New Ideas About Dark Matter
MIT CTP 50

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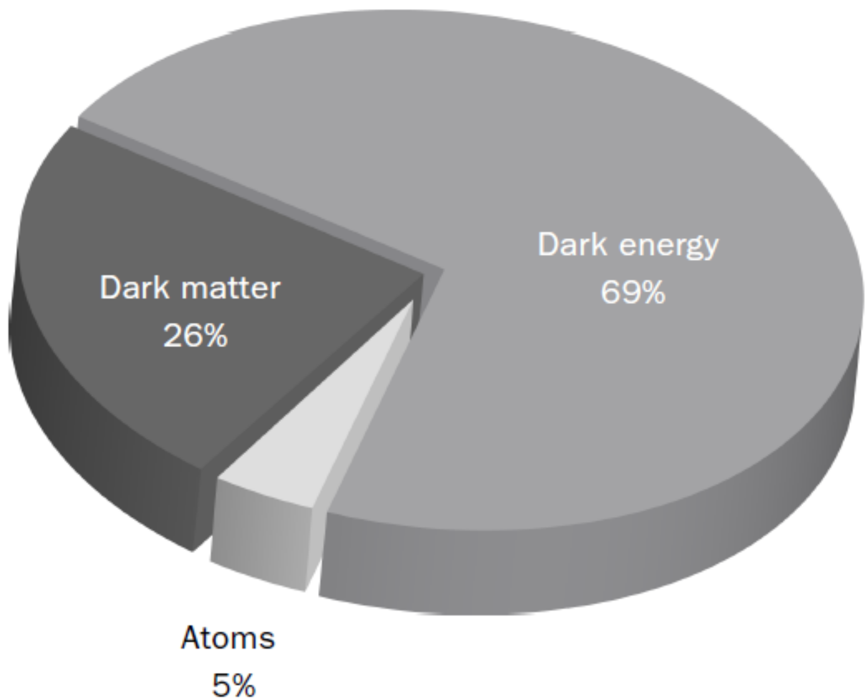
A Few Decades....

- 50 years CTP
  - 16.5 years ago for me
- What has changed?
  - Higgs found
    - Strong interactions, Supersymmetry, Extra Dim not YET
  - Dark Matter
    - Increasingly strong evidence
    - But
      - Much more sensitive WIMP searches—nothing
      - Much better astronomical studies
      - Growing awareness of other possible models
  - Gravity Waves, Black Holes
    - Hybrid Inflation and Black Holes
    - Nuclear Colloquium

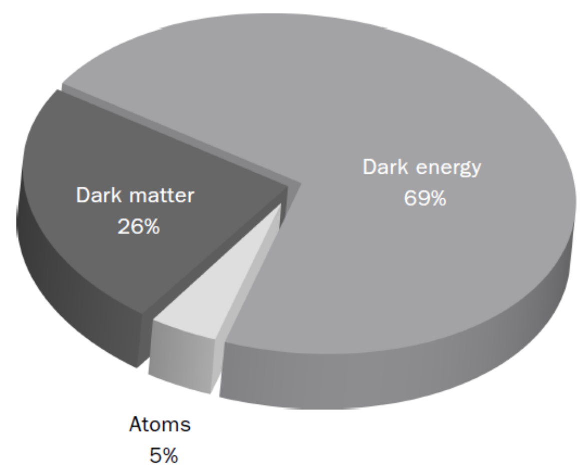
FOCUS TODAY ON DARK MATTER—PERCHED ON DISCOVERY?

MAKEUP OF UNIVERSE



Dark Matter

- Currently outstanding cosmological model
- But… leaves critical questions unanswered
  - Nature of most of the matter and energy in the Universe
- Actually not too surprising
  - We have only limited measuring tools
  - If something interacts only gravitationally we literally can't see it



How do we “see” (so far)

- Galactic rotation curves
- Galaxy clusters virial velocities
- Gravitational lensing
- Bullet cluster and others
- Supernovae
- Cosmic microwave background structure
- Existence of galaxies in lifetime of Universe
- Existence of galaxies on scale of Milky Way

- There is a lot of evidence
- And it’s all consistent
- Basically how any new phenomenon or thing established

What Is Dark Matter?

- Some form of matter
  - But is it a particle?
  - What is its mass?
  - What are interactions/charges
  - Is it just one type of particle
- We know only of gravitational interactions
  - No other discernible interactions (yet)
- Existence not necessarily so mysterious
- But makeup of the matter still is

Nature Dark Matter?

- 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?
- No promises
- Opportunity to consider new ideas
- Won't argue that any single idea has to be correct
  - In fact we should never have done that
- But will introduce possibilities
- And consider potential implications

- But how to find what it is?
  - Look under the lamppost
  - Find theoretical, experimental clues
- We need to consider all possibilities

WIMPs

- Until recently most "popular" candidate
- Weakly Interacting Massive Particle
- Merits
  - Occurs in extensions of the Standard Model
  - Testable because not only gravitational connection

WIMPS

- Demerits
  - Not seen
  - BSM not seen
  - Overhyped—other possibilities
- Searches to date always based on optimistic assumptions
  - Dark matter does interact with our matter at some level
  - WIMP “standard” paradigm
- But So Far
  - No direct detection
  - No indirect detection
  - LHC hasn’t shown any sign of new weak scale physics

Today

- Nature of dark matter remains a mystery
  - No sign of WIMPs
  - Sparse sign of new weak-scale physics
    - Perhaps signs of deviations in small-scale structure
- Some new model-building ideas
- If not WIMPs, best tests probably involve detailed structure
- Critical to find implications of models
- More generally understand models, and how to integrate into a bigger picture

Other interesting possibilities?

- Surprisingly, relatively unexplored option:
- Interacting dark matter; charged even!
- Thought Unlikely
  - Ellipticity of halos
  - Bullet Cluster type constraints
  - Survival of dwarf galaxies in halos (lack of evaporation)
- Seemed to significantly impinge on parameter space
- But many incorrect assumptions, analyses

Example: Ellipticity as function of radius

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

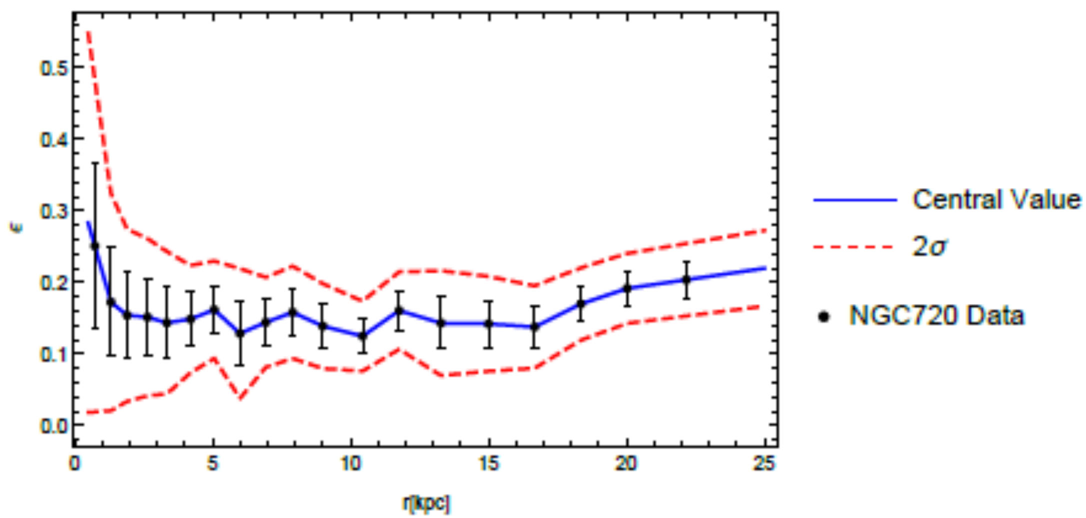
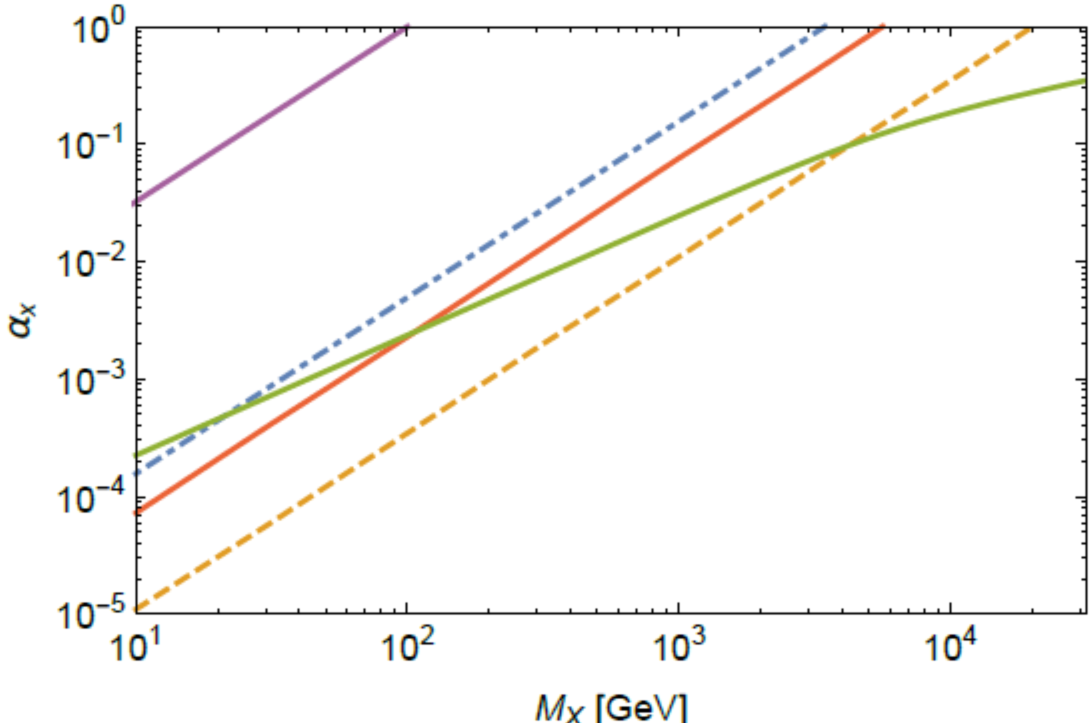


Figure 1: Ellipticity of the NGC720 potential as measured by [48]. The black data points show the results of [48] with 1σ error bars. The blue curve is our interpolation of their central values, while the 2σ error bands are in red.

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?

Our Result



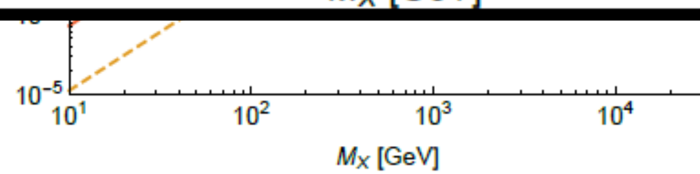


Figure 3: Constraints on the Charged Dark Matter parameter space in the $M_X - \alpha_X$ plane. The ellipticity constraints (discussed in section 3.1) are presented as two curves: the original Ref. [8] calculation [dashed yellow], the full calculation that includes the radius dependent constraints on 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

Darkly-Charged Dark Matter

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

New Regime of Interactions Duality—and new tests

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

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

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,

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

Another possibility: only a **fraction** interacts? Partially Interacting Dark Matter: **PIDM**

- Rather than assume all dark matter
- Assume it's only a fraction (maybe like baryons?)
- Fraction changes all constraints
- 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
- Lots of important implications for measurements

Partially Interacting Dark Matter

- Dark matter with its own force
  - Rather than assume all dark matter
  - Assume it's only a fraction –like baryons…
- 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 *componen*t of dark matter
- Introduces dissipative mechanism
  - Can lead to disks, pointlike sources

Dissipative Fraction

- Generates structure
  - Easier to detect
- Significant consequences
  - 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

Could interacting dark matter cool? Into a Dark Disk?

- To generate a disk, cooling required
- Baryons cool because electrons radiate and interact
  - 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: “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)
- 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
- Probably have both thermal and nonthermal components

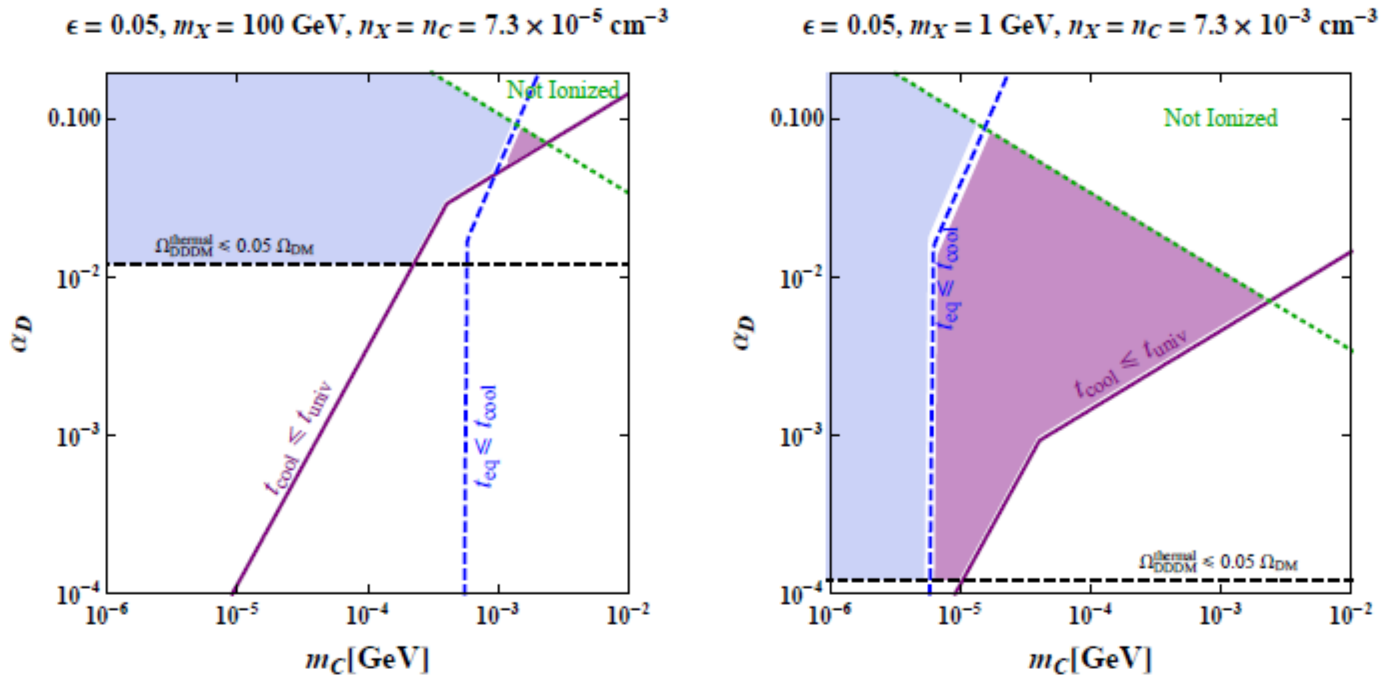


Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the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

Traditional (WIMPy) Methods

- Smaller direct detection, small velocity
  - Possibly other noncanonical possibilities
  - If found, different energy distribution, time depce
- Indirect detection
  - Possible if mediation between visible, invisible sectors
  - If found, dfferent spatial distribution

Distinctive Shape to Signal

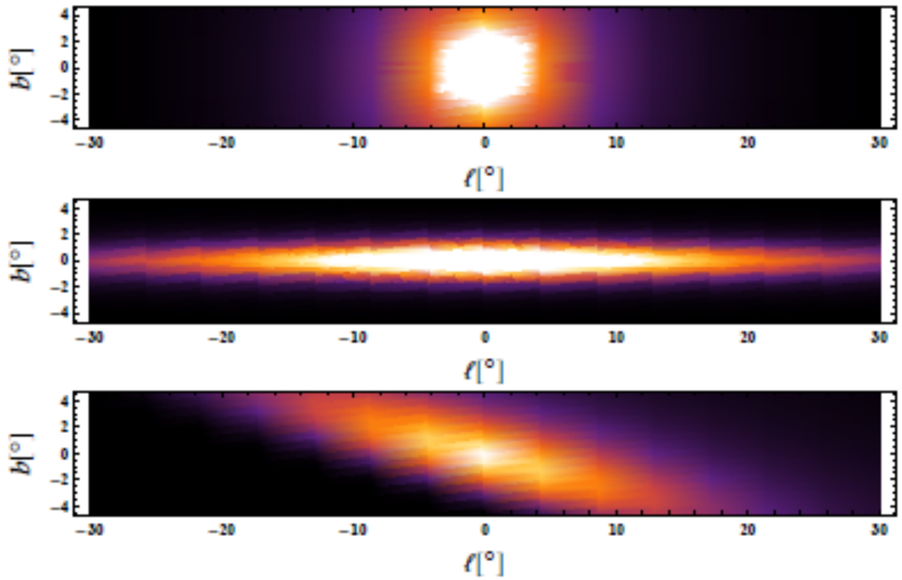


FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology

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(Dated: October 15, 2013)

Also new acoustic peak

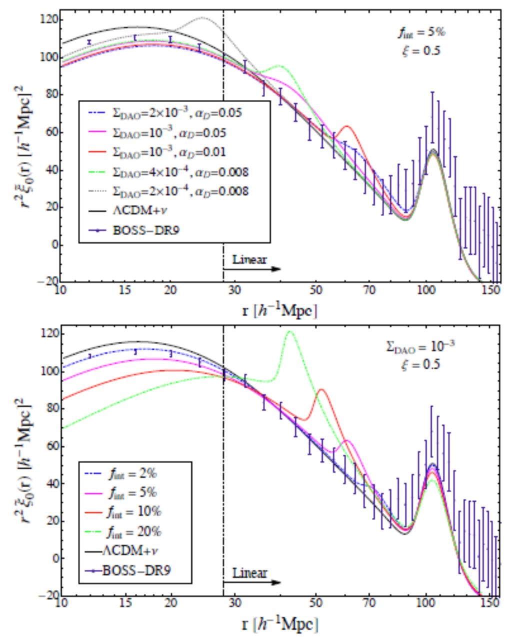

FIG. 2: Angle averaged galaxy correlation function $\tilde{\xi}_0(r)$ for different PIDM models. In the upper panel, we take $f_{\rm int} = 5\%$, $\xi = 0.5$ and vary $\Sigma_{\rm DAO}$ and α_D. In the lower panel, we fix $\Sigma_{\rm DAO} = 10^{-3}$, $\alpha_D = 0.01$ and $\xi = 0.5$, but let the fraction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

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
  - 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

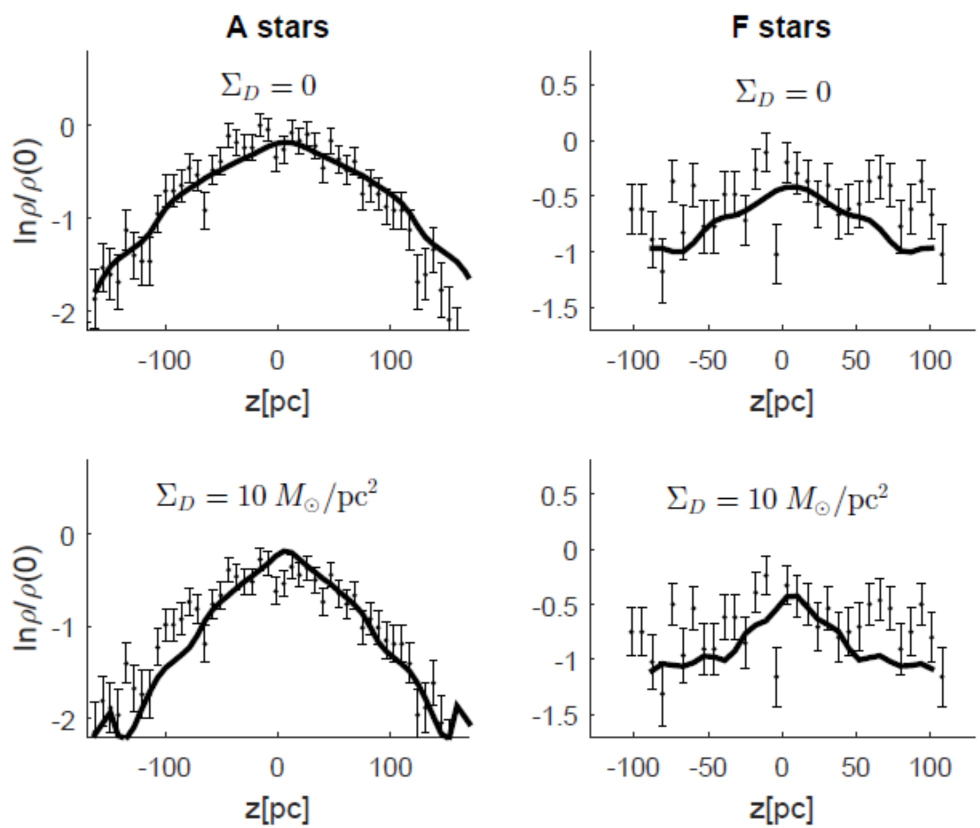

Fig. 2.— (Top) The HF2000 study. The HF2000 model with no disk dark matter agrees quite well with the A and F star data. (Bottom) The HF2000 result, this time including a dark disk with $\Sigma_D = 10\ M_\odot \mathrm{pc}^{-2}$ and $h_D = 10$ pc. We see that this model also may agree with the A and F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

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

But another theoretical lamppost?

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

Satellites of Andromeda Galaxy

w/Scholtz

- 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

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

Motion of Sun; Density Solar System Encounters

3

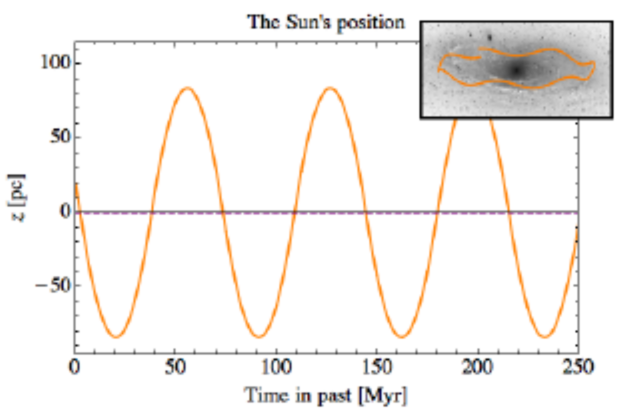

FIG. 1. The Sun's height above the galactic plane as a function of time, extrapolated backward via Eq. 2. The corresponding cratering probability is shown in Fig. 3. Inset: an illustration of how the Sun moves around the galactic center while also oscillating vertically; the vertical oscillation is exaggerated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

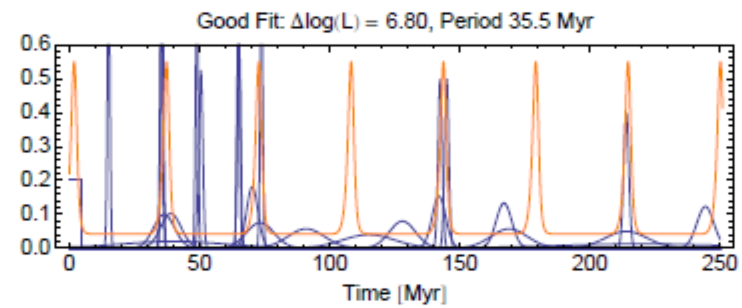

FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\mathrm{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\mathrm{pc}^2$. The local dark halo density is 0.037 $\mathrm{GeV/cm}^3$. $Z_\odot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

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pc

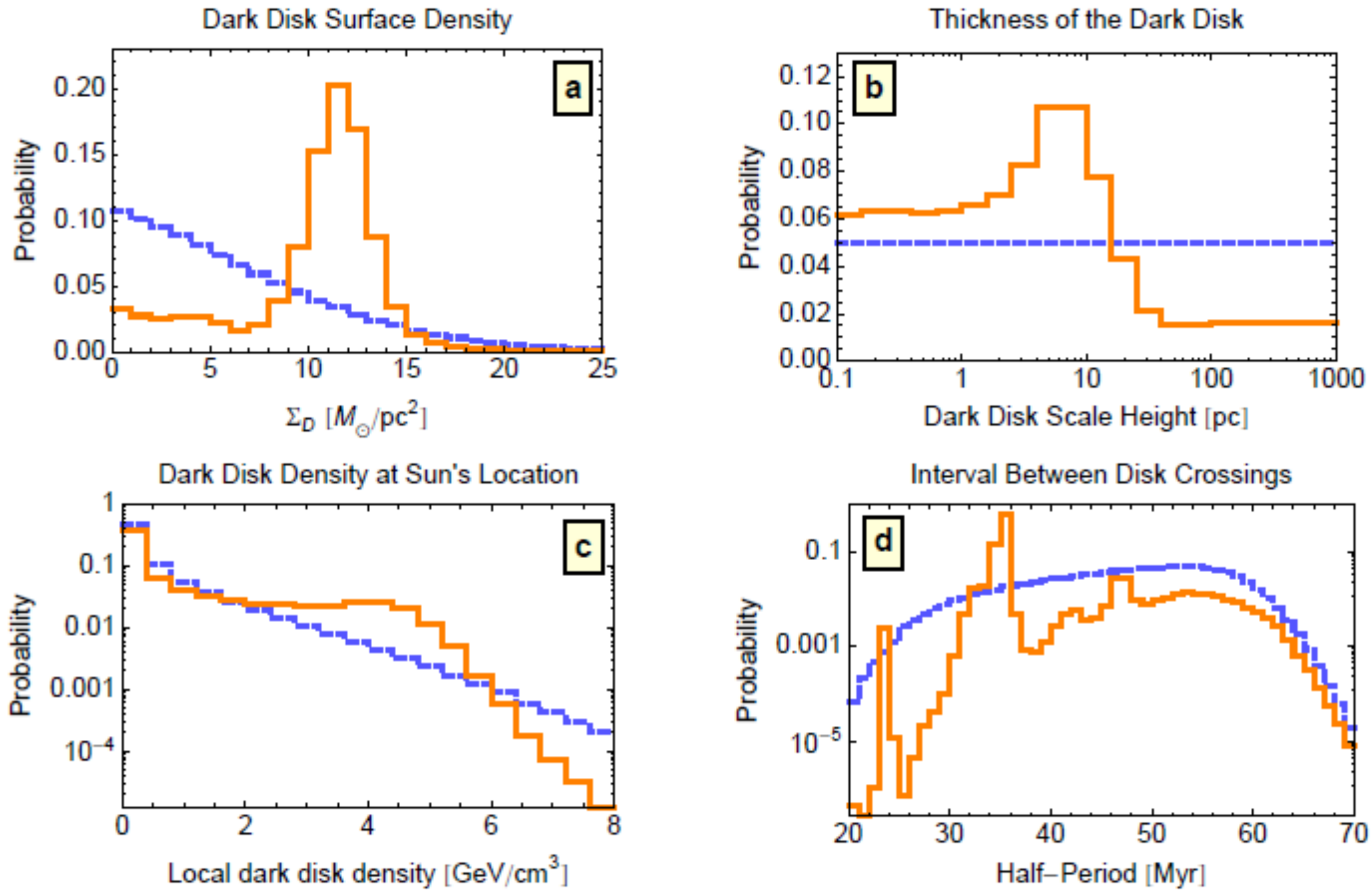

Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits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

- Clearly a big program
- Dark matter charged is clearly a possibility
- Many implications
- But can sometimes be more elusive or subtle than anticipated
  - Initial condition dependence
- We are beginning to get tremendous data
- Let’s find out what it means