...And now for something
Completely different
DOUBLE DISK DARK MATTER

LR w/Fan, Katz, Reece
w/McCullough
w/Reece
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?)
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…
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
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
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 $\sim 1000$
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
- 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
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 $(\tan \theta W^\prime, \xi_{RH}) = (\sqrt{3}/5, 0.8), (\sqrt{3}/5, 0.1), (10, 0.1)$ (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.
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]. Depending on the approximate upper bound on the local density of the PDDM disk at a distance $d_\odot \approx 8$ kpc from the galactic center:

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

$$\epsilon \lesssim 0.05.$$
About 4x stronger bound taking into account more recent data on baryon content of galaxy

\[ \Sigma_{\text{tot}}(|z| < 1.0 \text{ kpc}) = 67 \pm 6 \, M_\odot/\text{pc}^2. \]  

(21)

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

\[ \Sigma_{\text{baryon}}(|z| < 1.1 \text{ kpc}) = 55 \pm 5 \, M_\odot/\text{pc}^2. \]  

(22)

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

\[ \Sigma_{\text{dark halo}}(|z| < 1.0 \text{ kpc}) = 16 \pm 5.2 \, M_\odot/\text{pc}^2. \]  

(23)
Also bounds from new relativistic degrees of freedom

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

\[ \frac{g_{*s,D}^{\text{dec}}}{g_{*s,D}(t)\xi(t)^3} = \frac{g_{*s,\text{vis}}^{\text{dec}}}{g_{*s,\text{vis}}(t)} \]

\[ \xi \equiv \frac{T_{\text{hid}}}{T_{\text{vis}}} \]

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

\[ g_{s,D}^4(t_{\text{BBN}}) = \frac{7}{8} \times 2 \times \Delta N_{\text{eff,\nu}}^{\text{BBN}} \]

\[ \Delta N_{\text{eff,\nu}}^{\text{BBN}} = 0.20 \text{ for } U(1)_D \text{ and} \]

\[ \Delta N_{\text{eff,\nu}}^{\text{BBN}} = 0.07N^2 + 0.12N - 0.07 \text{ for } SU(N)_D \]

\[ \Delta N_{\text{eff,\nu}}^{\text{BBN}} < 1.44 \text{ at } 95\% \text{ C.L.,} \]

Interesting prediction for new degrees of freedom during BBN
Also measurable in CMB
Won’t violate Oort Limit with big enough alpha—reasonable values
Thermal abundance of C will however be too small

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 $X$. 
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
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 brehmstrahlung 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

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

(1)

where $T$ is expressed in units of K and the particle number density in 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-relativistic limit. In particular, the thermal bremsstrahlung cross section scales as $\sigma \nu \sim \alpha_D^3/(m_l^2 \nu)$. The velocity of the particles in a thermal gas is $v \sim \sqrt{k_BT/m_l}$. There is an exponential cutoff in the rate because the typical light particle energy is $\sim k_BT$, so they cannot produce photons with energy $h\nu$ much greater $k_BT$. Putting all these together, we arrive at Eq. 1.

The total energy loss rate is then

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

(2)

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

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

(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]

\[
J_{\text{Comp}} = \frac{8\sigma_e a T_D^4}{3 m_l} (T_D - T) n_l,
\]

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

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

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

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 $T_D$ ($t_{\text{Comp}} < \text{age of the Universe}$).

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

\[ \epsilon = 0.05, \ m_X = 1 \text{ GeV}, \ n_X = n_C = 7.3 \times 10^{-5} \text{ cm}^{-3} \]
Figure 5: Contours of the cooling time scale equal to the age of the Universe for different heavy PDDM mass in the plane \((\epsilon, m_\chi)\) (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 \(\alpha_P\) 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 physics as explained in the text.
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
- (?)
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 \( z \),

\[
\frac{\partial (\rho v_z^2)}{\partial z} + \rho \frac{\partial (\Phi)}{\partial z} = 0
\]

(9)

\[
4\pi G_N \rho = \frac{\partial^2 (\Phi)}{\partial z^2},
\]

(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 finds the scale height is [3]

\[
z_d = \sqrt{\frac{v_z^2}{8\pi G_N \rho}} = \sqrt{\frac{k_B T}{m_p 24\pi G_N \rho}},
\]

(11)

where in the second step, the thermal relation \( m_p v_z^2 = k_B T / 3 \) is used. Numerically,

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

(12)

where \( T \) is in unit of K and \( \rho \) is unit of GeV/cm\(^3\). Interstellar gas (and young stars) have velocity \( v \sim 10 \text{ km/s} \) which corresponds to \( T \sim 10^4 \text{ K} \). 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]).
In reality, gravitational heating can occur. Reasonable to assume disk height between $m_p/m_\chi$ 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: $t \approx \left( \frac{R^3}{GM} \right)^{1/2} \sqrt{\theta}$
- $R \sim 10 \text{ kpc}$
- $M \sim 10^{12} \text{ M}_{\odot}$

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

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

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

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

(35)

with:

$$J = \int_{roi} db \int_{1.0s} ds d\theta \cos b \left( \frac{\rho(r)}{\rho_\odot} \right)^2,$$

(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

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

(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 $b \in (-1^\circ, 1^\circ), l \in (-1^\circ, 1^\circ)$. Green: region within $b \in (-0.1^\circ, 0.1^\circ), l \in (-0.1^\circ, 0.1^\circ)$ (current Fermi-LAT angular resolution). Black: region within $b \in (-0.01^\circ, 0.01^\circ), l \in (-0.01^\circ, 0.01^\circ)$. 
Direct Detection of DDDM (CDMS vs Xenon)?
w/McCullough (also Fan, Katz, Shelton)
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
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
\[ v_{\min}(E_R) = \frac{1}{\sqrt{2M_N E_R}} \left| \frac{M_N E_R}{\mu_N} - \delta \right| \]

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

- 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
Much smaller velocity dispersion

Very distinguishable

Virtually no Gaussian tail giving rise to Xenon etc events
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 exo-thermic scattering of standard halo DM are shown in the upper panels, and ExoDDD 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]. ExoDDD scattering allows for a CDMS-Si interpretation with heavier DM mass (lower right). For lighter ExoDDD (lower left), the majority of the favored parameter space is consistent with the strongest bounds and the DM mass favored in asymmetric DM models.
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 $v_{\text{rel}} = 100$ 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
III Many Other Consequences
Things to think about

- New species (Planck can detect)
- Possibly small scale structure
  - Atomic physics
- Numerical simulations (structure, alignment)
- Velocity distributions, lensing (look for structure)
- Large scale structure
  - Acoustic Oscillations
  - galaxy-galaxy correlation functions
- 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. The mission aims to compile a 3D space catalogue of approximately 1 billion stars, or roughly 1% of stars in the Milky Way. 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
- 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
- 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

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.
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?

Rate is ~ 100 times larger than expected for a WIMP also - systematic concerns
Motivation: Fermi Lines

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

$$- \mathcal{L} \ni \lambda_X |X|^2 |S|^2,$$  \hspace{1cm} (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 $X^+X \to \gamma D \gamma D$

$$\Omega_{\text{HS}} h^2 \approx \frac{5.0 \times 10^{-27} \text{cm}^3/\text{s}}{(\sigma v)_{X^+X \to \gamma D \gamma D}},$$  \hspace{1cm} (14)

with

$$(\sigma v)_{X^+X \to \gamma D \gamma D} = \frac{2\pi \alpha_D^2 Q_D^4}{m_X^2},$$  \hspace{1cm} (15)

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

$$\sum |M|^2 = \frac{\alpha^2}{2\pi^2} \lambda_X^2 Q_s^4 A_0^2(\tau),$$  \hspace{1cm} (16)

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


Boost Factor

$\lambda_\phi s N_3 Q_3^2 = 1$

$\langle \sigma v \rangle_{\gamma \gamma} = 10^{-27} \text{ cm}^3/\text{s}$

**FIG. 1.** Fixing $(\sigma v)(\phi \phi \rightarrow \gamma \gamma) = 10^{-27} \text{ cm}^3/\text{s}^{-1}$, $N_3 Q_3^2 \lambda_\phi s = \text{ and } m_\phi = 130 \text{ GeV}$, the boost factor $B$ needed to generate a signal that current Fermi line search is sensitive to.
Sommerfeld Enhancement Not Enough!

Figure 2: Upper: velocity distribution as a function of distance from the galactic center \( v \); Lower: Sommerfeld enhancement factor as a function of \( \alpha_D Q^2 \), 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 \( \Omega_{HS}/0.11 \).
