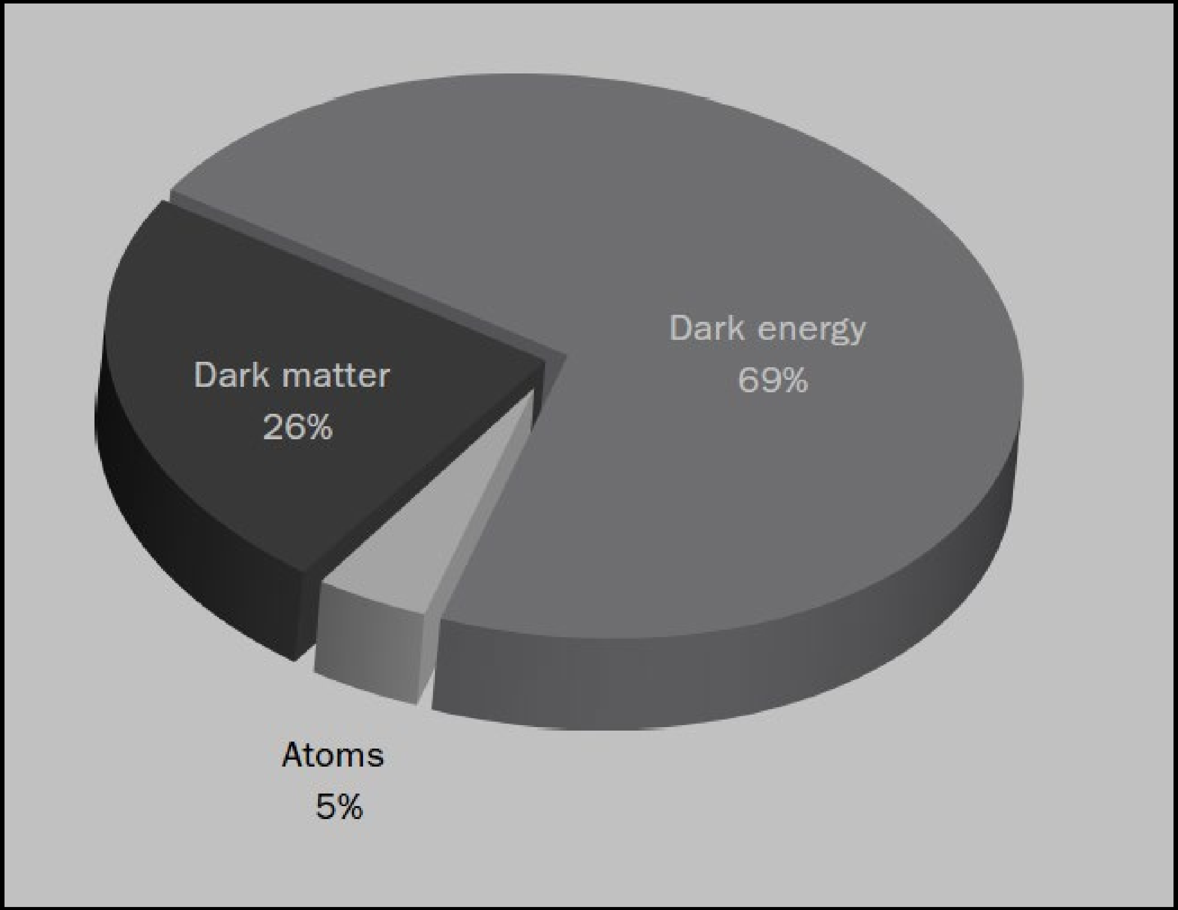
Darkly Charged Dark Matter

Lisa Randall Harvard University

Feynman100

MAKEUP OF OUR UNIVERSE



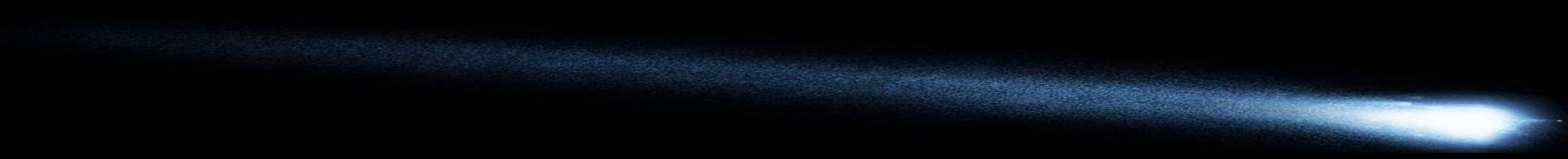
Dark Matter

- D: Dark Matter: Matter that interacts via gravity
  - But has very little (if any) other interactions
  - Certainly very little Standard Model interactions
- Not surprising that it should exist!
- Billions of dark matter particles pass through you every second
- You don't see them
- Nonetheless gave shape to the Universe

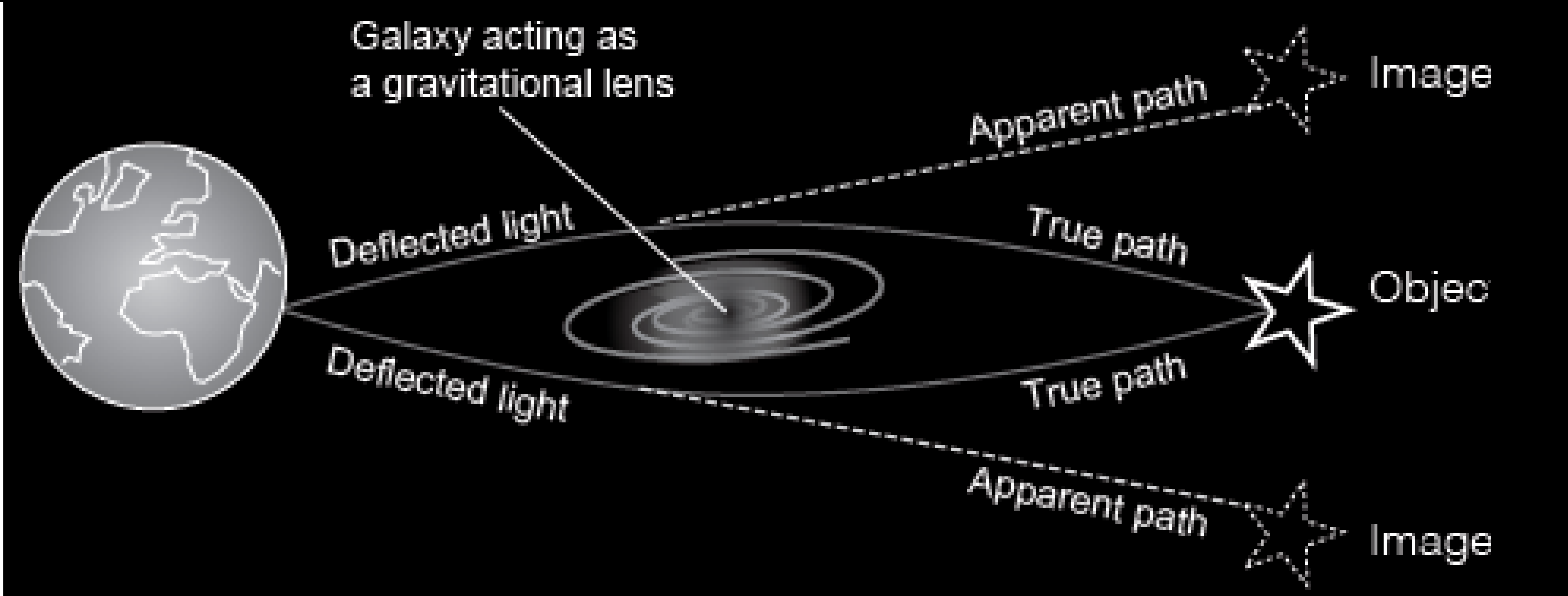
How do we “see” (so far)

- 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

DARK MATTER

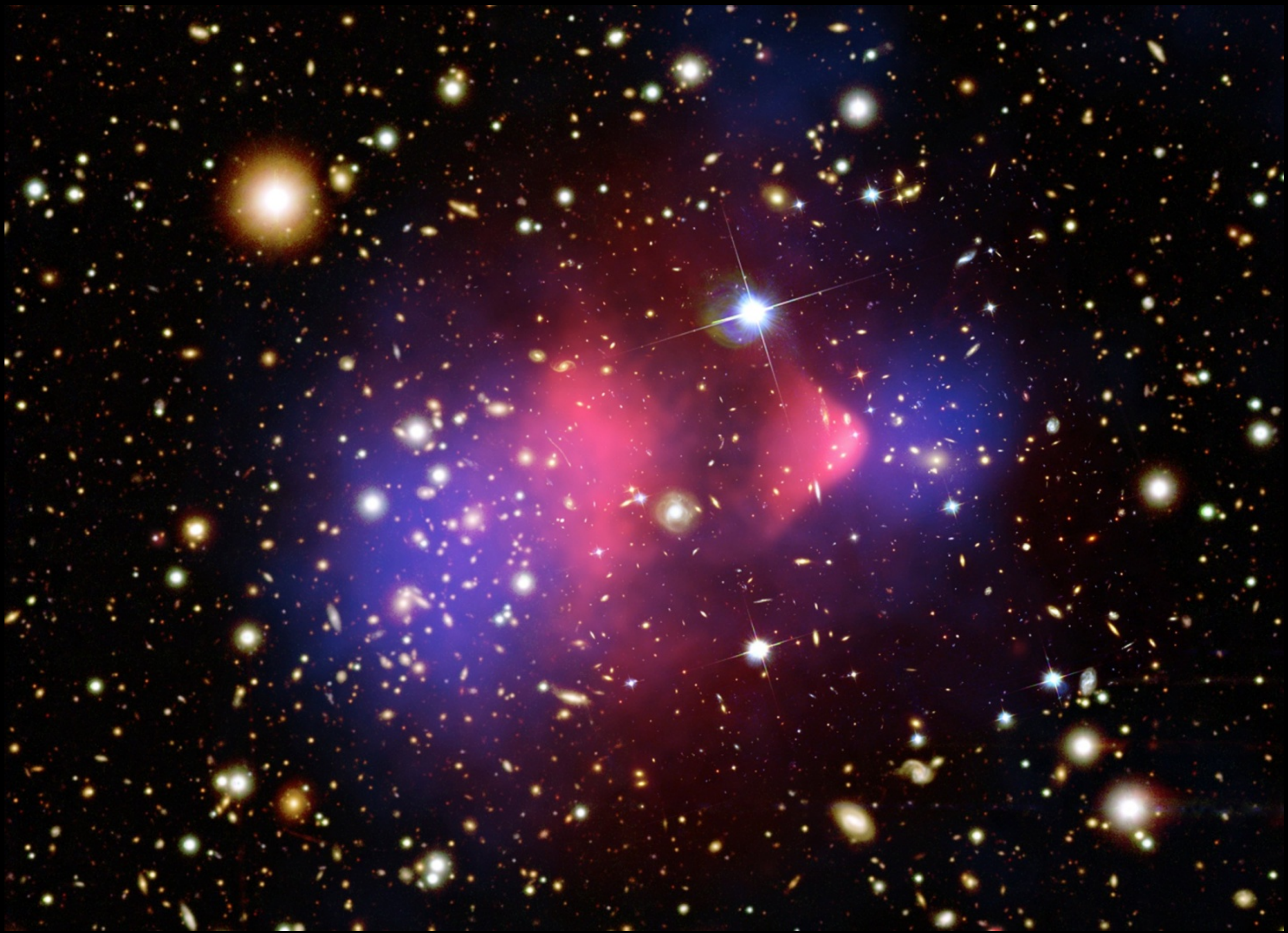


We (literally) don't see it. But we do see its influence



BULLET CLUSTER

Strong evidence for dark matter



Not Speculation

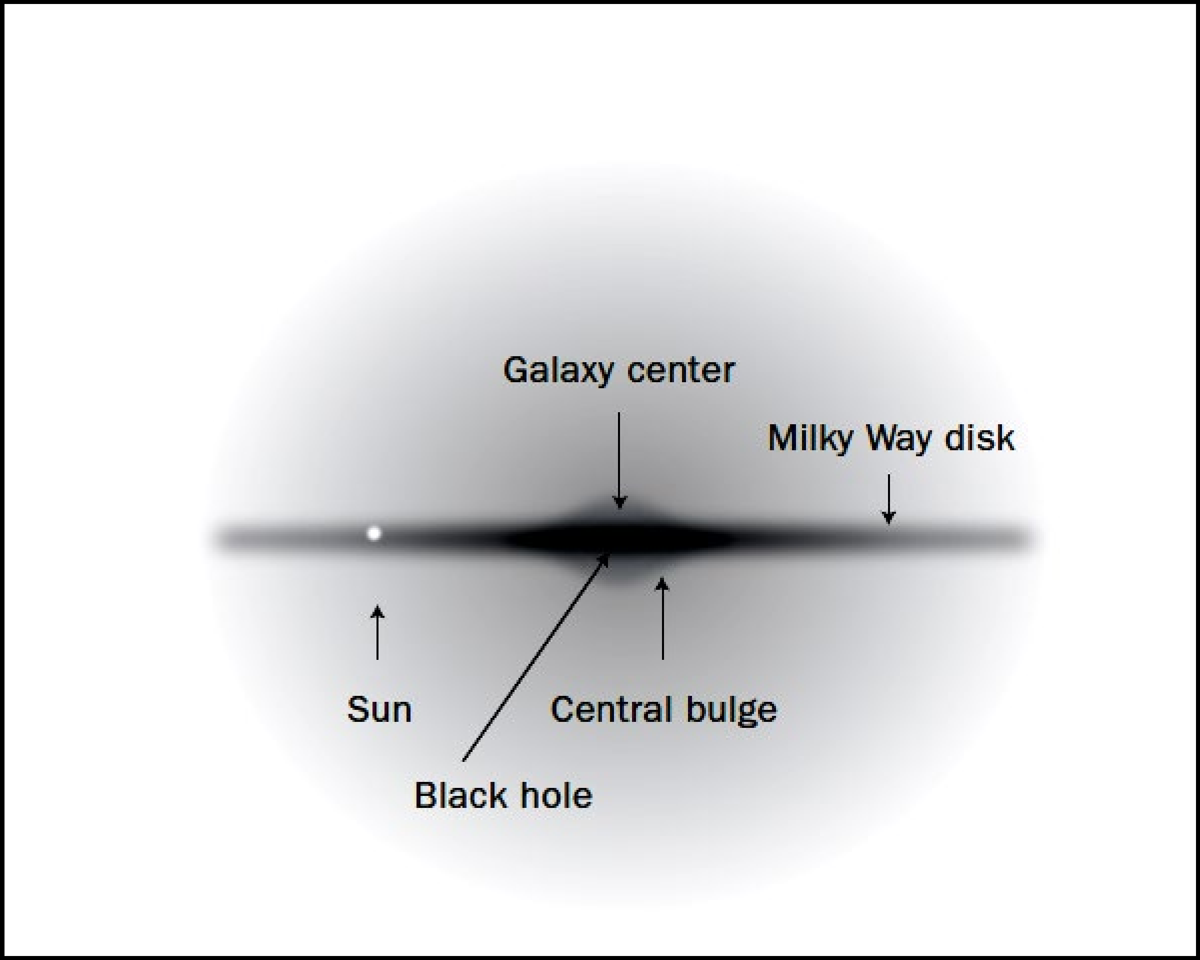
We know dark matter exists

Don’t see it with our eyes

Do observe gravitational influences

HALO AND DISK

Spherical halo, Disk of ordinary matter



Motivation for DM Research

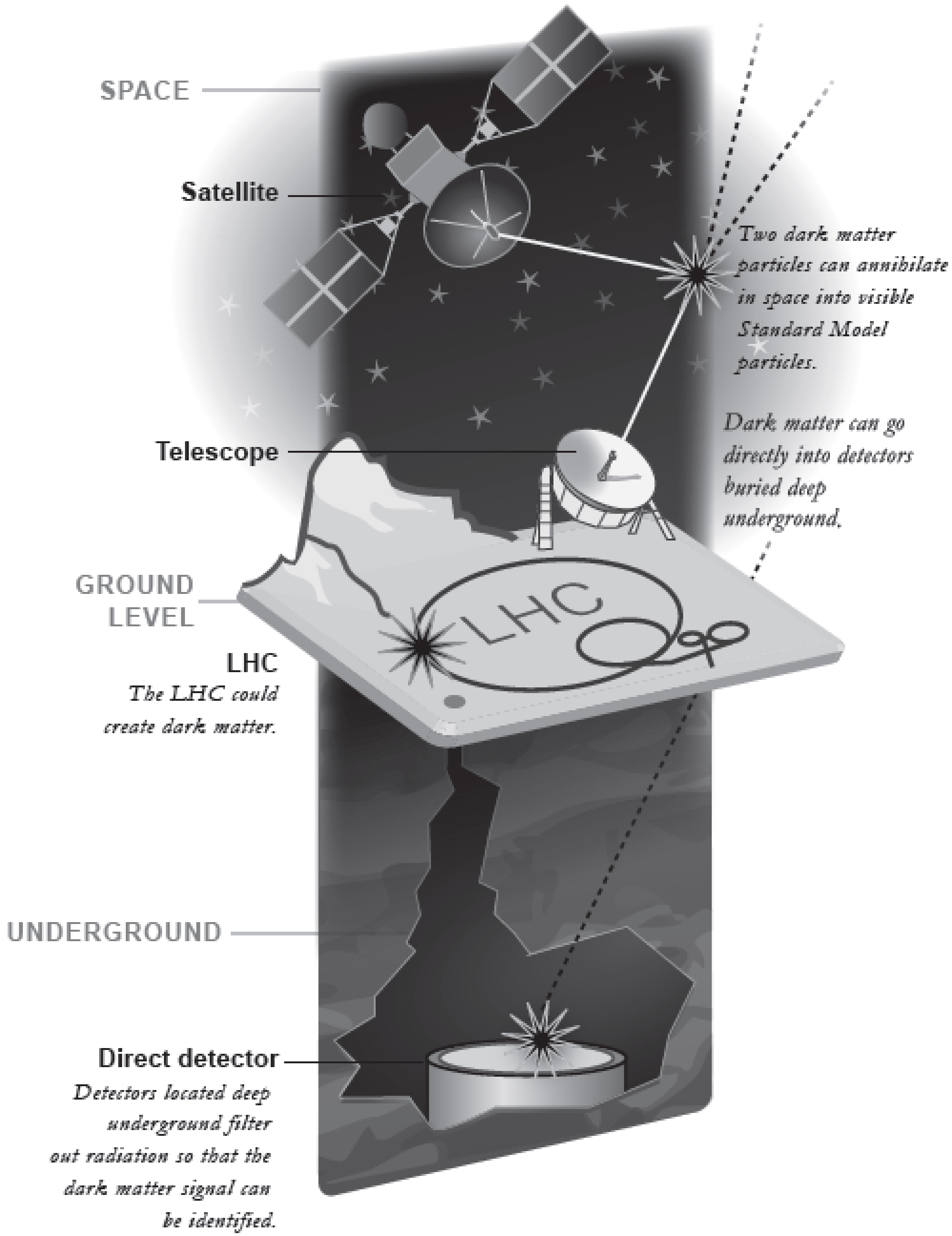
- We know dark matter exists
  - Many observations of its gravitational influences
- But we don't know at a fundamental level what it is
  - Is it a particle?
  - If so what is it
    - What is its mass
    - Does it interact (nongravitationally) with SM
    - Does it interact with itself
    - Is it a single particle?

Model Building

- Want to think about options
- Model Building: Characterizing possibilities
  - New ways of thinking
  - New possible tests

WIMPs
Weakly Interacting Massive Particles

- Many people’s favorite candidate
- Idea is particle is connected to SM
- Mass almost same as Higgs boson
  - Gives correct energ density
- Advantage from experimental vantage point
- Many ways to look
  - But searches for dark matter really searches for WIMPs!


SPACE
Satellite
Two dark matter particles can annihilate in space into visible Standard Model particles.
Dark matter can go directly into detectors buried deep underground.
Telescope
GROUND LEVEL
LHC
LHC
The LHC could create dark matter.
UNDERGROUND
Direct detector
Detectors located deep underground filter out radiation so that the dark matter signal can be identified.

Other interesting possibilities?

- 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
- Surprisingly, relatively unexplored (but increasingly explored) option:
- **Interacting dark matter**
  - **But interacting with itself**
  - **Not with our matter**

Speculation:
Our Basic Insight

Why should normal matter be the only type that’s special

Copernican Revolution?

Maybe dark matter: not just one non-interacting particle

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
  - Dark light??

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

I: Darkly-Charged Dark Matter Model

Dark matter charged under its own “electromagnetism”

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

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

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

Why Dark Charges Disfavored ⇔"Constraints"

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

- Seemed to significantly impinge on parameter space

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

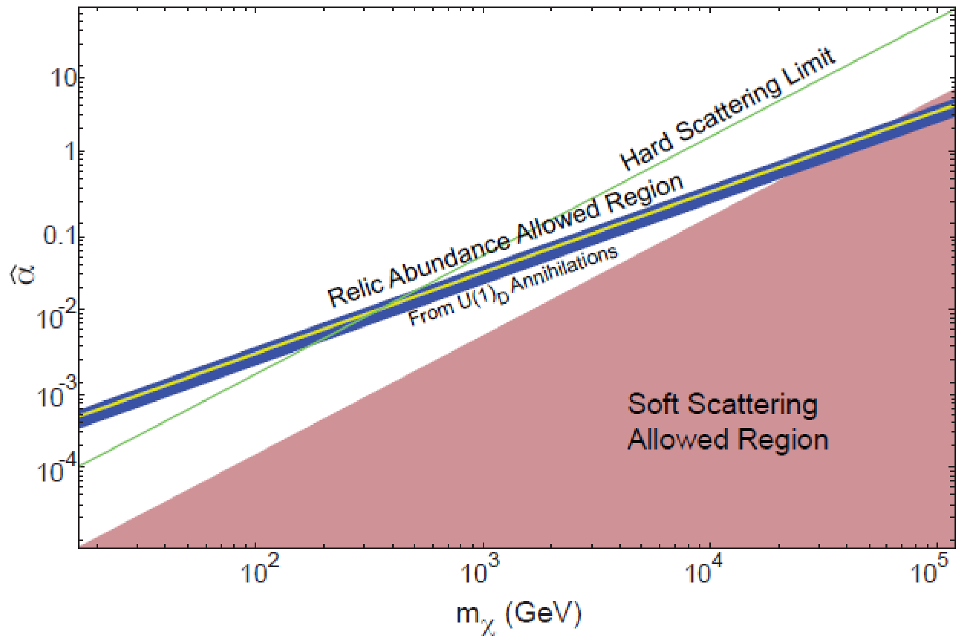

FIG. 3: The allowed regions of $\hat{\alpha}$ vs. m_χ parameter space. The relic abundance allowed region applies to models in which $U(1)_D$ is the only force coupled to the dark matter; in models where the DM is also weakly interacting, this provides only an upper limit on $\hat{\alpha}$. The thin yellow line is the allowed region from correct relic abundance assuming $\Omega_{\rm DM}h^2 = 0.106 \pm 0.08$, $\xi(T_{\rm RH}) = 1$, $g_{*{\rm vis}} \approx 100$, and $g_{\rm heavy} + g_{\rm light} = 5.5$ while the surrounding blue region is $g_{*{\rm vis}} = 228.75(60)$, $\xi(T_{\rm RH}) = 1(0.1)$, and $g_{\rm heavy} + g_{\rm light} = 100(5.5)$ at the lower(upper) edge. The diagonal green line is the upper limit on $\hat{\alpha}$ from effects of hard scattering on galactic dynamics; in the red region, even soft scatterings do not appreciably affect the DM dynamics. We consider this to be the allowed region of parameter space.

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

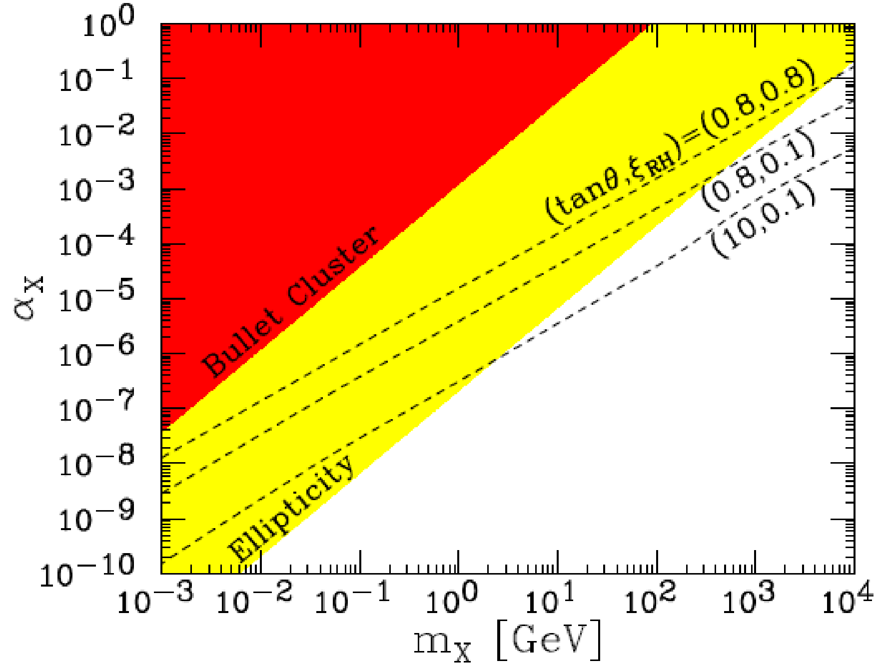

FIG. 1: Allowed regions in (m_X, α_X) plane, where m_X is the mass of the dark matter charged under the unbroken hidden sector $U(1)_{EM}$ with fine-structure constant α_X. Contours for fixed dark matter cosmological relic density consistent with WMAP results, $\Omega_X h^2 = 0.11$, are shown for $(\tan\theta_W^h, \xi_{RH}) = (\sqrt{3/5}, 0.8)$, $(\sqrt{3/5}, 0.1)$, $(10, 0.1)$ (dashed), from top to bottom, as indicated. The shaded regions are disfavored by constraints from the Bullet Cluster observations on self-interactions (dark red) and the observed ellipticity of galactic dark matter halos (light yellow). The Bullet Cluster and ellipticity constraints are derived in Secs. VIII and VII, respectively.

Previous results

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

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

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

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

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

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

But… details of calculation

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

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

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

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

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

Revisions: was wrong calculation

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

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

Ellipticity as function of radius

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

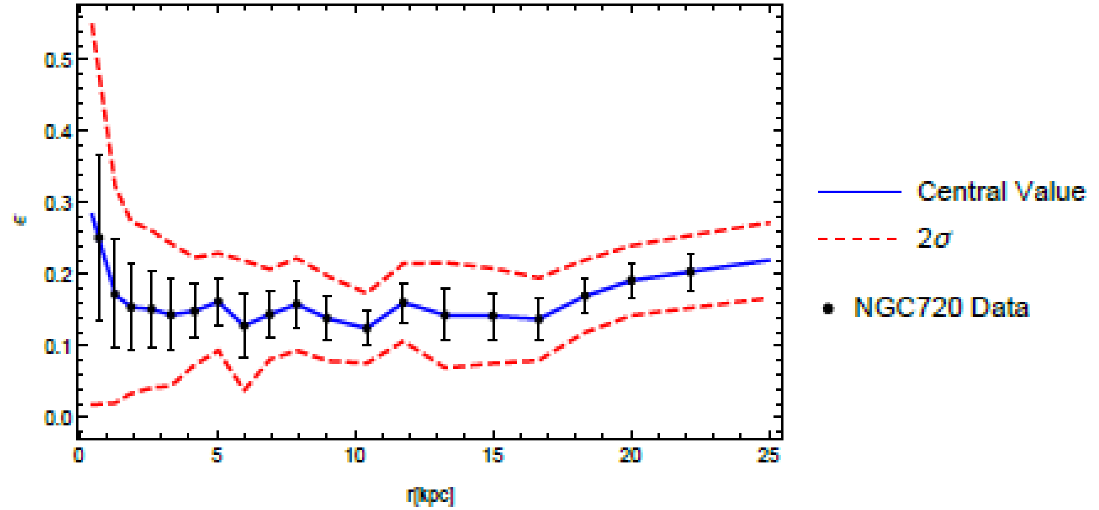

Figure 1: Ellipticity of the NGC720 potential as measured by [48]. The black data points show the results of [48] with 1σ error bars. The blue curve is our interpolation of their central values, while the 2σ error bands are in red.

Take into account saturation

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

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

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

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

Revisions: Not clear right target

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

Our Result

Ignoring last caveats
Just calculating time for
velocities to equilibrate

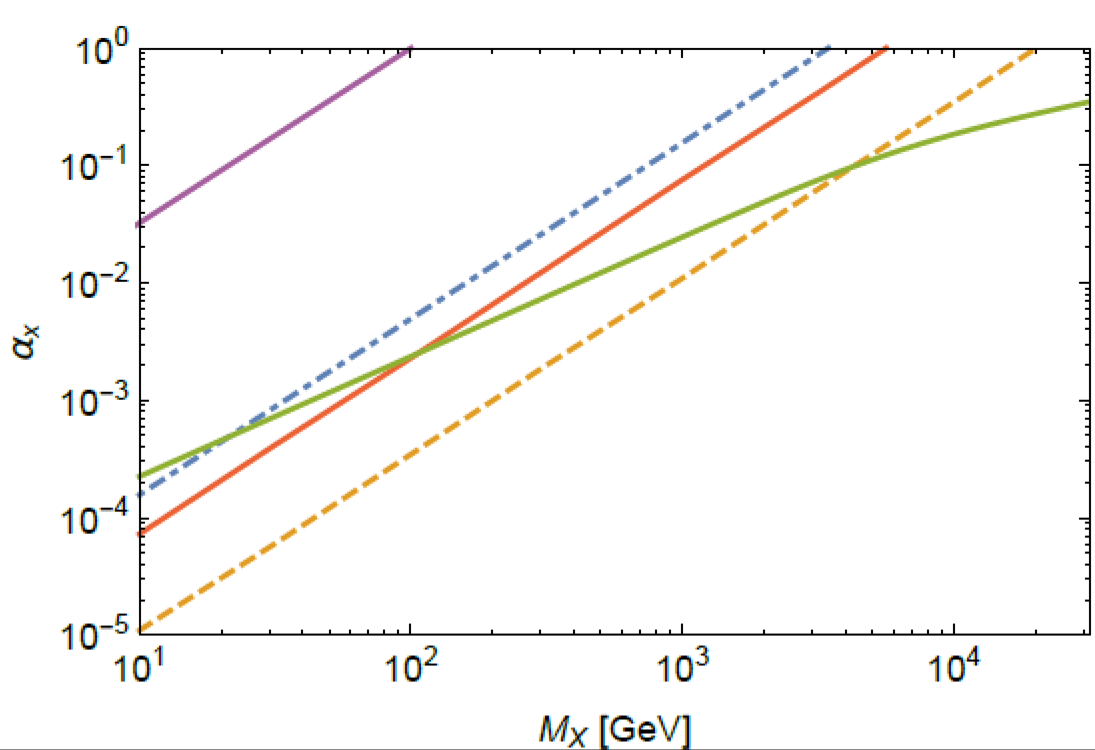

Figure 3: Constraints on the Charged Dark Matter parameter space in the $M_X - \alpha_X$ plane. The ellipticity constraints (discussed in section 3.1) are presented as two curves: the original Ref. [8] calculation [dashed yellow], the full calculation that includes the radius dependent constraints on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

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Other constraint: Dwarf Galaxy Survival

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

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

New Regime of Interactions

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

$$\frac{\sigma_T}{m_X} = \frac{8\pi\alpha_D^2}{m_X^3 v^4}\log\Lambda = \begin{cases} 1.7\times 10^4 \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{45}\right)\left(\frac{30\ \mathrm{km/s}}{v}\right)^4 & \text{Dwarf galaxies} \\ 2.1\times 10^0 \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{60}\right)\left(\frac{300\ \mathrm{km/s}}{v}\right)^4 & \text{Galaxies} \\ 2.0\times 10^{-2} \ \frac{\mathrm{cm}^2}{\mathrm{g}}\left(\frac{\alpha_D}{2.5\times10^{-3}}\right)^2\left(\frac{100\ \mathrm{GeV}}{m_X}\right)^3\left(\frac{\log\Lambda}{72}\right)\left(\frac{1000\ \mathrm{km/s}}{v}\right)^4 & \text{Clusters.} \end{cases} \tag{4.2}$$

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

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

Darkly-Charged Dark Matter

- Viable!!
- Constraints on mass considerably weaker than stated
- And perhaps not reliable
  - Important direction for future
  - Better theoretical work
  - Simulations and distributoins
- Exciting possibility that dark matter has its own world of interactions
  - And that conceivably we can detect them

Related alternative: only a **fraction** interacts: PIDM

- Rather than assume all dark matter self-interacting
- Maybe only a fraction (maybe like baryons?)
- Different types dark matter!
  - Conventional halo but also something more…
- 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

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…

Partially Interacting Dark Matter

- Dark matter with its own force
  - Rather than assume all dark matter
  - Assume it's only a fraction –like baryons…
- Why would we care?
  - Nonminimal assumption!
- 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

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 *componen*t 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

Dissipative Fraction

- 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 they radiate
  - They thereby lower kinetic energy and velocity
  - Get confined to small vertical region
- Disk because angular momentum conserved

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

Simple DDDM Model: Dark Light

- New DARK photon, its own charge
- DARK proton, DARK electron
- Opposite charges
- Radiate and cool
- Then bind into atoms
  - Just like usual matter!

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

Partially Interacting Dark Matter

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

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

Simple DDDM Model
New Ingredient: Light C

- Could be U(1) or a nonabelian group
- $U(1)_D$, α_D
- Two matter fields: a heavy fermion X and a light fermion C
  - For "coolant" as we will see
- $q_X=1$, $q_C=-1$
- (In principle, X and C could also be scalars)
- (in principle nonconfining nonabelian group)
- This in addition to dark matter particle that makes up the halo

Consequence

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

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

Brehmstrahlung and Compton

timescale of the bremsstrahlung cooling is

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

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

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

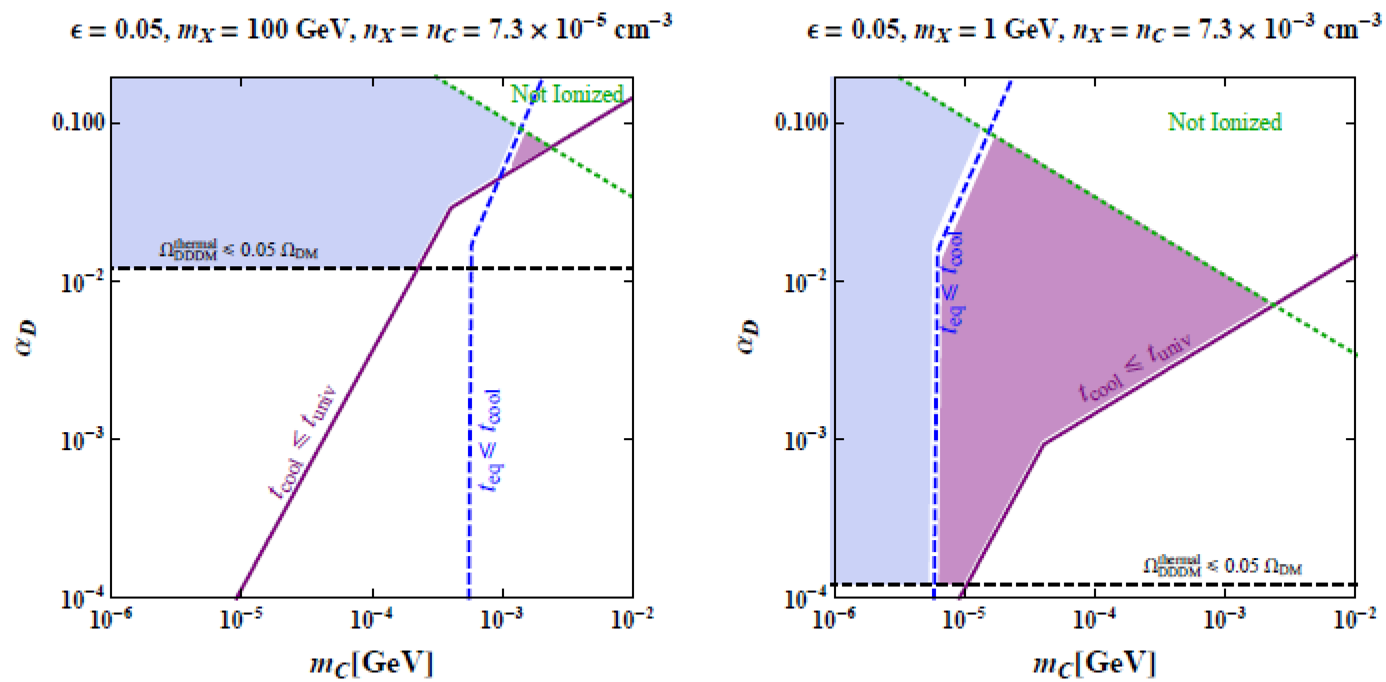


Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the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

$$z_d \approx 2.5\,\text{pc} \left(\frac{\alpha_D}{0.02}\right)^2 \frac{m_Y}{10^{-3}\ \text{GeV}} \frac{100\ \text{GeV}}{m_X} \tag{12}$$

where T is in unit of K and ρ is unit of GeV/cm^3. Interstellar gas (and young stars) have velocity $v \sim 10$ km/s which corresponds to $T \sim 10^4$ K. Plugging it in, we get the disk height is about 300 pc. For old stars, the velocity is about $20 - 30$ km/s and the local disk height is estimated to be 600 pc - 1 kpc, which agrees with the observations (see numbers in [2]).

Summary of model

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

Consequence

- Dark disk ould be much denser than plane of normal matter in our galaxy
- Very significant implications
  - Even though subdominant component
- Fraction constrained
  - Maybe we will see something new soon!
- Because it is in disk and dense signals can be rich

Bound from Structure

w/Kramer

- Gravitational potential measured
  - Both in and out of plane of galaxy
  - Star velocities
- Baryonic matter independently constrained
- Halo dark matter constrained
- Total constraint on any new form of matter
- Constrains (or helps discover!)any new (nonhalo) component in galactic plane

Searching for disk: Velocities of stars

w/Eric Kramer

- 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

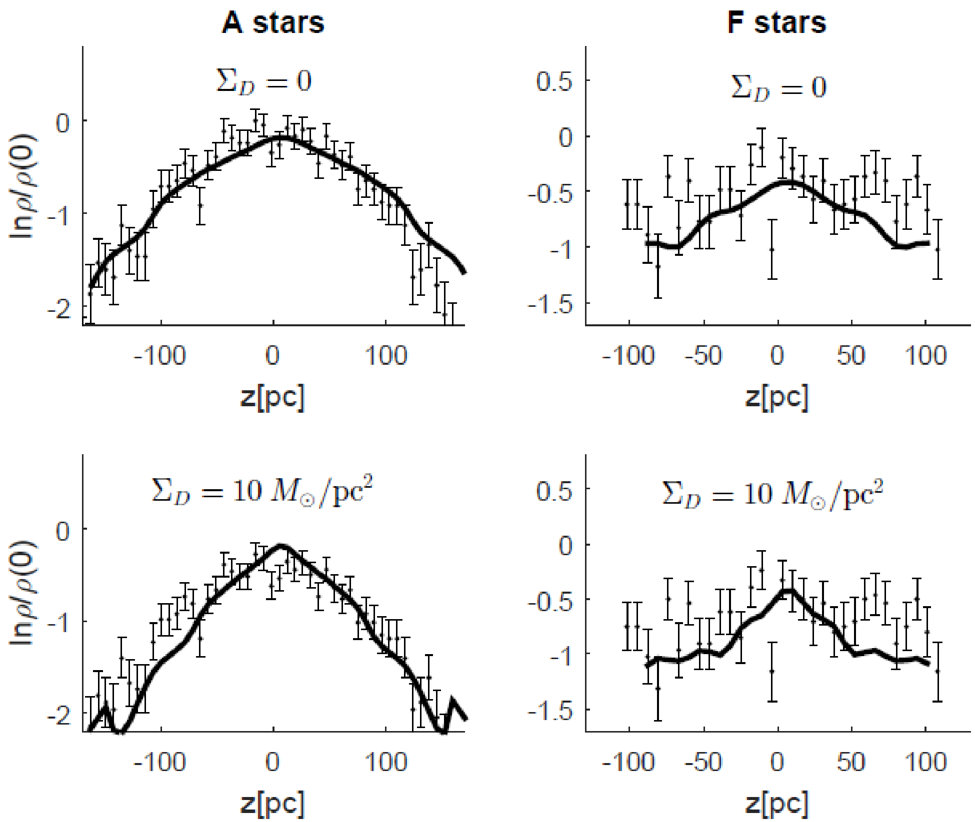


Fig. 2.— (Top) The HF2000 study. The HF2000 model with no disk dark matter agrees quite well with the A and F star data. (Bottom) The HF2000 result, this time including a dark disk with $\Sigma_D = 10\ M_\odot \mathrm{pc}^{-2}$ and $h_D = 10$ pc. We see that this model also may agree with the A and F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

Many effects to be accounted for

- First is self-consistency, “pinching”

– 12 –

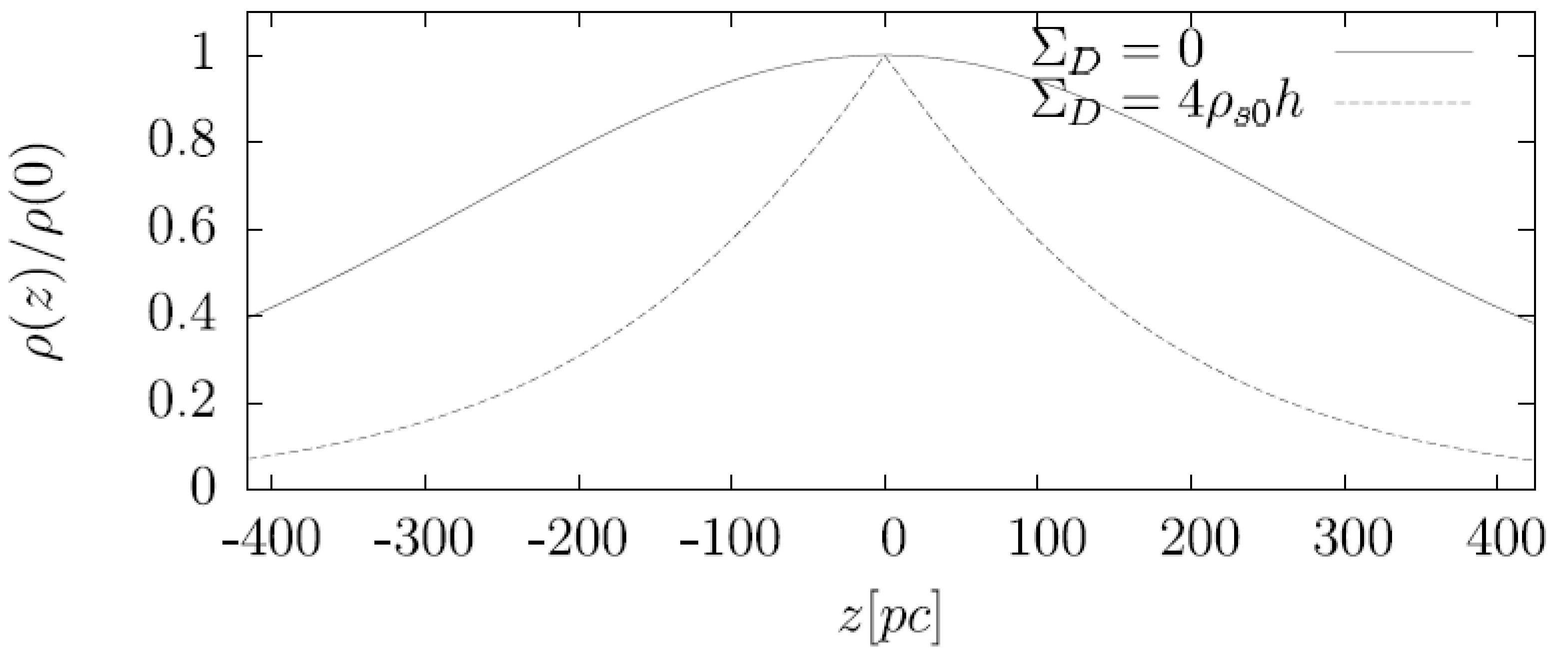


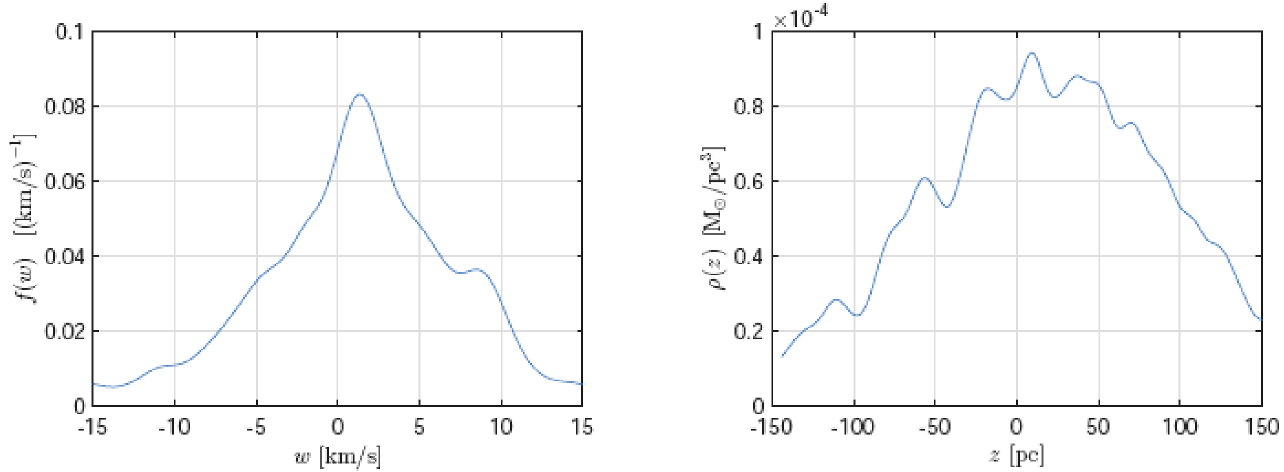
Fig. 2.— A plot of the exact solutions without and with a dark disk of $Q = 1$. The density is ‘pinched’ by the disk, in accordance with Equation 25.

Also eg

- Height of Sun unknown—where is disk?
- Gas uncertainties
  - Kinematics doesn’t distinguish dm from baryons
  - Need independent info on baryons
- Perhaps most important: **Non-Equilibrium behavior**

Density non-symmetric in Hyparcos data, Non-zero peak velocity

Fig. 4.— (Left) The A-star velocity distribution possesses a peak value of 1.3 ± 0.3 km s^{-1}. (Right) The A-star density distribution has a non-zero central value of 19 ± 5 pc relative to the Galactic plane, assuming a value for the solar position of $Z_0 = 26$ pc.



Non-eqm weaker constraint

- Less time in disk
- Less usable data
- Different constraint since automatically evolves in potential so usual constraint would be satisfied
- We ask how close distribution is to a mean value

Result

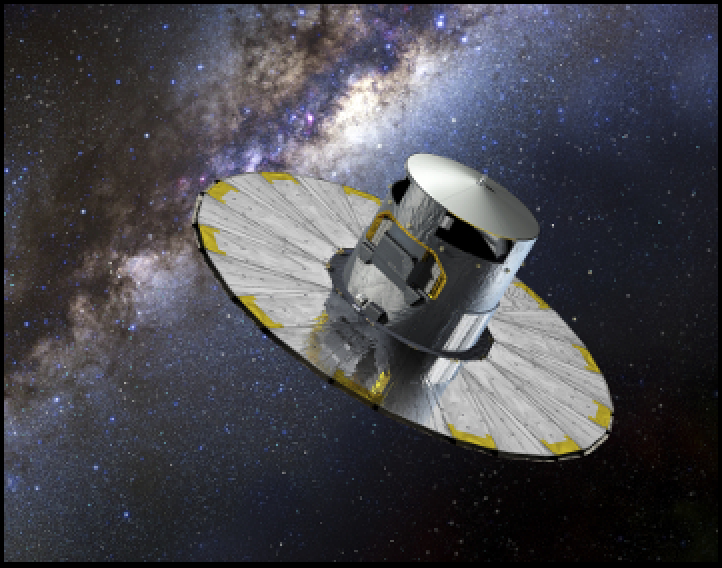
- Less constrained
  - Need to do self-consistently
- Our result A, F stars not in equlibrium
  - Opens up parameter space
  - Needs different statistical methods

OBSERVABLE CONSEQUENCES

Dark disk: affects motion of stars

GAIA satellite

Will test!



Newer results

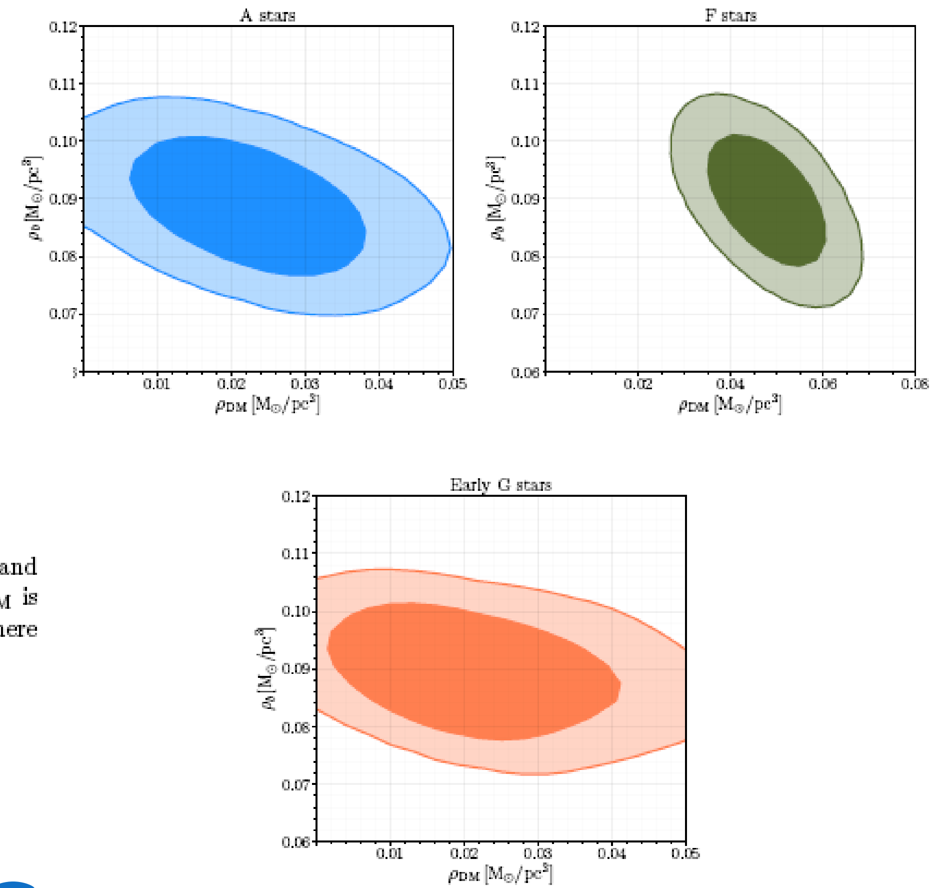
Jatan Buch [a,1] , Shing Chau (John) Leung[a] , and JiJi Fan[a]

- Still ambiguous!
- Population-dependent

Stellar type	$\rho_{\rm DM}$ [$\rm M_\odot/pc^3$]	$\rho_{\rm DM}$ [$\rm GeV/cm^3$]	ρ_b [$\rm M_\odot/pc^3$]	$z_\odot$ [pc]
A stars	$0.023^{+0.010}_{-0.010}$	$0.874^{+0.380}_{-0.380}$	$0.089^{+0.007}_{-0.007}$	$4.95^{+3.78}_{-4.15}$
F stars	$0.047^{+0.006}_{-0.007}$	$1.786^{+0.228}_{-0.266}$	$0.091^{+0.007}_{-0.006}$	$2.52^{+2.58}_{-2.74}$
G stars	$0.021^{+0.014}_{-0.011}$	$0.798^{+0.532}_{-0.418}$	$0.090^{+0.007}_{-0.007}$	$-8.46^{+4.61}_{-4.09}$

able 5: Median posterior values with 1σ errors for the local densities of baryons ρ_b and alo DM $\rho_{\rm DM}$, and height of the sun above the midplane $z_\odot$. The halo DM density $\rho_{\rm DM}$ is xpressed in both $\rm M_\odot/pc^3$ (astronomical unit) and $\rm GeV/cm^3$ (particle physics unit), where $\rm M_\odot/pc^3 \approx 38\ GeV/cm^3$.

NOTE DIFF SOLAR HEIGHTS



igure 7: Marginalized posteriors indicating the degeneracy between the local densities of baryons ρ_b and halo DM $\rho_{\rm DM}$.

Katelin Schutz,[1,*] Tongyan Lin,[1,2,3] Benjamin R. Safdi,[4] and Chih-Liang Wu[5]

Also: TGAS

Satellites of Andromeda Galaxy

w/Schatz

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

Point sources

- Evidence for GeV excess
- Seems to come from point sources
- Argued that pulsars are the source
- Could also be point sources from COMPACT dark matter objects
- Possible when dissipative!

Galactic Center Excess

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

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

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

PERIODIC COMET STRIKES

30-35 million year periodicity (?)

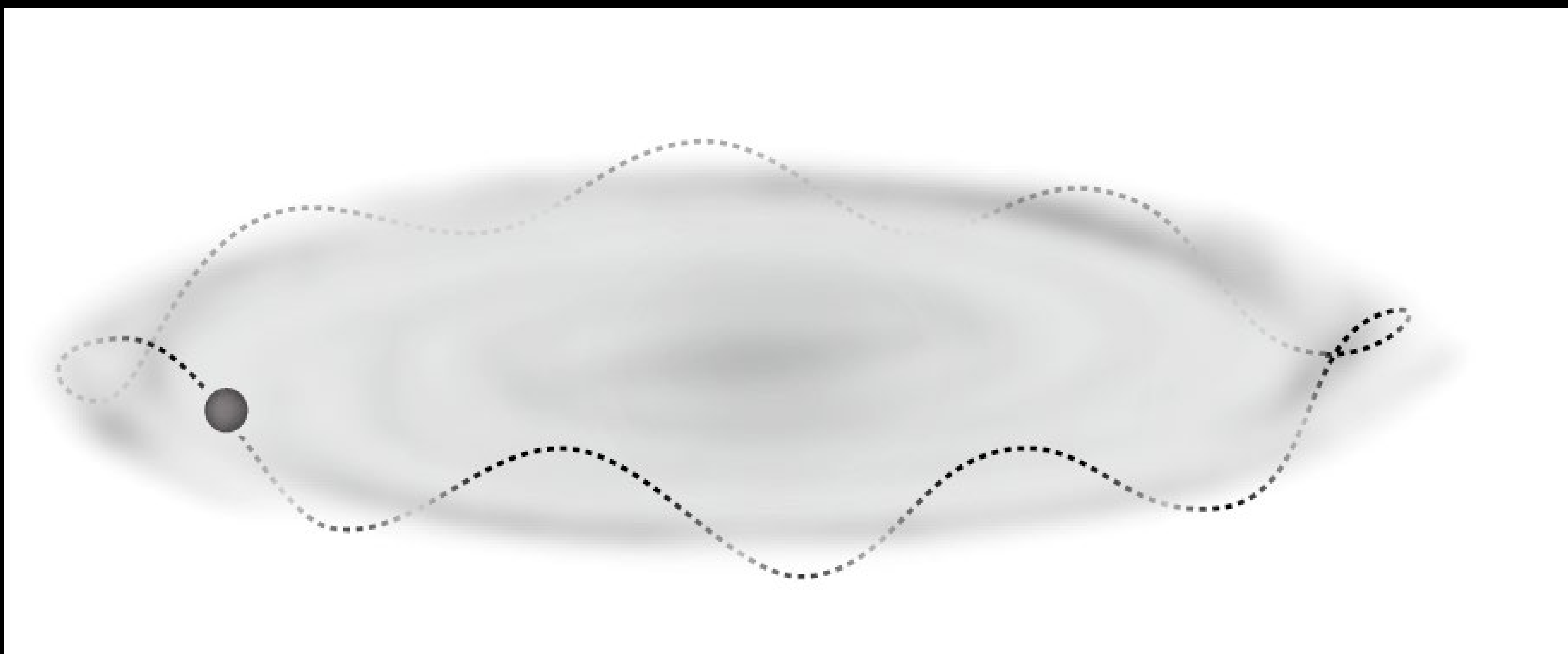
Comets ejected from the Oort cloud?

Failed explanations: Nemesis, spiral arm crossing

Milky Way Disk crossing

Dark disk addresses deficiencies

More matter and marked increase in density



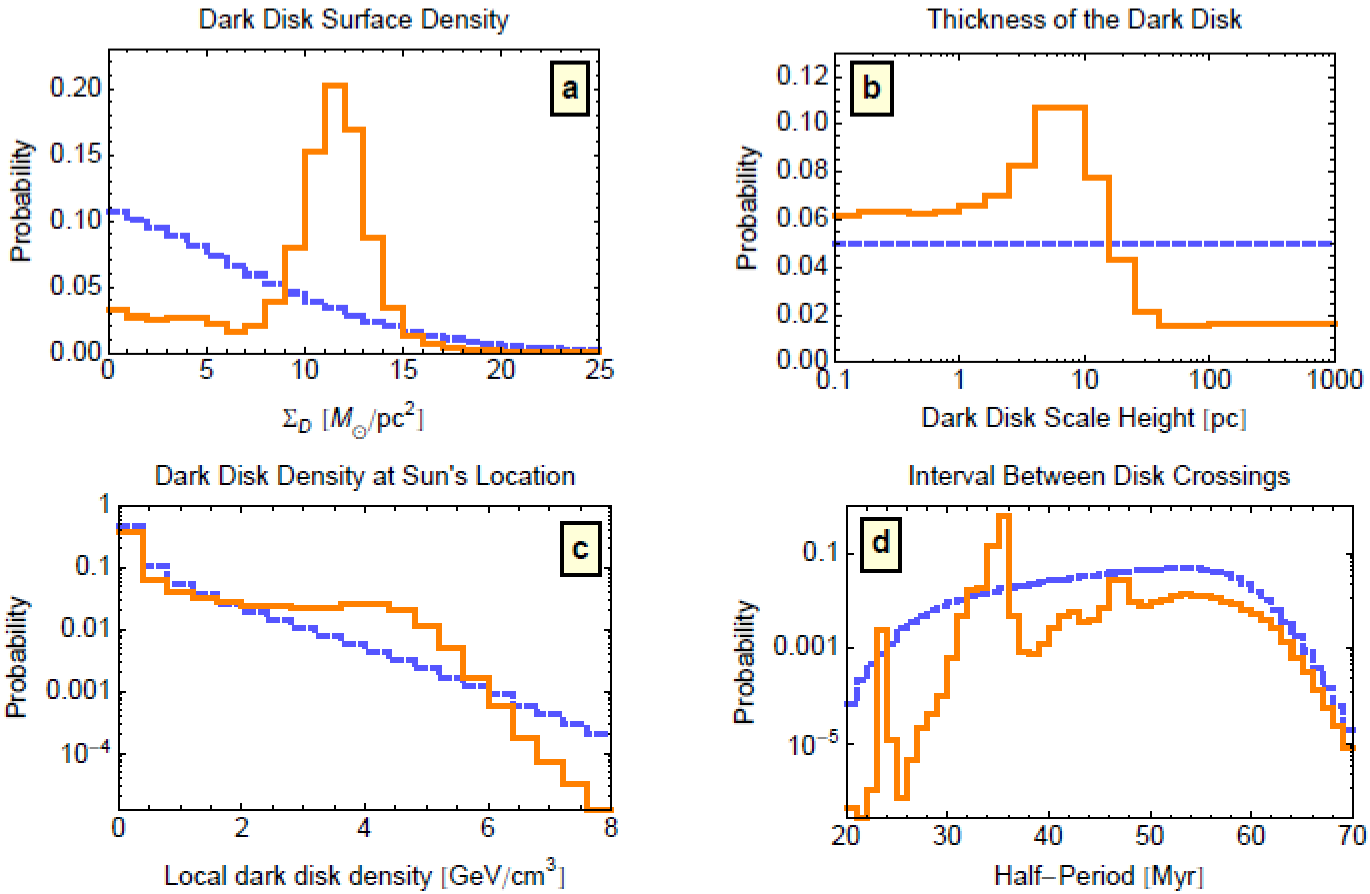


Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits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

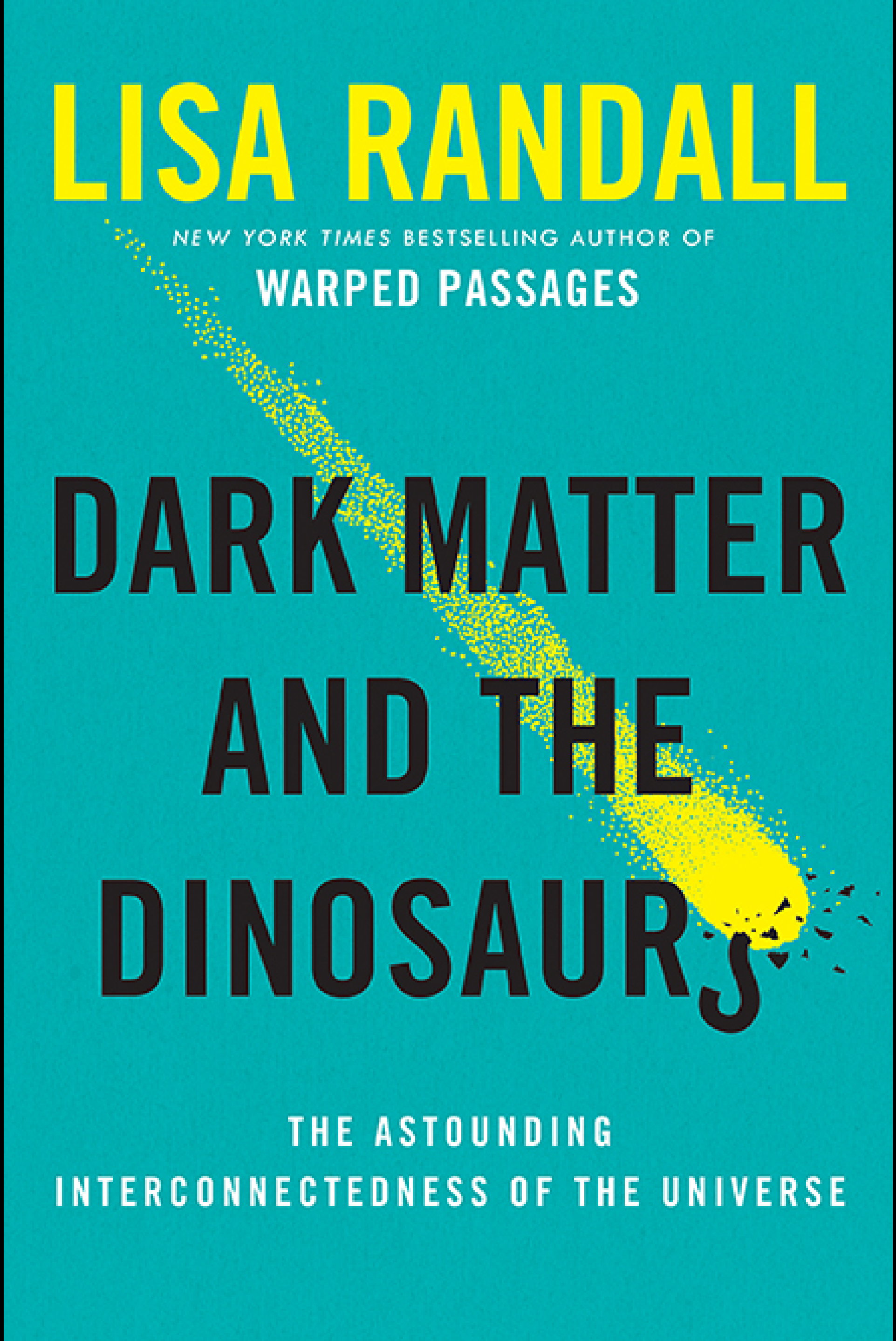
- A big program
- Dark matter charged is clearly a possibility
- Many implications
- But can sometimes be more elusive or subtle than anticipated
- We are beginning to get tremendous data
- Let’s find out what it means

Conclusion

- Critical time for dark matter searches
- New ideas, new ways of searching
- Convergence of large data sets, numerical methods
- Important to have targets
  - Not always obvious
    - Big differences with detailed investigations
  - Might stumble into observations
  - Or do a more targeted search ala particle searches

- Just getting started

New Idea for Dark Matter
New Ways of Looking


LISA RANDALL
NEW YORK TIMES BESTSELLING AUTHOR OF
WARPED PASSAGES
DARK MATTER AND THE DINOSAURS
THE ASTOUNDING INTERCONNECTEDNESS OF THE UNIVERSE

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

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

w/Fan, Katz, Reece

- 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…

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

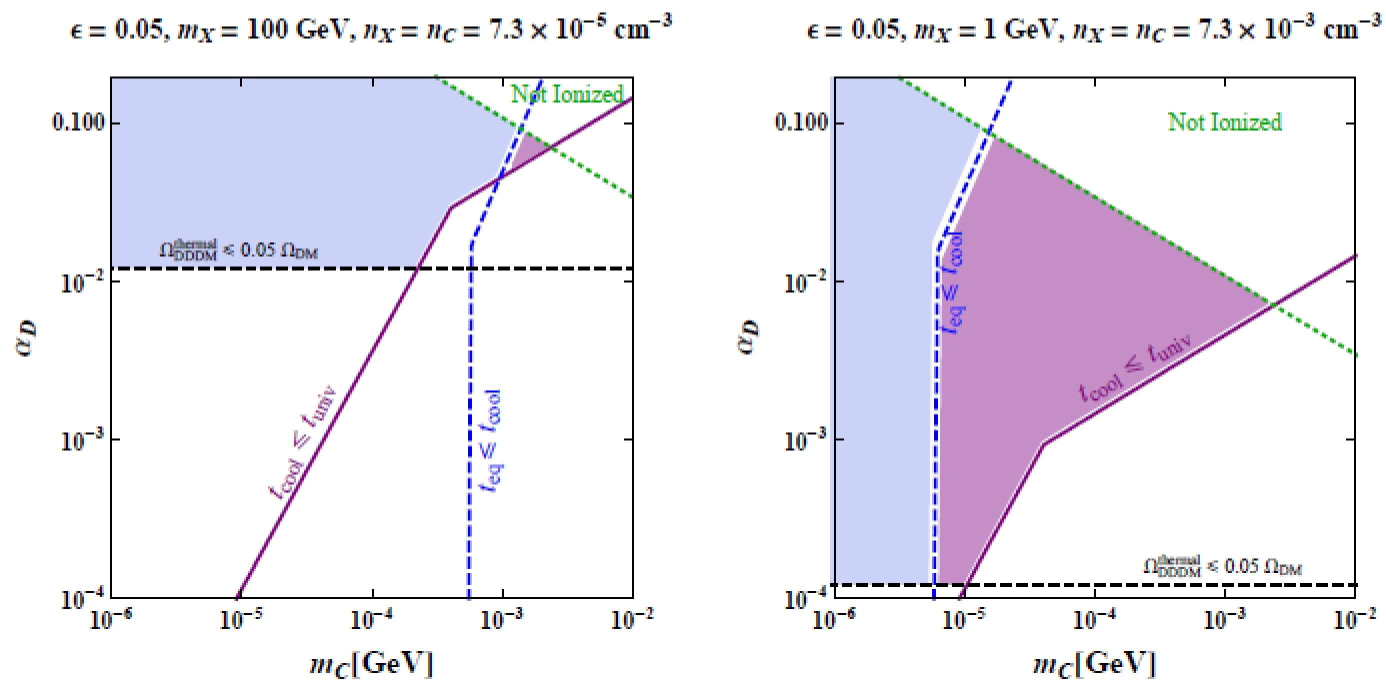


Figure 5: Cooling in the (m_C, α_D) plane. The purple shaded region is the allowed region that cools adiabatically within the age of the universe. The light blue region cools, but with heavy and light particles out of equilibrium. We take redshift $z = 2$ and $T_D = T_{\rm CMB}/2$. The two plots on the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

Disks at least approximately align

- Alignment time:
- R~10 kpc
- M~10^{12} M_{sun}

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

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

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

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

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
- 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

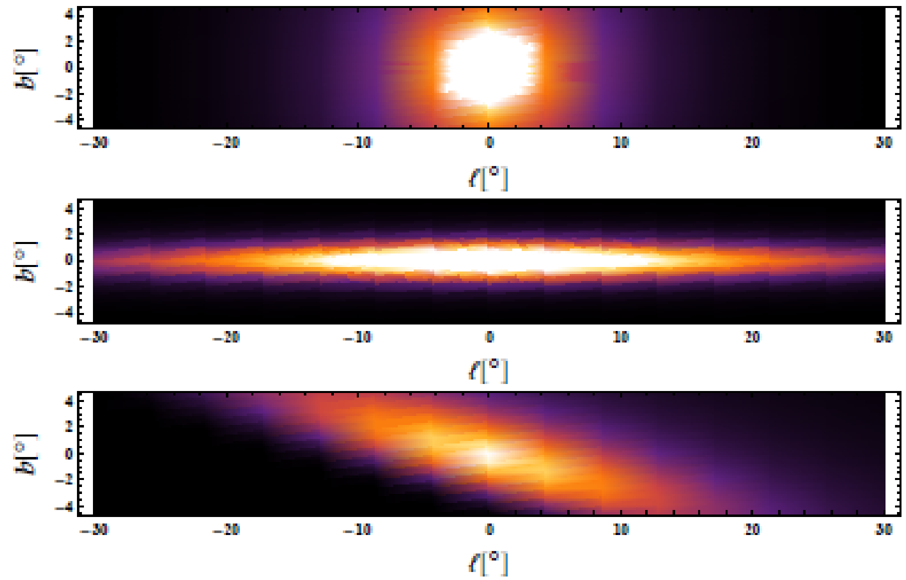


FIG. 10. Sky maps of the photon flux in A.U.s for different DM profiles. Upper: Normal DM with an Einasto profile. Middle: PDDM in a disk aligned with our disk. Lower: PDDM in a disk misaligned with our disk.

Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology

Francis-Yan Cyr-Racine*,† Roland de Putter, and Alvise Raccanelli
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA and
California Institute of Technology, Pasadena, CA 91125, USA

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

Also new acoustic peak

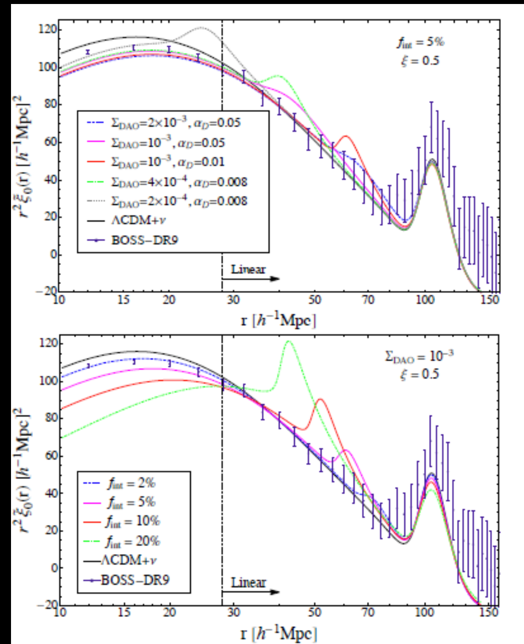


FIG. 2: Angle averaged galaxy correlation function $\tilde{\xi}_0(r)$ for different PIDM models. In the upper panel, we take $f_{\rm int} = 5\%$, $\xi = 0.5$ and vary $\Sigma_{\rm DAO}$ and α_D. In the lower panel, we fix $\Sigma_{\rm DAO} = 10^{-3}$, $\alpha_D = 0.01$ and $\xi = 0.5$, but let the fraction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

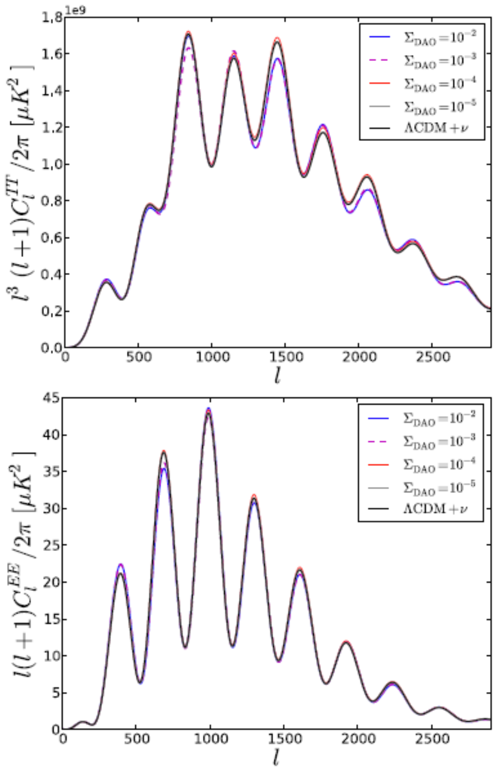
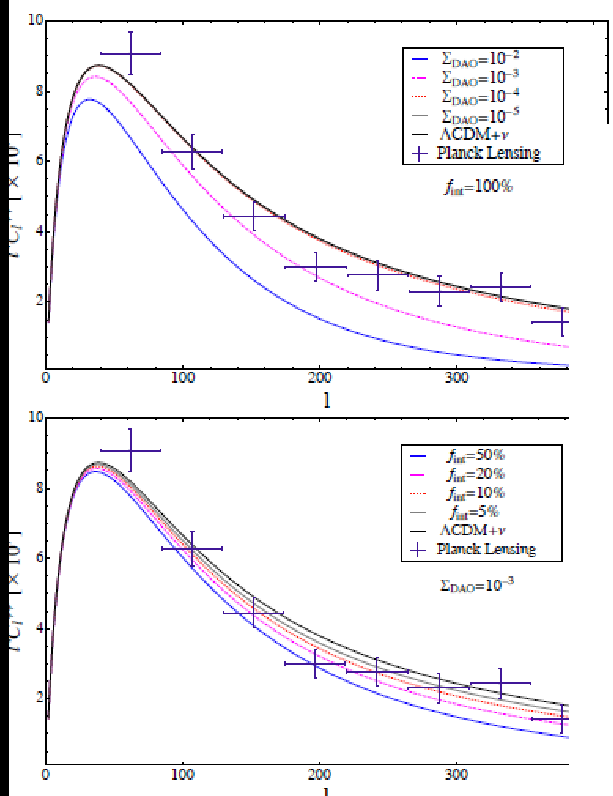


FIG. 6: CMB unlensed temperature (upper panel) and E polarization (lower panel) power spectra for four different PIDM models with $f_{\rm int}=100\%$. We have taken $\xi=0.5$. For comparison, we also show a standard ΛCDM model with an equivalent number of effective neutrinos.



IG. 7: CMB lensing power spectrum for different PIDM nodels. For both panels we use $\xi=0.5$. In the upper panel, e 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+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 ΛCDM model with an equivalent number of neutrinos.

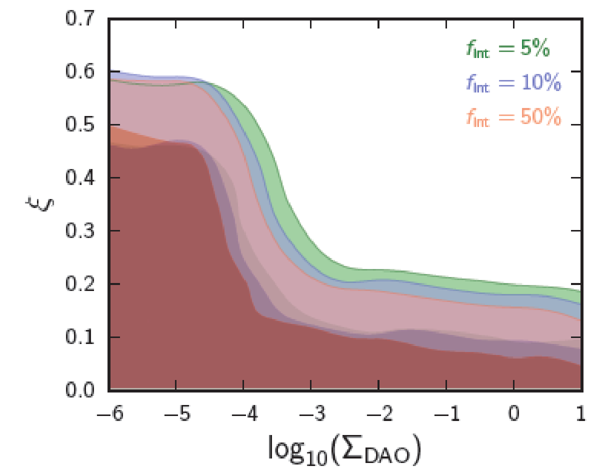


FIG. 11: Marginalized constraints on ξ and $\Sigma_{\rm DAO}$ for three fixed values of $f_{\rm int}$. We display the 68% and 95% confidence regions for the dataset "Planck+WP+High-l+BAO+Lens".

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

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

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

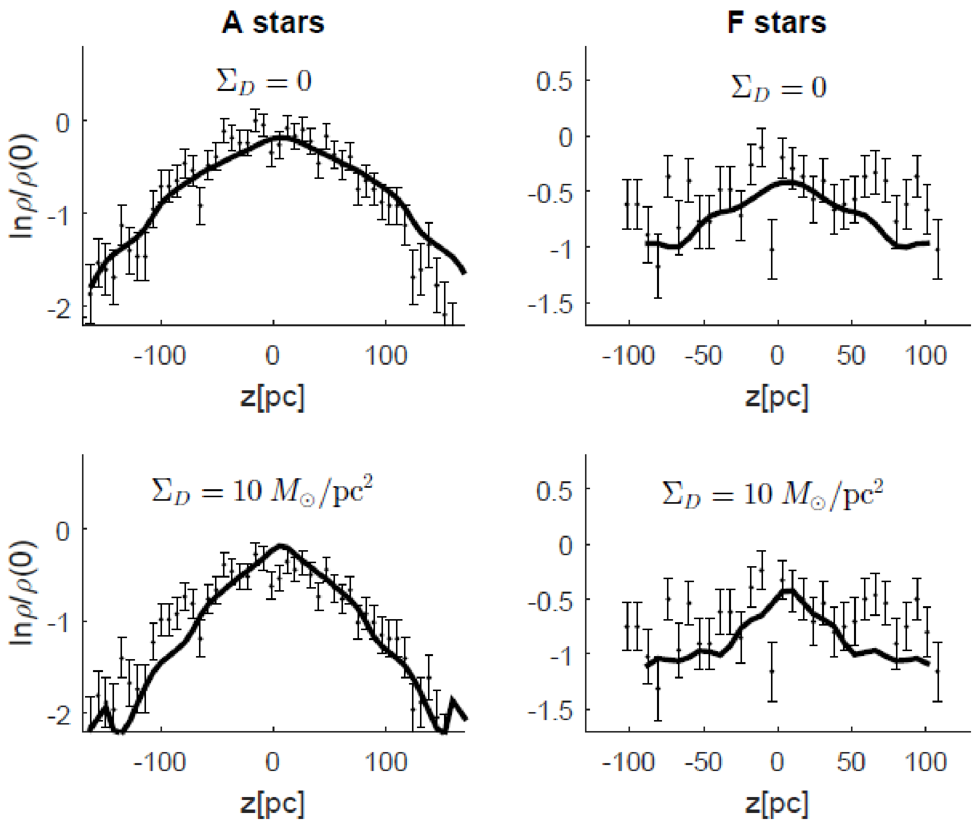


Fig. 2.— (Top) The HF2000 study. The HF2000 model with no disk dark matter agrees quite well with the A and F star data. (Bottom) The HF2000 result, this time including a dark disk with $\Sigma_D = 10\ M_\odot \mathrm{pc}^{-2}$ and $h_D = 10$ pc. We see that this model also may agree with the A and F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

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

Various effects

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

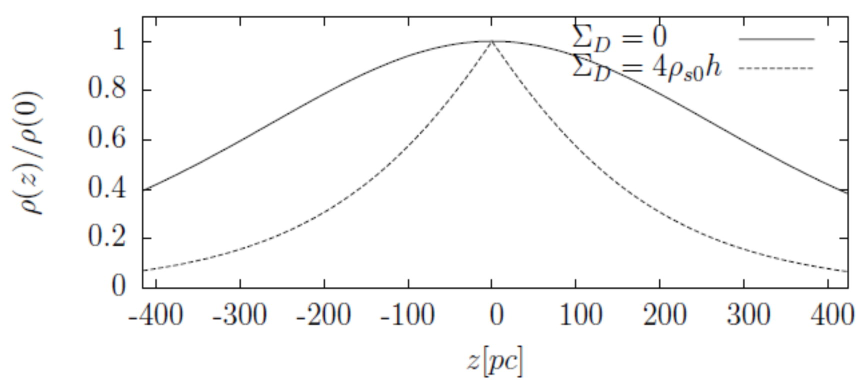


Figure 1: A plot of the exact solutions without and with a dark disk of $Q = 1$. The density is 'pinched' by the disk, in accordance with Eq. 31.

(Static) Kinematic Results

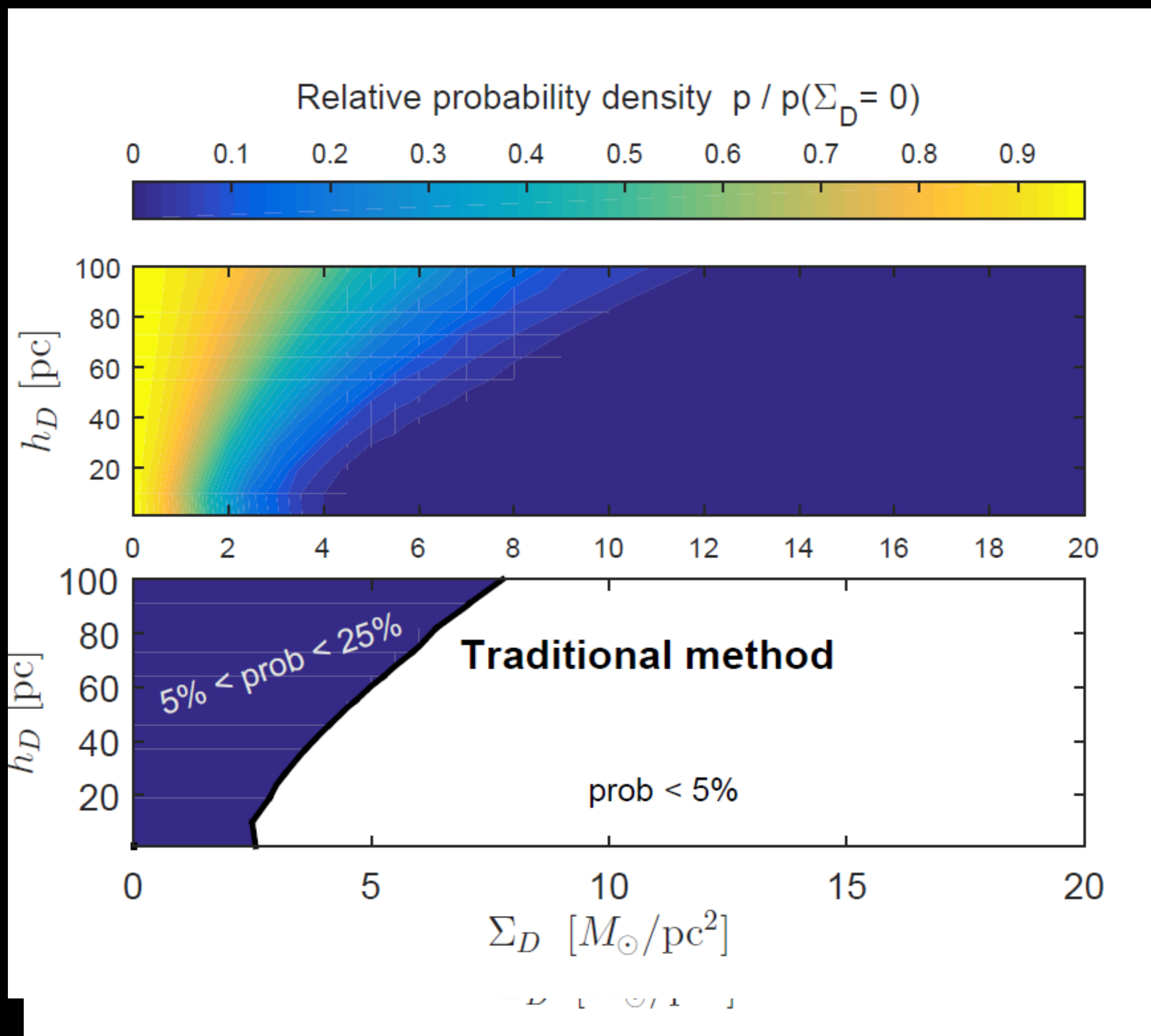
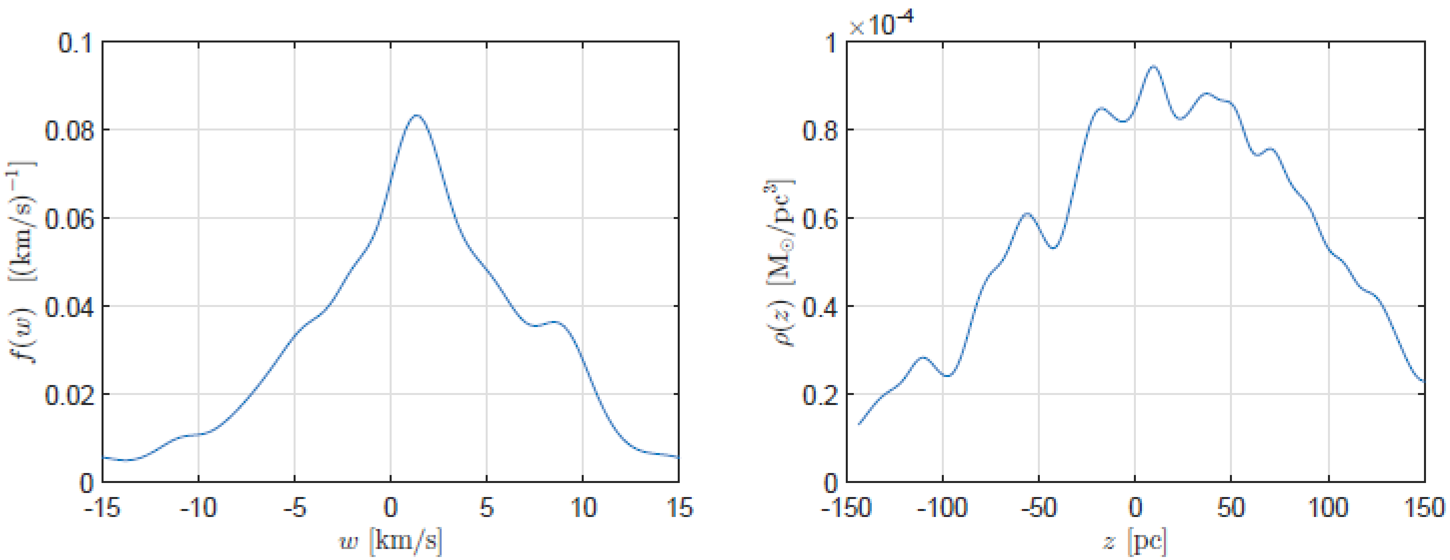
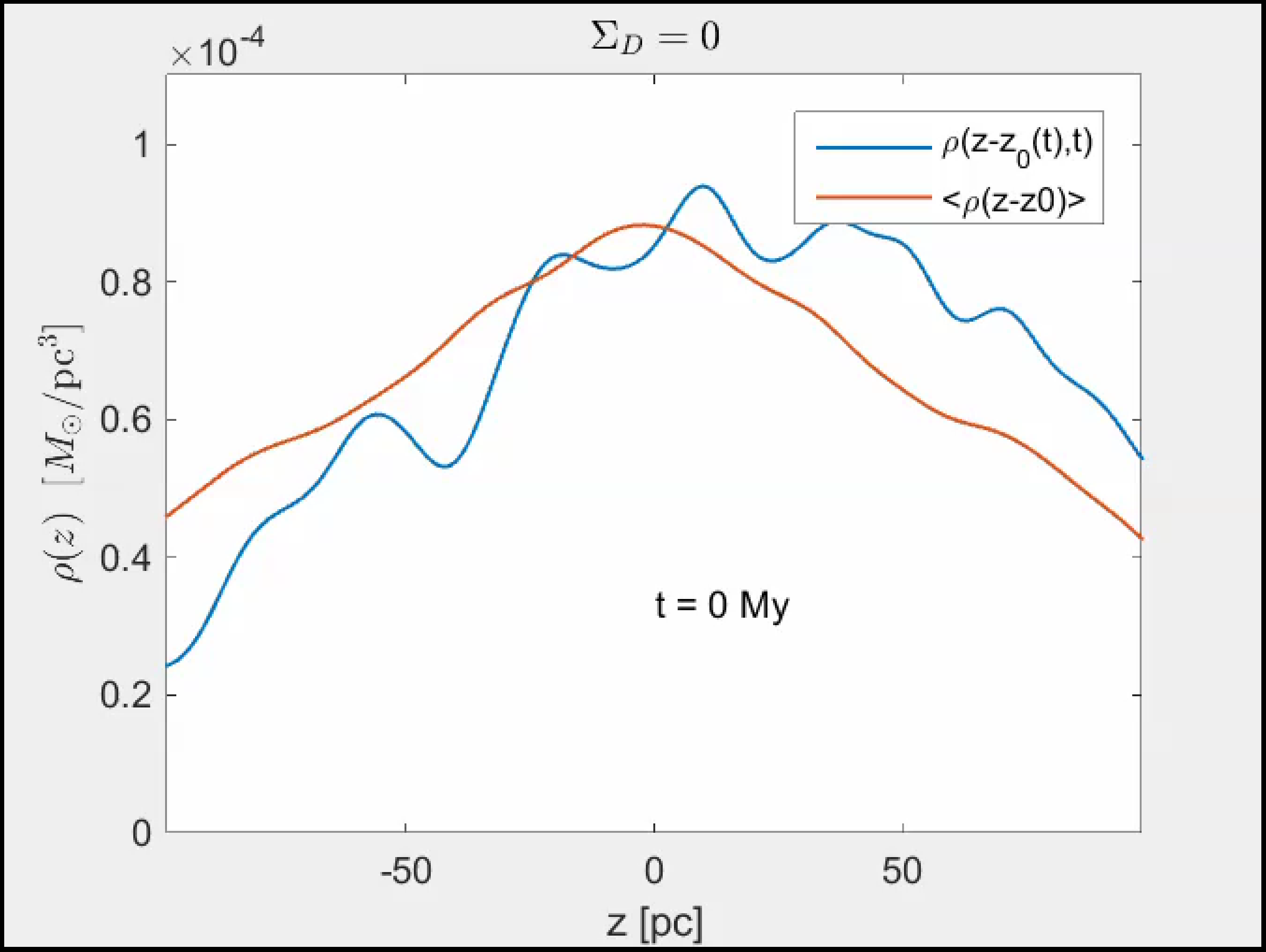


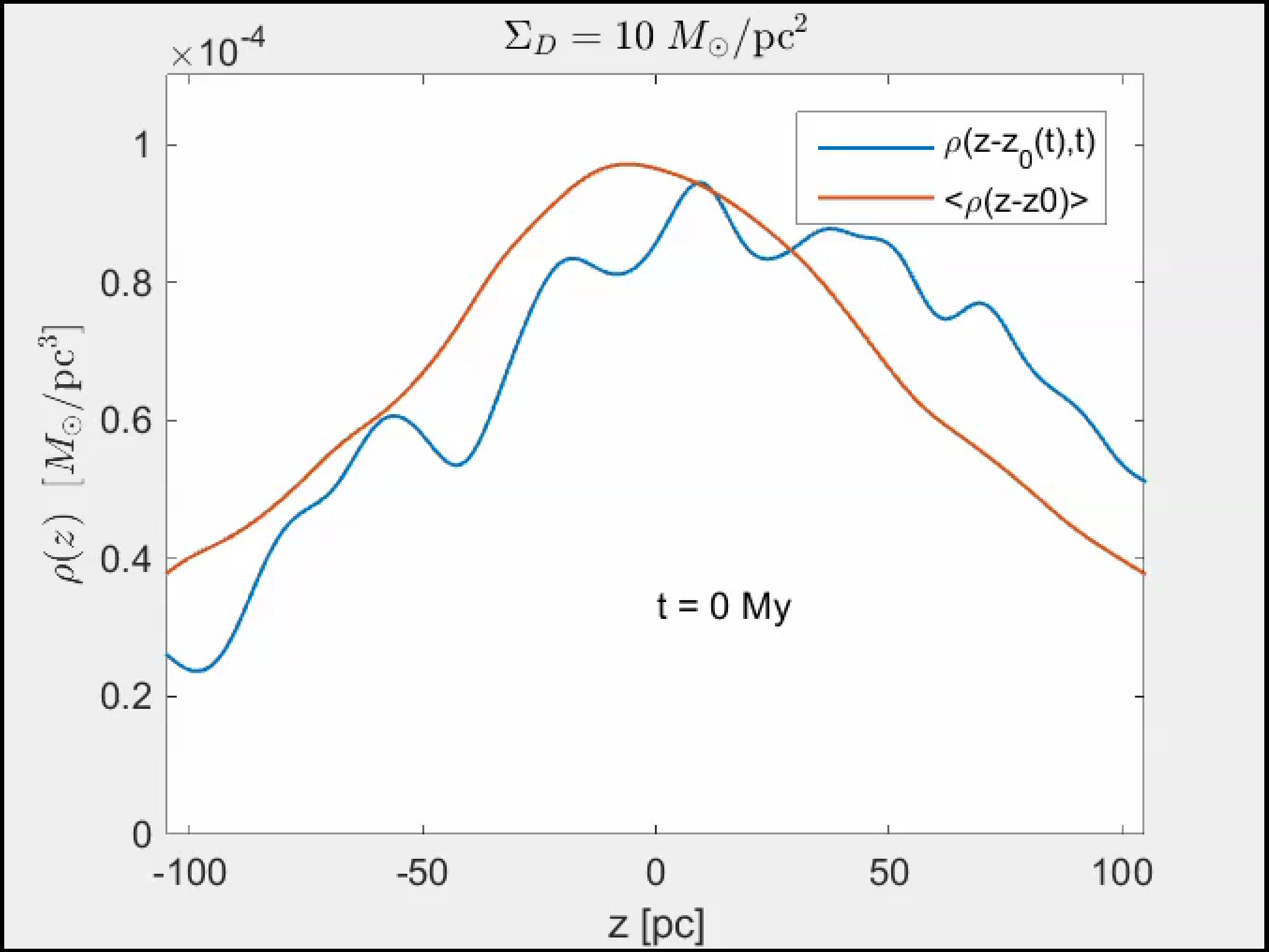
Figure 6: *(Left) The A-star velocity distribution possesses a peak value of* 1.3 ± 0.3 *km/s. (Right) The A-star density distribution has a non-zero central value of* 33 ± 5 *pc relative to the galactic plane, assuming a value for the solar position of* $Z_0 = 26$ *pc.*



Time dependence with no disk

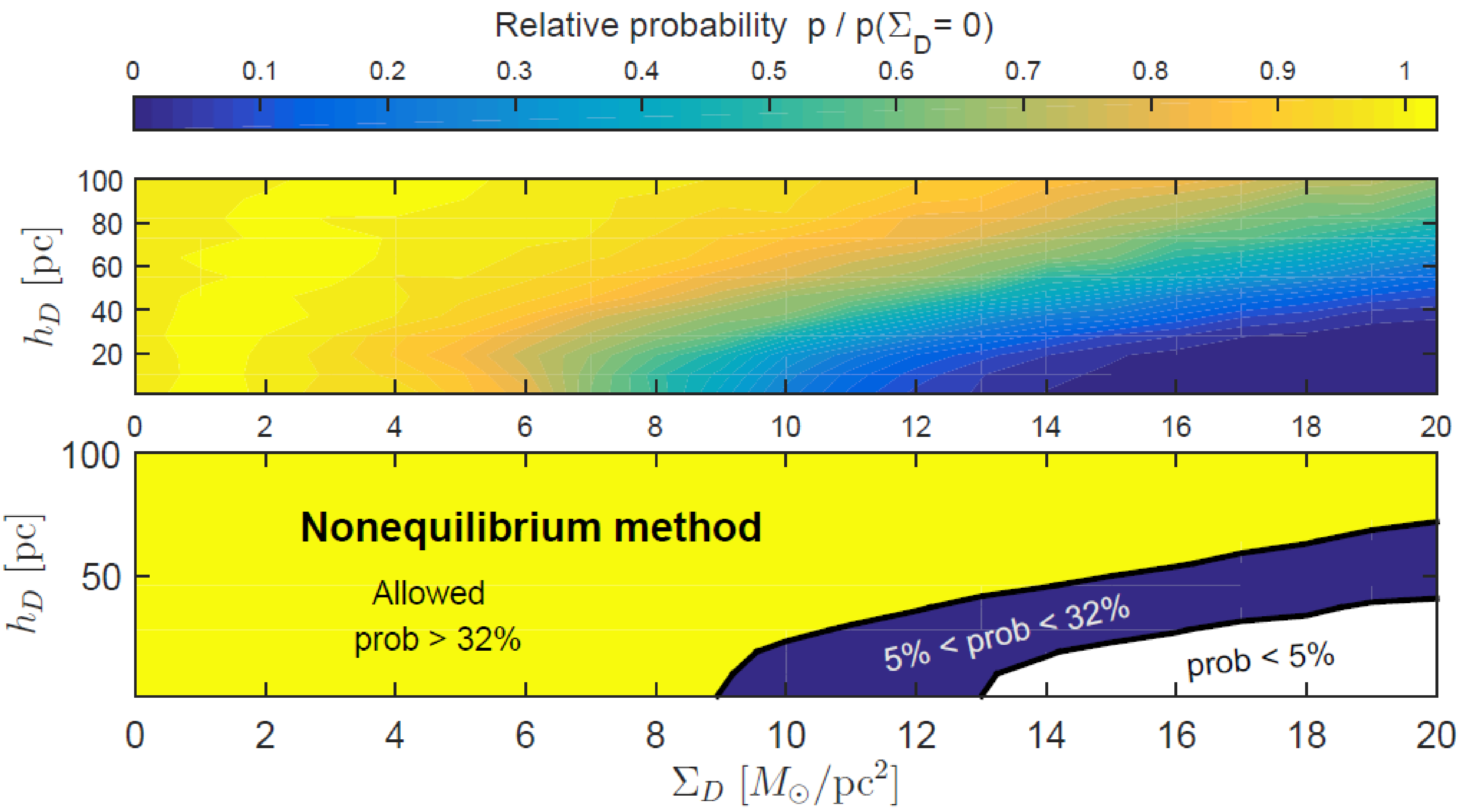


Time dependence with disk



Result

- Time average automatically agrees with potential
- But 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

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
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w/Reece

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- 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

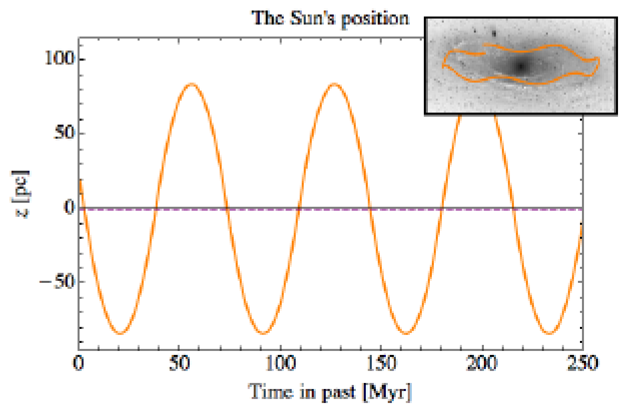

FIG. 1. The Sun's height above the galactic plane as a function of time, extrapolated backward via Eq. 2. The corresponding cratering probability is shown in Fig. 3. Inset: an illustration of how the Sun moves around the galactic center while also oscillating vertically; the vertical oscillation is exaggerated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

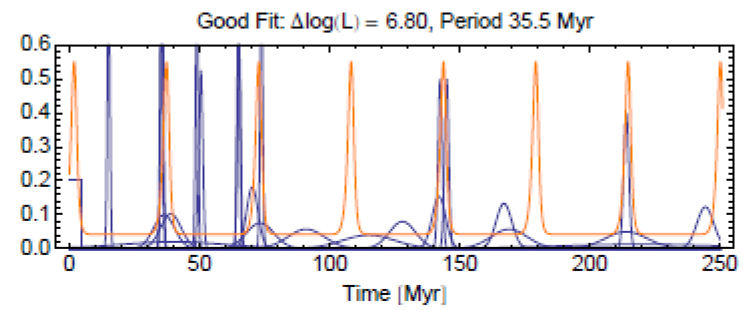

FIG. 3. An example of a model that provides a good fit. The parameters of the dark disk are $\Sigma_D = 13 M_\odot/\mathrm{pc}^2$ and $z_d^D = 5.4$ pc. The baryonic disk is 350 pc thick with total surface density 58 $M_\odot/\mathrm{pc}^2$. The local dark halo density is 0.037 $\mathrm{GeV/cm}^3$. $Z_\odot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

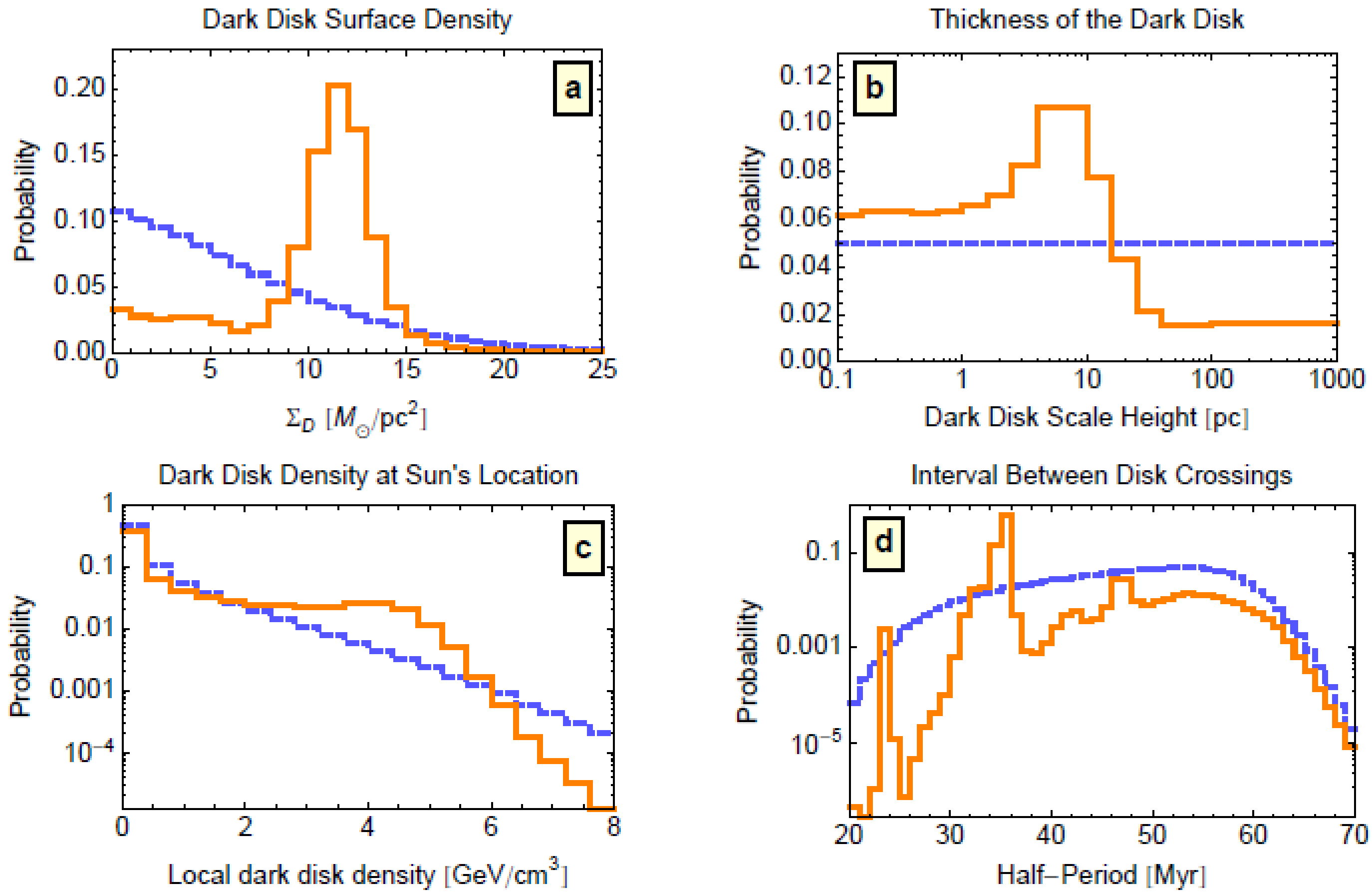

Figure 2: One-dimensional projections of the prior (blue, dashed) and posterior (orange, solid) probability distributions. (a) The surface density of the dark disk, which the posterior distribution prefers to be between about 10 and 15 $M_\odot/\mathrm{pc}^2$. (b) The dark disk thickness, which fits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

Summary of DDDM

- 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

Flooded Dark Matter (FDM)

w/Jakub Scholtz, James Unwin

- Unprejudiced attitude toward dark matter
- Assume dark matter, ordinary matter separate sectors
  - No thermal freezeout, decay, or subsequent production
  - No favoritism to SM
- DM, SM produced in comparable amounts at end of inflation (democratic production)
- Could this agree with observations?
- What would be required?

Cooler Dark Matter?

- Entropy in ordinary matter much greater than that in baryons
- Yet comparable energy in baryons and dark matter
  - Most of the energy in baryons
  - Most of the entropy in radiation
- Combined with lower limits on dark matter mass,
- Hints at cooler dark matter
    - Both sectors have their own temperature
      - Temp of dark matter sector generically lower
  - Note cooler dark matter would also help with degrees of freedom if generically many dark matter sectors

- Benchmarks:
  - GeV DM w/SM asymmetry, SM temp has DM entropy, energy
  - Generic thermal eV dark matter w/SM temp has SM entropy,
    - Ω_{DM}~ Ω_B ~GeV 10^{-9} s_{SM}
    - Higher mass=> Lower temperature
    - s_{DM}/s_{SM}~η Ω_{DM} / Ω_B m_B/m_{DM}
  - Any heavier mass dark matter w/ DM energy would have lower temperature and lower entropy

Consider energy fraction in dark matter

Rad dominated

$$R^{(\Gamma)} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\Gamma)}}{s_{\rm SM}^{(\Gamma)}}\right)^{4/3} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}}\right)^{4/3}$$

Require:

$$\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}} = \frac{2\pi^4}{45\zeta(3)}\Delta\frac{n_{\rm DM}}{n_B} = \frac{2\pi^4}{45\zeta(3)}\Delta\frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_B}{m_{\rm DM}},$$

Conclude:

$$\left.\frac{T_{\rm DM}}{T_{\rm SM}}\right|_{\infty} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}R^{(\Gamma)}\right)^{1/4}\left(\frac{g_{\rm SM}^{(\infty)}}{g_{\rm SM}^{(\Gamma)}}\right)^{1/3} = \left(\frac{g_{\rm SM}^{(\infty)}}{g_{\rm DM}^{(\Gamma)}}\frac{2\pi^4}{45\zeta(3)}\Delta\frac{\Omega_{\rm SM}}{\Omega_B}\frac{m_B}{m_{\rm DM}}\right)^{1/3}$$

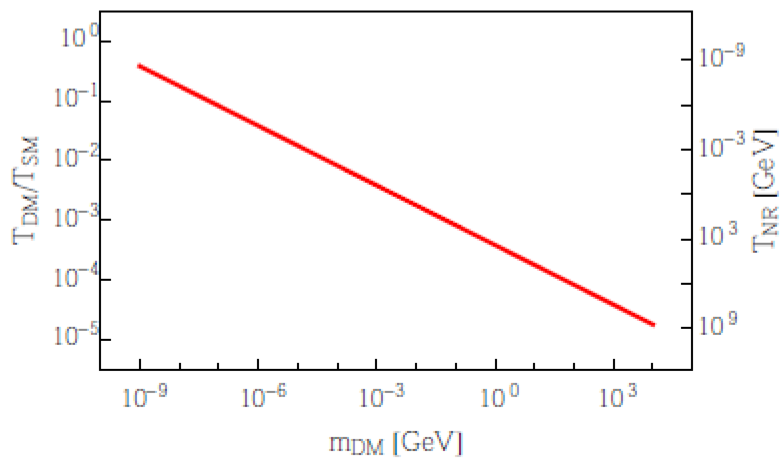

Figure 2. Ratio of dark to visible sector temperatures $T_{\rm DM}/T_{\rm SM}$ as a function of $m_{\rm DM}$. The right-hand y-axis shows the temperature of the Standard Model $T_{\rm NR}$ when dark matter becomes non-relativistic.

Late-time decay

- Higher entropy, temperature in ordinary sector naturally achieved by late-time decay
  - Assume a heavy long-lived particle
  - Assume dark matter dilutes like radiation
  - Scalar field dilutes like matter, comes to dominate
  - Decays into SM
- Can of course have late-decaying particle in DM sector too
  - But should decay earlier to allow for cooler, more dilute DM
  - Yields similar analysis but equivalent less dilution time

- Also of interest
  - Implications for baryogenesis
  - New types of models
  - Potential implications for free-streaming bounds, core-cusp

Scenario

- Heavy scalar Φ that redshifts nonrelativistically
- Whereas primordial DM redshifts relativistically
- At late time, Φ decays
  - Lifetime determines relative temperatures
- Note this dilutes entropy of all DM sectors
  - Solves potential issue of why not more DM entropy
- Final species to decay will dominate entropy, energy
  - Principle of maximum baroqueness
  - Most weakly coupled fields (smallest couplings) most influential

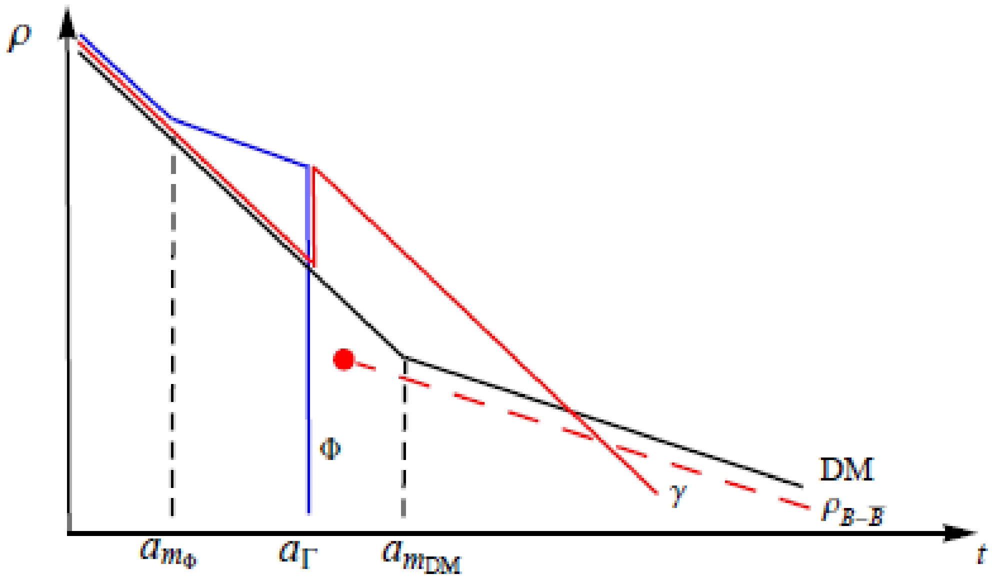

Figure 1. Schematic plot of the time evolution of the energy densities, showing the dark matter (DM), Standard Model photon bath γ, and heavy states Φ, for comparable initial densities $R^{(0)} \equiv \frac{\rho_{\rm DM}}{\rho_\Phi} \simeq 1$. Also shown is the evolution of the net baryon number $\rho_{B-\overline{B}} \sim m_B n_B$, which for definitiveness we assume here is generated at some point following Φ decays and mark by the red dot.

Temperature ratio required

$$R^{(\Gamma)} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\Gamma)}}{s_{\rm SM}^{(\Gamma)}}\right)^{4/3} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}}\right)^{4/3}$$

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implies

$$\left.\frac{T_{\rm DM}}{T_{\rm SM}}\right|_\infty = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}R^{(\Gamma)}\right)^{1/4}\left(\frac{g_{\rm SM}^{(\infty)}}{g_{\rm SM}^{(\Gamma)}}\right)^{1/3} = \left(\frac{g_{\rm SM}^{(\infty)}}{g_{\rm DM}^{(\Gamma)}}\frac{2\pi^4}{45\zeta(3)}\Delta\frac{\Omega_{\rm SM}}{\Omega_B}\frac{m_B}{m_{\rm DM}}\right)^{1/3}.$$

Light dof redshift

- Ratios of densities most generically start ~1
- Evolution of energy densities below

$$R^{(i)} \equiv R(a_i) \equiv \frac{\rho_{\rm DM}(a_i)}{\rho_\Phi(a_i)}$$

$$R_{\rm SM}^{(0)} \equiv \frac{\rho_{\rm SM}(a_0)}{\rho_\Phi(a_0)}; \qquad R_{\rm DS}^{(0)} \equiv \frac{\rho_{\rm DS}(a_0)}{\rho_\Phi(a_0)}$$

$$H^2(a) = \frac{\rho_{\rm tot}(a)}{3M_{\rm Pl}^2} \simeq \frac{g_\Phi \pi^2}{90}\frac{m_\Phi^4}{M_{\rm Pl}^2}\left[\left(\frac{a_0}{a}\right)^3 + R^{(0)}\left(\frac{a_0}{a}\right)^4 + R_{\rm SM}^{(0)}\left(\frac{a_0}{a}\right)^4 + R_{\rm DS}^{(0)}\left(\frac{a_0}{a}\right)^4\right]$$

Energy dominated by Φ
All other terms redshift

Scenario requires small coupling

$$H^2(a) = \frac{\rho_{\rm tot}(a)}{3M_{\rm Pl}^2} \simeq \frac{g_\Phi \pi^2}{90}\frac{m_\Phi^4}{M_{\rm Pl}^2}\left[\left(\frac{a_0}{a}\right)^3 + R^{(0)}\left(\frac{a_0}{a}\right)^4 + R^{(0)}_{\rm SM}\left(\frac{a_0}{a}\right)^4 + R^{(0)}_{\rm DS}\left(\frac{a_0}{a}\right)^4\right]$$

$3H = \Gamma$

First term above dominates implie $\left(\frac{a_0}{a_\Gamma}\right)^3 = \frac{10}{\pi^2}\frac{\Gamma^2 M_{\rm Pl}^2}{g_\Phi m_\Phi^4}$

$$R^{(\Gamma)} = R^{(0)}\left(\frac{a_0}{a_\Gamma}\right) = R^{(0)}\left[\frac{10}{\pi^2}\frac{\Gamma^2 M_{\rm Pl}^2}{g_\Phi m_\Phi^4}\right]^{1/3}$$

$$R^{(\Gamma)} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\Gamma)}}{s_{\rm SM}^{(\Gamma)}}\right)^{4/3} = \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3}\left(\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}}\right)^{4/3}$$

Required lifetime

$$\Gamma = \frac{\pi}{\sqrt{10}}\frac{m_\Phi^2}{M_{\rm Pl}}\left(\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}}\right)^2\left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}}\right)^{1/2}\left(\frac{g_{\rm SM}^{(\Gamma)}}{\left(R^{(0)}\right)^3}\right)^{1/2}$$

Small ratio of entropies implies lifetime is small

Reheat temp constraint follows

$$T_{\mathrm{RH}} \equiv T_{\mathrm{SM}}^{(\Gamma)} \simeq \left[\frac{30}{\pi^2 g_{\mathrm{SM}}^{(\Gamma)}} \rho_{\mathrm{SM}}(a_\Gamma)\right]^{1/4} \simeq \left[\frac{10}{\pi^2 g_{\mathrm{SM}}^{(\Gamma)}}\right]^{1/4} \sqrt{\Gamma M_{\mathrm{Pl}}}$$

Coupling can't be too small
Reheat temperature bigger than
10MeV??
100 GeV??

Constraint: Light Dark Matter

- Larger couplings require lighter dark matter
- Constraint on light dark matter from existence of small scale structure
- Test horizon scale at which dm goes nonrelativistic
- If temp same as SM, dwarf galaxy limit ~keV
- Constraints weaken when dark matter colder

$$T_{\rm NR} \simeq m_{\rm DM} \left.\frac{T_{\rm SM}}{T_{\rm DM}}\right|_{\rm NR} = m_{\rm DM} \left(\frac{g_{\rm SM}^{(\Gamma)}}{g_{\rm DM}^{(\Gamma)}} \frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}} \right)^{-1/3} \left(\frac{g_{\rm SM}^{(\rm NR)}}{g_{\rm SM}^{(\Gamma)}} \right)^{-1/3}$$

$$= m_{\rm DM} \left(\frac{g_{\rm SM}^{(\rm NR)}}{g_{\rm DM}^{(\Gamma)}} \frac{2\pi^4}{45\zeta(3)} \Delta \frac{\Omega_{\rm DM}}{\Omega_B} \frac{m_B}{m_{\rm DM}} \right)^{-1/3} .$$

$$\frac{l_F}{l_F^{\rm th}} \simeq \left(\frac{m_{\rm DM}}{T_{\rm NR}} \right) = \left(\frac{g_{\rm SM}^{(\rm NR)}}{g_{\rm DM}^{(\Gamma)}} \frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}} \right)^{1/3} \simeq 0.12 \times \left(\frac{g_{\rm SM}^{(\rm NR)}}{g_{\rm DM}^{(\Gamma)}} \frac{1\ {\rm keV}}{m_{\rm DM}} \right)^{1/3}$$

  - Dwarf galaxies m>200 eV
  - Lyman α slightly stronger constraint

$$m_{\rm DM} > 450\ {\rm eV} \left(\frac{4}{g_{\rm DM}} \right)^{1/4}$$

- Constraints relaxed relative to truly thermal
- Not relaxed arbitrarily because light dark mattter not as cool in FDM

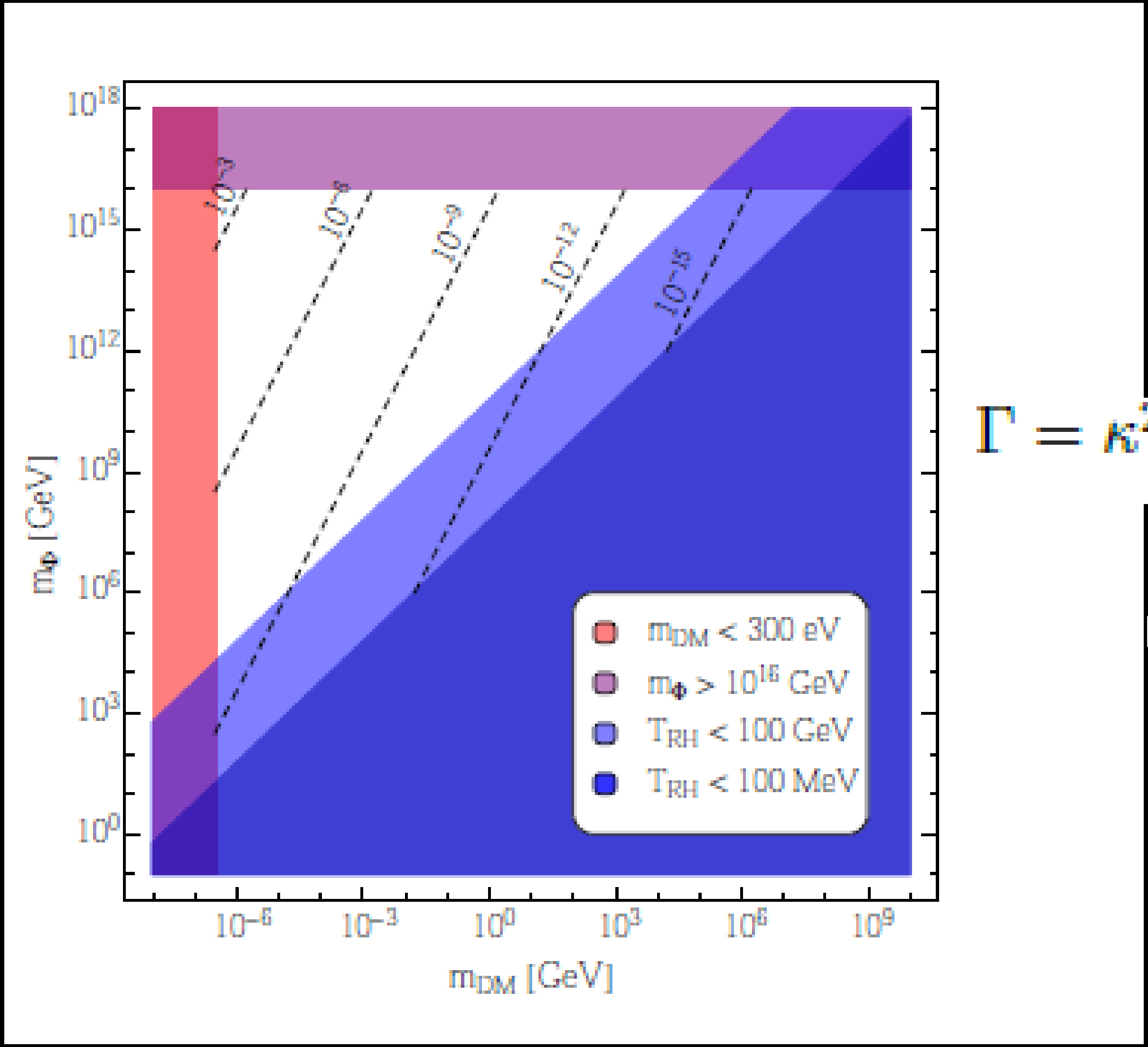
Additional Constraint:DOF

- Dark matter can be relativistic during BBN
  - Not at last scattering
- SM prediction DOF $N_{\rm eff}^{\rm (SM)} = 3.046$
- Current bound from BBN: $N_{\rm eff}^{\rm (BBN)} \approx 2.9 \pm 0.4$
- $\Delta N_{\rm eff}^{\rm (BBN)} \equiv N_{\rm eff}^{\rm (BBN)} - N_{\rm eff}^{\rm (SM)} < 0.25$
- Deviations: $\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{\rho_{\rm rad}}{3\rho_\gamma}$

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3} \frac{R^{(\Gamma)}}{3} \sim 0.05 \left(\frac{4}{g_{\rm DM}^{(\Gamma)}}\right)^{1/3} \left(\frac{300\ {\rm eV}}{m_{\rm DM}}\right)^{4/3}$$

- Safe and potentially interesting if DM light

Parameter space



$$\Gamma = \kappa^2 m_\Phi / 8\pi.$$

lines

Example: See-Saw Neutrino Model

$$\mathcal{L}_\nu = y_{ij} H \bar{L}_i N_j + M_{ij} N_i N_j$$

Large mixing angles
Usually o(1) entries
But lifetime turns out connect
To neutrino masses
Small Yukawa would generate
But single small Yukawa OK
We take ε ~ m_e/m_τ

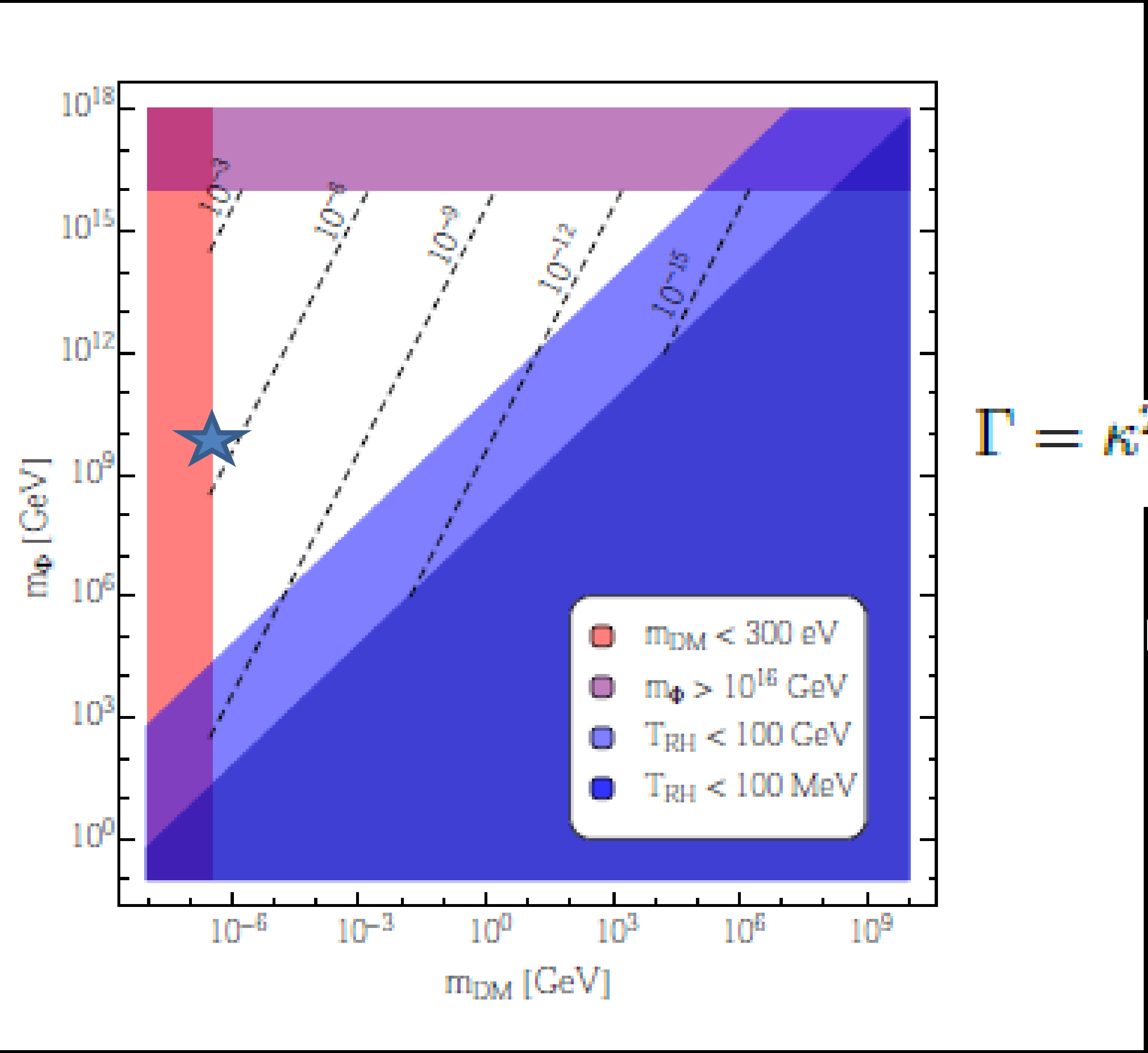
$$y_{ij} \sim \frac{m_\tau}{v} \times \begin{array}{cc} & \begin{array}{ccc} N_1 & N_2 & N_3 \end{array} \\ & \left(\begin{array}{ccc} 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \\ 1 & 1 & \epsilon \end{array}\right) \begin{array}{c} \nu_1 \\ \nu_2 \\ \nu_3 \end{array} \end{array}$$

(Abundance depends on $\Gamma_N (m_{\rm DM}/m_N)^2$ ~ $m_{\rm DM}^2 (y^2/M_N)$ If all o(1) DM mass would be too small)

$$\frac{\Omega_{\rm DM}}{\Omega_B} \simeq \left(\frac{45\zeta(3)}{2\pi^4}\right) \frac{y_e m_{\rm DM}}{m_B \Delta} \sqrt{\frac{M_{\rm Pl}}{8\pi M}} \sim 5 \times \left(\frac{m_{\rm DM}}{300 \text{ eV}}\right) \left(\frac{5\times 10^9 \text{ GeV}}{M}\right)^{1/2}$$

Thus for $y_{\nu_i} \sim y_{l_i}$ and an appropriate choice of $M \sim 10^9$ GeV $m_{\rm DM} \sim 300$ eV

Parameter space



$$\Gamma = \kappa^2 m_\Phi / 8\pi.$$

lines

Note

- Principle of maximum baroqueness applies
- Longest-lived RH neutrino is one coupled with electron Yukawa
- Decays last and reheats Universe

$$\Gamma \sim \frac{y_e^2 M_N}{8\pi} \sim 10^{-3}\ \mathrm{GeV}$$

Nice features

- For εdetermined by y_e/y_τ and m_{DM}~300 eV, falls nicely on our constraint plot
- Prediction is that neutrino masses (sum) at low end, since light mode indeed very light
- Naturally allows for leptogenesis
  - In fact less constrained since RH neutrino production decoupled from decay
  - Scales in agreement with rest of model
- This is more or less conventional lepto/baryogensis
- But our scenario implies other ways of thinking too

Baryogenesis

- New context in which to think about baryogenesis
- **Perhaps DM~Baryons, Photons separate population**
  – **Initial asymmetry in DM, Baryons**
  – **Entropy dumped into SM later**
- Or perhaps baryon asymmetry from Φ decay
  – Entropy dump produces asymmetry too
    - Eg Leptogenesis
- Or Φ carries asymmetry
- Or conventional late-time baryogenesis

Two Special Cases

- Minimum or Maximum Asymmetry

$$m_{\rm DM} \simeq \frac{2\pi^4}{45\zeta(3)} \frac{g_{\rm SM}^{(0)}}{g_{\rm DM}^{(0)}} \Delta_B^{(0)} \frac{\Omega_{\rm DM}}{\Omega_B} m_B \sim 5\ \text{GeV} \left(\frac{\Delta_B^{(0)}}{10^{-2}}\right) \left(\frac{4}{g_{\rm DM}^{(\Gamma)}}\right)$$

- Maximum asymmetry 10^{-9} associated with lightest dark matter
- Minimum asymmetry: 10^{-2} mass~GeV
  - Like **asymmetric dark matter**
  - But **late** entropy dump dilutes SM and DM together

Future Searches for Dark Matter

- DM search often means WIMP search
- W/o direct connection much less accessible
- Model specific possible
  - Some connection likely if abundance explained
    - Here light neutrinos
  - But connection could be early, high energy
- Alternative direction is detailed study of structure
  - Good time: large data sets, better processing power
- Here possible implications for core-cusp problem in dwarf galaxies
- Again not guaranteed
  - But would be a waste to miss

Profile including Fermi degeneracy

Match to data???

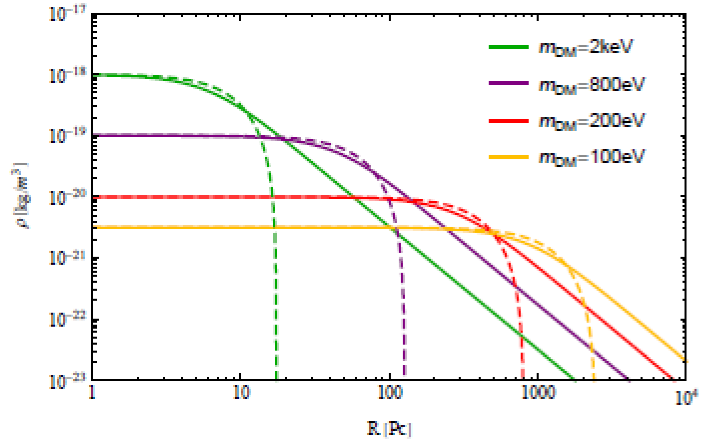


Figure 2. We treat the dark matter as a quasi-degenerate self-gravitating Fermi gas, for constituent fermions of mass of various masses. We find the density profiles which are solutions to the hydrostatic equilibrium equation. Observe, for 2 keV fermions the profile is decidedly cuspy, whereas the profiles for 100 eV and 200 eV dark matter exhibits flat cores of a few hundred parsecs. The dashed curves correspond to solutions to eq. (23), and give the distributions corresponding to fully degenerate Fermi gases.
what is the central density here?

Conclusion

- A sampling of new ideas about dark matter
- Rich arena for model building
- Also rich arena for thinking about new methods of detection
- A very different approach to dark matter searches
  - But even traditional searches will change
- Good physics to be thinking about now

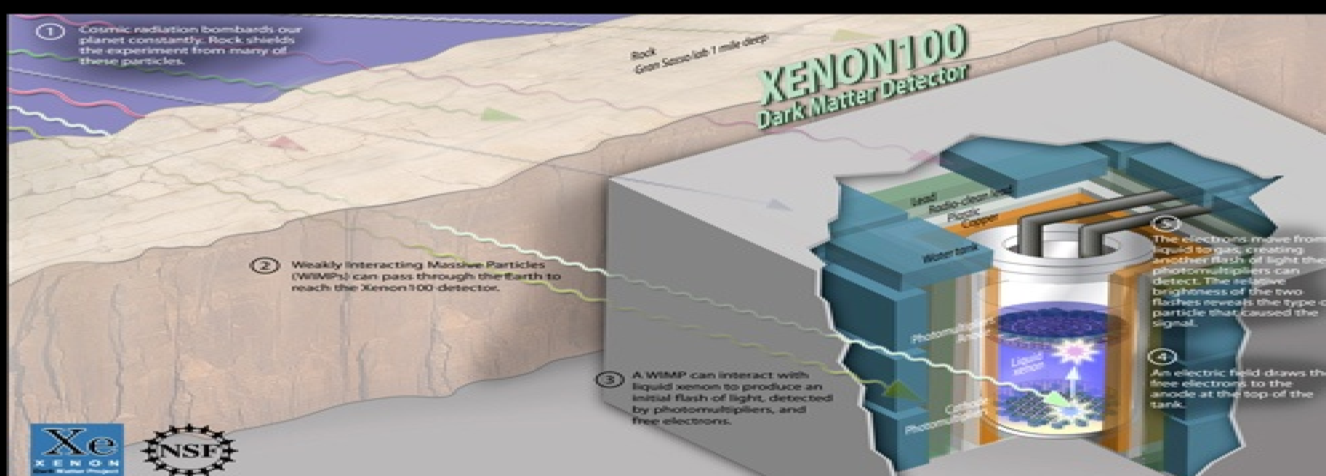
What Is Dark Matter?

- 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

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

Experimental Lampposts: Direct Detection

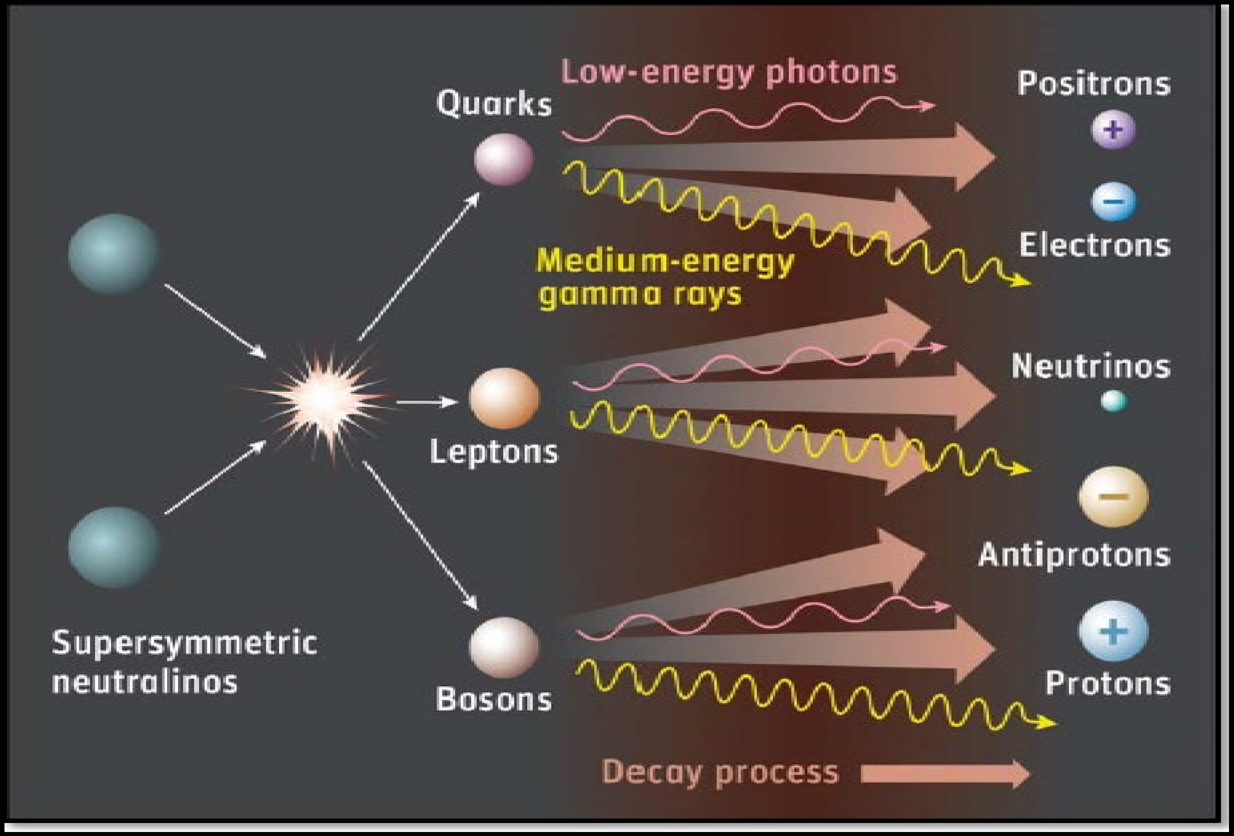
- Look for low probability dark matter interactions with large detectors
- Look for small nuclear recoil
- Good way to look for a well-motivated class of candidates (WIMPs)
- We haven't seen it yet
  - Waiting for more sensitive searches



Experimental Lampposts: LHC

- LHC: Look for evidence of a stable particle with weak scale mass
  - Remarkably, has the right energy density to constitute dark matter
- Such a particle likely in ANY weak scale model that supplements Higgs theory
  - WIMP not necessarily supersymmetric!
  - Any stable weak scale particle can be a candidate
- We haven't yet seen beyond Higgs
    - Waiting for higher energies, more intensity
- Don't yet know if this lamppost in the right region

Experimental Lampposts: Indirect Searches



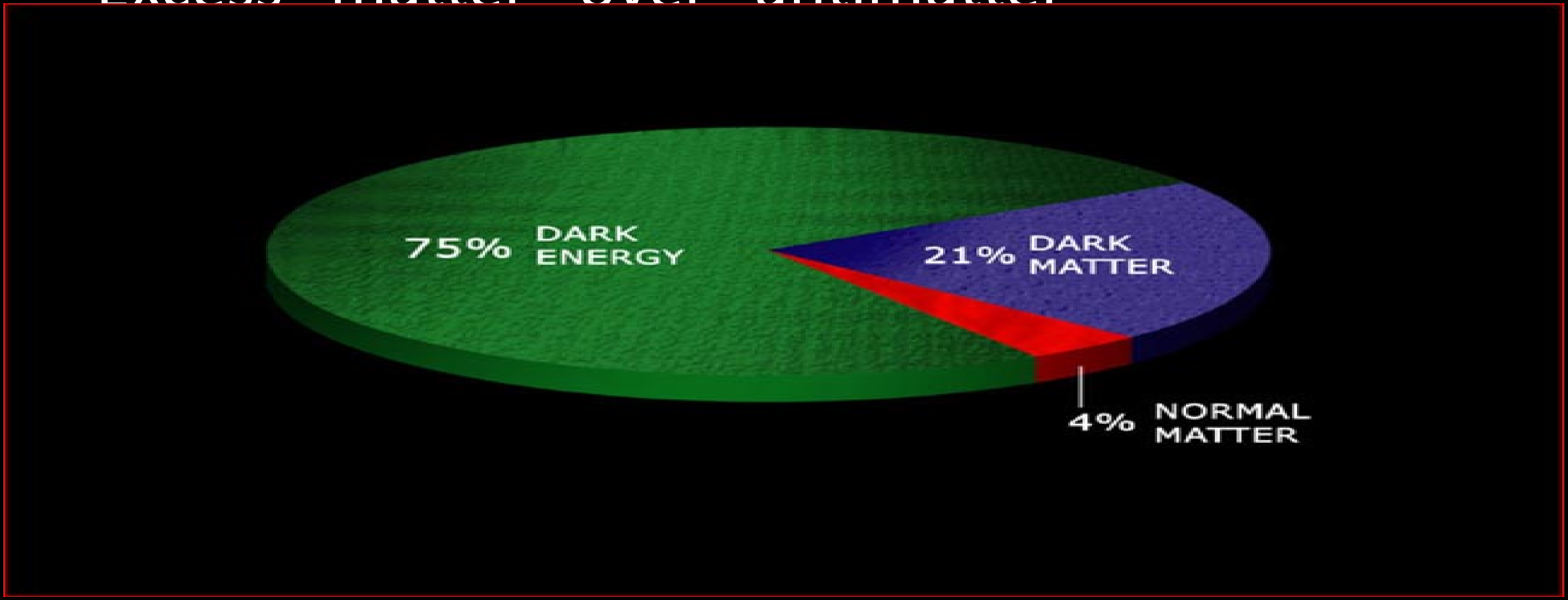
Dark Matter

- 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

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”



- Other ideas include
  - Asymmetric Dark Matter models promising
    - Hard to detect
  - Axions
    - Challenges to detection and narrow window
-
- But actually finding a dark matter particle will be tough
  - Almost all non-WIMP models extremely challenging to detect
- In principle could be purely gravitational coupling
  - **Or coupling only to its own sector**
- Given potentially empty-handed direct searches all potentially detectable alternatives worth investigating

Another possibility

- Don’t explain any miracle
- Theoretical motivation just what you might expect based on inflation and “democracy”

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- Unprejudiced attitude toward dark matter

w/Scholtz, Unwin

- Assume dark matter, ordinary matter separate sectors
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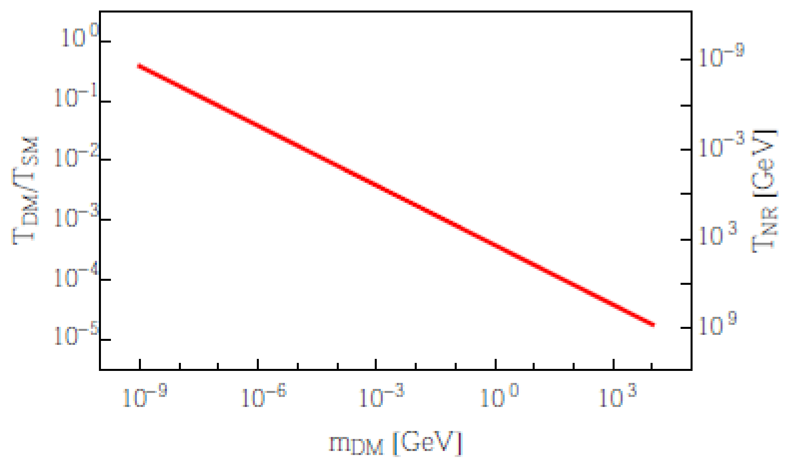

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- Also of interest
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  - New types of models
  - Potential implications for free-streaming bounds, core-cusp

Aside

- One can ask why we don’t see more light degrees of freedom (assuming decoupled dark sectors reheated after inflation)
  - They are not there
  - There are no heavy states in those sectors to heat them
  - **They are cooler**

Scenario

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- Primordial DM that redshifts relativistically
- At late time, Φ decays
  - Lifetime determines relative temperatures
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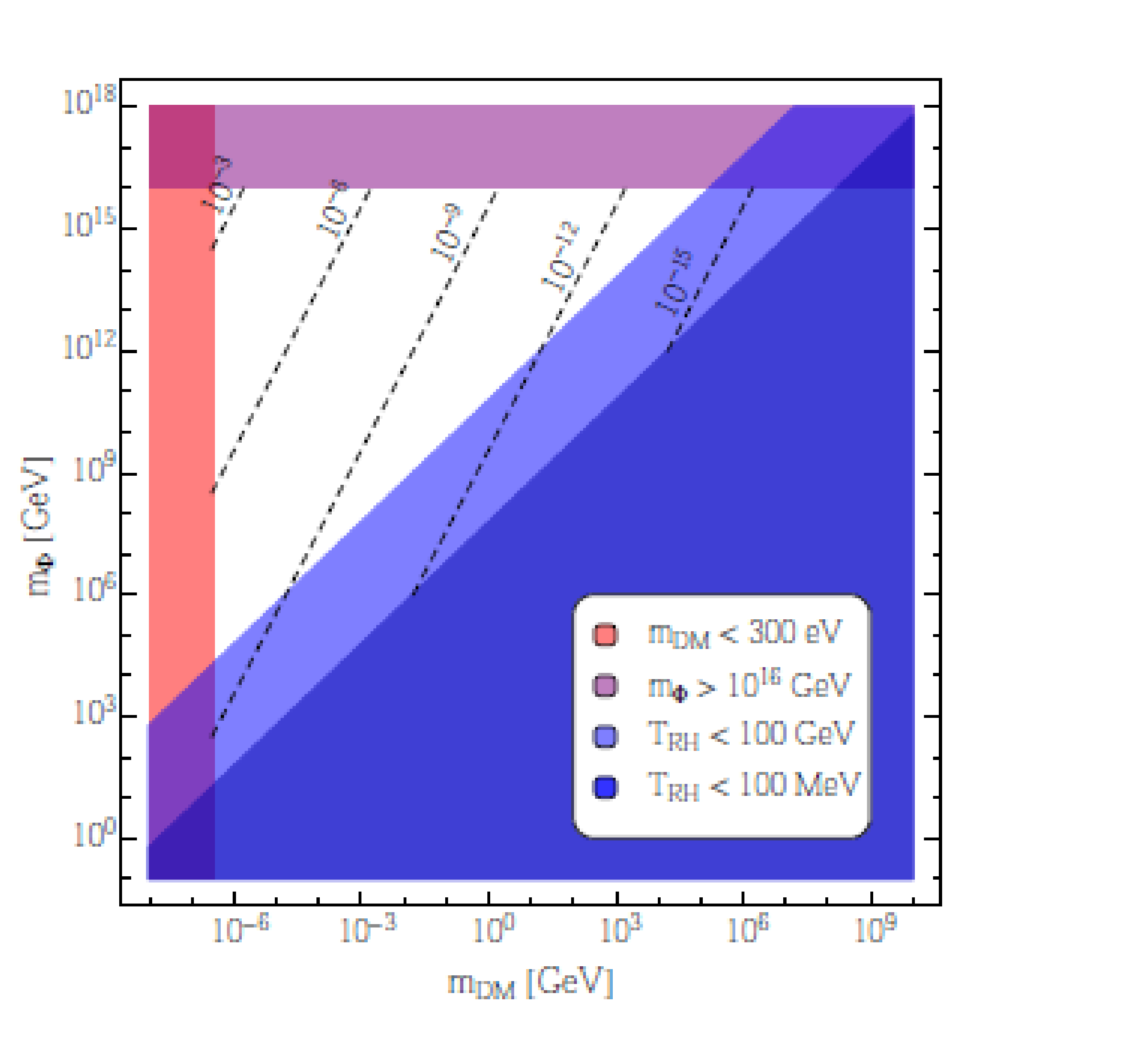

$$\Gamma = \kappa^2 m_\Phi / 8\pi .$$

Dashed lines
fixed κ

Example: See-Saw Neutrino Model

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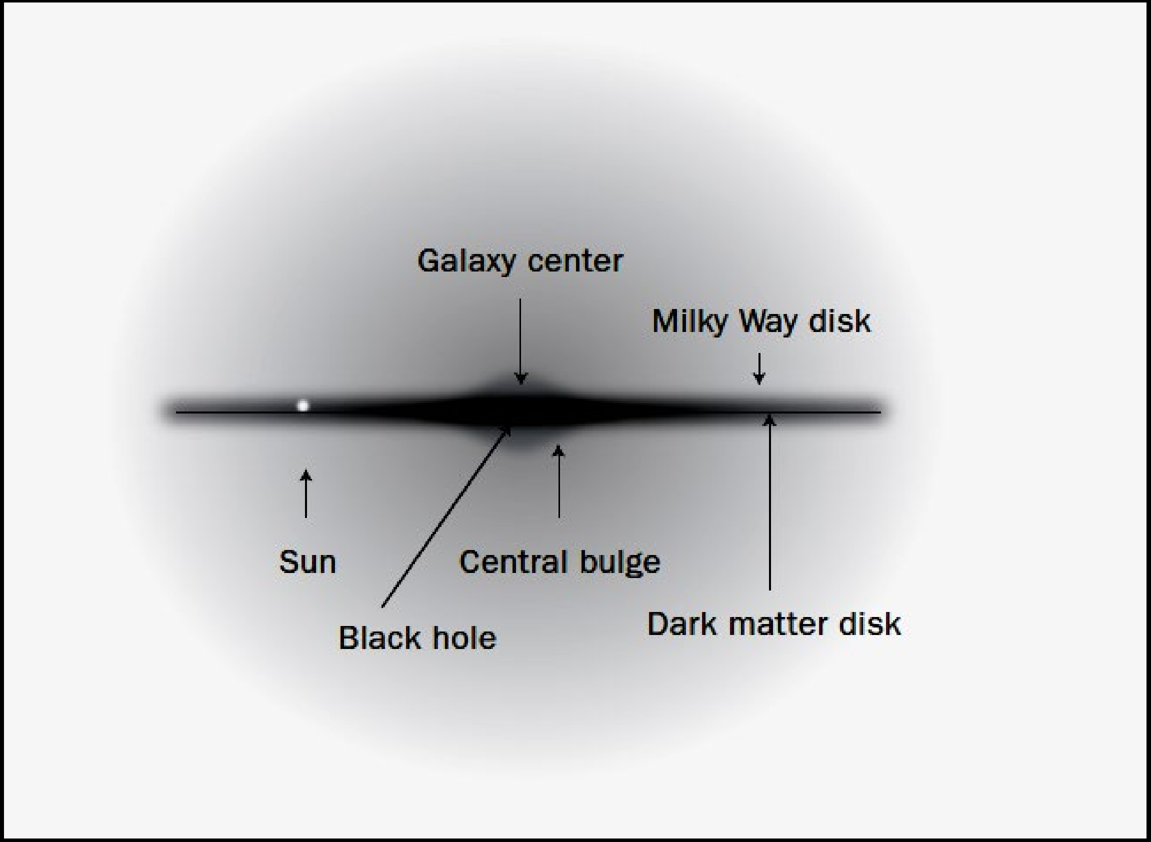
Thus for $y_{\nu_i} \sim y_{l_i}$ and an appropriate choice of $M \sim 10^9$ GeV $m_{\rm DM} \sim 300$ eV

DOUBLE DISK DARK MATTER

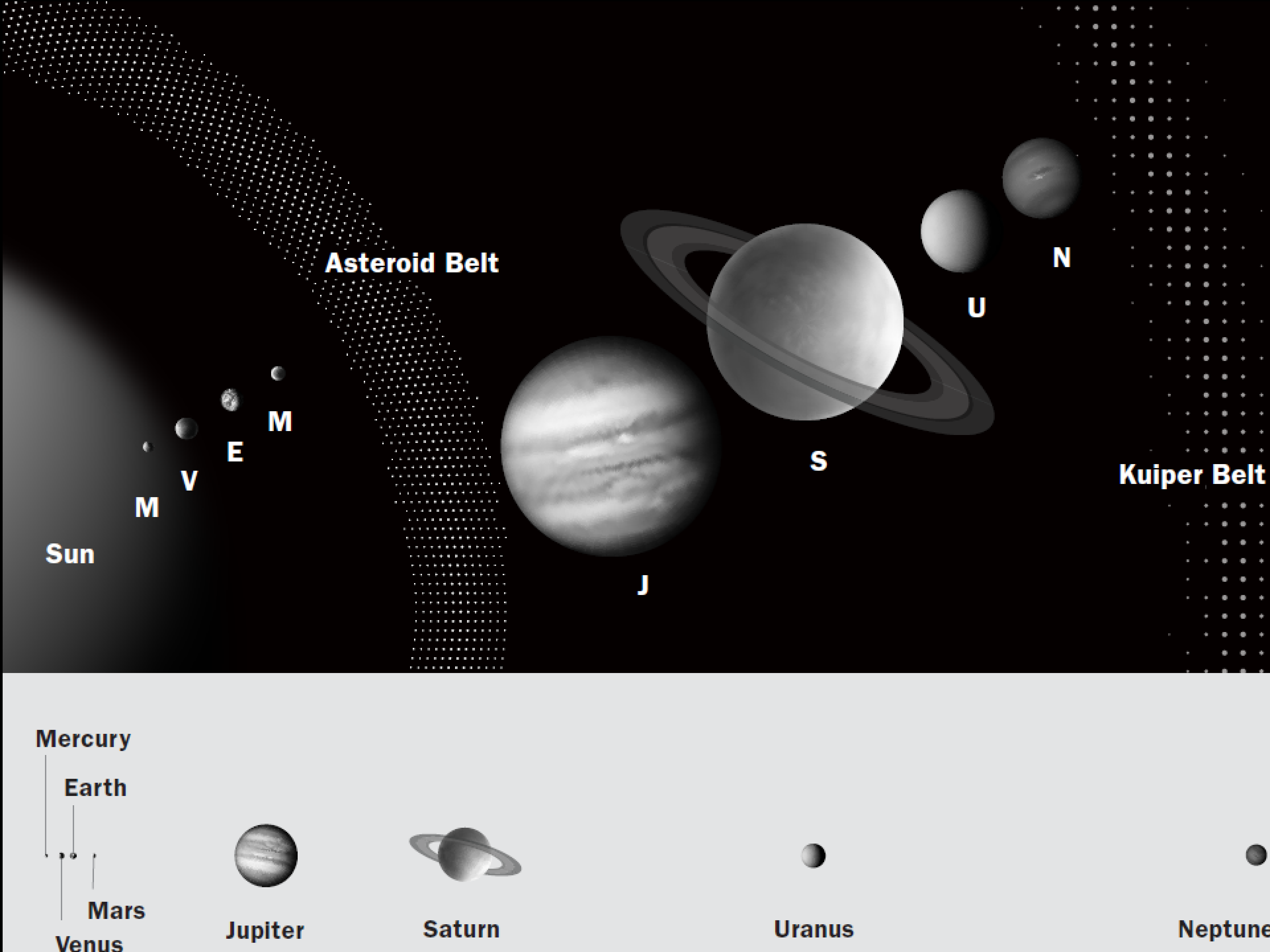
Thin disk of dark matter inside Milky Way disk!



Other Basic Insight

- Bringing in different fields of research:
- New ideas
- My collaborators and I are particle physicists
- Results have implications for astronomy, cosmology
  - Changes the shape of the galaxy: a dark disk
- Influences the motion of stars
- And perhaps more….

Other Consequences…

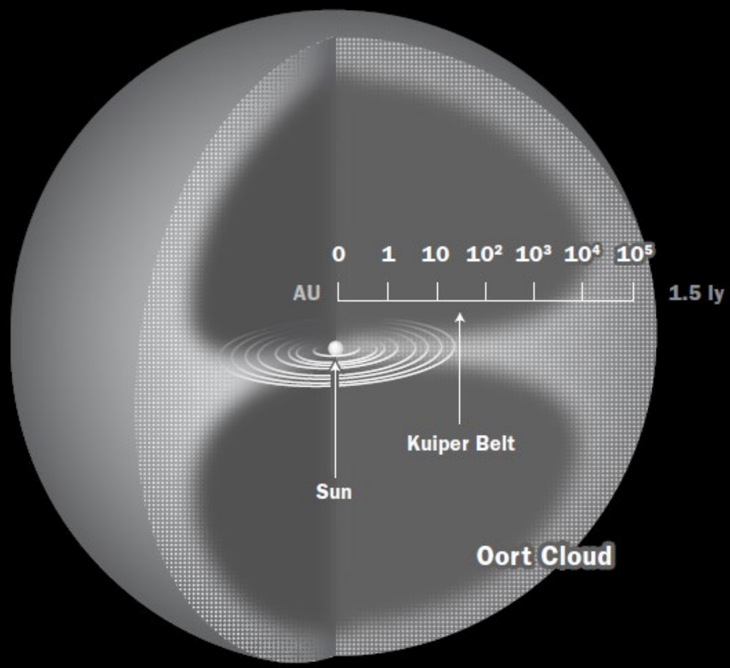

Asteroid Belt
N
U
M
E
V
S
M
Sun
J
Kuiper Belt
Mercury
Earth
Mars
Venus
Jupiter
Saturn
Uranus
Neptune

OORT CLOUD: LONG-PERIOD COMETS

Much Farther Away

Thousands of AUs

Good fraction of a light year



SOME STUFF HITS

Example: Meteor/Barringer Crater in Arizona shown below

Active Solar System

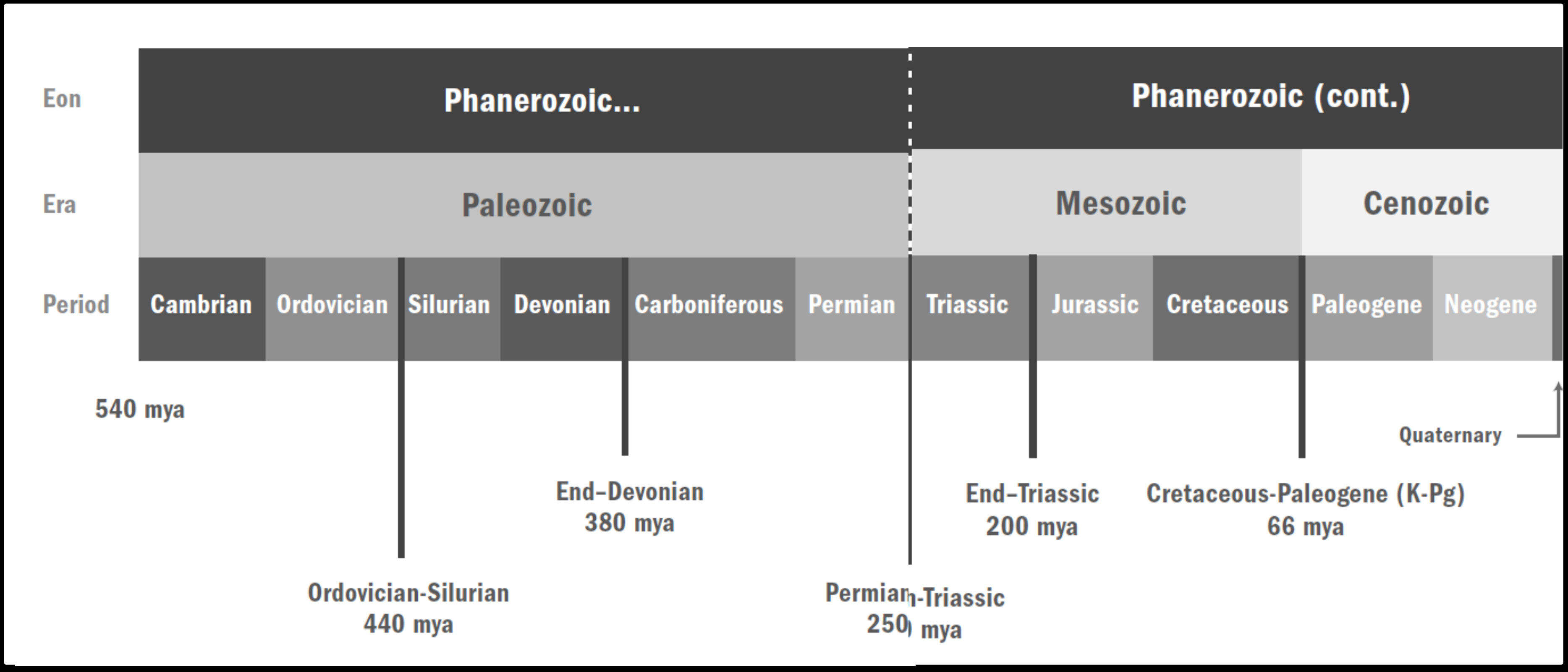
List of craters greater than 20 kilometers across From last 250 million years

Crater Name	Age (millions of years)		Diameter (km)
Saint Martin	220	± 32	40
Manicouagan	214	± 1	85
Rochechouart	201	± 2	23
Obolon'	169	± 7	20
Puchezh-Katunki	167	± 3	40
Morokweng	145.0	± 0.8	70
Gosses Bluff	142.5	± 0.8	22
Mjølnir	142.0	± 2.6	40
Tunnunik (Prince Albert)	> 130, < 450		25
Tookoonoka	128	+/- 5	55
Carswell	115	± 10	39
Steen River	91	± 7	25
Lappajärvi	76.20	± 0.29	23
Manson	74.1	± 0.1	35
Kara	70.3	± 2.2	65
Chicxulub	65.17	± 0.64	24
Boltysh	66	+/- 0.03	150
Montagnais	50.50	± 0.76	45
Kamensk	49.0	± 0.2	25
Logancha	40	± 20	20
Haughton	39		23
Mistastin	36.4	± 4	28
Popigai	35.7	± 0.2	90
Chesapeake Bay	35.3	± 0.1	40
Ries	15.1	± 0.1	24
Kara-Kul	< 5		52

From Earth Impact Data Base

DARK DISK, COMET STRIKES, K-PG EXTINCTION

Making way for emergence of large mammals—and us



AMAZING CONNECTIONS

- Star burning and composition determined by nuclear forces
- Our planet's geology (and hence carbon cycle and life) rely on nuclear processes too
- Cosmos, galaxies from dark matter collapse

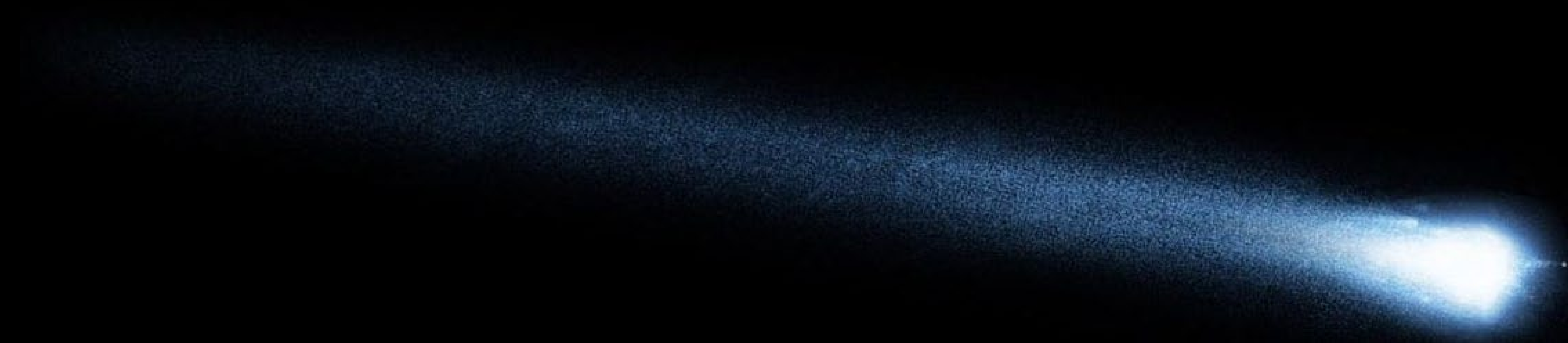
- Large mammals emerged only after dinosaurs eliminated:
- Can there be one more dark matter connection?

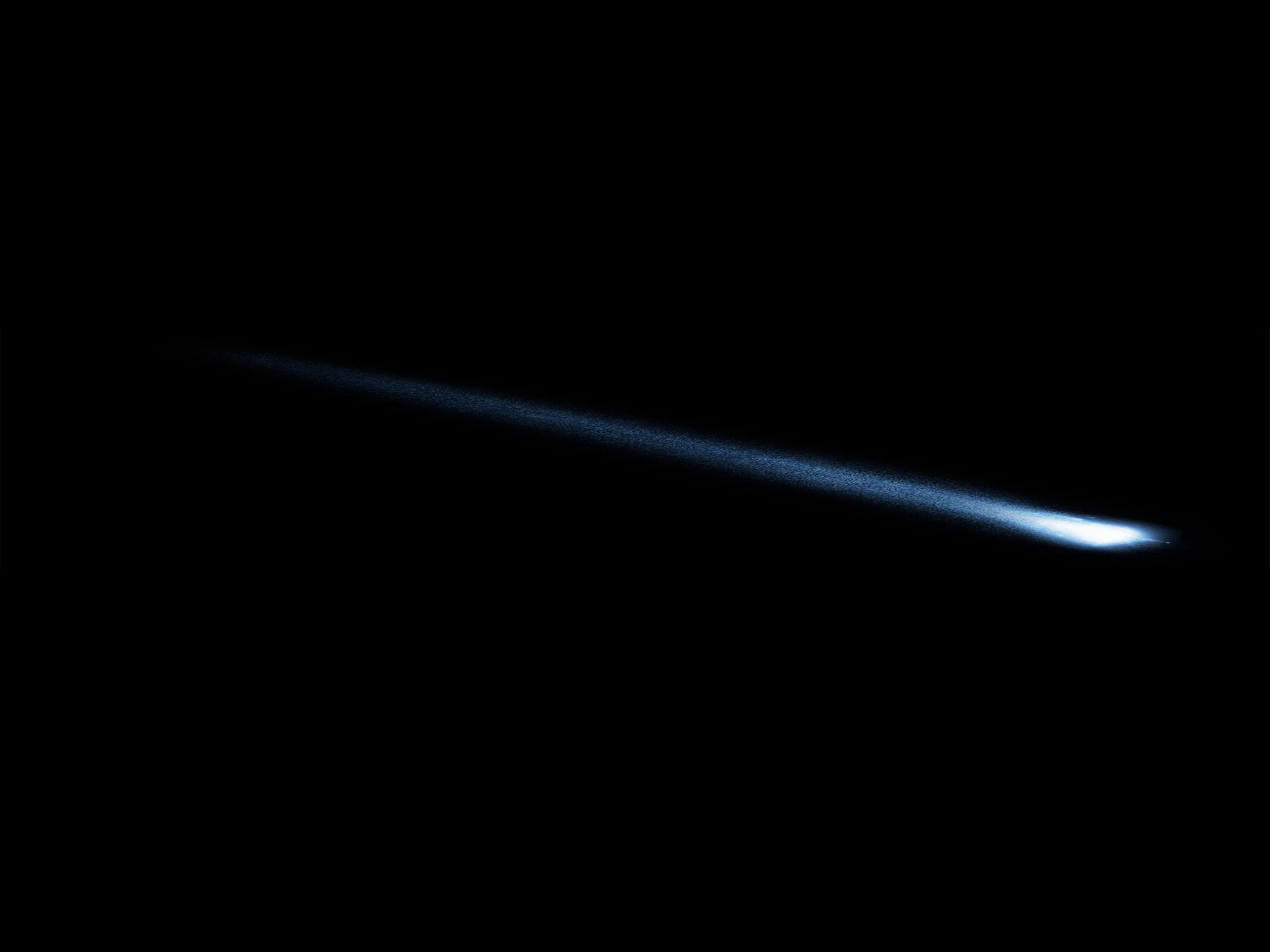
DMATD: Four Major Lessons (for me)

- Awe and wonder
- Many fields of science
- How recent is our understanding
- The importance of the rate of change

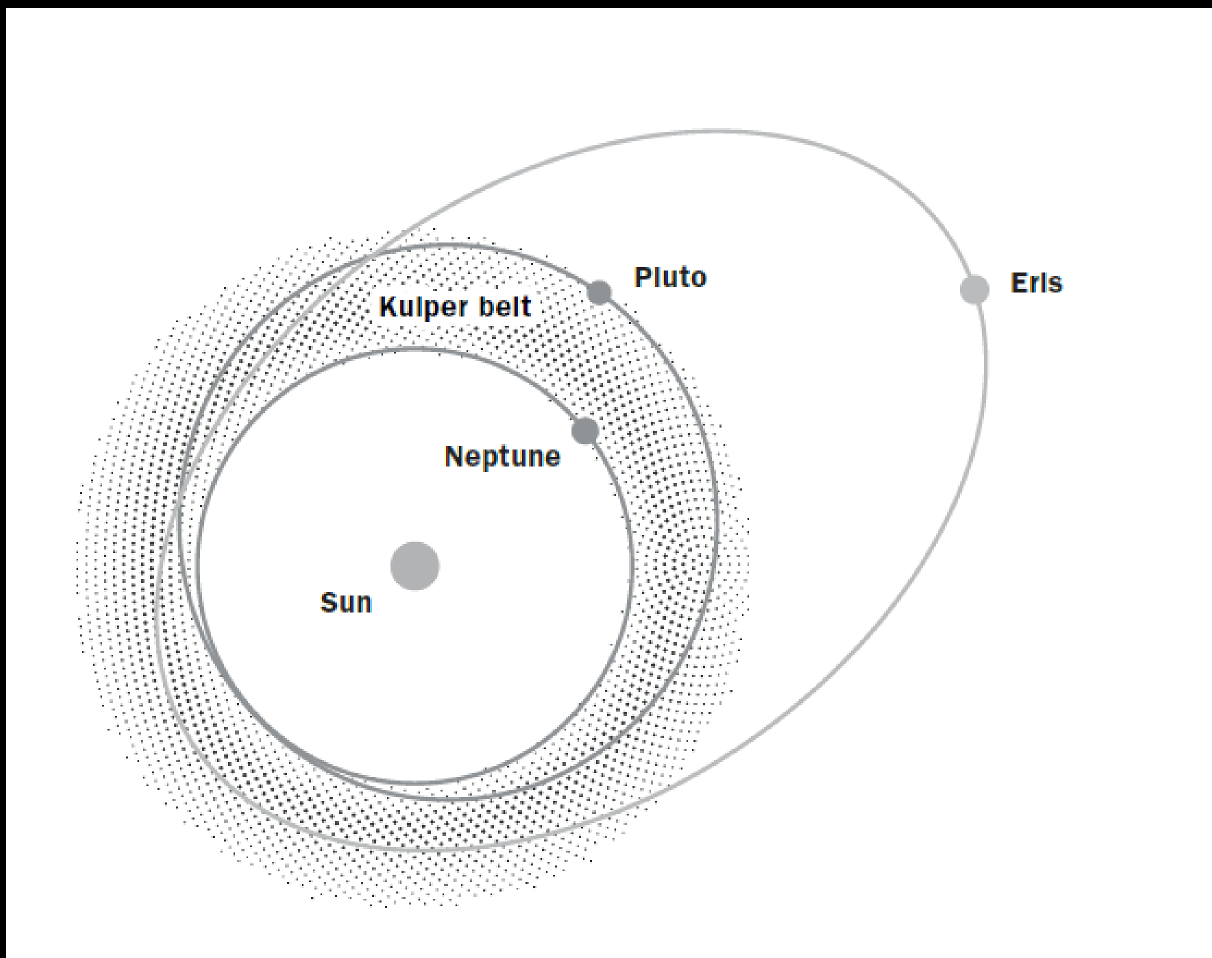
Connections

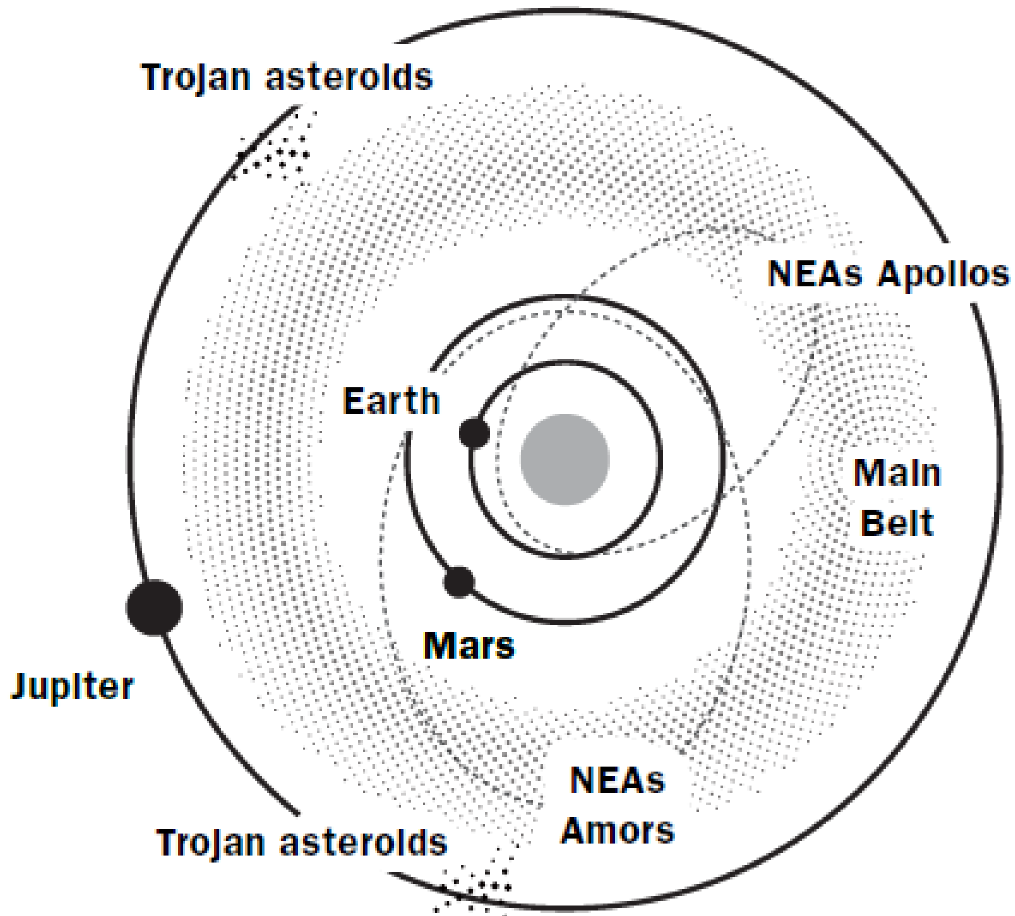
- I don’t know if dark disk is right
- search for it ongoing as we speak
  - Kinematics
  - Planar dwarf galaxies in Andromeda
  - Dwarf galaxy shapes
  - Effect on Cosmic Microwave Background
- I do know we will learn more about some amazing connections in the Universe—and ultimately to life





SHORT PERIOD COMETS FROM SCATTERED DISK
RIGHT OUTSIDE KUIPER BELT





Trojan asteroids
NEAs Apollos
Earth
Main
Belt
Mars
Jupiter
NEAs
Amors
Trojan asteroids

HOW DANGEROUS?

TABLE 2.2 Expected Fatalities per Year, Worldwide, from a Variety of Causes

Cause	Expected Deaths per Year
Shark attacks[a]	3-7
Asteroids[b]	91
Earthquakes[c]	36,000
Malaria[d]	1,000,000
Traffic accidents[e]	1,200,000
Air pollution[f]	2,000,000
HIV/AIDS[g]	2,100,000
Tobacco[h]	5,000,000

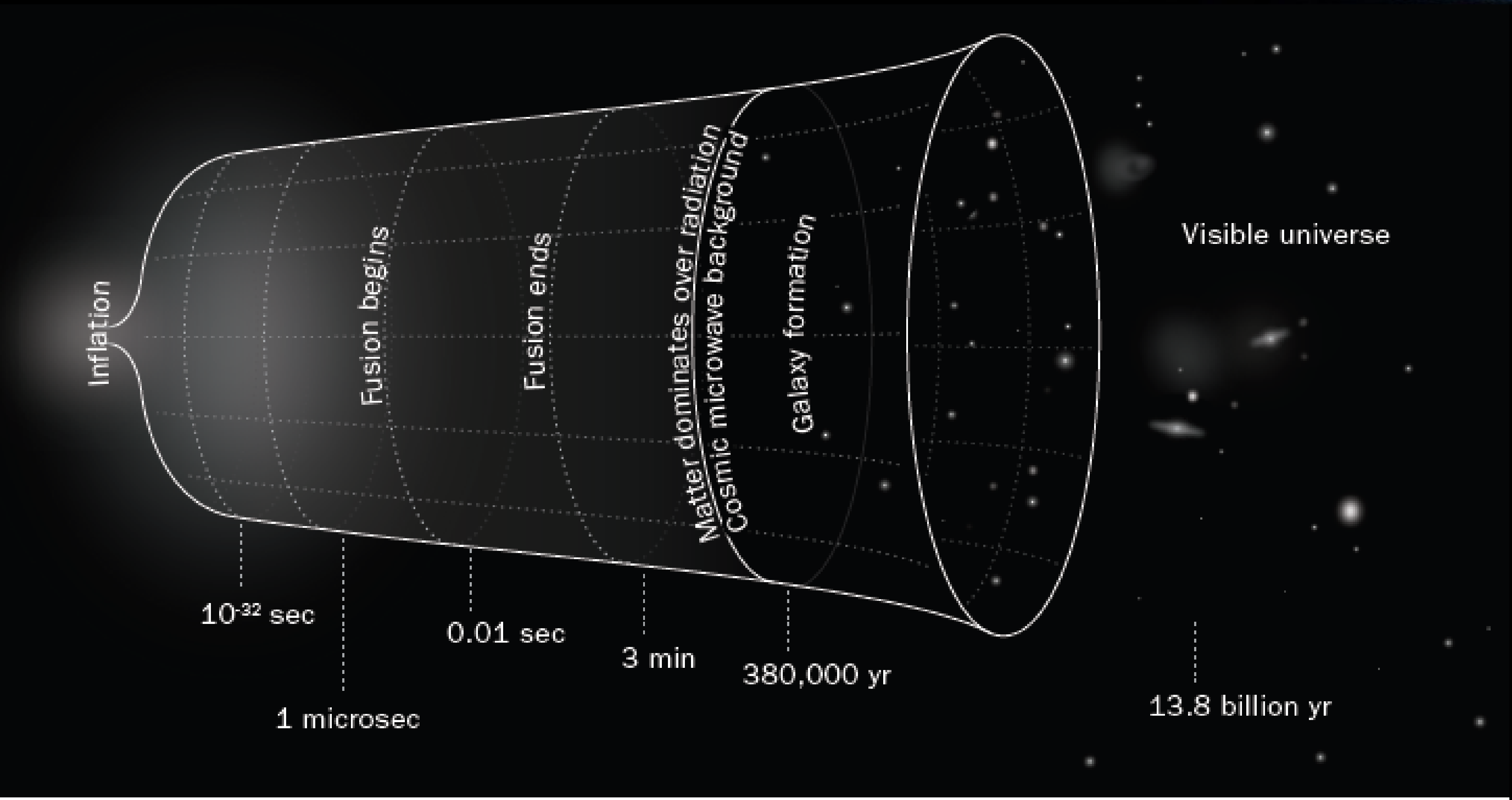
TABLE 2.1 Approximate Average Impact Interval and Impact Energy for Near-Earth Objects

Type of Event	Characteristic Diameter of Impacting Object	Approximate Impact Energy (MT)	Approximate Average Impact Interval (yrs)
Airburst	25 m	1	200
Local scale	50 m	10	2,000
Regional scale	140 m	300	30,000
Continental scale	300 m	2,000	100,000
Below global catastrophe threshold	600 m	20,000	200,000
Possible global catastrophe	1 km	100,000	700,000
Above global catastrophe threshold	5 km	10 million	30 million
Mass extinction	10 km	100 million	100 million

What you will know

Dark matter, dinosaurs, what's the connection
What's in the Universe
Expansion, accelerated expansion, exponential
Dark matter's role in structure of Universe
Where is it, Why it's a bad name, How will we find it
How dangerous are asteroids and comets
Where is the Oort cloud, nature of Solar System
How we know about dinosaur extinction cause
Love-hate relationship of Earth and its environment
Order and lack of order
Why should we care

BIG BANG THEORY AND INFLATION



IN THE DARK

- Dark matter, dark energy, atoms

- All pose big questions for cosmology
    - I’m focusing on dark matter
        - Most likely to be tested experimentally
        - And focus of many new ideas