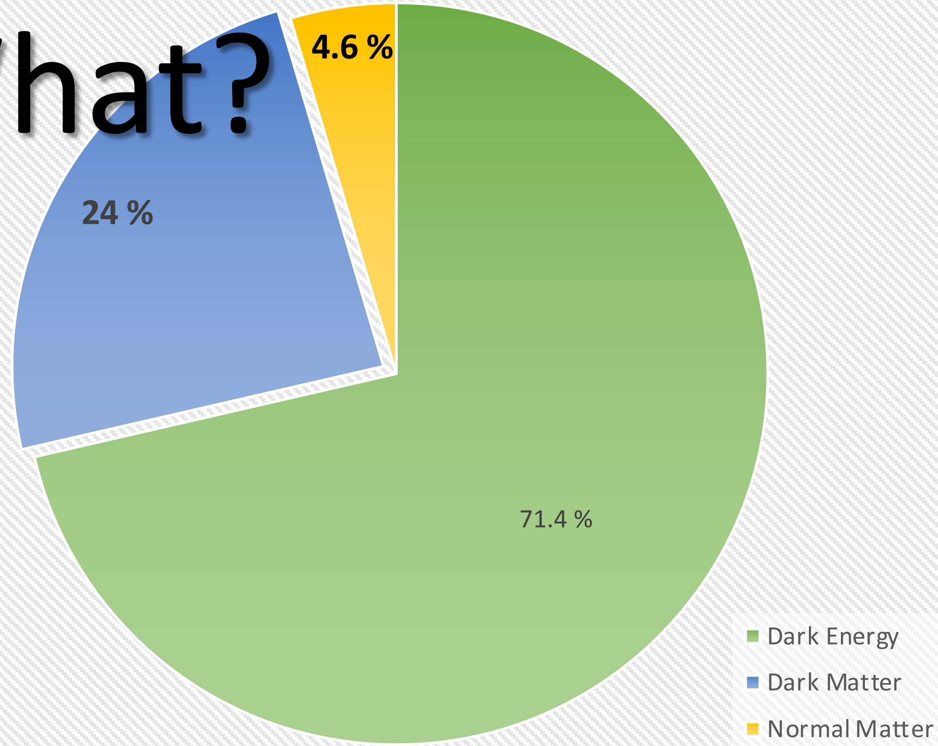
FIAS Frankfurt Institute for Advanced Studies

Dark Matter – Or What?

Sabine Hossenfelder



In collaboration with Tobias Mistele

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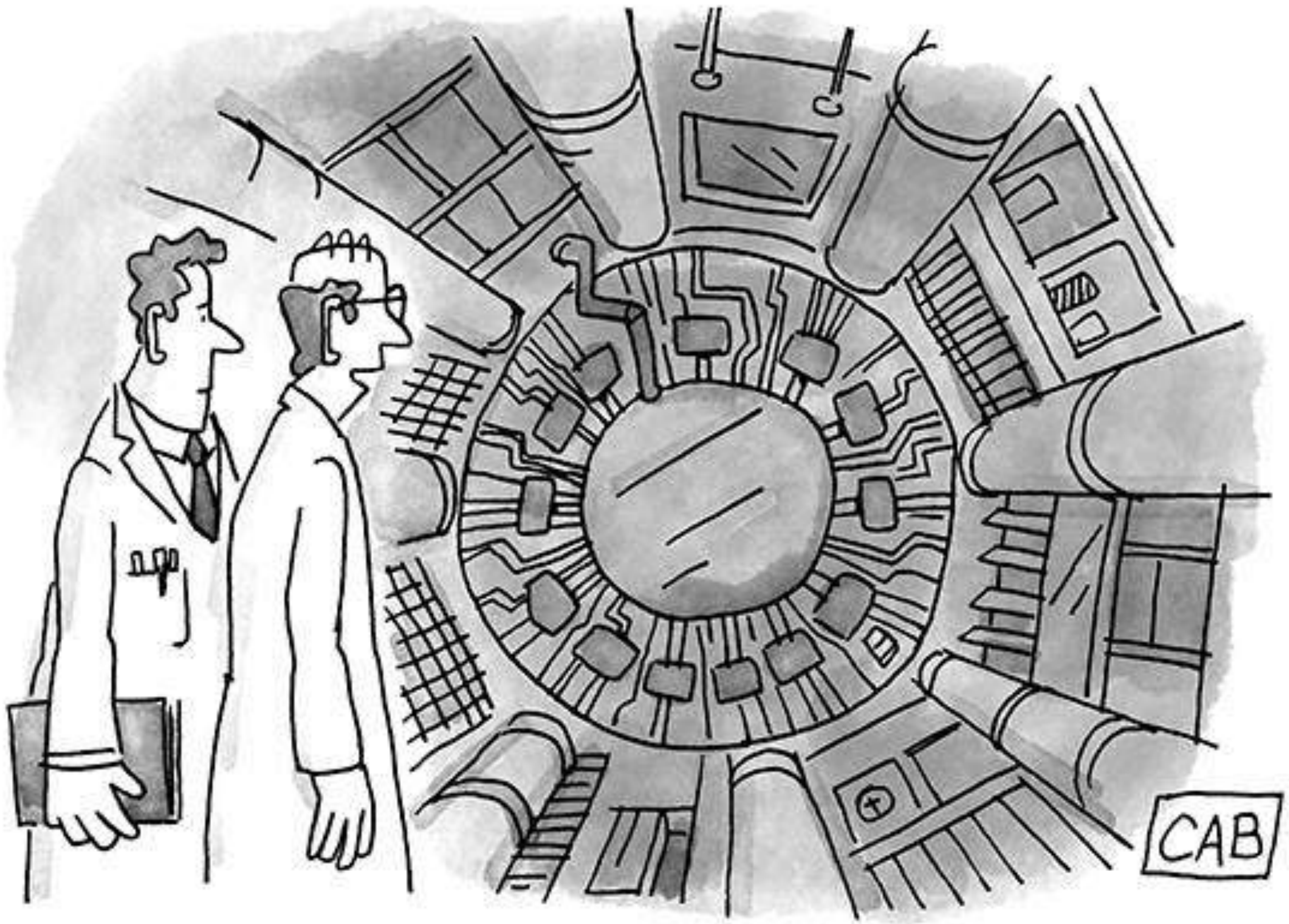


"Once you have a collider, every problem starts to look like a particle."

ASTROPHYSICS

IS DARK MATTER REAL?

Astrophysicists have piled up observations that are difficult to explain with dark matter. It is time to consider that there may be more to gravity than Einstein taught us

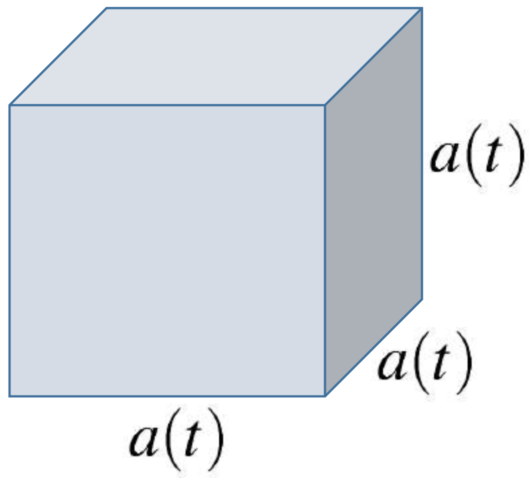
By Sabine Hossenfelder and Stacy S. McGaugh

[Scientific American, Sep 2018]

What is Dark Matter?

- Neither emits nor adsorbs light, not at any frequency. It's really transparent rather than dark.
- Its energy-density decreases with the inverse volume.
- It rarely interacts, both with itself and with normal matter. Just exactly how rarely, no one knows.

$$\rho_{\mathrm{DM}} = \frac{\rho_0}{a(t)^3}$$



Why do we think that dark matter exists?

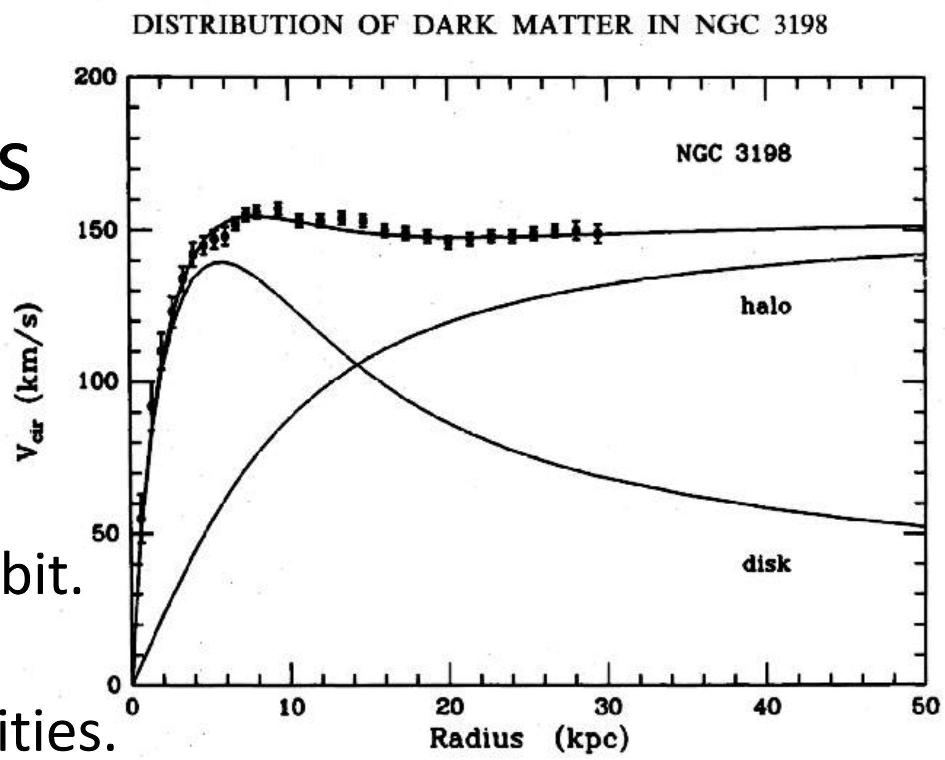
Numerous independent lines of evidence that have accumulated for more than 80 years.

1. Galaxy Clusters

- Ca 100-1000 Galaxies, held together by their own gravitational pull
- The higher the total mass in the cluster, the higher the average velocity of galaxies in the cluster (virial theorem)
- Observations show: The average velocity of galaxies in clusters is much higher than can be explained by the observed matter alone.
- Coma Cluster: Historically first evidence for dark matter (Zwicky)

2. Galactic Rotation Curves

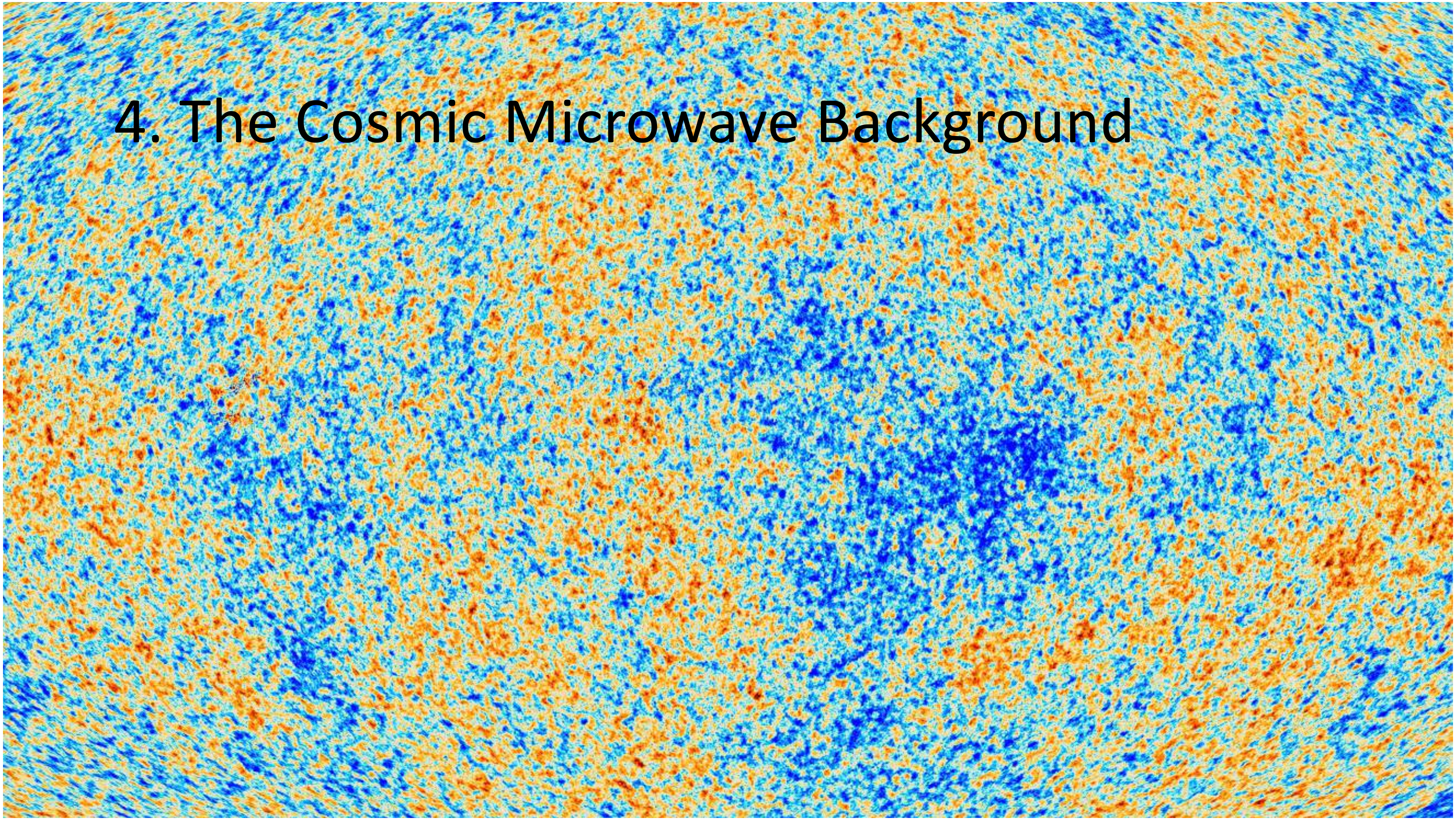
- Infer velocity of stars from red/blue shift of absorption lines.
- The velocity of a star on a stable orbits depends only on the mass inside the orbit.
- Known masses combined are not sufficient to explain the observed velocities.



3. Gravitational Lensing

- In General Relativity, masses curve space-time and bend light around them: They act like lenses.
- From the strength of the deviation one can calculate the mass of the lensing object.
- Observations show: Normal matter is not sufficient, neither for galaxies (strong lensing) nor galaxy clusters (weak lensing)

4. The Cosmic Microwave Background



4. The Cosmic Microwave Background

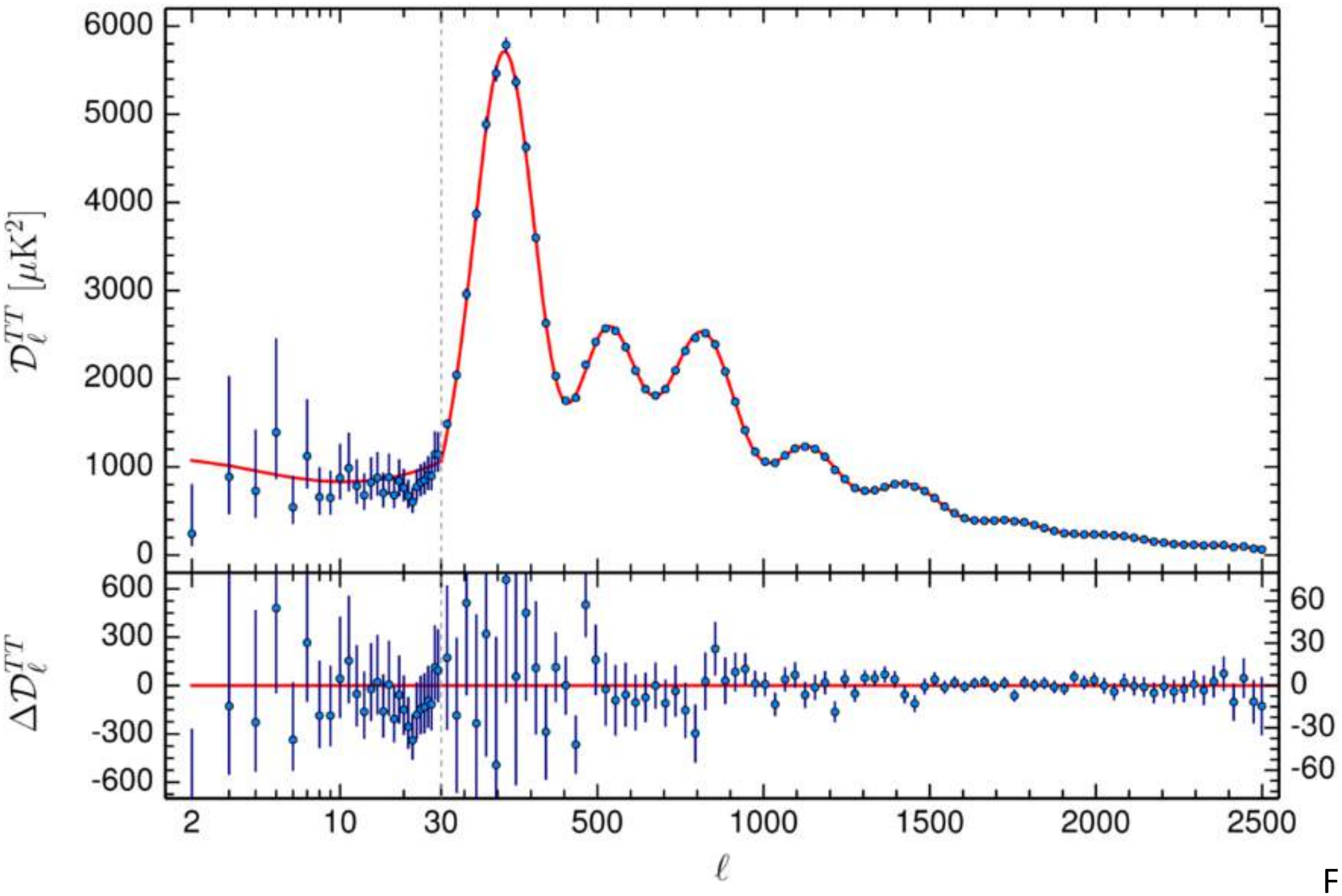


Fig: Planck Collaboration

4. The Cosmic Microwave Background

The relative height of the 2^{nd} to the 3^{rd} acoustic peak depends on the amount of dark matter.

Cosmologies without dark matter get the power spectrum wrong.

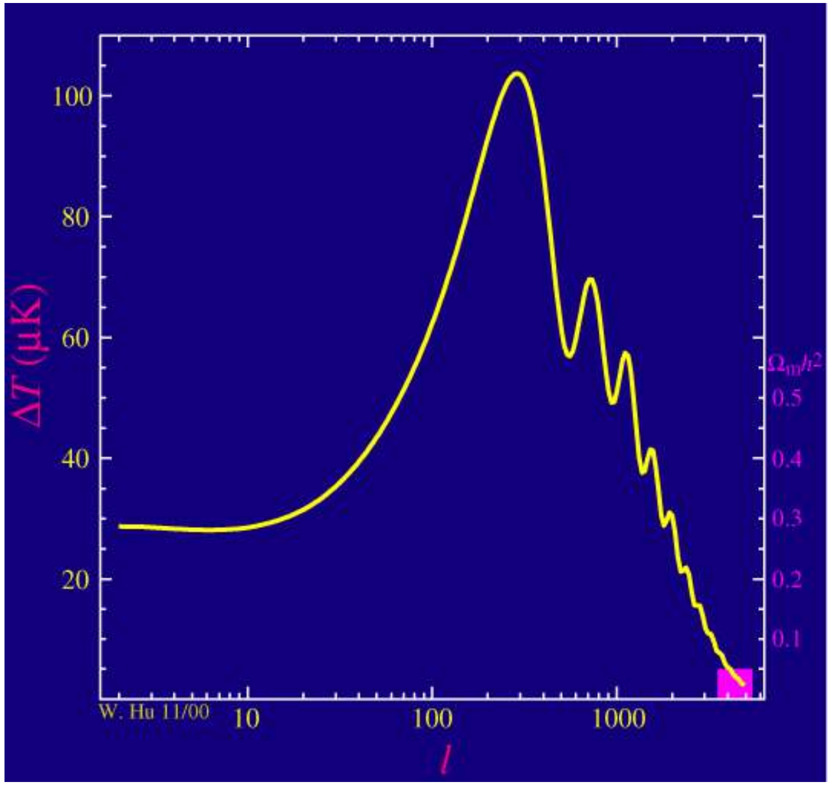


Fig: Wayne Hu

5. Structure Formation

- Dark matter cannot build up radiation pressure and therefore starts forming structures sooner than normal matter

- Normal matter on its own does not produce suffient structures on short scales to be compatible with observation

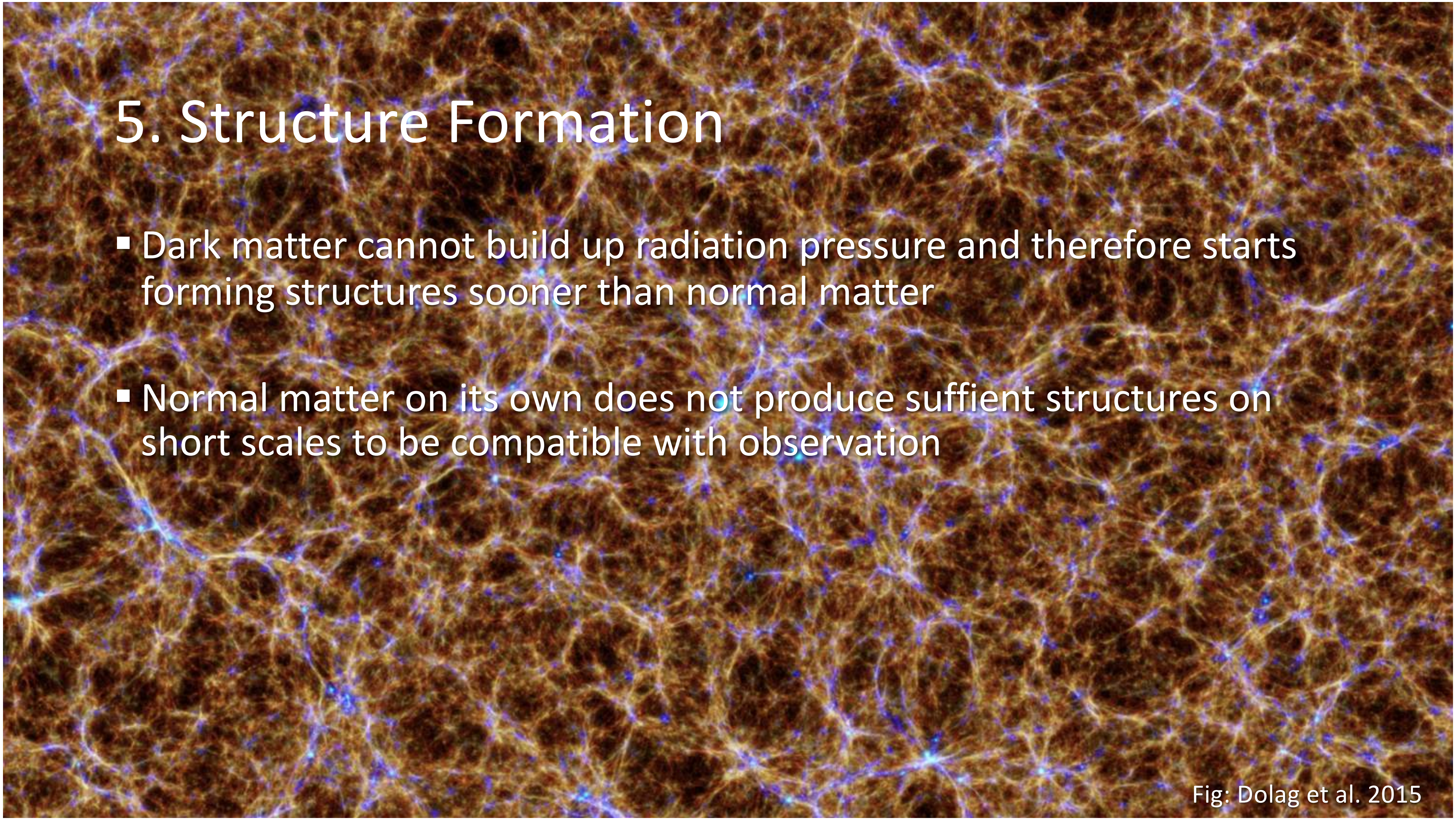


Fig: Dolag et al. 2015

How Dark Matter solves the problem

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = T_{\mu\nu} + X_{\mu\nu}$$

Function of (curvature) = (mass and energy) + X

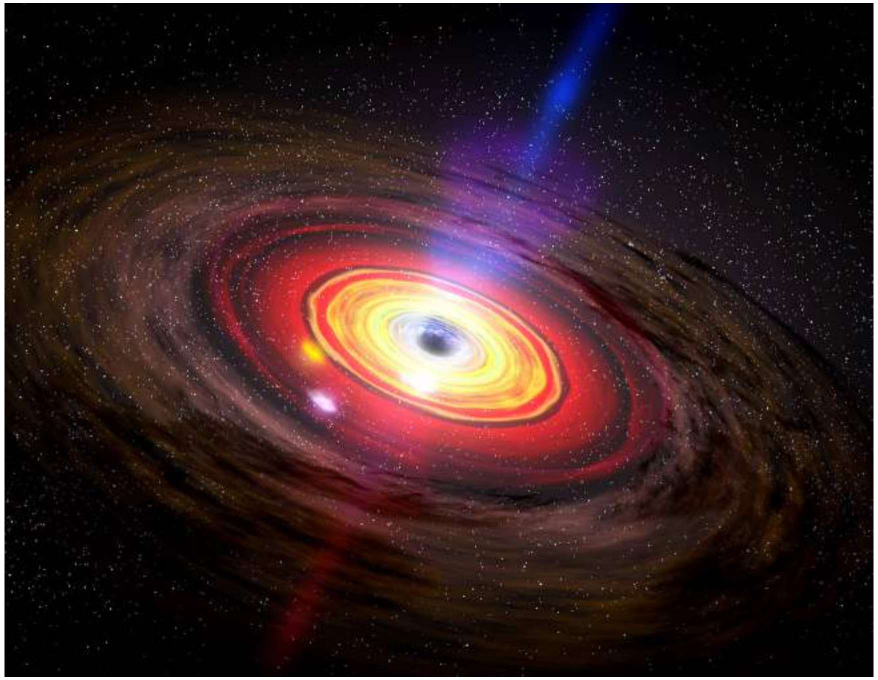
There is always an X! Important: X has properties of matter. That's not trivial. X is a Tensor with 10 entries. We need only one entry.

Dark matter is a parametrically simple explanation.

Can Dark Matter be "normal" matter?

No, because:

- No known particle fits the bill: They either interact with light or, in the case of neutrinos, don't clump enough.
- Brown dwarfs, black holes, and exotic compact, dark object: would make too many gravitational lenses which have not been seen.

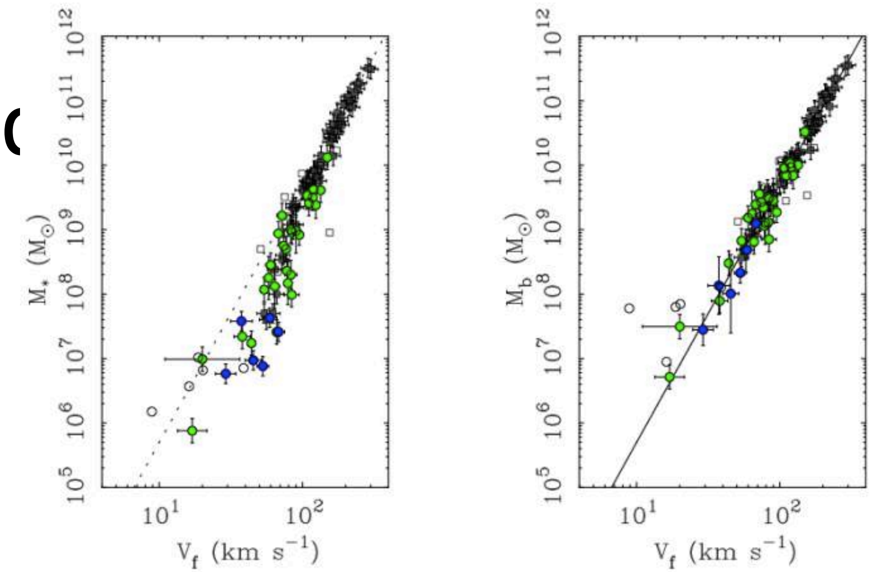


[Black hole, artist's impression]

It has to be something new.

Figure: McGaugh *et al*

Problems that Dark Matter
not solve

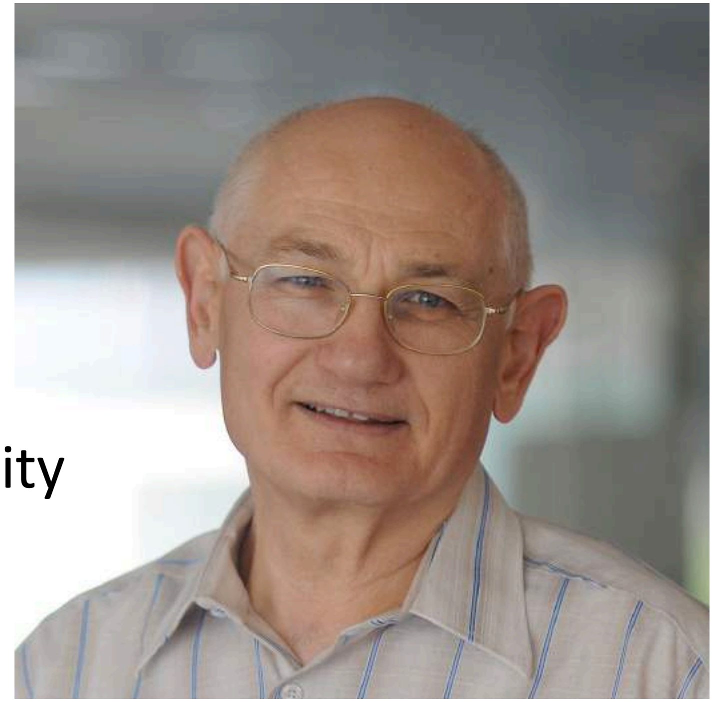


- The brightness of galaxies is strongly correlated with the (asymptotic) rotational velocity ("Tully-Fisher Law"). Dark matter doesn't explain this.
- Dark matter leads to density peaks in galactic centers which badly fits with observations ("galaxy cusps").
- Dark matter predicts too many dwarf galaxies.*
- Satellite galaxies are more often aligned in planes with their host than dark matter simulations predict.

* Or maybe too many ¯_(ツ)_/¯

Alternative Explanation: Modified Gravity

[Mordehai Milgrom. Photo: Wikipedia]



- Mordehai Milgrom, *Astrophysical Journal* **270**, 365–370 (1983): Modified Newtonian Dynamics (MOND)
- **We know that MOND is only an approximation**
- MOND relates to modified gravity the same way that Newtonian Gravity relates to General Relativity
- There are various approaches to the full theory of modified gravity

How does Modified Newtonian Dynamics work?

Newtonian Gravity

$$\Phi = -\frac{MG}{R}$$

for stable orbits

$$F = \frac{MG}{R^2} = \frac{v^2}{R}$$

$$v^2 = \frac{MG}{R}$$

→ falling rotation curves

Modified Newtonian Gravity

$$\Phi = \sqrt{MGa_0} \ln\left(\frac{R}{MG}\right)$$

for stable orbits

$$F = \frac{\sqrt{MGa_0}}{R} = \frac{v^2}{R}$$

$$v^2 = \sqrt{MGa_0}$$

→ flat rotation curves & Tully-Fisher

Modified Newtonian Dynam

$$\Phi = \sqrt{MGa_0}\ln\left(\frac{R}{MG}\right)$$
$$F = \frac{\sqrt{MGa_0}}{R}$$

Requires an “interpolation function” to transition between Newtonian gravity and modified Newtonian gravity

Effects of MOND become relevant below a certain acceleration (a_0) and **not** beyond a certain distance.

The acceleration scale that best fits the data turns out to be related to the cosmological constant. No one has any idea why:

$$a_0 \approx \sqrt{\Lambda/3}$$

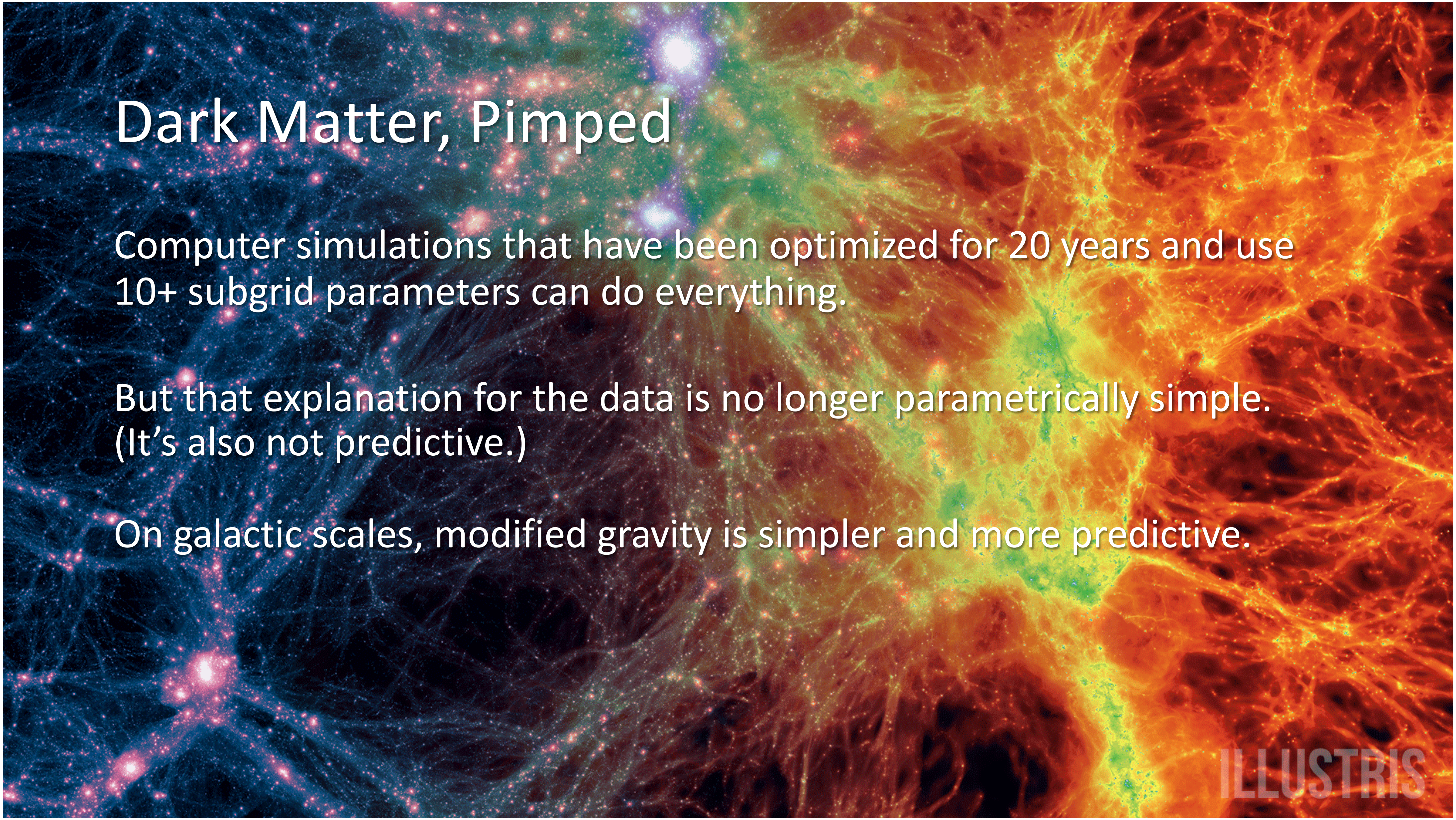
Modified Gravity

Can do:

- Correlation between mass and rotational velocity (giving rise to flat rotation curves and Tully-Fisher)
- Avoids galaxy cusps
- Reduces number of dwarf galaxies
- Helps with planar arrangements of satellite galaxies

Can’t do: CMB, early universe, galaxy clusters

Unclear: Solar System.


Dark Matter, Pimped
Computer simulations that have been optimized for 20 years and use 10+ subgrid parameters can do everything.
But that explanation for the data is no longer parametrically simple.
(It's also not predictive.)
On galactic scales, modified gravity is simpler and more predictive.
ILLUSTRIS

Verlinde's Emergent Gravity 2010

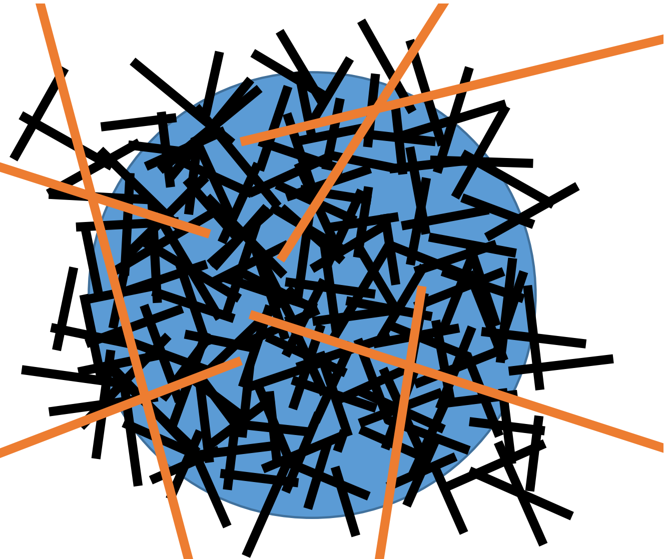
Erik Verlinde, JHEP 1104:029 (2011) arXiv:1001.0785 [hep-th]: Area-law entropy gives rise to normal Newtonian gravity.

A: There is a scalar field ϕ which obeys the Poisson equation $\nabla^2\phi = 4\pi G\rho$. A test-mass m in the background field of a mass M with field ϕ_M experiences a force $\vec{F} = m\vec{\nabla}\phi_M$.

B: There are two scalar quantities S and T and a continuous set of non-intersecting surfaces $\mathcal{S}$, the 'holographic screens,' whose union covers all of space $\mathbb{R}^3 = \cup\mathcal{S}$. The theory is defined by $2G\int_{(\mathcal{S})}\rho dV = \int_{\mathcal{S}} T dA \,\forall\mathcal{S}$, and the force acting on a particle with test-mass m is given by $F\delta x = \int_{\mathcal{S}} T\delta dS$, where the integral is taken over a screen that does not include the test-mass.

SH, arXiv:1003.1015 [gr-qc]

Verlinde’s Emergent Gravity 2017



- Entropy Area law from short-range entanglement
- Should have volume-scaling corrections from long-range entanglement
- Erik Verlinde, SciPost Phys. 2, 016 (2017) arXiv:1611.02269 [hep-th] Volume-law entropy gives rise to MOND.
- Introduces “displacement vector” with “strain tensor”

$$\varepsilon_{ij} = \frac{1}{2}\left(\nabla_i u_j + \nabla_j u_i\right).$$

Covariant Emergent Gravity

Covariant, Lagrangian formulation of Verlinde's ansatz.

$$\varepsilon_{\mu\nu} = \nabla_\mu u_\nu + \nabla_\nu u_\mu \qquad \chi = -\frac{1}{4}\varepsilon_{\mu\nu}\varepsilon^{\mu\nu} + \frac{1}{3}\varepsilon^2$$

$$\begin{aligned}
\mathcal{L}_{\rm tot} &= m_{\rm p}^2 \mathcal{R} + \mathcal{L}_{\rm M} + \mathcal{L}_{\rm int} + \mathcal{L}_\theta \,, \\
\mathcal{L}_{\rm int} &= -\frac{1}{L} u^\mu n^\nu T_{\mu\nu} = -\frac{u^\mu u^\nu}{Lu} T_{\mu\nu} \,, \\
\mathcal{L}_\theta &= \frac{m_{\rm p}^2}{L^2}\chi^{3/2} - \frac{\lambda^2 m_{\rm p}^2}{L^4} u_\kappa u^\kappa \,,
\end{aligned}$$

The "impostor-field".
Gives rise to a force that looks like gravity but isn't.

SH, Phys. Rev. D 95, 124018 (2017).

Covariant Emergent Gravi

$$
\begin{aligned}
\mathcal{L}_{\mathrm{tot}} &= m_{\mathrm{p}}^2 \mathcal{R} + \mathcal{L}_{\mathrm{M}} + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_{\theta} \ , \\
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\mathcal{L}_{\theta} &= \frac{m_{\mathrm{p}}^2}{L^2} \chi^{3/2} - \frac{\lambda^2 m_{\mathrm{p}}^2}{L^4} u_\kappa u^\kappa \ ,
\end{aligned}
$$

Advantages:

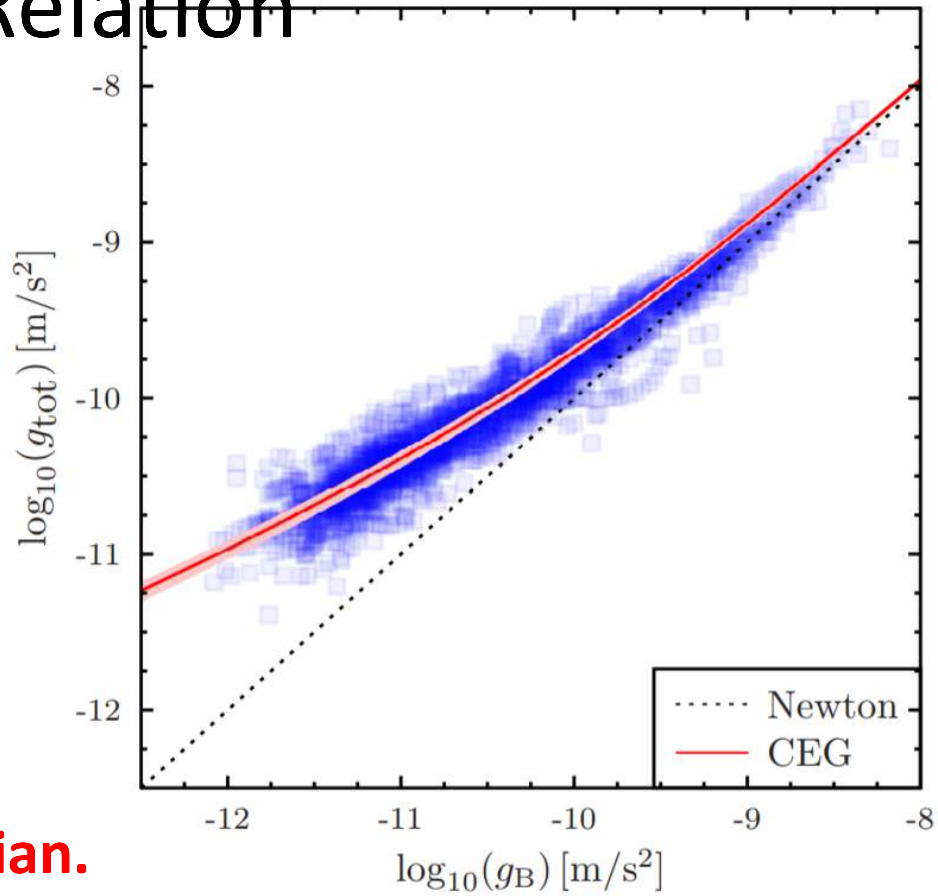
- Respects all symmetries and conservation laws
- Equations guaranteed to be consistent
- Can be used beyond the spherically-symmetric, non-relativistic case
- Lends itself to stability-analysis
- Limits of the effective description can be estimated
- Has a de-Sitter solution, ie gives rise to cosmological constant

The Radial Acceleration Relation

In MOND-like theories, the total observed acceleration is strongly correlated with the acceleration of normal matter. This correlation is clearly present in the data.

Covariant Emergent Gravity reproduces it reasonably well already in the spherically-symmetric limit.

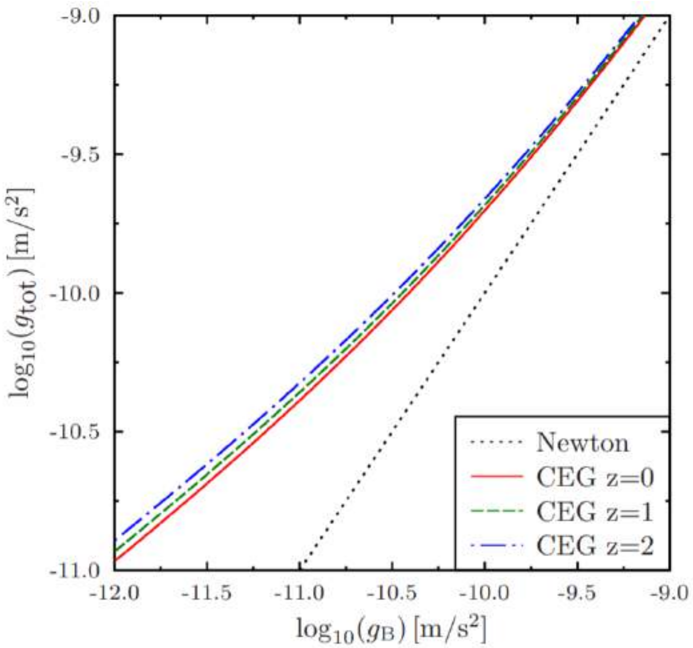
This curve is derived from the Lagrangian.
It has no free parameters.



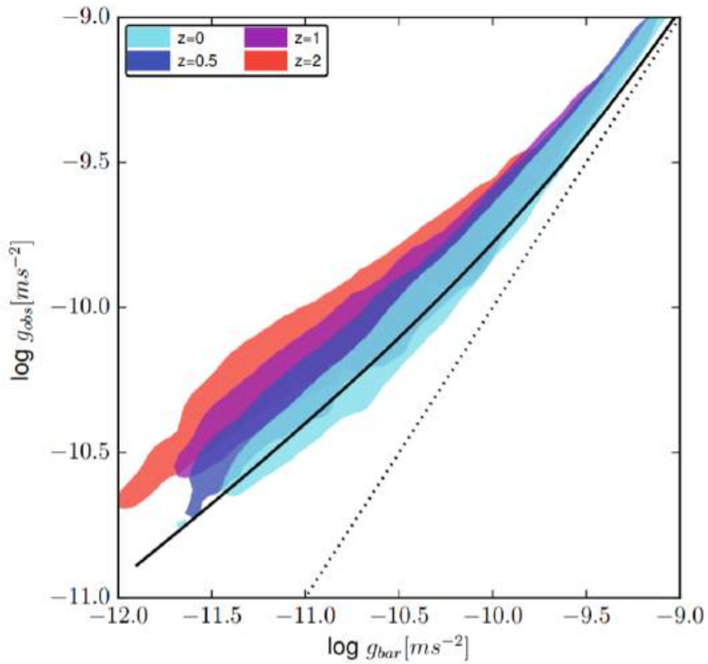
SH, Tobias Mistele, IJMPD 27, 14, 1847010 (2018)
Data from McGaugh *et al*, Phys. Rev. Lett. 117, 201101 (2016).

Reshift-Dependence of Radial Acceleration Relation:

Modified Gravity predicts less redshift-dependence of the radial acceleration relation than cold dark matter. May become observable soon.



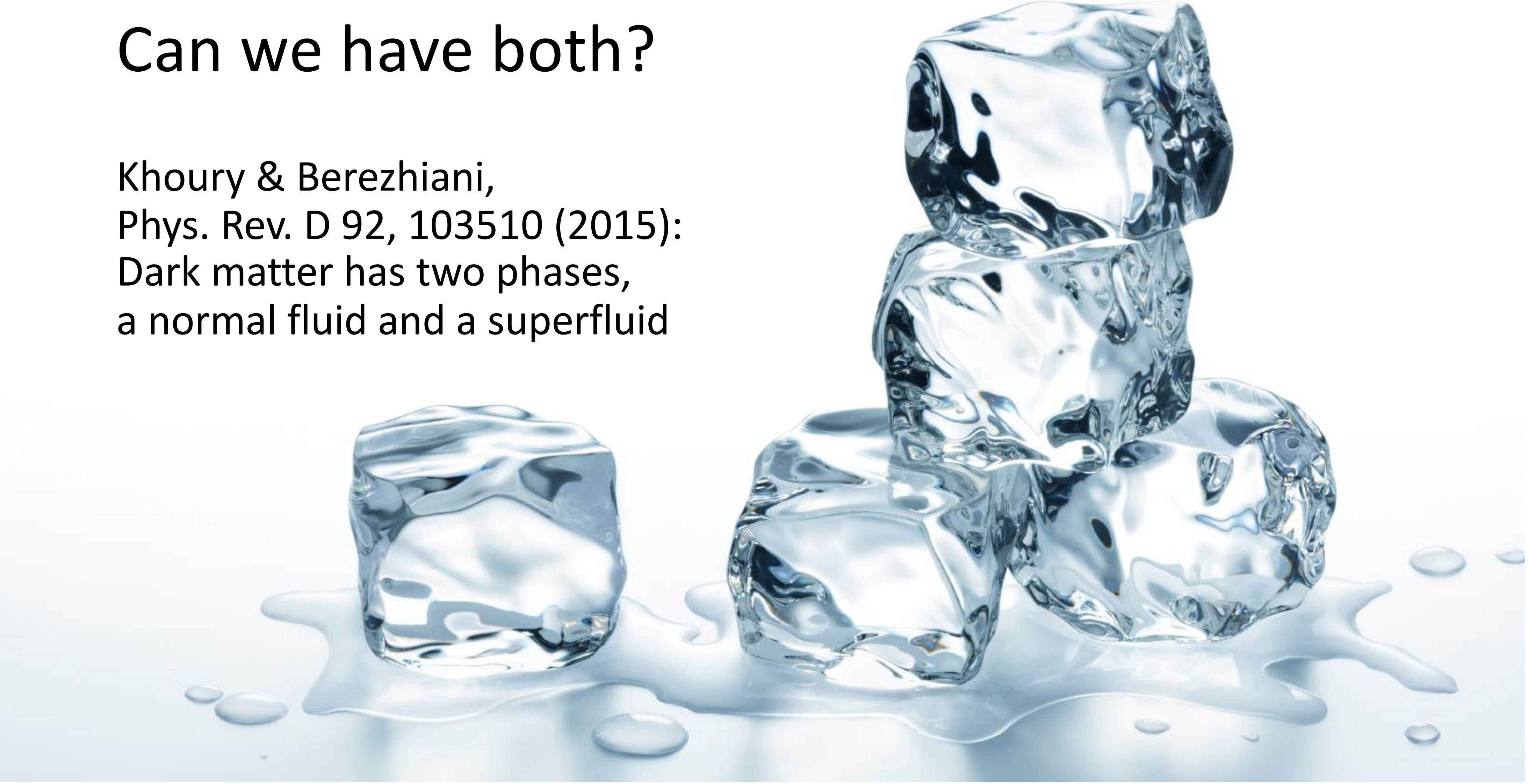
SH, Tobias Mistele, IJMPD 27, 14, 1847010 (2018)



CDM simulation: Keller & Wadsley, ApJL 835 L17 (2017)

Can we have both?

Khoury & Berezhiani,
Phys. Rev. D 92, 103510 (2015):
Dark matter has two phases,
a normal fluid and a superfluid



Superfluid Dark Matter

- Normal phase: At high temperatures, the fluid acts like particle dark matter, particles with masses of about eV.
- Superfluid phase: At low temperature, the fluid condenses and **phonons mediate a new long-range force that looks like modified gravity**

$$\chi = \dot{\theta} - m\Phi_N - \frac{(\vec{\nabla}\theta)^2}{2m}$$

$$\mathcal{L} = 2\Lambda \frac{(2m)^{3/2}}{3} \chi^{3/2} - \frac{\Lambda}{m_{Pl}} \theta \rho_B$$

This explains why sometimes particle dark matter works better and sometimes modified gravity! Requires no interpolation function!

Covariant Emergent Gravi

$$\begin{aligned}
\mathcal{L}_{\mathrm{tot}} &= m_{\mathrm{p}}^2 \mathcal{R} + \mathcal{L}_{\mathrm{M}} + \mathcal{L}_{\mathrm{int}} + \mathcal{L}_{\theta} \ , \\
\mathcal{L}_{\mathrm{int}} &= -\frac{1}{L} u^{\mu} n^{\nu} T_{\mu\nu} = -\frac{u^{\mu} u^{\nu}}{Lu} T_{\mu\nu} \ , \\
\mathcal{L}_{\theta} &= \frac{m_{\mathrm{p}}^2}{L^2} \chi^{3/2} - \frac{\lambda^2 m_{\mathrm{p}}^2}{L^4} u_{\kappa} u^{\kappa} \ ,
\end{aligned}$$

Relation to superfluid:

- Same power of kinetic term
- Same coupling to normal matter
- In non-relativistic limit, vector field is described by one scalar component
- On galactic scales, the two approaches are almost identical

SH, Phys. Rev. D 95, 124018 (2017).

Galaxy Lensing

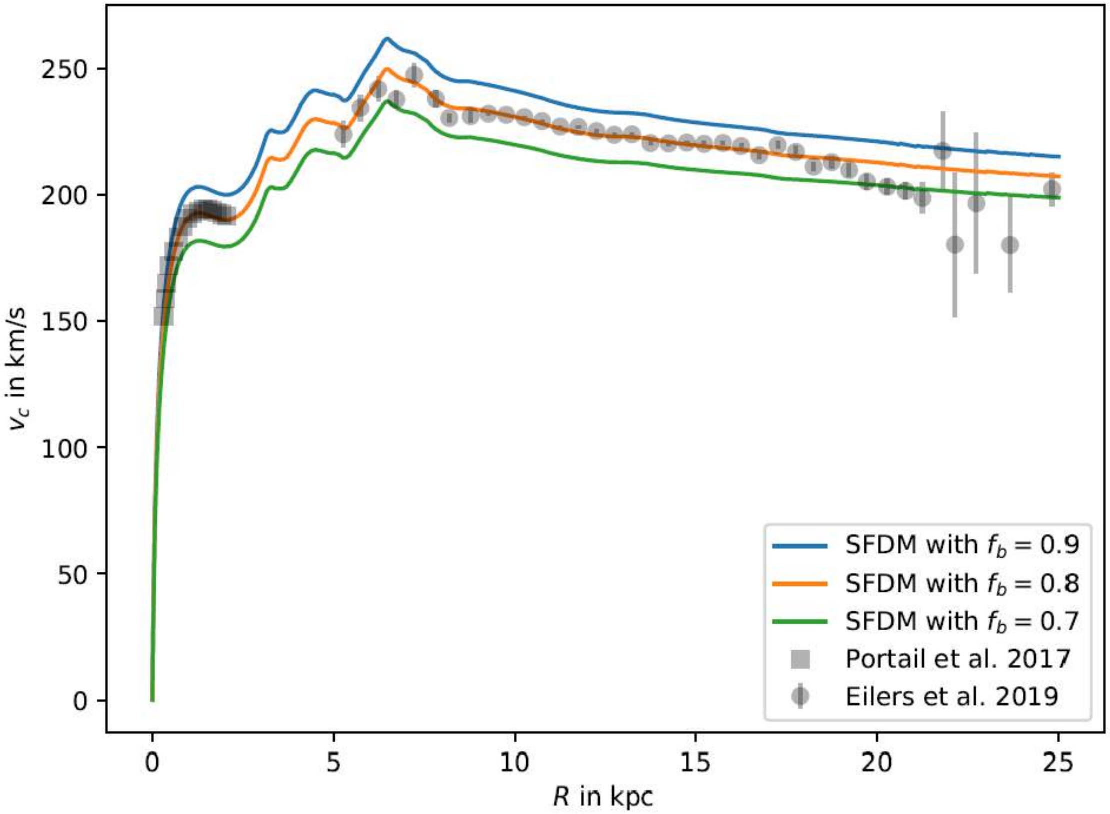
Superfluid/vector field cannot couple to photons because of constraints from neutron-star merger.

Consequence: Amount of dark matter inferred from gravitational lensing should be less than the amount inferred from kinematic measurements.

But: Strong gravitational lensing dominated by galactic core, ie by normal mass. Can always fit both kinematic and lensing measurements.

SH, Tobias Mistele, 1902 (2019) 001, arXiv: 1809.00840

Work in progress: Milky Way Rotation Curve



Other ways to test superfluid dark matter

- Look for particles in local experiments. Difficult because UV-completion is missing, thus unclear what to look for. Also, probably too weak/light to measure (guessing here).
- The phase-transition to a superfluid should leave a mark in the evolution of galaxies. This should in principle be observable. Problem: Unclear what to look for because equation of state unknown. Also, probably requires large-scale simulations.
- If superfluids collide, they can create interference patterns. Problem: current observational data can't resolve such the structures.

Summary

A two-phase system is almost certainly the parametrically most simple explanation of all current evidence for dark matter. It combines the achievements of both modified gravity and cold dark matter.

The hypothesis of dark matter being a superfluid is well-motivated and makes testable predictions.

After a long phase of stagnation, we are finally getting closer to solving an 80+ year old riddle.