Heating Halo Dark Matter *via* Gas Fluctuations

Amr El-Zant (Centre for Theoretical Physics, BUE, Cairo)

partly in collaboration with Jonathan Freundlich and Francoise Combes

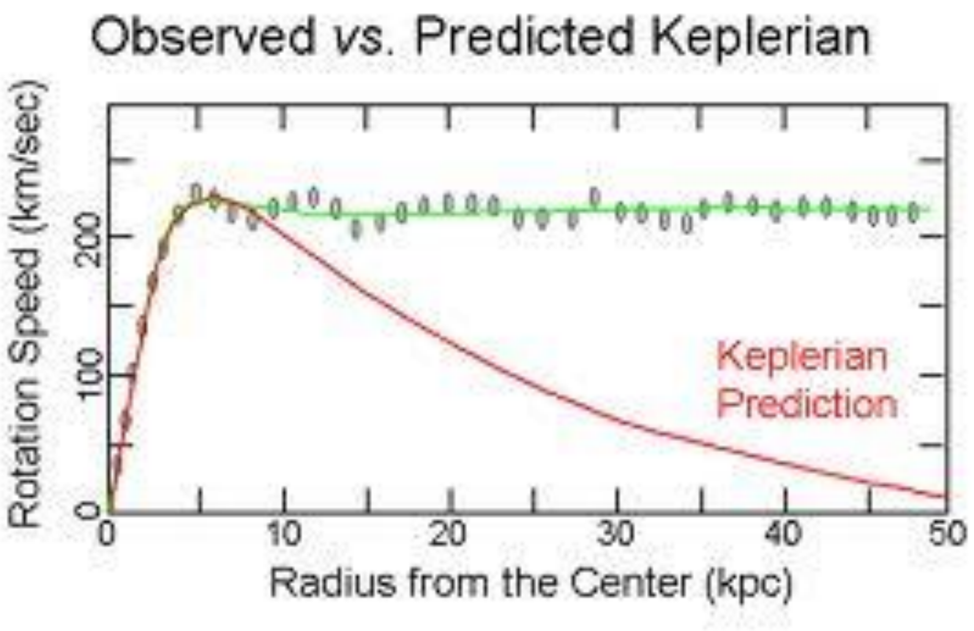
Obs. Paris/College de France

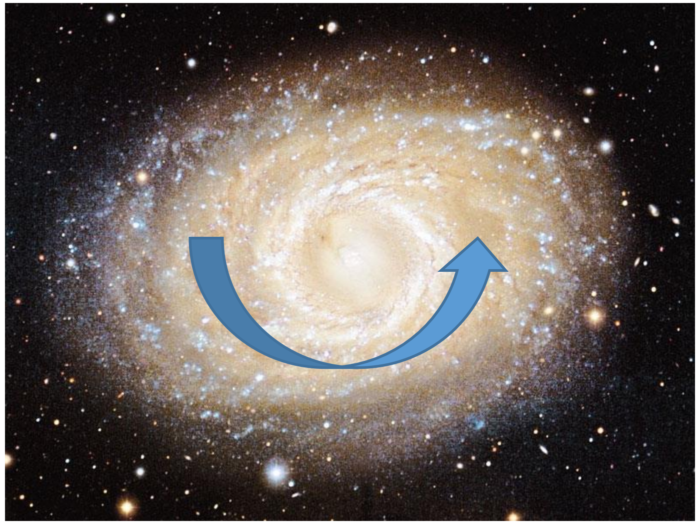
Some Issues Involved

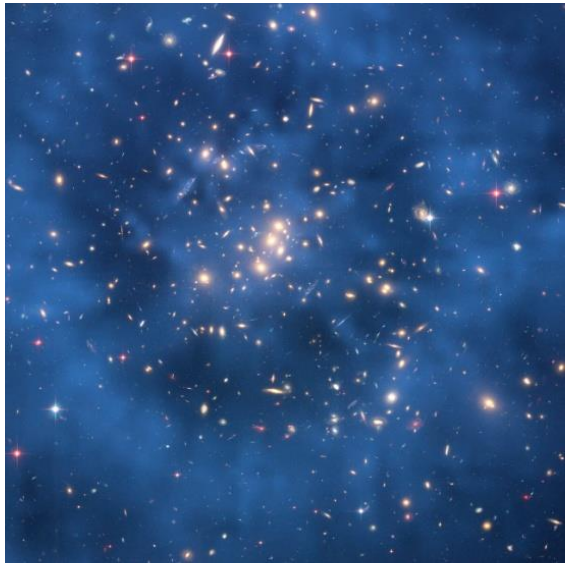
- **Why Dark matter? What type?**
- **Why so cold? → Successes on cosmological scales**
- **Problems on galactic scales → Why we need to heat it up.**
- **How we can heat it up → 'Gastrophysics' .vs. New Physics**

(has consequences for particle physics models and indirect detection)

Dark matter keeps galaxies and clusters bound







Does not cool!
Forms extended 'haloes'
Enveloping galaxies…

$$\frac{GM^2}{R} \sim MV^2 -> V \sim \left(\frac{GM}{R}\right)^{1/2}$$

The Case for (C) DM

- Explains **structure formation and CMB**
- The latter are **not easily explainable by modified gravity**

++

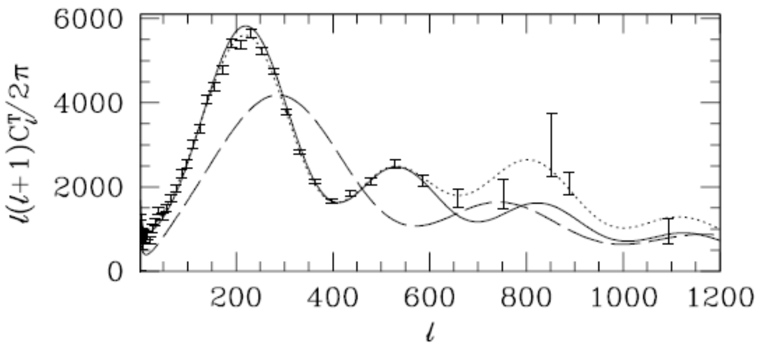
- ''Traditionally'' strong arguments for

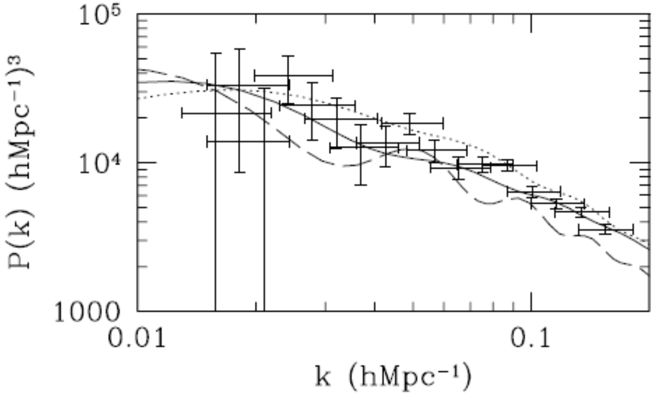
→ Predicted by natural Susy theories

→ Right thermal abundance

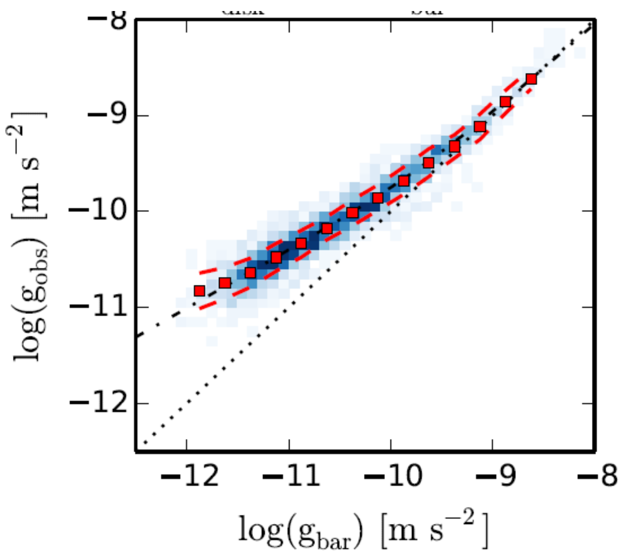
- **Current question:**

  can it fully explain MDAR? →





CMB. LSS and mod. Grav;
(Skordis et. al. 2006)



Galactic Scale Problems with CDM

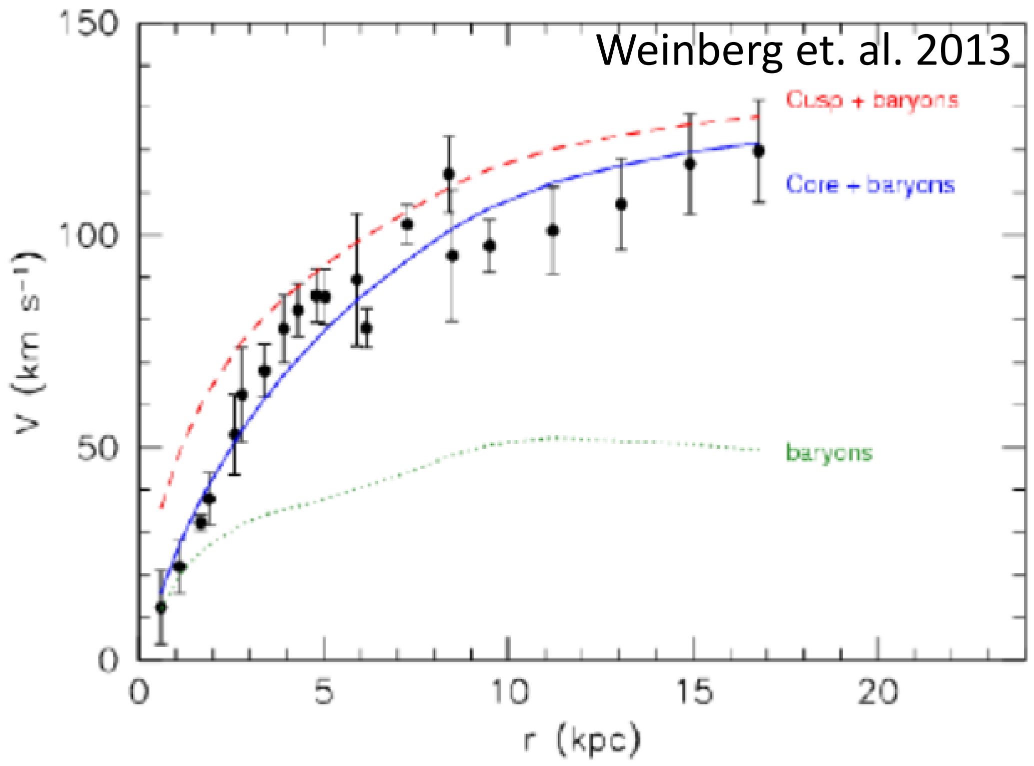
CDM compensates for mass deficit in outer parts

BUT **contributes too much mass to central parts**

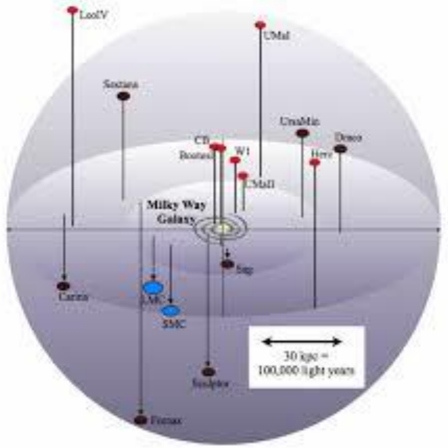
++Probably related problem: small haloes of wrong dynamics

- **Need smaller central density**

recall $\mathbf{v}^2 \sim \frac{M}{r} \sim \frac{1}{r}\int \rho\, r^2 dr$



Also, Missing Sat Problem… see however Kim et. al. 2017 →



Proposed solutions (heating CDM)

Pump energy → decrease DM density:

** **Warm DM** (smaller mass) → preheat!

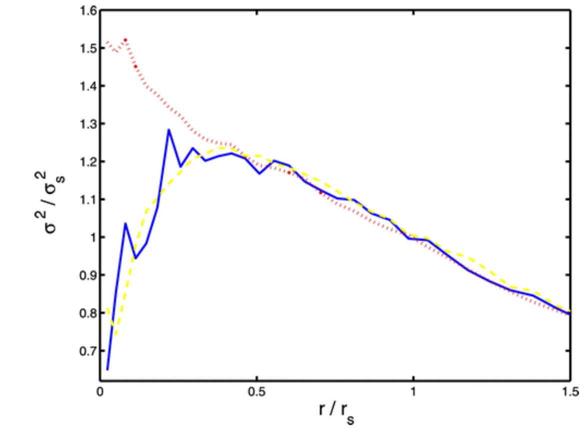
** **Self interacting DM** → Conduction

** **Quantum effects:** (de Broglie lengths ~ kpc!)

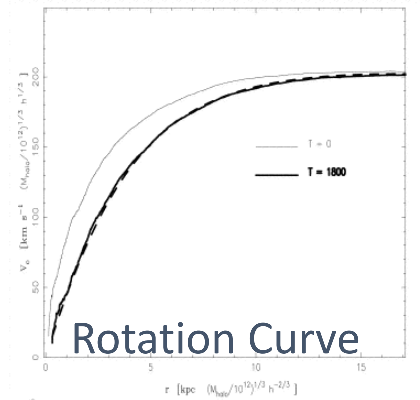
** **Baryonic solutions**: gas gives off energy to DM as it settles in

(e.g., El-Zant et. al 2001;2004; Ponzen & Governato 2014; El-Zant et. al. 2016)

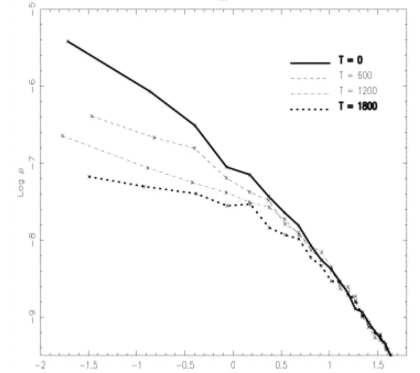
Recently: Direct Baryon DM interaction: Berezhiani et. al.; Salucci & Turini



Velocity dispersion



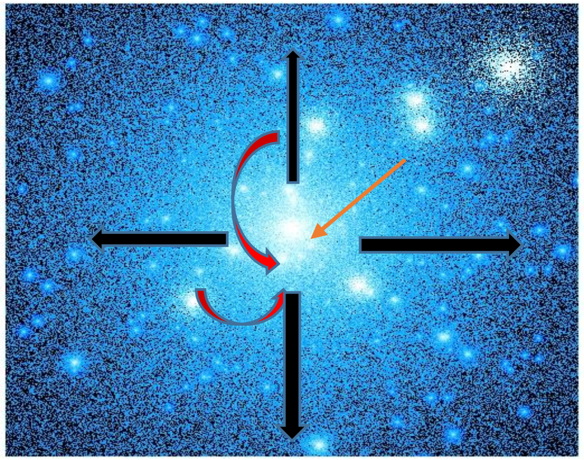
Rotation Curve

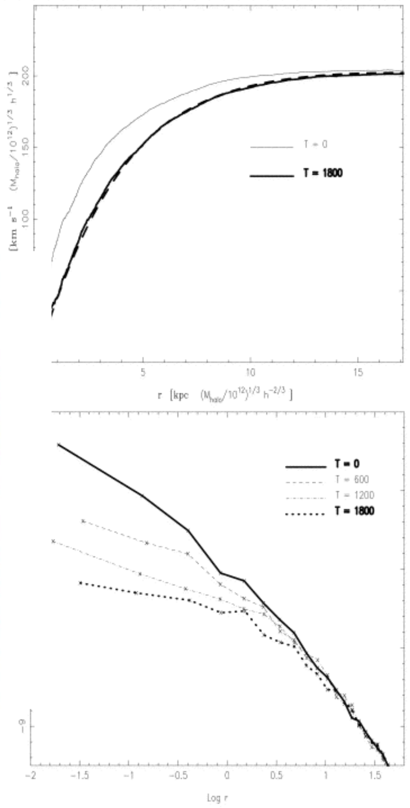


How Baryons can 'heat' the CDM

Baryonic clumps couple to CDM via dynamical friction

→ Lose energy → Heat CDM





El-Zant et. al. (2006, 2008))

Questions:

Can clumps survive? Have enough energy?

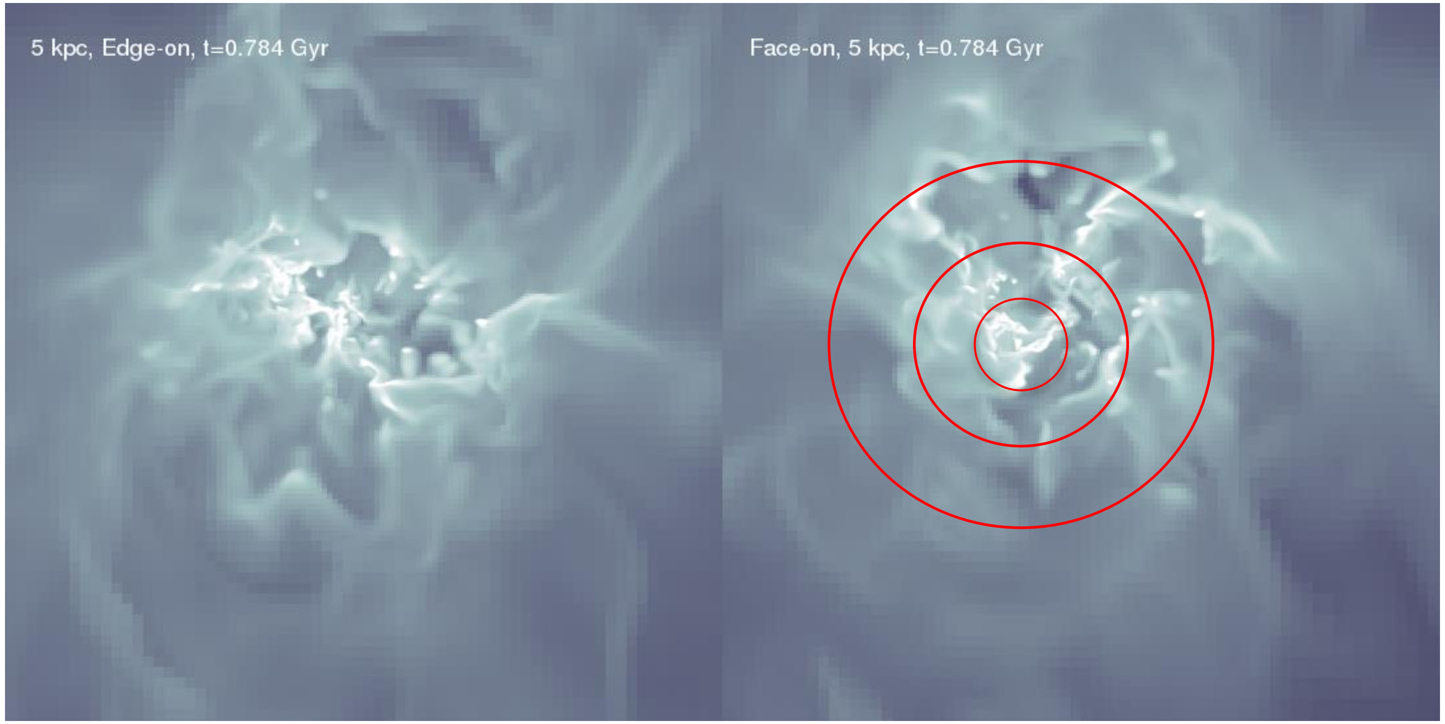
→ Alternative (e.g., Ponzen & Governato 2014, Nat. 506, 171):

Clumps are not monolithic

→ They are density fluctuations

→ Energetically driven by supernovae/AGN

Density and Mass Fluctuations in Hydro Simulations of feedback-driven gas in galaxies



Courtesy of Justin Read

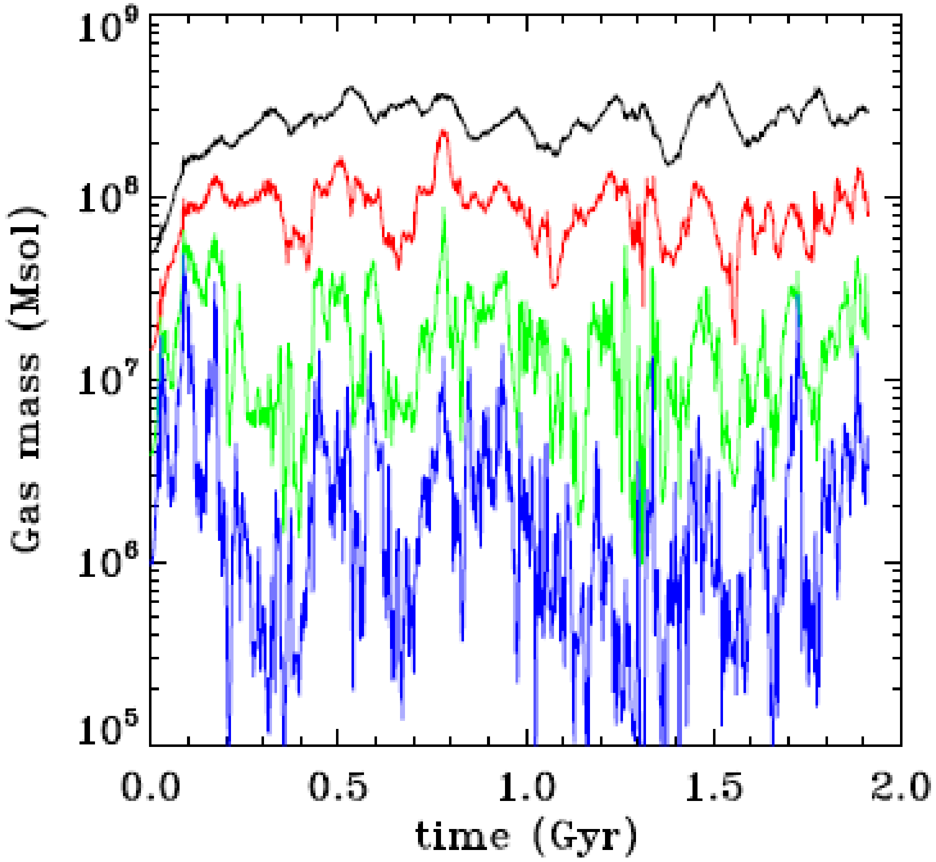


Figure 7. Time evolution of the total enclosed gas mass within spheres of radius 200 (blue), 400 (green), 800 (red) and 1600 (black) pc for the simulation with feedback.

Teyssier et. al. 2013

Deriving effect of fluctuating gas on CDM from first principles
(El-Zant et. al. 2016)

- **Can core formation be understood in simple terms independent of complexity of 'gastrophysics' and its computer images?**

- **Stochastic density fluctuations in gas**
  → Characterized by a power spectrum (stationary, Gaussian random)

- **Density fluctuations → potential fluctuations (via Poisson eq.)**

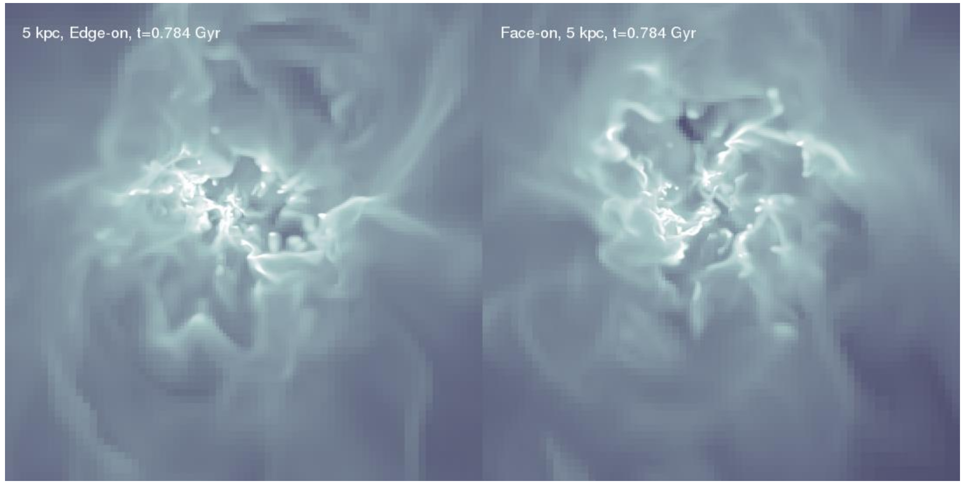
- **Fourier transform → Force correlation function**

- **Insert into stochastic equation (Langevin type - dissipation term)**

- **Derive 'relaxation time' for 'heating' central halo by perturbing CDM orbits**

Characterising fluctuations:

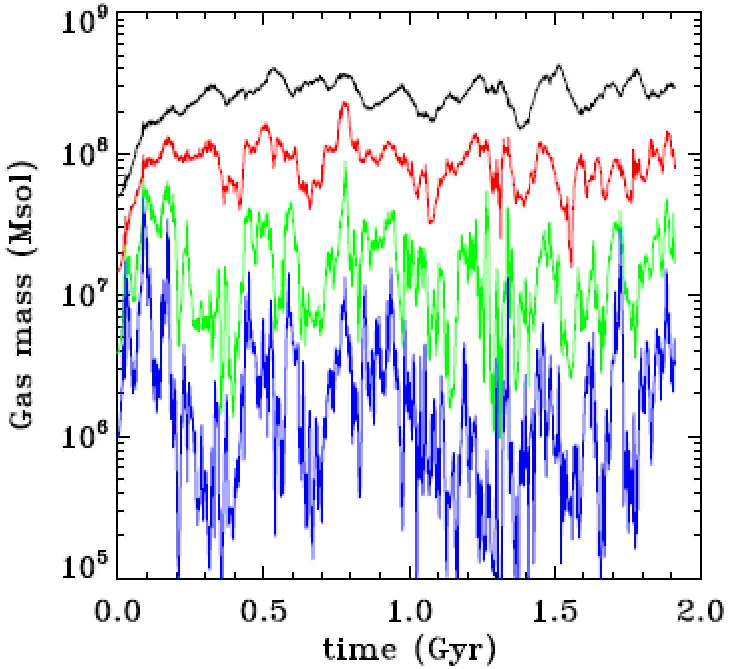
Within volume V fluctuations describe a **stationary stochastic process**



$$\delta(\mathbf{r}) = \frac{V}{(2\pi)^3} \int \delta_{\mathbf{k}} e^{-i\mathbf{k}.\mathbf{r}} d\mathbf{k}$$

Defined by power spectrum

$$\mathcal{P}(\mathbf{k}) = V\langle|\delta_{\mathbf{k}}|^2\rangle$$



Mass fluctuations

$$\frac{\langle(\delta M)^2\rangle}{\langle M\rangle^2} \Rightarrow \sigma_R^2 = \frac{1}{2\pi^2}\int_0^\infty W^2(k,R)\mathcal{P}(k)k^2 dk$$

Filter

From Density to Force fluctuations

- Use Poisson equation

$$\nabla^2 \Phi = 4\pi G \rho_0 \delta$$

- Assume stationary, isotropic, homogeneous stochastic process

$$\phi_{\mathbf{k}} = -4\pi G \rho_0 \delta_{\mathbf{k}} k^{-2}$$

→

- Define force fluctuation power

$$\mathcal{P}_F(k) = V k^2 \langle |\phi_k|^2 \rangle$$

Fourier Transform → Force Correlation Function

$$\langle \mathbf{F}(0).\mathbf{F}(r)\rangle = \frac{V}{(2\pi)^3}\int k^2\langle|\phi_k|^2\rangle\frac{\sin(kr)}{kr}4\pi k^2 dk$$

For **power law** **fluctuations** $\langle|\delta_k|^2\rangle = Ck^{-n}$

(In line with observations)

correlation fn can be found analytically

→ for large r $\langle \mathbf{F}(0).\mathbf{F}(r)\rangle \sim \frac{D}{r^2}\frac{1}{k_m^{n+1}}\cos(k_m r).$

$D = 8(G\rho_0)^2 C d^3$

Depends only on maximal scale k_m when >> minimal fluctuation scale…

Correlation function → Stochastic equation of motion

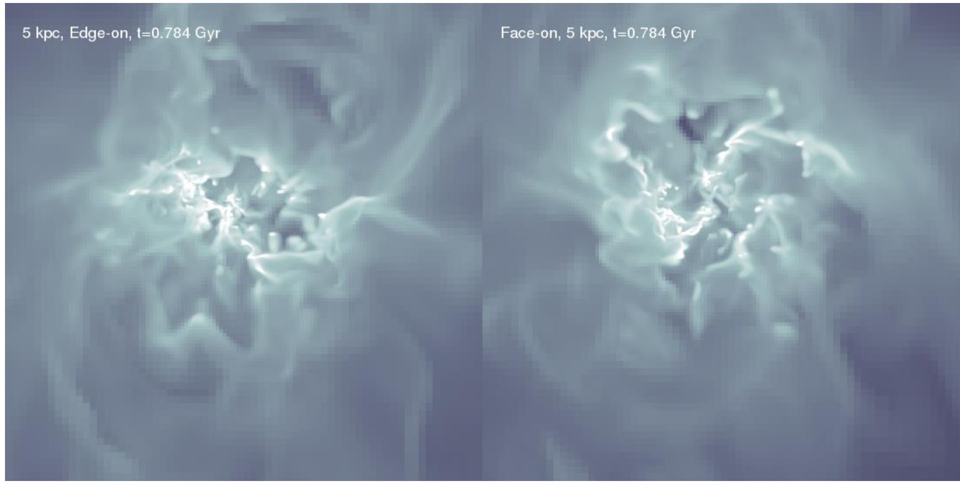
$$d\mathbf{v}/dt = \mathbf{F} \quad \longrightarrow \quad \langle(\Delta v)^2\rangle = 2\int_0^T (T-t)\langle\mathbf{F}(0).\mathbf{F}(t)\rangle dt$$

Sweeping (Taylor 1938) And random sweeping (Kraichman 1964; Tennekes 1972) →

turbulent flow.. transported ‘frozen in’ by large scale motions

$$\langle F(0)F(t)\rangle = \langle F(0)F(r = v_r t)\rangle$$

$$v_r = \sqrt{\langle v\rangle^2 + \langle u^2\rangle}$$



$$\langle(\Delta v)^2\rangle = \frac{2}{v_r^2}\int_0^{R=v_r T}(R-r)\langle\mathbf{F}(0).\mathbf{F}(r)\rangle dr$$

Diffusion Limit → Relaxation Time

When CDM particles moved 'long way' relative to fluctuating fluid

$$k_m R \gg 1 \quad \Longrightarrow \quad \langle(\Delta v)^2\rangle = \frac{\pi D}{n v_r}\frac{T}{k_m^n} \quad \Longrightarrow \quad t_{\mathrm{relax}} = \frac{n v_r \langle v\rangle^2}{8\pi(G\rho_0)^2\mathcal{P}(k_m)}$$

Depends primarily on

1) **Gas mass fraction**
2) **Strength of density fluctuations**

The CDM orbital speed and velocity relative to fluctuating gas determined by halo gravitation → given

The power law index *n* is constrained (~ 2 – 2.5)

Depends weakly on index of power law spectrum

Does not depend on maximal and minimal fluctuation scales

Gaussian Perturbations in Small Model Galaxy

Principal Dependence on Fluctuation Levels -- Gas Mass Fraction

- Use SCF code to simulate small CDM halo (mass $\sim 10^{11}$ solar mass, virial radius 30 kpc and NFW scale length $r_s \sim 1$ kpc)

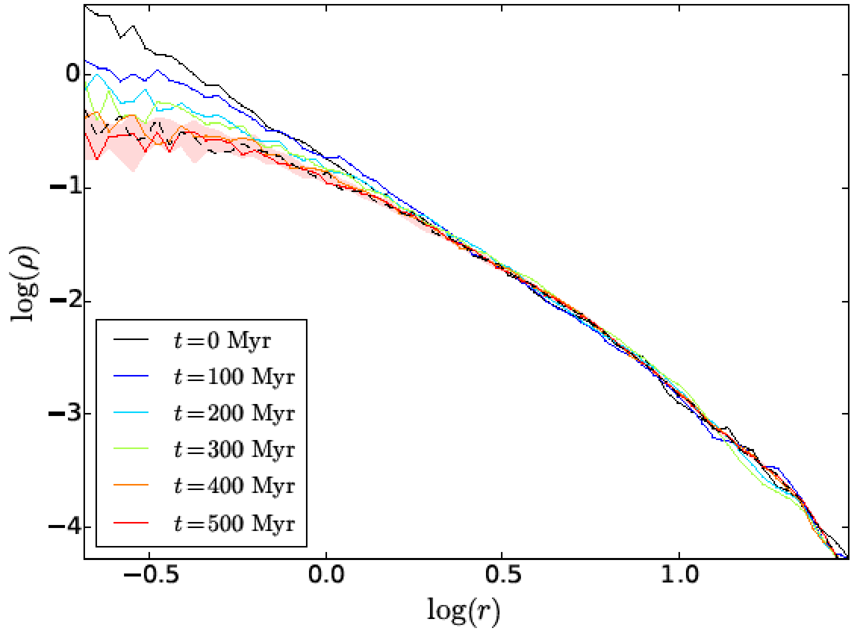
- **Perturb DM particles with Gaussian random field realization of fluctuation spectrum**

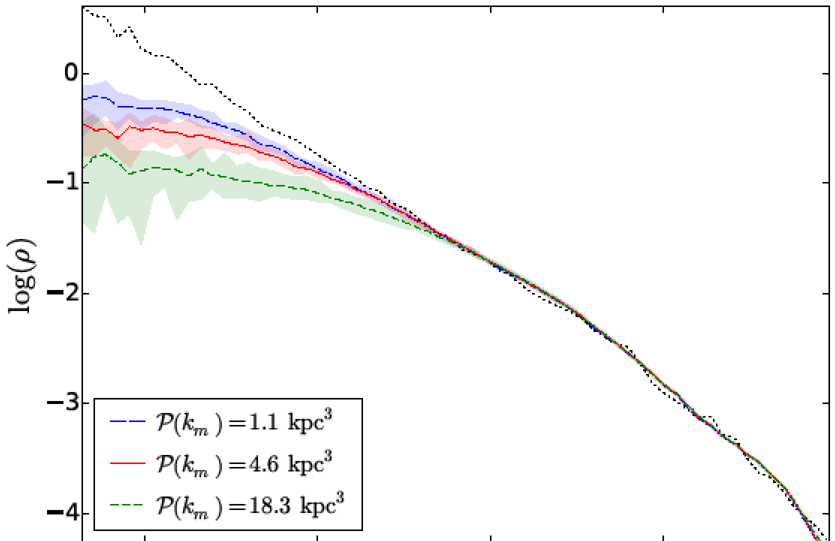
→ **Perturbations chosen such that:**

- **Gas mass fraction** inside region with fluctuations corresponds to **universal baryon fraction** (0.17)

- **Fluctuations normalized** such that relaxation time ~ Gyr inside the NFW scale length r_s $(P(k_m) = 1)$

  → RMS fluctuations **~ 10 at ~ 0.1 r_s**

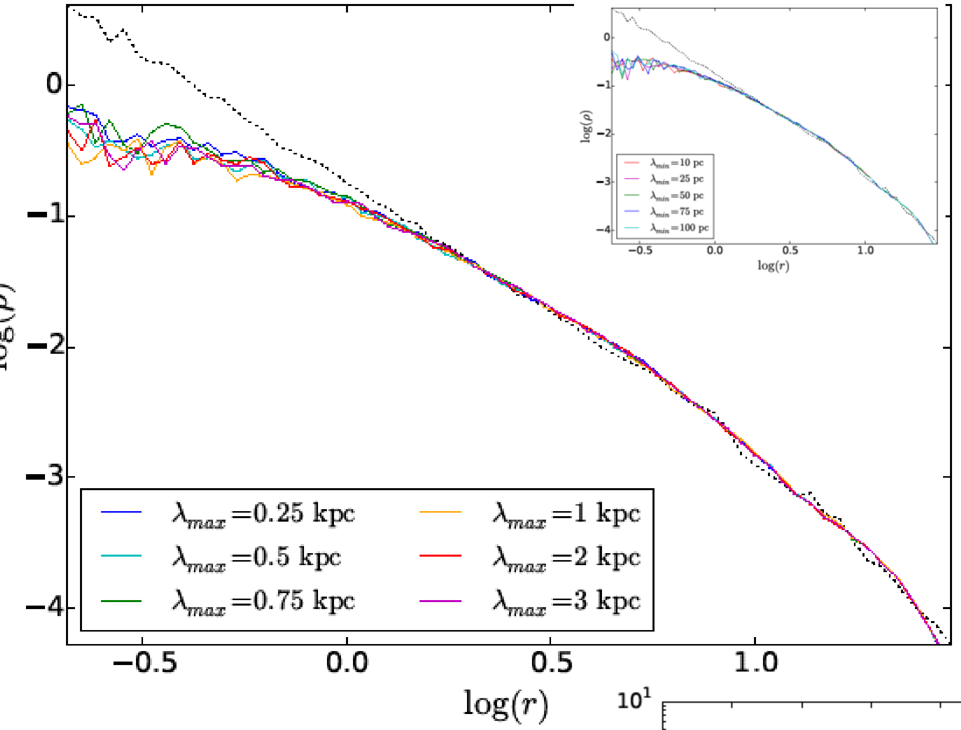




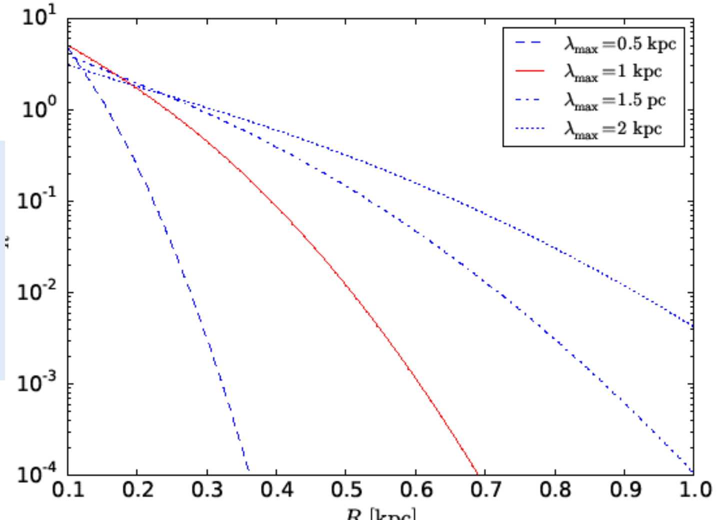
Independence on cutoff scales

As expected from relaxation time calculation and simple argument: $\langle(\Delta v)^2\rangle \propto N\ F^2\ \Delta t^2$

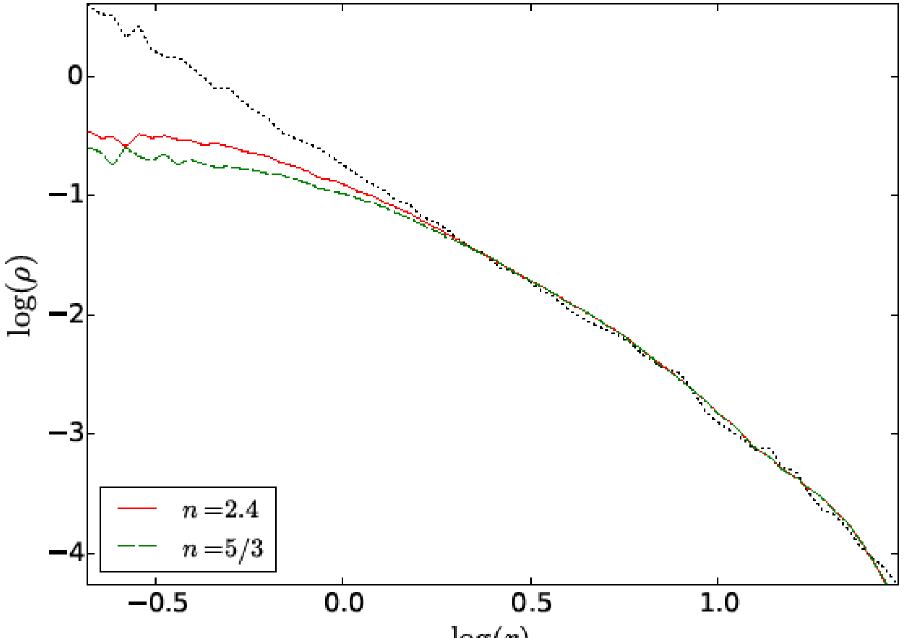
For N 'kicks' per orbit and $F^2 \sim \frac{1}{\lambda} \sim 1/\Delta t$



RMS density fluctuations
(with Gaussian cutoff R)
for different maximal cutoff scales



Weak dependence on spectrum tilt



Conclusion and Prospects

- **CDM particularly successful on large scales (where modified gravity fails)**
- **(Until recently) thought to be most 'natural' from particle physics view**
- **Small scale problems are part of a parcel that threatens CDM**

- **Density reduction leading to core in CDM haloes can be produced by dynamical friction or stochastic fluctuations modelled as Gaussian random field.**

- **Latter process effectively depends on two parameters (which may be correlated).**

- **Process may be understood in simple terms despite physical and numerical complexities**

→Interpret results as a function of physical input and numerical implementation → decide whether the core formation via baryonic feedback is generic and sufficient to save CDM

Question:

can Baryon-DM interactions through DF or feedback fluctuations also help explain MOND-like behaviour in galaxies (the MDAR relation)?

Fourier Transform → Force Correlation Function

$$\langle \mathbf{F}(0).\mathbf{F}(r)\rangle = \frac{V}{(2\pi)^3}\int k^2\langle|\phi_k|^2\rangle \frac{\sin(kr)}{kr} 4\pi k^2 dk$$

For power law fluctuations $\langle|\delta_k|^2\rangle = Ck^{-n}$

$$\langle|\phi_k|^2\rangle = (-4\pi G\rho_0)^2 C k^{-4-n}$$

Correlation fn can be found analytically → for large r

$$\langle \mathbf{F}(0).\mathbf{F}(r)\rangle \sim \frac{D}{r^2}\frac{1}{k_m^{n+1}}\cos(k_m r).$$

Depends only on maximal scale k_m
when >> minimal fluctuation scale…

for small r ~ k_m ~ maximal fluctuation scale

$$D = 8(G\rho_0)^2 C d^3$$

Stochastic equation and (random) sweeping

$$d\mathbf{v}/dt = \mathbf{F} \quad \longrightarrow \quad \langle(\Delta v)^2\rangle = 2\int_0^T (T-t)\langle \mathbf{F}(0).\mathbf{F}(t)\rangle dt$$

Sweeping (Taylor 1938) And random sweeping (Kraichman 1964; Tennekes 1972) → turbulent flow transported, 'frozen in', by large scale motions

$$\langle F(0)F(t)\rangle = \langle F(0)F(r = v_r t)\rangle \qquad v_r = \sqrt{\langle v\rangle^2 + \langle u^2\rangle}$$

$$\langle(\Delta v)^2\rangle = \frac{2}{v_r^2}\int_0^{R=v_r T} (R-r)\langle \mathbf{F}(0).\mathbf{F}(r)\rangle dr$$