Is Dark Matter Natural?
What Should Drive Model Building Today?
Double Disk Dark Matter

LR w/Fan, Katz, Reece
w/Reece
w/Kramer
w/Scholtz

Naturalness and Dark Matter

Dark matter models to date motivated in large part by naturalness considerations

- Coincidence of relic abundance with weak mass stable particle density
- Comparable contributions of dark matter, ordinary matter to net energy density
- Yet
  - Very few dark matter possibilites explored
  - And very much from myopic perspective
  - Perhaps better to be anti-anthropic, anti-natural when exploring options

Outline Talk

- Brief Naturalness Considerations
- Introduce Partially Interacting Dark Matter (PIDM) and Double Disk Dark Matter (DDDM)
- Conventional and unconventional search methods
  - Measure potential
- Implications for periodic meteoroid strikes
  - And dinosaur extinction—anthropic!
- Implications for Andromeda satellite dwarf galaxies

Wimp "Miracle"

- You all know this
- Works pretty well
- Major advantage is that it guarantees detection possibilities
  - Connections between visible and dark sectors
  - Possibility for dark matter to be seen in baryonic experiments, observations
- Limits being pushed
  - Model building continues

Asymmetric Dark Matter

- Different "miracle"
- Comparable amounts of ordinary and dark matter
  - Perhaps unlikely unless actual interaction, connection between two sectors
- Many models pushed as light dark matter candidates
  - Idea: if chemical potentials for proton and dark matter comparable, dark matter mass ~5 GeV gives dark matter density
- Models also pushed weak scale connection

More General

- W/Matthew Buckley, showed that dark matter can have weak scale mass
- Point is that amount determined by freezeout temperature
- Ratio of mass to temp of order ten still naturally gives correct abundance—lower density but higher mass

More General

- With Cui, Shuve studied more general connections between two sectors
- Showed several ways that early universe could have preserved single dark matter+baryon number
- Later universe breaks it
  - Two Higgs Model
  - Moduli Fields
  - Finite Temperature Effects

Dark Matter Model Building More Generally

- Natalia Toro: Wilson's Scalpel rather than Naturalness
  - Allow for experimentally testable possibilities
    - True in dark sector too
- I go a step further: Martha's Table
  - Don't have proper table with just knives
  - We are running into situation that we generally solve one problem at a time
  - We need to think more globally when addressing model building—explaining one thing doesn't suffice
  - Also broaden horizons more generally to experimentally accessible routes—whether or not problems obviously solved
- Experiments, observations rare and expensive:
  - Yet data rich
  - As model builders we should be thinking of ways to exploit them

What Is Dark Matter?

- Clearly we don't yet know
- We know gravitational interactions
  - But no other discernible interactions yet
- Existence of dark matter not necessarily so mysterious
- But how to find what it is?
  - Look under the lamppost
  - Find theoretical, experimental clues
- What are the right lampposts
- We need to consider all possibilities
  - Does dark matter interact as we might hope?
  - Does it interact differently (nonanthropically)?

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
- Alternative to standard WIMP paradigm
  - Partially interacting dark matter

Partially Interacting Dark Matter

- SIDM: Dark matter with its own force
- PIDM: Rather than assume all dark matter
  - Assume it's only a fraction
- Maybe like baryons?
- Nonminimal assumption
- But one with significant consequences
  - Will be tested
  - Leads to rethinking of implications of almost all dark matter, astronomical, cosmological measurements
- Since we don't know what dark matter is
  - Should keep an open mind
  - Especially in light of abundance of astronomical data

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…

On the surface surprising…

- Dark matter thought to be non-interacting
  - Or at best very weakly interacting
- First piece of evidence is spherical halo
  - No means of cooling down
- Second piece of evidence is some *nonsphericity* in core
  - Interactions would make it more uniform
- Third piece of evidence is Bullet Cluster
  - Gas left behind on merger but dark matter passes right through
- Finally: lack of detection
  - That of course just refers to interactions with ordinary matter
  - Doesn’t tell about self-interactions

Actually

1. None of these too serious anyway
2. But for us even less so: fraction changes everything!
3. Clearly Bullet Cluster okay if only a fraction –most dark matter would pass through
4. Shapes tricker—but even if the fraction very strongly interacting, can smooth out only that fraction at first

- ✓ Maybe? This is something that could be interesting to better understand

Why would we care?

- Will be tested!
- Implications of a subdominant component
  - Can be relevant for signals if it is denser
  - Can be relevant for structure (to be done…)
- Depends on “shape”
- Baryons matter because formed in a dense disk
- Perhaps same for *component* of dark matter
- Perhaps dark disk inside galactic plane
  - However, 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

Could interacting dark matter also 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 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

Thermal Abundance of X and C

- When X freezes out with weak scale mediators, could have half temp of SM particles
- If lighter mediator, could imagine comparable temps
- Find m_X, α_D to give ε=.05
  - Slightly stronger constraint now
  - Smaller α leads to violation of limit
  - Larger α requires nonthermal component even for X

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

Now that we have model Check Cooling:

- Bremsstrahlung
- Compton scattering off dark photons
  - We make assumption that cooling stops when recombination can occur
  - Approximately B/20

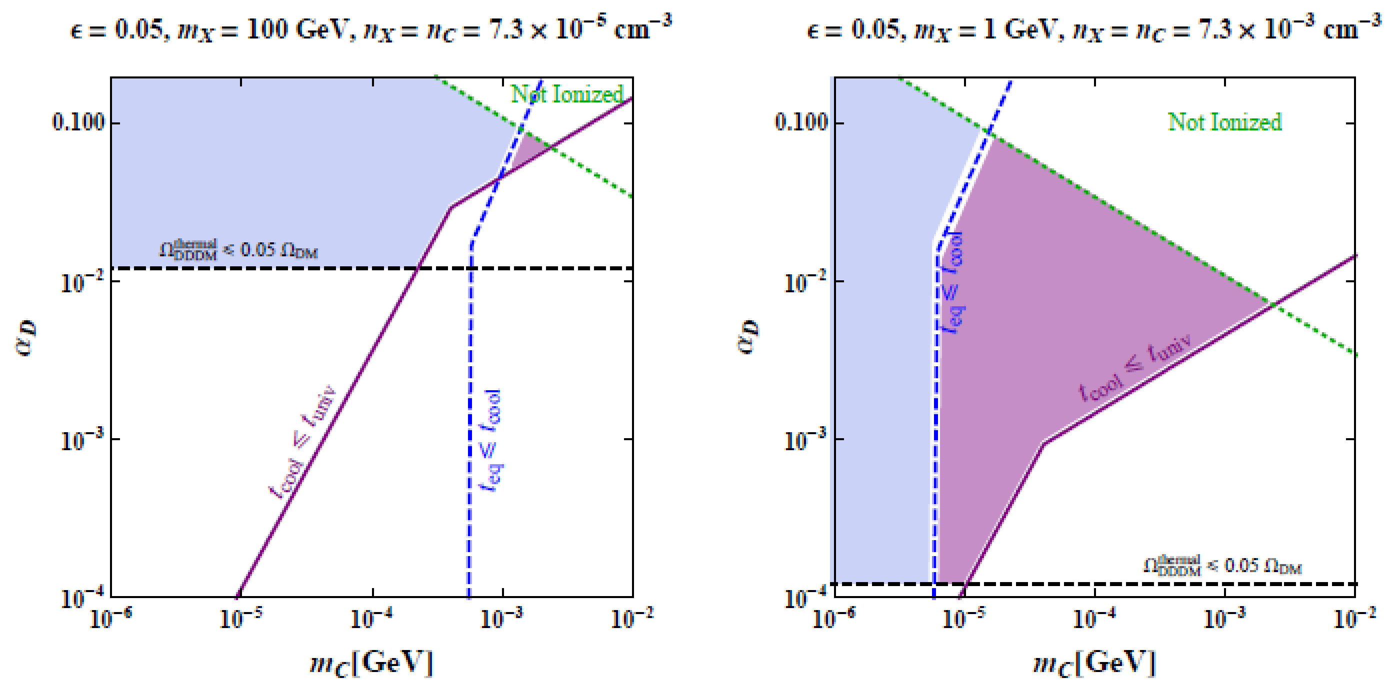

Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the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

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!

Disks at least approximately align

- Alignment time: $$t \approx \left(\frac{R^3}{GM}\right)^{1/2} \sqrt{\theta}$$
- R~10 kpc
- M~10^{12} M_{sun}

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

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

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

Summary of model

- 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
    - Aside: anthropic bound on electron mass!
- With these conditions, expect a dark disk
  - Might even be narrower than the gaseous disk
- Expect interesting signals
- And bounds (which we briefly consider now)

Consequence

- Dark disk
- Could be much denser and possibly titled with respect to plane of our galaxy
- Very significant implications
  - Even though subdominant component
- Velocity distributions in or near galactic plane constrain fraction to be comparable or less to that of baryons
- 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 preent

Distinctive Shape to Signal

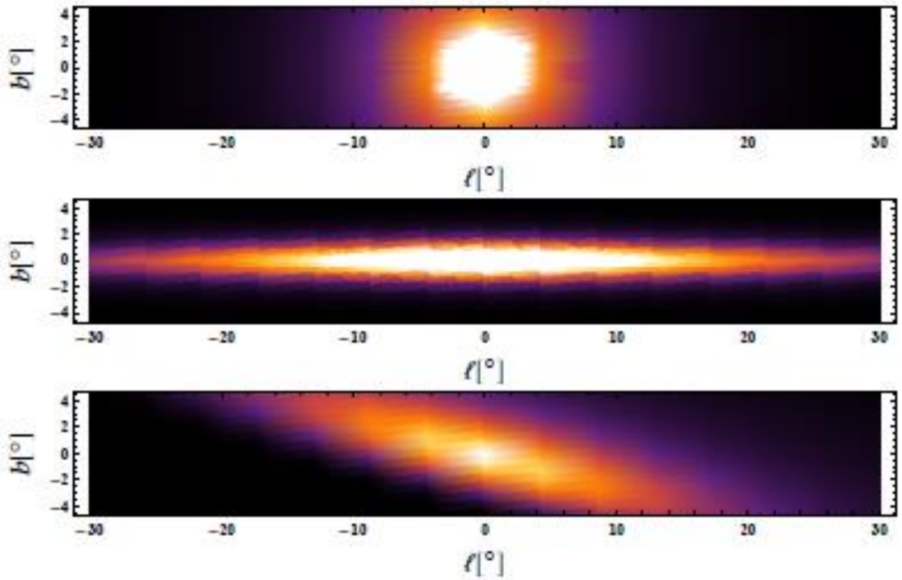

FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology

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(Dated: October 15, 2013)

Also new acoustic peak

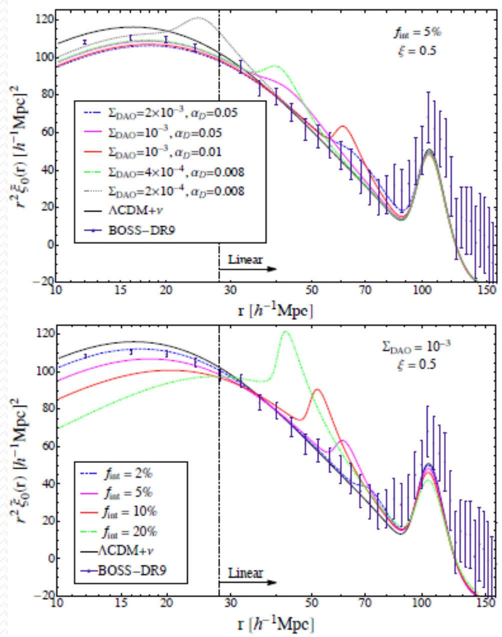


FIG. 2: Angle averaged galaxy correlation function $\tilde{\xi}_0(r)$ for different PIDM models. In the upper panel, we take $f_{\rm int} = 5\%$, $\xi = 0.5$ and vary $\Sigma_{\rm DAO}$ and α_D. In the lower panel, we fix $\Sigma_{\rm DAO} = 10^{-3}$, $\alpha_D = 0.01$ and $\xi = 0.5$, but let the fraction of interacting DM vary. We set the galaxy bias to $b = 2.2$ and the dilation scale to $\alpha = 1.016$. We compare theoretical predictions with BOSS-DR9 measurements from Ref. [86], and we also show a standard ΛCDM model with an equivalent number of effective neutrinos. In this work, we focus uniquely on linear scales, which lie to the right of the dashed vertical line on the plot.

From CMB

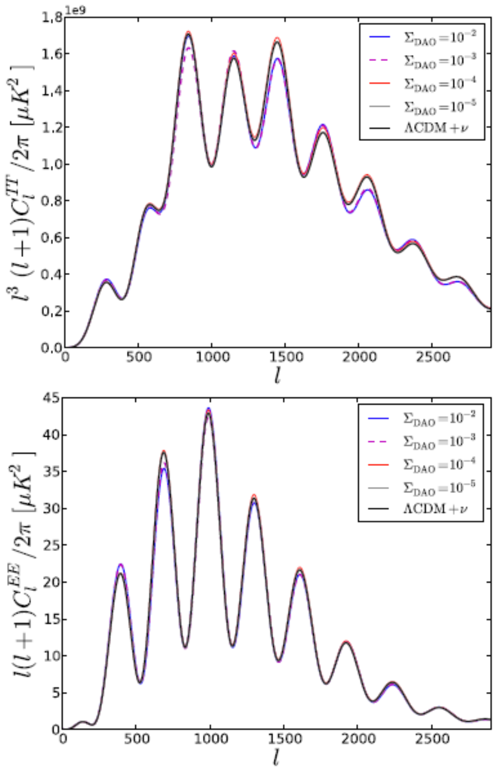
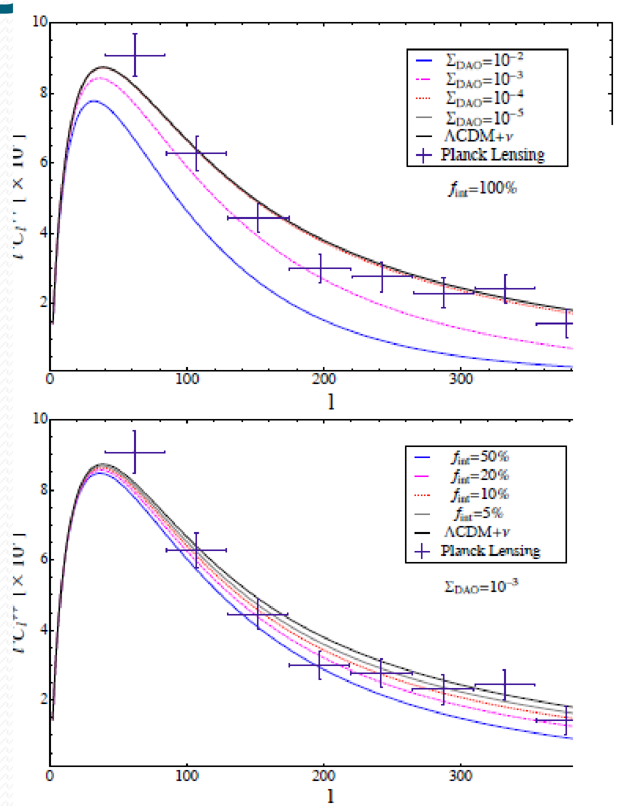


FIG. 6: CMB unlensed temperature (upper panel) and E polarization (lower panel) power spectra for four different PIDM models with $f_{\rm int}=100\%$. We have taken $\xi=0.5$. For comparison, we also show a standard ΛCDM model with an equivalent number of effective neutrinos.



'IG. 7: CMB lensing power spectrum for different PIDM nodels. For both panels we use $\xi=0.5$. In the upper panel, ve vary $\Sigma_{\rm DAO}$ while leaving $f_{\rm int}=100\%$ fixed. The model vith $\Sigma_{\rm DAO}=10^{-5}$ is essentially undistinguishable from the CDM$+\nu$ model. In the lower panel, we vary $f_{\rm int}$ but leave $\Sigma_{\rm DAO}=10^{-3}$ fixed. We show the eight band powers used in he Planck lensing likelihood. For comparison, we also show ΛCDM model with an equivalent number of neutrinos.

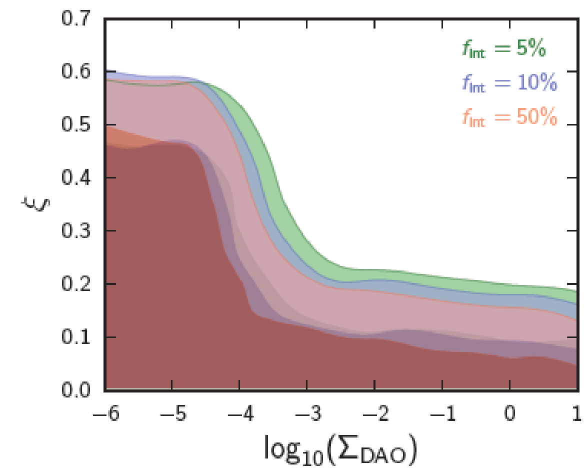


FIG. 11: Marginalized constraints on ξ and $\Sigma_{\rm DAO}$ for three fixed values of $f_{\rm int}$. We display the 68% and 95% confidence regions for the dataset "Planck+WP+High-l+BAO+Lens".

Bounds from new relativistic degrees of freedom: thermal history: summary

- Number of relativistic degrees of freedom safe
  - But close to bound so possibly testable
- Thermal relic abundance can be of order Oort limit for X
- Not for C so nonthermal required
- But implies possibility of comparable thermal and nonthermal components
- Relevant for potential annihilation signals

Bound from Structure w/Kramer

- Recall bound from shapes not so bad
  - But bound from from matter accounting
  - And detailed shape of galaxy
- Gravitational potential measured
  - Both in and out of plane of galaxy
  - Star velocities
- Baryonic matter independently constrained
- Dominant component of dark matter constrained
  - Extrapolate halo
- Total constraint on any new form of matter
- Constrains any new (nonhalo) component in galactic plane

Various effects

- Add new component
- Has different thickness
- Pinches other components
- Surface density and thickness ultimately constrained

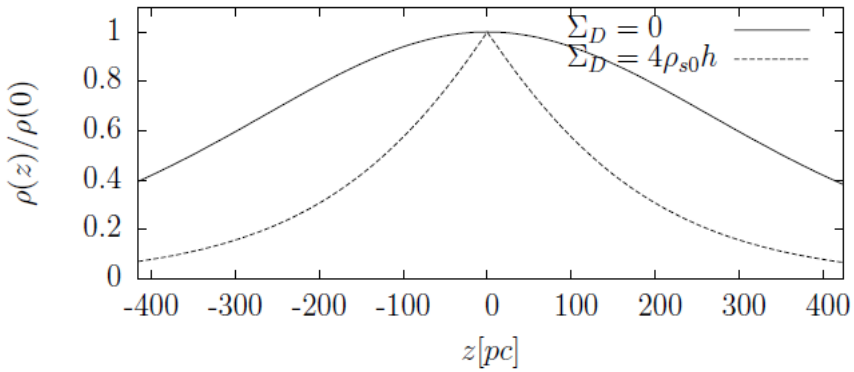


Figure 1: A plot of the exact solutions without and with a dark disk of $Q = 1$. The density is 'pinched' by the disk, in accordance with Eq. 31.

Table 2: The Bahcall model used by HF2000. The Σ_i were calculated by HF2000 from the solution to the Poisson-Jeans equation, except for the gas components, where the midplane densities were chosen to give the known the Σ_i.

i	Description	$\rho_i(0)$ ($M_\odot \mathrm{pc}^{-3}$)	σ_i (km s^{-2})	Σ_i ($M_\odot \mathrm{pc}^{-2}$)
1	H_2	0.021	4.0	3.0
2	$H_I(1)$	0.016	7.0	4.0
3	$H_I(2)$	0.012	9.0	4.0
4	warm gas	0.001	40.0	2.0
5	giants	0.0006	17.0	0.4
6	$M_V < 2.5$	0.0031	7.5	0.9
7	$2.5 < M_V < 3.0$	0.0015	10.5	0.6
8	$3.0 < M_V < 4.0$	0.0020	14.0	1.1
9	$4.0 < M_V < 5.0$	0.0024	19.5	2.0
10	$5.0 < M_V < 8.0$	0.0074	20.0	6.5
11	$M_V > 8.0$	0.014	20.0	12.3
12	white dwarfs	0.005	20.0	4.4
13	brown dwarfs	0.008	20.0	6.2
14	stellar halo	0.0001	100.0	0.6

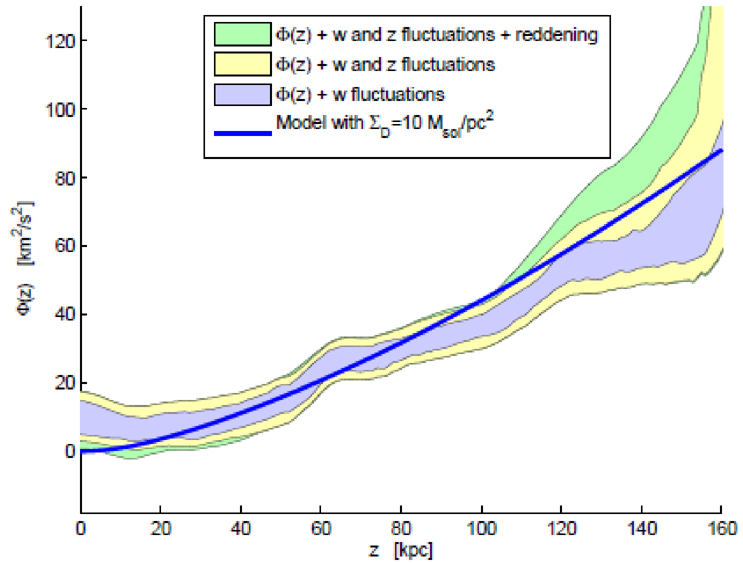
They found that a mass model with little or no dark matter in the disk was in very good agreement with the data [10], as can be seen in Figure 2, and as did previously Kuijken & Gilmore [7, 8] using a similar method. By adding and subtracting invisible mass to the various components to the model, HF then obtained a range on the acceptable mass models, which gave a range of acceptable densities as a function of height.

Hipparcos

Eric
Kramer

- Flynn Holberg looked at A and F type stars in inner portion of galaxy
- From Hipparcos, get velocity measured at midplane and density as function of vertical distance
- They get strong constraint on density .1 M_solar/pc^3
- Use galactic model with several isothermal components
- Claim matches data
- We are checking

Figure 3: Comparison of the model potential $\Phi(z)$ from a specific model with $\Sigma_D = 10\, M_{\odot}\mathrm{pc}^{-2}$ (solid line) to the potential extracted from the A-star kinematics, with ranges allowed by statistical uncertainties (thick bands).



Kinematics of Stars

Figure 5: Probability $p(X_{\rm model})$ for the X value associated with different Σ_D, for a dark disk with $h_D = 10$ pc and mean values for gas parameters (*cf*. Table 4). The "total" probability is obtained by multiplying the A and F-star probabilities. The probability shows a peak near $\Sigma_D = 4\, M_\odot{\rm pc}^{-2}$ and tips below the 95% bound at $\Sigma_D \simeq 14\, M_\odot{\rm pc}^{-2}$.

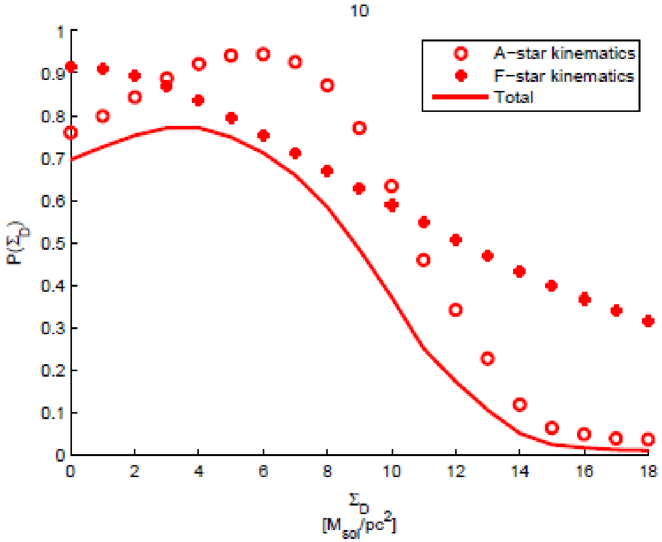


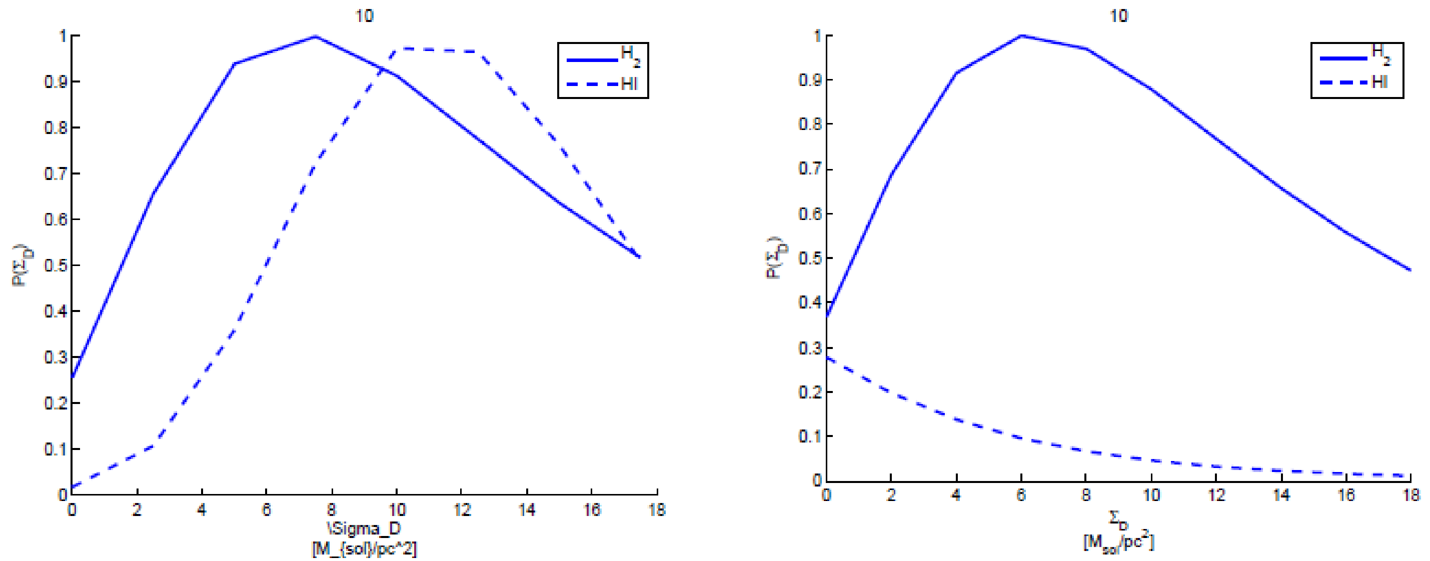
Table 4: Gas parameters explained in detail in Paper 2. Values on the right contain helium and other elements associated with the Hydrogen. Helium associated with H_2 was included in the HI component since it is not expected to clump the way H_2 does.

	$\rho(0)$ $[0.01 M_\odot \mathrm{pc}^{-3}]$	Σ $[M_\odot \mathrm{pc}^{-2}]$	$\rho_{+\mathrm{He}}(0)$ $[0.01 M_\odot \mathrm{pc}^{-3}]$	$\Sigma_{+\mathrm{He}}$ $[M_\odot \mathrm{pc}^{-2}]$
H_2	0.88 ± 0.17	1.50 ± 0.26	0.88 ± 0.17	1.50 ± 0.26
HI	1.70 ± 0.30	7.36 ± 3.81	2.79 ± 0.44	11.08 ± 5.41
HII	0.07 ± 0.02	1.75 ± 0.21	0.11 ± 0.03	2.49 ± 0.30
Total	$\mathbf{2.66 \pm 0.35}$	$\mathbf{10.61 \pm 3.83}$	$\mathbf{3.78 \pm 0.47}$	$\mathbf{15.07 \pm 5.43}$

The Table shows the gas parameters with and without the inclusion of the factor of 1.4 for Helium and other elements. The Helium associated with H_2 was included in the HI component since we do not expect it to clump the way H_2 does. The main uncertainty in the gas surface density is therefore the uncertainty associated with that of HI, both in midplane density and surface density. In this paper, however, we do not make use of any of the surface densities since it is the midplane densities that serve as inputs to the Poisson-Jeans equation. The measured surface densities can, on the other hand, be used to verify the consistency of the model, since, based on the midplane densities, the Poisson-Jeans equation predicts surface densities for all the gas components. This matter, potentially a very effective way to constrain a dark disk, will be investigated in Paper 2 [30].

Gas midplane, surface, eg

Figure 6:



This 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

Could maybe even explain crater periodicity…

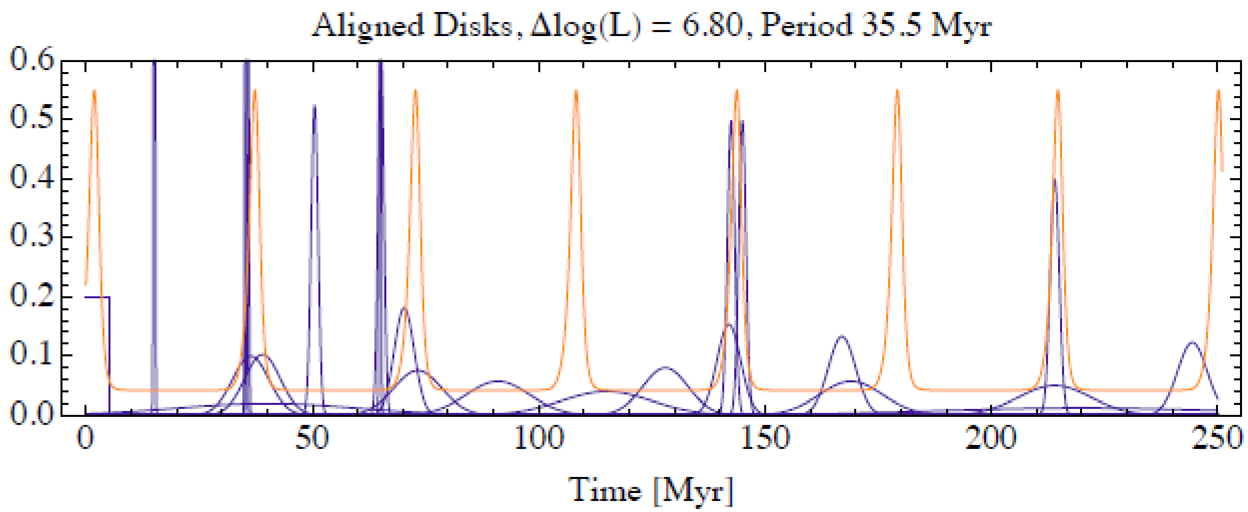


Figure 8: An example of a model that provides a good fit. In this case, the two disks are aligned, and the period between disk crossings is about 35 Myr.

w/Reece

Meteorite 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

Motion of Sun; Density Solar System Encounters

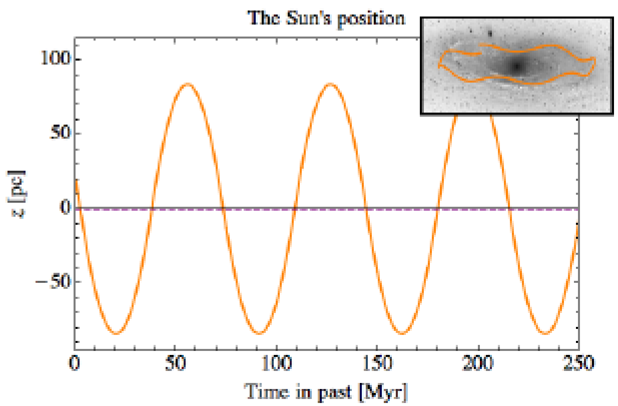


FIG. 1. The Sun's height above the galactic plane as a function of time, extrapolated backward via Eq. 2. The corresponding cratering probability is shown in Fig. 3. Inset: an illustration of how the Sun moves around the galactic center while also oscillating vertically; the vertical oscillation is exaggerated for visibility.

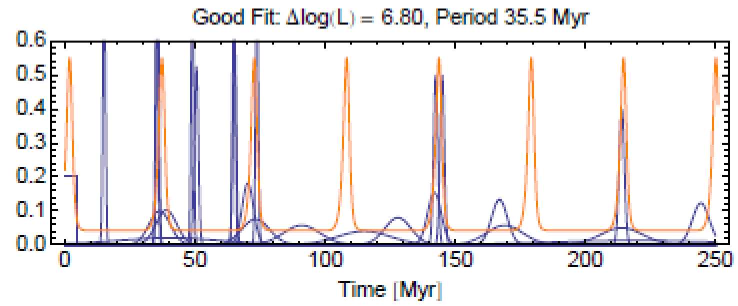


FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\mathrm{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\mathrm{pc}^2$. The local dark halo density is 0.037 GeV/cm^3. $Z_\odot = 20$ 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.

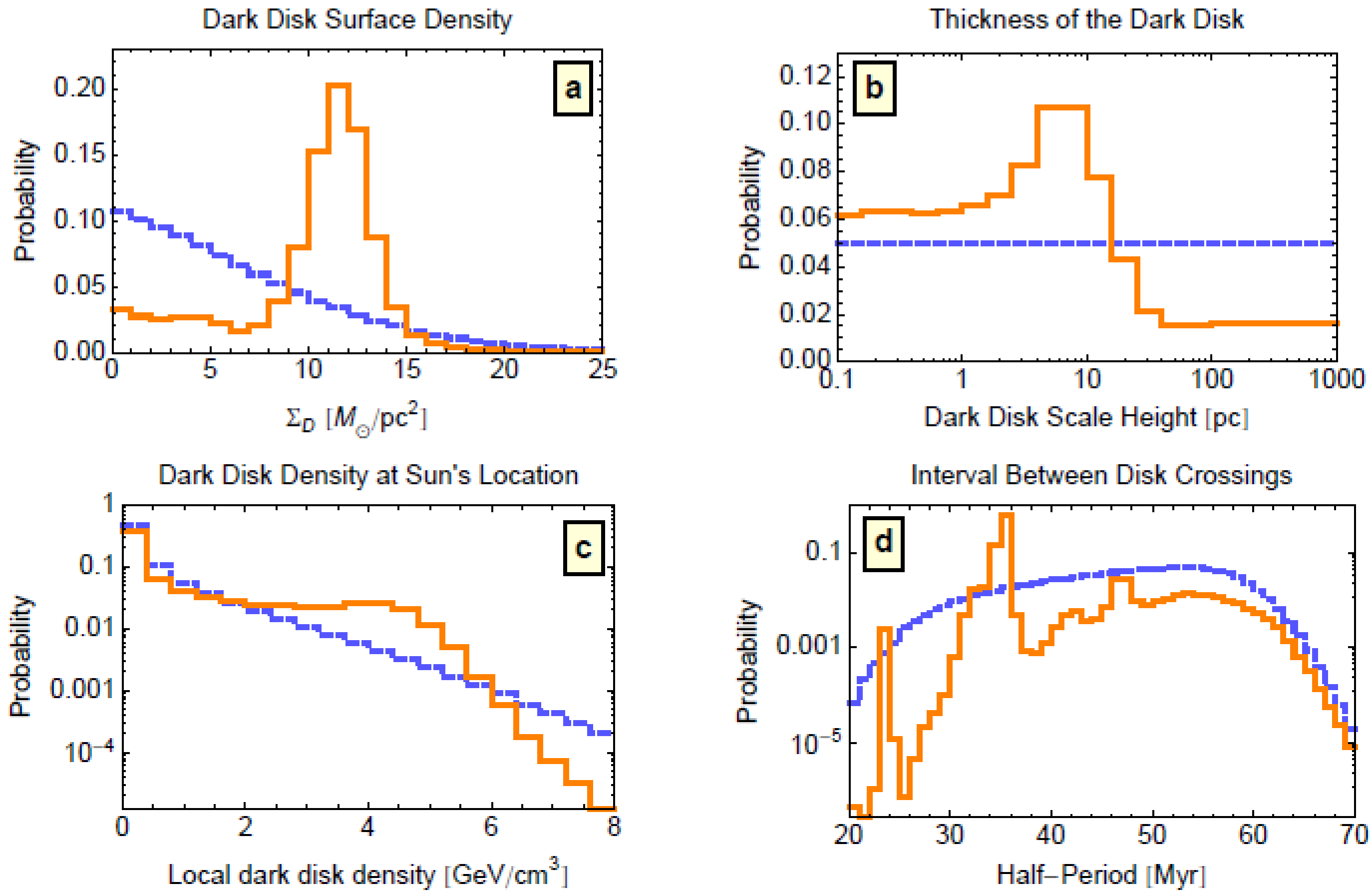


Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\text{pc}^2$. (b) The dark disk thickness, which fits best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

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

- We worked out consequence with dark disk
- Assume pull out patch on order of size of Toomre instability

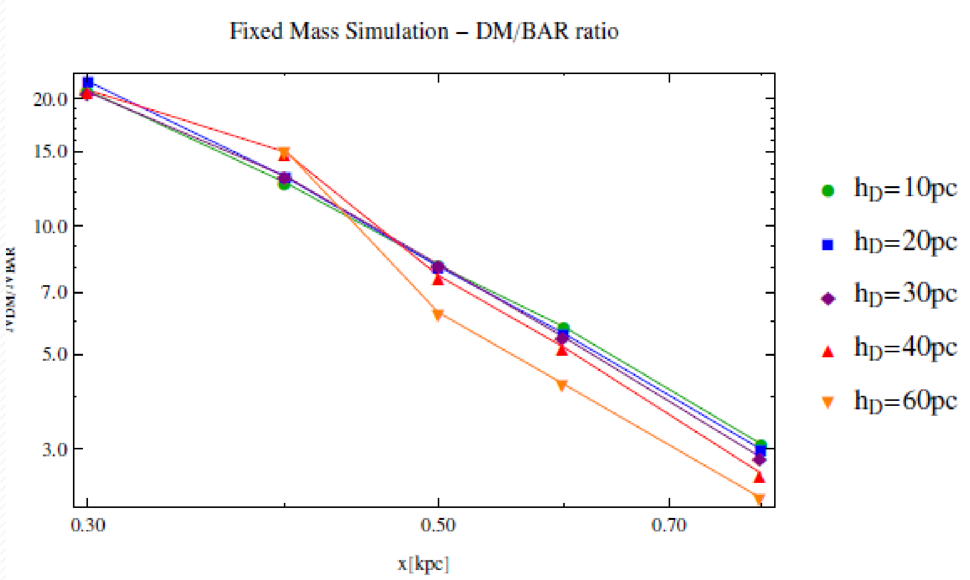


Figure 9: Dependence of the final DM to baryon ratio on the size of the initial patch.

Many Other Consequences Things to think about

- Can explain dwarf satellite galaxies
  - More general
  - No other explanation
- Possibly formation big black holes
- New results on dark disk constraints
  - Ways to discover
- Results on planar dwarf galaxy satellites
- Ultimate anthropic☺ Killing dinosaurs

Conclusions

- Whether or not annihilation “signals” survive,
- 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