Cosmological and Galactic signatures of the Scale-Invariant Vacuum Theory (SIVT)

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Outline of the Talk

- ➢ Motivation – problems with the standard Dark Matter models!
- ➢ Brief Math Background – SIVT for Gravity and Cosmology.
- ➢ The Growth of the Density Perturbations within the SIVT.
- ➢ More support for SIVT as viable competitor to ΛCDM and MOND.
  - ✧ Dwarf Spheroidal,
  - ✧ Hubble expansion and m-H data,
  - ✧ Early universe CMB and Nucleosynthesis.
- ➢ Conclusion Q&A.
- ❑ Motivation – problems with the standard Dark Matter models!
- ❑ Hubble expansion, m-H, CMB & Nucleosynthesis …

THE ROLE OF SYMMETRY IN PHYSICS – TOWARDS SIVT

> "It appears as one of the fundamental principles in Nature that the equations expressing basic laws should be invariant under the widest possible group of transformations" (Dirac 1973).

Newton Law	Special Relativity	General Relativity
Galilean invariance	Lorentz inv.	covariance

Maxwell equations are scale invariant in the empty space

$$ds' = \lambda(x^{\mu})\, ds$$

Einstein equations are also scale invariant in empty space if Λ=0,
they are not scale invariant if $\Lambda \neq 0$.

MOND and SCALE INVARIANCE

MOND THEORY (Milgrom 2009, 2014):

invariant to (t, r) → (λ r, λ t)

For $g >> a_0$ $g \rightarrow g_N$
$g << a_0$ $g \rightarrow (g_N a_0)^{1/2}$

$$g = \frac{g_N}{\left[1 - e^{-(g_N/a_0)^{\frac{1}{2}}}\right]}$$

Numerous successes in galactic dynamics, clusters, lensing, etc.

Bondi (1990): *«Einstein's disenchantment with the cosmological constant was partially motivated by a desire to preserve scale invariance of the empty space»*

The appropriate framework:

INTEGRABLE WEYL' GEOMETRY

(Weyl, 1923; Eddington, 1923; Dirac, 1973; Canuto, 1977; Bouvier & Maeder, 1978)

WEYL' GEOMETRY

$ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$

$P(x^\mu) \rightarrow P'(x^\mu + dx^\mu)$

$d\ell = \ell\, \kappa_\mu dx^\mu$

The lengths get multiplied by $\lambda(x^\mu)$

$$ds' = \lambda(x^\mu)\, ds$$

Gauge transformation

COTENSOR CALCULUS (Weyl Geometry) Einstein's objection!

Vector // transported on a closed loop

$$\Delta\ell = \ell\left(\partial_\nu \kappa_\mu - \partial_\mu \kappa_\nu\right) \sigma^{\mu\nu}$$

EM field $\mathbf{F}_{\mu\nu}$

But, if $\partial_\nu \kappa_\mu = \partial_\mu \kappa_\nu$, i.e. $\kappa_\nu = -\Phi_{,\nu} = -\dfrac{\partial \ln \lambda}{\partial x^\nu}$

κ_ν is the gradient of a scalar field $\Phi = \ln \lambda$

In particular the co-covariant derivative of a co-scalar S of power n will be

$$S_{*\mu} = \partial_\mu S - n\kappa_\mu S$$

and for co-vectors (n), we can write (after Dirac)

$$S' = \lambda^n S$$

$$A_{\mu*\nu} = \partial_\nu A_\mu - {}^*\Gamma^\alpha_{\mu\nu} A_\alpha - n\kappa_\nu A_\mu ,$$

$$A^\mu_{*\nu} = \partial_\nu A^\mu + {}^*\Gamma^\mu_{\nu\alpha} A^\alpha - n\kappa_\nu A^\mu ,$$

where

$${}^*\Gamma^\alpha_{\mu\nu} = \Gamma^\alpha_{\mu\nu} - g^\alpha_\mu \kappa_\nu - g^\alpha_\nu \kappa_\mu + g_{\mu\nu}\kappa^\alpha$$

One can further develop: **THE NEW FIELD EQUATION**

Second order co-covariant derivatives, modified Christoffel symbols, Riemann-Christoffel tensor, Ricci tensor, scalar curvature,

$$R'_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu} R' - \kappa_{\mu;\nu} - \kappa_{\nu;\mu} - 2\kappa_\mu \kappa_\nu + 2 g_{\mu\nu} \kappa^{\alpha}_{;\alpha} - g_{\mu\nu} \kappa^{\alpha} \kappa_\alpha = -8\pi G T_{\mu\nu} - \lambda^2 \Lambda_{\mathrm{E}}\, g_{\mu\nu}$$

GR — Additional terms

Dirac, 1973;
Canuto et al. 1977

$\Lambda \neq 0$ and scale invariance

It can also be derived from
an action principle (Canuto et al. 1977)

$$\delta \int \lambda^2 \, {}^*R \sqrt{g}\, d^4x = 0$$

λ is not constrained

Hypothesis of the Scale Invariant Vacuum Theory (SIVT):

The macroscopic empty space is scale invariant

$P_{vac} = -\rho_{vac}$ → ρ_{vac} constant for adiabatic exp. or contraction (S.Carroll, 1992).

As we use Einstein's theory at large scales, even if we do not have a quantum theory of gravitation, we consider that the large scale empty space is scale invariant, even if this is not true at the quantum level

$$R'_{\mu\nu} - \frac{1}{2}\, g_{\mu\nu} R' - \kappa_{\mu;\nu} - \kappa_{\nu;\mu} - 2\kappa_\mu \kappa_\nu + 2 g_{\mu\nu} \kappa^{\alpha}_{;\alpha} - g_{\mu\nu} \kappa^{\alpha} \kappa_{\alpha} = -8\pi G T_{\mu\nu} - \lambda^2 \Lambda_{\mathrm{E}}\, g_{\mu\nu}$$

This is what remains in empty space

Homogeneity and isotropy →

only the time component of κ_ν :

$$\kappa_0 = -\dot{\lambda}/\lambda$$

The time and space components give:

$$3\frac{\dot{\lambda}^2}{\lambda^2} = \lambda^2\, \Lambda_{\mathrm{E}} \quad \text{and} \quad 2\,\frac{\ddot{\lambda}}{\lambda} - \frac{\dot{\lambda}^2}{\lambda^2} = \lambda^2\, \Lambda_{\mathrm{E}}.$$

$\lambda \sim 1/t$

COSMOLOGY

The field equation with the R-W metric

$$\frac{8\,\pi G \varrho}{3} = \frac{k}{R^2} + \frac{\dot{R}^2}{R^2} + 2\,\frac{\dot{\lambda}\,\dot{R}}{\lambda\,R} + \frac{\dot{\lambda}^2}{\lambda^2} - \frac{\Lambda_{\mathrm{E}}\lambda^2}{3} \qquad (27)$$

$$-8\,\pi G p = \frac{k}{R^2} + 2\frac{\ddot{R}}{R} + 2\frac{\ddot{\lambda}}{\lambda} + \frac{\dot{R}^2}{R} + 4\frac{\dot{R}\,\dot{\lambda}}{R\,\lambda} - \frac{\dot{\lambda}^2}{\lambda^2} - \Lambda_{\mathrm{E}}\,\lambda^2.$$

Canuto et al 1977

Within SIVT:

The empty space!

$$3\,\frac{\dot{\lambda}^2}{\lambda^2} = \lambda^2\,\Lambda_{\mathrm{E}} \quad \text{and} \quad 2\,\frac{\ddot{\lambda}}{\lambda} - \frac{\dot{\lambda}^2}{\lambda^2} = \lambda^2\,\Lambda_{\mathrm{E}}$$

Maeder (2017)

Alike in GR, vacuum properties do not depend on the material content

The cosmological equations

$$\frac{8\,\pi G \varrho}{3} = \frac{k}{R^2} + \frac{\dot{R}^2}{R^2} + 2\,\frac{\dot{R}\dot{\lambda}}{R\lambda},$$

$$-8\,\pi G p = \frac{k}{R^2} + 2\frac{\ddot{R}}{R} + \frac{\dot{R}^2}{R^2} + 4\frac{\dot{R}\dot{\lambda}}{R\lambda}$$

If λ = const.

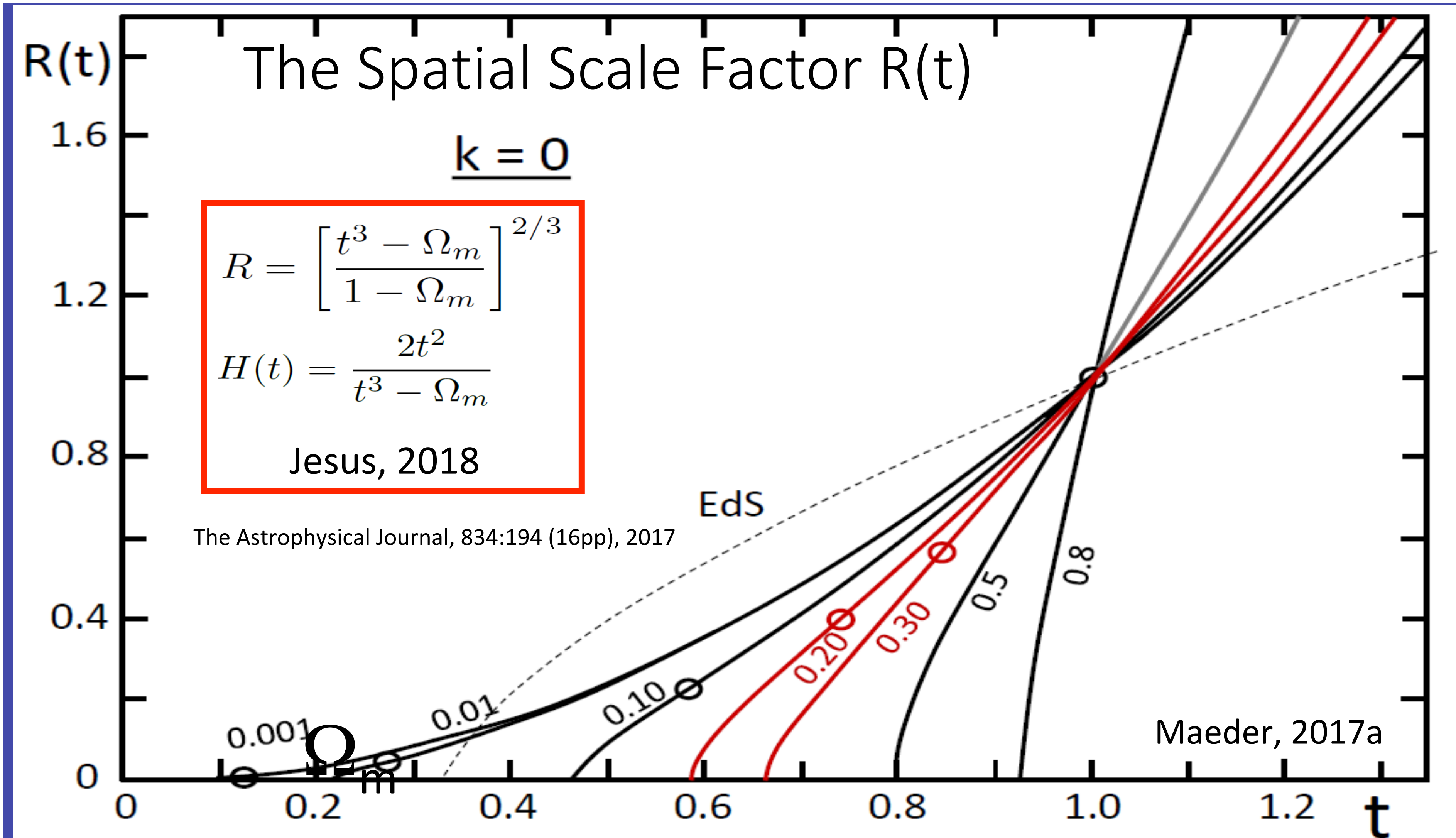
→ usual equations

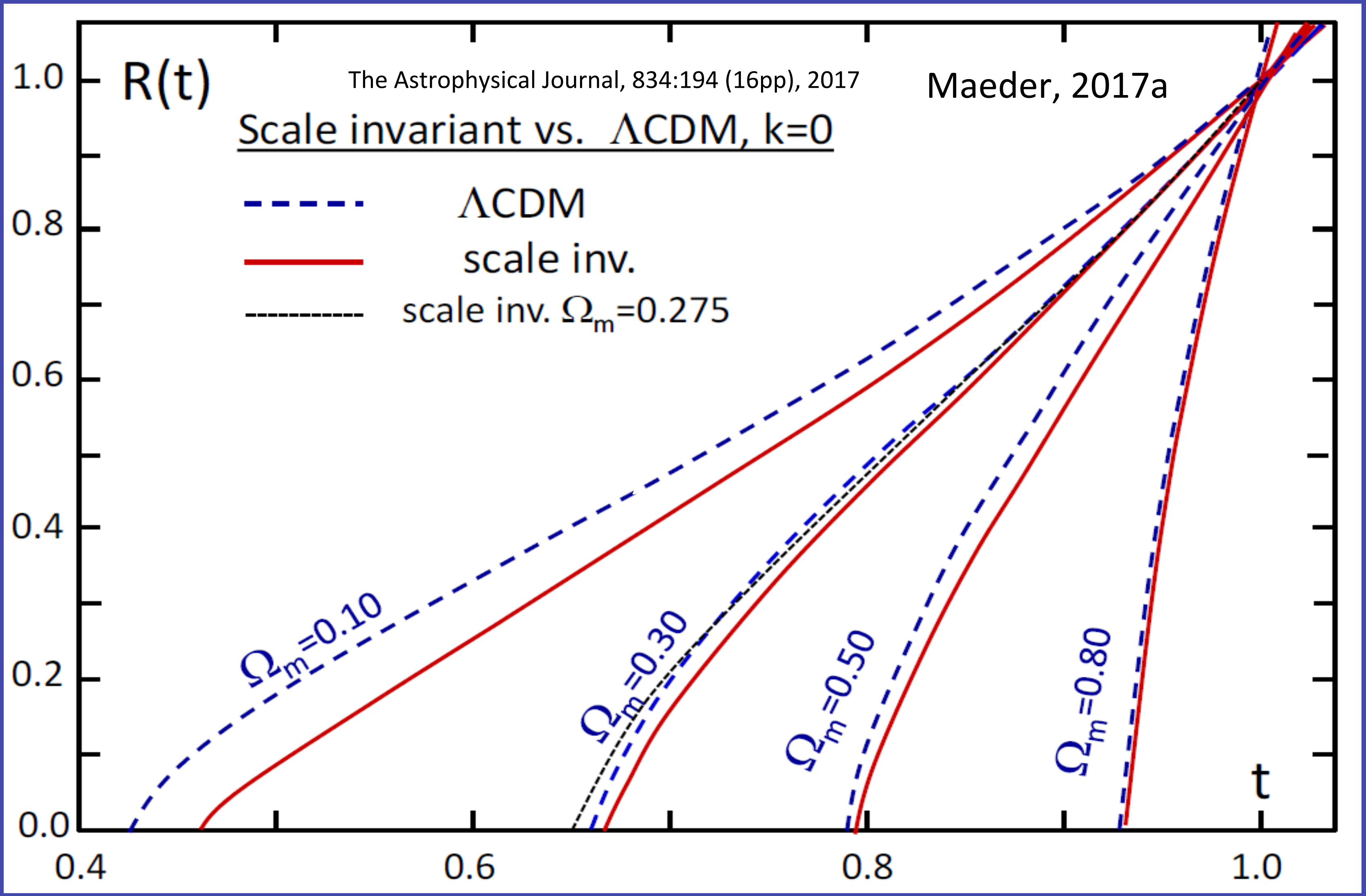
If dR/dt > 0, additional acceleration opposed to gravity.

$$-\frac{4\,\pi G}{3}\,(3p + \varrho) = \frac{\ddot{R}}{R} + \frac{\dot{R}\dot{\lambda}}{R\lambda}$$

$$-\frac{\Lambda}{3}$$

No need of unknown Dark Stuff!


R(t)
The Spatial Scale Factor R(t)
k = 0
$R = \left[\frac{t^3 - \Omega_m}{1 - \Omega_m}\right]^{2/3}$
$H(t) = \frac{2t^2}{t^3 - \Omega_m}$
Jesus, 2018
The Astrophysical Journal, 834:194 (16pp), 2017
EdS
0.001
Ω_m
0.01
0.10
0.20
0.30
0.5
0.8
Maeder, 2017a
1.6
1.2
0.8
0.4
0
0
0.2
0.4
0.6
0.8
1.0
1.2
t



R(t)
The Astrophysical Journal, 834:194 (16pp), 2017
Maeder, 2017a
Scale invariant vs. ΛCDM, k=0
ΛCDM
scale inv.
scale inv. Ω_m=0.275
Ω_m=0.10
Ω_m=0.30
Ω_m=0.50
Ω_m=0.80
t
1.0
0.8
0.6
0.4
0.2
0.0
0.4
0.6
0.8
1.0

The Growth of the Density Perturbation

Equations of continuity, of Euler, and Poisson within the SIVT:

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = \kappa \left[\rho + \vec{r} \cdot \vec{\nabla} \rho\right]$$

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right) \vec{v} = -\vec{\nabla}\Phi - \frac{1}{\rho}\vec{\nabla}p + \kappa \vec{v}$$

$$\vec{\nabla}^2 \Phi = \triangle \Phi = 4\pi G \rho$$

Applied to a density perturbation δ they give:

The time derivative of the first one and the divergence of the last one, with p=0, lead to:

$$\dot{\delta} + \vec{\nabla} \cdot \dot{\vec{x}} = n\,\kappa\delta\,,$$

$$\vec{\nabla}^2 \Psi = 4\pi G a^2 \rho_b \delta\,.$$

$$\ddot{\vec{x}} + 2H\dot{\vec{x}} + = -\frac{\vec{\nabla}\Psi}{a^2} - \frac{v_s^2}{a^2}\vec{\nabla}\delta + \kappa(t)\dot{\vec{x}}\,,$$

Euler h-order of δ.

$$n\delta = \vec{x} \cdot \vec{\nabla}\delta$$

Maeder & Gueorguiev, 2018

$$\ddot{\delta} + (2H - (1+n)\kappa)\dot{\delta} = 4\pi G \varrho_b \delta + 2n\kappa(H - \kappa)\delta\,.$$

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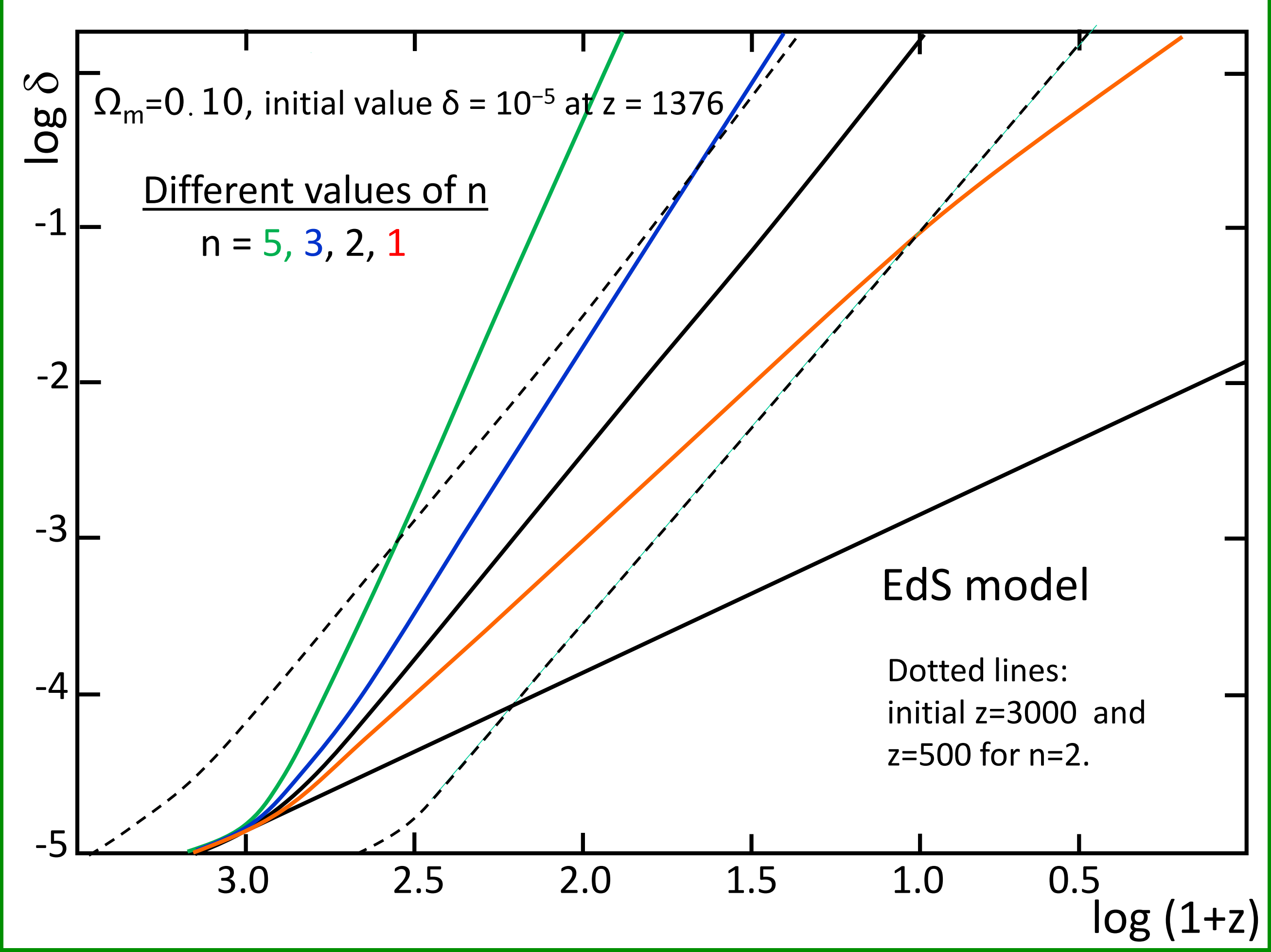
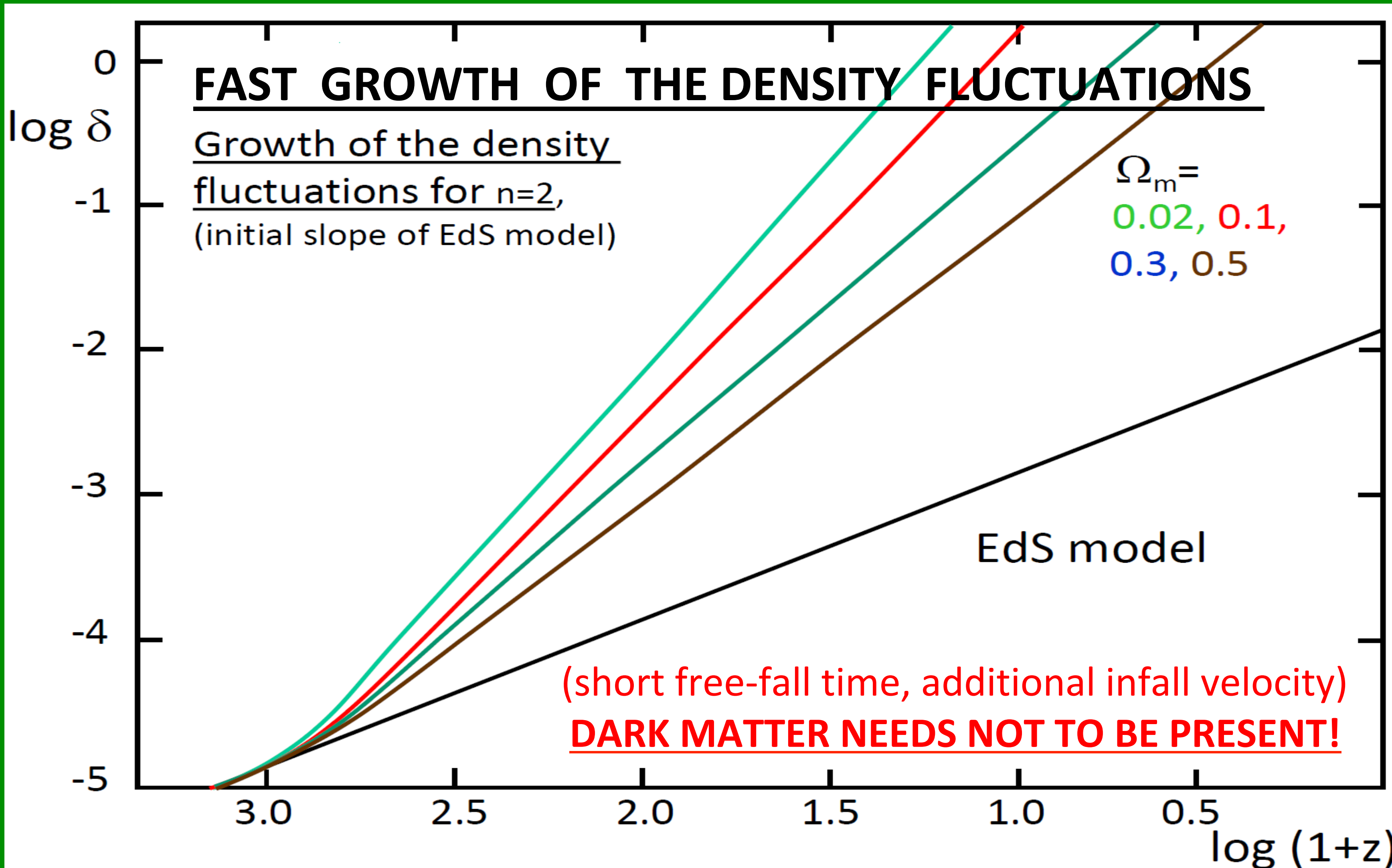
n-dependence of the growth




0
log δ
-1
-2
-3
-4
-5
FAST GROWTH OF THE DENSITY FLUCTUATIONS
Growth of the density
fluctuations for n=2,
(initial slope of EdS model)
Ωm=
0.02, 0.1,
0.3, 0.5
EdS model
(short free-fall time, additional infall velocity)
DARK MATTER NEEDS NOT TO BE PRESENT!
3.0
2.5
2.0
1.5
1.0
0.5
log (1+z)

The geodesics: curve whose tangent vector $u^\mu = dx^\mu/ds$ is transported by // displacement along the curve. Dirac, 1973

$$u^\mu_{*\lambda} = 0, \quad \Longrightarrow \quad \boxed{\frac{\mathrm{d}u^\mu}{\mathrm{d}s} + {}^*\Gamma^\mu_{\nu\lambda} u^\nu u^\lambda + \kappa_\lambda u^\lambda u^\mu = 0.}$$

From an action: Bouvier & Maeder, 1978

$$\delta \mathscr{I} = \int_{P_0}^{P_1} \delta(\mathrm{d}\tilde{s}) = \int \delta(\beta\, \mathrm{d}s) = \int \delta\left(\beta \frac{\mathrm{d}s}{\mathrm{d}\tau}\right) \mathrm{d}\tau = 0,$$

THE WEAK FIELD APPROXIMATION for SIVT

$$g_{i\,i} = -1, \quad \text{for } i = 1, 2, 3$$

$$g_{00} = 1 + (2\Phi/c^2).$$

$$\Gamma^i_{00} = \frac{1}{2}\frac{\partial g_{00}}{\partial x^i} = \frac{1}{2}\frac{\partial(1 + (2\Phi/c^2))}{\partial x^i} = \frac{1}{c^2}\frac{\partial \Phi}{\partial x^i}.$$

Potential $\Phi = GM/r$ is scale invariant

$$\boxed{\frac{d^2\mathbf{r}}{dt^2} = -\frac{G\,M}{r^2}\frac{\mathbf{r}}{r} + \kappa(t)\frac{d\mathbf{r}}{dt}}$$

$\kappa(t) = 1/t$

The ratio of the 2 terms is $\quad x = \dfrac{\kappa\, v\, r^2}{GM}$

TOWARDS the RAR

$$x = \frac{\kappa\, v\, r^2}{GM} \qquad \text{At any time, } \kappa = 1/t = \frac{H}{\xi}$$

Using $v = (r\, g_{obs})^{1/2}$ → $$x = \frac{H}{\xi} \frac{(r\, g_{obs})^{1/2}}{g_{bar}} \sim \frac{g_{obs} - g_{bar}}{g_{bar}}$$

Consider 2 gravit. systems 1 and 2 at the same t and r,

$$\frac{\left(\frac{g_{obs}-g_{bar}}{g_{bar}}\right)_2}{\left(\frac{g_{obs}-g_{bar}}{g_{bar}}\right)_1} = \left(\frac{g_{obs,2}}{g_{obs,1}}\right)^{1/2} \left(\frac{g_{bar,1}}{g_{bar,2}}\right)$$

Calling $g_{obs,2}$ → g and $g_{bar,2}$ → g_N for system 2, system 1 is a reference

2^{nd} degree equation

$$g^2 - g(2\, g_N + k^2) + g_N^2 = 0$$

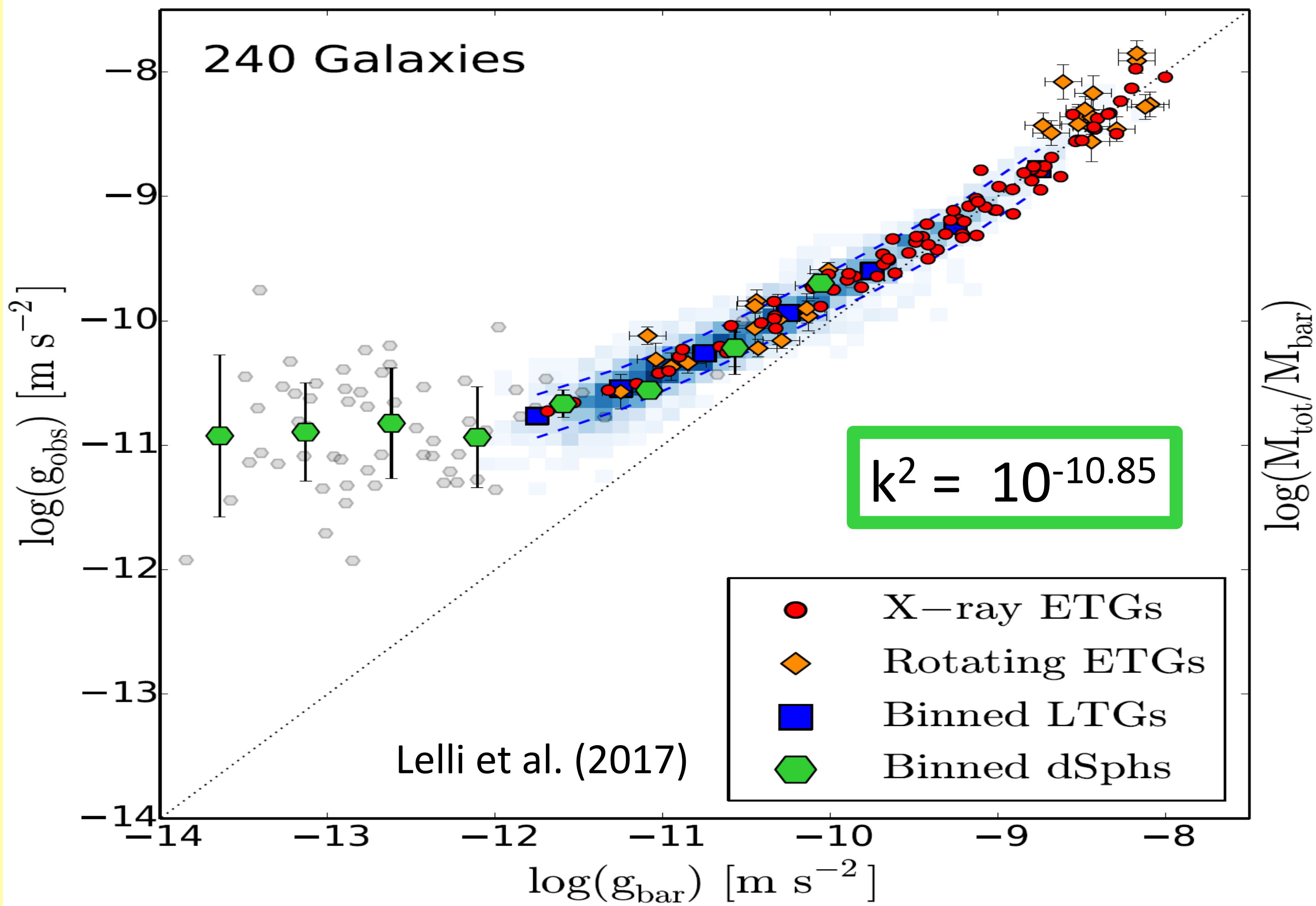
$$g = g_N + \frac{k^2}{2} \pm \frac{1}{2}\sqrt{4 g_N k^2 + k^4}$$

If $g_N \gg k^2$, then g → g_N

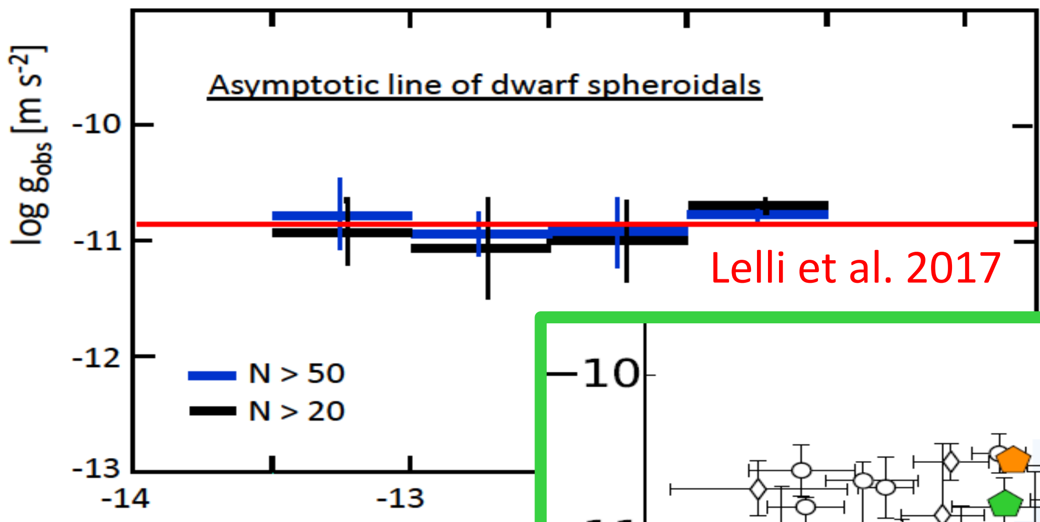
If g_N → 0 , then g → k^2 for any r

k^2 is the lower limit of g for g_N → 0, this limit is the same everywhere

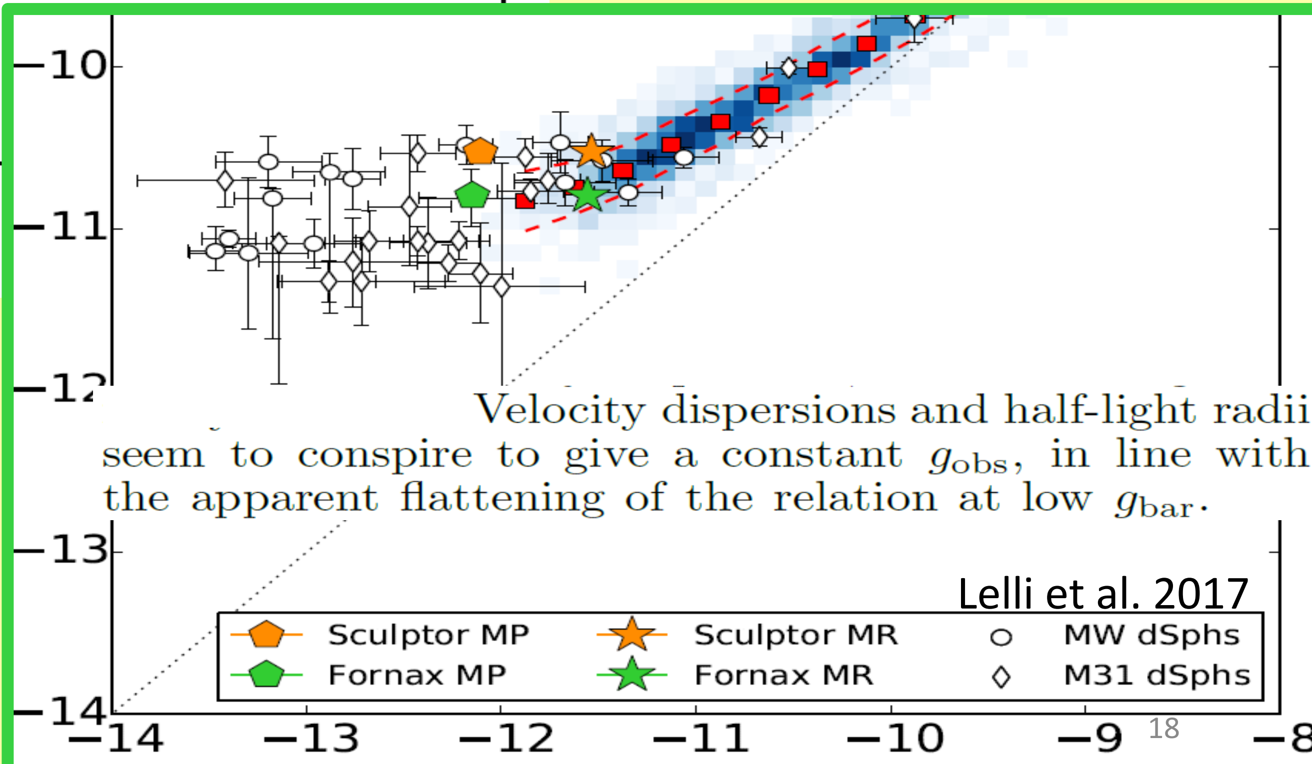
thus $k^2 \geq$ min $[g_N]$


240 Galaxies
k² = 10^-10.85
Lelli et al. (2017)
X−ray ETGs
Rotating ETGs
Binned LTGs
Binned dSphs
log(g_obs) [m s^−2]
log(g_bar) [m s^−2]
log(M_tot/M_bar)
−8
−9
−10
−11
−12
−13
−14

Under review



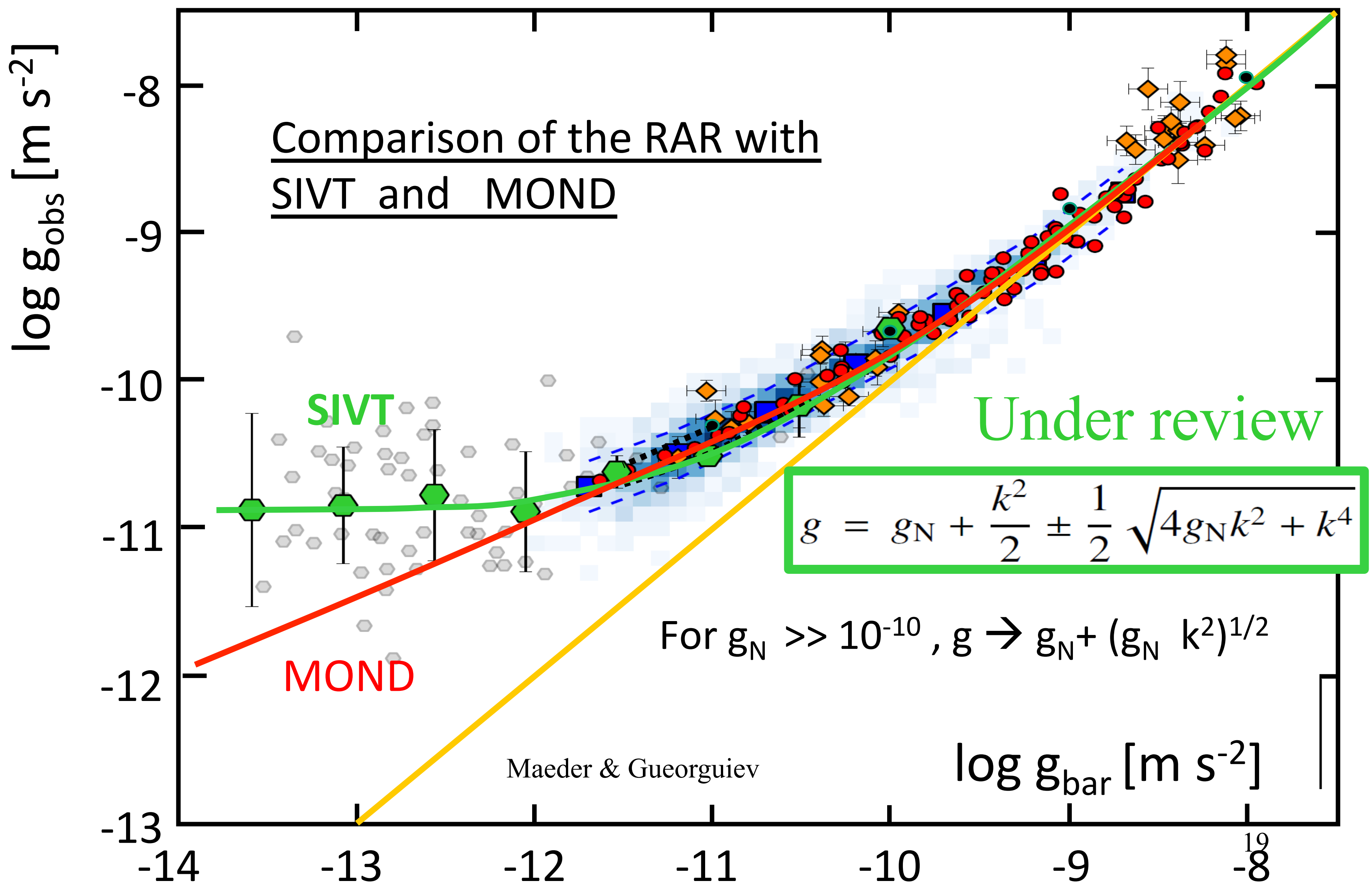
Different sampling give the same limit over 2 dex In log g_{bar}

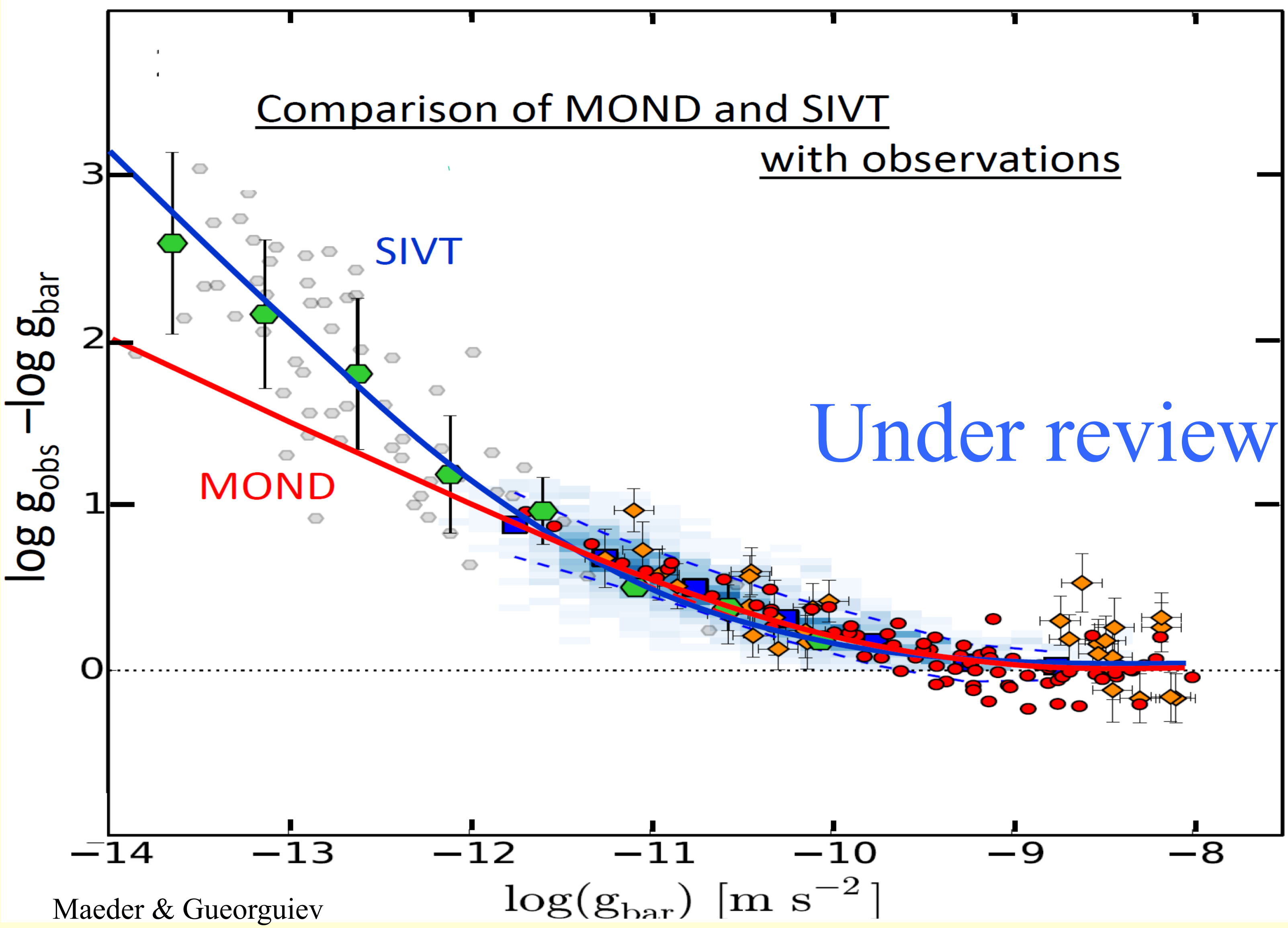


Fornax 2483 stars

Sculptor 1365 stars

Maeder & Gueorguiev


Comparison of the RAR with
SIVT and MOND
SIVT
MOND
Under review
$g = g_N + \frac{k^2}{2} \pm \frac{1}{2}\sqrt{4 g_N k^2 + k^4}$
For $g_N >> 10^{-10}$, $g \rightarrow g_N + (g_N \ k^2)^{1/2}$
Maeder & Gueorguiev
log g_{obs} [m s^{-2}]
log g_{bar} [m s^{-2}]
-8
-9
-10
-11
-12
-13
-14
-13
-12
-11
-10
-9
-8

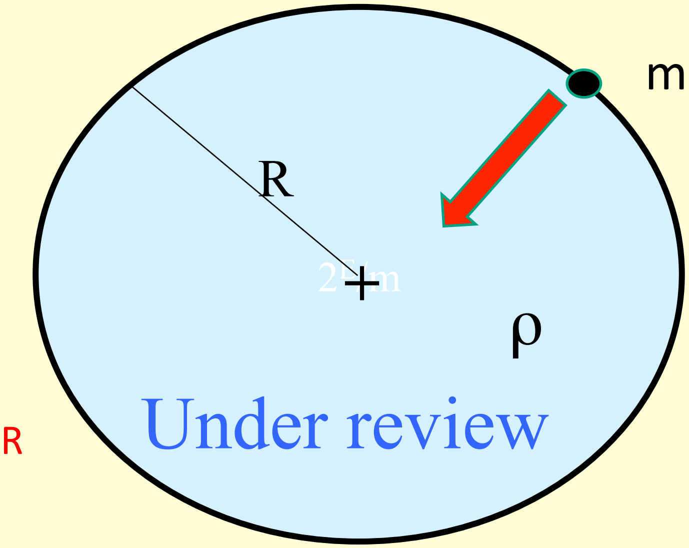


Maeder & Gueorguiev

In the Newtonian framework:

$E = U + T \qquad U = -GMm/R, \; T = (1/2)\, m \dot{R}^2$

$$\frac{8\pi G \varrho}{3} = \frac{\varepsilon}{R^2} + \frac{\dot{R}^2}{R^2} \qquad \varepsilon = -2E/m$$



Theory: $k^2 \geq \min\,[g_N]$

Limit for vanishing mass or/and large R

$$\mathit{min}\,[g_N] = \mathit{lim}\,[GM/R^2] = \mathit{lim}\,[\tfrac{4\pi}{3} G\rho R]$$

$$k^2 \rightarrow \frac{4\pi}{3} G \Omega_m \rho_c R_{lim} = \boxed{\frac{1}{2}\,\Omega_m\, c\, H_0}$$

With $\rho = \Omega_m \rho_c$
$\rho_c = 3 H_0^2/(8\pi G)$
$R_{lim} = c/H_0$

With $\Omega_m = \Omega_{bar} = 0.30$, $k^2 = 1.02 \; 10^{-10}$ m s^{-2} log k^2 = - 9.99

$\Omega_m = \Omega_{bar} = 0.10$, $k^2 = 3.40 \; 10^{-11}$ m s^{-2} log k^2 = -10.47

$\Omega_m = \Omega_{bar} = 0.04$, $k^2 = 1.36 \; 10^{-11}$ m s^{-2} log k^2 = -10.87

Background acceleration from baryon in the Newtonian framework

Conclusion:

- ✓ SIVT is a minimal generalization of the Einstein GR,
- ✓ Framework for Cosmology & Gravity,
  - ➢ Density perturbations can grow fast enough!
  - ➢ No need of Dark Matter!
- ✓ Explains the Dwarf Spheroidal, unlike MOND!
- ❖ Scale invariance might explain dark matter effects!
- ❑ New perspective on dark energy and CC problem?

Thank You!