Double Disk Dark Matter

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

What Is Dark Matter?

- Clearly we don't yet know
- We know gravitational interactions
  - Lensing, rotation curves, energy measurements
  - But no other discernible interactions
    - Yet
- We need to consider all possibilities
  - Does dark matter interact as we might hope?

Status

- Searches to date always based on optimistic assumptions
- Namely dark matter does interact with our matter at some level
- In principle could be purely gravity coupling
  - Or coupling only to its own sector
- Does dark matter have other interactions?
- Talk today: reasons to think it might
- Alternatives to standard WIMP paradigm
  - Asymmetric dark matter/Xogenesis
  - Partially interacting dark matter

Lampposts for Dark Matter?

- Existence of dark matter not necessarily so mysterious
  - Why should everything be like our matter?
  - What is mysterious is that energy stored in dark matter and ordinary matter so similar
- But how to find what it is?
  - Look under the lamppost
  - Find theoretical, experimental clues
- What are the right lampposts?

Where are we today?

- Direct dark matter detection
  - Tentative CDMS signal
    - But consistency with Xenon (w/McCullough)
      - Other even less likely signals
- LHC searches
  - Have seen …
- Indirect Searches
  - Lots of surprises
  - Signals?
    - Has motivated new model building directions

Lampposts: theoretical

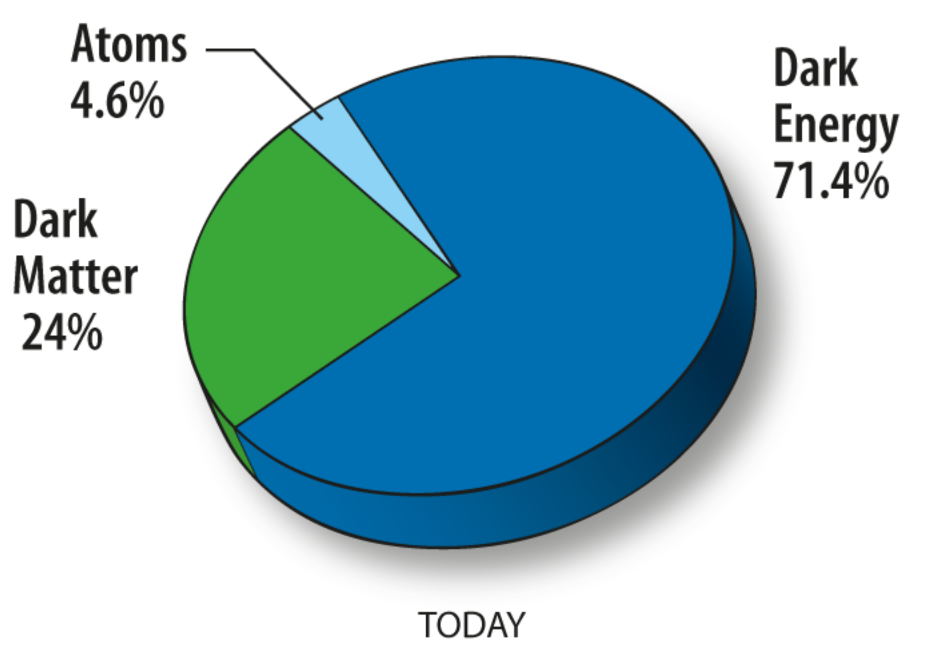
- WIMP: usual suspect
  - —coincidence that weak mass particle has measured abundance?
- Weak-scale mass good from experimental perspective
  - Mass such that it can be produced at LHC
  - And if connected to weak scale have reason to believe will be produced
- **But we haven’t yet seen it**

Other ideas?

- New ideas for both theory and detection
- DM could be different/more interesting than assumed/ searched for?
- Visible sector complex—maybe dark sector too?
- Here we don't try to solve all the problems with CDM
  - Though will be interesting to see implications
- Simply investigate new possibilities
  - First: nonthermal dark matter/ asymmetric
  - Second: Partially interacting dark matter
    - Reasonable extrapolation
    - With different/testable consequences

Theoretical lamppost?

- Similarity of amount of energy in dark matter and ordinary matter
- Maybe matter and dark matter are produced in similar ways?
- Excess "matter" over "antimatter"



Asymmetric Dark Matter

- Explain connection dark matter and ordinary matter energy densities
- Dark matter energy similar in spirit to that of baryons
  - Asymmetry in dark matter density; not thermal
- Need interactions between baryons and dark matter to explain the similar relative size
  - Chemical potentials related
  - Number densities are too nB~nX;
- Nonrelativistic solution allows more general possibilities
  - Xogenesis (w Buckley)
    - And DM created first

Can nature do better?

- ADM compelling
  - But origin of operators that mix two sectors?
- Higher-dimensional operators can violate both L (or B) and DM numbers
- **Don’t necessarily expect L, X conservation in early universe**

Emergent Lepton and Dark matter Numbers

w/Cui, Shuve

- Are B and X conserved?
- Maybe not in early universe
- Transfer and then restore
- Two Higgses, Modulus decay, higher-dimensional operators

Other interesting possibilities?

- 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
- Surprisingly, unexplored option:
- Interacting dark matter
- But rather than assume all dark matter
- Assume it's only a fraction (maybe like baryons?)
- w/fan,katz,reece

This changes everything!

- Almost all constraints on interacting dark matter assume it is the dominant component
- If it’s only a fraction, we’ll see most bounds generally don’t apply
  - structure
  - Galaxy or cluster interactions
- But if a fraction, you’d expect even smaller signals!
- However, not necessarily true…

PIDM

- Today talk about self-interacting dark matter
- But rather than assume all dark matter
- Assume it's only a fraction (PIDM)
  - maybe like baryons?
- Nonminimal assumption
- But one with significant consequences
- Will focus on dissipative –forms disk -DDDM
  - Will be tested
  - In any case leads to rethinking of implications of almost all dark matter, astronomical, cosmological measurements

Partially Interacting Dark Matter: What?

w/Fan, Katz, Reece

- Motivation for usual interacting dark matter
  - Small-scale structure
- Motivation for ADM
  - Similarity of DM and normal matter energy densities
- PIDM is maybe not motivated
  - Unless you believe 130 GeV excess
- Yet another Occam razor debate
  - Assumption is at least a small component of dark matter
  - With self-interactions
    - In fact its own gauge force and its own atomic structure

PIDM: Why?

- World we know not so simple
- Furthermore, a small component can be relevant
  - Baryons
    - Small component particularly relevant when interactions
- Here motivation and session: 130 GeV line
- But implications far beyond this initial suggestion
- Best reason for looking at new models:
  - Lots of data becoming available
  - Challenge to understand implications
  - Models are a way to target searches and better understand
  - And might actually exist and account for as-yet unexplained phenomena

Initial 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

Boost

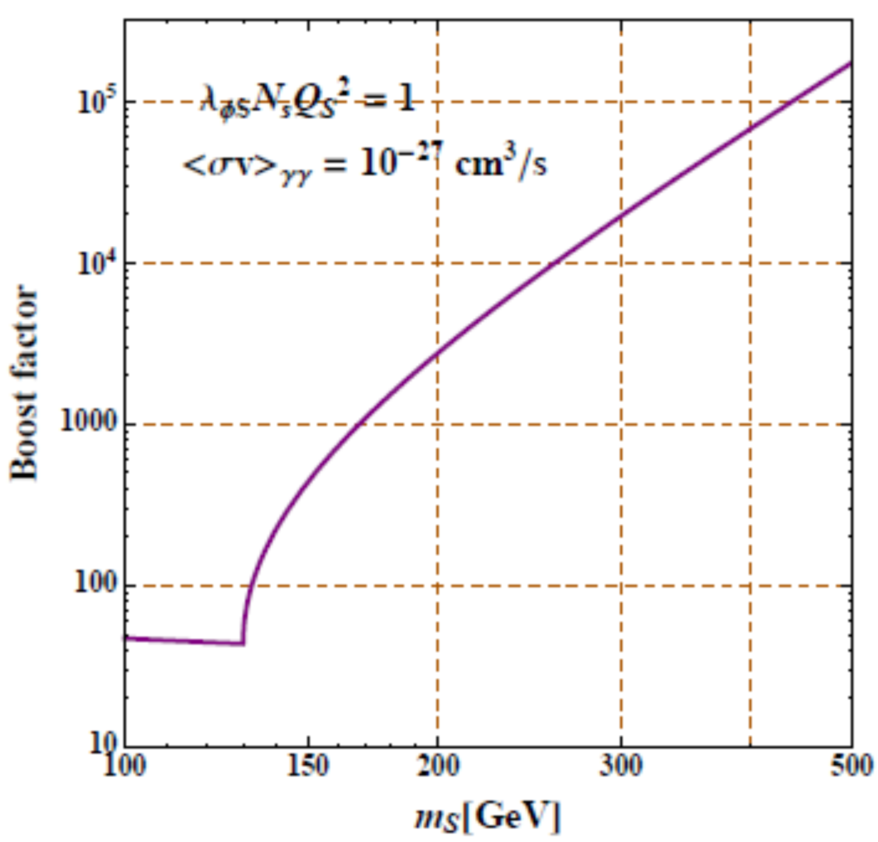


FIG. 1. Fixing $(\sigma v)(\phi\phi \to \gamma\gamma) = 10^{-27}$ cm^{3}s^{-1}, $N_S Q_S^2 \lambda_{\phi S} =$. and $m_\phi = 130$ GeV, the boost factor B needed to generate a signal that current Fermi line search is sensitive to.

Interacting Dark Matter and Indirect Signals

- Boost factor too high to assume clumping even with Somerfield enhancement
- But what if dark matter actually had structure?
  - Like baryons for example
- With interacting dark matter
  - Dissipative dark matter in particular
- Can 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

Could interacting dark matter cool into a disk?

- Requires a means of dissipating energy
- Assume interacting component has the requisite interaction
- Simplest option perhaps independent gauge symmetry
  - "Dark light"
- Could be U(1) or a nonabelian group
  - U(1) has fewer DOF: good for "neutrino constraint"
  - Nonabelian permits formation of stable dark atoms
  - Also good for U(1) mixing constraint
- Check when enough cooling can occur to form a disk

- Most interesting possibility

Simple PIDM/DDDM Model

- $U(1)_D$, α_D
- Two matter fields: a heavy fermion X and a light fermion C
  - For "coolant" as we will see
- $q_X=1$, $q_C=-1$
- (In principle, X and C could also be scalars)
- Also interesting will be nonabelian generalization $SU(N)_D$
  - X fundamental, C antifundamental
  - Assume confinement scale below relevant cooling temps

BBN Limit on DOF

The number of additional effective neutrino species is determined by $g_{*s,D}\xi^4(t_{\rm CMB}) = \left(\frac{4}{11}\right)^{4/3} \times \frac{7}{8} \times 2 \times \Delta N_{{\rm eff},\nu}^{\rm CMB}$, leading to:

$$\begin{aligned} \Delta N_{{\rm eff},\nu}^{\rm CMB} &= 0.22 \text{ for } {\rm U}(1)_D, \\ \Delta N_{{\rm eff},\nu}^{\rm CMB} &= 4.4(N^2-1)\xi^4 \text{ for } {\rm SU}(N)_D. \end{aligned} \tag{15}$$

Numerically, $\Delta N_{{\rm eff},\nu}^{\rm CMB}$ is 0.49 in the ${\rm SU}(2)_D$ model, 0.91 in the ${\rm SU}(3)_D$ model, and 1.45 in the

Weaker Constraints on Interaction Strength

- Shape constraints need to be rethought when only a portion interacts
- Cluster constraints much weaker
  - And can be reinterpreted
- Finally: lack of detection
  - That of course just refers to interactions with ordinary matter
  - Doesn’t tell about self-interactions

Relic Density X

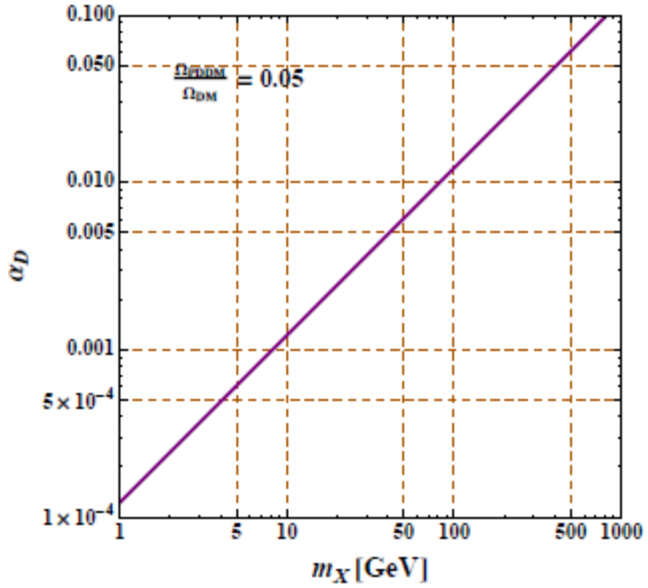


Figure 1: α_D needed to get the thermal relic abundance of X to be 5% of the total DM density for different masses of X.

Density of C?

- Thermal abundance of C will however be too small
- Will expect both thermal and nonthermal contributions to X
- Nonthermal to C
- Asymmetric Dark Matter works nicely in this context
- Interesting that thermal component of X can survive as well

The light species C with $m_C \ll m_X$ freezes out at much later times, and has a much larger annihilation rate than the heavy species, by a factor $(m_X/m_C)^2$. As a result, the thermal relic number density of C is much smaller than that of X, by a factor m_C/m_X. This means that we expect any symmetric component of C and $\bar{C}$ to annihilate away almost completely at dark sector temperatures a factor of 20 below the C mass. The existence of light C particles is crucial to dissipative dynamics, as we will see in detail in Section 5. This means that only a nonthermal mechanism for producing C particles can be consistent with dissipative dynamics.

Thermal and Nonthermal

- In principle other processes to produce C
- Still would annihilate away
  - Unless bound with X
- Possible in nonabelian scenarios
- We make simpler assumption of nonthermal component
  - Interesting that thermal component of X naturally survives as well

Brehmstrahlung and Compton

timescale of the bremsstrahlung cooling is

$$
\begin{aligned}
t_{\rm brem} &\approx \frac{3}{16}\frac{n_X+n_C}{n_X n_C}\frac{m_C^{3/2}T_{\rm vir}^{1/2}}{\alpha_D^3} \\
&\approx 10^4\,{\rm yr}\sqrt{\frac{T_{\rm vir}}{\rm K}}\frac{{\rm cm}^{-3}}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^3\left(\frac{m_C}{m_e}\right)^{\frac{3}{2}}
\end{aligned}
$$

where in the second line, we assume $n_X = n_C$ for simplicity. At the end of

$$
\begin{aligned}
t_{\rm Compton} &\approx \frac{135}{64\pi^3}\frac{n_X+n_C}{n_C}\frac{m_C^3}{\alpha_D^2\left(T_D^0(1+z)\right)^4} \\
&\approx 4\times 10^{12}\,{\rm yr}\,\frac{n_X+n_C}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^2\left(\frac{2\,{\rm K}}{T_D^0(1+z)}\right)^4\left(\frac{m_C}{m_e}\right)^3,
\end{aligned}
$$

Which dominates?

- Compton at early times
- Also for smaller α or m
- Either one can equal time of universe for reasonable parameters

Cooling for reasonable parameters

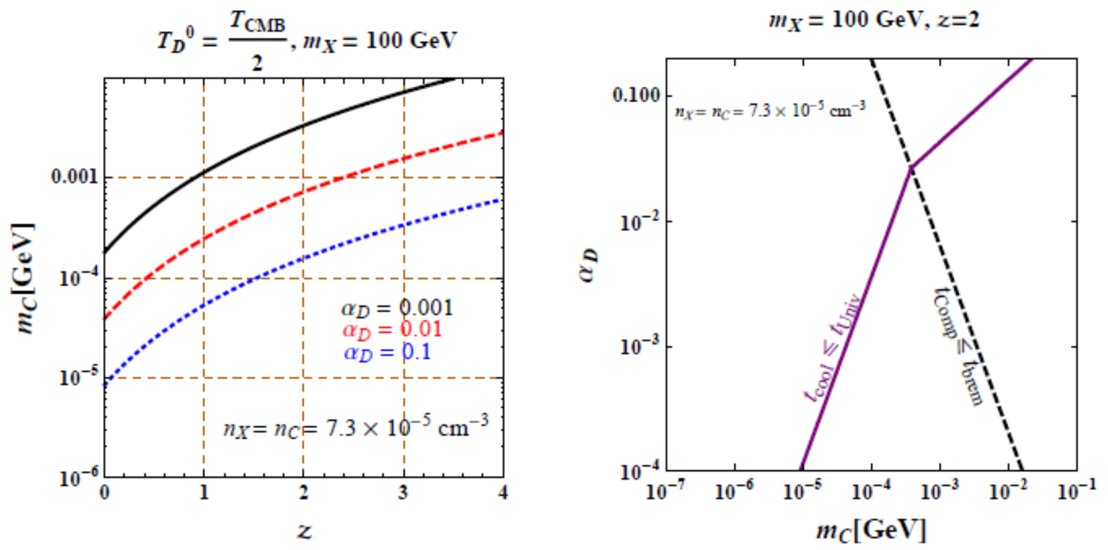


Figure 4: Comparison of the rates of bremsstrahlung and Compton cooling. At left: the value of m_C for which the rates are equal, as a function of redshift. To the right of the curves, i.e. at early times, Compton cooling dominates. At right: the contour in the (m_C, α_D) plane along which the bremsstrahlung cooling rate equals the Compton cooling rate (black dashed line) and the contour along which the cooling rate equals the age of the universe (solid purple line). This shows that Compton cooling is the dominant effect at small m_C and α_D, while bremsstrahlung dominates for larger values. In both plots, we have taken an NFW virial cluster of radius 20 kpc.

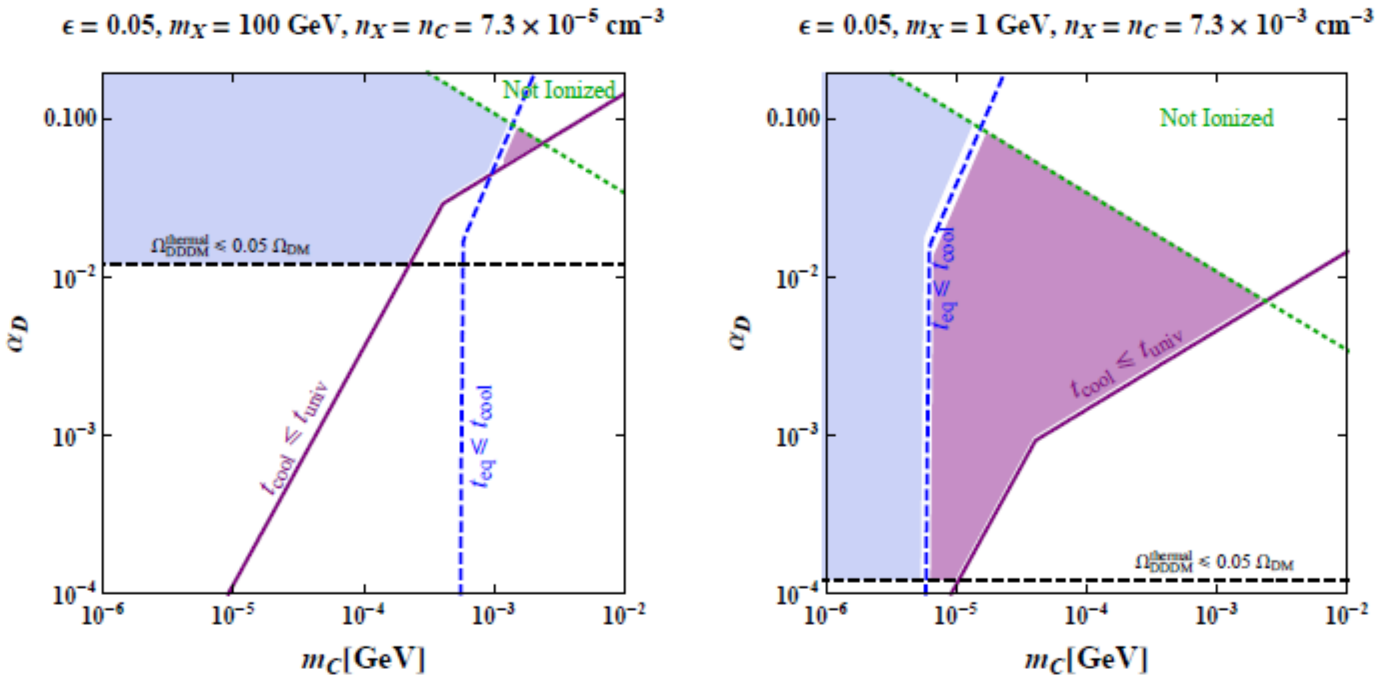


Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the left are for $m_X = 100$ GeV; on the right, $m_X = 1$ GeV. The upper plots are for a 110 kpc radius virial cluster; the lower plots, a 20 kpc NFW virial cluster. The solid purple curves show where the cooling time equals the age of the universe; they have a kink where Compton-dominated cooling (lower left) transitions to bremsstrahlung-dominated cooling (upper right). The dashed blue curve delineates fast equipartition of heavy and light particles. Below the dashed black curve, small α_D leads to a thermal relic $X, \bar{X}$ density in excess of the Oort limit. To the upper right of the dashed green curve, B_{XC} is high enough that dark atoms are not ionized and bremsstrahlung and Compton cooling do not apply (but atomic processes might lead to cooling).

When does it stop?

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

➢ This would be nice to simulate

➢ How thickened will disk become?

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,

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

where T is in unit of K and ρ 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 (for the fraction of PIDM)!

Note that disks should at least approximately align

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

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

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

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

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

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

Strongest Bounds

- Matter accounting: Oort-like limits
- Gravitational potential measured
  - Both in and out of plane of galaxy fromstar velocities
- Baryonic matter independently constrained
- Ordinary dark matter constrained
  - Extrapolate halo
- Total constraint on matter
- Constrains any new (nonhalo) component
- Work in progress w/Kramer

Another Bound

- CMB
  - Dark Atom Bounds
- This bound depends on relative temperatures
- Upshot will be bound 5-10% of dark matter can be in disk component
  - But strongly dependent on relative temperatures

Dark Matter “Detection”

- Can explain 130 GeV signal through boost factor
  - Of course any such model needs annihilation into SM—not essential to dark matter disk
- Interesting implications for direct detection
  - But only if exothermic
- Most interesting and robust implications have to do with structure itself

Indirect Detection?

- Rate can work
- Smoking gun would be 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

Distinctive Shape to Signal w/Fan, Katz, Reece

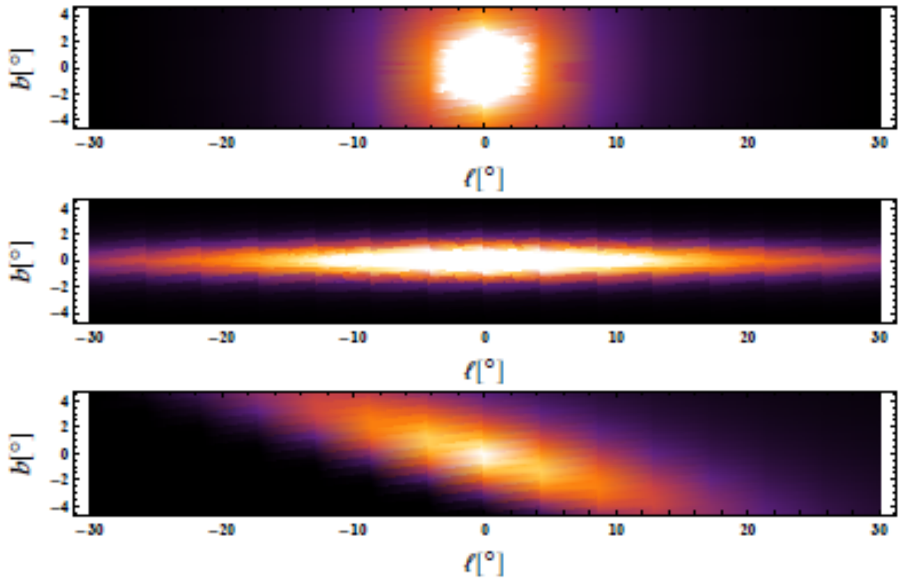


FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

DDDM for direct detection ?(w/McCullough)

- 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

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

- Solution to both issues (if expt real): ExoDDDM

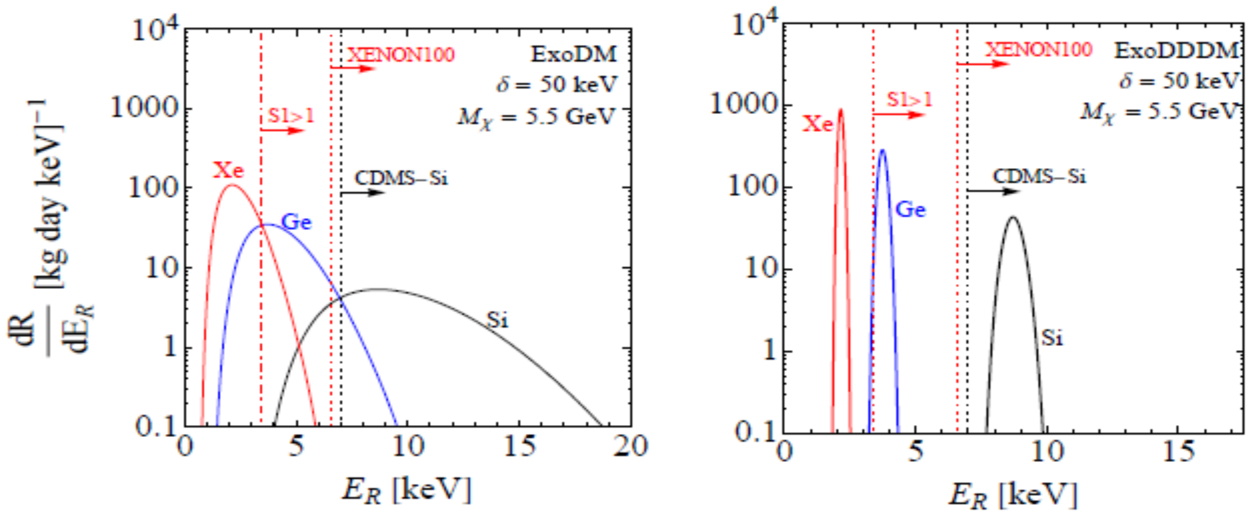
New Ingredient: ExoDDDM

- Recoil could be due to a mass splitting δ
- 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)

- Nuclear mass dependence works to favor consistent CDMS, Xe interpretation

Why ExoDDDM?

- Much smaller velocity dispersion
- Very distinguishable
- Virtually no Gaussian tail giving rise to Xenon etc events: ExoDDDM even more readily accommodated



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

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

- Elastic, heavy DM: In this case $v_{\text{thr}} \approx \sqrt{E_{\text{thr}}/2M_N}$. 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 $v_{\text{thr}} \approx \sqrt{E_{\text{thr}} M_N}/\sqrt{2}M$, 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 $v_{\text{thr}} = |v_{\text{thr}}(\delta = 0) - \delta/\sqrt{2M_N E_{\text{thr}}}|$. 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

Results

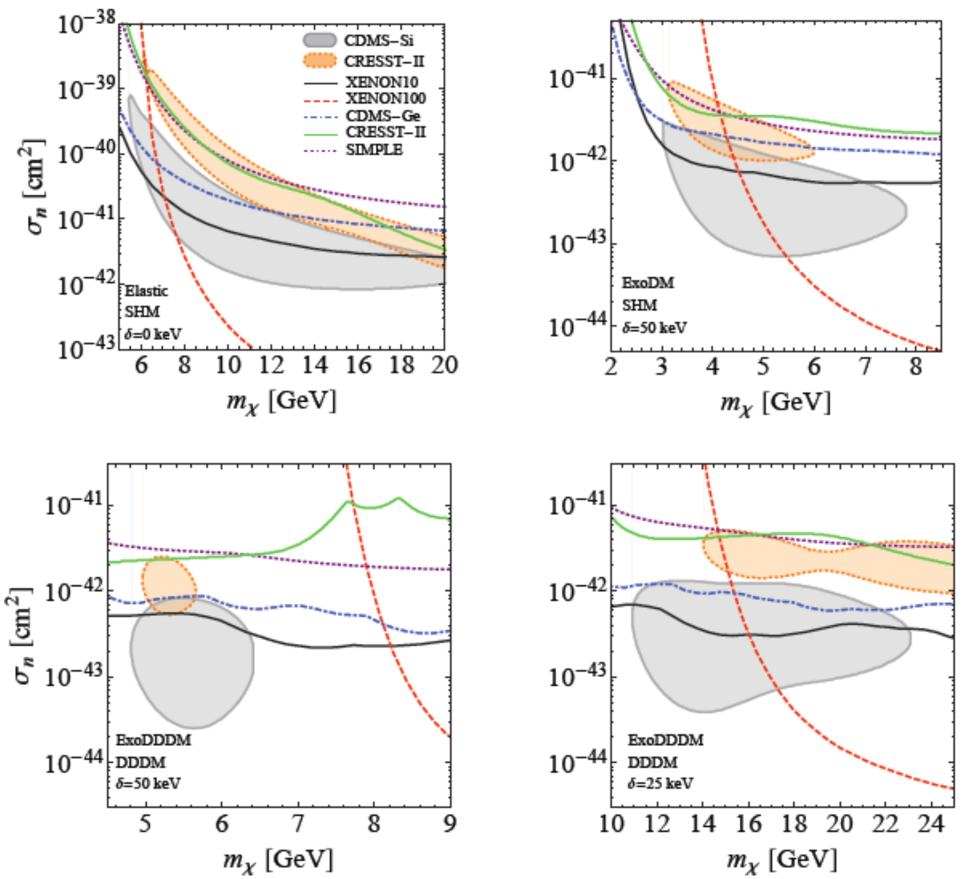
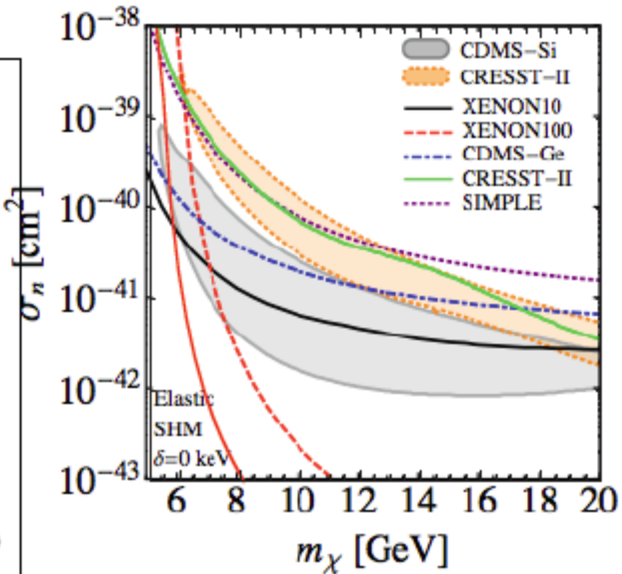
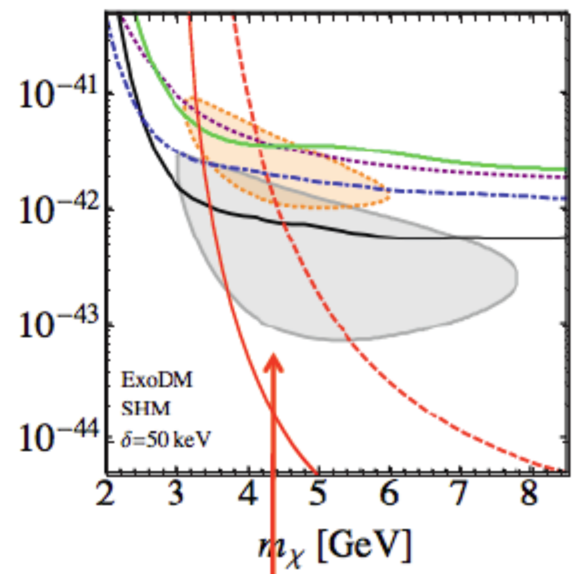


Figure 5: 90% best-fit regions (CDMS-SI shaded gray and CRESST-II shaded orange) and 90% exclusion limits (XENON10 solid black, XENON100 dashed red, CDMS-Ge dot-dashed blue, CRESST-II low threshold analysis solid green and SIMPLE in dotted purple). Elastic and exothermic scattering of standard halo DM 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.

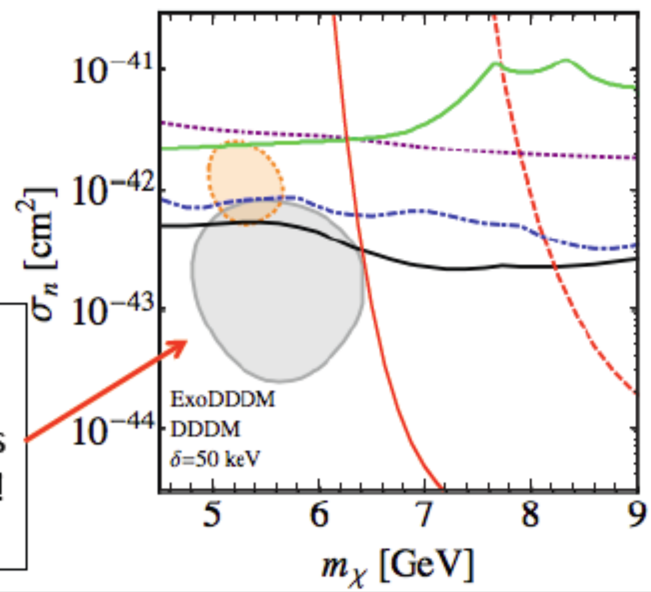
Plot same as Fig 5 of our paper, but now with new LUX limits overlaid in solid red line.

Anything to right of solid red line now excluded, to left still allowed.





Standard ExoDM explanation of CDMS-Si events now under considerable tension from LUX



ExoDDDM explanation of CDMS-Si events still untouched!

For future

- Lower threshold
  - Any events at low energies indicates this model wrong
  - Ordinary DM increases dramatically as you lower threshold
  - ExoDM increases somewhat
  - ExoDDDM not at all
- Phase dependence
  - Measure time dependence
  - Smaller for ExoDM in general
  - Different phase since no longer tail of Gaussian

More robust predictions

- Dynamical consequences of dark disk
- Oort-type limits
- But first possible effect on solar system motion

Perturb Oort Cloud Comets: Periodic Impacts? w/Matt Reece

- Possible support for ~35 million year periodicity in (large) crater record on Earth
  - Nonrandom underlying enhancement of meteoroid impacts?
- Proposal: due to tidal effects as Oort cloud passes through plane of galaxy
- But no good trigger in galaxy plane standard scenario
  - Period wrong (not enough density)
  - Gradient too small eg GMCs too stretched out
- Smooth dark disk in mid-plane addresses both issues
- Also w/ model and priors, statistical significance improves
- Also tells us a target surface density for dark disk

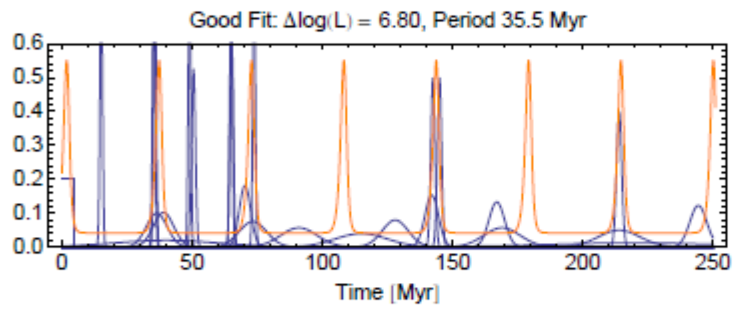


FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\mathrm{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\mathrm{pc}^2$. The local dark halo density is 0.037 $\mathrm{GeV/cm}^3$. $Z_\odot = 20$ pc and $W_\odot = 7.8$ km/s. In this case, the period between disk crossings is about 35 Myr. In orange is the rate $r(t)$ of comet impacts (with arbitrary normalization). This is approximately proportional to the local density, but convolved with the shower profile from Fig. 2. The various blue curves each correspond to one recorded crater impact.

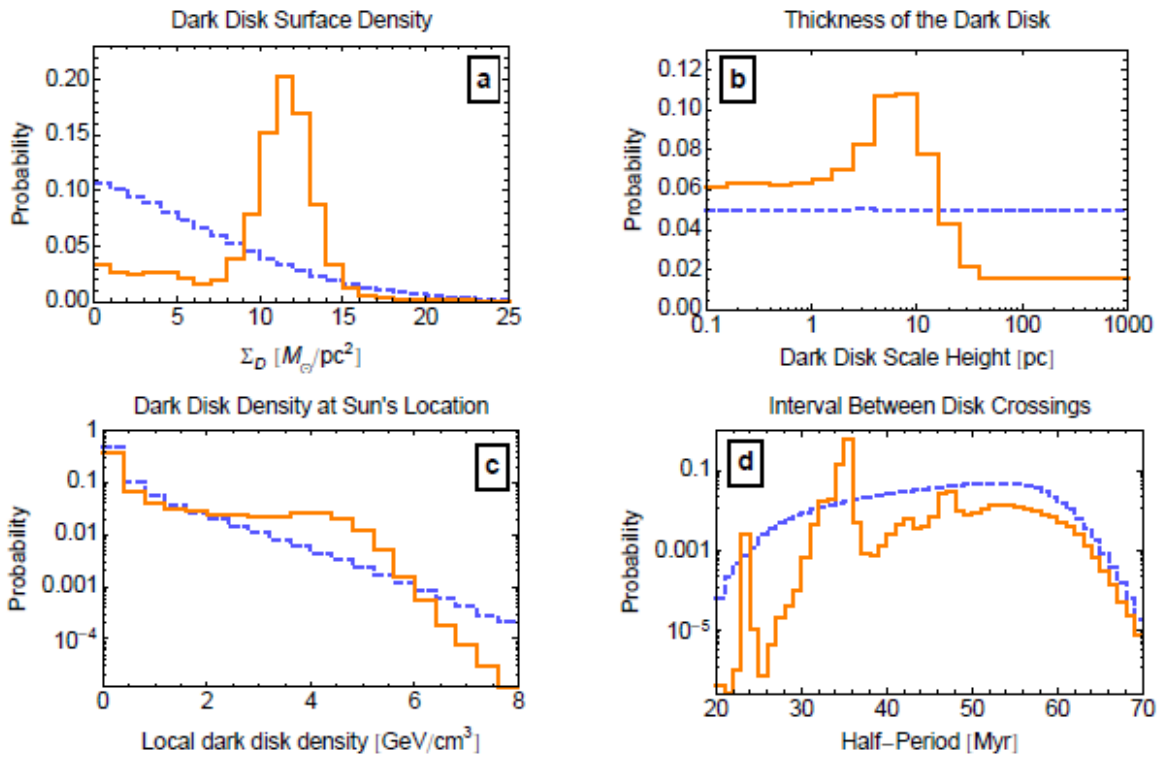


FIG. 4. Preferred parameters. One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits best at about 10 parsec scale height but extends to thinner disks. The posterior distribution is flat even for very thin disks, because comet showers last for around a million years even if the Solar System passes through the disk in a shorter time. (c) The local density of disk dark matter (relevant for solar capture or direct detection), which has significant weight up to several GeV/cm^3. (d) The interval between times when the Sun passes through the dark disk, which fits best at values of about 35 Myr.

Dark Disk w/this surface density Allowed?

- In literature, roughly dismissed
- Clearly dark disk with sufficently low surface density permissible
- What is current limit from Hipparcos data
- And of course what will future limit be—GAIA
- W/Eric Kramer looking at question
- Differences:
  - Don't just add to visible disk
  - Include midplane density priors
  - Include newer dust maps
  - Do analysis differently (issue is fitting potential that relates two measured distributions)
- Preliminary: Allowed and perhaps even favored

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
    - ExoDDDM-explain CDMS
      - Consistently with Xenon
- Affects structure, dynamics
- Current research on effects
- Also what will Hipparcos, GAIA tell us?