Direct Detection of Slow Dark Matter

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MORTIMER B. ZUCKERMAN STEM LEADERSHIP PROGRAM

Classic Direct Detection: The WIMP

- No signs of weak scale DM, weakly coupled LSP
- Direction detection landscape is changing
- New experiments searching for MeV and keV - scale dark matter
- Can these be used to find slow dark matter?

What is slow DM?

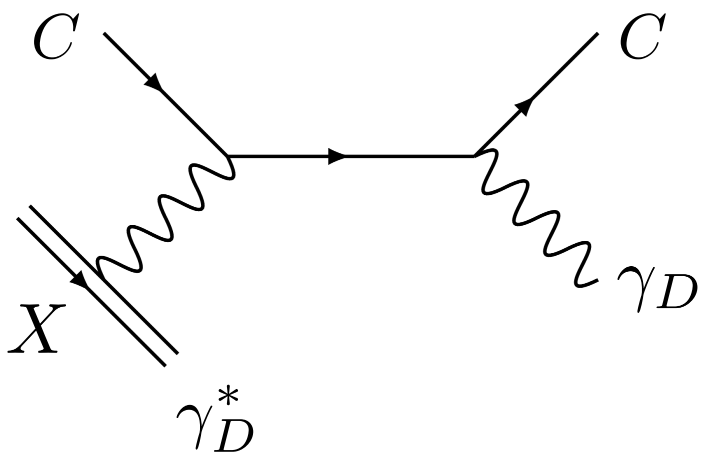
- Halo Dark Matter is expected to have velocity dispersion of $V_{\text{thermal}} \simeq 220\,\text{km/s} \sim 10^{-3}\,c$
- In elastic collision, deposits energy on light target $E_{\text{dep}} \sim m_{\text{target}} V_{\text{thermal}}^2 \sim \text{ keV}$
- For slow DM, $V \sim 10^{-4}$
- Need:
  - heavy target (large E_{dep}), or
  - low threshold, or
  - bound electrons (inelastic collision, $E_{\text{dep}} \sim m_X V^2$)

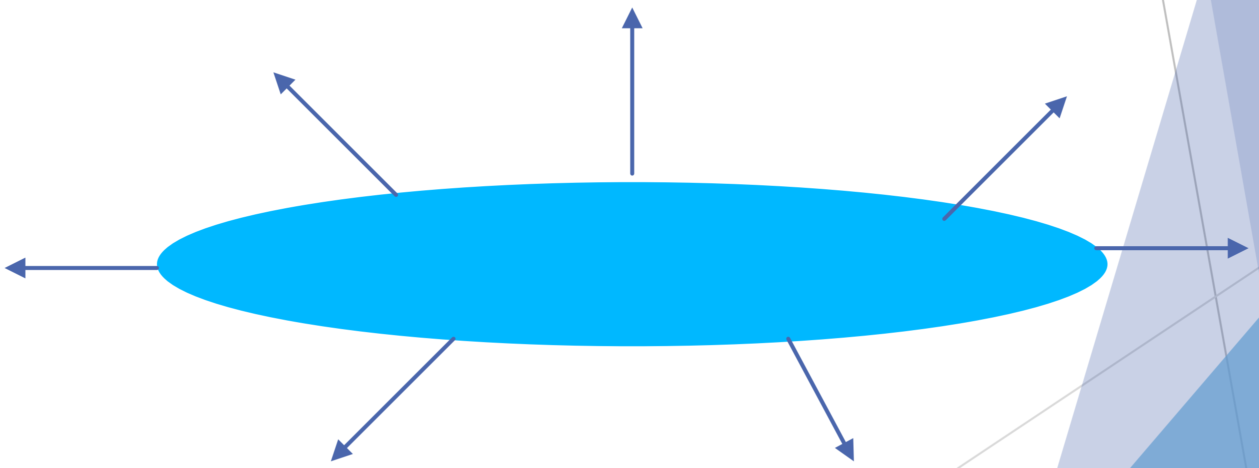
Example of Slow Dark Matter

- Fraction of Dark Matter is dissipative:
  - Collapses to form a disk
  - Disk corotating with the Milky Way
  - Relative velocity (earth - DM) reduced by an order of magnitude

Dissipative Dark Matter

- Jiji Fan, Andrey Katz, Lisa Randall, Matthew Reece study DDDM (1303.3271, 1303.1521)
  - % level fraction of DM
  - Dark interactions
  - dissipative —> cooling —> disk
- increased local dark matter density - possibly aligned with baryonic disk





Viable?

- 1711.03103
- Analysis redone using Gaia data
  - young A,F,G stars
- Dark Disk strongly constrained

1711.03103

Constraining a Thin Dark Matter Disk with *Gaia*

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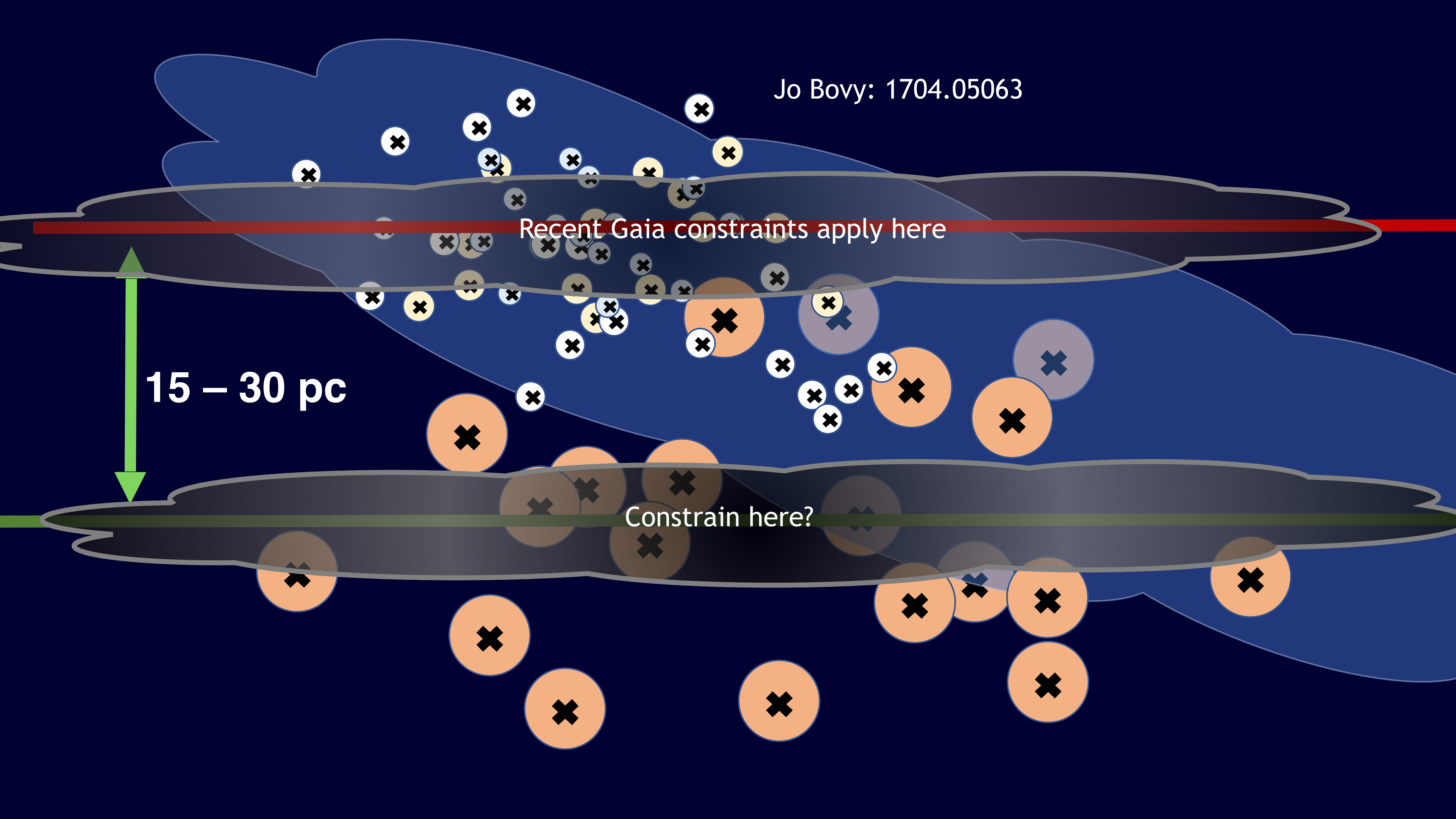
If a component of the dark matter has dissipative interactions, it could collapse to form a thin dark disk in our Galaxy that is coplanar with the baryonic disk. It has been suggested that dark disks could explain a variety of observed phenomena, including periodic comet impacts. Using the first data release from the *Gaia* space observatory, we search for a dark disk via its effect on stellar kinematics in the Milky Way. Our new limits disfavor the presence of a thin dark matter disk, and we present updated measurements on the total matter density in the solar neighborhood.



Jo Bovy: 1704.05063
Recent Gaia constraints apply here
15 – 30 pc
Constrain here?

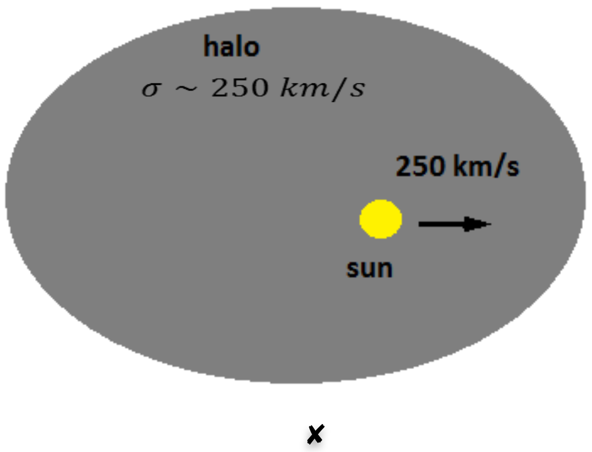
Corotating?

- Because of the virial theorem, rotation speed is the same:
  - $U = -2K_{\text{rot}} - 2K_{\text{thermal}}$
  - Halo:
    - $$\langle v_{\text{disp}}^2 \rangle \sim K_{\text{thermal}} \sim \frac{GM}{R} \sim (220\,\text{km/s})^2$$
  - Disk:
    - $$\langle V_{\text{rot}}^2 \rangle \sim K_{\text{rot}} \sim \frac{GM}{R} \sim (230\,\text{km/s})^2$$
- Assume angular momentum vectors are aligned

Corotating Dark Matter

- Traditional (halo) dark matter:

$$V_{\rm bar} = V_c \sim V$$
$$V_{\rm DM} = \langle v^2 \rangle^{1/2} = \sigma \sim V$$
$$V_{\rm rel} \simeq \sqrt{2}\, V + v_E(t)$$

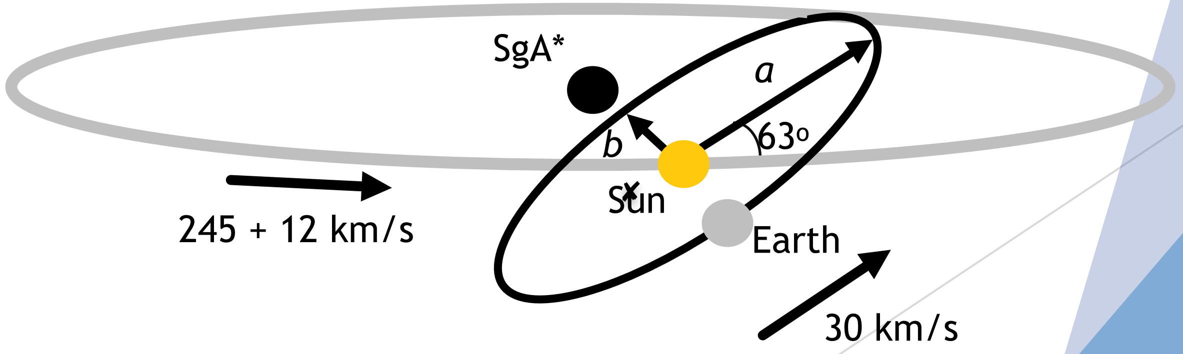


- Annual modulation due to Earth's velocity:

$$v_E \simeq 30\,{\rm km/s} = 10^{-4}\, c$$

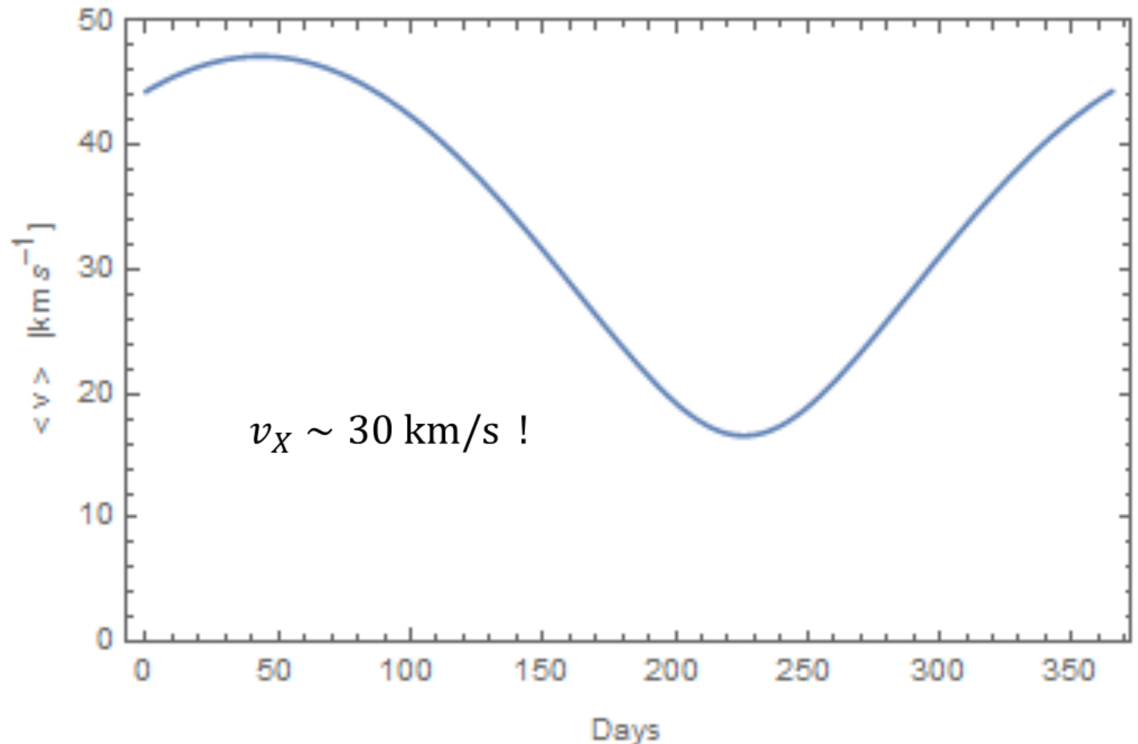
- Corotating (disk) dark matter:

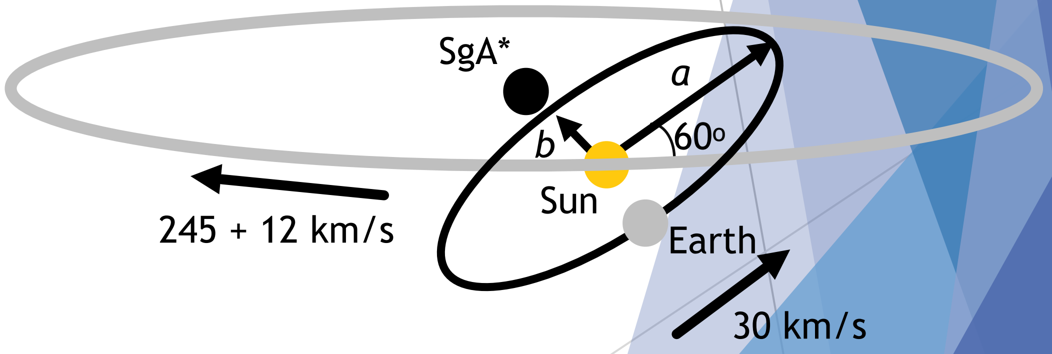
$$V_{\rm bar} = V_c \sim V$$
$$V_{\rm DM} = V_c \sim V$$
$$V_{\rm rel} \simeq v_E(t)$$



Corotating Dark Matter

- WIMP - target relative speed
- $t = 0$ corresponds to ~ Dec 10 (Sun in Saggitarius)
- $\vec{v}_{rel} \quad = \vec{V}_{\odot} + \ \vec{v}_E + \vec{r}(\sigma_0)$
- $\langle v_{rel} \rangle \simeq \sqrt{(V_{\odot} + v_E \cos\theta \cos t)^2 + (U_{\odot} + v_E \sin t)^2 + (W_{\odot} + v_E \sin\theta \cos t)^2 + \sigma_0^2}$

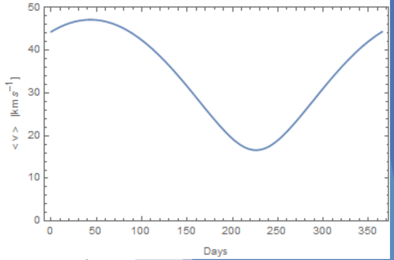


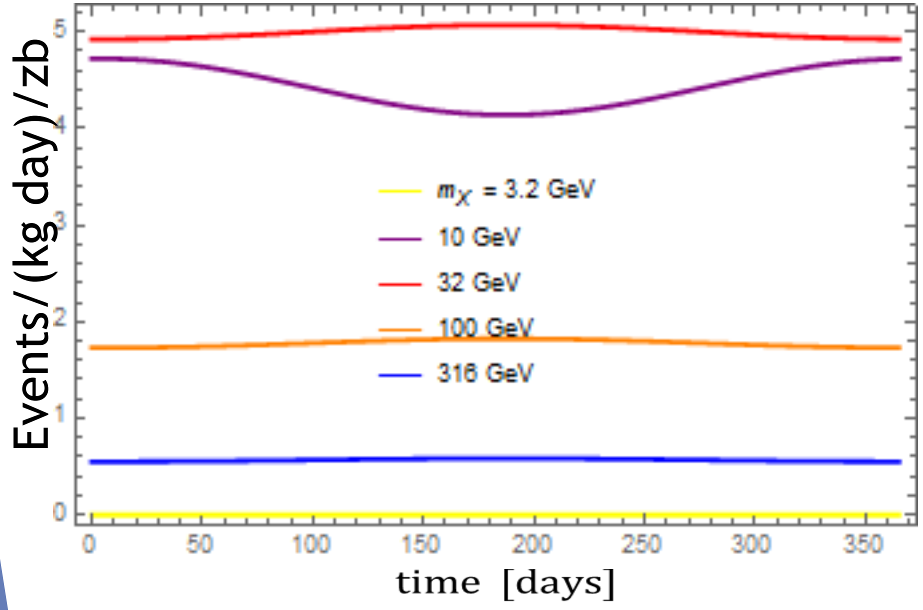


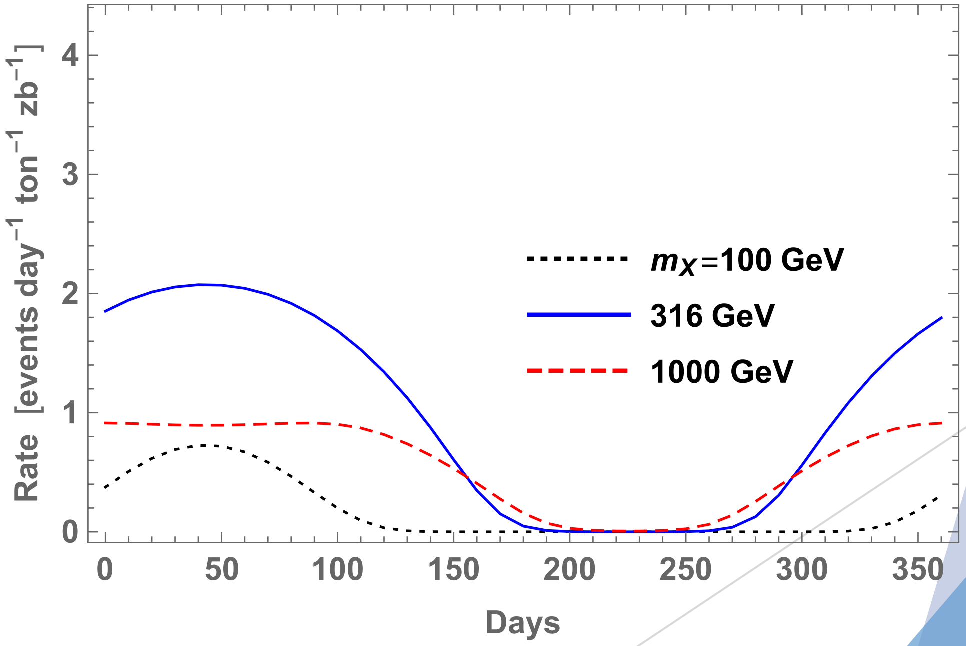
Nuclear Recoil Rates for Liquid Xe (2 keV threshold)

- **Halo dark matter**
- Xe nuclei: $m_T = 123$ GeV
- Local density:
- $\rho_{\text{halo}} = 0.38$ GeV / cm^3

- **Corotating dark matter**
- $\rho_{DM} = 3.8$ GeV / cm^3 $= 10\,\rho_{\text{halo}}$
- $v_X \simeq 20 - 50$ km/s
- $v_{\text{threshold}} = \sqrt{\dfrac{E_{th}}{2m_T}} \simeq 27$ km/s
- (no signal in summer months)

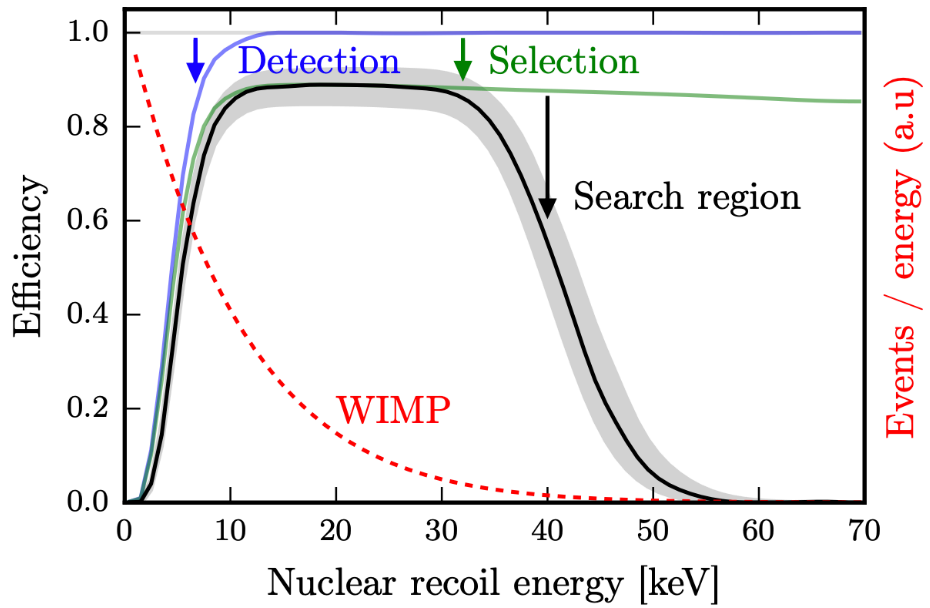


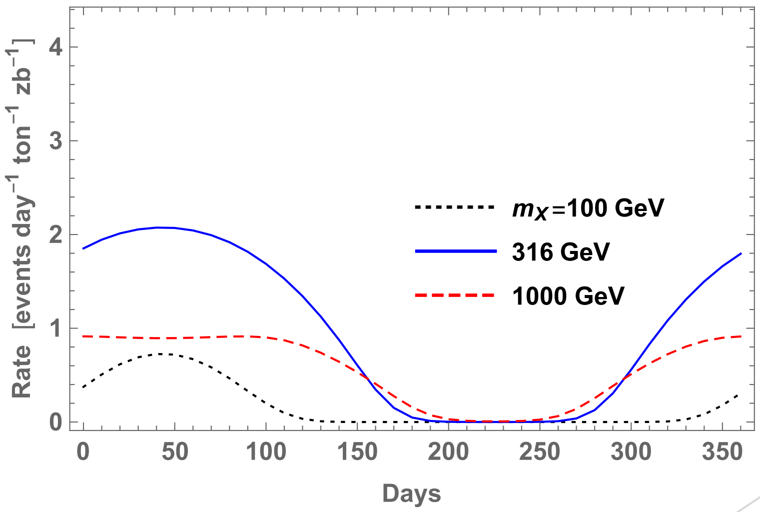




XENON1t detector threshold

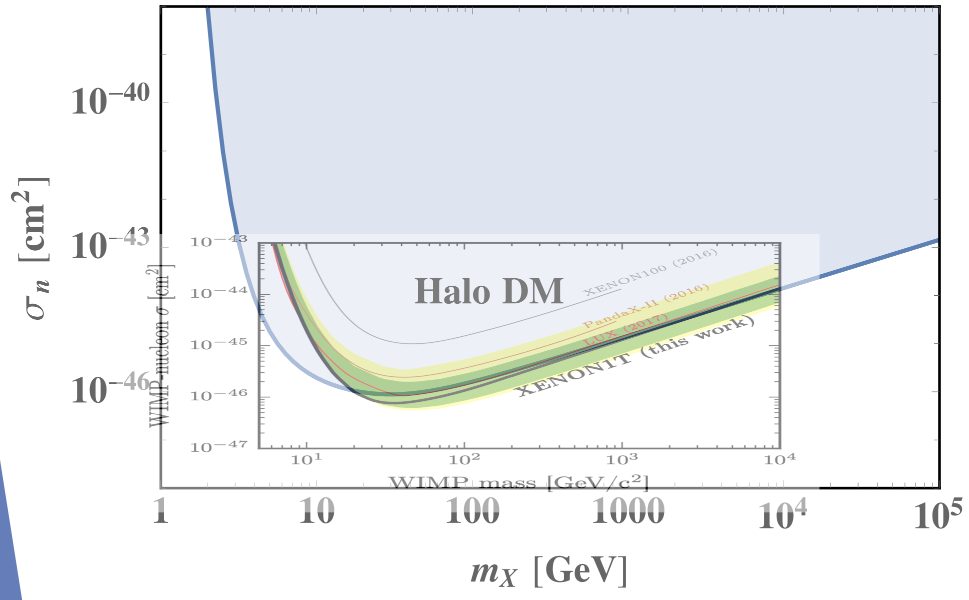
- ~ 2 keV threshold (1705.06655)
- $v_{\text{threshold}} = \sqrt{\dfrac{E_{\text{th}}}{2m_T}} \simeq 27\,\text{km/s}$ (Xe)

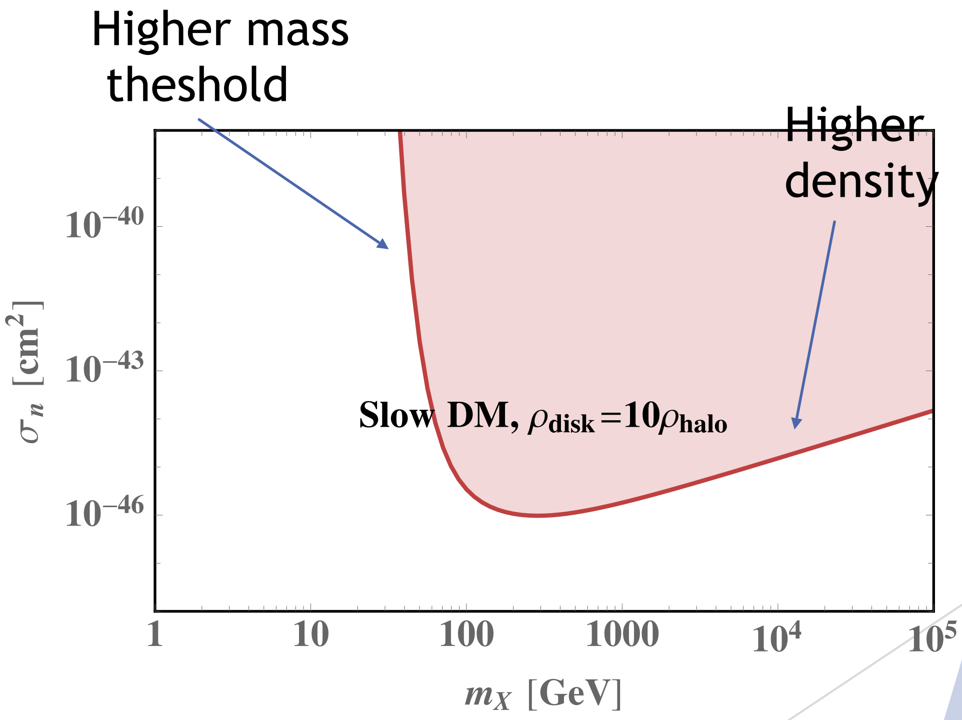




Nuclear Recoil Reach for Slow DM

* Comparable reach (enhanced density of disk)
* Higher threshold





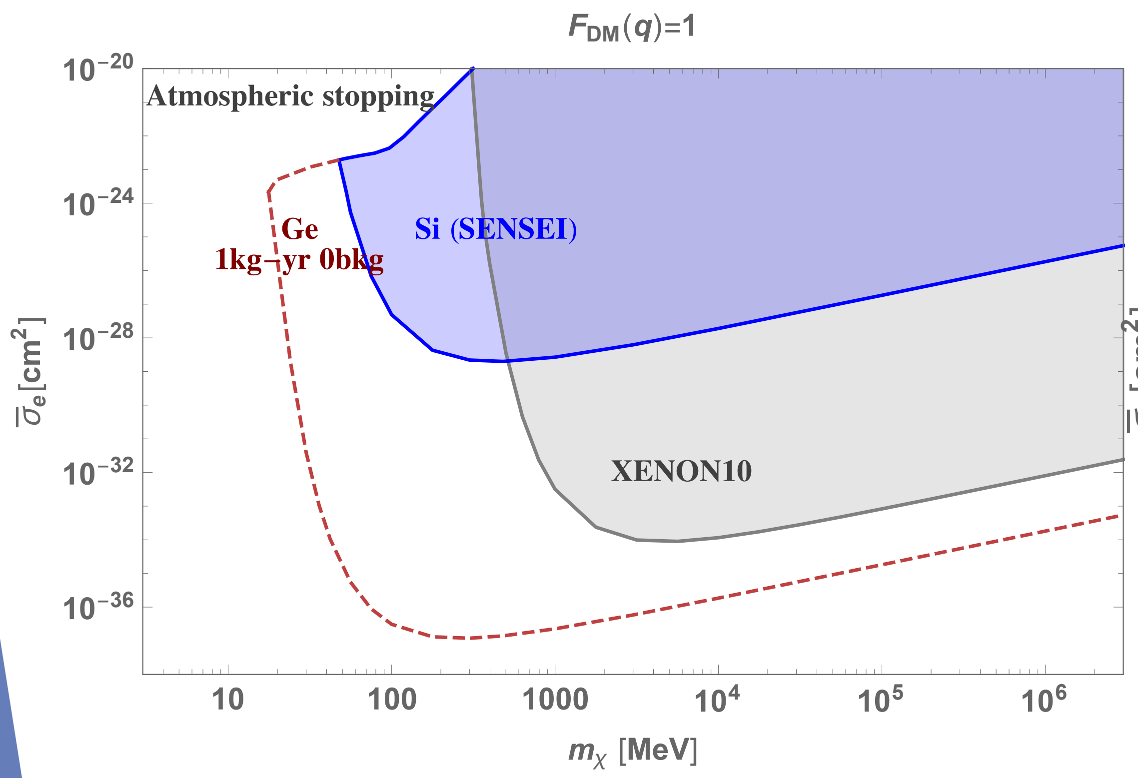
Electron Recoil

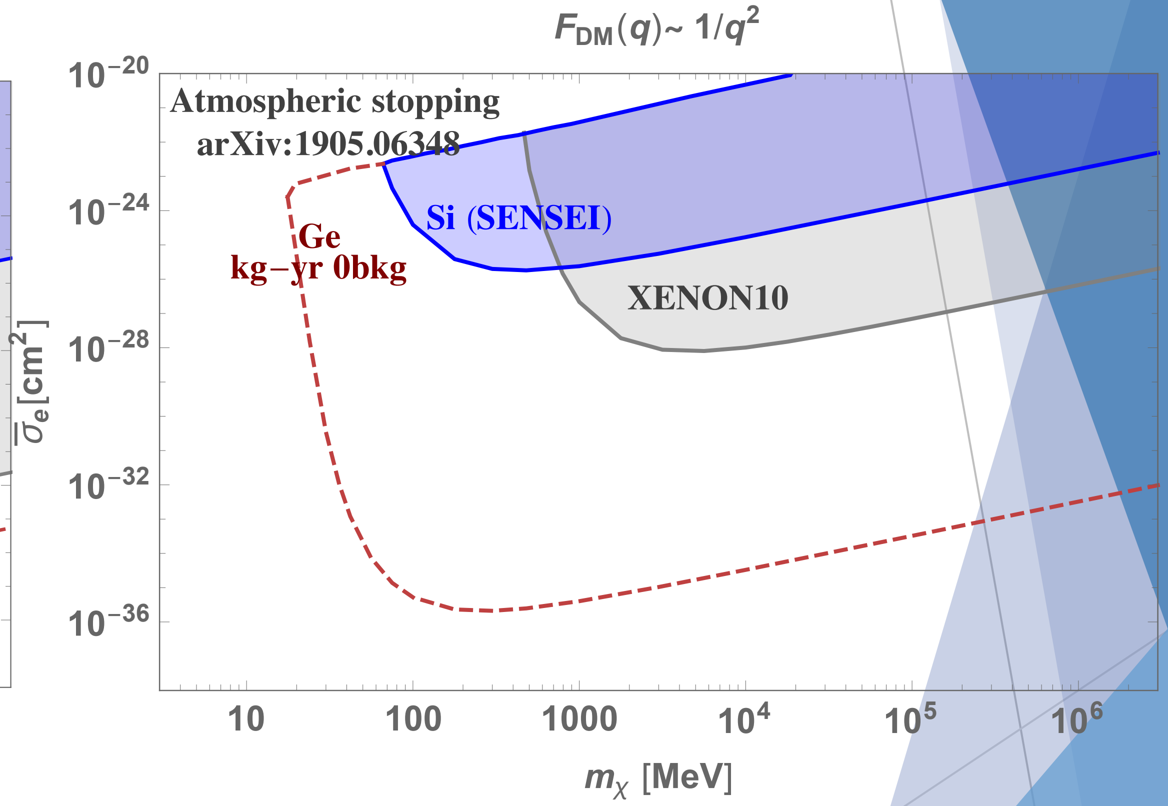
- Ionization in Xenon (1108.5383, 1206.2644)
  - 12 eV threshold

- Semiconductors (1108.5383, 1509.01598)
  - eV threshold (band gap)

- Superconductors and Fermi-degenerate materials (1708.08929)

Slow DM Reach with Electron Recoil

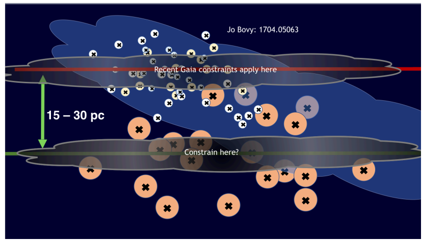




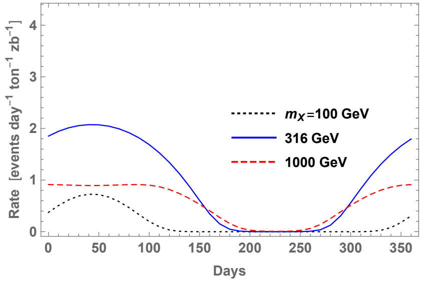
* Thresholds are important, because relying on tail of MB distribution, v ~ 10^-3 ~ 10 sigma
* Ge kg-yr marginally better than XENON10
* Atmospheric stopping is important

Conclusions

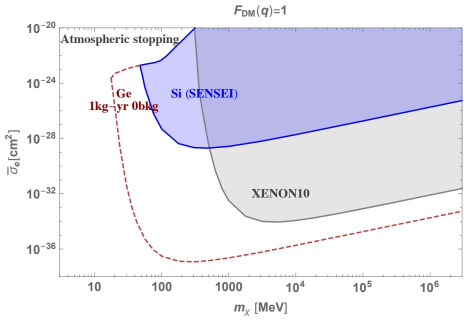
- Viability: displaced disk



- Threshold: O(1) AM signal



- Reach: 10^-36 cm^2



How Do We Know the Local DM Density?

- PDG:

$$\rho_{\rm DM}^{\rm local} = (0.39 \pm 0.03) \cdot (1.2 \pm 0.2) \cdot (1 \pm \delta_{\rm triax}) \, \frac{\rm GeV}{\rm cm^3} \, .$$

- Global fit (e.g. Catena & Ullio 2009)
  - Mainly Rotation curve
  - Assume spherical halo → determine ρ_{halo}
- Does not bound $\rho_{dark\ disk}$!
- For most measurements in the literature, can replace $\rho_{DM} \rightarrow \rho_{halo}$

Constraining a Dark Disk with Kinematics of Local Stars (Hipparcos, Gaia, etc.)

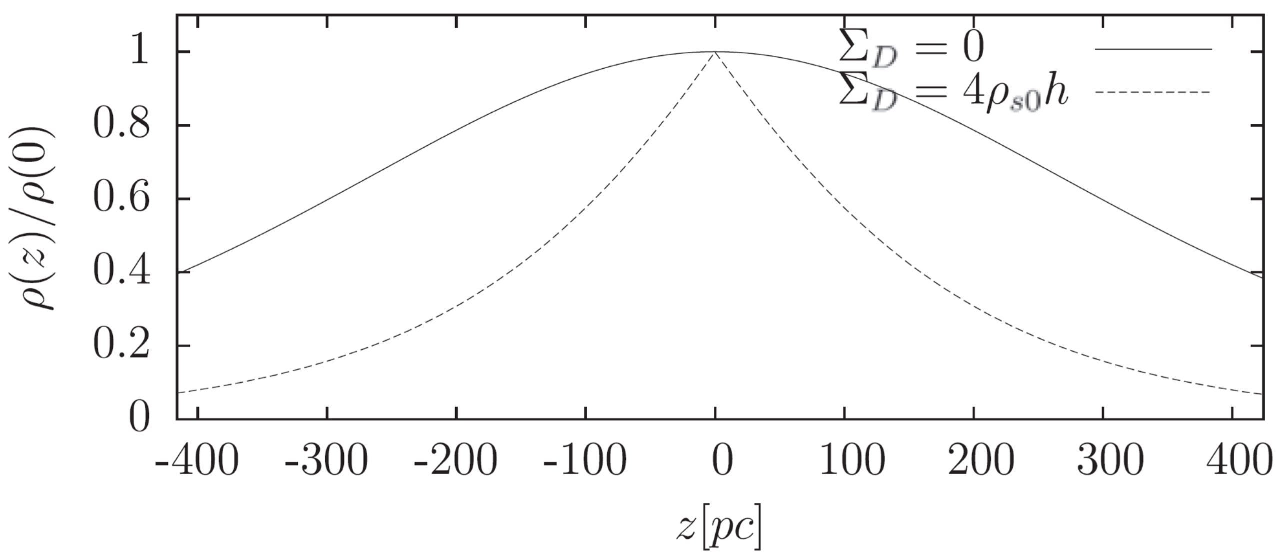
- Distribution of local stars tells us the Galactic potential
- Equilibrium: Boltzmann distribution

$$n \sim e^{-E/T}$$

- For isothermal population:

$$\langle v_z^2 \rangle \equiv \sigma^2$$

$$\Phi(z) = -\sigma^2 \log n(z)$$



Local Stellar Kinematics

- Holmberg & Flynn (2000)
  - astro-ph/9812404
  - young A,F stars
  - found

$$\rho_{\rm local} \simeq 0.010 \pm 0.001 M_\odot/\mathrm{pc}^2$$

- Seems to rule out a dark disk

Table 1

Bounds on the Surface Density and Local Density of Total Matter and Visible Matter in the Galaxy

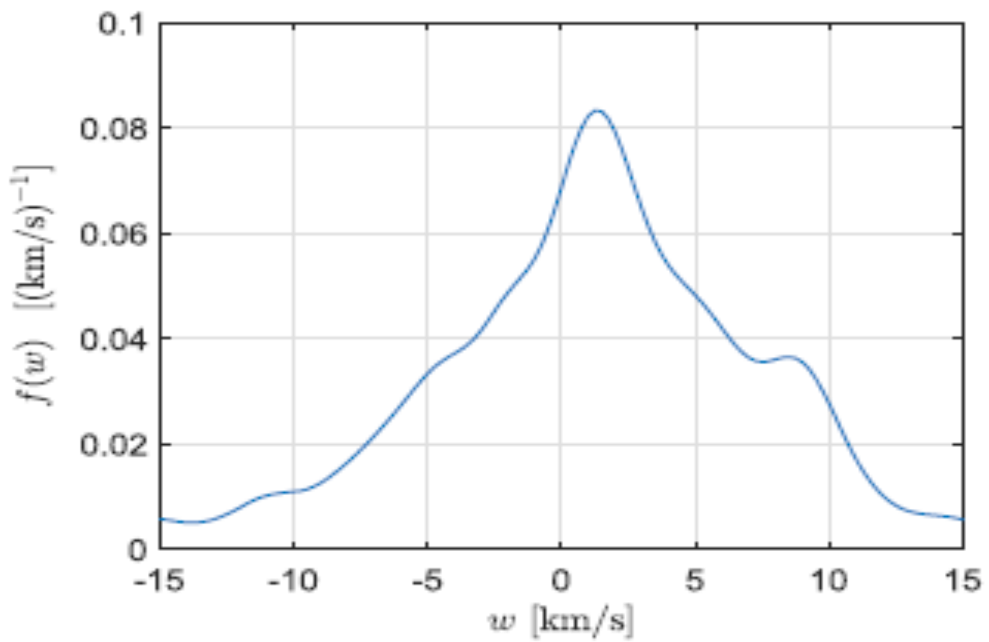
Authors	Year	Bound ($M_\odot\ \mathrm{pc}^{-n}$)	Category
Oort	1932	$\Sigma_{\rm tot}(100\ \mathrm{pc}) = 31$	2
Oort	1960	$\Sigma_{\rm tot}(100\ \mathrm{pc}) = 29 \pm 10\%$	2
Bahcall		$\rho_{\rm tot}(0) \leqslant 0.24$	3
Bahcall		$\rho_{\rm tot}(0) = 0.17$–0.25	3
Bienayme et a		or thick dark disk	3
Kuijken & Gi		1 ± 6	1
Bahcall et al.			3
Flynn & Fuch			3[a]
Pham		0.01	NA
Creze et al.		0.015 (assumed constant density)	1[a]
Holmberg & F		0.010 $\rho_{\rm vis} = 0.095$	3[a]
Korchagin et		± 6	2
Siebert et al.		5^{+25}_{-12}	1
Holmberg & F		4 ± 6	3
Bienaymé et a		–66	1
Garbari et al.		33	3
Moni Bidin et al.	2012b	$\Sigma_{\rm tot}(1.5\ \mathrm{kpc}) = 55.6 \pm 4.7$	2
Bovy & Tremaine	2012	$\rho_{\rm halo} = 0.008 \pm 0.003$	2
Zhang et al.	2013	$\Sigma_{\rm tot}(1\ \mathrm{kpc}) = 67 \pm 6$	
		$\rho_{\rm halo}(0) = 0.0065 \pm 0.0023$	1
Bovy & Rix	2013	$\Sigma_{1100} = 68 \pm 4$	1
Bienaymé et al.	2014	$\Sigma_{\rm tot}(1.1\ \mathrm{kpc}) = 68.5 \pm 1$	
		$\Sigma_{\rm tot}(350\ \mathrm{pc}) = 44.2^{+2.3}_{-2.9}$	1

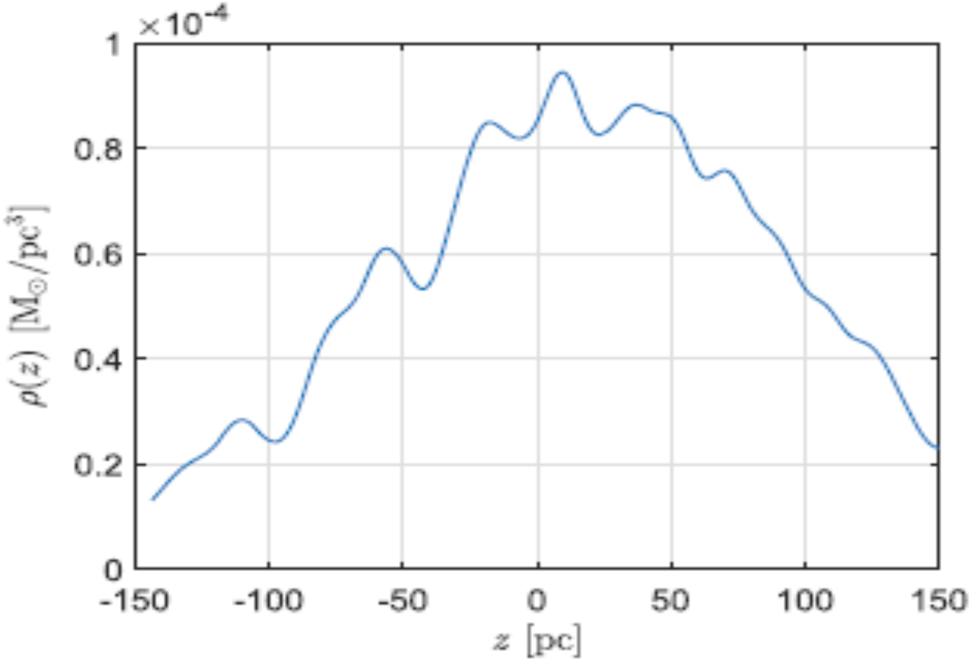
Note.

[a] Denotes bounds derived using HF technique.

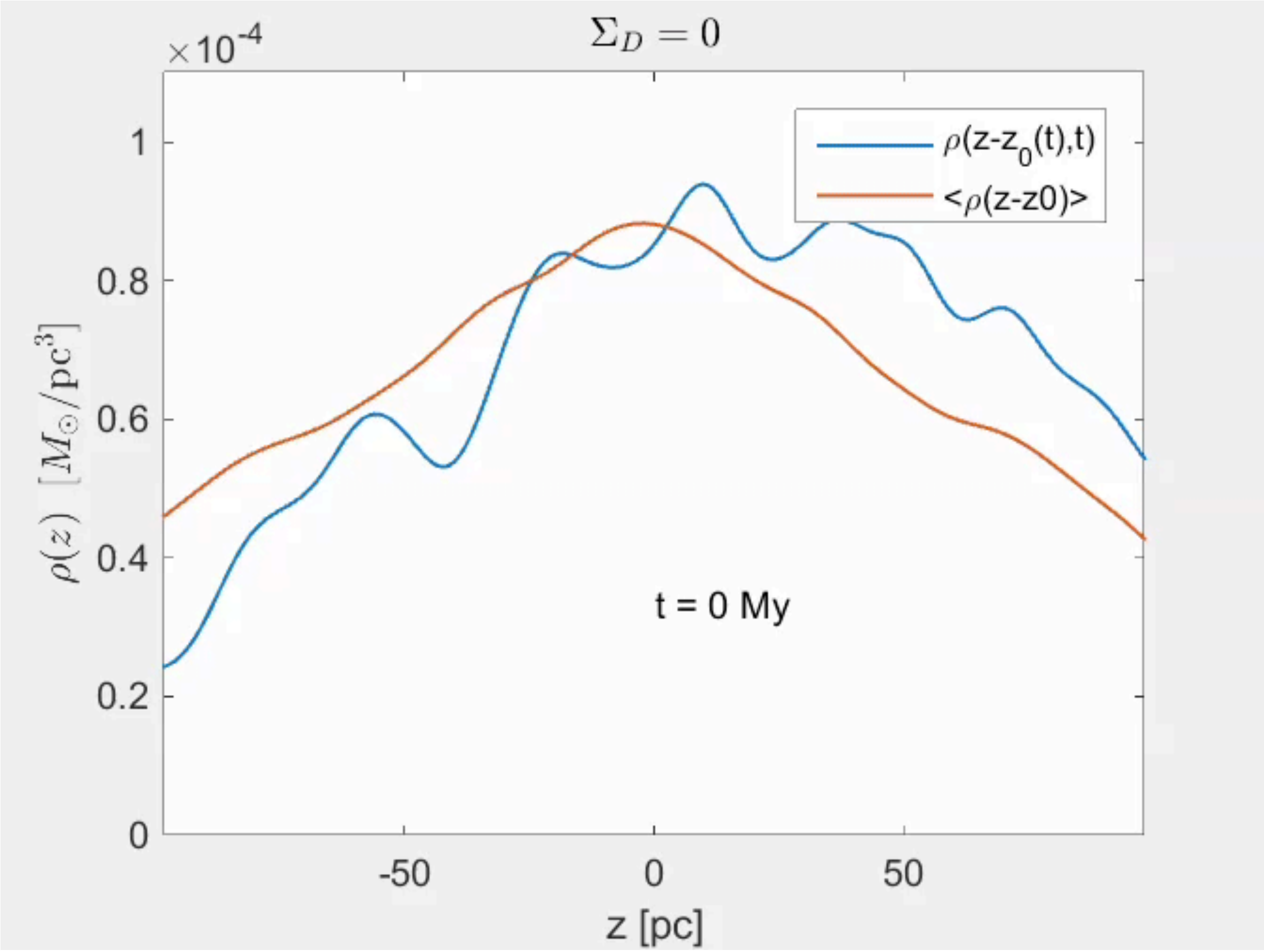
Holmberg & Flynn Revised

- EDK & Lisa Randall (1604.01407)
- Nonequilibrium effects:
  - Epicyclic oscillations
- → less time in the disk → weaken its effect



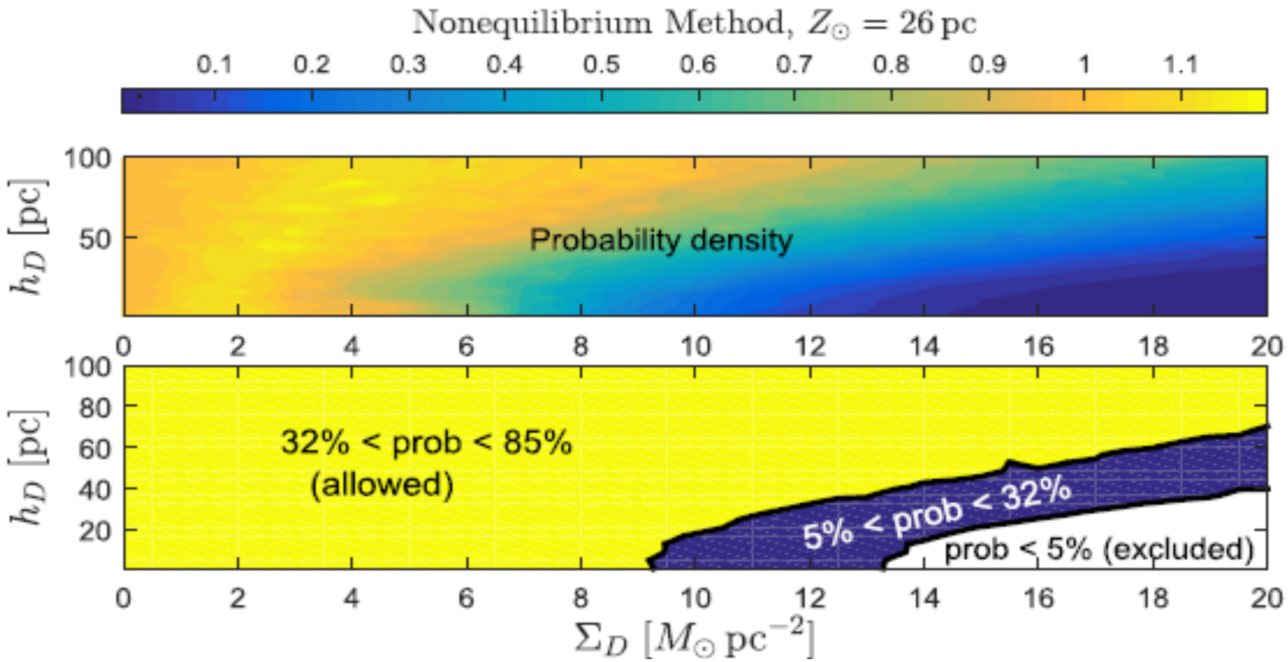


Non-Equilibrium Effects: A Short Video



- Simulation:
  - Hipparcos data, evolved in time under gravitational potential

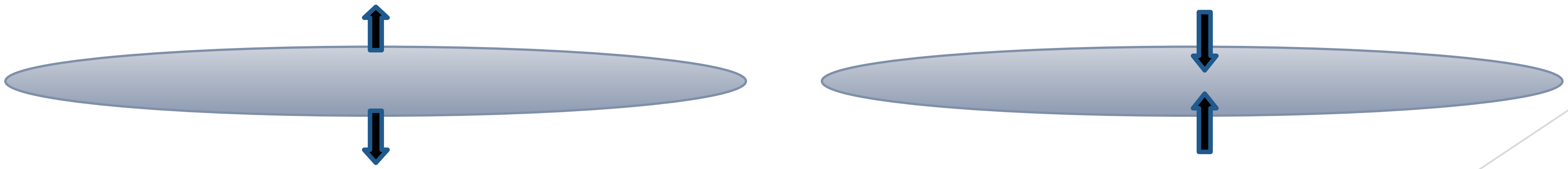
Non-Equilibrium Kinematic Bound



Non-Equilibrium Modes

- Shaviv (1606.02595)
  - Contraction: signature of recent spiral arm crossing
  - New estimate with nonequilibrium features:
  - ρlocal = 0.0135 +/- 0.015 Msol/pc3

- Banik, Widrow & Dodelson (1608.03338)
  - Nonequilibrium modes
    - Can offset measurement of Σdisk by 25%



Recent Bounds Gaia Data

- 1711.03103
- Analysis redone using Gaia data
  - young A,F,G stars
- Claim no non-equilibrium effects found
  - Center of population vertically at rest
  - Center of population in midplane
- Therefore bound is same as HF2000
- Dark Disk strongly constrained

1711.03103

Constraining a Thin Dark Matter Disk with *Gaia*

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Position of Local Midplane?

- Most studies find midplane to be 15-25 pc below the Sun
  - (E.g. 26 pc from Cepheids 0903.4206)
- Local A,F,G stars have their midplane at the Sun
- Jo Bovy: 1704.05063
  - young A and F stars have high midplane
  - possibly inherited from fluctuations of gas

Stellar Inventory of the Solar Neighborhood using *Gaia* DR1

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May 18, 2017

6 THE SUN'S HEIGHT ABOVE THE MID-PLANE

The value of the Sun's offset from the mid-plane defined by each spectral subtype from A0V to G3V is displayed in Figure 19. For later-type dwarfs we are unable to determine $Z_\odot$, because the stellar density for these stars is almost entirely flat within the observed Z range (see Figure 11). Remarkably, the Sun is consistent with being at the mid-plane defined by each spectral type, with a combined measurement of $Z_\odot = -0.9 \pm 0.9\,\mathrm{pc}$. For A and F dwarfs, $Z_\odot$ is determined from the vertical distribution over ≈ 4 scale heights

(Hints of a Dark Disk?)

- Nir Shaviv
  - paleoclimate data (1606.02851)
  - Periodicity of 32 My rather than 45 My requires dark disk with

$$\rho_d \simeq \rho_{\rm bar}$$

- Comet impacts:
  - dark matter disk needed to get periodicity of 32 My rather than 45 My

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SUBJECT AREAS:
GALAXIES AND CLUSTERS
PALAEOCLIMATE

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Is the Solar System's Galactic Motion Imprinted in the Phanerozoic Climate?

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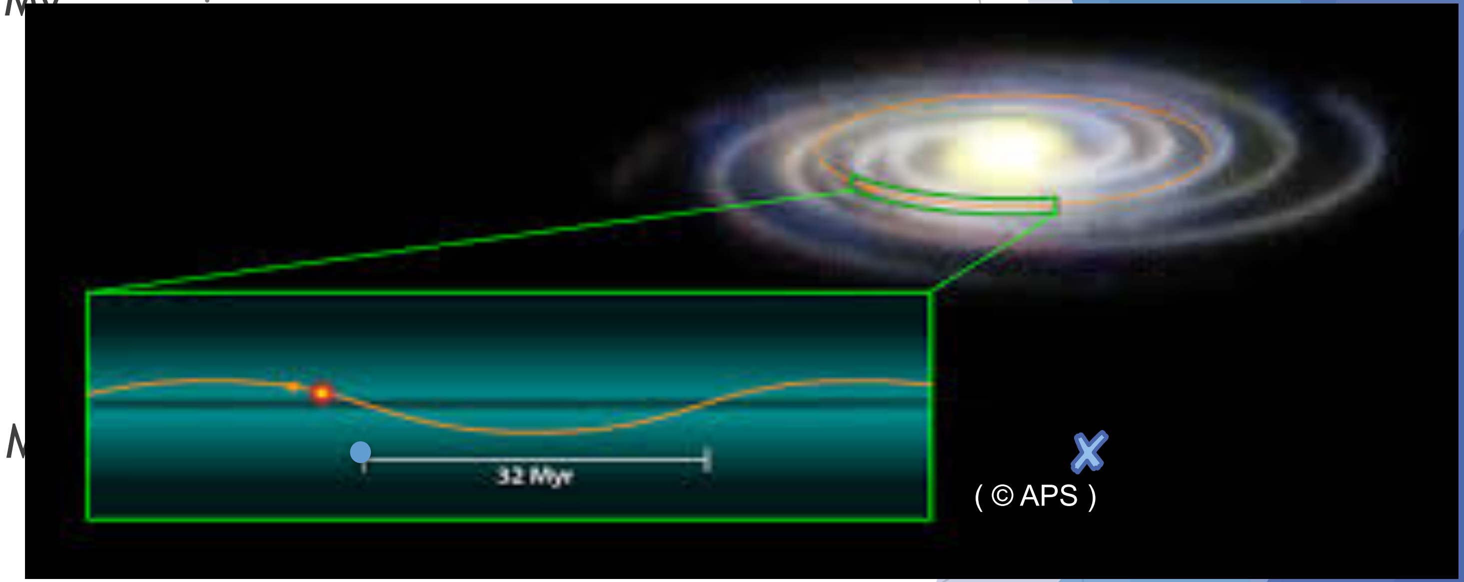
[1]Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem 91904, Israel, [2]Speedstat, Ottawa ON K1G 5J5, Canada, [3]Ottawa-Carleton Geoscience Center, University of Ottawa, Ottawa ON K1N 6N5, Canada.

A new $\delta^{18}O$ Phanerozoic database, based on 24,000 low-Mg calcitic fossil shells, yields a prominent 32 Ma oscillation with a secondary 175 Ma frequency modulation. The periodicities and phases of these oscillations are consistent with parameters postulated for the vertical motion of the solar system across the galactic plane, modulated by the radial epicyclic motion. We propose therefore that the galactic motion left an imprint on the terrestrial climate record. Based on its vertical motion, the effective average galactic density encountered by the solar system is $0.172 \pm 0.006_{\rm stat} \pm 0.006_{\rm sys} M_{\odot} pc^{-3}$. This suggests the presence of a disk dark matter component.

.02851

The Paleoclimatic evidence for Strongly Interacting Dark Matter Present in the Galactic Disk



Dark Matter as a Trigger for Periodic Comet Impacts

Lisa Randall and Matthew Reece
Department of Physics, Harvard University, Cambridge, MA, 02138

Although statistical evidence is not overwhelming, possible support for an approximately 35 million year periodicity in the crater record on Earth could indicate a nonrandom underlying enhance-

REVISITING THE DARK MATTER - COMET SHOWER CONNECTION

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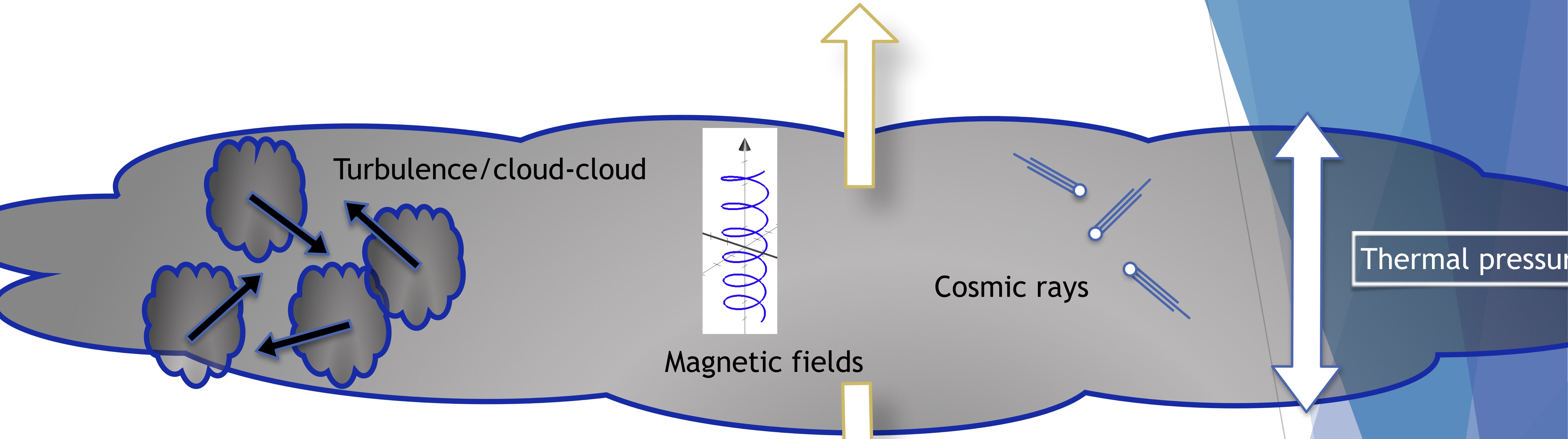
[1] *Department of Physics, Harvard University, Cambridge, MA, 02138*

Conclusions

- Direct Detections Prospects:
  - O(1) annual modulation signal
  - Lower recoil energy - important to reach lower threshold
- If local young star populations are in equilibrium, a dark disk is severely constrained (ϵ<1 %) (known since 2000)
- Reason to suspect that local Gaia stars are out of equilibrium
- Lots of evidence that the Sun is above the plane (Sun is at center of young star populations AFG) and therefore out of equilibrium
- Dark Disk model is still viable
  - need to redo non-eqm analysis with new Gaia data
  - look for non-eqm features over larger area (patterns)

The Value of the Circular Velocity

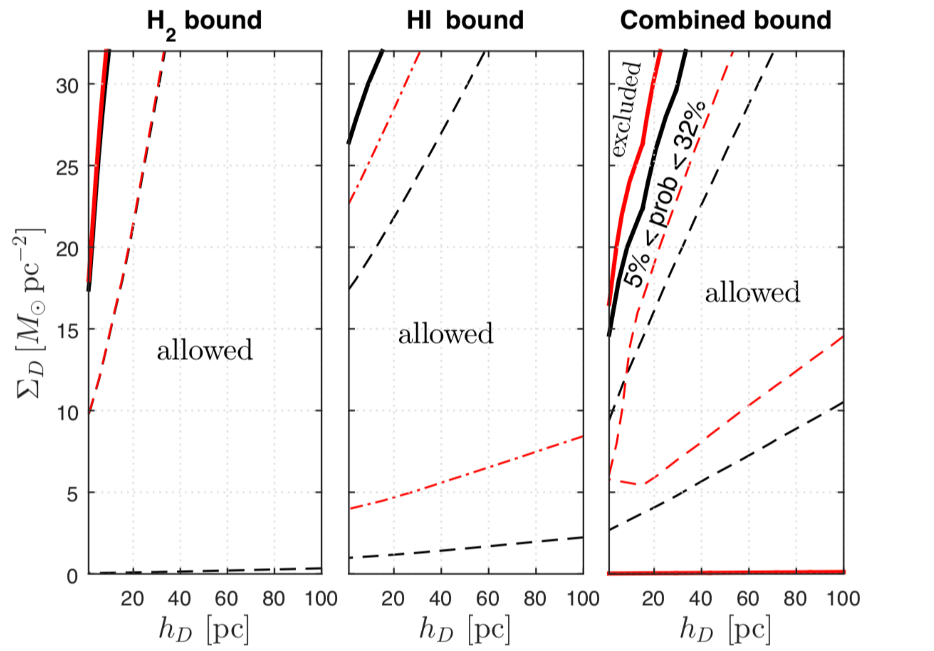
- Oort Constants:
- $A - B = \frac{V_c}{R_\odot} = 29.45 \pm 0.15\ km\ s^{-1}\ kpc^{-1}$ (Reid & Brunthaler 2004, ApJ 616 872)
- Solar Radius:
- $R_\odot = 8.33 \pm 0.35\ kpc$ (Gillesen et al. 2009, ApJ 692 1075)
- Implies
- $V_c = 245 \pm 10\ \frac{km}{s}$
- (IAU value: $V_c = 220\ \frac{km}{s}$)
- Important for halo DM but drops out from corotating DM analysis



- EDK & Lisa Randall (1603.03058)
- Balance between pressure and gravity:

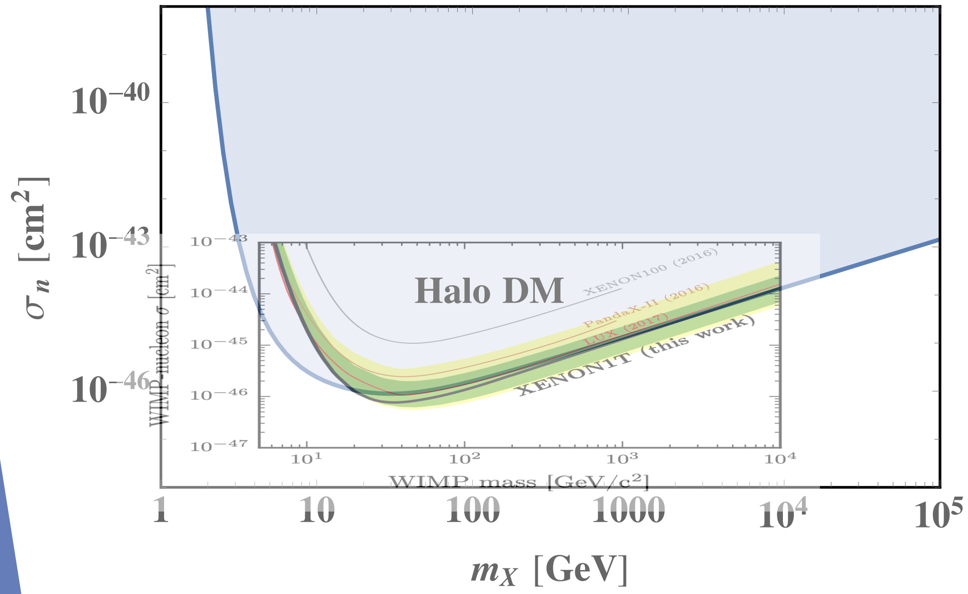
$$\frac{\partial}{\partial z}(\rho_i \sigma_i^2 + \rho_i c_i k_B T_i) + \rho_i \frac{\partial \Phi}{\partial z} = 0$$

- Some evidence for a dark disk



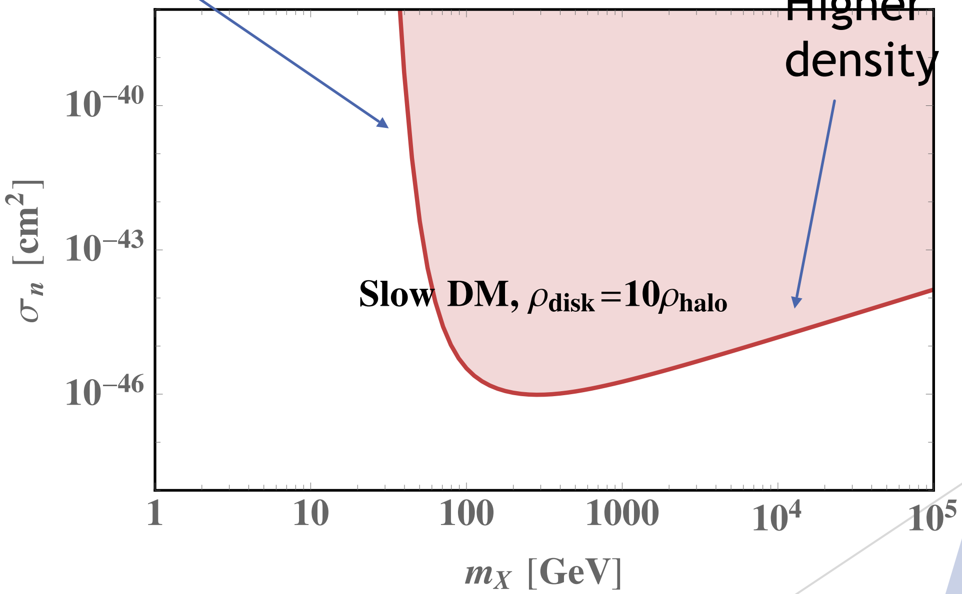
Slow DM in Nuclear Recoil

* Comparable reach (enhanced density of disk)
* Higher threshold



Higher mass theshold

Higher density



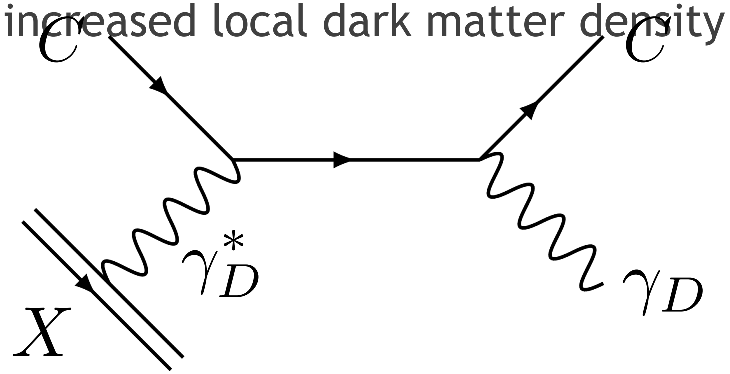
The Virial theorem

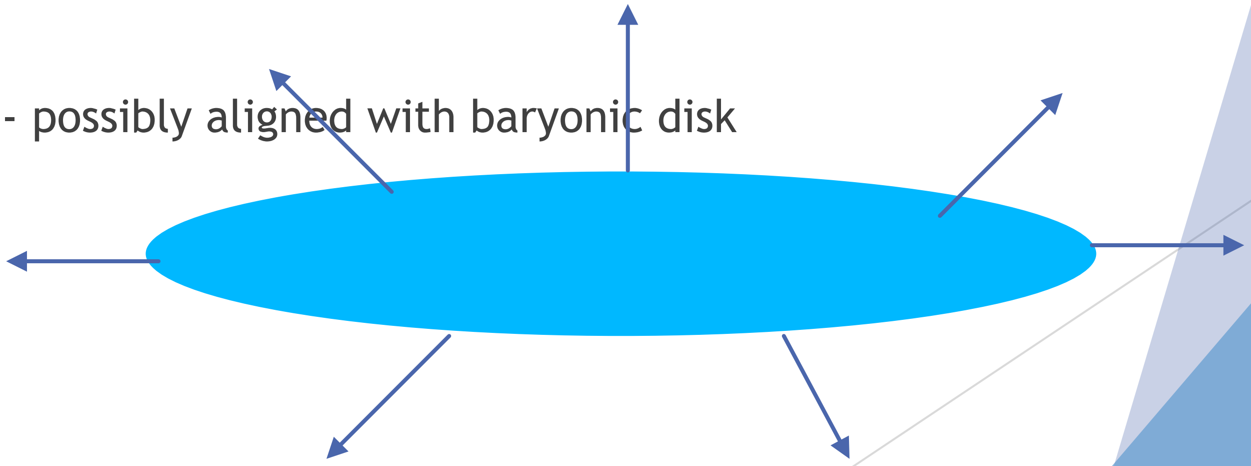
- $V^2 \sim \frac{GM}{R}$
- For halo DM, $\langle V_{\rm thermal}^2 \rangle \sim \frac{GM}{R}$
- For rotating disk, $V_{\rm rot}^2 \sim \frac{GM}{R}$

- E.g. Halo $V_{\rm thermal} \simeq 220\,{\rm km/s}$
- Milky Way Galactic Disk $V_{\rm rot} \simeq 230\,{\rm km/s}$

Dissipative Dark Matter

- Jiji Fan, Andrey Katz, Lisa Randall, Matthew Reece study DDDM (1303.3271, 1303.1521)
  - Bounds on dark interactions come from sphericity, also e.g. bullet cluster
  - Current bounds only imply that majority of DM is collisionless
  - Subsector could be
  - Model:
  - Dark photon $U(1)_D$
    - Heavy particle *X*, charge +1
    - Light particle C, charge -1
  - dissipative —> cooling —> disk
- increased local dark matter density - possibly aligned with baryonic disk





Dissipation

- System dissipates by radiating energy
- Will continue to dissipate until temperature becomes of order the *XC* binding energy

$$E_B = \frac{1}{2} m_C \alpha_D^2$$

- Once bound states are formed, the system will have velocity dispersion

$$\langle v^2 \rangle^{1/2} \sim \sqrt{\frac{m_C}{m_X}}\,\alpha_D$$

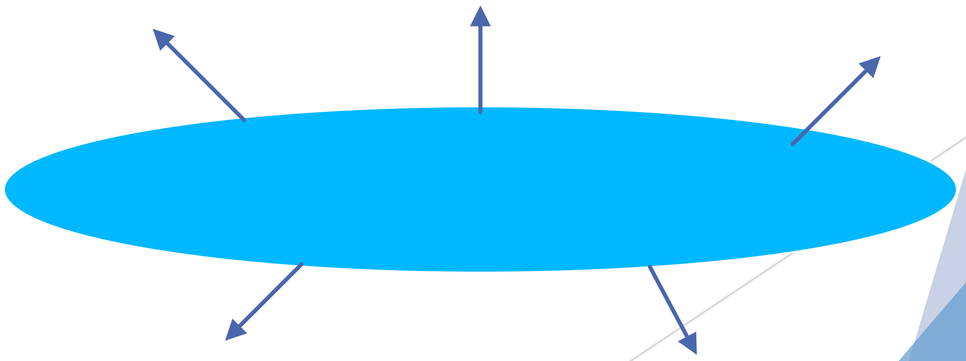
- For $\dfrac{m_C}{m_X} \sim 10^{-3}, \quad \alpha_D \sim 10^{-3}$

$$\langle v^2 \rangle^{1/2} \sim 10\ \mathrm{km/s}$$

astro people call this the "dispersion"

- By conservation of angular momentum, the "dark plasma" will cool to a dark disk with scale height

$$h \sim \langle v^2 \rangle^{1/2}$$



Sensitivity Ranges