Constraints from disk heating

News from the dark 8

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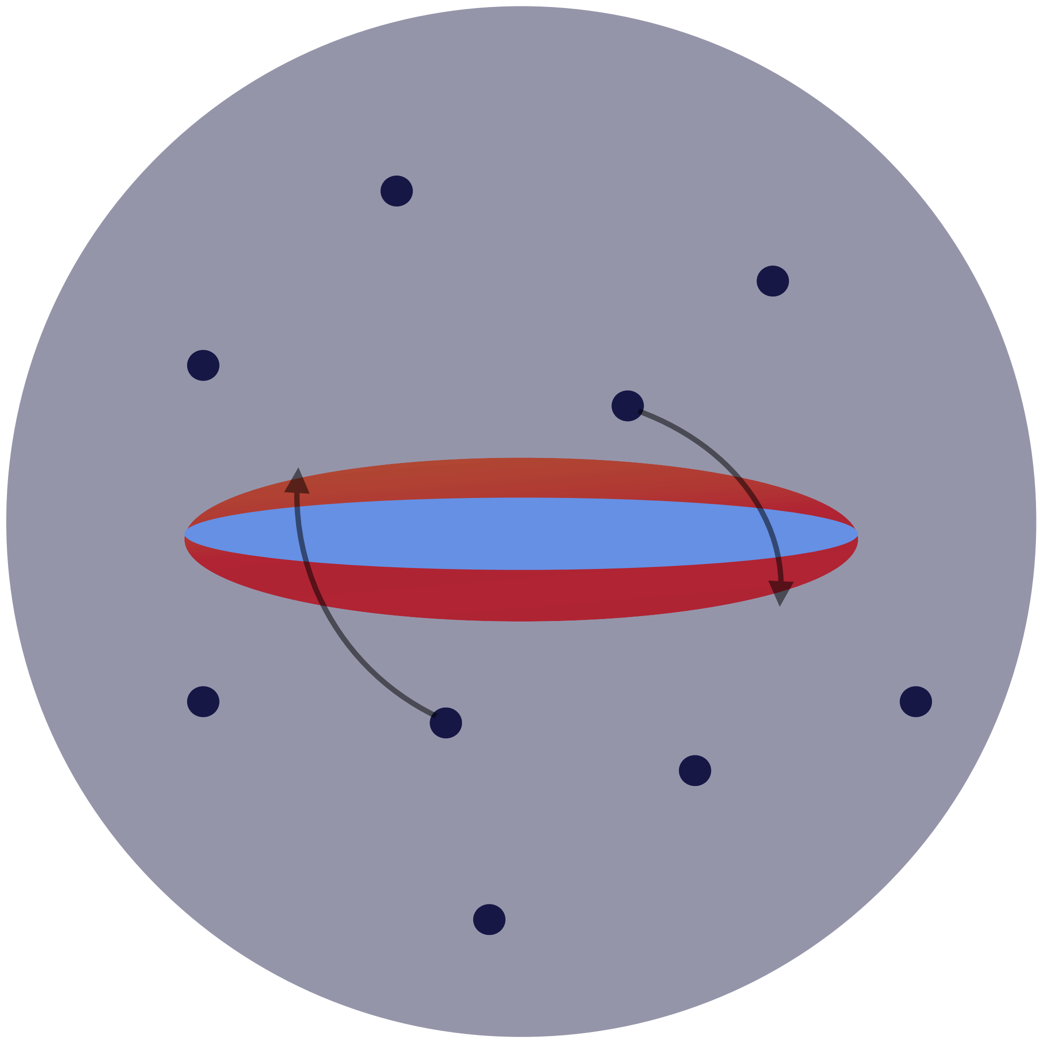
Heating of the galactic disk



Heating of the galactic disk

- MACHOs / PBHs

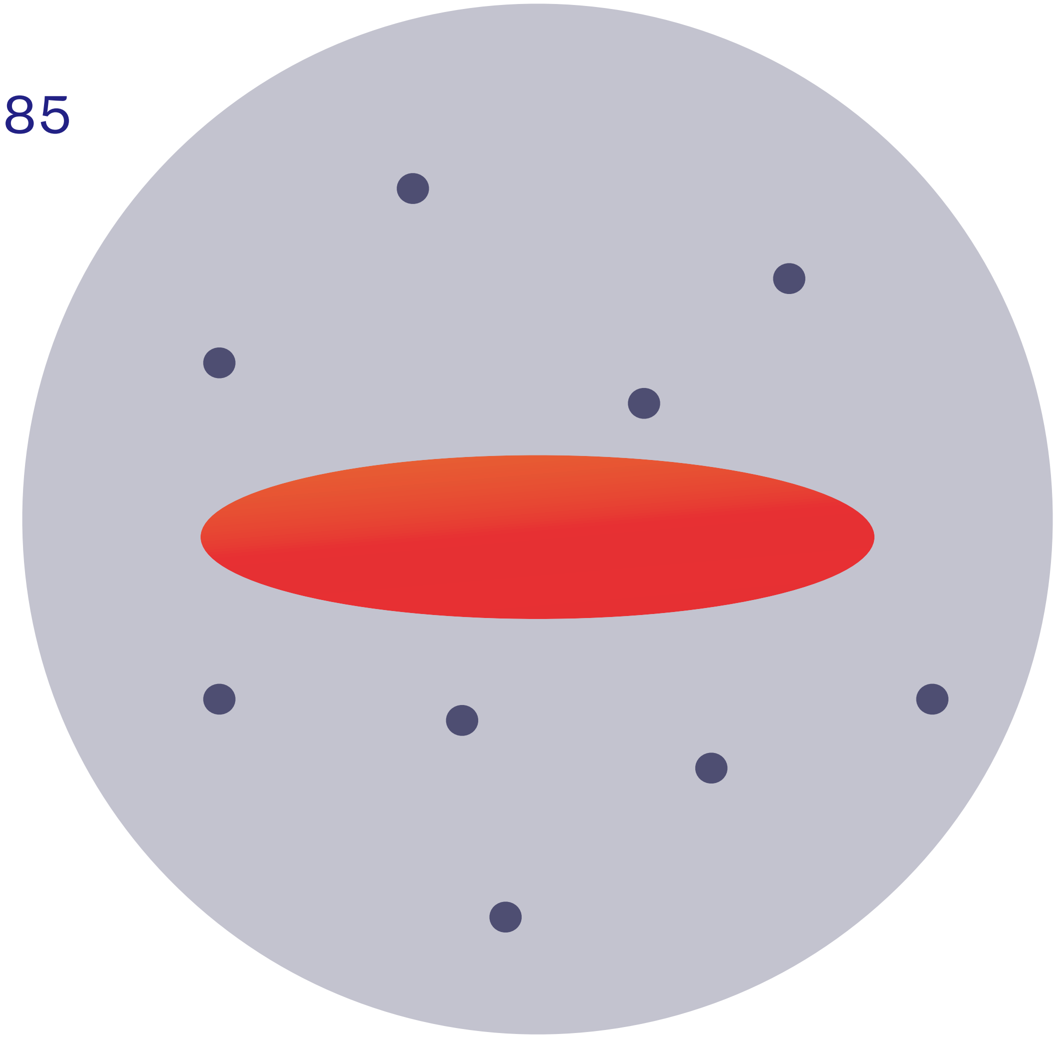
Lacey and Ostriker 1985

M $\sim 10^6 M_\odot$

Carr and Lacey 1986

- Fuzzy DM

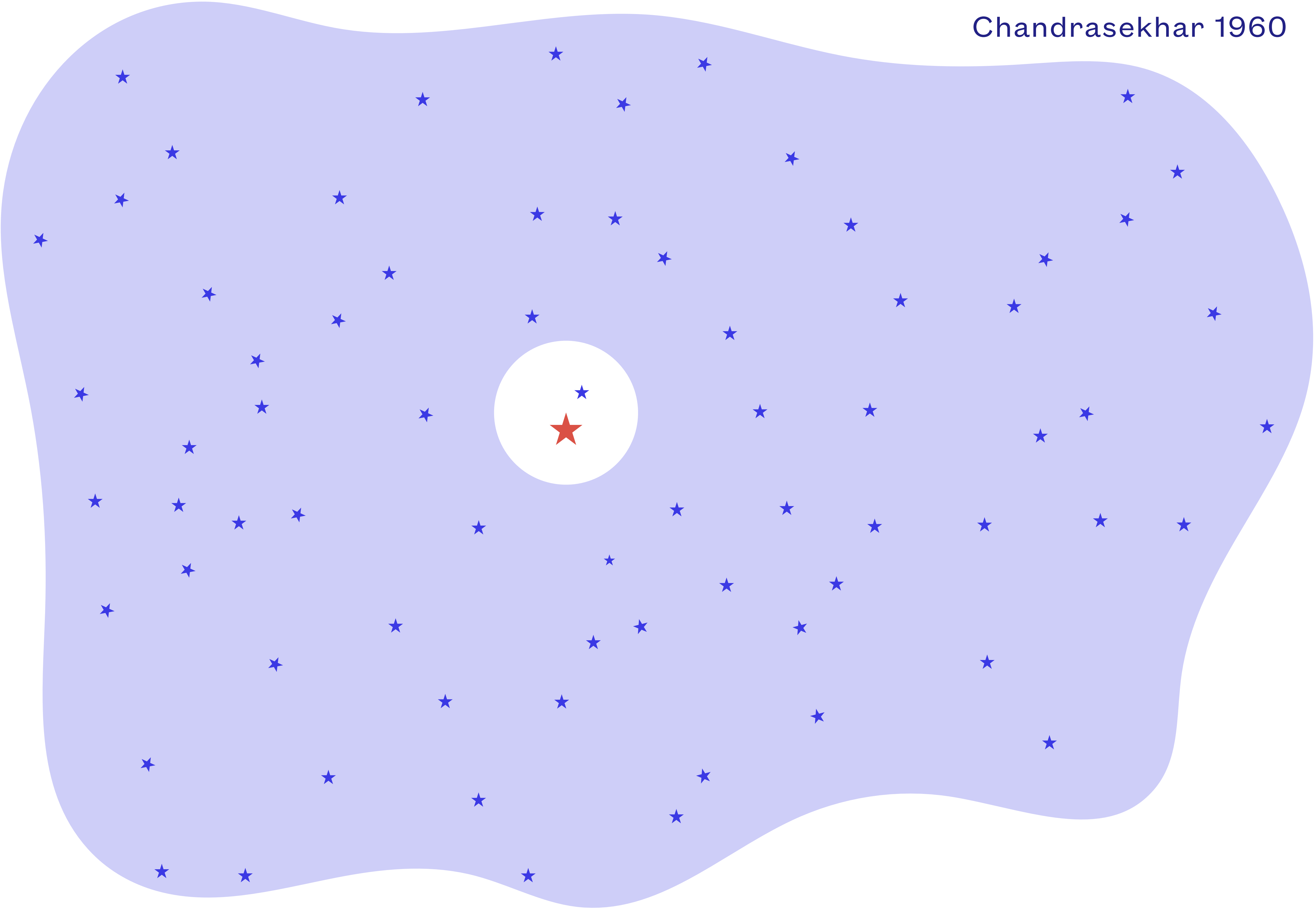
2211.07452



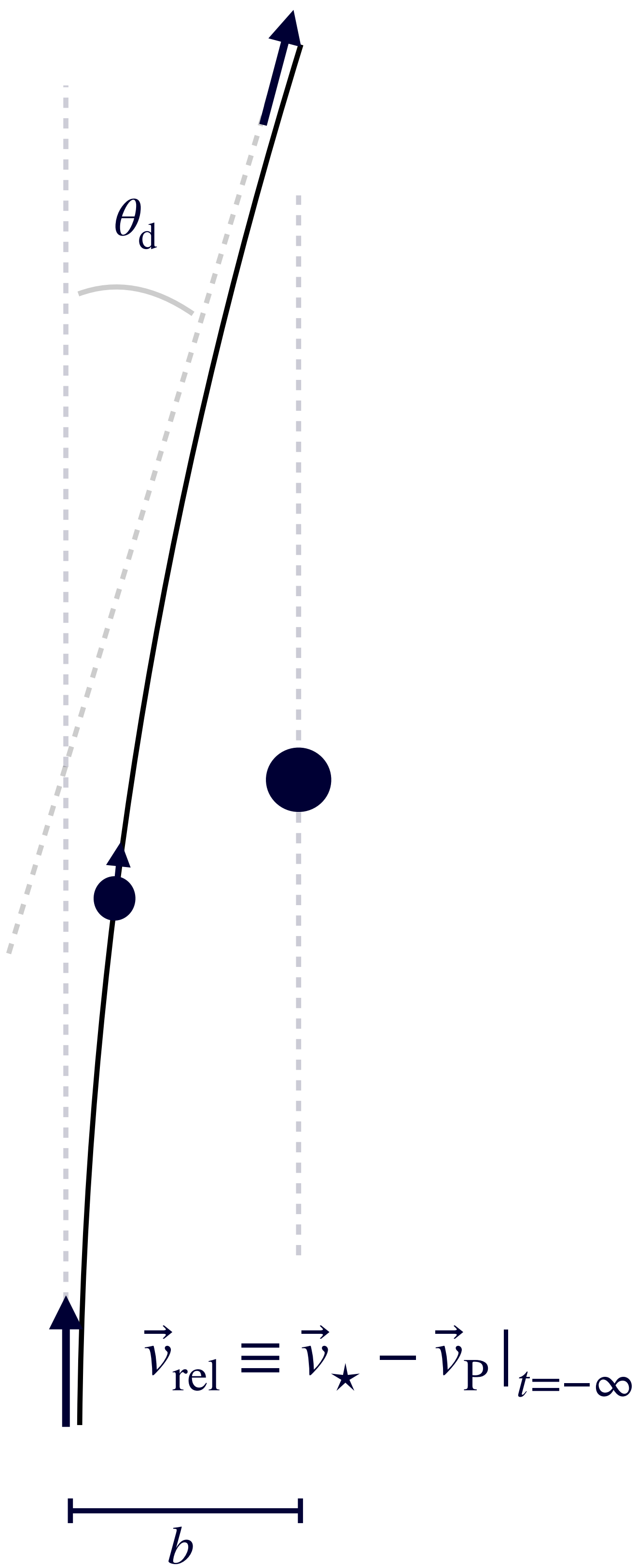
- DM galactic substructures:
    - PBH clusters
- Ultracompact minihalos
    - …

- Very precise observations of the velocity dispersion of MW stars
    - Sharma et al. 2004.06556 (Gaia DR2)

The classical calculation: setup



Variation of the star velocity



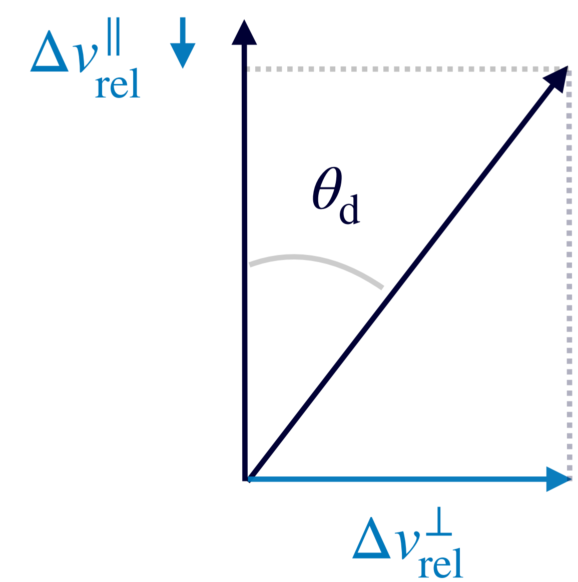
- Deflection angle

$$b_{90} \equiv \frac{G\left(m_\mathrm{P} + m_\star\right)}{v_\mathrm{rel}^2}$$

$$\theta_\mathrm{d} = 2\tan^{-1}\left(\frac{b_{90}}{b}\right)$$

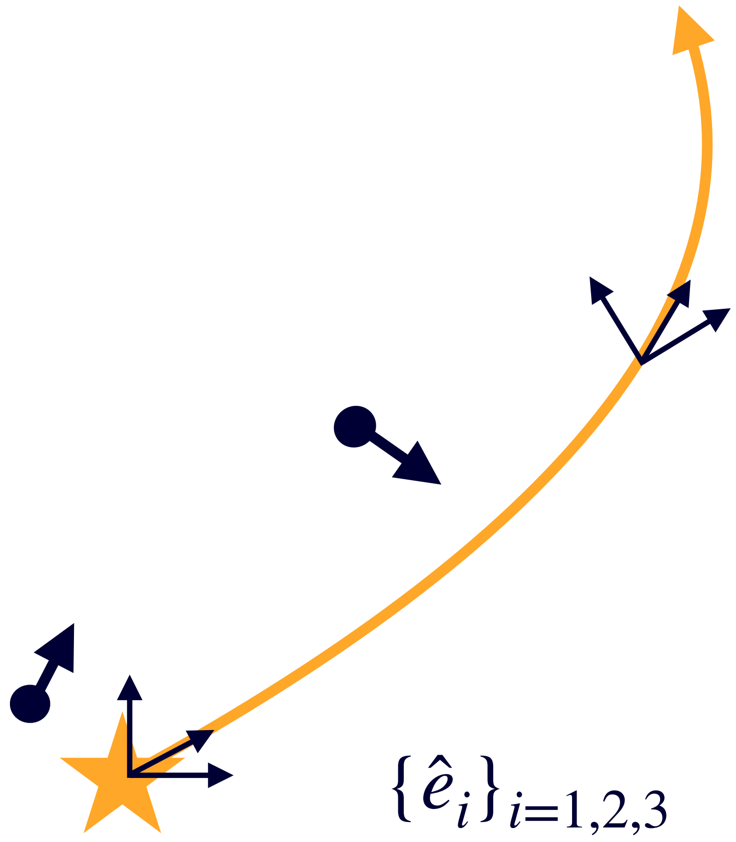
- For $b \gg b_{90}$

$$\begin{cases} \Delta v_\star^\perp \simeq \dfrac{2 v_\mathrm{rel} m_\mathrm{P}}{m_\mathrm{P} + m_\star} \dfrac{b_{90}}{b} = \dfrac{2 G m_\mathrm{P}}{b v_\mathrm{rel}} \\[2ex] \Delta v_\star^\parallel \simeq -\dfrac{2 v_\mathrm{rel} m_\mathrm{P}}{m_\mathrm{P} + m_\star} \left(\dfrac{b_{90}}{b}\right)^2 \end{cases}$$



Isotropy and projection on star coordinate system

- Assume isotropy $\langle \Delta v_\star^\perp \rangle = 0$
- Project along star trajectory



$$\Delta v_i \doteq -|\Delta v_\star^\parallel| \langle \hat{e}_i | \hat{v}_{\rm rel} \rangle \qquad \propto \left(\frac{b_{90}}{b}\right)^2$$

$$\Delta v_i \Delta v_j \doteq \frac{1}{2} |\Delta v_\star^\perp|^2 \left(\delta_{ij} - \langle \hat{e}_i | \hat{v}_{\rm rel} \rangle \langle \hat{e}_j | \hat{v}_{\rm rel} \rangle\right) \qquad \propto \left(\frac{b_{90}}{b}\right)^2$$

- The star velocity varies by

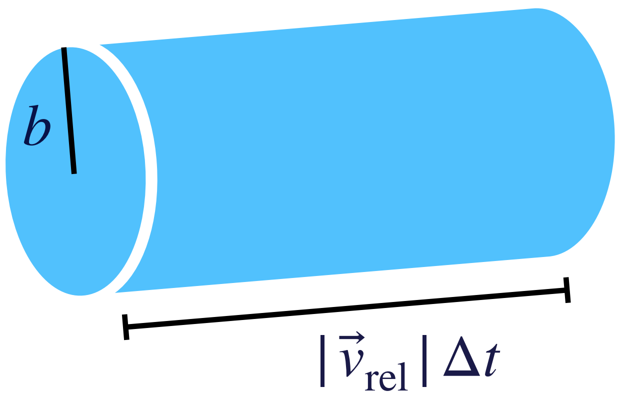
$$\Delta v_i \simeq -\frac{2G^2(m_{\rm P} + m_\star)m_{\rm P}}{|v_{\rm rel}| b^2} \frac{\partial}{\partial v_i}\left(\frac{1}{|v_{\rm rel}|}\right)$$

$$\Delta v_i \Delta v_j \simeq \frac{2G^2 m_{\rm P}^2}{|v_{\rm rel}| b^2} \frac{\partial^2}{\partial v_i \partial v_j} |v_{\rm rel}|$$

Summing over many encounters

- Number of encounters with impact parameter [b, b+db], relative velocity $[\vec{v}_{\rm rel}, \vec{v}_{\rm rel} + {\rm d}^3\vec{v}_{\rm rel}]$, in time interval Δt

$$
{\rm d}N(b, \vec{v}_{\rm rel}) = n_{\rm P}\, 2\pi\, b\, {\rm d}b\, |\vec{v}_{\rm rel}|\, \Delta t\, f(\vec{v}_{\rm rel}){\rm d}^3\vec{v}_{\rm rel}
$$



- Density of perturbers n_P approximately constant in neighbourhood of star
- Velocity distribution $f(\vec{v}_{\rm rel})$ independent of b

- Integrate over $\vec{v}_{\rm rel} = \vec{v}_\star - \vec{v}_{\rm P}$
  - $\vec{v}_\star = {\rm const} \quad (\Delta v_\star \ll v_\star)$
  - $\vec{v}_{\rm P} \sim MB\,(\sigma_{\rm P})$

$$
h(\vec{v}_\star) = \int {\rm d}^3 v_{\rm P} \frac{f(\vec{v}_{\rm P})}{|\vec{v}_\star - \vec{v}_{\rm P}|}
$$

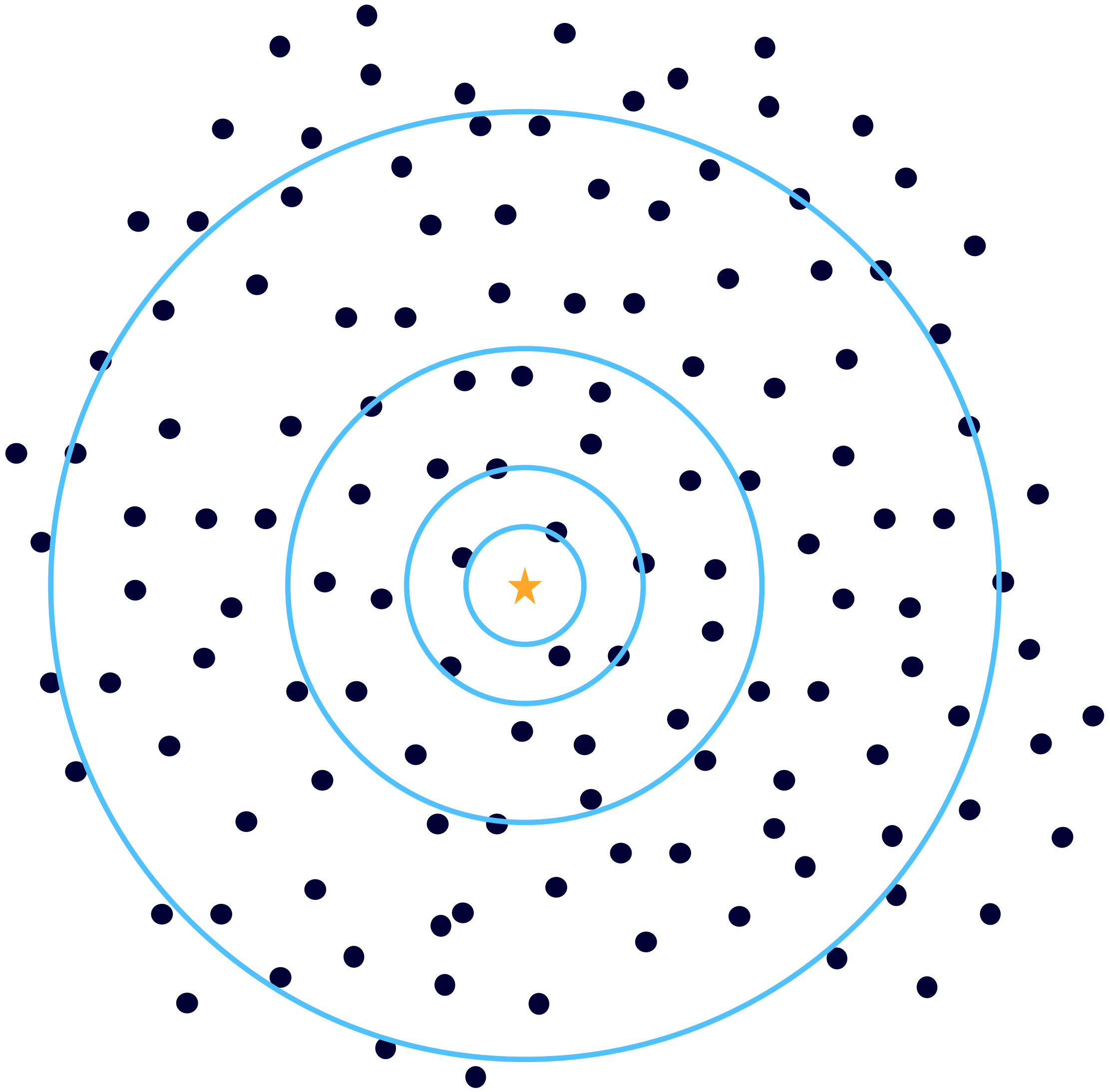
$$
g(\vec{v}_\star) = \int {\rm d}^3 v_{\rm P} f(\vec{v}_{\rm P})\, |\vec{v}_\star - \vec{v}_{\rm P}|
$$

Integral over the impact parameter

- Integrate over the impact parameter

$$\int_{b_{\min}}^{b_{\max}} \frac{\mathrm{d}b}{b} = \log \frac{b_{\max}}{b_{\min}} \equiv \log \Lambda$$

- Logarithmic divergence with $b_{\min}$, $b_{\max}$
- Minimum impact parameter $b_{\min} > b_{90}$
- $b_{\max}$ to be set to reasonable value



Velocity change of the star due to many encounters

- Components parallel and perpendicular to the star's velocity

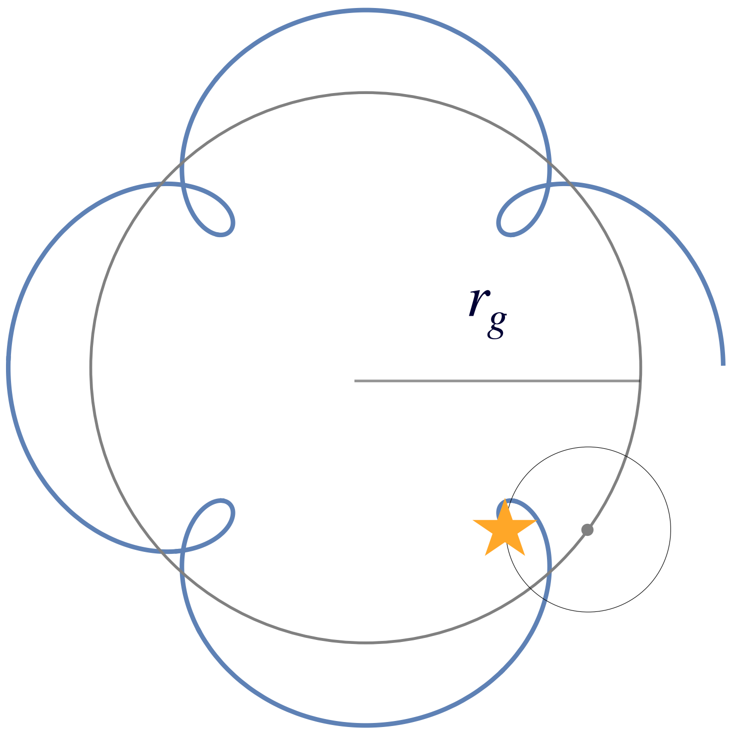
$$\frac{\langle \Delta v_{\parallel} \rangle}{\Delta t} = -\frac{4\pi G^2 n_{\mathrm{P}} m_{\mathrm{P}} (m_{\mathrm{P}} + m_\star) \ln \Lambda}{\sigma_{\mathrm{P}}^2} G(X)$$

$$\frac{\langle \Delta v_{\parallel}^2 \rangle}{\Delta t} = \frac{4\sqrt{2}\pi G^2 n_{\mathrm{P}} m_{\mathrm{P}}^2 \ln \Lambda}{\sigma_{\mathrm{P}}} \frac{G(X)}{X}$$

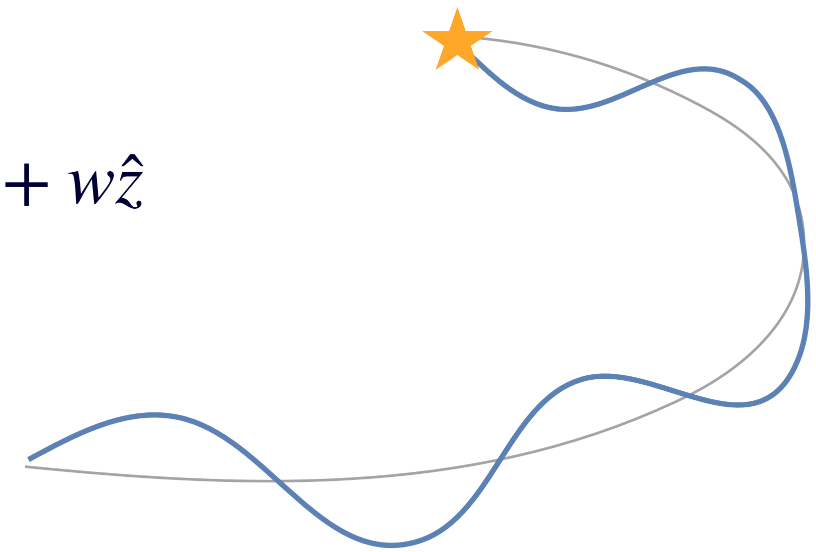
$$X \equiv \frac{v_\star}{\sqrt{2}\sigma_P}$$

$$\frac{\langle \Delta v_{\perp}^2 \rangle}{\Delta t} = \frac{4\sqrt{2}\pi G^2 n_{\mathrm{P}} m_{\mathrm{P}}^2 \ln \Lambda}{\sigma_{\mathrm{P}}} \frac{\mathrm{Erf}(X) - G(X)}{X}$$

Application to epicyclic orbits



$$\vec{v}_\star = u\hat{r} + \left(\mathrm{v}_c(r) + v\right)\hat{\theta} + w\hat{z}$$



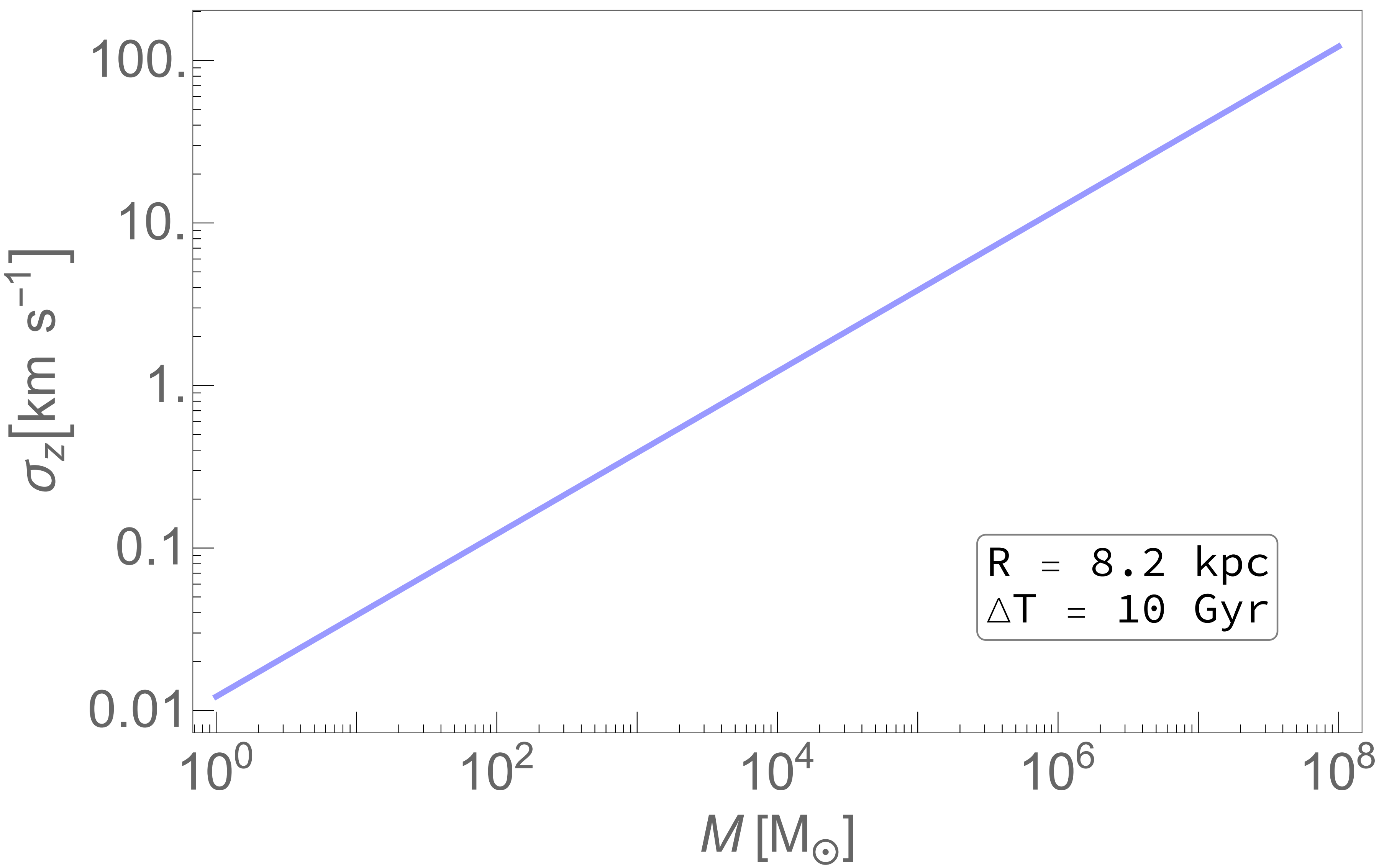
$$\frac{\mathrm{d}\sigma_r^2}{\mathrm{d}t} = \beta^2 \frac{\mathrm{d}\sigma_\theta^2}{\mathrm{d}t} = D_e \qquad D_e \equiv \frac{1}{4}\frac{\langle \Delta v_\perp^2 \rangle_{\mathrm{v}_c}}{\Delta t} + \frac{\beta^2}{2}\frac{\langle \Delta v_\parallel^2 \rangle_{\mathrm{v}_c}}{\Delta t}$$

$$\frac{\mathrm{d}\sigma_z^2}{\mathrm{d}t} = D_z \qquad D_z \equiv \frac{1}{4}\frac{\langle \Delta v_\perp^2 \rangle_{\mathrm{v}_c}}{\Delta t}$$

$$\beta = \frac{2\Omega_g}{\kappa}$$

Vertical heating

$$\frac{\mathrm{d}\sigma_z^2}{\mathrm{d}t} = \frac{\sqrt{2}\pi G^2 n_\mathrm{P} m_\mathrm{P}^2 \ln\Lambda}{\sigma_\mathrm{P}} \frac{\mathrm{Erf}(X) - G(X)}{X}$$

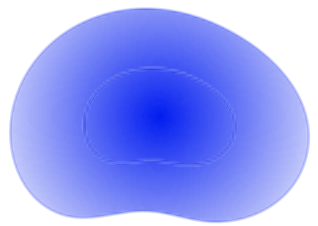


- Bkg potential from McMillan 2016 + NFW halo
- Jeans equation for σ_P
- $\ln\Lambda = 3$

Prospect: extended objects

- Validity of the pointlike approximation
    - Interstellar distance ~ 1 pc

- Tidal stripping → mass loss



    - R dependent
    - Mass concentration relation

Conclusions

- Disk heating can allow us to constrain the dark matter distribution on small scale through observations of stellar motion

- Timely: stellar dynamics data

- Ongoing work on theoretical modelling: penetrative encounters, tidal stripping, ….

- Stay tuned !