# …And now for something Completely different

# DOUBLE DISK DARK MATTER

LR w/Fan, Katz, Reece
w/McCullough
w/Reece

# Introduction

- Lots of attention devoted to dark matter
- Both theory and detection
- Sometimes signals are unexpected
  - They might be wrong
  - They might lead to interesting  unexplored options
- We don’t know what dark matter is
  - Should keep an open mind
  - Especially in light of abundance of astronomical data
- Today talk about an almost-explored option
- Interacting dark matter
- But rather than assume all dark matter
- Assume it’s only a fraction (maybe like baryons?)

# This changes everything!

- Almost all constraints on interacting dark matter assume it is the dominant component
- If it's only a fraction, most bounds far weaker
  - Structure
  - Galaxy or cluster interactions
- But if a fraction, you'd expect even smaller signals!
- However, not necessarily true…

# Summary

- A component of self-interacting dark matter can collapse into a disk
  - Like ordinary matter
- Maybe even denser than ordinary matter
- Indirect signals: boost factor
- Direct signals: low threshold
  - In fact too low for most detection
  - w/McCullough ExoDDDM-explain CDMS
    - Consistently with Xenon
- Affects structure, dynamics
  - Fun stuff w/Reece if time

# I:Interacting Dark Matter and Indirect Signals

- An enormous boost factor is needed to account for any indirect signal so far
  - Eg Of order 1000 for reasonable parameters for Fermi signal
- Too high to assume clumping
- But what if dark matter actually had structure?
  - Like baryons for example!
- Consider interacting dark matter
  - Dissipative dark matter in particular
- Idea is to have more collapsed component of dark matter
- Even if only a fraction of dark matter, will be most important for signals

# Density enhancement

- Consider possibility that due to interactions, dark matter (like baryons) collapses into a disk
- Involves
  - Dark force (we take $U(1)_D$ or nonabelian group)
  - Additional light particle in dark sector
    - Necessary for cooling in time as we will see
- Even if new component a fraction of dark matter, if it collapsed to baryonic disk (eg) enhancement factors ~1000

# Constraints on Interacting Dark Matter

- Before proceeding, let's examine some of the constraints on dark matter interactions
- Interacting dark matter (when all of it) has very restricted interactions
  - In fact tough to make it thermal relic abundance
- However, most constrain dark matter only when it is the dominant component
- Structure is not observed in enough detail to constrain a small component

# Bounds (that don't apply)

- Hard and soft scattering: Ackerman et al
- Scattering of dominant component would
  - Reduce phase space of dark matter
  - Destroy nonspherical cores that have been observed

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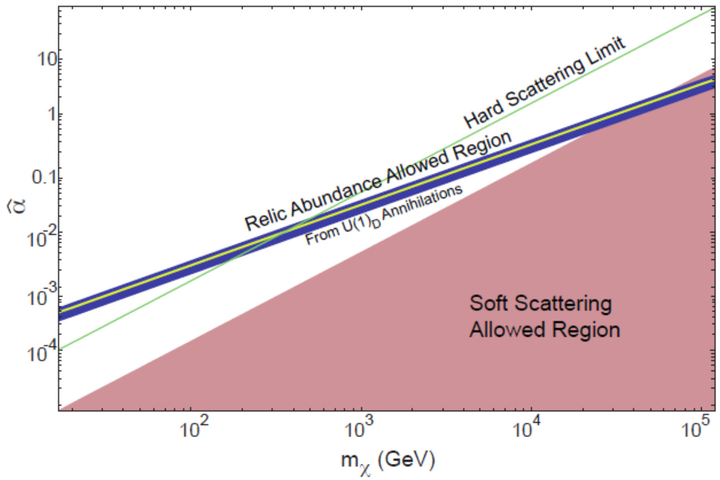


FIG. 3: The allowed regions of $\hat{\alpha}$ vs. $m_\chi$ parameter space. The relic abundance allowed region applies to models in which $U(1)_D$ is the only force coupled to the dark matter; in models where the DM is also weakly interacting, this provides only an upper limit on $\hat{\alpha}$. The thin yellow line is the allowed region from correct relic abundance assuming $\Omega_{\rm DM}h^2 = 0.106 \pm 0.08$, $\xi(T_{\rm RH}) = 1$, $g_{*\rm vis} \approx 100$, and $g_{\rm heavy} + g_{\rm light} = 5.5$ while the surrounding blue region is $g_{*\rm vis} = 228.75(60)$, $\xi(T_{\rm RH}) = 1(0.1)$, and $g_{\rm heavy} + g_{\rm light} = 100(5.5)$ at the lower(upper) edge. The diagonal green line is the upper limit on $\hat{\alpha}$ from effects of hard scattering on galactic dynamics; in the red region, even soft scatterings do not appreciably affect the DM dynamics. We consider this to be the allowed region of parameter space.

# More Inapplicable Bounds

- Bullet Cluster and Ellipticity: Feng, Kaplinghat, Tu, Wu

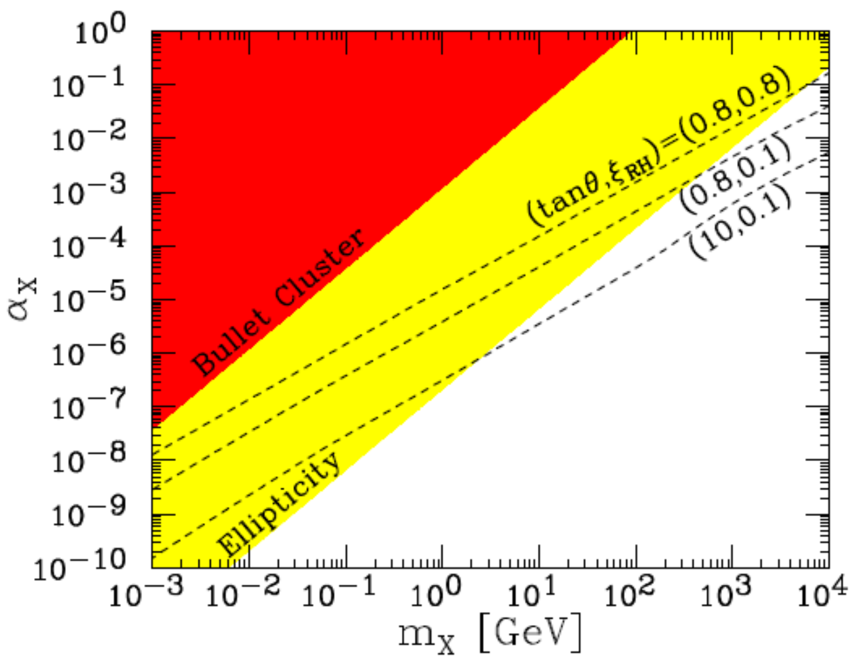


FIG. 1: Allowed regions in $(m_X, \alpha_X)$ plane, where $m_X$ is the mass of the dark matter charged under the unbroken hidden sector $U(1)_{EM}$ with fine-structure constant $\alpha_X$. Contours for fixed dark matter cosmological relic density consistent with WMAP results, $\Omega_X h^2 = 0.11$, are shown for $(\tan\theta_W^h, \xi_{RH}) = (\sqrt{3/5}, 0.8)$, $(\sqrt{3/5}, 0.1)$, $(10, 0.1)$ (dashed), from top to bottom, as indicated. The shaded regions are disfavored by constraints from the Bullet Cluster observations on self-interactions (dark red) and the observed ellipticity of galactic dark matter halos (light yellow). The Bullet Cluster and ellipticity constraints are derived in Secs. VIII and VII, respectively.

# Strongest bound for us: Oort Limit

A recent determination that the local dark matter density is $0.3 \pm 0.1$ GeV/cm$^3$ [33] relied on the kinematics of stars between 1 and 4 kpc above the galactic plane. Older results were based on stars within 100 pc of the Sun, surveyed by the Hipparcos satellite, and another sample of stars extending out to 1 kpc [34, 35]. In the presence of a possible dark disk [32] these observations were estimated to be consistent with a local dark matter density between 0.2 and 0.7 GeV/cm$^3$ [35]. Depend-

an approximate upper bound on the local density of the PDDM disk at a distance $d_\odot \approx 8$ kpc from the galactic center:

$$\rho(d_\odot) \lesssim 0.5 \text{ GeV/cm}^3. \tag{33}$$

$$\epsilon \lesssim 0.05.$$

$$\epsilon \equiv \frac{\Omega_{\rm PDDM}}{\Omega_{\rm DM}}.$$

# Updated Bound

- About 4x stronger bound taking into account more recent data on baryon content of galaxy

$$\Sigma_{\rm tot}(|z| < 1.0\ {\rm kpc}) = 67 \pm 6\ M_\odot/{\rm pc}^2. \tag{21}$$

Note that 1 GeV/cm$^3$ $\approx 0.026\ M_\odot/{\rm pc}^3$. They find a total baryonic (stellar and gas) disk surface density of

$$\Sigma_{\rm baryon}(|z| < 1.1\ {\rm kpc}) = 55 \pm 5\ M_\odot/{\rm pc}^2. \tag{22}$$

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The contribution to the surface density from ordinary dark matter, which from observations between 1 and 4 kpc has volume density $0.3 \pm 0.1$ GeV/cm$^3$ [18], is

$$\Sigma_{\rm dark\ halo}(|z| < 1.0\ {\rm kpc}) = 16 \pm 5.2\ {\rm M}_\odot/{\rm pc}^2. \tag{23}$$

# Also bounds from new relativistic degrees of freedom

- Need to follow thermal history
- Entropy conserved separately in both sectors after they decouple

$$\frac{g^{\rm dec}_{*s,D}}{g_{*s,D}(t)\xi(t)^3} = \frac{g^{\rm dec}_{*s,\rm vis}}{g_{*s,\rm vis}(t)}$$

$$\xi \equiv (T_{\rm hid}/T_{\rm vis})$$

$$\xi(t_{\rm BBN}) = \left(\frac{10.75}{86.25}\right)^{1/3} \approx 0.5.$$

$$g_{*s,D}\xi^4(t_{\rm BBN}) = \tfrac{7}{8}\times 2\times \Delta N^{\rm BBN}_{{\rm eff},\nu}$$

$$\begin{aligned}\Delta N^{\rm BBN}_{{\rm eff},\nu} &= 0.20 \text{ for } {\rm U}(1)_D \text{ and}\\ \Delta N^{\rm BBN}_{{\rm eff},\nu} &= 0.07N^2 + 0.12N - 0.07 \text{ for } {\rm SU}(N)_D\end{aligned}$$

$$\Delta N^{\rm BBN}_{{\rm eff},\nu} < 1.44 \quad \text{at} \quad 95\% \text{ C.L.},$$

Interesting prediction for new degrees of freedom during BBN
Also measurable in CMB

# Relic Density X

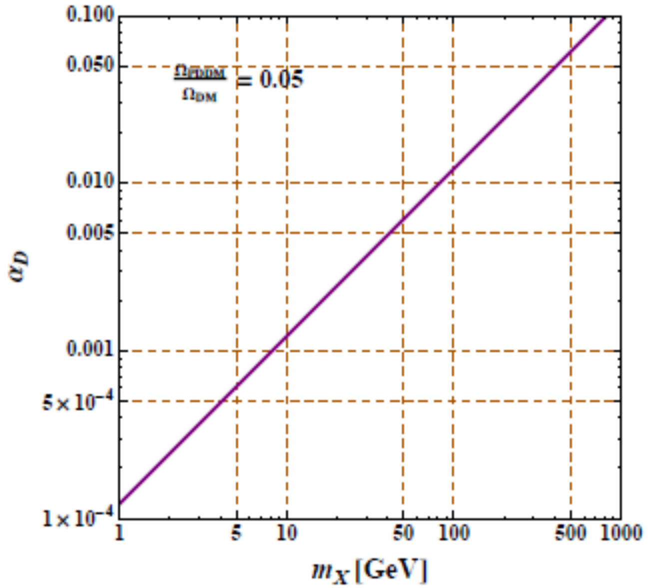



**Figure 1:** $\alpha_D$ needed to get the thermal relic abundance of $X$ to be 5% of the total DM density for different masses of $X$.

Won't violate Oort Limi t with big enough alpha—reasonable values
Thermal abundance of C will however be too small

# Implication

- If dark matter interacts, either
  - Tuned small wedge of parameter space
  - Or it's not all the dark matter!—at most about baryonic energy density
- Why would we care about a subdominant component?
  - Can be relevant for signals if it is denser
    - Perhaps even collapses into a disk
  - Can be relevant for structure (to be done…)
- However, to form a disk, cooling required
- Check when enough cooling can occur

# Cooling:

- Three cooling processes can be relevant
  - Bremsstrahlung
  - Compton scattering off dark photons
  - Recombination cooling (only relevant when an additional light species, which we will need)

  - Heating processes (since that's when cooling stops!)
    - For normal matter, photoionization
    - Gravitational heating (small)
    - Compton heating can be relevant for us
    - At very least will be recombination, which stops brehmstrahllung and Compton
    - We make assumption that  cooling stops when recombination can occur

## Bremsstrahlung Cooling Rate

In a fully ionized gas consisting a light charged specie with mass $m_l$ and number density $n_l$(e.g., dark electrons) and a heavy one with mass $m_h$ and number density $n_h$ (e.g., dark protons), the radiative cooling rate through bremsstrahlung emission of a photon with frequency $\nu$ is

$$j(\nu) = 3.4 \times 10^{-36} \frac{1}{\sqrt{T}} n_l n_h e^{-h\nu/k_B T} \left(\frac{\alpha_D}{\alpha_{EM}}\right)^3 \left(\frac{m_e}{m_l}\right)^{3/2} \mathrm{GeV\,cm^{-3}\,s^{-1}\,ster^{-1}Hz^{-1}}, \qquad (1)$$

where $T$ is expressed in units of K and the particle number density in $\mathrm{cm}^{-3}$. $\alpha_D$ is the coupling strength. The detailed derivation based on classical electrodynamics could be found in [1]. The parameter dependence could also be understood from field theory calculations taking the non-relativisitc limit. In particular, the thermal bremsstrahlung cross section scales as $\sigma v \sim \alpha_D^3/(m_l^2 v)$. The velocity of the particles in a thermal gas is $v \sim \sqrt{k_B T/m_l}$. There is an exponential cutoff in the rate because the typical light particle energy is $\sim k_B T$, so they cannot produce photons with energy $h\nu$ much greater $k_B T$. Putting all these together, we arrive at Eq. 1.

The total energy loss rate is then

$$J = 4\pi \int j_\nu d\nu = 8.9 \times 10^{-25} \sqrt{T} n_l n_h \left(\frac{\alpha_D}{\alpha_{EM}}\right)^3 \left(\frac{m_e}{m_l}\right)^{3/2} \mathrm{GeV\,cm^{-3}\,s^{-1}}. \qquad (2)$$

Given the thermal energy per volume is $3n_h k_B T$, the characteristic cooling time is

$$t_{brem} = 10^4\,\mathrm{years}\,\sqrt{T}\frac{1}{n_l} \left(\frac{\alpha_{EM}}{\alpha_D}\right)^3 \left(\frac{m_l}{m_e}\right)^{3/2}. \qquad (3)$$

Need a light species! Need it to be nonthermal

# Compton scattering rate

When the dark electron temperature $T$ drops below the dark photon temperature, i.e., $T_D$, the dark CMB temperature, the dark electron-photon Compton scattering will heat up the dark electron plasma with a rate [1]

$$J_{Comp} = \frac{8\sigma_c a T_D^4}{3m_l}(T_D - T)n_l, \tag{6}$$

$$= 5.0 \times 10^{-35}\,\mathrm{GeV/cm^3/s}\left(\frac{T_D}{1\,\mathrm{K}}\right)^4 \frac{T_D - T}{1\,\mathrm{K}} \frac{n_l}{\mathrm{cm}^{-3}} \left(\frac{\alpha_D}{\alpha_{EM}}\right)^2 \left(\frac{m_e}{m_l}\right)^3 \tag{7}$$

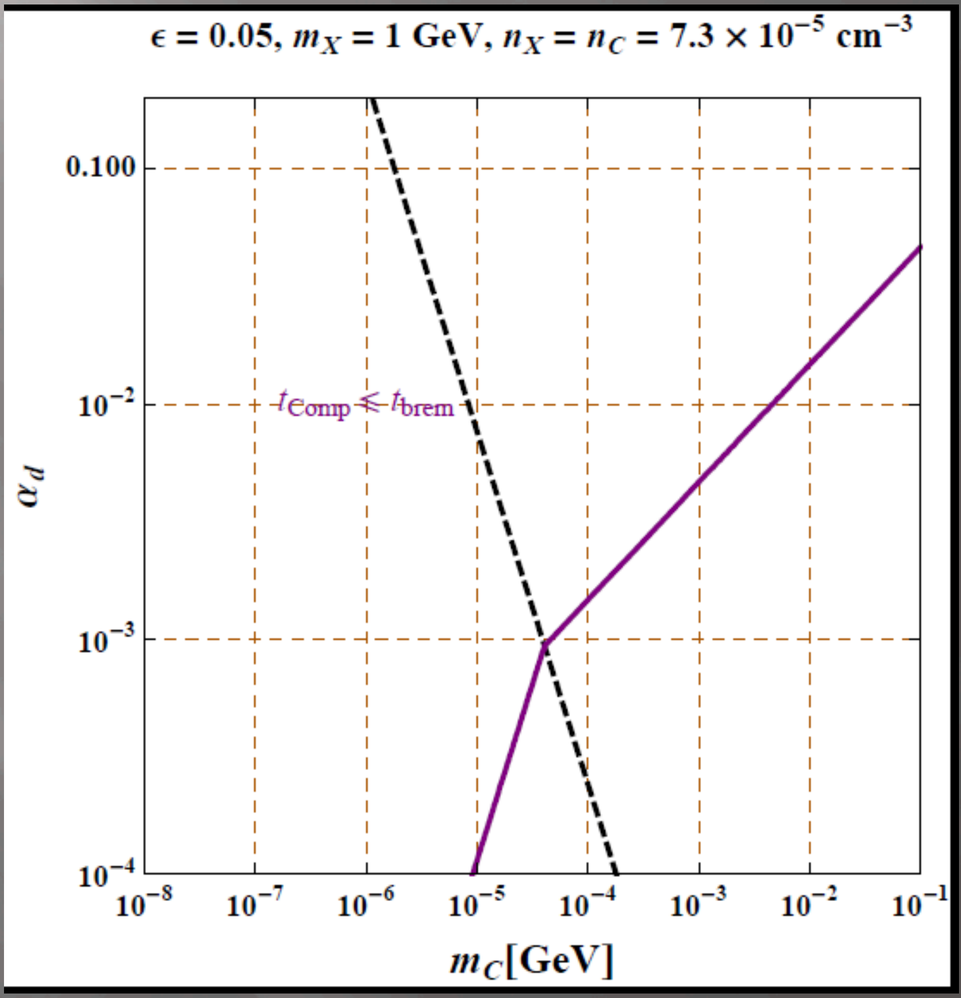
where in the first line, $a = \pi^2/15$; the Compton scattering cross section is $\sigma_c = 8\pi\alpha_D^2/(3m_l^2)$. The heating time scale is

$$t_{Comp} = 1.7 \times 10^{14}\,\mathrm{years}\left(\frac{T_l}{1\,\mathrm{K}}\right)\left(\frac{1\,\mathrm{K}}{T_D}\right)^5 \left(\frac{\alpha_{EM}}{\alpha_D}\right)^2 \left(\frac{m_l}{m_e}\right)^3, \tag{8}$$

where we assumed $T_l \ll T_D$. For $T_D$ above 10 K (at higher redshift), Compton scattering might be able to heat up the dark electron $T$ to $T_D$ ($t_{Comp} <$ age of the Universe).

Note it is light species that heats or cools—but equilibration time with heavy matter is short

# Cooling



$\epsilon = 0.05,\ m_X = 1\ \text{GeV},\ n_X = n_C = 7.3 \times 10^{-5}\ \text{cm}^{-3}$
0.100
$10^{-2}$
$10^{-3}$
$10^{-4}$
$\alpha_d$
$t_{\text{Comp}} \leqslant t_{\text{brem}}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
$m_C$[GeV]

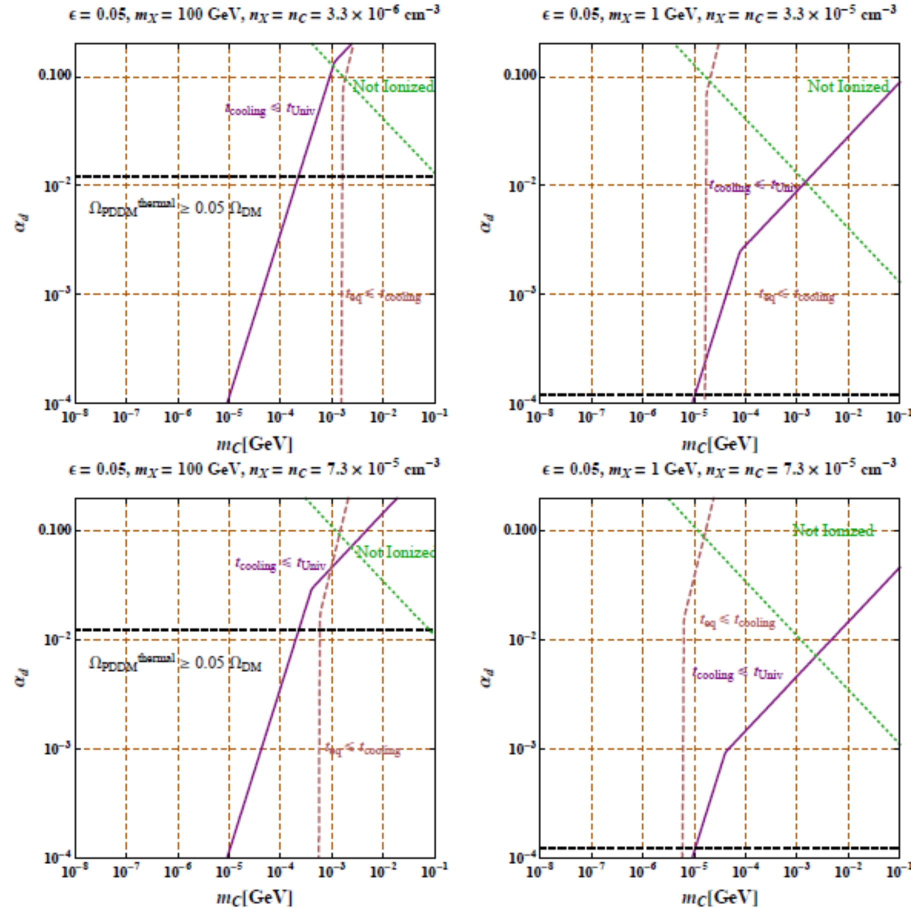



**Figure 5:** Contours of the cooling time scale equal to the age of the Universe for different heavy PDDM mass in the plane $(m_C, \alpha_d)$ (purple solid curves). We always assume that the PDDM mass is 5% of the total mass in the Milky Way (i.e., $\epsilon = 0.05$) and redshift $z = 2$. Above the curves, the cooling time scale is shorter than the age of the Universe. The two plots in the upper row are obtained via assuming a virial cluster with radius 110 kpc; the two plots in the lower row are obtained via assuming a virial cluster with an NFW profile with radius 20 kpc. The kinks in the curves are the transition points between bremsstrahlung process and Compton process. Above the kinks, the curves are determined by bremsstrahlung time scale, which is shorter, and below the kinks, by Compton time scale. The green dotted curves at the upper right correspond to when the binding energy is equal to the virial temperature; above them, shock heating will not ionize the gas, so our bremsstrahlung/Compton calculation does not apply but atomic and molecular processes may be important for cooling. The black dashed curve corresponds to $\alpha_D$ that leads to the thermal relic of PDDM being 5% of the total DM relic; below them, PDDM relic could overclose the Universe in the absence of late-time dilution. The pink dashed lines are the contours when the equilibration time scale is equal to the cooling time scale. To the right of them, cooling would occur adiabatically while to the left, the cooling process may involve nonequilibrium physic as explained in the text.

# Thermal + Nonthermal

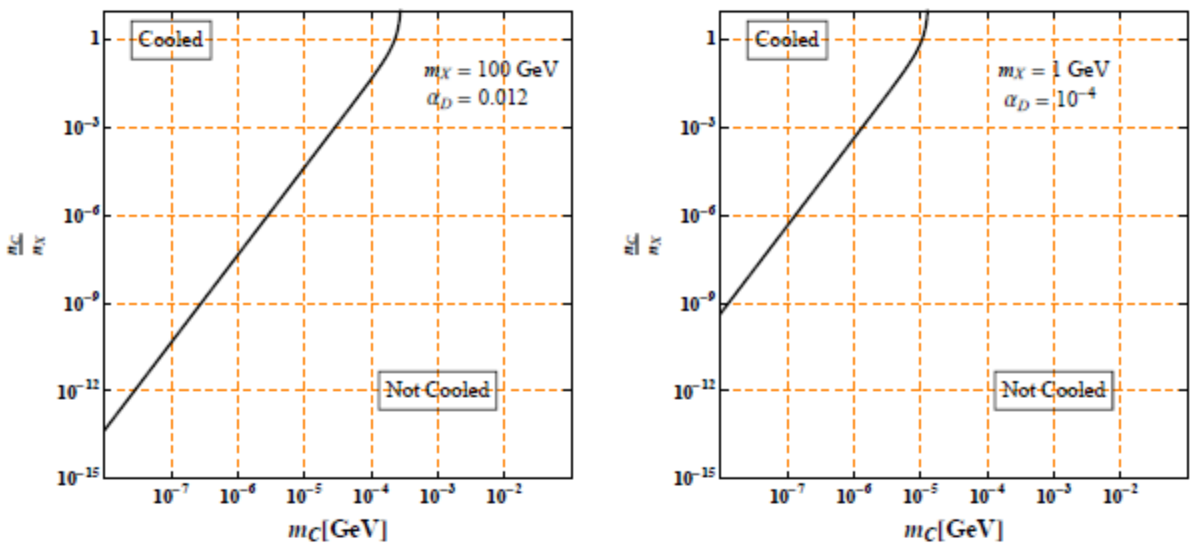



**Figure 6:** Fixing $\alpha_D$ so that the thermal relic of PDDM is 5% of the total DM relic abundance, the minimal $n_C/n_X$ with a cooling time scale equal to the age of the Universe as a function of $m_C$ for $m_X = 100, 1$ GeV. We choose redshift to be $z = 2$. The bounds are from the Compton cooling process, which for the chosen $m_X$ and $\alpha_D$ is always faster than the bremsstrahlung process and thus the bounds are independent of the PDDM density profile.

# When does it stop?

- Presumably when dense enough no longer ionized
- Cooling very suppressed at that point
-  (?)

# Temp at recombination

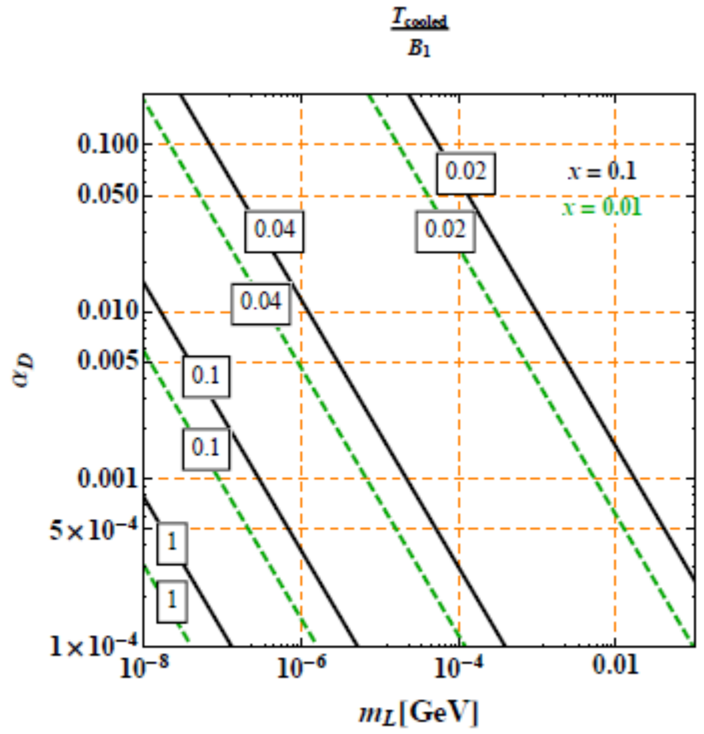



FIG. 8. Estimates of cooling temperature $T_{\text{cooled}}/B_{XY}$ in the $(m_Y, \alpha_d)$ plane. Blue solid curves: $x = 0.1$; green dashed curves: $x = 0.01$.

# Cooling temp determines disk height

- And therefore density of new component

The disk scale height could be estimated as follows. In an axisymmetric gravitational system with height $z$,

$$\frac{\partial(\rho \bar{v_z^2})}{\partial z} + \rho \frac{\partial(\Phi)}{\partial z} = 0 \tag{9}$$

$$4\pi G_N \rho = \frac{\partial^2(\Phi)}{\partial z^2}, \tag{10}$$

where the first equation is the Jeans equation neglecting the radial derivative (see Eq. (4.222b) in [2]) and the second is the Poisson equation. Solving these two equations, one find the scale height is [3]

$$z_d = \sqrt{\frac{v_z^2}{8\pi G_N \rho}} = \sqrt{\frac{k_B T}{m_p 24\pi G_N \rho}}, \tag{11}$$

where in the second step, the thermal relation $m_p \bar{v_z^2} = k_B T/3$ is used. Numerically,

$$z_d \approx 2.5\,\mathrm{pc} \left(\frac{\alpha_D}{0.02}\right)^2 \frac{m_Y}{10^{-3}\ \mathrm{GeV}} \frac{100\ \mathrm{GeV}}{m_X} \tag{12}$$

where $T$ is in unit of K and $\rho$ is unit of GeV/cm$^3$. Interstellar gas (and young stars) have velocity $v \sim 10$ km/s which corresponds to $T \sim 10^4$ K. Plugging it in, we get the disk height is about 300 pc. For old stars, the velocity is about $20 - 30$ km/s and the local disk height is estimated to be 600 pc - 1 kpc, which agrees with the observations (see numbers in [2]).

# Disk Height

- In reality, gravitational heating can occur
- Reasonable to assume disk height between
- $m_P/m_X$---1 times baryonic disk height
- Can be very narrow disk
- For 100 GeV particle, can get boost factor of 10,000!

# Note that disks should at least approximately align

- Alignment time:
- R~10 kpc
- M~10^12 M_sun

$$t \approx \left(\frac{R^3}{GM}\right)^{1/2} \sqrt{\theta}$$

$$10^{12} M_{Sun} = 1.99 \times 10^{45} \text{ gr}$$

$$G = 6.67 \times 10^{-8} \text{ cm}^3 \text{gr}^{-1} \text{sec}^{-2}$$

$$t \sim \left(\frac{R^3}{GM}\right)^{1/2} \sim \sqrt{2.2 \times 10^{29}} \text{ sec} \sim 4.7 \times 10^{14} \text{ sec} \sim 1.5 \times 10^7 \text{ years}$$

# More on alignment

but disks can be misaligned with the overall halo by angles typically near 45°, and only rarely as large as 90°. Nonetheless, particularly strong correlations have been found between the angular momentum of the disk and of the *inner part* of the halo (cf. Fig. 17 of Ref. [29] or Table 2 of Ref. [30]), suggesting that locally, gravitational interactions will tend to align these structures. One would expect the timescale of such gravitational alignments to be, very roughly, $t \sim R\sqrt{R/GM_{\rm disk}} \sim 10^7$ yr. Still, the inner halo alignment with the disk in Ref. [30] is imperfect, with median angle 18°. The Earth sits about 10 to 20 parsecs above the galactic plane [31] and about 8

# Summary of model

- For photon signal want a heavy component
- For disk to form, require light component
  - Can't be thermal (density would be too low)
  - Constraint on density vs mass
- Aside: anthropic bound on electron mass!
  - Very robust
- But with these conditions, we expect a dark disk
  - Might even be narrower than gaseous disk
- Expect interesting signals

# Implication?

- Photons from plane of galaxy!
- Not only center but unassociated sources throughout plane would be expected
- Seems rather specific to this type of model
  - Component of dark matter sitting in small disk in plane of galaxy
- Furthermore will affect structure formatoin
  - Work not yet in progress….

# Indirect Signal

a typical halo. The gamma-ray intensity in a given direction is the line-of-sight integral of the DM number density squared along a given direction,

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{8\pi}\frac{\langle\sigma v\rangle_{\gamma\gamma}}{m_{DM}^2} 2\delta(E - E_\gamma) d_\odot \rho_\odot^2 J, \qquad (35)$$

with:

$$J = \int_{\rm roi} db\, dl \int_{\rm l.o.s} \frac{ds}{d_\odot} \cos b \left(\frac{\rho(r)}{\rho_\odot}\right)^2, \qquad (36)$$

where $\rho_\odot$ is the normal DM density at the sun, $\rho_\odot = 0.3$ GeV cm$^{-3}$. $d_\odot$ is the distance from sun to the GC, $d_\odot \approx 8.3$ kpc. The integral is over the region of interest (roi) at the Galactic Center (GC). The smallest region centered around GC that Fermi-LAT experiment is sensitive to is a $0.2^\circ \times 0.2^\circ$ square due to finite angular resolution, which corresponds to a 28 pc $\times$ 28 pc region around GC. Thus for disk height $z_d > 28$ pc, we expect that $J_{PDDM}$ scaling as $z_d^{-2}$. Fig. 9 shows the local density enhancement of PDDM compared to the normal DM defined as

$$\frac{J_{PDDM}}{J_{DM}}$$

as a function of PDDM disk height $z_d$, where for normal DM, we used Einasto profile

$$\rho_{\rm Einasto}(r) = \rho_s \exp\left(-(2/\alpha_E)\left((r/r_s)^{\alpha_E} - 1\right)\right), \quad (37)$$

where $r_s = 20$ kpc and $\alpha_E = 0.17$. $\rho_s$ is fixed to achieve the correct $\rho_\odot$.

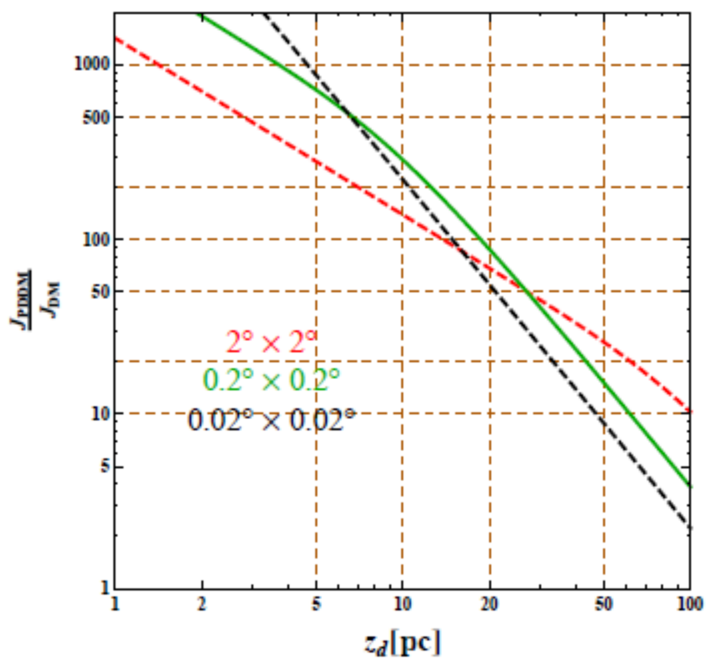



FIG. 9. Local density enhancement in PDDM in a square region around the GC fixing $\epsilon = 0.05$ that PDDM is 5% of the total DM density. Red: region within $b \subset (-1^\circ, 1^\circ), l \subset (-1^\circ, 1^\circ)$. Green: region within $b \subset (-0.1^\circ, 0.1^\circ), l \subset (-0.1^\circ, 0.1^\circ)$ (current Fermi-LAT angular resolution). Black: region within $b \subset (-0.01^\circ, 0.01^\circ), l \subset (-0.01^\circ, 0.01^\circ)$.

# Distinctive Shape to Signal

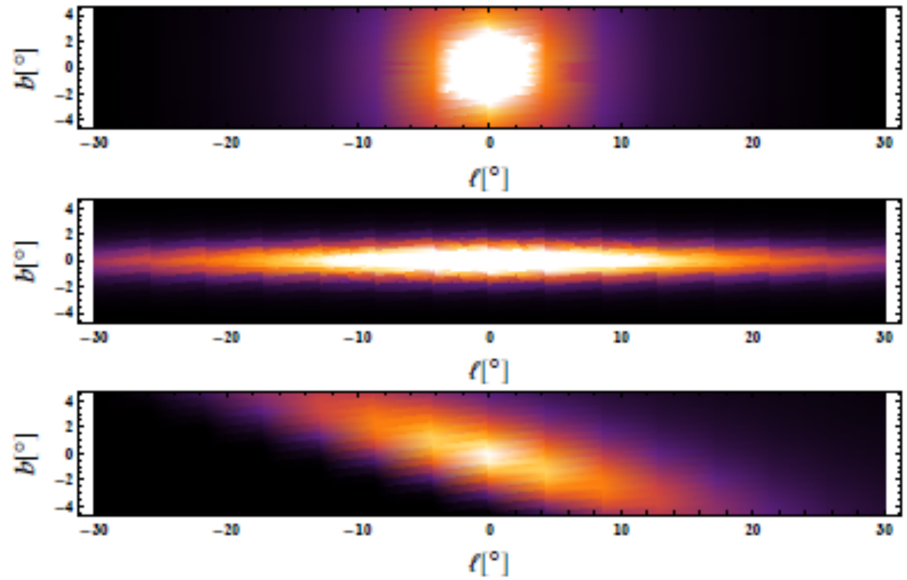



FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

# Direct Detection of DDDM (CDMS vs Xenon)? w/McCullough (also Fan, Katz, Shelton)

# II:Why consider DDDM for direct detection?

- Key observation: low threshold events indicate small kinetic energy
- Two possible reasons
  - Small mass
  - Small velocity
- In fact velocity so small in DDDM that ordinarily you evade detection completely
- Good: low threshold
  - Why? Mass could be big but
  - *velocity is small*
- Bad: too small
  - Usually recoil below threshold
    - Furthermore, co-rotating with sun,
    - Peculiar velocity, Earth motion too small
  - Furthermore heavy dark matter (assumed) hard to reconcile CDMS and Xenon
- Solution to both issues (if expt real): ExoDDDM

$$
\begin{aligned}
E_R^{\max} &= \frac{2\mu_N^2}{m_N} v_X^2 \\
&\approx 0.5\,\mathrm{keVnr} \left(\frac{\mu_N}{50\,\mathrm{GeV}}\right)^2 \frac{100\,\mathrm{GeV}}{m_N} \left(\frac{v_X}{10^{-4}}\right)^2
\end{aligned}
$$

# New Ingredient: ExoDDDM

- Recoil could be due to a mass splitting $\delta$
- ExoDM (Graham, Harnik, Rajendran, Saraswat)
- Like IDM but reverse—long-lived excited state
- Downscatters inelastically off nuclei
- Recoil energy reflects mass difference (as well as kinematics)

- We will see nuclear mass dependence works to favor consistent CDMS, Xe interpretation

$$v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}} \left| \frac{M_N E_R}{\mu_N} - \delta \right|$$

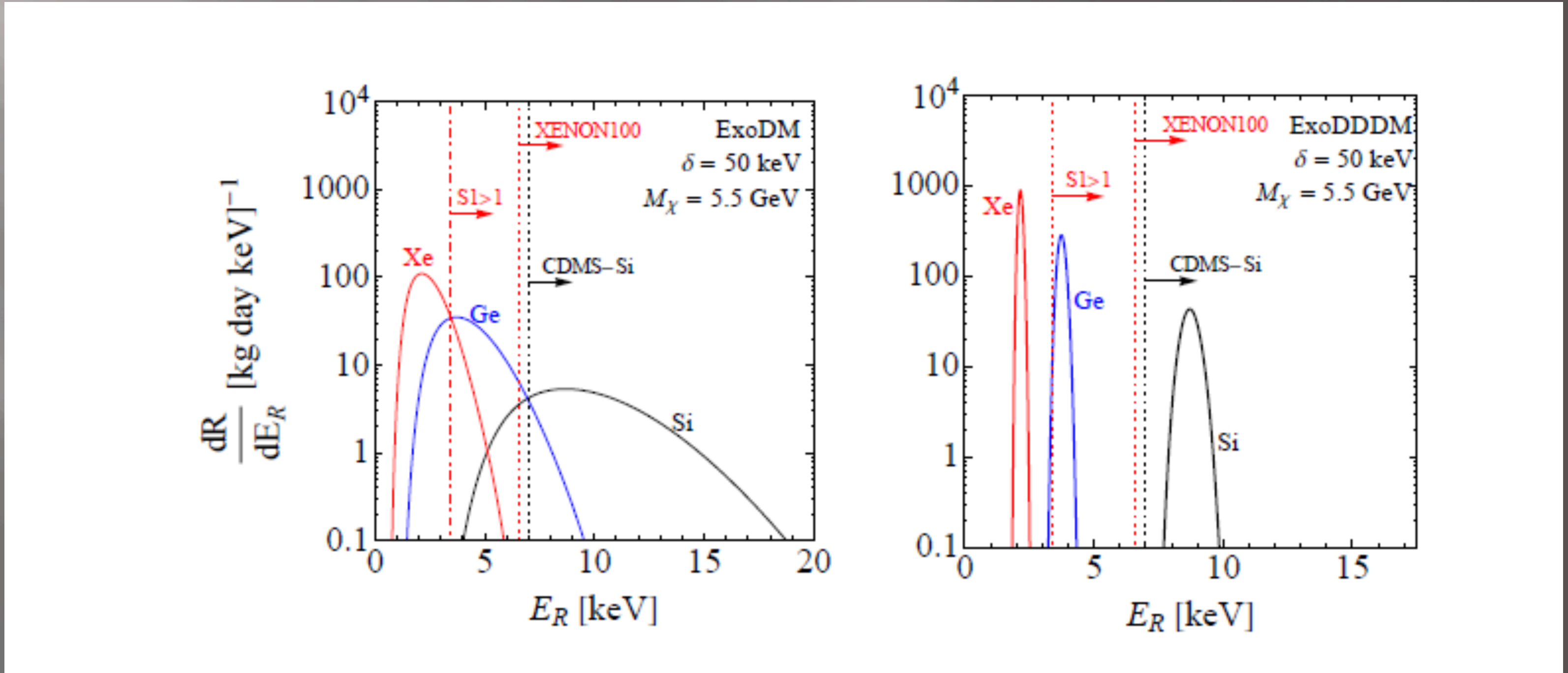
$$v_{\rm thr} = \begin{cases} v_{\min}(E_{\rm thr}) & \delta < E_{\rm thr} M_N/\mu_N \\ 0 & \delta > E_{\rm thr} M_N/\mu_N \end{cases}$$

- Elastic, heavy DM: In this case $v_{\rm thr} \approx \sqrt{E_{\rm thr}/2M_N}$. Heavier nuclei lead to reduced minimum velocity thresholds and will thus sample more of the DM velocity distribution, leading to greater sensitivity.
- Elastic, light DM: In this case $v_{\rm thr} \approx \sqrt{E_{\rm thr} M_N}/\sqrt{2}M$, the minimum velocity threshold is reduced for lighter nuclei, and detectors with lighter nuclei will sample more of the DM velocity distribution, improving the sensitivity to light DM.
- Exothermic: To the minimum velocity of the previous two elastic scattering cases we subtract an additional component such that $v_{\rm thr} = |v_{\rm thr}(\delta = 0) - \delta/\sqrt{2M_N E_{\rm thr}}|$. This extra exothermic term leads to a reduction in the minimum velocity, and can in some cases reduce it to zero. The reduction is greatest for light nuclei, leading to preferential scattering of the DM on lighter target nuclei. For light exothermic DM this further enhances the sensitivity of light nuclei detectors over heavy nuclei detectors.

- CDMS (silicon) A=28, Xenon A=131
- Clearly light dark matter preferred if CDMS sees something and Xenon doesn't
- Exothermic even better, with greater reduction in threshold v for light nuclei

# Why ExoDDDM?

- Much smaller velocity dispersion
- Very distinguishable
- Virtually no Gaussian tail giving rise to Xenon etc events



# Results

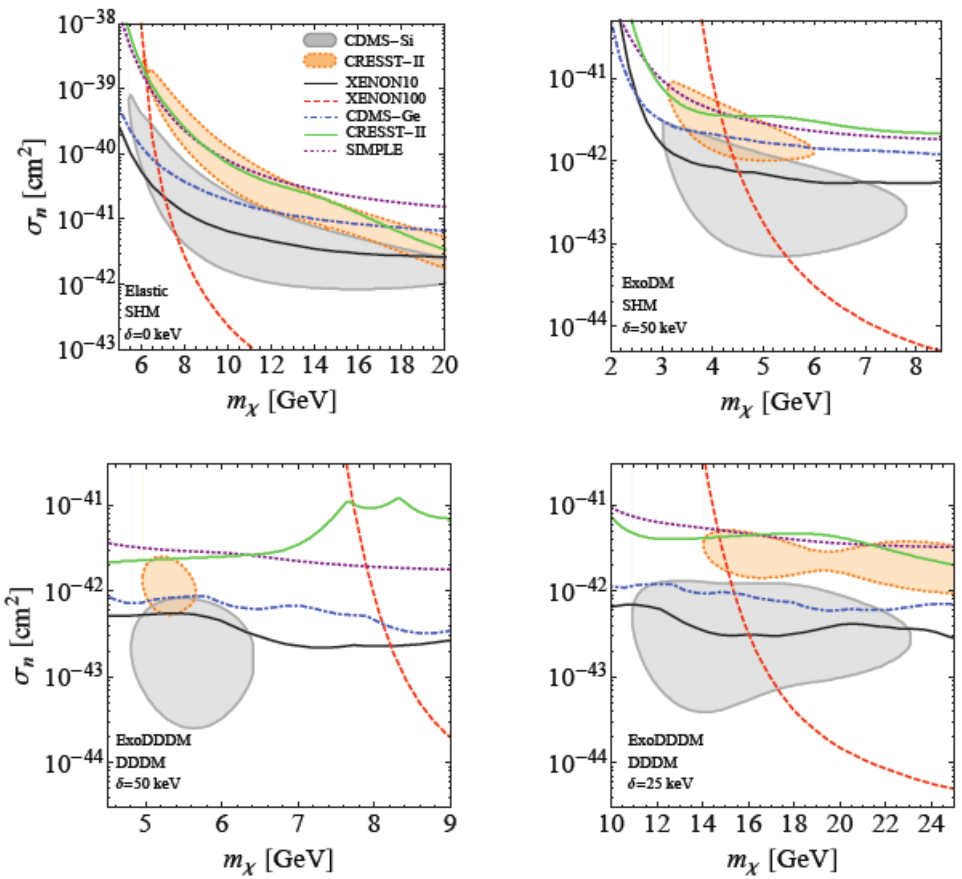



**Figure 5**: 90% best-fit regions (CDMS-SI shaded gray and CRESST-II shaded orange) and 90% exclusion limits (XENON10 solid black, XENON100 dashed red, CDMS-Ge dot-dashed blue, CRESST-II low threshold analysis solid green and SIMPLE in dotted purple). Elastic and exothermic scattering of standard halo DM are shown in the upper panels, and ExoDDDM below. Elastic scattering of light DM gives a good fit to the CDMS-Si events, although there is significant tension with null results. ExoDM reduces the tension and opens up additional parameter space consistent with CDMS-Si and limits from the null search results [30]. ExoDDDM scattering allows for a CDMS-Si interpretation with heavier DM mass (lower right). For lighter ExoDDDM (lower left), the majority of the favored parameter space is consistent with the strongest bounds and the DM mass favored in asymmetric DM models.

# CRESST-II, CDMS-Si consistent

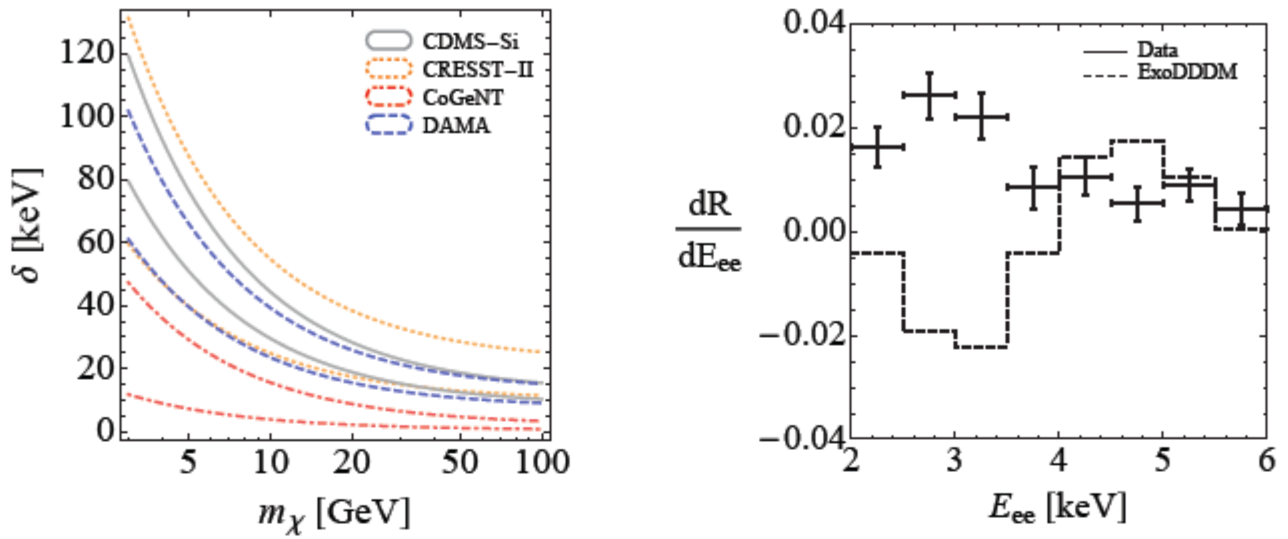



**Figure 7**: The required exothermic splitting $\delta$ required to give nuclear recoil energies in the typical range required by the various anomalies (left panel). Required values for a given experiment lie between the two corresponding contours. Splittings required for CoGeNT are inconsistent with those required for CRESST-II, CDMS-Si and unquenched DAMA. We also show the modulation spectrum at unquenched DAMA for $\delta = 50$ keV, $M = 5.5$ GeV (right panel). We have increased the relative rotational velocity to $v_{rel} = 100$ km/s to give dates of maximum and minimum relative velocity closer to the dates of maximum and minimum event rates in DAMA, however the spectrum is in anti-phase with the data.

# For future

- Lower threshold
  - Any events essentially indicates this model wrong
  - Ordinary DM increases dramatically as you lower threshold
  - ExoDM increases somewhat
- Phase dependence
  - Measure time dependence
  - Smaller for ExoDM  in general
  - Different phase since no longer tail of Gaussian

# Many other interesting directions

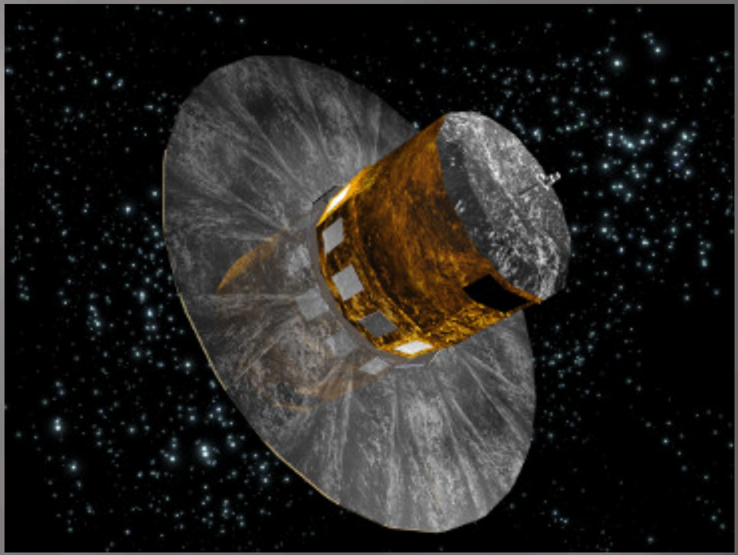
- Structure: predict
- Structure: determine constraints via vastly improved measurements of velocities
- Black holes
- Reanalyze Planck (non free-streaming DOF)
- Predict solar system motion

# For Future:
# Many interesting directions

# IIIMany Other Consequences Things to think about

- New species (Planck can detect)
- Possibly small scale structure
  - Atomic physicbs
- Numerical simulations (structure, alignment)
- Velocity distributions, lensing (look for structure)
- Large scale structure
  - Acoustic Oscillations
  - galaxy-galaxy correlation funcionts
- Indirect detection
- Direct detection (at very low threshold)
- Aside: anthropic limits

# Particularly Interesting NOW



- GAIA mission of ESA

*Gaia* is a space observatory to be launched by the European Space Agency (ESA) in October 2013.[1] The mission aims to compile a 3D space catalogue of approximately 1 billion stars, or roughly 1% of stars in the Milky Way.[4][5][6] Successor to the *Hipparcos* mission, it is part of ESA's Horizon 2000 Plus long-term scientific program. Gaia will monitor each of its target stars about 70 times to a magnitude 20 over a period of 5 years. Its objectives comprise:

determining the positions, distances, and annual proper motions of 1 billion stars with an accuracy of about 20 µas (microarcsecond) at 15 mag, and 200 µas at 20 mag

detection of tens of thousands of extra-solar planetary systems[7]

capacity to discover Apohele asteroids with orbits that lie between bEarth and the Sun, a region that is difficult for Earth-based telescopes to monitor since this region is only in the sky during or near the daytime[8]

detection of up to 500,000 distant quasars

more accurate tests of Albert Einstein's general relativity theory

*Gaia* will create an extremely precise three-dimensional map of stars throughout our Milky Way galaxy and beyond, and map their motions which encode the origin and subsequent evolution of the Milky Way. The spectrophotometric measurements will provide the detailed physical properties of each star observed, characterising their luminosity, effective temperature, gravity and elemental composition. This massive stellar census will provide the basic observational data to tackle a wide range of important problems related to the origin, structure, and evolutionary history of our Galaxy. Large numbers of quasars, galaxies, extrasolar planets and Solar System bodies will be measured at the same time.

- **Objectives**
- The Gaia space mission has the following objectives:
- To determine the intrinsic luminosity of a star requires knowledge of its distance. One of the few ways to achieve this without physical assumptions is through the star's parallax. Ground-based observations would not measure such parallaxes with sufficient precision due to the effects of the atmosphere and instrumental biases.
- Observations of the faintest objects will provide a more complete view of the stellar luminosity function. All objects up to a certain magnitude must be measured in order to have unbiased samples.
- A large number of objects are needed to examine the more rapid stages of stellar evolution. Observing a large number of objects in the galaxy is also important in order to understand the dynamics of our galaxy. Note that a billion stars represents less than 1% of the content of our Milky Way galaxy.
- Measuring the astrometric and kinematic properties of a star is necessary in order to understand the various stellar populations, especially the most distant.
- Gaia is expected to:
- Measure the astrometric properties of over a billion stars down to an apparent magnitude (V) of V = 20
- Determine the positions of stars at a magnitude of V=10 down to a precision of 7 millionths of an arcsecond ( $\mu$ as) (this is equivalent to measuring the diameter of a hair from 1000 km away); between 12 and 25 $\mu$ as down to V = 15, and between 100 and 300 $\mu$ as to V = 20, depending on the color of the star
- Determine the distances to the nearest stars within 0.001%, and to stars near the galactic center, 30,000 light years away, within 20%
- Measure the tangential speed of 40 million stars to a precision of better than 0.5 km/s
- Measure the orbits and inclinations of a thousand extrasolar planets accurately, determining their true masses using astrometric planet detection methods [11]
- Among other results relevant to fundamental physics, Gaia will detect the bending of starlight by the Sun's gravitational field, as predicted by Albert Einstein's General Theory of Relativity, and therefore directly observe the structure of space-time.[7]

# Conclusions

- Whether or not 130 GeV signal survives,
- Very interesting new possibility for dark matter
  - That one might expect to see signals from
- Since in some sense only minor modification (just a fraction of dark matter)
- hard to know whether or not it's likely
- But  presumably would affect structure
  - Just like baryons do
  - Research area
- Rich arena: lots of questions to answer

# IV:Could maybe even explain dinosaur extinction…

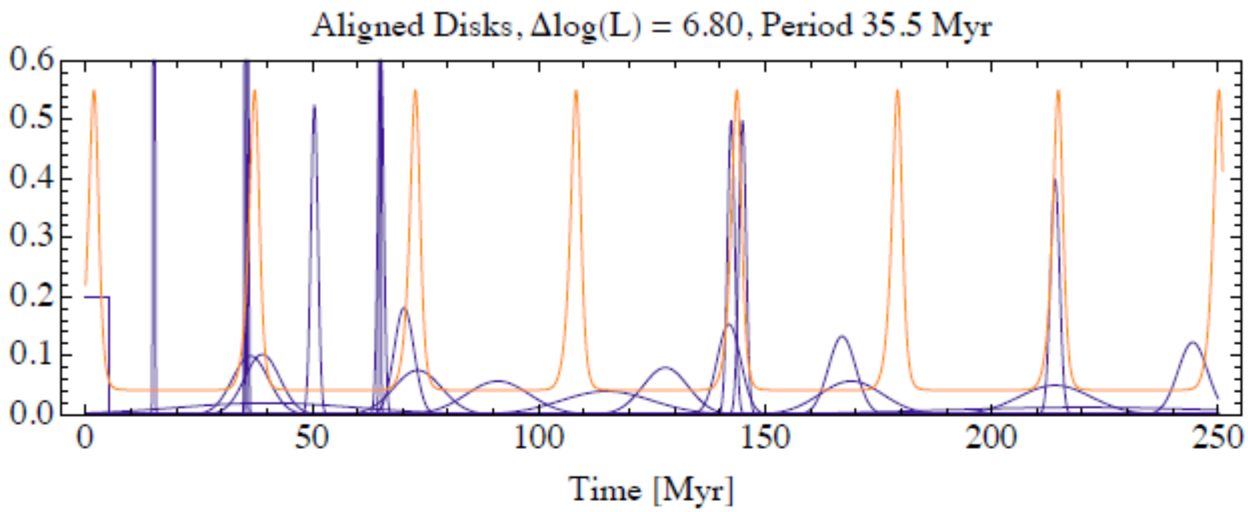
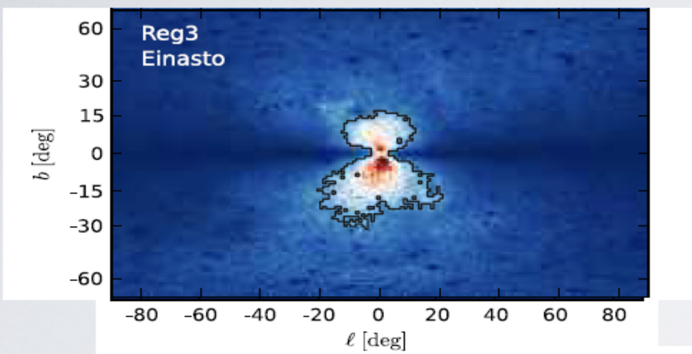


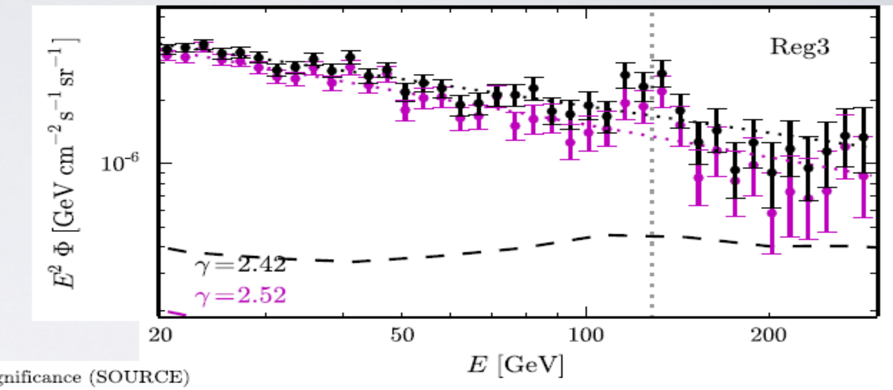

**Figure 8:** An example of a model that provides a good fit. In this case, the two disks are aligned, and the period between disk crossings is about 35 Myr.

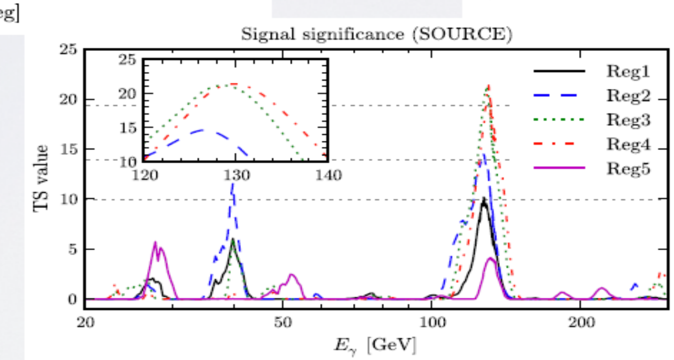
# Motivation: Gamma Ray Signal

## A FERMI LINE?

Weniger, '12; Bringmann et al '12



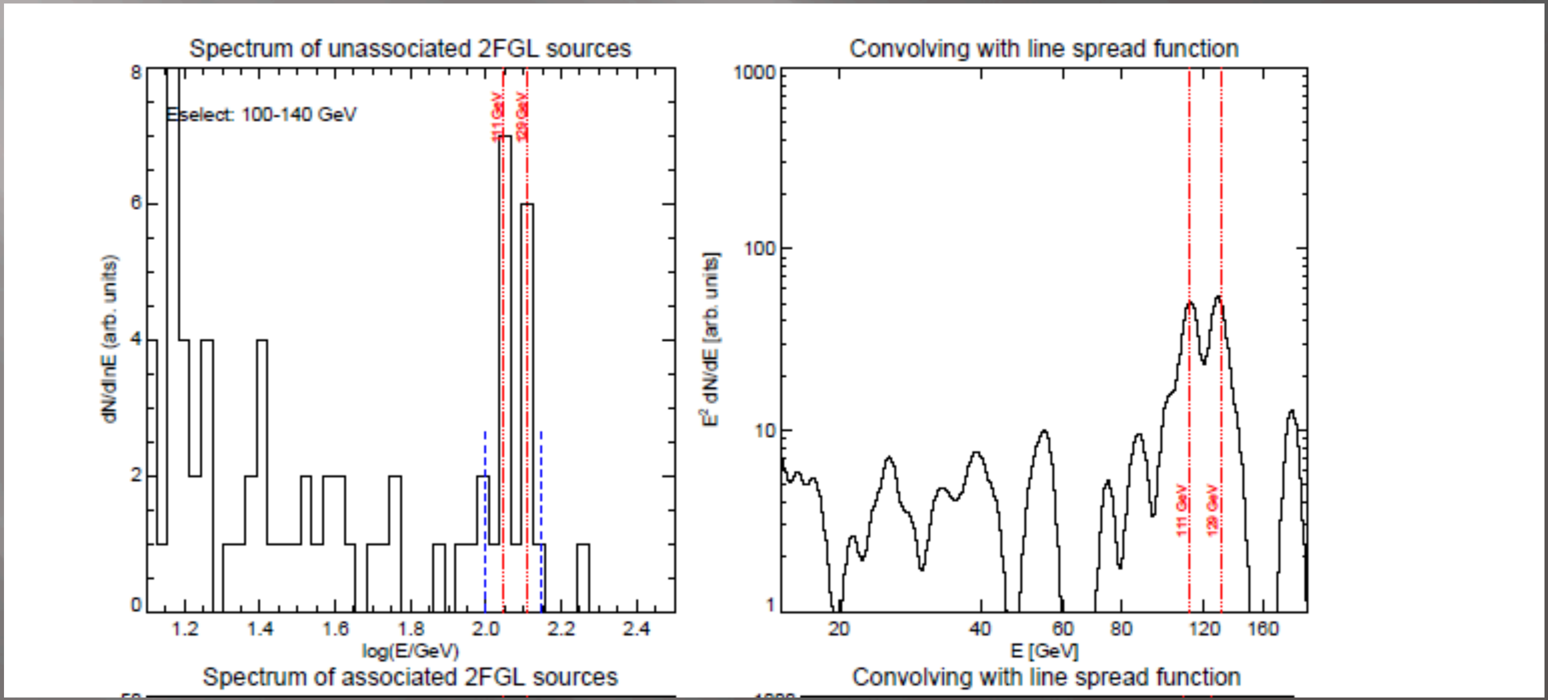

Rate is ~ 100 times larger than expected for a WIMP

also - systematic concerns

Neil Weiner's talk

# Motivation: Fermi Lines

- Finkbeiner, Sug



# Motivation: Fermi 130 GeV line

- Suppose you want to explain Fermi signal with dark matter
- If you also assume relic thermal abundance want annihilation into something to be about an order of magnitude bigger
- However can’t annihilate into charged particles since the signal would already rule it out
- One option is to annihilate to photons through a loop of charged particle that is kinematically inaccessible

# But tough

- Rate to photons generically won't be big enough
- Need charged intermediate state to be heavier than dark matter
- But actually a very narrow splitting or else rate too low
- And even then you need some new interactions uncomfortably large

# Look concretely at rate

## Model: Scalar coupled to Charged Scalar

In the first model, the DM is a complex scalar $X$ with a coupling to another complex scalar $S$

$$-\mathcal{L} \supset \lambda_X |X|^2 |S|^2, \tag{13}$$

where $X$ is only charged under hidden $U(1)_D$ with charge $Q_D$ and $S$ is charged under the SM weak gauge group with electric charge $Q_s$. The relic abundance is determined by the process $X^\dagger X \to \gamma_D \gamma_D$

$$\Omega_{HS} h^2 \approx \frac{5.0 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}}{(\sigma v)_{X^\dagger X \to \gamma_D \gamma_D}} \tag{14}$$

$$\text{with} \qquad (\sigma v)_{X^\dagger X \to \gamma_D \gamma_D} = \frac{2\pi \alpha_D^2 Q_D^4}{m_X^2}, \tag{15}$$

$$\langle \sigma v \rangle_{X^\dagger X \to \gamma\gamma} = \frac{\sum |M|^2}{64 \pi m_X^2},$$

$$\sum |M|^2 = \frac{\alpha^2}{2\pi^2} \lambda_X^2 Q_s^4 \tau^2 A_0^2(\tau), \tag{16}$$

with $\tau = m_X^2/m_S^2$ and $\tau A_0(\tau) = 1 - \tau^{-1} \mathrm{arcsin}^2(\sqrt{\tau})$. The line strength for the hypothesis DM DM $\to \gamma\gamma$ with only one component of DM estimated in the literature is $10^{-27}$ cm$^3$/s.

# Boost Factor

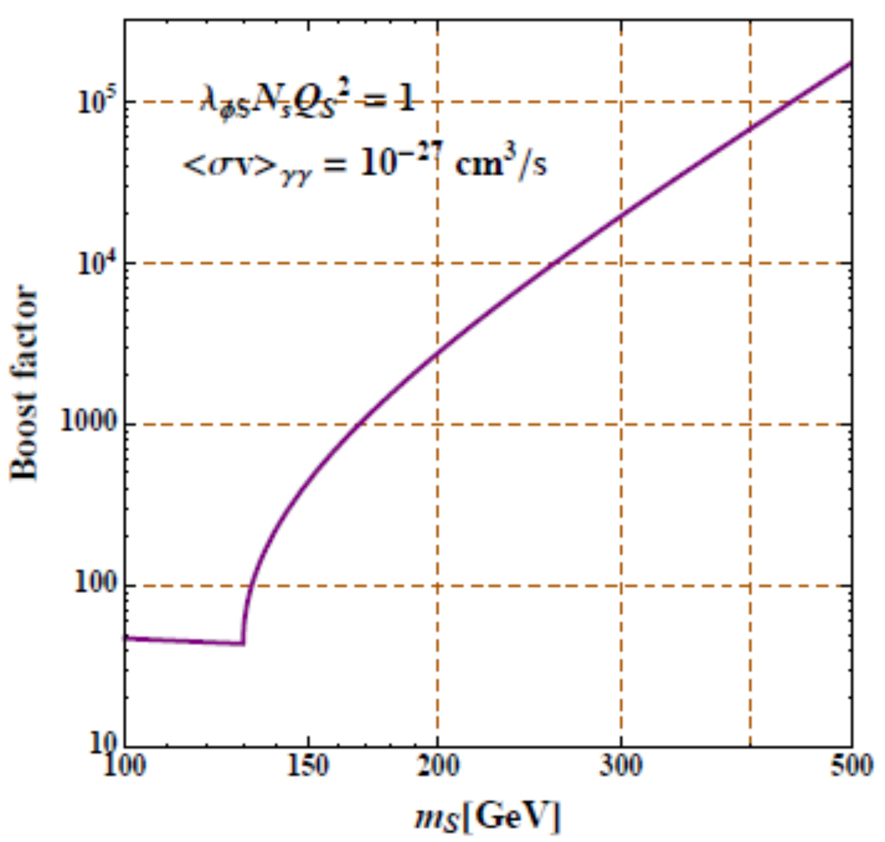



FIG. 1. Fixing $(\sigma v)(\phi\phi \to \gamma\gamma) = 10^{-27}$ cm$^3$s$^{-1}$, $N_S Q_S^2 \lambda_{\phi S} =$ 1 and $m_\phi = 130$ GeV, the boost factor $B$ needed to generate a signal that current Fermi line search is sensitive to.

# Somerfeld Enhancement Not Enough!

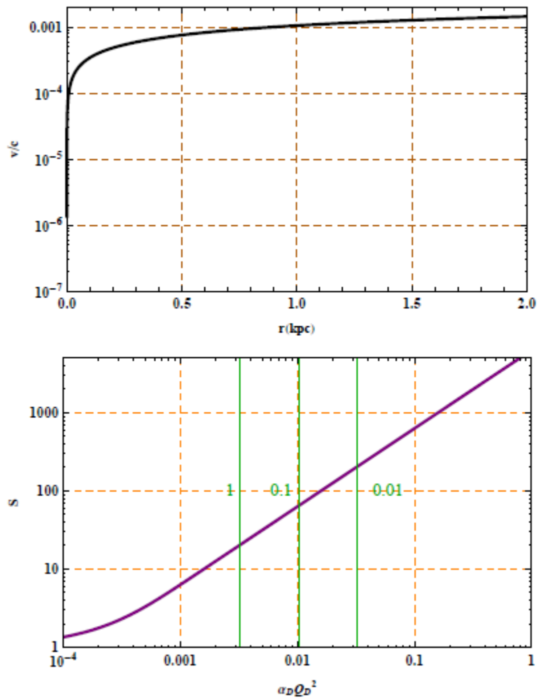



**Figure 2:** Upper: velocity distribution as a function of distance from the galactic center $r$; Lower: Sommerfield enhancement factor as a function of $\alpha_D Q_D^2$ assuming $v/c = 10^{-3}$. In the lower plot, the green lines stand for fraction of the hidden charged DM density in the whole DM density $\Omega_{HS}/0.11$.


[3] J. M. Cline, Phys. Rev. D **86**, 015016 (2012) [arXiv:1205.2688 [hep-ph]].

[4] N. Weiner and I. Yavin, "How Dark Are Majorana WIMPs? Signals from MiDM and Rayleigh Dark Matter," arXiv:1206.2910 [hep-ph].