Astrophysical Signatures of Dissipative Dark Matter

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Does Dark Matter Exist?

- Yes!
  - Rotation Curves
  - Gravitational Lensing (Bullet Cluster)
  - Old Galaxies (z~10)
- What is it?
  - ???

A Dissipative Model

- $U(1)_D$, heavy fermion X, light fermion C
- Dissipation
- Radiative cooling (Bremsstrahlung & Compton)
- Rutherford scattering
- Conservation of angular momentum → form a disk

→ increased local dark matter density

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)
- Local stellar kinematics (e.g. Holmberg & Flynn 2000; Bovy & Tremaine 2012)
- For any bound on the local dark matter density, replace $\rho_{DM} \rightarrow \rho_{halo}$

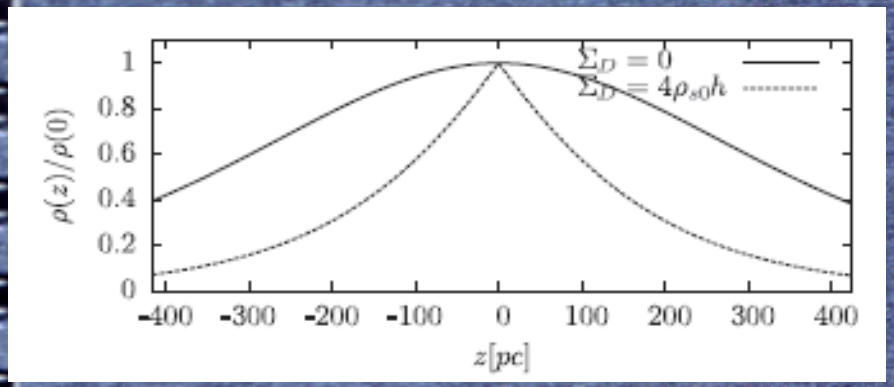
Local Stellar Kinematics

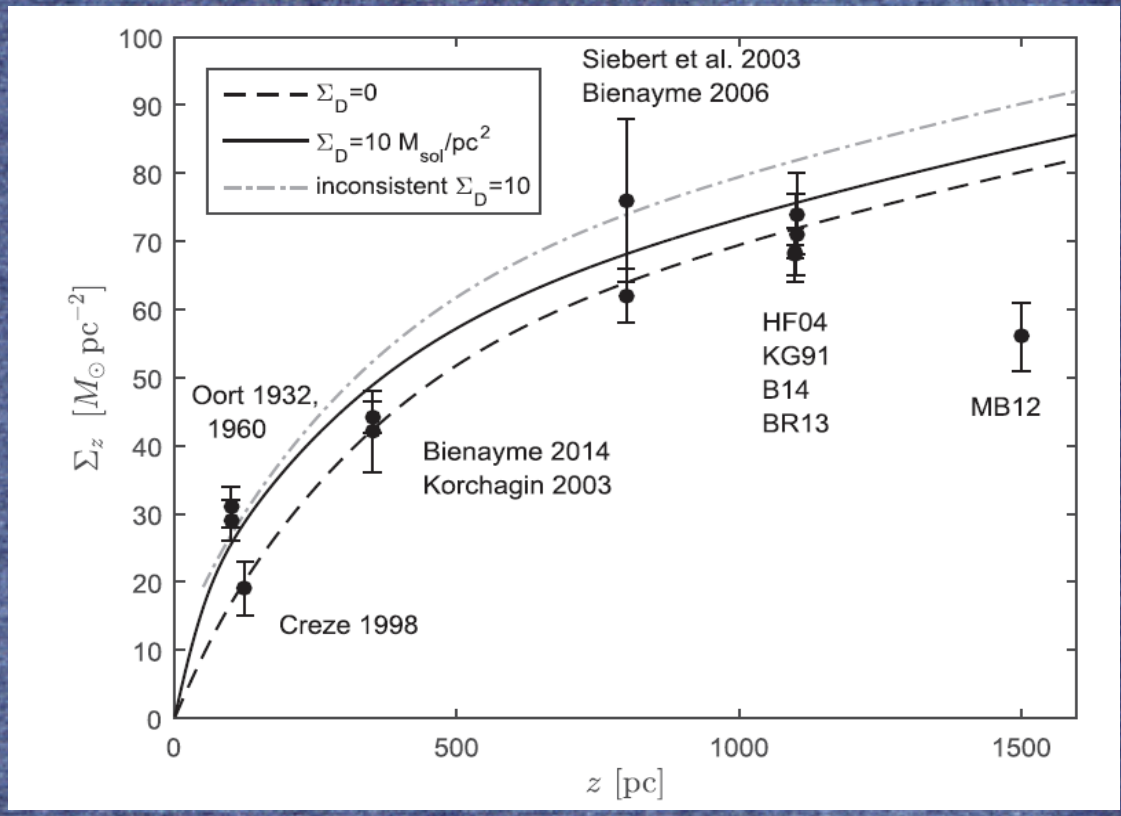
Table 1
Bounds on the Surface Density and Local Density of Total Matter and Visible Matter in the Galaxy

Authors	Year	Bound ($M_\odot$ pc^{-n})	Category
Oort	1932	$\Sigma_{tot}(100\text{ pc}) = 31$	2
Oort	1960	$\Sigma_{tot}(100\text{ pc}) = 29 \pm 10\%$	2
Bahcall	1984a	$\Sigma_{D,thin} \leqslant 17$ $\rho_{tot}(0) \leqslant 0.24$	3
Bahcall	1984b	$\Sigma_{tot} = 55$–83 $\rho_{tot}(0) = 0.17$–0.25	3
Bienayme et al.	1987	$\rho_{DM}(0) \leqslant 0.03$ for thick dark disk	3
Kuijken & Gilmore	1991	$\Sigma_{tot}(1.1\text{ kpc}) = 71 \pm 6$	1
Bahcall et al.	1992	$\Sigma_{tot} = 70^{+24}_{-16}$	3
Flynn & Fuchs	1994	$\Sigma_{tot} = 52 \pm 13$	3[a]
Pham	1997	$\rho_{tot}(0) = 0.11 \pm 0.01$	NA
Creze et al.	1998	$\rho_{tot}(0) = 0.076 \pm 0.015$ (assumed constant density)	1[a]
Holmberg & Flynn	2000	$\rho_{tot}(0) = 0.102 \pm 0.010$ $\rho_{vis} = 0.095$	3[a]
Korchagin et al.	2003	$\Sigma_{tot}(350\text{ pc}) = 42 \pm 6$	2
Siebert et al.	2003	$\Sigma_{tot}(800\text{ pc}) = 76^{+25}_{-12}$	1
Holmberg & Flynn	2004	$\Sigma_{tot}(1.1\text{ kpc}) = 74 \pm 6$	3
Bienaymé et al.	2006	$\Sigma_{tot}(800\text{ pc}) = 57$–$66$	1
Garbari et al.	2011	$\rho_{halo} = 0.003$–0.033	3
Moni Bidin et al.	2012b	$\Sigma_{tot}(1.5\text{ kpc}) = 55.6 \pm 4.7$	2
Bovy & Tremaine	2012	$\rho_{halo} = 0.008 \pm 0.003$	2
Zhang et al.	2013	$\Sigma_{tot}(1\text{ kpc}) = 67 \pm 6$	
		$\rho_{halo}(0) = 0.0065 \pm 0.0023$	1
Bovy & Rix	2013	$\Sigma_{1100} = 68 \pm 4$	1
Bienaymé et al.	2014	$\Sigma_{tot}(1.1\text{ kpc}) = 68.5 \pm 1$	
		$\Sigma_{tot}(350\text{ pc}) = 44.2^{+2.3}_{-2.9}$	1

Note.
[a] Denotes bounds derived using HF technique.

Pinching





$$\Sigma(\text{visible matter} + \text{dark disk}) \leqslant \Sigma(\text{visible matter alone}) + \Sigma(\text{dark disk}).$$

Invincible Model?

- Not quite
- Holmberg & Flynn 2000
- Self consistent approach
- $P \approx 0.010 +/- 0.001\ M_{sol}/pc^2$
- May exclude a dark disk

Holmberg & Flynn (2000)

Second moment of Boltzmann equation:

$$\frac{\partial}{\partial t}(\rho_i \overline{v}_z) + \frac{1}{R}\frac{\partial}{\partial R}(R\rho_i \overline{v_R v_z}) + \frac{\partial(\rho_i \overline{v_z^2})}{\partial z} = -\rho_i \frac{\partial \Phi}{\partial z}.$$

Use this to derive vertical Jeans equation, solve for galactic potential (Poisson-Jeans solver)

- Continuity:

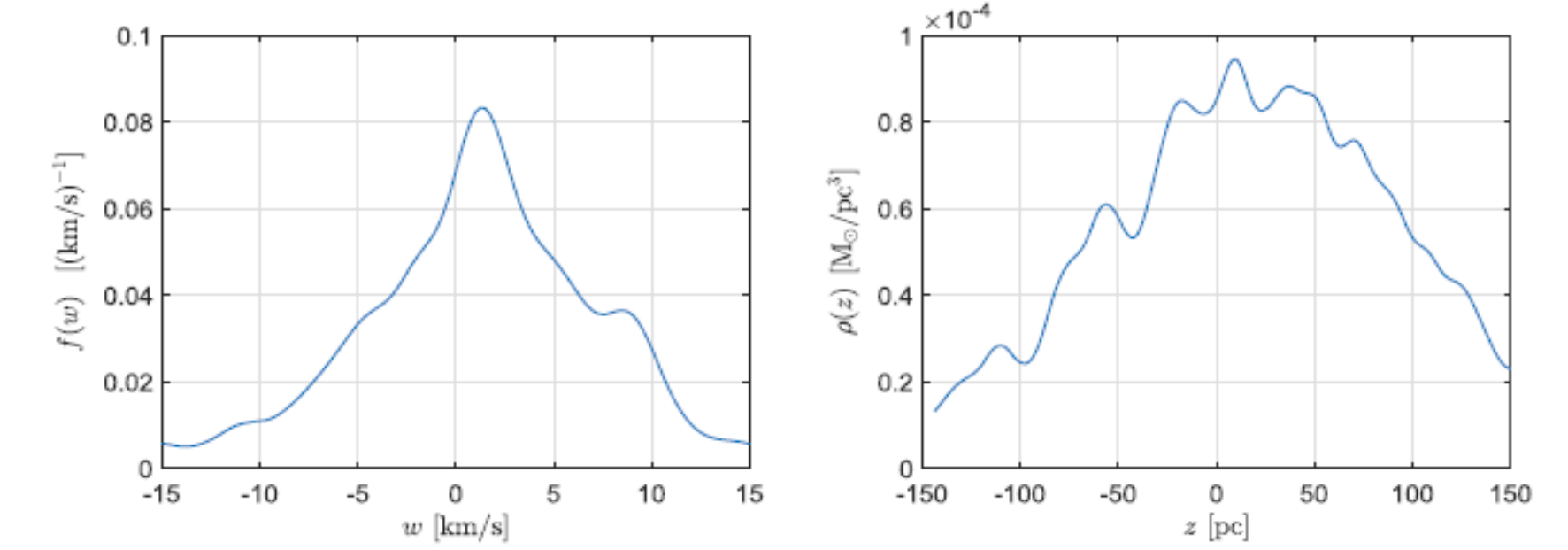
$$\frac{\partial f}{\partial t} = -v_i \frac{\partial f}{\partial x_i} + \frac{\partial \Phi}{\partial x_i}\frac{\partial f}{\partial v_i}.$$

$$\int_{-\infty}^{\infty} dw f_{z=0,i}\left(\sqrt{w^2 + 2\Phi(z)}\right) \equiv \nu(\Phi).$$

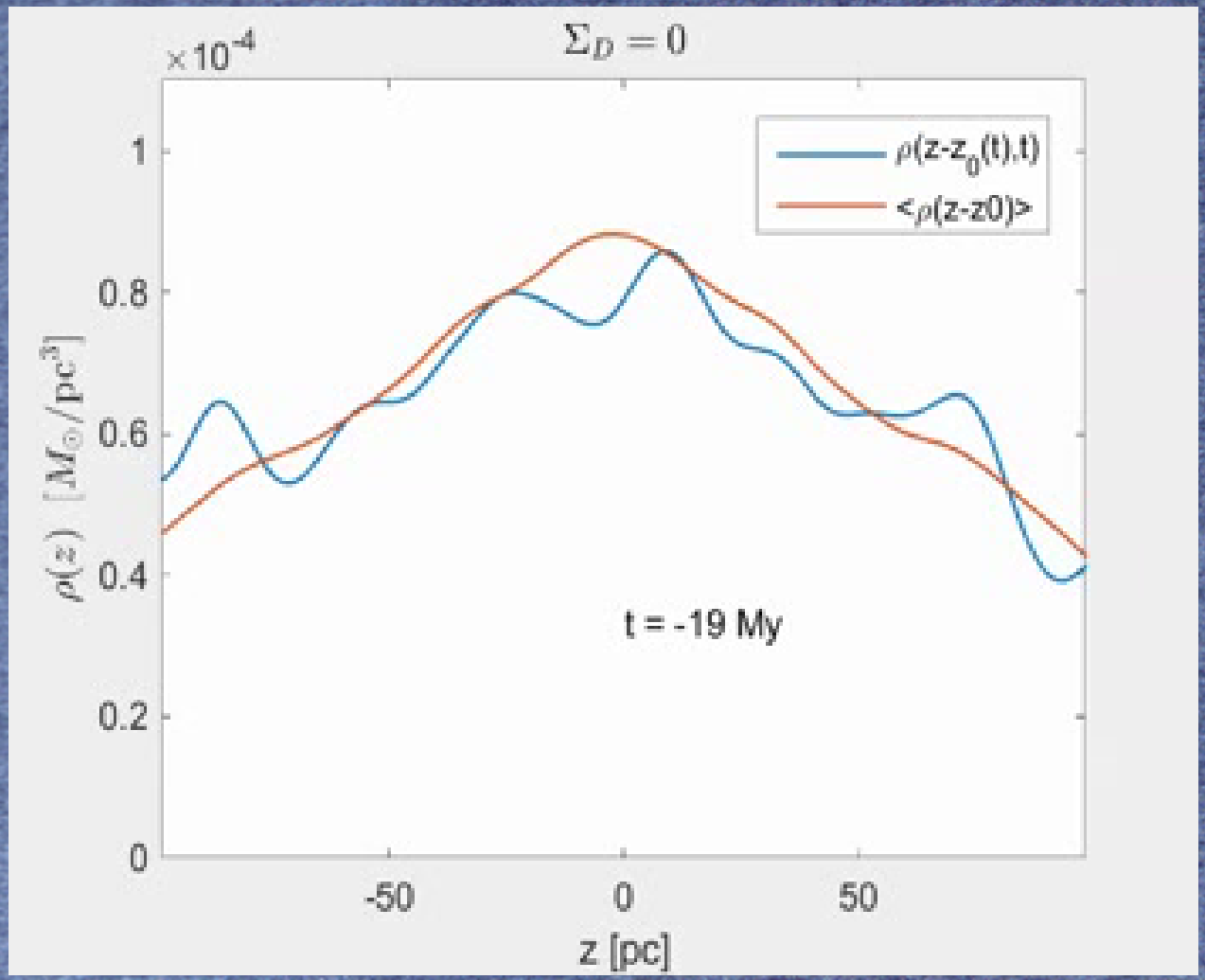
- Use this to derive density for more general velocity distribution

Holmberg & Flynn Revised

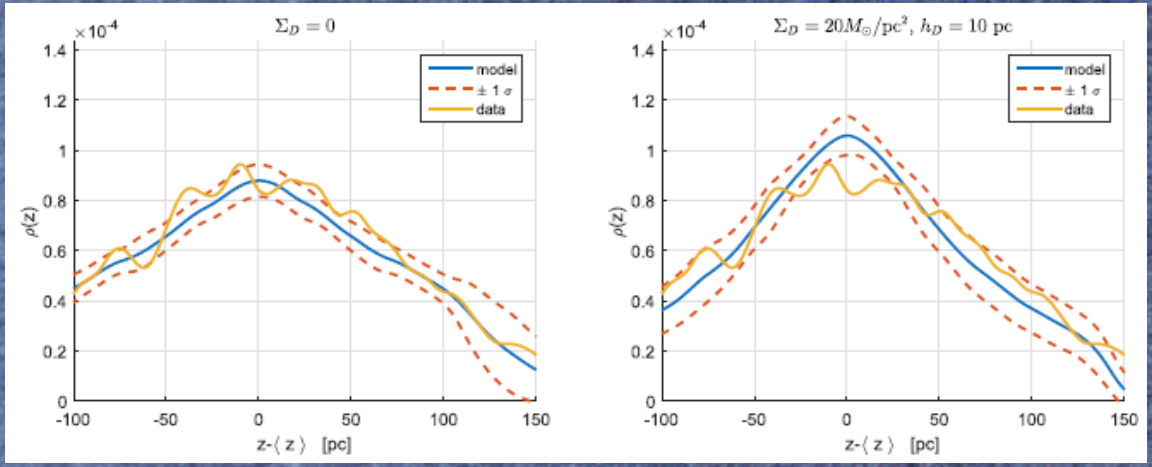
- Kramer & Randall 2016 (1604.01407)
- Nonequilibrium effects:
  - Epicyclic oscillations
- → less time in the disk → lower bound (compare to vis and tot)



Non-Equilibrium Effects: A Short Video



Non-Equilibrium Kinematic Bound



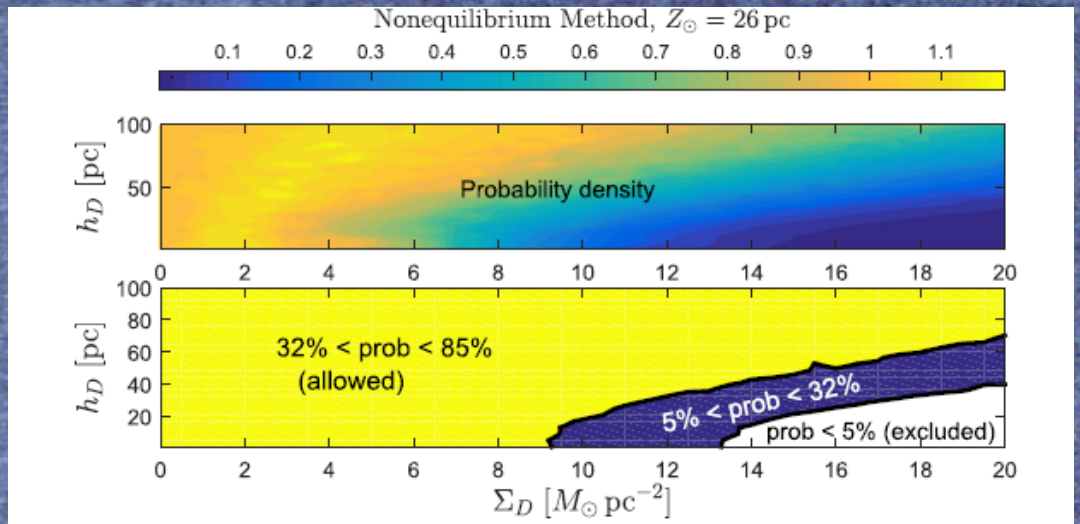


Figure 10. 68% and 95% bounds on DDDM parameter space using the non-equilibrium version of the HF method for A stars only.

Mass Extinctions

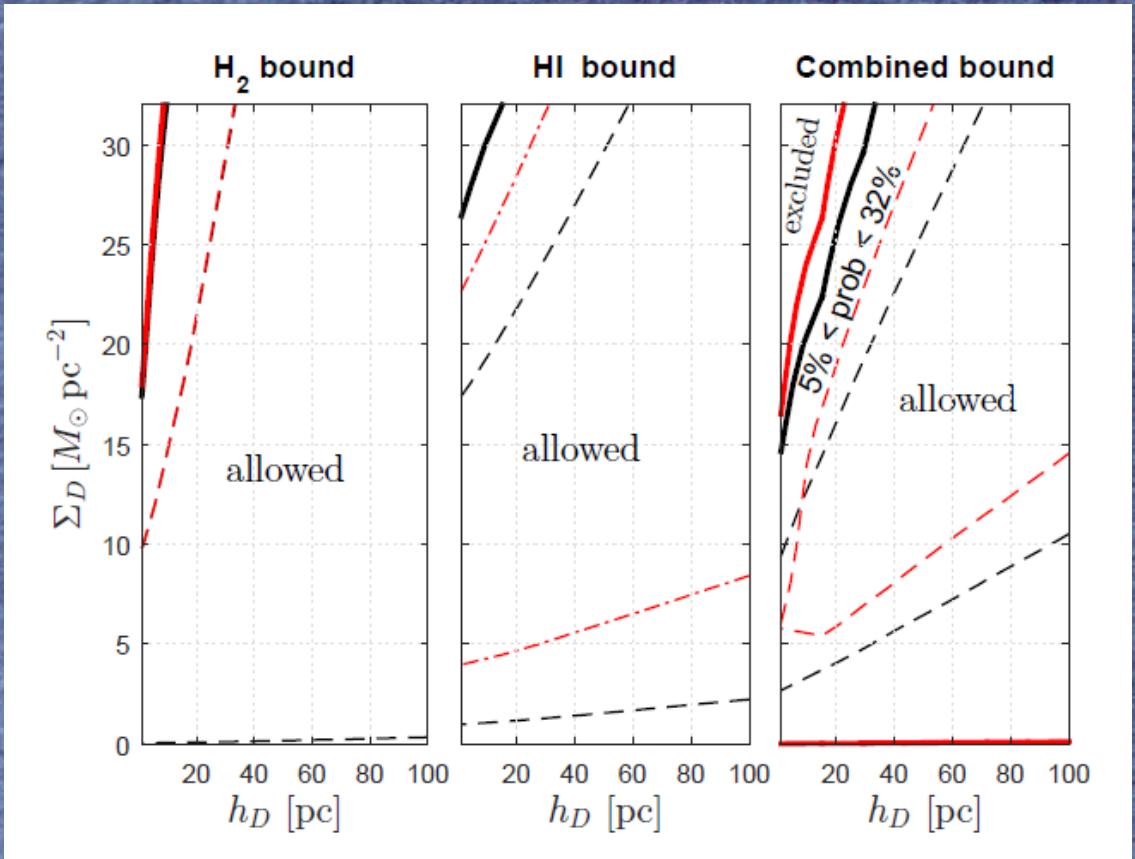
- Randall & Reece 2014 (1403.0576)
  - $\Sigma_D \sim 10\ M_{sol}/pc^2$, $h_D \sim 10$ pc

- Shaviv 2014, 2016b paleoclimate data:

$$\rho_D \sim 0.08\ M_{sol}/pc^2 = 3\ GeV/cm^3$$

Gas Equilibrium

- Magnetic fields must be included



$$\sum_i \frac{\partial}{\partial z}(\rho_i(\sigma_i^2 + \sigma_{i,T}^2)) + \frac{\partial}{\partial z}\left\langle \frac{\mathrm{B}^2}{2\mu_0} \right\rangle + \rho\frac{\partial \Phi}{\partial z} = 0.$$

Conclusions

- Most constraints only apply to the halo
- Direct approach to constraining surface density is best approach
- Non-equilibrium effects lower the bound
- Parameters needed to explain mass extinctions and gas distribution are allowed

Future:

- Gaia will give us a better picture of the galactic potential