Challenging the CDM paradigm: Constraining DM properties with CMB data

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In collaboration with
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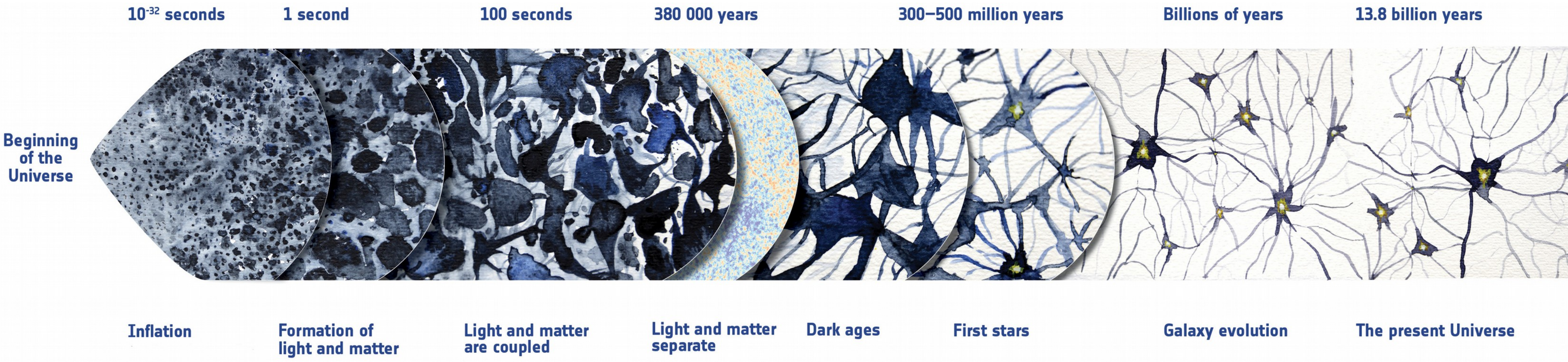
The standard model of cosmology

- The ΛCDM paradigm: a (relatively) simple model, with many successes…



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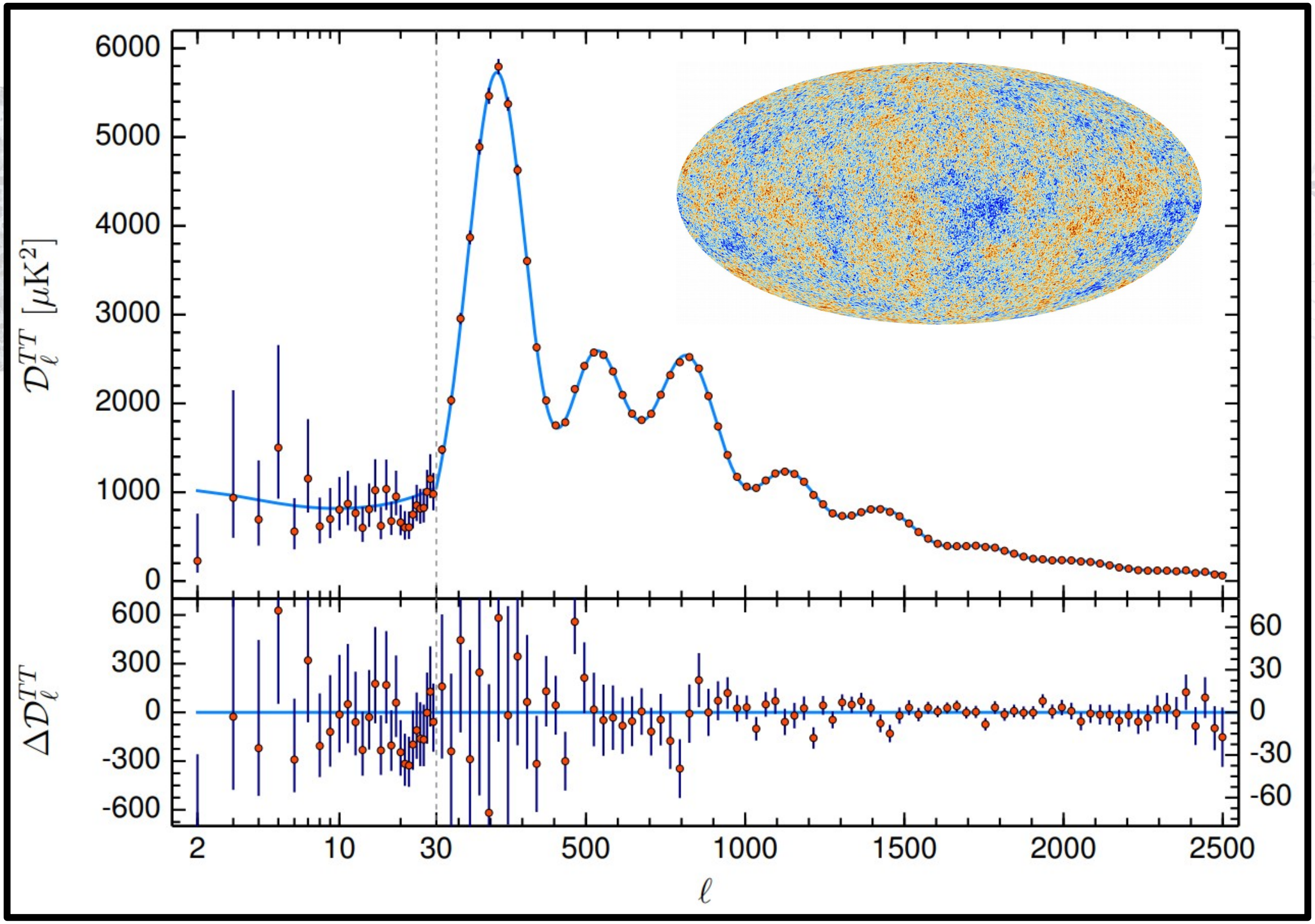

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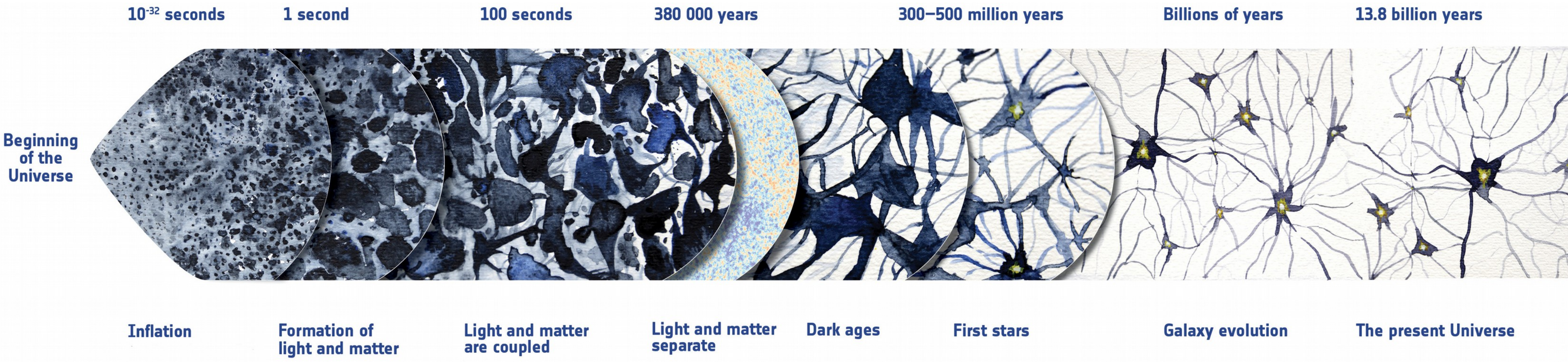

- … but rests on some pillars that are "shrouded in darkness":
  - Primordial Universe, inflation
  - Dark ages & reionisation
  - Dark matter (''CDM'')
  - Dark energy (''Λ'')

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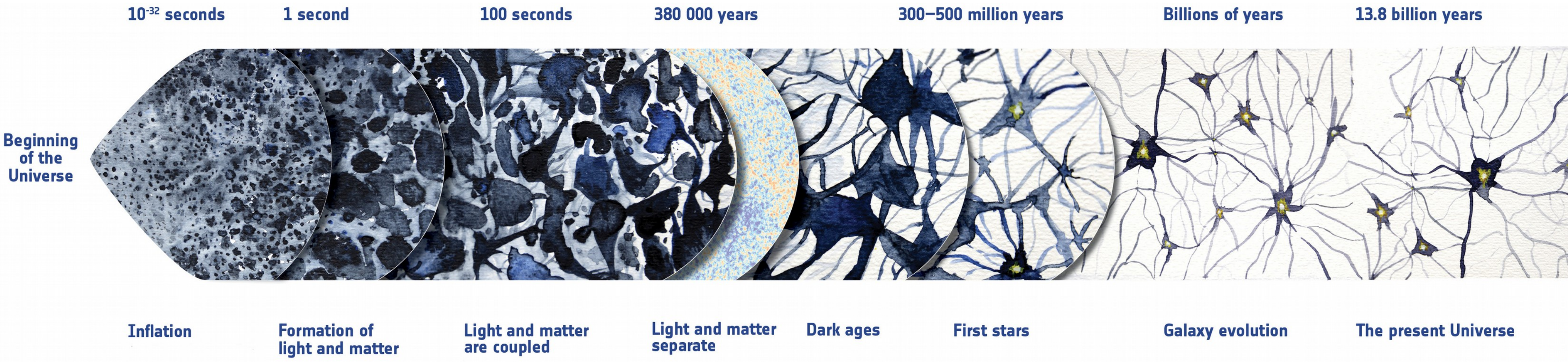

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- … and is shaken by some persistent tensions :
  - H_0 discrepancies
  - σ_8 tensions
  - ISW excess
  - CMB “anomalies”

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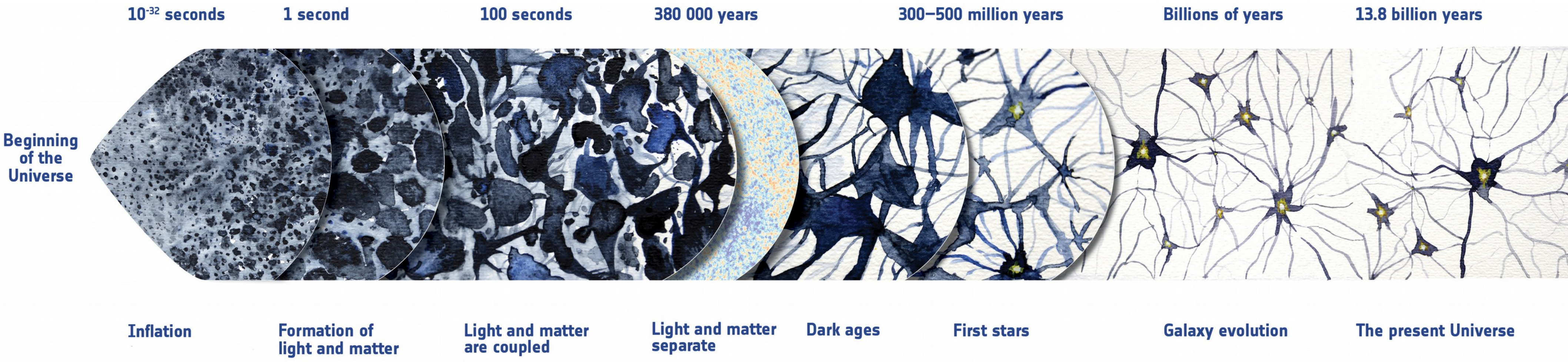

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Cold dark matter, hot questions

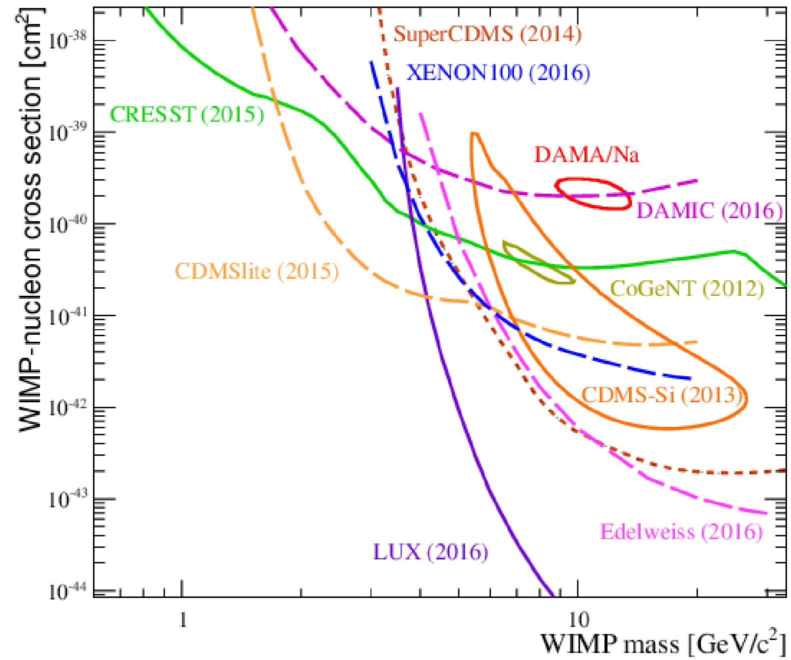
- Is it really there ?

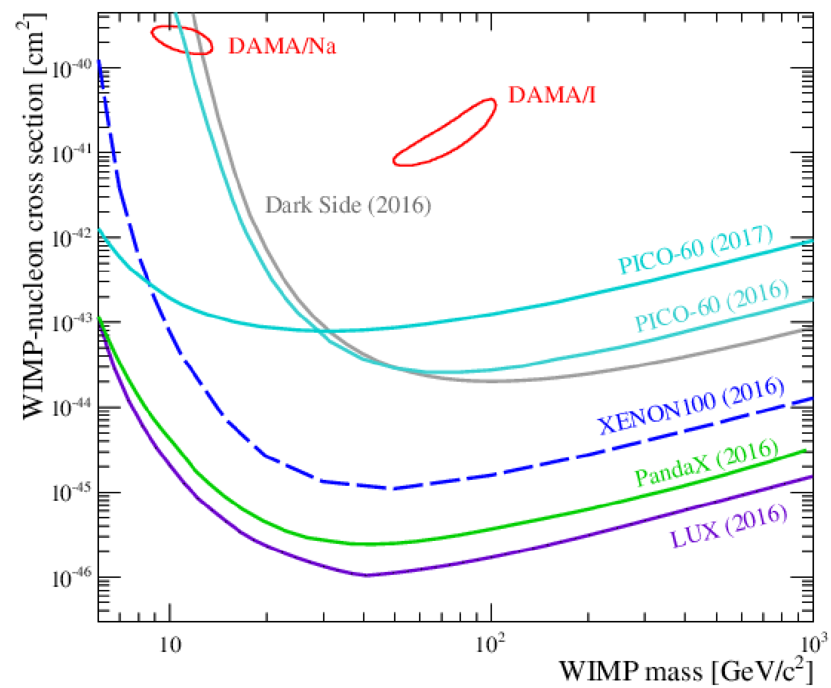
Probing dark matter

- Direct detection:

Probing dark matter

- Direct detection:
  - Colliders
  - Nuclear recoils





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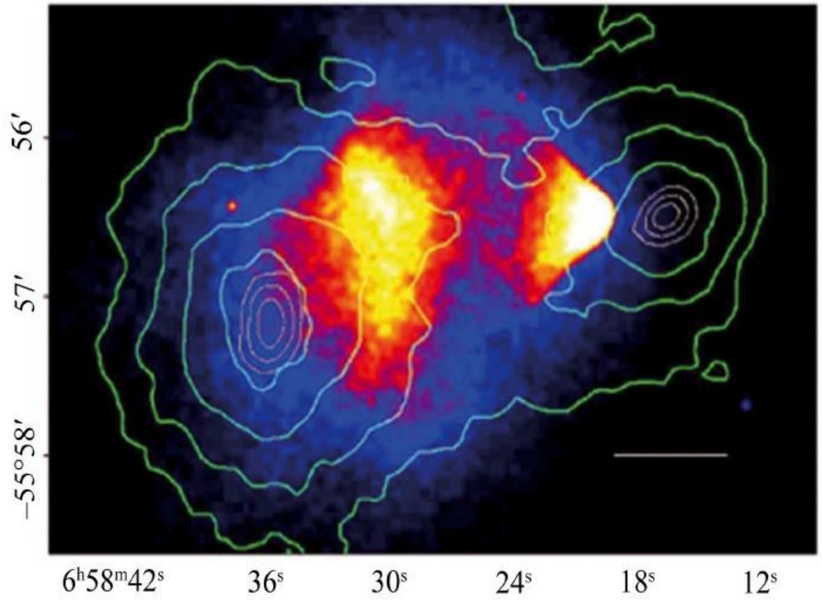
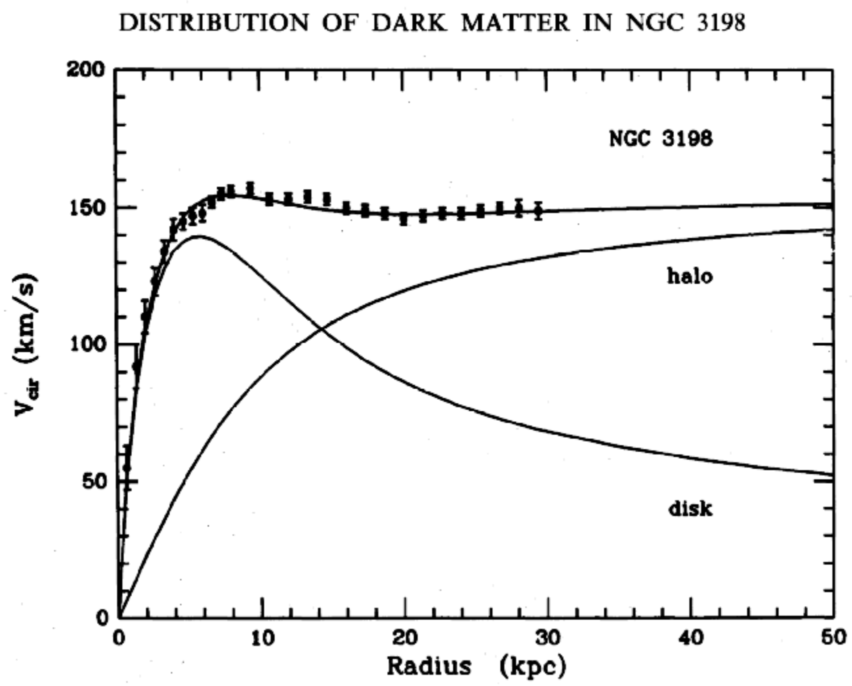
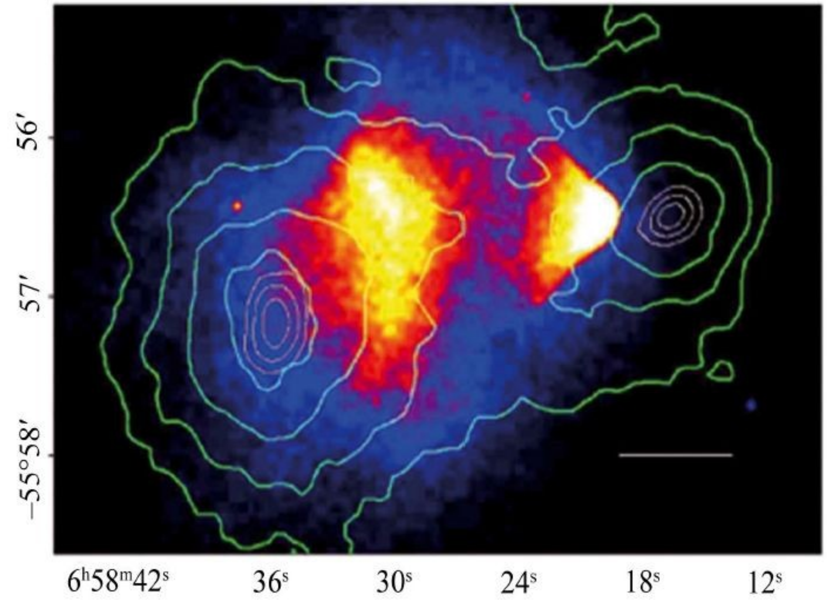
  - Gravitational effects

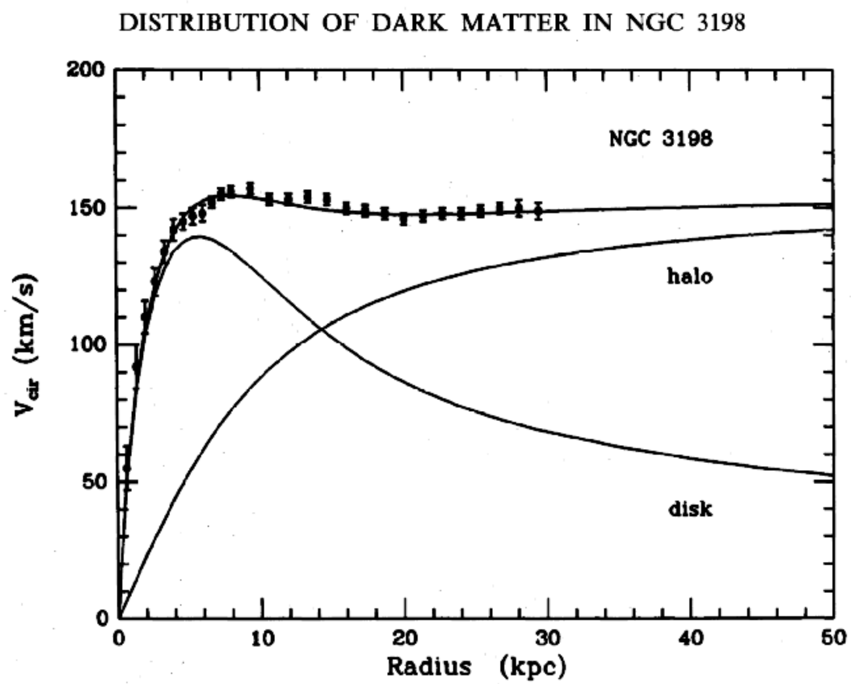




Probing dark matter

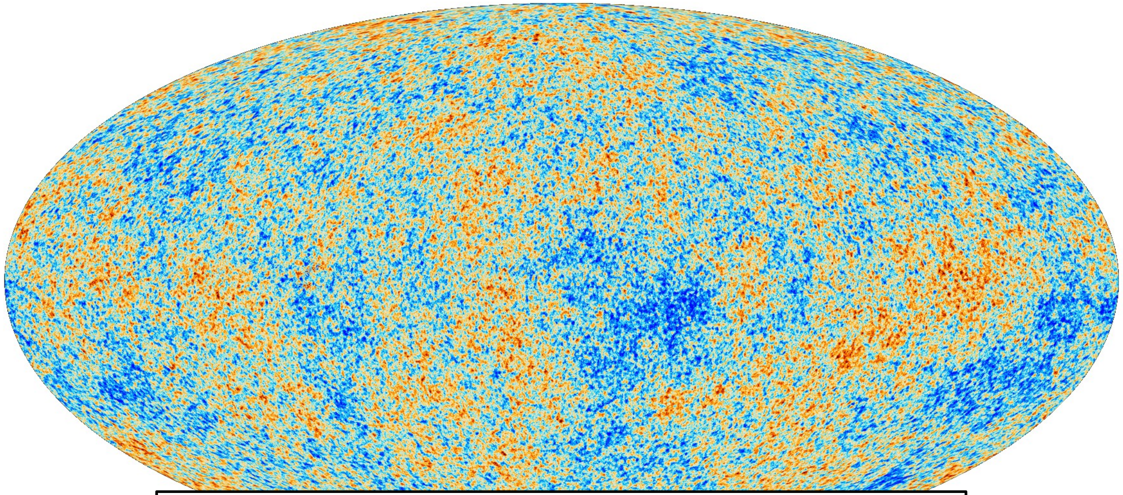
- Direct detection:
  - Colliders
  - Nuclear recoils
- Indirect detection:
  - (Late) gravitational effects

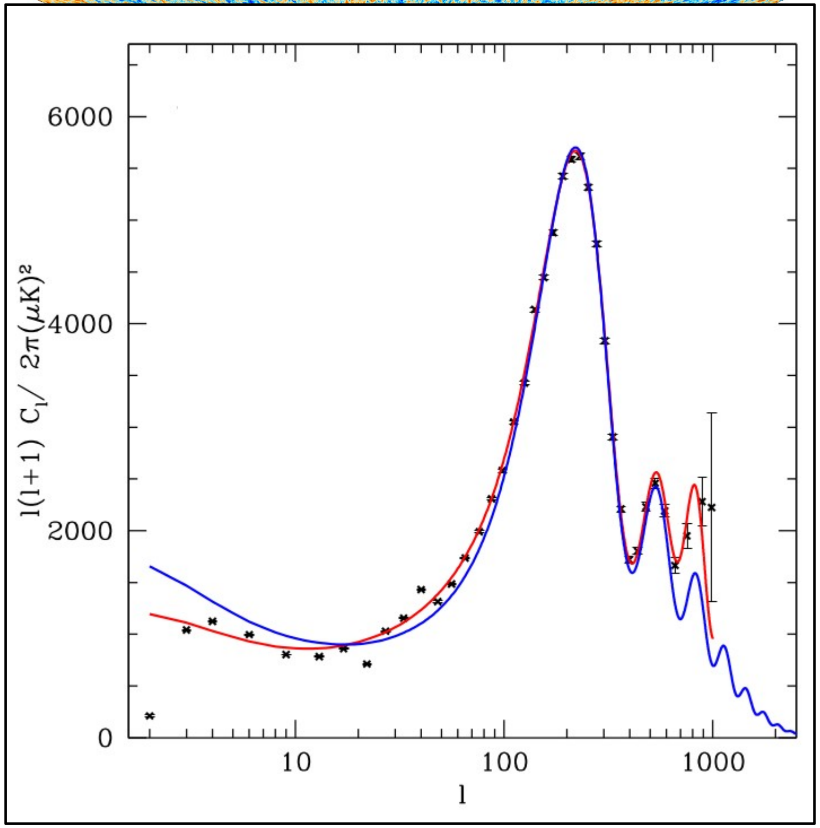




Probing dark matter

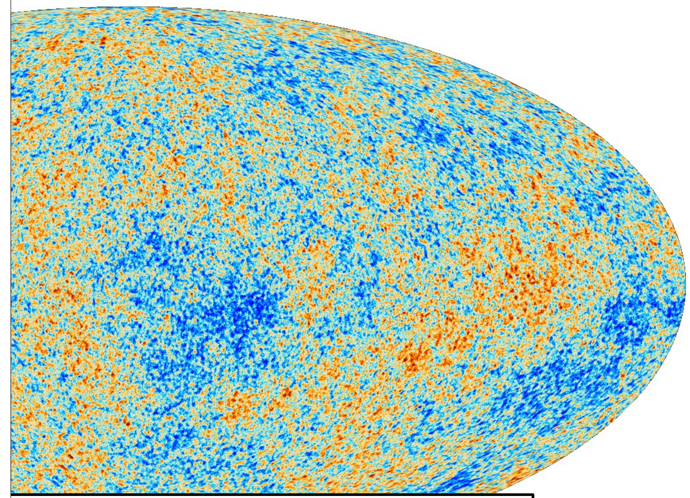
- **Direct detection:**
  - Colliders
  - Nuclear recoils
- **Indirect detection:**
  - (Late) gravitational effects
  - (Early) gravitational effects

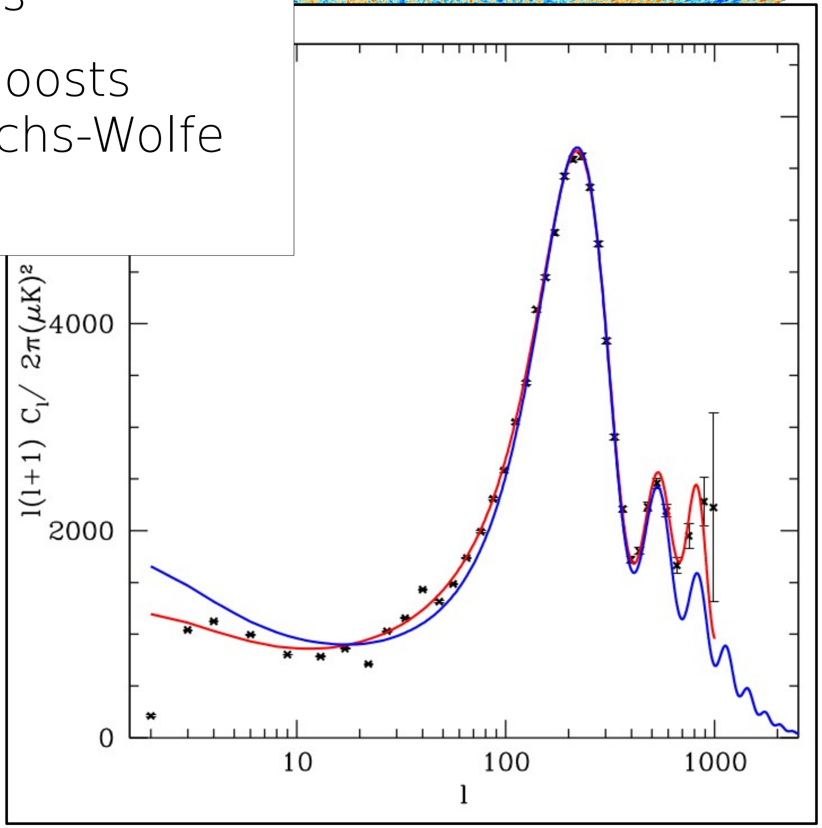




Probing dark matter

- Baryons raise odd peaks relative to even peaks
- Increasing CDM density, moves equality forward in time
- Potentials decay during radiation era, constant in matter era
- Potential decay during tight-coupling (before recombination) drives the anisotropies
- Potential decay after recombination boosts anisotropies due to the Integrated Sachs-Wolfe effect





- (Late) gravitational effects
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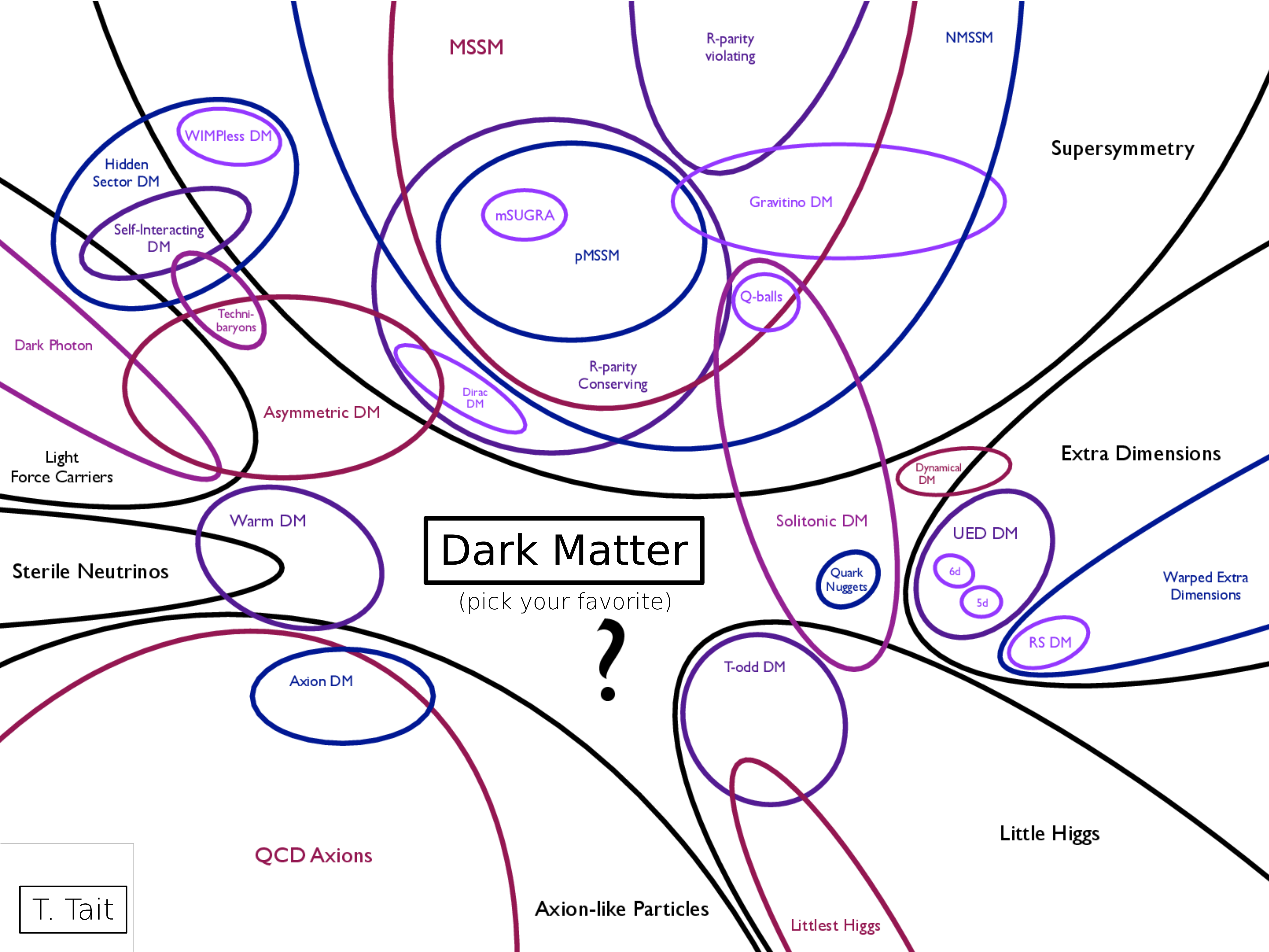
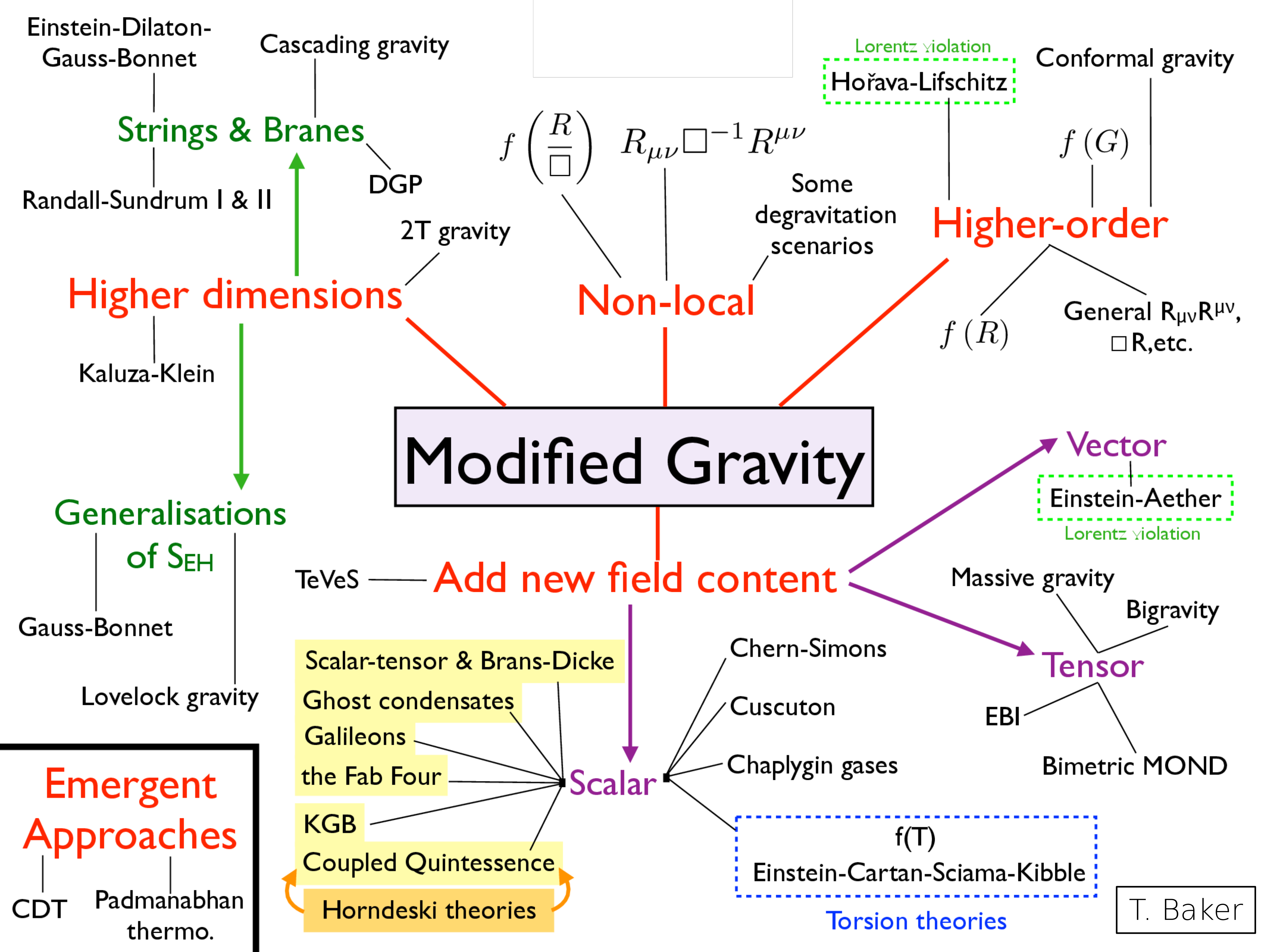
- If yes, what it is made of ?


MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
R-parity Conserving
Dirac DM
Asymmetric DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Dark Matter
(pick your favorite)
?
Solitonic DM
UED DM
6d
5d
Quark Nuggets
Warped Extra Dimensions
Sterile Neutrinos
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T. Tait

Cold dark matter, hot questions

- Is it really there ?
- If yes, what it is made of ?
- If not, what is the cause for those observations ?


Einstein-Dilaton-Gauss-Bonnet
Cascading gravity
Strings & Branes
DGP
Randall-Sundrum I & II
2T gravity
Higher dimensions
Kaluza-Klein
Generalisations of S_{EH}
Gauss-Bonnet
Lovelock gravity
$f\left(\frac{R}{\Box}\right)$
$R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
Some degravitation scenarios
Non-local
Lorentz violation
Hořava-Lifschitz
Conformal gravity
$f(G)$
Higher-order
$f(R)$
General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$, etc.
Modified Gravity
Vector
Einstein-Aether
Lorentz violation
TeVeS
Add new field content
Massive gravity
Bigravity
Tensor
EBI
Bimetric MOND
Scalar-tensor & Brans-Dicke
Ghost condensates
Galileons
the Fab Four
KGB
Coupled Quintessence
Horndeski theories
Scalar
Chern-Simons
Cuscuton
Chaplygin gases
f(T)
Einstein-Cartan-Sciama-Kibble
Torsion theories
Emergent Approaches
CDT
Padmanabhan thermo.
T. Baker

Outline

I. Going beyond CDM

DM as a (more) general fluid

$$T_{\mu\nu} = \rho u_\mu u_\nu$$

- CDM: non-interacting, pressureless perfect fluid

$\omega_c \equiv \Omega_c h^2 = 0.1200 \pm 0.0012$ (Planck 2018 results. VI)

$< 1.3\%$ isocurv. IC contribution (Planck 2018 results. X)

DM as a (more) general fluid

$$T_{\mu\nu} = \rho u_\mu u_\nu + P(g_{\mu\nu} + u_\mu u_\nu)$$

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- But general fluid has pressure...

DM as a (more) general fluid

$$T_{\mu\nu} = \rho u_\mu u_\nu + P(g_{\mu\nu} + u_\mu u_\nu) + \Sigma_{\mu\nu}$$

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- But general fluid has pressure...

- ...and non-zero shear

Generalized Dark Matter (GDM, Hu 1998)

- Defined for FLRW, linear perturbations
- <u>Background</u>: (non-zero) equation of state $w(\tau)$
- <u>Perturbations</u>: sound speed $c_s^2(\tau, k)$ & viscosity $c_{vis}^2(\tau, k)$
- Standard eqs. for density contrast & velocity divergence
- Closure equations (postulated by Hu):

$$\Pi \equiv \frac{\delta P}{\bar{\rho}} = c_s^2 \delta + 3(1+w)(c_s^2 - c_a^2)\frac{\dot{a}}{a}\theta \qquad \dot{\Sigma} = -3\frac{\dot{a}}{a}\Sigma + \frac{4}{1+w} c_{\text{vis}}^2 \theta^{(CN)}$$

$$\left(c_a^2 = \frac{\dot{\bar{P}}_g}{\dot{\bar{\rho}}_g} = w - \frac{\dot{w}}{3\mathcal{H}(1+w)} \right)$$

GDM phenomenology

- Equation of state:

$$\dot{\rho} = -3H\rho(1+w)$$

for constant w : $a^3\bar{\rho} \propto \omega_0(1 + 3w\ln(1+z))$

→ early rad/matter ratio, changes peak heights

→ angular diam. dist., changes peak heights

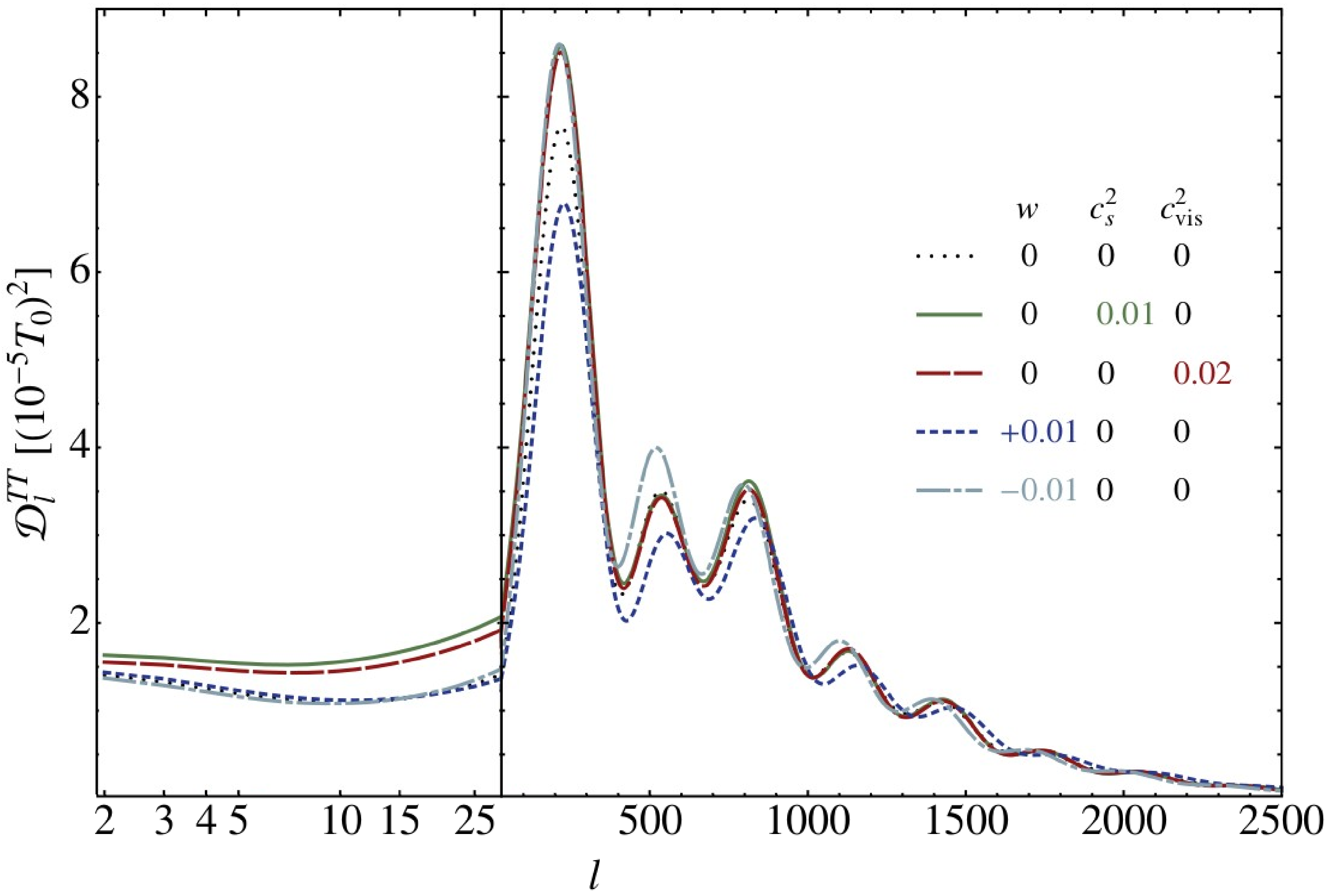
- Sound speed & viscosity:

$$k_{decay}^{-1}(\tau) \equiv \tau\sqrt{c_s^2 + \frac{8}{15}c_v^2}$$

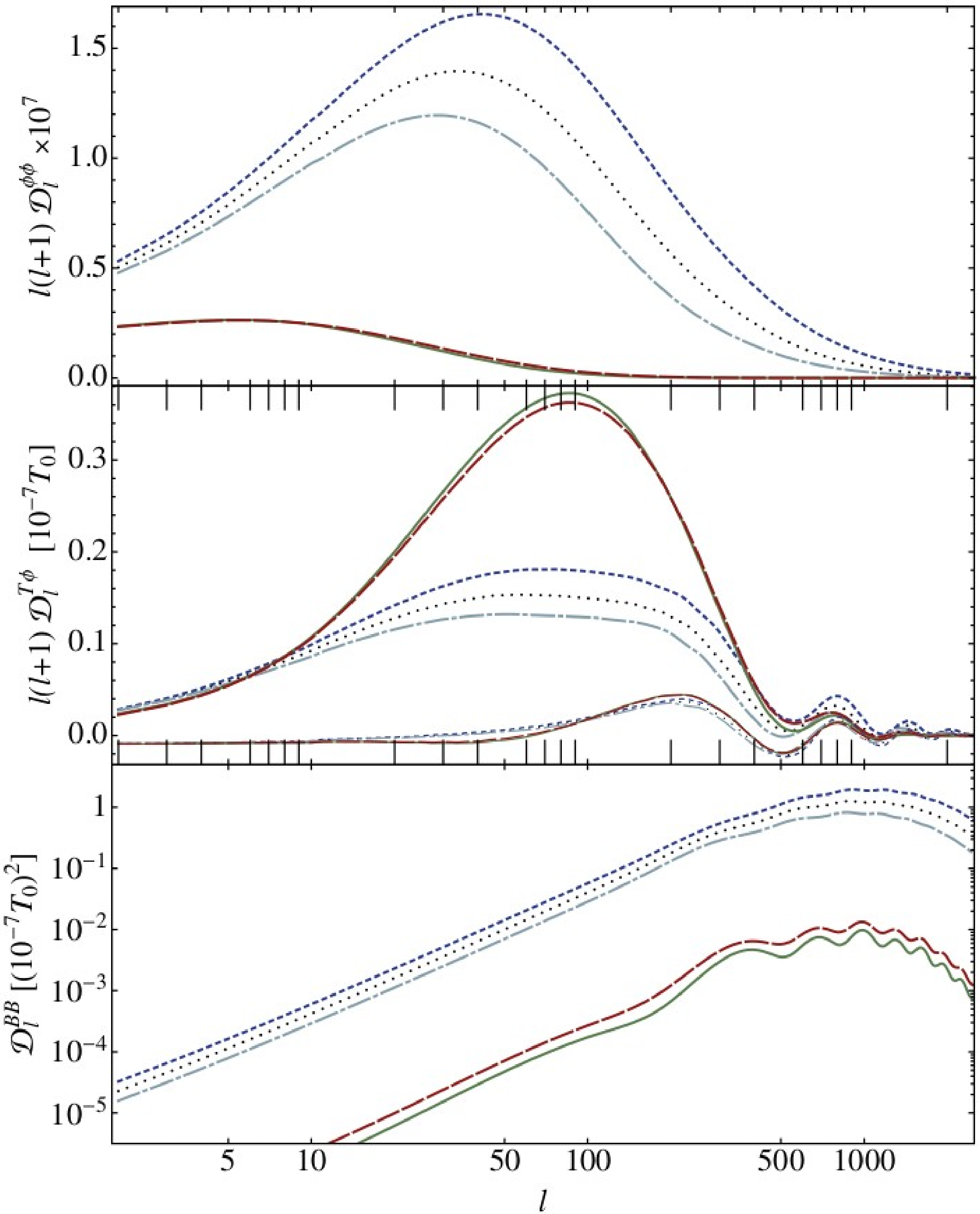
→ potentials decay below k_decay

Expected degeneracy for constant $c_s^2 + \frac{8}{15}c_v^2$

GDM phenomenology and the CMB



GDM phenomenology and the CMB



Relating GDM to realistic theories

Particles (Boltzmann equation)

- Freely streaming warm dark matter
  Armendariz-Picon, Neelakanta, JCAP 2014
- Specific models, like self interacting massive neutrinos and dark atoms + dark photons
  Oldengott et al JCAP 2015
  Cyr-Racine, Sigurdson, PRD 2013

Fields (effective or fundamental)

- Axion condensates.
  Sikivie, Yang, PRL 2009
  Hlozek, et al, PRD 2015
- Effective theory of large scale structure: Landau-Lifshitz type energy momentum tensor for CDM due to small scale nonlinearities
  Baumann et al, JCAP 2012
- K-essence and more general constrained-norm scalar field theories.
  Scherrer, PRL 2004
  Ballesteros, JCAP 2015

Fluids (imperfect, or coupled perfect)
Kopp et al, 1605.00649

(courtesy of M. Kopp)

Outline

I. Going beyond CDM

II. Cosmological constraints on GDM

Ingredients for cosmological constraints

- Theoretical predictions:
  custom modified version of public code CLASS, solving for arbitrary w, c_s^2, and c_v^2

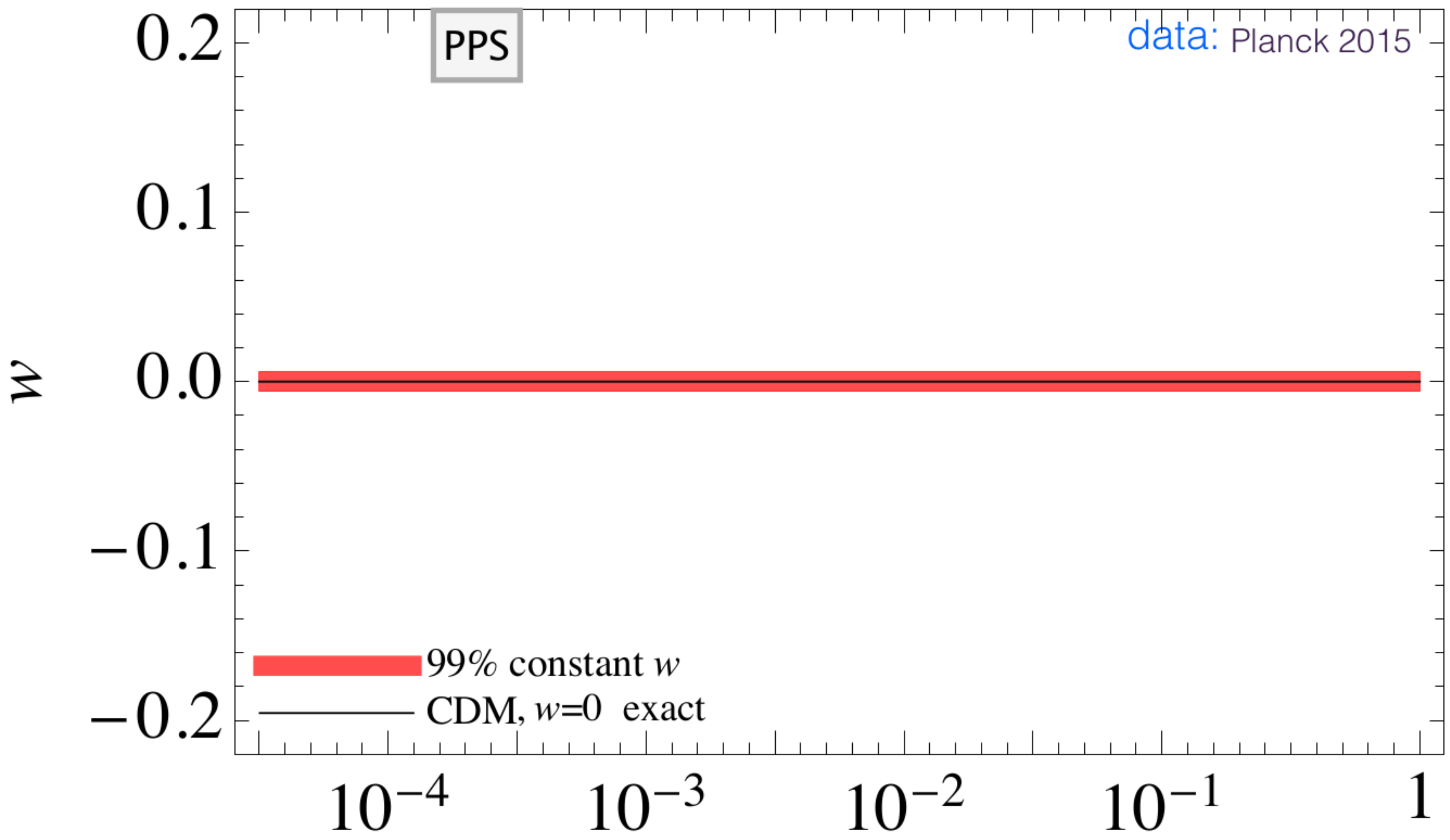
- Datasets:
  Planck 2015 low/high-ell T/E/B data + lensing
  H_0 (Riess) measurement
  Assortment of BAO data

- Sampling:
  Affine Invariant Markov chain Monte Carlo Ensemble sampler

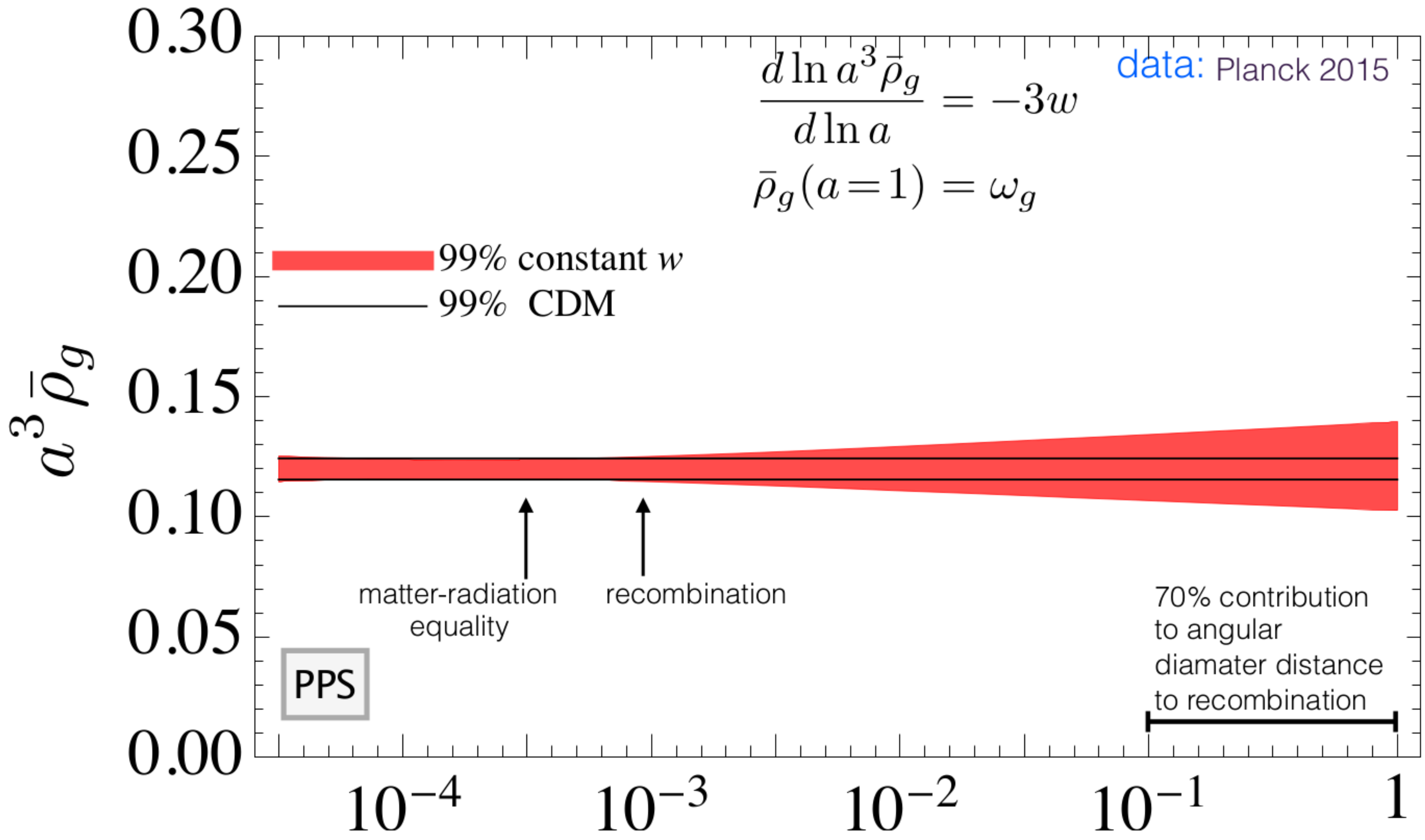
- Assembled in a custom and optimized "CosmoBox"

(soon to be public)

Constant w, c_s^2, and c_v^2 constraints



Constant w, c_s^2, and c_v^2 constraints



Constant w, c_s^2, and c_v^2 constraints

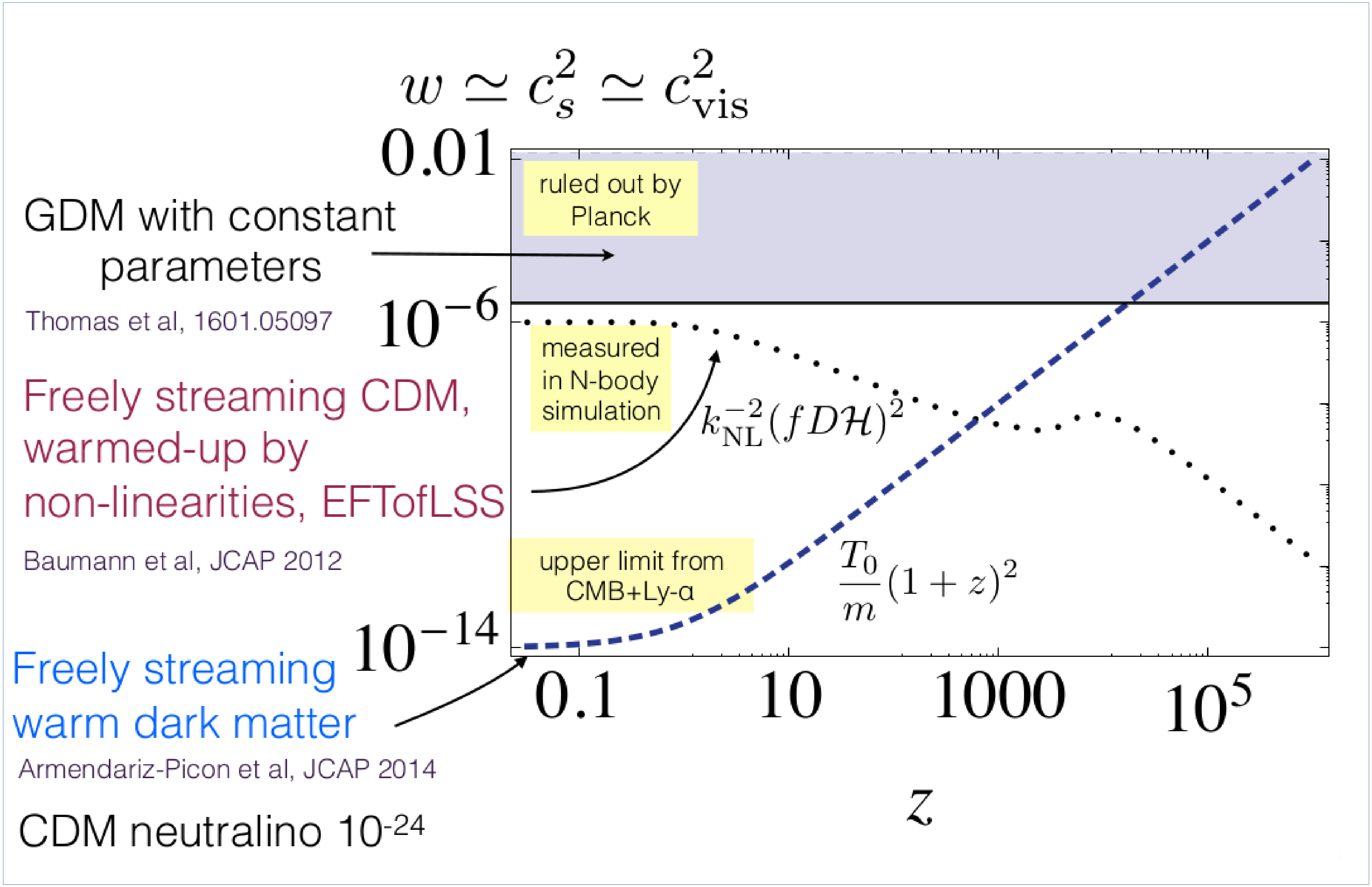
Constraints
(99.7% c.l.)

$$w < 2.4 \times 10^{-3}$$
$$w > -0.9 \times 10^{-3}$$

$$c_s^2 < 3.21 \times 10^{-6}$$
$$c_{\rm vis}^2 < 6.06 \times 10^{-6}$$

Thomas et al., 2016, arXiv:1601.05097

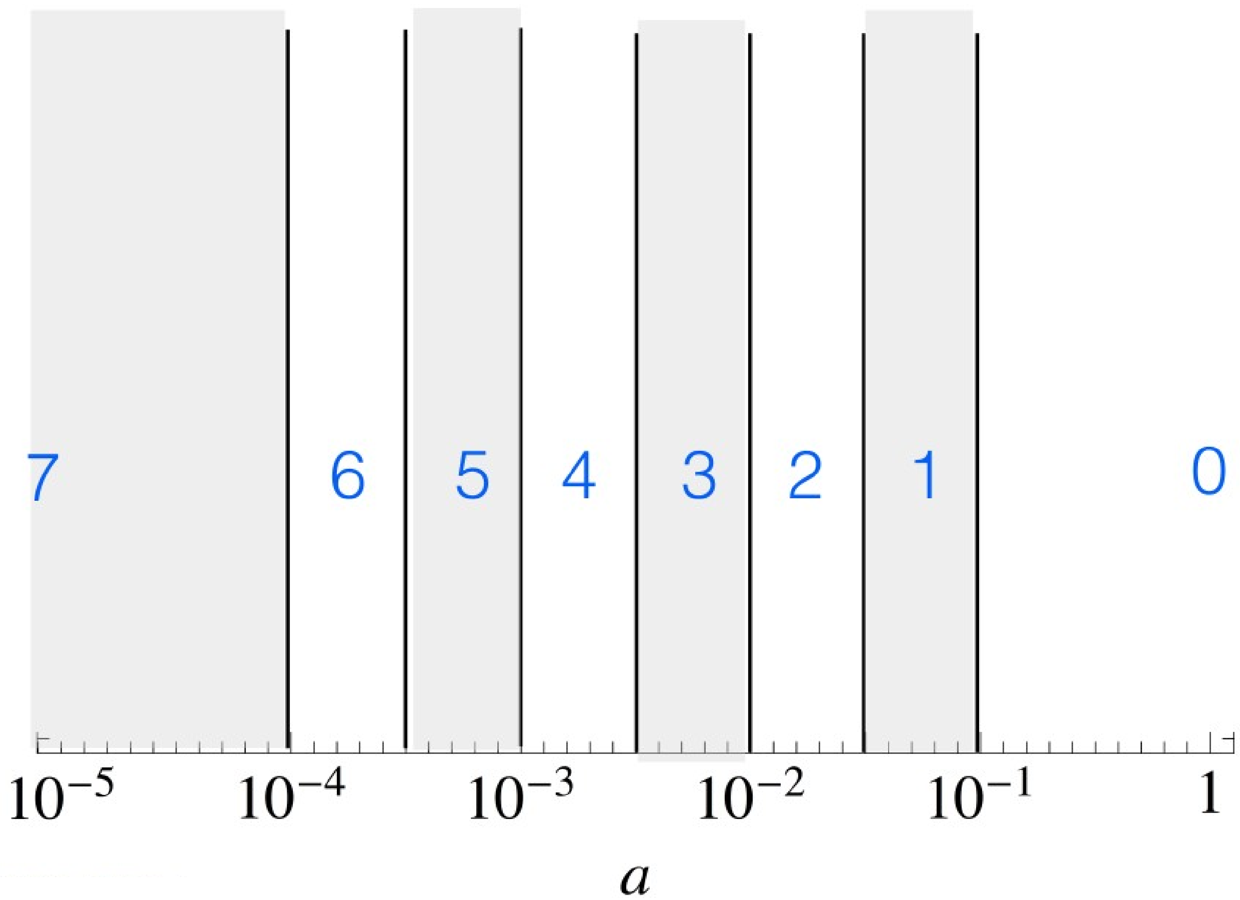
Constant w, c_s^2, and c_v^2 constraints



(courtesy of M. Kopp)

Binned w, $c_s^2 = c_v^2 = 0$ constraints

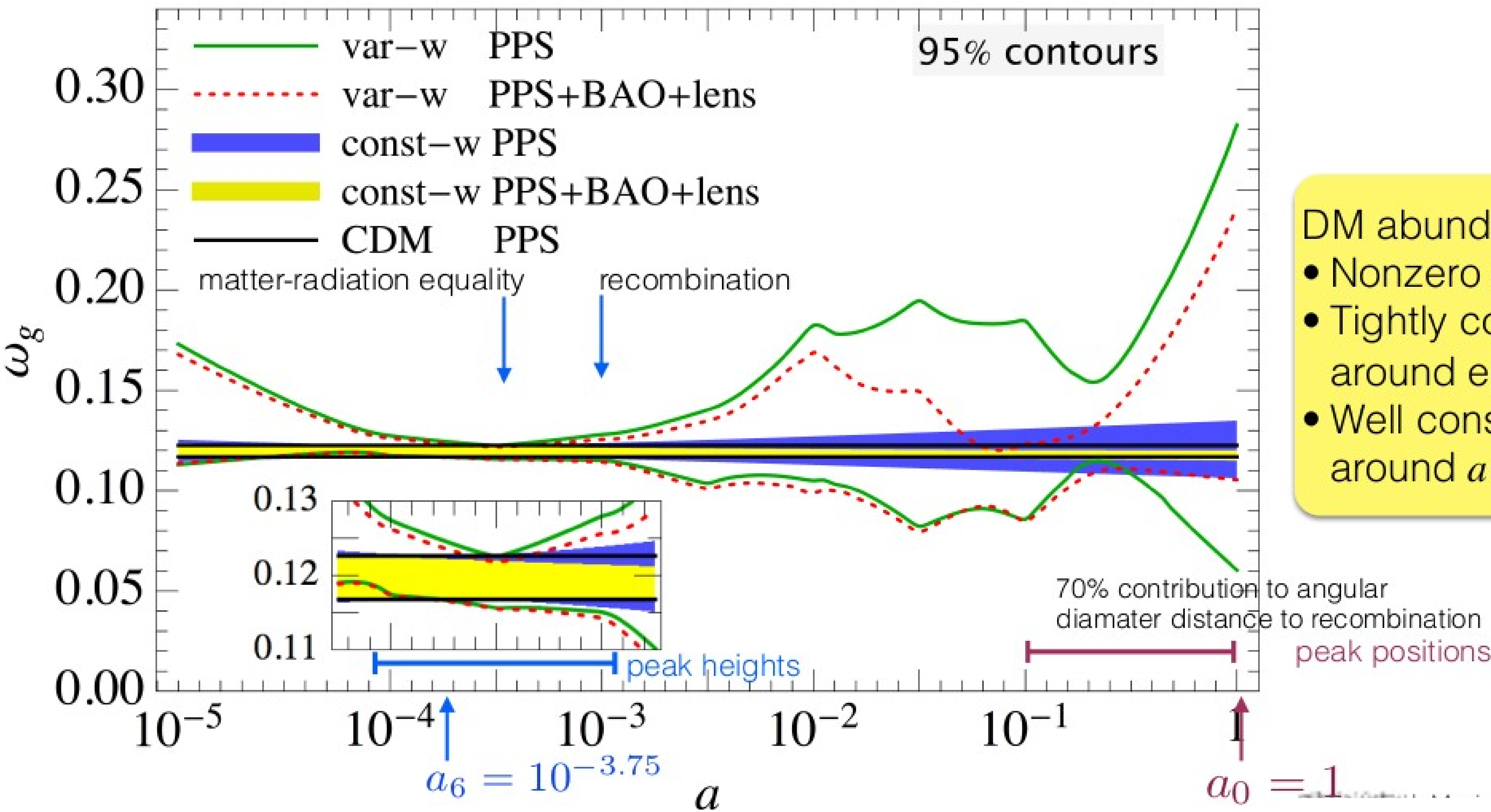
Kopp, Thomas, Skordis, SI, PRD, 2018



8 w bins

Binned w, $c_s^2 = c_v^2 = 0$ constraints

Kopp, Thomas, Skordis, SI, PRD, 2018



DM abundance is:

- Nonzero at all times
- Tightly constrained around equality
- Well constrained around a=[0.2-0.4]

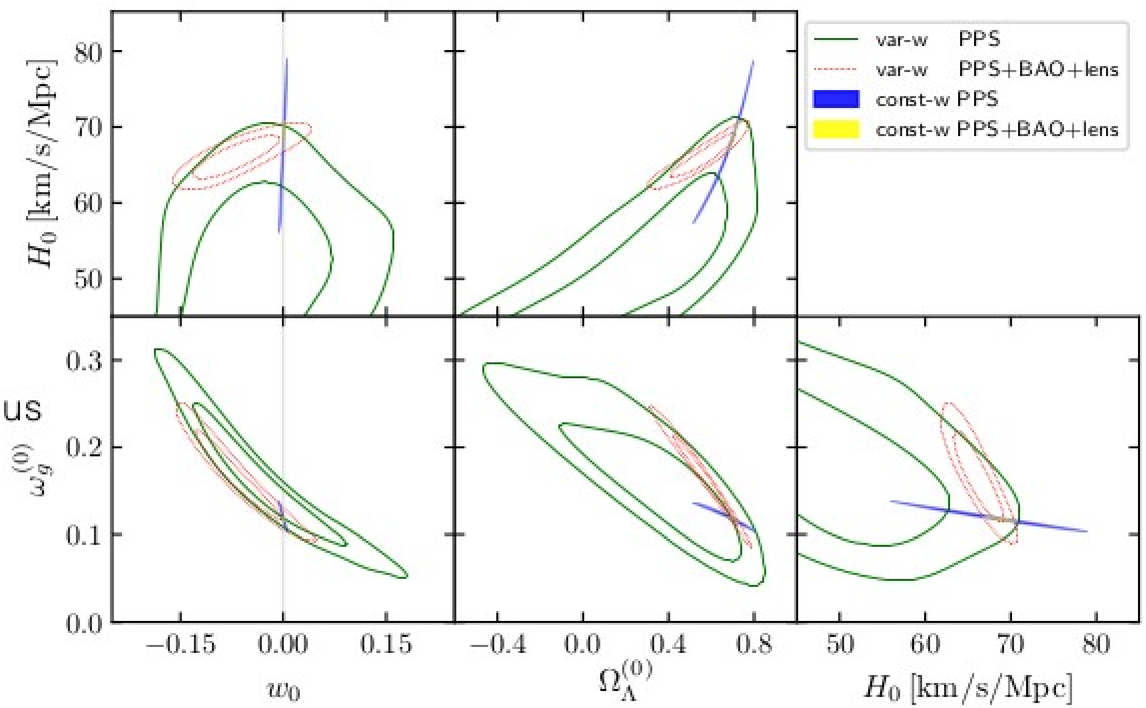
Binned w, $c_s^2 = c_v^2 = 0$ constraints

Kopp, Thomas, Skordis, SI, PRD, 2018

68% and 95% contours of 2D marginalised posteriors

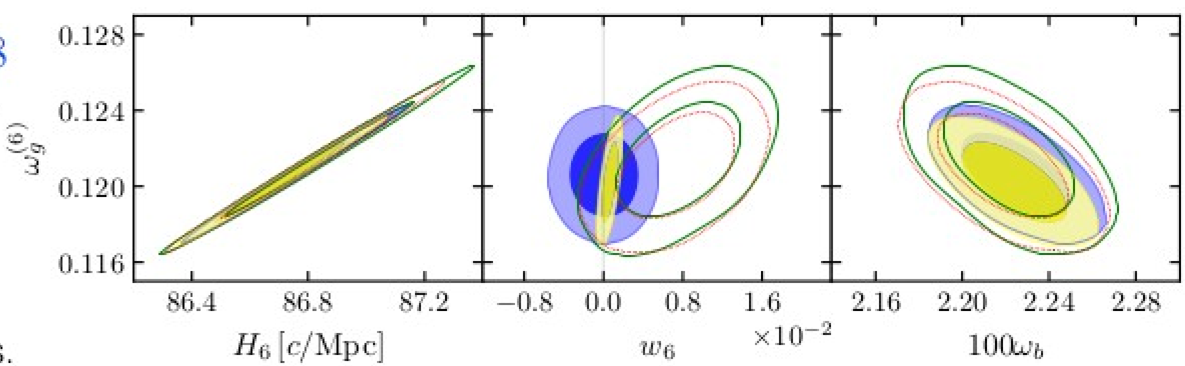
$a_0 = 1$

- Loss of constraining power at late times in the var-w model since the late Universe behaviour disassociates from the early Universe.
- Adding BAO or HST data thus strongly affects contours
- ω_g is anticorrelated with Ω_Λ since combination of CDM and Λ can be modeled by wDM.



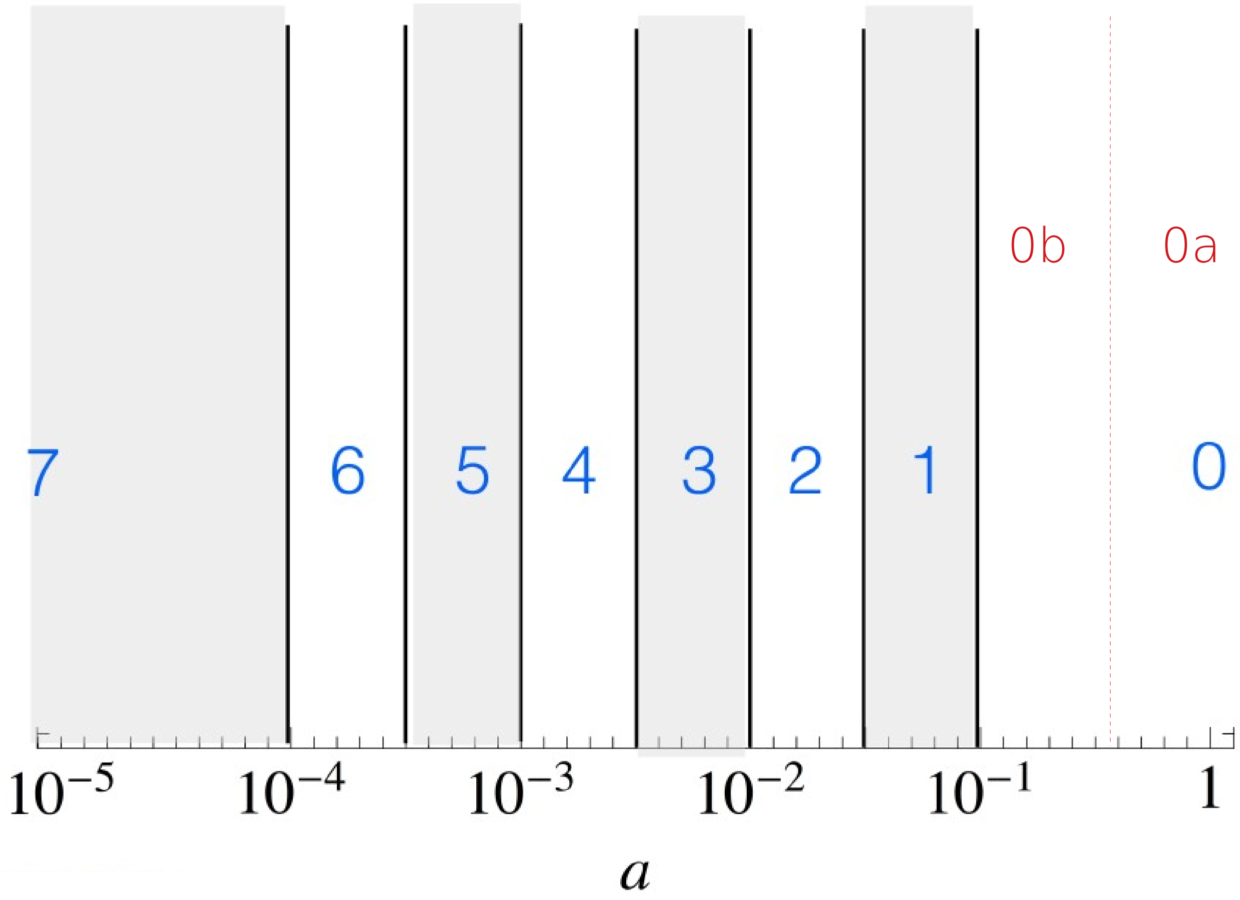
$a_6 = 10^{-3.75} = 0.00018$

- Strong constraining power at early times. Nearly as good as const w or CDM
- ω_g is better constrained then w. Causes correlations.



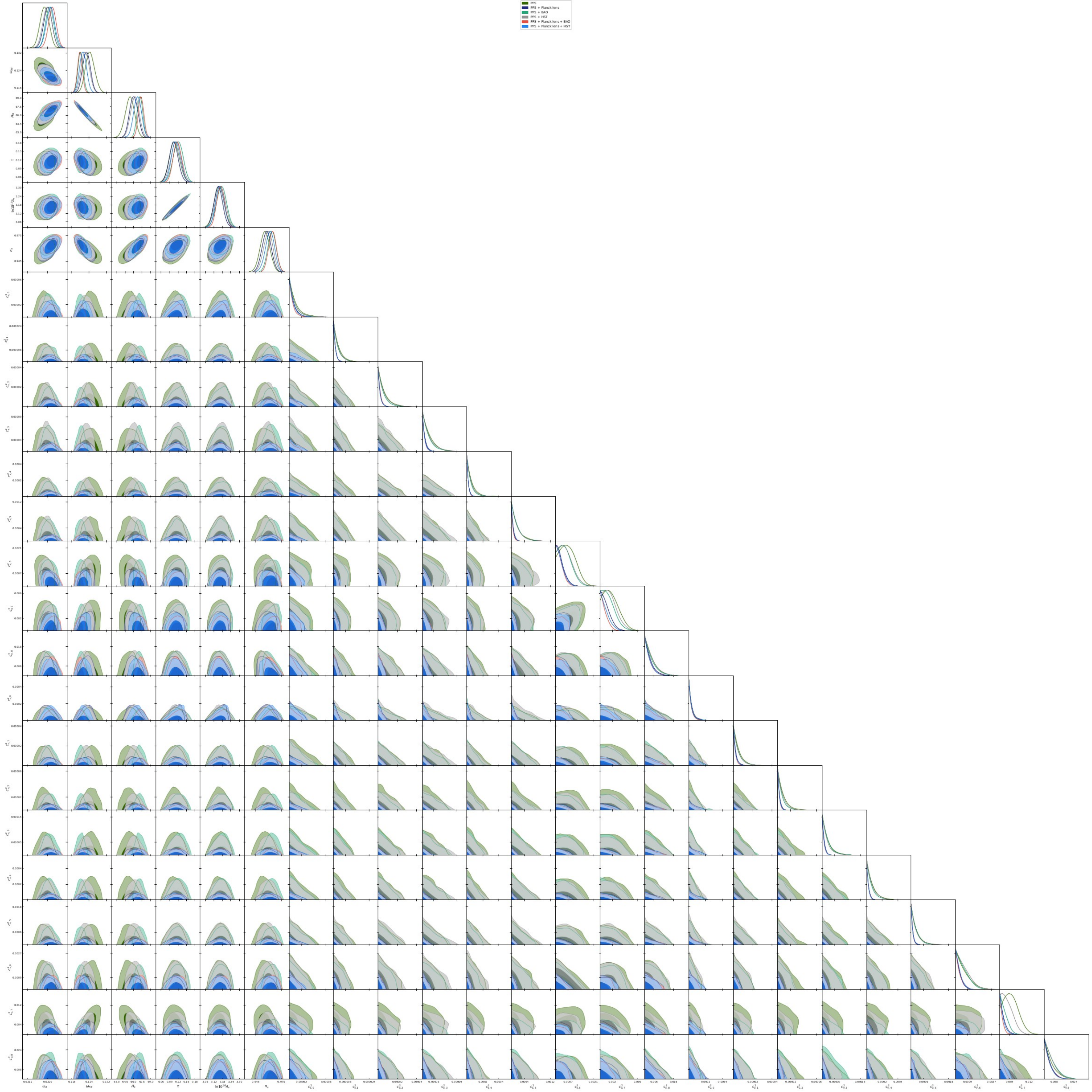
Binned w, c_s^2, and c_v^2 constraints

Ilic et al, in prep



8 w bins (or w=0)

9 c_s^2, and c_v^2 bins


PPS
PPS + Planck lens
PPS + BAO
PPS + HST
PPS + Planck lens + BAO
PPS + Planck lens + HST

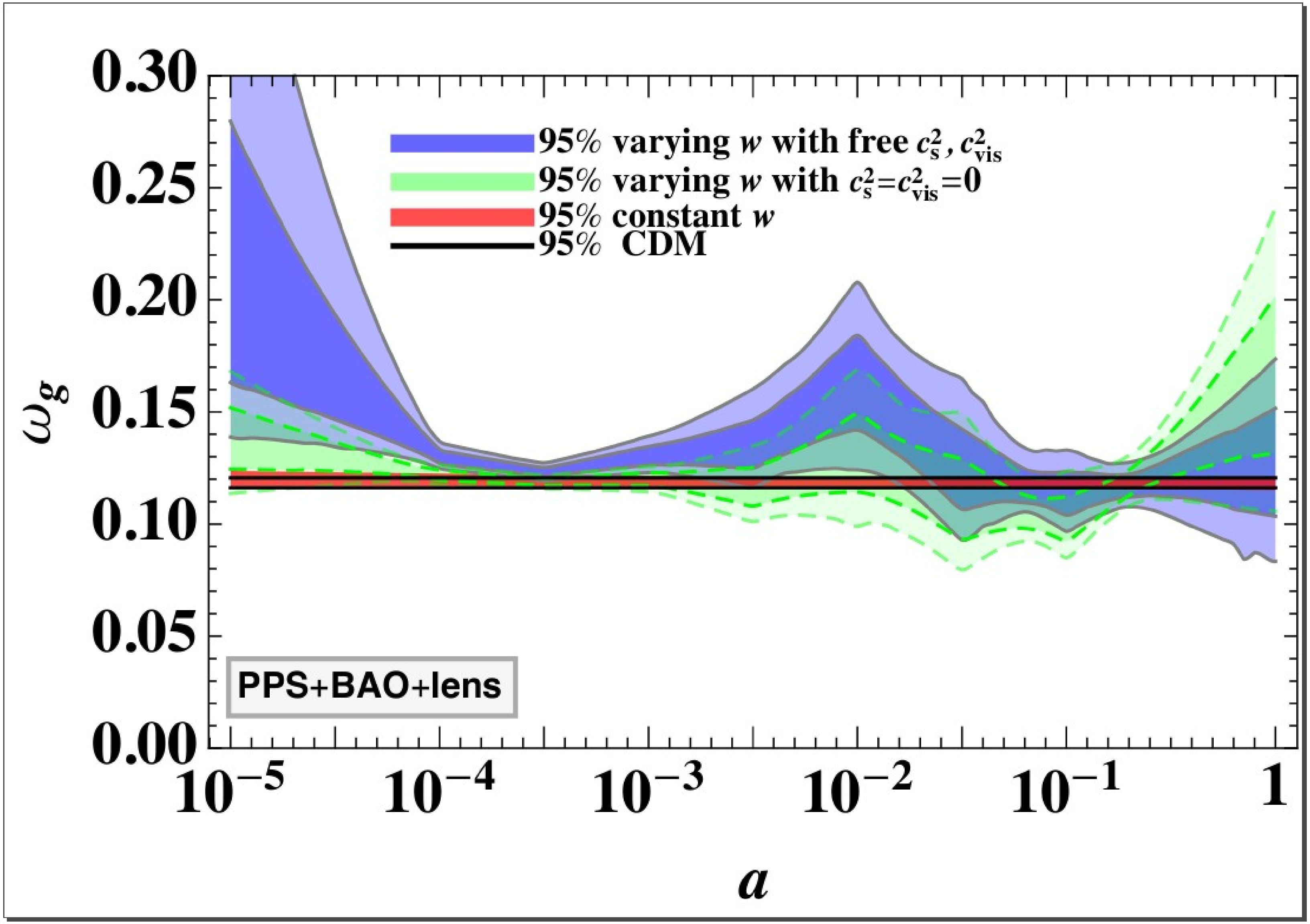
Binned w, c_s^2, and c_v^2 constraints

Ilic et al, in prep

- "Loss of constraints" ~ factor 2.5-3 vs. constant model
- 3 sigma detection of non-zero w_6 & w_7
- Strong correlation between w & c_s in last bin
- 2 sigma detection of $c_+^2 \equiv c_s^2 + \frac{8}{15} c_v^2$ in last 3 bins

Binned w, c_s^2, and c_v^2 constraints

Ilic et al, in prep



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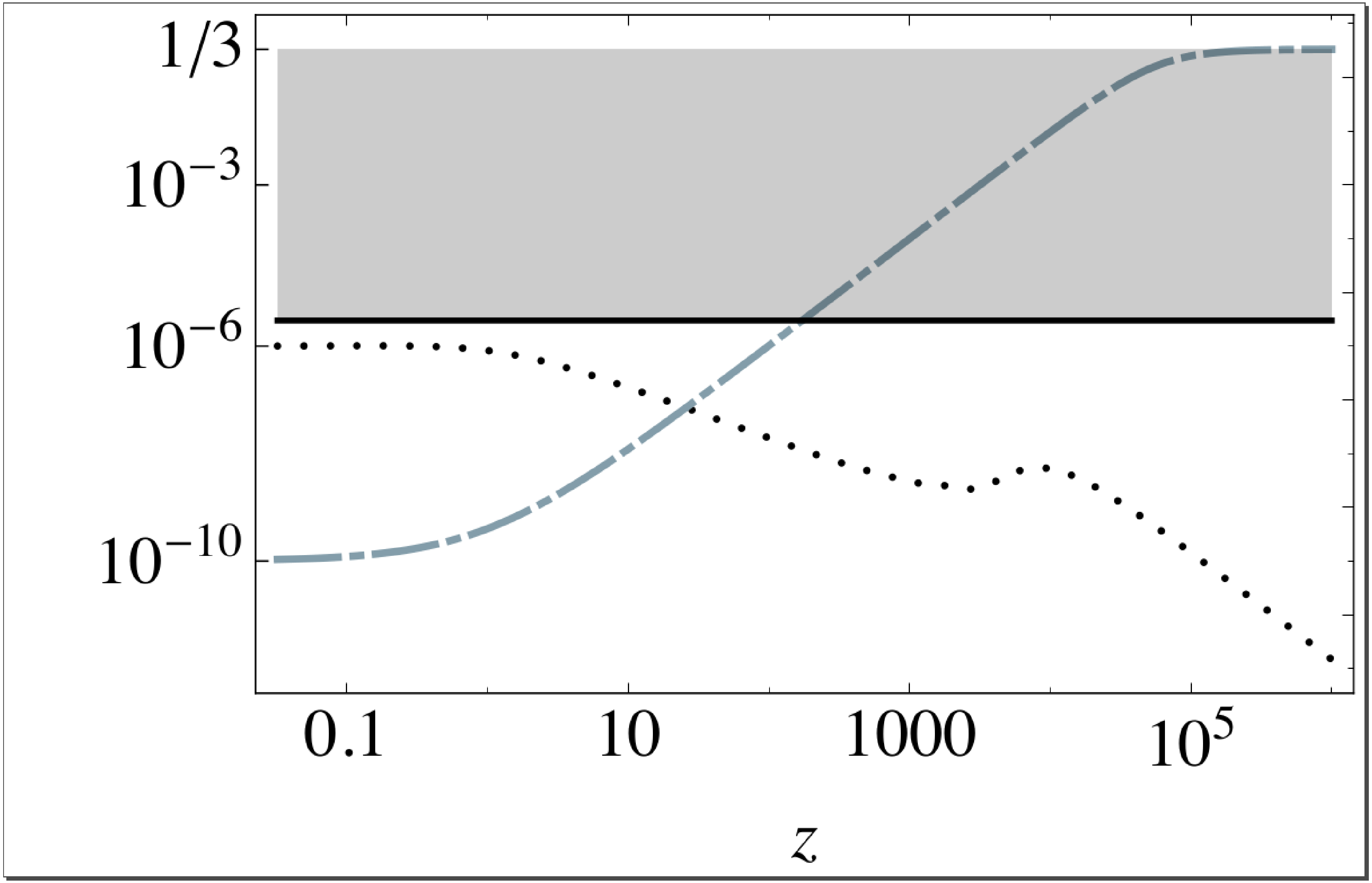

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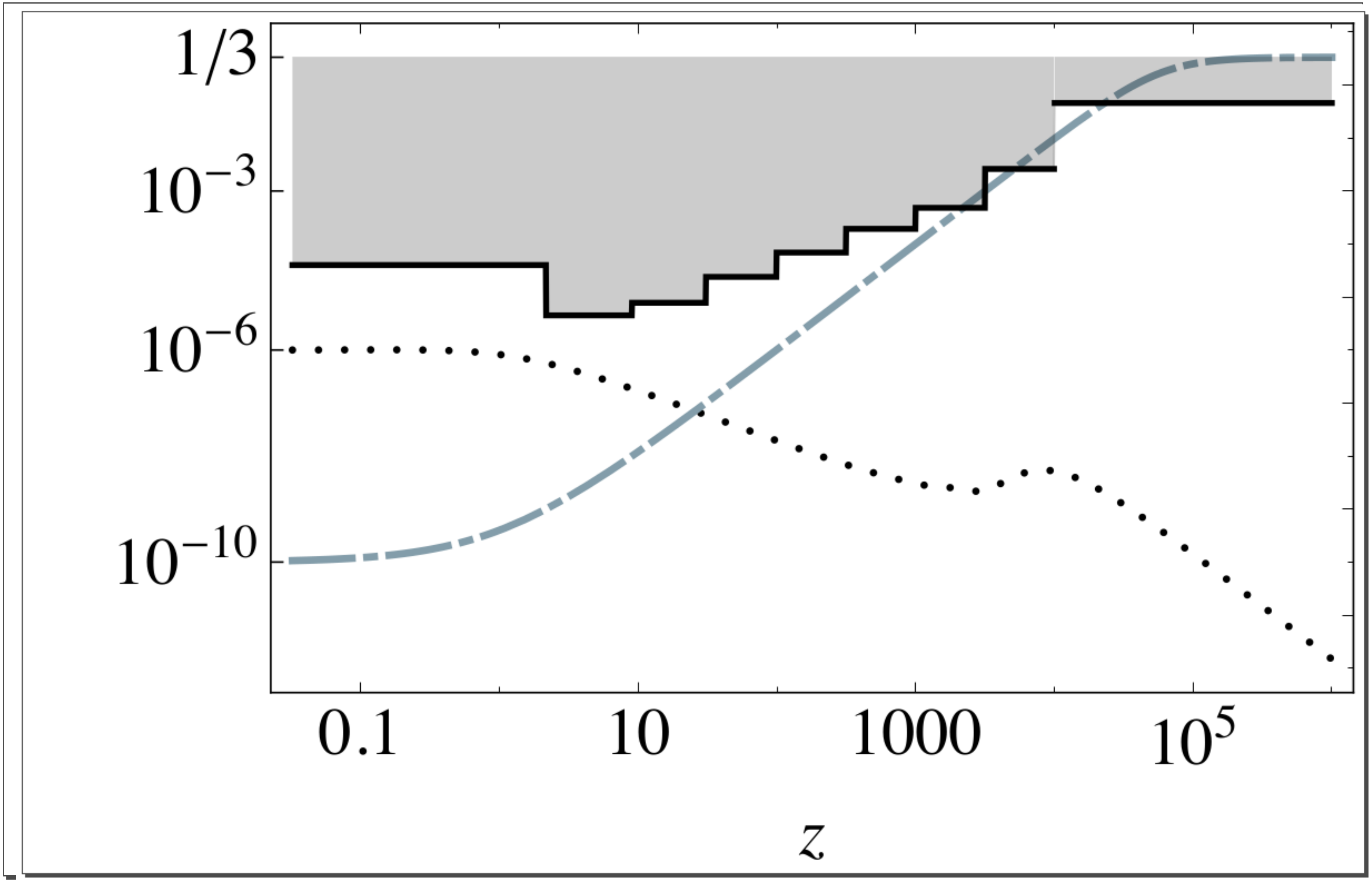

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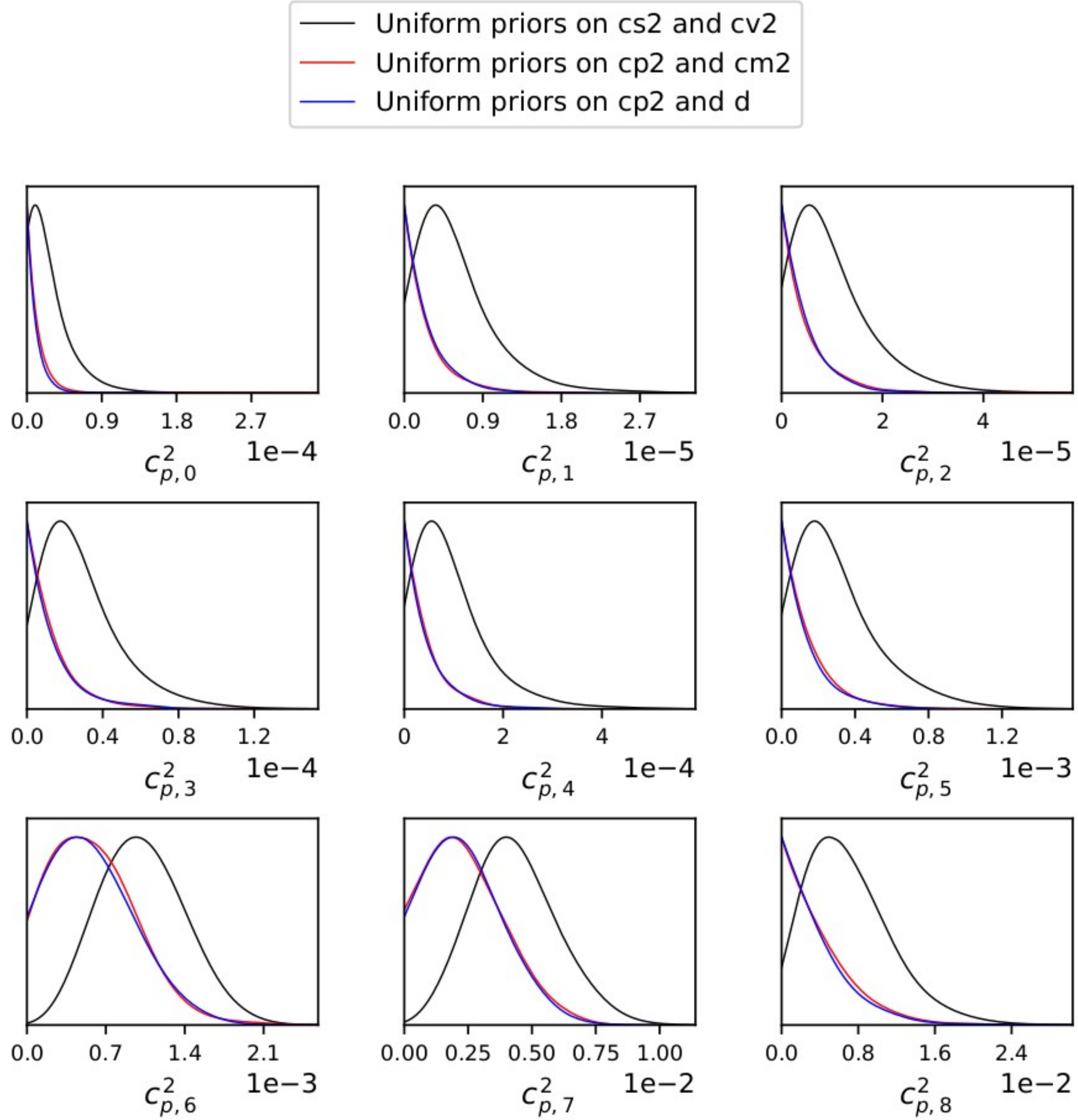
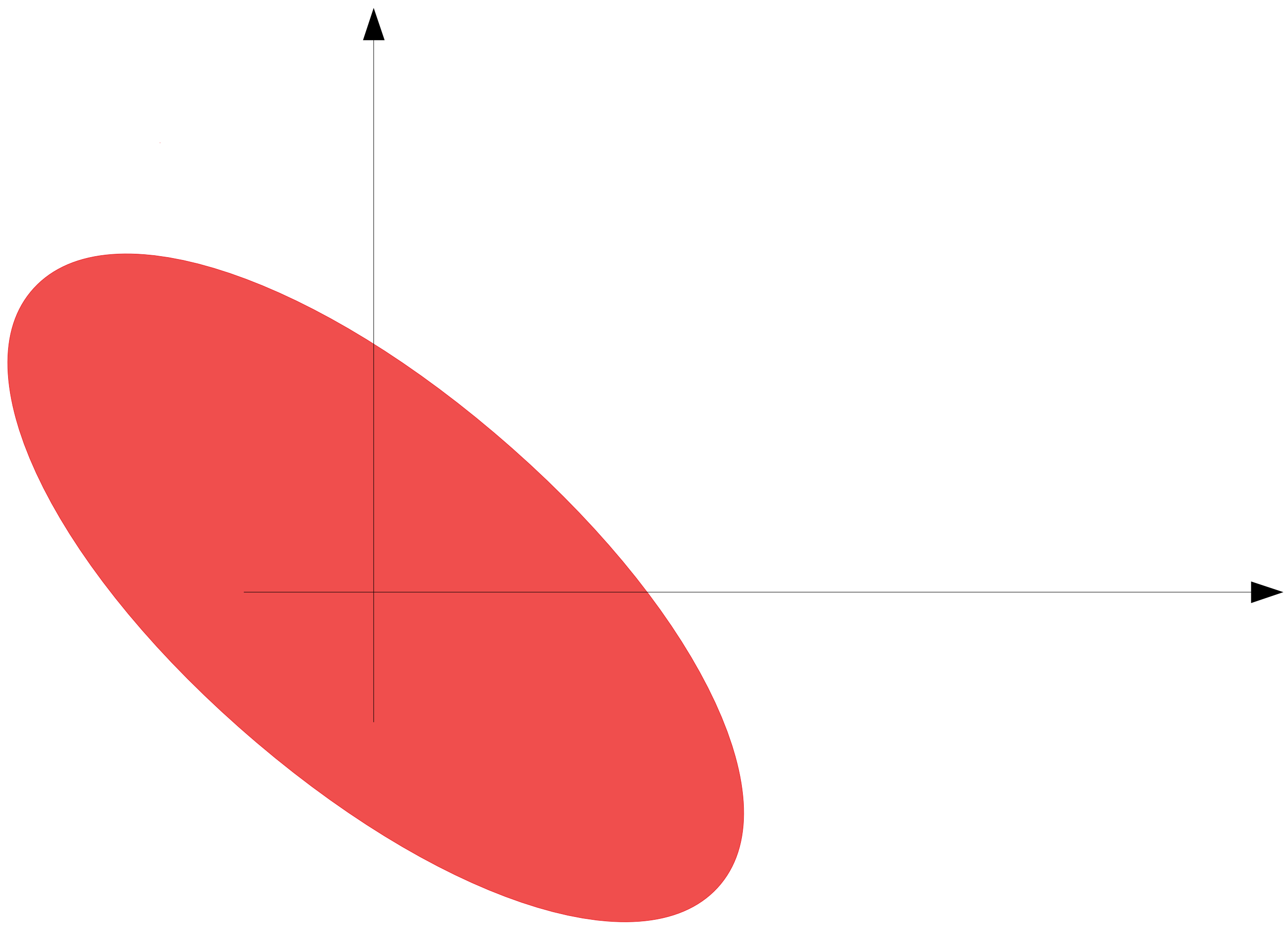
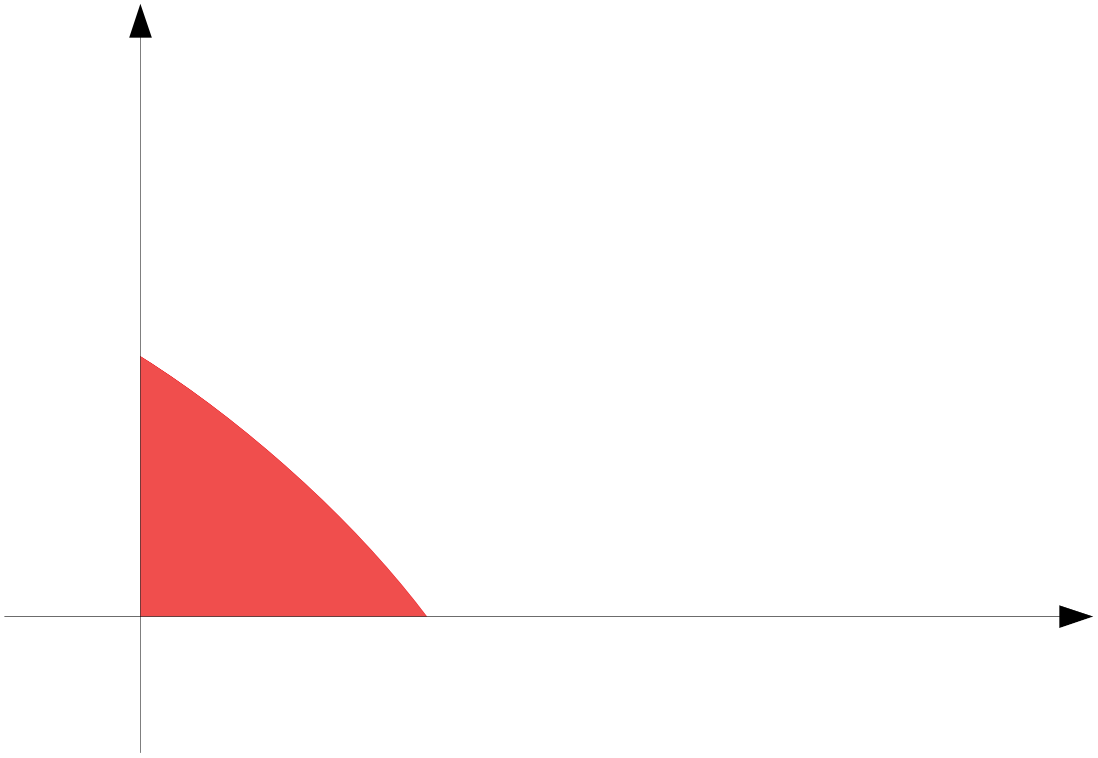


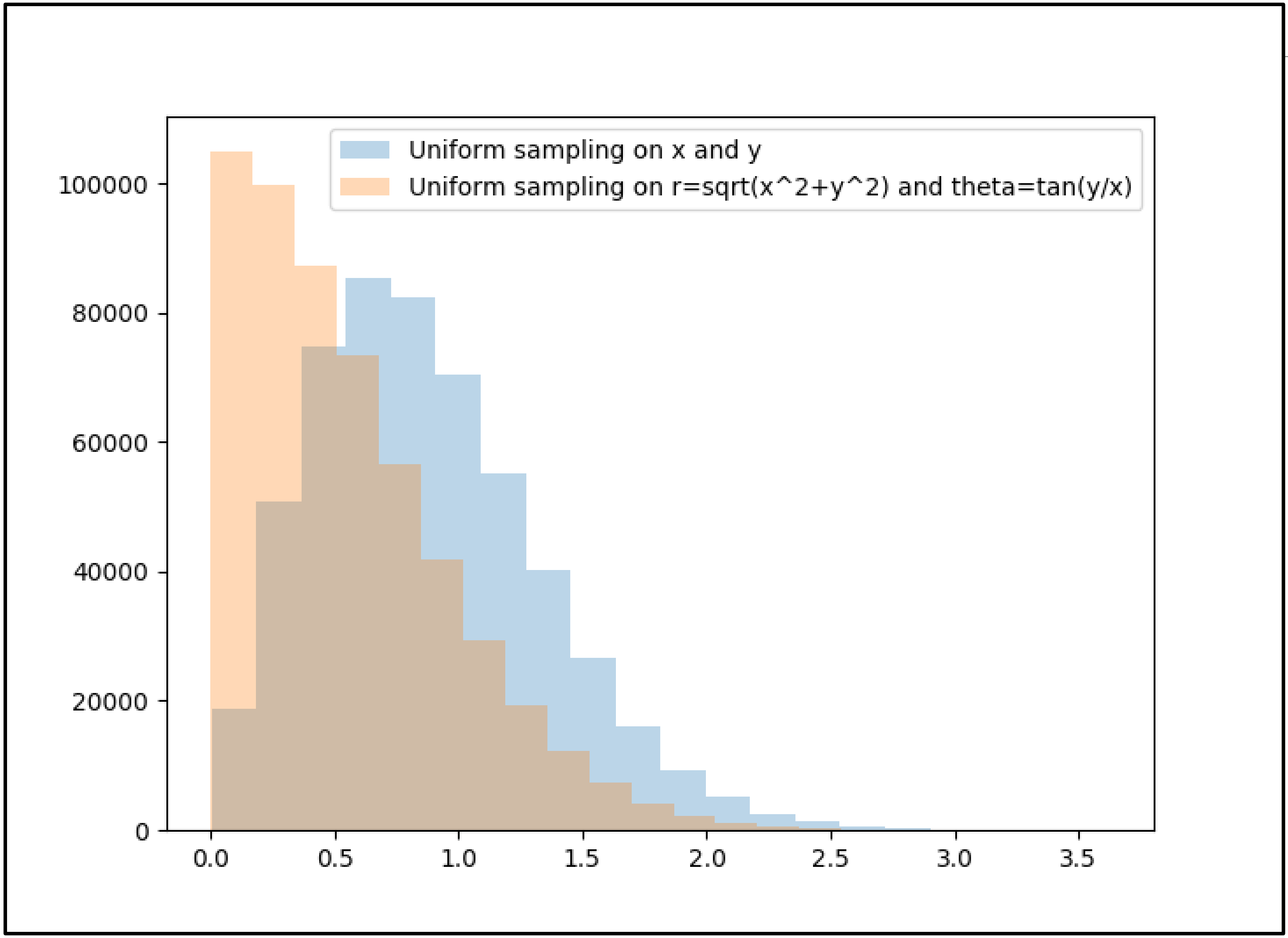
Effects of priors

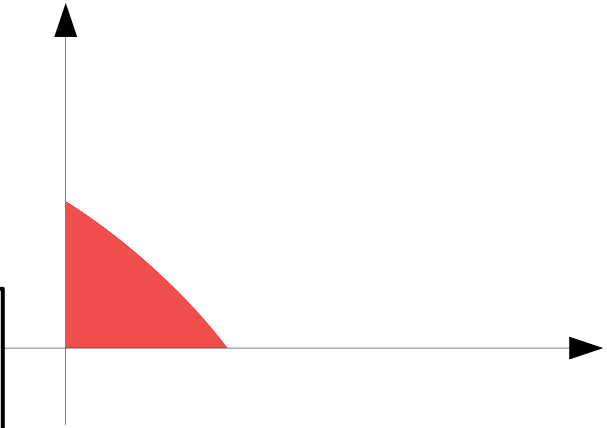


Effects of priors



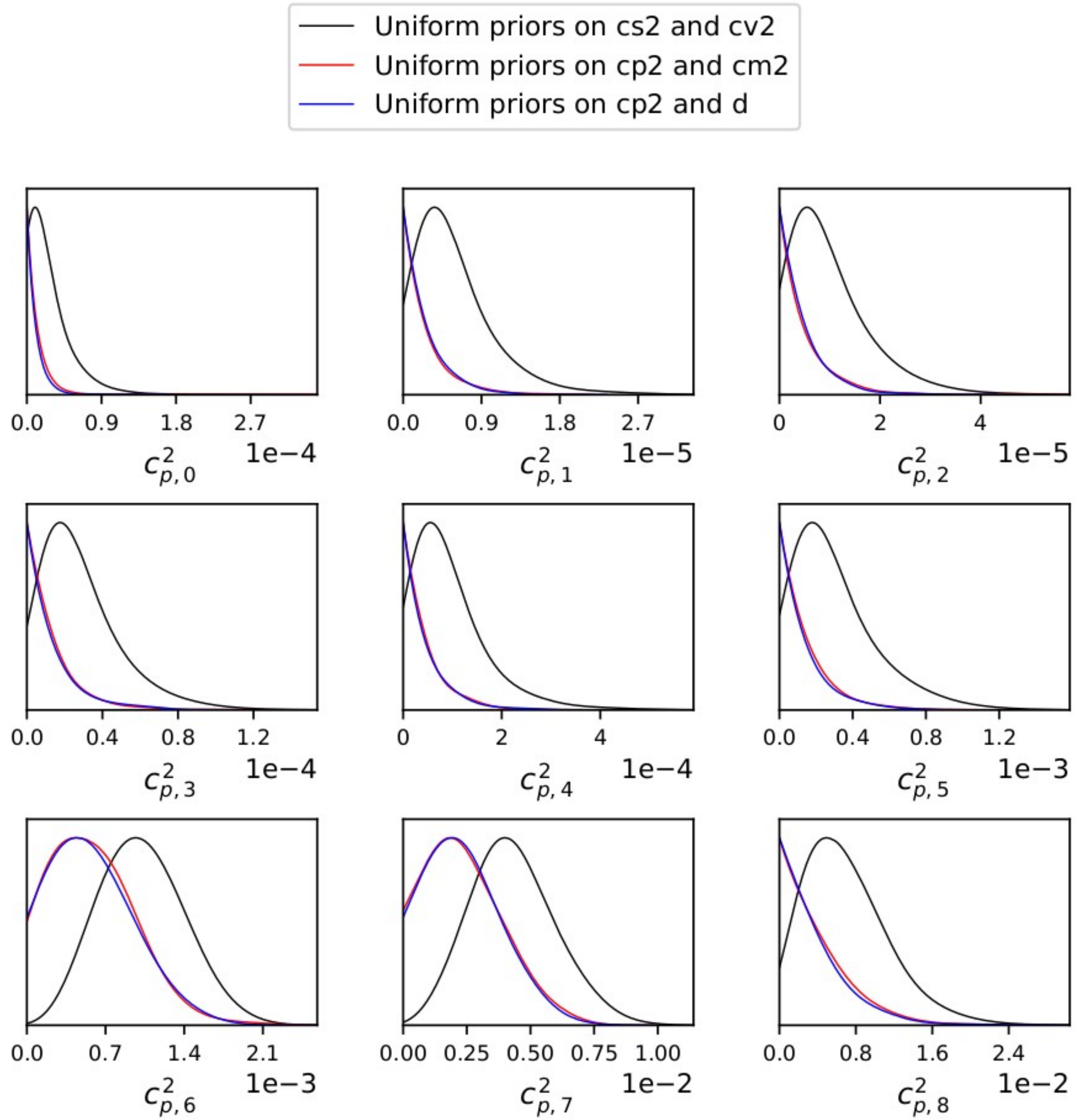
Effects of priors





Binned w, c_s^2, and c_v^2 constraints

Ilic et al, in prep



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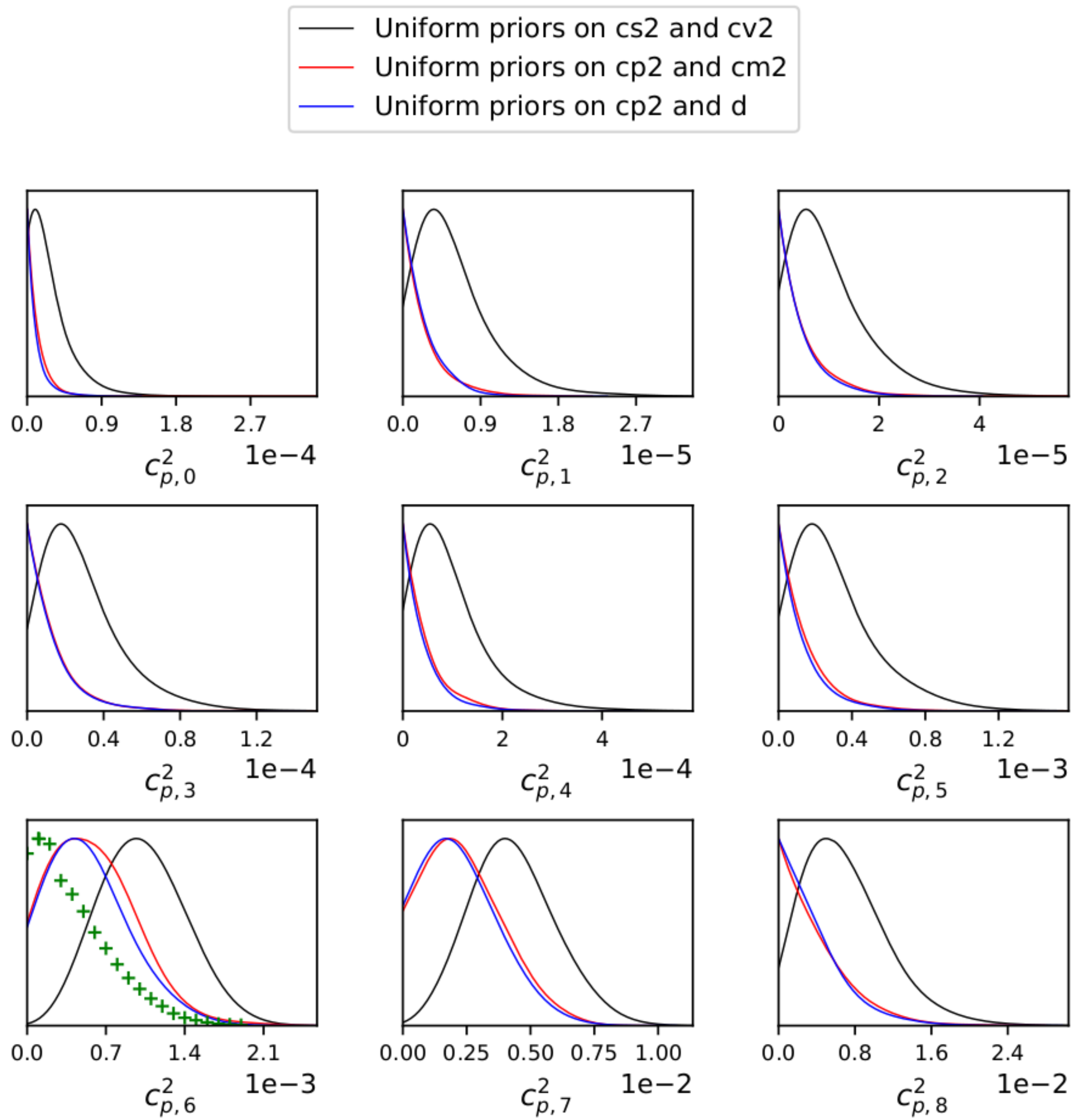


Frequentist approach : profile likelihood

Outline

I. Going beyond CDM

II. Cosmological constraints on GDM

III. Ongoing work and prospects

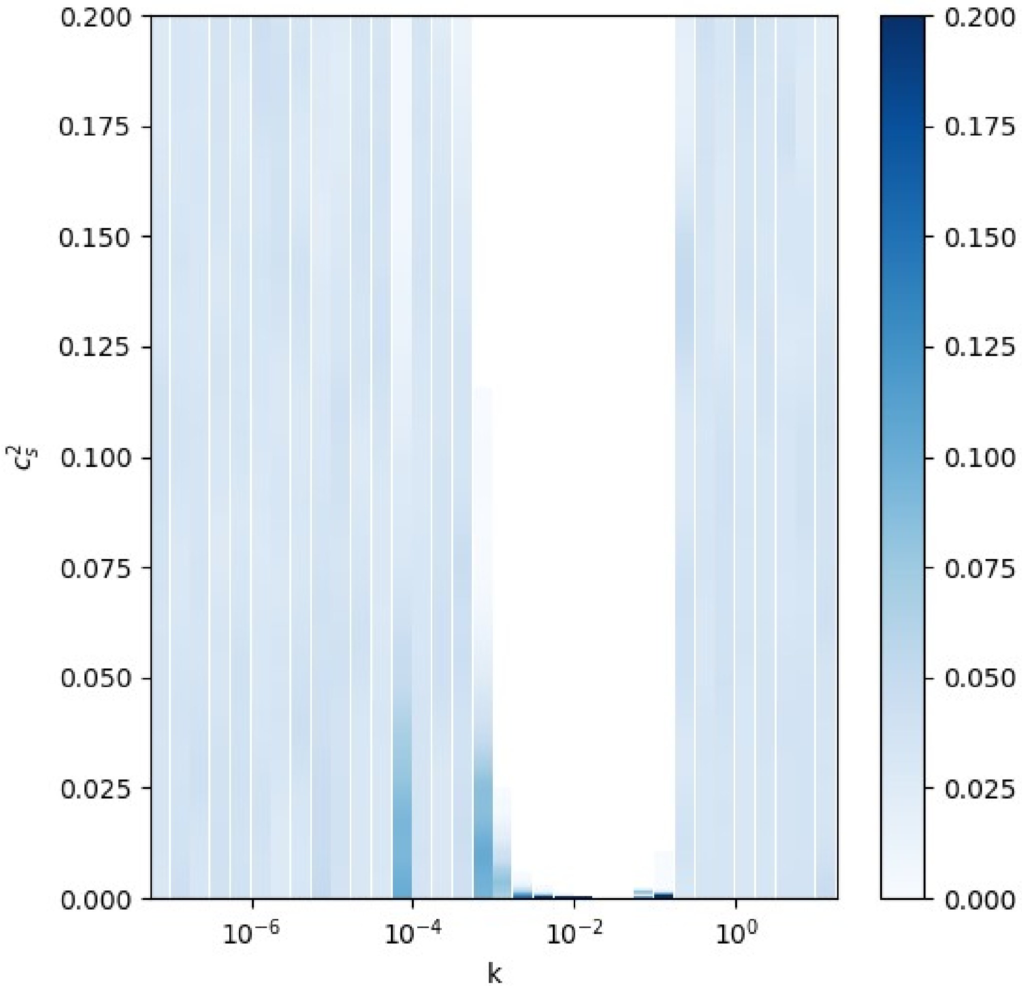
Scale-dependent GDM

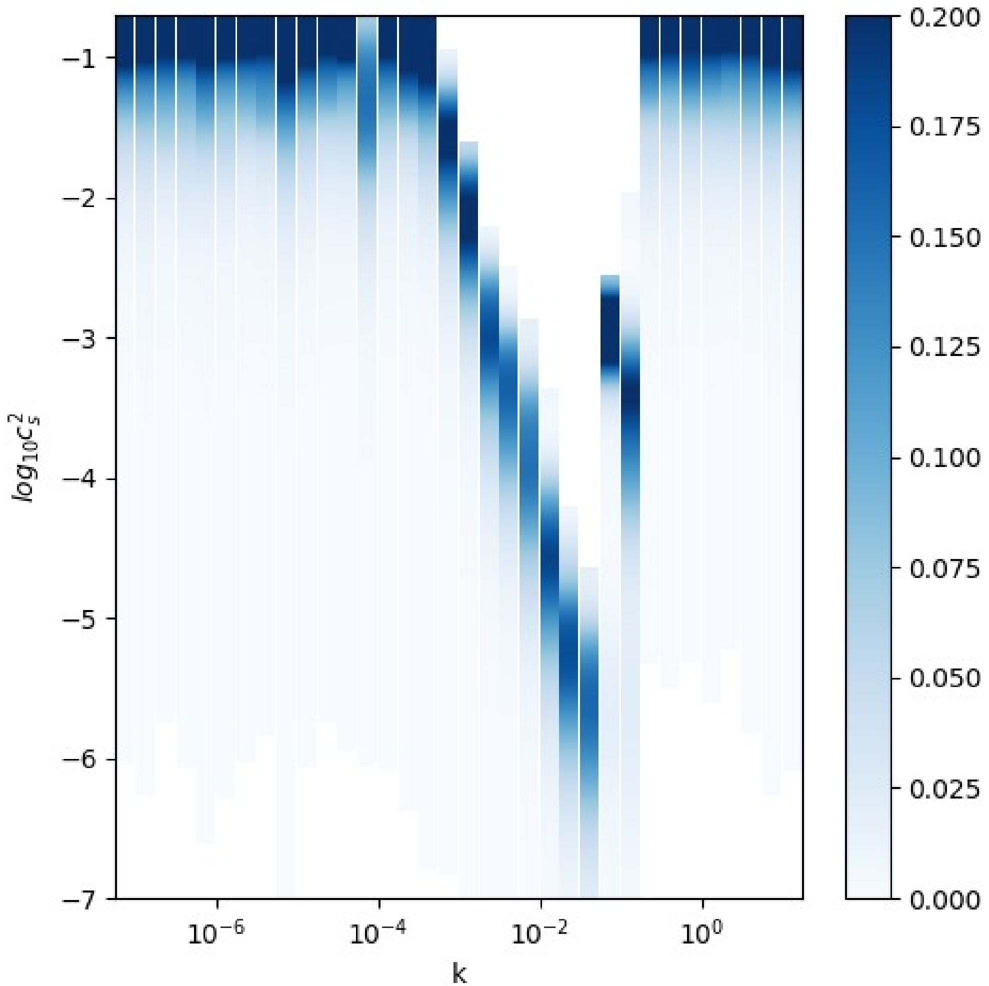
Relaxing the scale independence

of the GDM w, c_s^2, and c_v^2

Scale-dependent GDM

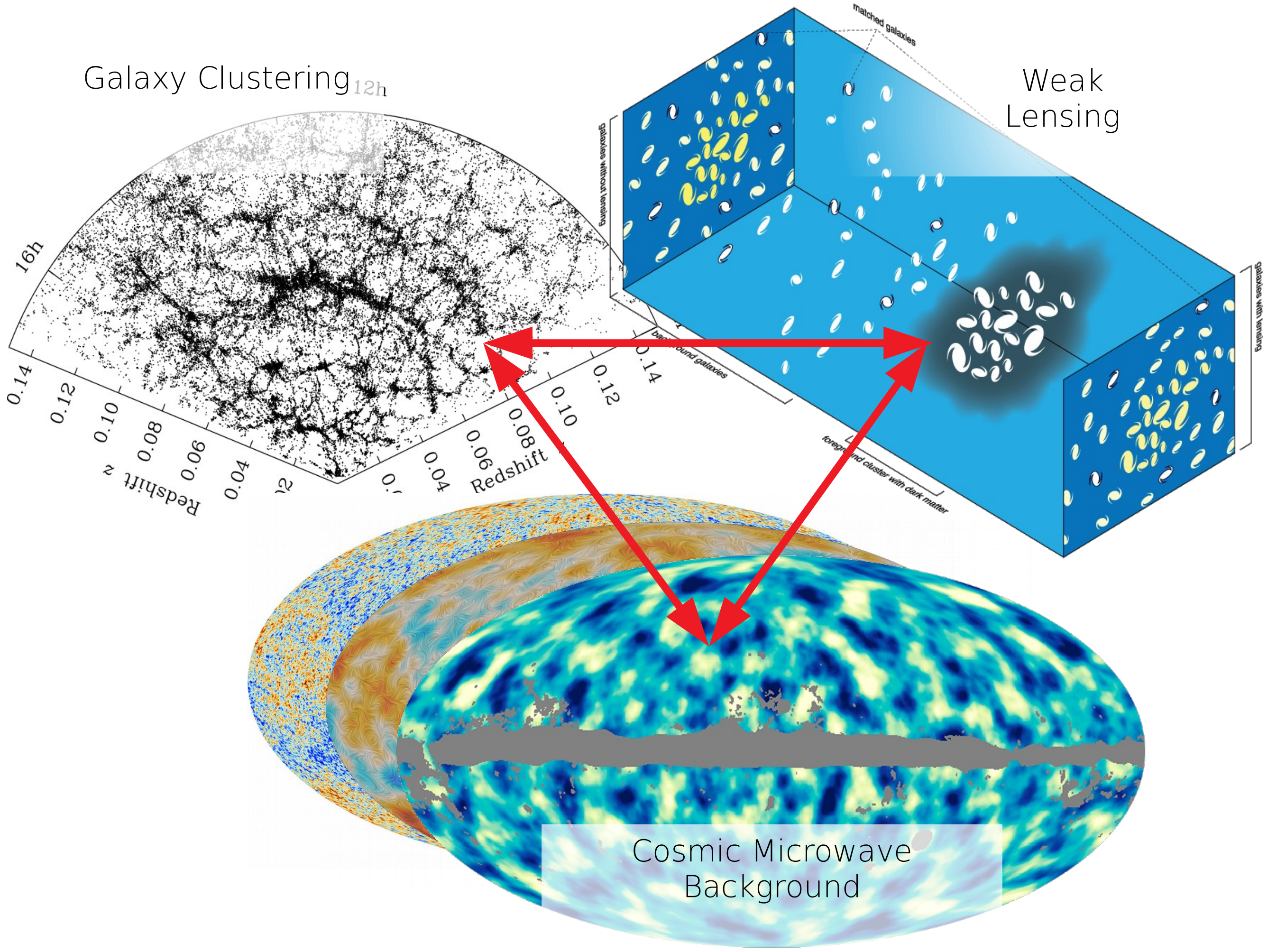
Relaxing the scale independence of the GDM w, c_s^2, and c_v^2





PRELIMINARY

Beyond CMB-only constraints



GDM Halo model & LSS constraints

Thomas et al., 2019, arXiv:1905.02739

GDM cosmological constraints

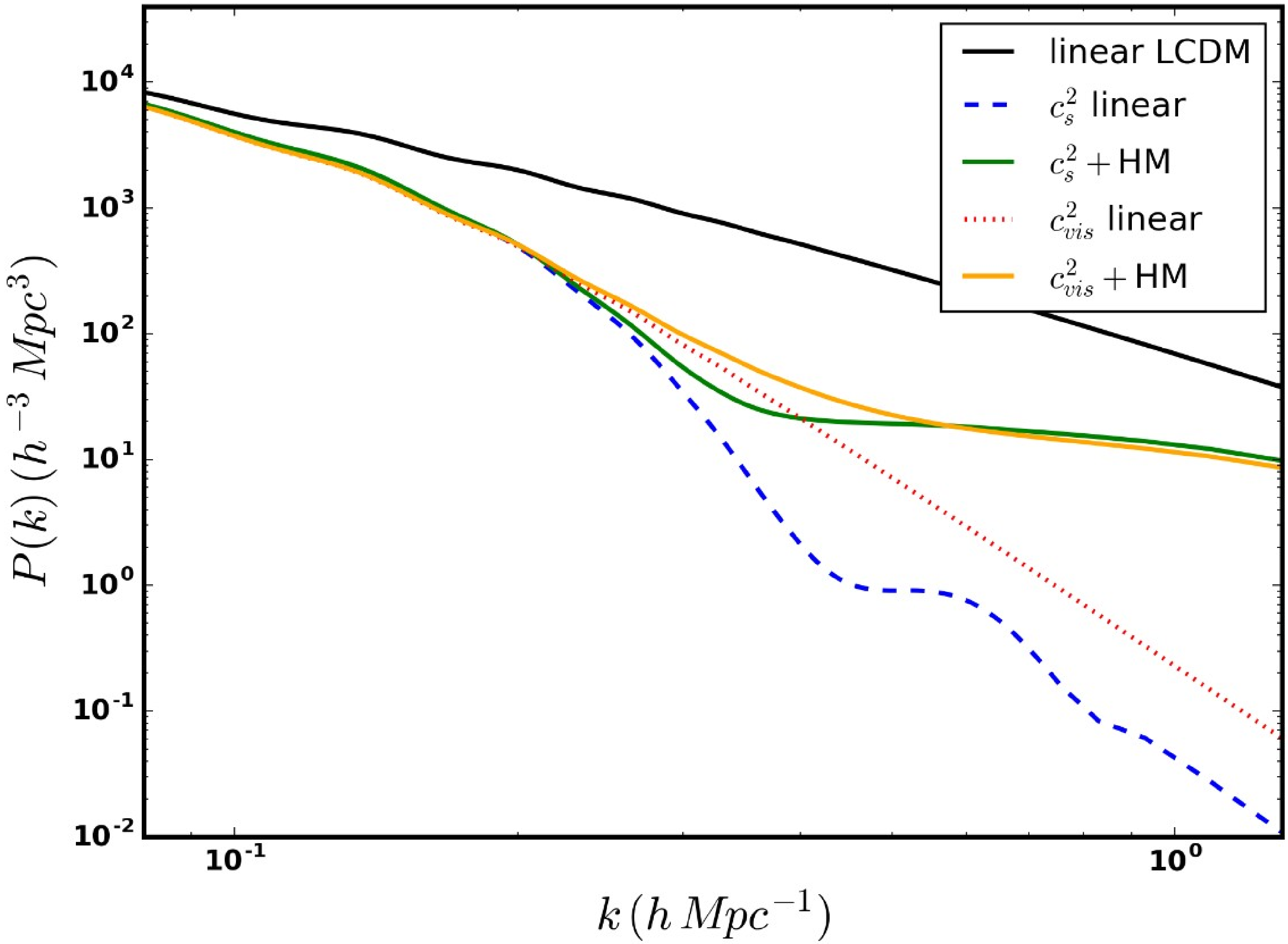
with free, constant w, c_s^2, and c_v^2

+ New Halo model for non-linearities

+ LSS data : WiggleZ matter power spectrum

GDM Halo model & LSS constraints

Thomas et al., 2019, arXiv:1905.02739



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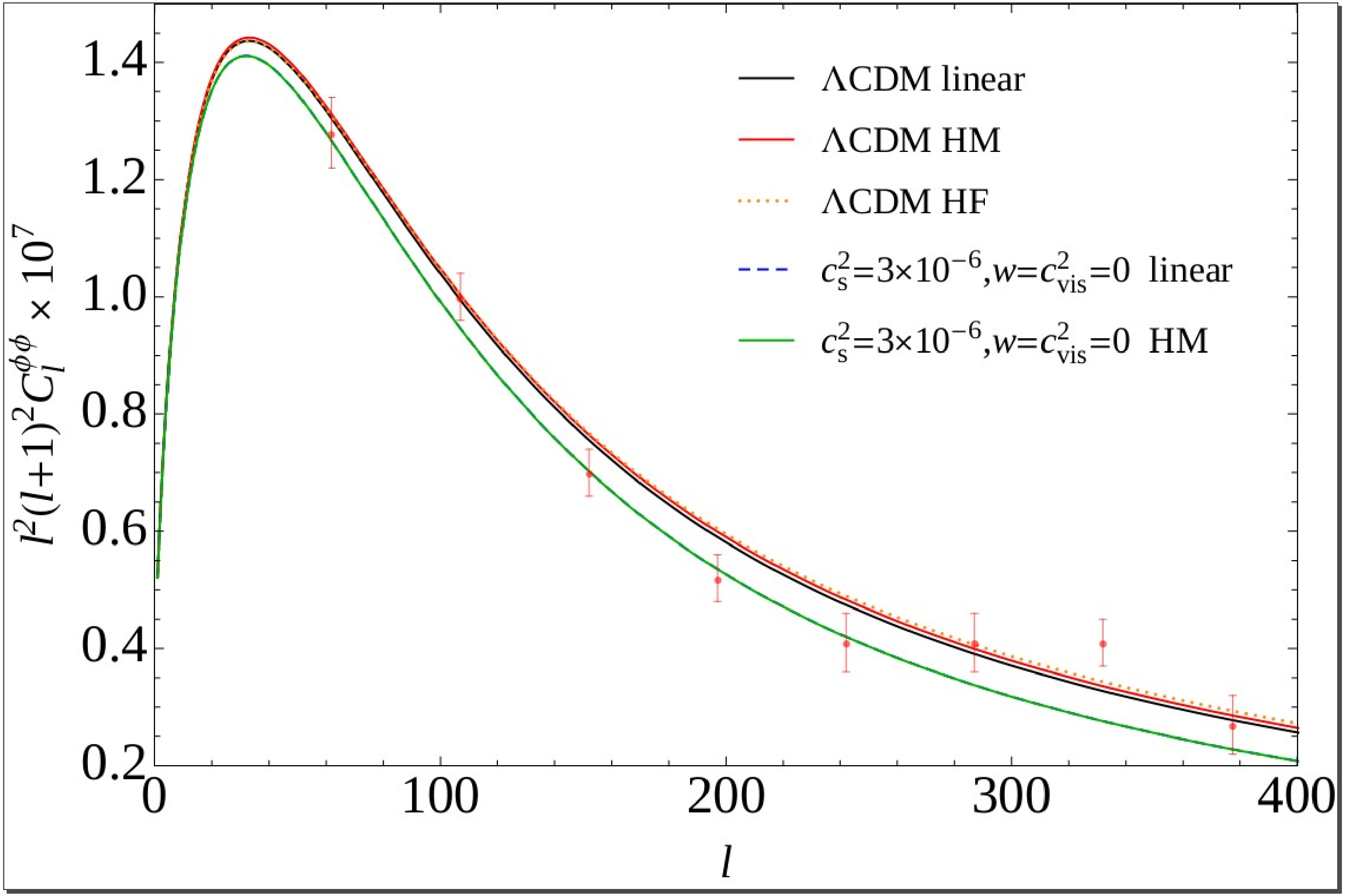

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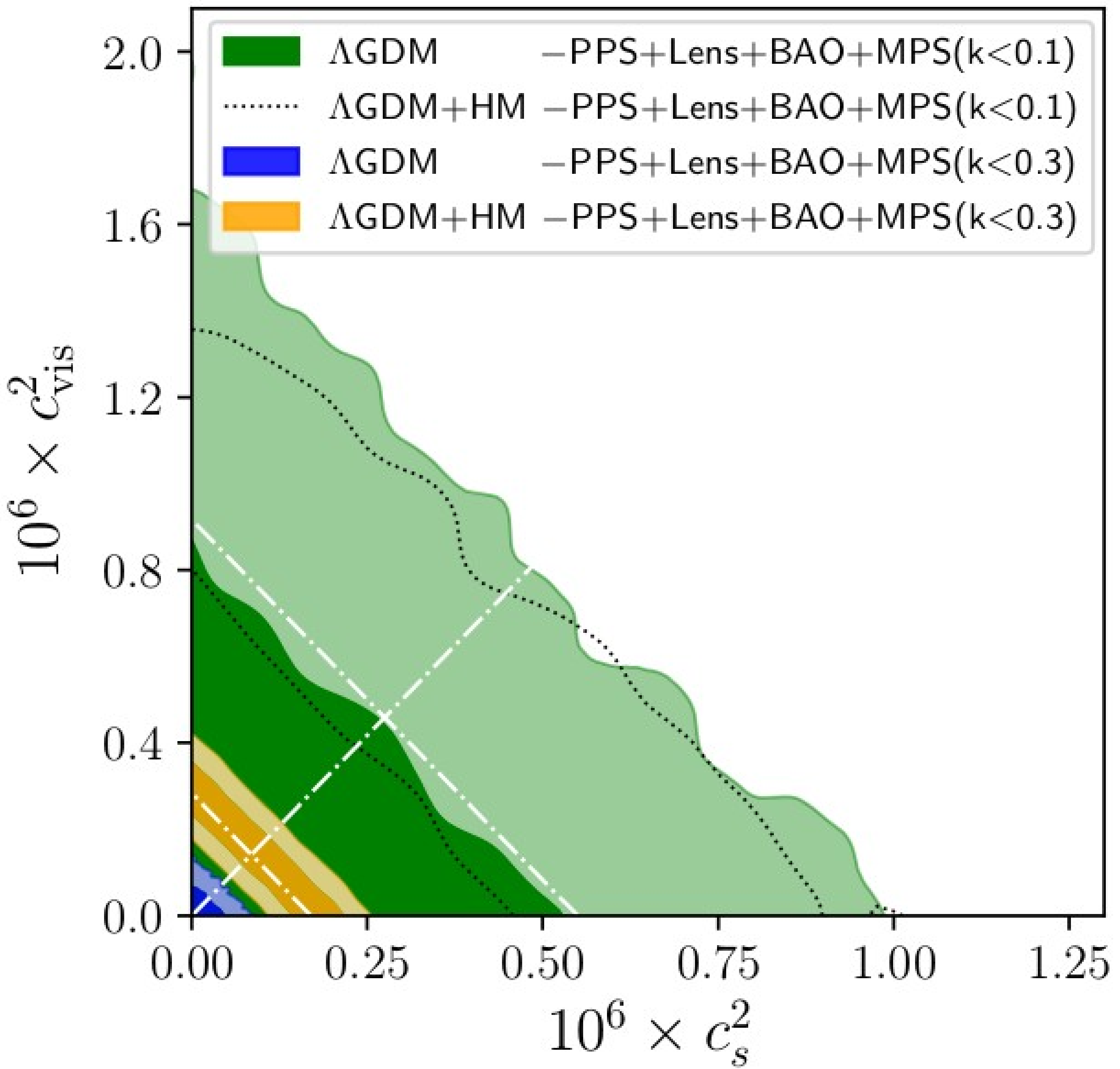
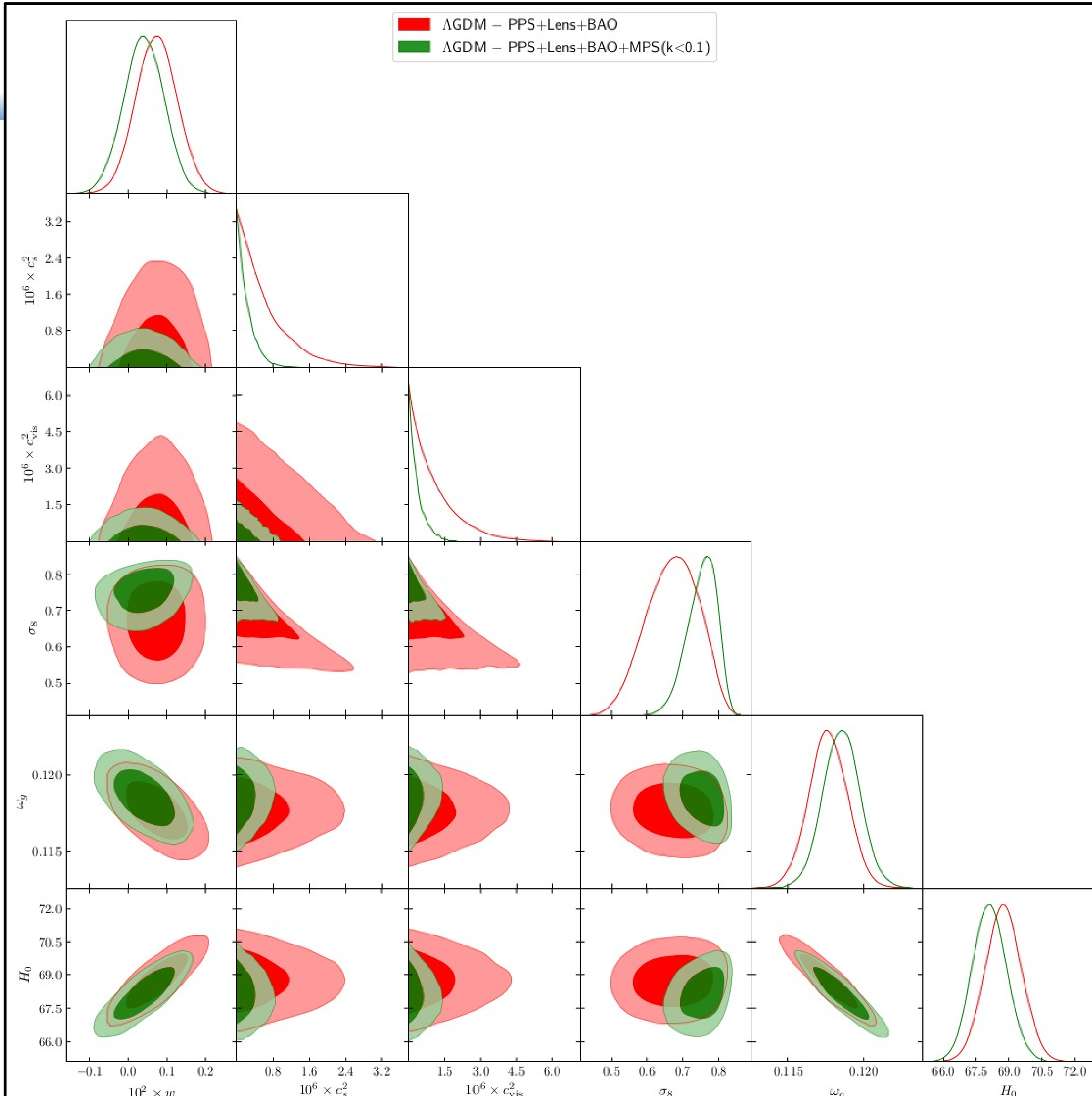


GDM



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GDM and massive neutrinos

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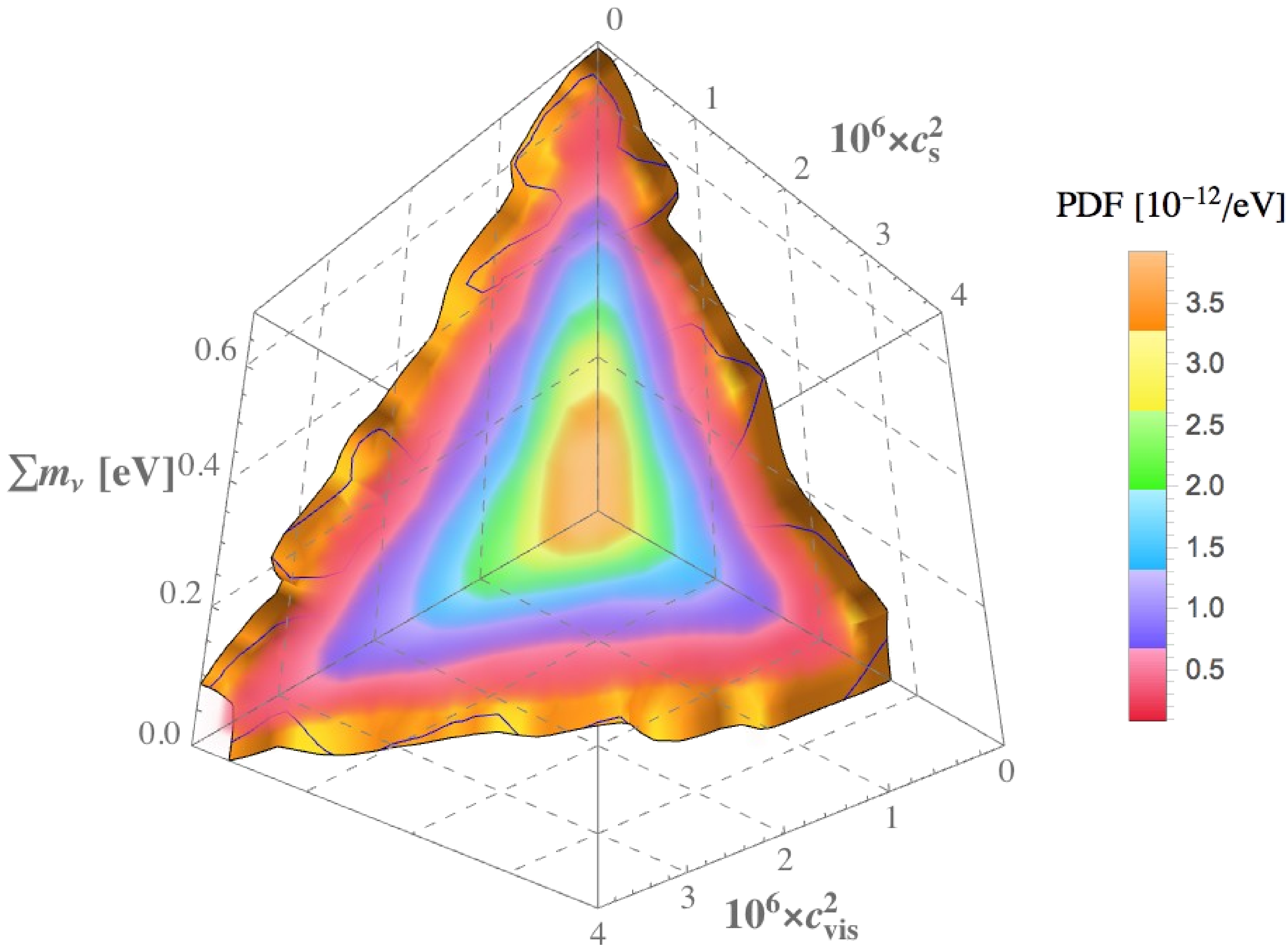

GDM and massive neutrinos

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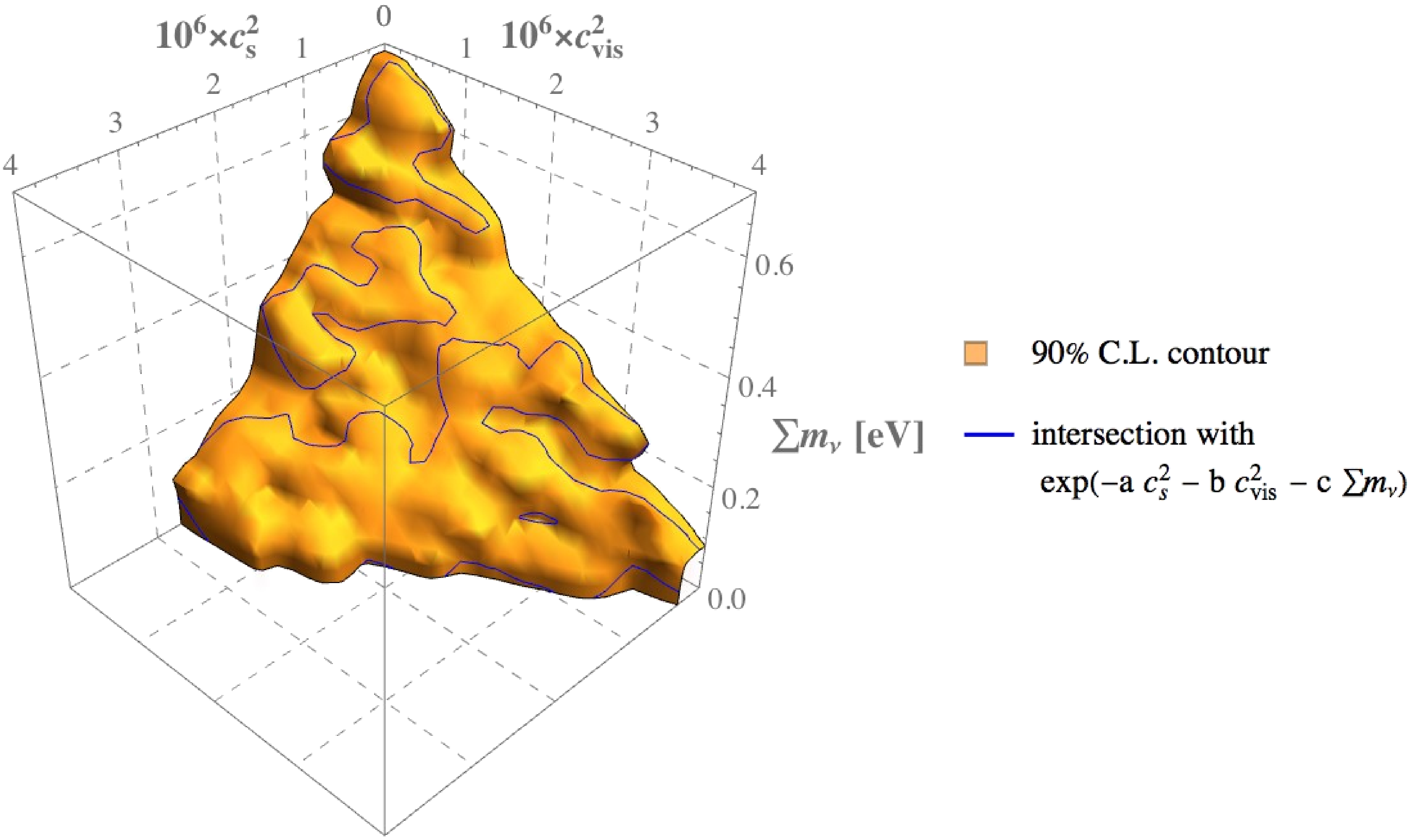
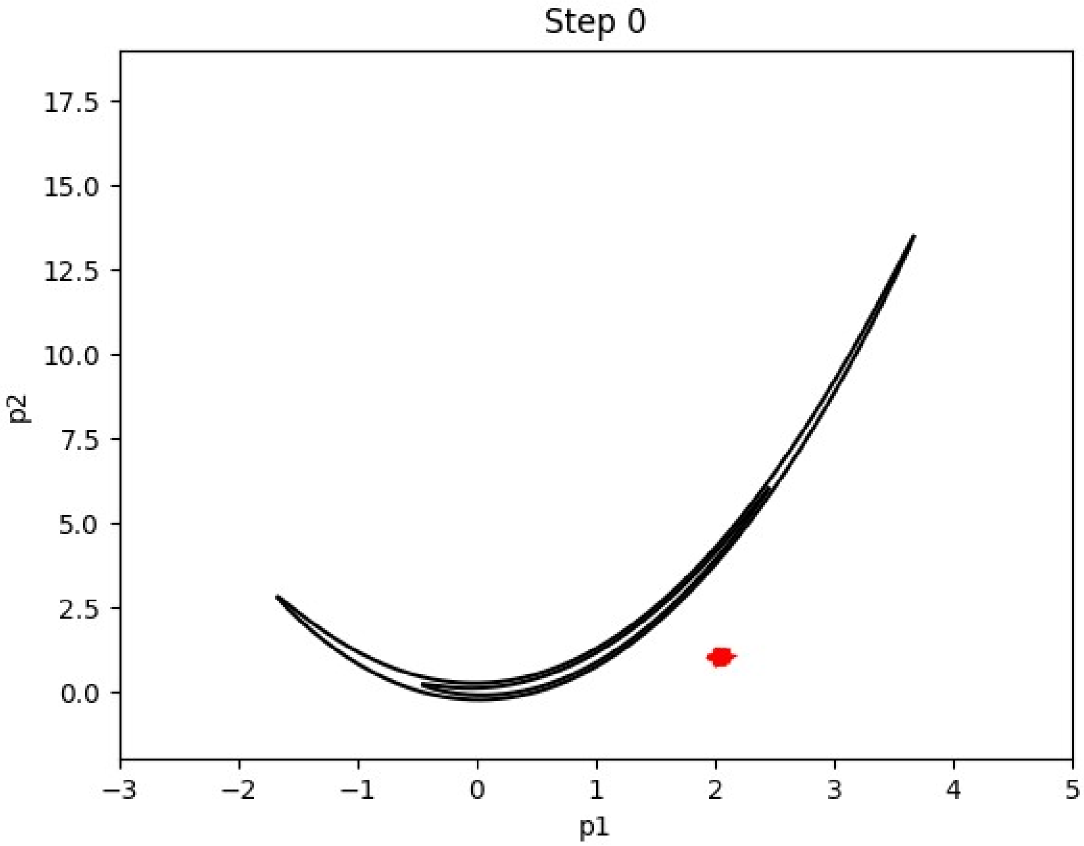


Take-away message(s)

- CDM remains unchallenged
- Plethora of contenders
- GDM model : efficient way of pruning model space
- Constraints on free, non-parametric functions describing GDM properties
- Applied on current state-of-the-art data
- Ongoing preparation for new era of instruments

Thank you
for your attention !

Ensemble sampling



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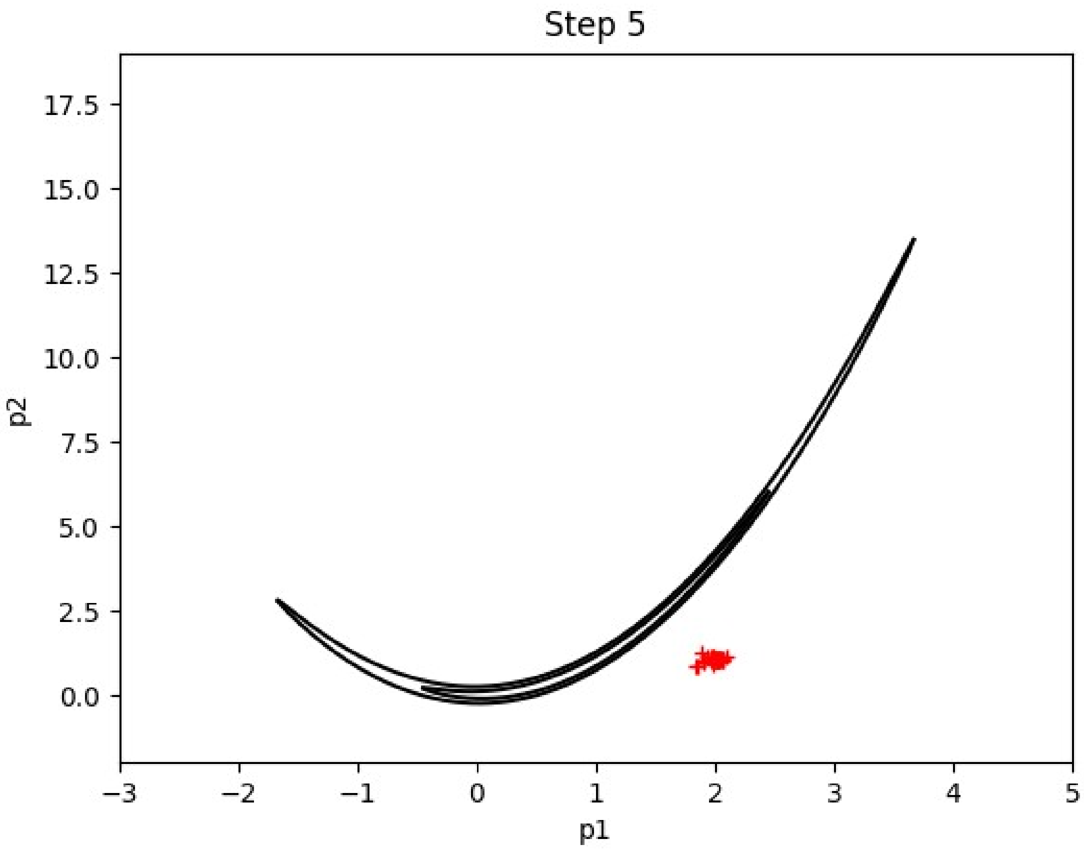

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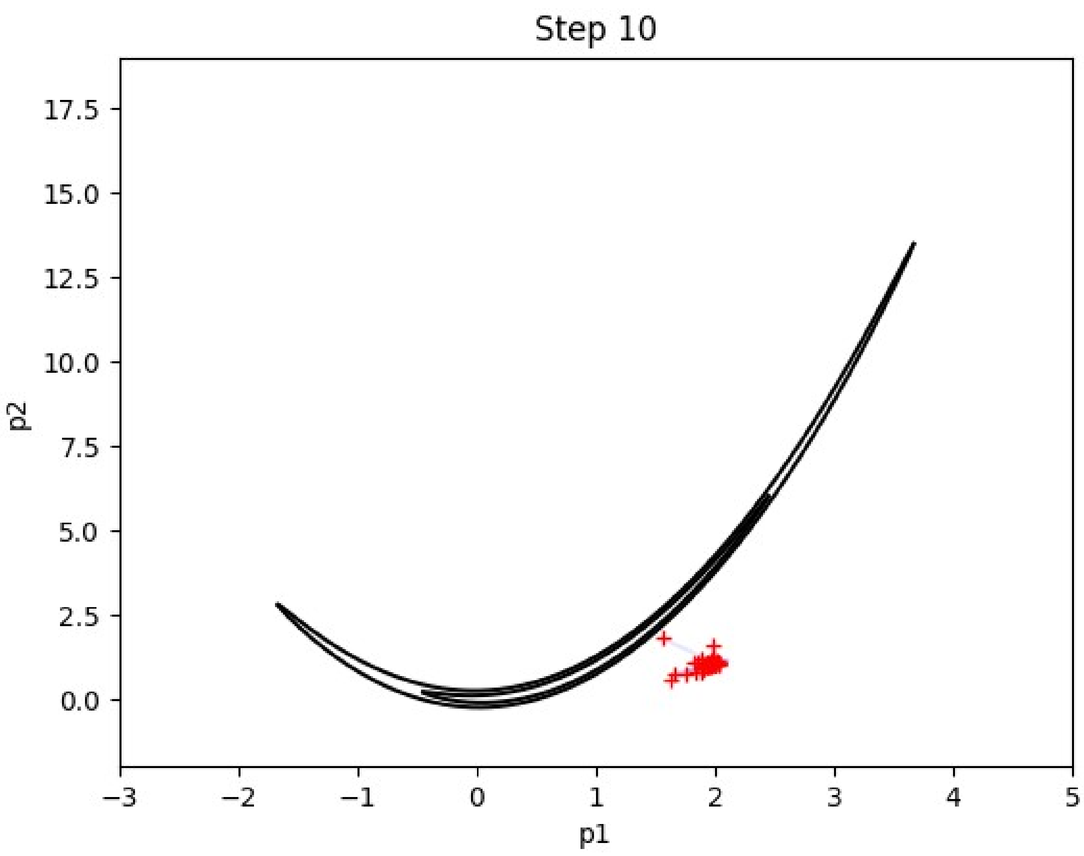

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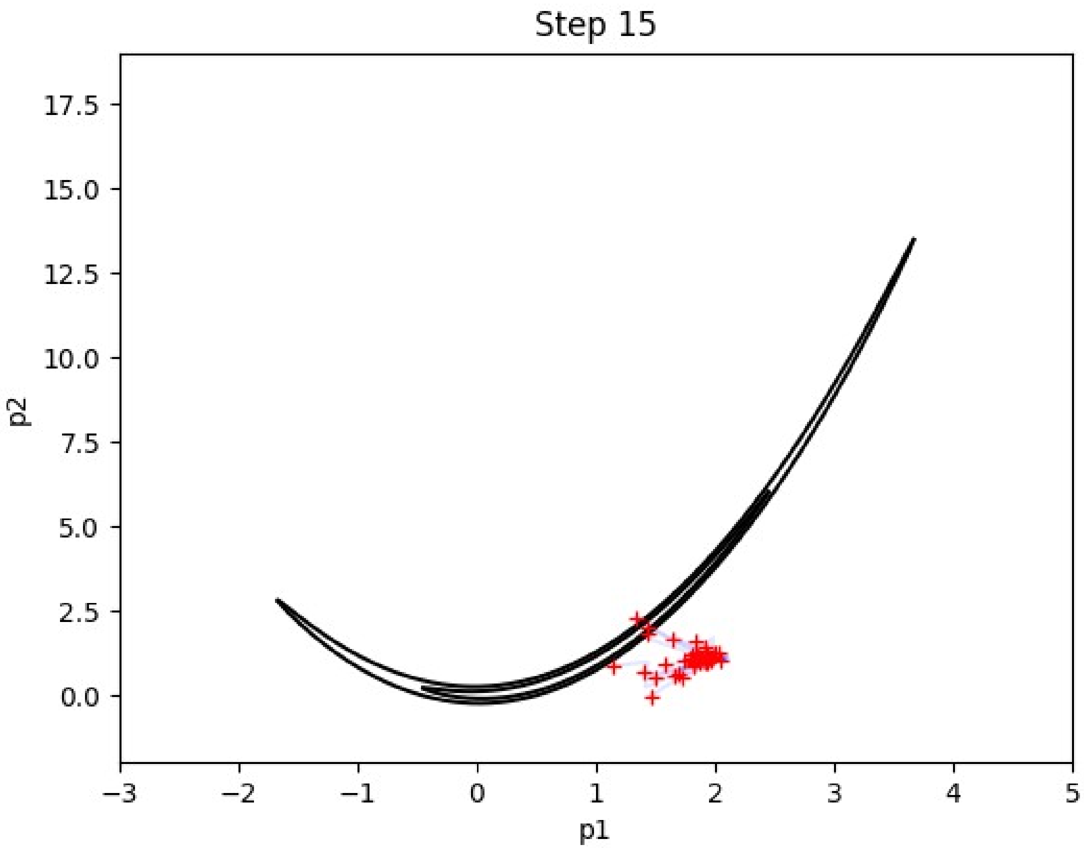

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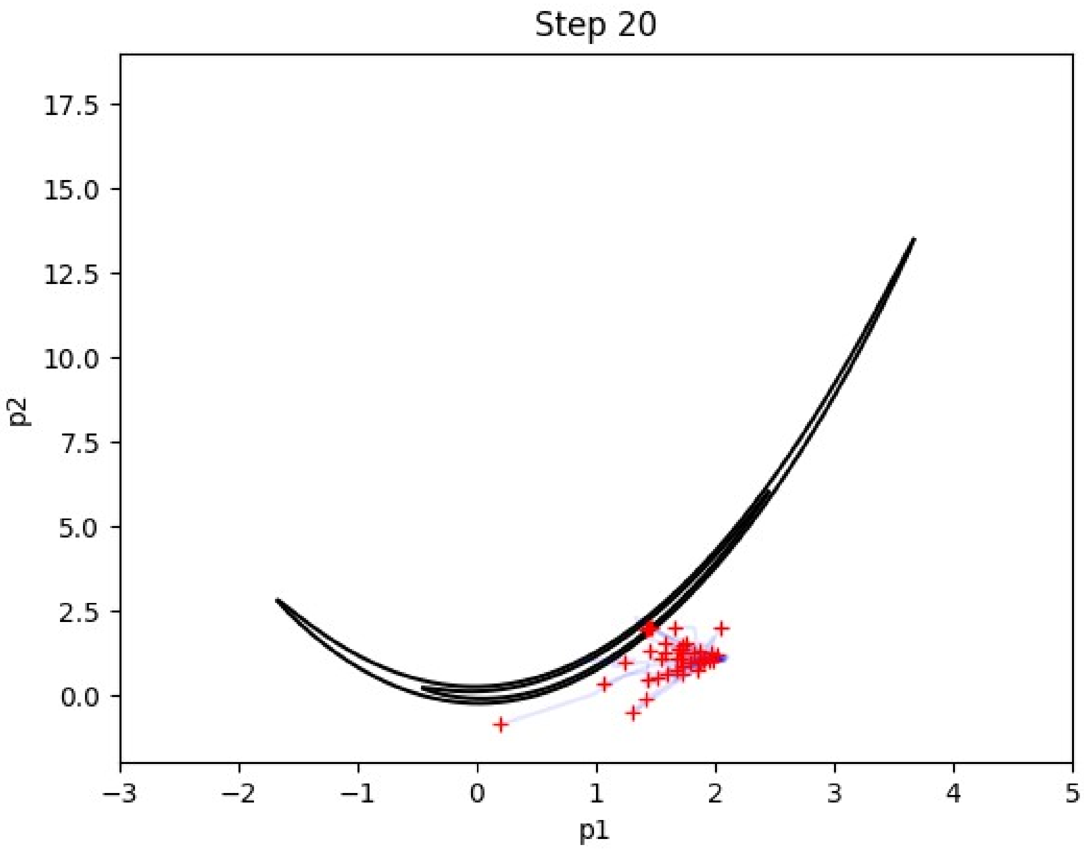

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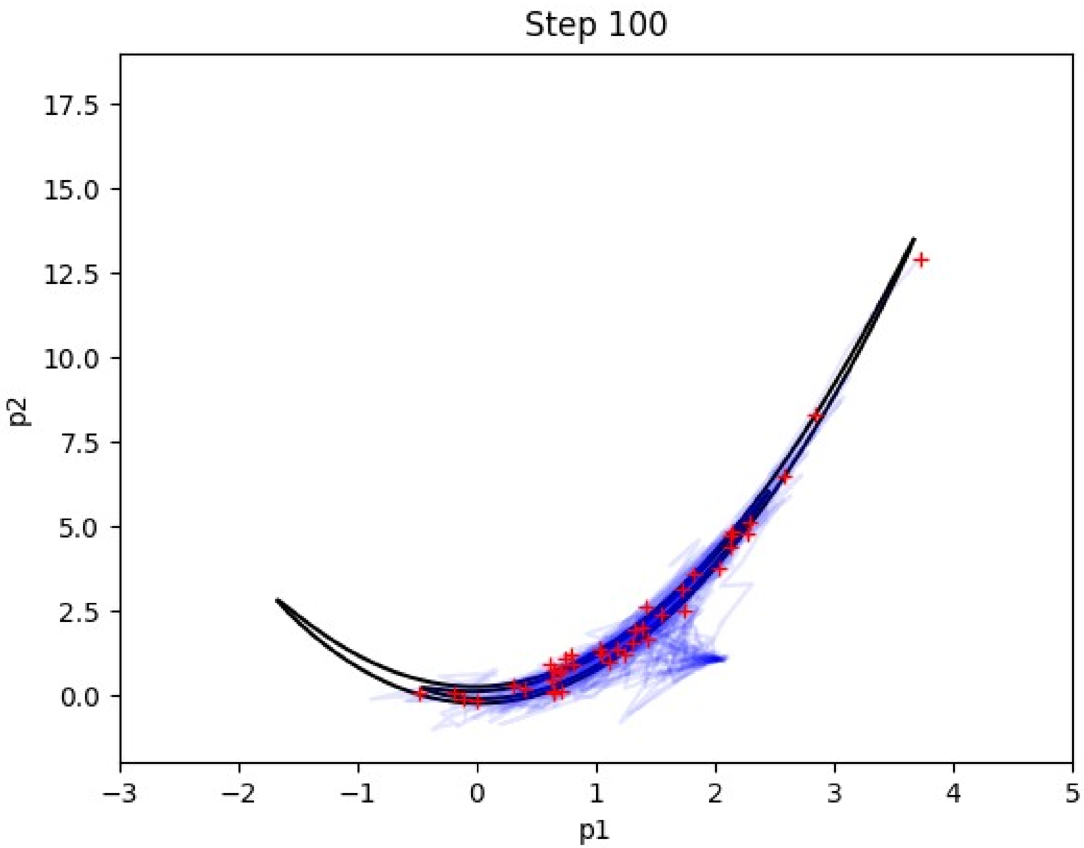

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