Title: Substructure, Sommerfeld, and CR Signals

Date: Sep 22, 2011 03:40 PM

URL: http://pirsa.org/11090092

Abstract: Models of dark matter with Sommerfeld-enhanced annihilation have been proposed to explain the CR excess observed by the PAMELA and Fermi experiments. In such models, the local annihilation signal can easily be dominated by small, dense, cold subhalos, instead of by the smooth DM halo as usually assumed. I will discuss how such a "substructure+Sommerfeld" scenario modifies constraints from the CMB, limits on DM self-interaction, and bounds from measurements of inner-Galaxy gamma rays and the extragalactic diffuse background. These constraints provide stringent limits on the usual smooth-halo scenario, robustly ruling out force carrier masses below ~200 MeV (in the context of explaining the PAMELA/Fermi signals) and causing tension for higher mediator masses, but in the presence of a modest amount of local substructure, force carrier masses down to 20 MeV or even lower can still be consistent with these bounds.

Substructure, Sommerfeld, and CR Signals

Unravelling Dark Matter
22 September 2011

Tracy Slatyer
Institute for Advanced Study

based on arXiv:1107.3546, in collaboration with
Natalia Toro (Perimeter Institute)
Neal Weiner (NYU Center for Cosmology and Particle Physics)

Background

- Benchmark models for fitting PAMELA/Fermi excesses generally assume zero local substructure.
  - "Conservative" in the sense that signal is only increased by substructure.
  - Models with Sommerfeld enhancement from low-mass force carriers, in particular, strongly constrained by CMB + bounds from extragalactic gammas.
  - Also limits from dwarfs, Galactic center, etc (more dependent on DM density profile).
- What happens if we allow a contribution to *signal* from local substructure? (*required* for self-consistent extragalactic gamma bounds, since EG signal comes mostly from unresolved substructure)

Outline

- Simple parameterization for combined boost factors from Sommerfeld enhancement and substructure.
- Constraints from low-velocity systems.
- Constraints on DM self-interaction.
- The collective effect of substructure-independent constraints on the allowed parameter space, and maximum permitted combined "boost factors".
- Consistency with substructure-*dependent* constraints, such as extragalactic gamma-ray limits.

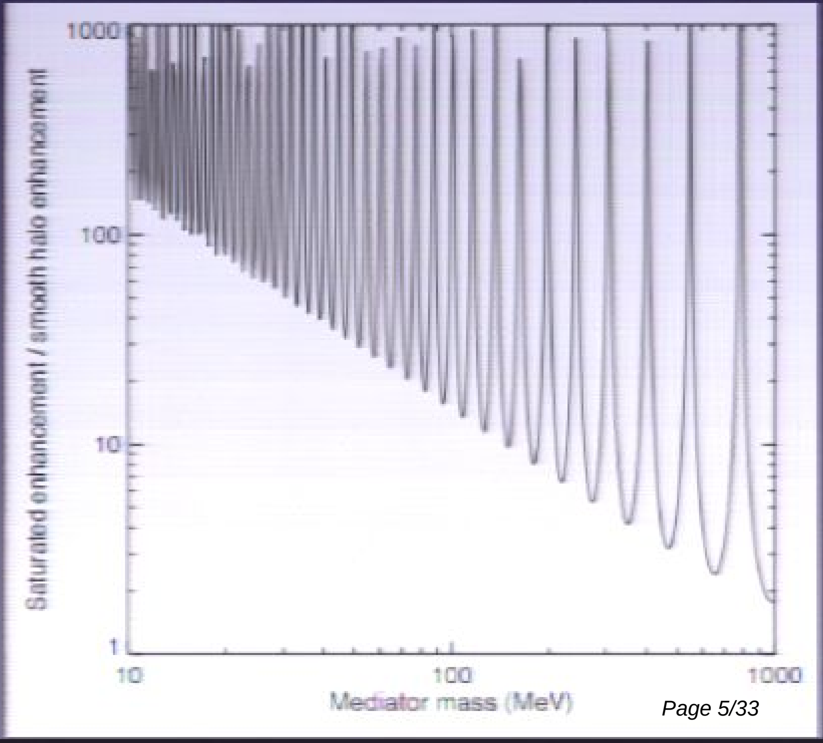
Sommerfeld enhancement: lightning review

- Sommerfeld enhancement: ~1/v enhancement to annihilation down to some cutoff "saturation" velocity, $v_{\mathrm{sat}}/c \sim m_\phi/m_\chi$

  m_φ = force carrier mass,
  m_χ = DM mass

- Ratio of saturated to local enhancement scales as $m_\chi v_{\mathrm{local}}/m_\phi$

- Resonance peaks set by ratio $\alpha_D m_\chi/m_\phi$



Substructure + Sommerfeld: lightning review

- DM substructure = small, dense DM clumps with low velocity dispersion.
- High annihilation cross section in Sommerfeld-enhanced models! (not a new idea: pointed out by Lattanzi & Silk 08, Bovy 09, Yuan et al 09, Vincent et al 09, Kamionkowski et al 10, etc...)
- Especially in Sommerfeld-enhanced models, dominated by smallest, most dense subhaloes: generally safe to assume Sommerfeld enhancement is always saturated for subhalo signal (Kamionkowski, Koushiappas & Kuhlen 2010: $v_{min} \sim 10^{-3}$ km/s).
- Lighter force carrier mass = greater low-velocity enhancement, subhaloes more important.

A combined "boost factor"

- Parameterize "boost factor" from substructure by Δ: signal including substructure (but no Sommerfeld enhancement)

  is $\propto \rho^2(1+\Delta)$, where ρ is the density of the smooth halo.

- Then to a good approximation, the signal with Sommerfeld enhancement is just:

$$\rho^2 \langle \sigma v \rangle_{\text{smooth}} \left(1 + \Delta \frac{\langle \sigma v \rangle_{\text{sat}}}{\langle \sigma v \rangle_{\text{smooth}}} \right)$$

Smooth component — Substructure

Two limiting cases

$$\Delta \ll \frac{\langle \sigma v \rangle_{\rm smooth}}{\langle \sigma v \rangle_{\rm sat}}, \quad \Delta \gg \frac{\langle \sigma v \rangle_{\rm smooth}}{\langle \sigma v \rangle_{\rm sat}}$$

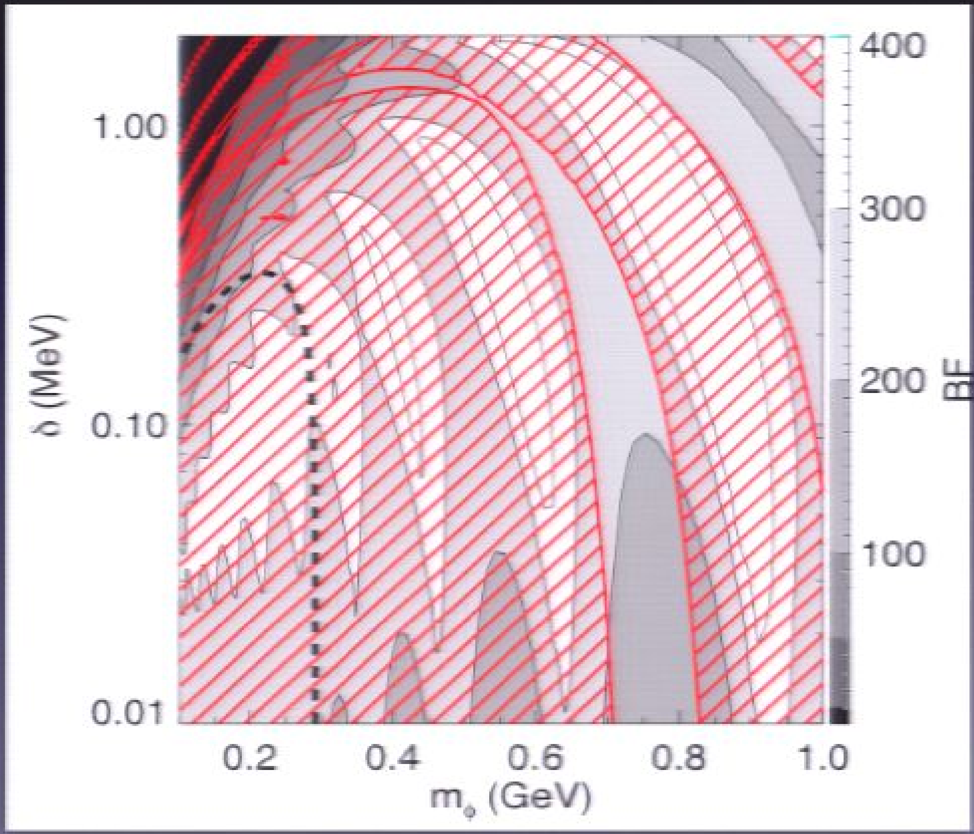
Low-substructure limit　　Substructure-dominated limit

- Low-substructure limit: smooth halo dominates signal completely, standard fits to CR excesses and standard constraints apply.
- Substructure-dominated limit: occurs for large Δ OR large saturated cross section. Benchmark models must be adjusted. Smooth halo parameters largely irrelevant, only smallest substructure matters.

CMB limits

Padmanabhan & Finkbeiner astro-ph/0503486
Galli et al 0905.0003
TRS, Padmanabhan & Finkbeiner 0906.1197
Hutsi et al 1103.2766
Galli et al 1106.1528

- DM annihilation injects ionizing particles at z~100-1000, modifies ionization history and CMB.
- Very robust - independent of DM structure formation, CR propagation, etc.
- Typical velocity of WIMP at z~1000 is very low (~10^{-8} c), since no bound structures yet - i.e. constraint is on saturated cross section.



Example benchmark model assuming zero local substructure (1011.3082), red-hatched regions ruled out by WMAP5.

Substructure domination and the CMB

- CMB constrains saturated xsec. To convert to a bound on the local CR signal, we generally need to know the local halo velocity, and the ratio m_φ/m_χ.
- BUT if substructure dominates, and the relevant "local velocity" is thus very small (below saturation velocity), the signal today *also* depends only on the saturated xsec, and the amount of substructure.
- In the substructure-dominated limit, the CMB bound translates directly into a limit on (present-day signal)/Δ.

Example

- Suppose we have a 1 TeV WIMP annihilating to a light mediator, which then decays to electrons.
  - To fit PAMELA/Fermi we require a local boost factor of ~70.
  - CMB constrains the saturated xsec to be less than ~170*thermal relic xsec.
- Case 1: $\frac{m_\chi \times 5 \times 10^{-4}}{m_\phi} \lesssim \frac{\langle \sigma v \rangle_{\rm sat}}{\langle \sigma v \rangle_{\rm smooth}} \leq \frac{170}{70} \Rightarrow m_\phi \gtrsim 200 \text{MeV}$
- Case 2: $\frac{\langle \sigma v \rangle_{\rm sat}}{\Delta \langle \sigma v \rangle_{\rm sat}} \leq \frac{170}{70} \Rightarrow \Delta \gtrsim 0.4$

If $\Delta > 0.4$, WMAP5 cannot constrain small mediator masses.

The bottom line

- Same principle applies to other constraints on the saturated or low-velocity enhancement (e.g. 1007.4199 for dwarf galaxies, Jesus' talk for EG gamma-rays), which use the ratio $m_\varphi/m_\chi v_{local}$ to set strong limits on the local signal for small mediator masses.
- In the substructure-dominated limit, this ratio becomes irrelevant as local signal also measures saturated xsec. Only Δ matters.
- Very small values of m_φ become allowed again for O(1) Δ, in the context of explaining the CR excesses.

Self-interaction limits

- Light force carrier => long-range force. Constraints from (summarized and discussed by Buckley & Fox 0911.3898):
  - Observations of the Bullet Cluster,
  - Evaporation of galaxies and dwarf galaxies,
  - Stability of elliptical cores in galaxy clusters,
  - Growth rate of supermassive black holes,
  - Thermodynamics of galaxies,
  - Structure of dwarf galaxies.
- Bounds are weakened in substructure-dominated case - because lower couplings α_D are implied - but not negated.

Evaporation of galaxies

- Bound substructures can be evaporated by collisions with the faster-moving particles of the host halo.
- Timescale depends only on properties of the host halo - density + particle velocity distribution - and scattering cross section, not on the subhalo.
- We observe dwarfs in the Milky Way, and galaxies within clusters, and can use this to place a bound on the scattering cross section, given velocity/density estimates.

$$\sigma_T/m_\chi \lesssim 0.1\mathrm{cm}^2/\mathrm{g} \quad v \sim 100\mathrm{km/s} \quad \Rightarrow \quad \alpha_D \lesssim 0.01,\ m_\phi < 20\mathrm{MeV}$$

Dwarf halo shapes

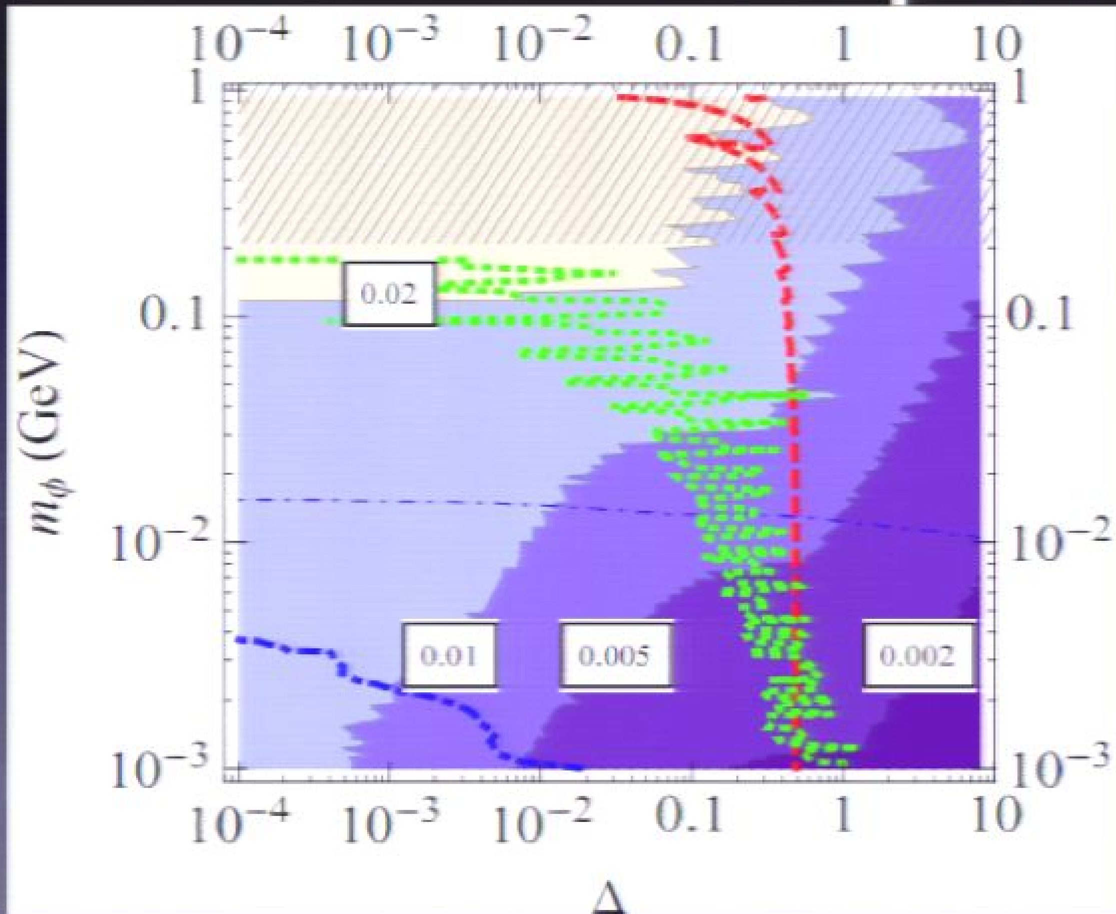
- DM self-interactions give rise to flattening of cores in dwarf galaxies at intermediate cross sections. Has been proposed as a way to alleviate core-cusp problem (e.g. Hannestad astro-ph/0008422 and references therein).
- At high cross sections, the same self-interactions cause core collapse - but usually the evaporation constraints rule out such models, at least for simple cases with a Yukawa-like potential.
- Define "self-interaction threshold", where effect of self-interaction is notably different from CDM (leading to cored profiles). Requiring xsec below this threshold provides strong "bound" at low mediator masses:

$$\sigma_T/m_\chi \lesssim 0.1\mathrm{cm}^2/\mathrm{g} \qquad v \sim 10\mathrm{km/s}$$

$$\alpha_D \lesssim 0.023 \times \left(\frac{20\mathrm{MeV}}{m_\phi}\right)^{4.7}, \qquad 7\mathrm{MeV} \lesssim m_\phi \lesssim 20\mathrm{MeV}$$

The limits so far: an example

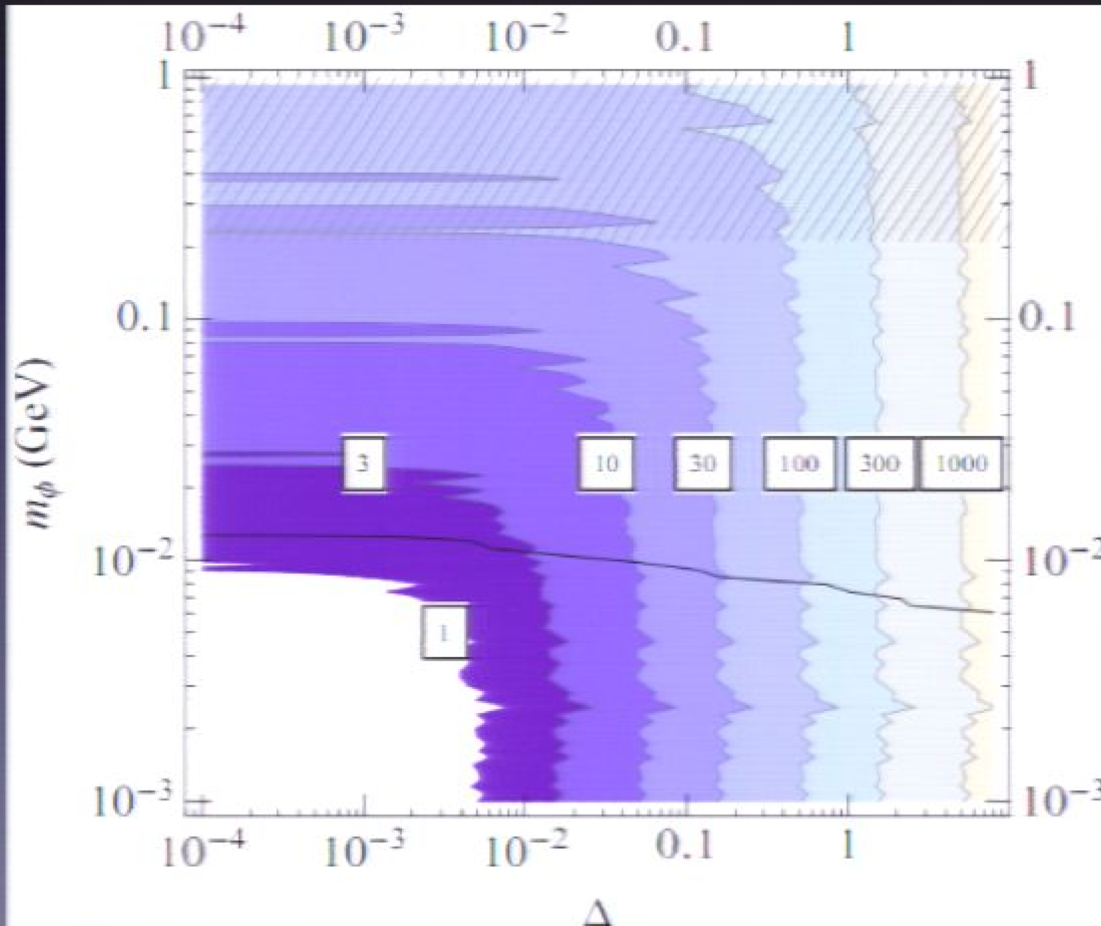
- Use simplest Sommerfeld enhancement model, based on Yukawa potential.
- Demand a local (combined) "boost factor" of 100, assume 1.2 TeV DM.
- Require that xsec does not over-deplete relic density (assume additional annihilation channels are present in early universe, if xsec is too low).



Contours of dark sector coupling α_D
Red = CMB, thick blue = evaporation, thin blue = self-interaction threshold, green = WIMPonium region

Maximum boost factor

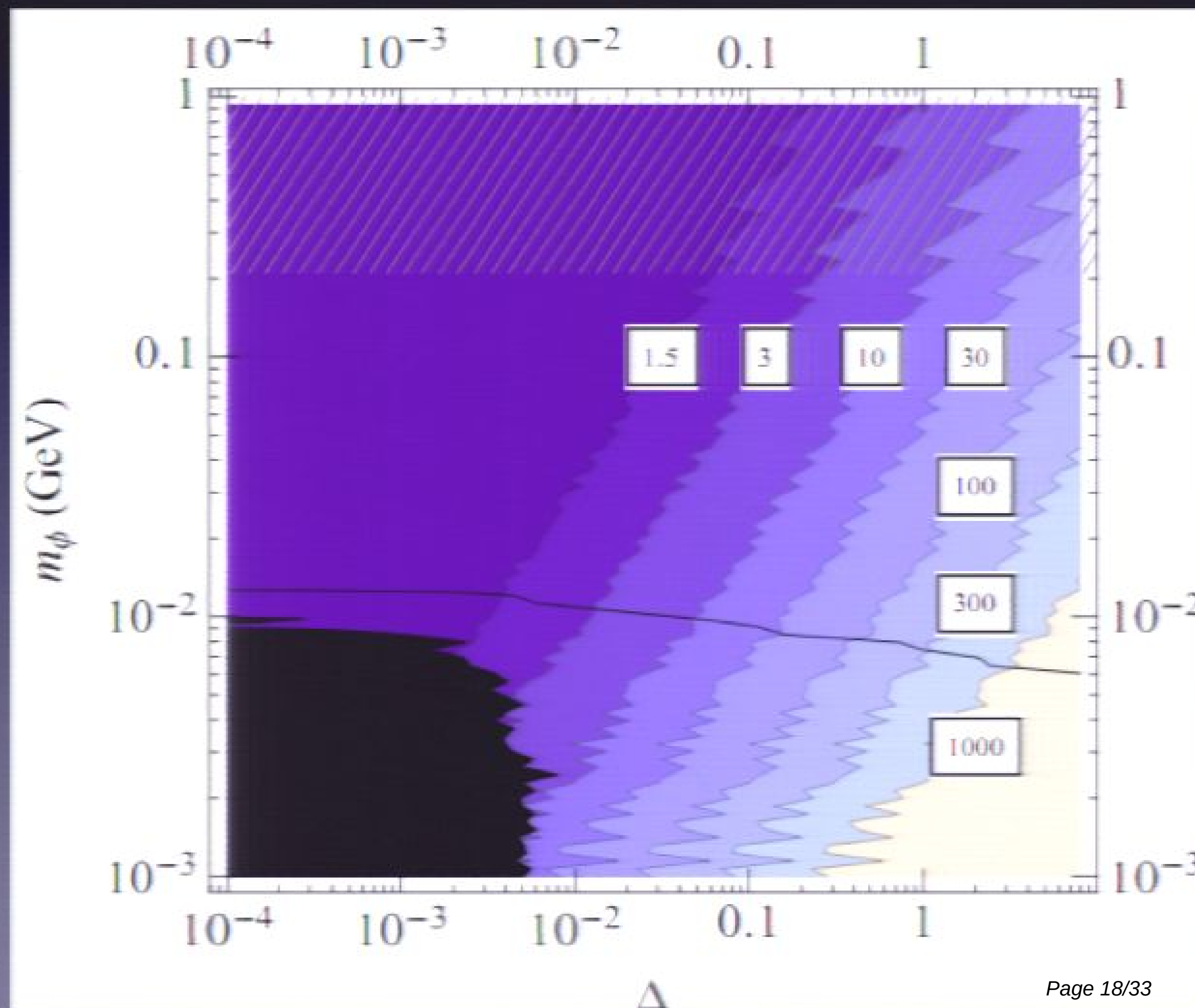
- Alternative way of looking at the parameter space; plot maximum BF consistent with all constraints discussed so far.
- Again assume Yukawa potential and 1.2 TeV DM.



Thin black line = contour of BF=1 if self-interaction threshold is imposed

Improvement in maximum BF

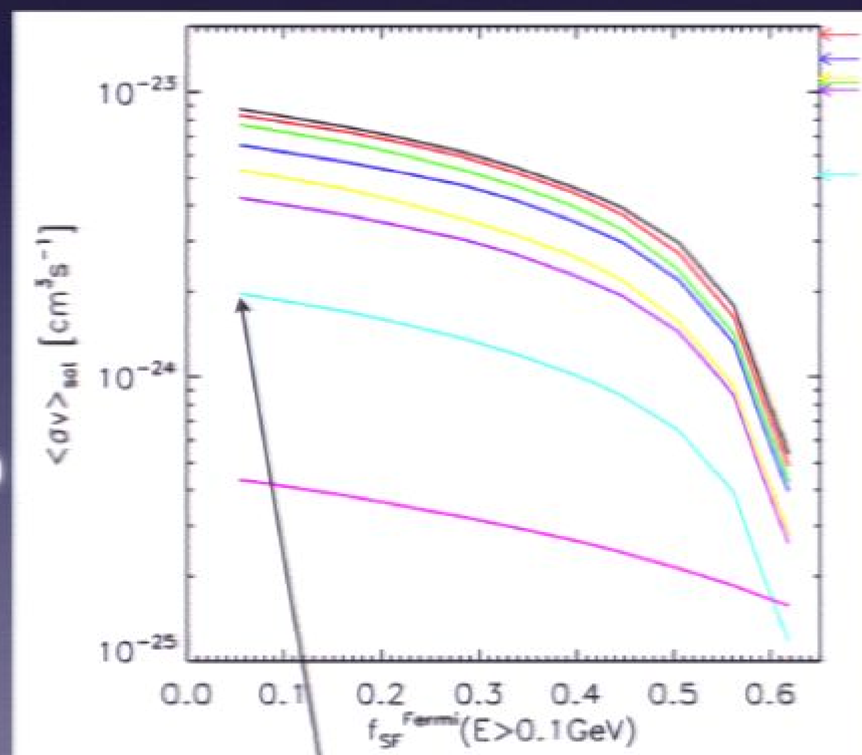
- A second alternative: ask by what factor the maximum permitted BF *increases*, in the presence of substructure.
- Again assume Yukawa potential and 1.2 TeV DM.



Substructure-dependent constraints

Zavala et al 1103.0776

- Have not yet considered constraints that *themselves* depend on the amount of substructure.
- Example: EG gamma-ray limits (see previous talk by Jesus Zavala). Assume:
  - Minimal astrophysical background (from blazars + star-forming galaxies)
  - Minimal estimate for unresolved substructure, with $M_{min} = 10^{-6} M_{sol}$.
- Then the limit on saturated xsec is ~ xsec required to fit PAMELA/Fermi with annihilation in the smooth halo.

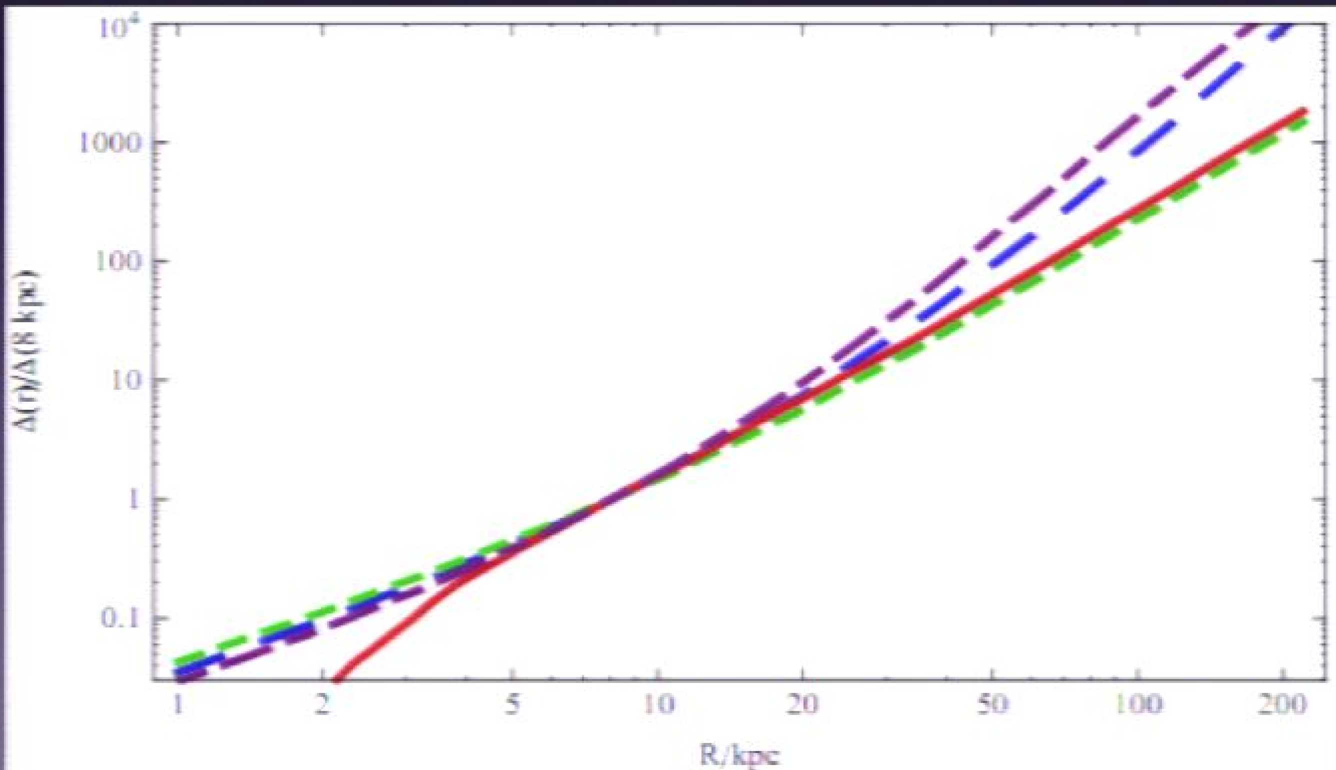


Benchmark model for 1 TeV DM annihilating to $\varphi\varphi$, $\varphi \rightarrow e^+e^-$

Substructure for both signal and limits

- In the substructure-dominated case, consistency with these constraints implies $\Delta \sim 1$ in the case of minimal unresolved substructure. Can this be consistent?
- More generally, if we increase the amount of unresolved substructure for the EG signal, how does Δ increase?
- Several independent (?) parameters here:
  - Disruption of substructure toward the inner Galaxy (affects Δ, not EG signal)
  - Normalization / power law slope of population of small main haloes below simulation resolution (affects EG signal, not Δ)
  - Normalization / power law slope of substructure in main haloes (affects both EG signal and Δ)

Substructure in the inner Galaxy



Purple long-short-dashed: Kistler & Siegal-Gaskins, 0909.0519, based on Aquarius

Blue long-dashed: Kamionkowski, Koushiappas & Kuhlen 1001.3144, based on VLII

Green short-dashed: Pieri et al, 0908.0195, based on VLII

Red solid: as green short-dashed, but including tidal disruption

- Four different estimates for variation of Δ with Galactocentric radius (from VLII and Aquarius).

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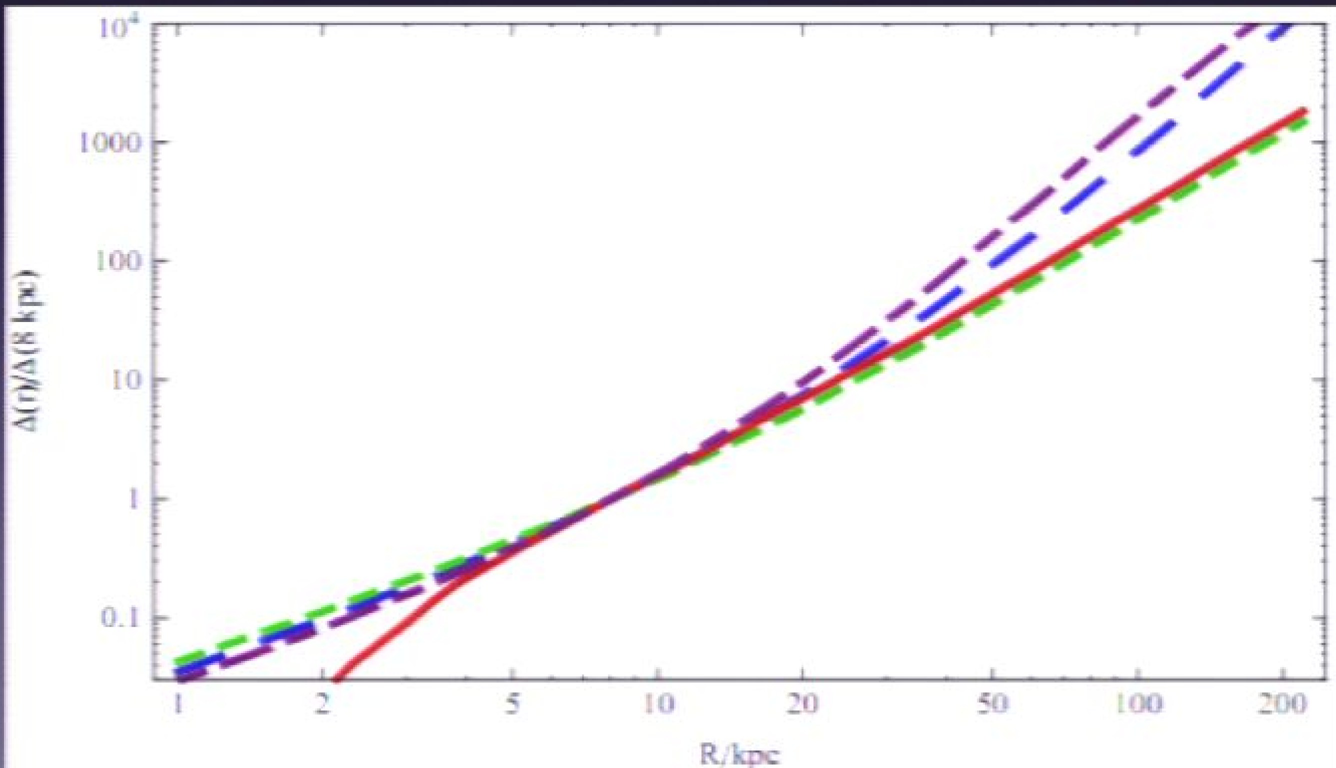

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Substructure in the inner Galaxy

- Ratio of signal in inner 1kpc to local signal is suppressed by a factor of at least ~20, compared to smooth-halo expectation.
- Relaxes bounds from gamma-rays in the inner Galaxy (previously discussed by e.g. Vincent, Xue & Cline 1009.5383).
- Using curves for VLII, the total integrated boost (distant observer) for a MW-size halo is ~5-30 x Δ(8.5 kpc). Use this to estimate Δ(8.5 kpc) in terms of power-law parameters for main halos and subhalos.
- Note: the simulations do not include baryons or self-interactions, which might well deplete local substructure further (especially interactions with baryons in the disk).

Consistency?

- Can a substructure-dominated scenario for PAMELA/Fermi be consistent with EG gamma-ray limits?
    - **Yes!** (see 1107.3546 for preferred parameters) But...
    - Usually rather borderline; would get significantly more difficult if a larger astrophysical background was assumed.
    - The parameters that work best are not generally those with the least unresolved substructure; the increase to local signal compensates the higher EG boost.
    - Much easier if the power-law for the unresolved main halos is varied slightly, as well as the substructure parameters.
    - Increasing the minimum subhalo mass (natural in light mediator models) improves consistency somewhat.

A note: evaporation of substructure

- Previously used presence of dwarf galaxies in MW to put an upper bound on the scattering cross section.
- Turn the question around: for what host halo parameters *will* substructure be depleted?
- Take estimate from 1001.3144,

$v \propto n^{-1.75}$ $\tau_{\text{evap}} \propto (n\sigma(v)v)^{-1} \propto (v^{0.43}\sigma(v))^{-1}$

$\sigma(v) \propto v^{-0.7}$ for small v, transitioning to logarithmic dependence at very small v (equivalent of saturation)

Conclusions

- Non-negligible local substructure can relax constraints on explanations for the CR excesses in terms of Sommerfeld-enhanced DM annihilation, including:
  - Constraints from low-velocity systems, including bounds from the CMB.
  - Limits on DM self-interaction.
  - Bounds from gamma rays in the inner Galaxy.
  - Bounds from extragalactic diffuse gamma ray emission.
- In particular, models with mediator masses below ~200 MeV, which appear ruled out (or at least unconnected to the CR excesses) in the absence of substructure, can be accommodated in this framework with an O(1) boost from local substructure. Relevant mass range for terrestrial direct searches.

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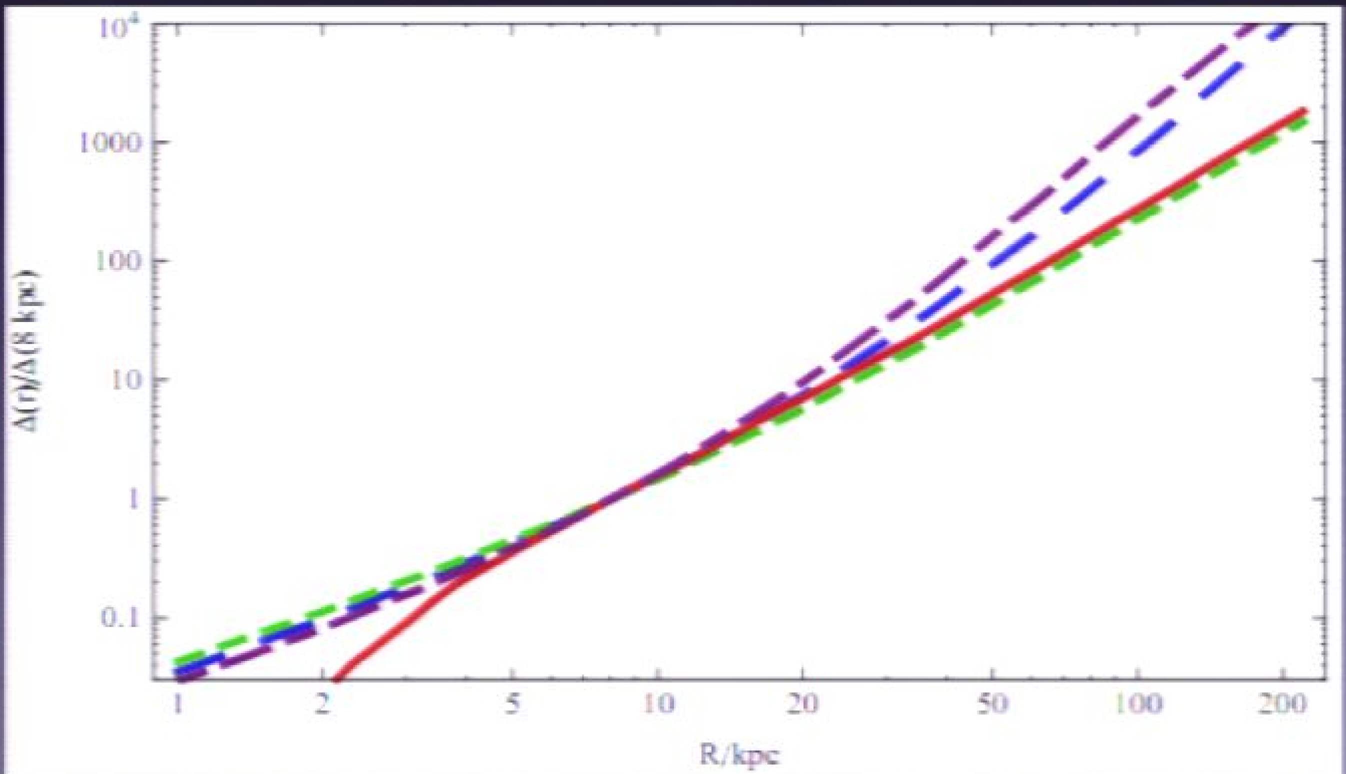

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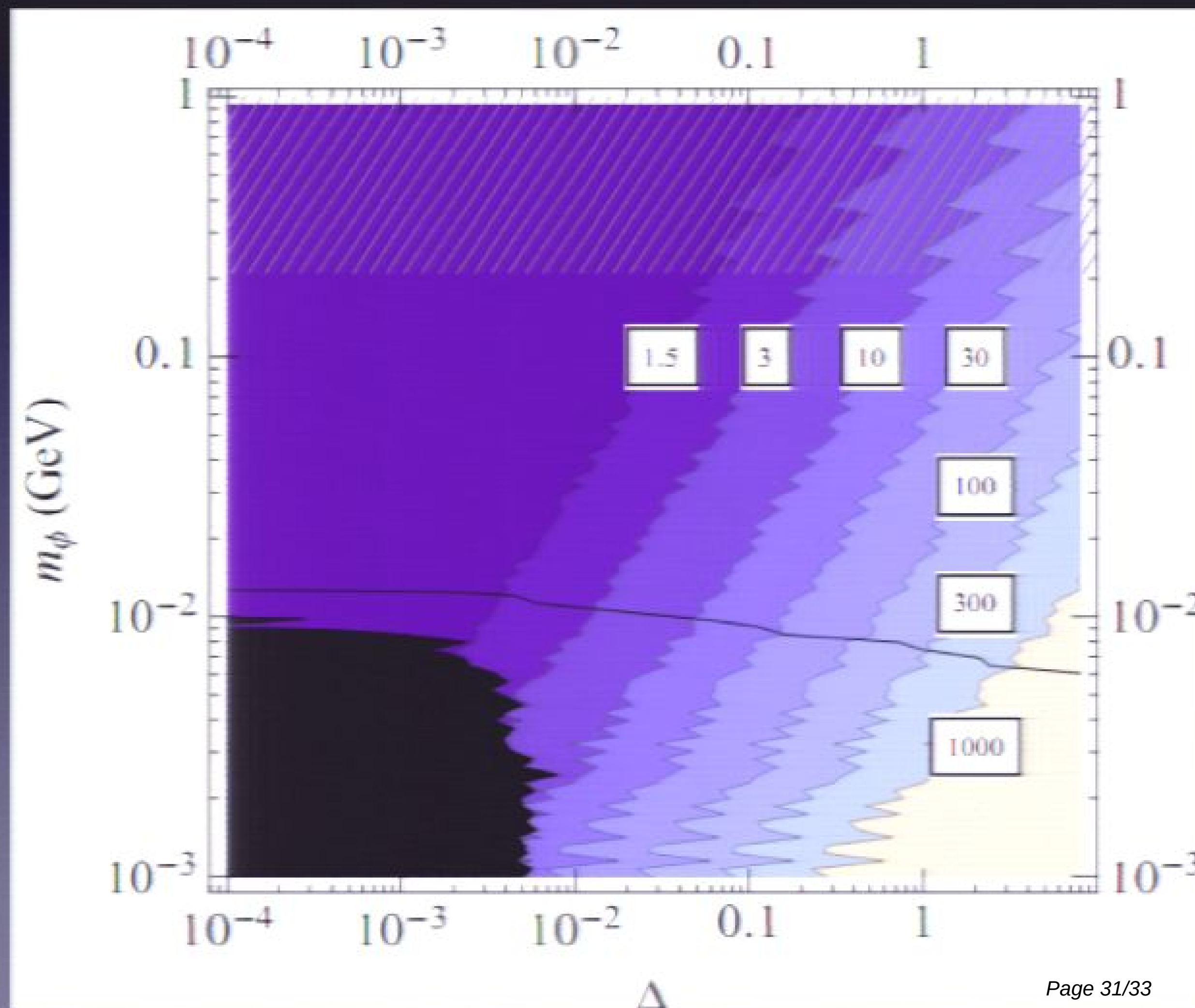

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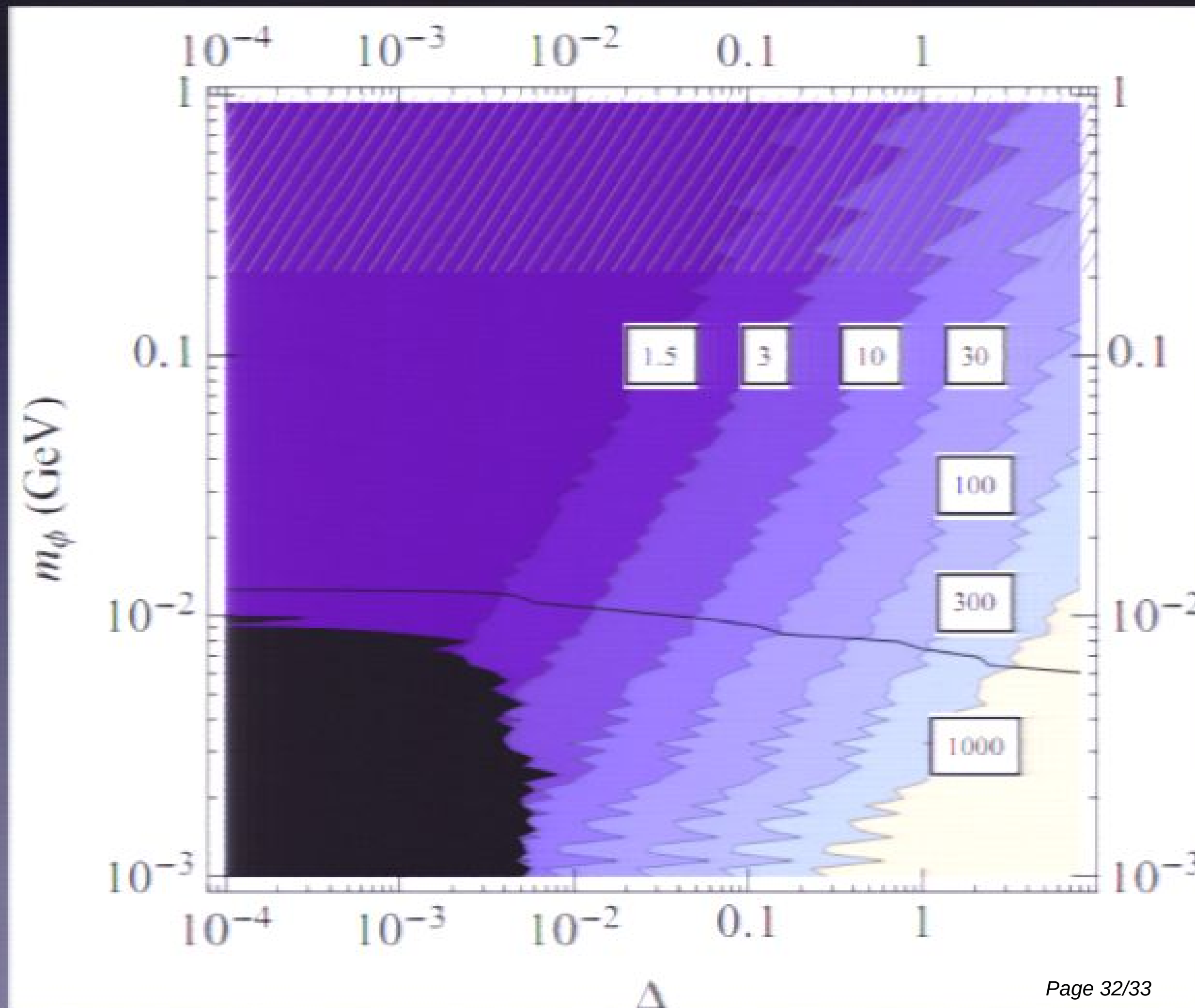

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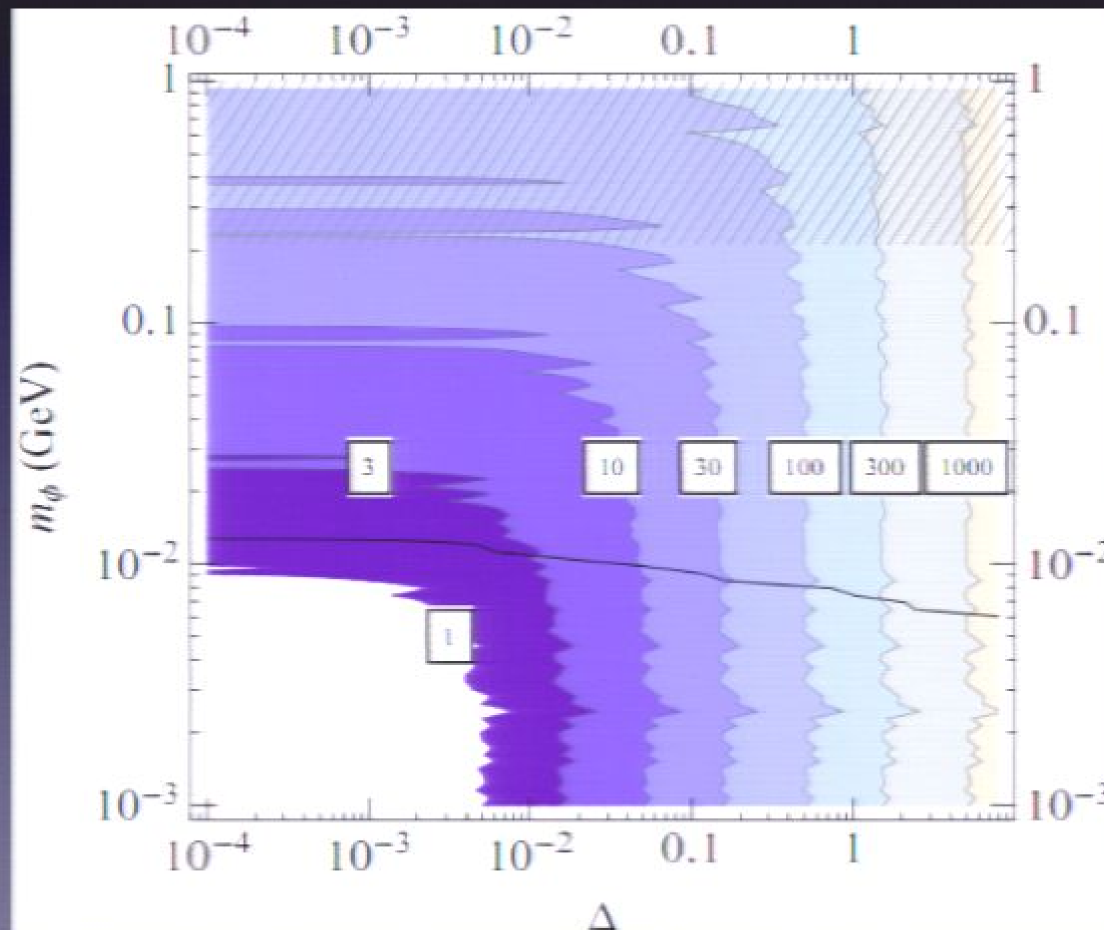

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