UiO : Universitetet i Oslo

Ultra-Light Axion dark matter

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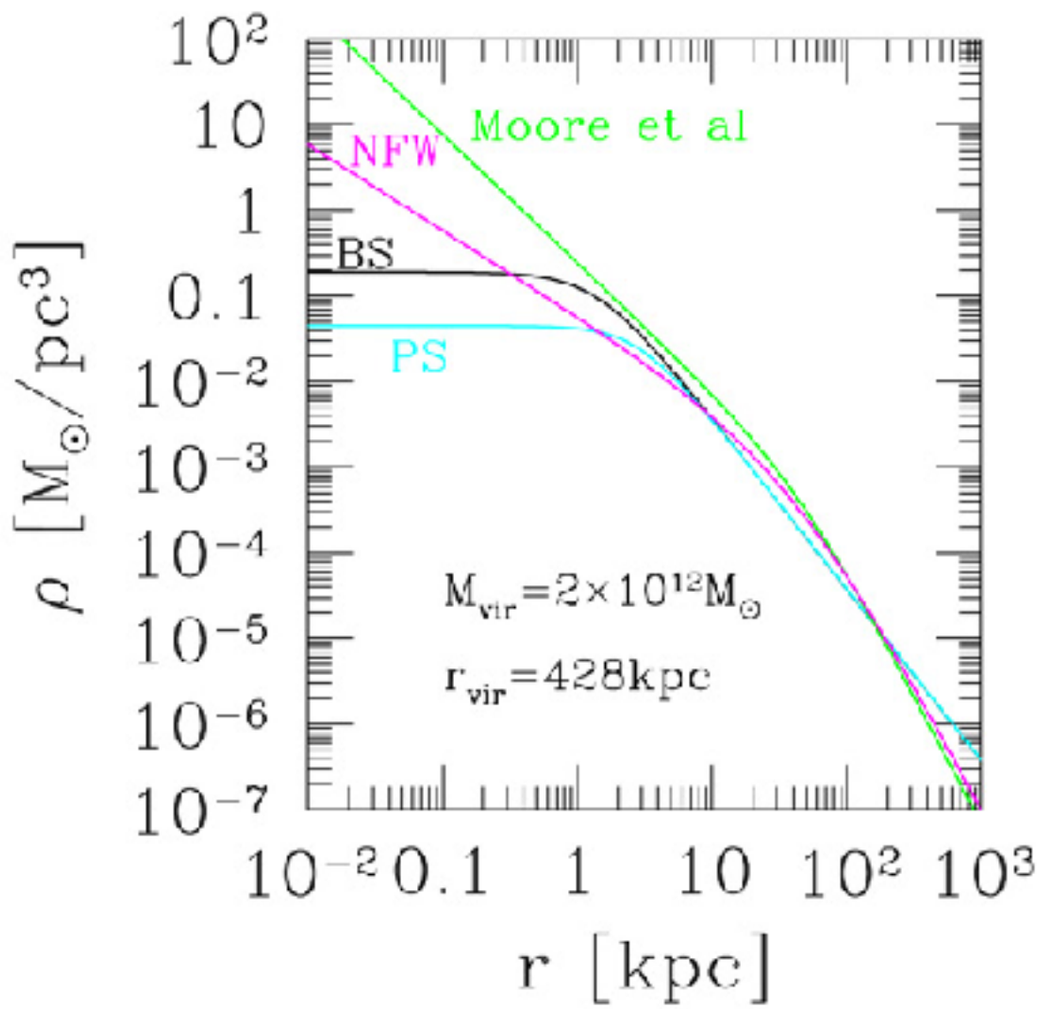
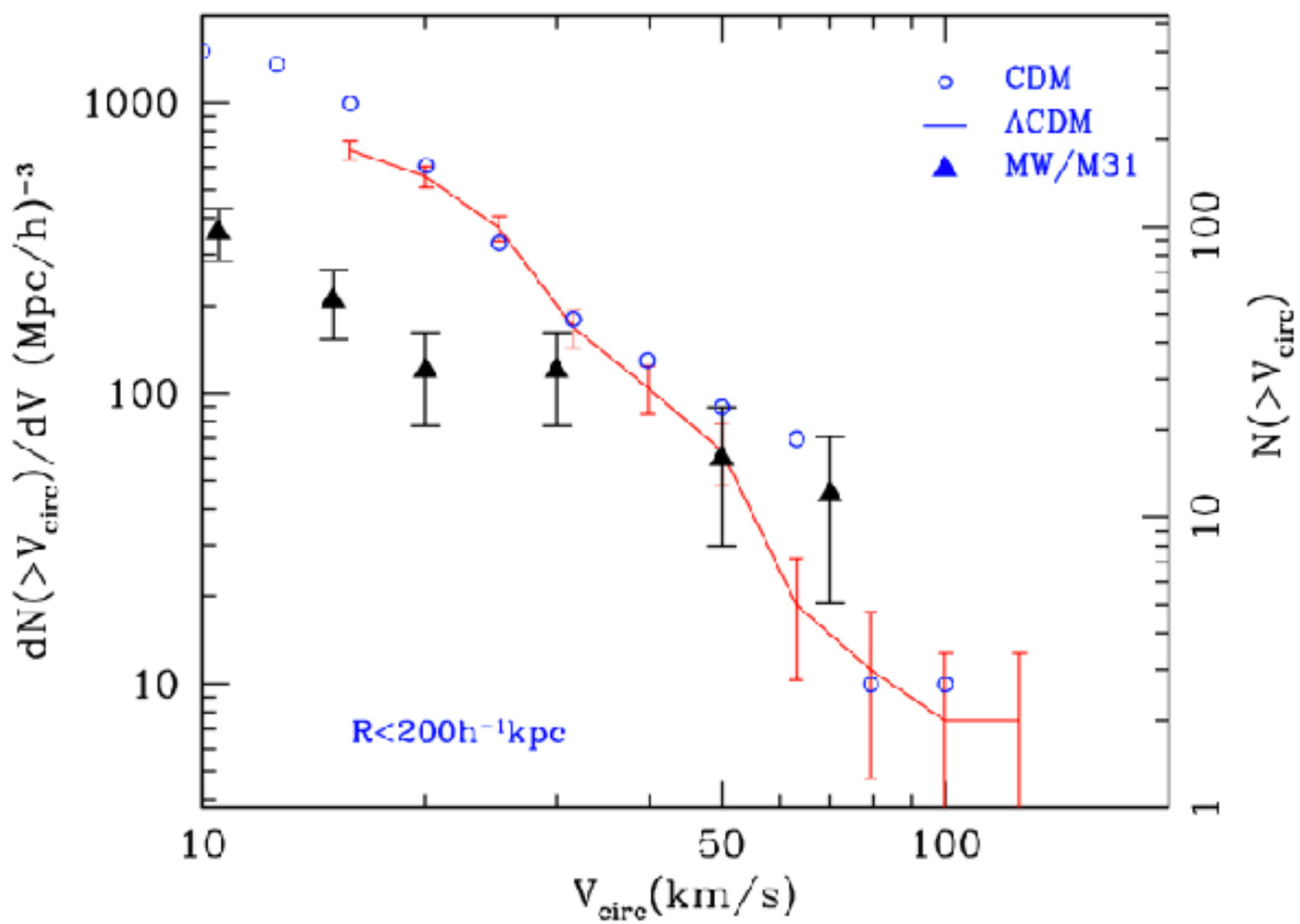
Core/cusp



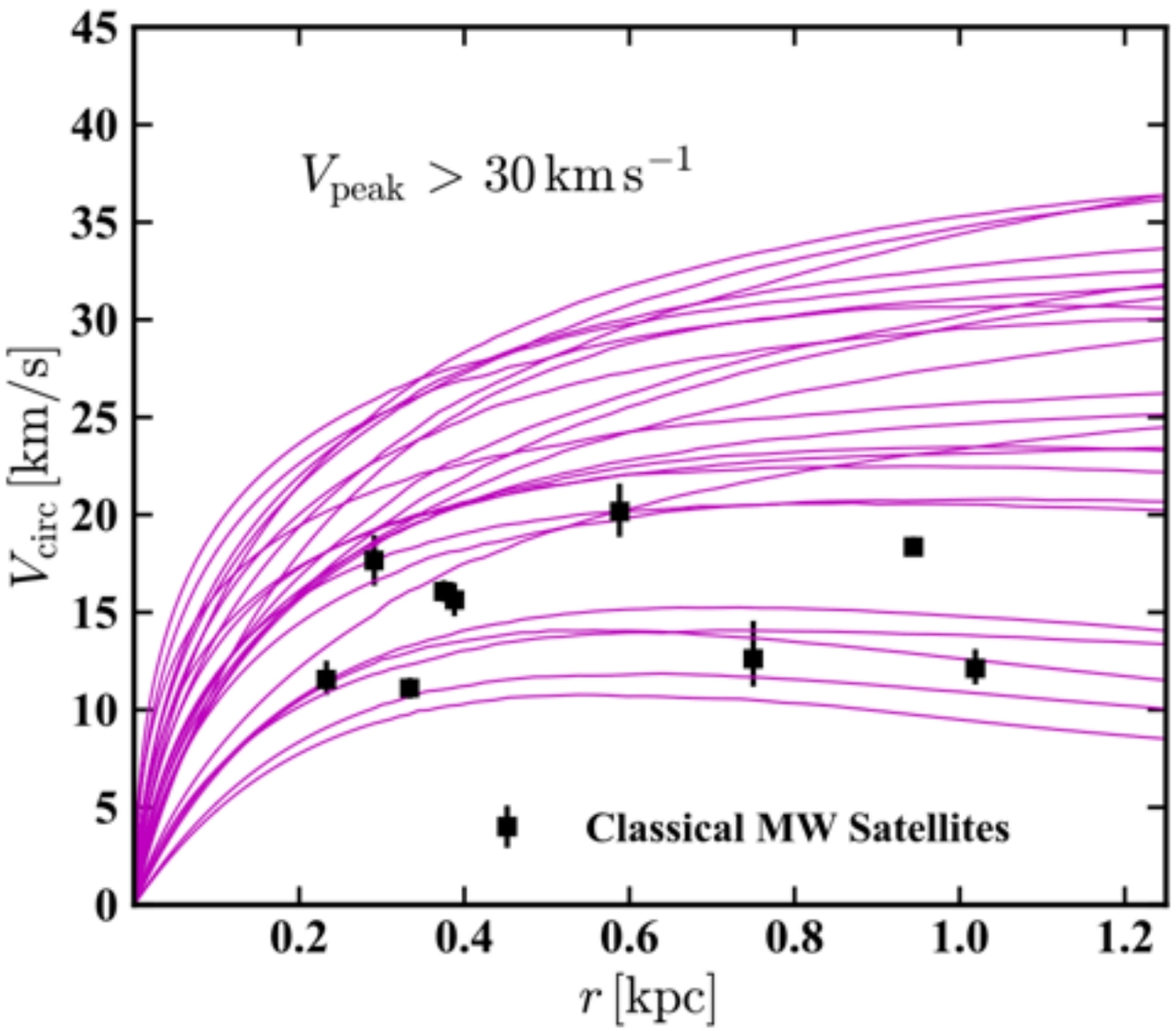
Brook et al. (2015)

Missing satellites



Klypin et al. (1999)

Too big to fail



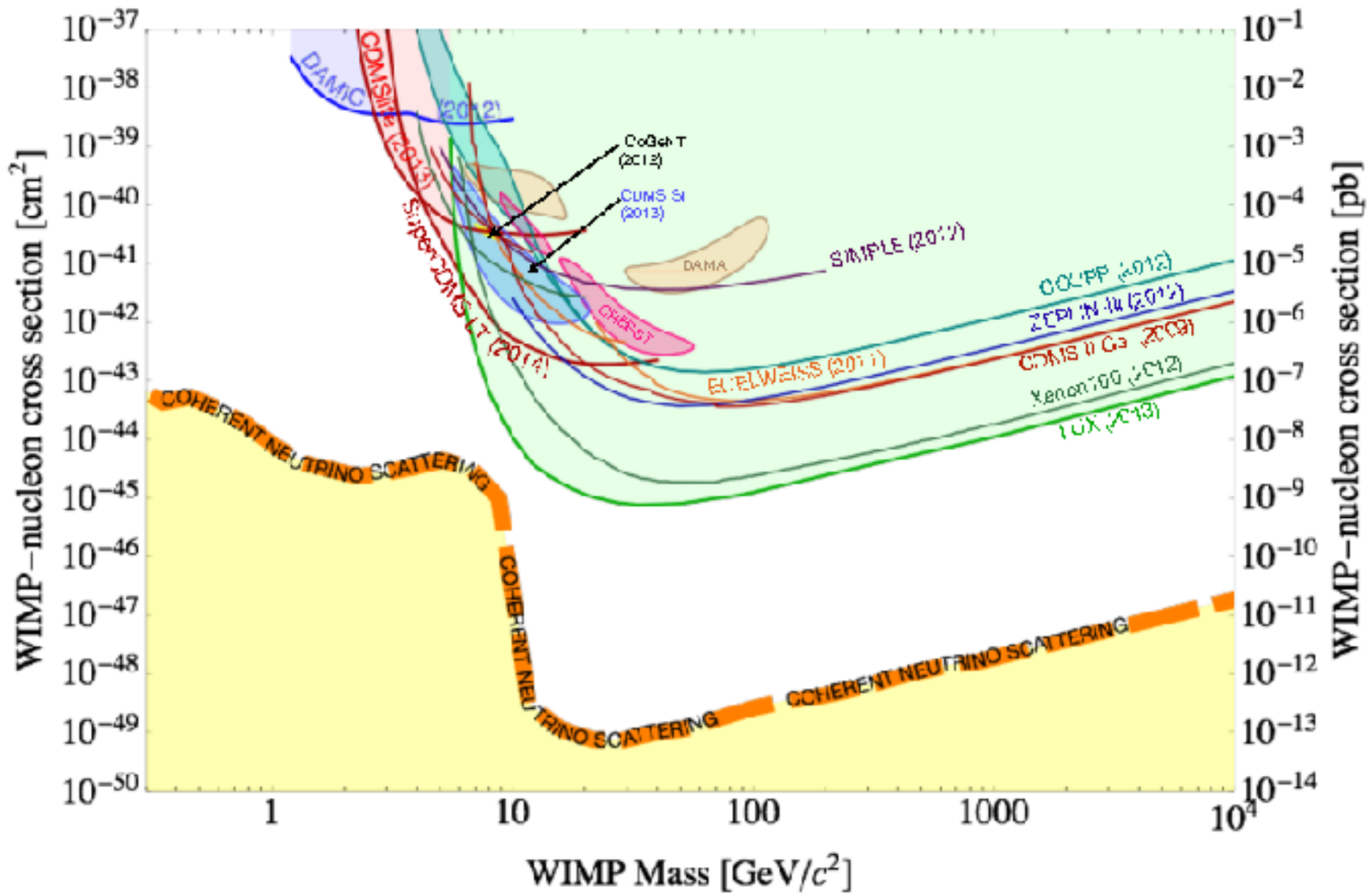
Bullock et al. (2017)

Sub-halos of a Milky Way-size host that have peak maximum circular velocities Vmax > 30 km/s: resistant to strong star formation suppression by reionization and too big to have failed to form stars.

Alternative DM models

- WIMP
- Warm/Hot DM
- Axion DM
- Self-Interacting DM
- Altogether???
- …

WIMP miracle?



Akimov et al. (2015)

An axion like particle is…

$$S_a = \int d^4x\sqrt{-g}\left[\frac{1}{2}F^2 g^{\mu\nu}\partial_\mu a \partial_\nu a - \mu^2(1 - cosa)\right]$$

- Axion decay constant:

$$10^{16}\mathrm{GeV} \lesssim F \lesssim 10^{18}\mathrm{GeV}$$

- Mass:

$$10^{-33}\mathrm{eV} \lesssim m_a \lesssim 10^{-18}\mathrm{eV}$$

$$m_a = \frac{\mu^2}{F}$$

$$\lambda_{dB} = \frac{2\pi\hbar}{mv}$$

- Strength of the potential:

$$\mu^4 \sim M_p^2 \Lambda^2 e^{-S}$$

$$10^4\mathrm{GeV} \lesssim \Lambda \lesssim 10^{18}\mathrm{GeV}$$

$$\boxed{\Omega_a \sim 0.1\left(\frac{F}{10^{17}\mathrm{GeV}}\right)^2\left(\frac{m_a}{10^{-22}\mathrm{eV}}\right)^{\frac{1}{2}}}$$

Non-relativistic limit

$$S_\phi = \int \frac{d^4x}{\hbar c^2}\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{m^2c^2}{2\hbar^2}\phi^2\right] \longleftarrow \left(\phi = aF\right)$$

$$\phi = \sqrt{\frac{\hbar^3 c}{2m_a}}\left(\psi e^{-imc^2t/\hbar} + \psi^* e^{imc^2t/\hbar}\right)$$

$$\left|\frac{\partial^2\psi}{\partial t^2}\right| << \left|\frac{mc^2}{\hbar}\frac{\partial\psi}{\partial t}\right|$$

$$i\hbar\left(\frac{\partial\psi}{\partial t} + \frac{3}{2}H\psi\right) = \left(-\frac{\hbar^2}{2m_a R^2}\nabla^2 + m_a\Phi\right)\psi$$

Quantum effects

$$\psi = \sqrt{\frac{\rho}{m_a}} e^{i\theta} \qquad \vec{v} = \frac{\hbar}{m_a R} \vec{\nabla}\theta$$

$$\Downarrow$$

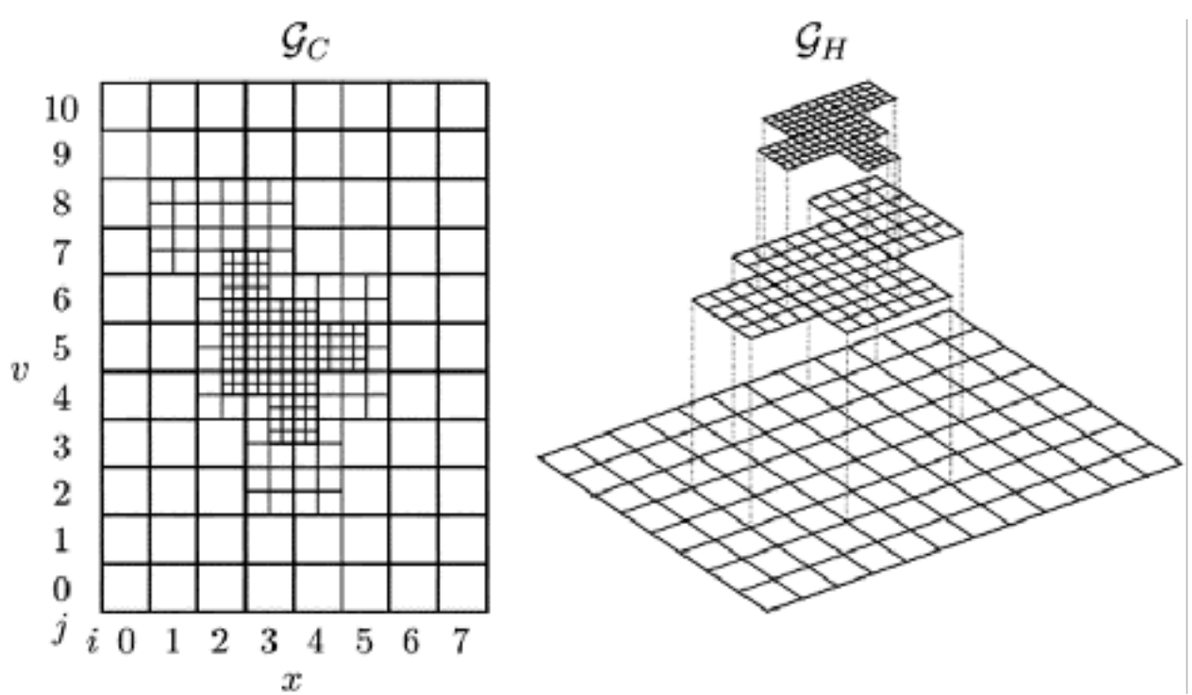
$$\frac{\partial \rho}{\partial t} + 3H\rho + \frac{1}{R}\vec{\nabla}\cdot(\rho\vec{v}) = 0$$

$$\frac{\partial \vec{v}}{\partial t} + H\vec{v} + \frac{1}{R}\left(\vec{v}\cdot\vec{\nabla}\right)\vec{v} - \frac{\hbar^2}{2m_a^2 R^3}\vec{\nabla}\left(\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right) = -\frac{1}{R}\vec{\nabla}\Phi$$

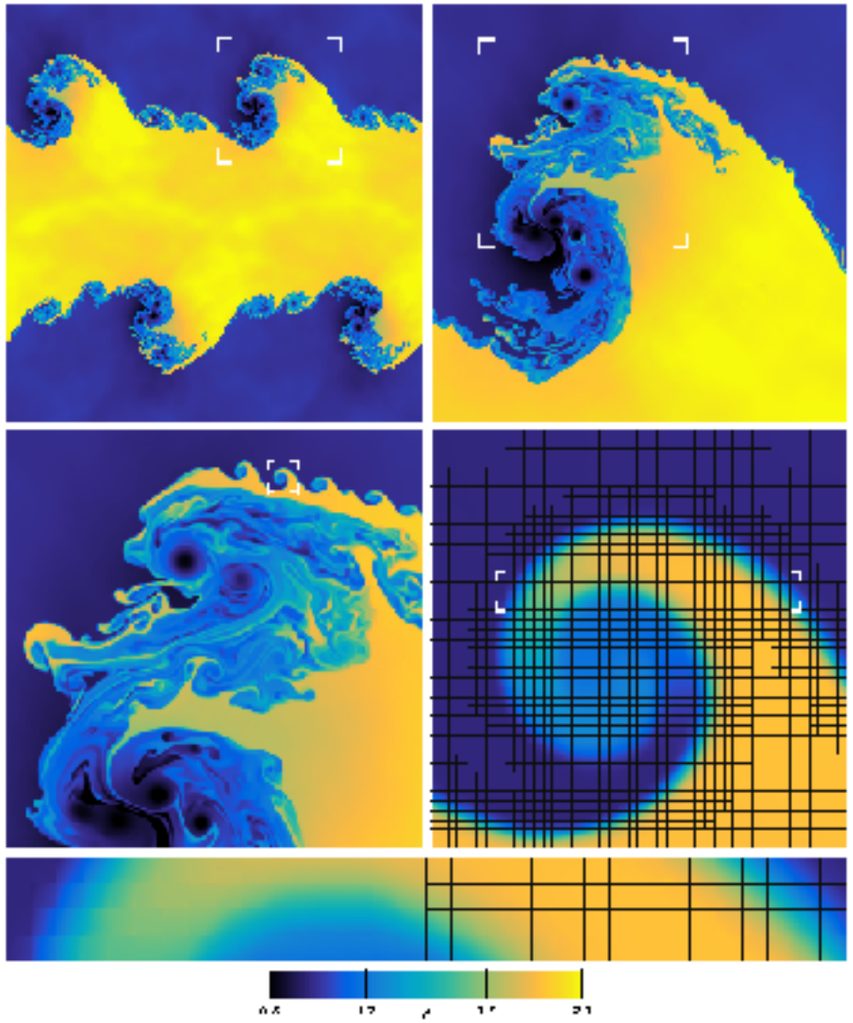
Numerical approach

Adaptive Mesh Refinement (i.e. RAMSES)

- Euclidean mesh
- Solve the Schrödinger-Poisson system, not the Madelung equations
- Complete control of the resolution (it doesn't happen in other codes)



Patil et al. (2015)

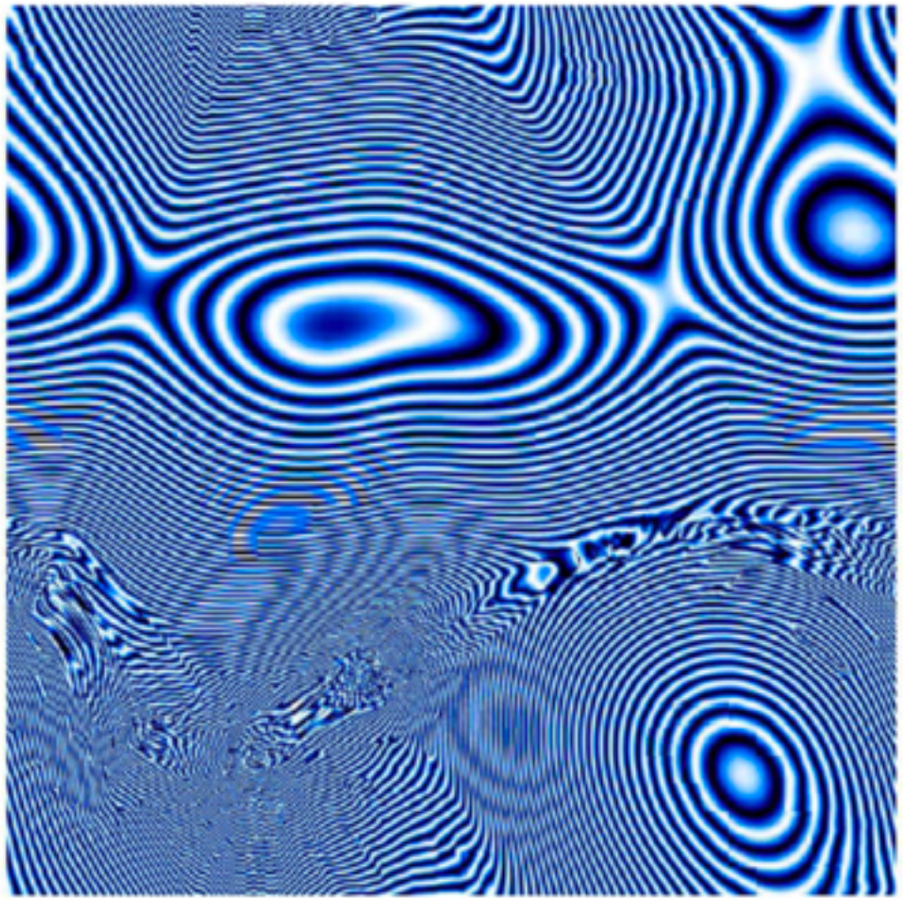


Schall et al. (2015)

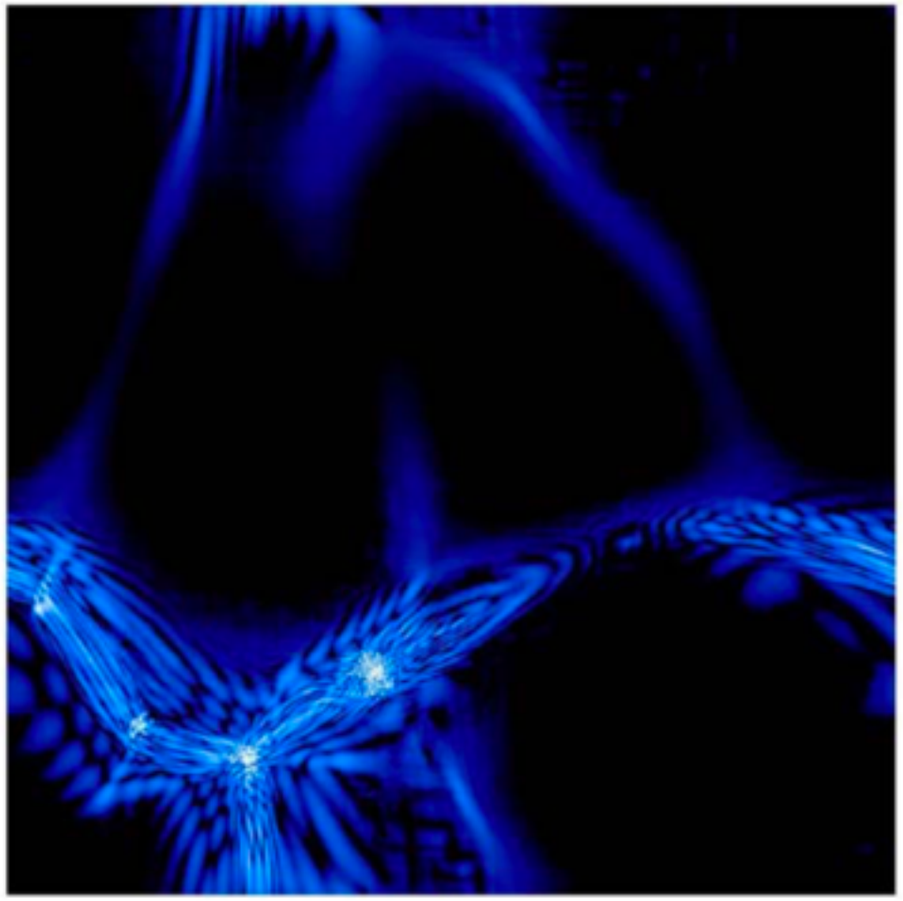
Problems & challenges

- Extremely high resolution
- Limitations on the simulation box size
- Limitations on the statistics (~10 compact objects for a box of L ~ 50 Mpc)
- New numerical methods (i.e. Spectral Elements)…?
- …

Simulations

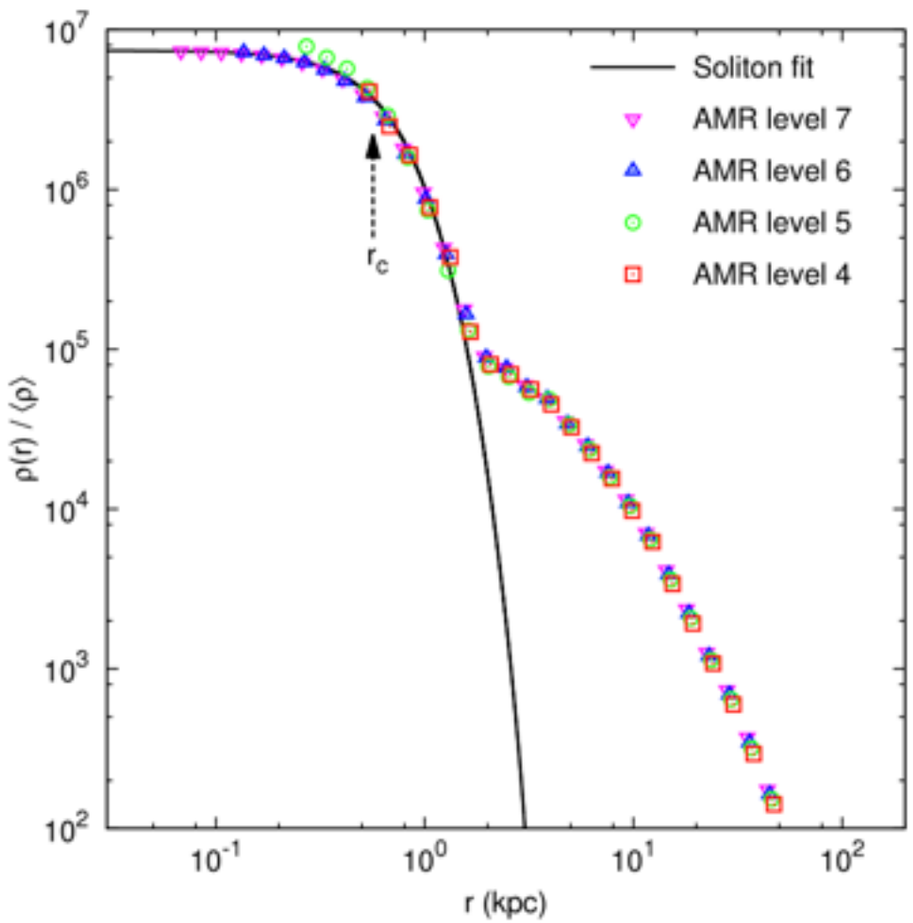


Schive et al. (2014)

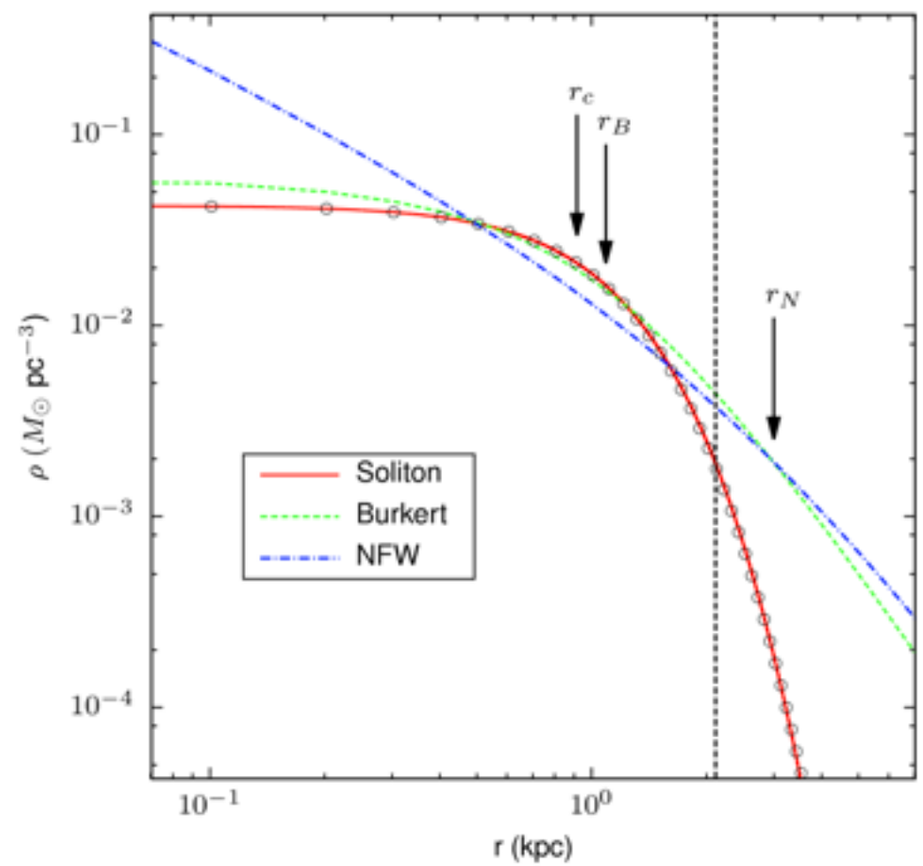


Schive et al. (2014)

Results



Schive et al. (2014)



Schive et al. (2014)

Conclusions

Cosmological axion dark matter simulations:

- Off: n-body - On: AMR for Schrödinger equation
- Baryons, can they solve the tensions?
- Spectral elements

Comparison with observations:

- Solitonic cores
- Lyman–α forest
- Weak lensing?

Backup

Missing satellite revisited

De Broglie wavelength cannot exceed the viral radius:

$$r_{1/2} \geq 3.925 \frac{\hbar^2}{GMm^2} = 0.335\,\mathrm{kpc}\,\frac{10^9 M_\odot}{M}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)^2 .$$

$$\rho_c \leq 0.0044\left(\frac{Gm^2}{\hbar^2}\right)^3 M^4 = 7.05\,M_\odot\,\mathrm{pc}^{-3}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^6\left(\frac{M}{10^9 M_\odot}\right)^4$$

↓

Sub-halos are more vulnerable to tidal disruption

Too big to fail revisited

- Abundance of sub-halos suppressed at all masses below ~10^{10} M_{sun}
- Sub-halo masses estimated observationally by the maximum circular velocity, which is lower in ADM than CDM for halos of a given mass - Marsh at al. (2014)

Structure formation

“ADM tends to suppress formation of small galaxies at high redshift compared to CDM. Thus it becomes a serious question as to whether the ADM model would allow galaxies to be formed that were capable of reproducing the high-redshift galaxy luminosity function, reionizing the universe at z=8–9, and producing the early, small-scale structure probed by the Lyman–α forest.”

Hui et al. (2017)