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The KBC void & Hubble tension in standard cosmology & Milgromian dynamics

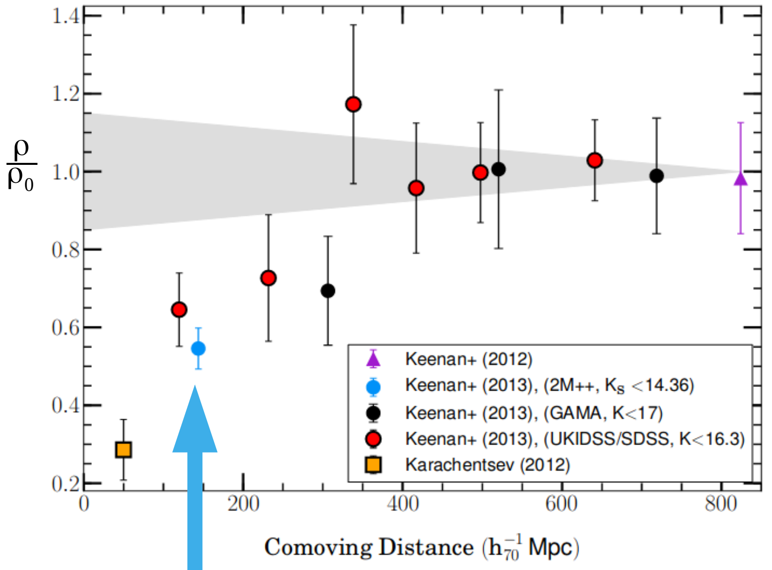
Authors: **Moritz Haslbauer**, **Indranil Banik** & Pavel Kroupa

Publication: The KBC void and Hubble tension contradict ΛCDM on a Gpc scale – Milgromian dynamics as a possible solution (MNRAS, 499, 2845)

The Keenan-Barger-Cowie (KBC) void

- **A local underdensity is evident across the entire electromagnetic spectrum, ranging from radio to X-ray**
  - Optical: Maddox+1990, Zucca+1997
  - Radio: Rubart & Schwarz 2013, Rubart, Bacon & Schwarz 2014, Secrest+ 2020
  - X-ray: Böhringer+2015, Böhringer, Chan, Collins 2020
- **NIR: Keenan, Barger, Cowie 2013, ApJ, 775, 62**
  - 2M++ galaxy catalogue with spectroscopic redshift
  - void evident in number counts (luminosity function)
  - density about 0.5x cosmic mean between 40 and 300 Mpc over 90% of the sky based on 57%-75% of luminosity function

$$\delta_{obs} \equiv 1 - \frac{\rho}{\rho_0} \approx 0.46 \pm 0.06$$



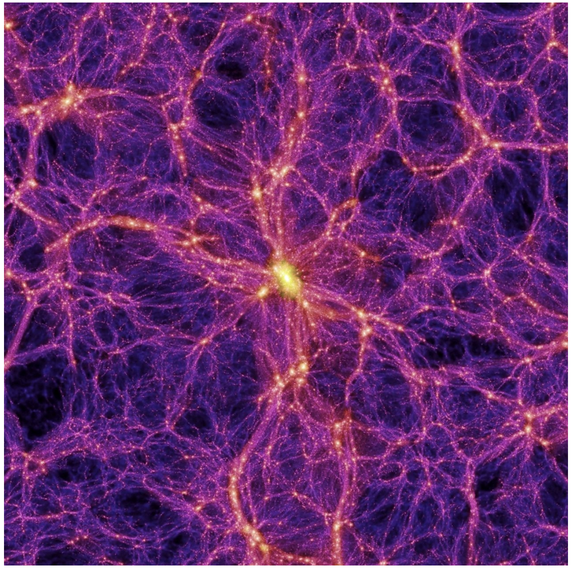
Credit: Kroupa (2015)

Keenan+ (2013): 2M++ with K_s < 14.36

The KBC void in ΛCDM

- **Millennium (MXXL) simulation (Angulo+ 2012)**
  - ΛCDM simulation consistent with WMAP-1 parameters
  - biggest suitable simulation (box size of 4.1 Gpc)
  - Stellar masses assigned semi-analytically

- **Mimic observations (2M++ survey)**
  - select subhaloes with $M_* > 1e10\ M_\odot/h$ at $z = 0$
  - calculate luminosity density contrasts over (40 – 300) Mpc for 1e6 vantage points



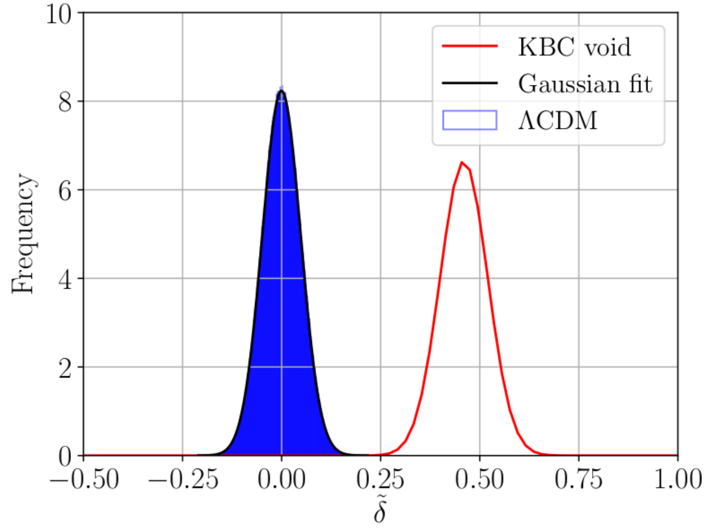
Source: Millennium simulation

⇒ Expected rms density fluctuations for scale-invariant spectrum: 0.032

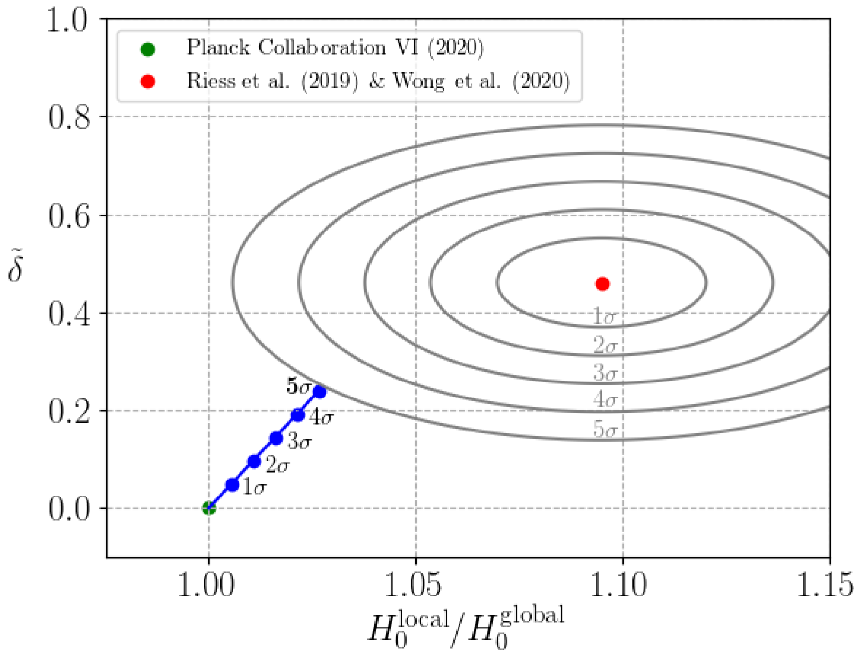
Observed density fluctuation: 0.46±0.06

The KBC void and Hubble tension in ΛCDM

Spheres with an inner radius of 40 Mpc
and an outer radius of 300 Mpc



Allowance made for redshift space distortion (RSD): Higher local H



The KBC void falsifies ΛCDM at 6.04σ

Combined, the KBC void + Hubble tension falsify ΛCDM at 7.09σ

Large scale failure of ΛCDM

- **The KBC void is physically impossible in a ΛCDM universe**

  It is impossible to get from the $z = 1100$ (CMB) to the $z < 0.2$ (observed nearby Universe) boundary conditions

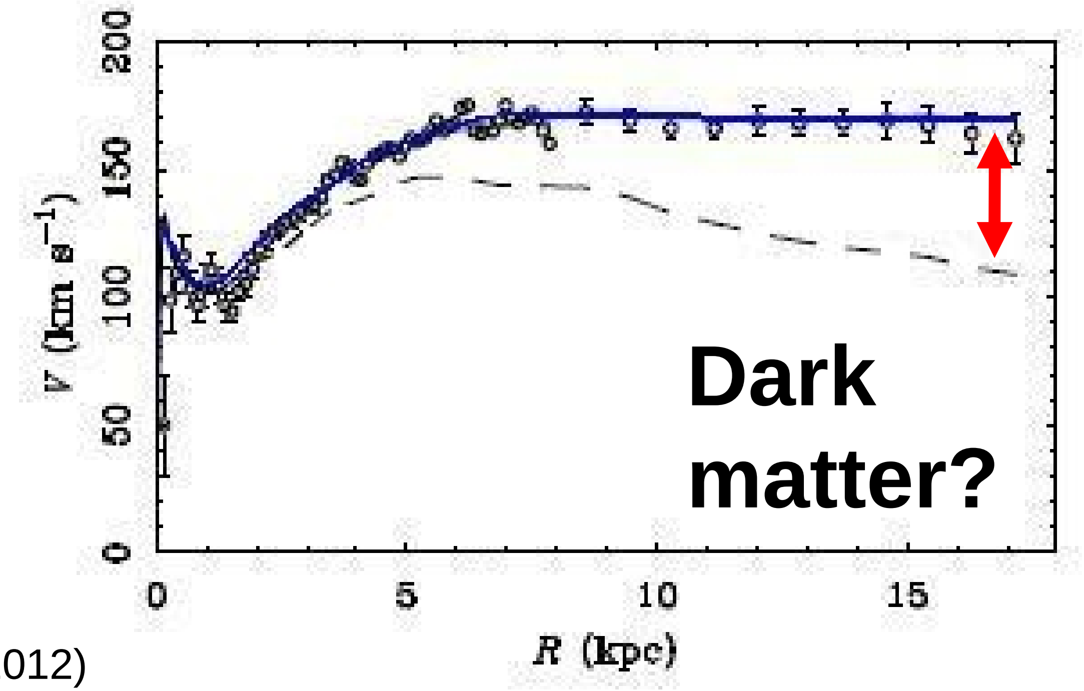
  - Problem arises on 300 Mpc scale, so independent of galaxy-scale baryonic physics

⇒ **To get from the CMB ($z = 1100$) to the $z = 0$ observations, need effectively stronger gravity to grow structures faster**

Galaxies

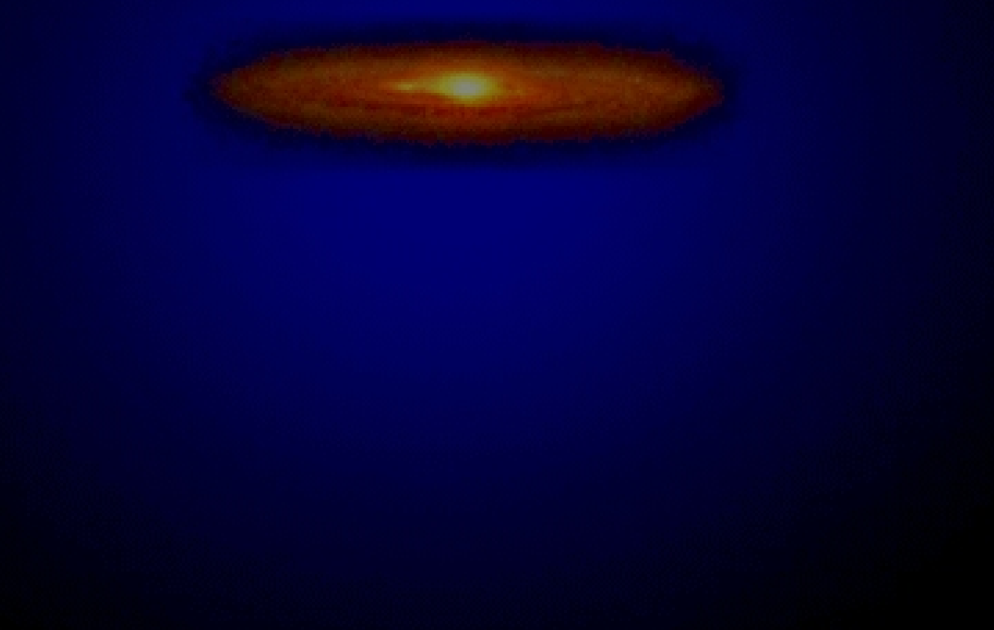
Visible mass X Newtonian Gravity = Acceleration

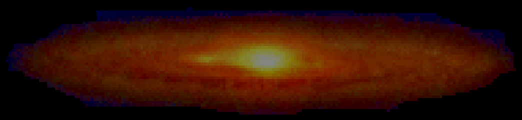
- **The observed acceleration is discrepant with this prediction**



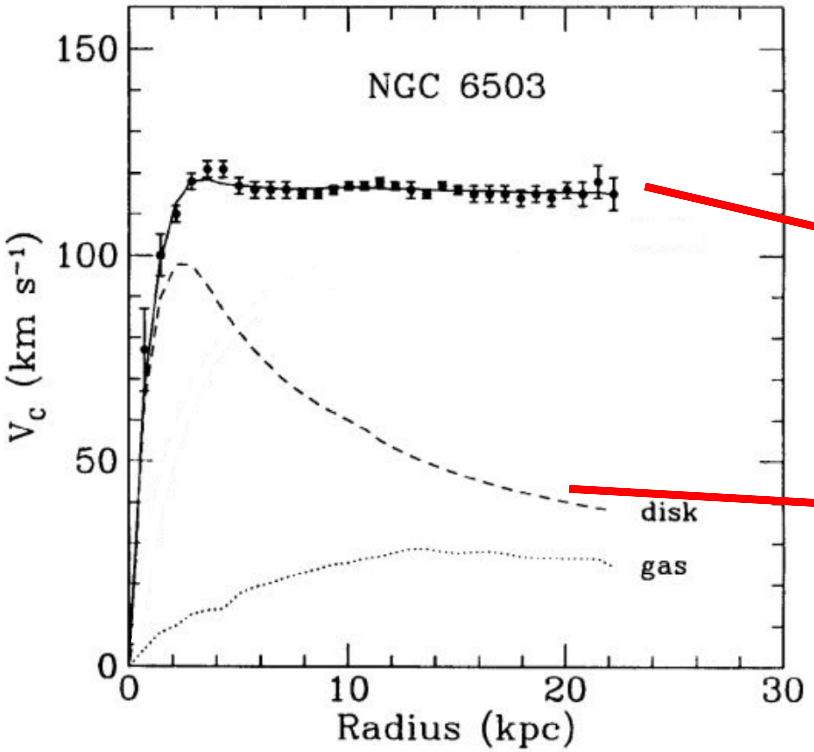
Living Reviews in Relativity, **15**, 10 (2012)

No direct evidence

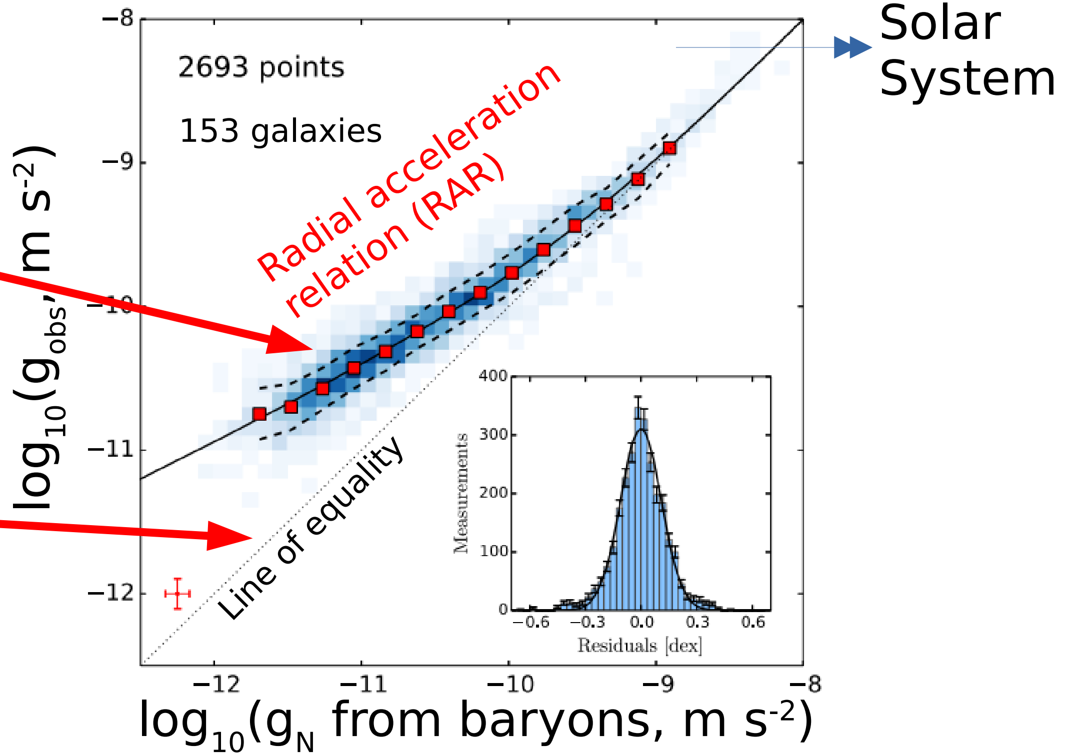




Constraints from galaxies



Freese 2008



McGaugh, Lelli, Schombert 2016

Milgromian dynamics (MOND)

- **Newton gravity/GR developed using Solar System constraints**
- **Developed by M. Milgrom (1983) to address rotation curves without cold dark matter by going beyond Newton**
- **Lagrangian formalism**

$$L = L_K - L_P = \rho\left(\frac{1}{2}v^2 - \Phi\right) - \frac{1}{8\pi G}\left(2\mathbf{g}\cdot\mathbf{g}_N - a_0^2 f[g_N]\right)$$

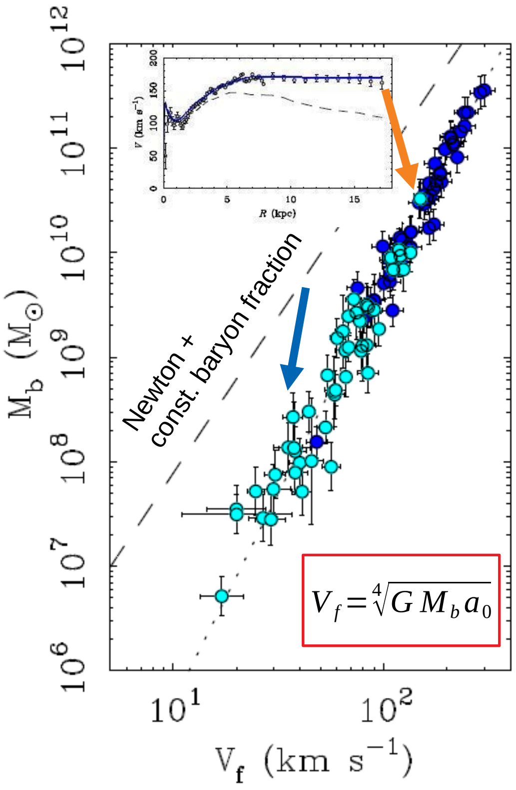
  - Milgrom 2010

Extremize action

- **Non-linear generalization of the Poisson eqn.:**

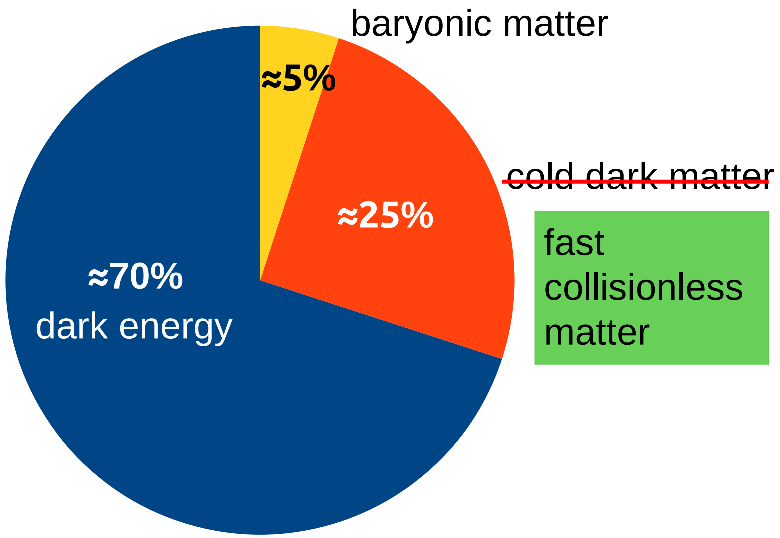
$$\nabla\cdot\mathbf{g} = \nabla\cdot\left(\nu\left(\frac{g_N}{a_0}\right)\mathbf{g}_N\right), \quad f \Leftrightarrow \nu$$

  - external field effect (EFE, Milgrom 1986)
  - breaks strong equivalence principle (as observed by Chae+ 2020 in rotation curves)
- **Milgrom's constant (from RAR):** $a_0 = 1.2\times10^{-10} m/s^2$
- **Asymptotic limits in spherical symmetry:** $g_N \ll a_0:\ g = \sqrt{a_0 g_N}, \quad g_N \gg a_0:\ g = g_N$
- **Relativistic MOND theory where gravitational waves travel at *c* (Skordis & Zlosnik 2019)**



Cosmological MOND framework (vHDM): overview

- **Proposed by Angus 2009 (MNRAS, 394, 527)**
- **Cold dark matter (CDM) replaced by fast collisionless matter**
  - e.g. 11 eV/c^2 sterile neutrinos (e.g. Angus+2007)
  - same overall mass-energy budget as in ΛCDM
- **Standard background cosmology *a(t)* → Nucleosynthesis (BBN)**
  - e.g. Skordis 2006 (Phys. Rev. D, 74, 103513)
- **MOND is applied only to perturbations**
  - e.g. Nusser 2002, Llinares+ 2008, Angus+ 2013, Katz+ 2013, Candlish 2016
- **External field effect from surrounding structures**
  - consequence of the non-linearity of MOND (e.g. Banik+ 2018, ArXiv1808.10545)



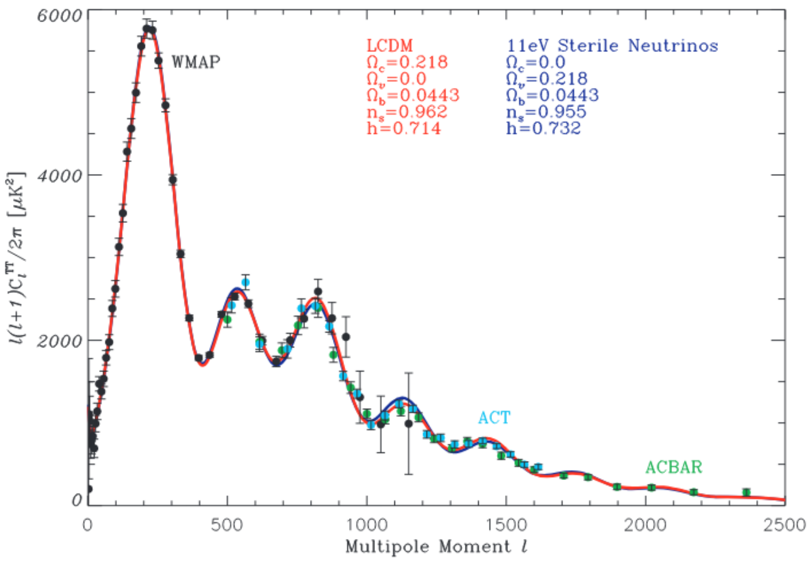
vHDM framework: Impact on CMB

- **Standard expansion history**

  → same angular diameter distance to CMB
- **MOND is sub-dominant at time of recombination ($z = 1100$) because $g \approx 20\ a_0$**
- **Free streaming effects negligible if $m_\nu > 10$ eV/c^2**

  We impose a prior on the physical thermal mass, $m_{\text{sterile}}^{\text{thermal}} < 10$ eV, when generating parameter chains, to exclude regions of parameter space in which the particles are so massive that their effect on the CMB spectra is identical to that of cold dark matter.

  Planck Collaboration XIII (2016), section 6.4.3
- **MOND effects become important only at $z < 50$**

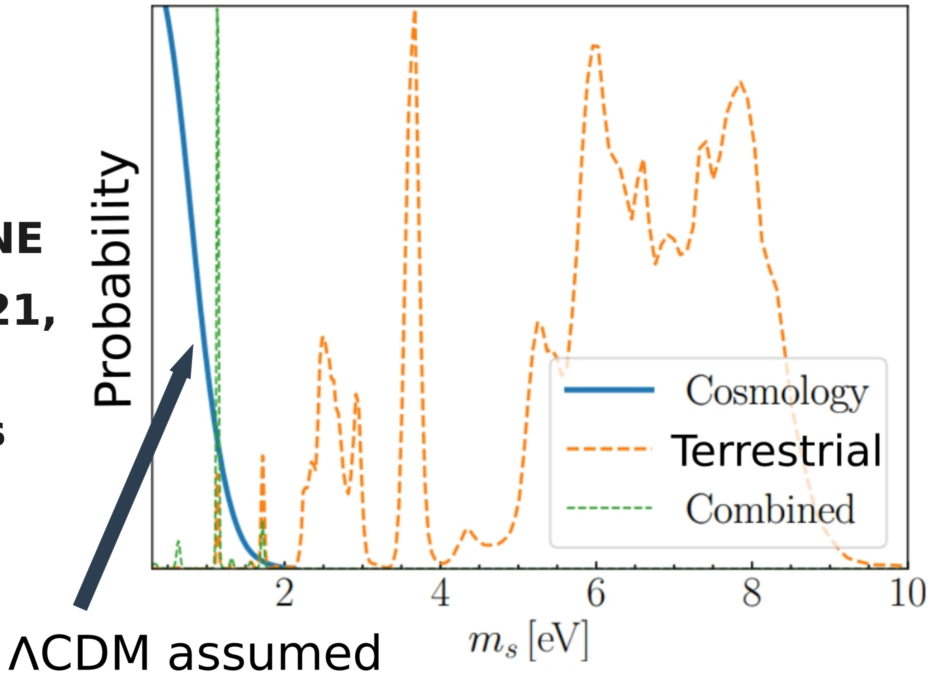


Angus & Diaferio (2011)

Terrestrial evidence for light sterile neutrinos

- Sterile neutrinos proposed to explain ordinary neutrino oscillations & their non-zero rest mass (seesaw mechanism)
- Hints of sterile neutrino found by MiniBooNE

  (Aguilar-Arevalo+ 2018, Phys. Rev. Lett. 121, 221801)
- Must avoid prior limit that $m_\nu < 10$ eV/c^2 as terrestrial experiments are so far quite compatible with slightly larger mass

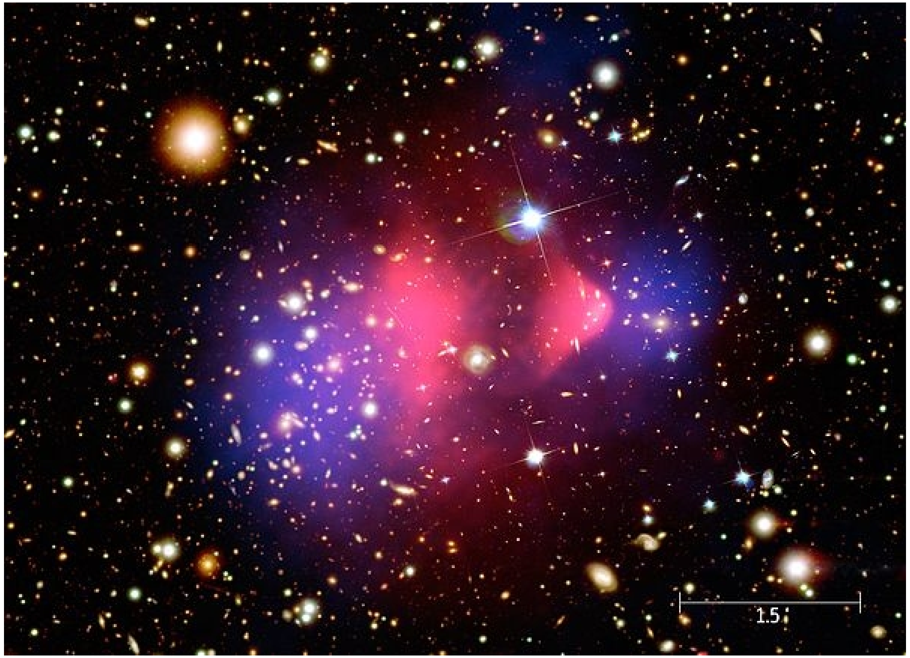


Archidiacono+ 2020

Astronomical evidence for fast collisionless matter

- **Offset X-ray and weak lensing peaks**
- **$g > a_0$: MOND effects small**

  → Collisionless matter required
- **Tremaine-Gunn limit: $m_\nu > 2$ eV/c² (Angus+ 2007, ApJ, 654, L13)**
- **Current constraints imply collisionless particle mass >10 eV/c² (strongest limits from CMB)**



Bullet Cluster, credits: NASA/CXC/M. Weiss

νHDM framework can explain:

- **Expansion history *a(t)* → BBN**
- **CMB**
- **Bullet Cluster and 30 virialized clusters (Angus+ 2010, MNRAS, 402, 395)**
- **Galaxy rotation curves**
  - unaffected by neutrinos if $m_\nu < 100$ eV/c^2 (Angus+ 2010)
- **νHDM solves problems with ΛCDM on galaxy scales**
  - plane of satellites with high internal σ around MW (Pawlowski & Kroupa 2020), M31 (Ibata+ 2013, Sohn+ 2020), Centaurus A (Müller+ 2018, 2021)
  - ΛCDM explanations rejected (Pawlowski+ 2014, MNRAS, 442, 2362)
  - other small scale failures (e.g. Kormendy 2010, Peebles & Nusser 2010, Kroupa 2015, Algorry+ 2017, Peebles 2020, Roshan+ 2021)
- **Large-scale structure?**

The local ($z < 0.1$) Universe in MOND

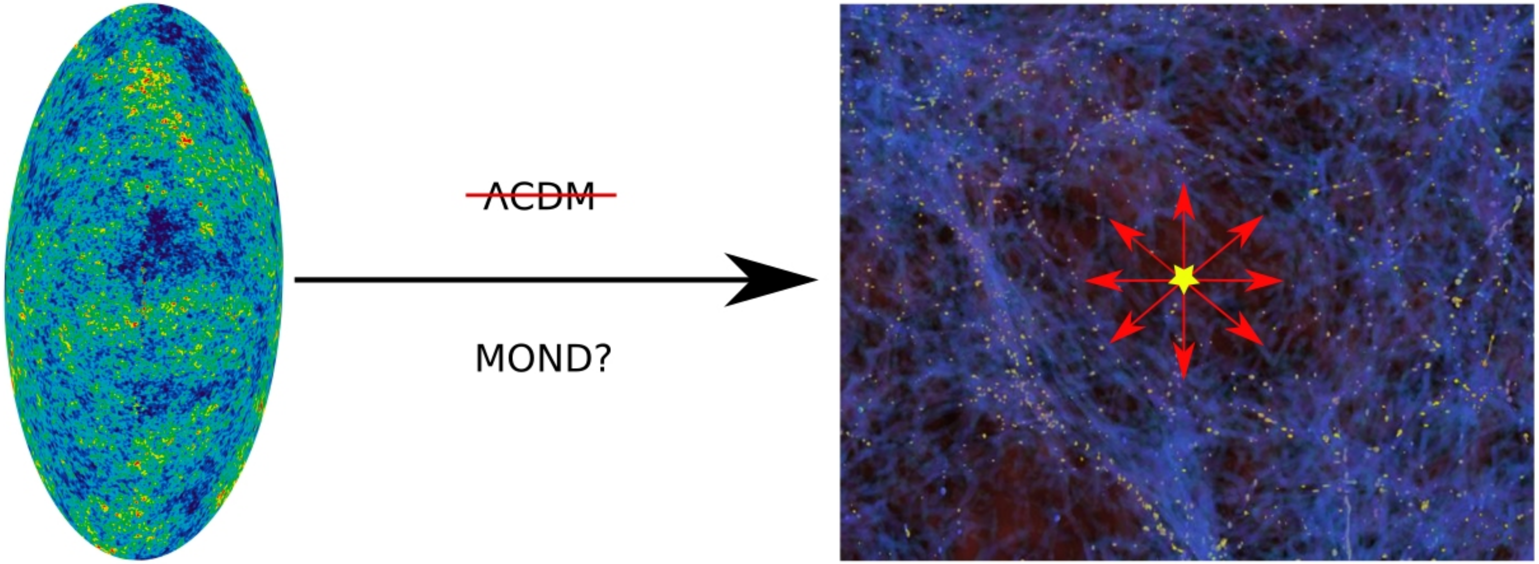
Overview: Keenan-Barger-Cowie void and H_0 tension

observed KBC void

diameter: ≈1 Gpc

density contrast: ≈50%

CMB at $z = 1100$
density contrast ≈ 1e-5



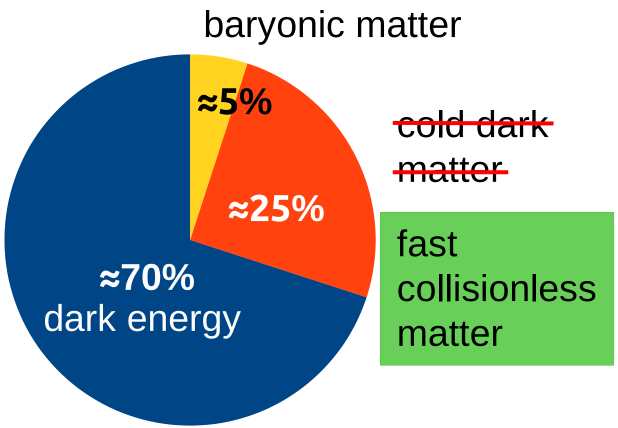
+ Hubble tension solved?

Cosmological MOND model (νHDM framework) (Angus 2009, MNRAS, 394, 527)

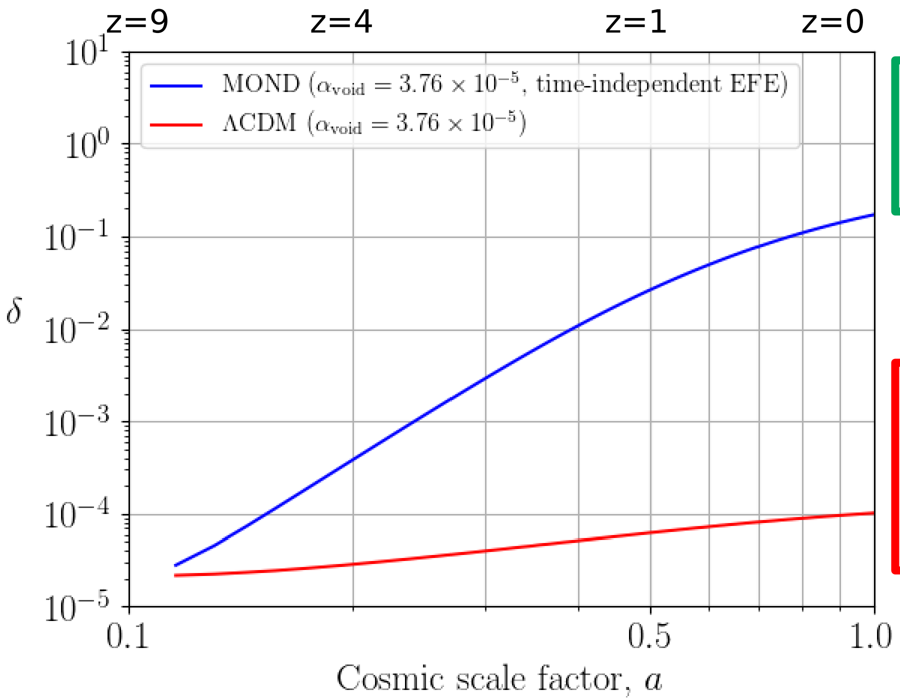
- **Standard expansion history & overall mass budget (CDM → light sterile neutrinos)**
  - e.g. 11 eV/c^2 sterile neutrinos (e.g. Angus+2007)
- **MOND applied only to density perturbations**

  e.g. Nusser 2002, Llinares+ 2008, Angus+ 2013, Katz+ 2013, Candlish 2016
- **Semi-analytical model starting from z = 9**
- **Initial amplitude consistent with CMB**
- **External field effect from large scale structure (Milgrom 1986)**
  - gravity from beyond the void

    ⇒ void as a whole moves



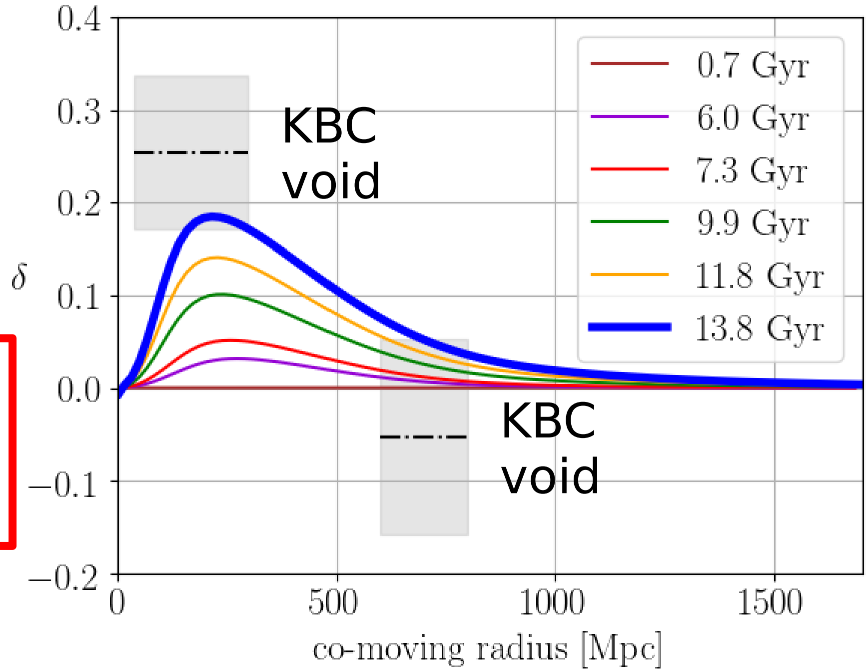
Growth of structure



300 cMpc sphere

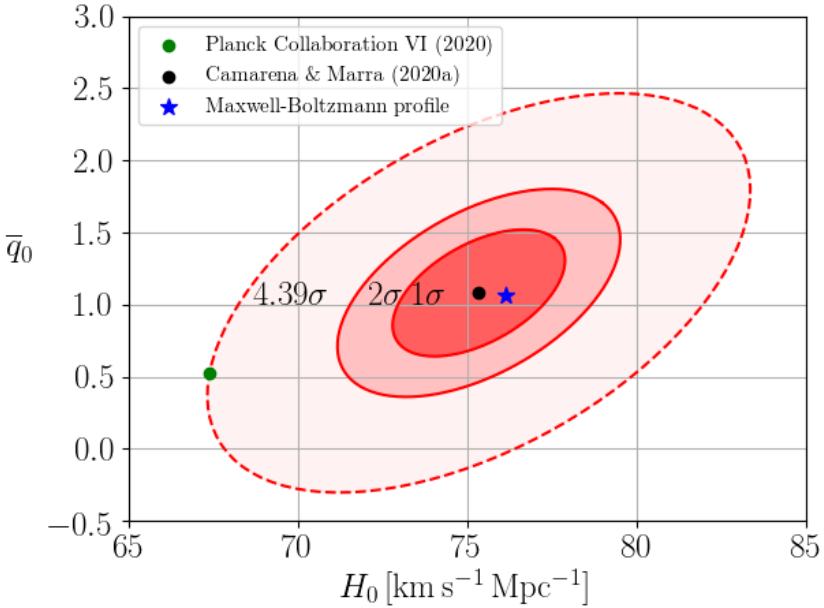
At 300 Mpc:
$g = 0.1a_0$
$g_{ext} = 0.055a_0$

Redshift space distortion (RSD) correction applied



Local Hubble diagram

- **Effects of a local void on cosmological parameters:**
  - local expansion rate is increased: $H_0^{local} \equiv \frac{\dot{a}}{a} (today)$
  - apparent expansion rate appears to accelerate at late times: (extra curvature $\overline{q}_0$ of Hubble diagram) $\overline{q}_0^{local} \equiv \frac{\ddot{a}\, a}{\dot{a}^2} (today)$
- **Camarena & Marra 2020a,b jointly derived H_0 and $\overline{q}_0$ from SNe at redshifts 0.023 – 0.15**
  - $\overline{q}_0$ is 2x standard value of 0.55
    → suggestive of a local void
  - see also Colgain (2019), Kazantzidis & Perivolaropoulos (2020), Kazantzidis+ (2021)
  - high local $\overline{q}_0$ missed in Kenworthy+ 2019 ($\overline{q}_0$ fixed at 0.55)
  - hint of dipole in Hubble diagram (Colin+ 2019, Migkas+ 2020)



$H_0^{obs,local} = 75.35 \pm 1.68\, km/s/Mpc$

$\overline{q}_0^{obs,\,local} = 1.08 \pm 0.29$

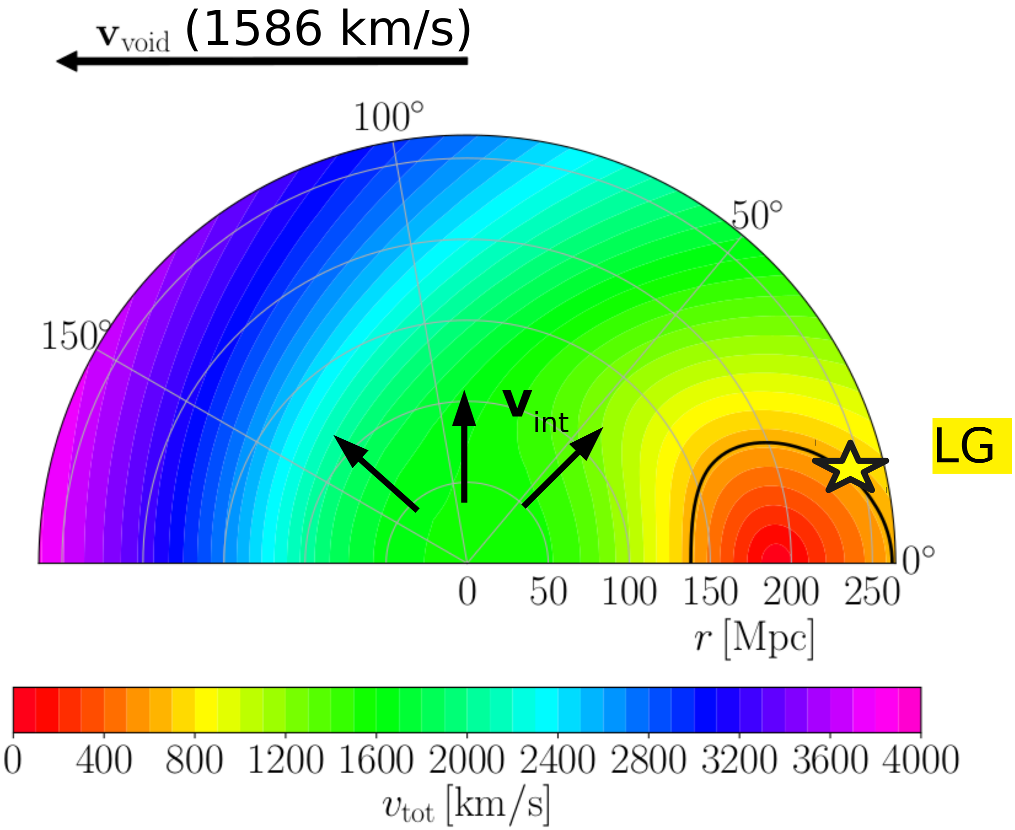
$H_0^{model} = 76.15\, km/s/Mpc$

$\overline{q}_0^{model} = 1.07$

High local H_0 and $\overline{q}_0$ are explained naturally in MOND by outflow from a KBC-like void

Peculiar velocity field

- **Only half of the void rms size is shown**
- **The entire void is moving due to gravity from beyond the void**
- **Partial cancellation between void motion and internal velocities**
- **Large region with peculiar velocity $v_{tot} < v_{LG}$ = 627 km/s (≈0.015 a_0/H_0)**
  - Local Group (LG) is off-centered
  - LG not at a special position
- **High peculiar velocities towards void edge consistent with kinematic Sunyaev-Zel'dovich effect (Hoscheit & Barger 2018, Ding+ 2020)**



Comparison of data with ΛCDM & νHDM models

ΛCDM model

Observational constraints	Level of tension
KBC void (40 – 300 Mpc, 90% of sky)	6.04σ
H_0 (Riess+ 2019 & Wong+ 2020)	5.3σ

Parameters fixed by CMB

Combined tension: 7.09σ

Recent worsening of H_0 tension:
Early: Aiola+ 2020 (ACT)
Late: Soltis+ 2021 (TRGB)

νHDM model

Observational constraints	Level of tension
KBC void δ (40 – 300 Mpc)	0.99σ
KBC void δ (600 – 800 Mpc)	0.97σ
H_0 and $\overline{q}_0$ from SNe data	0.20σ
H_0 from 7 strong lens time-delays	2.05σ
Motion of the LG wrt. CMB	2.34σ

3 free parameters
(initial void size & strength, g_{ext})
12 data points

Combined tension: 2.53σ

Summary & Conclusions (MNRAS, 499, 2845):

- **KBC void falsifies ΛCDM at 6.04σ**
- **KBC void + Hubble tension falsify ΛCDM at 7.09σ**
  - failures of ΛCDM model cover all scales from dwarf galaxies (e.g. disk of satellites, Pawlowski+ 2014) to Gpc scales (this work, see also Kroupa et al. 2010, Kroupa 2012, 2015, Sellwood+ 2019, Asencio+2021 (MNRAS, 500, 5249 - 5267))
  - matter distribution on a Gpc scale requires enhanced growth of structure

    e.g. Milgromian gravitation (MOND) would also explain galaxy dynamics (RAR), M33 disk stability (Banik+, ApJ, 2021)
- **MOND cosmology with fast collisionless matter (e.g. 11eV/c^2 sterile neutrinos, Angus 2009)**
  - standard expansion history, BBN, CMB anisotropies, and Bullet Cluster + 30 virialized clusters (Angus+ 2010)
  - structure growth enhanced and self-regulated by external fields from surrounding structures
- **MOND describes the local observations at 2.53σ**
  - enhanced growth of structure allows the formation of KBC-like voids
  - outflow from large void explains high local H_0 and $\overline{q}_0$
  - common objections to void scenario addressed in Section 5.3 of our paper
  - blogs describing paper: **tritonstation.com** & **darkmattercrisis.wordpress.com**