Theoretical Cosmology of the 21st Century

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The Spacetime Odyssey in Stockholm

Status: Concordance but Big Questions

- Dark Matter
- Dark Energy
- Inflation
- Earliest stars
- Black Holes
- Cosmic Rays
- Matter/Antimatter Asymmetry
- Astronomical Big Data

- (courtesy KIPAC)

What do these share?

1. We don’t know answers
2. For some we are unlikely to know answers
3. For some we might be likely and know answers
4. And for some, we are reasonably likely to make progress

Status: Big Questions

- Dark Matter 3/4
- Dark Energy 2
- Inflation 3
- Earliest stars 4 (but partial)
- Black Holes 4 (but time scale?)
- Cosmic Rays 4 (but partial)
- Matter/Antimatter Asymmetry 2
- Astronomical Big Data **4**

- All 1!
- 4 Astrophysical
- (courtesy KIPAC)

What to do?

- Model building a good way to target new ideas
- Take advantage of big data
- Think of LHC—need models
- Give one example in dark matter
- I do think this will be direction of 21st century
- Precision less likely to get answers
- Big data has potential
- But we need to think more broadly

What does this mean?

- Model building
- Targeting models
- Analyzing data with models in mind
- Illustrate by a specific class of models

Double Disk Dark Matter

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

Outline Rest of Talk

- Dark Matter Status
- Introduce Partially Interacting Dark Matter (PIDM) and Double Disk Dark Matter (DDDM)
- Conventional and unconventional search methods
  - Measure gravitational potential of galaxy
- Implications for Andromeda satellite dwarf galaxies
- Implications for periodic meteoroid strikes

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 ?
  - Does it interact differently?

Dark Matter

- WIMP "standard" paradigm
- But
  - No direct detection
  - No indirect detection
  - LHC hasn't shown any sign of new weak scale physics
- Searches to date always based on optimistic assumptions
- Namely dark matter does interact with our matter at some level

Status

- Other ideas?
  - Asymmetric Dark Matter models promising
    - Hard to detect
  - Axion Models possible
    - Challenges to detection and narrow window
- Lots of other dark matter candidates too
  - Working on some generic ones now
- But actually finding a dark matter particle will be tough
  - Almost all non-WIMP models extremely challenging to detect

Status

- 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

Self-Interacting Dark Matter

- Best option might turn out to be returning to the way we always knew about dark matter
  - **Gravitational effects**
- Look for signs of dark matter properties
  - Interactions

- Suppose dark matter interacts
  - But only with itself
- Conventional search constraints no longer apply
- However not entirely unconstrained

Constraints on Self-Interactions

- First piece of evidence is spherical halo
- Second piece of evidence is some *nonsphericity* in core
  - Interactions would make it more uniform
- Third piece of evidence is Bullet Cluster (and similar)
  - 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

Partially Interacting Dark Matter Suppose only a **fraction** interacts

- Fraction changes everything
- Clearly Bullet Cluster okay if only a fraction –most dark matter would pass through
- Shapes tricker—but even if the fraction very strongly interacting, can smooth out only a fraction at first

Partially Interacting Dark Matter

- Dark matter with its own force
  - 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

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

Why would we care?

- Implications of a subdominant component
  - Can be relevant for signals if it is denser
  - Can be relevant for structure
- 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 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 independent gauge symmetry
  - “Dark light”

Simple DDDM Model: Dark Light

- 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)

Check Cooling:

- Bremsstrahlung
- Compton scattering off dark photons

  - We make assumption that cooling stops when recombination can occur
  - Approximately B/20

Brehmstrahlung and Compton

timescale of the bremsstrahlung cooling is

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

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

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

Relic Density X

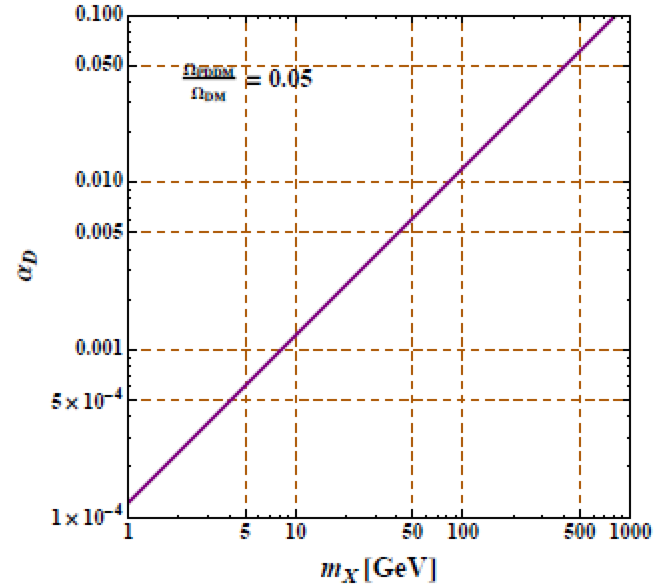

Figure 1: α_D needed to get the thermal relic abundance of X to be 5% of the total DM density for different masses of X.

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.

- 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
- Probably have both thermal and nonthermal components

Cooling for reasonable parameters

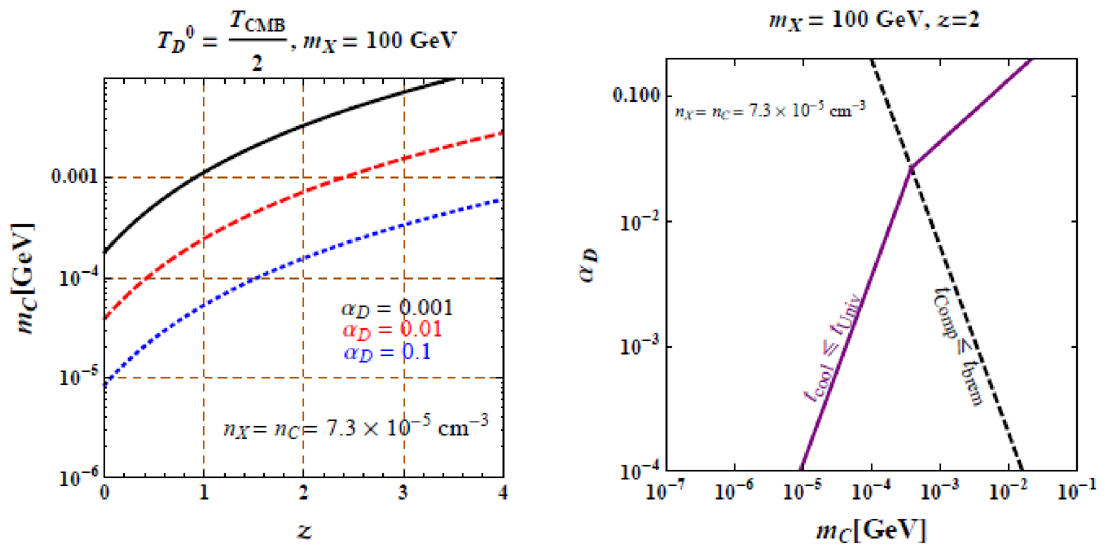

Figure 4: Comparison of the rates of bremsstrahlung and Compton cooling. At left: the value of m_C for which the rates are equal, as a function of redshift. To the right of the curves, i.e. at early times, Compton cooling dominates. At right: the contour in the (m_C, α_D) plane along which the bremsstrahlung 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.

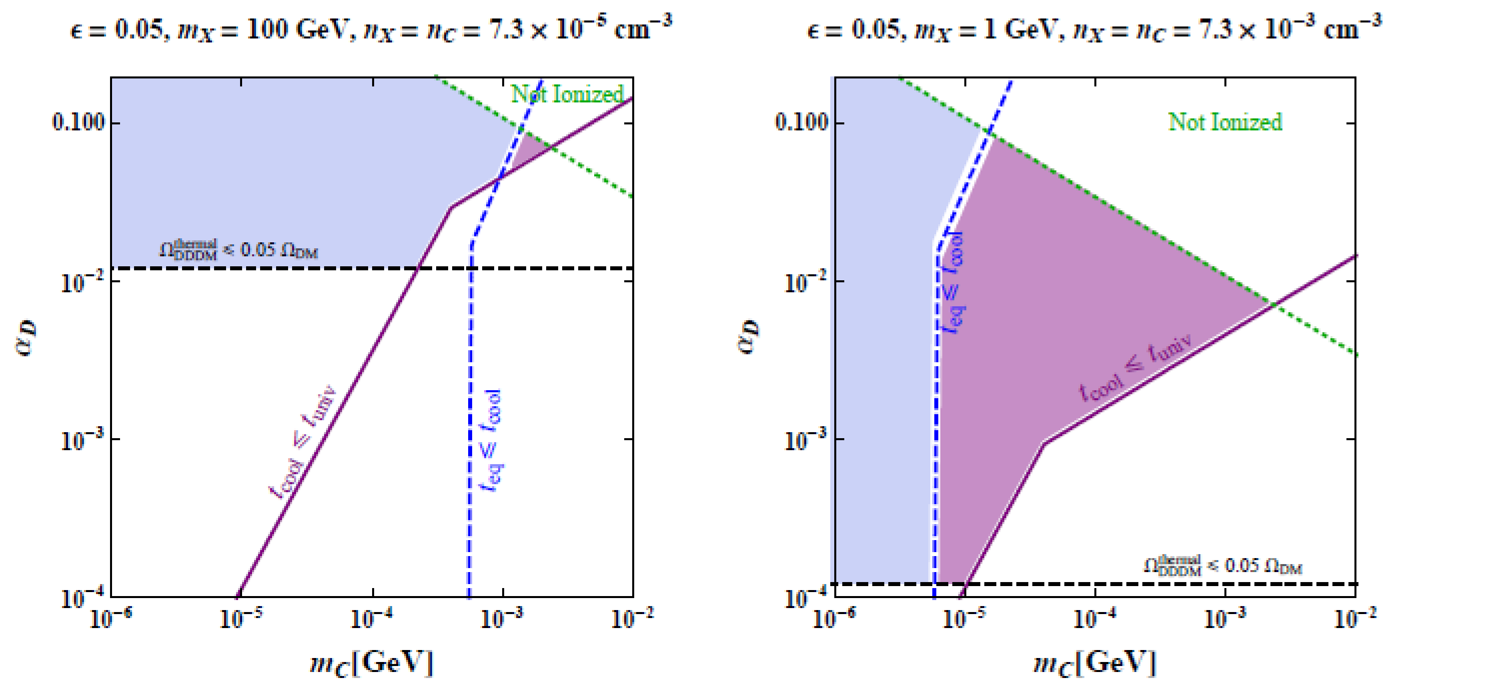

Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the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

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:
- R~10 kpc
- M~10^{12} M$_{sun}$

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

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

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

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

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
- With these conditions, expect a dark disk
  - Even narrower than the gaseous disk

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

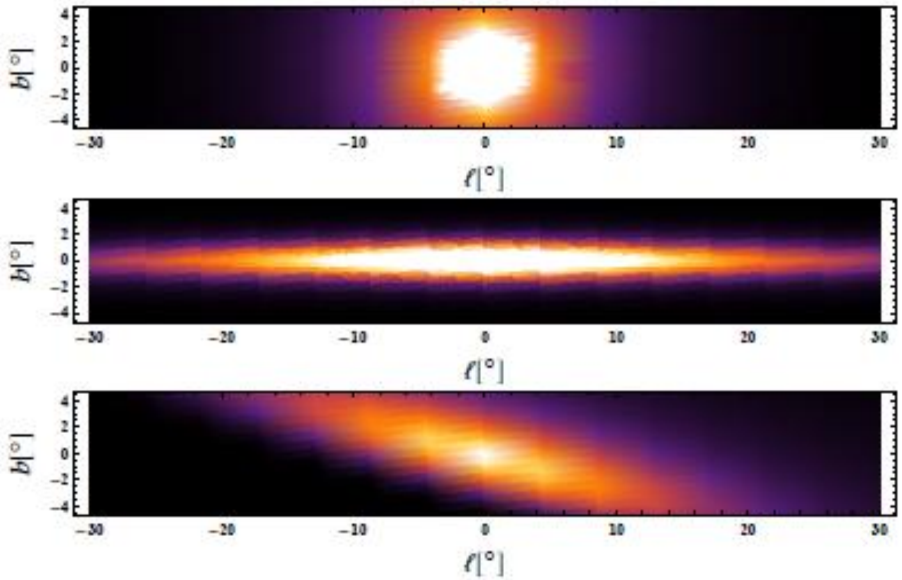

FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

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

Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology

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Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, V6T 1Z1, Canada
(Dated: October 15, 2013)

Also new acoustic peak

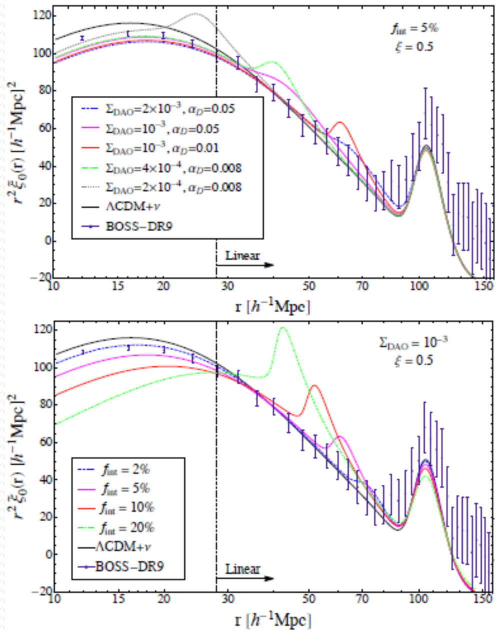


FIG. 2: Angle averaged galaxy correlation function $\tilde{\xi}_0(r)$ for different PIDM models. In the upper panel, we take $f_{\rm int} = 5\%$, $\xi = 0.5$ and vary $\Sigma_{\rm DAO}$ and α_D. In the lower panel, we fix $\Sigma_{\rm DAO} = 10^{-3}$, $\alpha_D = 0.01$ and $\xi = 0.5$, but let the fraction 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

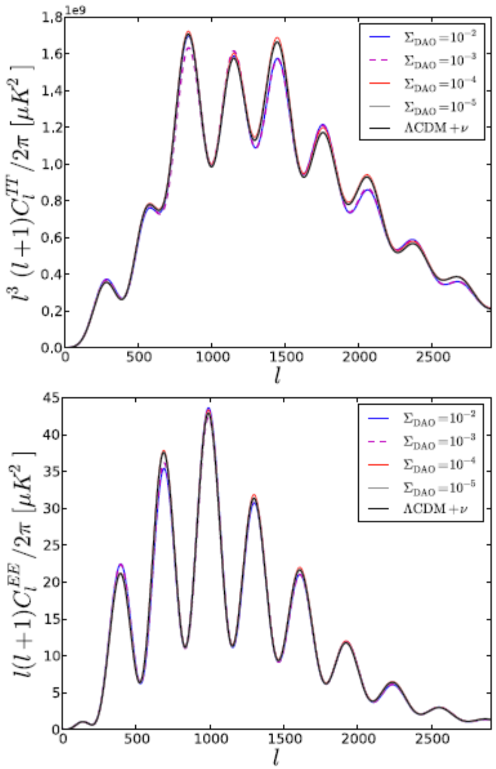
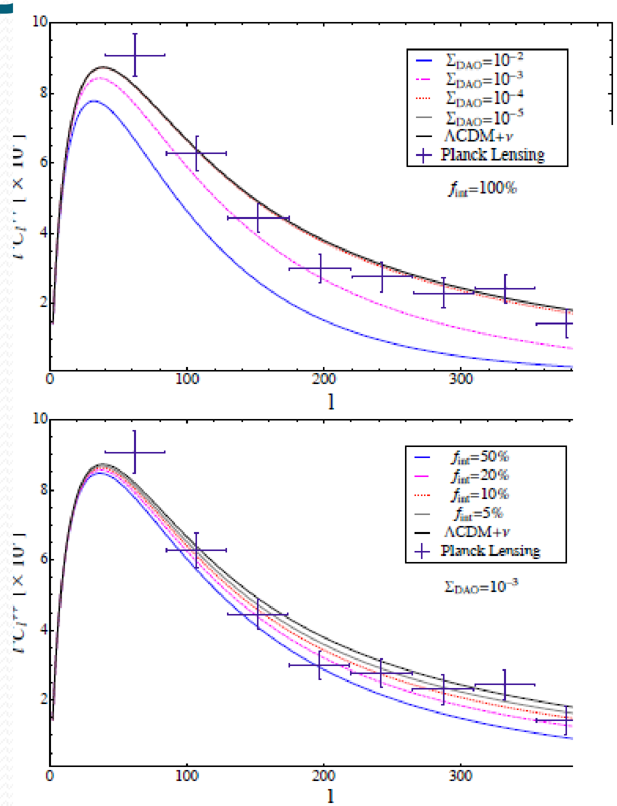


FIG. 6: CMB unlensed temperature (upper panel) and E polarization (lower panel) power spectra for four different PIDM models with $f_{\rm int}$ = 100%. We have taken $\xi = 0.5$. For comparison, we also show a standard ΛCDM model with an equivalent number of effective neutrinos.



'IG. 7: CMB lensing power spectrum for different PIDM
ıodels. 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
ΛCDM+ν 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
ı ΛCDM model with an equivalent number of neutrinos.

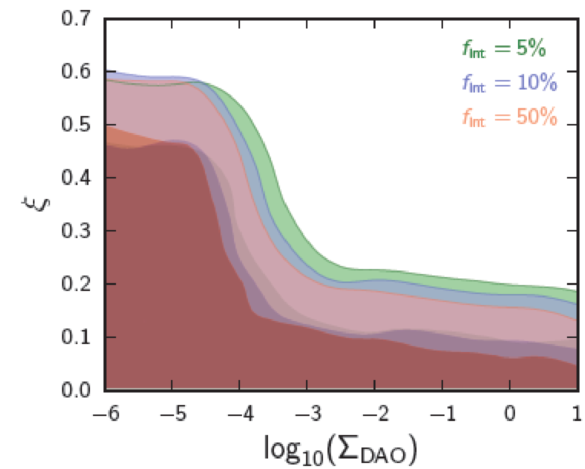


FIG. 11: Marginalized constraints on ξ and $\Sigma_{\rm DAO}$ for three fixed values of $f_{\rm int}$. We display the 68% and 95% confidence regions for the dataset "Planck+WP+High-l+BAO+Lens".

$$\Sigma_{\rm DAO} \equiv \alpha_D \left(\frac{B_D}{\rm eV}\right)^{-1} \left(\frac{m_D}{\rm GeV}\right)^{-1/6} .$$

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

Eric
Kramer

Hipparcos

- 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
- Distribution falls off more or less exponentially over a scale height
- Solve Jeans equation
- Use Poisson's equation to introduce the different sources/components

$$\frac{\partial}{\partial z}(\rho_i \sigma_i^2) + \rho_i \frac{\partial \Phi}{\partial z} = 0$$

$$\frac{1}{\rho_i \sigma_i^2} \frac{\partial}{\partial z}(\rho_i \sigma_i^2) + \frac{1}{\sigma_i^2} \frac{\partial \Phi}{\partial z} = 0,$$

ately see that the solution is

$$\rho_i \, \sigma_i^2 \propto \exp\left(- \int dz \, \frac{1}{\sigma_i^2} \frac{\partial \Phi}{\partial z} \right).$$

stellar population to be isothermal, th
urther to

$$R, z) = \rho_i(R, 0) \, e^{-(\Phi(R,z) - \Phi(R,0))/\sigma_i^2}.$$

$R = R_\odot$, where we will fix $\Phi(R_\odot, 0)$ =

$$\rho_i(z) = \rho_i(0) \, e^{-\Phi(z)/\sigma_i^2}.$$

ssumed equilibrium, vanishing tilt, an
a gas at temperature $\frac{1}{2}kT_i = \frac{1}{2}\sigma_i^2$ an
his solution to the Jeans equation

$$\nabla^2 \Phi = 4\pi G \sum_i \rho_i.$$

$$\frac{\partial^2 \Phi}{\partial z^2} = 4\pi G \sum_i \rho_i. \tag{20}$$

ombining Eq. 20 with the Jeans equation (14), we have the Poisson-Jeans equation
r the potential Φ

$$\frac{\partial^2 \Phi}{\partial z^2} = 4\pi G \sum_i \rho_i(0) e^{-\Phi/\sigma_i^2}. \tag{21}$$

here we have dropped the R coordinate label. This can also be cast in integral form
ssuming z-reflection symmetry)

$$\frac{\rho_i(z)}{\rho_i(0)} = \exp\left(-\frac{4\pi G}{\sigma_i^2} \sum_k \int_0^z dz' \int_0^{z'} dz'' \, \rho_k(z'') \right) \tag{22}$$

hich is the form used in our Poisson-Jeans solver.

Various effects

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

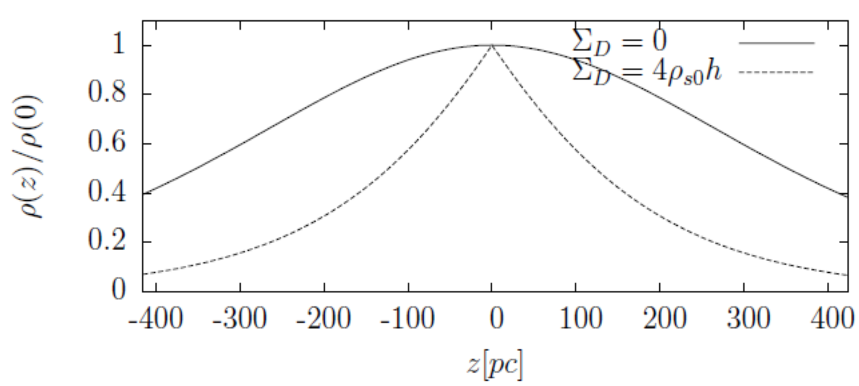


Figure 1: A plot of the exact solutions without and with a dark disk of $Q = 1$. The density is 'pinched' by the disk, in accordance with Eq. 31.

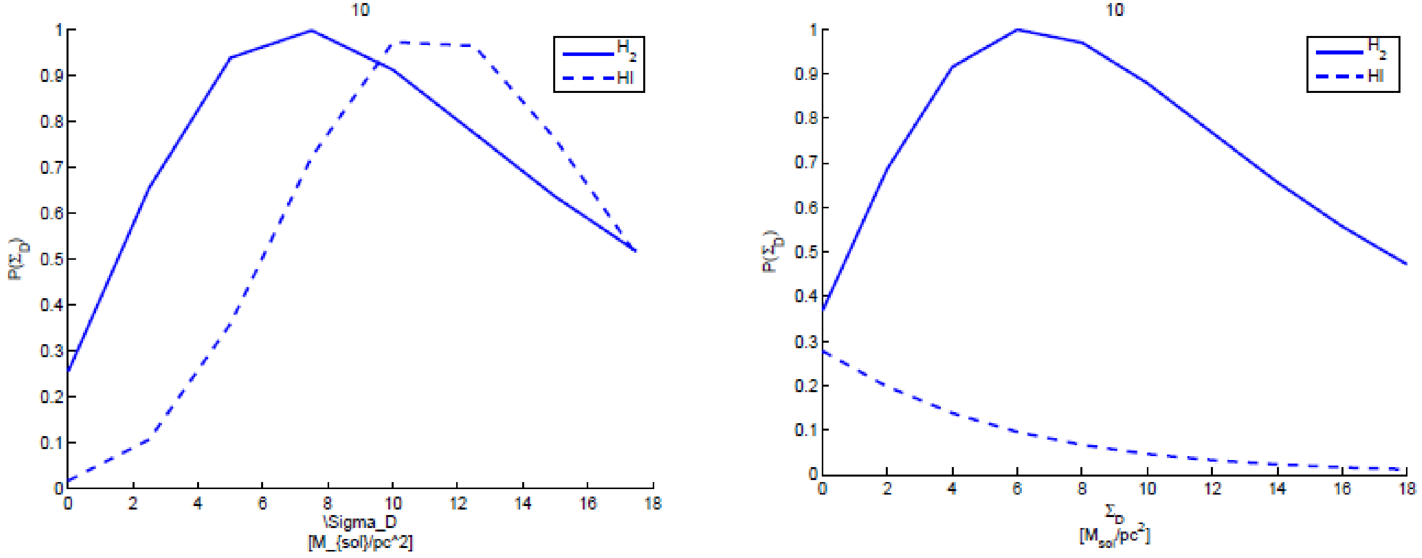
Table 2: The Bahcall model used by HF2000. The Σ_i were calculated by HF2000 from the solution to the Poisson-Jeans equation, except for the gas components, where the midplane densities were chosen to give the known the Σ_i.

i	Description	$\rho_i(0)$ ($M_{\odot}$pc^{-3})	σ_i (km s^{-2})	Σ_i ($M_{\odot}$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.

Gas midplane, surface, eg

Figure 6:



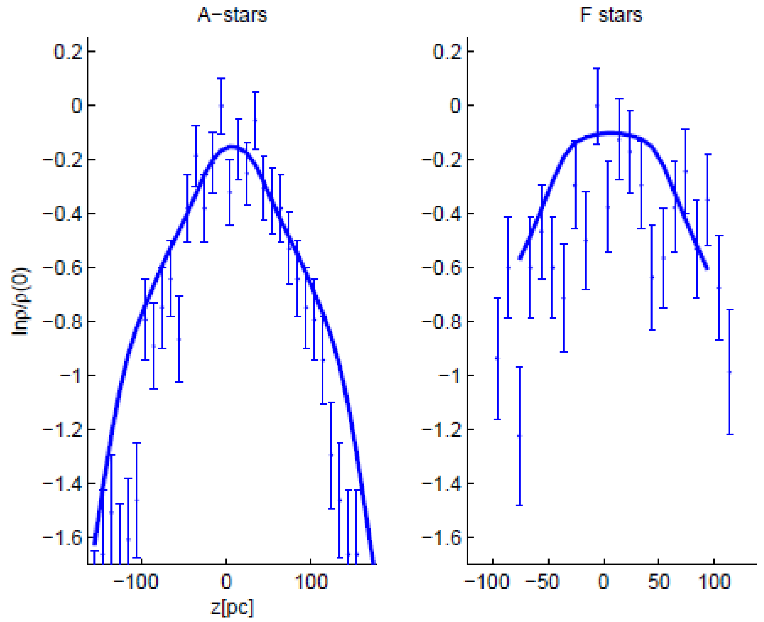


Figure 2: *The HF2000 study. The HF2000 model with no disk dark matter agrees quite well with the A and F star data.*

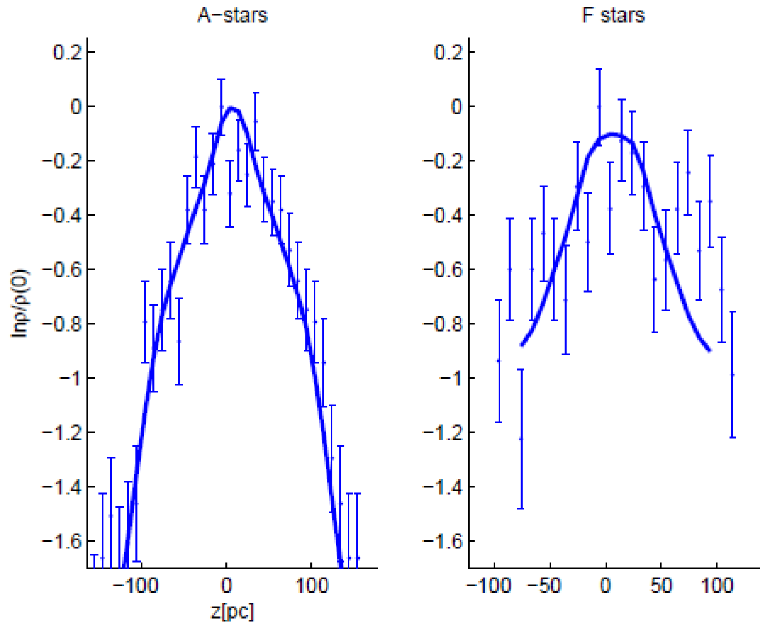
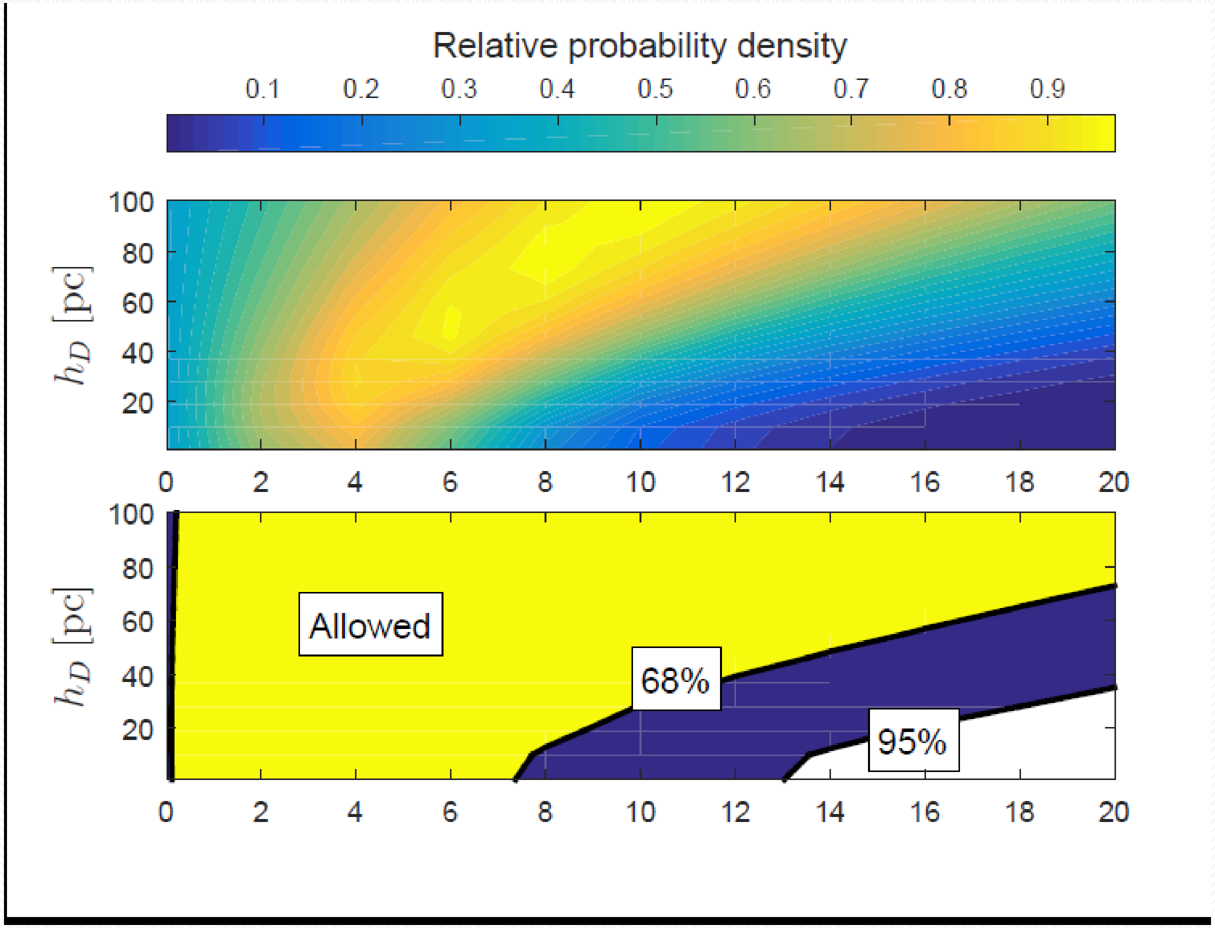


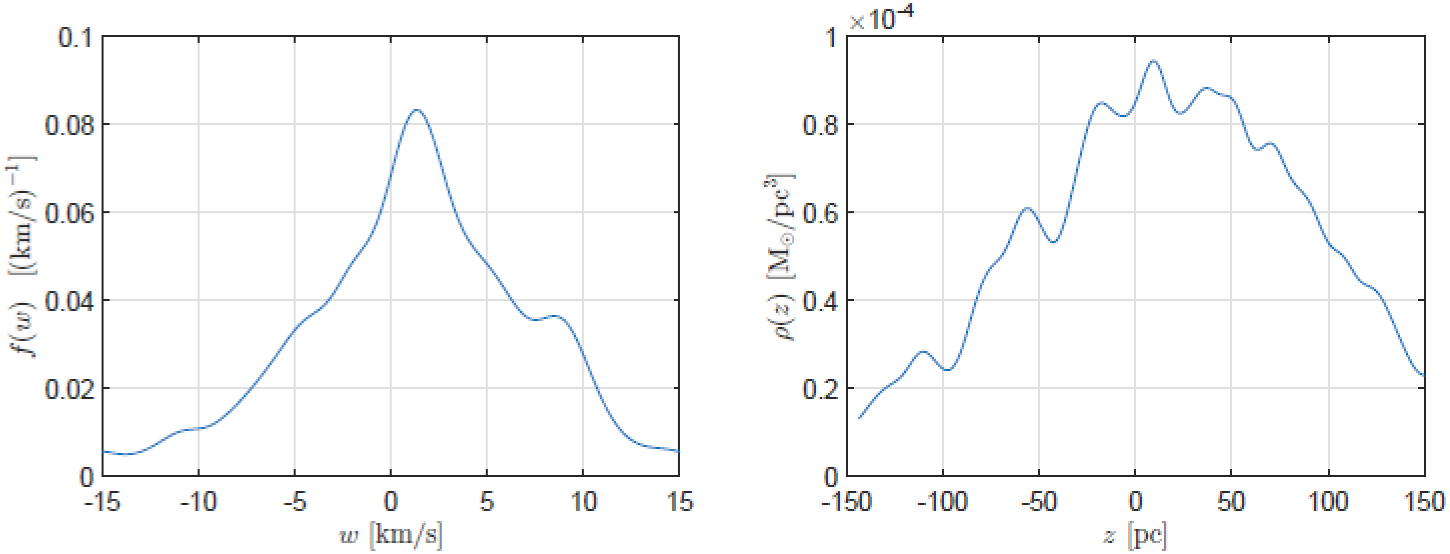
Figure 3: *The HF2000 result, this time including a dark disk with* $\Sigma_D = 10\, M_\odot \mathrm{pc}^{-2}$ *and* $h_D = 10$ *pc. We see that this model also agrees quite well with the A and F star data.*

Kinematics Results

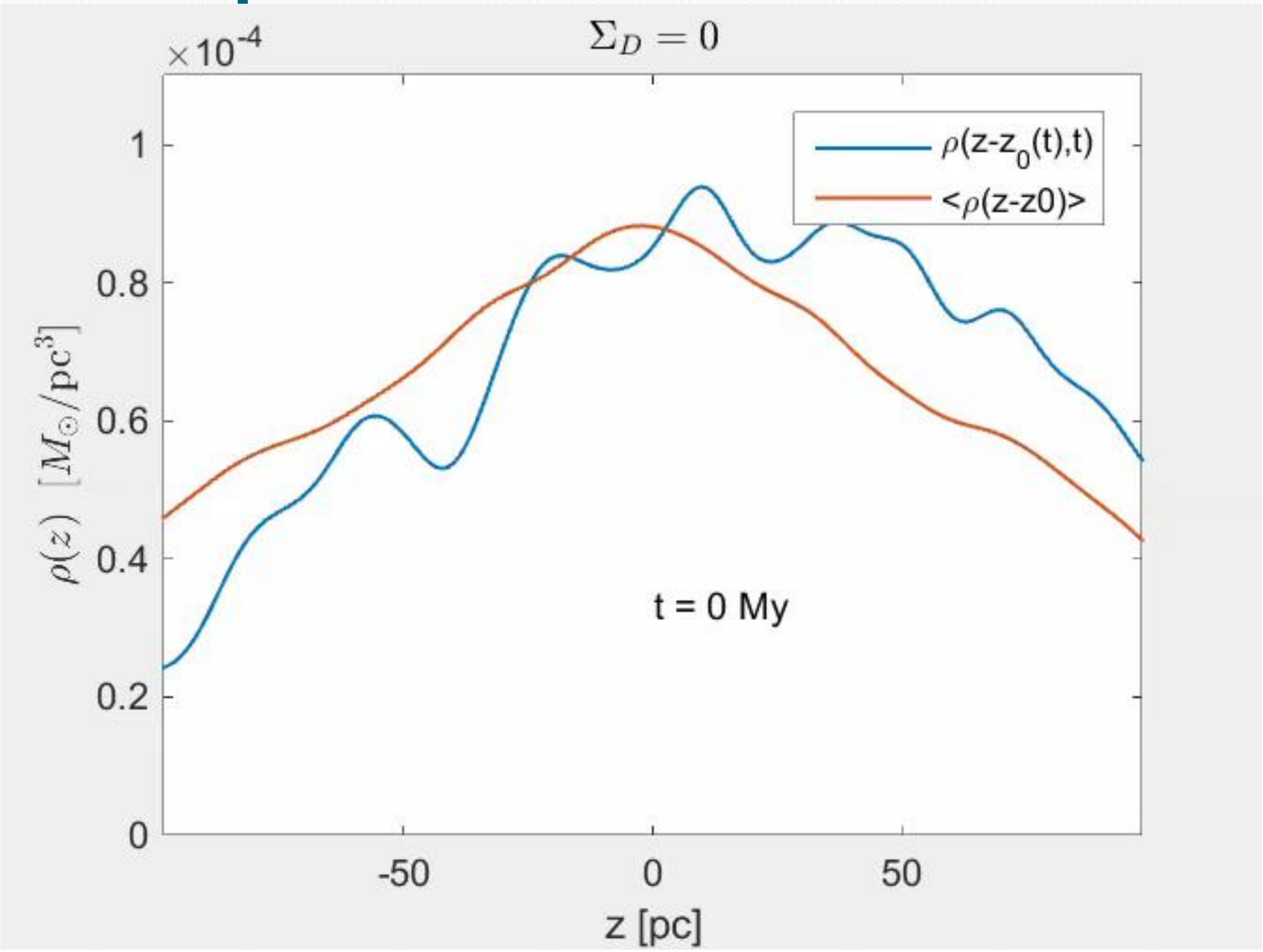


Static: Compared to potential

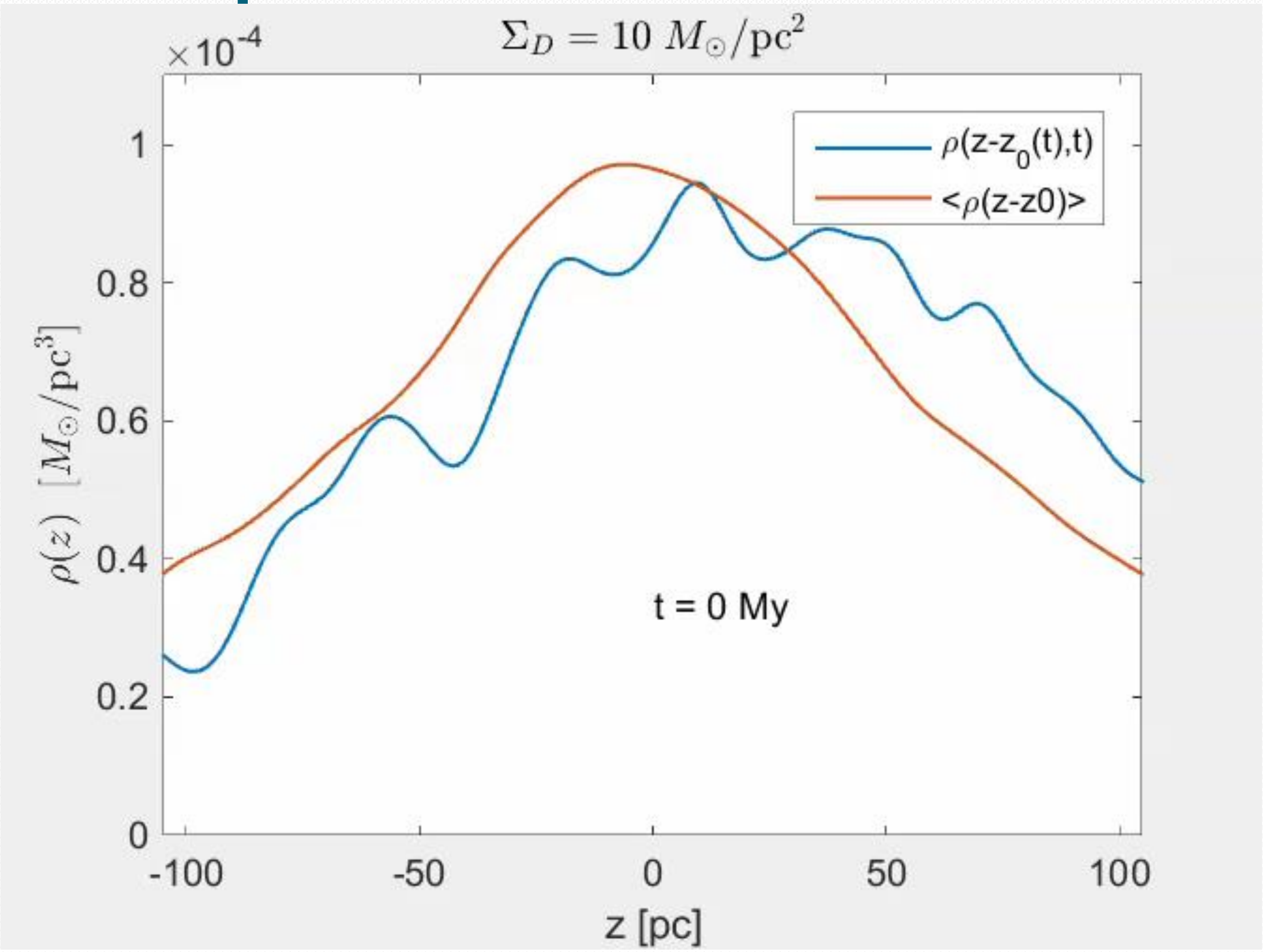
Figure 6: *(Left) The A-star velocity distribution possesses a peak value of* 1.3 ± 0.3 *km/s. (Right) The A-star density distribution has a non-zero central value of* 33 ± 5 *pc relative to the galactic plane, assuming a value for the solar position of* $Z_0 = 26$ *pc.*



Time dependence with no disk

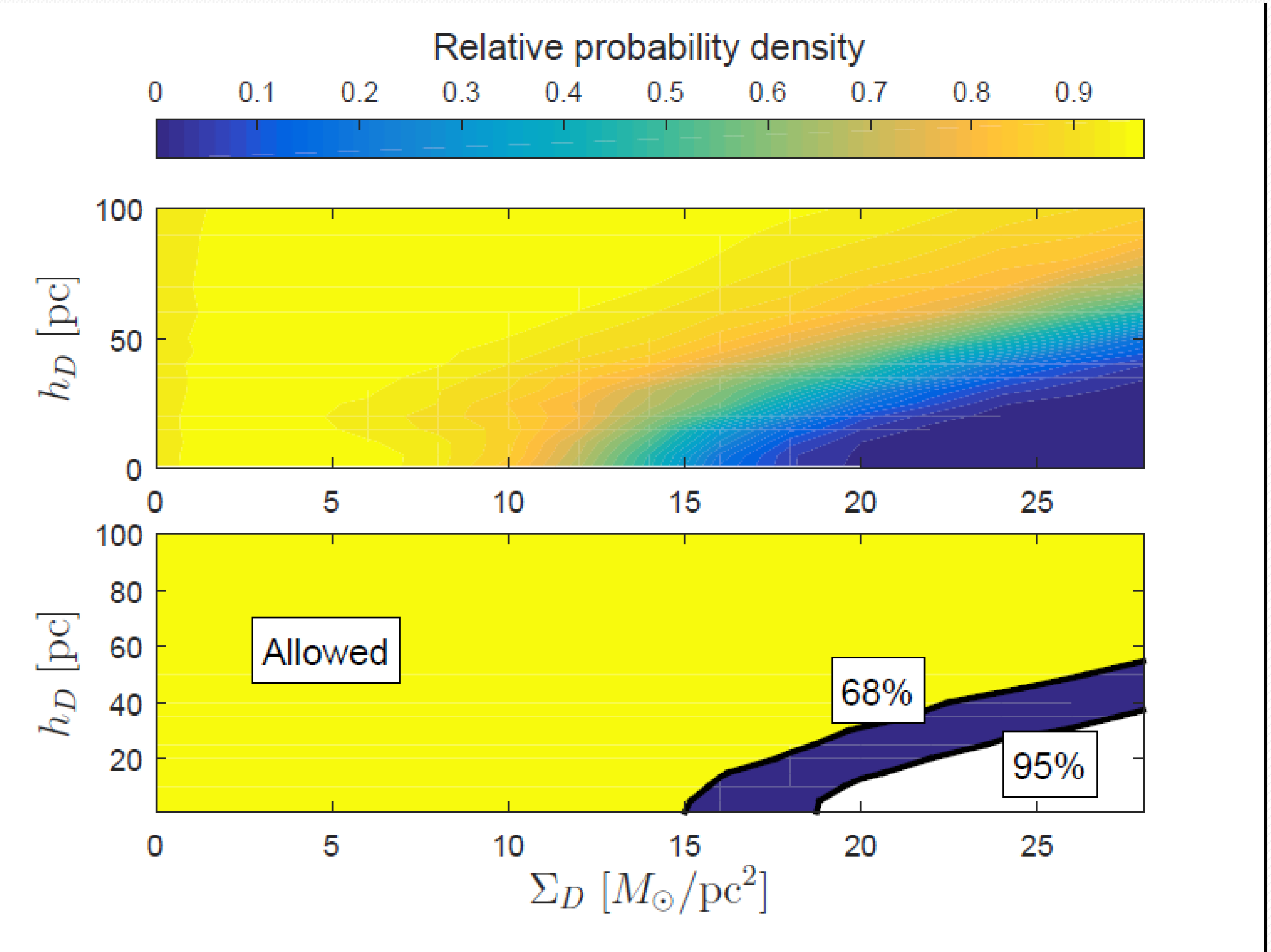


Time dependence with disk



Result

- Time average automatically agrees with potential
- Cut can compare current distribution to time average



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

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

Dark Matter in Disk

Two advantages:

1) Dark matter in disk
2) Dark matter has low velocity, more readily bound

$$\Sigma_{dm} = 10^7 M_\odot/\mathrm{kpc}^2$$
$$\Sigma_{bar} = 5 \times 10^7 M_\odot/\mathrm{kpc}^2$$
$$h_b = 0.3\mathrm{kpc}$$

$$\rho_b = \frac{\Sigma_b(R)}{2z_b} \exp\left(-\frac{|z|}{z_b}\right)$$
$$\rho_{dm} = \frac{\Sigma_{dm}(R)}{2z_{dm}} \exp\left(-\frac{|z|}{z_{dm}}\right)$$

$$h_{dm}/\mathrm{kpc} \in \{0.01, 0.02, 0.03, 0.04, 0.05, 0.06\}$$
$$x/\mathrm{kpc} \in \{0.3, 0.4, 0.5, 0.6, 0.8, 1.0\}$$

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

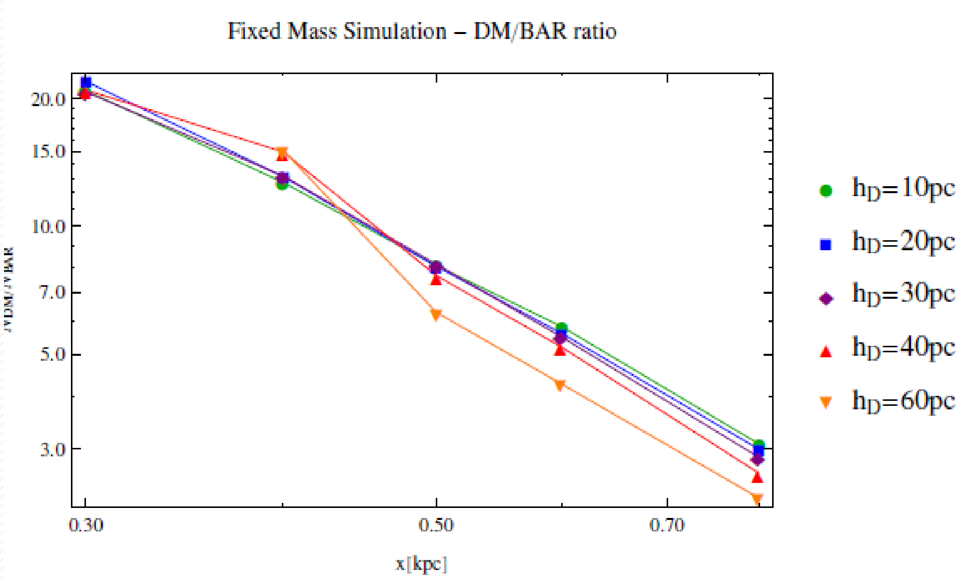


Figure 9: Dependence of the final DM to baryon ratio on the size of the initial patch.

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

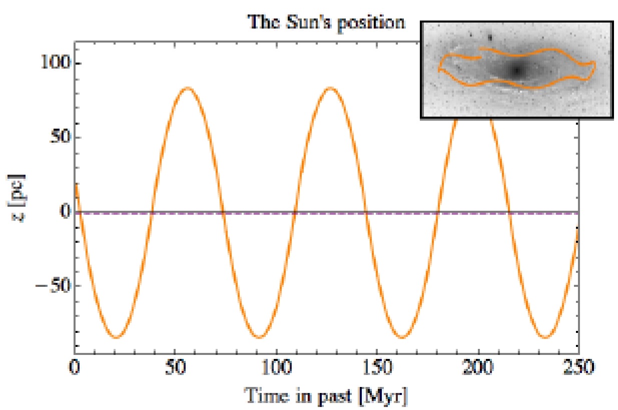


FIG. 1. The Sun's height above the galactic plane as a function of time, extrapolated backward via Eq. 2. The corresponding cratering probability is shown in Fig. 3. Inset: an illustration of how the Sun moves around the galactic center while also oscillating vertically; the vertical oscillation is exaggerated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

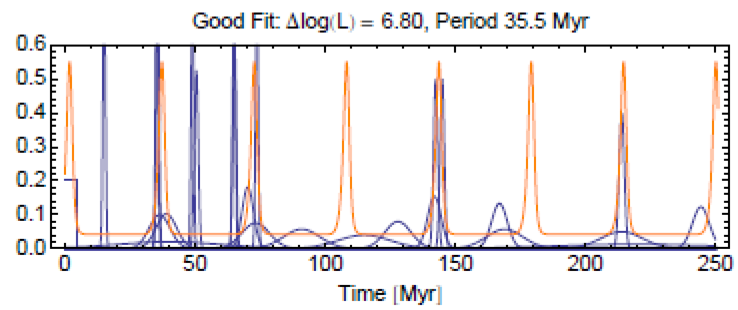


FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\text{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\text{pc}^2$. The local dark halo density is 0.037 GeV/cm^3. $Z_\odot = 20$ pc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

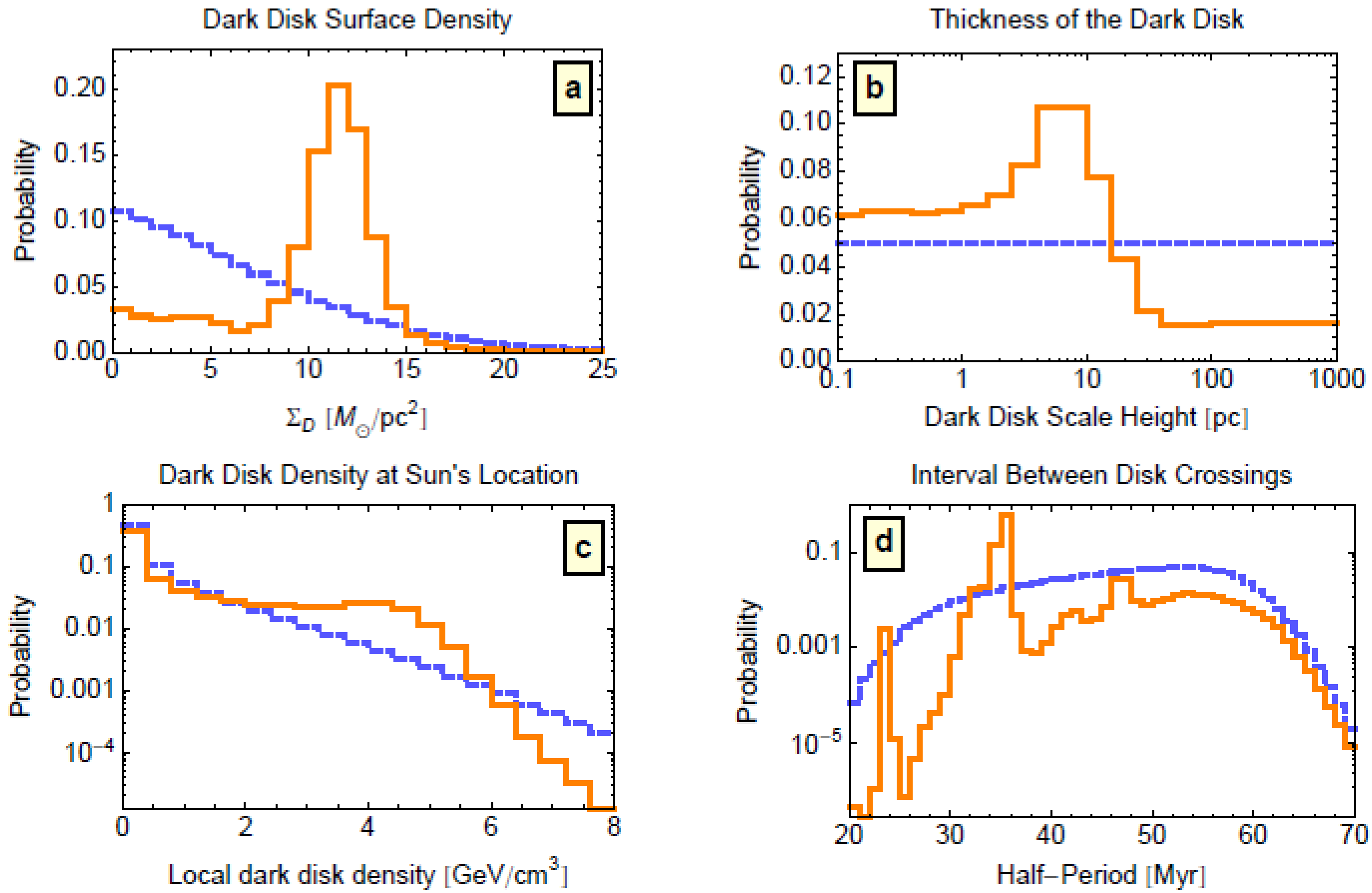


Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits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

For Future

- Clearly 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
- 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