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IAP, Paris, 18 Oct 2022

Addressing the dark matter problem using extensions of GR

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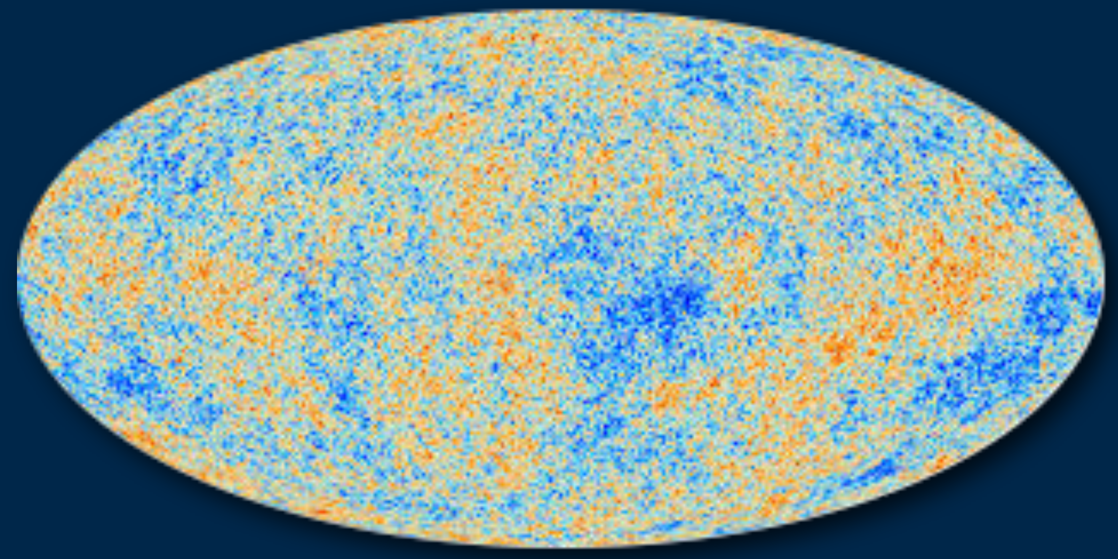
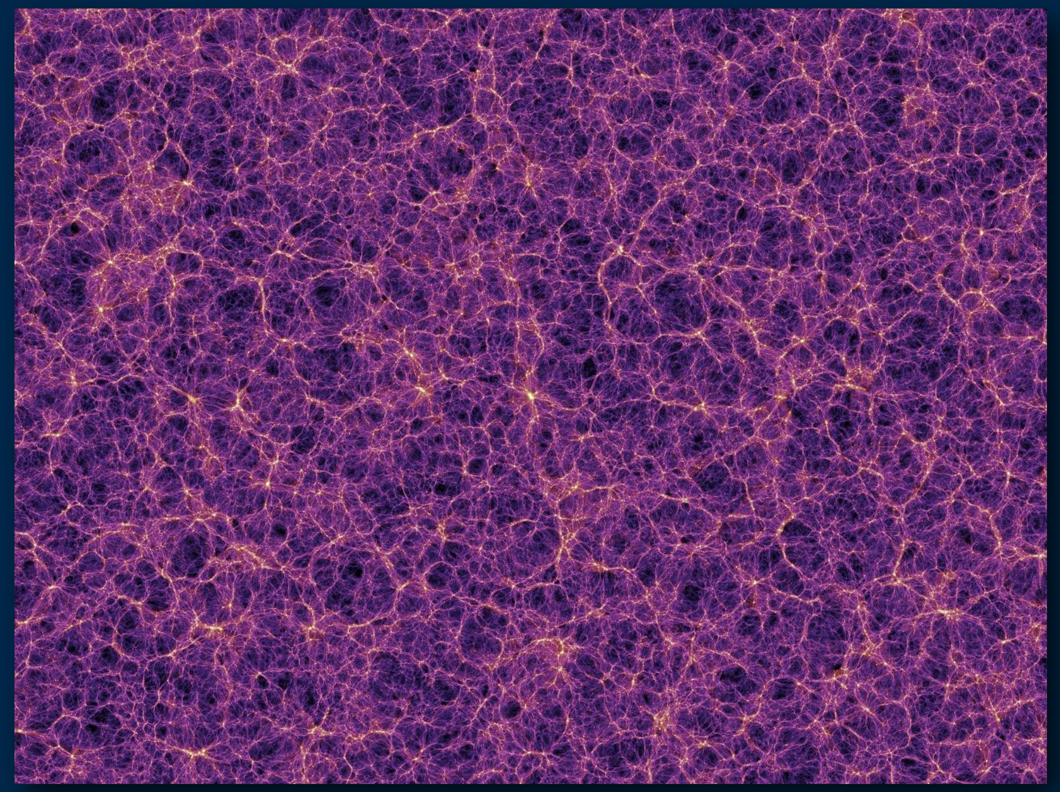


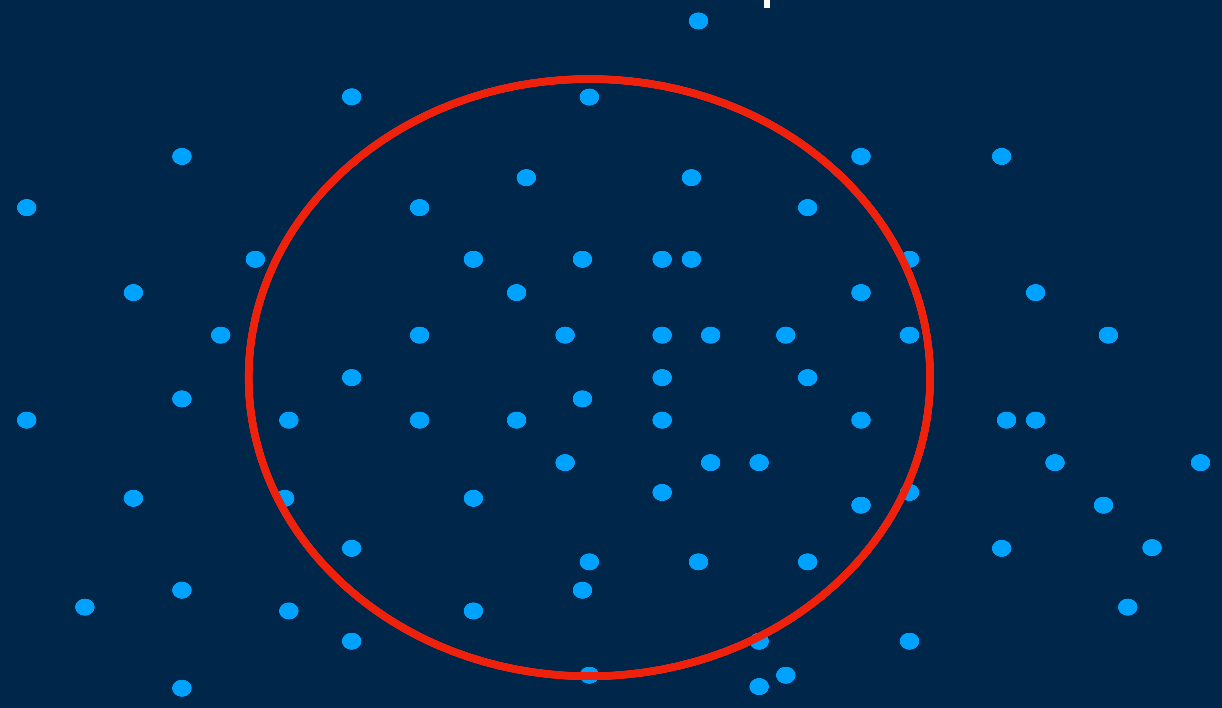


Mismatch between

observed dynamics of visible matter ↔ its gravitational influence

Dark matter

Statistical description



Particle DM

New matter dof

Wave DM

$\langle \vec{x} | \Psi(t) \rangle$

Schrödinger (or Klein-Gordon) eq.

Schrödinger-Vlasov correspondence

On galactic scales ($\sim kpc$) and larger

Distribution function (d.f.) $f(t, \vec{x}, \vec{u})$

- Evolves in phase-space
- Boltzmann equation

$$\frac{\partial f}{\partial t} + \vec{u} \cdot \vec{\nabla}_x f + \vec{\nabla}_x \Phi \cdot \vec{\nabla}_u f = C[f]$$

Widrow & Kaiser ApJ Lett 416, L71 (1993)
Kopp, Vattis & C.S, PRD (2017) (and ref. therein)

Λ

Cosmological constant

Primordial Black holes

· · · · · · ·

New particle not in standard model — e.g. neutralino

Cold Dark Matter

CDM

ΛCDM

Cosmological scales

FLRW

$$\bar{\rho}_{CDM} \propto \frac{1}{a^3} \qquad \bar{\rho}_{\Lambda} \rightarrow constant$$

Fluctuations

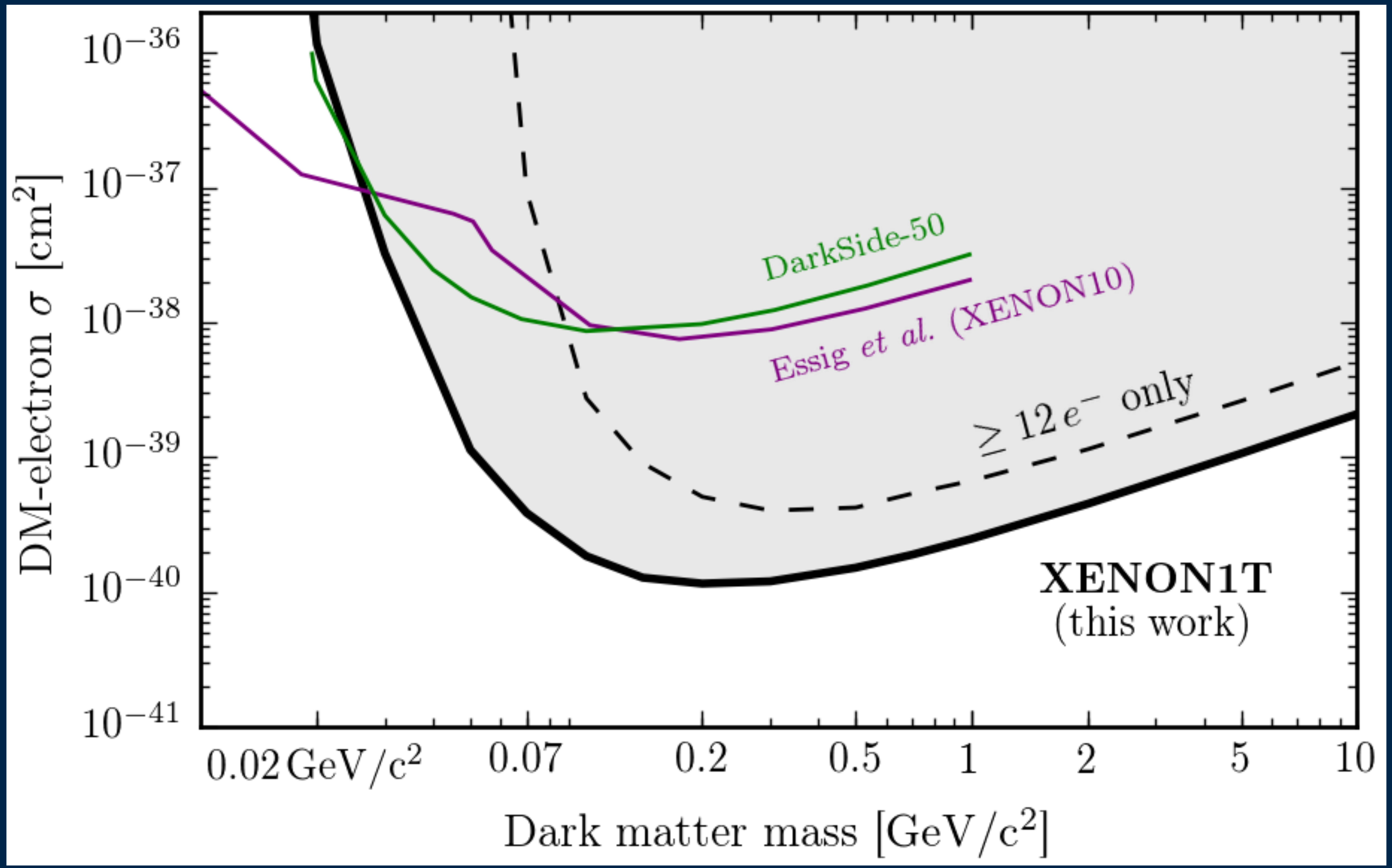
Density contrast $\delta \equiv \frac{\delta\rho}{\bar{\rho}}$

Velocity divergence $\theta \equiv -\frac{i\vec{k}\cdot\vec{v}}{k^2}$

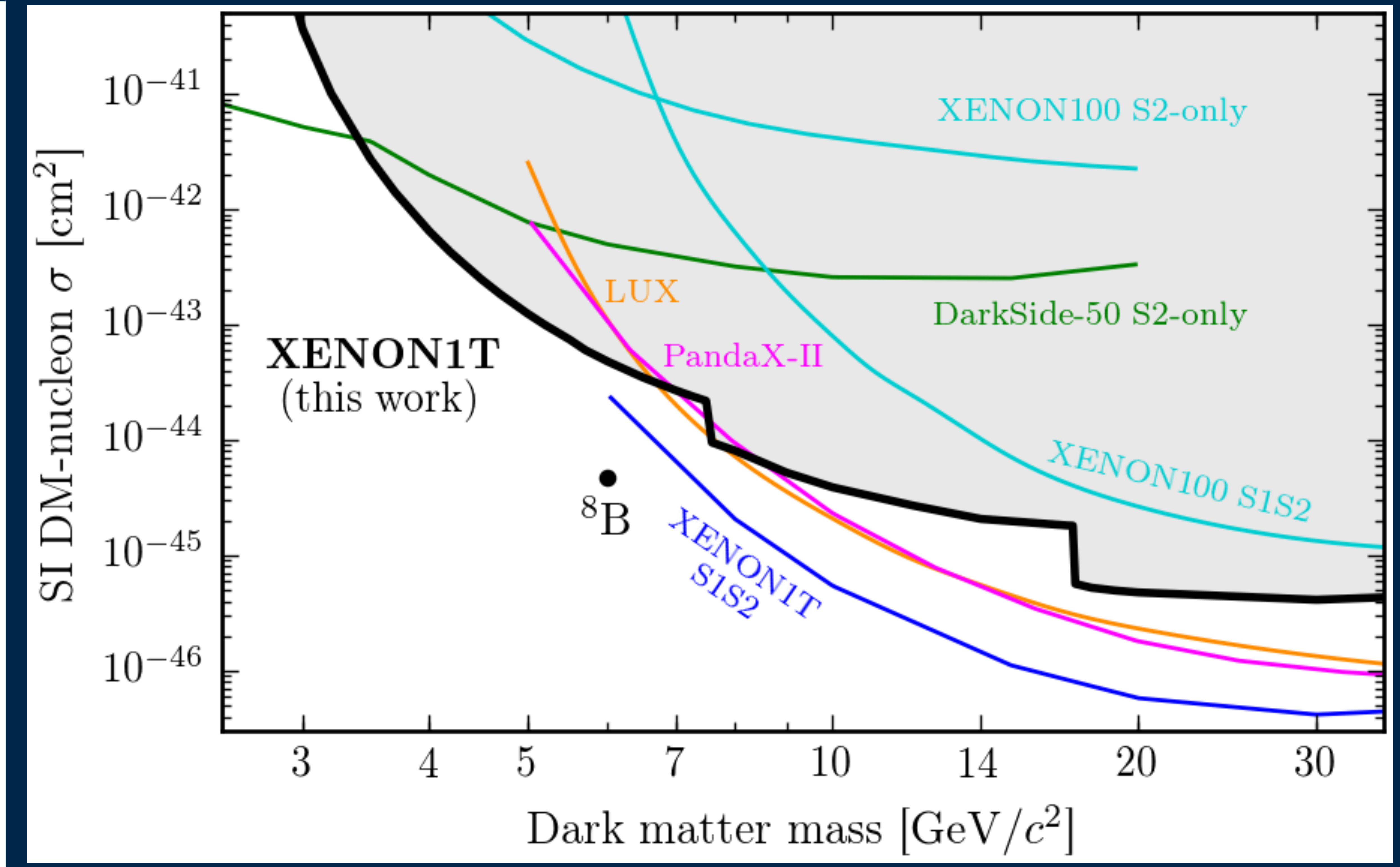
$$\dot{\delta}_{CDM} = 3\dot{\Phi} - \frac{k^2}{a^2}\theta_{CDM}$$

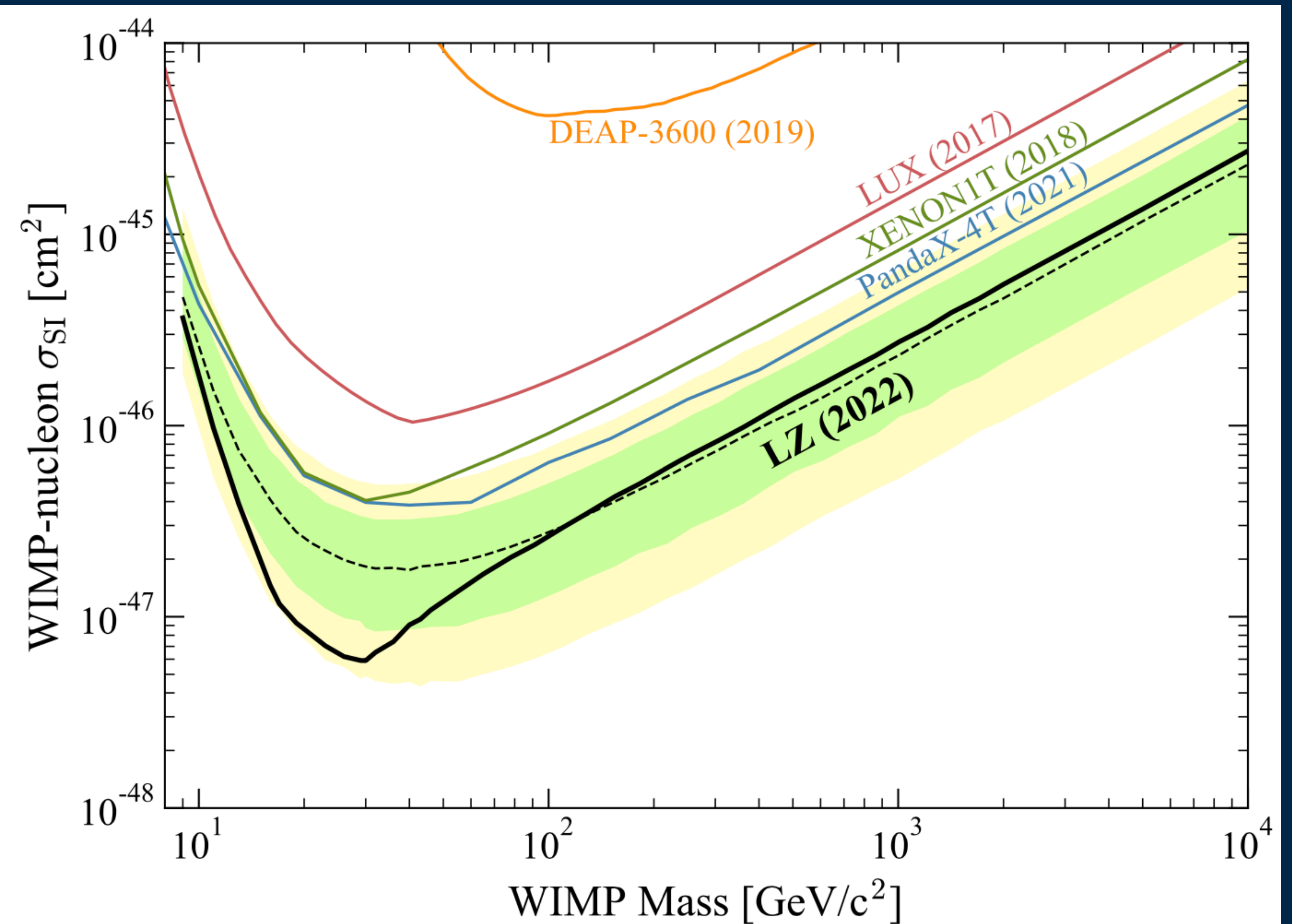
$$\dot{\theta}_{CDM} = \Psi$$

Xenon 1T collaboration



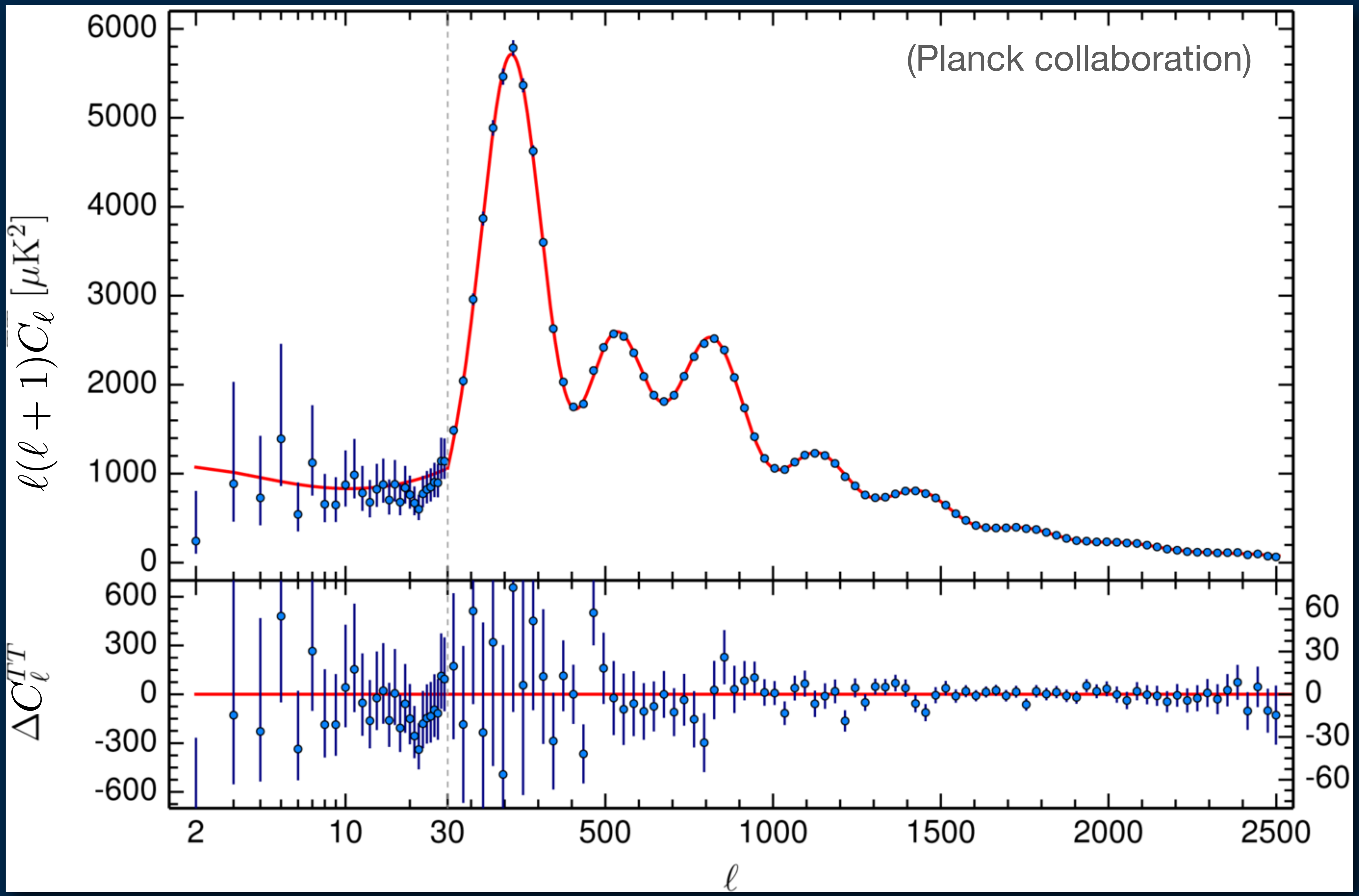
PhysRevLett, 123, 251801 (2019)

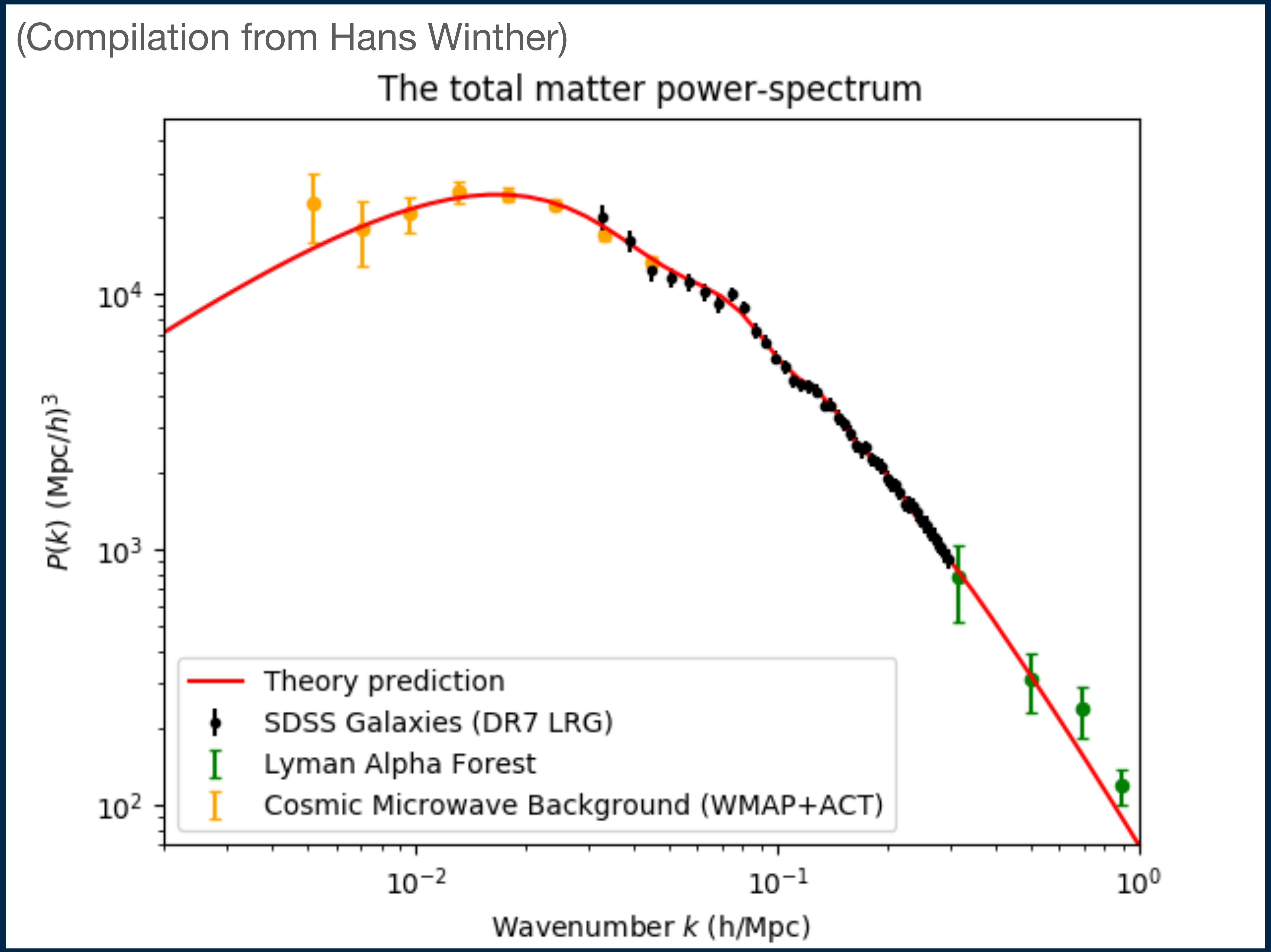




LZ collaboration
arXiv:2207.03764

ΛCDM: Success on large scales

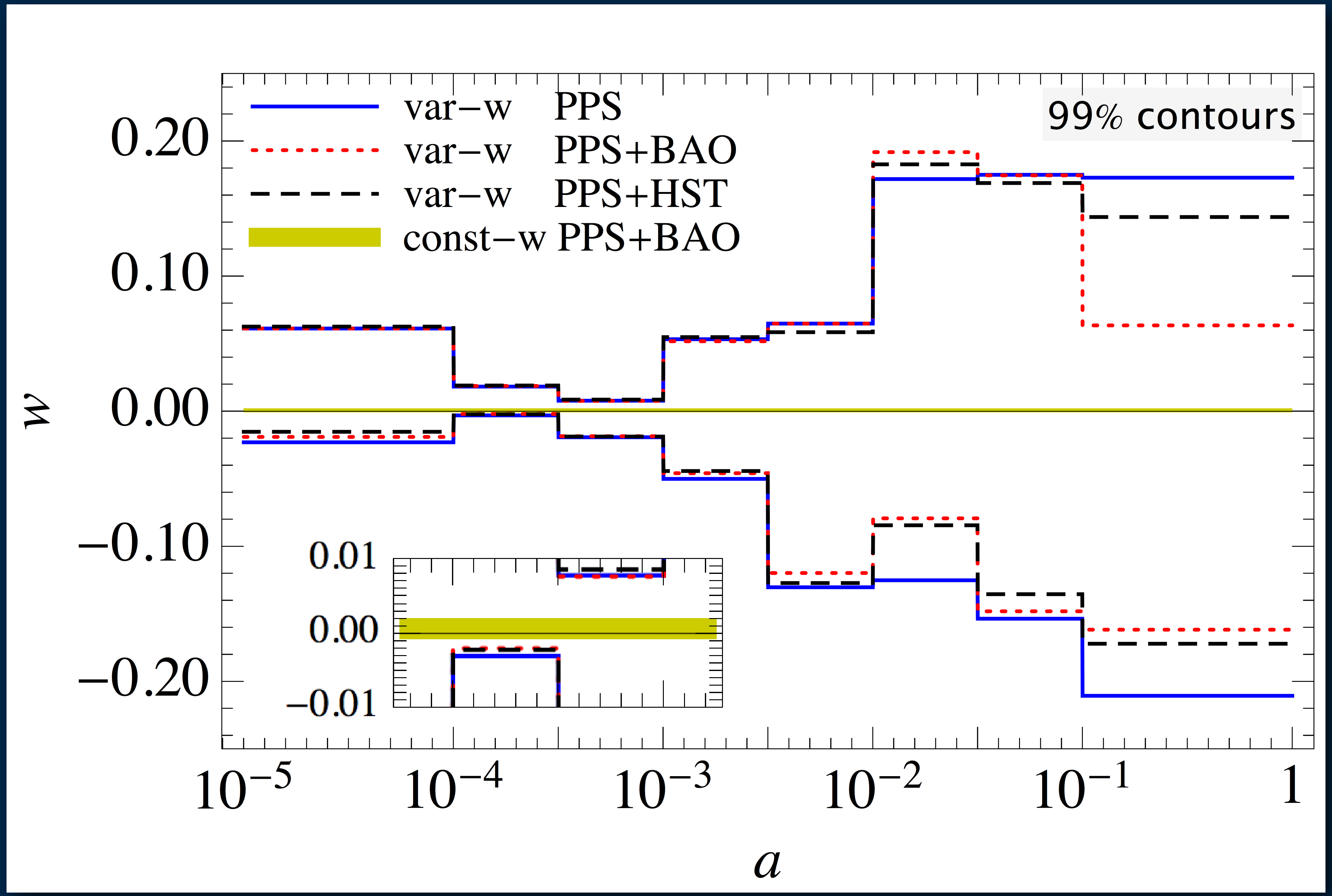


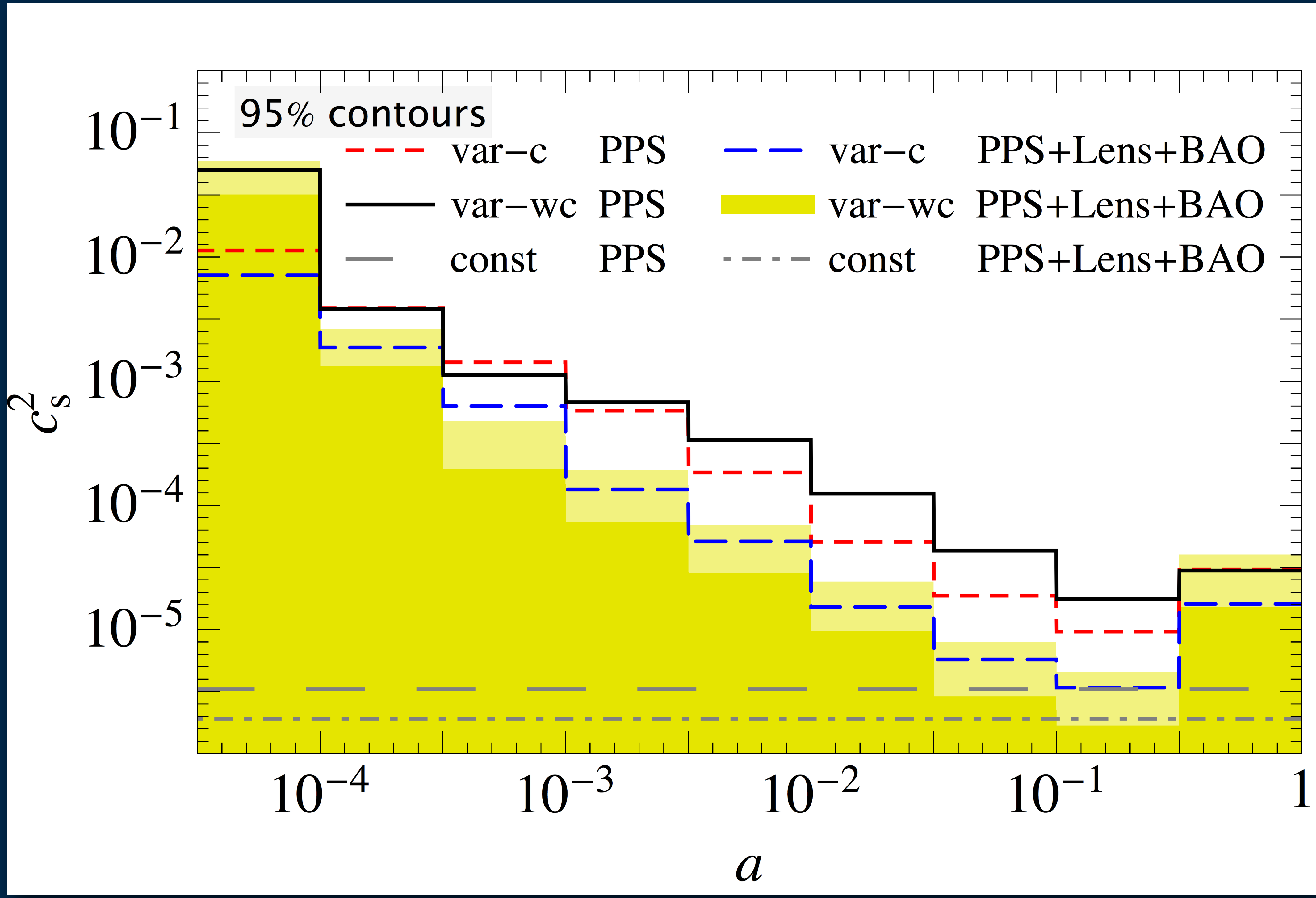


Generalized Dark Matter

$$P = w\rho$$
$$\delta P \sim c_s^2 \delta\rho$$

W. Hu, ApJ 506, 485 (1998)





GR + dust: large scale description of Universe is ΛCDM

$$0 < k \lesssim 0.1 (hMpc)^{-1}$$

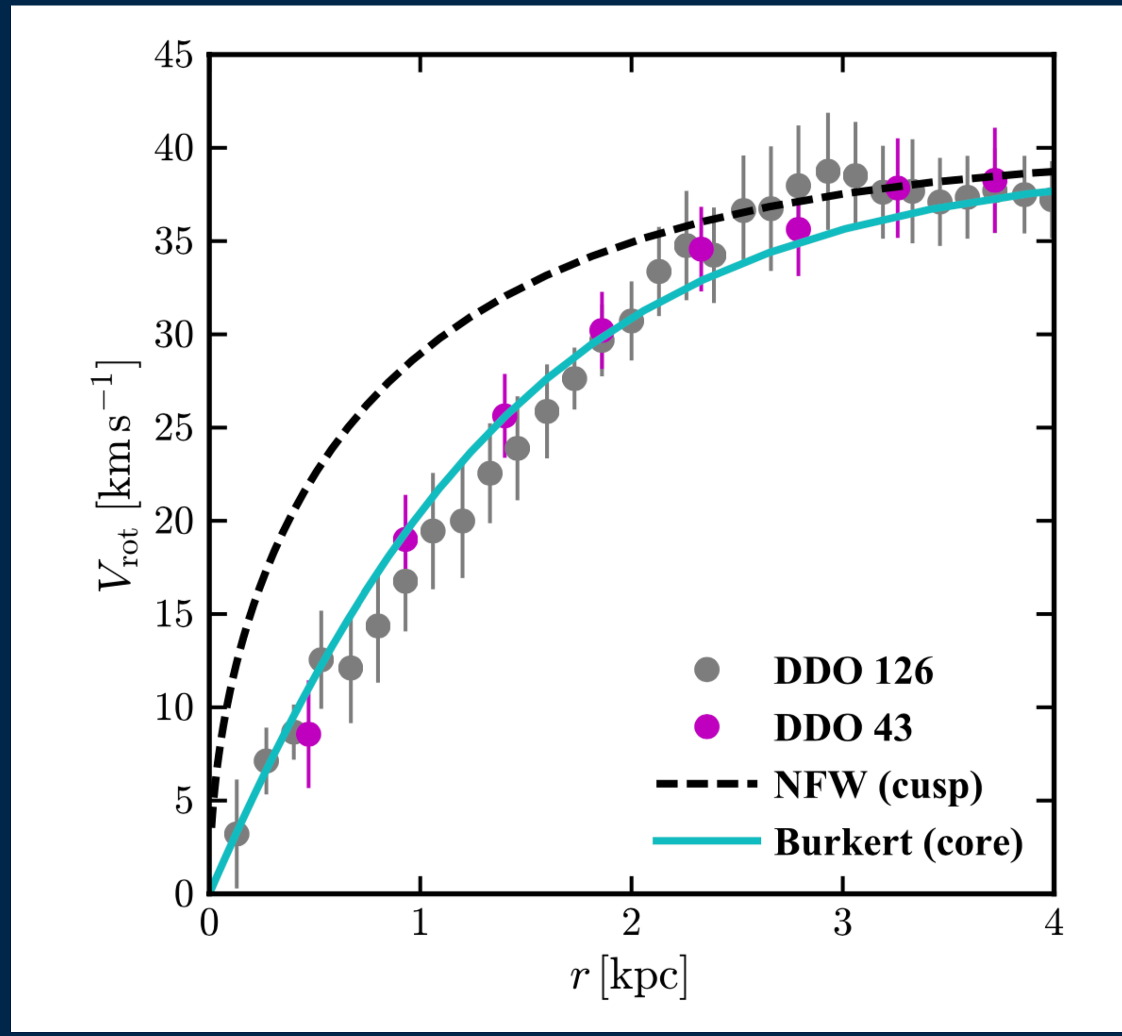
D. Thomas, M. Kopp, CS, S. Ilic, PRL120, 221102 (2018)

S. Ilic, M. Kopp, CS, D. Thomas, PRD 104, 043520 (2021)

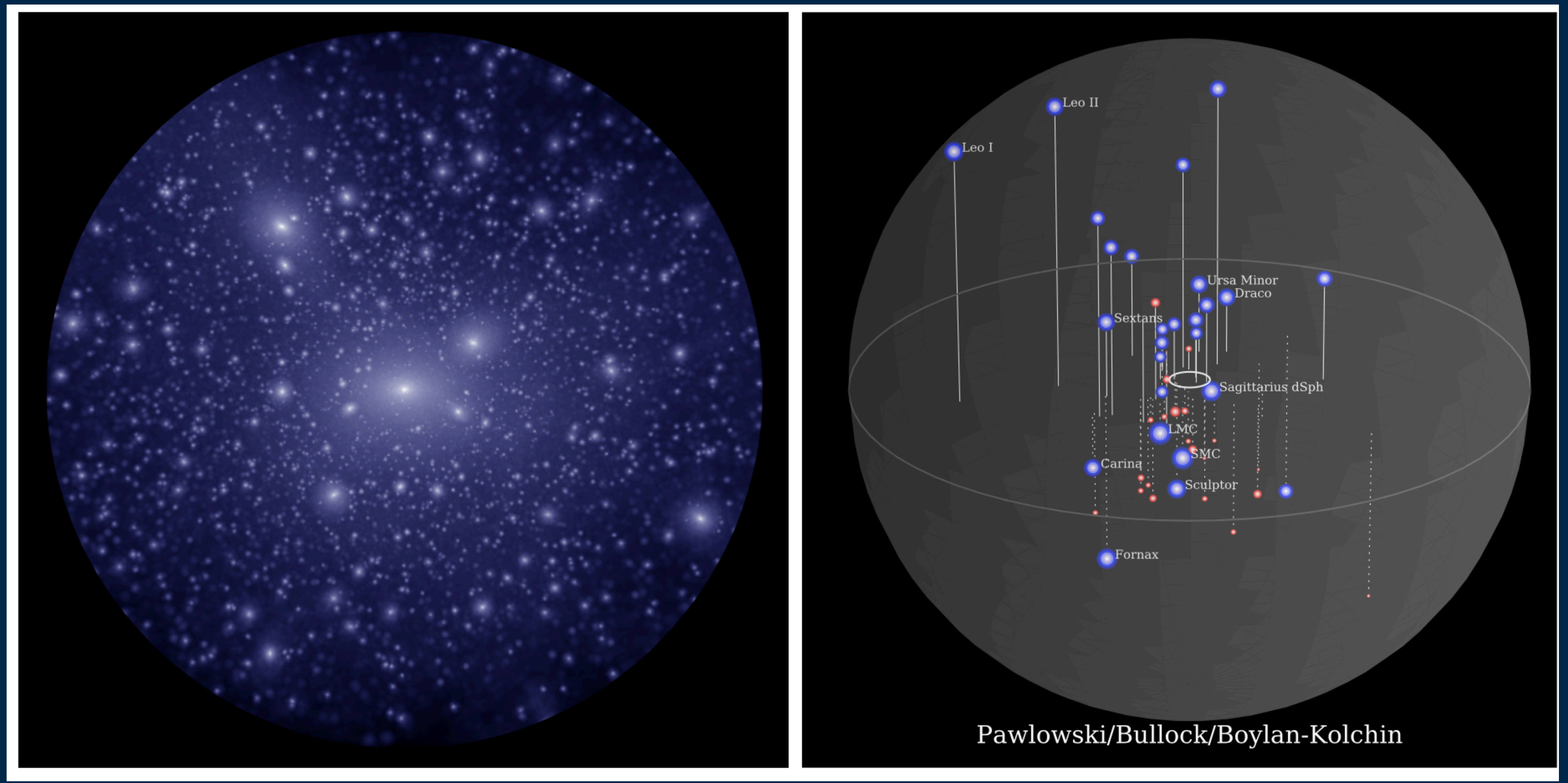
ΛCDM: small scales

See e.g. Bullock & Boylan-Kolchin (2017)

Core-Cusp — a.k.a diversity of rotation curves



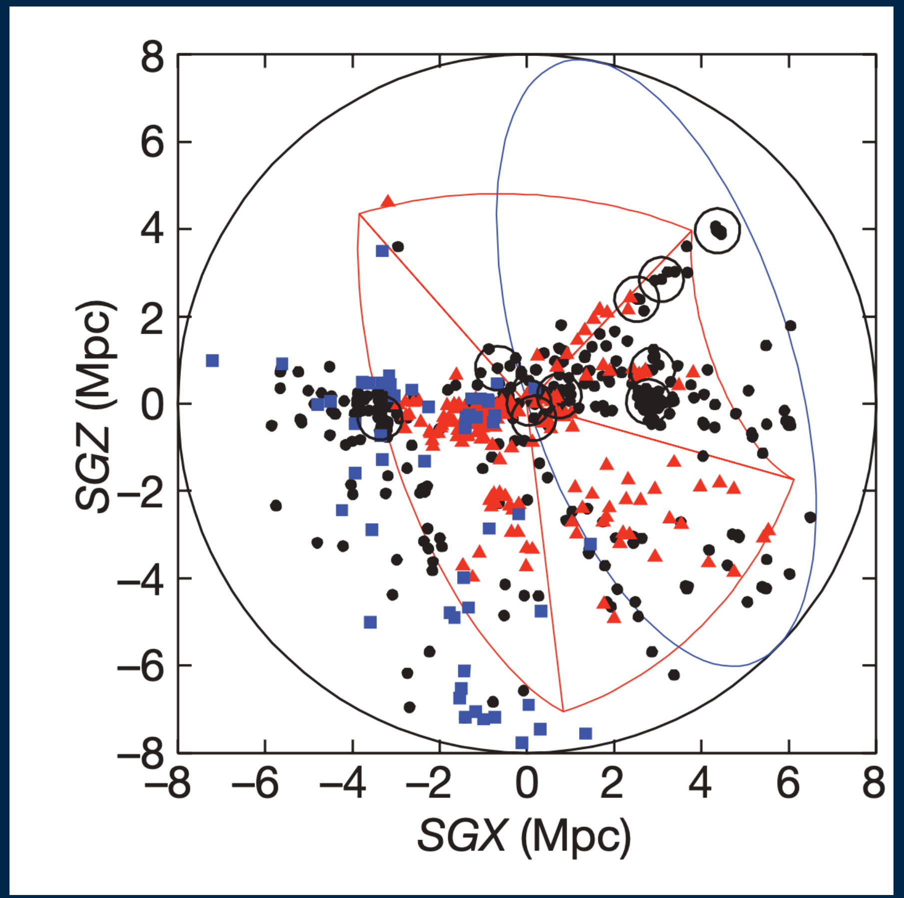
Missing satellites



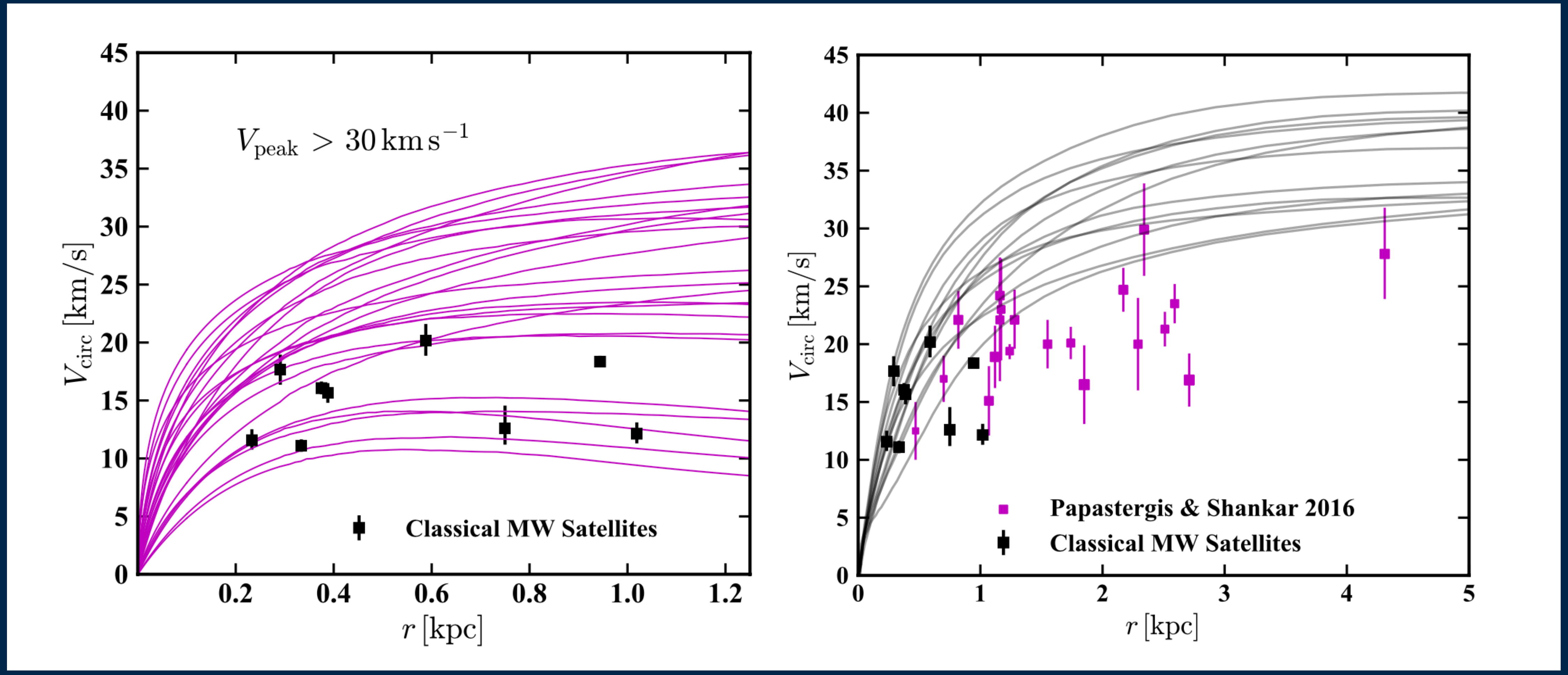
Challenges

Local void too empty

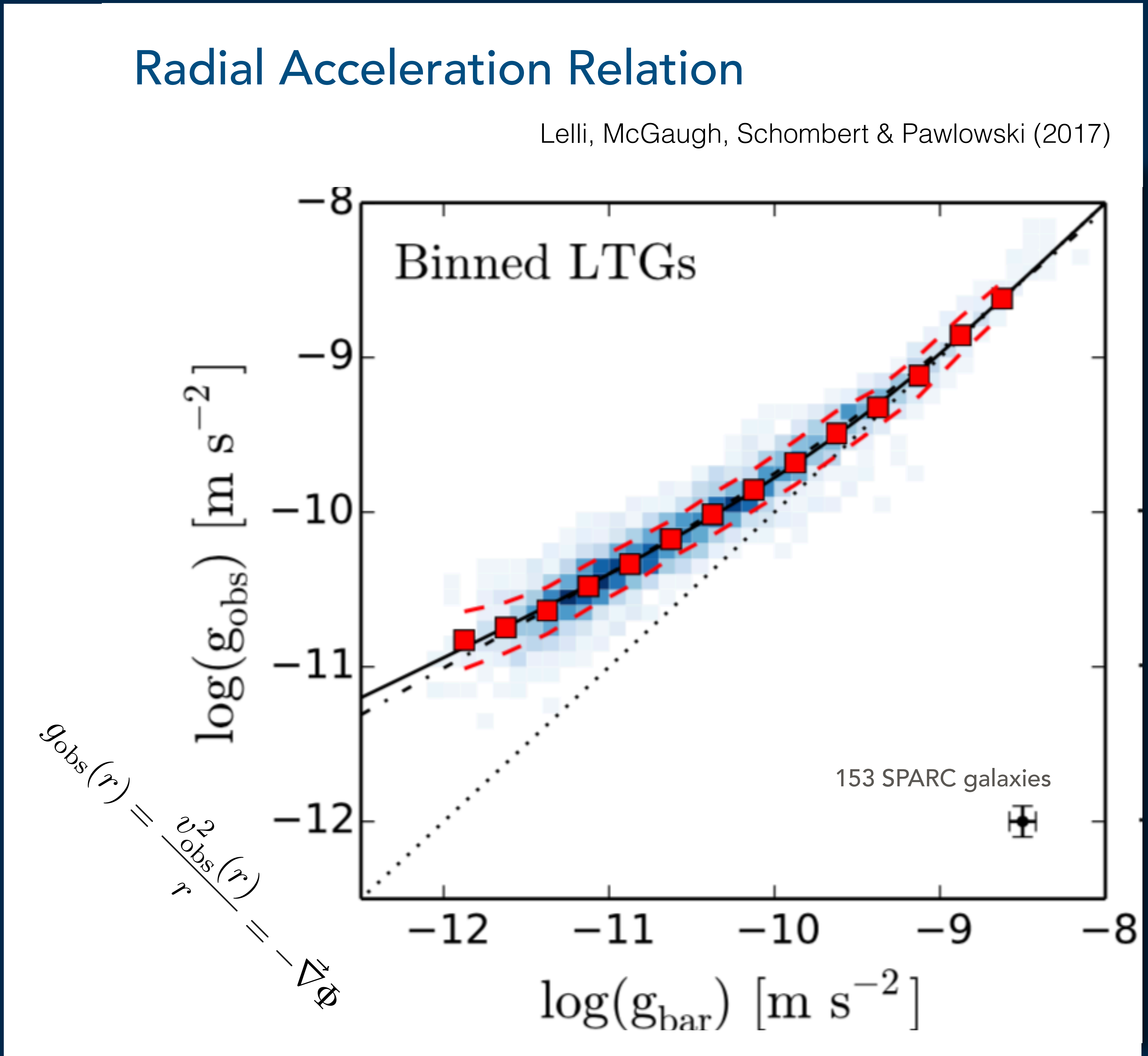
(Peebles & Nusser, Nature 2010)



Too-big-to-fail

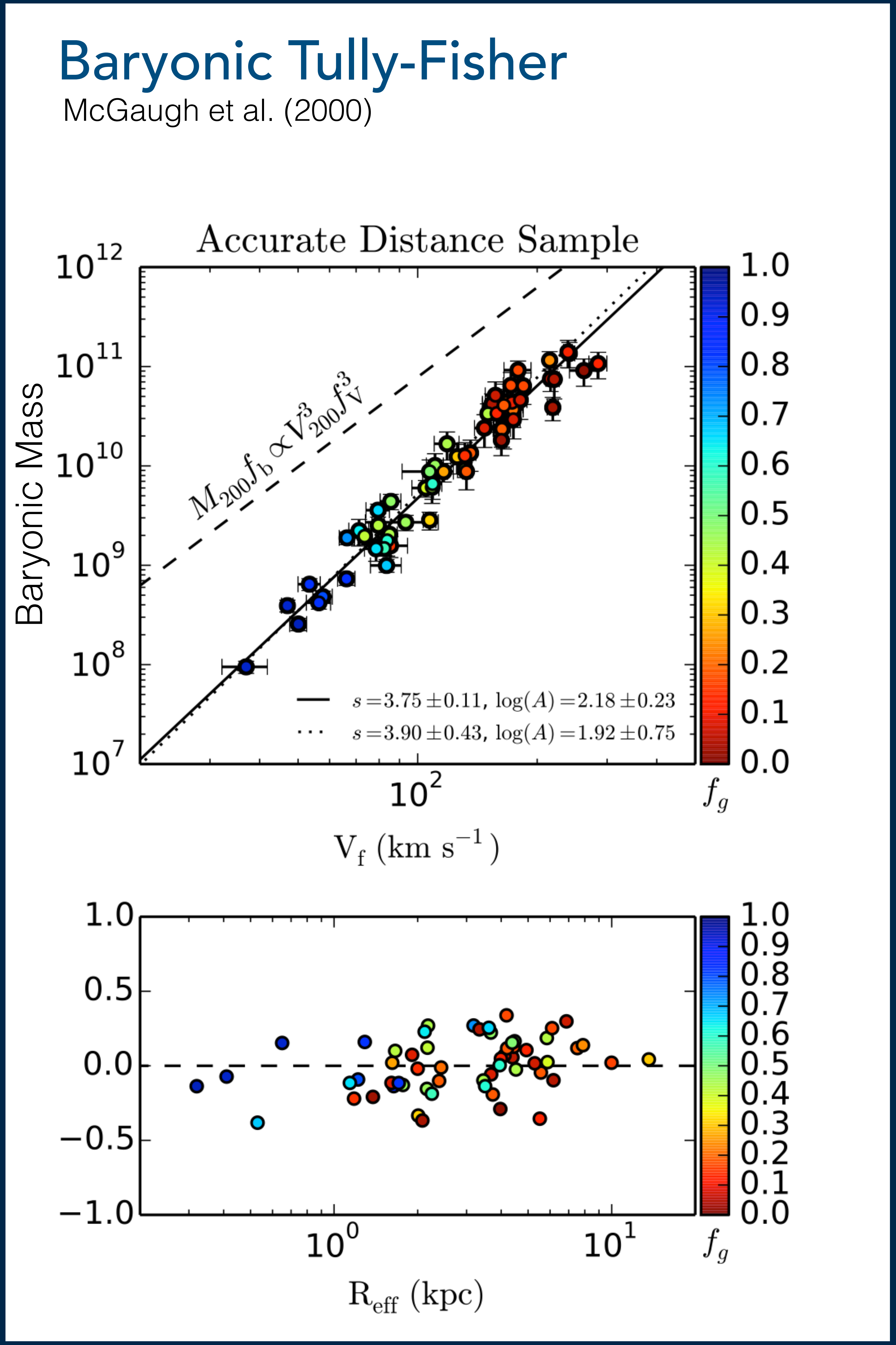


Regularity in galaxies



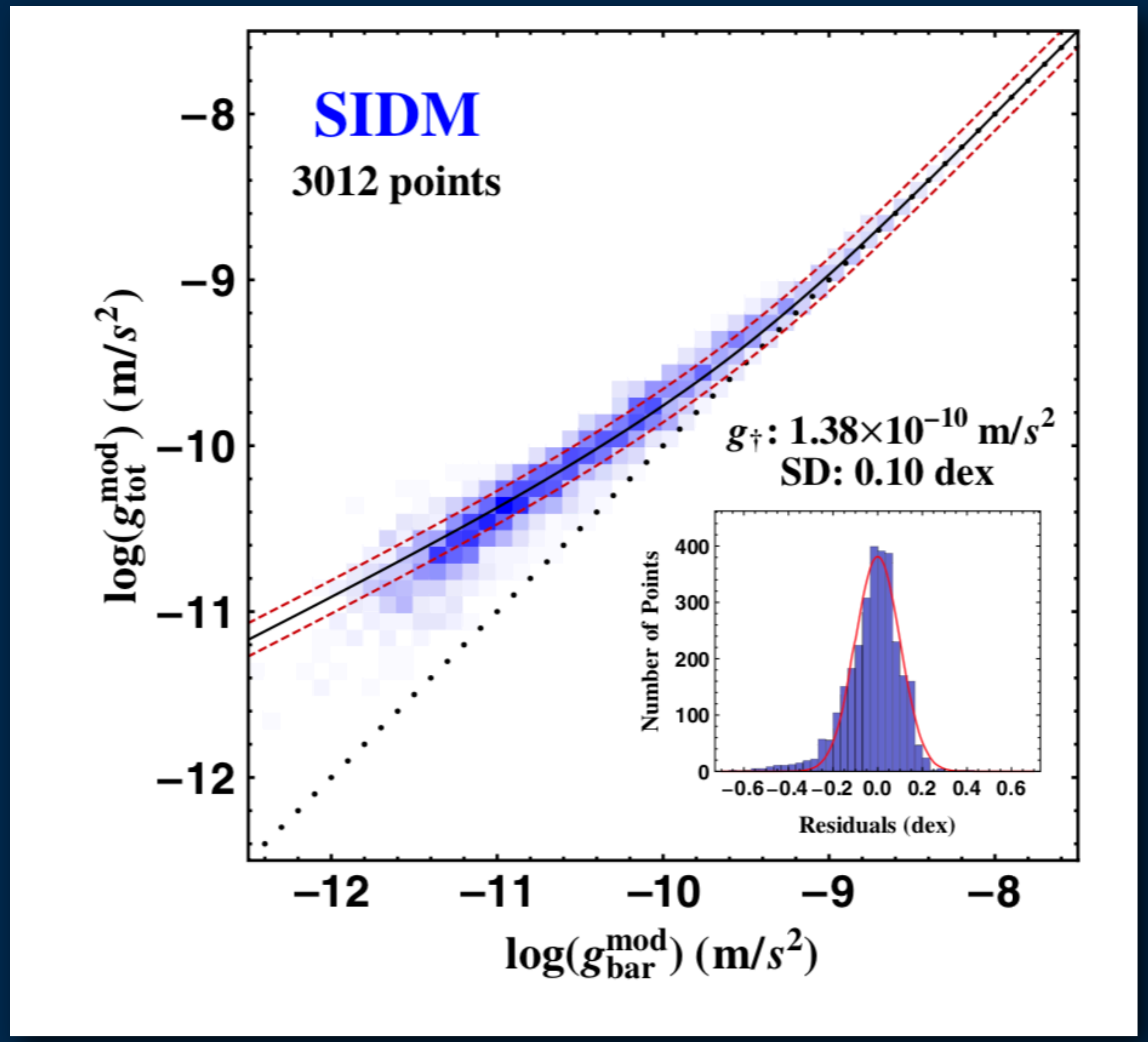
$$g_{obs}(r) = \frac{v_{obs}^2(r)}{r} = -\vec{\nabla}\Phi$$

$$g_{bar}(r) = \frac{v_{bar}^2(r)}{r} = -\vec{\nabla}\Phi_{bar}$$



DARK MATTER ++

Self-interacting Dark Matter



Spergel & Steinhardt, PRL 84, 3760 (2000)

Ren et al, PRX 9, 031020 (2019)

Vogelsberger, Zavala, et al

Dipolar dark matter (Blanchet 2007)

"gravitational polarization" → dipole moment → Emergence of universality (MOND)

Superfluid dark matter (Khoury & Berezhiani, 2015)

- Axion-like particles with mass of order eV and strong self-interactions.
- Aptly described as collective excitations: phonons
- Superfluid phonons: Goldstone bosons of a spontaneously broken global U(1) symmetry.
- Lagrangian put in by hand (no fundamental theory)


To summarize
No detection so far
Cold
Dark
Matter
Large scales $\gtrsim 100 Mpc$
No competing model fits so well
ΛCDM
Intermediate scales $\lesssim 100 Mpc$
Model fits very well $\gtrsim 1 Mpc$
Baryonic Feedback
ΛSiDM
ΛFDM
ΛDipDM
Λ SuperfluidDM
Λ?DM
Small scales $\lesssim 1 Mpc$
Challenges emerge
?
Regularity

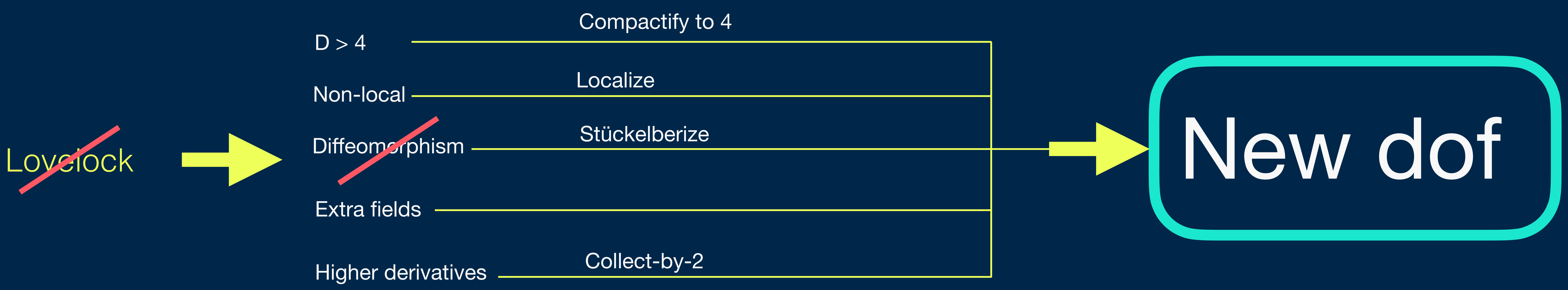
Extending GR

Lovelock's Theorem (1967) The only

- local,
- diffeomorphism invariant action,
- which leads to 2nd order field equations
- and which depends only on a metric

in 4D

is a linear combination of the Einstein-Hilbert action with a cosmological constant up to a total derivative: GR



New dof

$\varphi^{(I)} \quad \alpha_\mu^{(I)}$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Minkowski

$h_{\mu\nu}$

$\varphi^{(I)} \qquad \alpha_\mu^{(I)}$

Matter

e.g. $\mathcal{L} \sim (\partial h)^2 + (\partial\varphi)^2$

Transformations

$h_{\mu\nu} \leftrightarrow \alpha_\mu^{(I)}$

$\varphi^{(I)}$

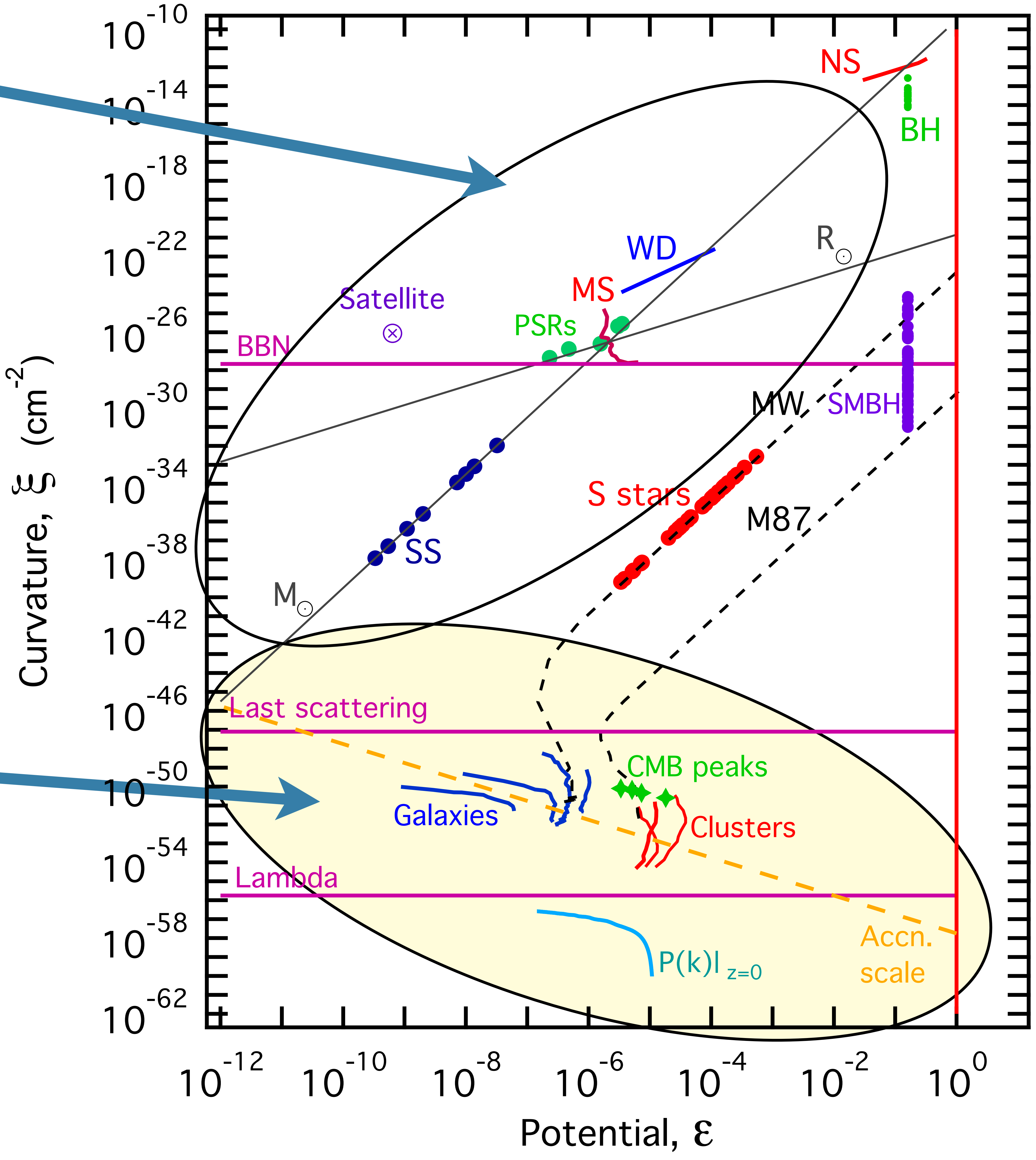
Gravity

e.g. $\mathcal{L} \sim (\partial h)^2 + (\partial\varphi)^2 + (\partial h)(\partial\varphi)$

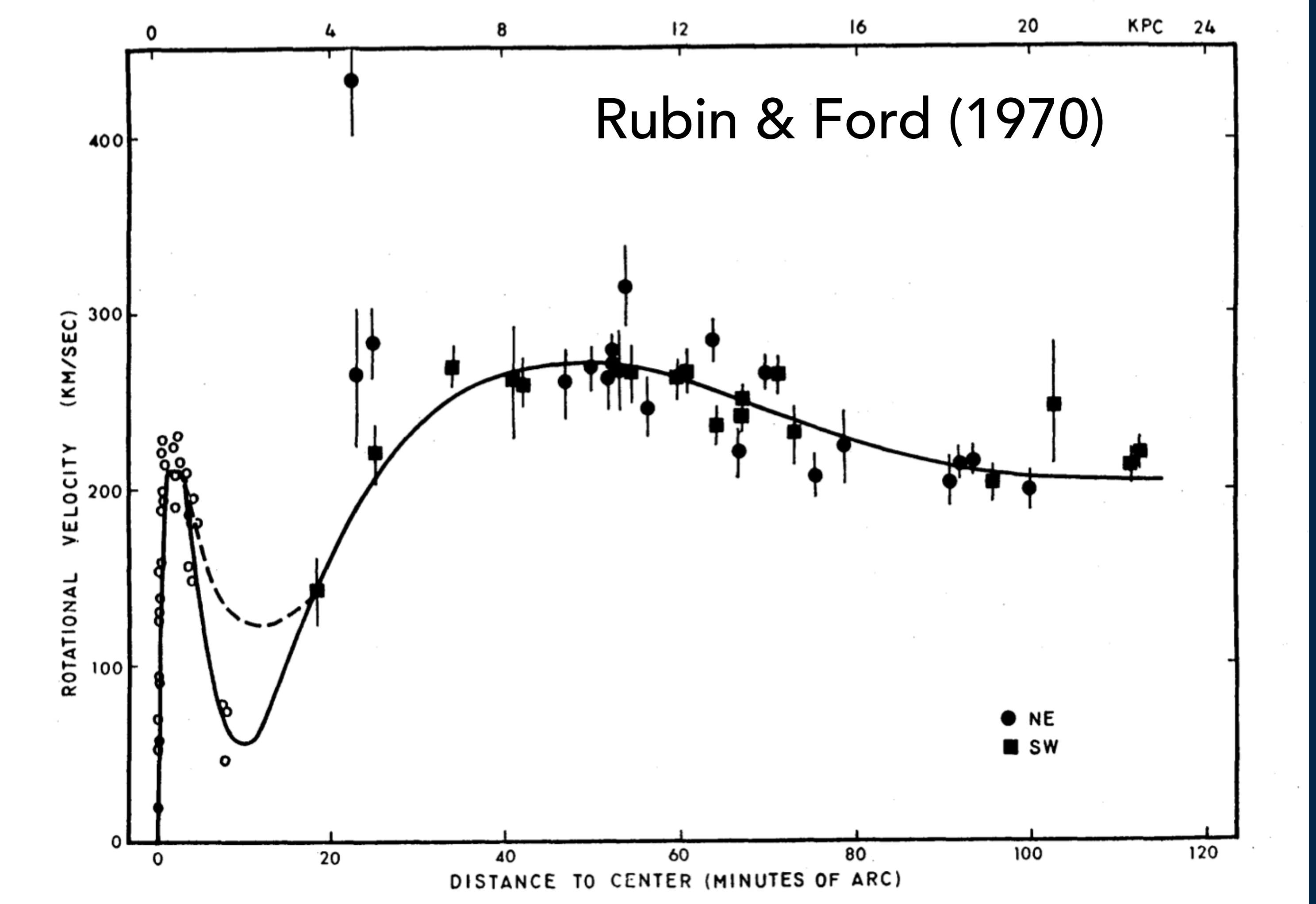
T. Baker, D. Psaltis and C.S., Astrophys. J. 802, 63 (2015)

- GR experimentally tested
- Deviations at $10^{-4} - 10^{-8}$ level
- New dof suppressed

- Need DM
- GR not tested
- New dof active

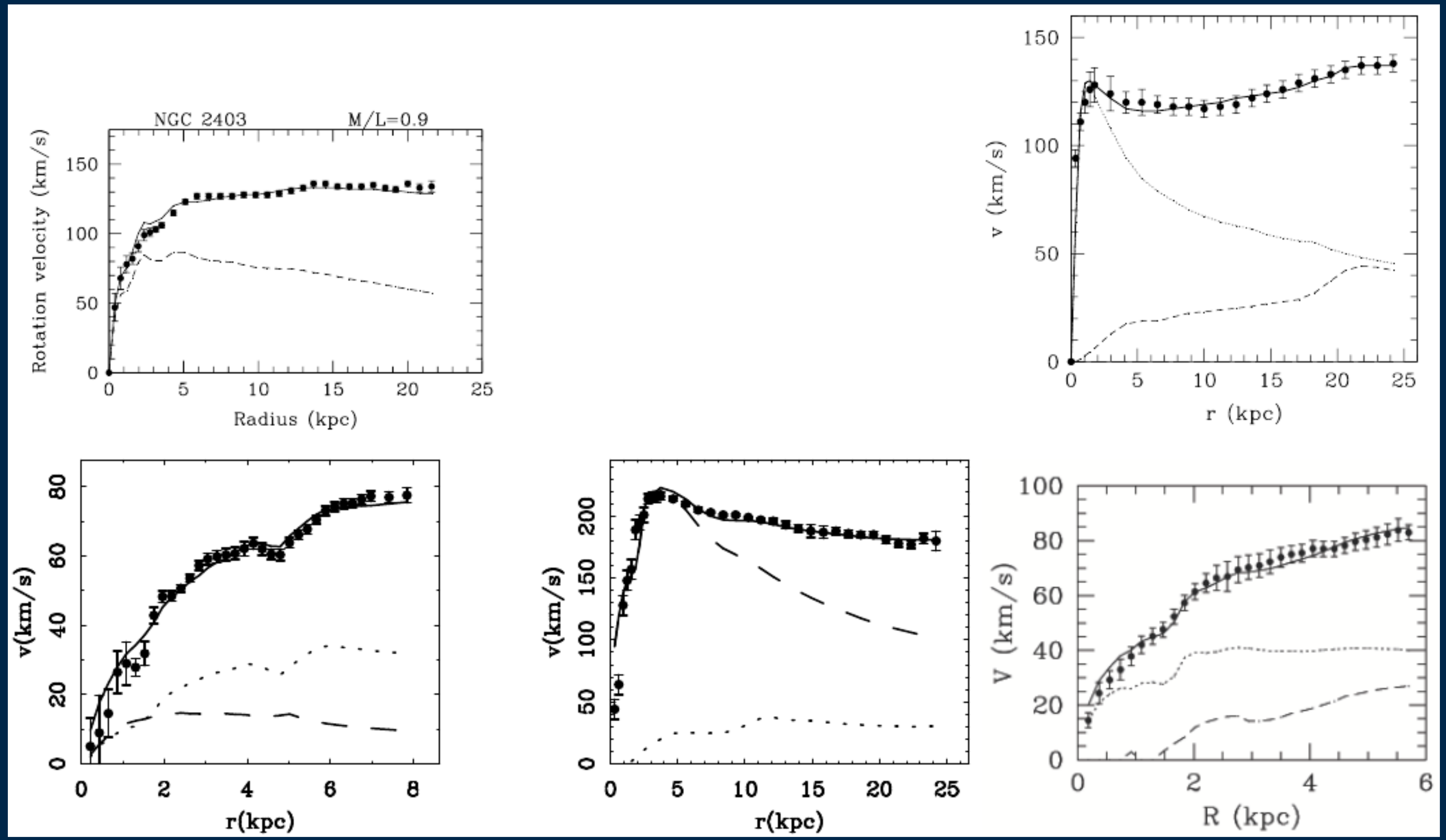


Phenomenology: galaxies



$v \sim$ const

$$\Rightarrow a \sim \frac{v^2}{r} \sim \frac{1}{r}$$



Modified Newtonian Dynamics

Milgrom (1983), Bekenstein & Milgrom (1984)

Deviation from Newton when

$$a < a_0 \sim 1.2 \times 10^{-10} m/s^2$$

Universal constant

$$\vec{\nabla} \cdot \left(\frac{|\vec{\nabla}\Phi|}{a_0} \vec{\nabla}\Phi \right) = 4\pi G_{\rm N} \rho$$

Not valid for

- Gravitational Lensing
- CMB
- LSS

→ Relativistic description

EXTENSION OF GR

?

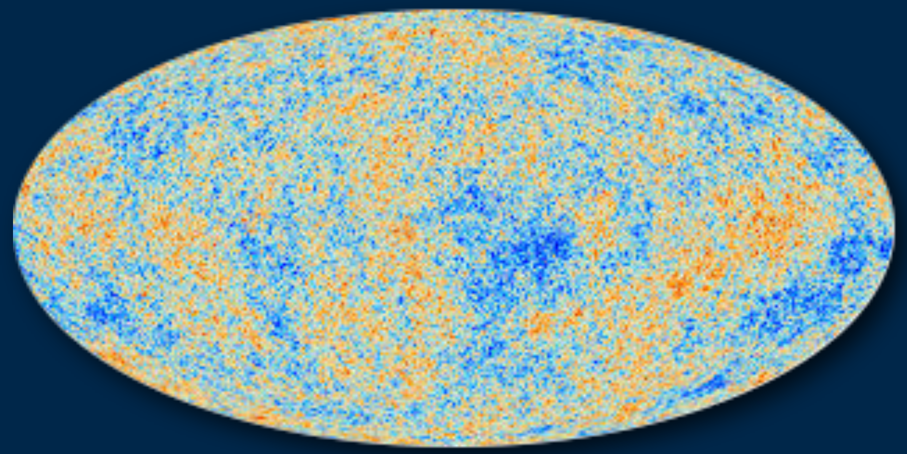
Φ

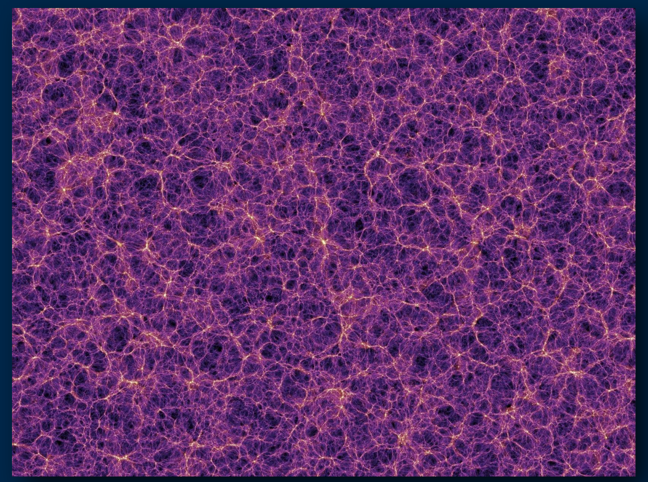
Non-relativistic, static: MOND

Bekenstein & Milgrom 1984

FRW + linear fluctuations

Effective description: ΛCDM





$\Phi = \Psi$

Lensing

aLIGO/Virgo + EM (2017)

Tensor speed = 1

New scalar dof. ϕ

Bekenstein & Milgrom (1984)

(Scalar-tensor theory)

$$g_{\mu\nu} = e^{-2\phi}\tilde{g}_{\mu\nu}$$

AQUAL

$$\vec{\nabla}\cdot\left(\frac{d\mathcal{J}}{d\mathcal{Y}}\vec{\nabla}\phi\right) = 4\pi G_N \rho$$

$$\vec{\nabla}\phi \sim \frac{G_N M}{r^2} + \vec{\nabla}\varphi$$

Parameter

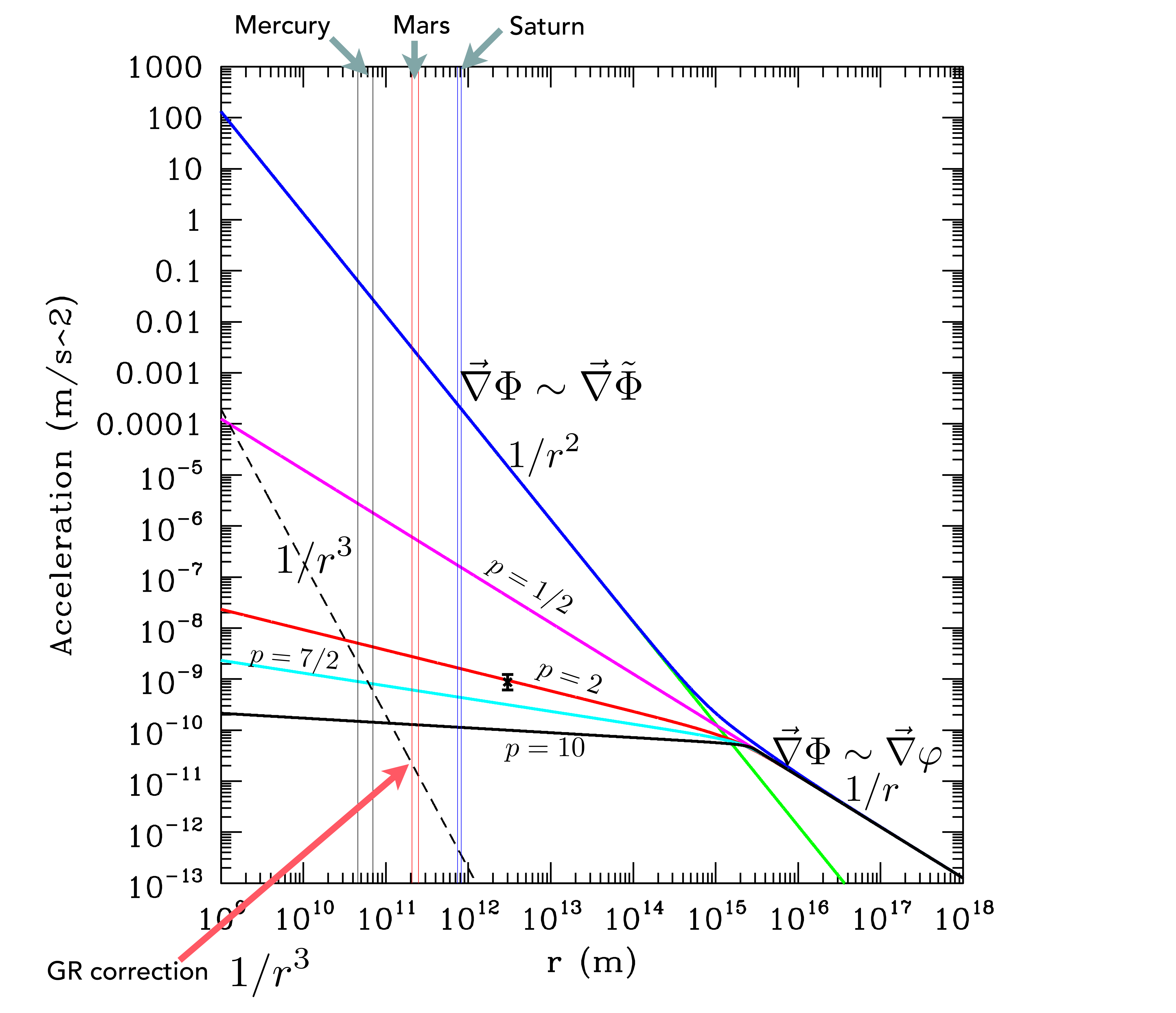
$$\mathcal{J}(\mathcal{Y}) \to \lambda_s \mathcal{Y} = \lambda_s |\vec{\nabla}\phi|^2 \qquad |\vec{\nabla}\phi| \gg a_0$$

$$\mathcal{J}(\mathcal{Y}) \to \frac{\mathcal{Y}^{3/2}}{a_0} = \frac{|\vec{\nabla}\varphi|^3}{a_0} \qquad |\vec{\nabla}\phi| \ll a_0$$

Parameter

Relativistic version gives wrong lensing formula

Quasistatic weak-field limit



Screening

$$\mathcal{L} \sim \mathcal{J}(\mathcal{Y}) \sim \frac{|\vec{\nabla}\varphi|^3}{a_0} + \beta_p \frac{|\vec{\nabla}\varphi|^{2(p+1)}}{a_0^{2p}}$$

$$p \to \infty \quad \Rightarrow \quad \vec{\nabla}\phi \to \text{const}$$

DBion — Burrage & Khoury (2014)

$$f \equiv \frac{d\mathcal{J}}{d\mathcal{Y}}$$

Tracking

$$\vec{\nabla} \cdot \left[f\left(\frac{|\vec{\nabla}\varphi|}{a_0}\right) \vec{\nabla}\varphi \right] = 4\pi G\rho$$

Interpolation function: $f\left(\frac{|\vec{\nabla}\varphi|}{a_0}\right)$

$\frac{|\vec{\nabla}\varphi|}{a_0} \gg 1$ → Const.

$\frac{|\vec{\nabla}\varphi|}{a_0} \ll 1$ → $\frac{|\vec{\nabla}\varphi|}{a_0}$

?

$$\vec{\nabla} \cdot \left(\frac{d\mathcal{J}}{d\mathcal{Y}} \vec{\nabla}\phi \right) = 4\pi G_N \rho$$

$$\vec{\nabla}\phi \sim \frac{G_N M}{r^2} + \vec{\nabla}\varphi$$

Parameter (λ_s)

$$\mathcal{J}(\mathcal{Y}) \to \lambda_s \mathcal{Y} = \lambda_s |\vec{\nabla}\phi|^2 \qquad |\vec{\nabla}\phi| \gg a_0$$

$$\mathcal{J}(\mathcal{Y}) \to \frac{\mathcal{Y}^{3/2}}{a_0} = \frac{|\vec{\nabla}\varphi|^3}{a_0} \qquad |\vec{\nabla}\phi| \ll a_0$$

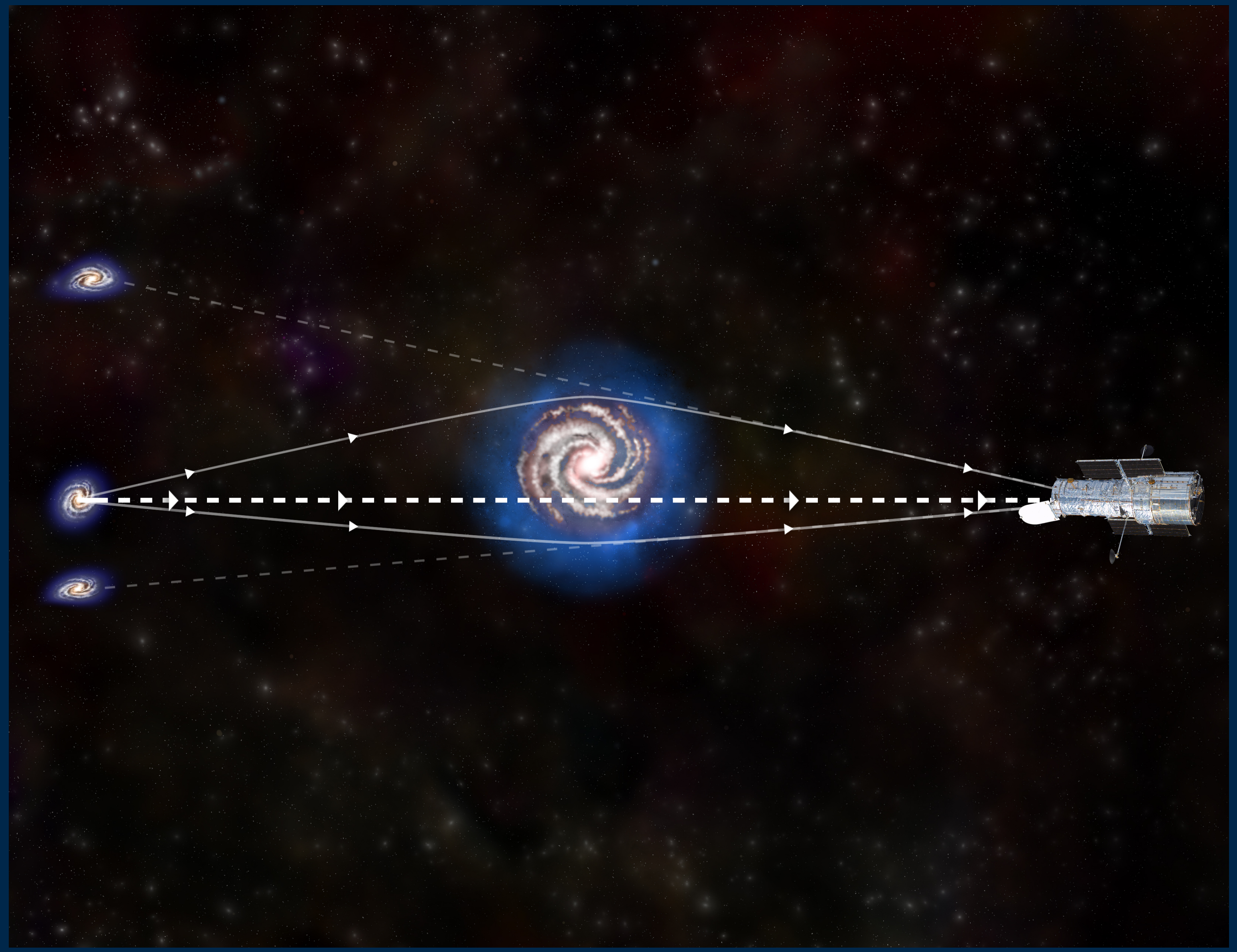
Parameter (a_0)

Screening: $\lambda_s \to \infty$

Tracking: requires $\mathcal{J}(\mathcal{Y})$ To be non-analytic

Example: $\mathcal{J} = \lambda_s \left\{ \mathcal{Y} - 2a_0(1+\lambda_s)\sqrt{\mathcal{Y}} + 2(1+\lambda_s)^2 a_0^2 \ln\left[1 + \frac{\sqrt{\mathcal{Y}}}{(1+\lambda_s)a_0} \right] \right\}$

New time-like vector dof A_μ



$$ds^2 = -(1+2\Phi)dt^2 + (1-2\Phi)d\vec{x}^2$$

$$\Phi = \tilde{\Phi} + \varphi$$

$\rightarrow$ $ds^2 \neq e^{\pm 2\varphi}\left[-e^{2\tilde{\Phi}}dt^2 + e^{-2\tilde{\Phi}}d\vec{x}^2\right]$

But:

$$g_{\mu\nu} = e^{-2\phi}\tilde{g}_{\mu\nu} - \left(e^{2\phi} - e^{-2\phi}\right)A_\mu A_\nu$$

$$\tilde{g}^{\mu\nu}A_\mu A_\nu = -1$$

Sanders, ApJ 480, 492 (1997)

$\downarrow$

Tensor-Vector-Scalar theory: Bekenstein, PRD 70, 083509 (2004)

Disagreement with CMB

Agreement with matter power spectrum

Skordis, Mota, Ferreira, Boehm, PRL 96, 011301 (2006)
Dodelson & Liguori, PRL 97, 231301 (2006)

Tensor mode speed $\neq 1$

Boran et al., PRD 97, 041501 (2018)
C.S & Zlosnik, PRD 100, 104013 (2019)

C.S. & Zlosnik, PRL 127, 161302 (2021)

•Aether Scalar Tensor (AeST)

MOND

On galactic scales

Λ CDM

On cosmological scales

One metric: $g_{\mu\nu}$

TeVeS theory

(Sanders (1997), Bekenstein (2004) : two metrics)

Tensor mode speed $\neq 1$

Disagreement with CMB

New scalar dof. ϕ

ΛCDM

Scherrer (2004)

Arkani-Hamed et al (2004)

Bekenstein & Milgrom (1984)

MOND

Sanders (1997), Bekenstein (2004)

TeVeS theory

Aether:

New time-like vector dof. A_μ

Gauge ghost condensate

Cheng et al (2006)

Dirac's new theory of electrons (1963)

Lorentz violation

Einstein-Aether theory

Jacobson. & Mattingly (2002)

Bumblebee field

Kostelecky & Samuel, PRD 40, 1886 (1989)

C.S. & Zlosnik, PRL 127, 161302 (2021)

Ingredients:

$g_{\mu\nu}$ ϕ A_μ

Tensor speed = 1

Skordis & Zlosnik (2019)

Parameter

"Magic function"

$A^\mu A_\mu = -1$

Unit-timelike

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi\tilde{G}} \left[R - \frac{K_B}{2} F^{\mu\nu} F_{\mu\nu} + 2(2 - K_B) J^\mu \nabla_\mu \phi - (2 - K_B)\mathcal{Y} - \mathcal{F}(\mathcal{Y}, \mathcal{Q}) - \lambda \left(A^\mu A_\mu + 1\right) \right] + S_m[g]$$

$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$

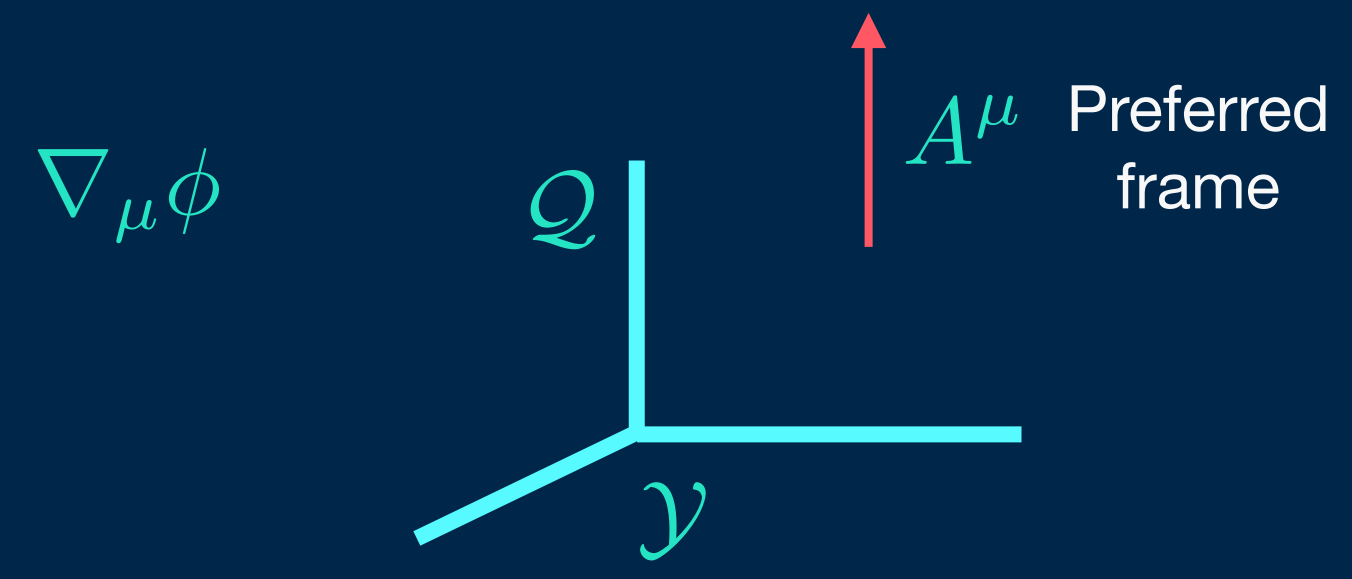
$J_\mu = A^\nu \nabla_\nu A_\mu$

Spatial gradients

$$\mathcal{Y} = \left(g^{\mu\nu} + A^\mu A^\nu\right) \nabla_\mu \phi \nabla_\nu \phi \to |\vec{\nabla}\phi|^2$$

$$\mathcal{Q} = A^\mu \nabla_\mu \phi \to \dot{\phi}$$

Time evolution



Quasistatic weak-field limit

$$\phi = \mathcal{Q}_0 t + \varphi(\vec{x})$$

$$ds^2 = -\left(1 + 2\Psi\right) dt^2 + \left(1 - 2\Phi\right) d\vec{x}^2$$

$$A^0 = 1 - \Psi$$

Symmetry: $\dot{\xi}_T = 0$

$$A_i \to A_i - \vec{\nabla}_i \xi_T$$

$$\varphi \to \varphi + \mathcal{Q}_0 \xi_T$$

Ignoring curl, set $A_i = 0$

$$\vec{\nabla}\phi = \vec{\nabla}\varphi$$

$$\mathcal{Y} \to |\vec{\nabla}\varphi|^2$$

$$\mathcal{Q} \to \mathcal{Q}_0$$

$$\mathcal{F}\left(\mathcal{Y}, \mathcal{Q}\right) \to \mathcal{J}\left(\mathcal{Y}\right)$$

MOND:

$$\mathcal{J} \sim \frac{\mathcal{Y}^{3/2}}{a_0} \sim \frac{|\vec{\nabla}\varphi|^3}{a_0}$$

Field equations

Constraint:

$$\Psi = \Phi$$

Lensing ok

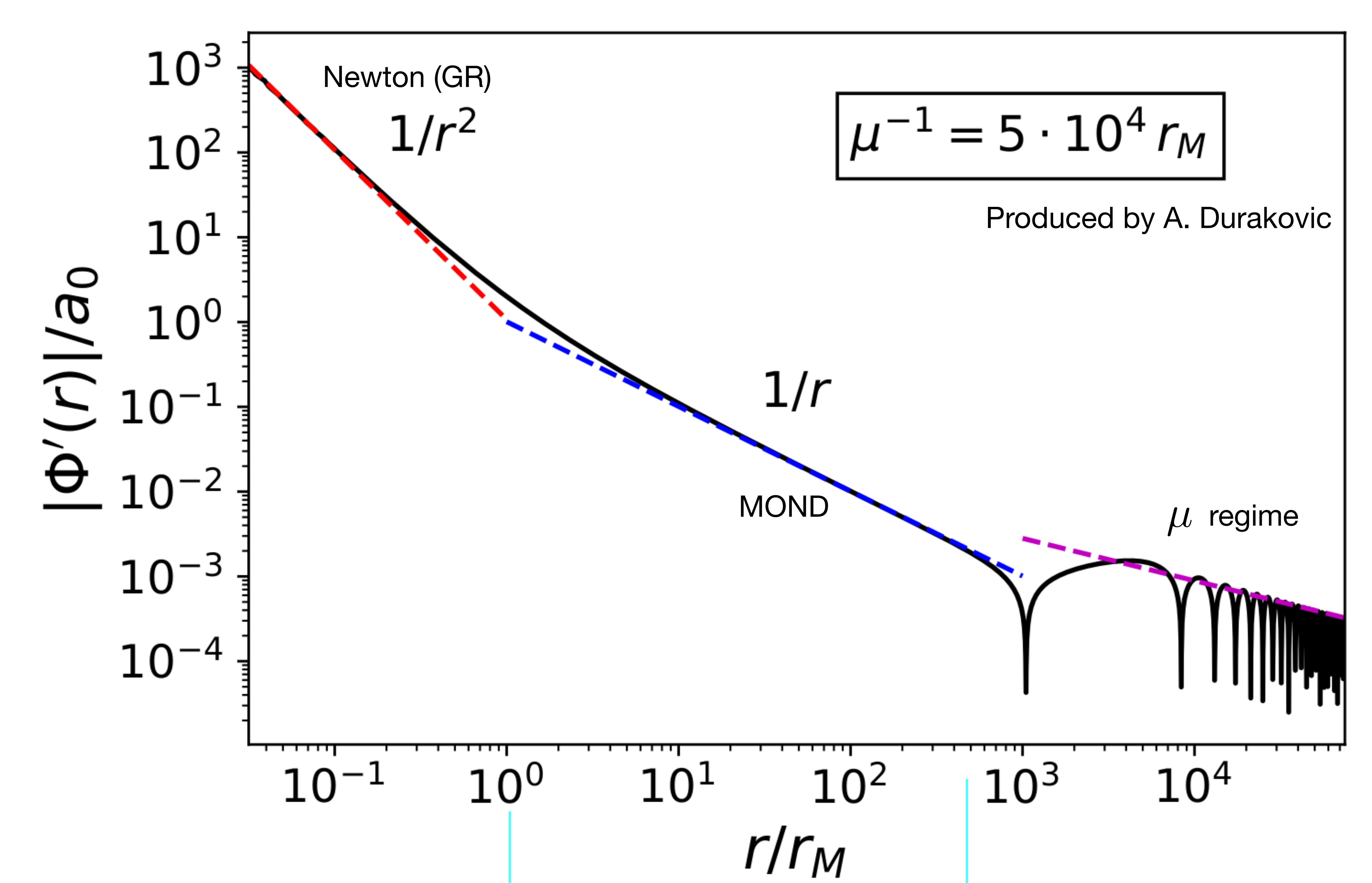
If Ψ correctly given by baryons alone
then
Ψ also gives correct lensing potential

Quasistatic weak-field limit

$$\vec{\nabla}^2(\Phi-\varphi)=\vec{\nabla}\cdot\left(\frac{d\mathcal{J}}{d\mathcal{Y}}\vec{\nabla}\varphi\right)$$

$$\vec{\nabla}^2(\Phi-\varphi)+\mu^2\Phi=\frac{8\pi\tilde{G}}{2-K_{\rm B}}\rho$$

$$\mu^2=\frac{2\mathcal{K}_2}{2-K_B}Q_0^2$$



Galaxies ok

?

$r_M\sim\sqrt{\frac{GM}{a_0}}$

$r_C\sim\left(\frac{r_M}{\mu^2}\right)^{1/3}$

$\mu^{-1}\gtrsim Mpc$ $(\mu\lesssim 6\times10^{-30}eV)$

$\mathcal{J}(\mathcal{Y})\to(2-K_{\rm B})\lambda_s\mathcal{Y}$

$\mathcal{J}(\mathcal{Y})\to\frac{\mathcal{Y}^{3/2}}{a_0}=\frac{|\vec{\nabla}\varphi|^3}{a_0}$

FLRW cosmology

$$\phi = \bar{\phi}(t)$$

$$A^0 \to 1$$

$$ds^2 = -dt^2 + a^2 d\vec{x}^2$$

→

$$\mathcal{Y} = 0$$
$$\mathcal{Q} = \mathcal{Q}(t)$$

→

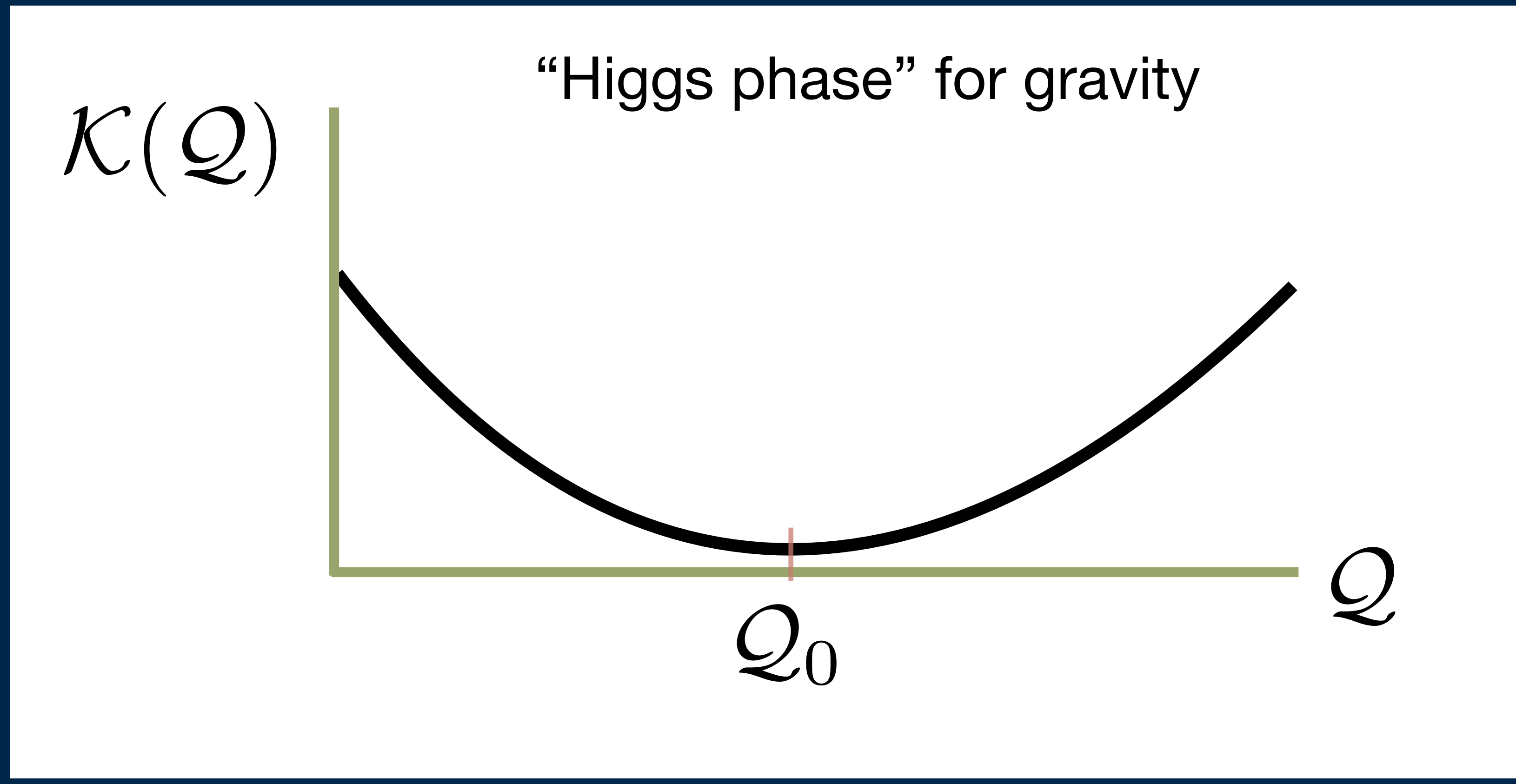
$$\mathcal{F}(\mathcal{Y}, \mathcal{Q}) \to -2\mathcal{K}(\mathcal{Q})$$

(K-essence)

ΛCDM →

$$\mathcal{K}(\mathcal{Q}) = \mathcal{K}_2 \left(\mathcal{Q} - \mathcal{Q}_0\right)^2 + \ldots$$

Parameter



Spontaneous breaking of Lorentz symmetry: Massive fields generated

Shift-symmetric k-essence:

Scherrer, Phys.Rev.Lett. 93, 011301 (2004)

FLRW Limit of Ghost condensate

Arkani-Hamed et al., JHEP 05, 074 (2004)

New scalar dof mixing with metric:

$$\phi = \mathcal{Q}_0 t + \varphi$$

$$h_{00} \to h_{00} - 2\dot{\xi}$$
$$\varphi \to \varphi + \mathcal{Q}_0 \xi$$

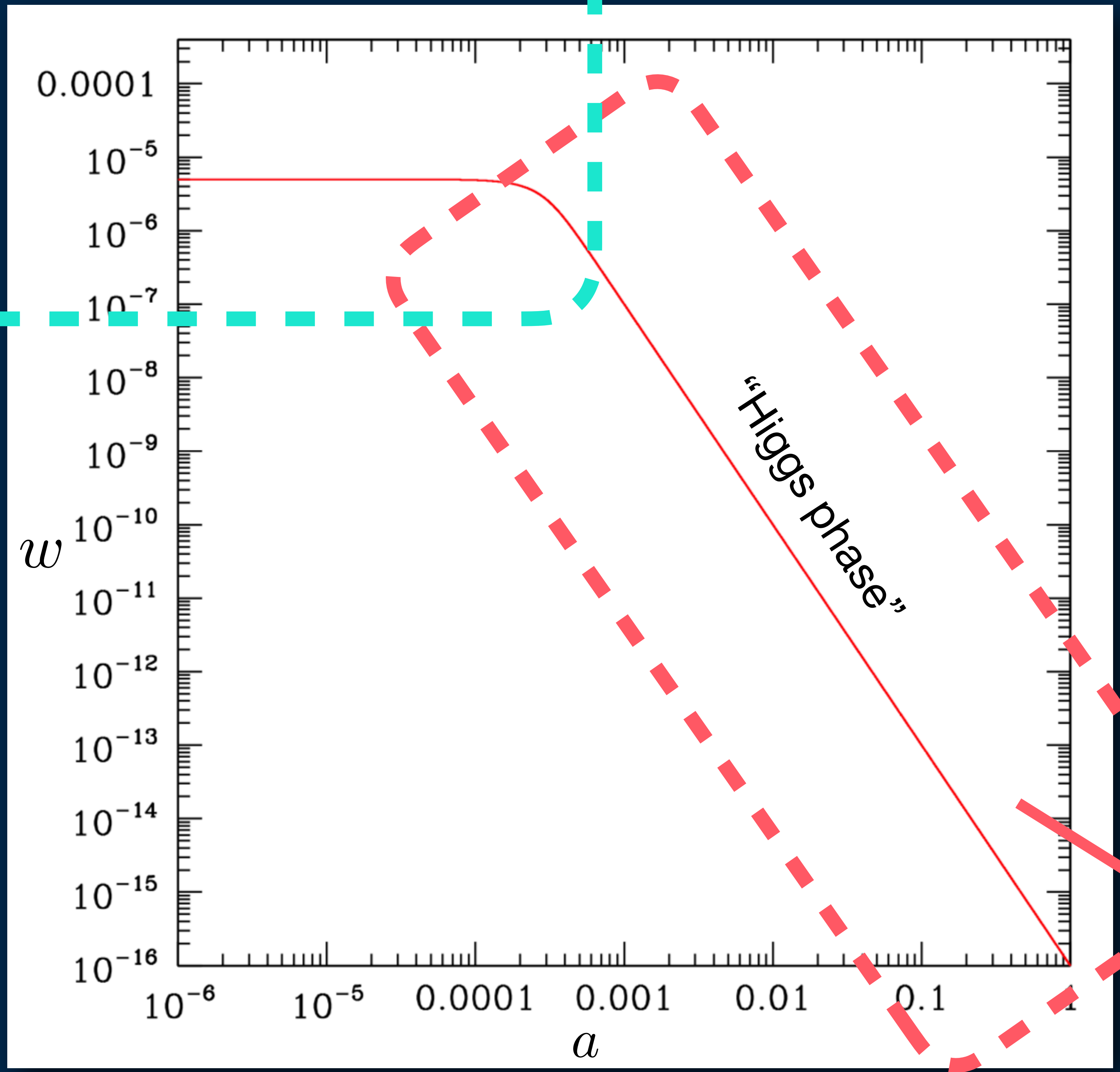
FLRW cosmology

Initial condition

EOM: $\frac{d}{dt}\left(a^3 \frac{d\mathcal{K}}{d\mathcal{Q}}\right) = 0 \qquad \Rightarrow \dot{\bar{\phi}} = \mathcal{Q}_0 + \frac{I_0/2\mathcal{K}_2}{a^3}$

Early region: depends on form of $\mathcal{K}(\bar{\mathcal{Q}})$

Equation of state w(t)



Higgs phase: "effective dust"

$\rho = \frac{Q_0 I_0}{a^3} + \ldots$ Density

$w = \frac{w_0}{a^3} + \ldots$ Equation of state

$c_{\rm ad}^2 = \frac{2w_0}{a^3} + \ldots$ Adiabatic sound speed

Late region: Universal

$$\mathcal{K} = -2\Lambda + \mathcal{K}_2(\bar{\mathcal{Q}} - \mathcal{Q}_0)^2 + \ldots$$

FLRW cosmology

MOND compatibility

$$\mu^2 = \frac{2\mathcal{K}_2}{2 - K_B}\mathcal{Q}_0^2$$

$$\mu^{-1} \gtrsim Mpc$$

Higgs phase:

$$w \approx \frac{w_0}{a^3} + \dots$$

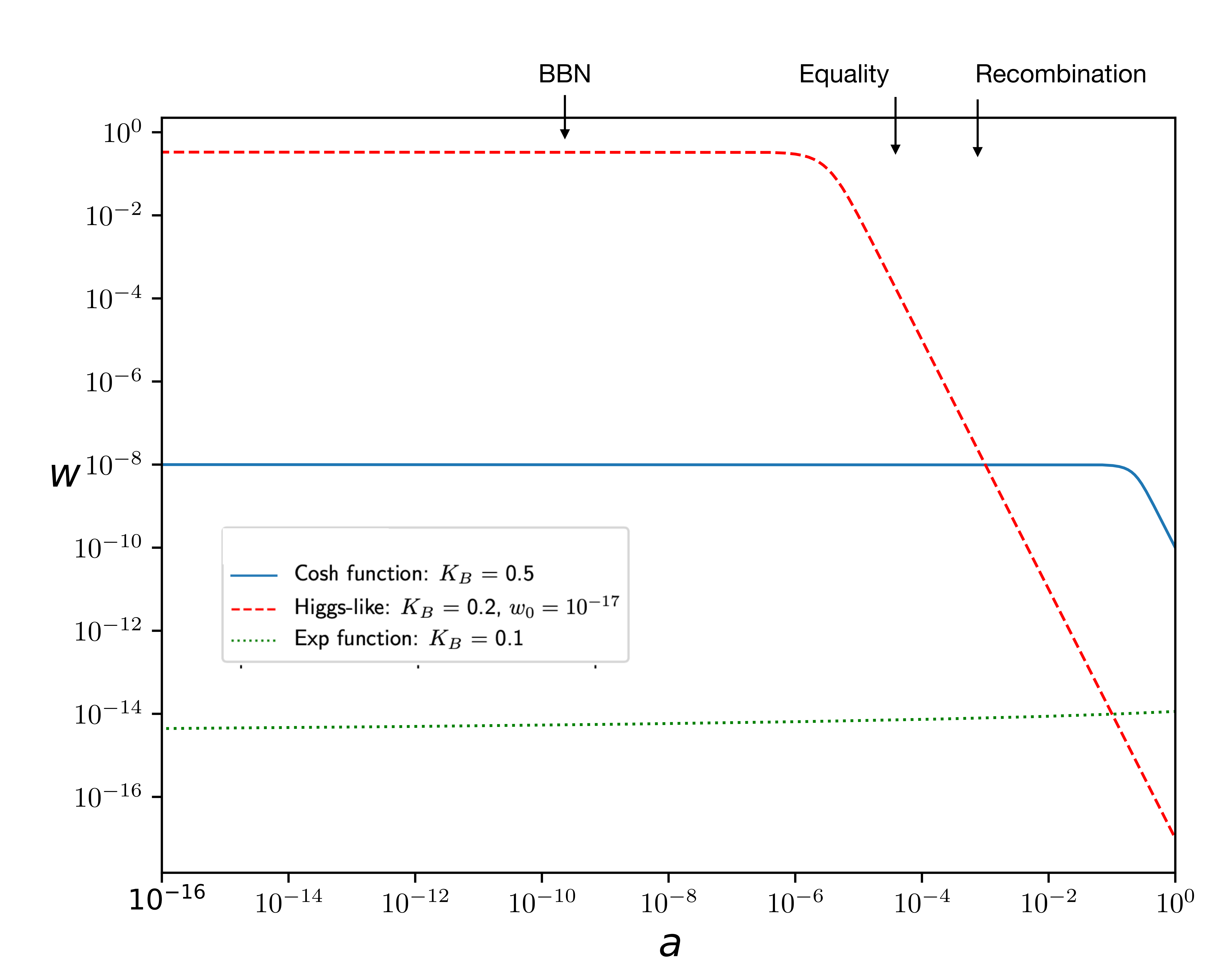
$$w_0 = \frac{3H_0^2\Omega_{\mathcal{Q}}}{4\mathcal{Q}_0^2\mathcal{K}_2} = \frac{3H_0^2\Omega_{\mathcal{Q}}}{2(2 - K_B)\mu^2}$$

$$w_0 \gtrsim 10^{-8}$$

$$w_{rec} \sim O(1)$$

Data: $w_{rec} \lesssim 10^{-4}$

✗	Higgs-like	$\mathcal{K} \sim \left(\mathcal{Q}^2 - \mathcal{Q}_0^2\right)^2$
✓	Cosh	$\mathcal{K} \sim \cosh\left(\frac{\mathcal{Q} - \mathcal{Q}_0}{\mathcal{Z}_0}\right)$
✓	Exp	$\mathcal{K} \sim e^{\left(\frac{\mathcal{Q} - \mathcal{Q}_0}{\mathcal{Z}_0}\right)^2}$



FLRW + Perturbations

$$\phi = \bar{\phi} + \varphi$$

$$A_i = \vec{\nabla}_i \alpha$$

$$E = \dot{\alpha} + \Psi$$

$$\chi = \varphi + \dot{\bar{\phi}}\alpha$$

$$\gamma = \dot{\varphi} - \dot{\bar{\phi}}\Psi$$

Density contrast $\delta = \frac{1+w}{\dot{\bar{\phi}} c_{\rm ad}^2}\gamma + \frac{1}{8\pi G a^2 \bar{\rho}}\vec{\nabla}^2 \left[K_B E + (2-K_B)\,\chi\right]$

Velocity divergence $\theta = \frac{\varphi}{\dot{\bar{\phi}}}$

Pressure contrast $\Pi = c_{\rm ad}^2 \delta - \frac{c_{\rm ad}^2}{8\pi G a^2 \bar{\rho}}\vec{\nabla}^2 \left[K_B E + (2-K_B)\,\chi\right]$

Fluid-like

$$\dot{\delta} = 3H\left(w\delta - \Pi\right) + (1+w)\left(3\dot{\Phi} - \frac{k^2}{a^2}\theta\right)$$

$$\dot{\theta} = 3c_{\rm ad}^2 H\theta + \frac{\Pi}{1+w} + \Psi$$

Field

$$K_B\left(\dot{E} + HE\right) = \frac{d\mathcal{K}}{d\mathcal{Q}}\chi - (2-K_B)\left[\frac{\dot{\bar{\phi}}}{1+w}\Pi + \left(H + \dot{\bar{\phi}}\right)\chi - 3c_{\rm ad}^2 H\dot{\bar{\phi}}\alpha\right]$$

$w \to 0$

$c_{\rm ad} \to 0$

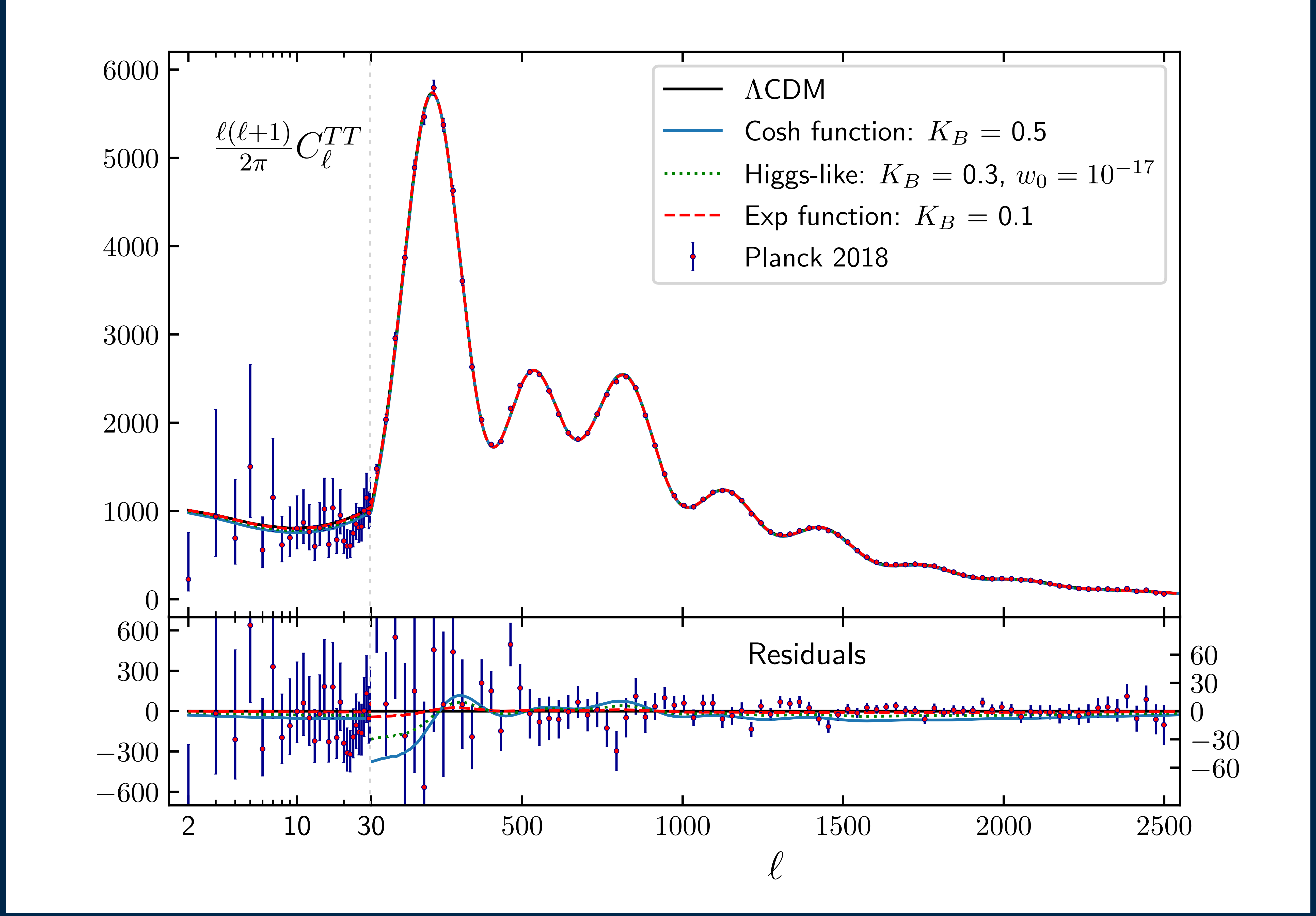
CDM-like

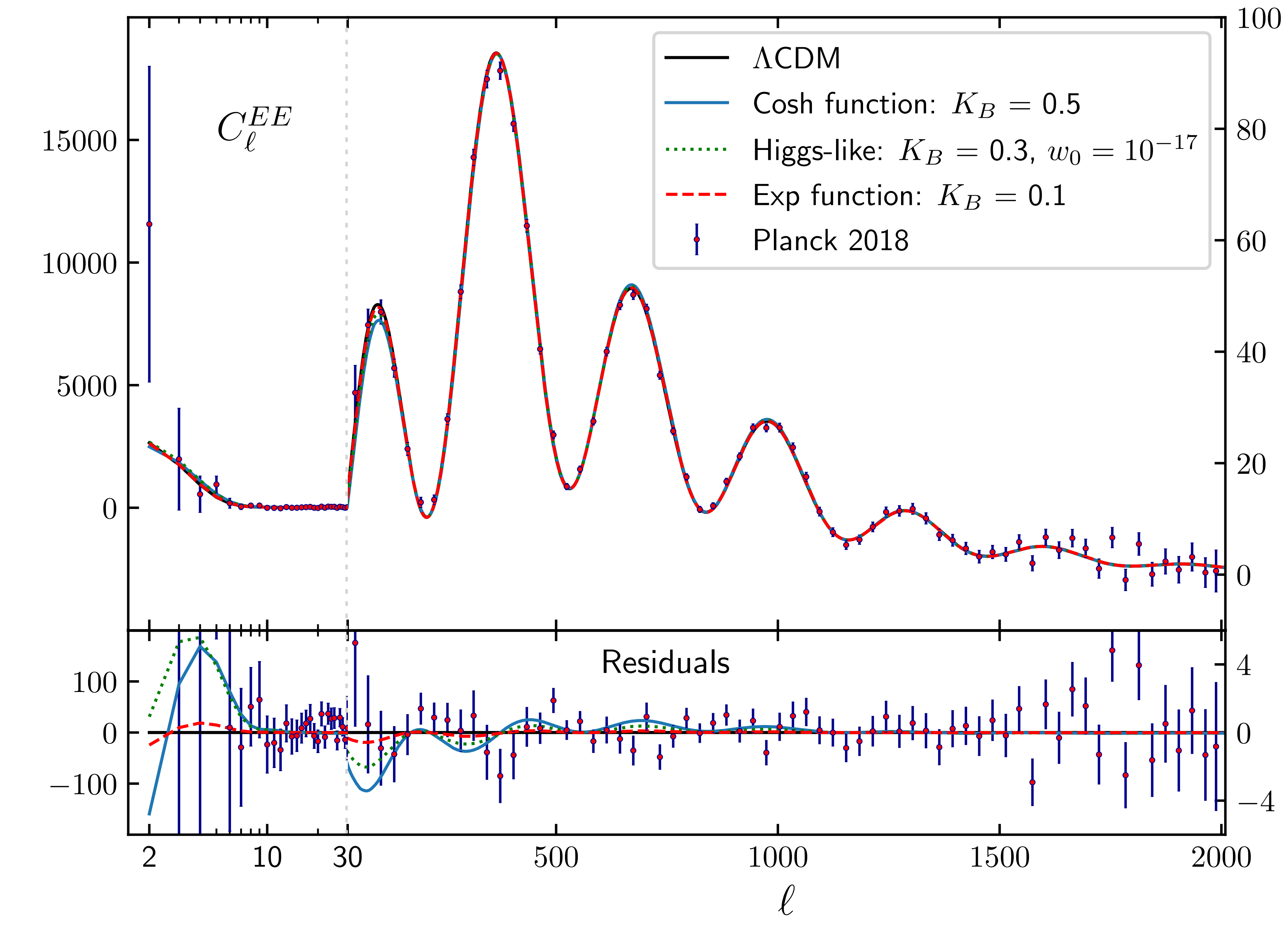
$$\dot{\delta} \approx 3\dot{\Phi} - \frac{k^2}{a^2}\theta$$

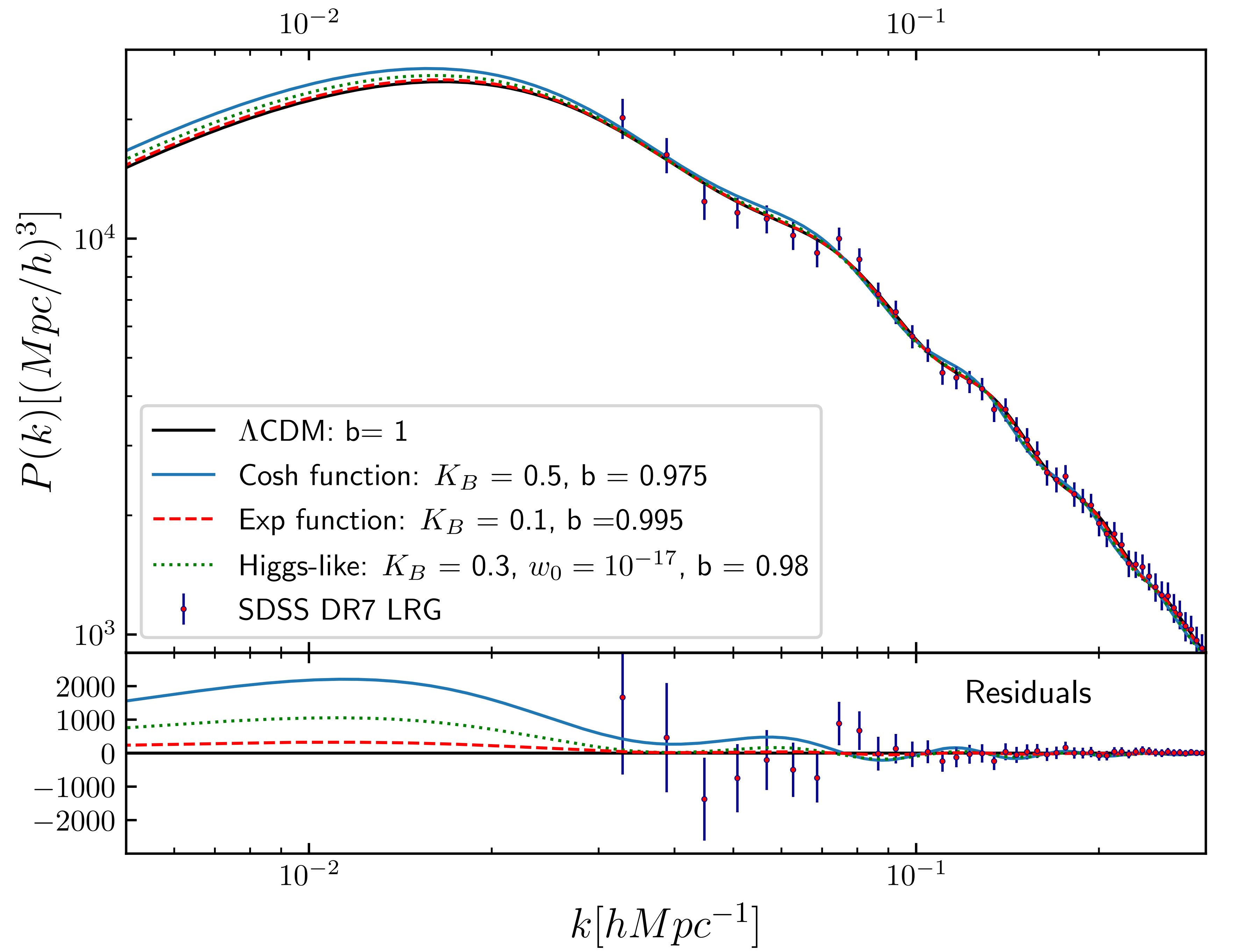
$$\dot{\theta} \approx \Psi$$

Field (decoupled)

$$K_B\left(\dot{E} + HE\right) \approx \left[\frac{3H_0^2\Omega_{0\mathcal{Q}}}{a^3} - (2-K_B)H\mathcal{Q}_0\right](\theta + \alpha)$$







C.S. & Zlosnik, PRL 127, 161302 (2021)

AeST parameters:

$K_{\rm B}$ $\quad \mathcal{Q}_0$ $\quad \mathcal{K}_2$

Initial condition: $I_0 \to \rho_{0c}$

(MCMC pending)

Gravity vs. Matter fields: on Minkowski
$g^{\mu\nu} = \eta^{\mu\nu} - h^{\mu\nu}$
$A_0 = -1 + \frac{1}{2}h^{00}$
$A_i = \hat{A}_i$
$\dot{\phi} = \mathcal{Q}_0 + \dot{\varphi}$
$\vec{\nabla}_i\phi = \vec{\nabla}_i\varphi$
Background
Fluctuations
Mix
$\hat{A}_i$
$h_{\mu\nu}$
φ
Gauge transformations
$h_{\mu\nu} \to h_{\mu\nu} + \partial_\mu\xi_\nu + \partial_\nu\xi_\mu$
$\varphi \to \varphi - \mathcal{Q}_0\xi_0$
(e.g. ghost condensate)
$\hat{A}_i \to \hat{A}_i + \vec{\nabla}_i\xi_0$
(e.g. gauged ghost condensate)
N.B.
Dark fields (e.g. DM)
$\chi \to \chi$
No mixing with $h_{\mu\nu}$
C.S. & Zlosnik, arXiv:2109.13287

Quadratic action on Minkowski

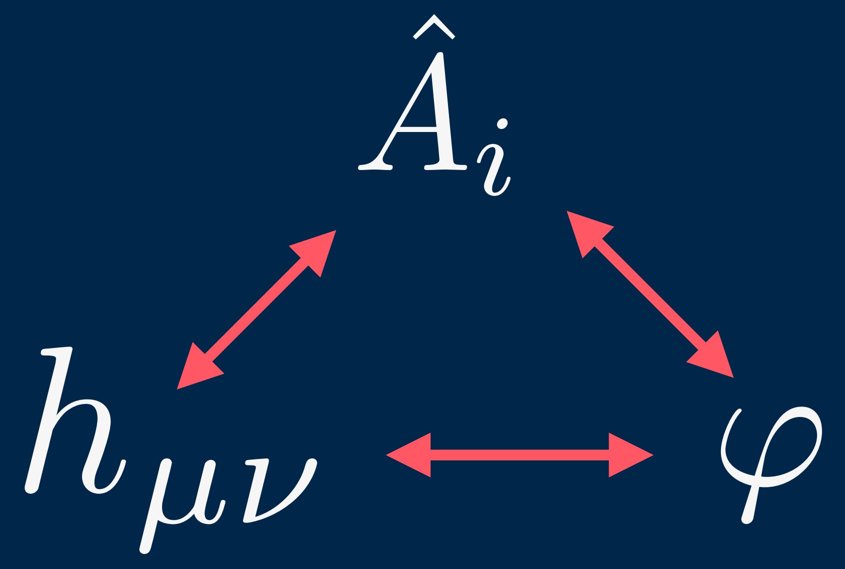
C.S. & Zlosnik, PRL 127, 161302 (2021)
C.S. & Zlosnik, arXiv:2109.13287

Tensor mode graviton $c_T = 1$

$$h_{00} \to h_{00} - 2\dot{\xi}_T$$
$$h_{0i} \to h_{0i} + \dot{\xi}_i - \vec{\nabla}_i \xi_T$$
$$h_{ij} \to h_{ij} + \vec{\nabla}_i \xi_j + \vec{\nabla}_j \xi_i$$

$$S = \int d^4x \Big\{ -\frac{1}{2}\partial_\mu h \partial_\nu h^{\mu\nu} + \frac{1}{4}\partial_\rho h \partial^\rho h + \frac{1}{2}\partial_\mu h^{\mu\rho}\partial_\nu h^\nu{}_\rho - \frac{1}{4}\partial^\rho h^{\mu\nu}\partial_\rho h_{\mu\nu} + K_B \Big|\dot{\vec{\hat{A}}} - \frac{1}{2}\vec{\nabla} h^{00}\Big|^2 - 2K_B \vec{\nabla}_{[i}\hat{A}_{j]}\vec{\nabla}^{[i}\hat{A}^{j]}$$
$$+ (2 - K_B)\left[2\Big(\dot{\vec{\hat{A}}} - \frac{1}{2}\vec{\nabla} h^{00}\Big)\cdot\Big(\vec{\nabla}\varphi + \mathcal{Q}_0 \vec{\hat{A}}\Big) - (1+\lambda_s)\Big|\vec{\nabla}\varphi + \mathcal{Q}_0\vec{\hat{A}}\Big|^2\right] + 2\mathcal{K}_2\left|\dot{\varphi} + \frac{1}{2}\mathcal{Q}_0 h^{00}\right|^2 + \frac{1}{\tilde{M}_p^2} T_{\mu\nu}h^{\mu\nu}\Big\}$$

Gauge Invariant terms



Mixing: genuine modification of gravity

$$h_{00} \to h_{00} - 2\dot{\xi}_T$$
$$A_i \to A_i - \vec{\nabla}_i \xi_T$$
$$\varphi \to \varphi + \mathcal{Q}_0 \xi_T$$

Emergent symmetry for static fields:

Only $\chi \equiv \varphi + \mathcal{Q}_0 \alpha$ Relevant

$$\vec{A} = \vec{\nabla}\alpha + \vec{\nabla}\times\vec{\beta}$$

Normal modes

C.S. & Zlosnik, PRL 127, 161302 (2021)

C.S. & Zlosnik, arXiv:2109.13287

Tensor modes (as in GR): $\omega^2 = k^2$

Vector modes: $\omega^2 = k^2 + \mathcal{M}^2$

Scalar modes: $\omega^2 = c_s^2 k^2 + \mathcal{M}^2$

$$\mathcal{M}^2 = \frac{2-K_B}{K_B}(1+\lambda_s)\,\mathcal{Q}_0^2$$

$$c_s^2 = \frac{2-K_B}{\mathcal{K}_2 K_B}\left(1+\frac{K_B}{2}\lambda_s\right)$$

Positive Hamiltonian

$\omega^2 = 0$ (Non-propagating)

- Positive Hamiltonian $k > \mu (\sim Mpc^{-1} \text{or smaller})$
- Negative Hamiltonian $k < \mu$ → Linear instability (Cosmology?)

$\mathcal{K}_2 > 0$

$0 < K_B < 2$

$\lambda_s > 0$

Black Holes

C. Skordis, in preparation.

Bernardo & Chen, arxiv:2202.08460 (consider a disconnected sector where) $\phi = \phi(r)$ → Schwarzchild BH, ϕ Singular at horizon

Better assumption is:

Continuity with cosmology demands that $\nabla_\mu \phi$ be timelike → Global time coordinate: $\phi = \mathcal{Q}_0 t$

- Assume static, spherically symmetric →

$$ds^2 = -e^{2\Phi(r)} dt^2 + e^{2\Psi(r)} dr^2 + r^2 d\Omega$$

$$A_\mu = \{-e^{\Phi}\chi(r), A(r), 0, 0\}$$

$$\chi = \sqrt{1 + e^{-2\Psi} A^2}$$ (From unit timelike constraint)

- Take strong-field limit: $\mathcal{F} = (2 - K_B)\lambda_s \mathcal{Y}$ (Assumes relevant scales are smaller than $r_M \sim \sqrt{\frac{GM}{a_0}} \ll \mu^{-1}$

- Three functions to be determined: $\Phi(r)$ $\Psi(r)$ $A(r)$, depend on two additional parameters: K_B, λ_s

C. Skordis, in preparation.

Unique solution: Reissner-Nordstrom:

(Schwarzschild not a solution)

$$ds^2 = -\left(1 + \frac{C_0}{r} + \frac{q^2}{r^2}\right) dt^2 + \frac{dr^2}{1 + \frac{C_0}{r} + \frac{q^2}{r^2}} + r^2 d\Omega$$

$$q^2 = \left(1 + \frac{K_B}{2}\lambda_s\right)\left(1 + \lambda_s\right) \mathcal{Q}_0^2 \alpha_0^2$$

With: $A = \frac{\alpha_0}{r^2}$

Connect with linearised solution

$$C_0 = -2G_N M$$

$$\alpha_0 = \frac{GM}{\lambda_s \mathcal{Q}_0}$$

$$ds^2 = -\left(1 - \frac{2G_N M}{r} + \frac{2\delta_\beta (G_N M)^2}{r^2}\right) dt^2 + \frac{dr^2}{1 - \frac{2G_N M}{r} + \frac{2\delta_\beta (G_N M)^2}{r^2}} + r^2 d\Omega$$

$$\delta_\beta = \beta_{PPN} - 1 = \frac{1}{2}\left(\frac{K_B}{2} + \frac{1}{\lambda_s}\right)\left(1 + \frac{1}{\lambda_s}\right) < 8 \times 10^{-5}$$

(BH always sub-extremal)

$$K_B < 3.2 \times 10^{-4} \qquad \frac{1}{\lambda_s} < 1.6 \times 10^{-4}$$

A possibility

EXTENSION OF GR

$$\hat{A}_i \qquad h_{\mu\nu} \qquad \varphi$$

Same fields: $g_{\mu\nu}$ A_μ ϕ

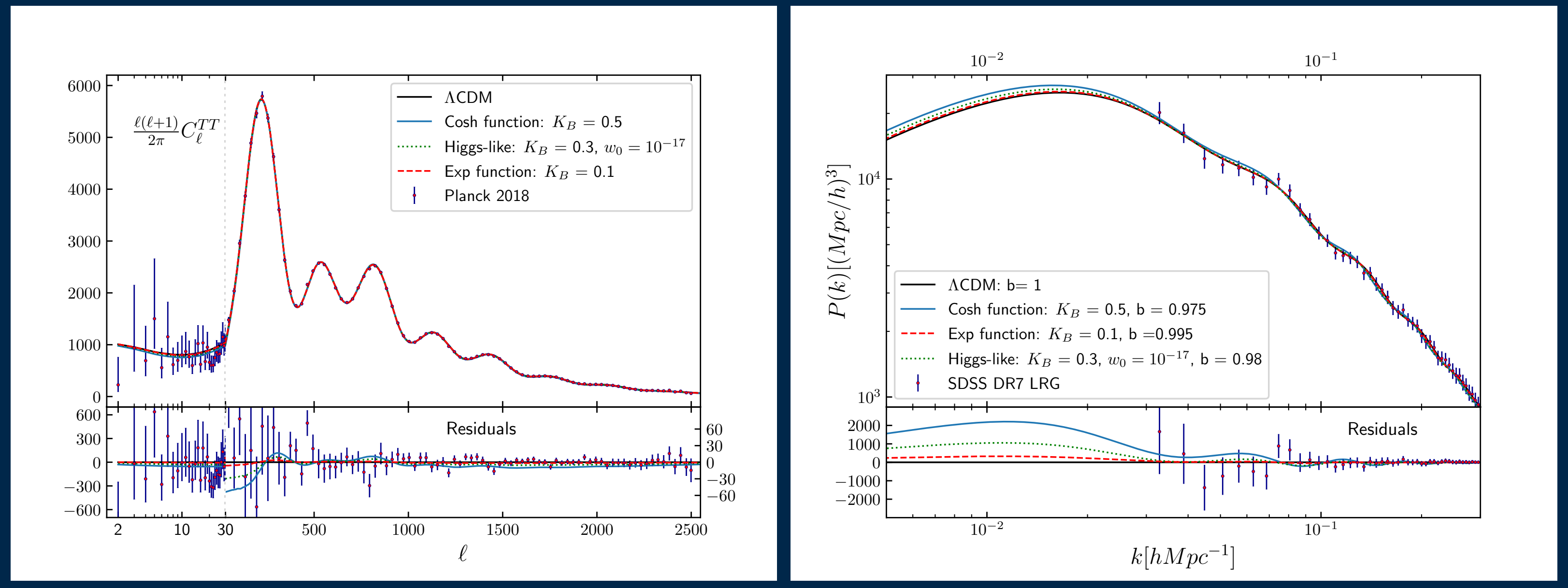
Φ

Non-relativistic, static: MOND

Bekenstein & Milgrom 1984

FRW + linear fluctuations

Effective description: ΛCDM



$\Phi = \Psi$

Lensing

aLIGO/Virgo + EM (2017)

Tensor speed = 1

•Aether Scalar Tensor (AeST)

- New dof mixing with metric perturbation: 1 scalar and 1 unit-timeline vector (Aether)

$\hat{A}_i$

$h_{\mu\nu} \leftrightarrow \varphi$

- This is not a MOND theory:
  - **MOND** — On galactic scales
  - **ΛCDM** — On cosmological scales → **Excellent fits to CMB + LSS**

- BH solutions: Reisner-Nordstrom with charge related to (baryonic) mass

- Static solutions: only exist if baryonic mass is present (no non-trivial scalar/vector profiles)

- Non-zero PPN parameters expected

$$\gamma = 1$$

$$\beta \approx 1 + \frac{K_B}{4} + \frac{1}{2\lambda_s}$$

$$\alpha_1 \neq 0$$

$$\alpha_2 \neq 0$$

→

$$K_B < 3.2 \times 10^{-4}$$

$$\frac{1}{\lambda_s} < 1.6 \times 10^{-4}$$

What now?

Upcoming work:

- Hamiltonian formulation (with M. Bataki (PhD student) & T. Zlosnik)
- Weak-field spherically symmetric solutions (w. A. Durakovic, P. Verwayen (PhD st.), C. Boehm, D. Mota, C. Llinares,)
- PPN parameters
- Black Holes
- MCMC (Cosmological parameters) (w. S. Ilic & T. Zlosnik)

- Non-linear cosmology →
  - N-body simulations
  - EFTofLSS (done in the case of CDM — Senatore, Zaldarriaga, Baumann, et al.)

- Theory needs improvements:
  - ~~Magic function~~
  - Term $|\vec{\nabla}\varphi|^3$ Is non-local in Fourier space — not nice

- Scalar gravitational waves →
  - Cosmological background (as wave-like isocurvature modes)
  - Stellar pulsations
  - Stochastic background

Current collaborators: T. Zlosnik (CEICO), S. Ilic (former CEICO, current APC), M. Bataki (PhD student, U. Cyprus & CEICO)
A. Durakovic (CEICO), D. Mota (Oslo), C. Boehm (Sydney), P. Verwayen (Sydney), C. Llinares (Lisbon)