p-wave Annihilating Dark Matter and the Galactic Center Excess

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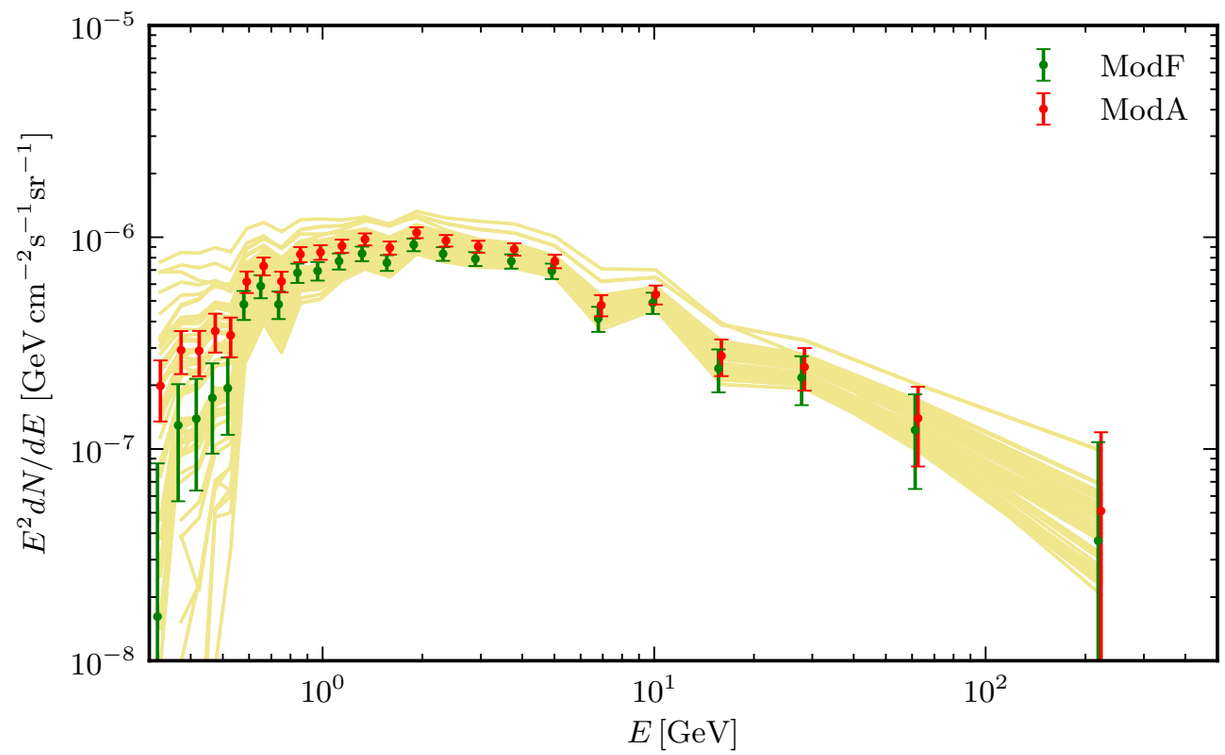
The Galactic Center Gamma-Ray Excess

Two classes of explanations:

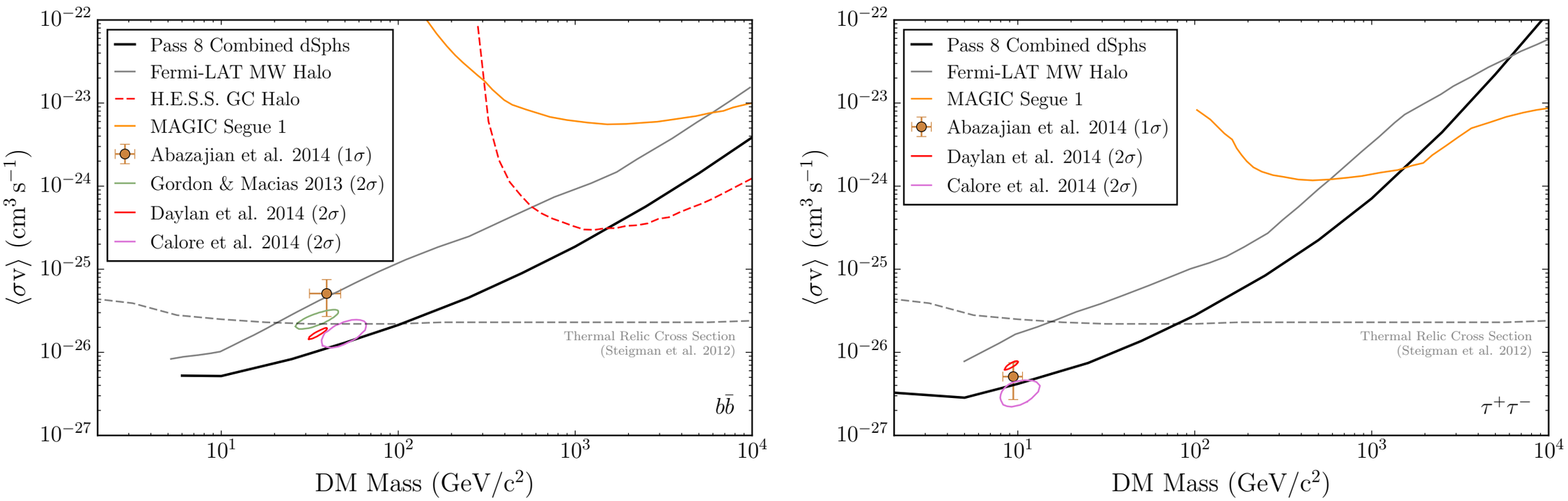
1. *Astrophysical* — Millisecond pulsars, burst events

2. *Dark matter annihilation!*



Calore, Cholis, Weniger (2014)

The Galactic Center vs. Dwarf Spheroidal Galaxies

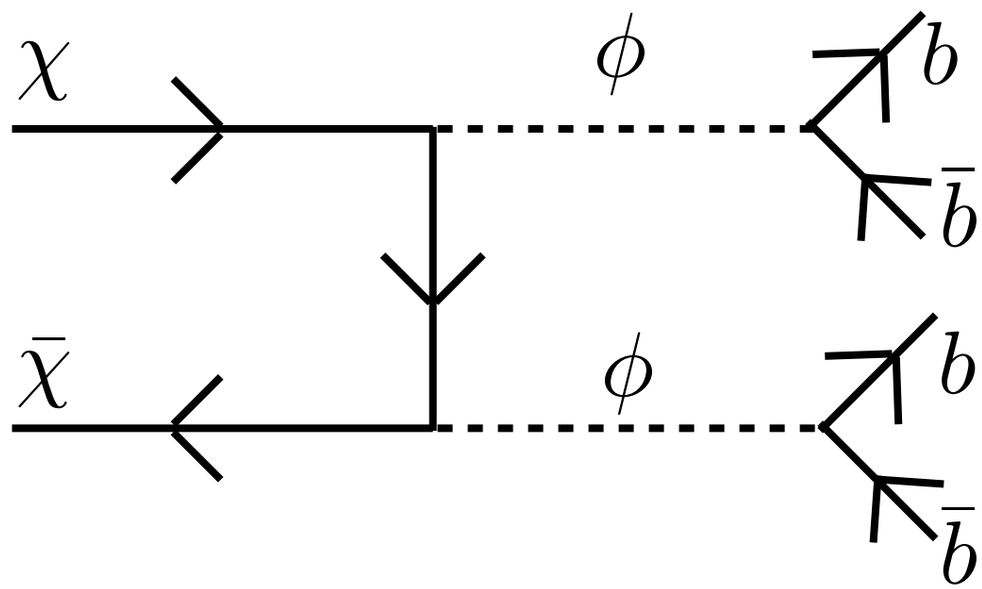


Fermi-LAT (2015)

- The best fit *s*-wave cross section and DM mass to the galactic center excess are in tension with limits from dwarf galaxies

- A solution: *p*-wave annihilating DM — velocity dispersion is low in dwarfs relative to the GC.

Scalar Mediator Model

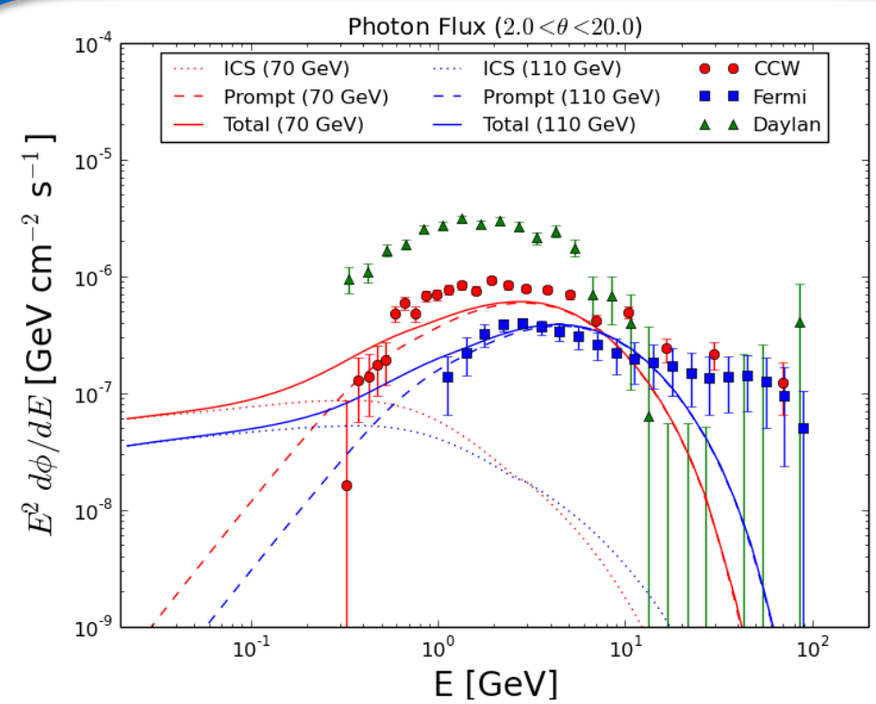


- Velocity dependent annihilation cross section to on-shell mediators.

- By putting mediator on-shell, coupling to SM does not matter for annihilation rate, so constraints from direct detection and LHC can be avoided. Abdullah, et. al. (2014)

- In calculation of gamma-ray spectrum, we include *prompt photon emission* as well as secondary *inverse Compton scattering* and *bremsstrahlung* from *b*-quark shower products.

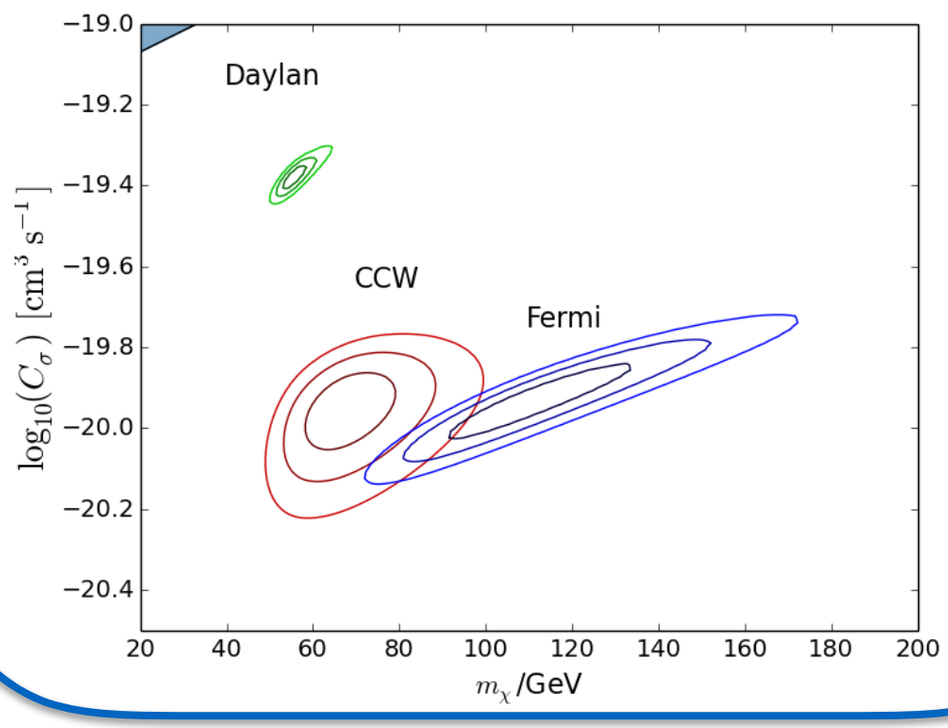
Fitting calculated spectra to the excess:



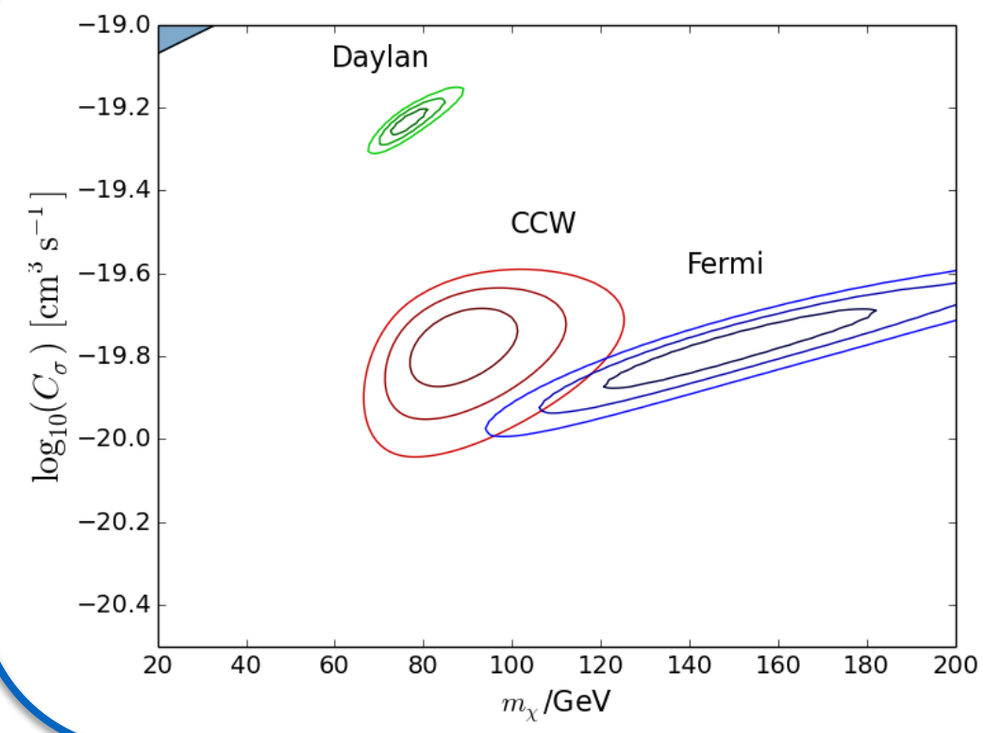
$$\langle \sigma v \rangle = C_\sigma (\sigma_v / c)^2$$

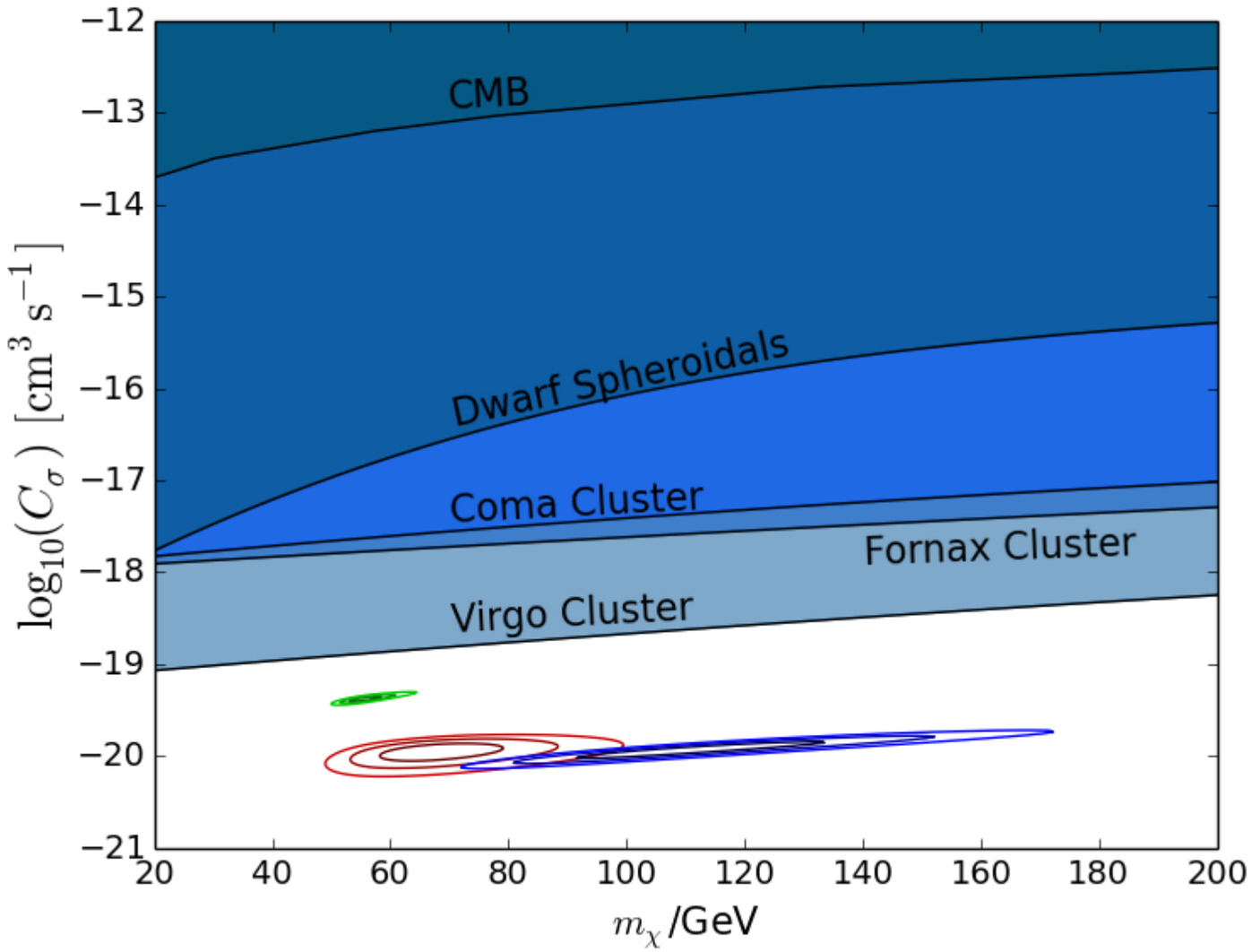
velocity dispersion

$m_\phi = 12$ GeV



$m_\phi = 50$ GeV

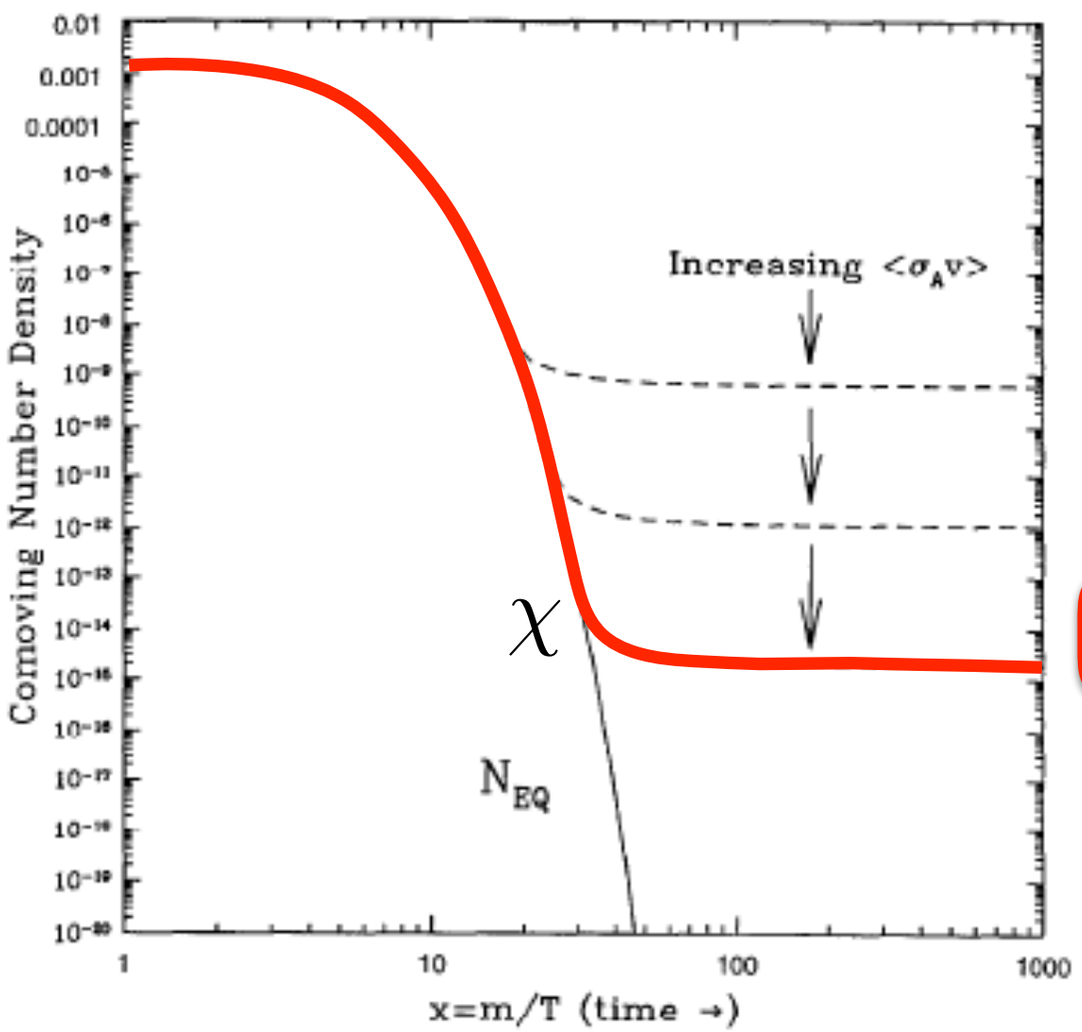




- We avoid constraints from *dwarf spheroidals* entirely.
- However, *galaxy clusters*, with their large velocity dispersions, could possibly constrain this scenario.

The Relic Density

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \frac{\langle\sigma v\rangle}{2}\left(n_\chi^2 - n_\chi^{\mathrm{EQ}\,2}\right)$$



For p-wave annihilating DM with parameters that fit GC excess,

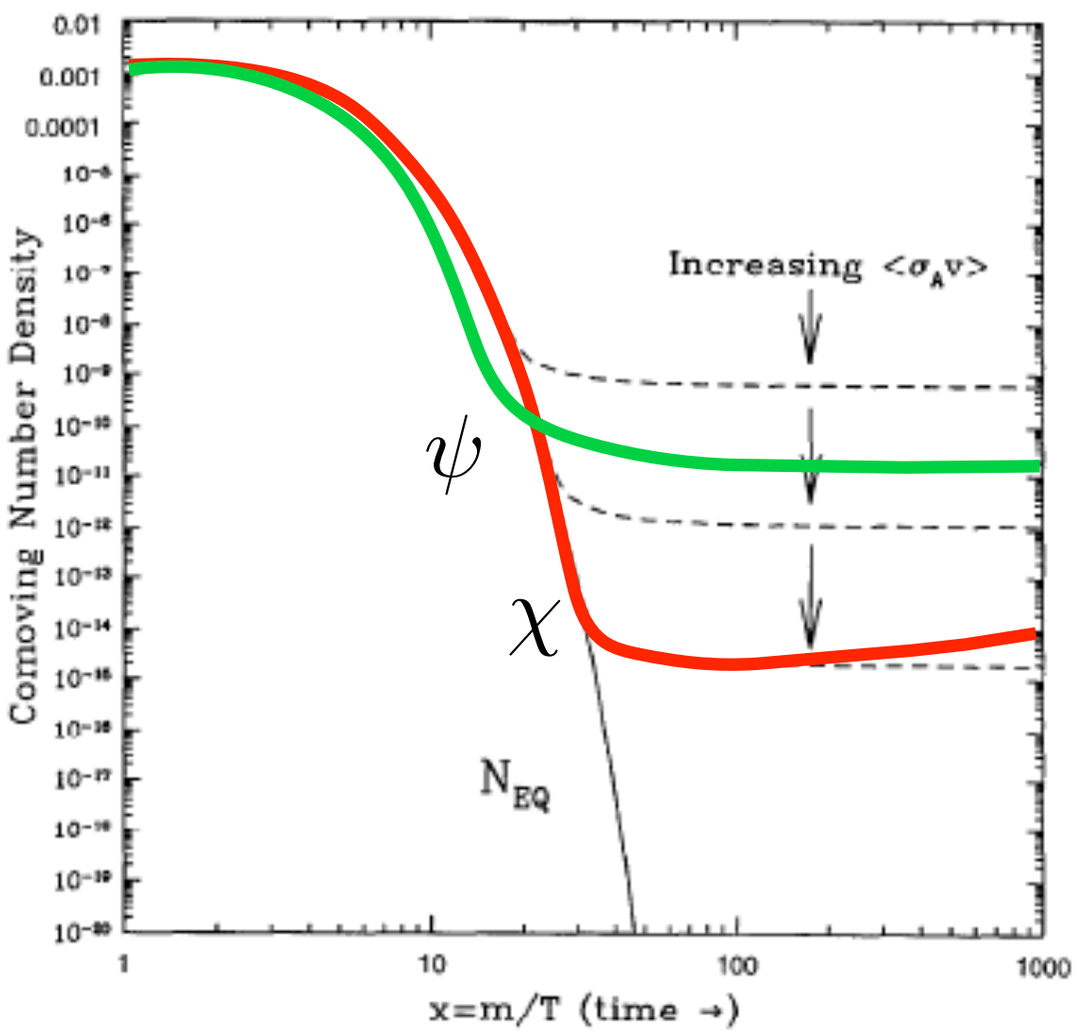
$$m_\chi \sim 90\,\mathrm{GeV}, \quad \mathrm{C}_\sigma \sim 10^{-20}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$$

$$\boxed{\Omega_\chi = 3.6 \times 10^{-5}}$$

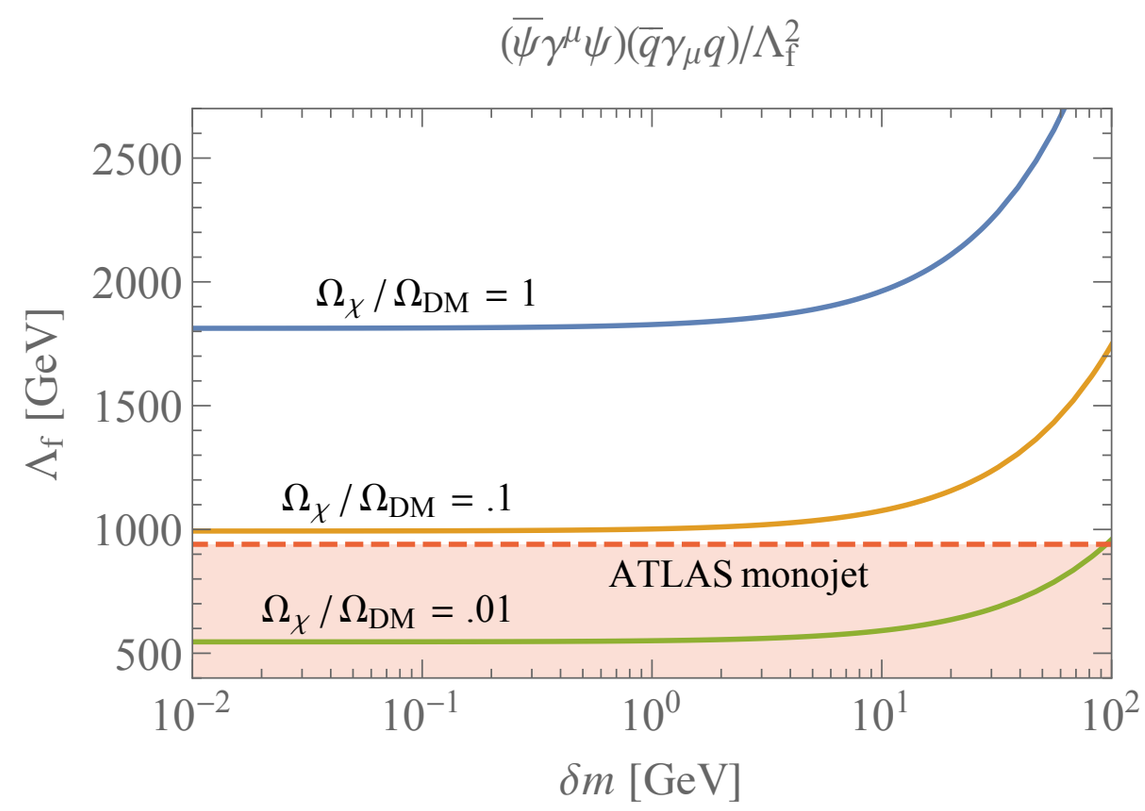
Much too small!

The Relic Density

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \frac{\langle \sigma v \rangle}{2}\left(n_\chi^2 - n_\chi^{\mathrm{EQ}^2}\right)$$



Solution: A heavier state ψ that freezes out earlier than χ and then decays to χ



3 Possible Decay Channels

Photon	e^+/e^-	Hadronic
$\frac{1}{\Lambda_\gamma}\,\bar{\chi}\sigma_{\mu\nu}\psi\,F^{\mu\nu},$	$\frac{(\bar{\chi}\gamma^\mu\psi)(\bar{e}\gamma_\mu e)}{\Lambda_e^2},$	$\frac{(\bar{\chi}\gamma^\mu\psi)(\bar{b}\gamma_\mu b)}{\Lambda_b^2}$

Lead to a more complicated Boltzmann equation:

$$\frac{dn_\chi}{dt} = -3Hn_\chi \boxed{-\frac{\langle\sigma_{\chi\bar{\chi}}\rangle}{2}(n_\chi^2 - n_\chi^{\mathrm{EQ}^2})} \boxed{-\frac{\langle\sigma_{\chi\psi}\rangle}{2}(n_\chi n_\psi - n_\chi^{\mathrm{EQ}} n_\psi^{\mathrm{EQ}})}$$

Anti-particle annihilation

Co-annihilation

$$\boxed{-\left(\langle\sigma'_{\chi f}\rangle n_\chi n_f - \langle\sigma'_{\psi f}\rangle n_\psi n_f\right)} \boxed{-\Gamma(n_\chi - n_\chi^{\mathrm{EQ}})}$$

Inelastic scattering

Decay

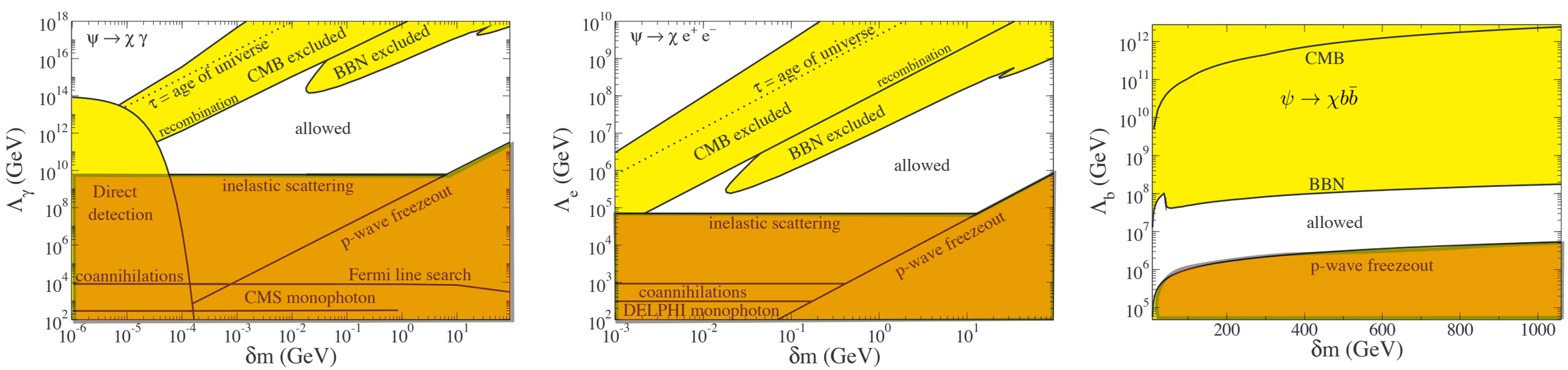
Conditions needed to get correct relic density:

- **Decays:** Lifetime of ψ should be longer than freeze-out time of χ: $\Gamma < H(t_f)$

- **Co-annihilations:** Should not deplete number density below measured relic density

- **Inelastic scatters:** Should occur at a smaller rate than $\bar{\psi}\,\psi$ annihilations:

$$(n_e + n_{\bar{e}})\langle\sigma v\rangle_{\psi e \to \chi e} < n_\psi \langle\sigma v\rangle_{\psi\bar{\psi}\to f\bar{f}}$$



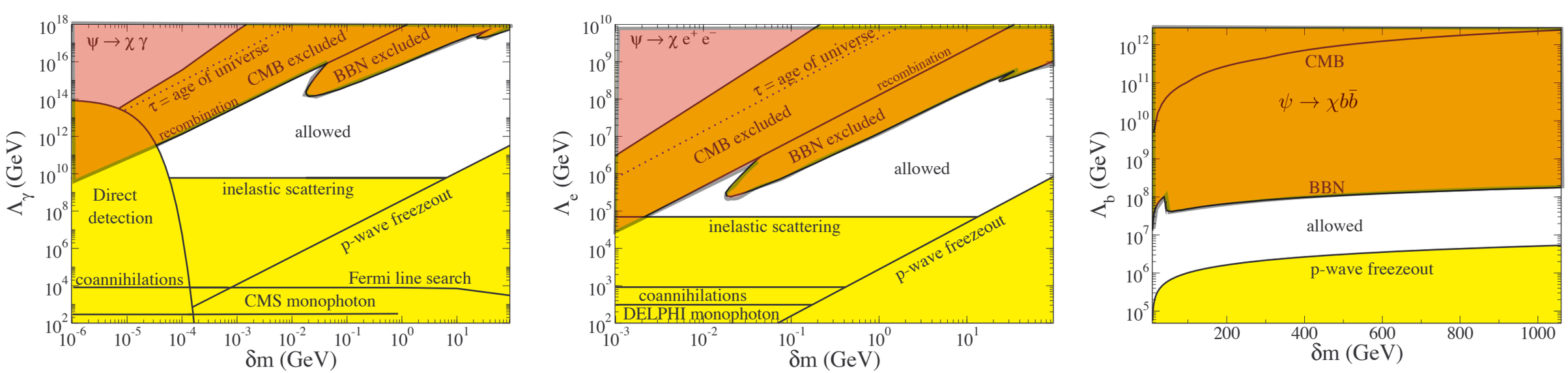
Late time decays can also cause problems:

- **Big Bang Nucleosynthesis:** Photo-disassociation as well as hadronic processes lead to incorrect element abundances (particularly constrained by ratios of $^3He/^2H$ and $^6Li/^7Li$).

  Jedamzik (2006)

- **Cosmic Microwave Background:** Injection of energy at recombination causes CMB distortion.

  Slatyer (2013)



Conclusions

- p-*wave annihilating DM* is an avenue to alleviate the tension between the possible signal of DM annihilation to gamma-rays in the galactic center and a lack of corresponding observations in dwarf spheroidal galaxies.

- Such a DM candidate can be produced with the correct abundance by a *decaying progenitor particle*.

- This model predicts a large gamma-ray signal from nearby *galaxy clusters*.