# Emergent MDAR from Baryon-Dark Matter Particle Interactions

Justin Khoury (U. Penn)

w. Benoit Famaey & Riccardo Penco

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(Newtonian gravity. No new long-range forces.)

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- MDAR tells us precisely DM mass profile in galaxies:

$$M_{\rm DM}(r) = \frac{r^2}{G_{\rm N}} F(a_{\rm b})$$

(Federico's talk)

Suggests: DM-baryon interactions.

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Suggests: DM-baryon interactions.

- In low-acceleration regime (where DM dominates),

$$v^2(r) \equiv \frac{T(r)}{m} \sim \sqrt{a_0 G_{\rm N} M_{\rm b}(r)}$$

Suggests: Heat exchange.

# What we hope for

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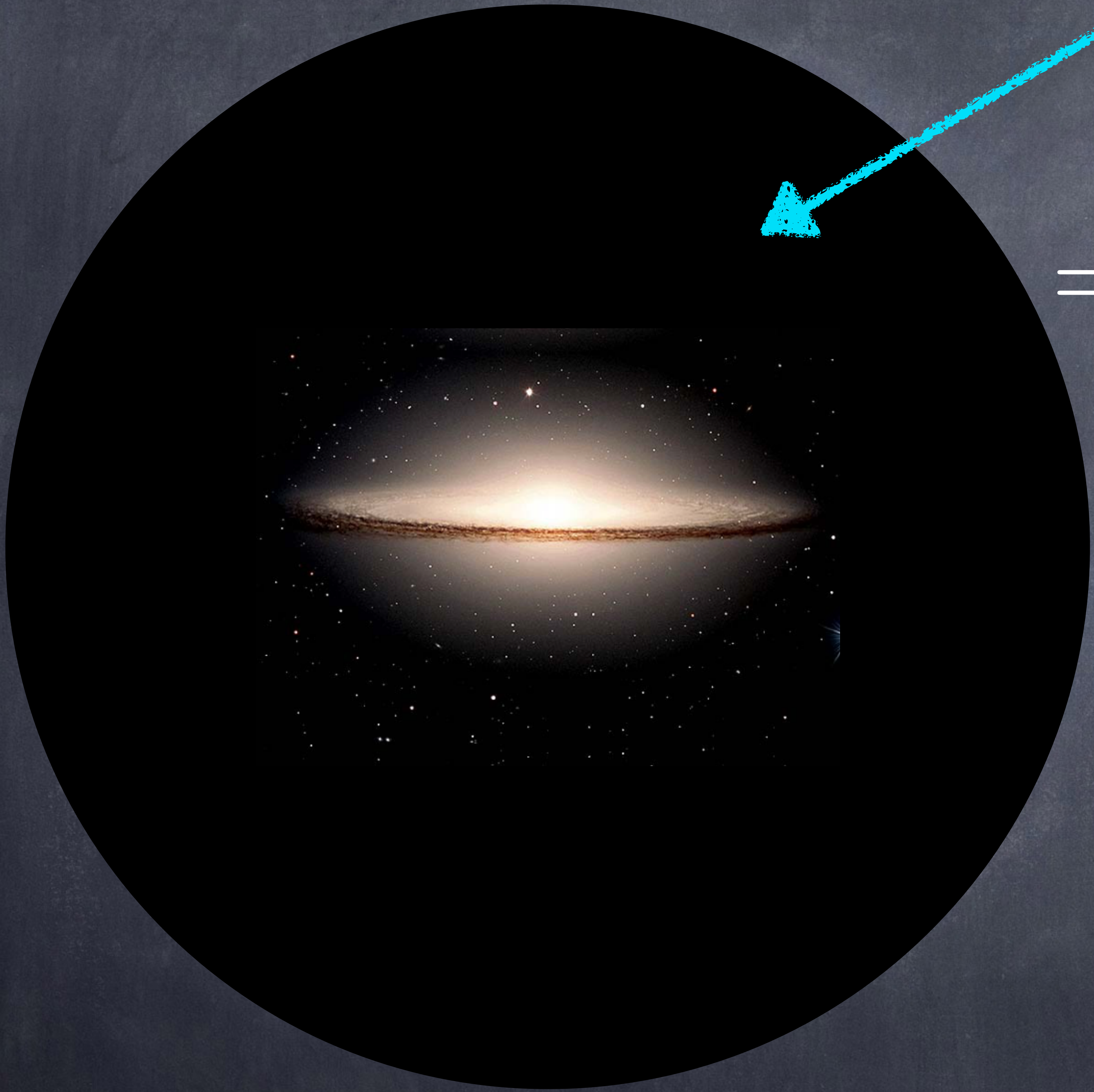

DM dominates acceleration
("MONDian" regime)

$$a \simeq a_{\mathrm{DM}}$$

$$\Longrightarrow \boxed{v^4(r) \sim a_0 G_{\mathrm{N}} M_{\mathrm{b}}(r)}$$

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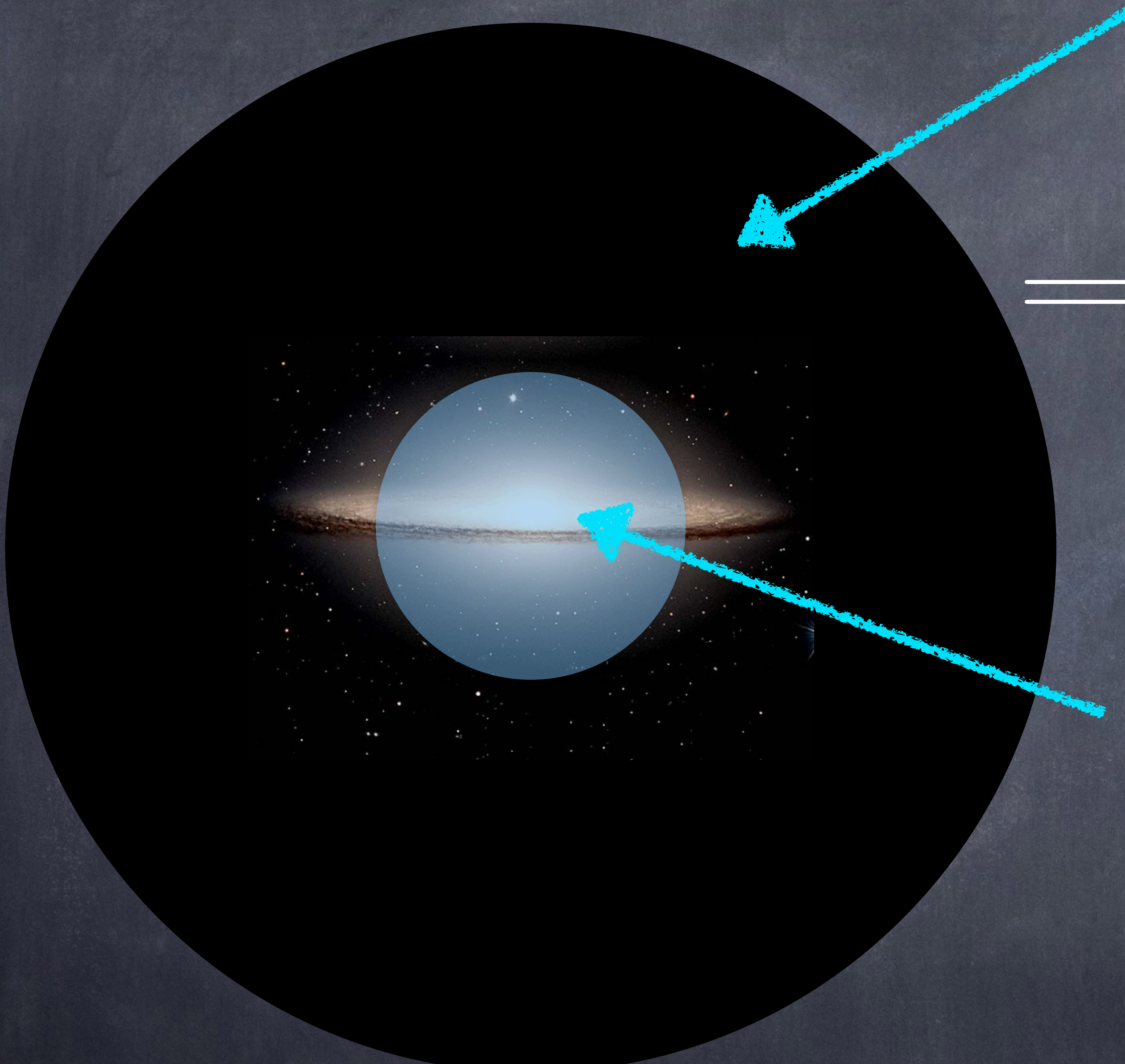

DM dominates acceleration
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$$a \simeq a_{\rm DM}$$

$$\Longrightarrow \quad \boxed{v^4(r) \sim a_0 G_{\rm N} M_{\rm b}(r)}$$

Baryons dominate acceleration
("Newtonian" regime)

$$a \simeq a_{\rm b}$$

This region need not exist, i.e., LSB galaxies.

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$$\lambda_{\mathrm{MFP}} > r$$

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Distinguishes rotationally-
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Distinguishes rotationally- vs pressured-supported

- DM-baryon interactions satisfy

$$n\,\frac{\sigma_{\mathrm{int}}}{m_{\mathrm{b}}}\epsilon = a_0$$

DM number density

# What is our set-up?

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Assume standard bovine symmetry.

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- Treat DM as ideal gas,

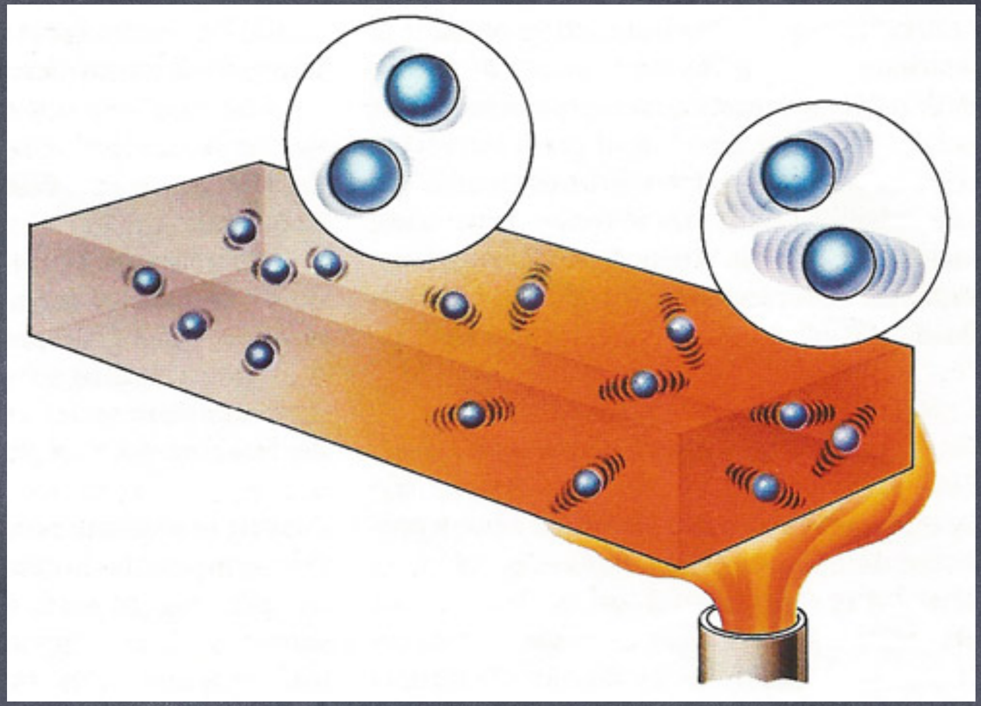
$$P = v^2 \rho$$

in hydrostatic equilibrium

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{1}{\rho}\frac{\mathrm{d}\Phi}{\mathrm{d}r} \implies \frac{\mathrm{d}\log\rho}{\mathrm{d}r} + \frac{\mathrm{d}\log v^2}{\mathrm{d}r} = -\frac{1}{v^2}\frac{\mathrm{d}\Phi}{\mathrm{d}r}$$

- Heat equation

  DM temperature determined by heat transport equation:



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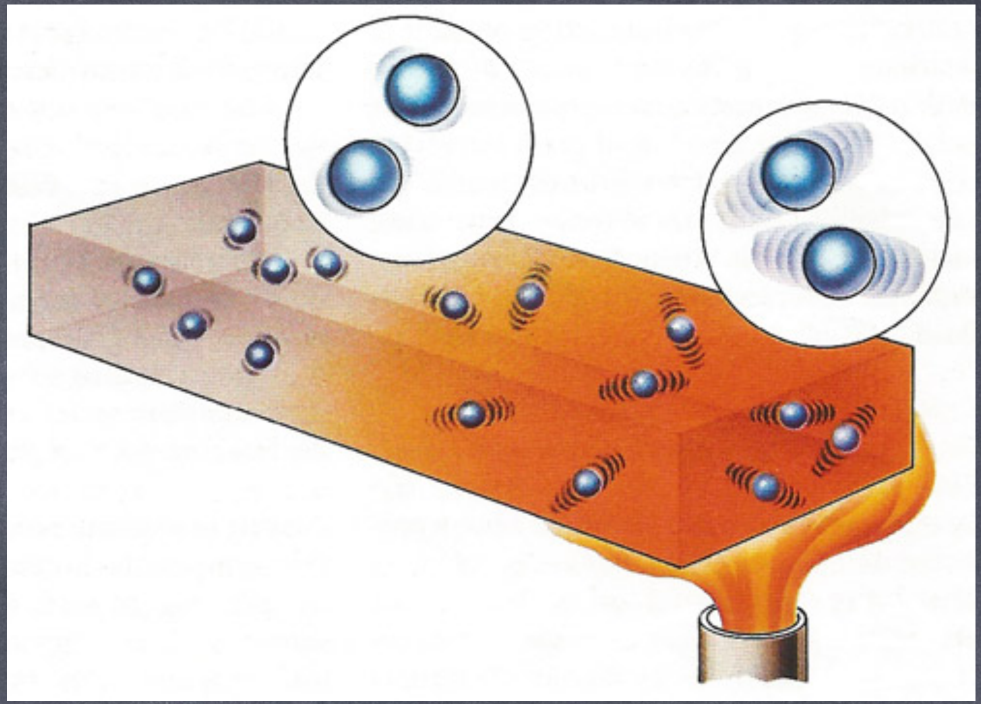

$$\frac{m}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\kappa r^2 \frac{\mathrm{d}v^2}{\mathrm{d}r}\right) = n \times \underbrace{\rho_\mathrm{b}\frac{\sigma_\mathrm{int}}{m_\mathrm{b}}v}_{\Gamma_\mathrm{int}} \times \epsilon$$

DM-baryon cross section $\sigma_\mathrm{int}$

Energy exchanged per collision $\epsilon > 0$ Baryons as 'coolant'.

Thermal conductivity $\kappa$ More on this soon...

# Heat equation (cont'd)

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To reproduce the MDAR, we need master relation:

$$\boxed{\sigma_\mathrm{int}\epsilon = \frac{m_\mathrm{b} a_0}{n}}$$

Will see later how this arises naturally in particle physics models.

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Using this, our eq'n simplifies to:

$$\frac{m}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\kappa r^2 \frac{\mathrm{d}v^2}{\mathrm{d}r}\right) = a_0 v\, \rho_\mathrm{b} \implies m\,\kappa\frac{\mathrm{d}v^2}{\mathrm{d}r} = a_0 v\, \frac{M_\mathrm{b}(r)}{4\pi r^2}$$

treating $v \simeq$ const.

Fourier's law

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Our heat equation: $$\frac{m}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\kappa r^2 \frac{\mathrm{d}v^2}{\mathrm{d}r}\right) = a_0 v\,\rho_{\mathrm{b}}$$

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Hydrostatic equilibrium: $$v^2 \sim \Phi$$

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Hydrostatic equilibrium:

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$\Longrightarrow$ Effective "modified" Poisson eq'n:

$$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(\kappa r^2 \frac{\mathrm{d}\Phi}{\mathrm{d}r}\right) \sim a_0 \rho_\mathrm{b}$$

Depends on DM density

# Baryons as coolant

$$m\,\kappa\frac{\mathrm{d}v^2}{\mathrm{d}r} = a_0 v\,\frac{M_\mathrm{b}(r)}{4\pi r^2} \geq 0$$

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sign of $\epsilon$

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  MW neighborhood

$$\frac{\sigma_\mathrm{int}}{m} = \frac{a_0}{v^2 \rho} \simeq 5\ \frac{\mathrm{cm}^2}{\mathrm{g}}$$

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$$\frac{\sigma_{\rm int}}{m} = \frac{a_0}{v^2\rho} \simeq 5\,\frac{\rm cm^2}{\rm g}$$

- Inelastic scattering: This regime requires $m \ll m_{\rm b}$

Henceforth focus on elastic case (with $m \gg m_{\rm b}$ )

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In general,

$$\kappa = \frac{n\,\ell^2}{t_{\rm relax}}$$

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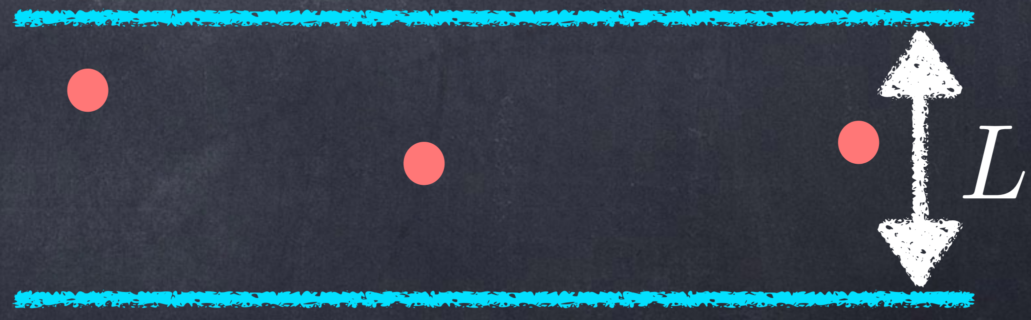

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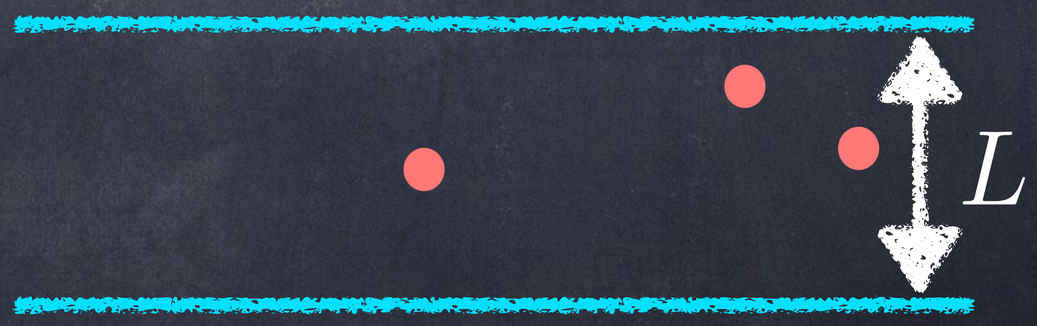

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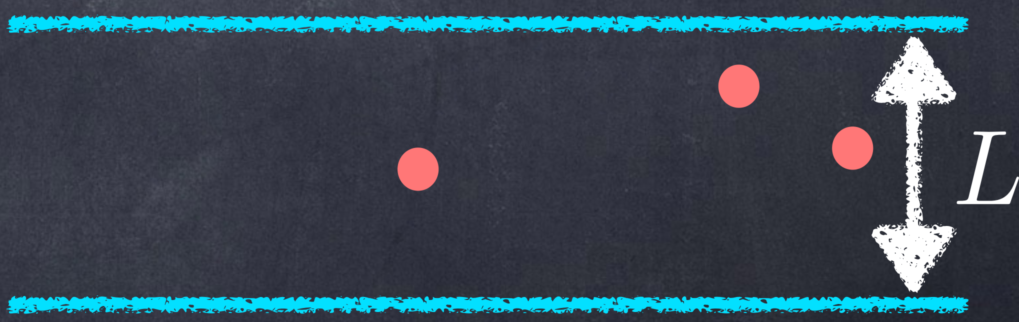
$$\ell \sim L$$

$$t_{\rm relax} \sim \frac{L}{v} \quad \Longrightarrow \quad \kappa \sim nvL$$



Rotationally-supported systems

- Knudsen (optically-thin) regime

DM-DM interactions are suff. infrequent that $\lambda_{\mathrm{MFP}} > r$

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Similar to globular clusters (Lynden-Bell & Eggleton, 1980)

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$$\therefore \quad \boxed{\kappa = \frac{n\,\ell^2}{t_{\mathrm{relax}}} \sim n\,v\,r}$$

Our integrated heat equation (Fourier's law)

$$m\,\kappa\,\frac{\mathrm{d}v^2}{\mathrm{d}r} = a_0 v\,\frac{M_{\mathrm{b}}(r)}{4\pi r^2}$$

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We will now solve this equation in DM-dominated and baryon-dominated regimes.

# DM-dominated ('MONDian') regime

Quick & dirty argument:

$$\rho(r)\, r\, \frac{\mathrm{d}v^2}{\mathrm{d}r} = a_0 \frac{M_\mathrm{b}(r)}{4\pi r^2}$$

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More carefully: Hydrostatic eqn + heat eqn give

$$r \frac{\mathrm{d}v^4}{\mathrm{d}r} \sim a_0 G_\mathrm{N} M_\mathrm{b}(r)$$

which, up to a logarithm, implies the deep-MOND relation

$$\boxed{v^4(r) \sim a_0 G_\mathrm{N} M_\mathrm{b}(r)}$$

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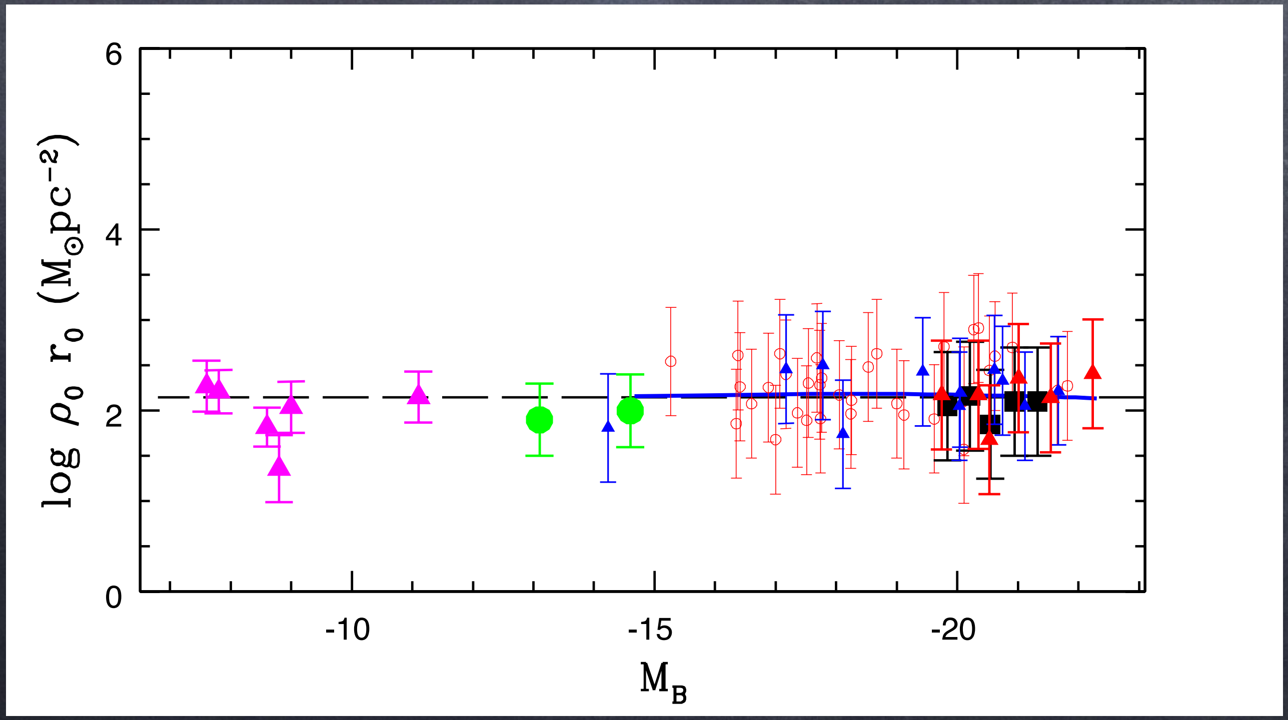
$$\sim \frac{v^2}{r} \simeq \frac{G_\mathrm{N} M_\mathrm{b}(r)}{r^2}$$

$$\Longrightarrow \quad \Sigma_\mathrm{DM} \equiv \rho\, r \sim \frac{a_0}{4\pi G_\mathrm{N}} \quad ✓$$




Donato et al. (2009)

## Milgrom's 3rd postulate: $a_0$ sets transition scale

DM-domination $\longleftrightarrow$ $a \ll a_0$

$$a_{\rm b} \ll a_{\rm DM} \simeq a \simeq \sqrt{a_0 a_{\rm b}}$$

$$\Longrightarrow \quad a \simeq \sqrt{a_0 a_{\rm b}} \ll a_0 \quad ✓$$

Baryon-domination $\longleftrightarrow$ $a \gg a_0$

$$a \simeq a_{\rm b} \gg a_{\rm DM} \sim 4\pi G_{\rm N}\Sigma_{\rm DM} \simeq a_0$$

$$\Longrightarrow \quad a \gg a_0 \quad ✓$$

# Important time scales

- Characteristic time $\tau$ for DM energy loss

$$\frac{\mathrm{d}E_{\mathrm{kin}}}{\mathrm{d}t} = -n_{\mathrm{b}} v \sigma_{\mathrm{int}} \epsilon \equiv -\frac{E_{\mathrm{kin}}}{\tau}$$

$$\sigma_{\mathrm{int}}\epsilon = \frac{m_{\mathrm{b}} a_0}{n}$$

Can show that

$$\frac{\tau}{t_{\mathrm{dyn}}} \sim 10 \, \frac{a}{a_0} \frac{\rho}{\rho_{\mathrm{b}}}$$

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Can show that $$\frac{\tau}{t_{\mathrm{dyn}}} \sim 10 \frac{a}{a_0} \frac{\rho}{\rho_{\mathrm{b}}}$$

- Away from disk, $\rho \gtrsim 10^2 \rho_{\mathrm{b}} \Longrightarrow \tau_{\mathrm{halo}} > t_{\mathrm{dyn}}$

- In the disk, $\rho \sim \rho_{\mathrm{b}} \Longrightarrow \tau_{\mathrm{disk}} < t_{\mathrm{dyn}}$

$$\therefore \quad \tau_{\mathrm{halo}} > t_{\mathrm{dyn}} > \tau_{\mathrm{disk}} \quad ✓$$

# Another time scale — DM self-interactions

Knudsen: Are DM self-interactions sufficiently infrequent?

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Knudsen: Are DM self-interactions sufficiently infrequent?

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Combine with earlier result $\dfrac{\sigma_{\rm int}}{m} = \dfrac{a_0}{v^2\rho}$ to obtain:

$$\boxed{\frac{\sigma}{\sigma_{\rm int}} < \frac{a}{a_0}}$$

DM self-interactions must be somewhat weaker (not many orders-of-magnitude weaker) than DM-baryon interactions.

Pressure-supported systems

Key difference: Baryons not segregated in disk

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- <u>Galaxy clusters</u>

  Have they reached equilibrium?

$$H_0 \tau \sim 10^2 \, v \frac{\rho}{\rho_{\mathrm{b}}} \sim \mathcal{O}(10)$$

Galaxy clusters have not yet relaxed to our equilibrium

$\Longrightarrow$ isothermal, NFW...?

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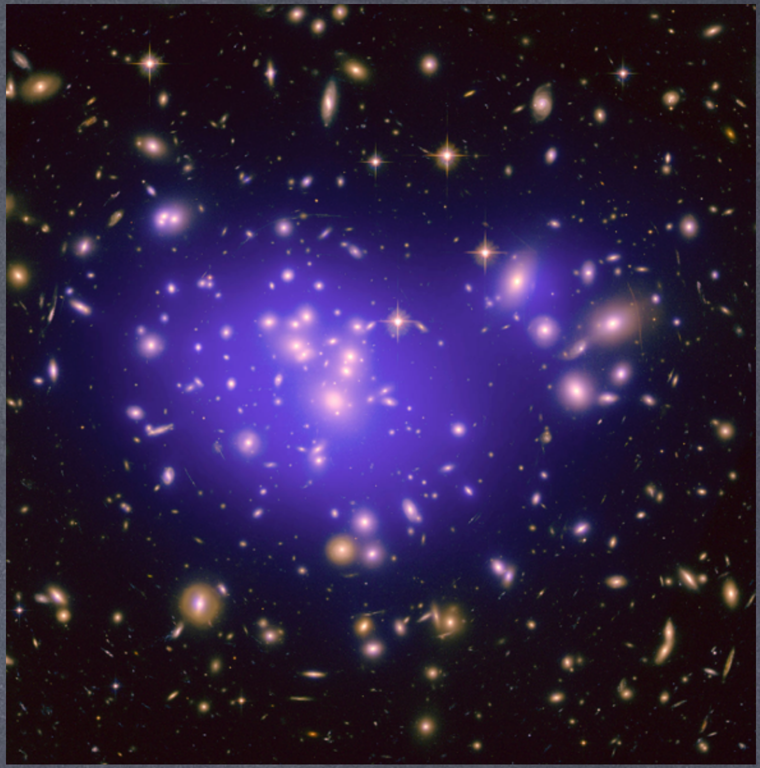

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- Dwarf spheroidals

  Equilibrium? $H_0 \tau \sim 10^2 \, v \frac{\rho}{\rho_{\mathrm{b}}} < 1 \quad ?$

  Knudsen? $\frac{\tau}{t_{\mathrm{dyn}}} \sim 10 \, \frac{a}{a_0} \, \frac{\rho}{\rho_{\mathrm{b}}} > 1 \; ?$

Unfortunately, even when these are satisfied, heat eq'n does not provide more info than hydrostatic.

# Phenomenological constraints

$$v^2 \frac{\sigma_{\rm int}}{m} = \frac{a_0}{\rho}$$

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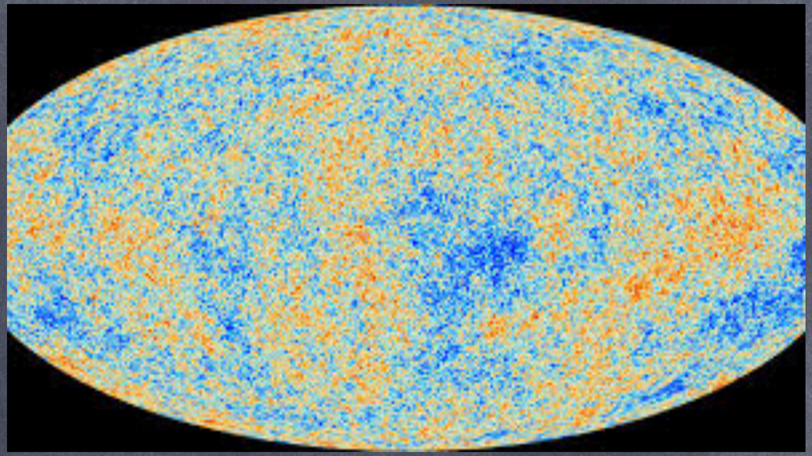
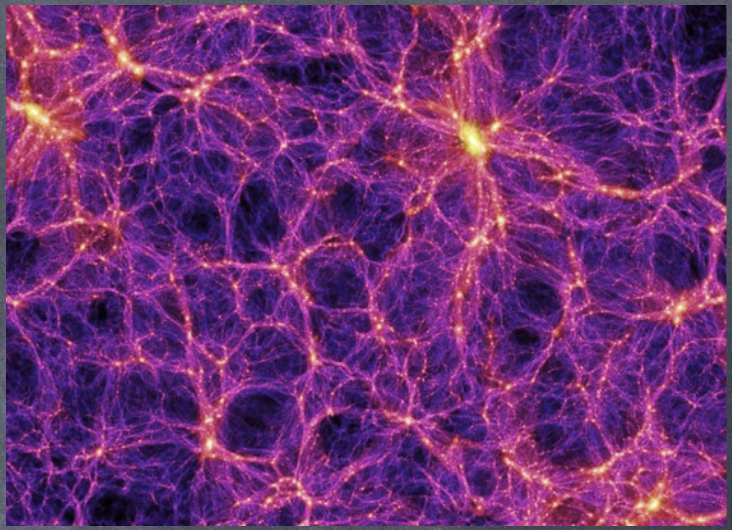
- CMB/Lyman-$\alpha$:

$$v^2 \frac{\sigma_{\rm int}}{m} < 6 \times 10^{-10} \ \frac{\rm cm^2}{\rm g}$$

Dvorkin et al. (2014)





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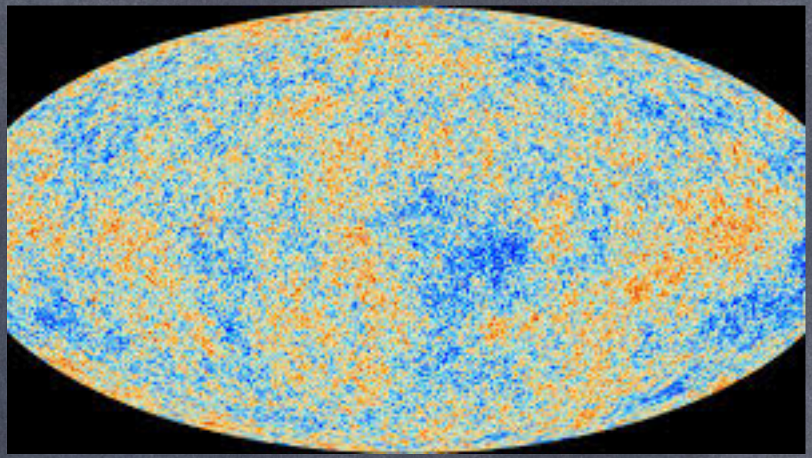

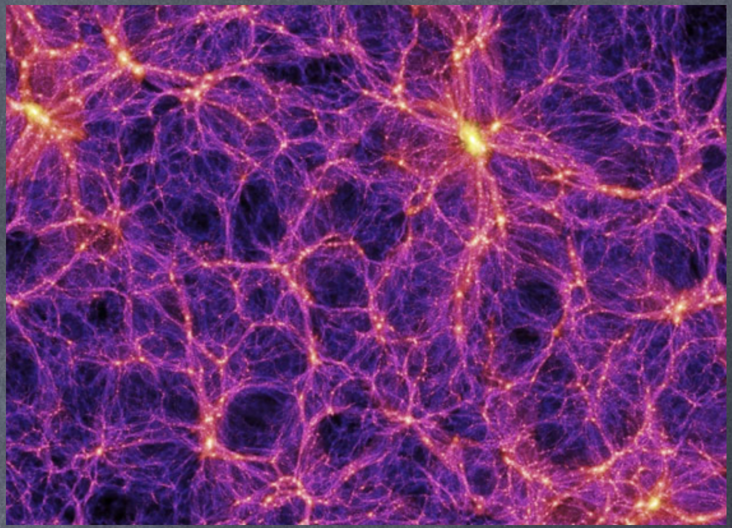

$$v^2 \frac{\sigma_{\rm int}}{m} < 6 \times 10^{-10} \ \frac{\rm cm^2}{\rm g}$$

Dvorkin et al. (2014)

We get

$$v^2 \frac{\sigma_{\rm int}}{m}\Big|_{z=10^4} = 7.5 \times 10^{-13} \ \frac{\rm cm^2}{\rm g}$$

✓

Note: $\Gamma_{\rm int} \sim H$ at $z \sim 10^2$ $\Longrightarrow$ 21-cm imprint?

Tashiro, Kadota & Silk (2014)

# Phenomenological constraints

$$v^2 \frac{\sigma_{\rm int}}{m} = \frac{a_0}{\rho}$$

- Merging clusters

$$\frac{\sigma}{m} \lesssim 0.5 - 2 \ \frac{\rm cm^2}{\rm g}$$

Harvey et al. (2015) Wittman et al. (2017)

- Cluster heating ( $\sigma \sim v^{-2}$ )

$$\frac{\sigma_{\rm int}}{m} \lesssim 0.1 \ \frac{\rm cm^2}{\rm g}$$

Hu & Lou (2007)

We get

$$\frac{\sigma_{\rm int}}{m} \simeq 0.08 \ \frac{\rm cm^2}{\rm g}$$

Particle Physics Models

$$\sigma_{\text{int}} \sim \frac{1}{v^2 n} \ ?$$

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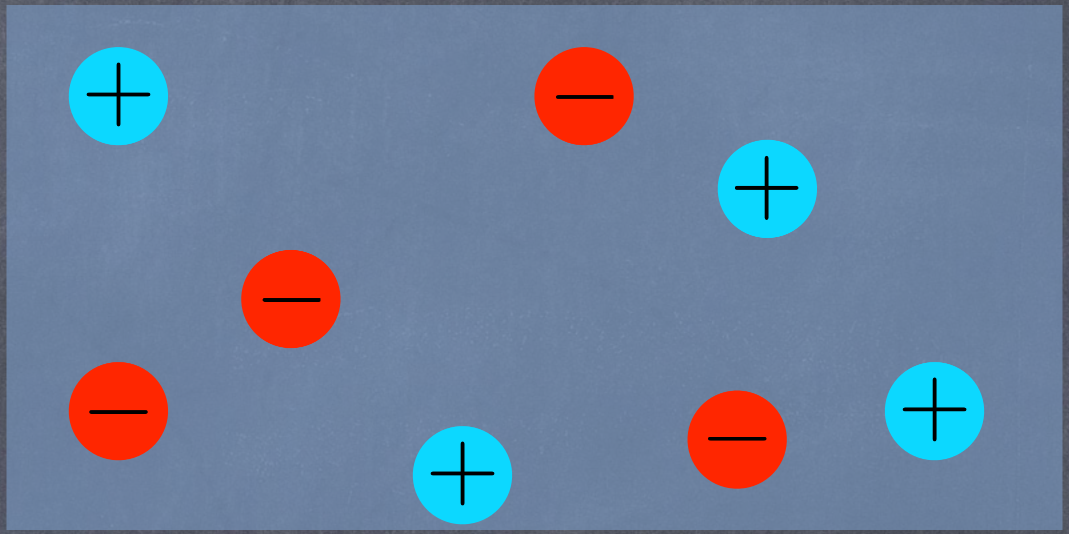
$$\sigma_{\rm int} \sim \frac{1}{v^2 n} \;?$$

e.g. DM as weakly-charged electrolyte
(charged under dark photon)



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$$\sigma_{\rm int} \sim \frac{1}{v^2 n} \;?$$

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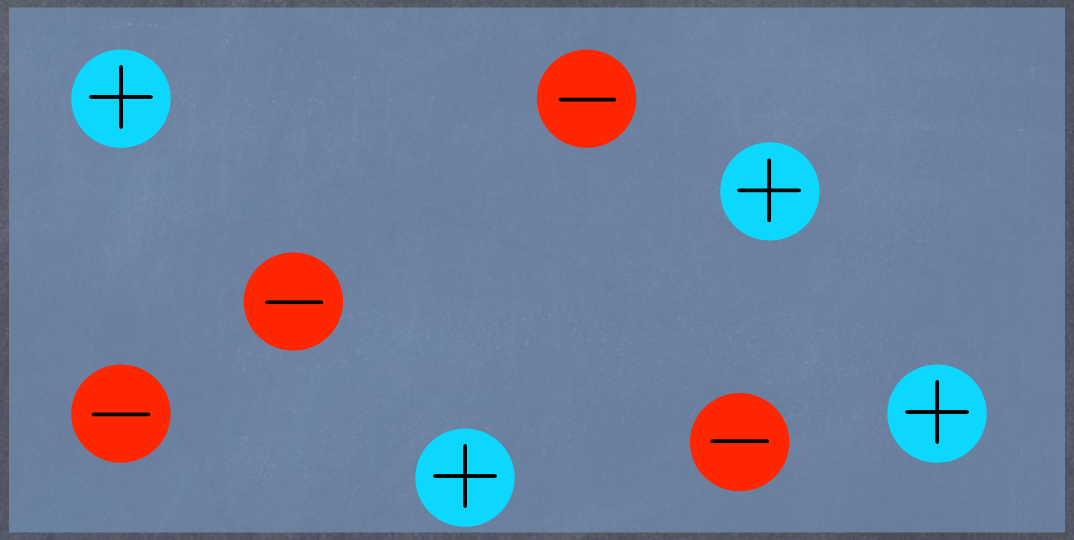

- Screened potential

$$\boxed{U(r) = \frac{e}{4\pi r} e^{-r/\lambda_{\rm D}}}$$

where

$$\lambda_{\rm D} = \sqrt{\frac{k_{\rm B} T}{2 e^2 n}}$$

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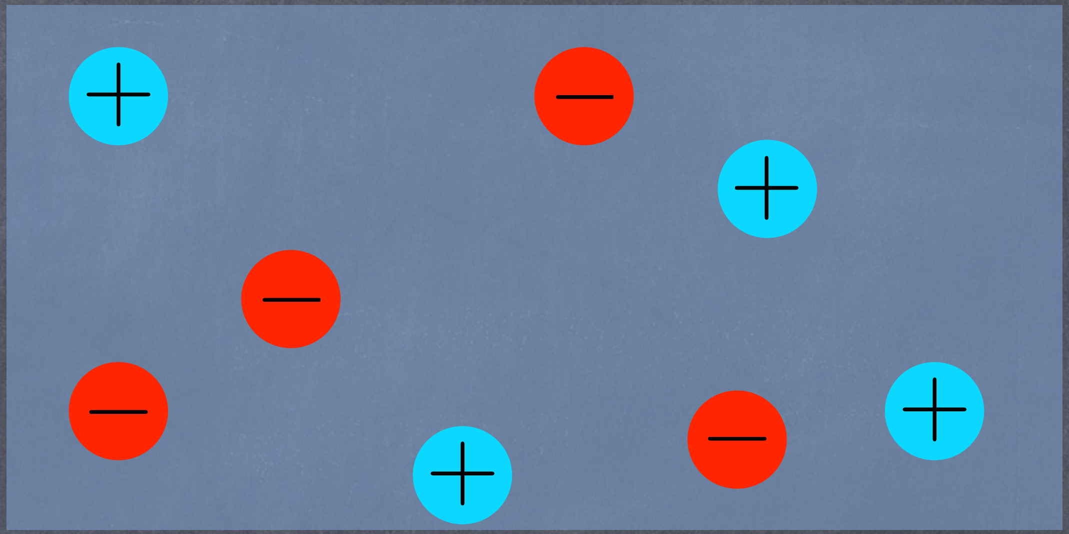


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Debye screening length

- Born approx'n in high energy limit ( $k\lambda_{\rm D} \gg 1$)

$$\sigma_{\rm int} \simeq 8\pi e^2 e_{\rm b}^2 \frac{\lambda_{\rm D}^2}{v^2} \sim \frac{1}{v^2 n}$$

✓

## Open Questions

- Uniqueness?
- Scatter?
- Dynamics: approach to equilibrium? Need simulations...
- Best-motivated particle physics model? Origin of $a_0$ ?
- No external field effect (as far as I can tell)

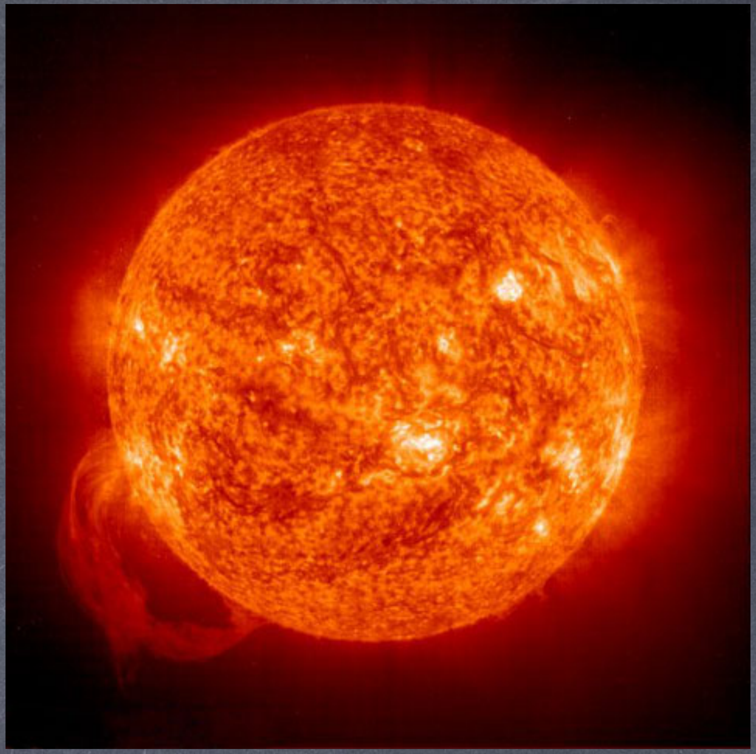
  $\Longrightarrow$ Is this a problem?

## Gas vs Stars

So far we modeled baryons as homogeneous gas:

$$\Gamma_{\rm int} \simeq \frac{\rho_{\rm gas} v a_0}{\epsilon n}$$

What about stars?



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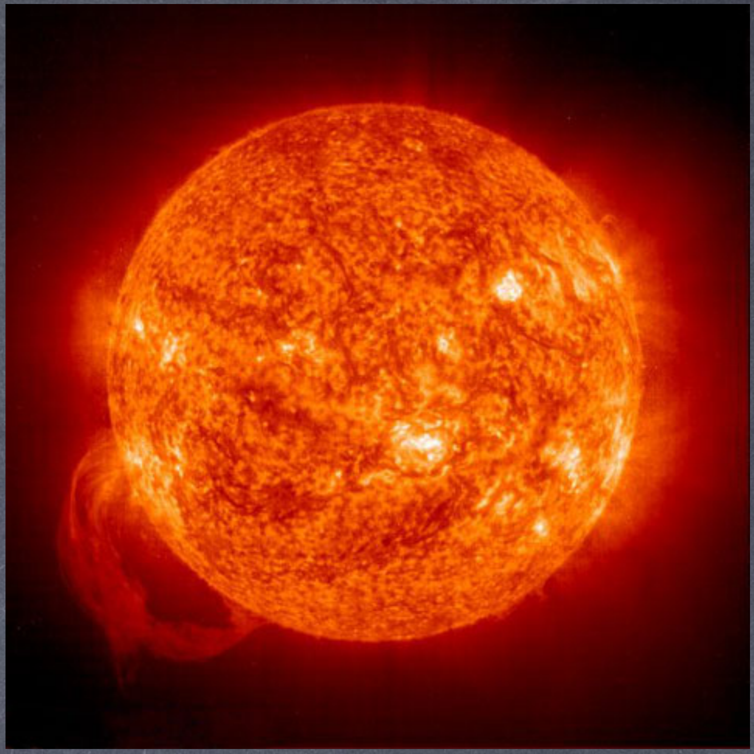

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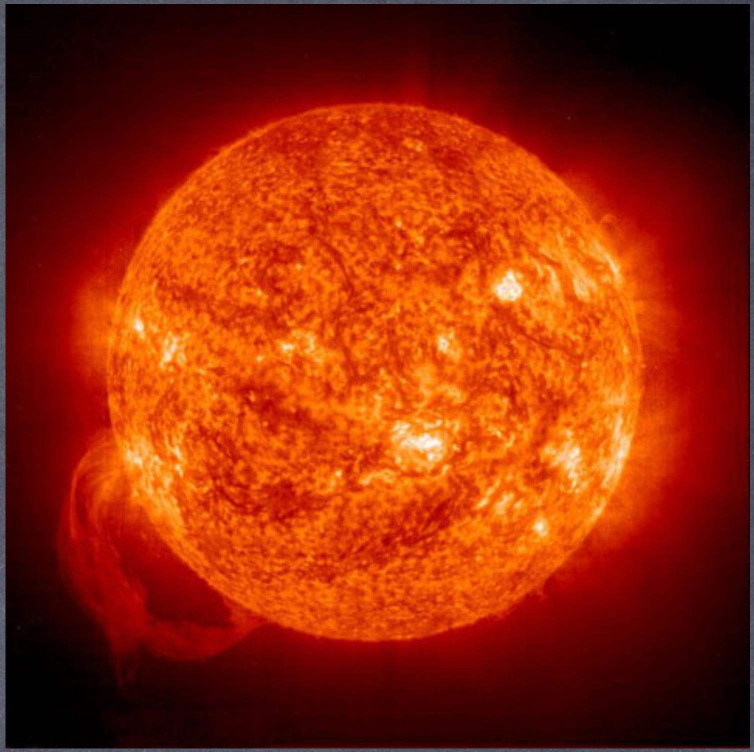

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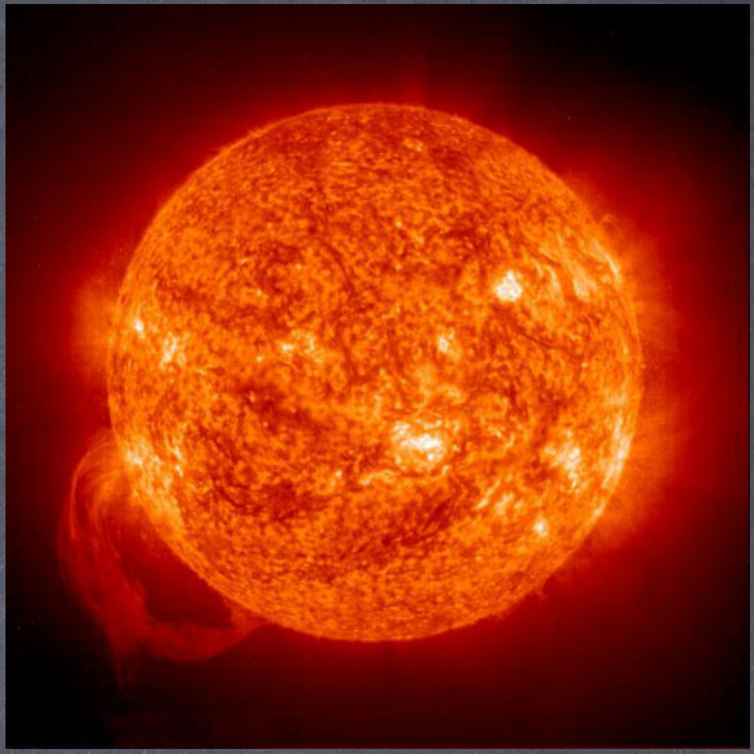

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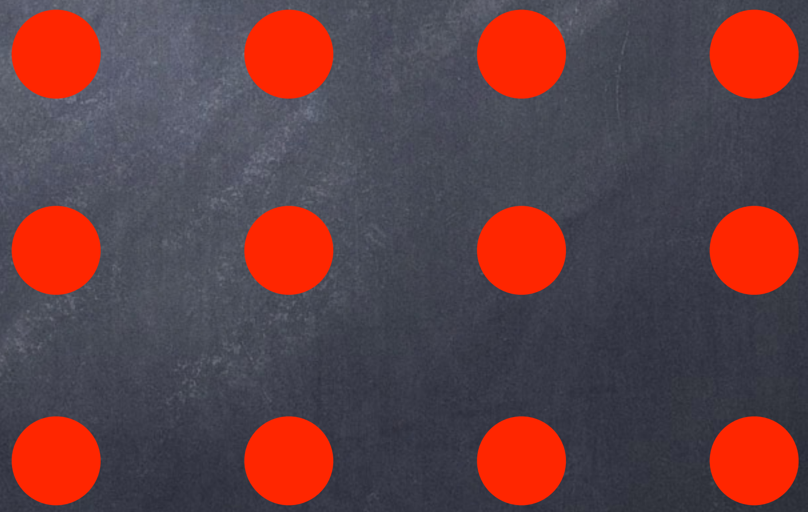

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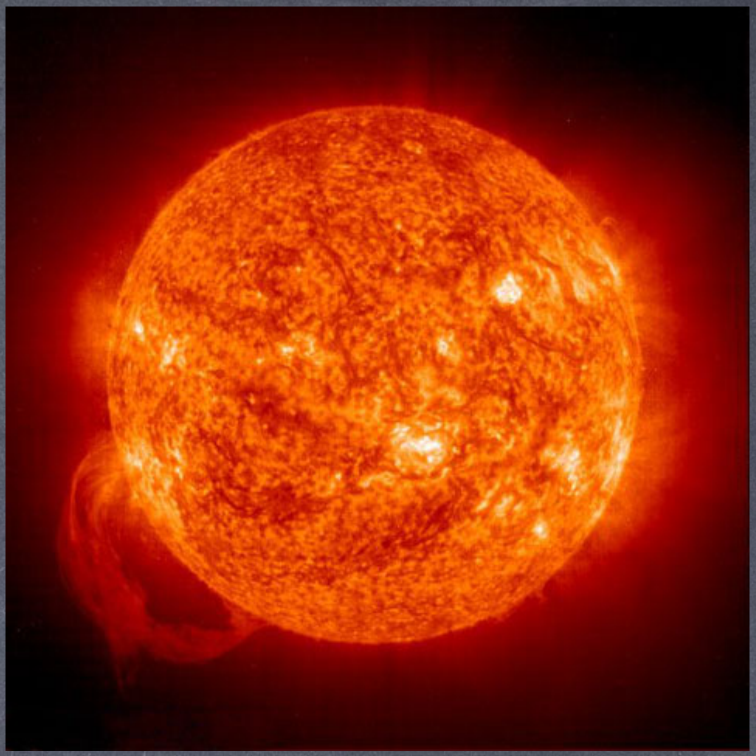

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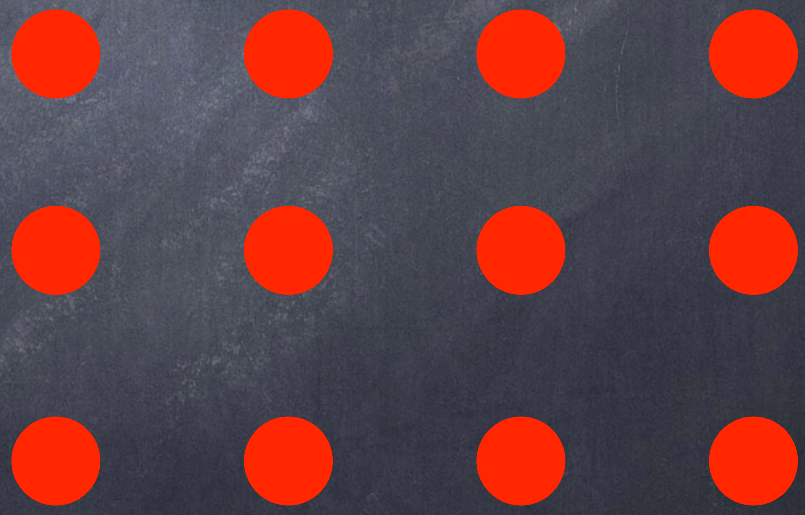
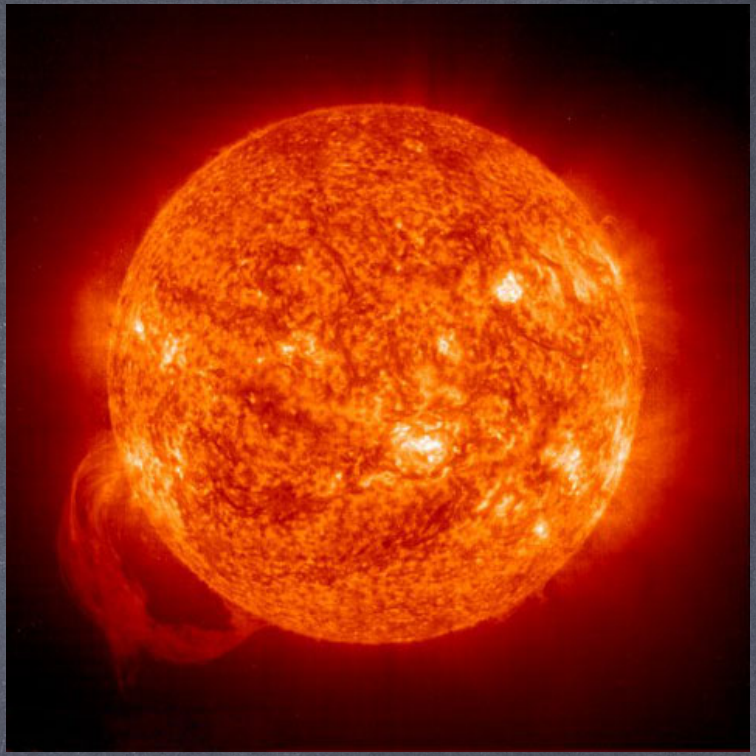


$$\Longrightarrow \quad \Gamma_{\rm int} \simeq \frac{\rho_{\rm stars} v a_0}{\epsilon n}$$

What matters is total # of targets.

## Gas vs Stars (cont'd)



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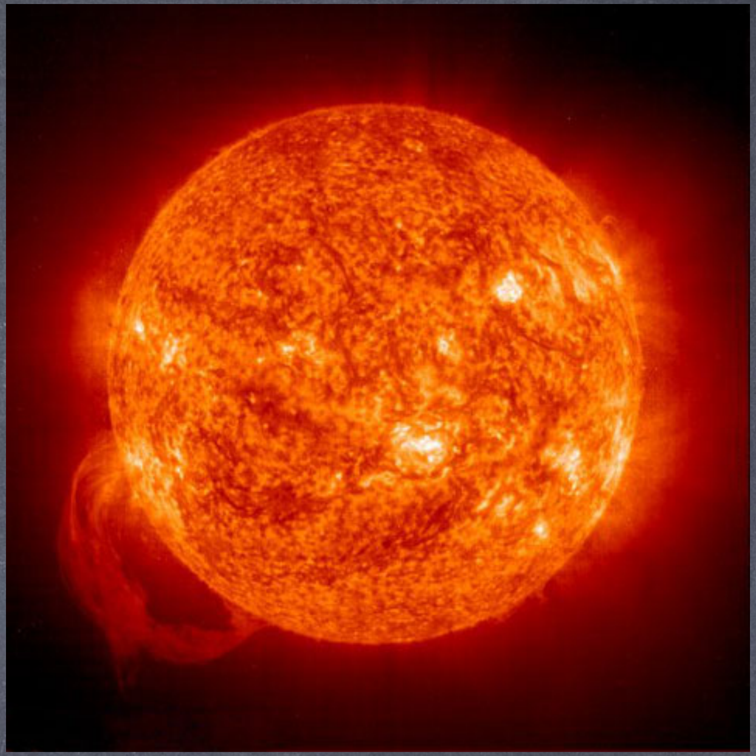

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Sommerfeld enhancement

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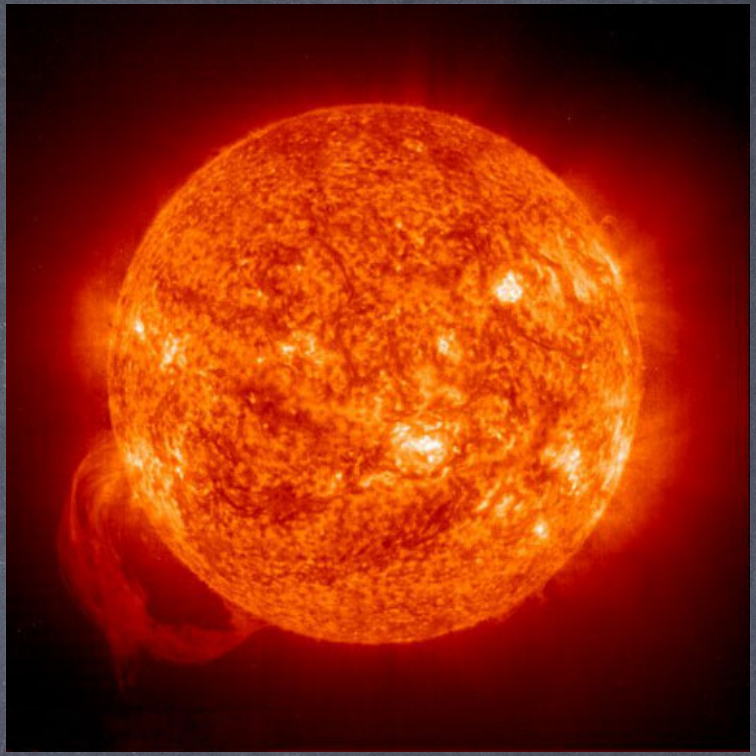

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Local DM enhancement
(Xavier's talk)

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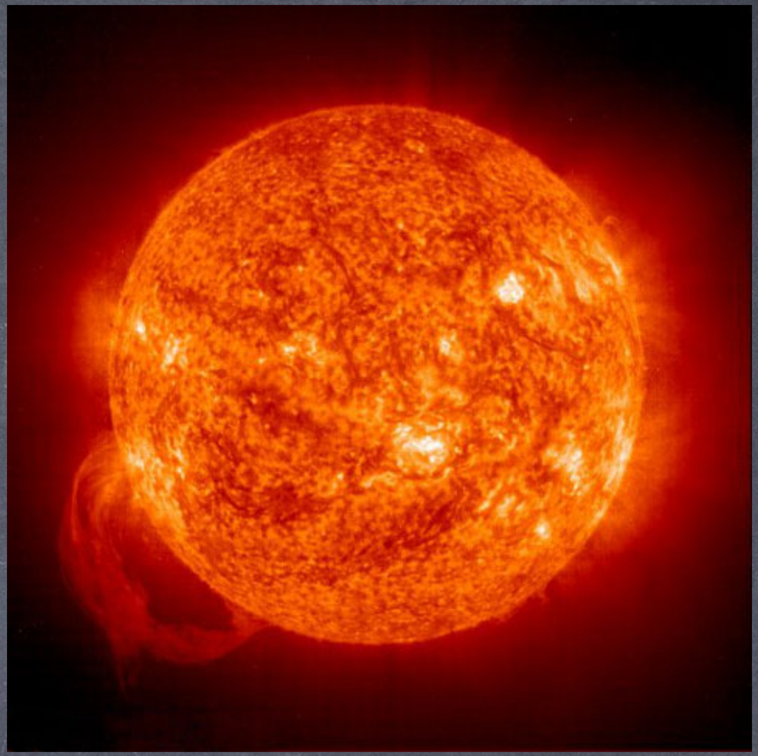

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These two factors cancel out, and we recover

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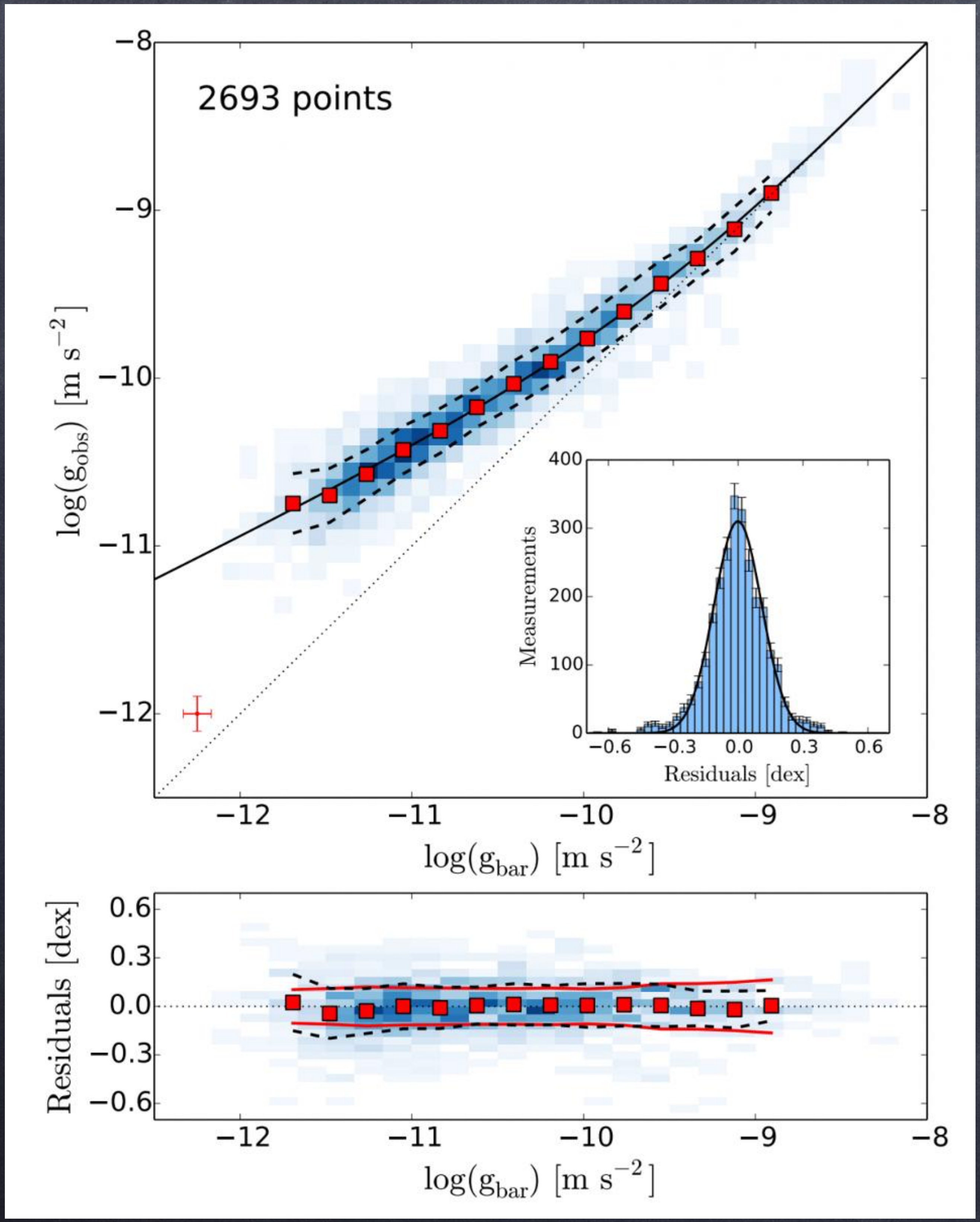
# Mass Discrepancy Acceleration Relation (MDAR)

McGaugh, Lelli & Schombert, PRL (2016)



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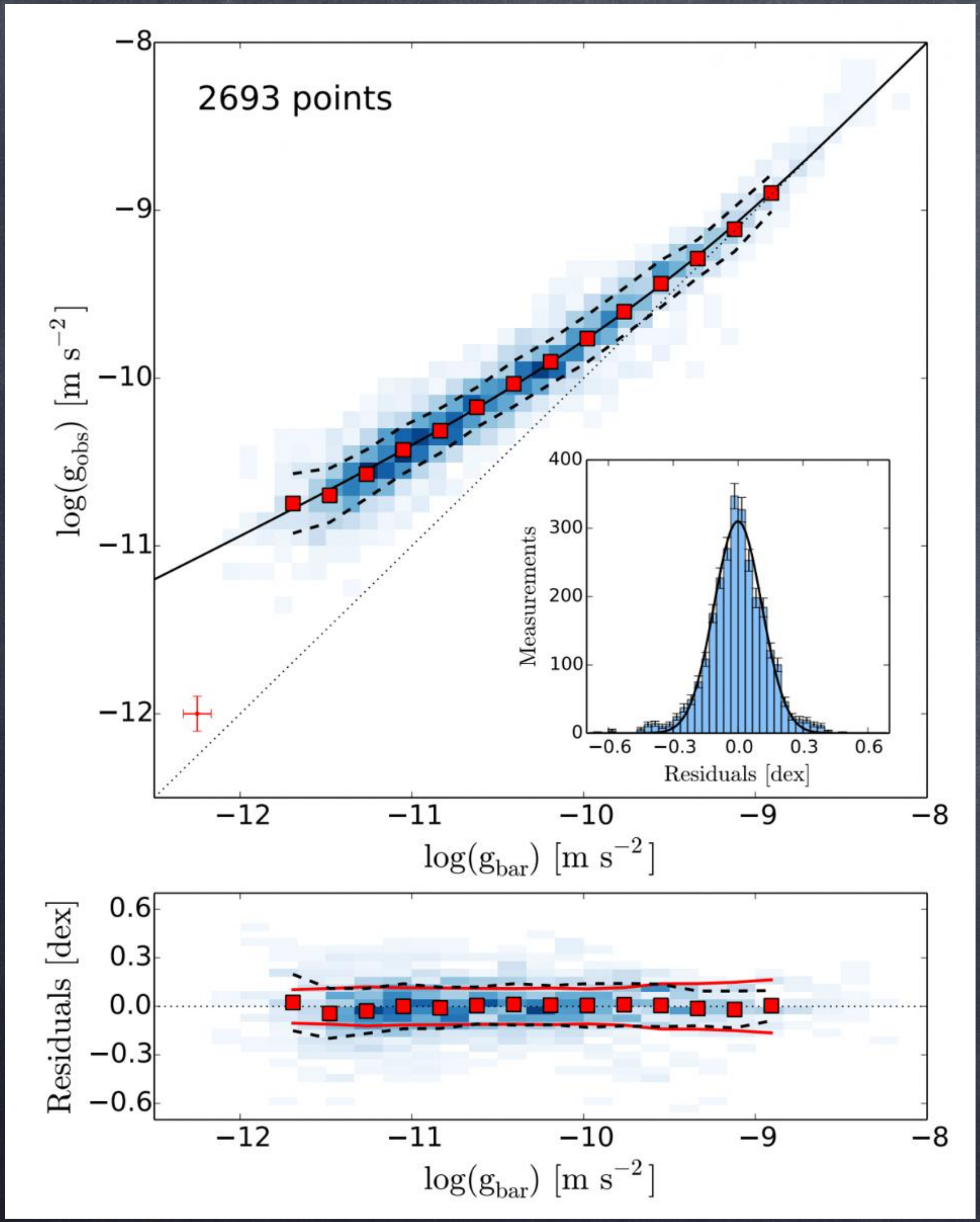


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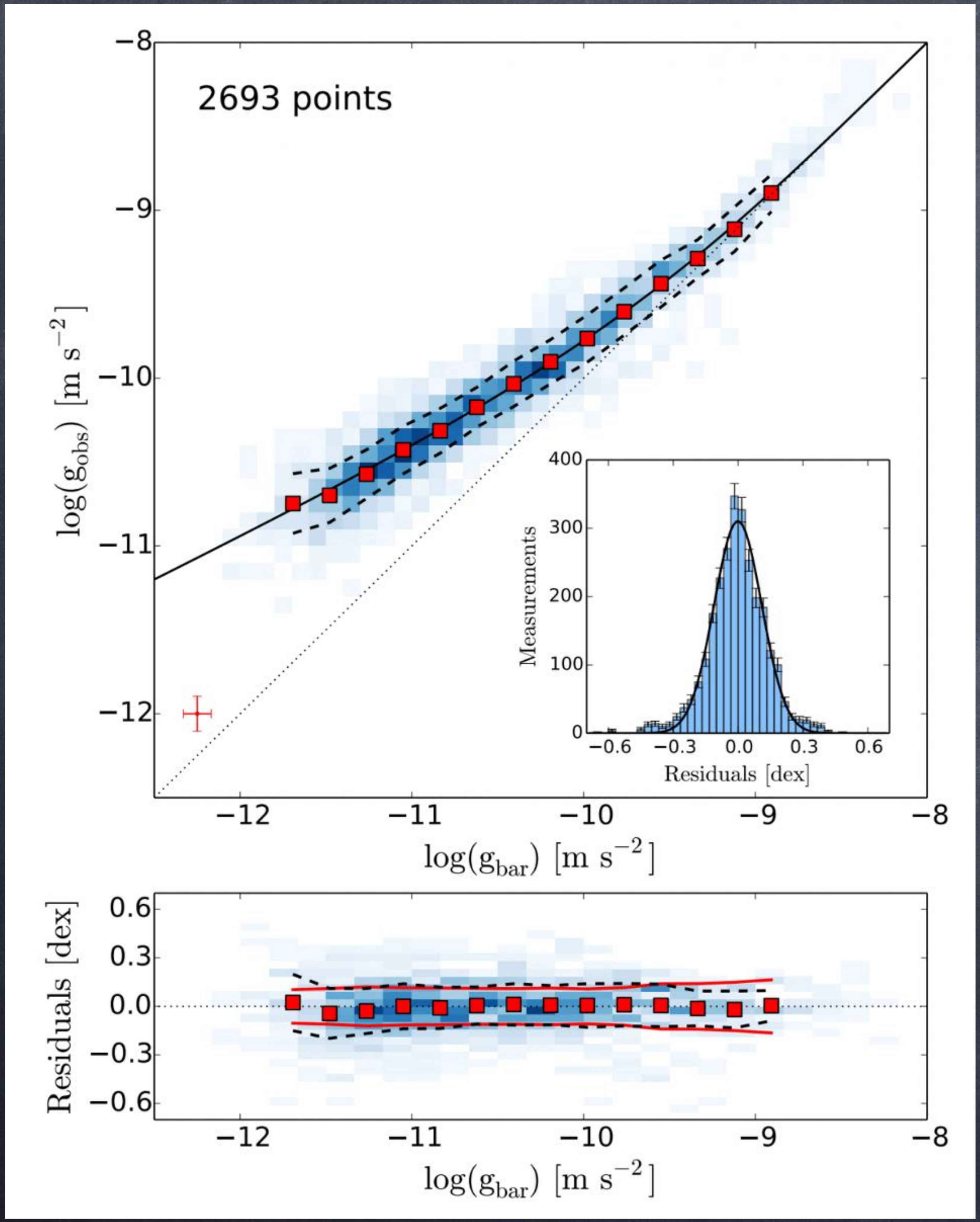


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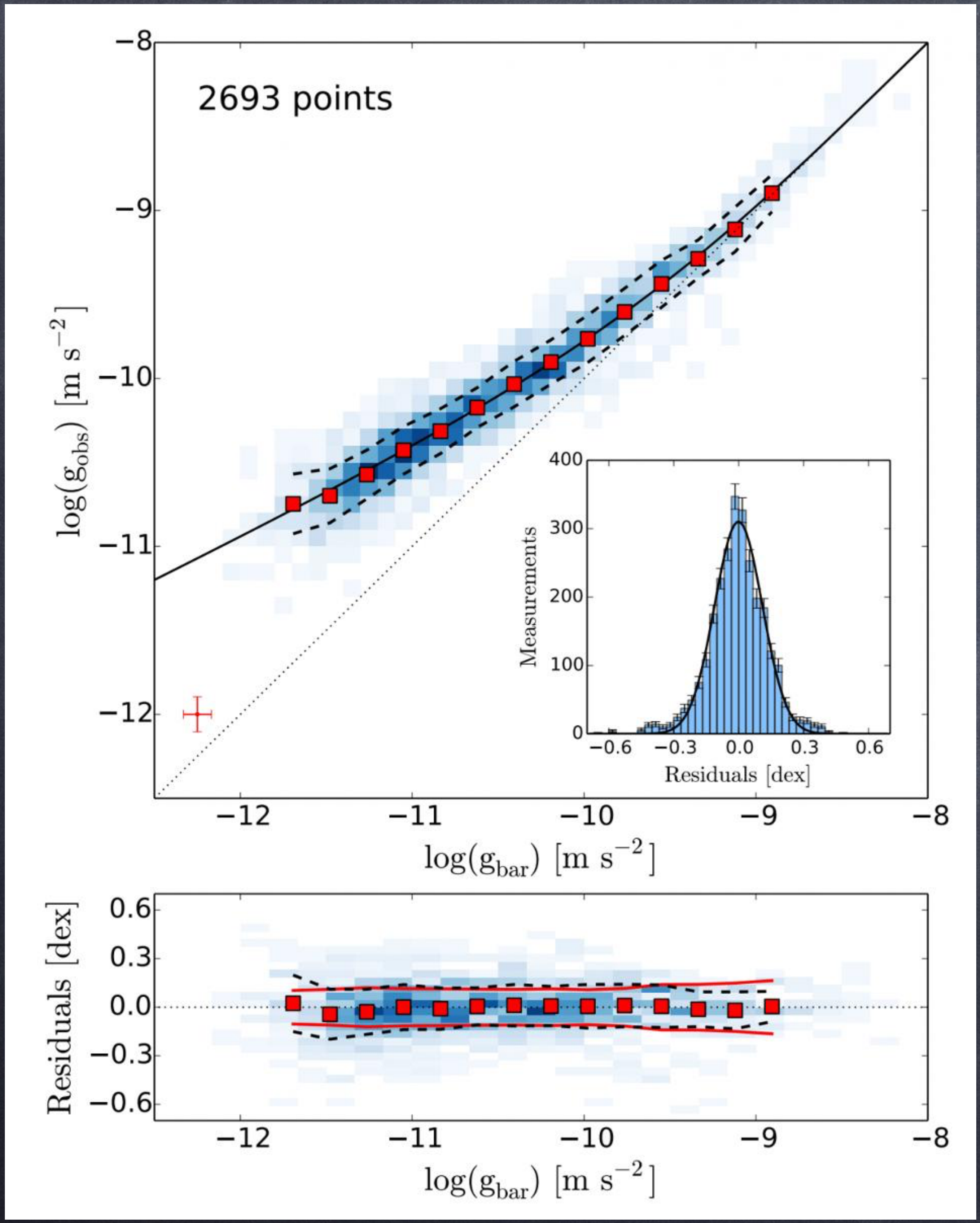


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- New dark sector physics

- Dipolar DM (Blanchet)
- Superfluid DM (Berezhiani & JK)