The KBC void & Hubble tension in ΛCDM & Milgromian dynamics

Speaker: Moritz Haslbauer

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
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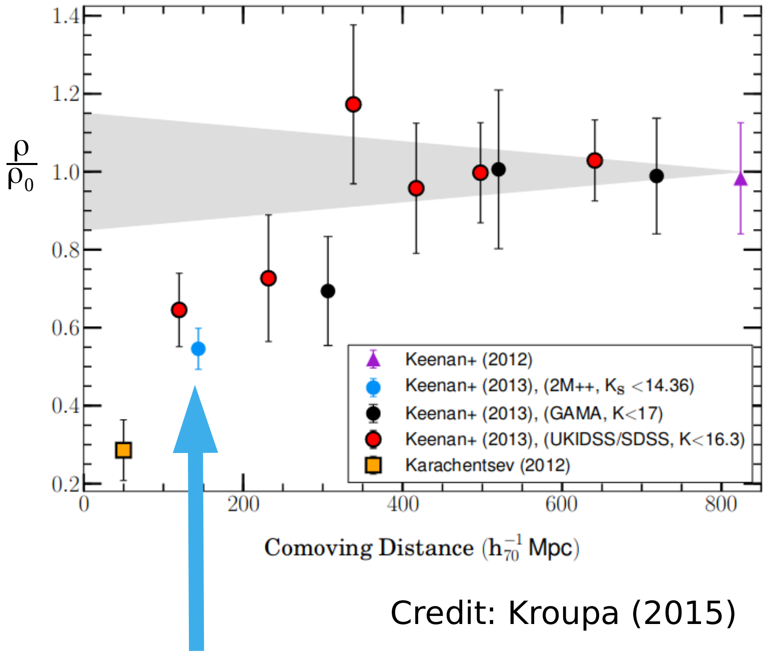
- **NIR: Keenan, Barger, Cowie 2013, ApJ, 775, 62**
  - 2M++ galaxy catalogue with spectroscopic redshift
  - void evident in number counts (luminosity function)
  - density about **0.5x cosmic mean** between **40 – 300 Mpc** over 90% of the sky (see also Wong+ 2022)



Credit: Kroupa (2015)

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

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

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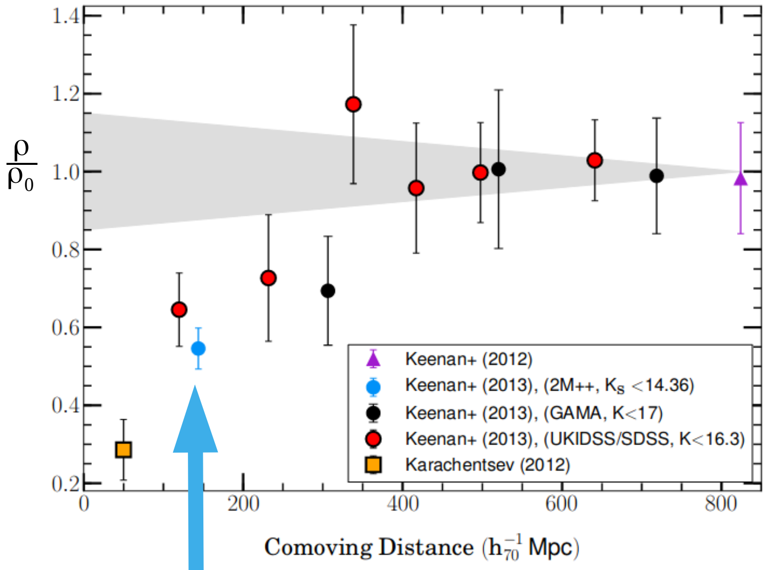

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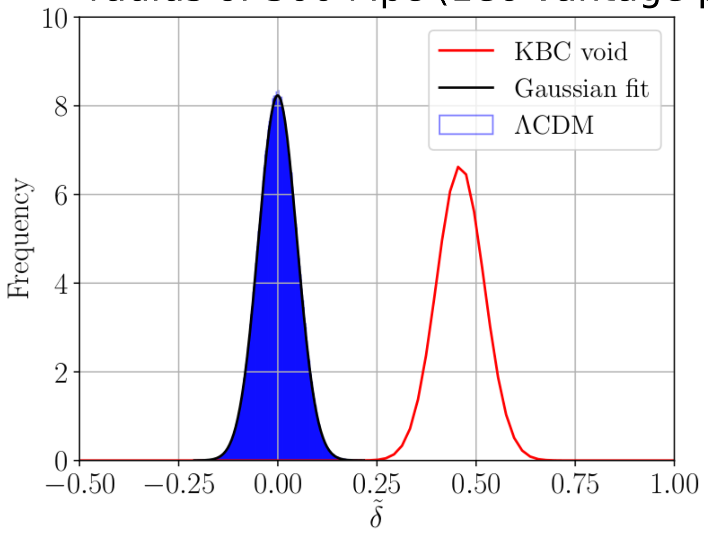
⇒ ΛCDM: expected rms density fluctuations for scale-invariant spectrum: 0.032

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

The KBC void and Hubble tension in ΛCDM

Millennium XXL simulation (box size of 4.1 Gpc):
Spheres with an inner radius of 40 Mpc and an outer radius of 300 Mpc (1e6 vantage points)



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

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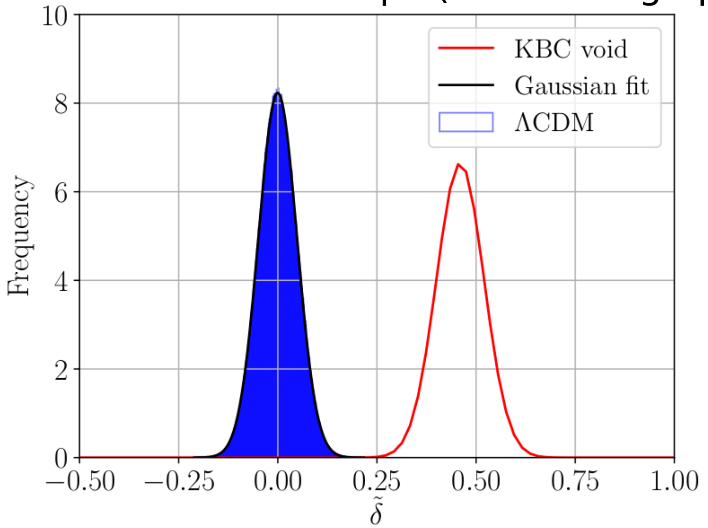

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The KBC void falsifies ΛCDM at 6.04σ

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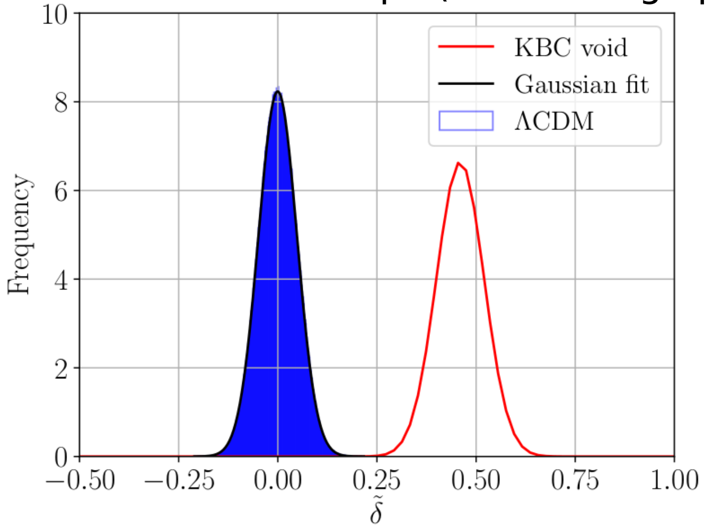

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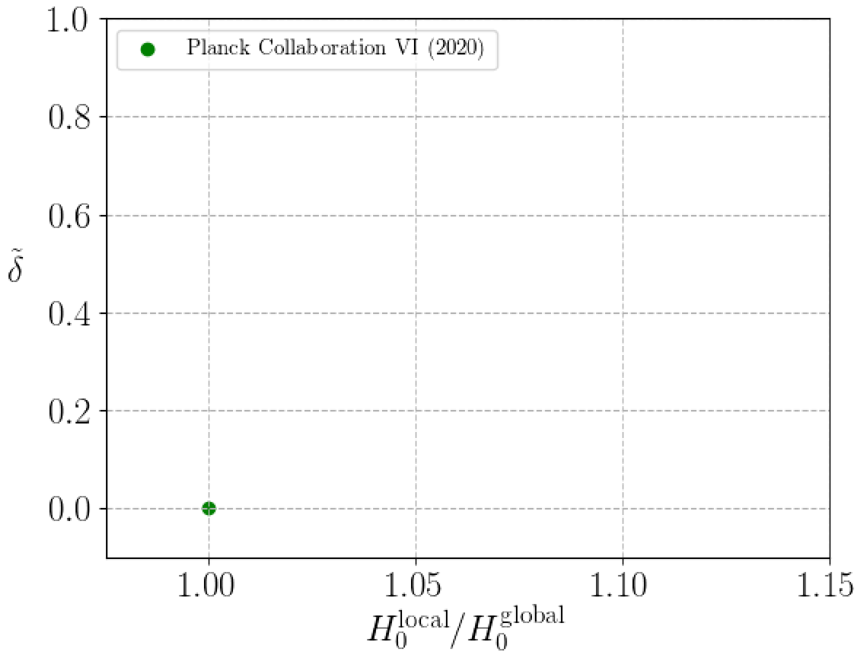

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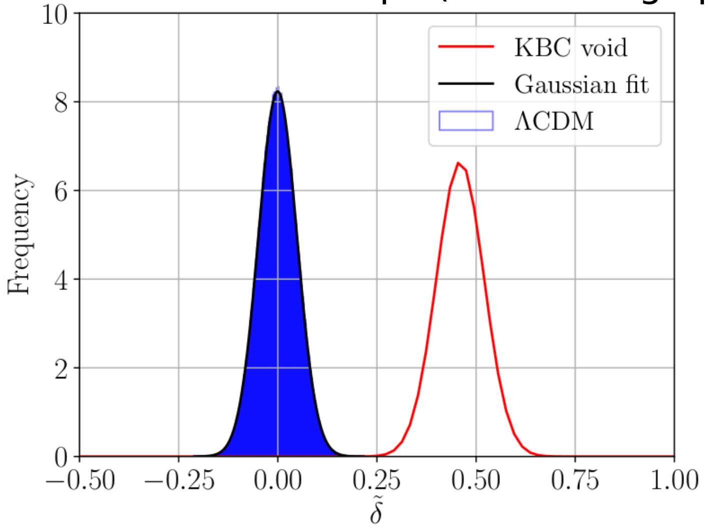

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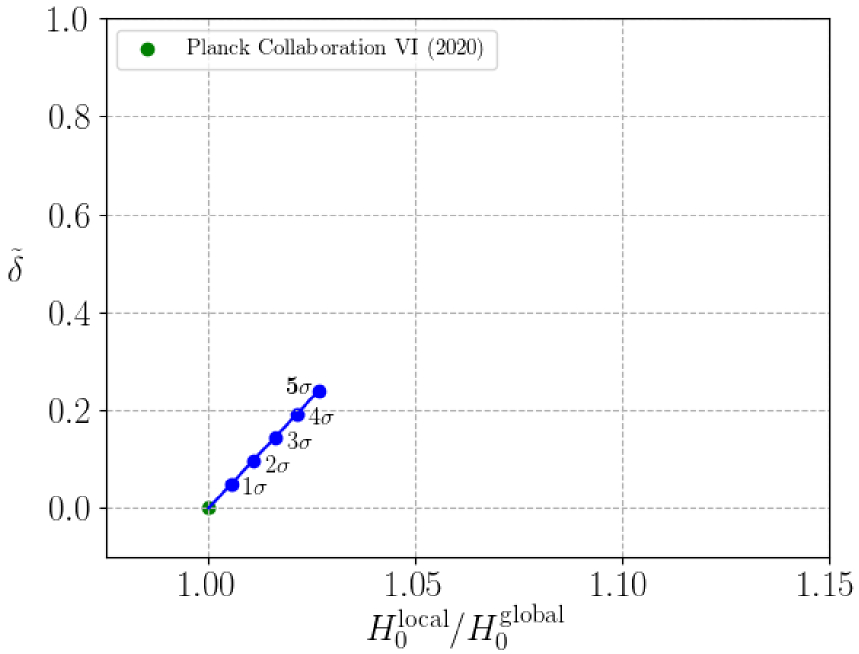

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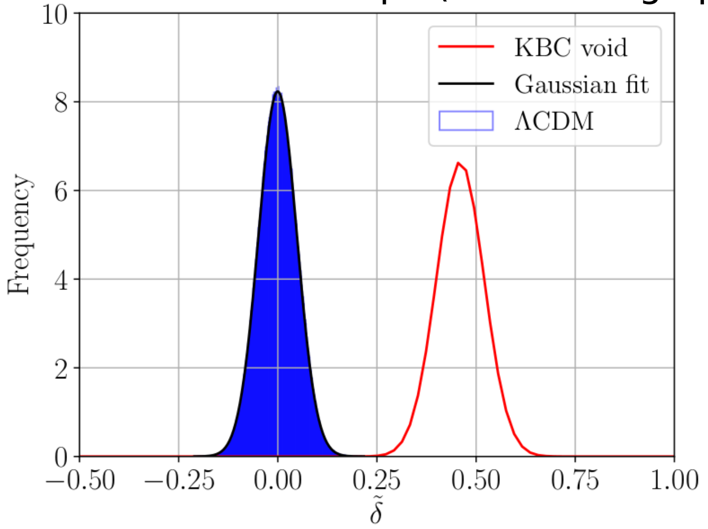

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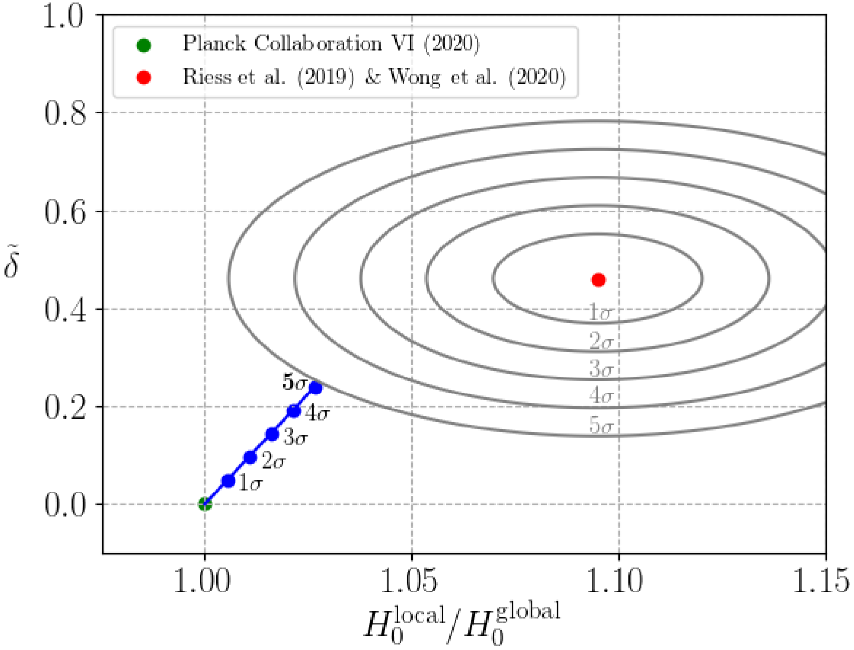


The KBC void falsifies ΛCDM at 6.04σ

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

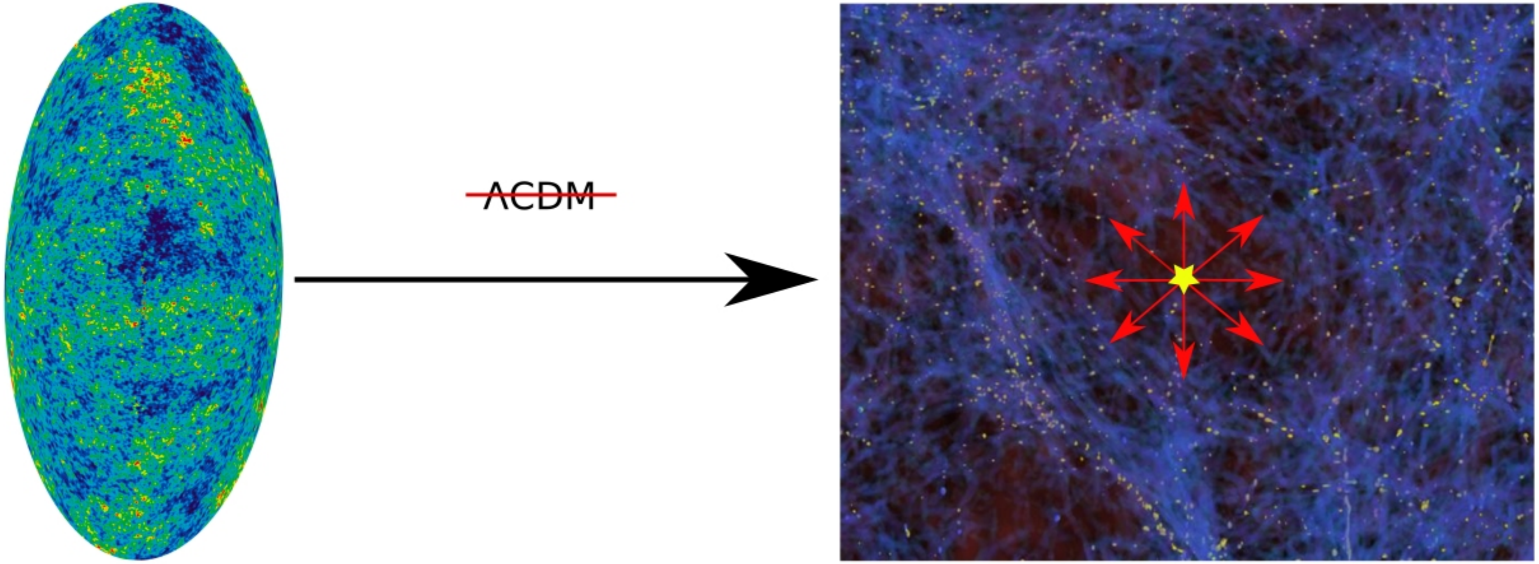
Overview: Keenan-Barger-Cowie void and H_0 tension

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

observed KBC void

diameter: ≈1 Gpc

density contrast: ≈50%



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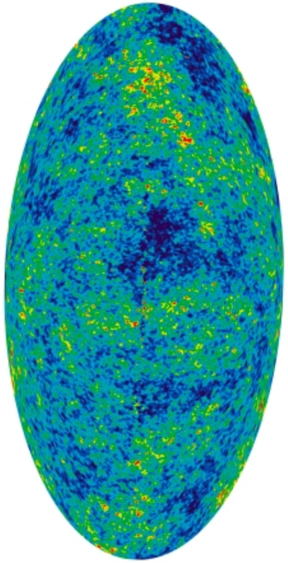
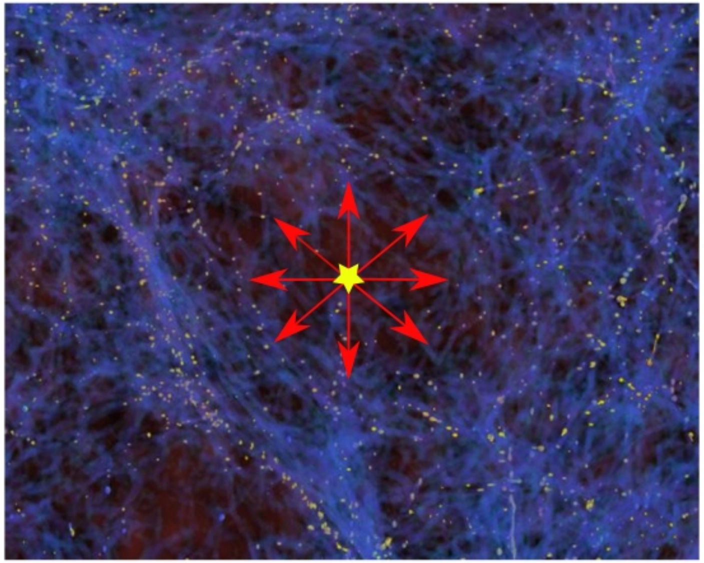


~~ΛCDM~~

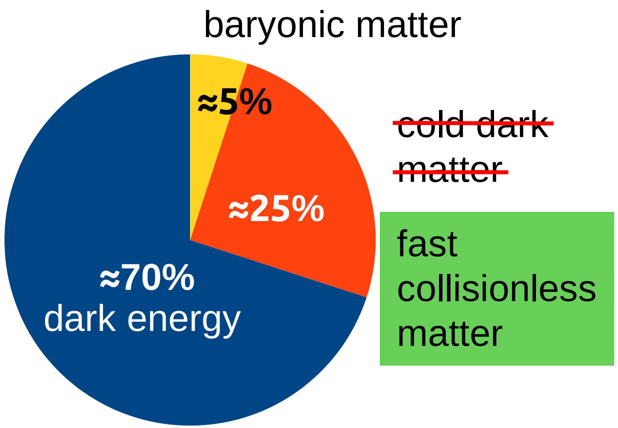
MOND?



\+ 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)



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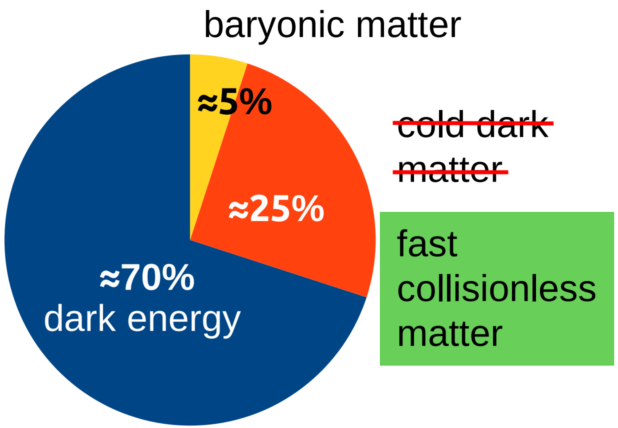
- **MOND applied only to density perturbations**

  e.g. Nusser 2002, Llinares+ 2008, Angus+ 2013, Katz+ 2013, Candlish 2016



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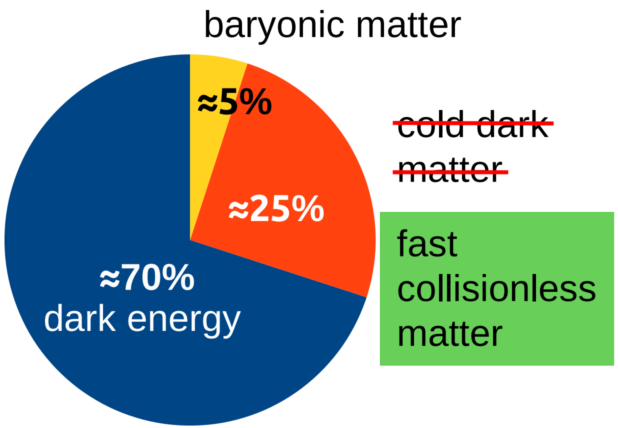
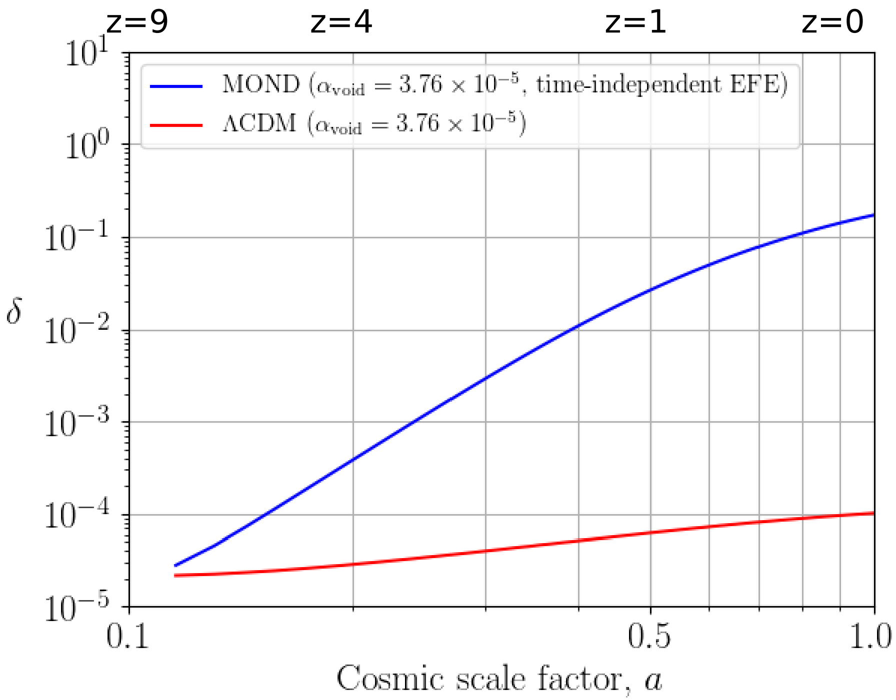
- **Semi-analytical model starting from z = 9**
- **Initial amplitude consistent with CMB**



Growth of structure



sphere of radius 300 cMpc

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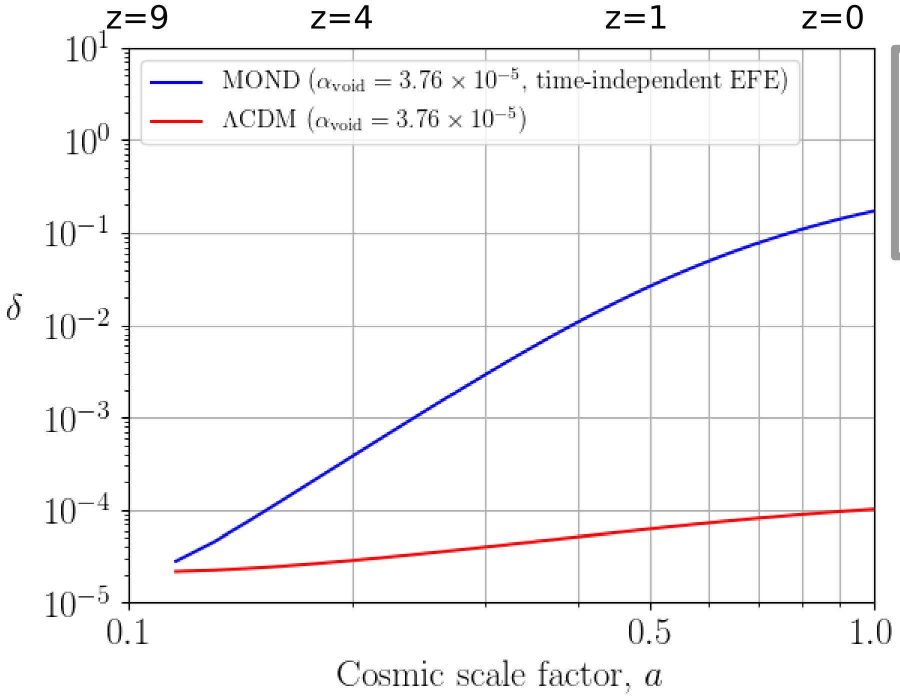
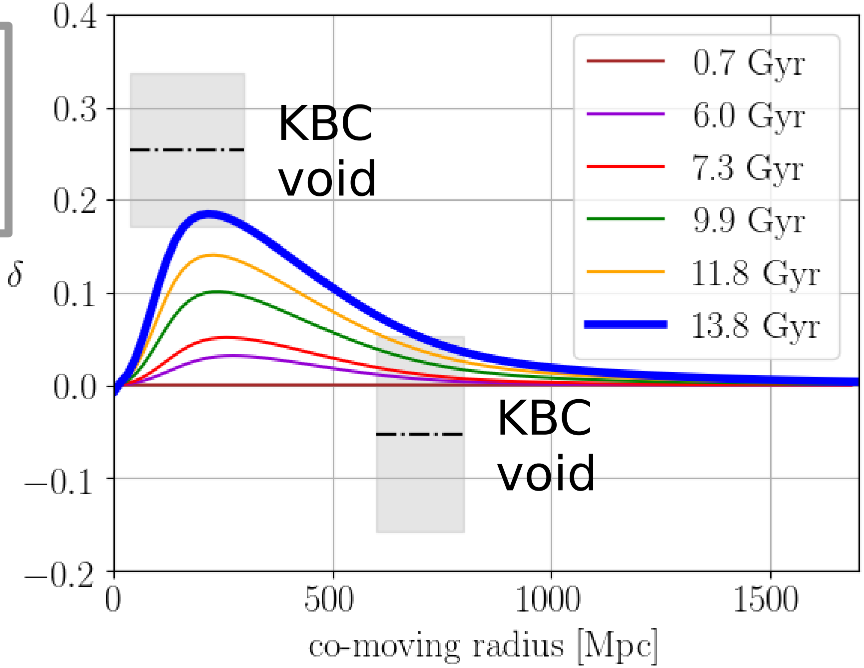


sphere of radius 300 cMpc

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) $\overline{q}_0^{local} \equiv \frac{\ddot{a}\,a}{\dot{a}^2}(today)$

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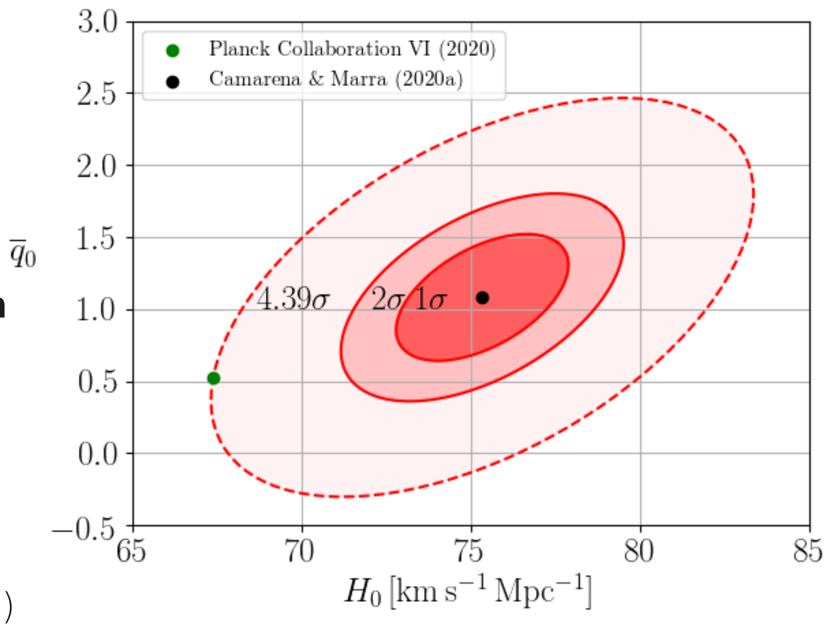
- **Camarena & Marra 2020a,b jointly derived H_0 and $\overline{q}_0$ from SNe at redshifts 0.023 – 0.15**
  - $\overline{q}_0$ is 2x standard value of 0.55
    → suggestive of a local void
  - high local $\overline{q}_0$ missed in Kenworthy+ 2019 ($\overline{q}_0$ fixed at 0.55)
  - hint of dipole in Hubble diagram (Colin+ 2019, Migkas+ 2020)



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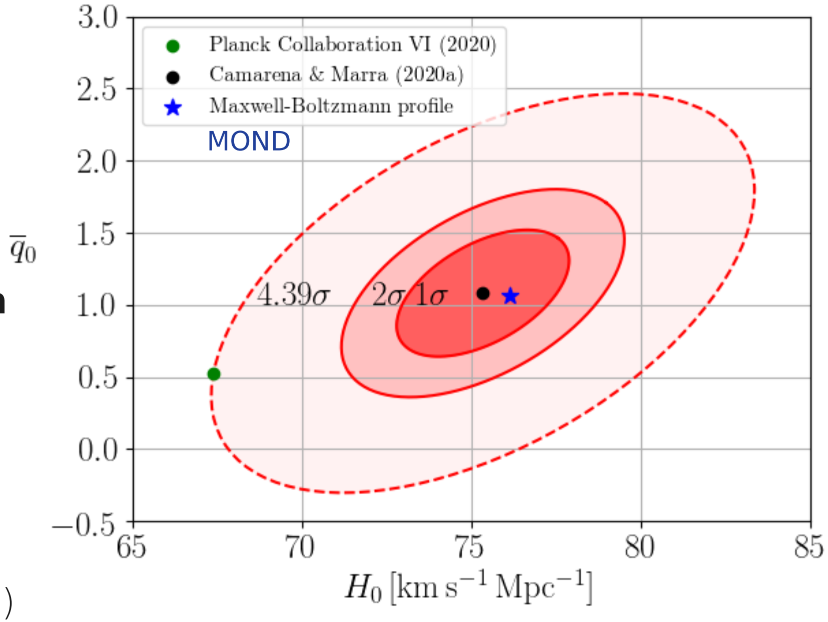

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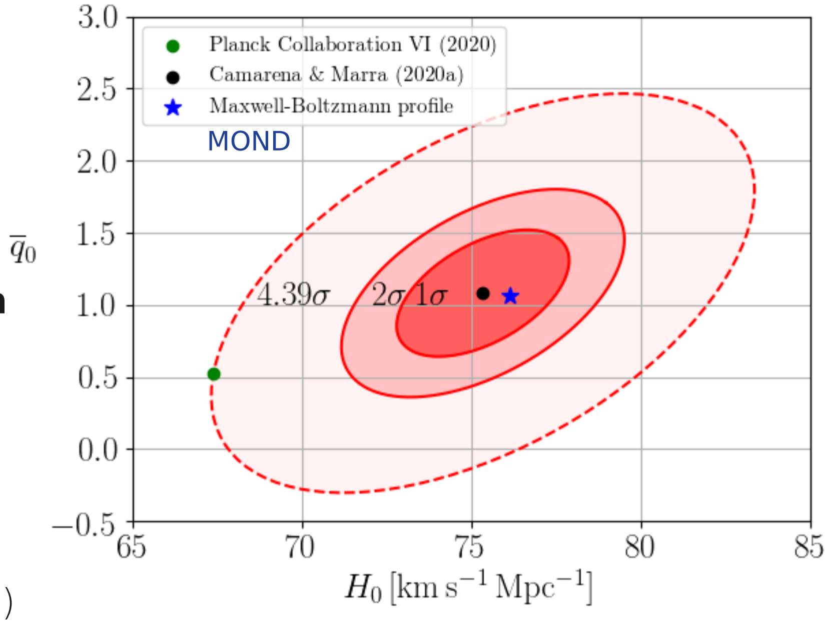

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High local H_0 and $\overline{q}_0$ are explained naturally in MOND by outflow from a KBC-like void

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

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νHDM model

Observational constraints	Level of tension
KBC void (40 – 300 Mpc)	0.99σ
KBC void (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 model parameters
12 data points

Combined tension: 2.53σ

Summary & Conclusions (MNRAS, 499, 2845):

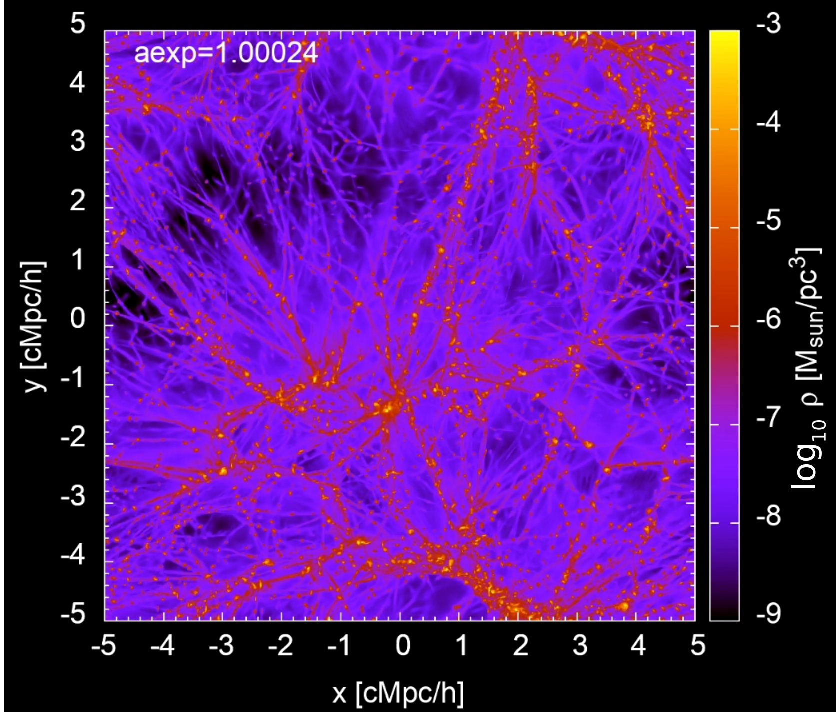
- **KBC void falsifies ΛCDM at 6.04σ**
- **KBC void + Hubble tension falsify ΛCDM at 7.09σ**
  - failures of ΛCDM model cover all scales from dwarf galaxies (e.g. disk of satellites, Pawlowski+ 2014) to Gpc scales (this work, see also Kroupa et al. 2010, Kroupa 2012, 2015, Asencio+ 2021)
  - matter distribution on a Gpc scale requires enhanced growth of structure
- **MOND consistent with local observations (2.53σ)**
  - enhanced growth of structure allows the formation of KBC-like voids
  - outflow from large void explains high local H_0 and $\overline{q}_0$
- **Blog "The Dark Matter Crisis": darkmattercrisis.wordpress.com**

Appendix

Outlook

- **Enable standard RAMSES hydrodynamics and cosmology to study galaxy formation with Phantom of RAMSES (PoR MOND patch: Lüghausen+ 2015; user guide: Nagesh+ 2021)**
  - Simulation by Nils Wittenburg
  - SPODYR group (University of Bonn)
- **Self-consistent cosmological MOND simulation on much larger scales**
  - study formation of voids in a large simulation box
  - What does a typical KBC-like void look like?
  - cosmic variance

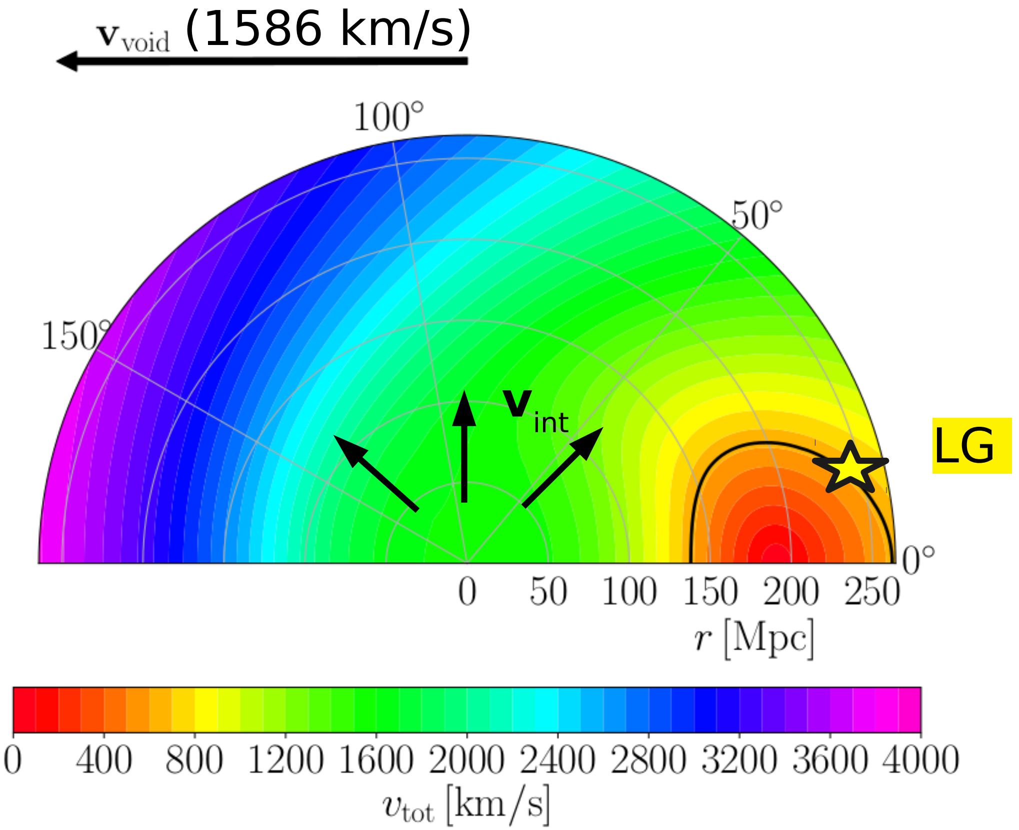
Origin of galaxies in a MOND cosmology



Wittenburg+ (in prep.)

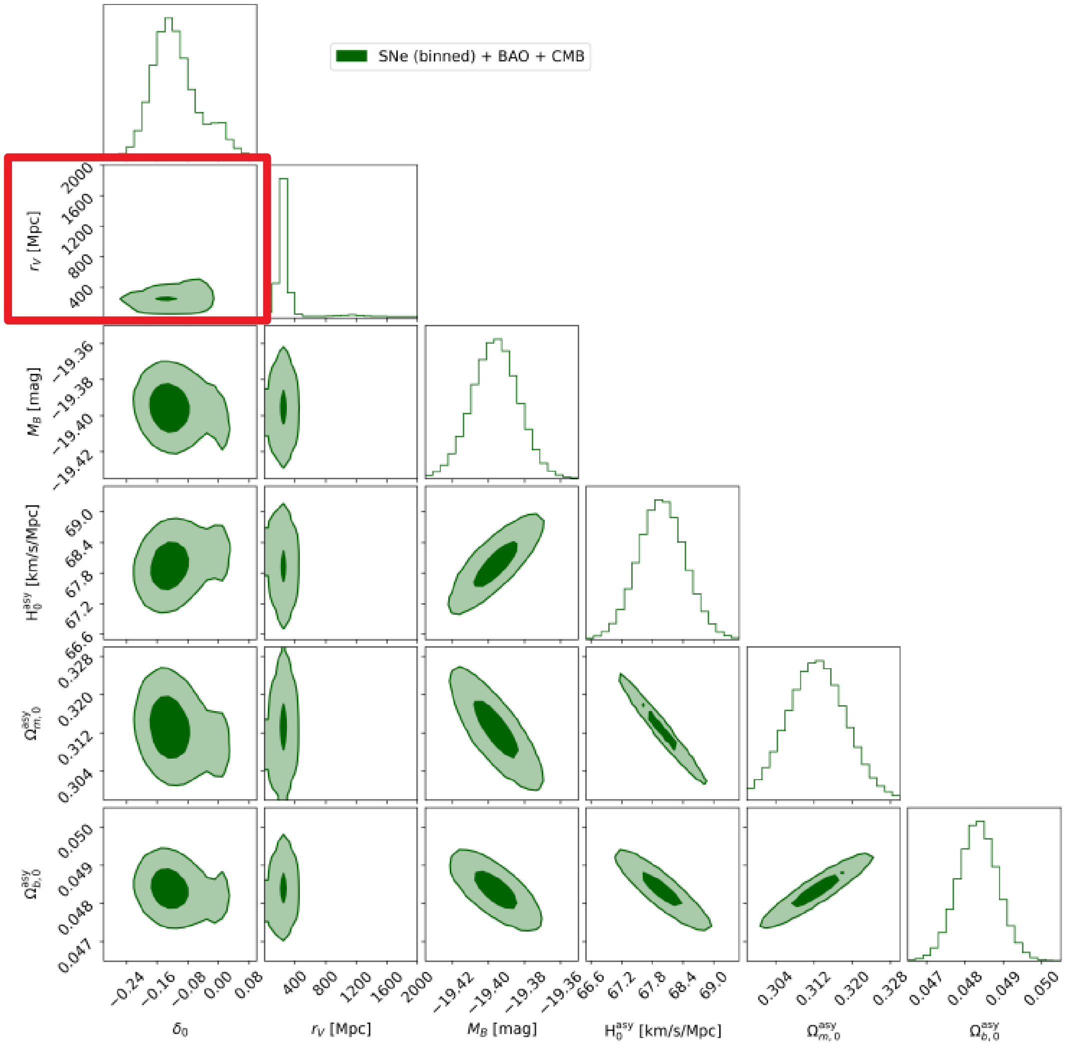
Peculiar velocity field

- **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)**



Void evident from supernovae alone

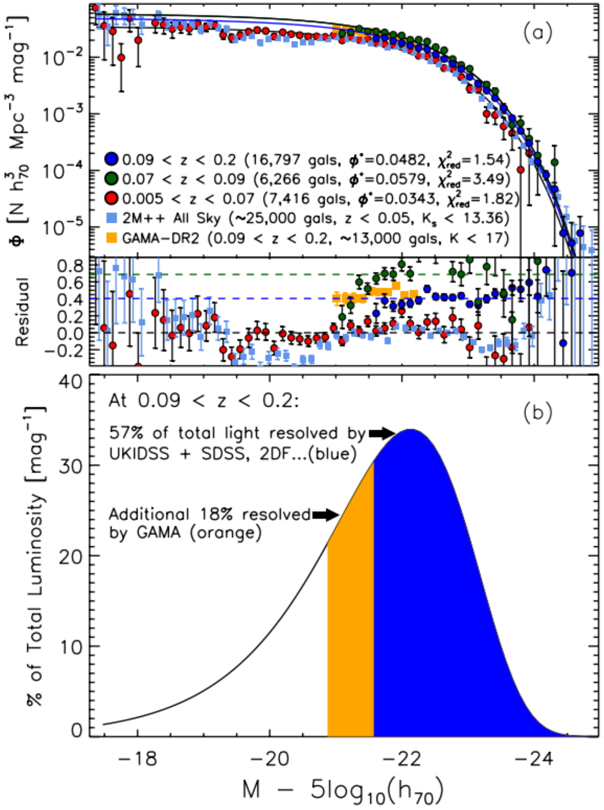
- **preferred parameters very similar to that of the KBC void (RSD-corrected)**



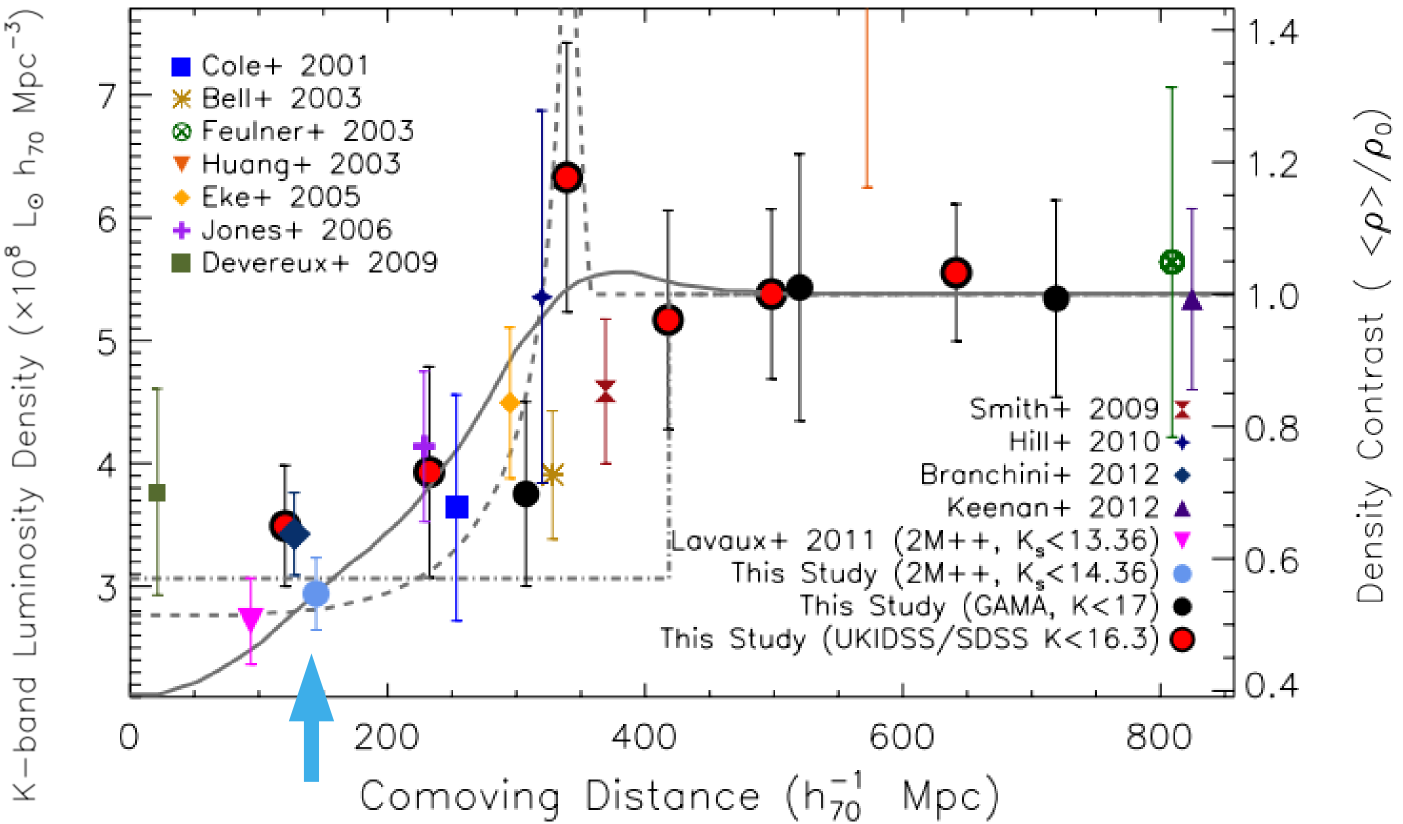
Castello+ 2021 (Arxiv: 2110.04226)

KBC 2013, ApJ, 775, 62: luminosity function

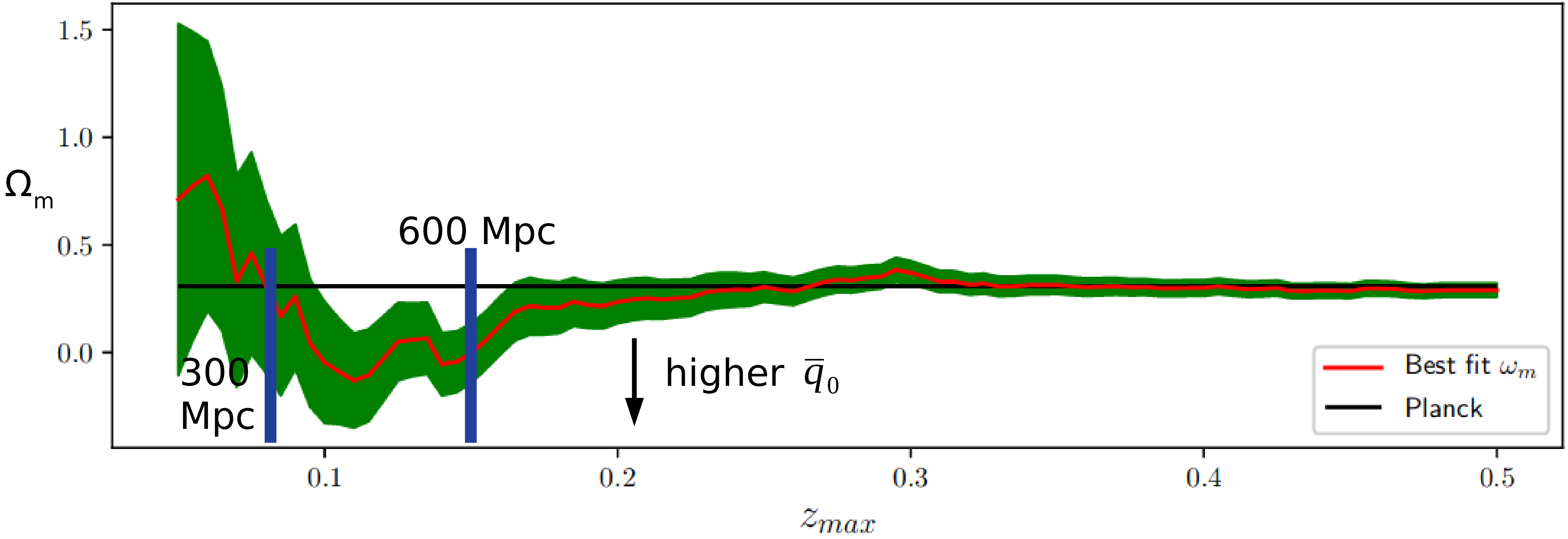
- **Shape of luminosity function clearly determined based on 90% of the sky based on 57%-75% of luminosity function**
- **Normalization systematically lower at low z**
- **Density contrast similar between magnitude bins**



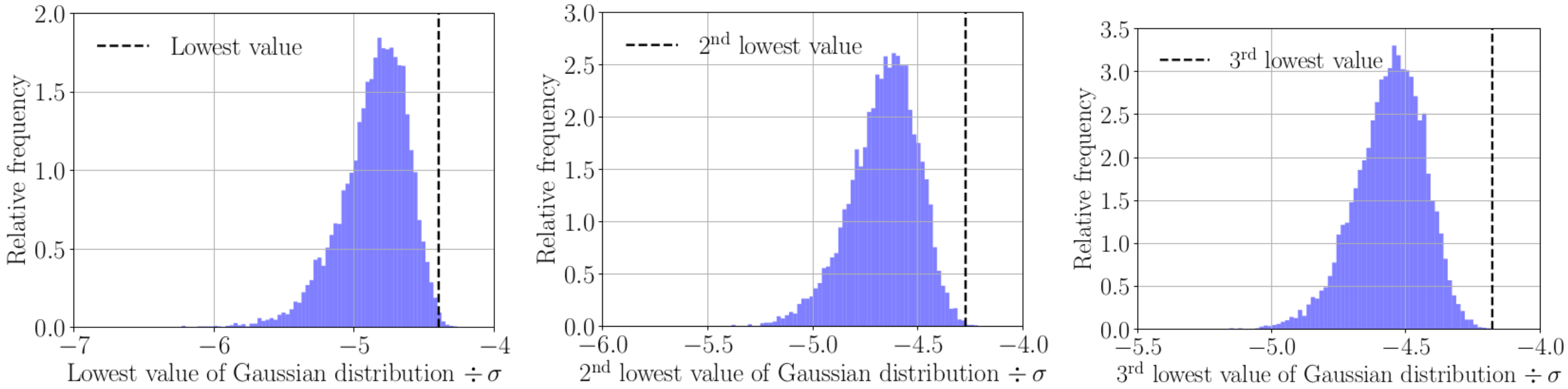
KBC 2013, ApJ, 775, 62: density profile



Colgáin (2019): SNe Hubble diagram



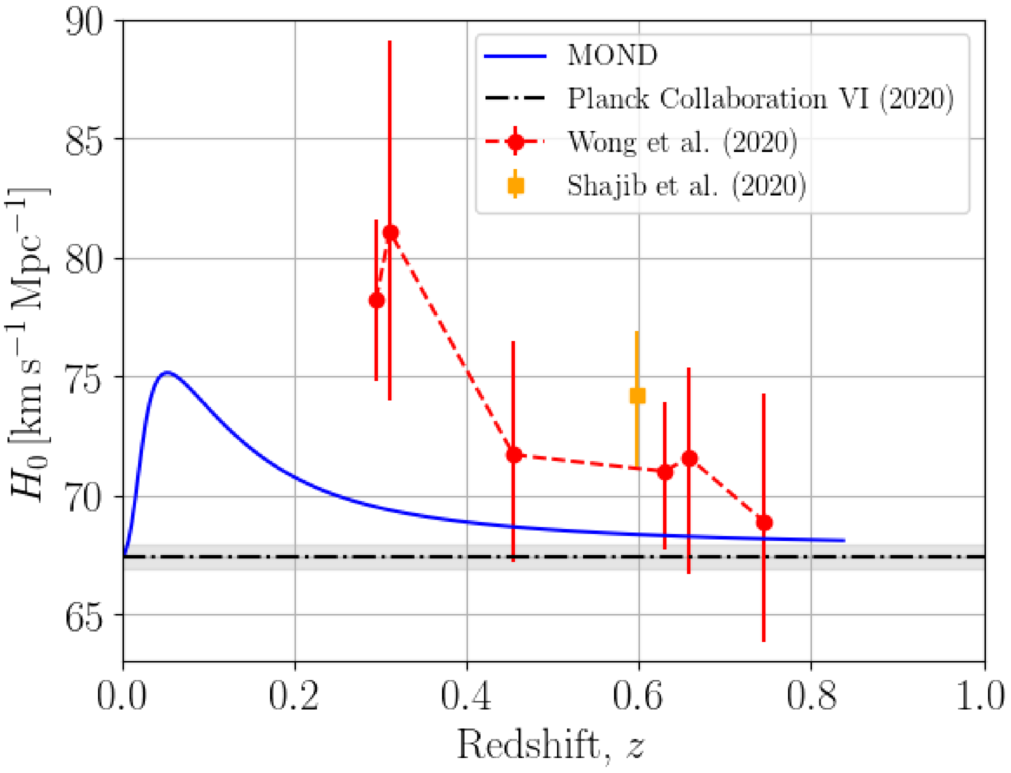
Results: Gaussianity test of the selected density fluctuations in the MXXL simulation



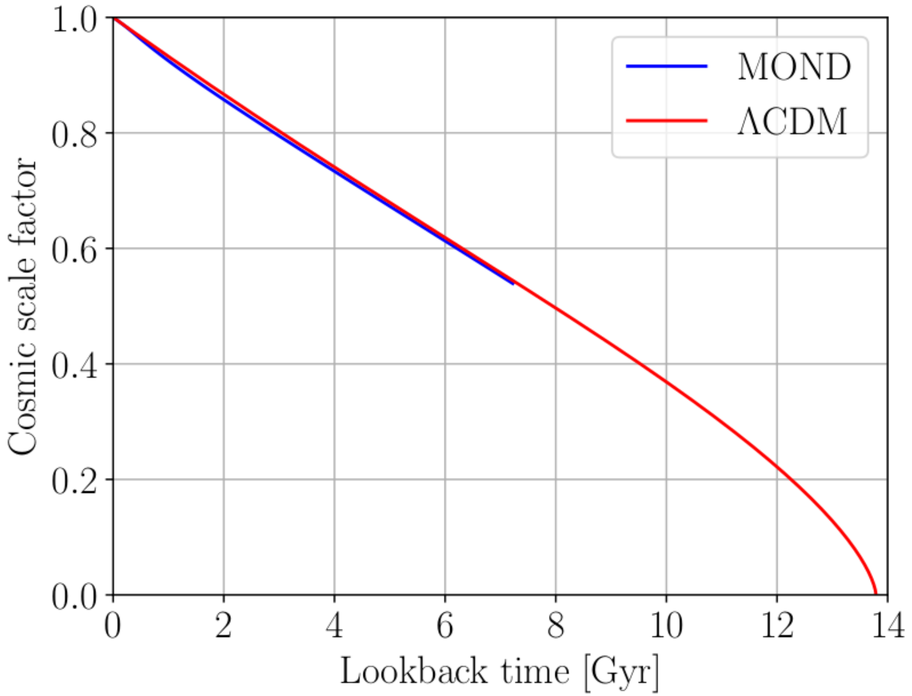
Results: H_0 from strong lensed systems

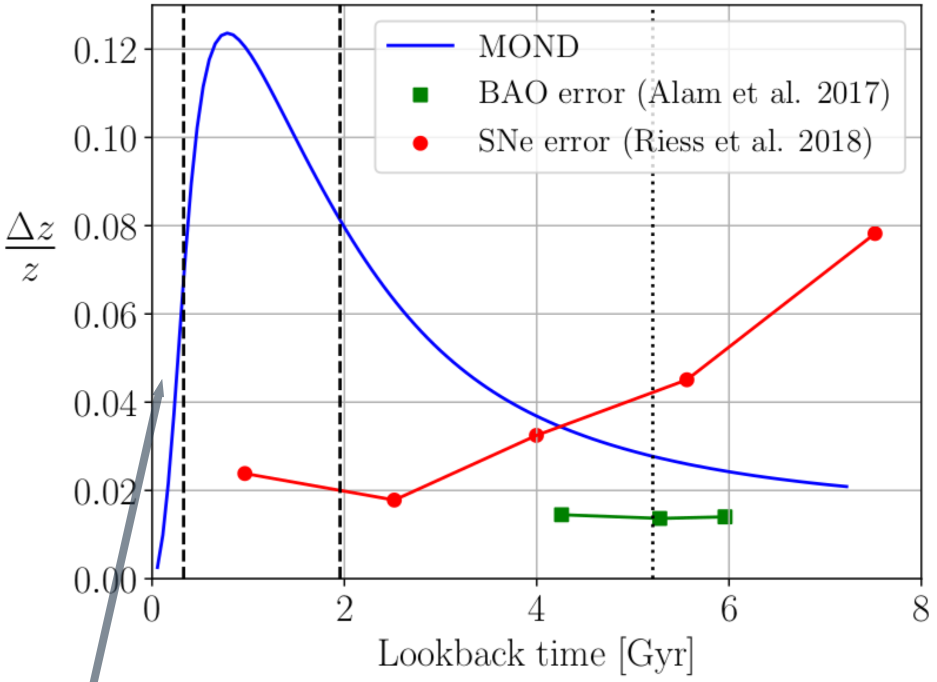
- **Empirically, light deflection in strong lenses works similar to General Relativity for the same non-relativistic** g **(Collett+ 2018)**
- **Relativistic MOND theories exist where gravitational waves travel at the speed of light (Skordis & Złośnik 2019)**
- **Decreasing inferred H_0 with lens redshift (Wong+2020) evident at 1.9σ**

  ⇒ curvature in Hubble diagram (like with SNe)
- **Consistent with MOND model (2.05σ), but suggestive of a larger void than KBC data**



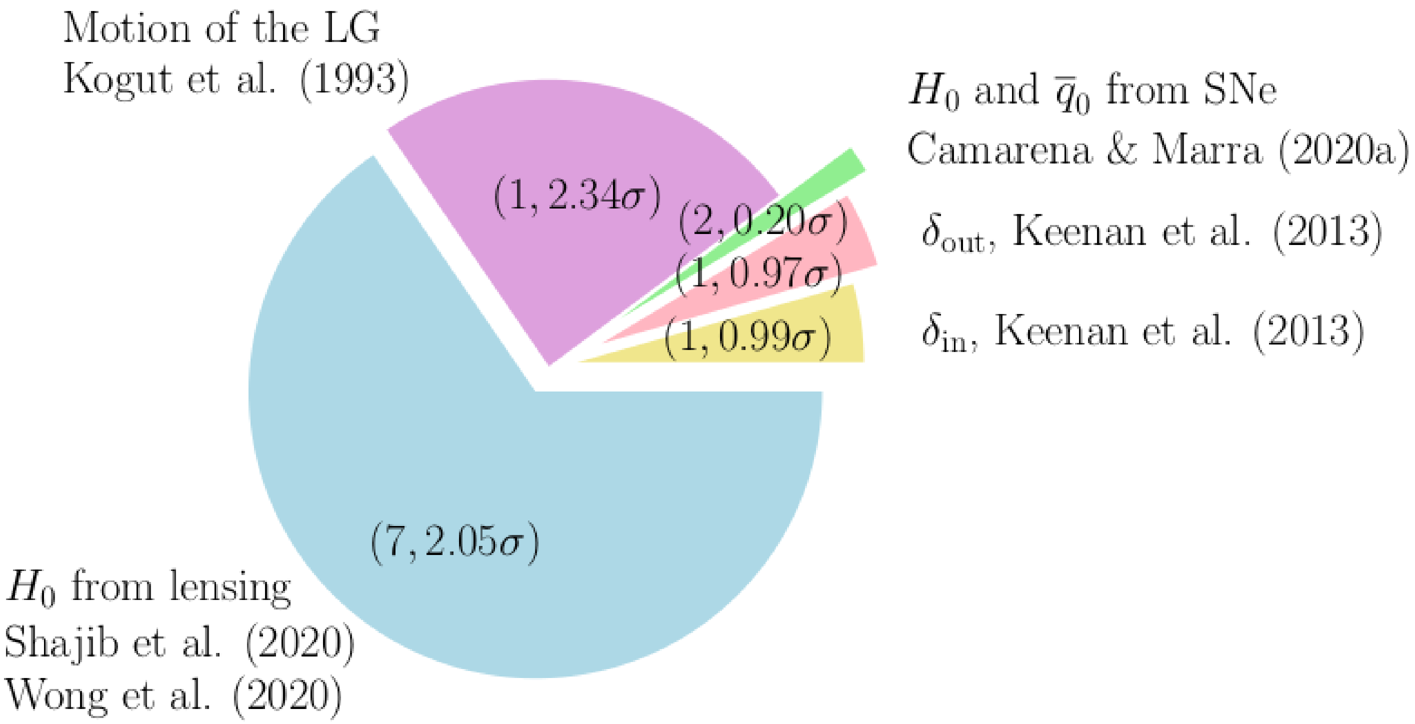
vHDM framework: apparent expansion history



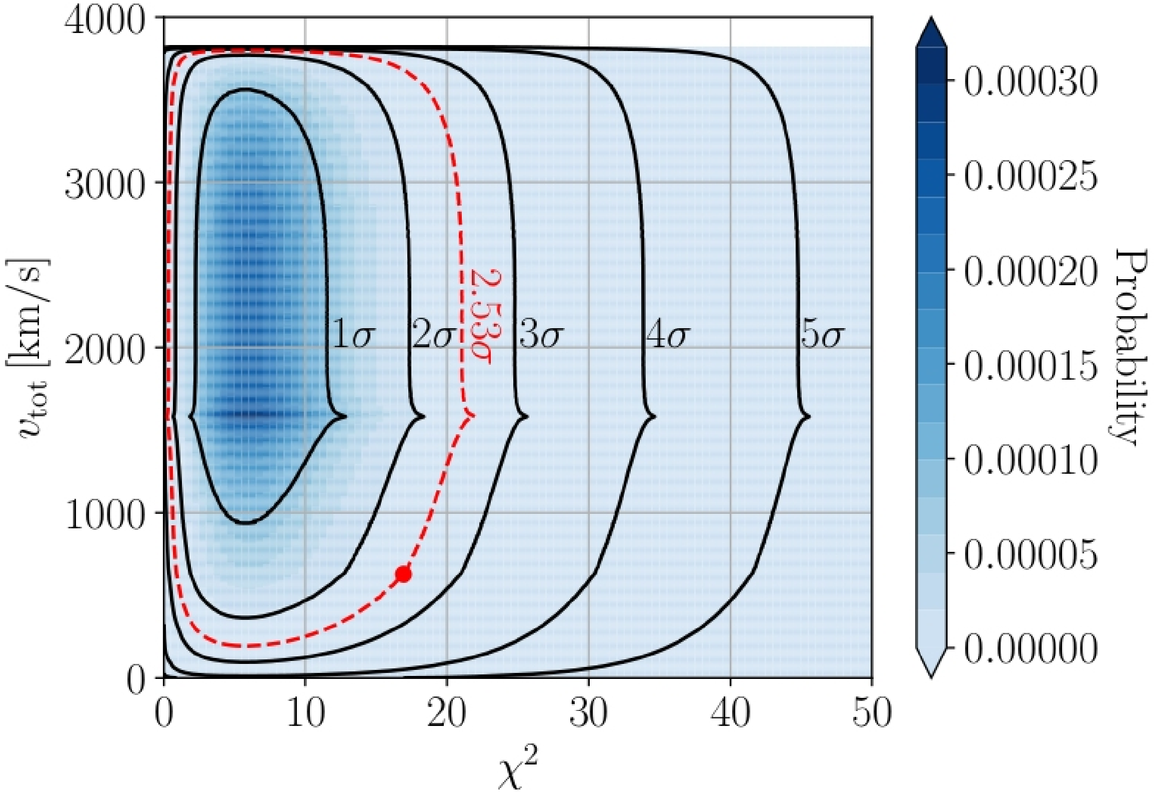


Hubble flow velocity very small: v_{Hubble} ~~>>~~ v_{pec}
(e.g. Kim+2020)

Results:


Motion of the LG
Kogut et al. (1993)
H_0 and $\overline{q}_0$ from SNe
Camarena & Marra (2020a)
$\delta_{\rm out}$, Keenan et al. (2013)
$\delta_{\rm in}$, Keenan et al. (2013)
$(1, 2.34\sigma)$
$(2, 0.20\sigma)$
$(1, 0.97\sigma)$
$(1, 0.99\sigma)$
$(7, 2.05\sigma)$
H_0 from lensing
Shajib et al. (2020)
Wong et al. (2020)

Results:



4000
3000
2000
1000
0
v_{tot} [km/s]
0
10
20
30
40
50
χ^2
1σ
2σ
2.53σ
3σ
4σ
5σ
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
Probability

Results:

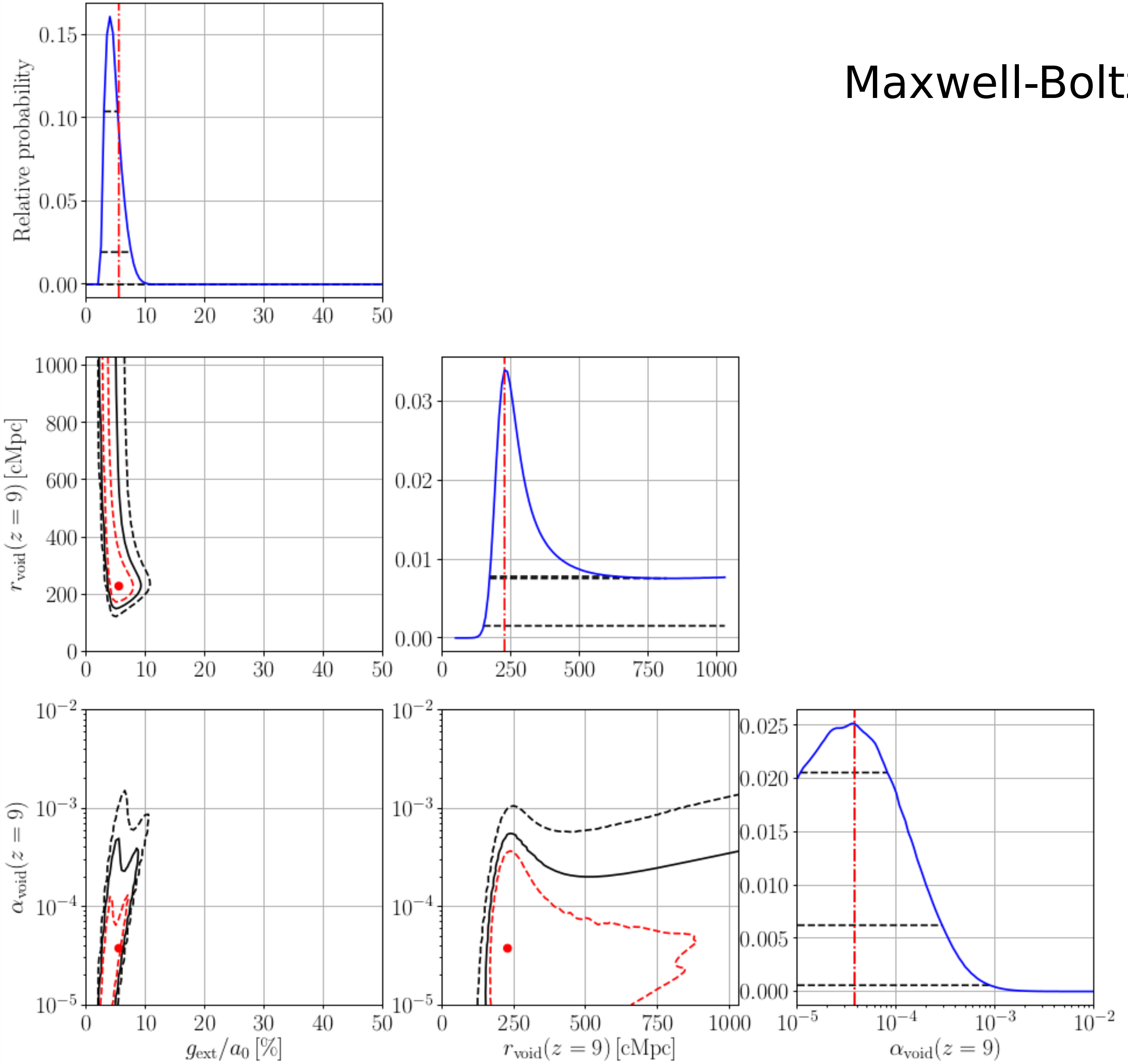
Maxwell-Boltzmann density profile, $g_{ext} = 0.055\,a_0$, $r_{void} = 228.2$ cMpc, $\alpha_{void} = 3.76 \times 10^{-5}$, $v_{void} = 1586\,\mathrm{km\,s^{-1}}$, $r^{rms}_{void} = 528.7$ Mpc, $n_{EFE} = 0$						
Parameter	H_0^{local} [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	$\overline{q}_0^{local}$	$H_0^{lensing}$ [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	v_{LG} [$\mathrm{km\,s^{-1}}$]	δ_{in}	δ_{out}
Observations	75.35 ± 1.68	1.08 ± 0.29	−−	627	0.254 ± 0.083	-0.052 ± 0.105
MOND model	76.15	1.07	See Figure 7	See Figure 8	0.172	0.050
χ^2	0.34		14.66	−−	0.99	0.94
Degrees of freedom	2		7	−−	1	1
χ (1D Gaussian equivalent)	0.20		2.05	2.34	0.99	0.97

Gaussian density profile, $g_{ext} = 0.070\,a_0$, $r_{void} = 1030.0$ cMpc, $\alpha_{void} = 3.76 \times 10^{-5}$, $v_{void} = 2018\,\mathrm{km\,s^{-1}}$, $r^{rms}_{void} = 744.7$ Mpc, $n_{EFE} = 0$						
Parameter	H_0^{local} [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	$\overline{q}_0^{local}$	$H_0^{lensing}$ [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	v_{LG} [$\mathrm{km\,s^{-1}}$]	δ_{in}	δ_{out}
Observations	75.35 ± 1.68	1.08 ± 0.29	−−	627	0.274 ± 0.081	-0.085 ± 0.108
MOND model	77.24	1.43	−−	−−	0.155	0.078
χ^2	1.79		12.74	−−	2.19	2.26
Degrees of freedom	2		7	−−	1	1
χ (1D Gaussian equivalent)	0.83		1.76	2.35	1.48	1.50

Exponential density profile, $g_{ext} = 0.080\,a_0$, $r_{void} = 1030.0$ cMpc, $\alpha_{void} = 7.56 \times 10^{-5}$, $v_{void} = 2307\,\mathrm{km\,s^{-1}}$, $r^{rms}_{void} = 730.4$ Mpc, $n_{EFE} = 0$						
Parameter	H_0^{local} [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	$\overline{q}_0^{local}$	$H_0^{lensing}$ [$\mathrm{km\,s^{-1}\,Mpc^{-1}}$]	v_{LG} [$\mathrm{km\,s^{-1}}$]	δ_{in}	δ_{out}
Observations	75.35 ± 1.68	1.08 ± 0.29	−−	627	0.276 ± 0.080	-0.078 ± 0.108
MOND model	77.25	1.46	−−	−−	0.158	0.073
χ^2	1.98		13.19	−−	2.17	1.97
Degrees of freedom	2		7	−−	1	1
χ (1D Gaussian equivalent)	0.89		1.83	2.47	1.47	1.40

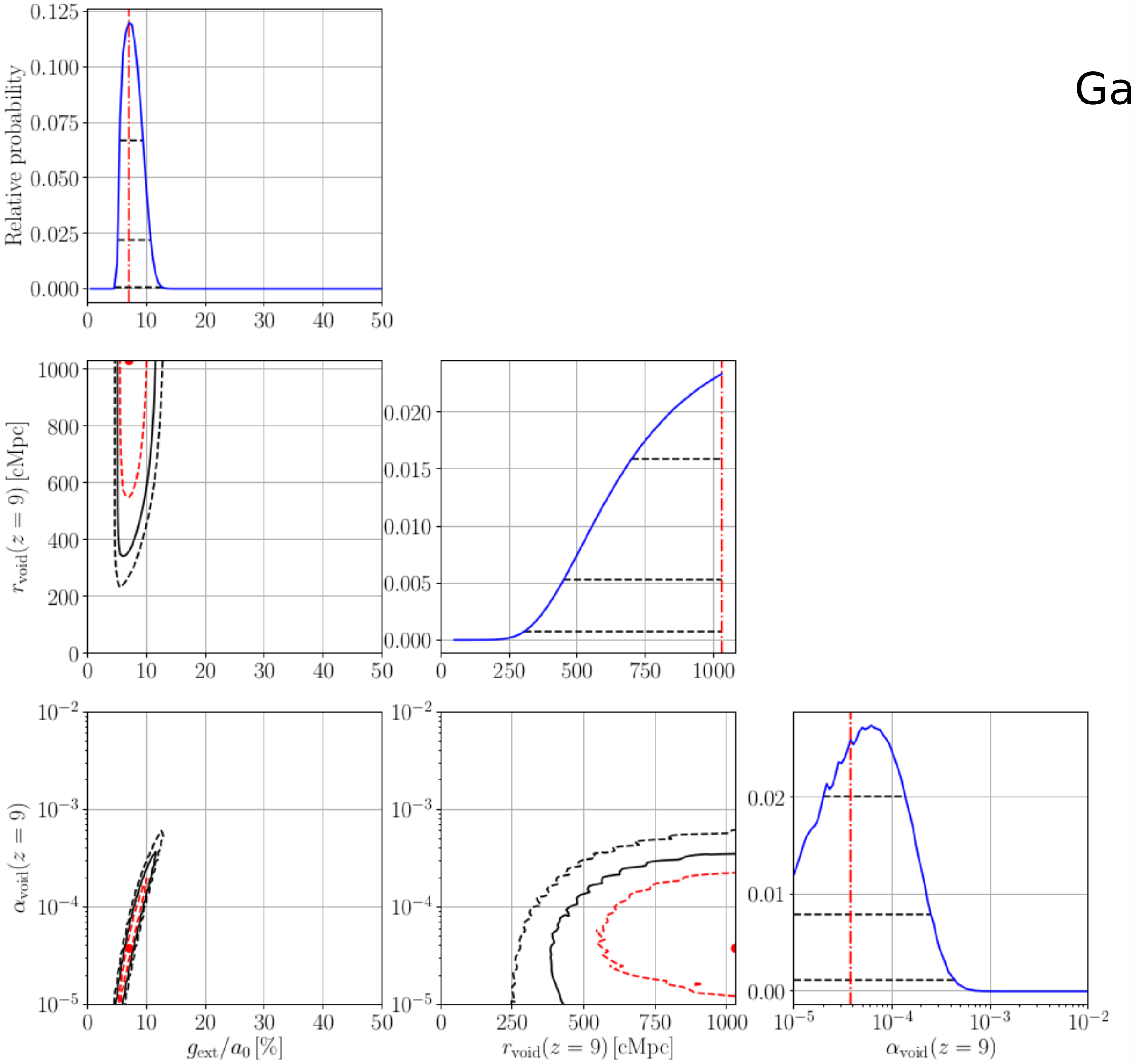
Results:

Maxwell-Boltzmann profile

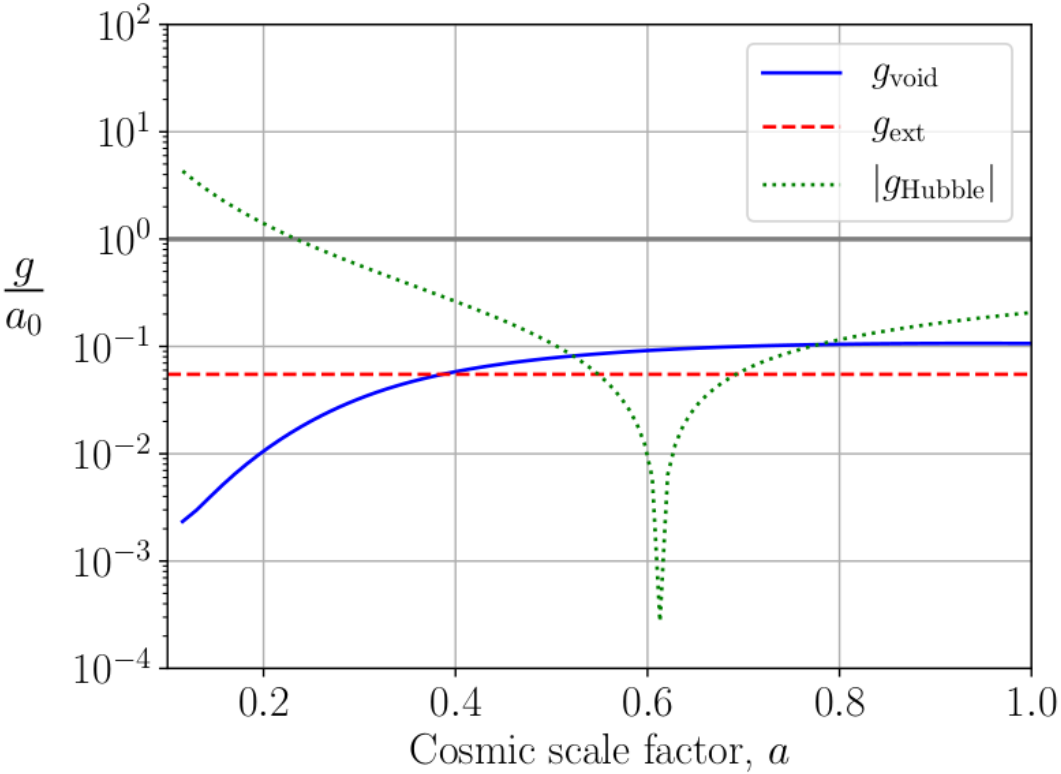


Results:

Gaussian profile



Results: Hubble field effect



Results: Time-dependent external field effect

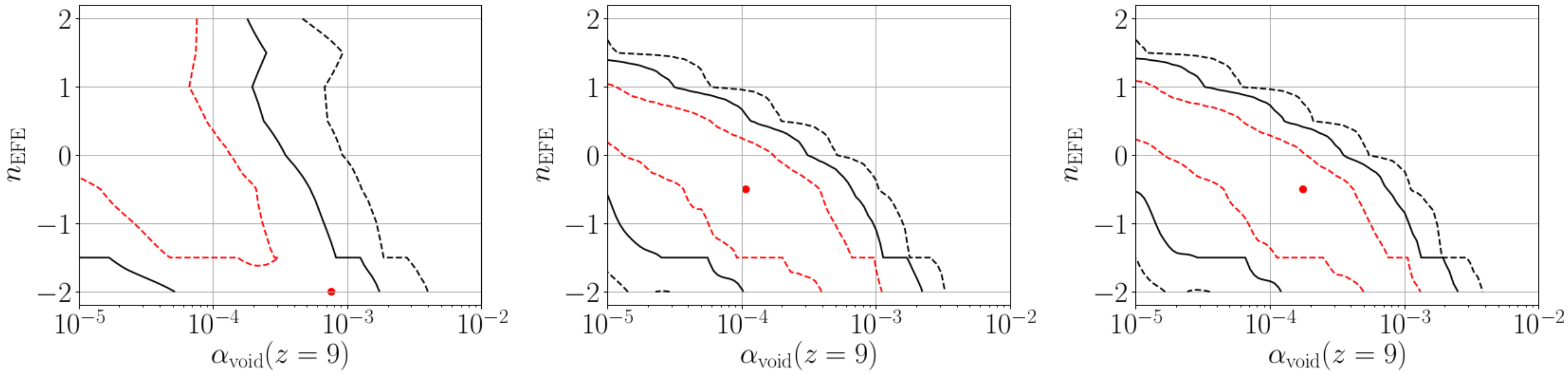
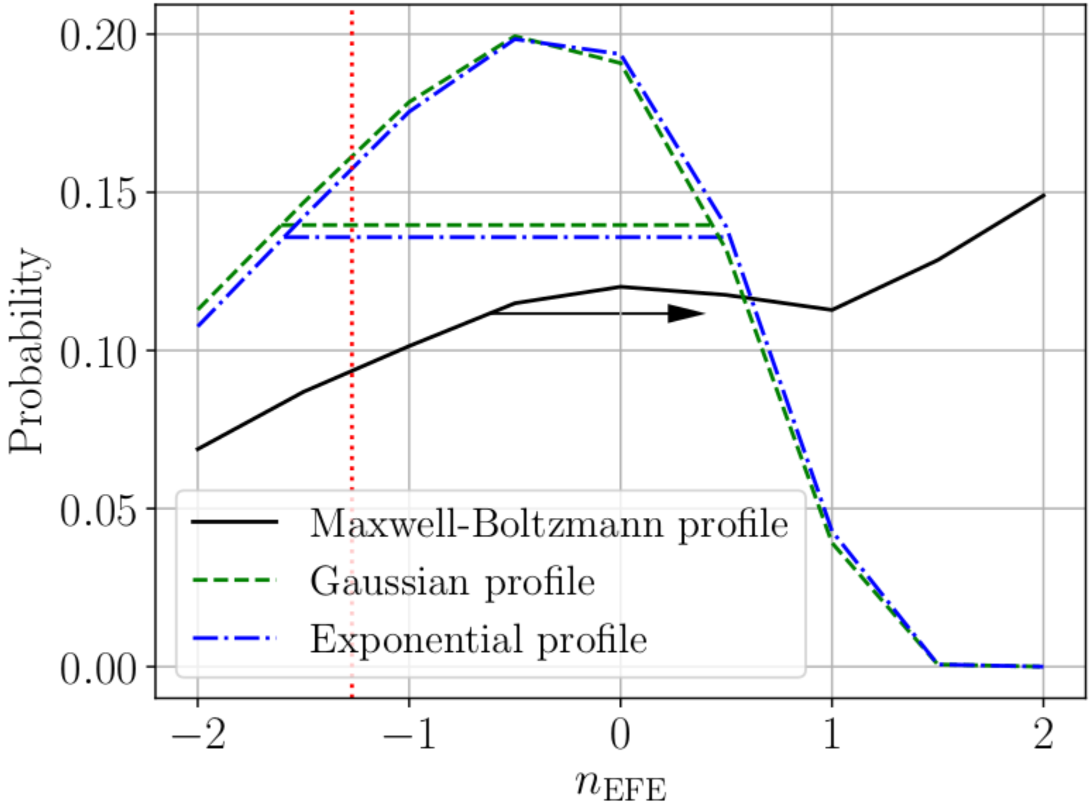


Figure 14. Marginalized posterior distribution of the indicated model parameters based on 9×10^6 MOND models for a Maxwell-Boltzmann (left), Gaussian (middle), and exponential (right) initial profile. The red dashed, black solid, and black dashed lines mark the 1σ, 2σ, and 3σ confidence levels, respectively. A stronger EFE in the past ($n_{EFE} < 0$) requires a stronger initial void strength at $z = 9$. The red dots mark the best-fitting models: $g_{ext} = 0.030\,a_0$, $r_{void} = 218.3$ cMpc, $\alpha_{void} = 7.56 \times 10^{-4}$, $n_{EFE} = -2$ (Maxwell-Boltzmann profile, left-hand panel); $g_{ext} = 0.065\,a_0$, $r_{void} = 1030.0$ cMpc, $\alpha_{void} = 1.07 \times 10^{-4}$, $n_{EFE} = -0.5$ (Gaussian profile, middle panel); and $g_{ext} = 0.070\,a_0$, $r_{void} = 1030.0$ cMpc, $\alpha_{void} = 1.75 \times 10^{-4}$, $n_{EFE} = -0.5$ (exponential profile, right-hand panel).

Results: Time-dependent external field effect



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**
  - Milgrom 2010

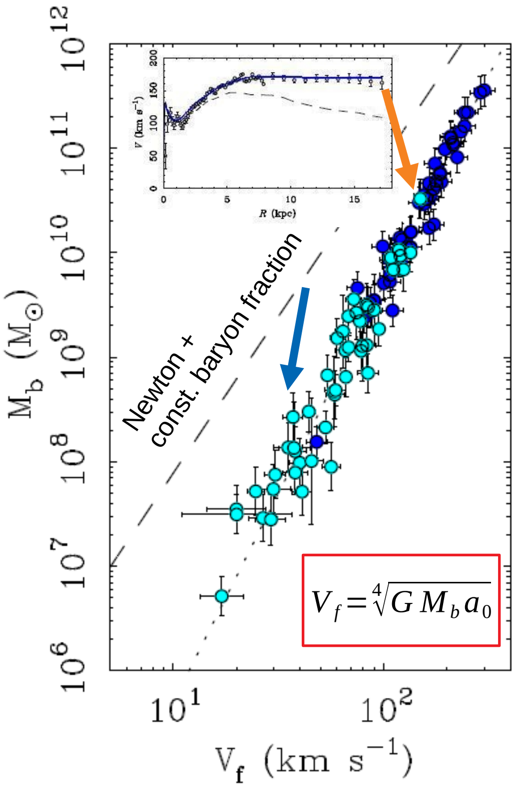
$$L = L_K - L_P = \rho\left(\frac{1}{2}v^2 - \Phi\right) - \frac{1}{8\pi G}\left(2\boldsymbol{g}\cdot\boldsymbol{g}_N - a_0^2 f[g_N]\right)$$

Extremize action

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

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

  - 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)**



νHDM framework: Impact on CMB

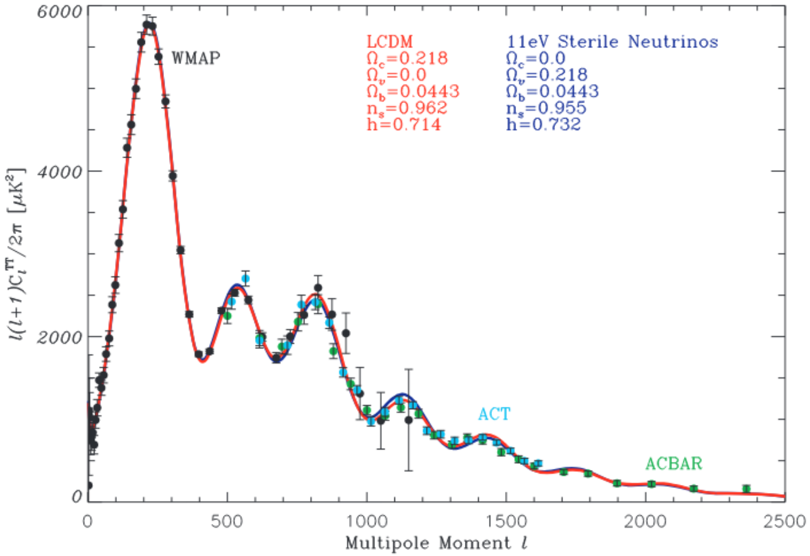
- **Standard expansion history**

  → same angular diameter distance to CMB
- **MOND is sub-dominant at time of recombination**

  (z = 1100) because g ≈ 20 a_0
- **Free streaming effects negligible if m_ν > 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.

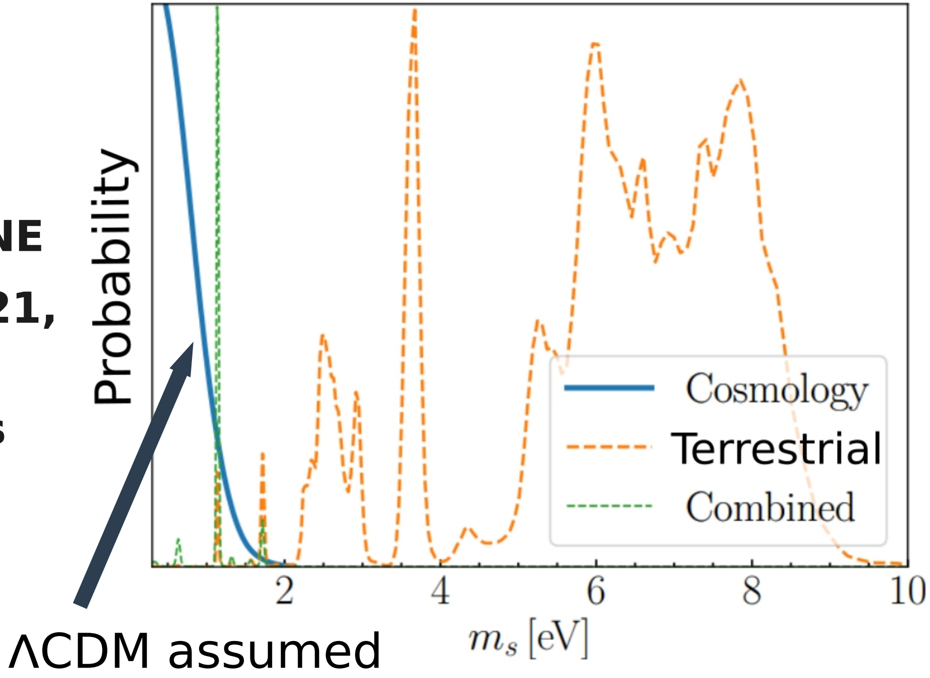
  Planck Collaboration XIII (2016), section 6.4.3
- **MOND effects become important only at z < 50**



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/c² as terrestrial experiments are so far quite compatible with slightly larger mass**

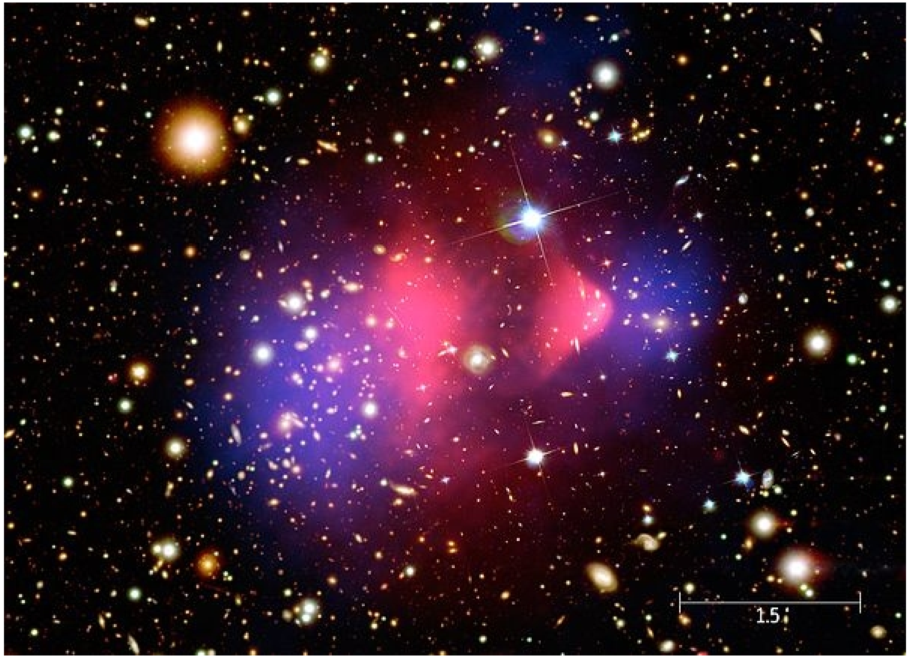


Archidiacono+ 2020

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_ν>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)
- **Large-scale structure?**