A self-consistent wave description of axion miniclusters and their survival in the galaxy

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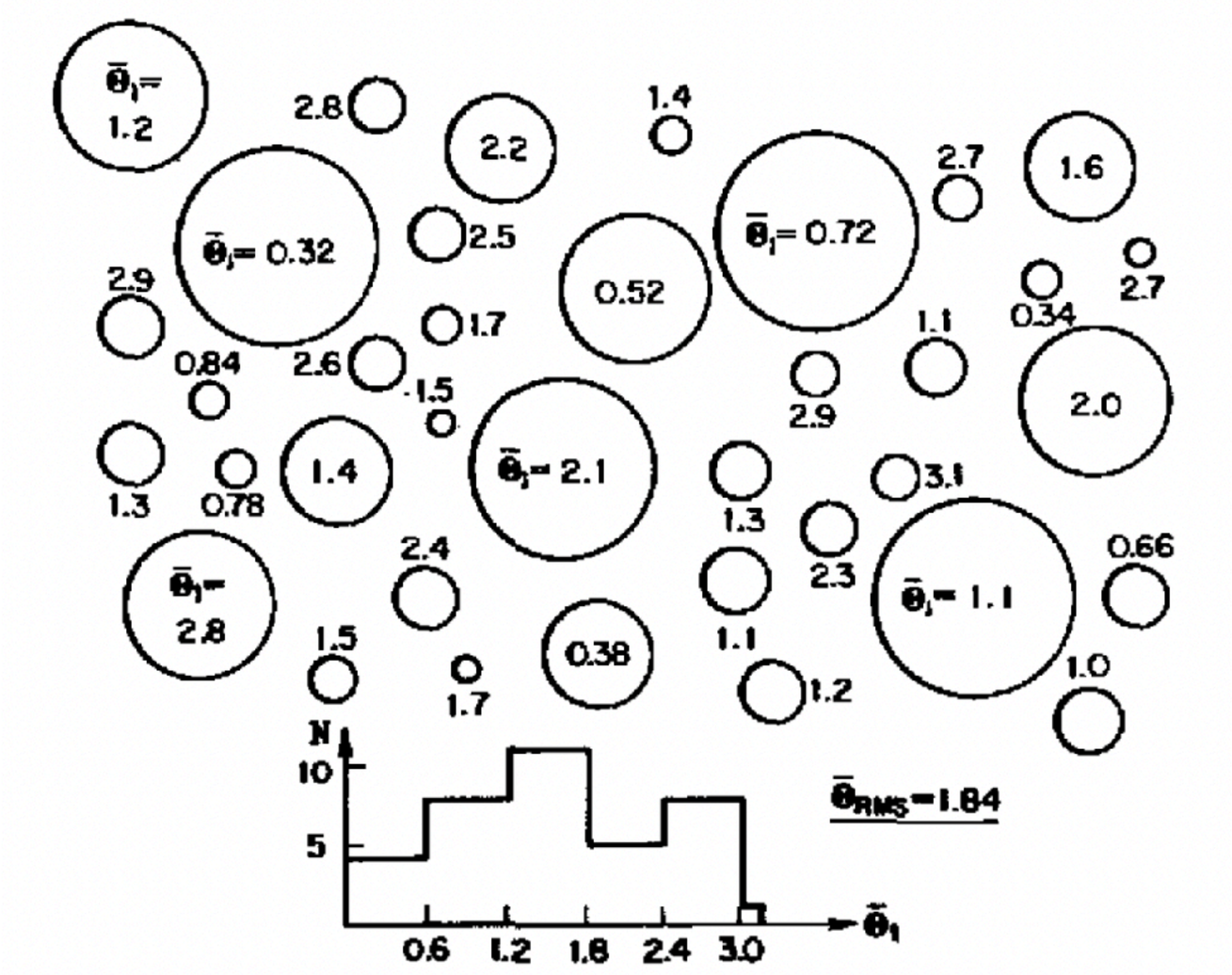
with V. Dandoy, T. Schwetz (KIT)

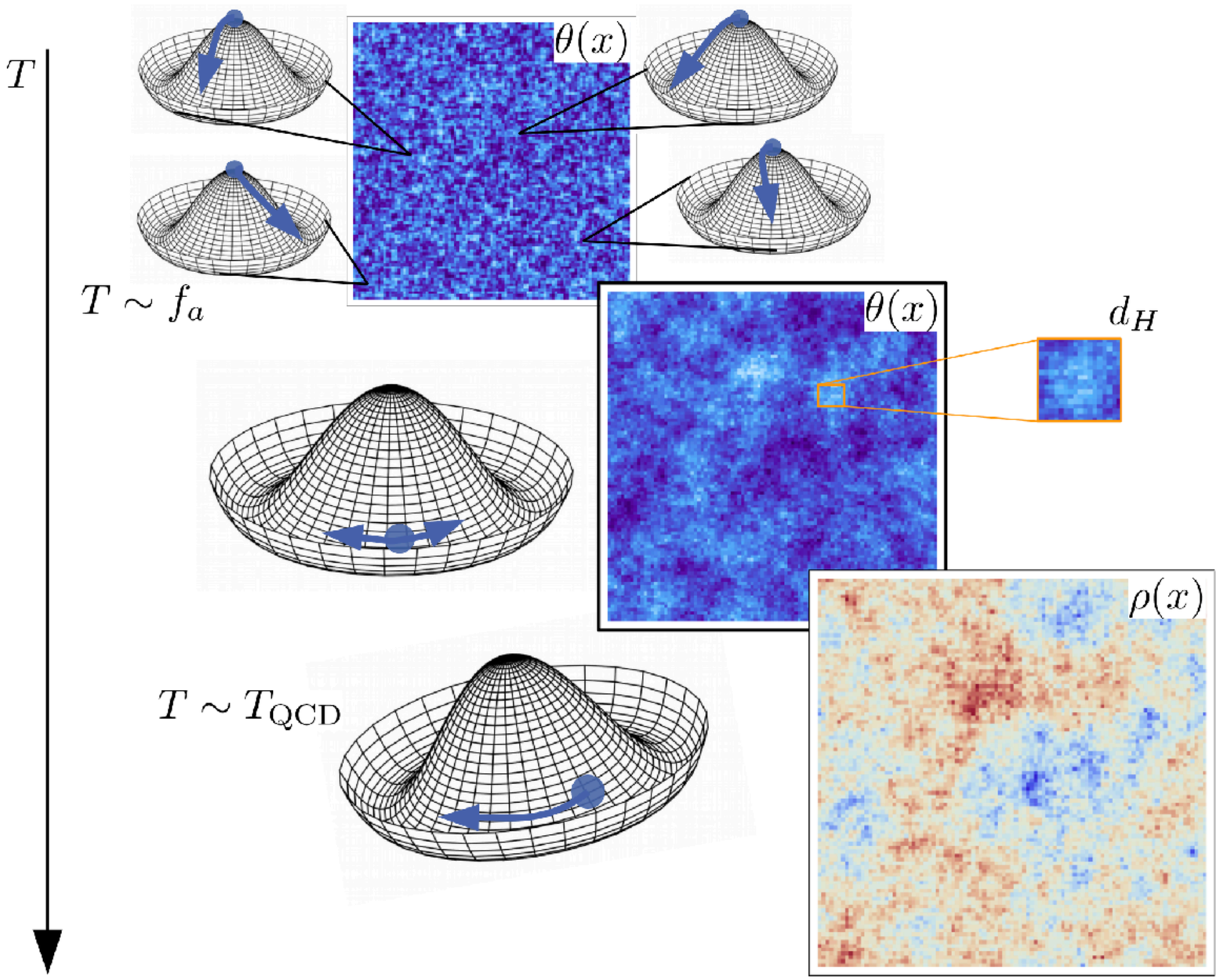
Based on 2206.04619
(to appear in JCAP)

Padova, 12.09.2022

Axion miniclusters



Kolb &Turner



A. Pargner, 10.5445/IR/1000092362

Occupation numbers

- (Very) rough estimates for a QCD axion with $m_a = 10^{-5}\ \mathrm{eV}$
- Axion mass is turned on at $m_a(t_1) \simeq H(t_1)$
- Typical radius and mass of miniclusters are determined by the size of the horizon at t_1

$$R \sim 10^8\ \mathrm{km} \qquad M \sim 10^{-12}\ M_\odot$$

- Typical phase space occupancy $\mathcal{N} \sim 10^{51}$
- We describe the minicluster as an incoherent superposition of classical axion waves

minutephysics

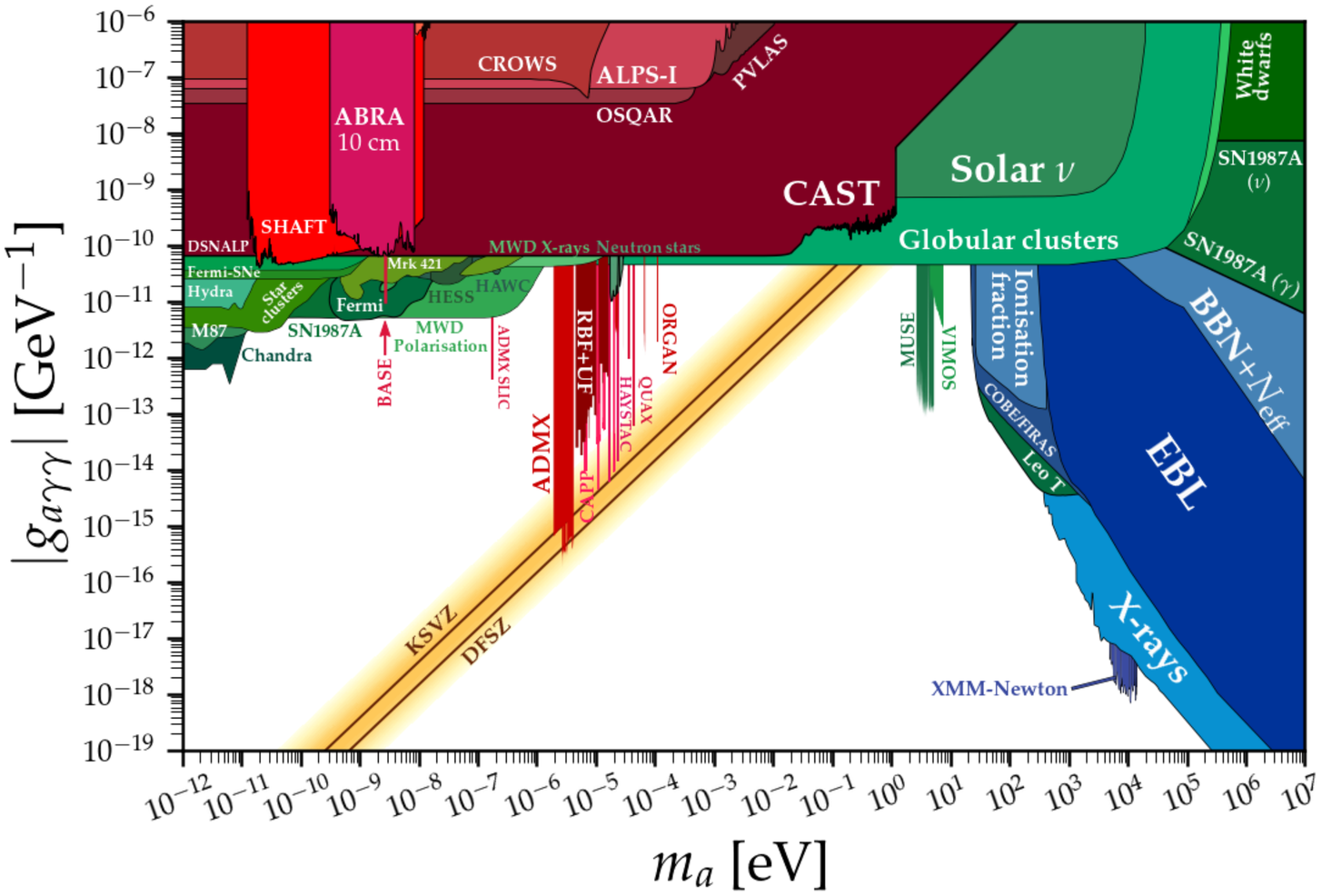
Miniclusters and dark matter detection

- If all the local dark matter is in miniclusters, the rate of encounters with Earth is

$$R_{enc} \sim 10^{-4}\ \mathrm{yr}^{-1}$$

- Problem for haloscope type experiments!

- Astrophysical signatures



https://github.com/cajohare/AxionLimits

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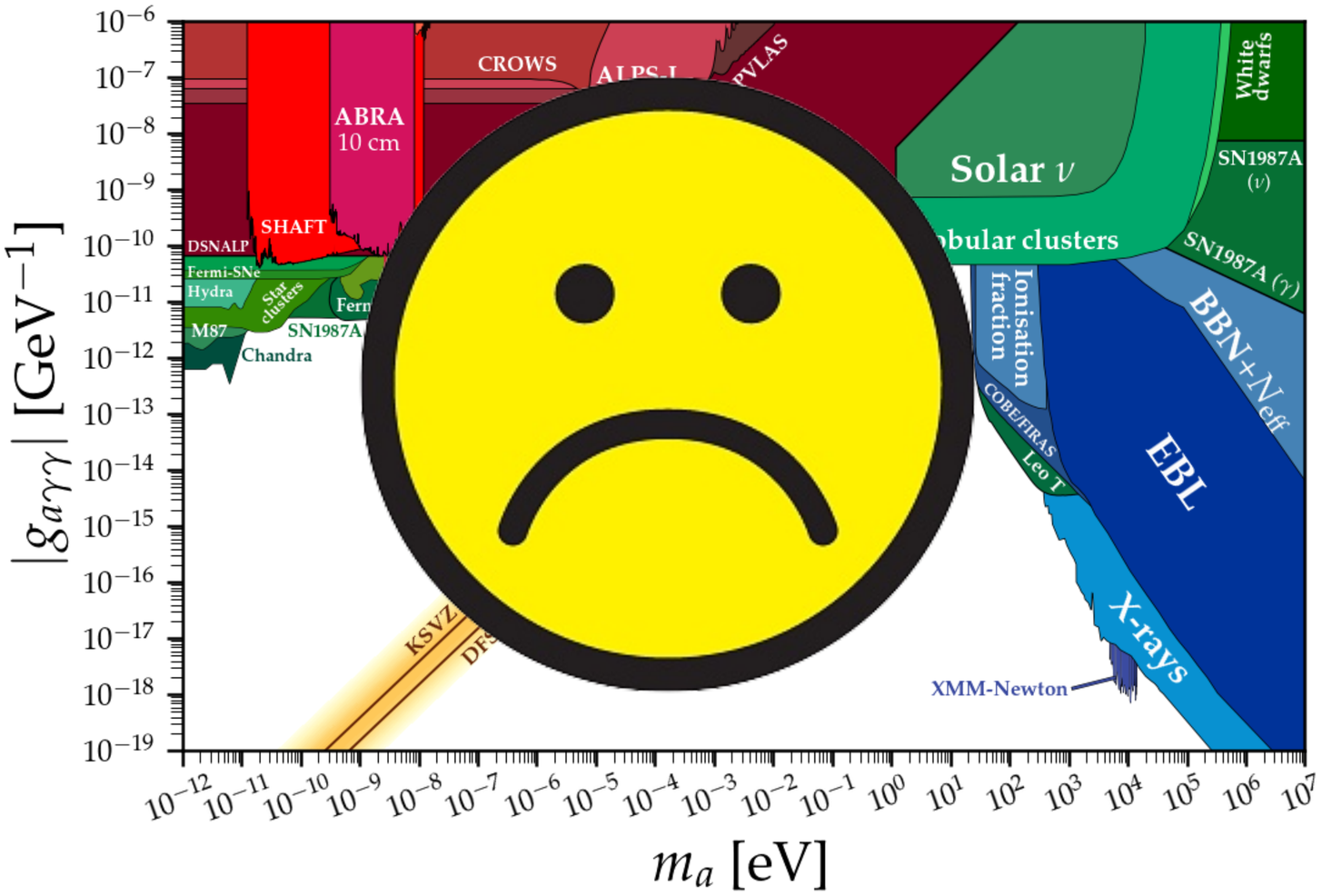

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Miniclusters and dark matter detection

- If all the local dark matter is in miniclusters, the rate of encounters with Earth is

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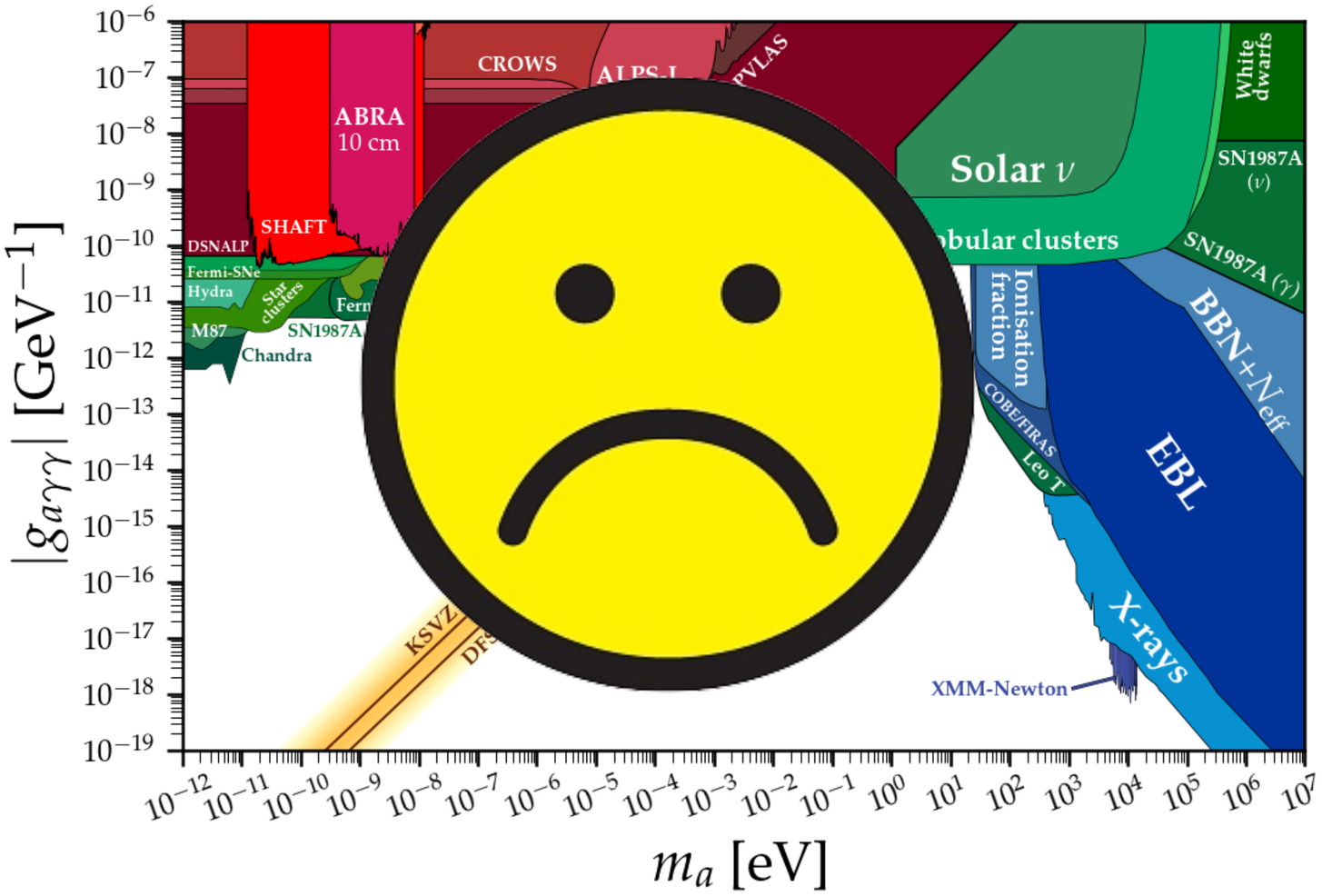
- Problem for haloscope type experiments!
- Astrophysical signatures
- We need to understand if miniclusters survive until today
- Tidal disruption in the galaxy effective?

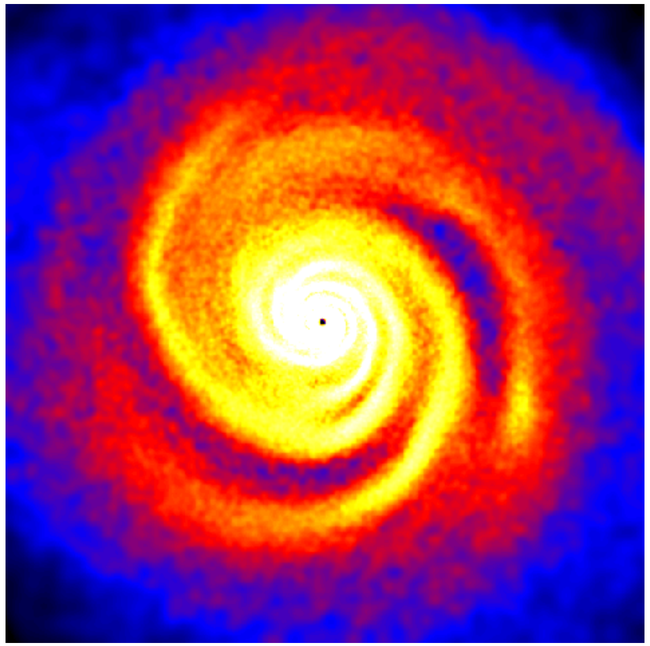


https://github.com/cajohare/AxionLimits

Other work on tidal disruption of miniclusters

- P. Tinyakov, I. Tkachev, and K. Zioutas, JCAP 1601 (2016), no. 01 035, [1512.02884]
- V. I. Dokuchaev, Y. N. Eroshenko, and I. I. Tkachev, J. Exp. Theor. Phys. 125 (2017), no. 3 434–442, [1710.09586]
- B. J. Kavanagh, T. D. P. Edwards, L. Visinelli, and C. Weniger, Phys. Rev. D 104 (2021), no. 6 063038, [2011.05377]
- X. Shen, H. Xiao, P. F. Hopkins, K. M. Zurek, [2207.11276]

Construction of a self-gravitating system



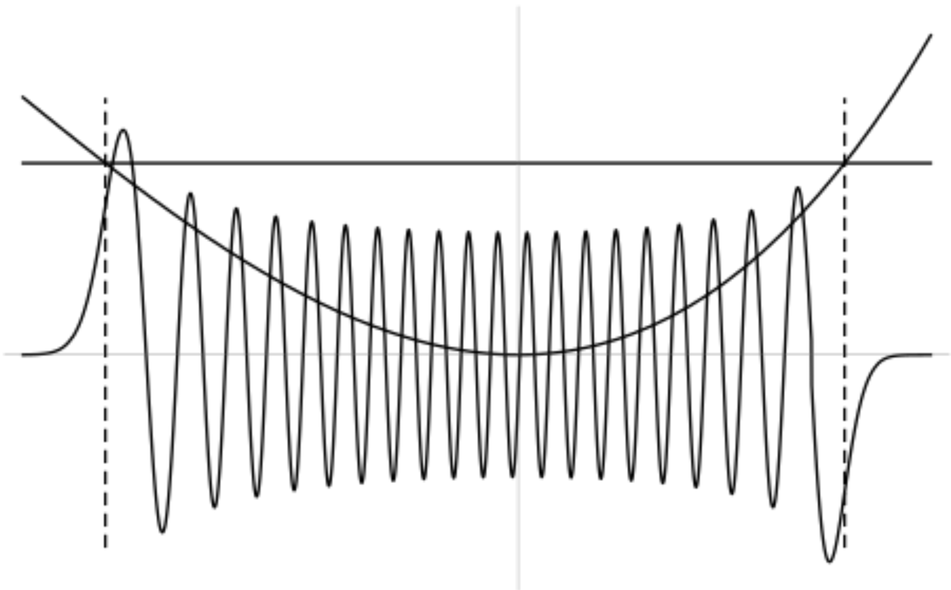
WKB solution to Schrödinger equation

- Eigenfunctions

$$\psi_{nlm}(\vec{r}) = R_{nl}(r) Y_{lm}(\theta, \varphi)$$

- $R_{nl}(r)$ is WKB solution to the radial equation with effective potential

$$V_l(r) = \frac{l^2}{2m_a r^2} + m_a \phi(r)$$



- Validity of WKB

$$\frac{\lambda}{2\pi} = \frac{1}{\sqrt{2m_a(E_n - V_l(r))}} \ll R$$

Typical angular momentum

$$l \sim m_a \sqrt{GMR}$$

must be large

WKB solution to Schrödinger equation

$$\psi(\vec{r},t) = \sum_{nlm} C_{nlm} R_{nl}(r) Y_{lm}(\theta,\varphi) e^{-iE_n t}$$

- Coefficients with random phases

$$C_{nlm} = \sqrt{(2\pi)^3 f(E_n)\, dn/dE_n\, dE_n}\; e^{i\phi_{nlm}}$$

- Energy density

$$\begin{aligned} \rho(r) &= m_a \langle |\psi(\vec{r},t)|^2 \rangle \\ &= 4\pi m_a^2 \int_{m_a\phi(r)}^{0} dE\, f(E)\, \sqrt{2m_a(E - m_a\phi(r))} \end{aligned}$$

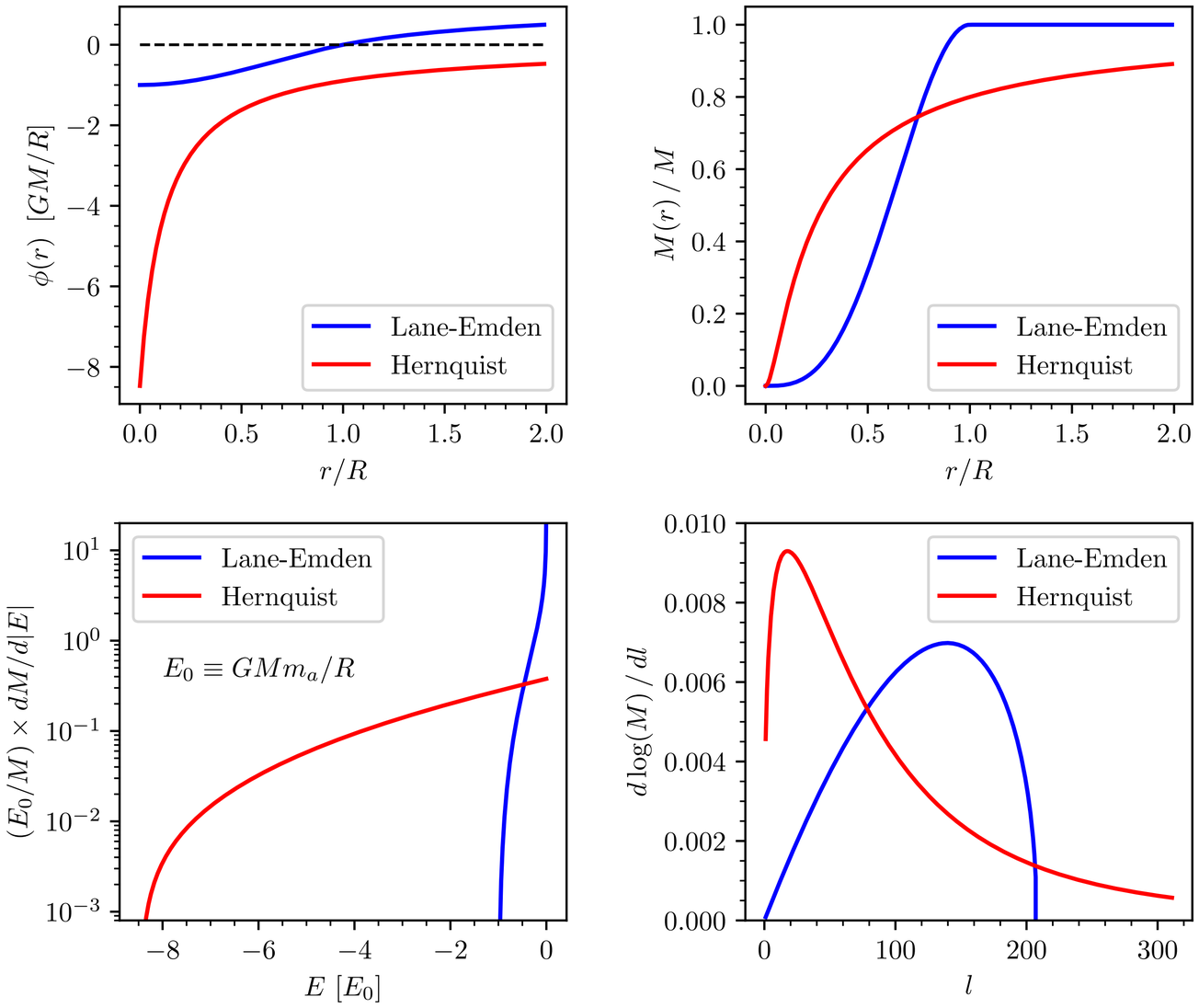
Construction of a self-gravitating system

- Choose a $\phi(r),\ \rho(r)$ pair that satisfies Poisson equation
- Find $\rho(\phi)$
- Use Eddington's formula to obtain $f(E)$

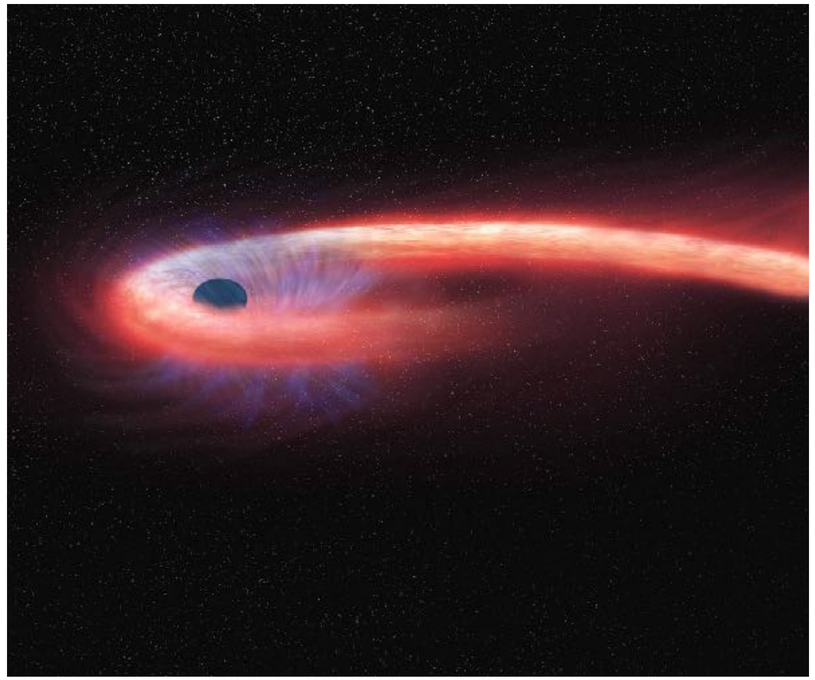
$$f(E) = \frac{1}{2\pi^2 m_a^2}\frac{d}{dE}\int_{E/m_a}^{0} d\phi\, \frac{d\rho/d\phi}{\sqrt{2m_a(m_a\phi - E)}}$$

- Construct WKB eigenfunctions
- Construct coefficients
- Resulting average clump is in viral equilibrium

Two density profiles



Tidal perturbation of the clump

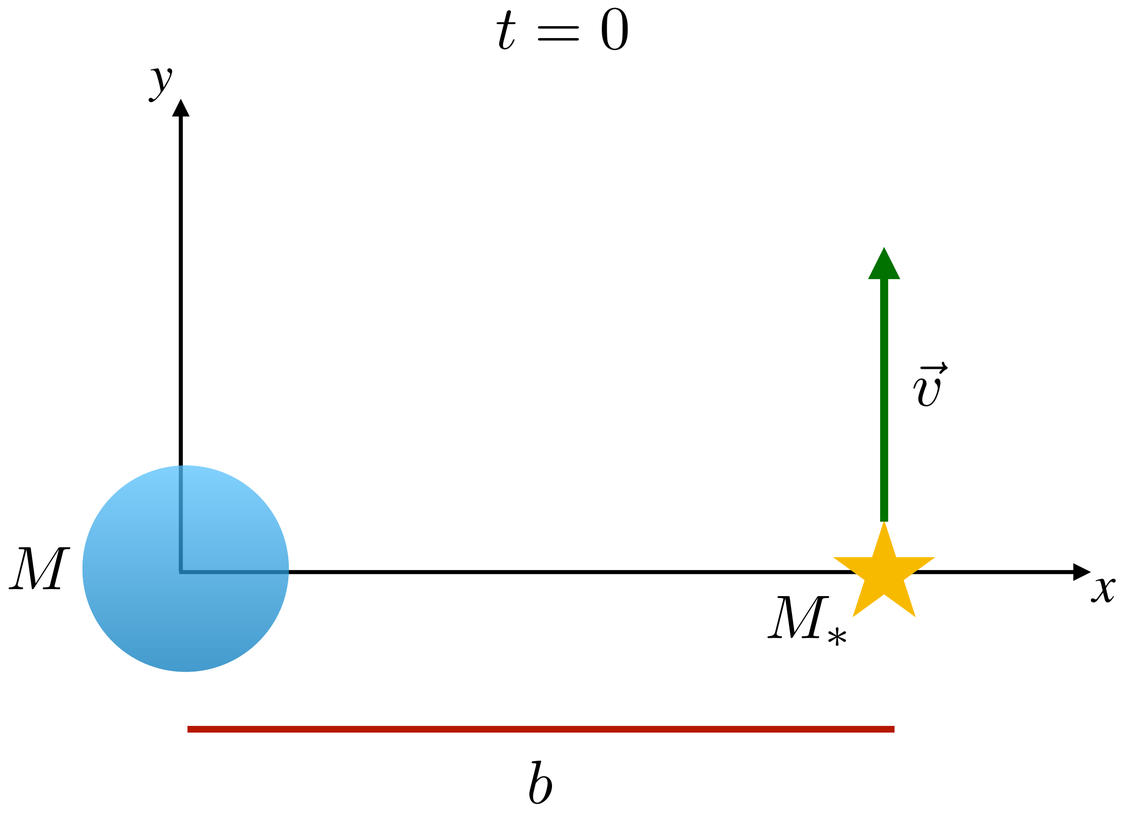


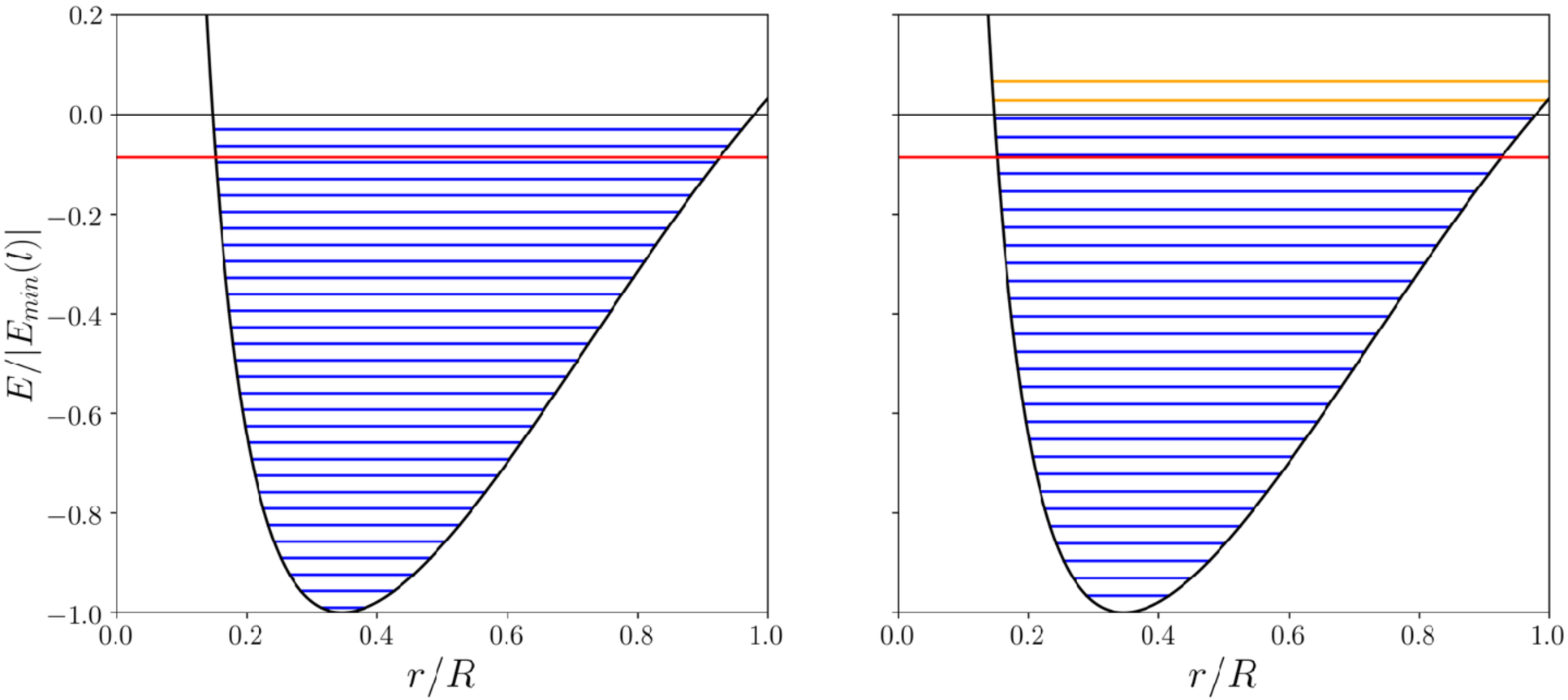
A star passing by

$$H_1(\vec{r}, t) = -\frac{GM_* m_a r^2}{(b^2 + v^2 t^2)^{3/2}} P_2(\cos\gamma(t))$$

- Perturb the coefficients C_{nlm} up to second order
- Impulse approximation

$$\frac{b}{v} \ll R\sqrt{\frac{R}{GM}}$$





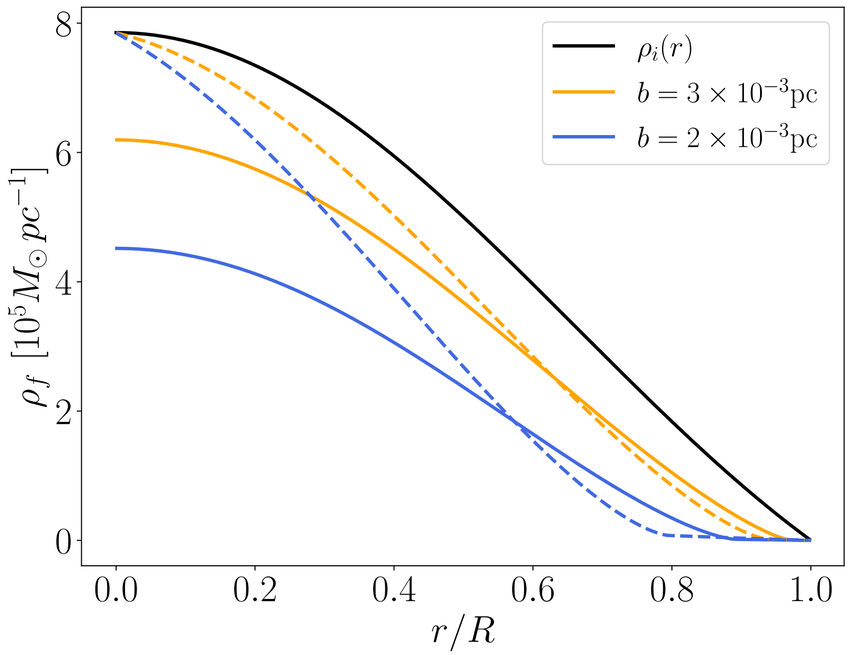
- Energy shift of a level due to the impact of the star

$$\delta E(E,l) = \left(\frac{2GM_*}{b^2 v}\right)^2 \frac{m_a}{4}\langle nl|r^2|nl\rangle$$

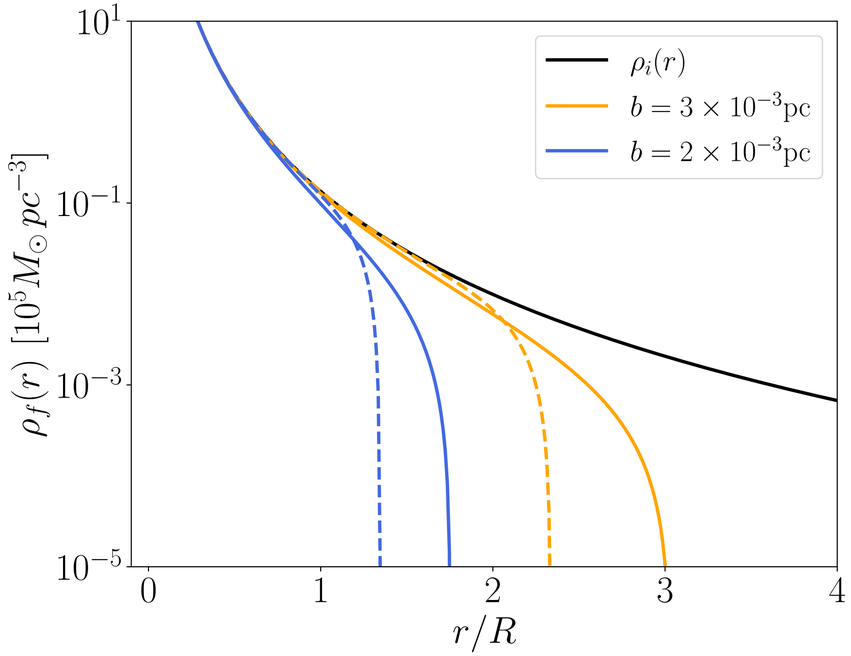
- All level with energy above a critical value become unbound

Density profile after encounter

Lane-Emden

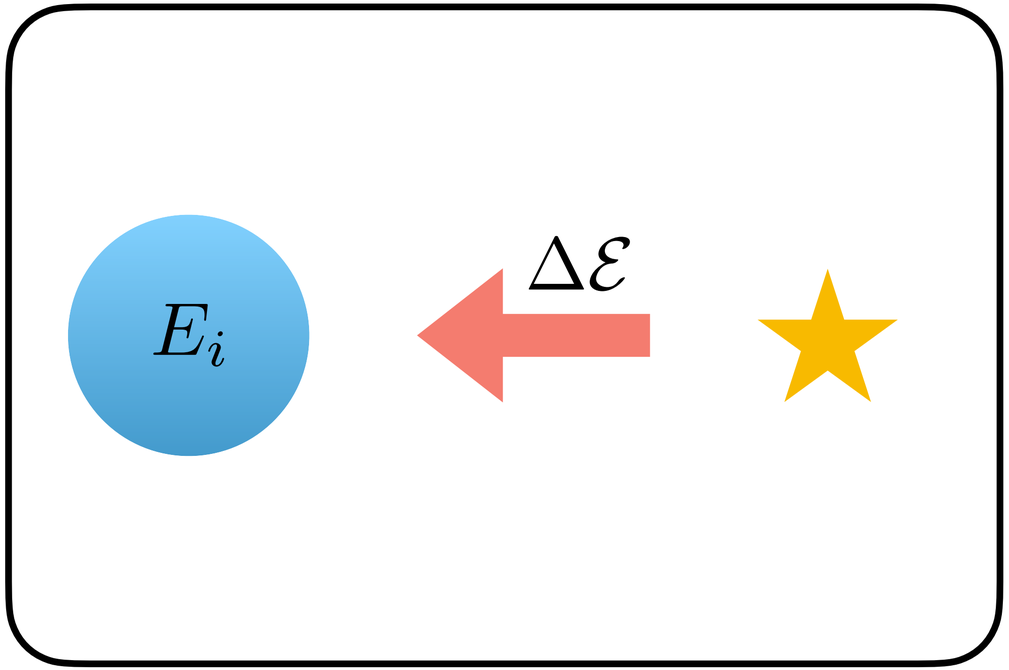


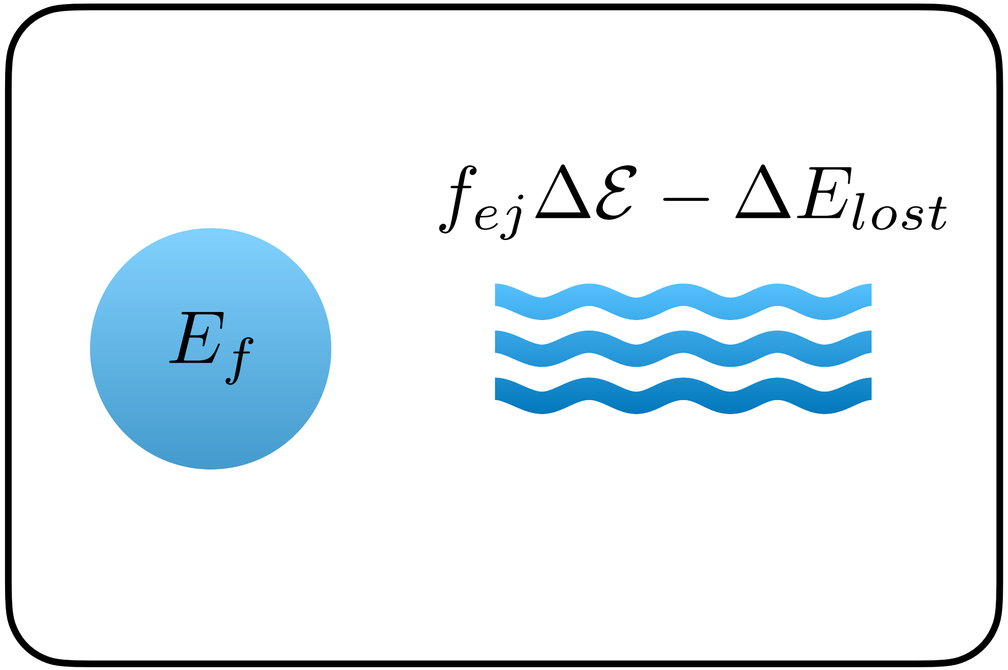
Hernquist



$$M = 10^{-12} M_\odot,\ R = 10^{-6} pc,\ M_* = M_\odot,\ v = 10^{-4}$$

Energy balance





$$E_f = E_i + \underbrace{\Delta E_{lost} + (1 - f_{ej})\Delta\mathcal{E}}_{\Delta E}$$

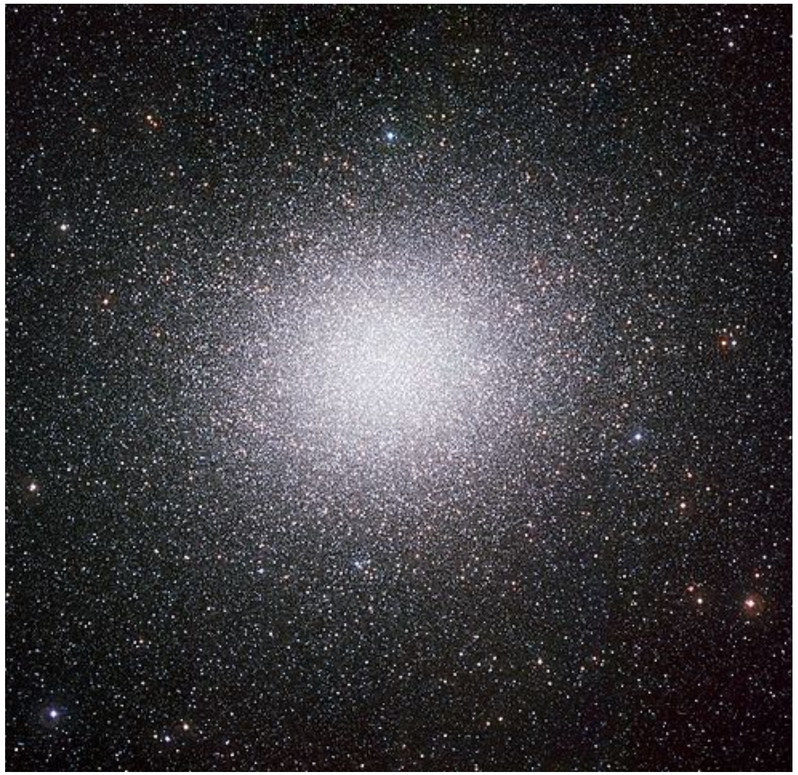
$$\Delta E_{lost} = \Delta E_K + \Delta E_B$$

Re-virialization and new radius

- Assume cluster re-virializes to the same profile keeping it's total energy fixed
- Relaxation time is smaller than times between star encounters for our typical cluster
- Virial equilibrium

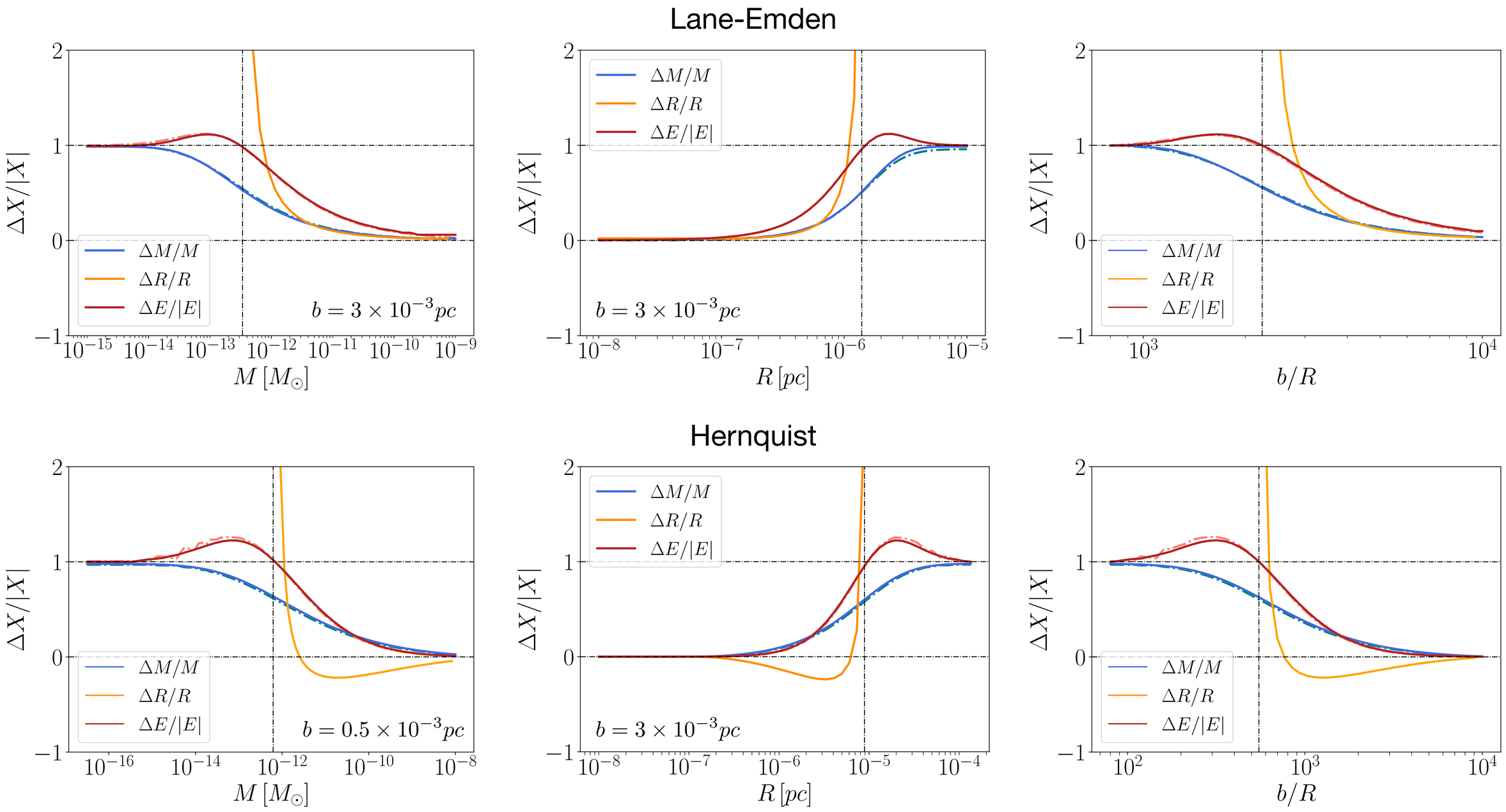
$$E_{tot} = \frac{E_B}{2}$$

- New radius



$$E_f = -\alpha \frac{G(M - \Delta M)^2}{R_f} \quad \Rightarrow \quad R_f = R_i \left(1 - 2\frac{\Delta M}{M} + \frac{\Delta E}{|E_i|}\right)$$

See 2207.11276 for a different approach



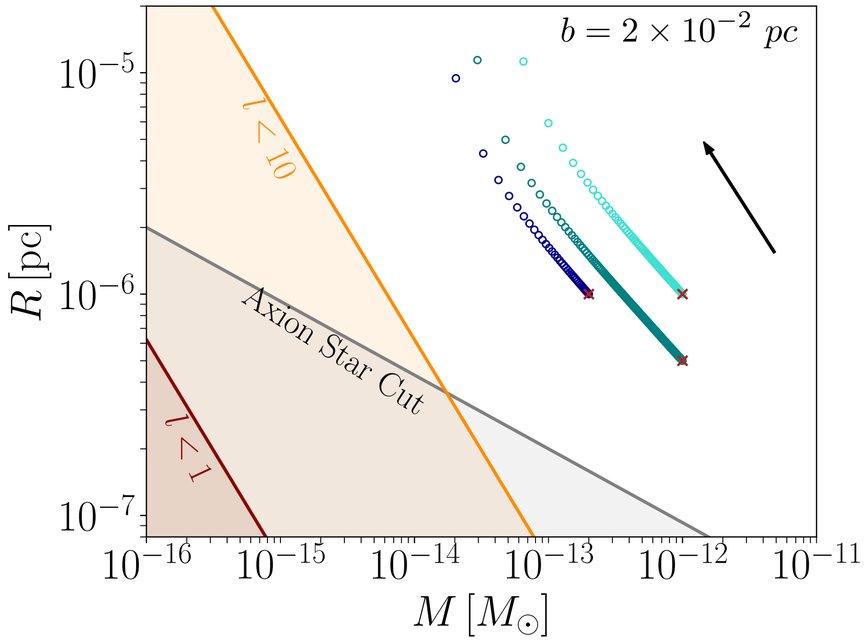
$$M = 10^{-12} M_\odot,\ R = 10^{-6} pc,\ M_* = M_\odot,\ v = 10^{-4}$$

Critical density and repeated perturbations

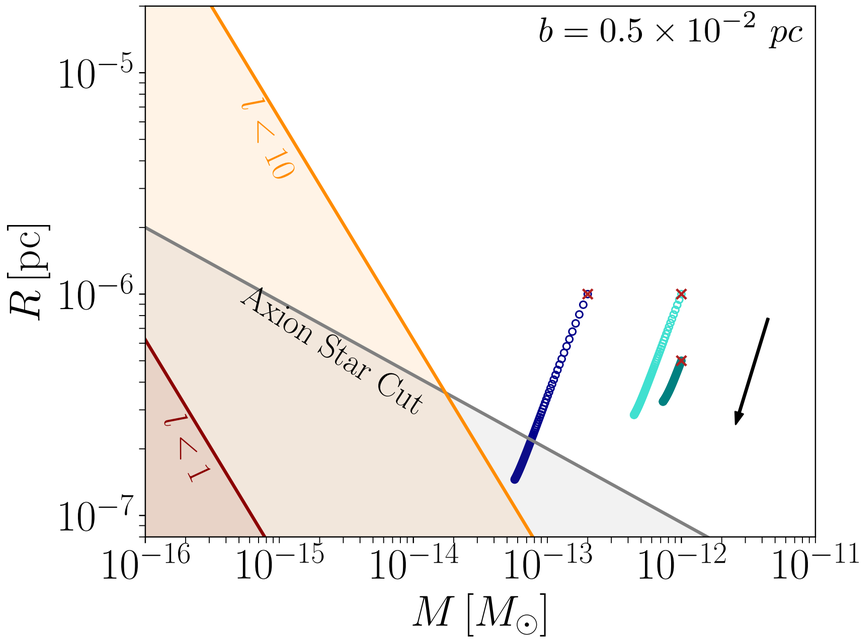
- Critical density, below which the cluster gets destroyed

$$\bar{\rho}_{\rm crit} \approx \left(\frac{M_*}{1\,M_\odot}\right)^2 \left(\frac{10^{-3}\,{\rm pc}}{b}\right)^4 \left(\frac{10^{-4}}{v}\right)^2 \times \begin{cases} 0.7\times 10^{-11}\,M_\odot\,(10^{-6}\,{\rm pc})^{-3} & \text{(LE)} \\ 2.1\times 10^{-14}\,M_\odot\,(10^{-6}\,{\rm pc})^{-3} & \text{(H)} \end{cases}$$

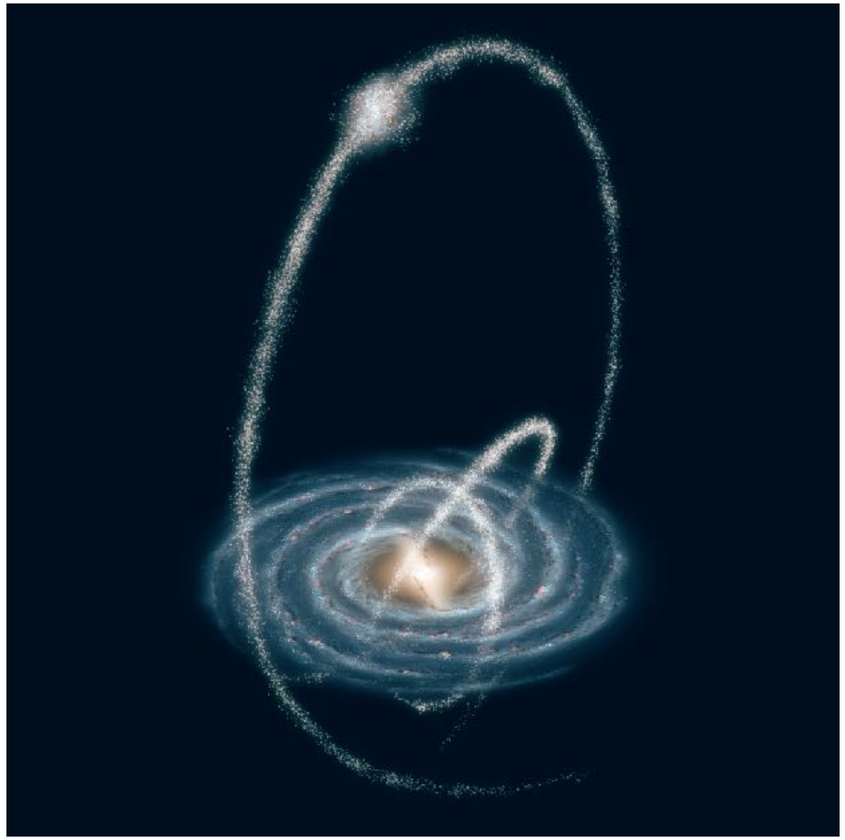
Lane-Emden



Hernquist



Survival in the galaxy



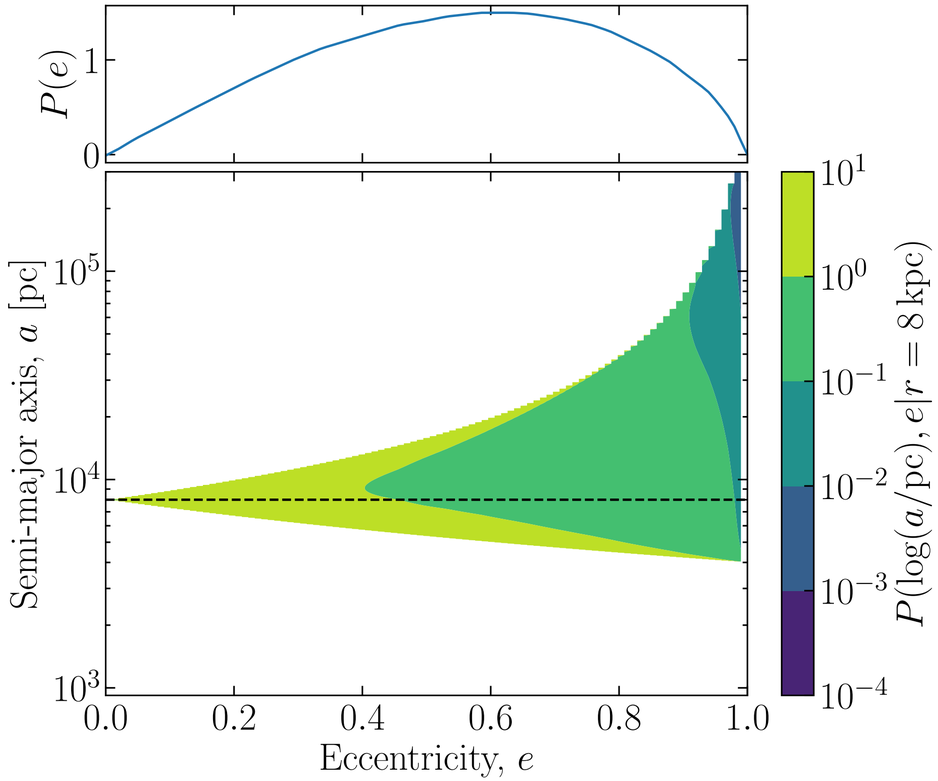
A halo made of miniclusters

- Fix $M,\ R$ and the galactic radius r
- Probability that a minicluster at r is on an orbit with given semi-major axis and eccentricity

$$P(a, e|r)$$

such that the galaxy has an NFW density profile

- Create sample $N_{\rm MC}^{(i)}(M, R, r)$
- The orbit fixes the average number of star encounters as a minicluster travels in the galaxy
- For each encounter sample $P(b),\ P(v)$



Kavanagh et al.
Phys. Rev. D 104, 063038 (2021)

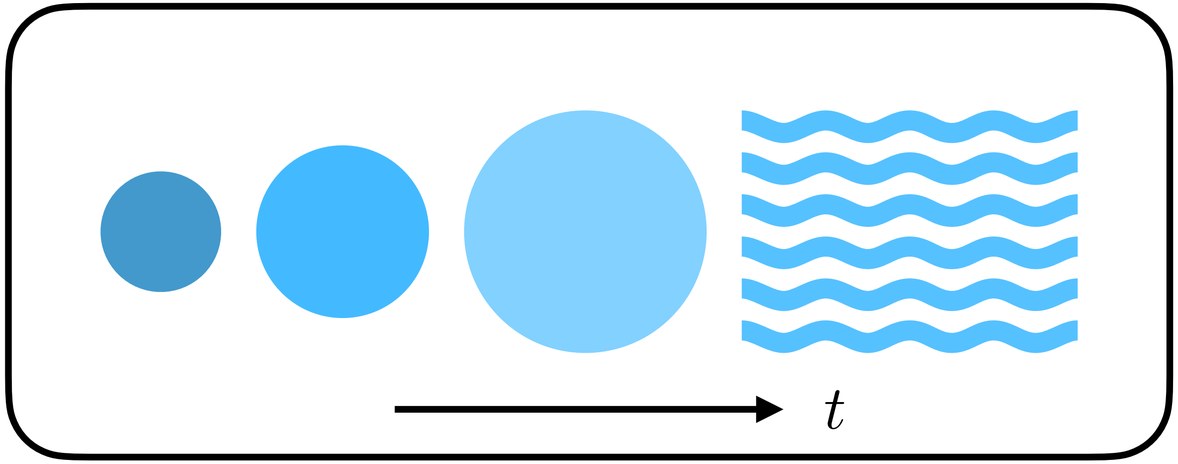
Survival probability

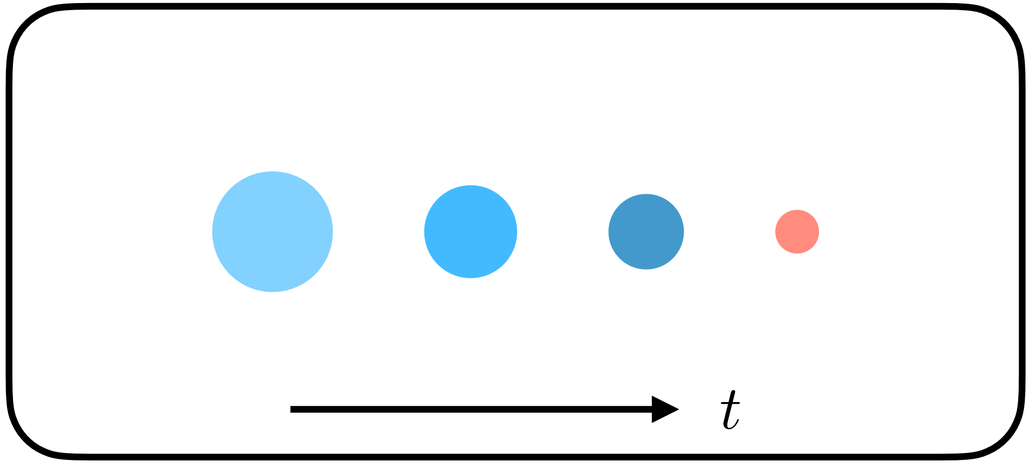
$$P_{\rm surv}(M, R, t, r) = \frac{N_{\rm MC}^{(f)}(M, R, r, t)}{N_{\rm MC}^{(i)}(M, R, r)}$$

- 2 ways for a minicluster to be destroyed

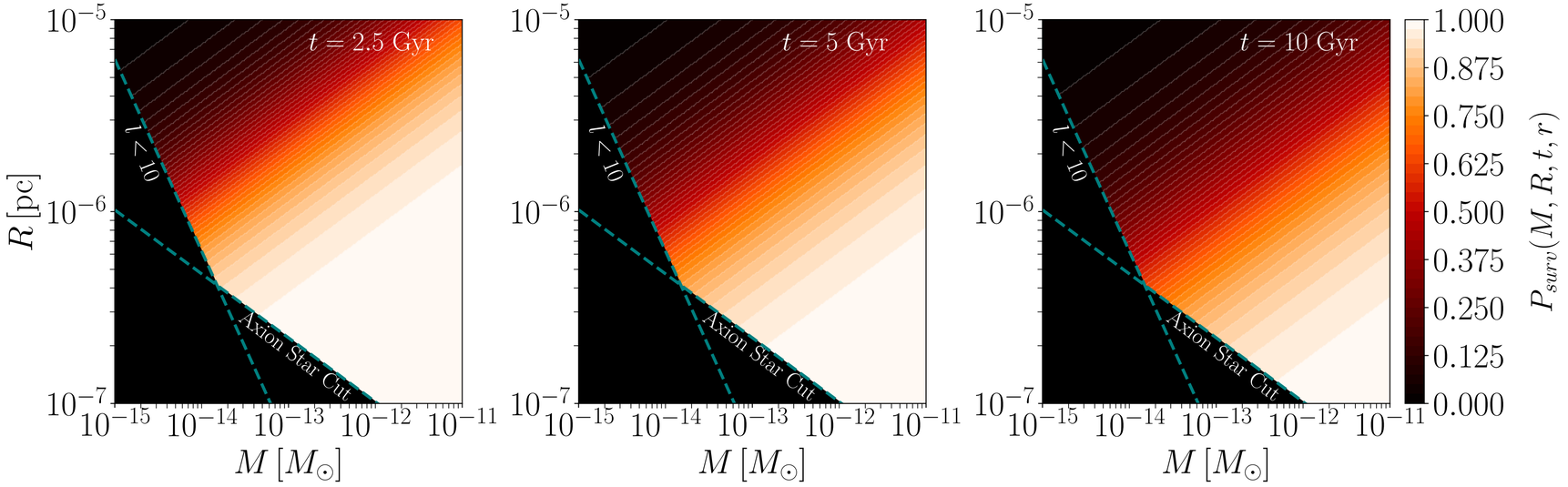
  1. Become less and less tightly bound until completely unbound

  2. Become more and more tightly bound until turning into an axion star

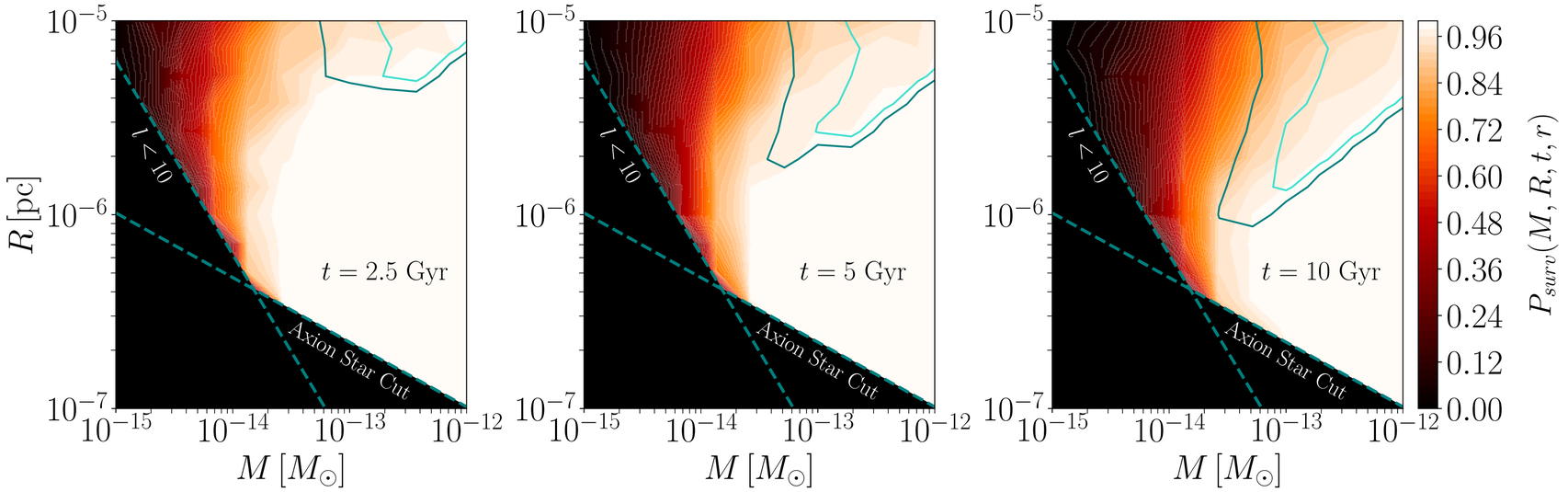




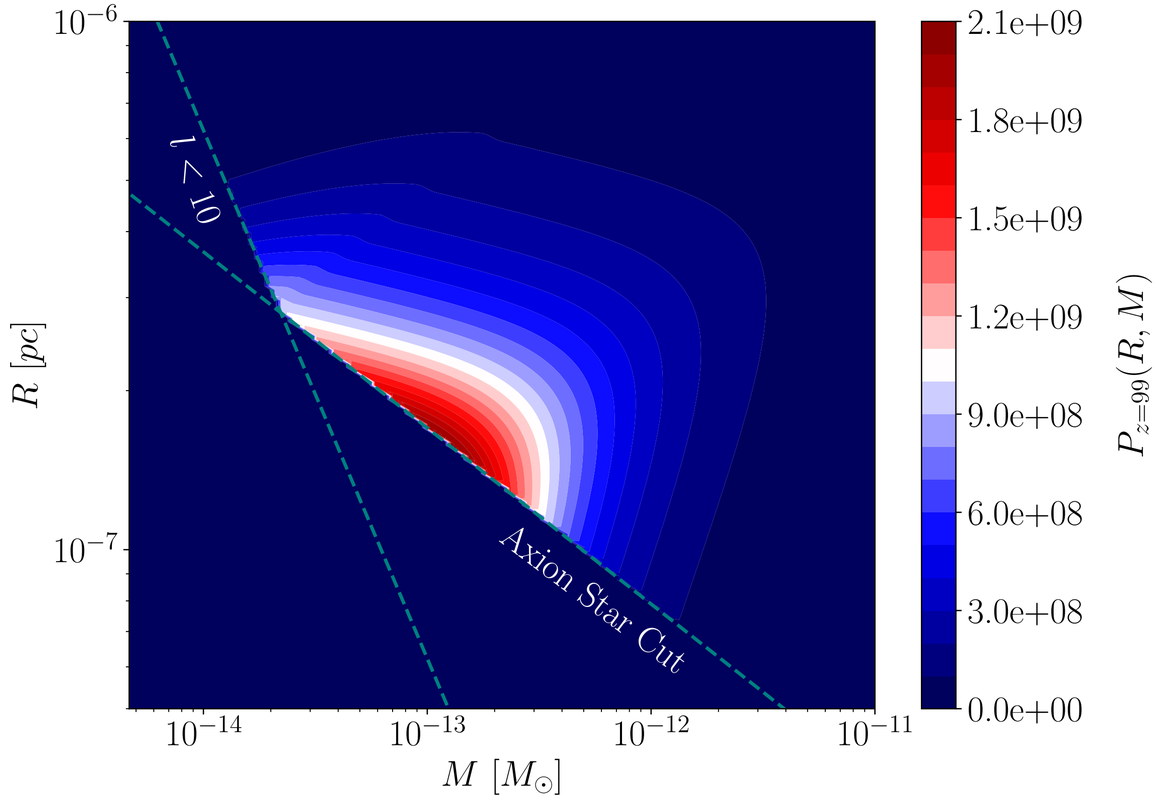
Lane-Emden

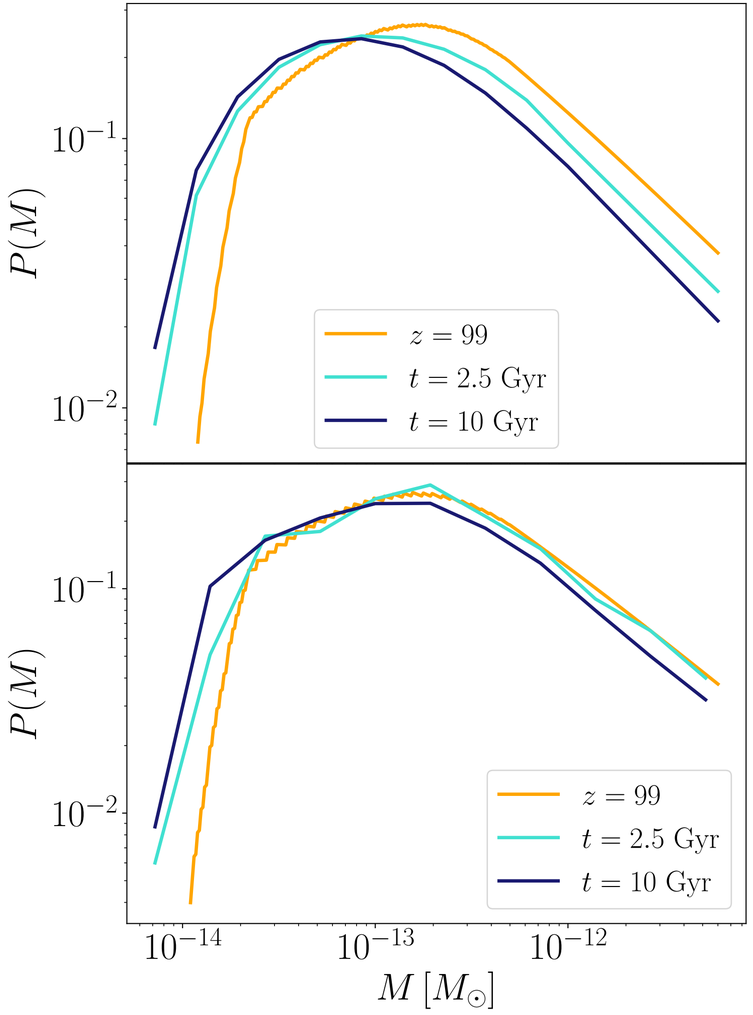


Hernquist



Distribution of radii and masses





Lane-Emden

Hernquist

Kavanagh et al., PRD 104, 063038 (2021)
Eggemeier et al., PRL 125, 041301 (2020)
Fairbairn et al., PRL 119, 021101 (2017)
Buschmann et al., PRL 124, 161103 (2020)

Results

	$P_{\rm surv}$		
	$t = 2.5$ Gyr	$t = 5$ Gyr	$t = 10$ Gyr
Lane-Emden	0.94	0.90	0.82
Hernquist	0.99	0.98	0.94

Kavanagh et al., Phys. Rev. D 104 (Particle phase-space density)

Power law profile

$$P_{\rm surv} = 0.99$$

NFW profile

$$P_{\rm surv} = 0.46$$

Run for $t = 13.5$ Gyr

Shen et al., 2207.11276 (N-Body)

NFW profile

$$P_{\rm surv} = 0.87$$

Different initial distribution of miniclusters

No relaxation between encounters

Conclusions

- Construction of self-consistent clump of axion waves in the WKB limit (see also Yavetz et al., PRD 105 (2022) 2, 023512)
- Calculation of survival against tidal stripping from encounters with stars
- Limitations and future work
  - Modelling of relaxation after encounter
  - Effect of axion star
  - Evolution of the Milky Way
  - Initial distribution of minicluster masses and radii

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