Darkly-Charged Dark Matter Double Disk Dark Matter and Point Sources

LR w/Agrawal, Cyr-Racine, Scholtz
w/Fan, Katz, Reece
w/Kramer
w/Scholtz
w/Reece
w/Agrawal

Dark Matter

- WIMP “standard” paradigm but
  - No direct detection
  - No indirect detection
  - LHC hasn’t shown any sign of new weak scale physics
- Given potentially empty-handed direct searches all potentially detectable alternatives worth investigating
- In principle could be purely gravitational coupling
  - **Or coupling only to its own sector**
  - **Or coupling to its own sector as portal to mixing with our sector**

What is dark matter?

- Whether or not a WIMP, have to better understand it's gravitational influences
- If not WIMP might be ONLY way to know more
- Today consider self-interaction through dark photon
  - Surprisingly unconstrained
  - But many potential consequences

Outline Talk

- I: Introduce Darkly-Charged Dark Matter
  - Show why constraints in literature too strong
  - Even weak-scale EM-strength charged DM allowed
- II: Introduce Partially Interacting Dark Matter (PIDM) and Double Disk Dark Matter (DDDM)
  - Assume dark matter has some of richness of Standard Model
- III: Point sources for GeV excess

I: Darkly-Charged Dark Matter Model

Dark matter charged under its own "electromagnetism"

The simplest model consists of a heavy particle X carrying positive charge under a new dark $U(1)$ gauge symmetry and its antiparticle $\bar{X}$ with opposite charge. For concreteness we will consider X to be a Dirac fermion through out this paper. The Lagrangian is

$$\mathcal{L} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \bar{X}\not{D}X - m_X\bar{X}X \tag{2.1}$$

where V_μ is the dark photon. In this simple model, the dark matter relic abundance can be set by a thermal freezeout.

Darkly-Charged Dark Matter

- If only self-interactions "3 DM detection methods" don't apply
- However not unconstrained
- Rely on the way we always knew about dark matter
  - **Gravitational effects**
- Look for signs of dark matter redistribution
- Effects good in that it means interactions are potentially detectable

Why Dark Charges Disfavored ⇔"Constraints"

- Ellipticity of halos
- Bullet Cluster type constraints
- Survival of dwarf galaxies in halos (lack of evaporation)

- Seemed to significantly impinge on parameter space

Lotty Ackerman, Matthew R. Buckley, Sean M. Carroll, and Marc Kamionkowski

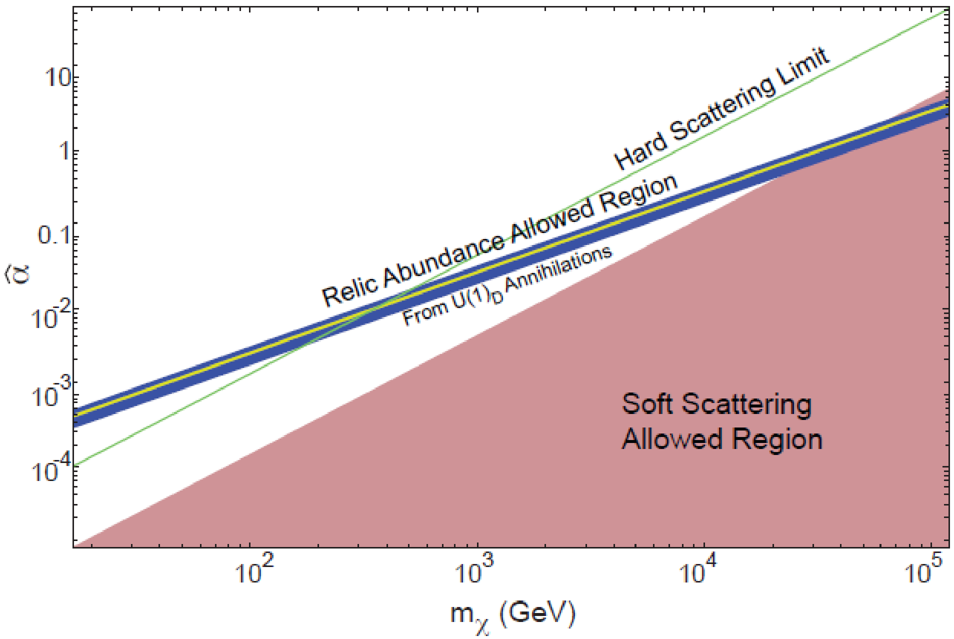

FIG. 3: The allowed regions of $\hat{\alpha}$ vs. m_χ parameter space. The relic abundance allowed region applies to models in which $U(1)_D$ is the only force coupled to the dark matter; in models where the DM is also weakly interacting, this provides only an upper limit on $\hat{\alpha}$. The thin 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.

Jonathan L. Feng, Manoj Kaplinghat, Huitzu Tu, and Hai-Bo Yu

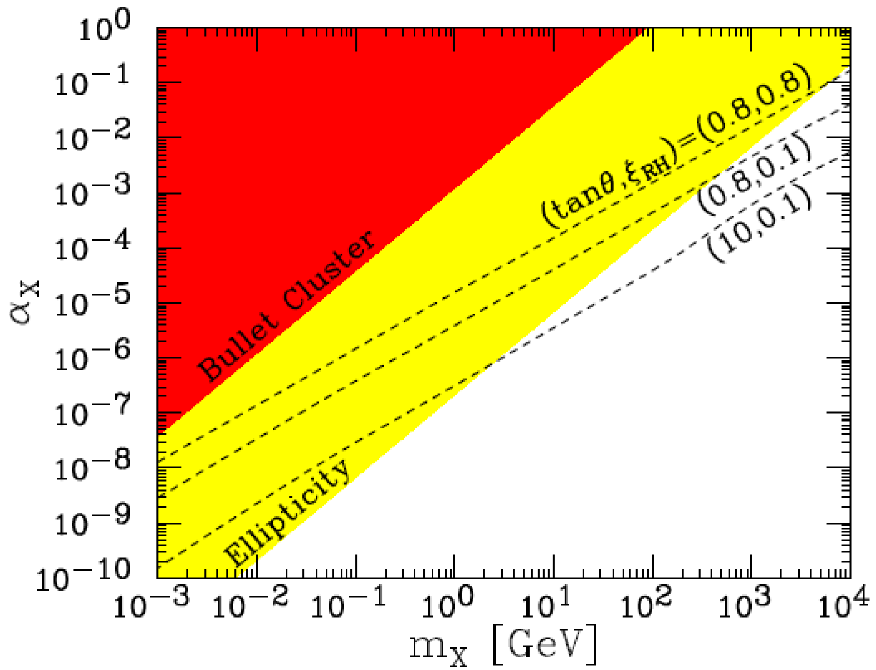

FIG. 1: Allowed regions in (m_X, α_X) plane, where m_X is the mass of the dark matter charged under the unbroken hidden sector $U(1)_{EM}$ with fine-structure constant α_X. Contours for fixed dark matter cosmological relic density consistent with WMAP results, $\Omega_X h^2 = 0.11$, are shown for $(\tan\theta_W^h, \xi_{RH}) = (\sqrt{3/5}, 0.8)$, $(\sqrt{3/5}, 0.1)$, $(10, 0.1)$ (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.

Previous results

- Ellipticity (in galaxies) the strongest constraint in plots
- How to evaluate?
- Previous references find time to equilibrate unequal velocity dispersions in orthogonal directions
  - Approx as time it takes for particle to change kinetic energy by O(1) factor

$$\tau_F = \frac{\langle E_k \rangle}{\langle \dot{E}_k \rangle} = \frac{\langle E_k \rangle}{\langle \sigma n v \times \delta E_k \rangle},$$

where the $\langle \cdot \rangle$ means thermal average. Ref. [8] arrive at:

$$\tau_F = \frac{m_X^3 v_0^3}{4\sqrt{\pi}\alpha^2 \rho_X} \left(\log \frac{(b_{\max} m_X v_0^2/\alpha)^2 + 1}{2} \right)^{-1} = \frac{m_X^3 v_0^3}{4\sqrt{\pi}\alpha^2 \rho_X} \log^{-1} \Lambda_F$$

We now repeat the same calculation for charged matter self-scattering cross-section:

$$\frac{d\sigma}{d\Omega} = \frac{4\alpha^2}{m^2 |v_1 - v_2|^4 (1 - \cos\theta_{\mathrm{CM}})^2}.$$

But… details of calculation

- Soft interactions require a cutoff on the logarithm that appears in the cross section. Originally set by the size of the galaxy [7] and subsequently set by the Debye screening length [8], the true cutoff is even smaller and is set by the inter-particle spacing in the galaxy (or galaxy cluster). On average, the effects from the positively and negatively charged dark matter particles cancel (up to a much smaller dipole contribution). We will see this decreases the rate velocity isotropization by a factor of 3/2.

- In NGC720 the baryonic component dominates the gravitational mass until about $r \sim 6$ kpc. Therefore, we should not consider ellipticity measurements as constraining the dark matter potential within this radius. As a result the isotropization rate should be smaller because the local density is lower in the outer regions of NGC720. Compared to Ref. [8], this reduces the rate of velocity isotropization by a factor of 3.

- Ref. [8] uses a smaller cross-section by a factor of 4 and also overestimates the energy transfer by a factor of 2. Moreover, the normalization by kinetic energy in the end of calculation in Ref. [8] is missing a factor of 3/2 that comes from proper normalization of the velocity distribution.

These factors alone are responsible for a shift in the bound, the characteristic timescales to isotropize velocity distribution lengthens by roughly:

$$\frac{\tau}{\tau_F} = \underbrace{\frac{3}{2}}_{\log \Lambda} \times \underbrace{\frac{3}{1}}_{\rho} \times \underbrace{\frac{1}{4}}_{d\sigma/d\Omega} \times \underbrace{\frac{3}{2}}_{\langle v^2\rangle = 3v_0^2/2} \times \underbrace{\frac{2}{1}}_{\delta E_k} = \frac{27}{8} \sim 3.4\,. \tag{3.1}$$

Revisions: was wrong calculation

- It is not sufficient to simply calculate the interaction rate, or even the rate at which energy transfers from one velocity component to another. The rate at which the interaction occurs is sensitive to velocity anisotropy. As the initially smaller component of the velocity grows comparable to the larger one, the rate of energy transfer slows down. (Otherwise the smaller one would continue to grow exponentially which of course is not the case.) This saturation effect can relax the bounds from ellipticity significantly.

- Furthermore, the constraint depends on the radius at which the ellipticity is measured. This is important because the best ellipticity measurements apply in the outer regions of galaxies where the density is lowest and therefore interactions are the least frequent.

Ellipticity as function of radius

$$\epsilon = 1 - \frac{b}{a} \sim 1 - \frac{\langle v_a^2 \rangle}{\langle v_b^2 \rangle} .$$

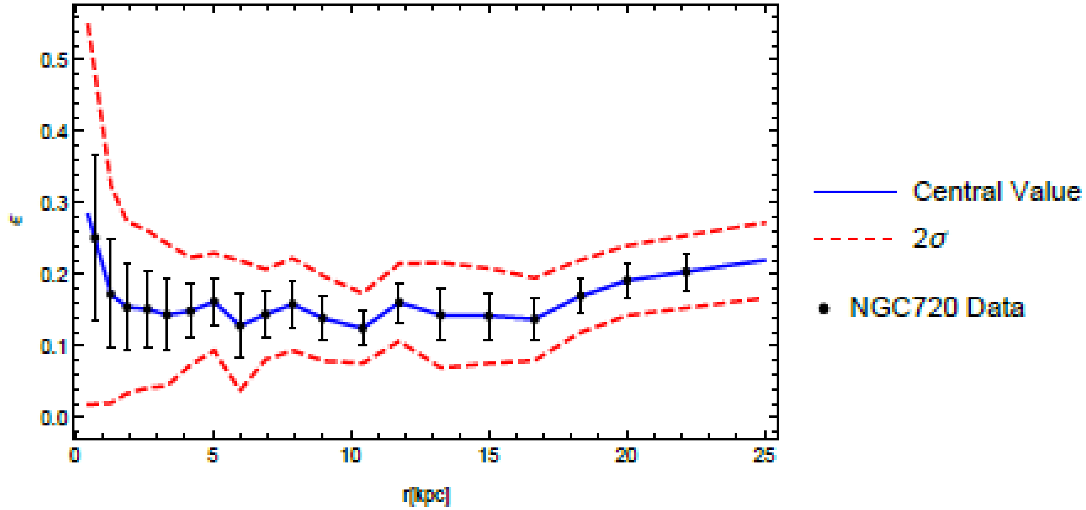

Figure 1: Ellipticity of the NGC720 potential as measured by [48]. The black data points show the results of [48] with 1σ error bars. The blue curve is our interpolation of their central values, while the 2σ error bands are in red.

In this section, we illustrate how ellipticity evolves as a function of time. We model ellipticity as an anisotropy in velocity distribution (a strong assumption). In particular, in a virialized halo, $\langle v^2 \rangle \sim R^{-1}$ and therefore:

$$\epsilon = 1 - \frac{b}{a} \sim 1 - \frac{\langle v_a^2 \rangle}{\langle v_b^2 \rangle} \,. \tag{3.12}$$

The timescale calculation above estimates the growth of ellipticity only when $\langle v_a^2 \rangle \ll \langle v_b^2 \rangle$, that is for large ellipticities $\epsilon \lesssim 1$. However, when $\langle v_a^2 \rangle \lesssim \langle v_b^2 \rangle$, we expect a much smaller growth of the subleading velocity component because the process is proportional to the velocity anisotropy:

$$\frac{d\langle v_a^2 \rangle}{dt} \propto \left(\langle v_b^2 \rangle - \langle v_a^2 \rangle \right)^{\gamma} \,. \tag{3.13}$$

Revisions: Not clear right target

- Relative importance velocity anistropy versus that in potential?
  - Substructure, dark matter streams, asymmetric accretion
- Galaxy constraint stronger than galaxy clusters
  - But only NGC720 measured
- Merger history also important –enough time for ellipticity to be erased?

Implication

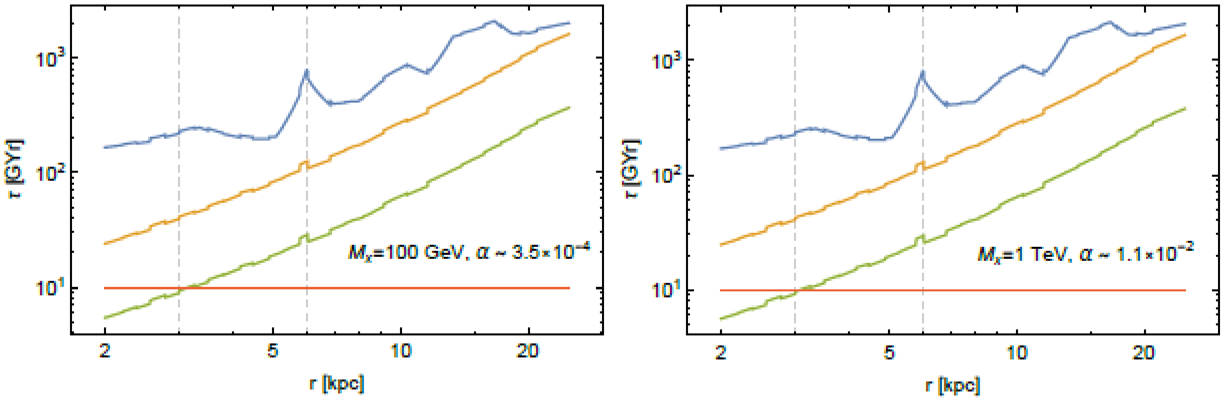

Figure 2: Times to remove ellipticity caused by velocity anisotropy. The blue curve represents time reduce ellipticity down to $\epsilon(r)$ as given by the lower bound from figure 1. The orange curve shows the time it takes to reduce ellipticity down to fixed $\epsilon = 0.2$ for each r. The green curve shows the timescale from Ref. [8]. We show the 10 billion year mark in red and the 3 kpc and 6 kpc by dashed and dotted vertical lines. The left plot shows $M_X = 100$ GeV and $\alpha = 3.5 \times 10^{-4}$ and right

Our Result

Ignoring last caveats
Just calculating time for velocities to equilibrate

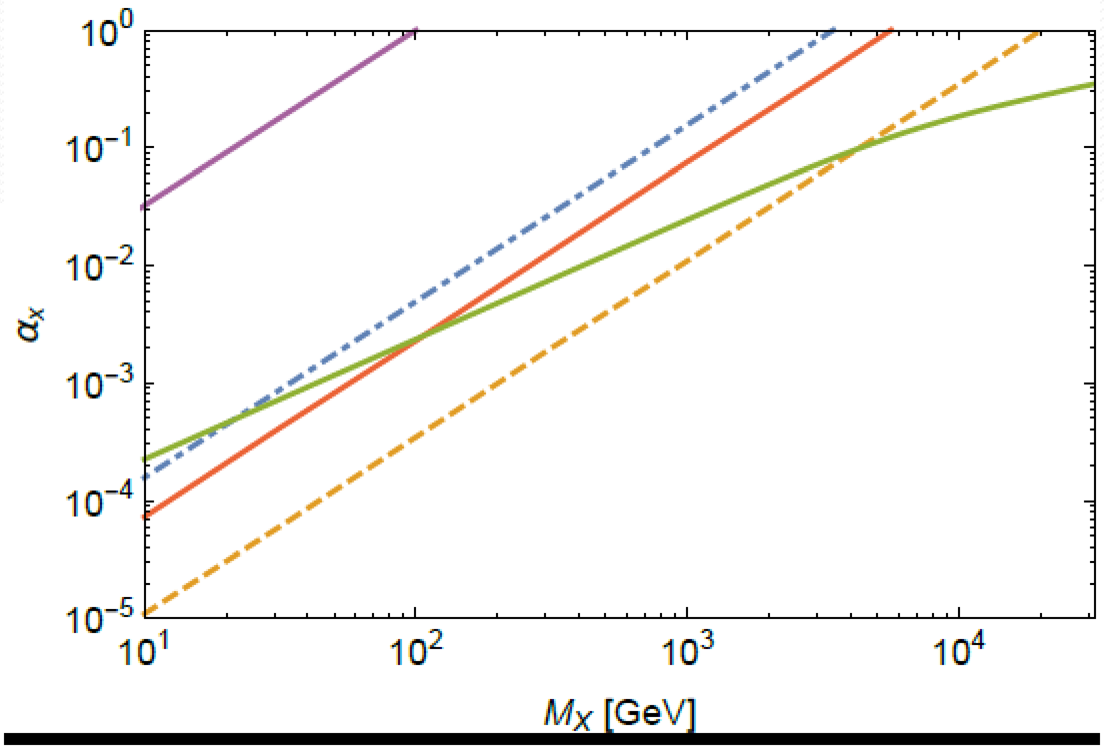

Figure 3: Constraints on the Charged Dark Matter parameter space in the $M_X - \alpha_X$ plane. The ellipticity constraints (discussed in section 3.1) are presented as two curves: the original Ref. [8] calculation [dashed yellow], the full calculation that includes the radius dependent constraints on ellipticity from figure 2 [red]. We show additional constraints from evaporation of Milky Way dwarf galaxies we adopted from Ref. [42] and discuss in section 3.2 [dot-dashed blue], Bullet cluster collision adopted from Ref. [41] and discussed in section 3.3 [purple]. Finally we also show the $M_X - \alpha_X$ curve for which the freeze-out mechanism produces the correct relic density for ChDM [green], which

Other Curves/Constraints

- Bullet Cluster—so weak we don't re-evaluate
  - But note precise bound is questionable
  - Existing bound comes from requiring no more than 30% of dark matter lost in merging
  - But we don't know initial dark matter content
    - Or baryon to dark matter ratio
  - Could be that considerably more dark matter can be lost

Other constraint: Dwarf Galaxy Survival

F. Kahlhoefer, K. Schmidt-Hoberg, M. T. Frandsen and S. Sarkar,

- Dwarf galaxy survival as they orbit halo host galaxy
- Too strong interaction and they will be stripped
  - Again soft scattering dominated $\frac{\alpha_D^2}{m_X^3} < 10^{-11}\mathrm{GeV}^{-3}.$
- Again details
  - Log, wrong cross section, wrong density $f = \underbrace{\frac{3}{2}}_{\log\Lambda} \times \underbrace{2}_{d\sigma/d\Omega} \times \underbrace{3}_{\rho} = 9$
- More importantly, calculation neglects interaction in dwarf: denser, slower
  - Possible that instead of evaporating it puffs out
  - Depends on cooling mechanisms
  - Address core-cusp??

New Regime of Interactions

$$Kn = \frac{\lambda}{R}$$

$$\frac{\sigma_T}{m_X} = \frac{8\pi\alpha_D^2}{m_X^3 v^4}\log\Lambda = \begin{cases} 1.7\times10^4 \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{45}\right)\left(\frac{30\ \mathrm{km/s}}{v}\right)^4 & \text{Dwarf galaxies} \\ 2.1\times10^0 \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{60}\right)\left(\frac{300\ \mathrm{km/s}}{v}\right)^4 & \text{Galaxies} \\ 2.0\times10^{-2} \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{72}\right)\left(\frac{1000\ \mathrm{km/s}}{v}\right)^4 & \text{Clusters.} \end{cases} \tag{4.2}$$

The interaction cross section in dwarf galaxies is several orders of magnitude greater than the value for which Ref. [39] found evidence for core collapse. For these values of the parameters, we can estimate the Knudsen numbers in various systems,

$$Kn \simeq \begin{cases} 10^{-3}\left(\frac{1\ \mathrm{kpc}}{R}\right)\left(\frac{9\ \mathrm{GeV/cm}^3}{\rho}\right)\left(\frac{1.7\times10^4\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Dwarf galaxies} \\ 10^1\ \left(\frac{30\ \mathrm{kpc}}{R}\right)\left(\frac{0.3\ \mathrm{GeV/cm}^3}{\rho}\right)\left(\frac{2.1\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Galaxies} \\ 10^5\ \left(\frac{10\ \mathrm{Mpc}}{R}\right)\left(\frac{9\times10^{-6}\ \mathrm{GeV/cm}^3}{\rho}\right)\left(\frac{2.0\times10^{-2}\mathrm{cm}^2/\mathrm{g}}{\sigma_T/m_X}\right) & \text{Clusters.} \end{cases} \tag{4.3}$$

Darkly-Charged Dark Matter

- Clearly viable!!
- Constraints on mass considerably weaker than stated
- Not yet reliable
  - Simulations can help
- Exciting possibility that dark matter has its own world of interactions
  - And that conceivably we can detect them

II: Also viable: Partially Interacting Dark Matter
Suppose only a **fraction** interacts

- Dark matter with its own force
  - Rather than assume all dark matter
  - Assume it's only a fraction –like baryons…
- Conventional constraints even weaker
- If only a fraction interacting, wouldn't make entire thing isotropic very efficiently
- Clearly Bullet Cluster okay if only a fraction –most dark matter would pass through
- And dwarf galaxies would survive

Partially Interacting Dark Matter

- Nonminimal assumption: why would we care?
- Implications of a subdominant component
  - Can be relevant for signals if it is denser
  - Can be relevant for structure –like baryons
    - Baryons matter because formed in a dense disk
      - Perhaps same for *component* of dark matter
- Dark disk inside galactic plane

- Potentially significant consequences
  - Leads to rethinking of implications of almost all dark matter, astronomical, cosmological measurements
- Detectable!

Could interacting dark matter cool into a Dark Disk?

- To generate a disk, cooling required
- Baryons cool because they radiate
  - They thereby lower kinetic energy and velocity
  - Get confined to small vertical region
- Disk because angular momentum conserved

- Dark disk too requires a means of dissipating energy
- Assume interacting component has the requisite interaction
- Simplest option darkly-charged dark matter

Simple DDDM Model
New Ingredient: Light C

- Could be U(1) or a nonabelian group
- $U(1)_D$, 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)
- (in principle nonconfining nonabelian group)
- This in addition to dark matter particle that makes up the halo

- When X freezes out with weak scale mediators, could have half temp of SM particles
- In any case, thermal abundance of weak scale particle naturally gives rise to fraction of dark matter abundance
- For C need nonthermal component
- Probably have both thermal and nonthermal components

Brehmstrahlung and Compton

timescale of the bremsstrahlung cooling is

$$t_{\rm brem} \approx \frac{3}{16}\frac{n_X+n_C}{n_X n_C}\frac{m_C^{3/2}T_{\rm vir}^{1/2}}{\alpha_D^3}$$

$$\approx 10^4\,{\rm yr}\sqrt{\frac{T_{\rm vir}}{\rm K}}\frac{\rm cm^{-3}}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^3\left(\frac{m_C}{m_e}\right)^{\frac{3}{2}}$$

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

$$t_{\rm Compton} \approx \frac{135}{64\pi^3}\frac{n_X+n_C}{n_C}\frac{m_C^3}{\alpha_D^2\left(T_D^0(1+z)\right)^4}$$

$$\approx 4\times10^{12}\,{\rm yr}\,\frac{n_X+n_C}{n_C}\left(\frac{\alpha_{\rm EM}}{\alpha_D}\right)^2\left(\frac{2\,{\rm K}}{T_D^0(1+z)}\right)^4\left(\frac{m_C}{m_e}\right)^3,$$

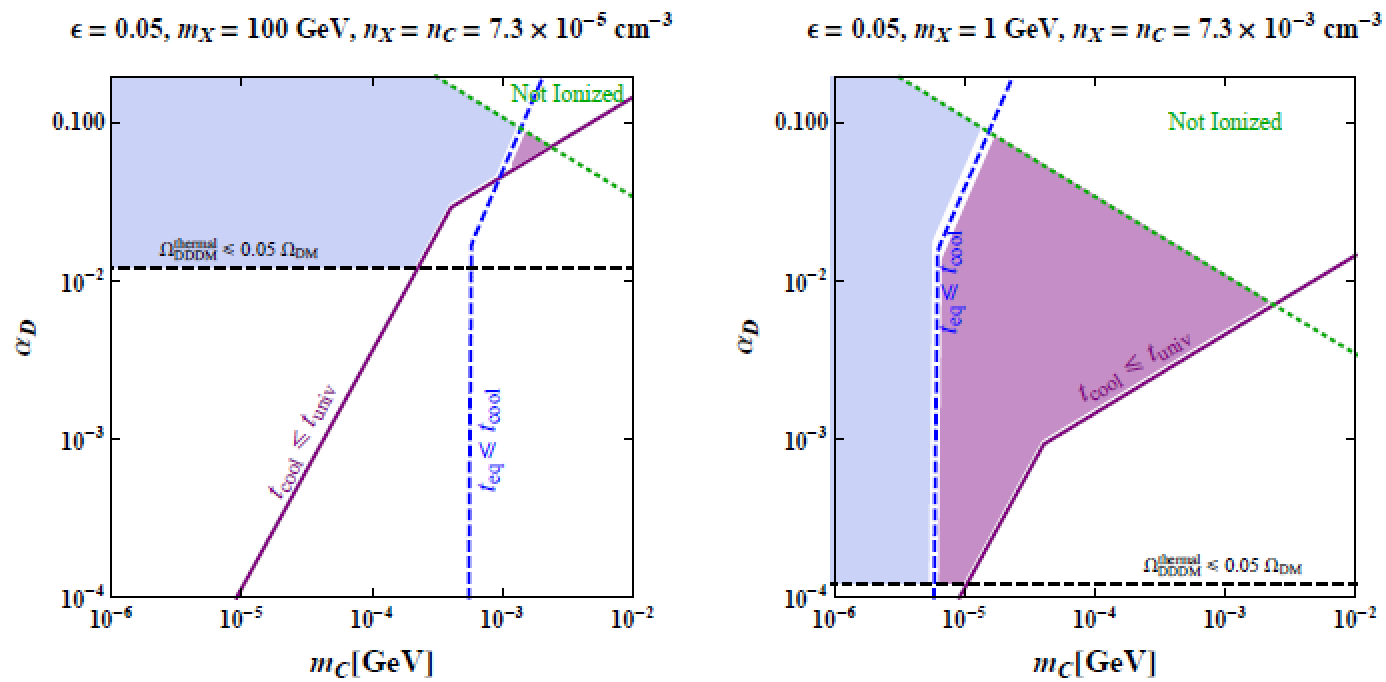

Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the 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).

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 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]).

Summary of model

- A heavy component
  - Was initially motivated by Fermi signal
- For disk to form, require light component
  - Can’t be thermal (density would be too low)
  - Constraint on density vs mass
- With these conditions, expect a dark disk
  - Even narrower than the gaseous disk

Consequence

- Dark disk
- Could be much denser
- Significant implications
  - Even though subdominant component
- Velocity distributions in or near galactic plane constrain fraction to be comparable or less to that of baryons
- Further constraints from CMB
- But because it is in disk and dense signals can be rich

Traditional Methods

- Smaller direct detection, small velocity
  - Possibly other noncanonical possibilities
- Indirect detection
  - Possible if mediation between visible, invisible sectors
- Good thing there is distinctive shape to signal if present

- Specific methods—look at stars in galaxy
- Vertical velocity/density relation determined by potential

Searching for disk: w/Eric Kramer
Velocities of stars

- Flynn Holberg looked at A and F type stars in inner portion of galaxy
  - Bright star population—enough near midplane
- From Hipparcos, get velocity measured at midplane and density as function of vertical distance
- Use galactic model with several isothermal components
- Asked whether equilibrium distribution fit potential generated by Milky Way disk

General Lesson

- Role for particle physics approach in astronomy
- “constraint” on dark disk came from fitting standard components
  - Turns out errors on standard components not properly accounted for
  - Reddening important near midplane
  - Has to be done self-consistently
    - Here different components influence each other through gravity
- Big messy data sets
- Targeting a model helps

Fit potential/star distributions

- Boltzmann/vertical Jeans equation
- Use Poisson's equation to introduce the different sources/components

- What we found:
- Need to put in model first
- Also data indicates non static distribution of tracer stars
- With errors, gas measurements, dark disk allowed

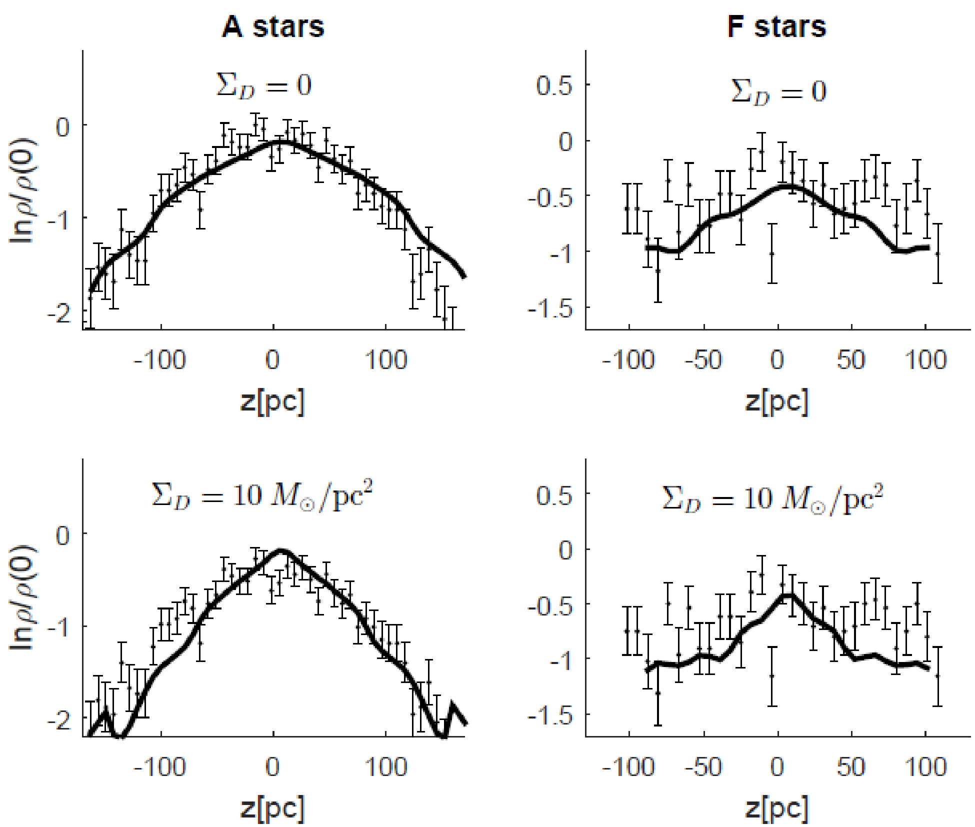

Fig. 2.— (Top) The HF2000 study. The HF2000 model with no disk dark matter agrees quite well with the A and F star data. (Bottom) The HF2000 result, this time including a dark disk with $\Sigma_D = 10\ M_\odot \mathrm{pc}^{-2}$ and $h_D = 10$ pc. We see that this model also may agree with the A and F star data.

Result will improve dramatically

- Gaia survey measuring position and velocity of stars in solar neighborhood
- Will significantly constrain properties of our galaxy
- In particular, new disk component will give measurable signal if surface density sufficiently height
- Don't know how much gas measurements will improve but they should too

w/Scholtz

Satellites of Andromeda Galaxy

- About half the satellites are approximately in a (big plane)
  - 14kpc thick, 400 kpc wide
- Hard to explain
- Proposed explanation: tidal force of two merging galaxies
- Fine except of excessive dark matter content
- Tidal force would usually pull out only baryonic matter from disk
- Not true if dark disk
- Pulls out dark matter
  - Slower velocity—more likely to be bound

Meteoroid Periodicity?

- Meteorite database gives 21 craters bigger than 20 km in circumference in last 250 years
- Evidence for about 35 million year periodicity
- Evidence however goes away when look elsewhere effect incorporated
- This will change with a model and measured priors
- We assume a dark disk take into account constraints on measured parameters, and determine whether likelihood ratio prefers model to flat distribution
- And what a posteriori distribution is favored

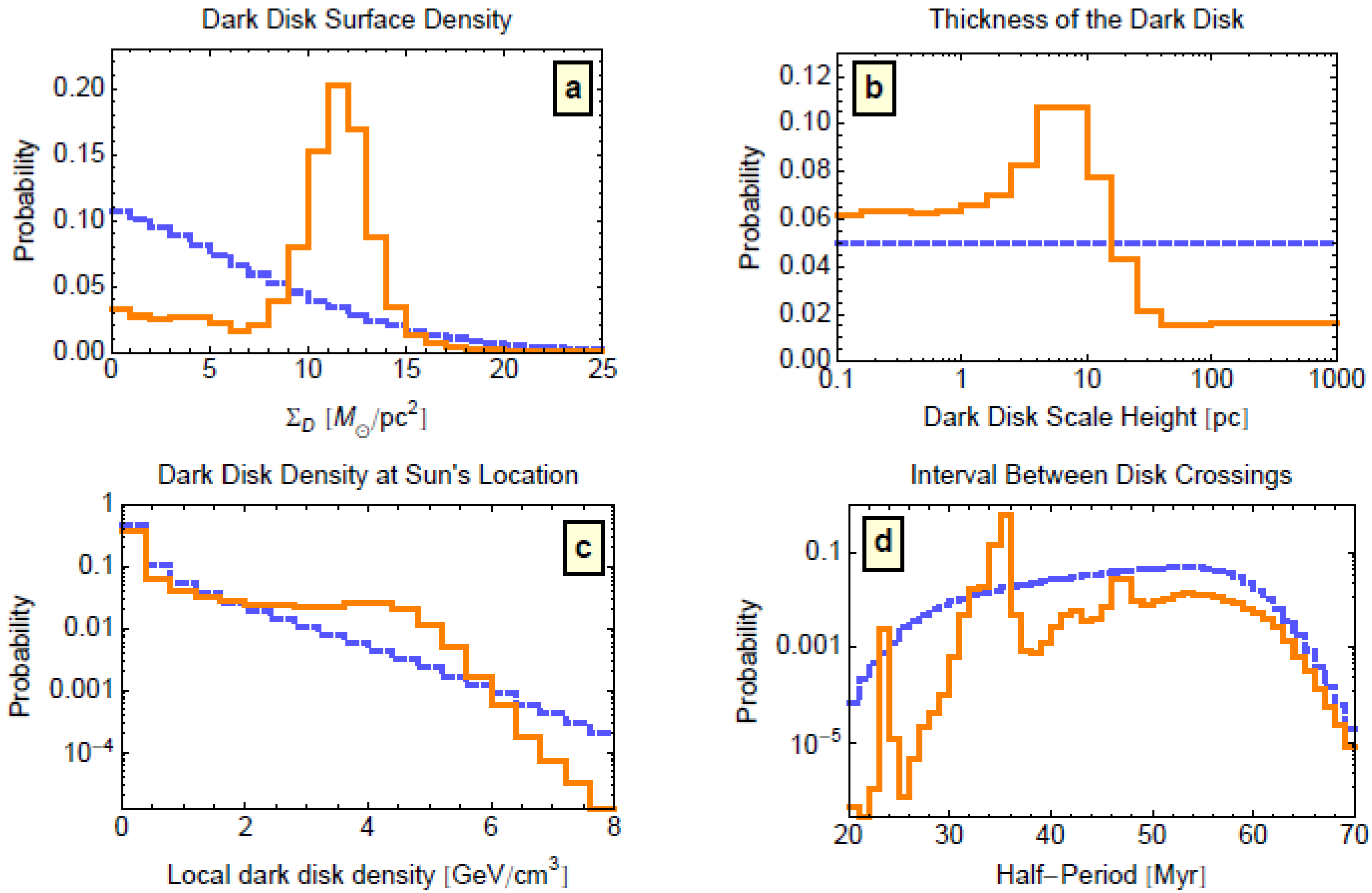

Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits best at about 10 parsec scale height but extends to thinner disks. (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.

III:Point Sources: GeV Excess?? w/Agrawal

- Disk interesting because of dense dark matter
  - Leads to visible consequences on structure
- Compact objects from fragmentation also interesting
  - If mixing with Standard Model
  - Again denser
  - Also volume not surface effect on radiation
    - But does require mixing into SM -
- Disk fragmentation or initial fragmentation
  - Leads to compact objects
  - Turns out Toomre instability gives right size to give observed GeV excess as point sources ~

Model DDDM with SM Portal

- X,C, dark photon, dark Z'
  - Symmetric component
  - And antisymmetric component
- Photon couples to X, C
- Z' : only X carries charge
- Z' mixes with hypercharge

$$a = \frac{n_X - n_{\bar{X}}}{n_X + n_{\bar{X}}}$$

$$f = \frac{\Omega_X}{\Omega_{DM}}$$

$$r = \frac{Y_{\bar{X}}}{Y_X}$$

Portal Model

$$\mathcal{L} = -\frac{\epsilon}{2} Z'_{\mu\nu} F^{\mu\nu} + Z'_{\mu} g_Z \bar{X} \gamma^{\mu} X$$

$X\bar{X} \to Z'Z'.$

$$\langle \sigma v \rangle = \frac{\pi \alpha_{Z'}^2}{m_X^2}$$

Galactic Center Excess

- FERMI: excess of gamma ray emission from galactic center
  - Somewhat consistent with dark matter annihilation
- BUT: Statistical preference for point-source emission
  - Argues against dark matter, prefers milli-second pulsars
- We can reproduce point signal in this model
  - Spectrum from continuum analysis
  - Annihilation rate, size, and mass from point-source analysis

Fit to spectrum

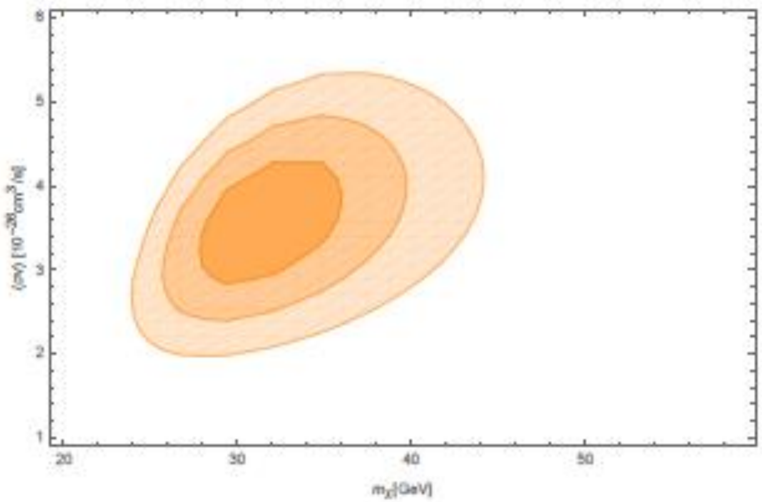

Figure 6: The best-fit m_X for the Z' model. The best-fit value of $\langle\sigma v\rangle$ depends on the region-of-interest and the energy range chosen for the analysis. We will fit the total flux to point source separately. For this plot we have assumed an NFW profile for dark matter to obtain the best-fit $\langle\sigma v\rangle$.

Point Sources for GeV excess

- Signal appears to originate from point-like sources
- With NFW squared profile
  - 0.5 degrees pixel
  - 50-100 pc at about 75 pac from galactic center
  - 10-30 pc size clouds, m~30 GeV
  - Approx 1.5 photons per annihilation
  - A few hundred point sources
  - Flux from each source $\Phi = 1.4 \pm 0.3 \times 10^{-10}$ photons/cm^2/s.

Idea

- Dark photon leads to cooling
- Instabilities leads to compact objects
- Annihilations through Z' lead to visible signals
  - Due to mixing with photon
- Would appear as point sources

Big Program

- Darkly-charged dark matter a viable option
  - Many implications
  - But can sometimes be more elusive or subtle than anticipated
    - Initial condition dependence
- New arena
  - N-body simulations, understand fragmentations
  - Role in early black hole formation
  - More on role in dwarf galaxies
  - Supplementary chemical data on meteoroid impacts
  - GAIA –much better measured kinematics

Conclusions

- Very interesting new possibility for dark matter
  - That one might expect to see signals from
- We are beginning to get tremendous data
- Goal is to find out what it means
- Charged dark matter affects structure
- Subtle to work out dynamics, constraints
- Even a small component
  - Just like baryons
- Rich arena: lots of questions