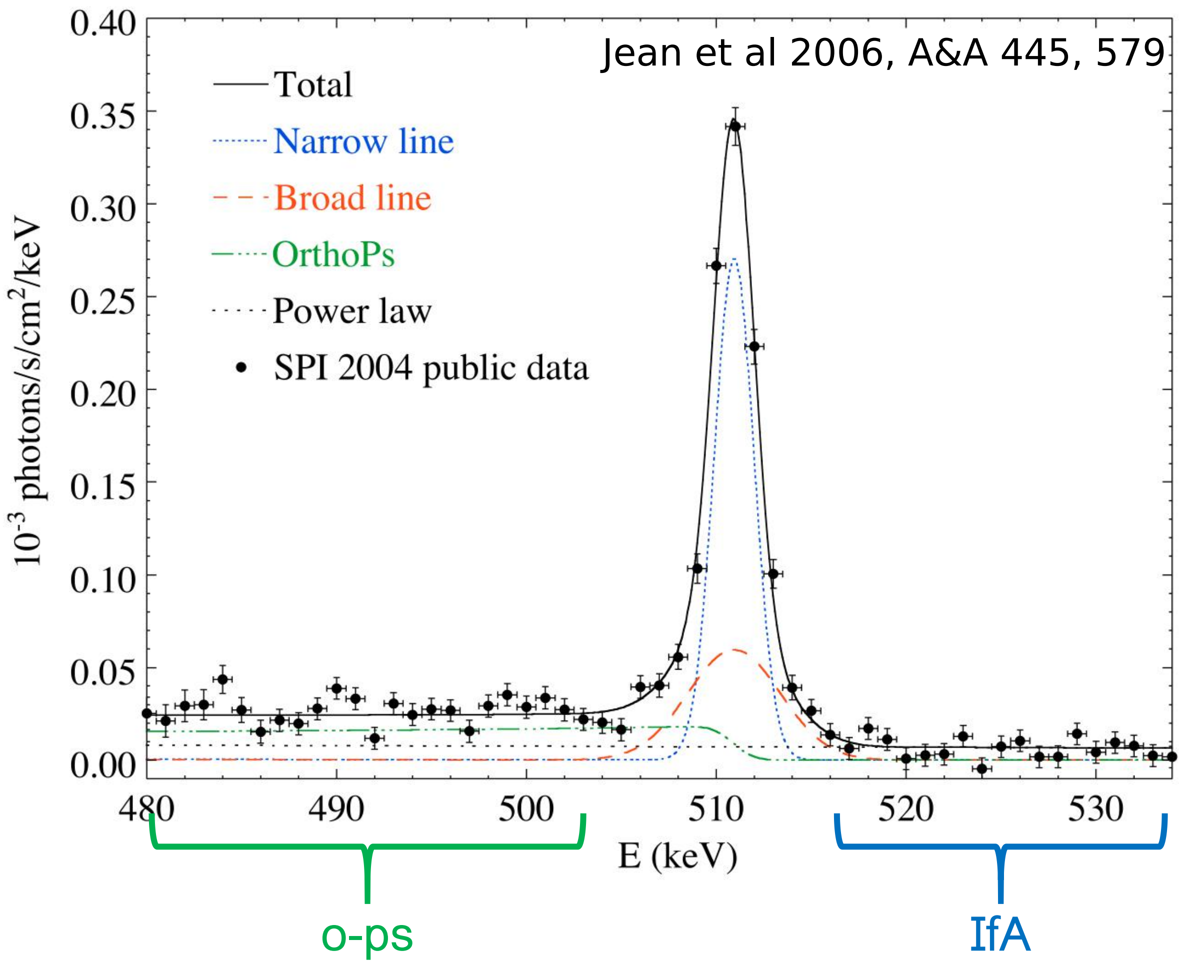

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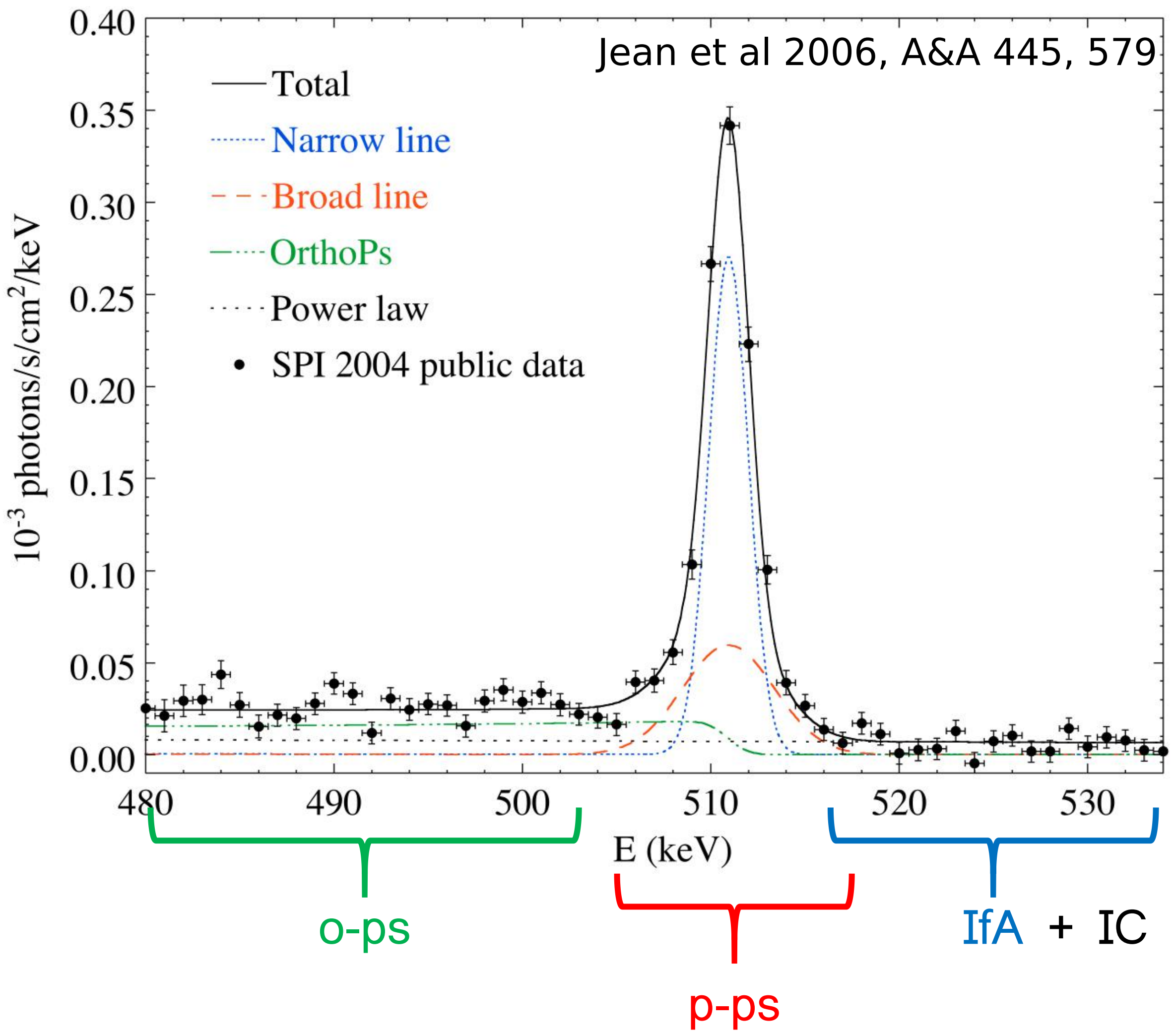
- Inverse Compton Scattering (IC)



# 511 KeV line -- History

- 70s

The 511 keV gamma-ray line was first detected by balloon-based experiments.

- 80s

The HEAO-3 satellite and balloon-borne detectors provided more refined measurements, confirming the line's association with the Galactic Center region.

- 90s

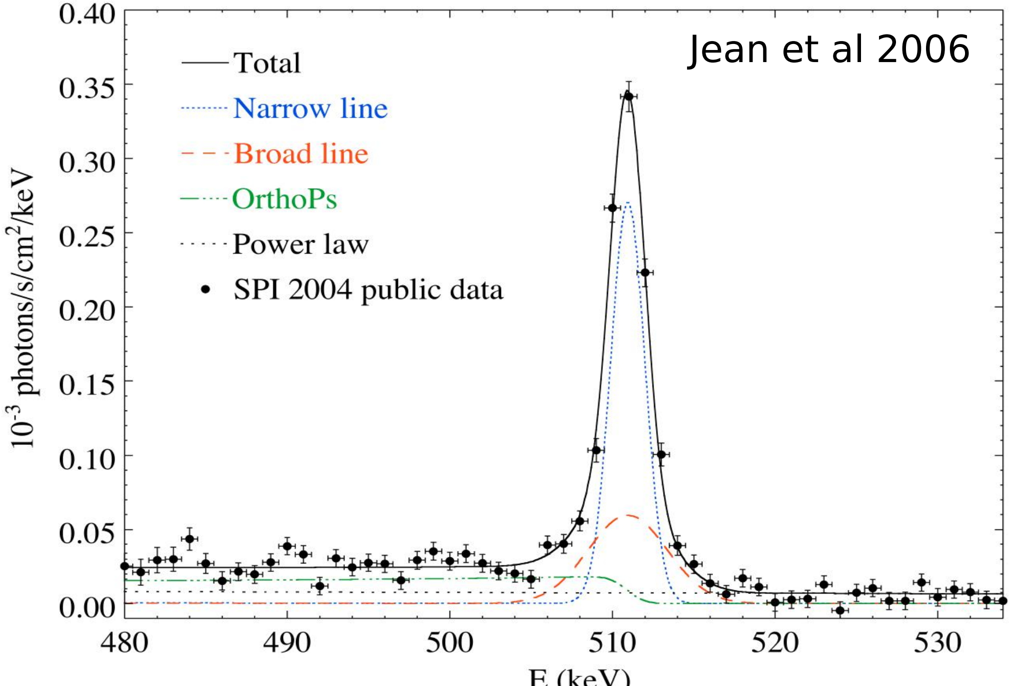
The Compton Gamma-Ray Observatory (CGRO) and its instruments, particularly OSSE (Oriented Scintillation Spectrometer Experiment), mapped the spatial distribution of the 511 keV emission. The observations suggested the excess was concentrated in the Galactic bulge, with weaker contributions from the disk.

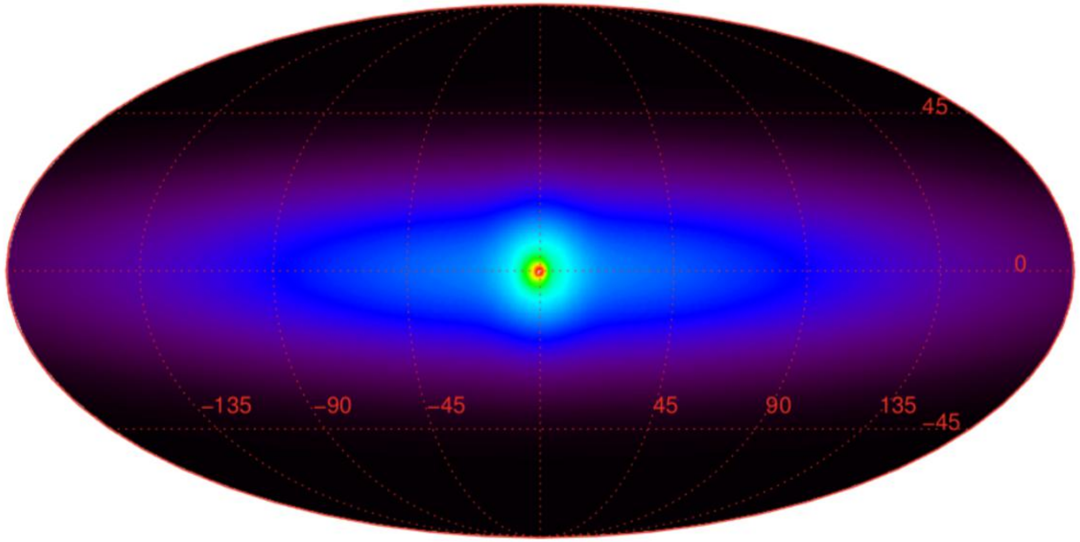
- 2002

The INTEGRAL (International Gamma-Ray Astrophysics Laboratory) satellite, launched in 2002, provided the most detailed data to date on the 511 keV line.

# 511 KeV line -- Properties

- The 511 keV emission from the galactic bulge is measured with a significance of 56σ
- The 511 keV emission from the galactic disk is measured with a significance of 12σ
- The excess is almost symmetric around the galactic bulge!




Very peaked emission towards the center (bulge emission) + a very extended disk emission

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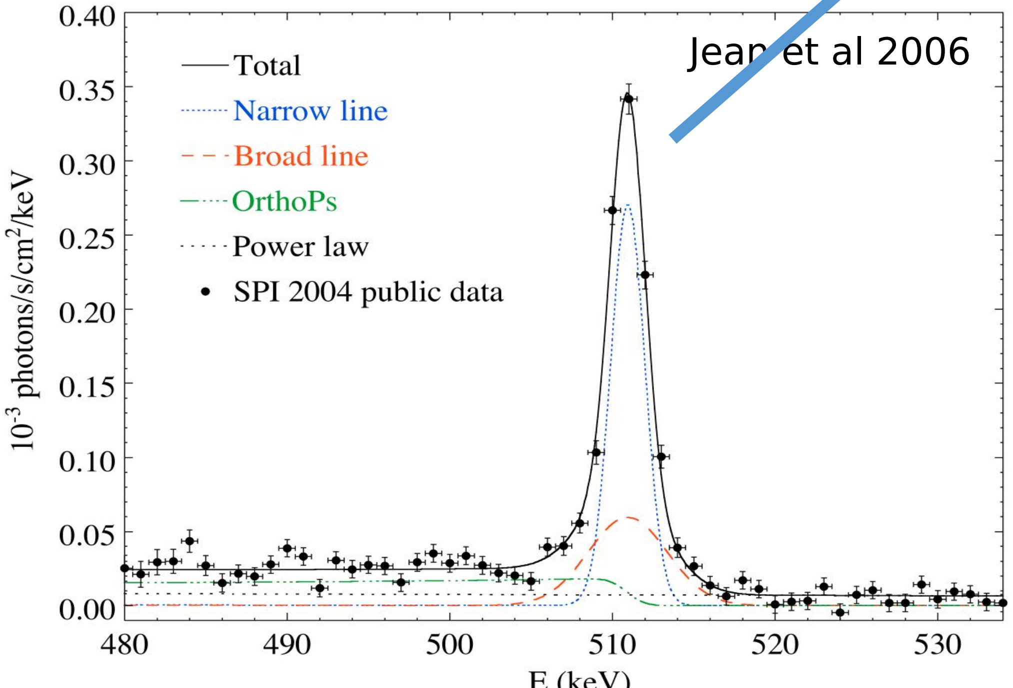
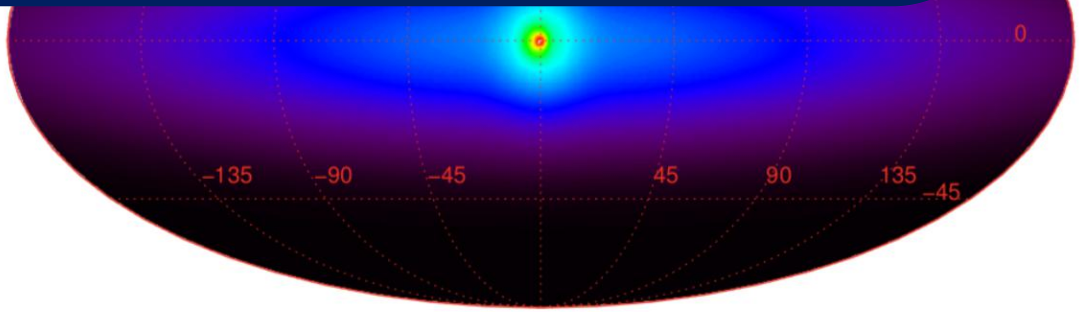


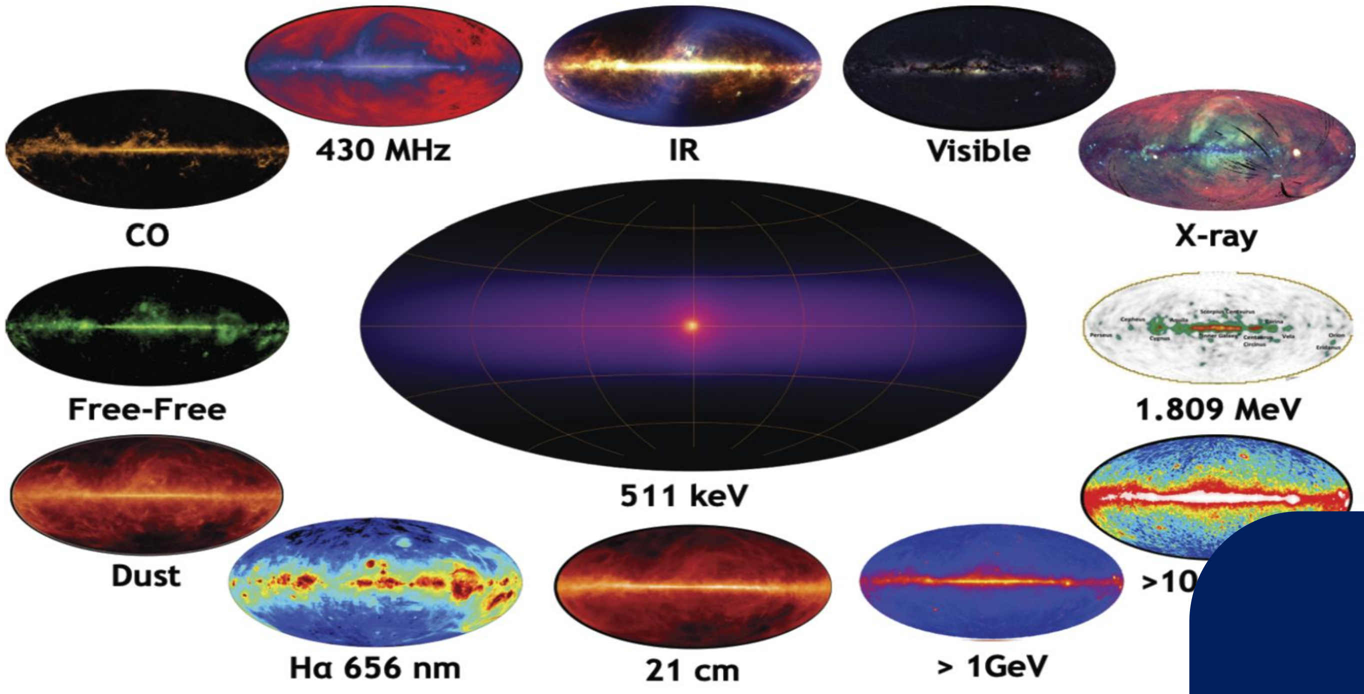

**511 KeV line puzzle:**

**Q1. The line is so pronounced. What sources the excess?**




Very peaked emission towards the center (bulge emission) + a very extended disk emission

# The Universe across colors

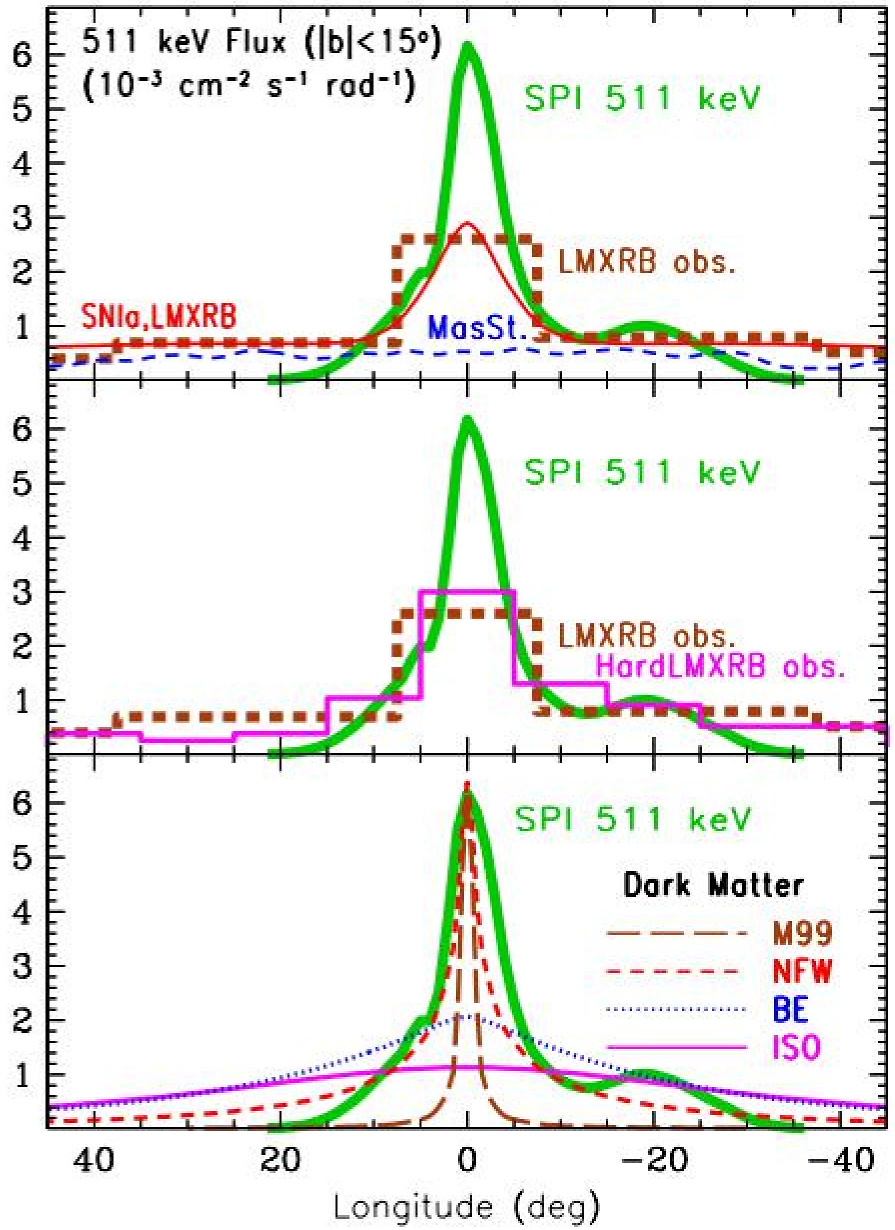



**511 KeV line puzzle:**

**Q2. The gamma-ray emission in all energies is extended in the galactic disk. Why is it brighter in the Galactic bulge?**

# 511 KeV line -- Interpretations

- “Convential” Astrophysics (i.e. not requiring BSM explanation)
  - $\beta^+$ decay of the radioactive nuclei in proton-rich environ
    - Massive stars: $^{26}Al$, $^{44}Ti$
    - Supernoave: $^{56}Ni$, $^{56}Co$
  - Low mass X-ray binaries
  - High energy processes in compact objects
    - pp collision in Blackhole accretion disk
    - γγ pair production in pulsars and magnetars
- Dark Matter :)



# MeV Dark Matter

- Celine Boehm et al. proposed a thermal MeV dark matter candidate with a mass (1-100 MeV) annihilating into electron-positron pair as a solution to the 511 KeV line in 2004.
- They realized that the DM decay could not fit the morphology of the observed emission
- Also, they found the DM annihilation cross that fit the data is

$$\langle \sigma v_r \rangle_{\rm now} \approx a + v_0^2\, b \lesssim 10^{-31} m_{\rm MeV}^2 \ {\rm cm}^3 {\rm s}^{-1}$$

- This is in tension with the relic abundance consideration which requires DM annihilation cross section to be $10^{-26}$ $cm^3$ $s^{-1}$.
- So, natural solution was DM with p-wave annihilation cross-section.

**The Boehm studies showed that thermal MeV DM (1-100 MeV) can explain both the magnitude and morphology of the excess.**

# MeV Dark Matter

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**But...**

In 2006, Beacom studied the gamma-ray spectrum due to inflight annihilation and found

$$K_{e^+} < 3 \text{ MeV}$$

So for the MeV dark matter candidate that annihilates directly into electron positrons

$$M_{DM} < 3 \text{ MeV}$$

Later in 2007, in a more detailed anaylysis this bound was corrected to be

$$M_{DM} < 10 \text{ MeV}$$

**MeV can explain both the magnitude and morphology of the excess.**

# MeV Dark Matter

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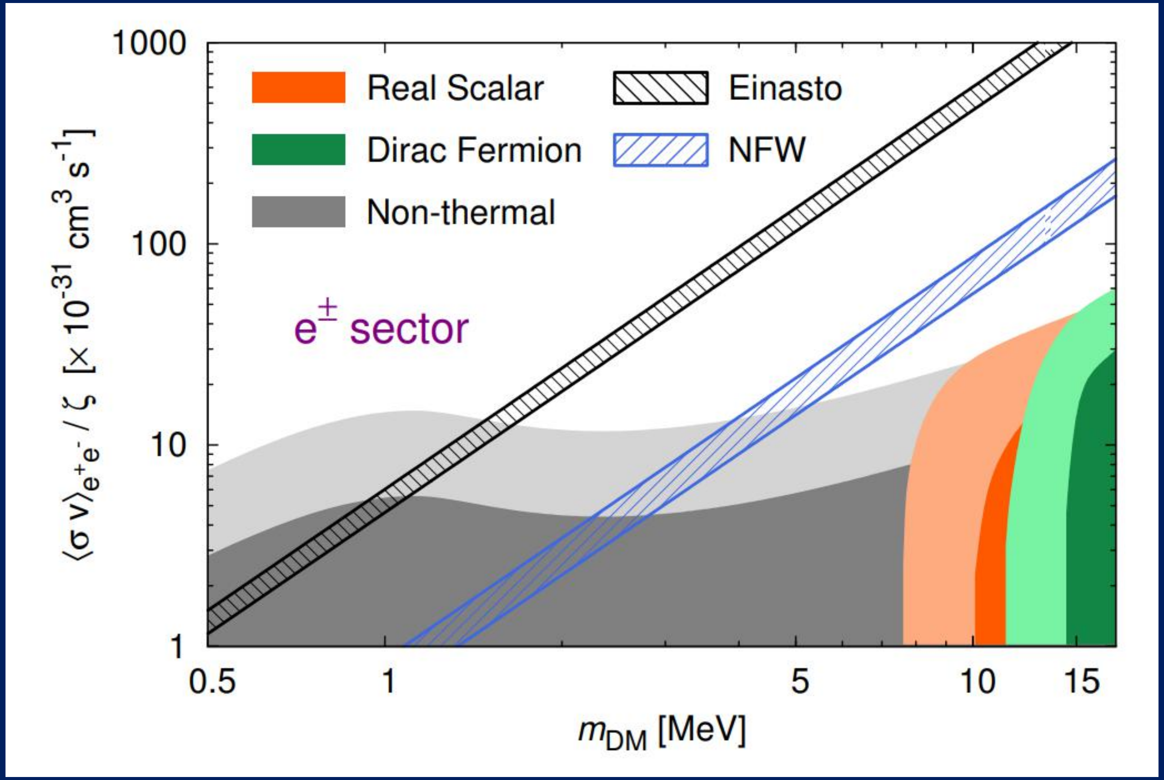
**But…**

In 2016, Aaron Vincent studied the cosmological bounds on a thermal dark matter with a velocity-dependent (p-wave) annihilation cross section into electrons and found

$m_{DM}$ > 11 MeV (thermal fermionic WIMP)



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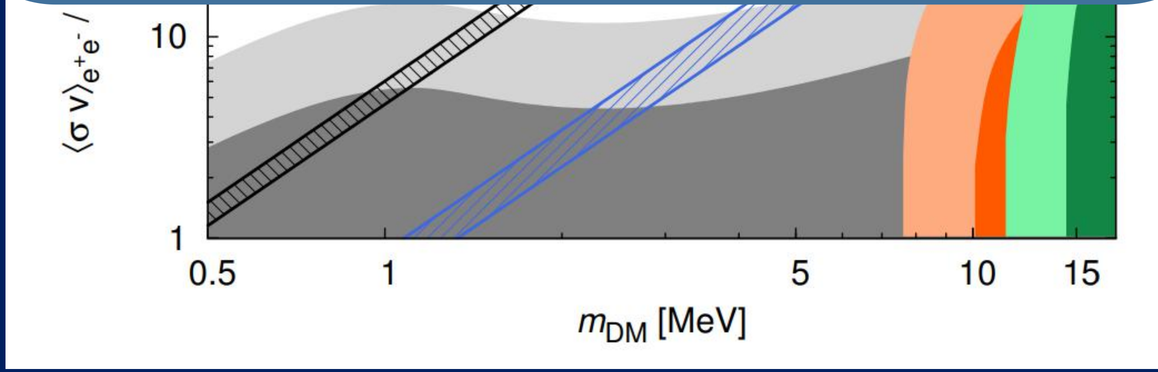
Finito!

DM è Morto**???**



# H(ALP) comes to save the day

We extend the matter content of the SM with a fermionic DM candidate that talks to SM via the ALP portal.

$$\mathcal{L}_{\text{int}} \supset ia\left(g_\chi \bar{\chi}\gamma_5\chi + g_e \bar{e}\gamma_5 e\right)$$

$g_e$ and $g_\chi$ are real.

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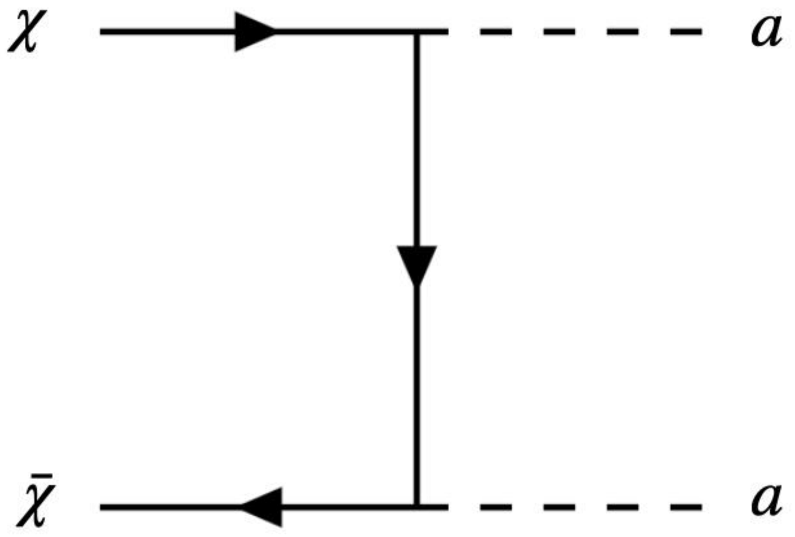
In this scenario the DM candidate, $\chi$ annihilates via two main processes

- p-wave annihilation into two axions

$$\langle\sigma v\rangle_{aa} = \frac{6}{z}\frac{g_\chi^4}{24\pi}\frac{m_\chi^2(m_\chi^2-m_a^2)^2}{(2m_\chi^2-m_a^2)^4}\sqrt{1-\frac{m_a^2}{m_\chi^2}}$$




*p-wave*

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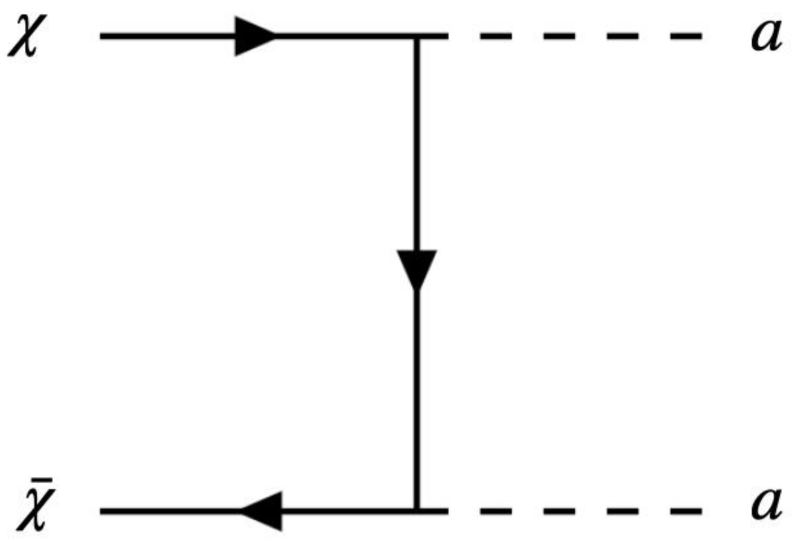



1. This process is dominant in the early universe and generates the relic abundance of the dark matter.

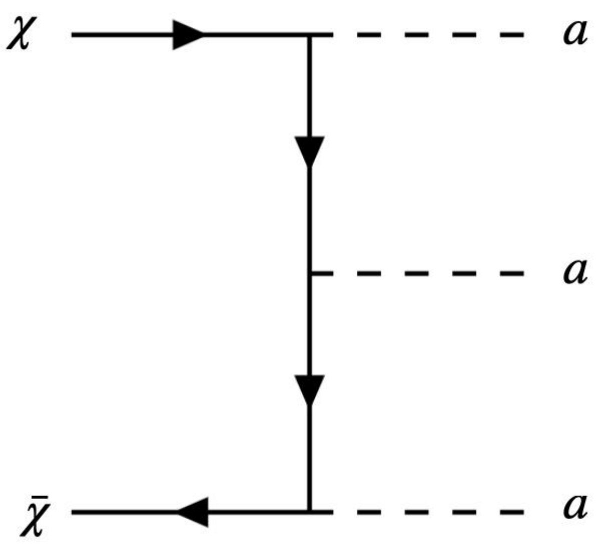
2. Solving the Boltzmann equation, and fixing the DM abundance to the relic abundance we find $g_\chi$ as a function of DM mass!

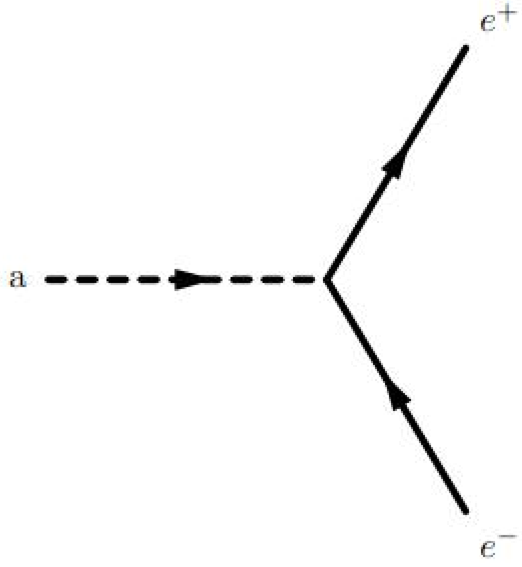
# H(ALP) comes to save the day

s-wave annihilation into three axions

$$\langle \sigma v \rangle_{aaa} \simeq \frac{(7\pi^2 - 60) g_\chi^6}{1536 \pi^3 m_\chi^2}$$

(In the limit $m_a$ --> 0)




1. Using the $g_x$ fixed by relic, we get a cross section

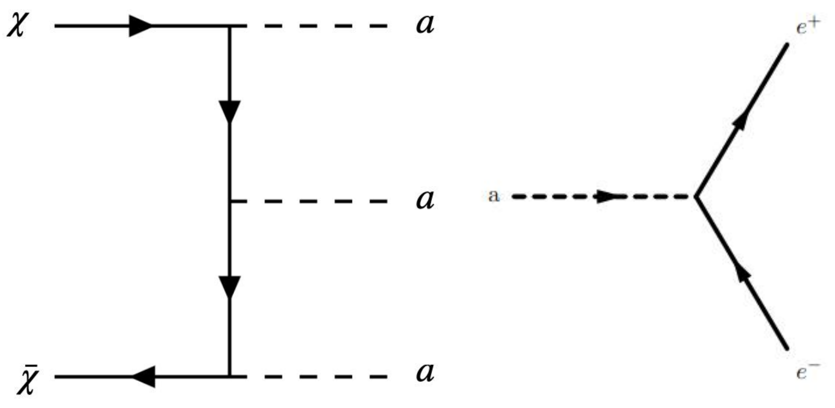
$$\langle \sigma v \rangle_{aaa} \simeq \mathcal{O}(10^{-31})$$

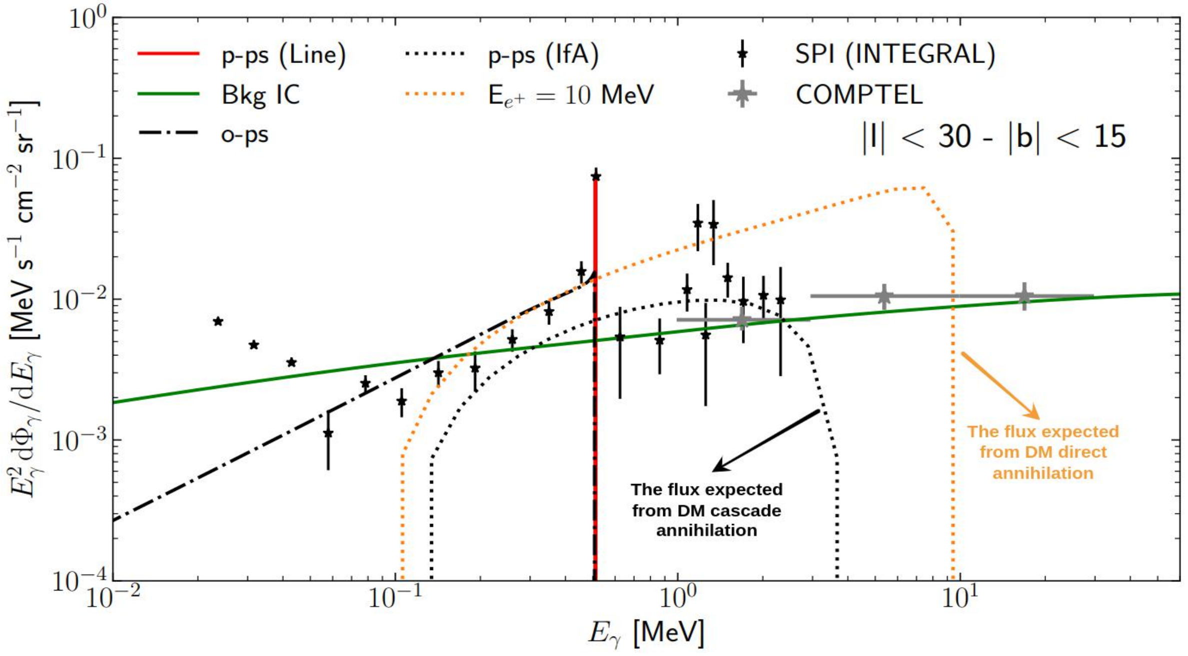
2. The process is s-wave and it might be able to fit the morphology of the data.
3. Every annihilation produces 3 pairs and this might make it easier to fit the magnitude.

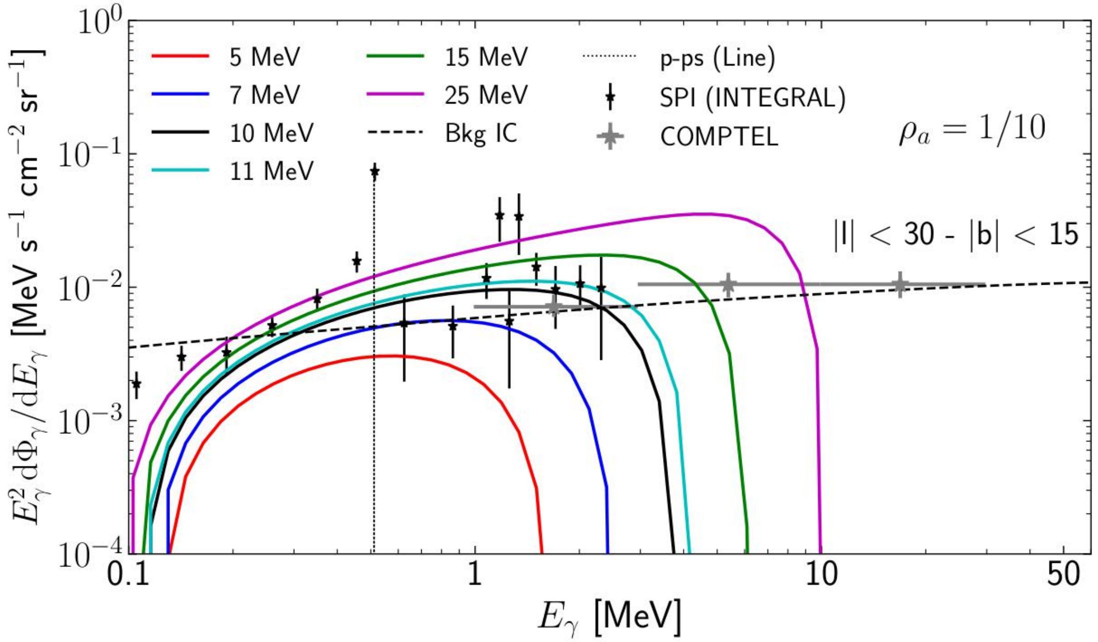
# Moreover!!

One can easily see

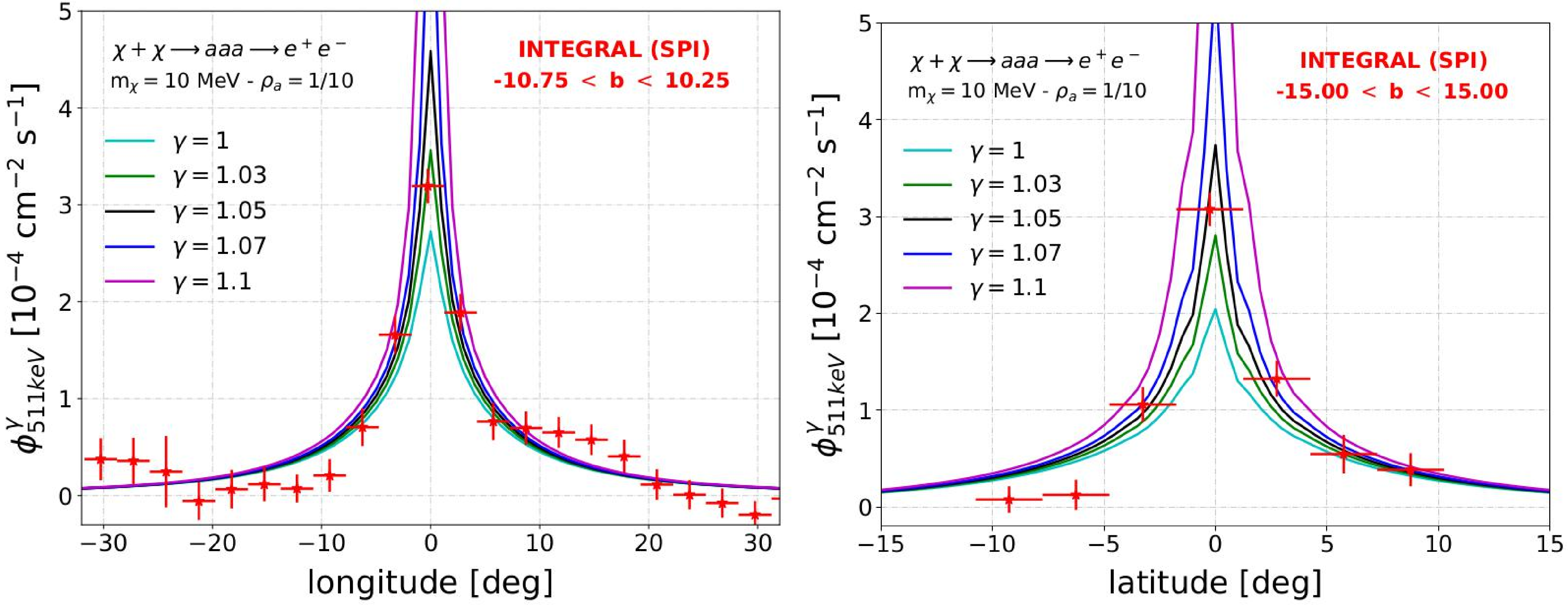
$$2m_\chi > 3m_a > 6m_e \Rightarrow K_{e^+}^{Max} = \frac{m_\chi}{3} - m_e$$



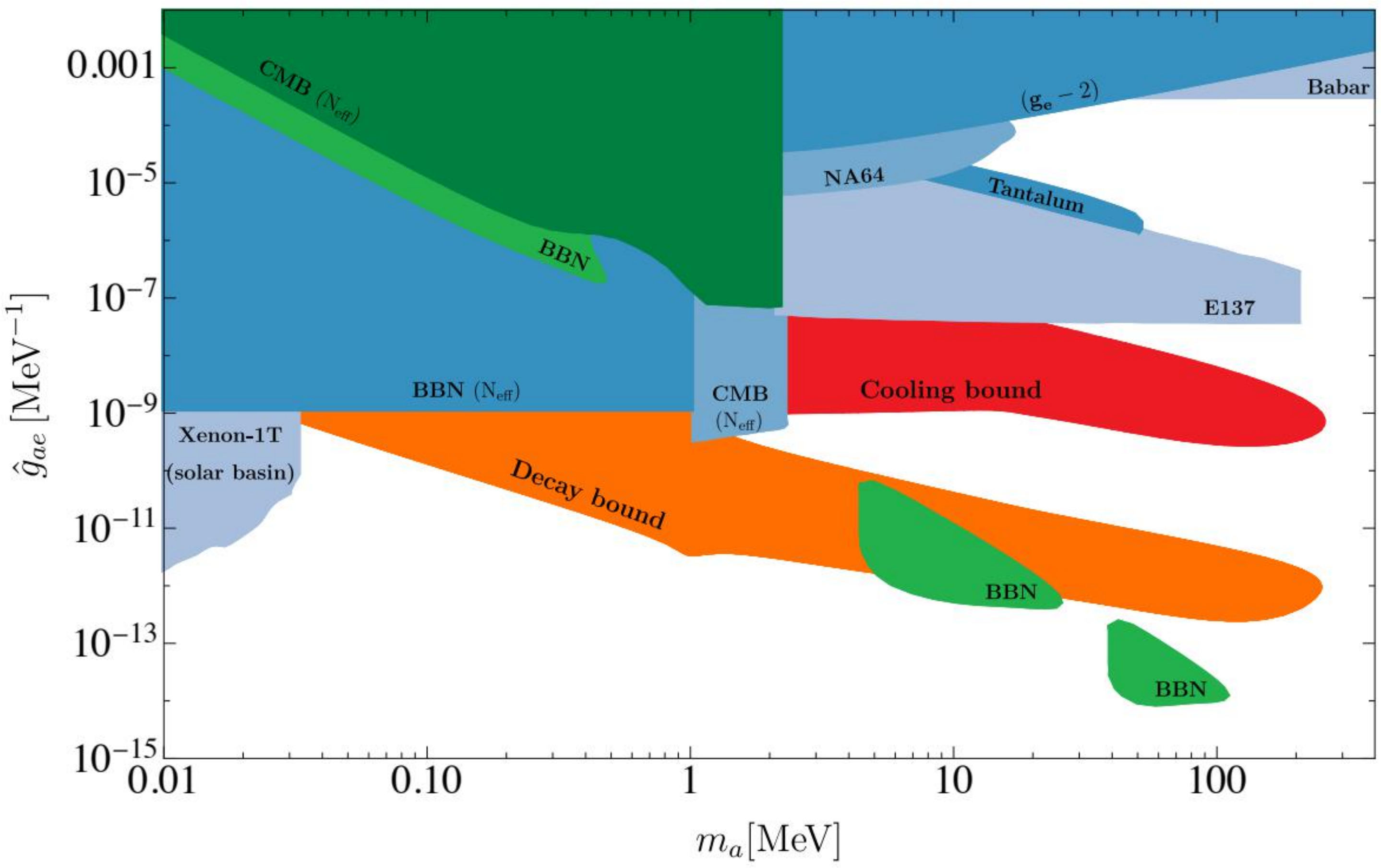



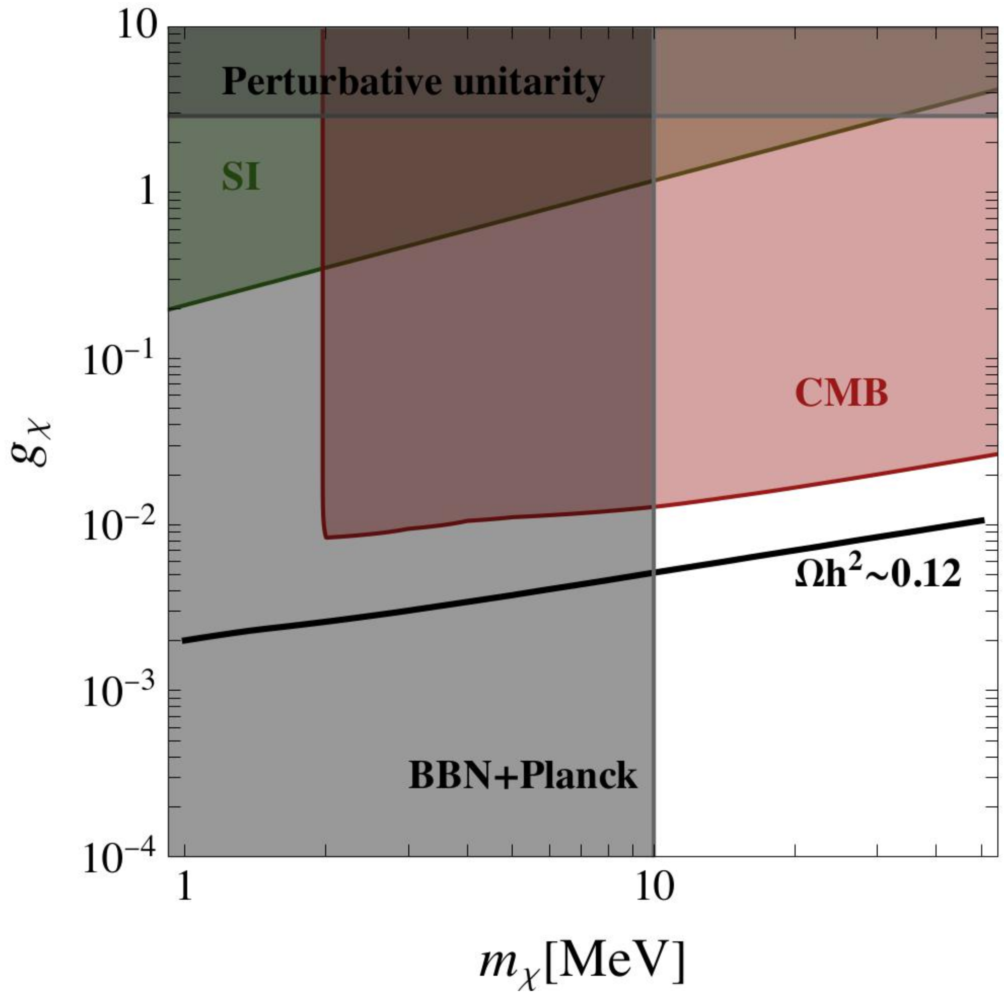



# Our DM model explains 511 KeV line



# Cosmological bounds



# Summary and Prospect

- The 511 KeV line excess is still there!
- Known Astrophysical Phenomena struggle in explaining its morphology.
- The early Beacom bound was too stringent.
- MeV DM candidate with a cascade annihilation via an ALP mediator explains the anomaly, perfectly.
- CMB-S4 is going to be able to probe the parameter space of our DM candidate.

Thank you!