Challenging the CDM paradigm:
Constraining DM properties with CMB data

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In collaboration with
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European Research Council
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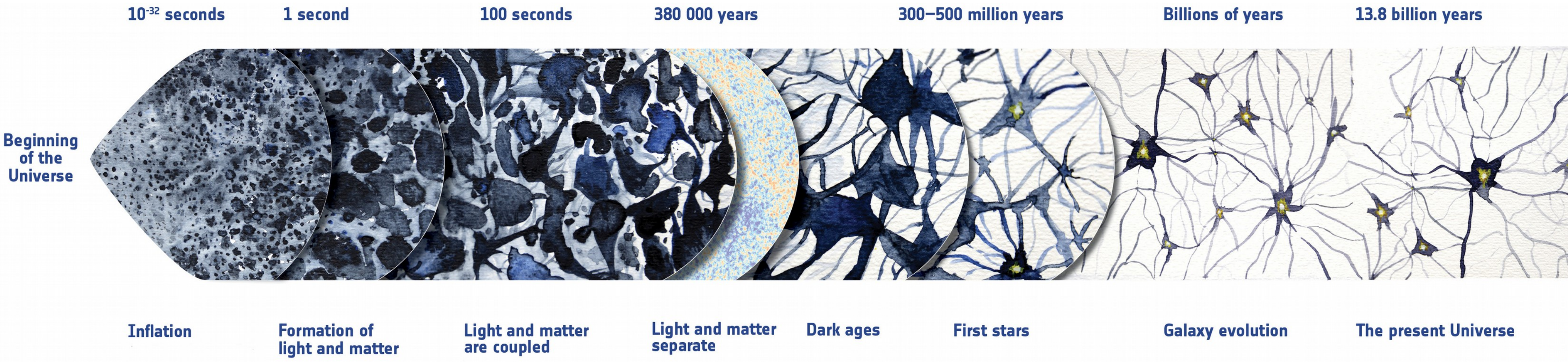
Atelier Théorie, Univers et Gravitation
@ IHP, 15/12/2021

The standard model of cosmology

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



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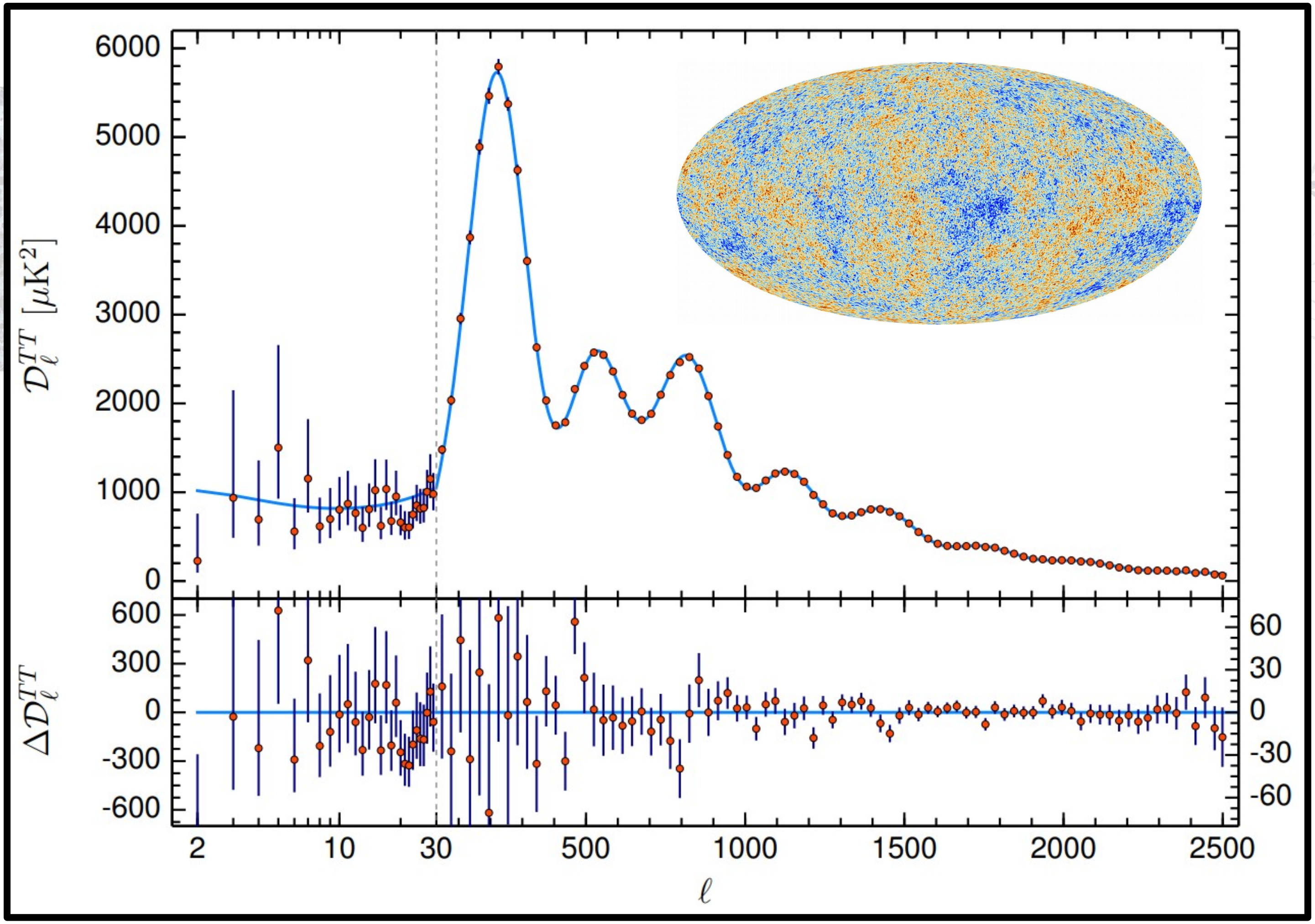
10⁻³² seconds

Beginning of the Universe

Inflation



13.8 billion years

The present Universe

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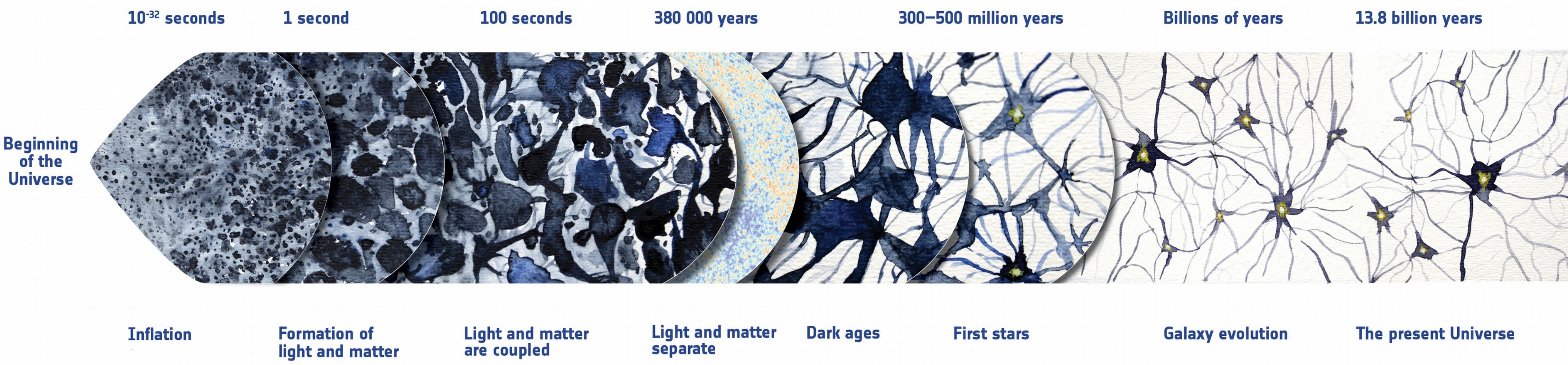

- … but rests on some pillars that are “shrouded in darkness”:
  - Primordial Universe, inflation
  - Dark matter (''CDM'')
  - Dark ages & reionisation
  - Dark energy (''Λ'')
- … and is shaken by some persistent tensions :
  - H_0 discrepancies
  - σ_8 tensions
  - ISW excess
  - CMB “anomalies”

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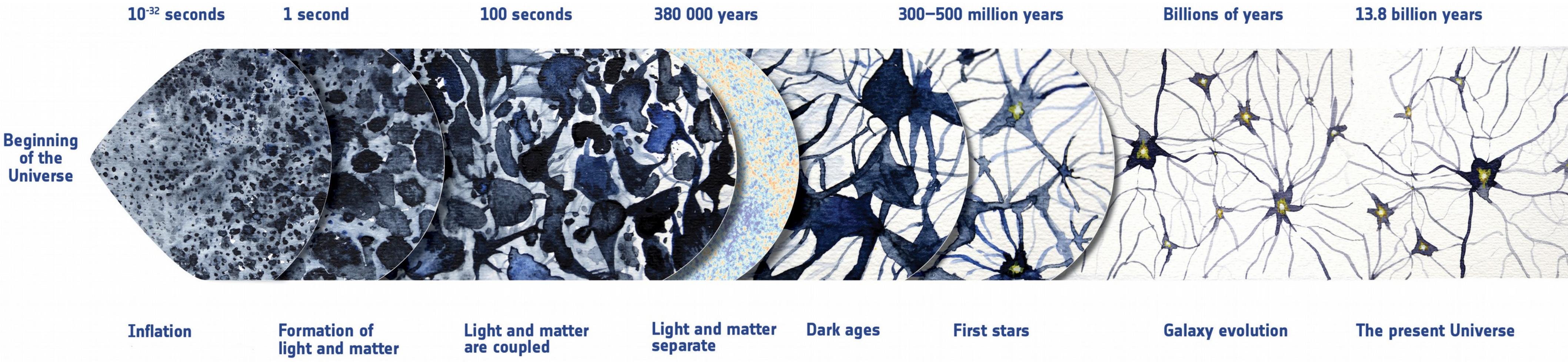

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Cold dark matter, hot questions

- Is it really there ?

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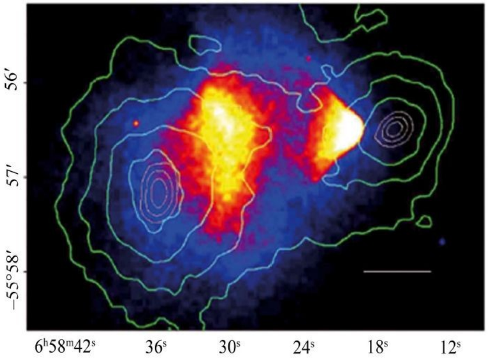
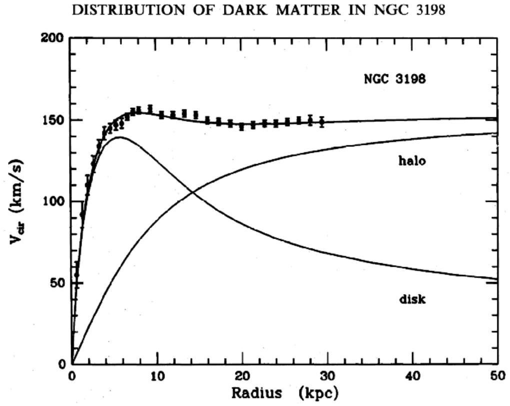
- Direct detection:
  - Colliders
  - Nuclear recoils
  - → Inconclusive so far
- Indirect detection:
  - Late gravitational effects (rot. curves, Bullet cluster)





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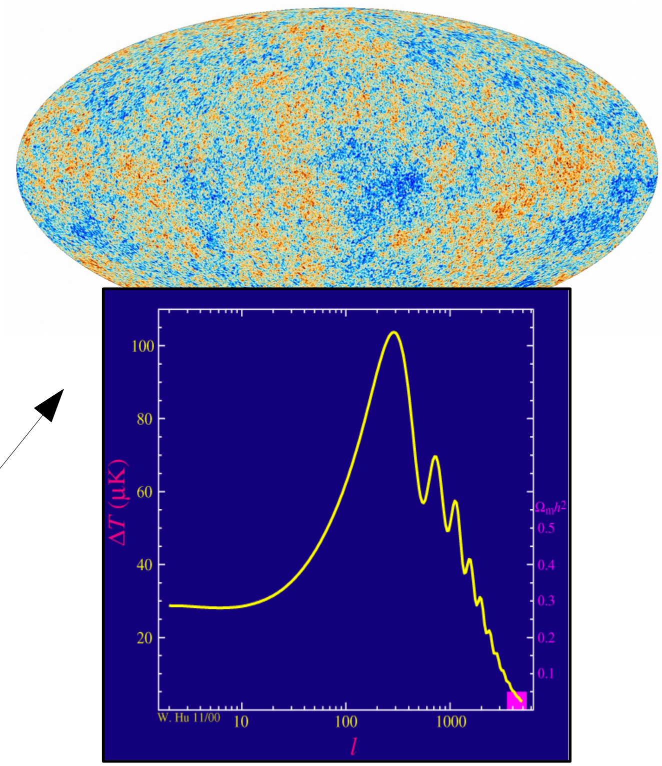

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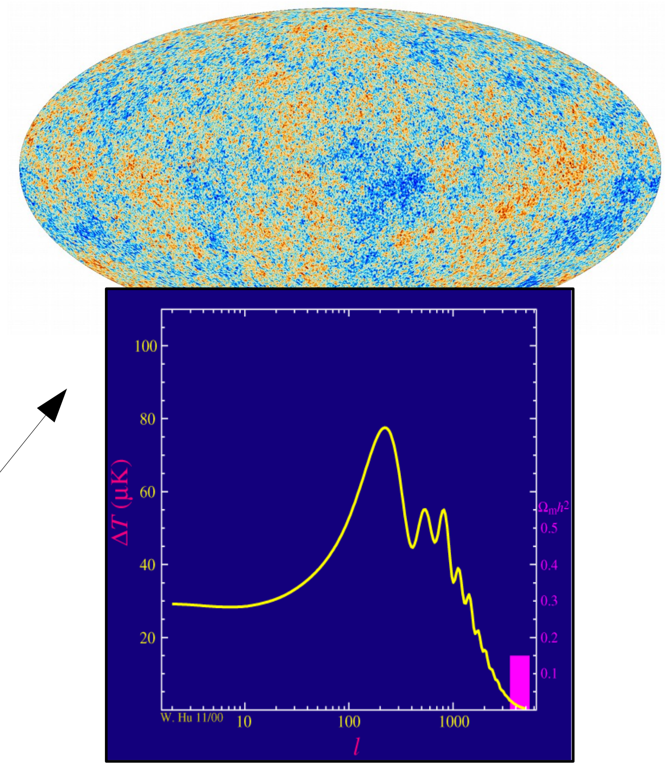

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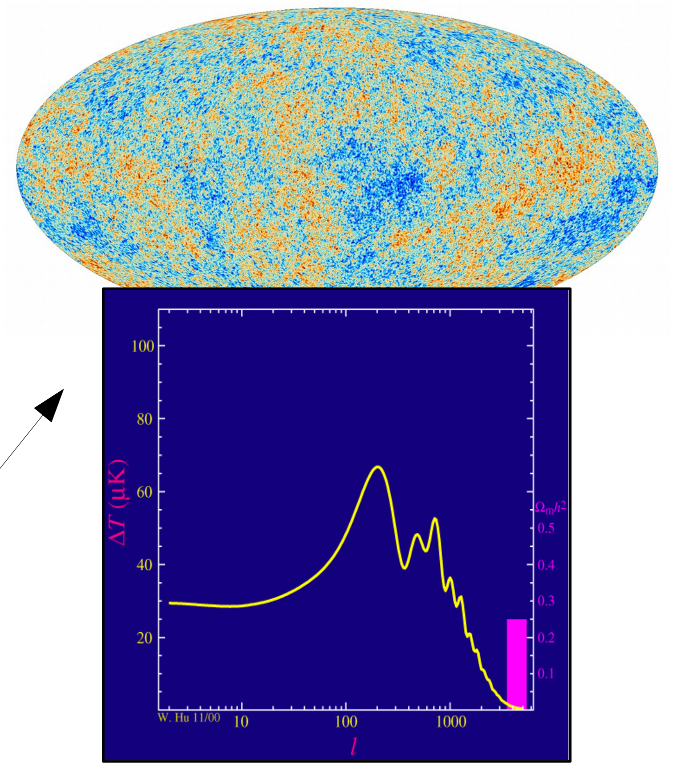

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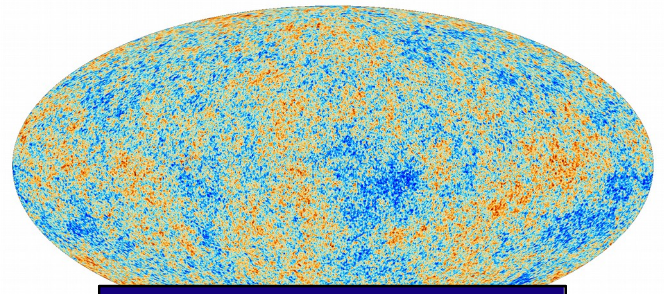
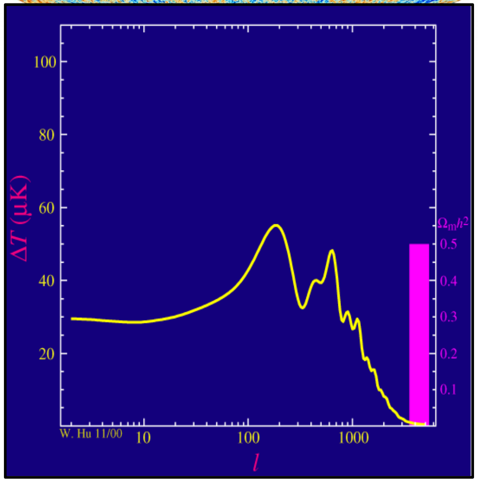
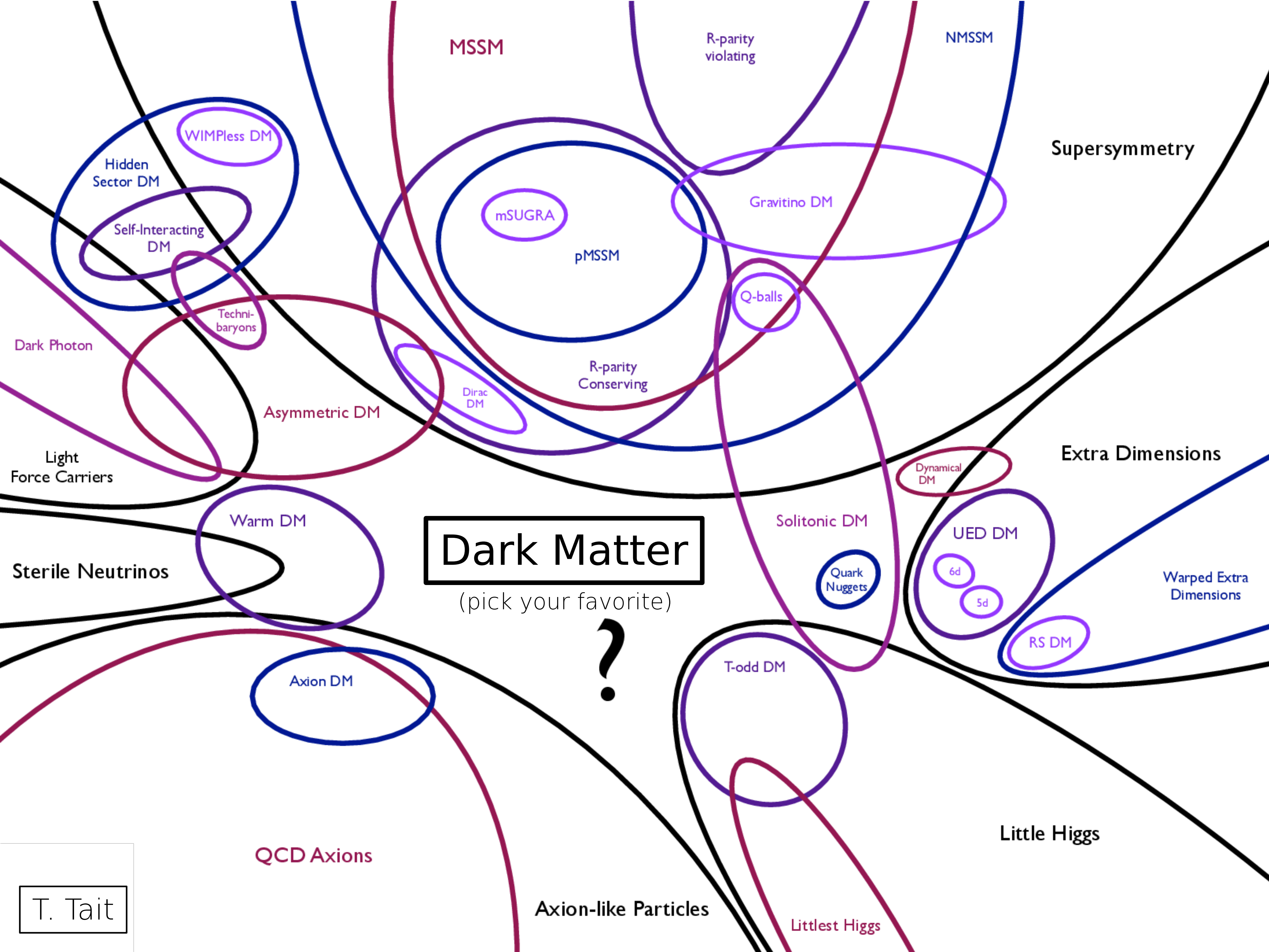




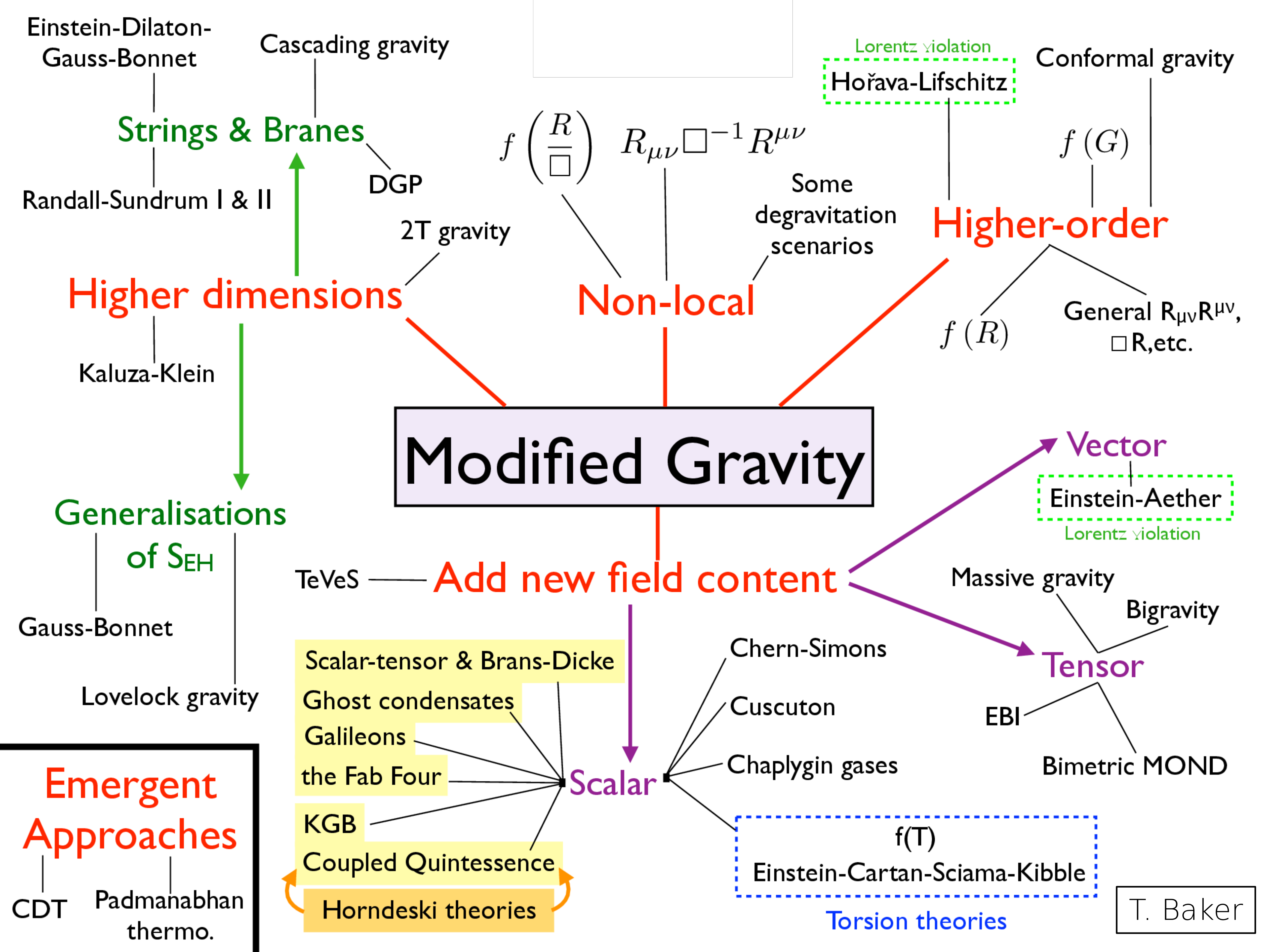
Cold dark matter, hot questions

- Is it really there ?

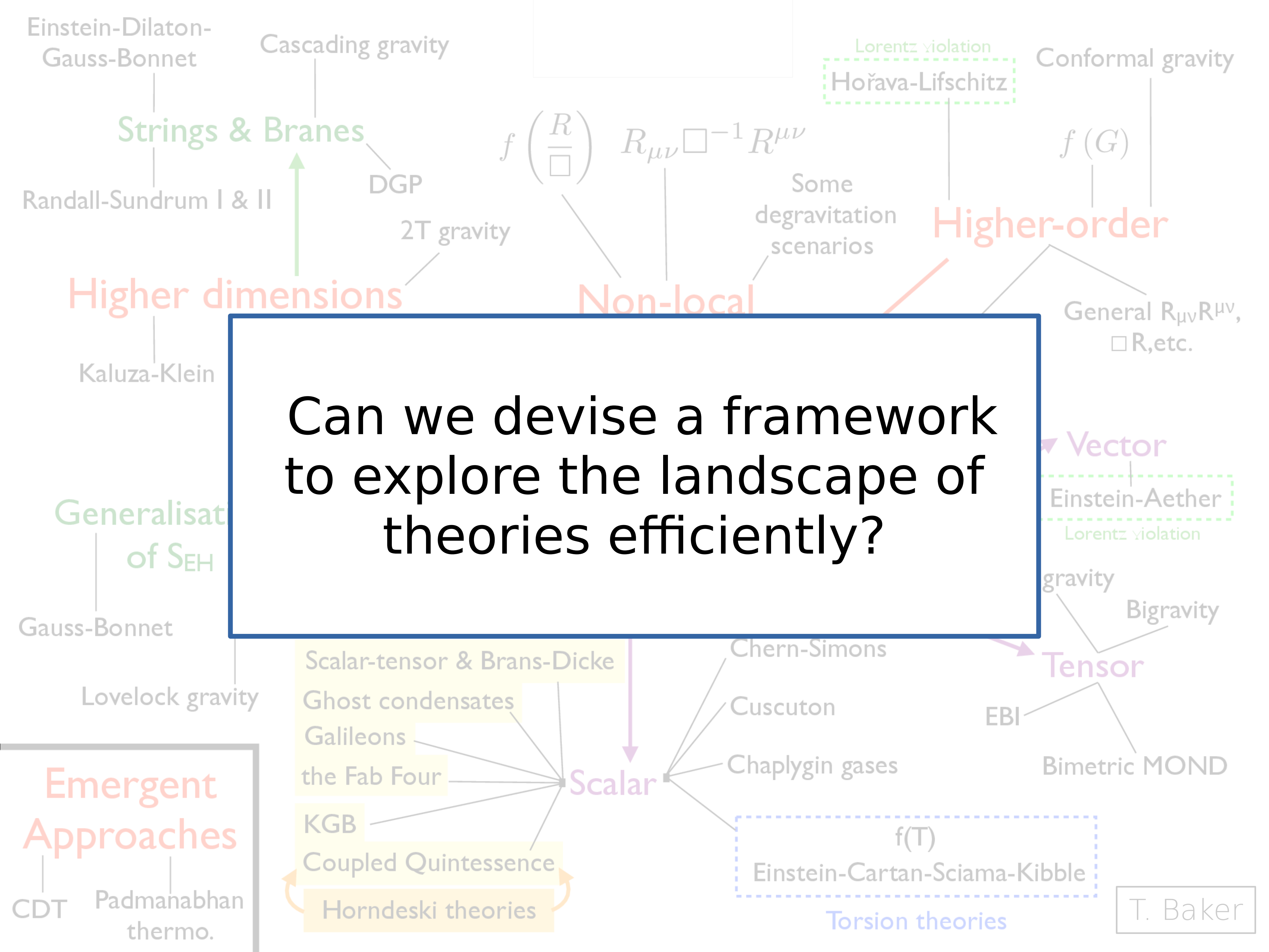
- If yes, what it is made of ?



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



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



Can we devise a framework to explore the landscape of theories efficiently?

DM as a (more) general fluid

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

- 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)

- But general fluid has pressure…

e.g. ultralight axions quantum pressure

- …and non-zero shear

e.g. free-streaming warm dark matter (sterile neutrinos, …)

→ e.g. CDM + EFTofLSS

Generalized Dark Matter (GDM, Hu 1998)

- Defined for FLRW, linear perturbations
- Background: (non-zero) equation of state $w(\tau)$
- Perturbations: sound speed $c_s^2(\tau,k)$ & viscosity $c_{vis}^2(\tau,k)$
- Standard eqs. for density contrast & velocity divergence
- Continuity & Euler eqs. : requires closure equations (here by Hu):

$$\Pi_{\rm g} \equiv \frac{\delta P_{\rm g}}{\bar{\rho}_{\rm g}} = c_a^2 \delta_{\rm g} + (c_s^2 - c_a^2)\hat{\Delta}_{\rm g}^{\rm rest\ \ frame} \qquad \dot{\Sigma}_{\rm g} = -3\mathcal{H}\Sigma_{\rm g} + \frac{4}{1+w} c_{\rm vis}^2 \hat{\Theta}_{\rm g}^{\rm Newt.}$$

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

GDM phenomenology

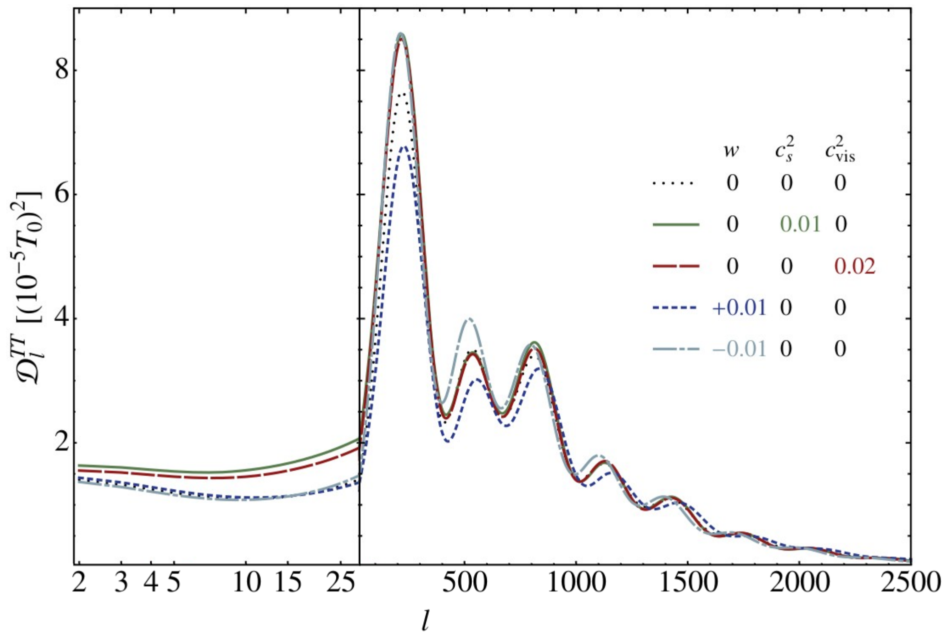
- Equation of state:

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

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

→ angular diam. dist., changes peak positions

→ early rad/matter ratio, changes peak heights



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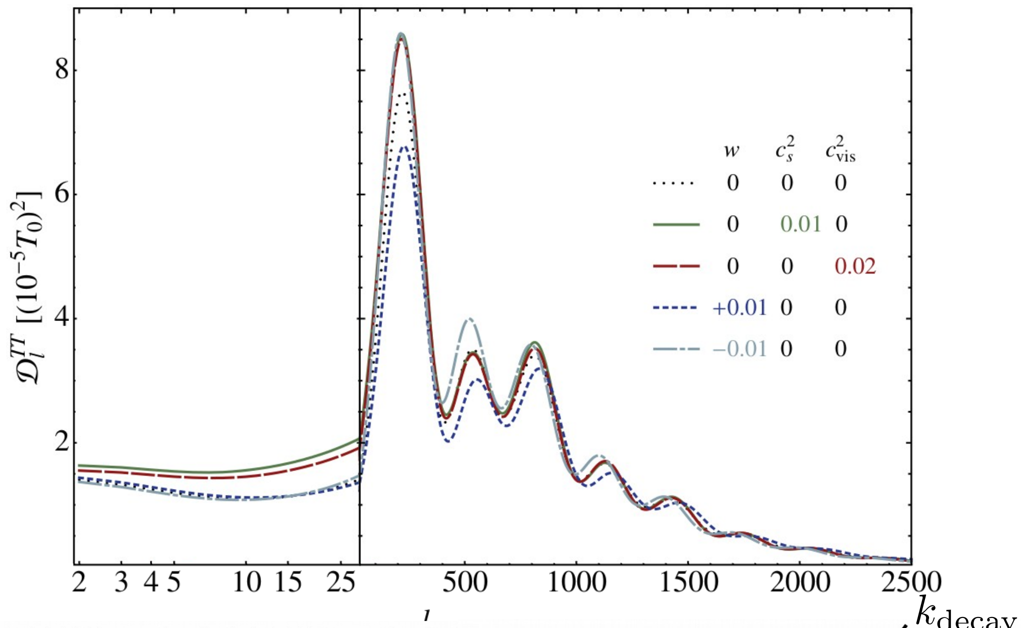
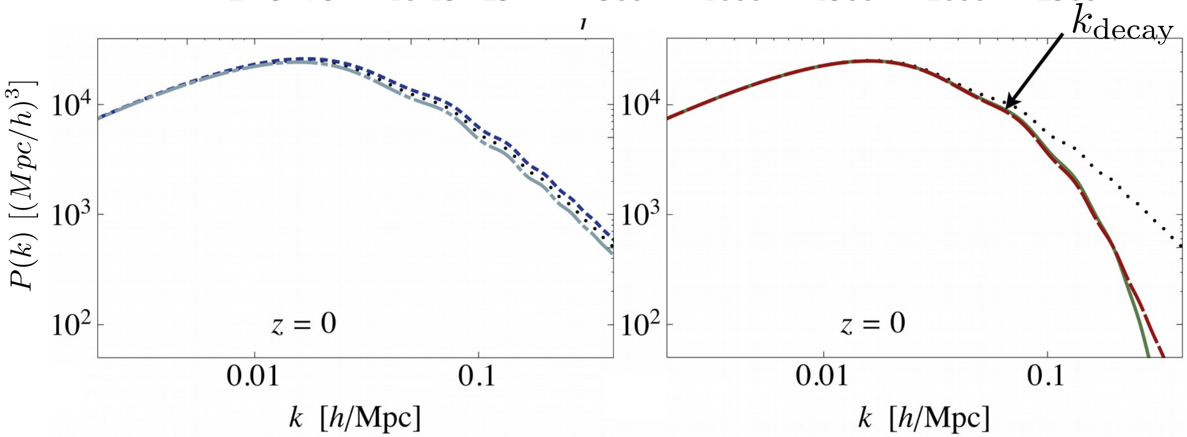


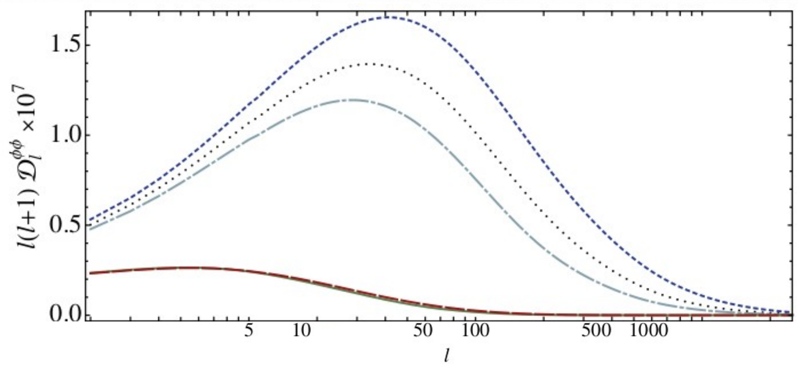


- Sound speed & viscosity:

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

(expected degeneracy)

→ potentials decay below k_{decay}



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

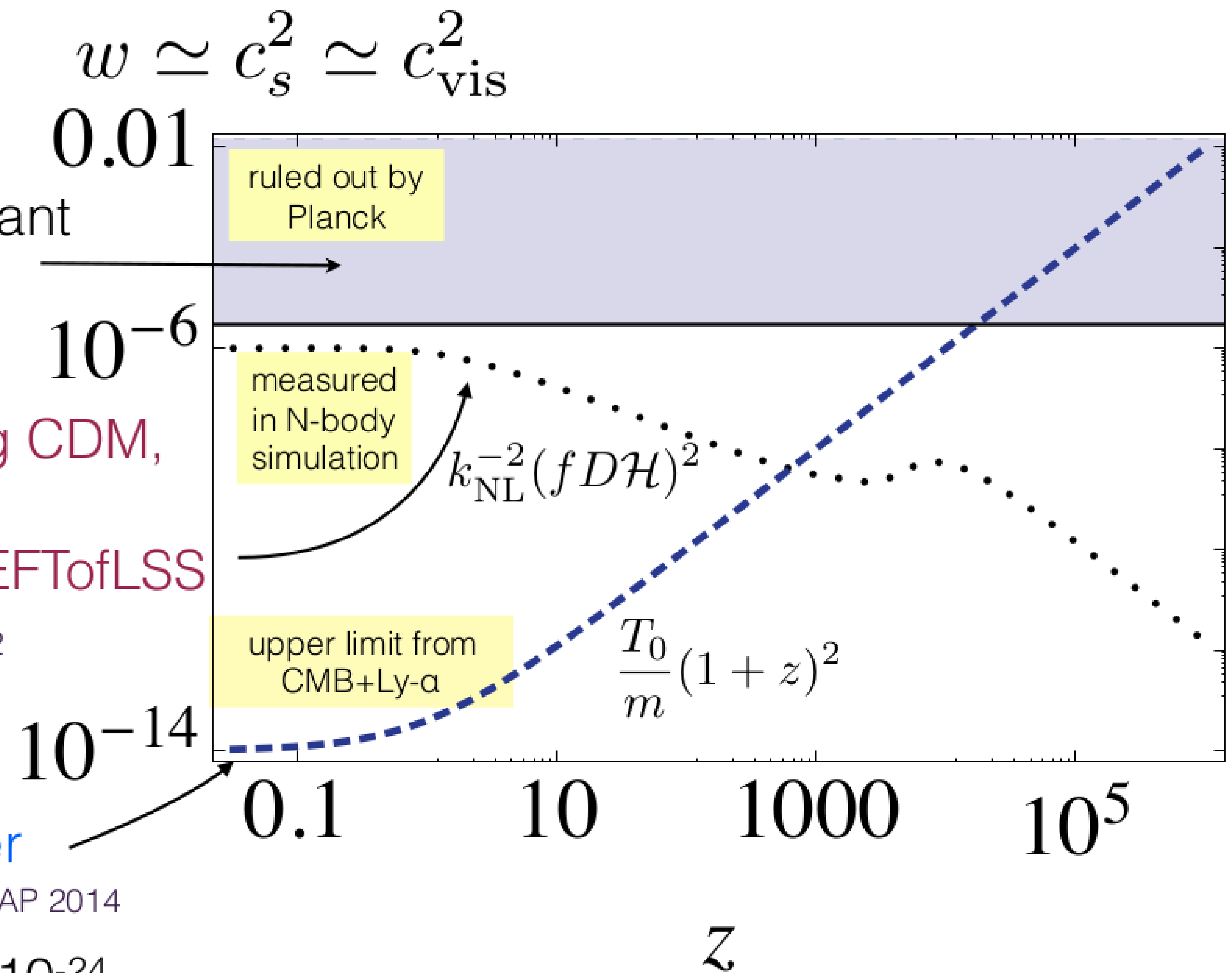
Fields (effective or fundamental)

- 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)

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



GDM with constant parameters

Thomas et al, 1601.05097

Freely streaming CDM, warmed-up by non-linearities, EFTofLSS

Baumann et al, JCAP 2012

Freely streaming warm dark matter

Armendariz-Picon et al, JCAP 2014

CDM neutralino 10^{-24}

(courtesy of M. Kopp)

Ingredients for constraining GDM

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

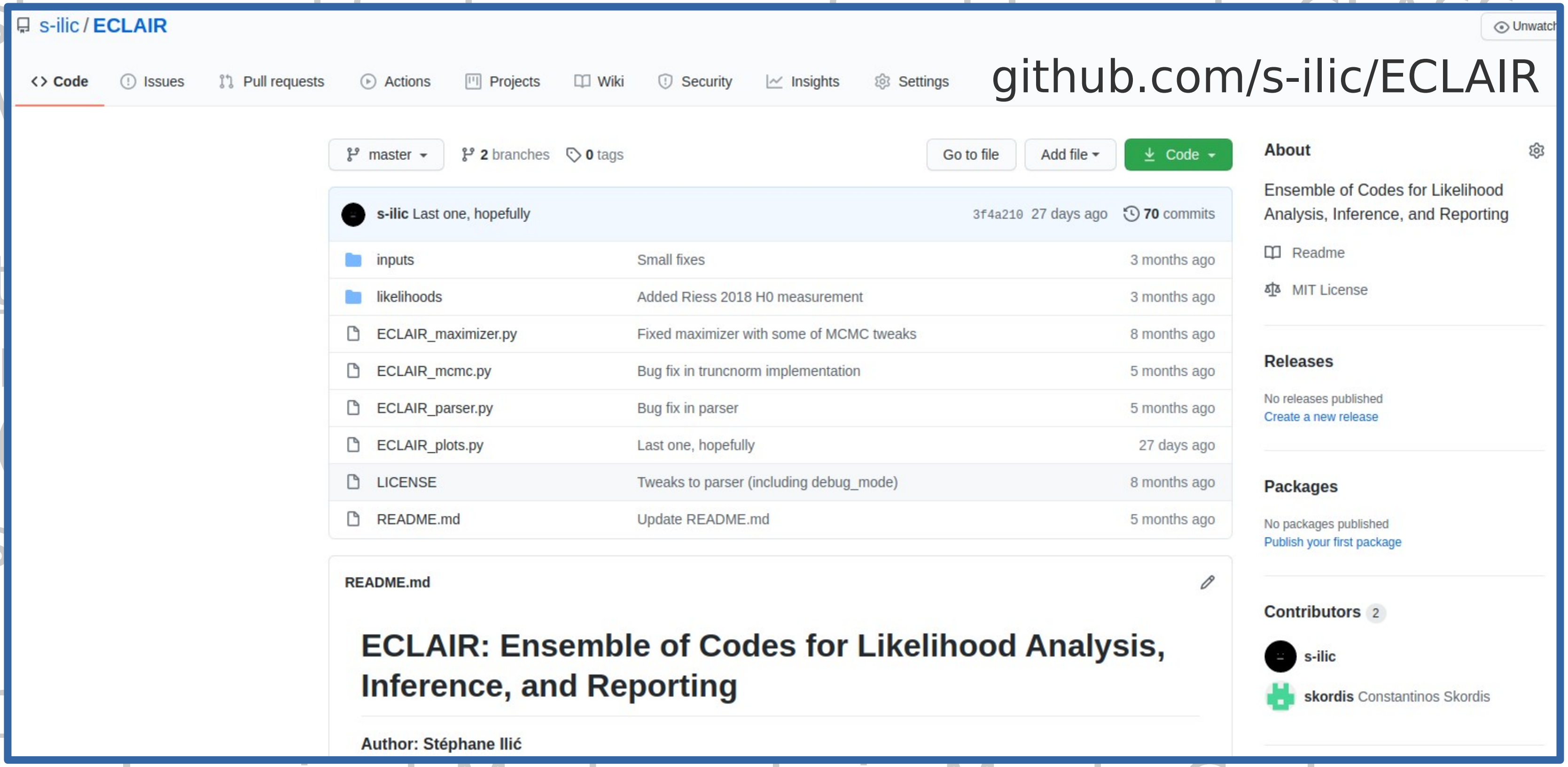
- <u>Datasets:</u>
  - Planck 2015 low/high-ell T/E/B data + lensing
  - H_0 (Riess) measurement
  - Assortment of BAO data

- <u>Sampling:</u>
  Affine Invariant Markov chain Monte Carlo Ensemble sampler

Ingredients for constraining GDM

- Theoretical predictions:
  cus
  sol

- Dat
  - Pla
  - H_0 (
  - Ass



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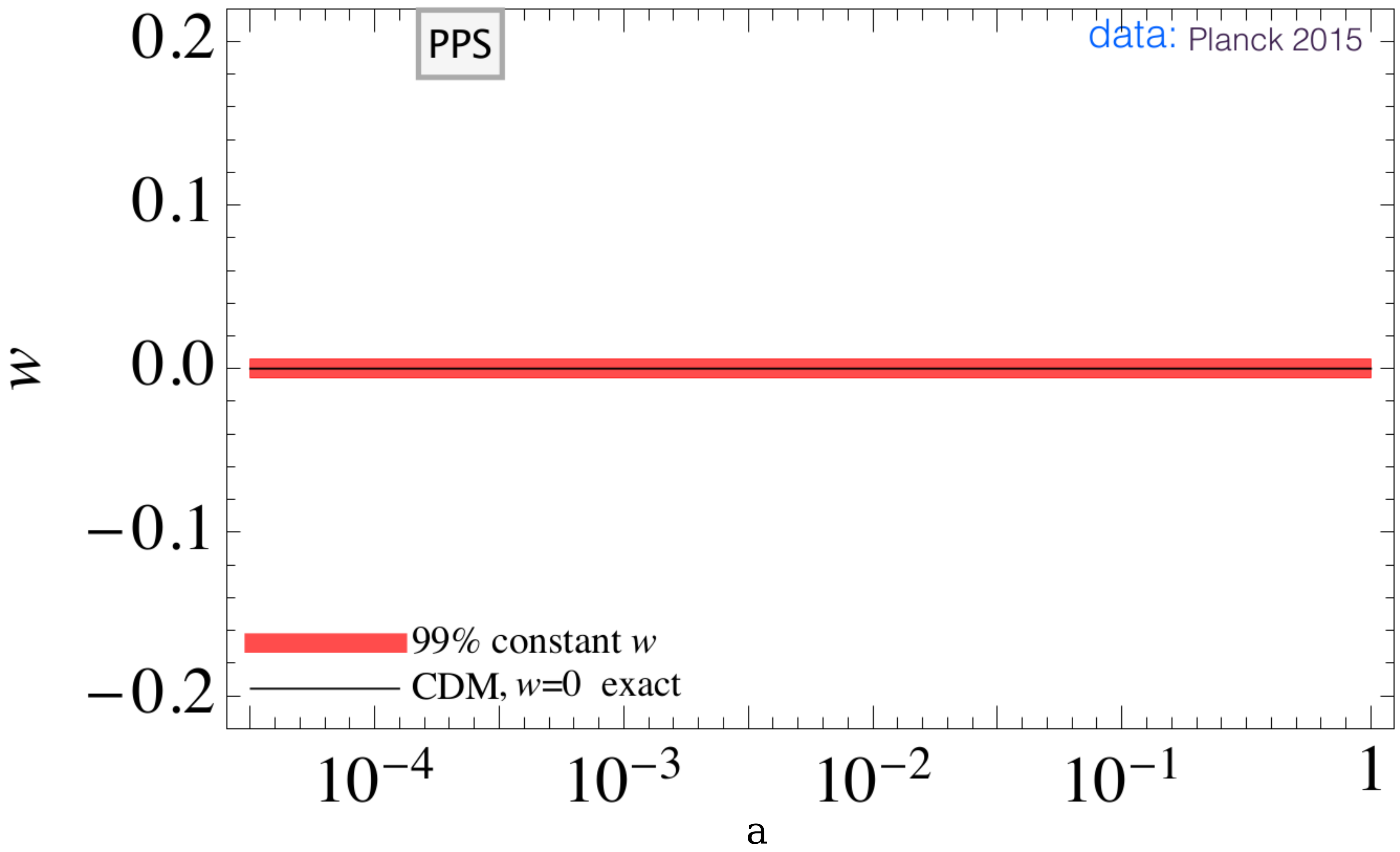

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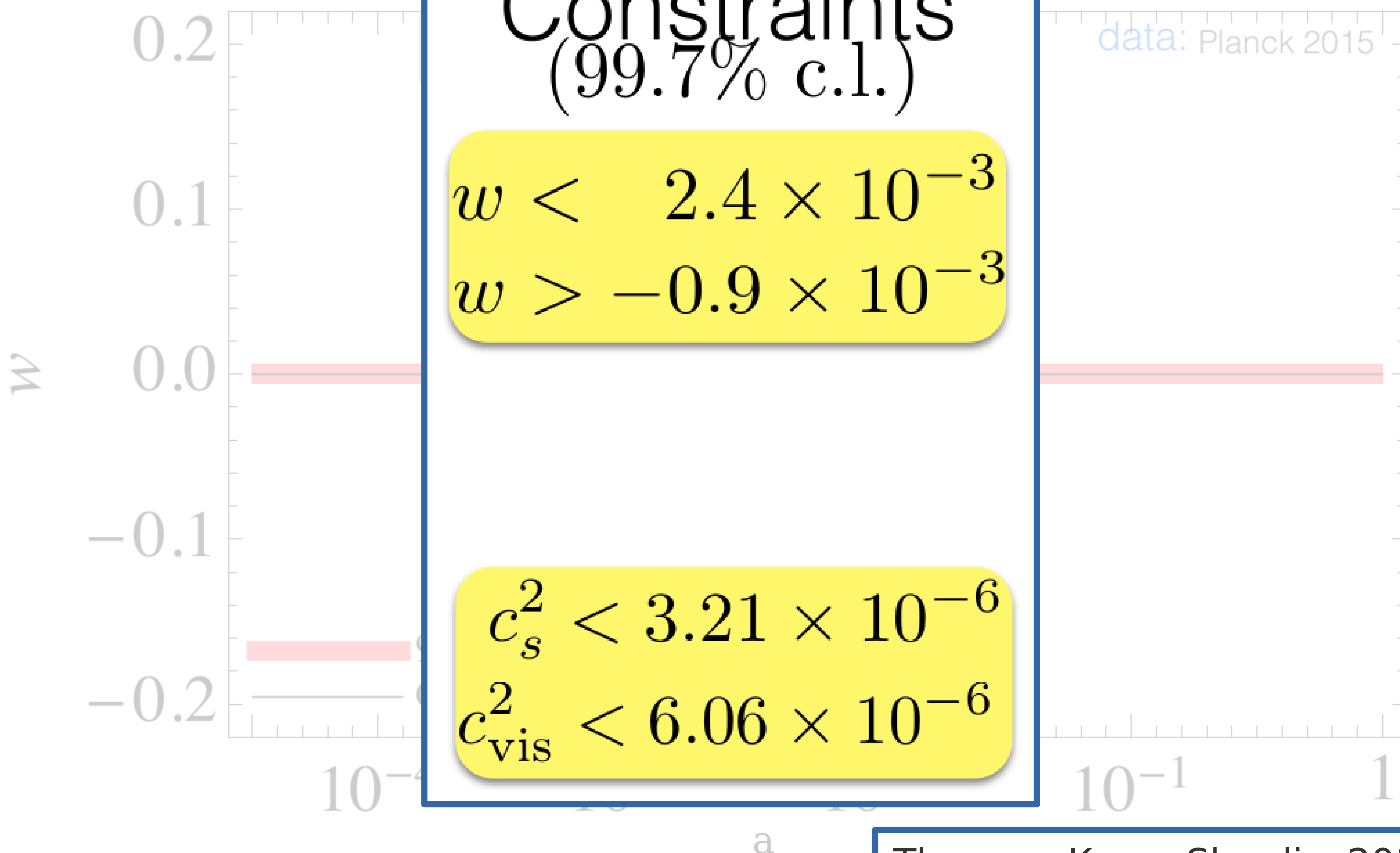


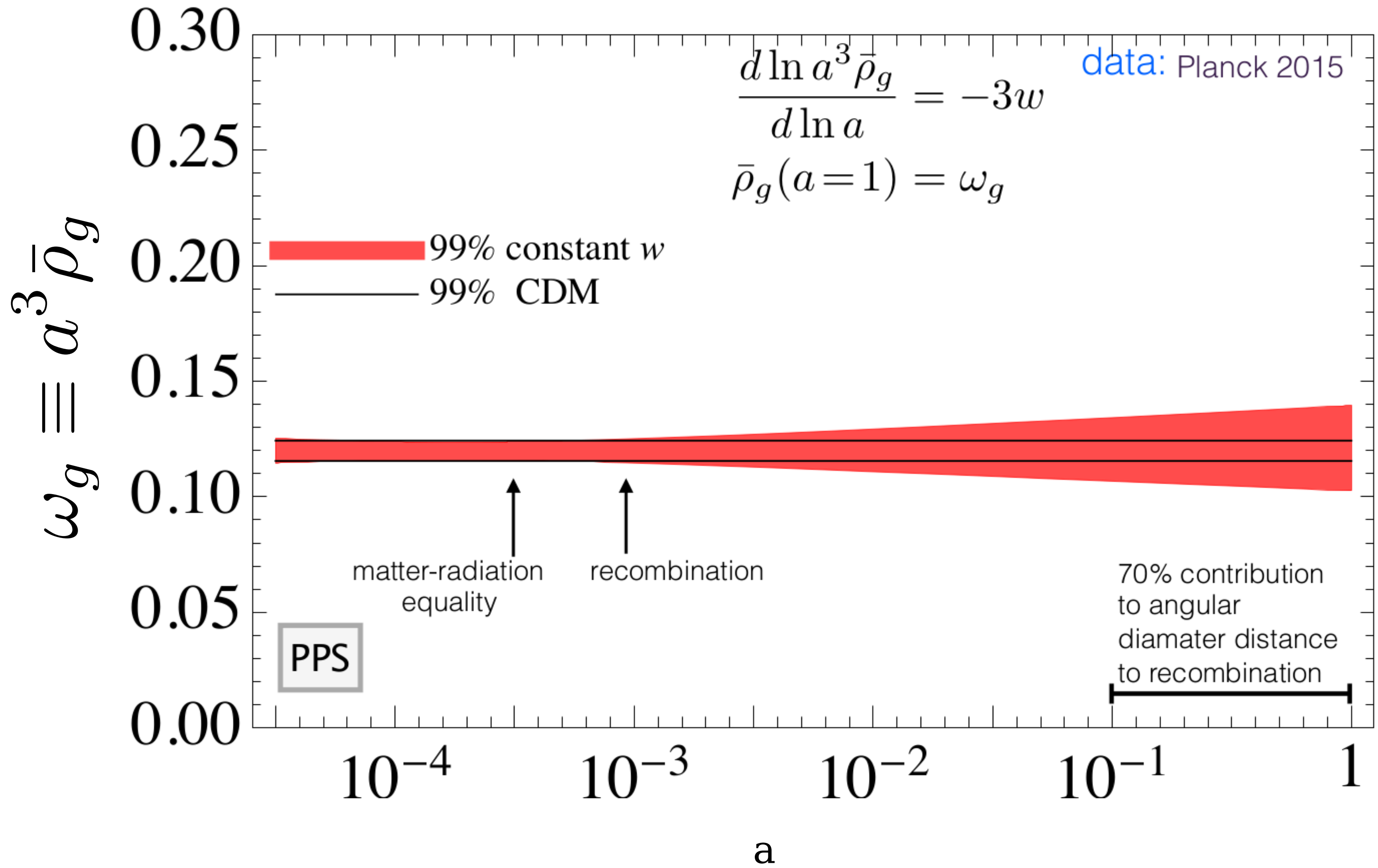
Constraints
(99.7% c.l.)

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

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

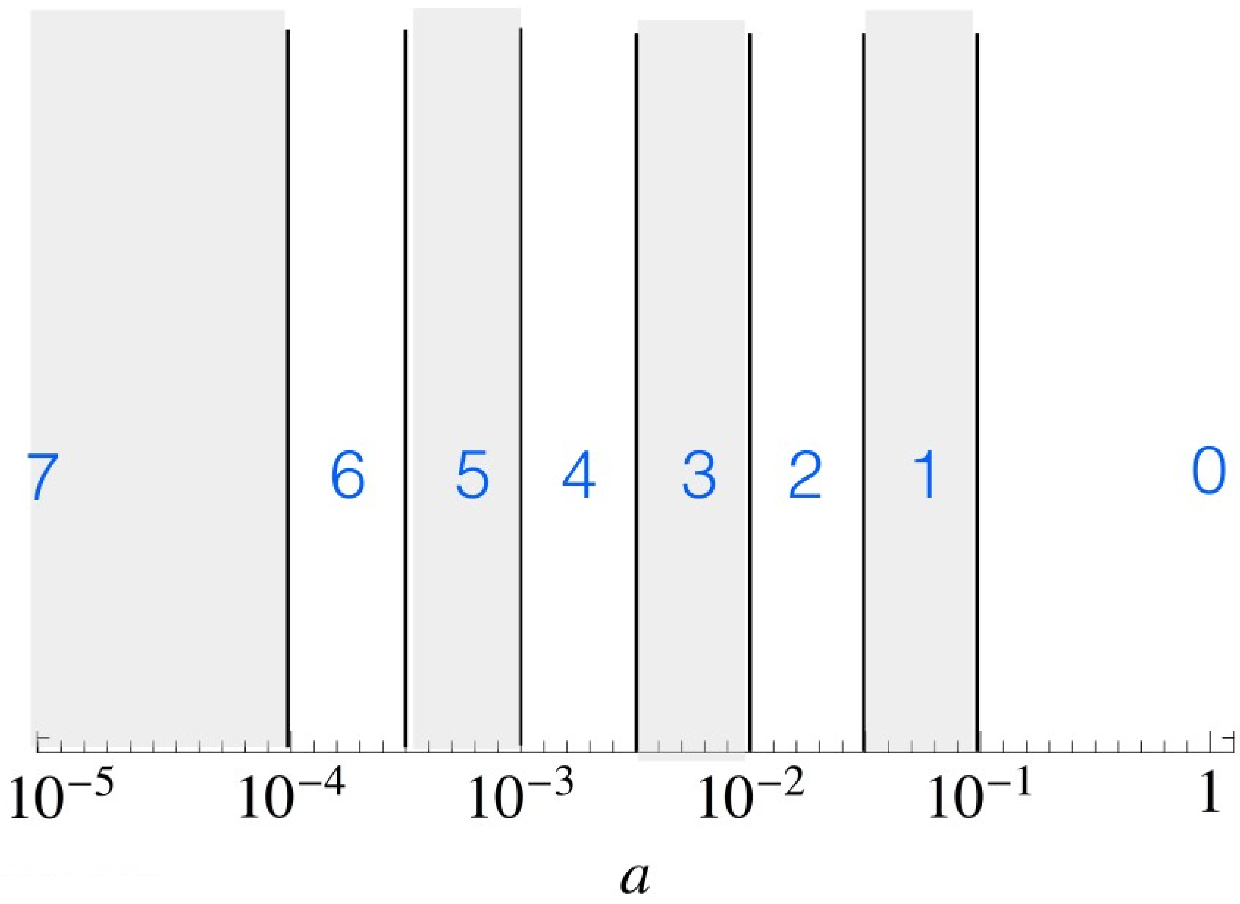
Thomas, Kopp, Skordis, 2016, arXiv:1601.05097

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



Binned w(a), $c_s^2 = c_v^2 = 0$ constraints

Kopp, Thomas, Skordis, Ilić, 2018, arXiv:1802.09541



8 w bins

Binned w(a), $c_s^2 = c_v^2 = 0$ constraints

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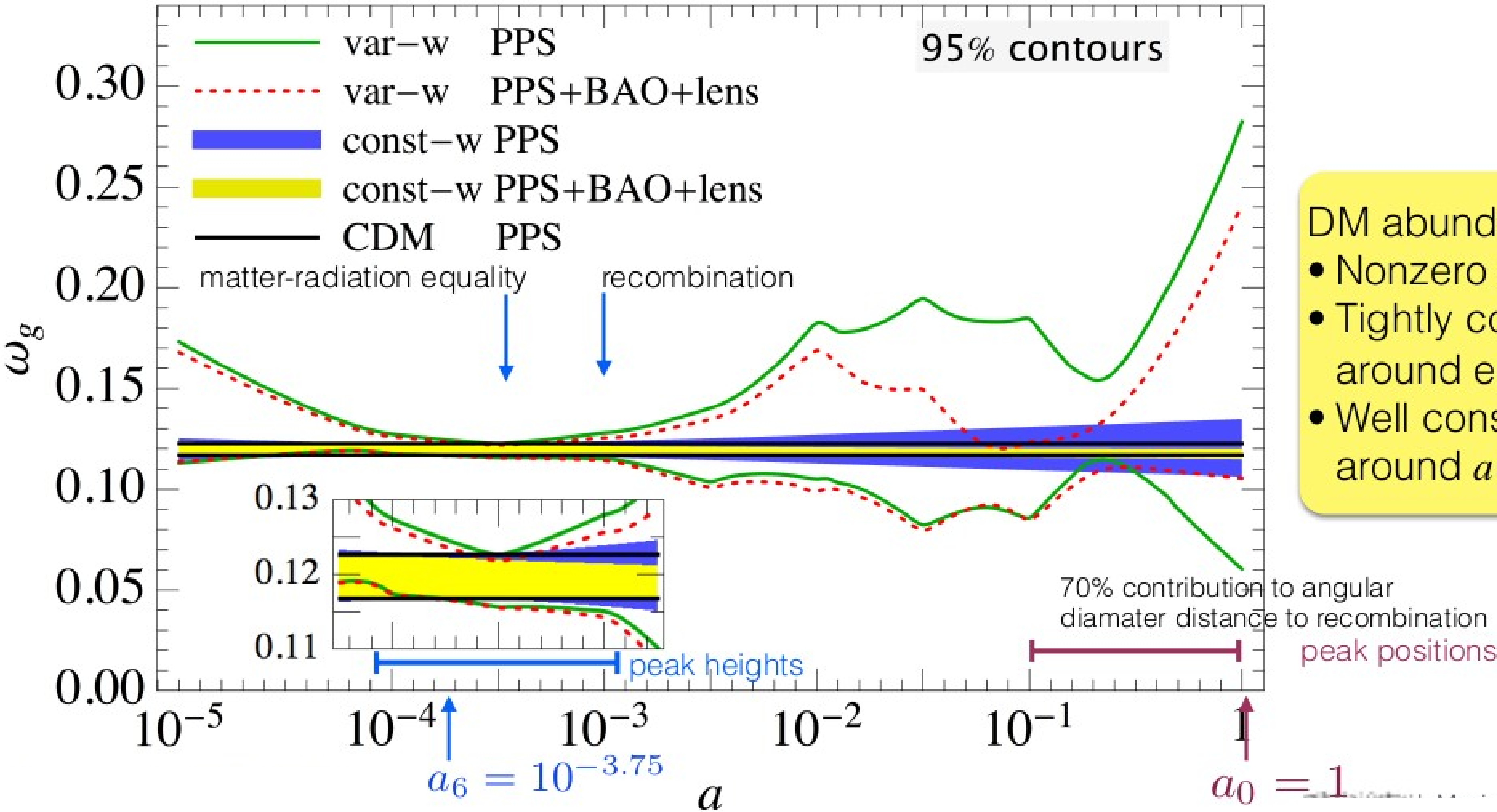


DM abundance is:
- Nonzero at all times
- Tightly constrained around equality
- Well constrained around a=[0.2-0.4]

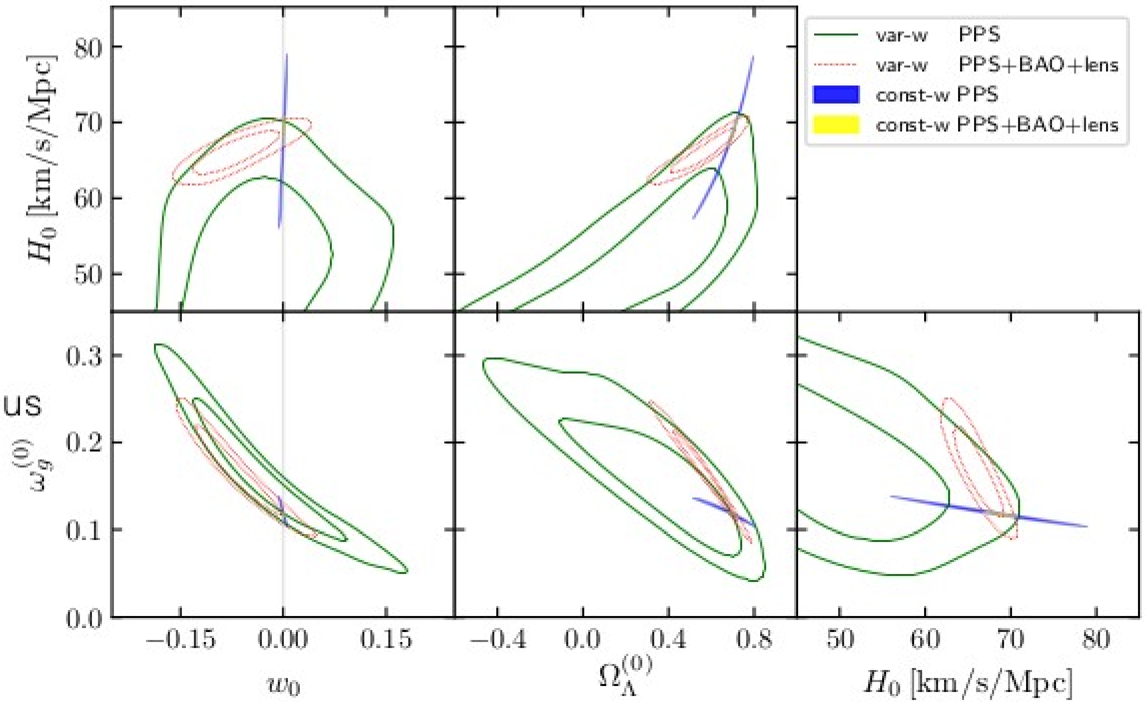
Binned w(a), $c_s^2 = c_v^2 = 0$ constraints

Kopp, Thomas, Skordis, Ilić, 2018, arXiv:1802.09541

68% and 95% contours of 2D marginalised posteriors

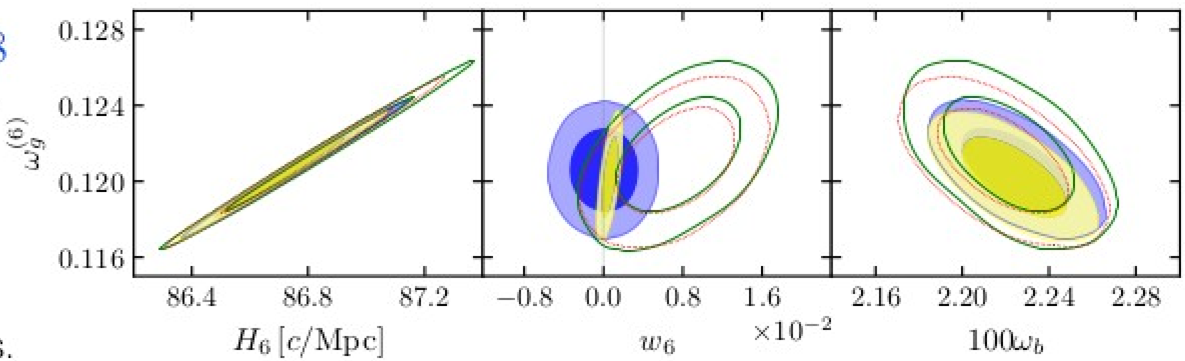
$a_0 = 1$

- 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.



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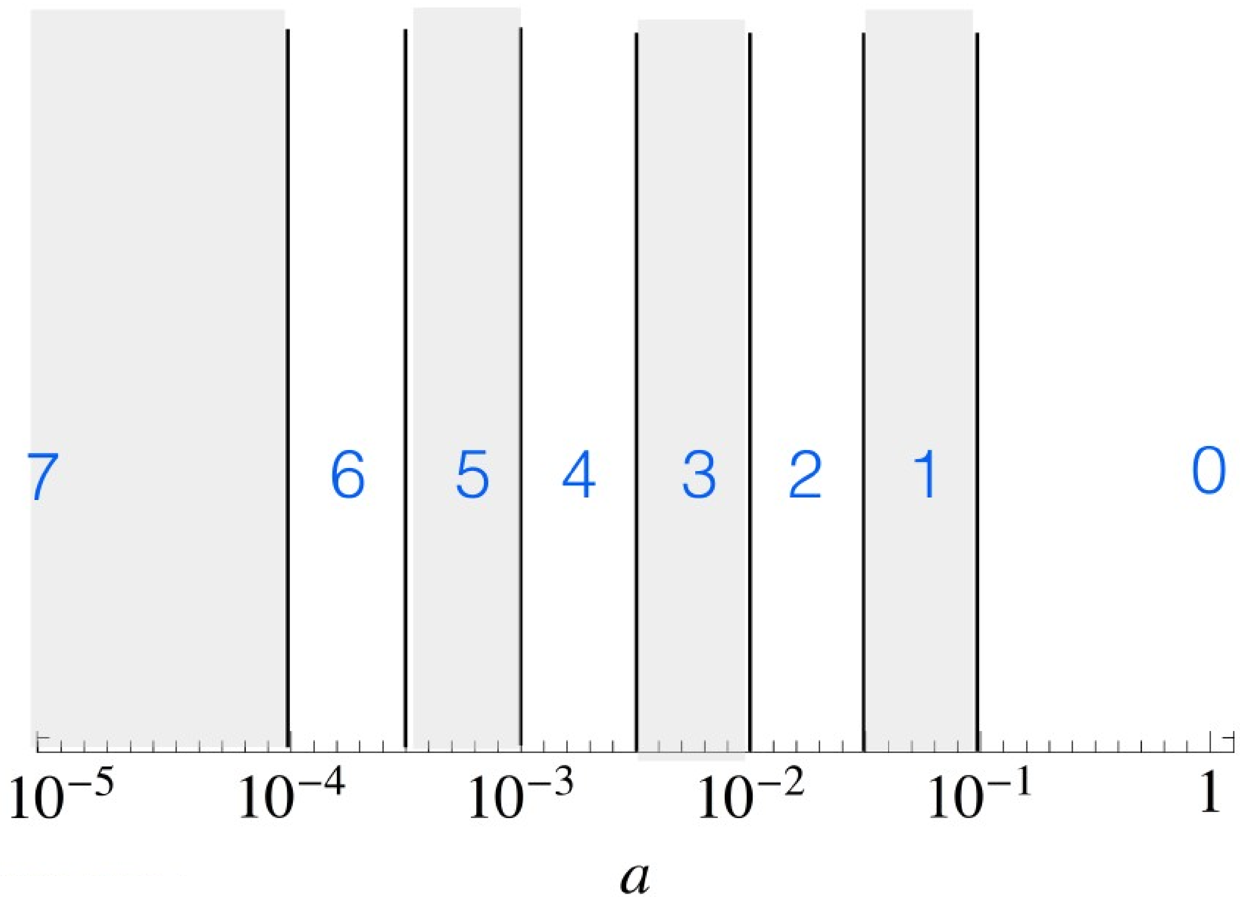

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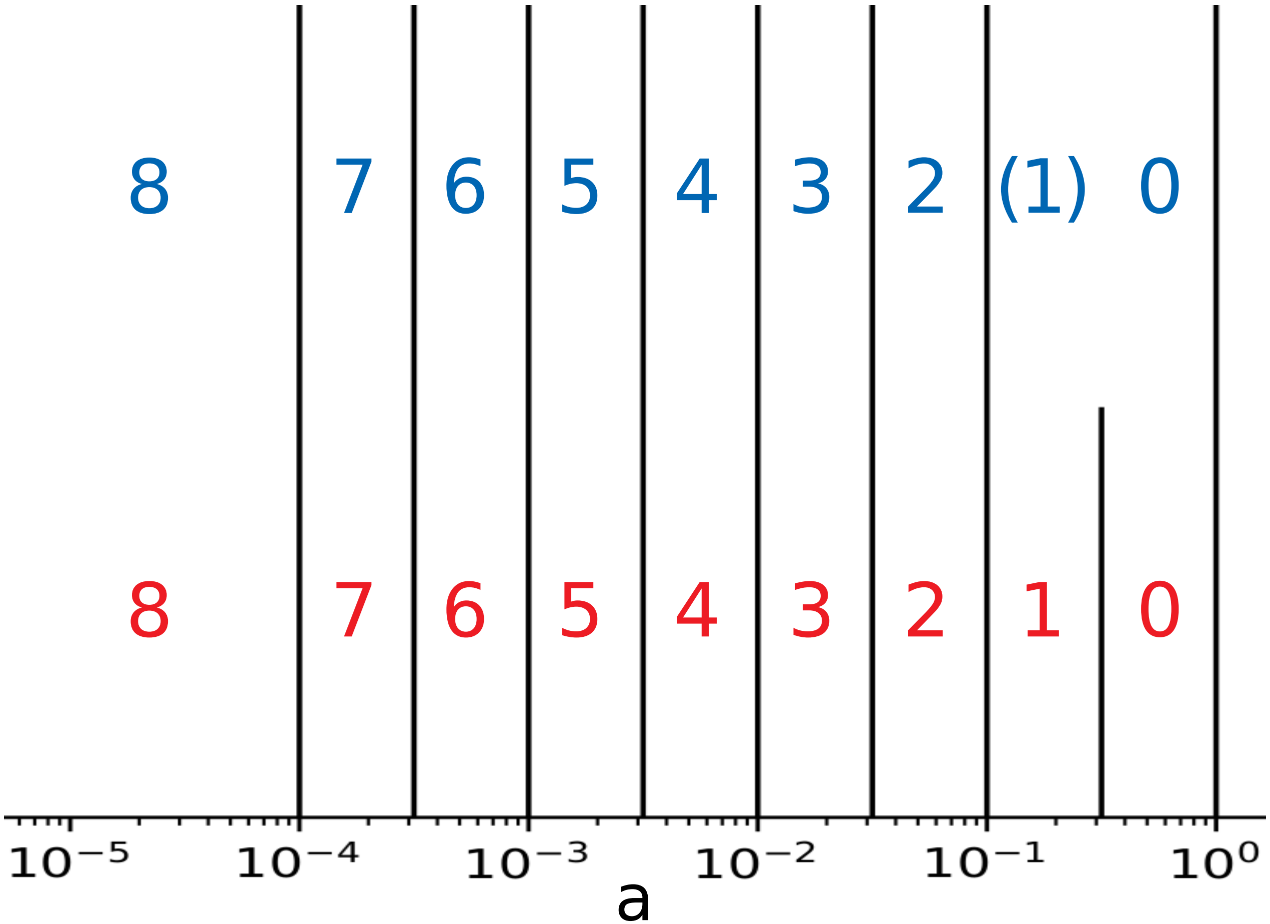
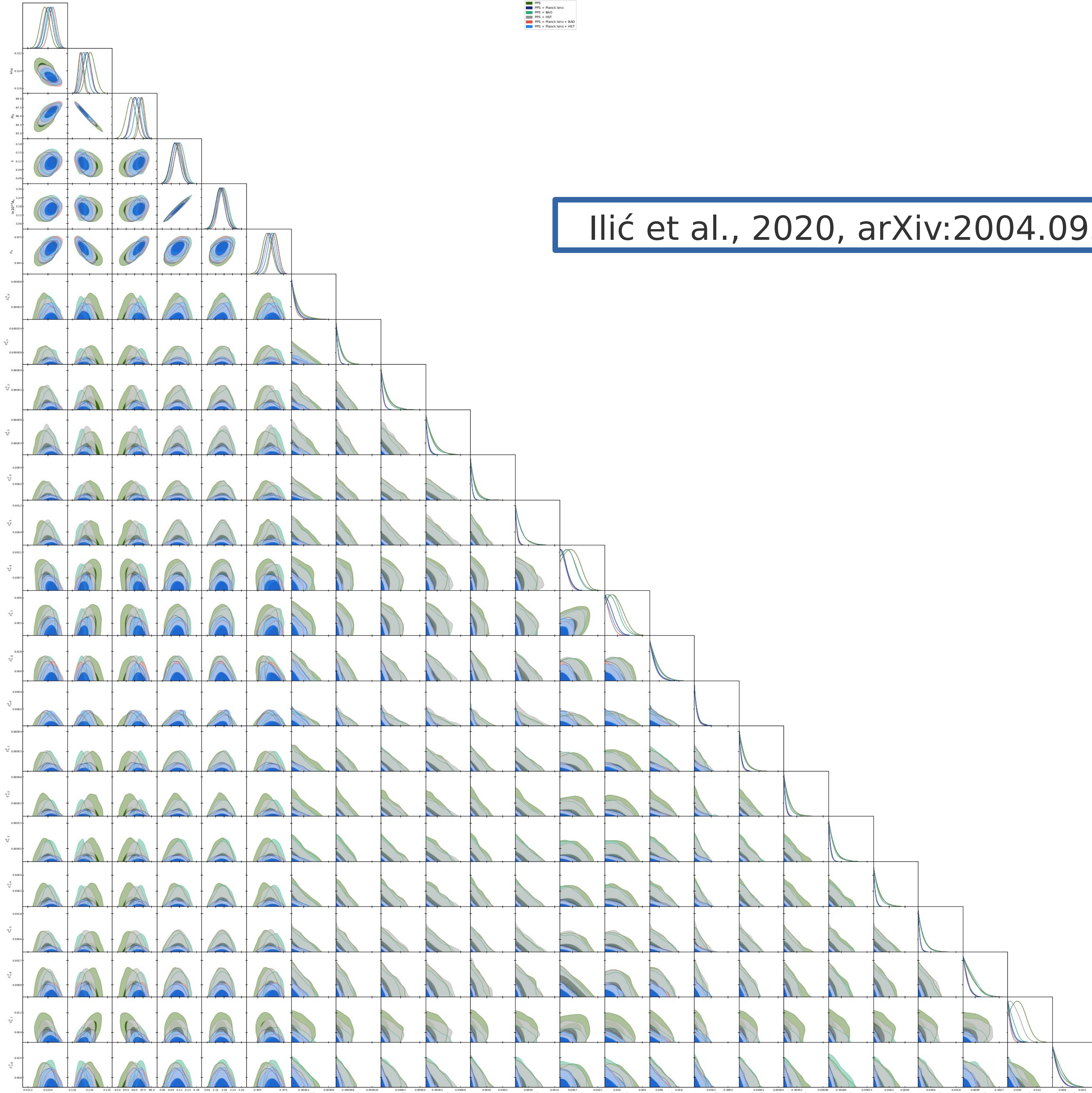
Ilić et al., 2020, arXiv:2004.09572



9 c_s^2, and c_v^2 bins

+ 8 w bins or w=0



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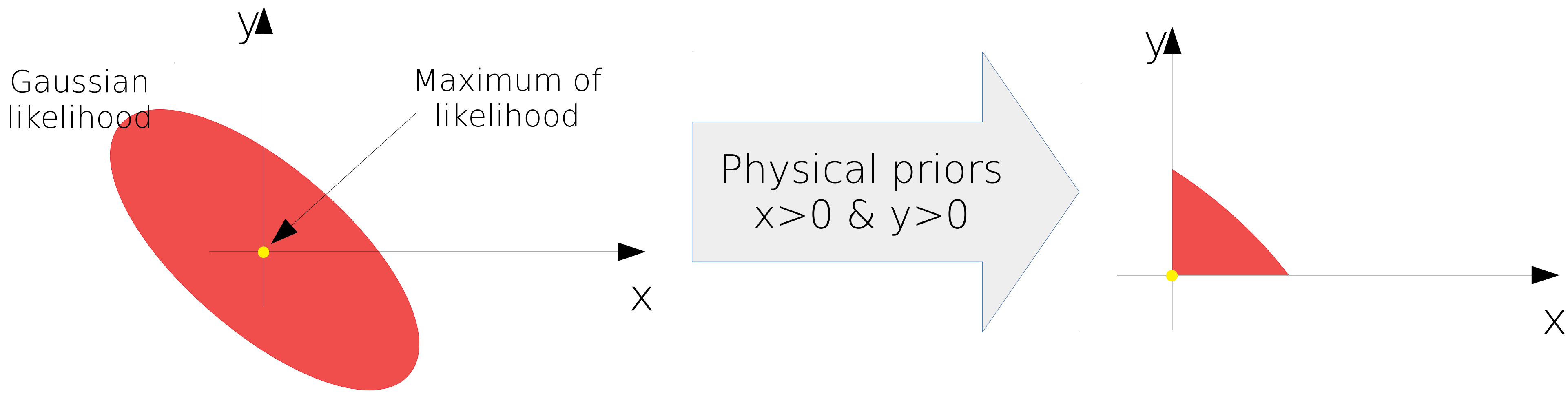
Effects of priors



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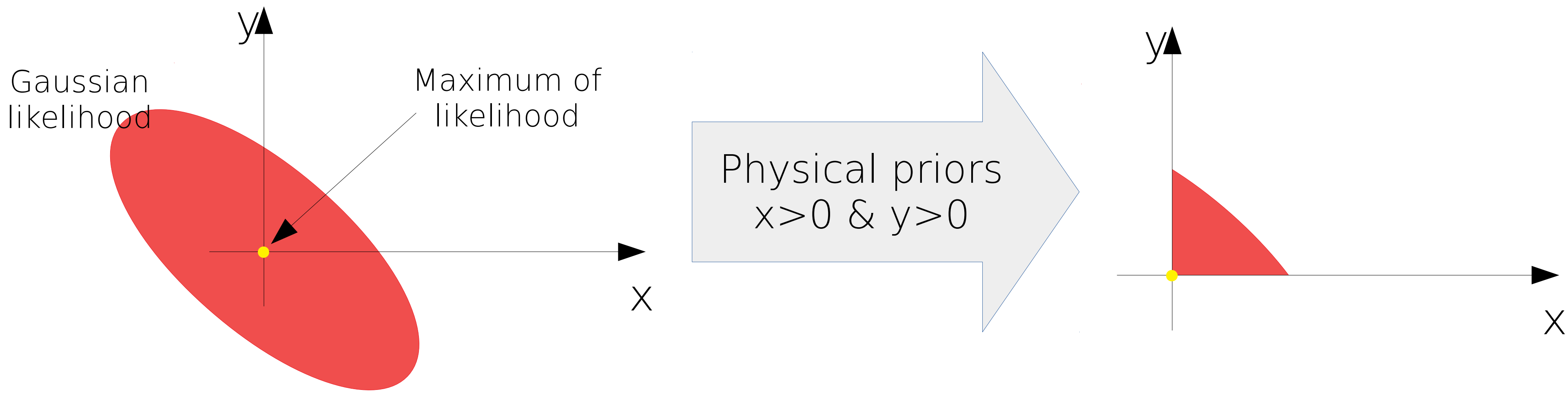
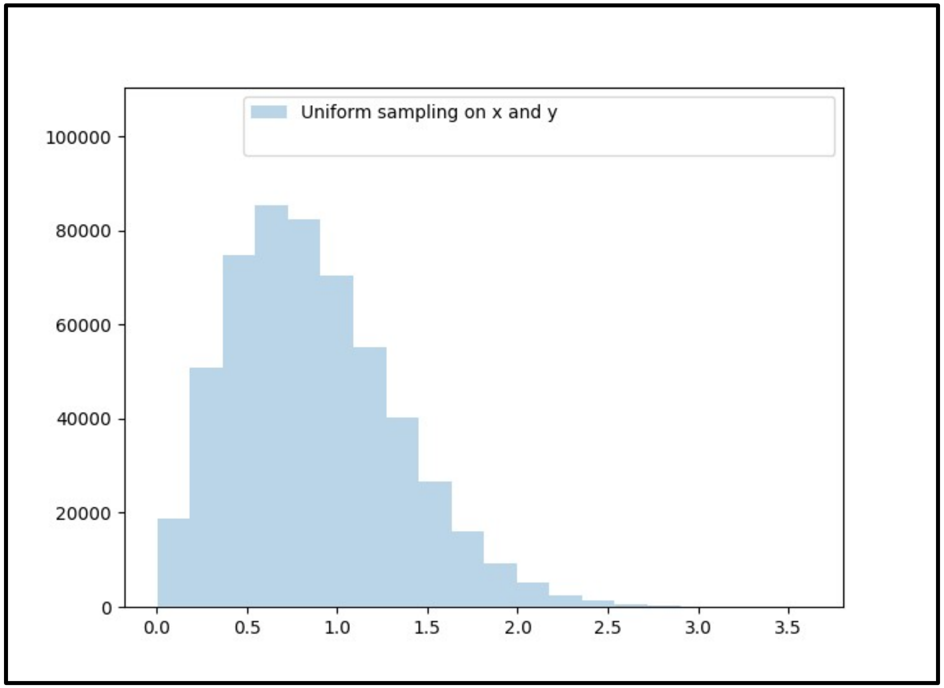
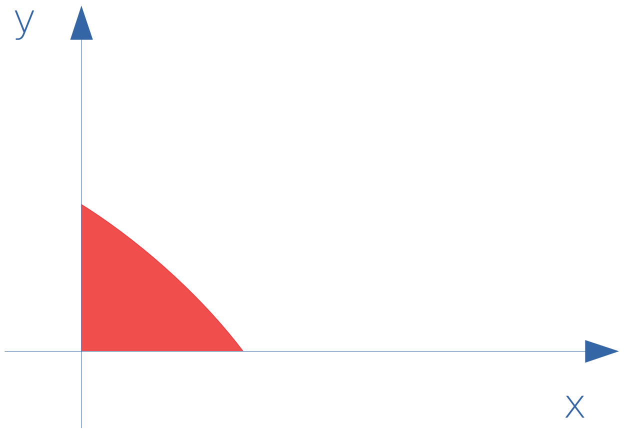


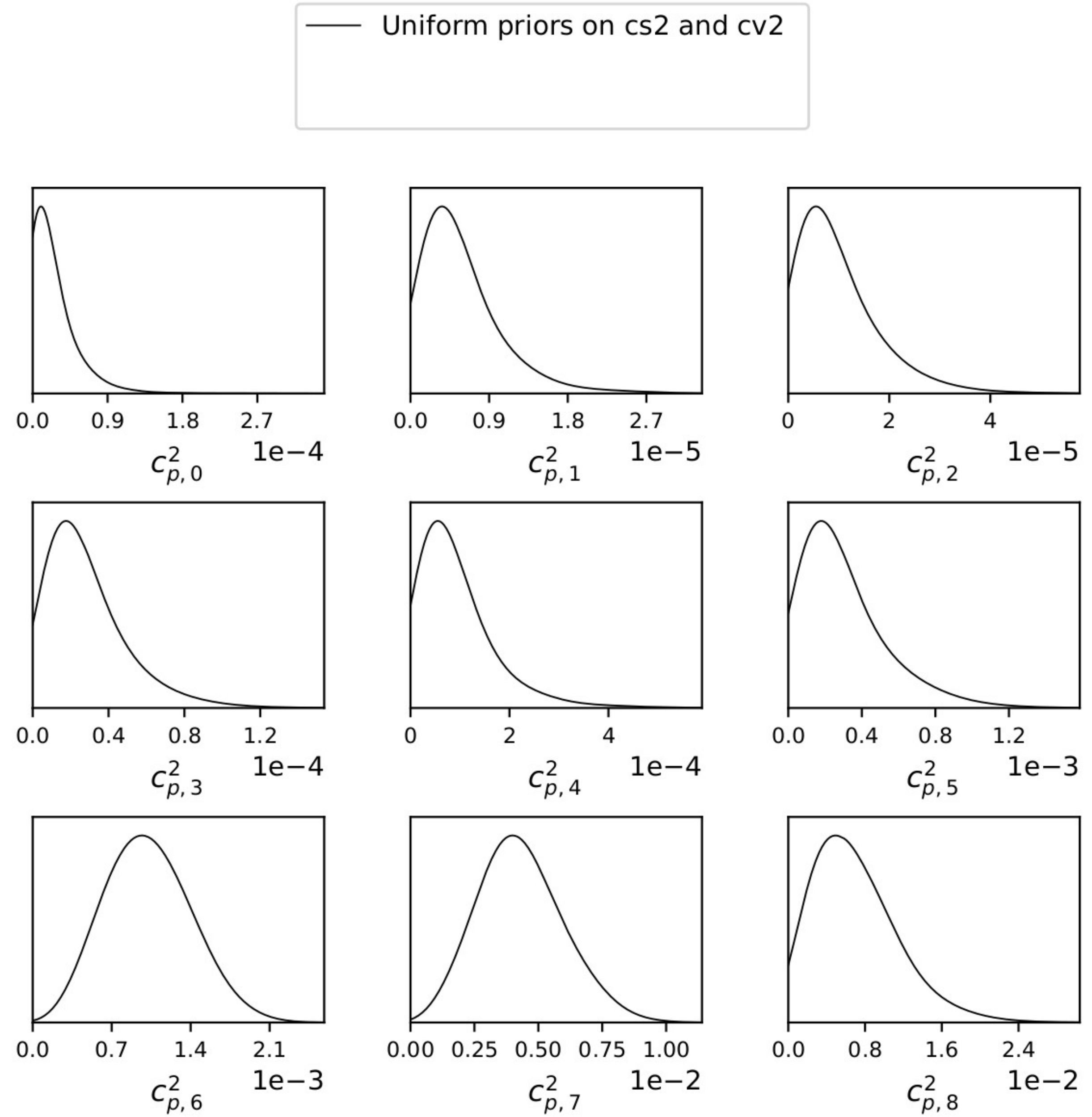




Effects of priors

$$c_p^2 = c_s^2 + \frac{8}{15} c_v^2$$

$$(c_s^2, c_v^2)$$



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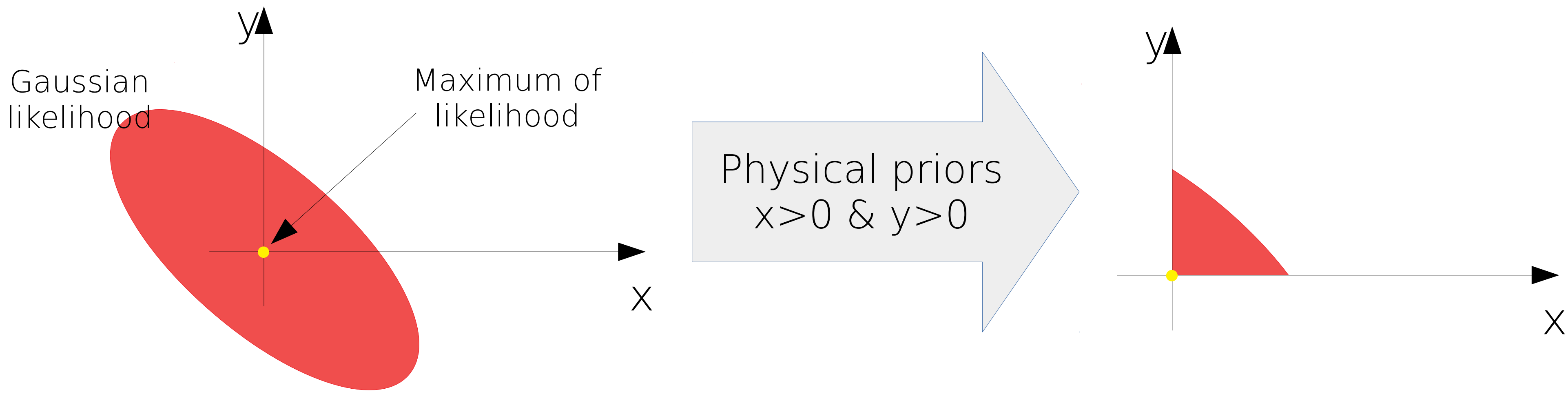
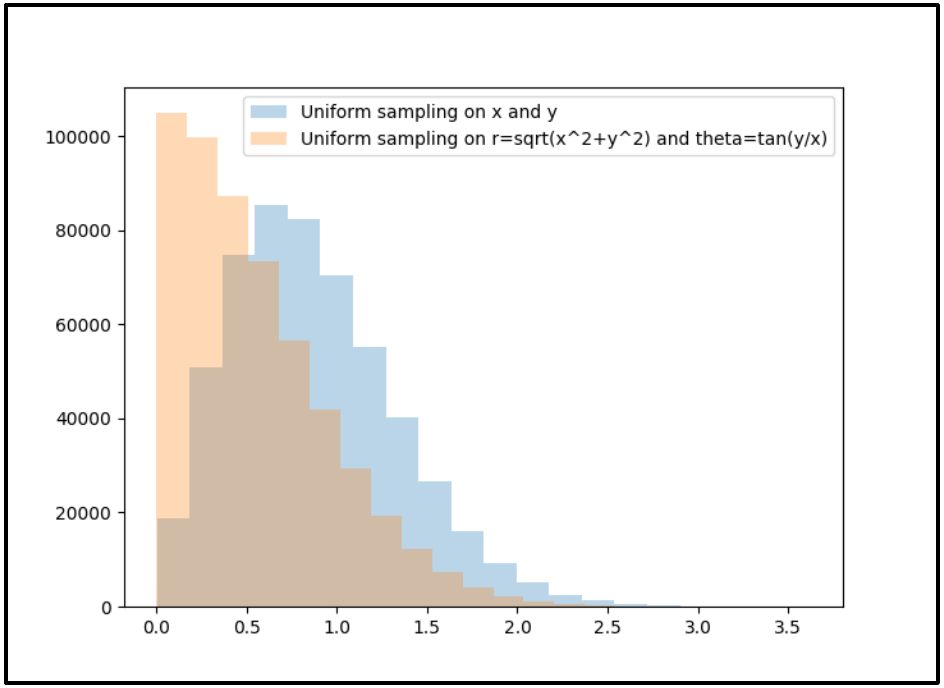
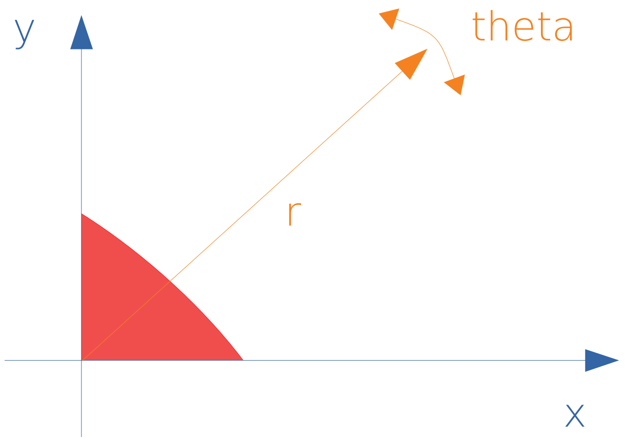






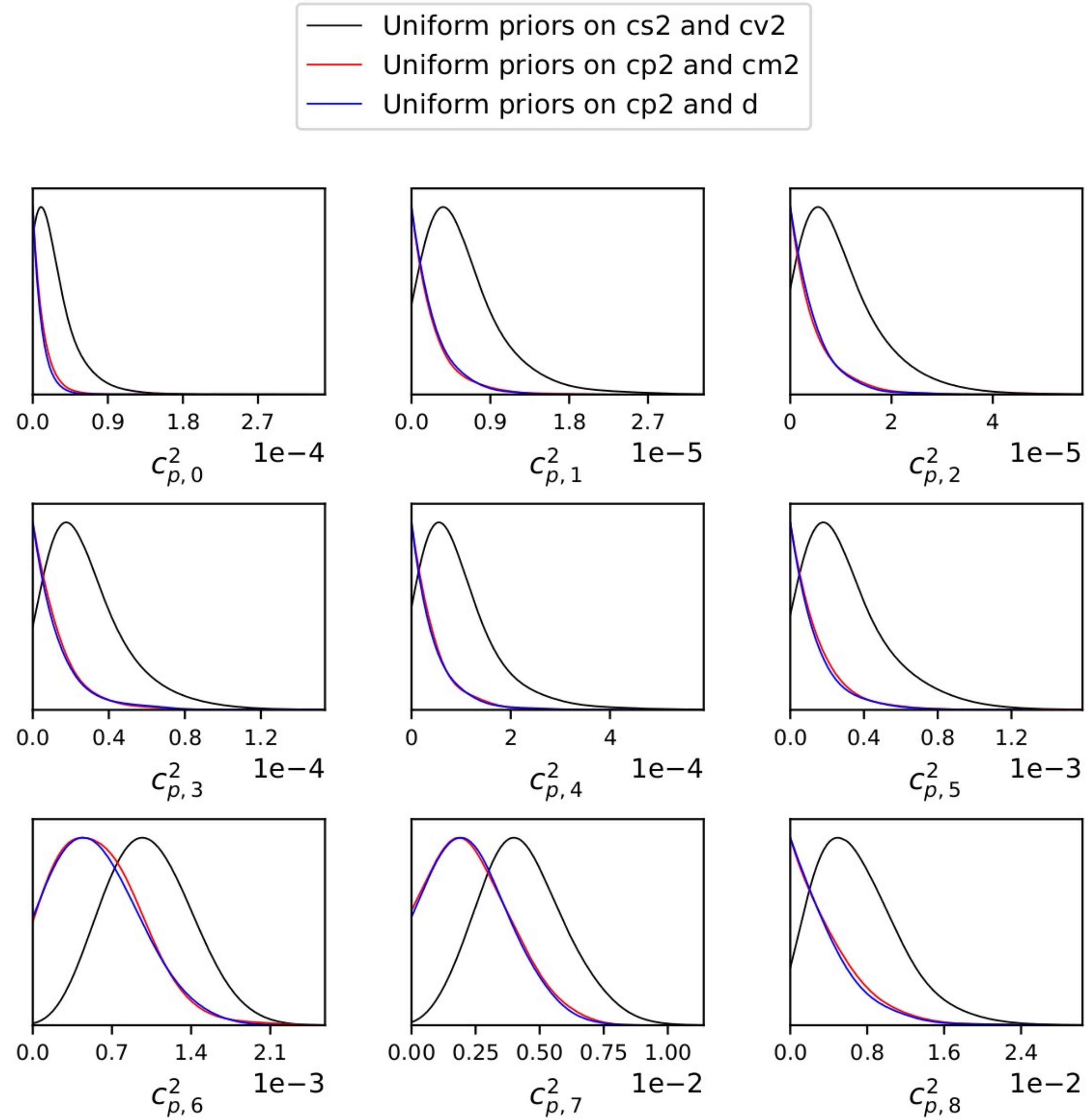
Effects of priors

$$c_p^2 = c_s^2 + \frac{8}{15} c_v^2$$

$$(c_s^2, c_v^2)$$

$$(c_p^2, c_m^2) \qquad (c_p^2, d)$$

$$c_m^2 = \arctan\left(\frac{8}{15}\frac{c_v^2}{c_s^2}\right) \qquad d = \frac{c_s^2}{c_p^2}$$



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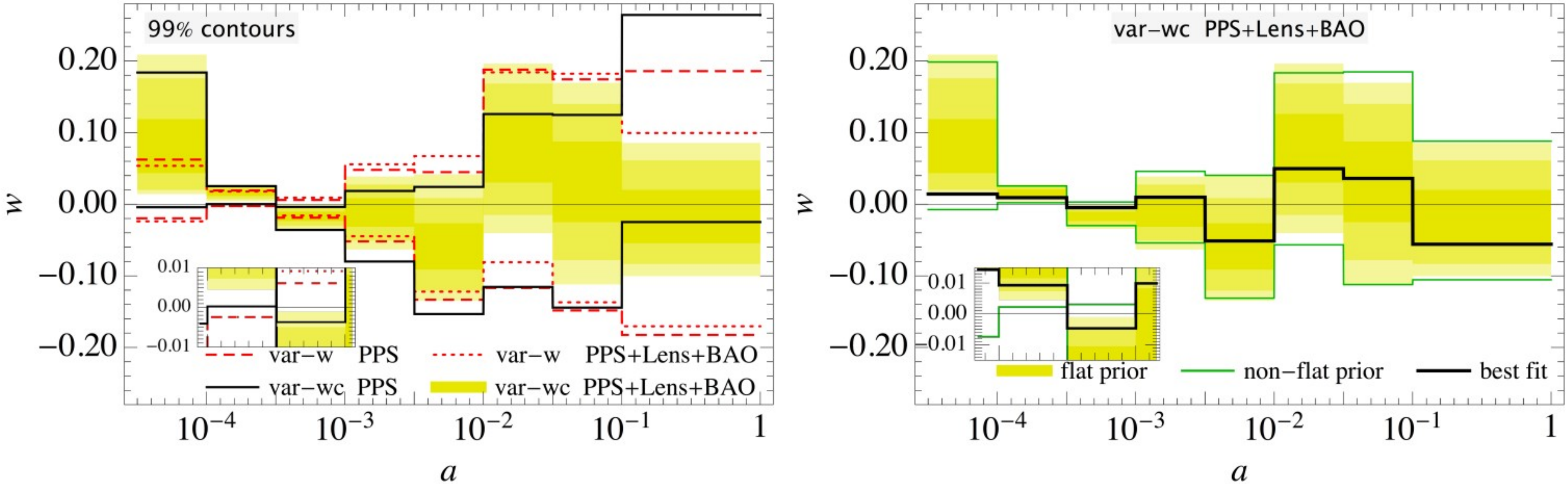

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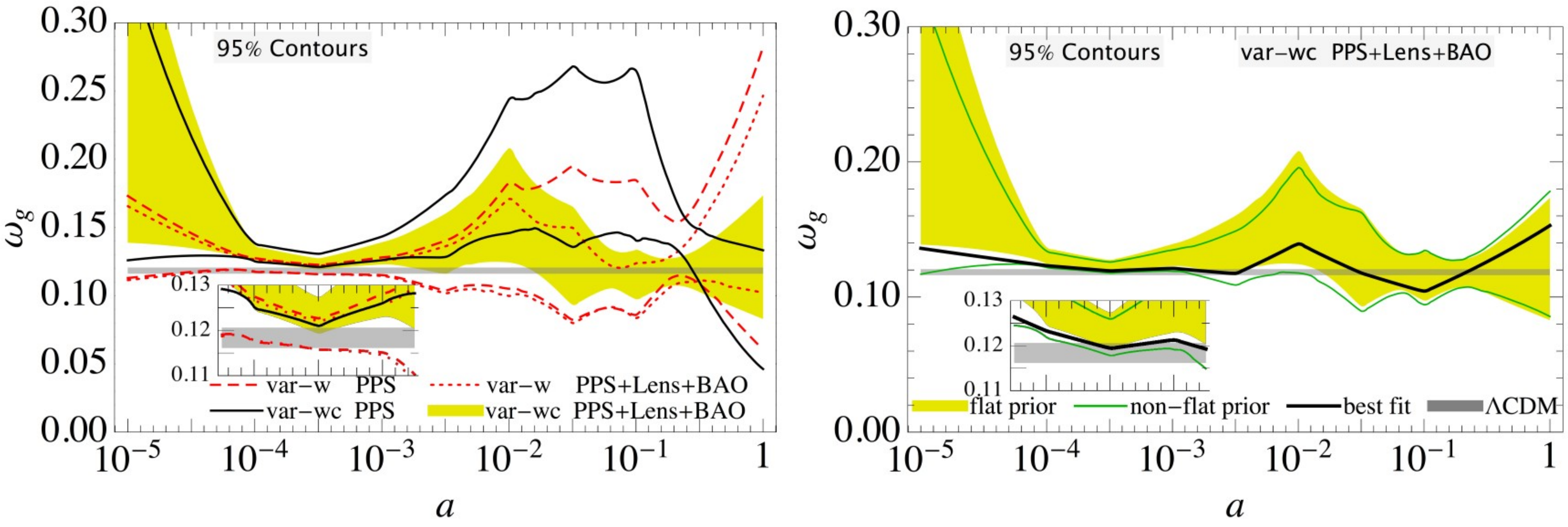

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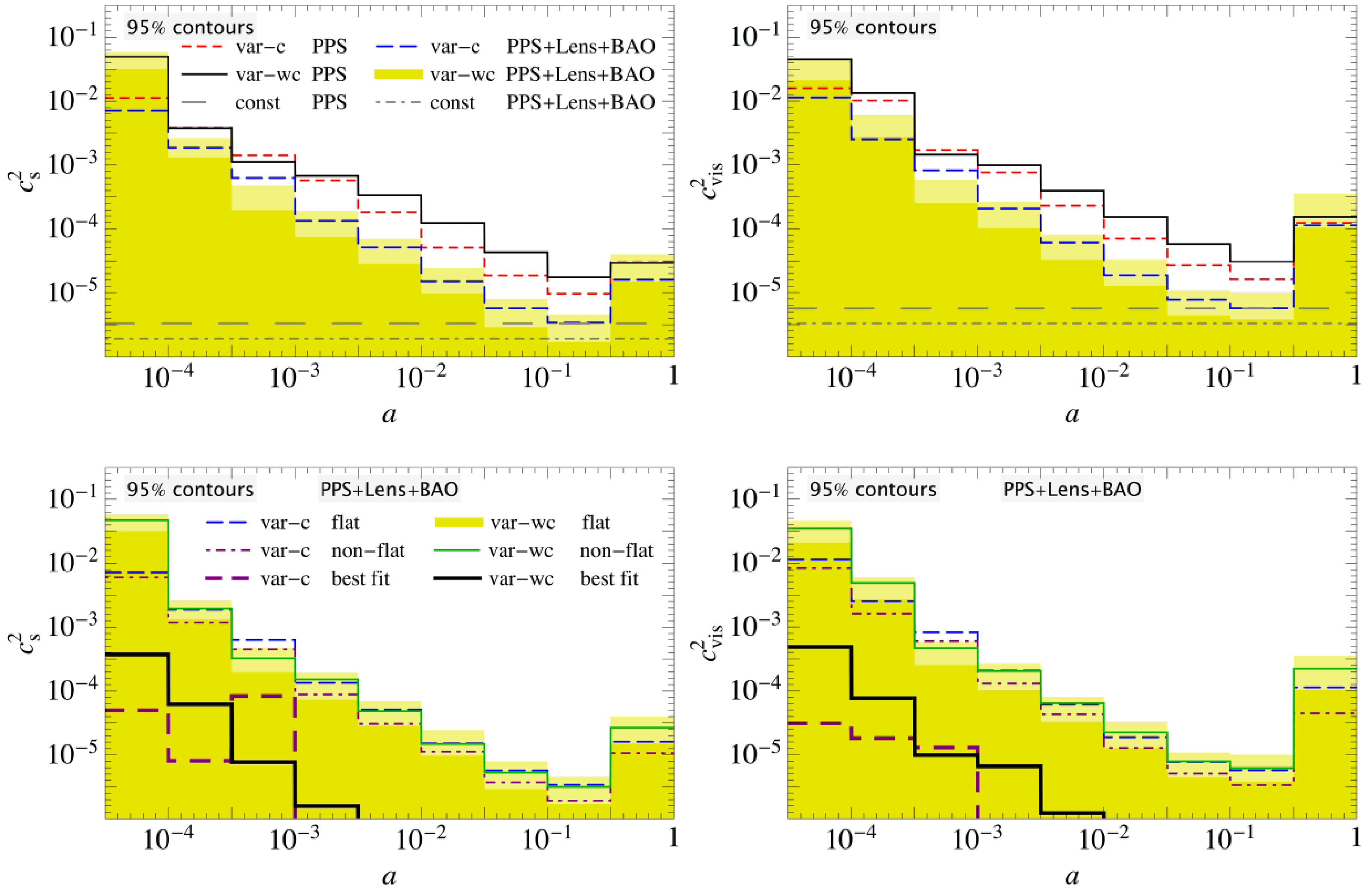
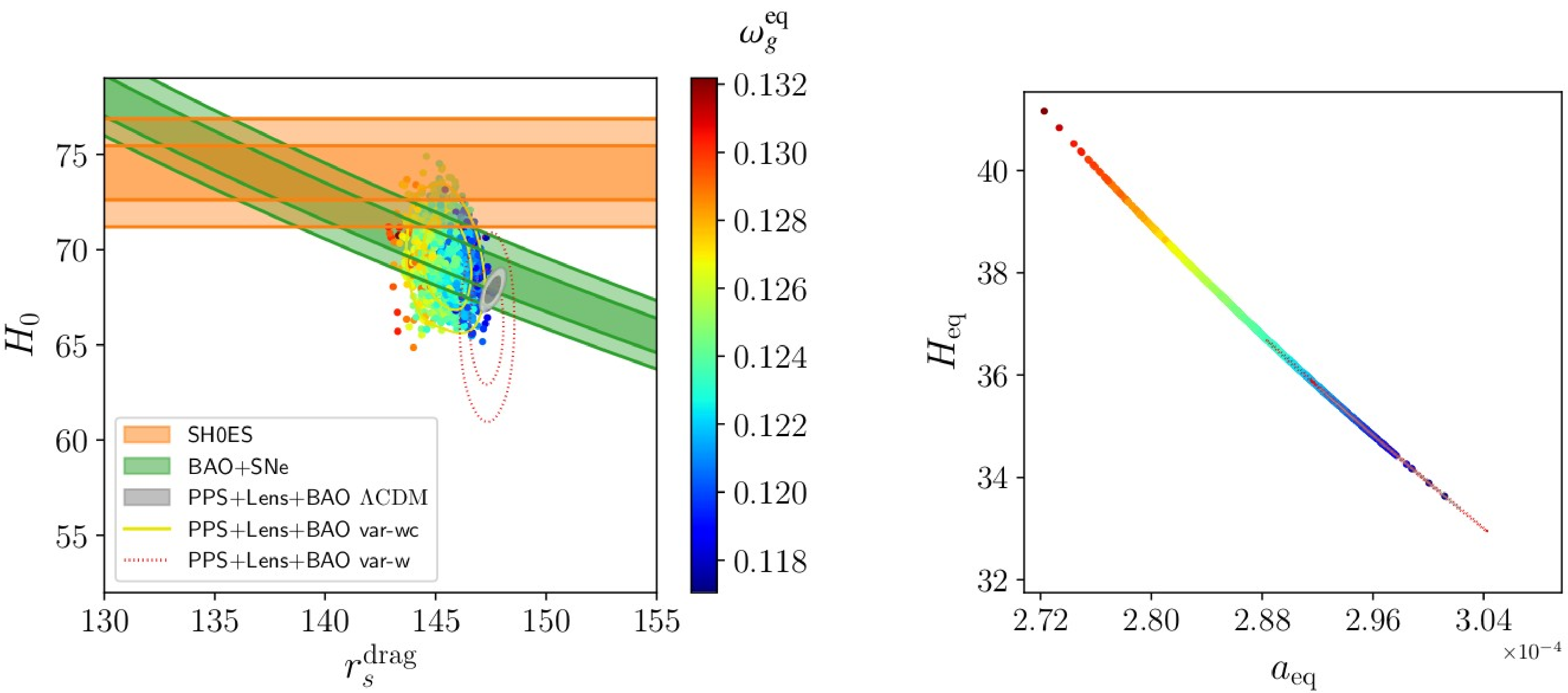


GDM and H0

Ilić et al., 2020, arXiv:2004.09572



Identifying prior effects with ECLAIR

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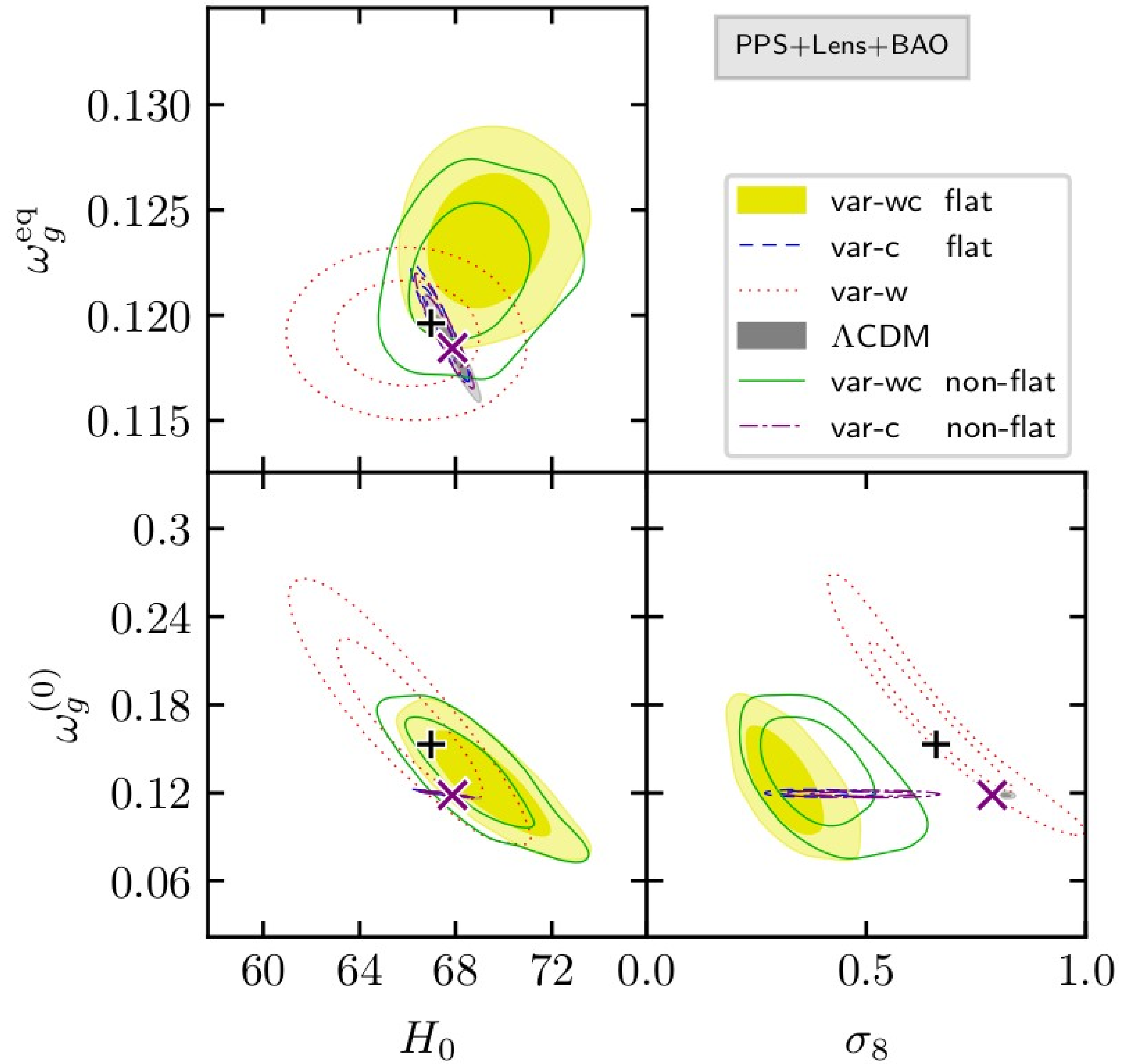
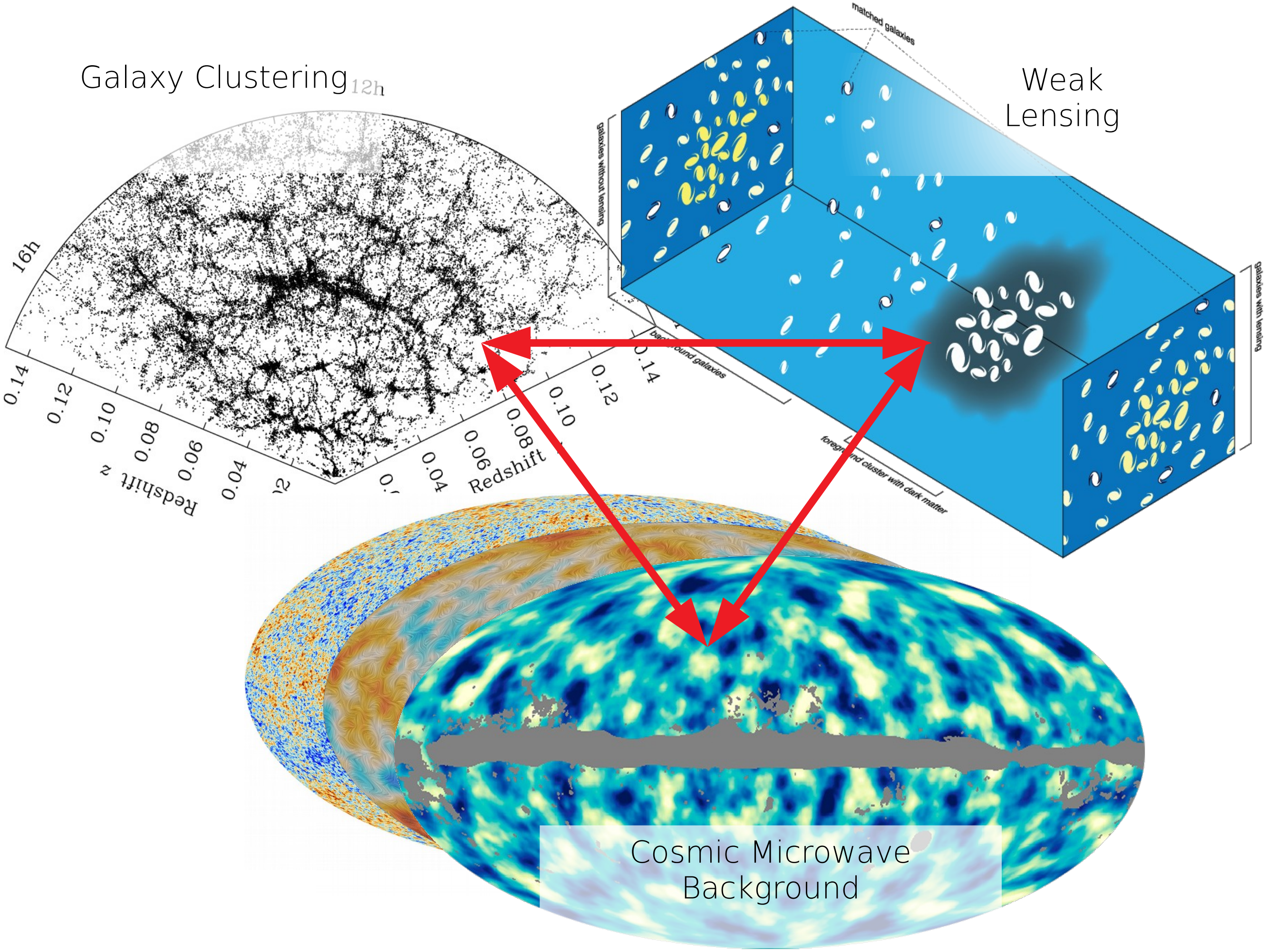


Summary

Ilić et al., 2020, arXiv:2004.09572

- No convincing evidence for w, cs2, cv2 to be nonzero
- Varying w improved fit marginally
- Only free cs2 and cv2 → virtually no improvement
- w+cs2+cv2 free: DM abundance around equality ++
  while abundance today, H0, and s8 – –
  → help in solving s8 and H0 tensions ?

Beyond CMB-only constraints

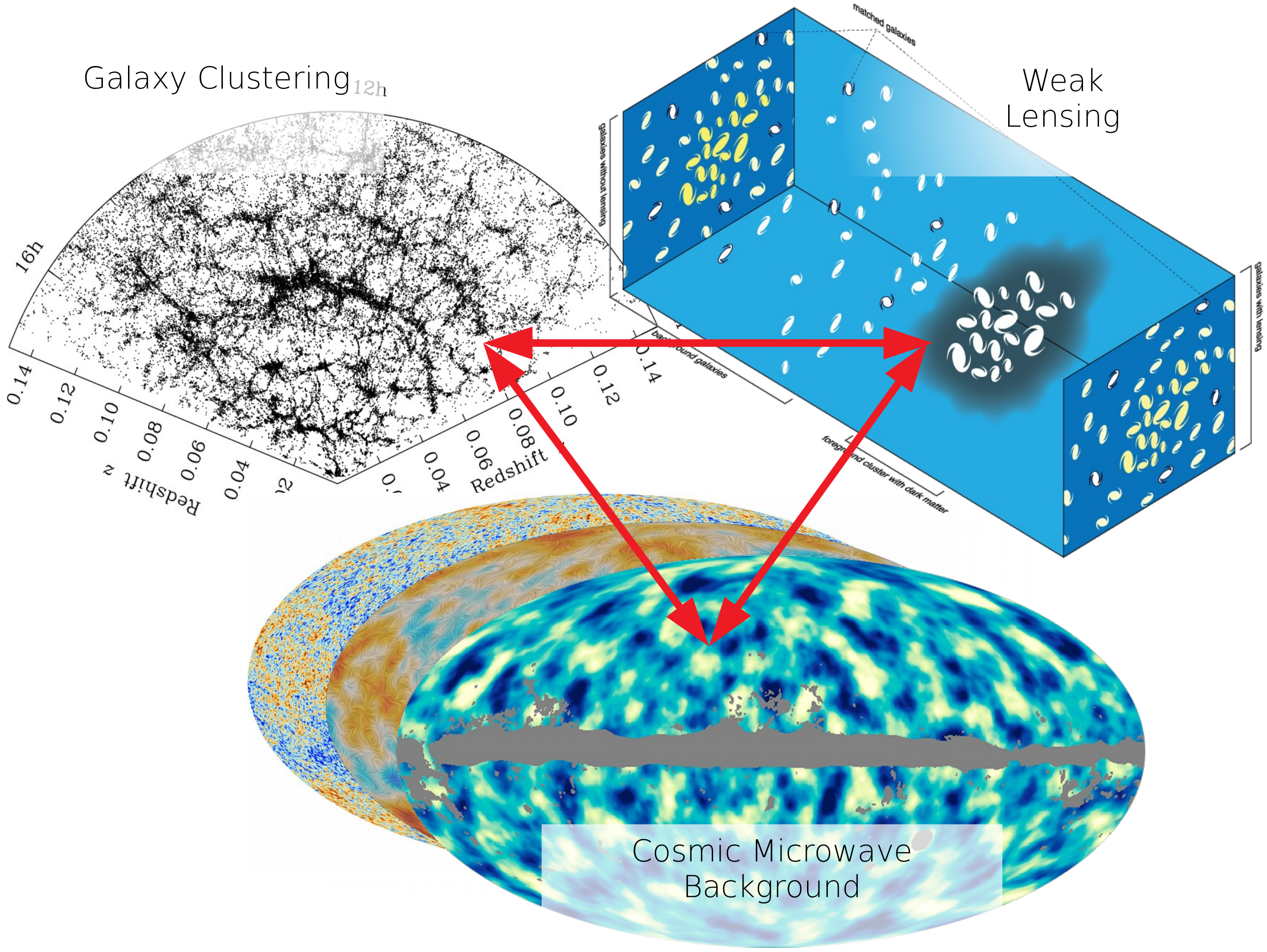


Take-away message(s)

- CDM remains (mostly) unchallenged
- Plethora of contenders
- GDM model : efficient way of pruning model space
- We put constraints on free, non-parametric functions describing GDM properties
- We applied GDM on current state-of-the-art data
- Ongoing preparation for new era of instruments, with some promising first results

Thank you
for your attention !

Beyond CMB-only constraints



GDM Halo model & LSS constraints

Thomas et al., 2019, arXiv:1905.02739

GDM cosmological constraints

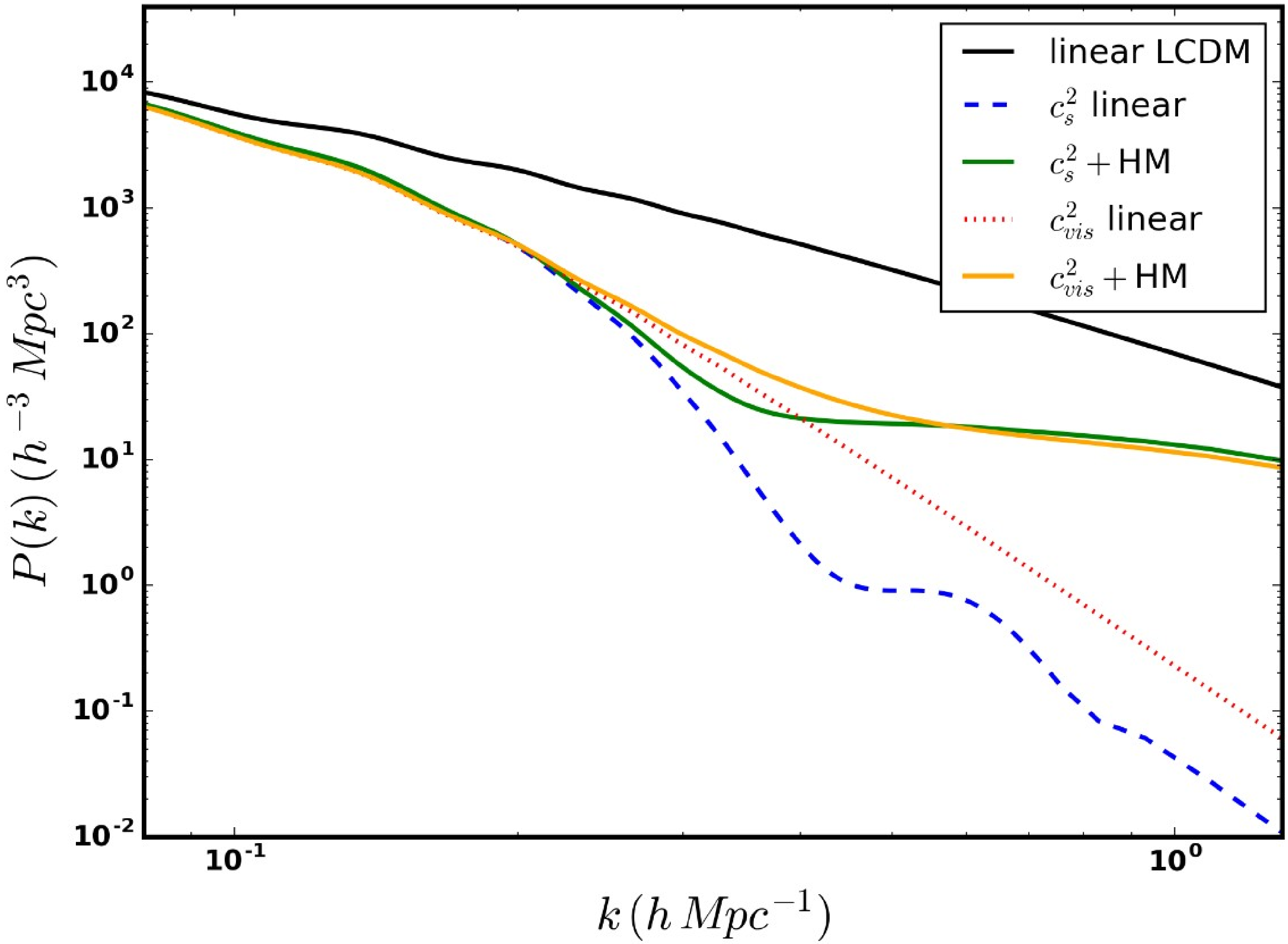
with free, constant w, c_s^2, and c_v^2

+ 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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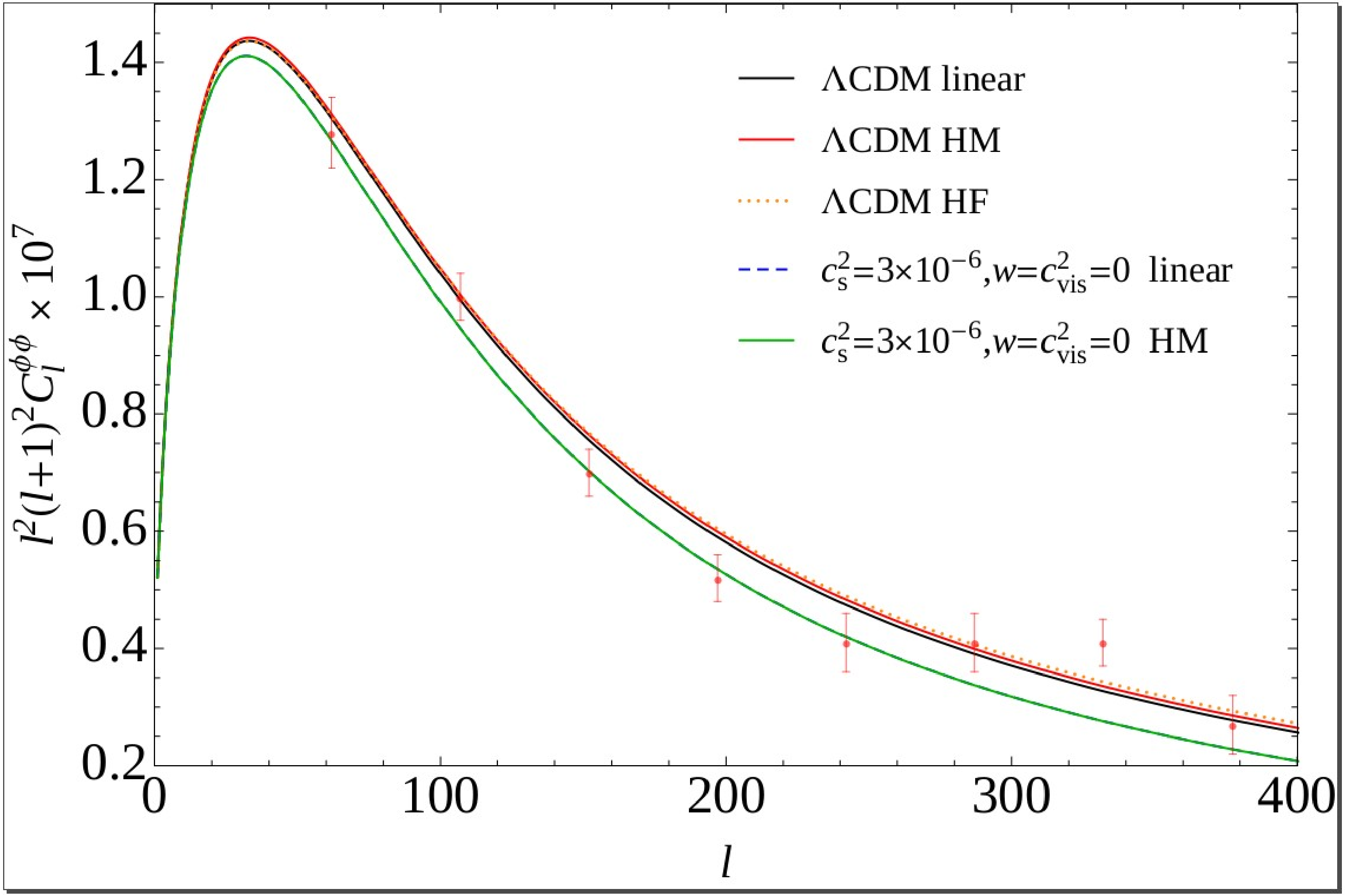

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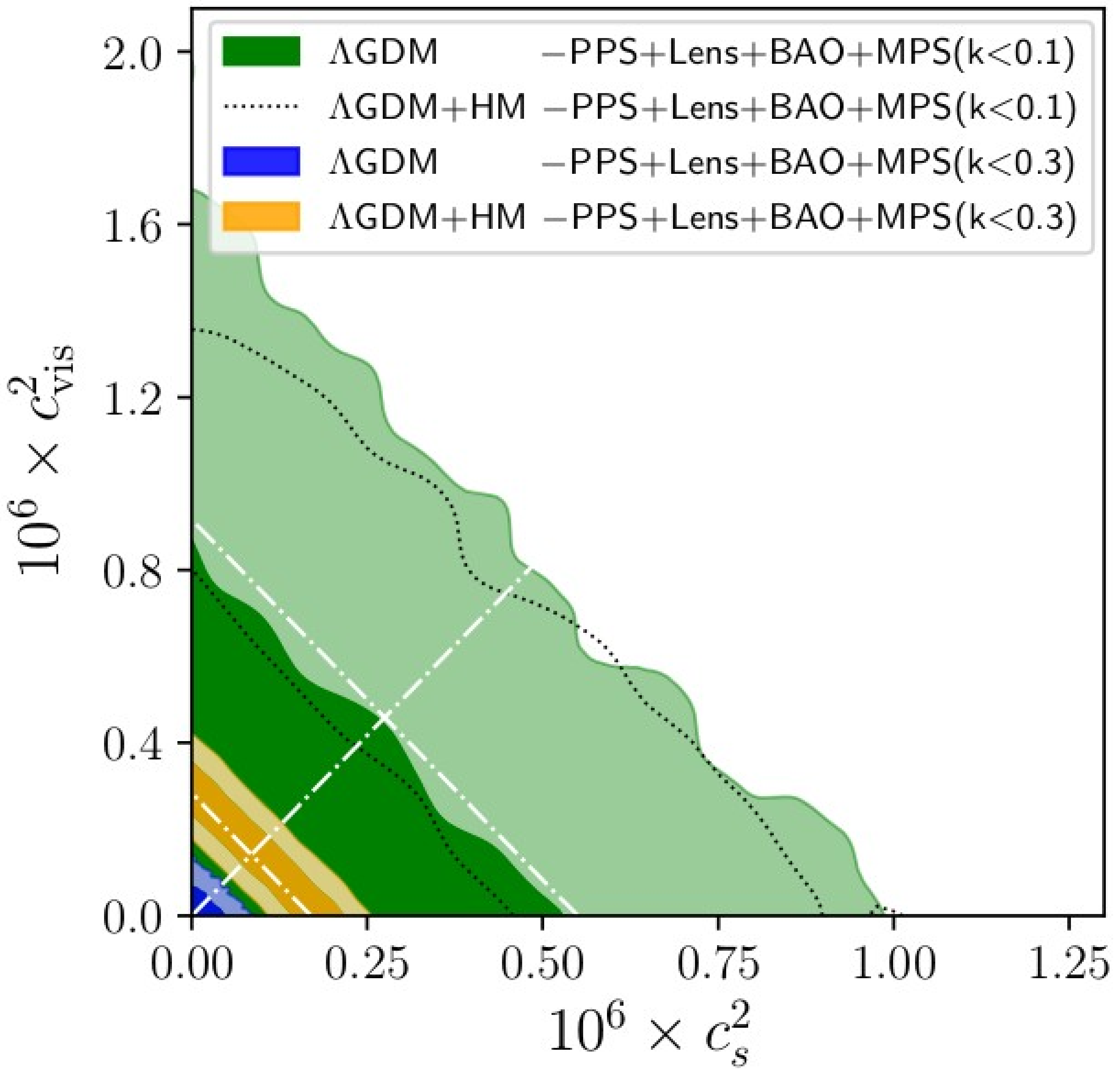
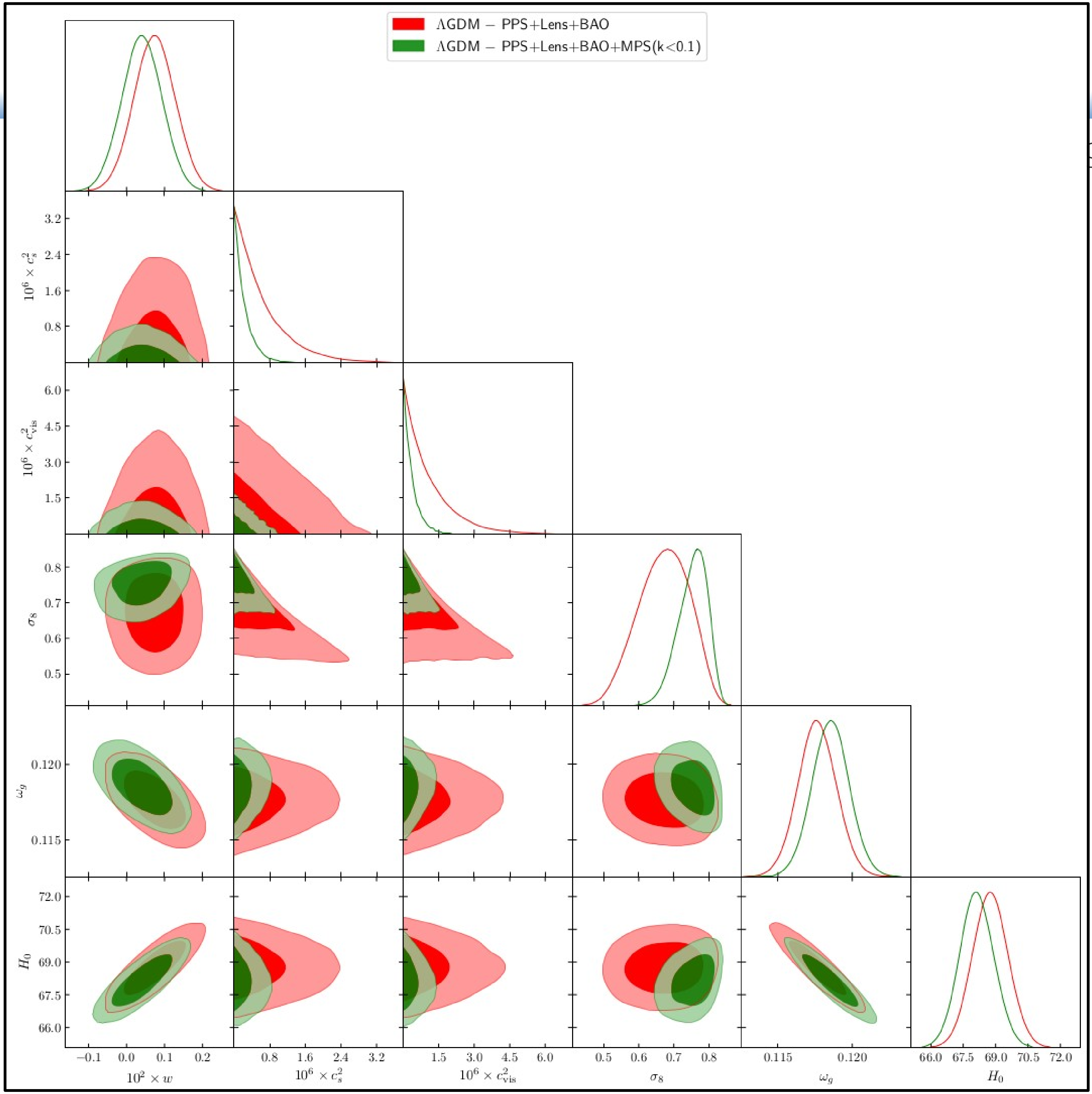


GDM



905.02739

GDM and massive neutrinos

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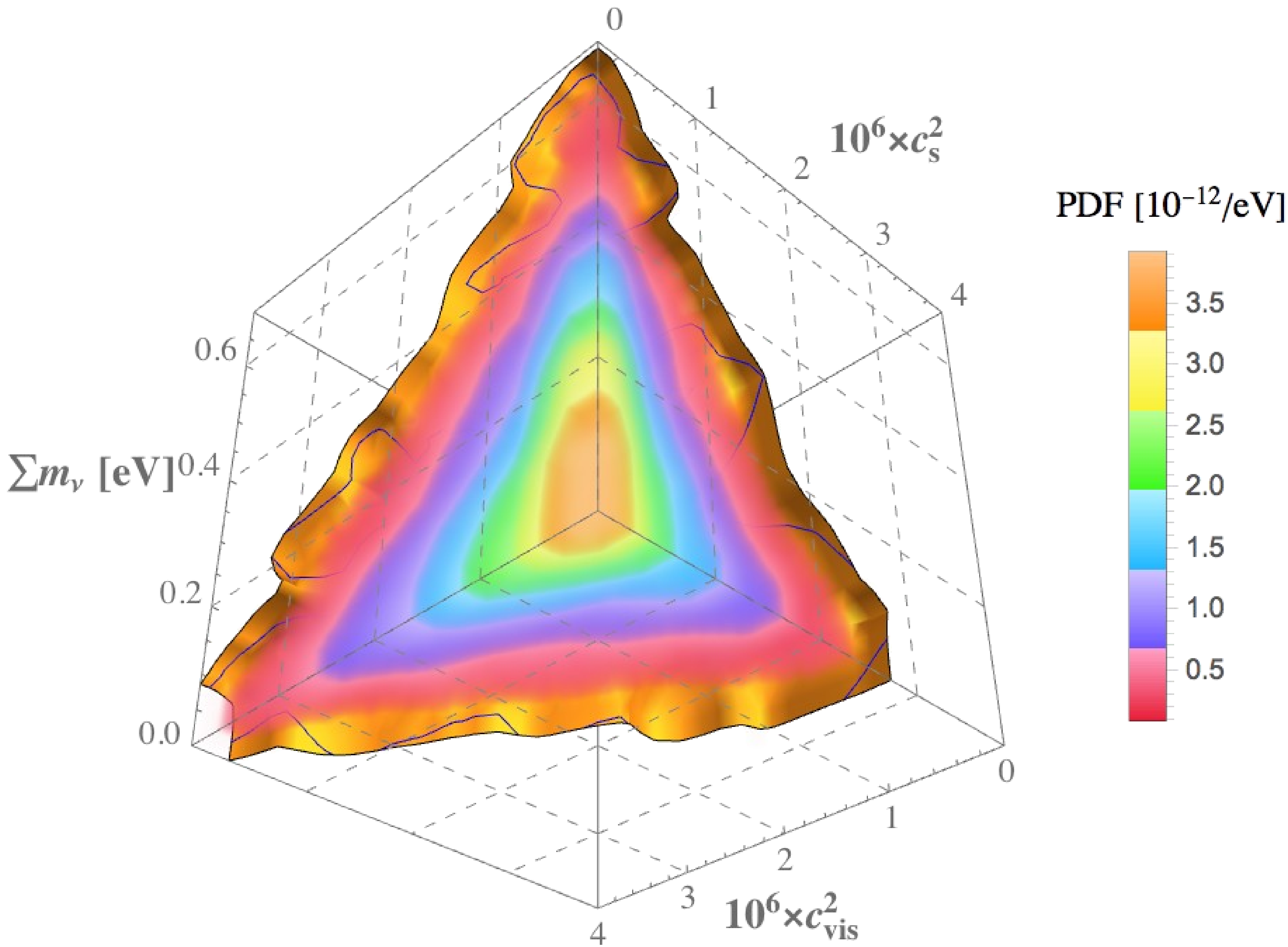

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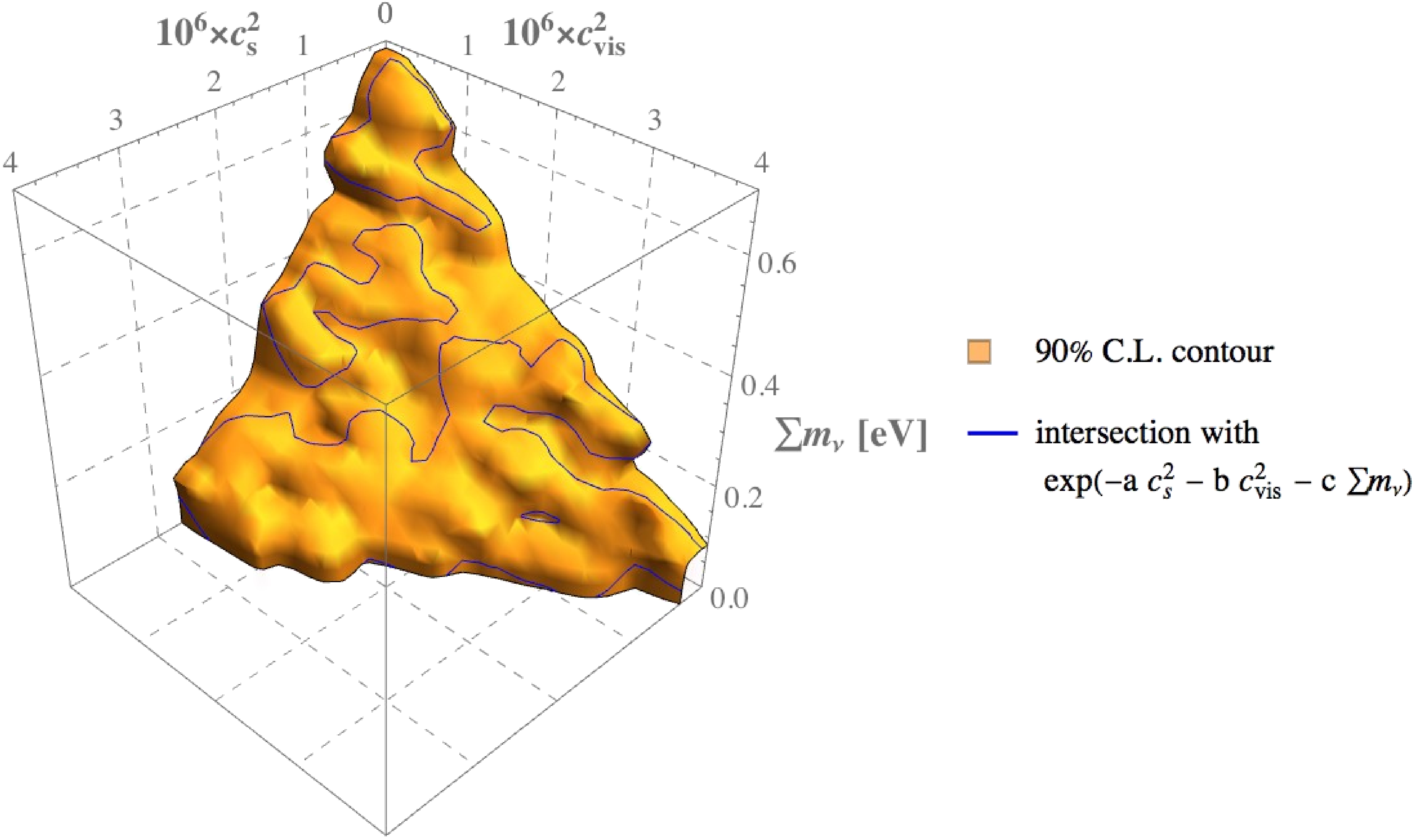
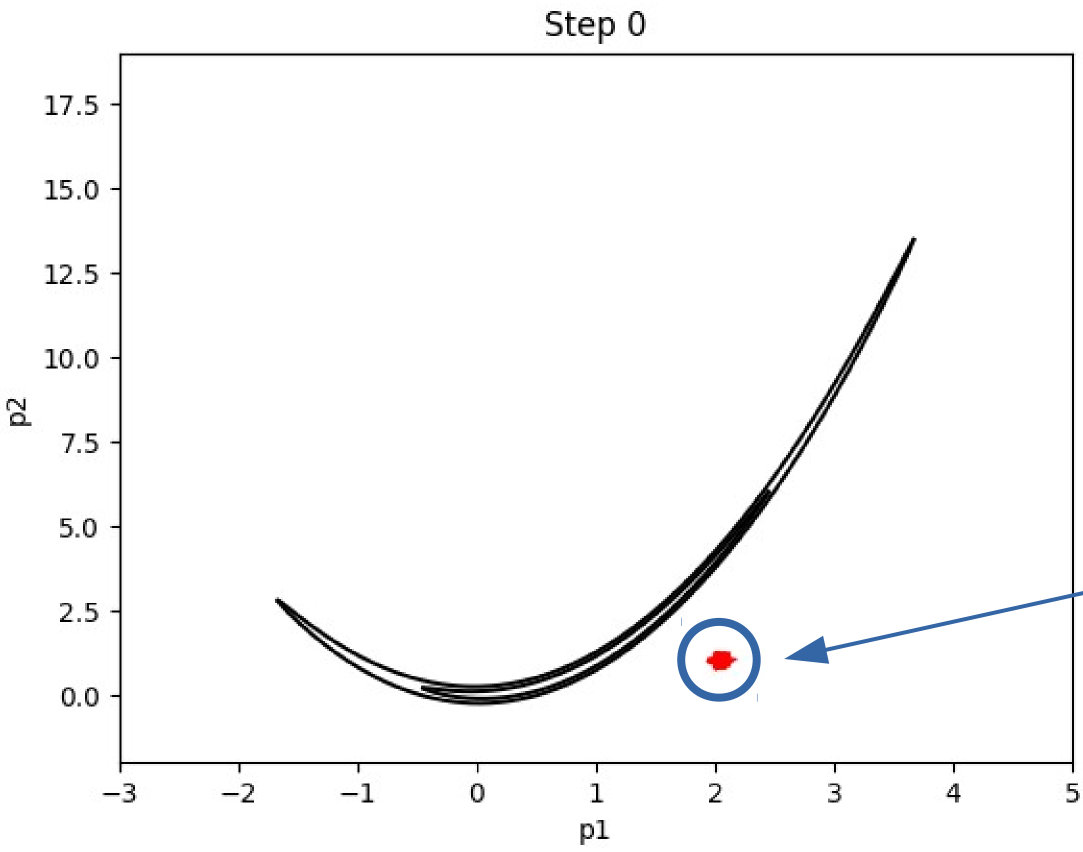


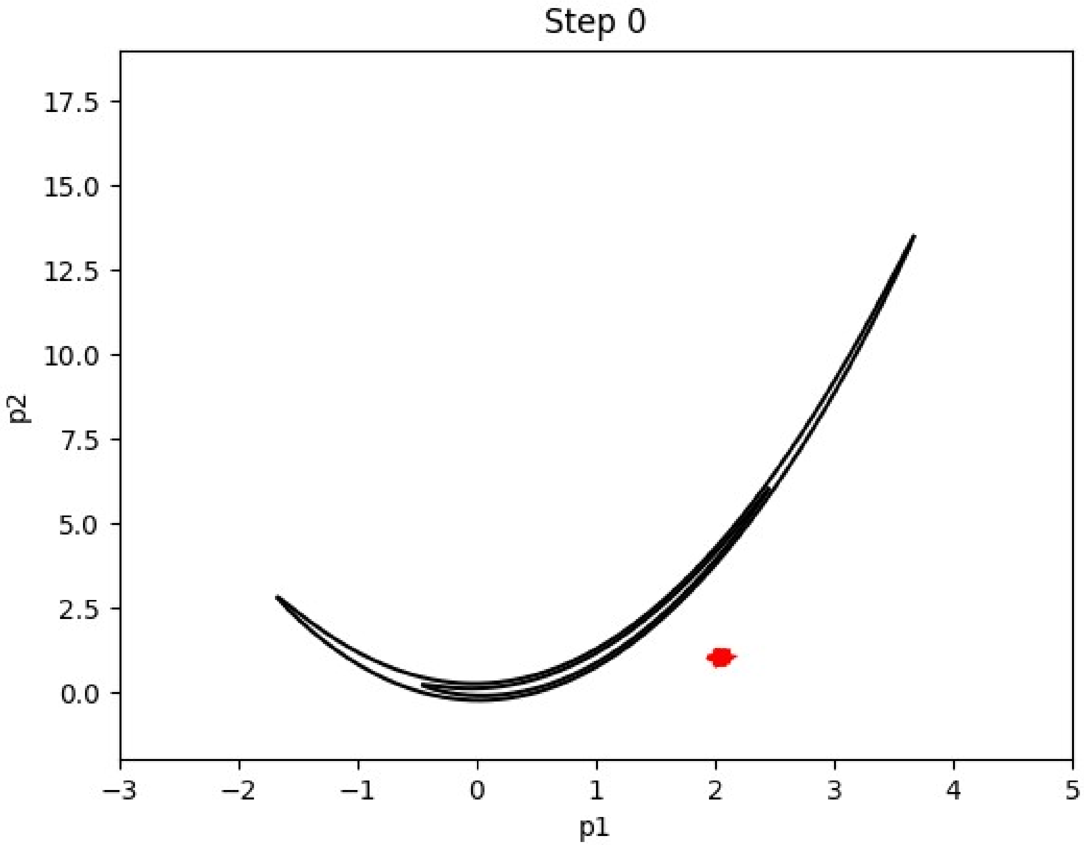
Ensemble sampling with ECLAIR

Ensemble sampling



Collection of “walkers” initialized at random positions

Ensemble sampling



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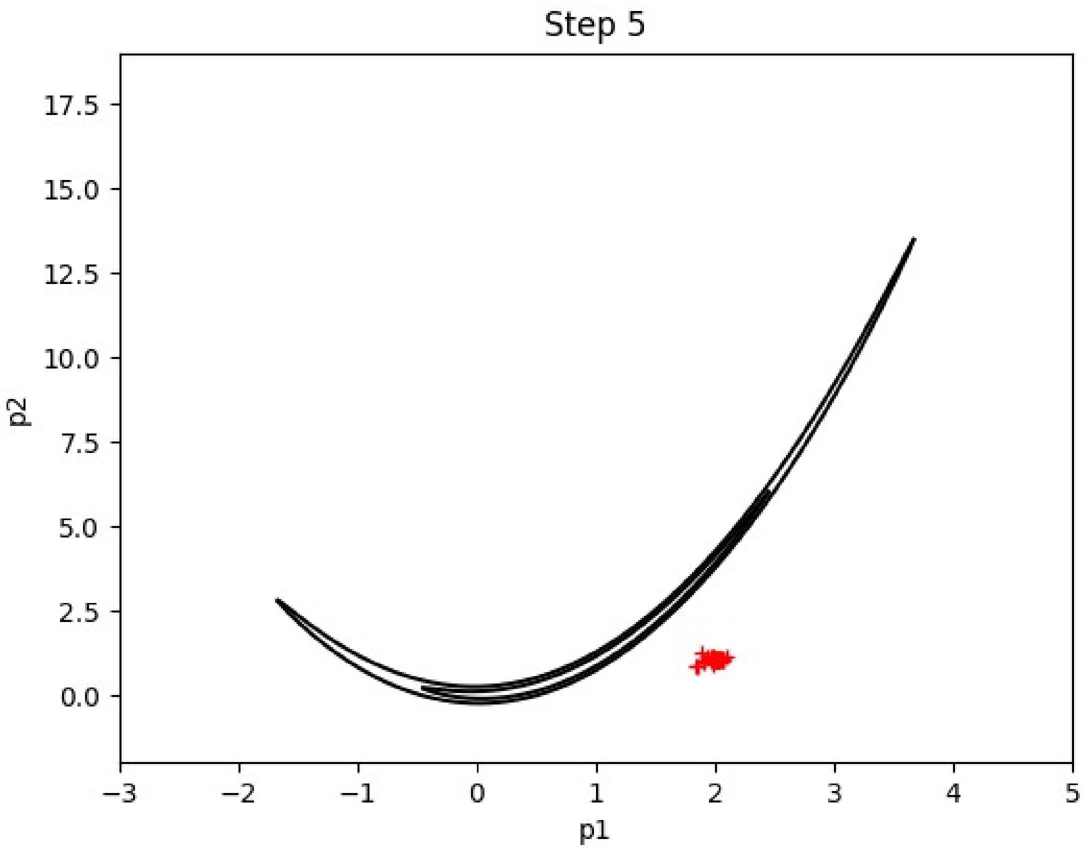

"Walkers" quickly spread throughout parameter space, using each other's position to propose jumps

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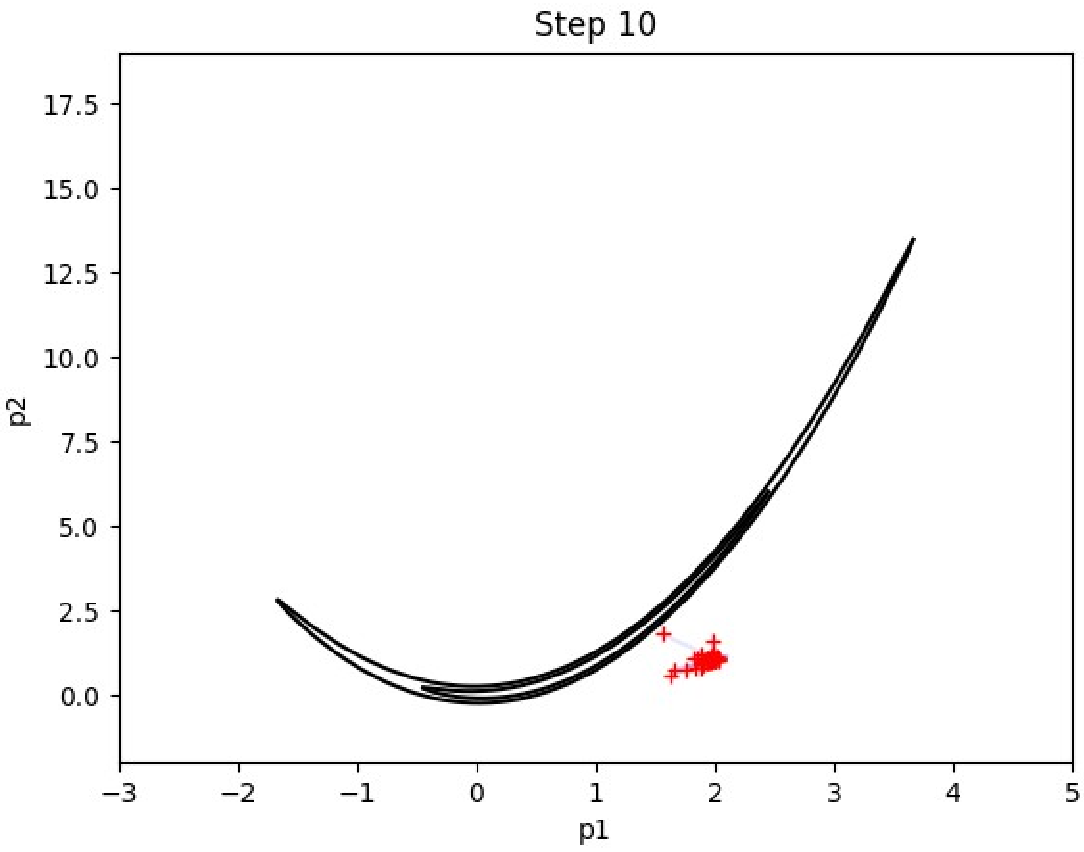

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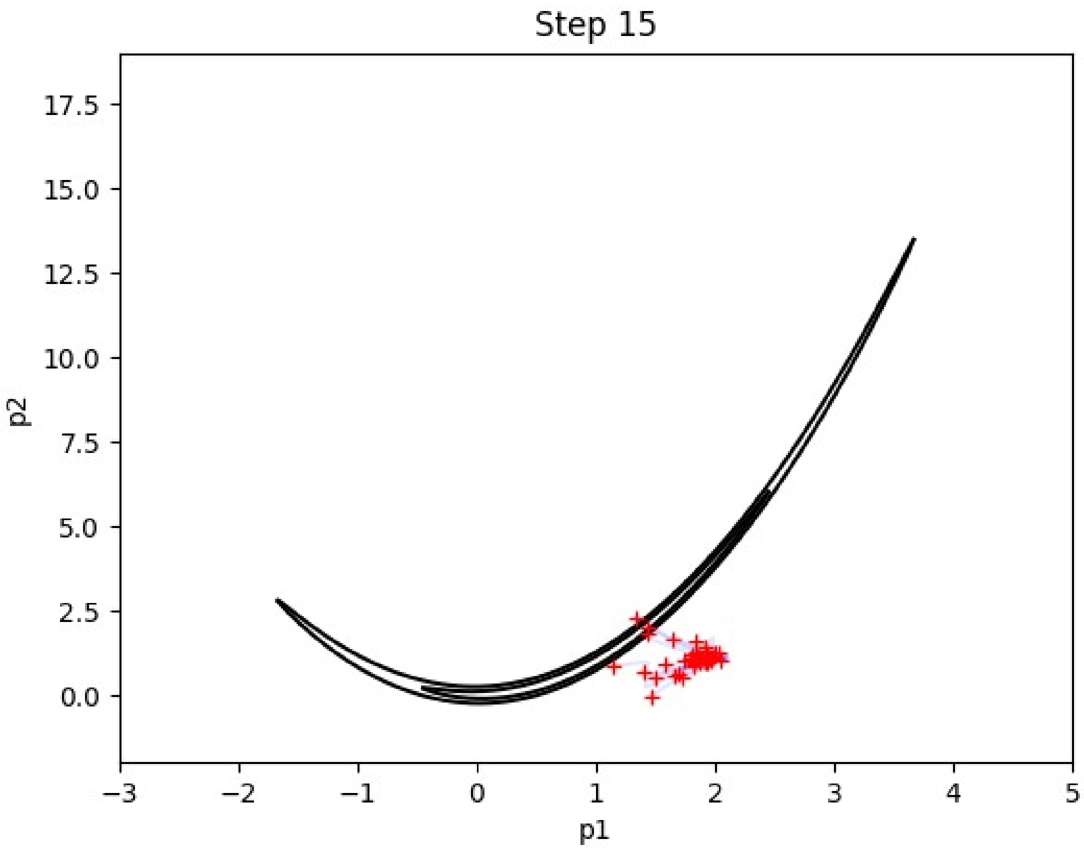

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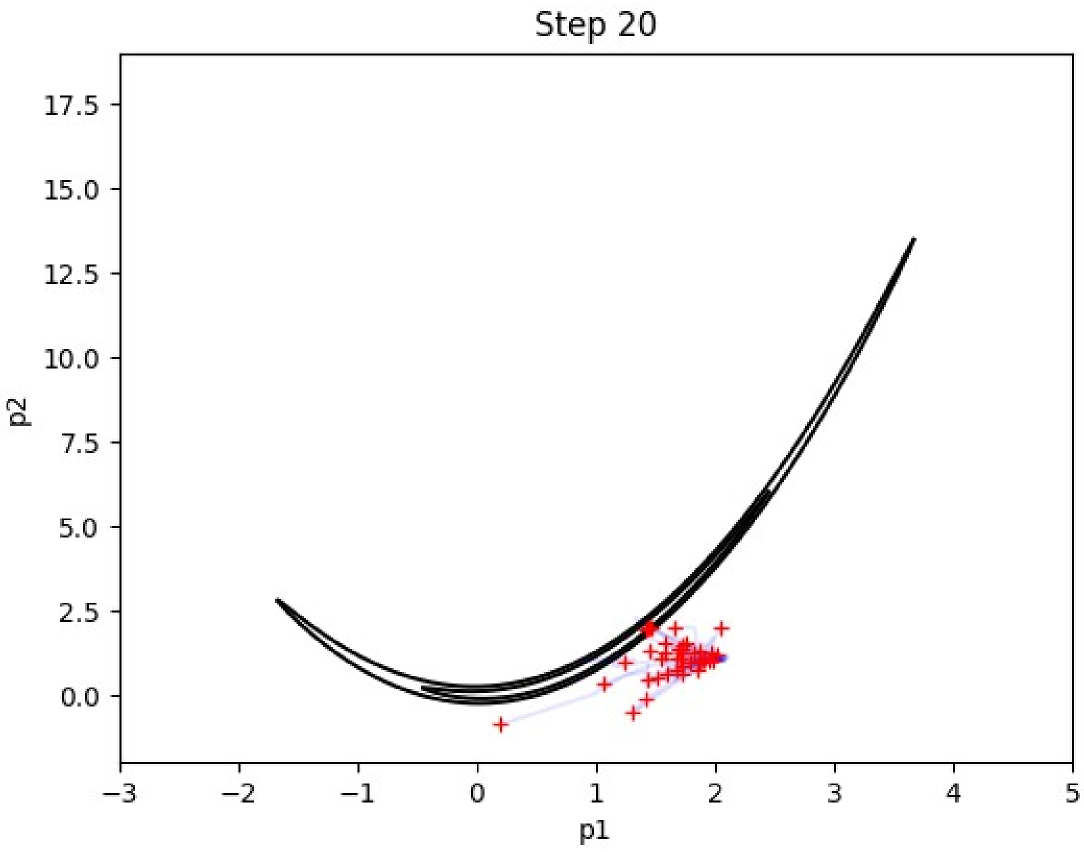

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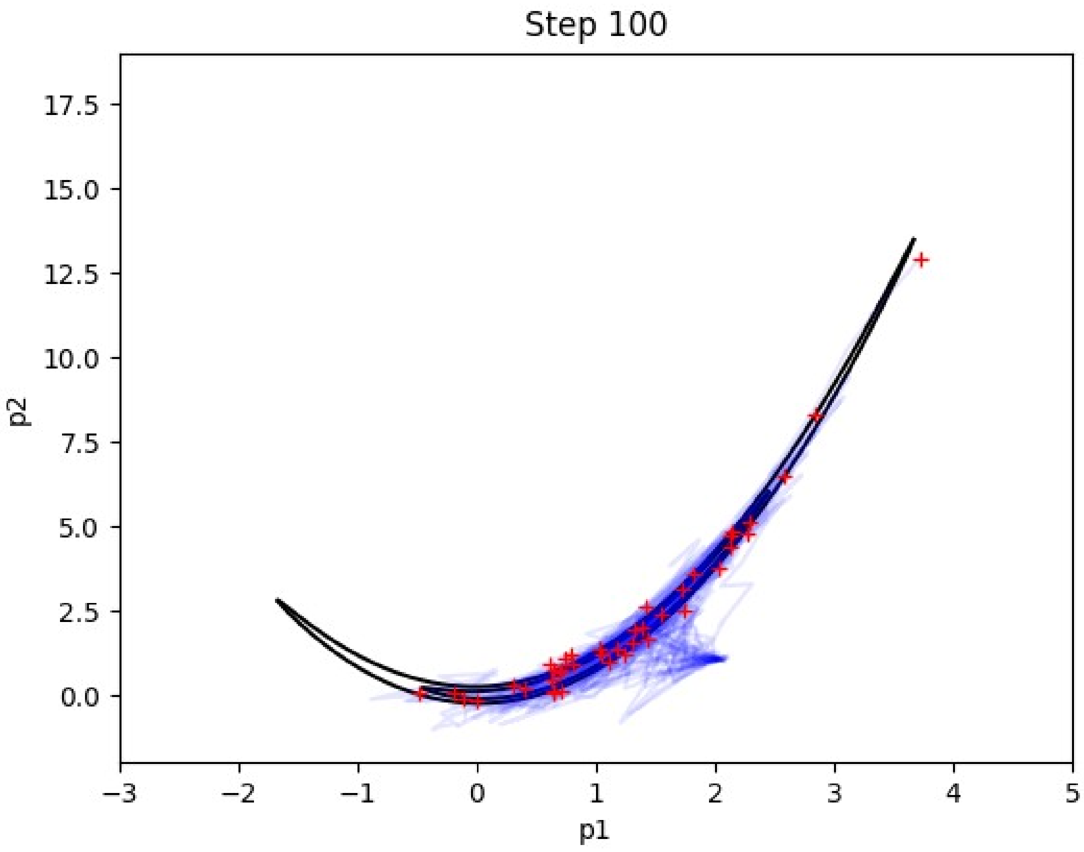
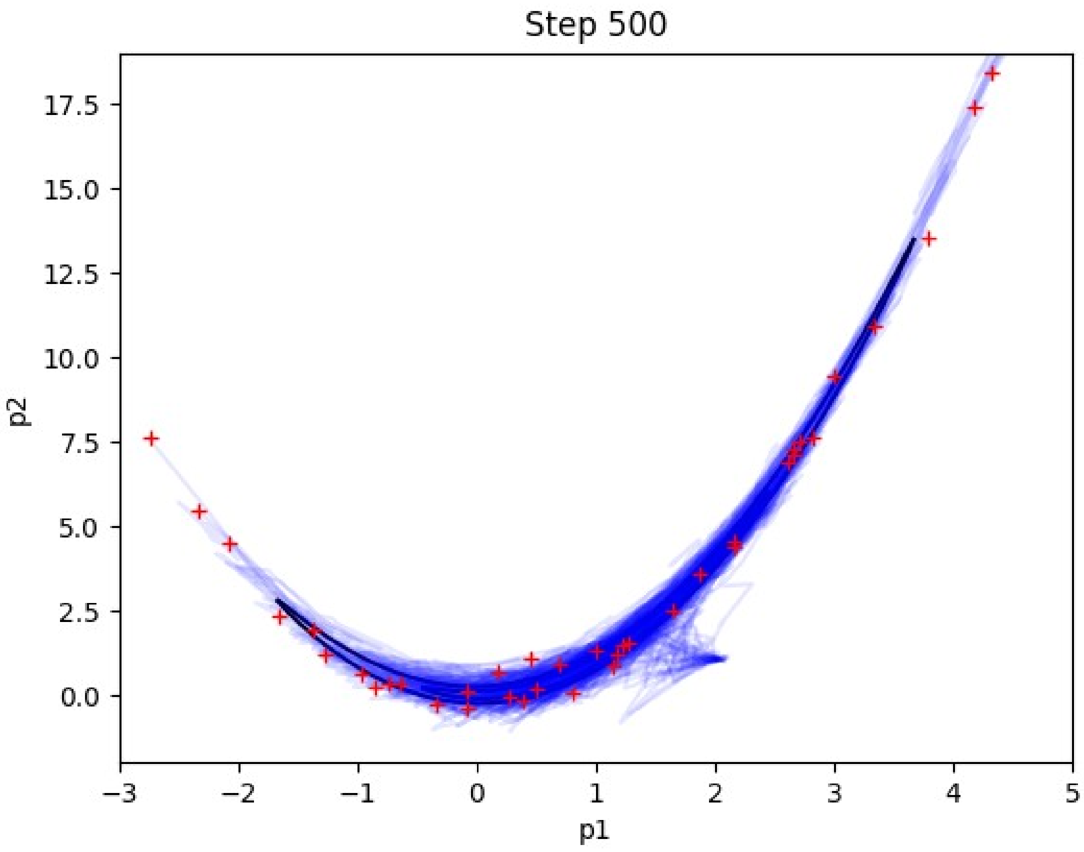


...and end up sitting in the "interesting" region of parameter space

Ensemble sampling

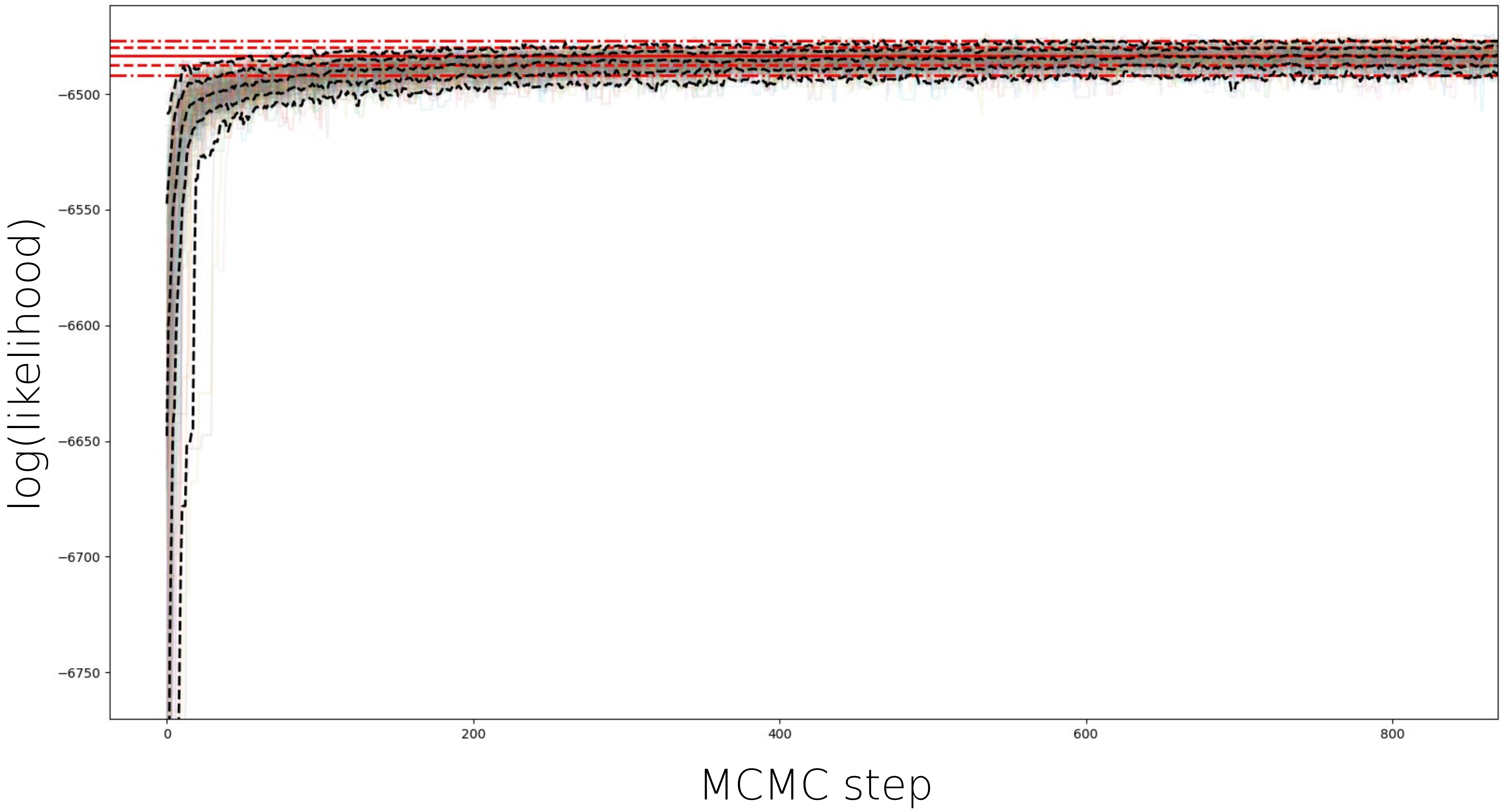


A single snapshot of walkers positions
=
A representative sample of the posterior distribution

Introducing : ECLAIR

- Written in python (2 & 3 compatible)
- Two (fairly) short files : main (~200) & parser (~500)
- Human-readable/tweakable, well-commented
- Working with any CLASS variant, no modification required
- Growing number of likelihoods/datasets implemented (easy to add new ones)
- Intuitive visualization scripts to assess convergence

Visualization tools



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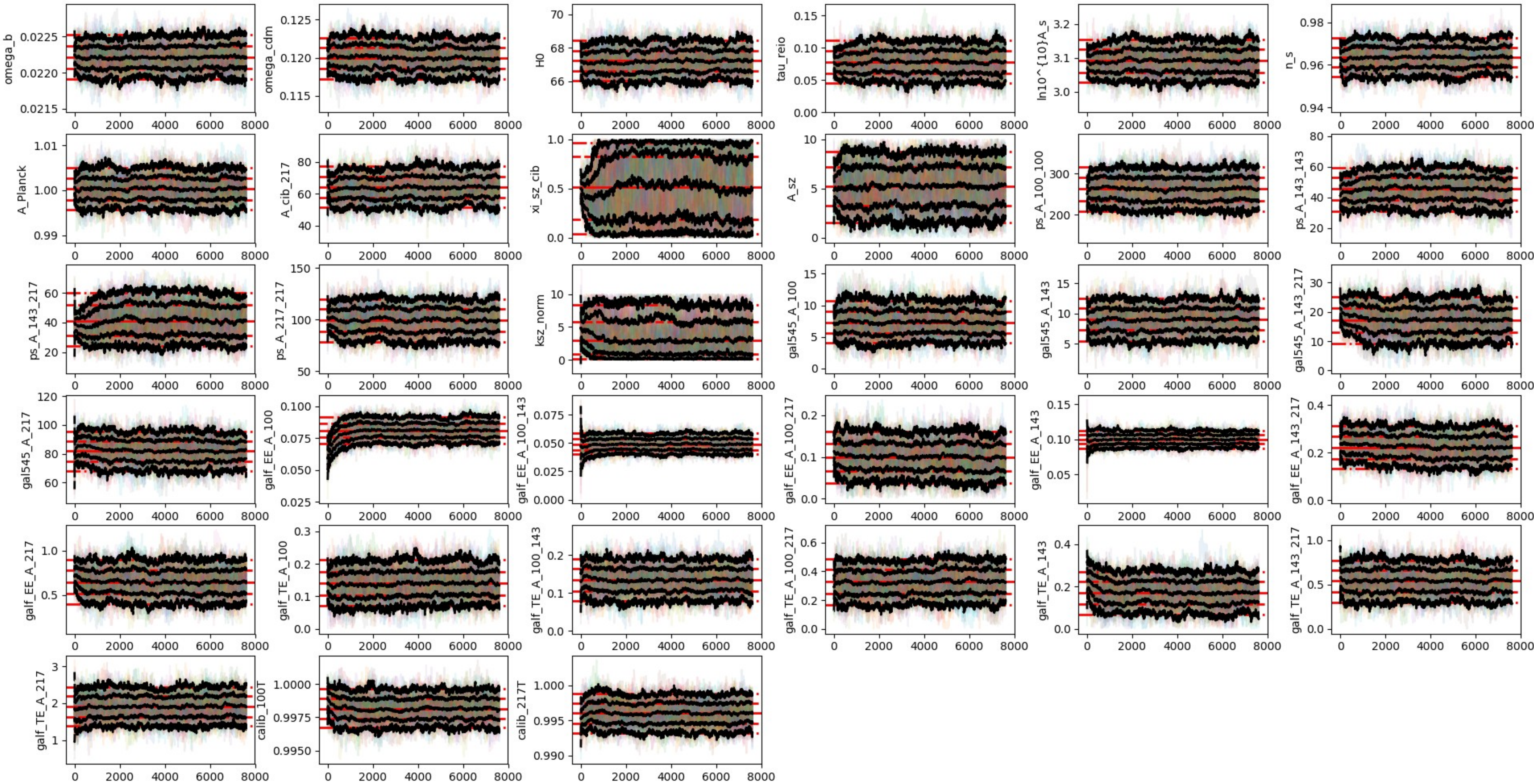

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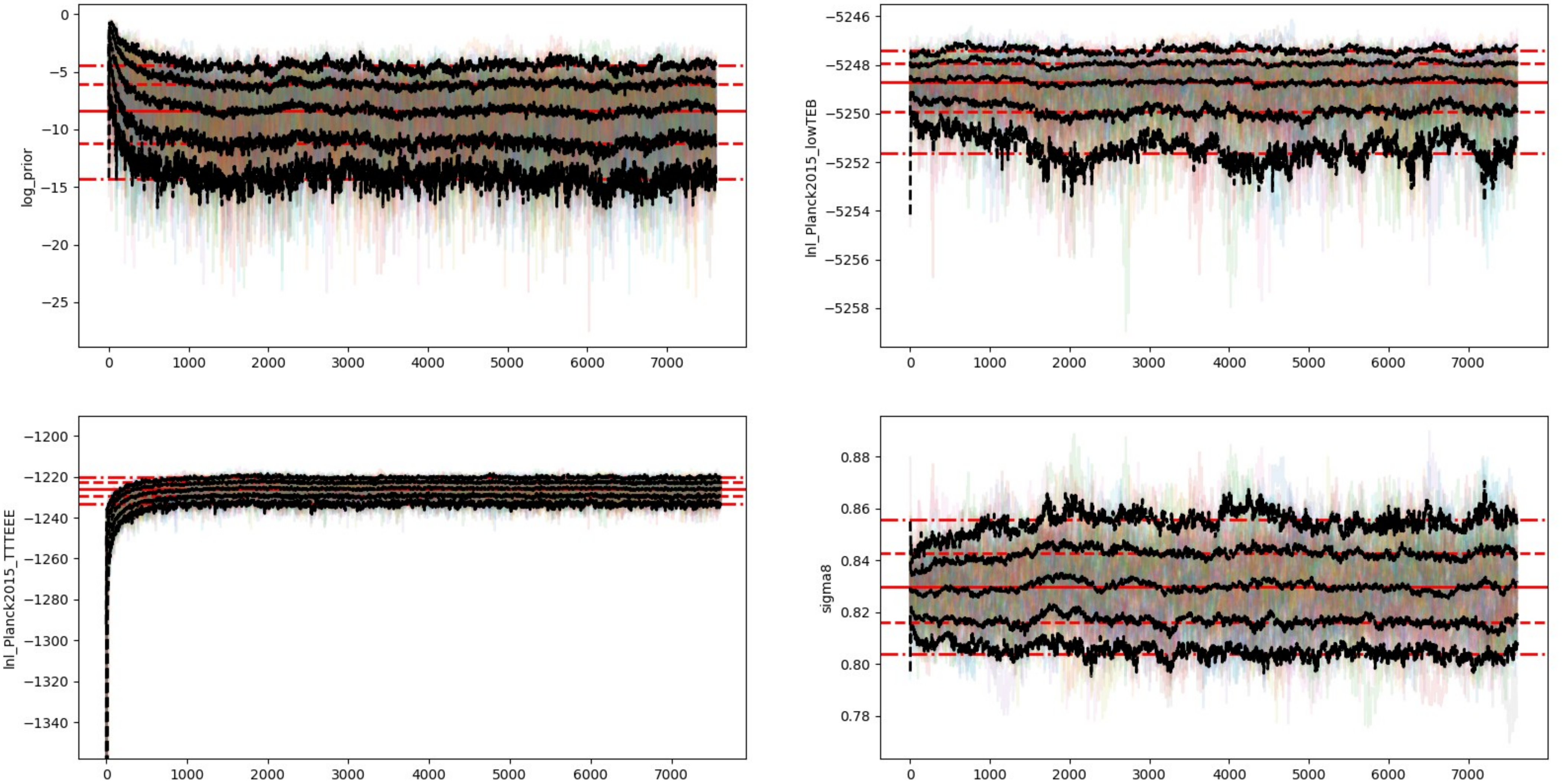

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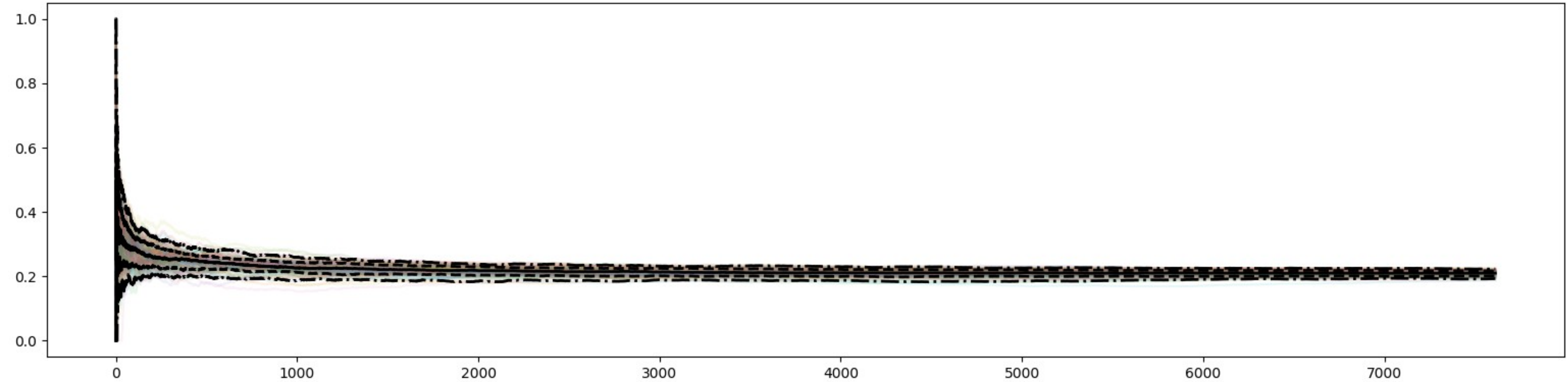

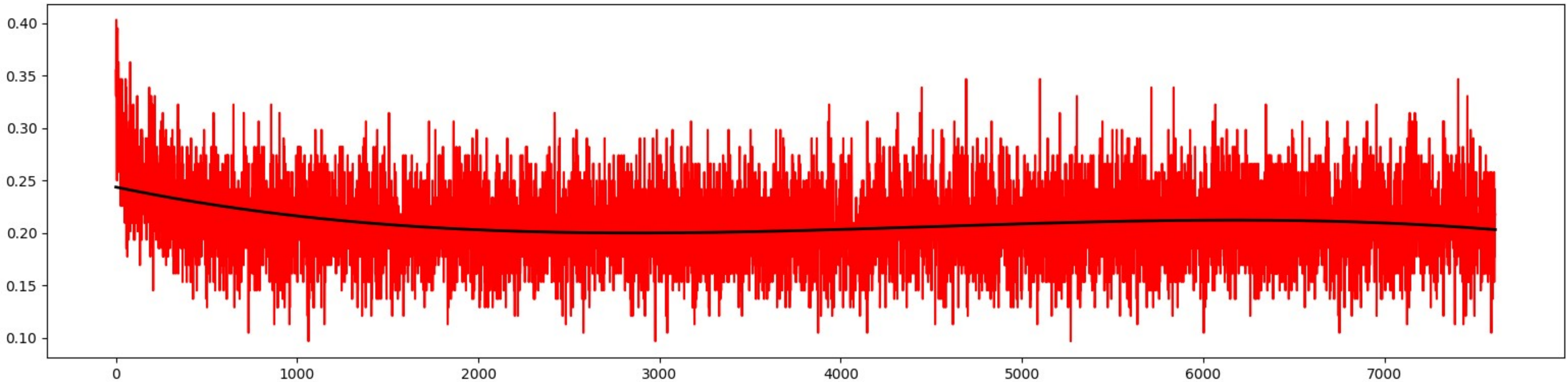

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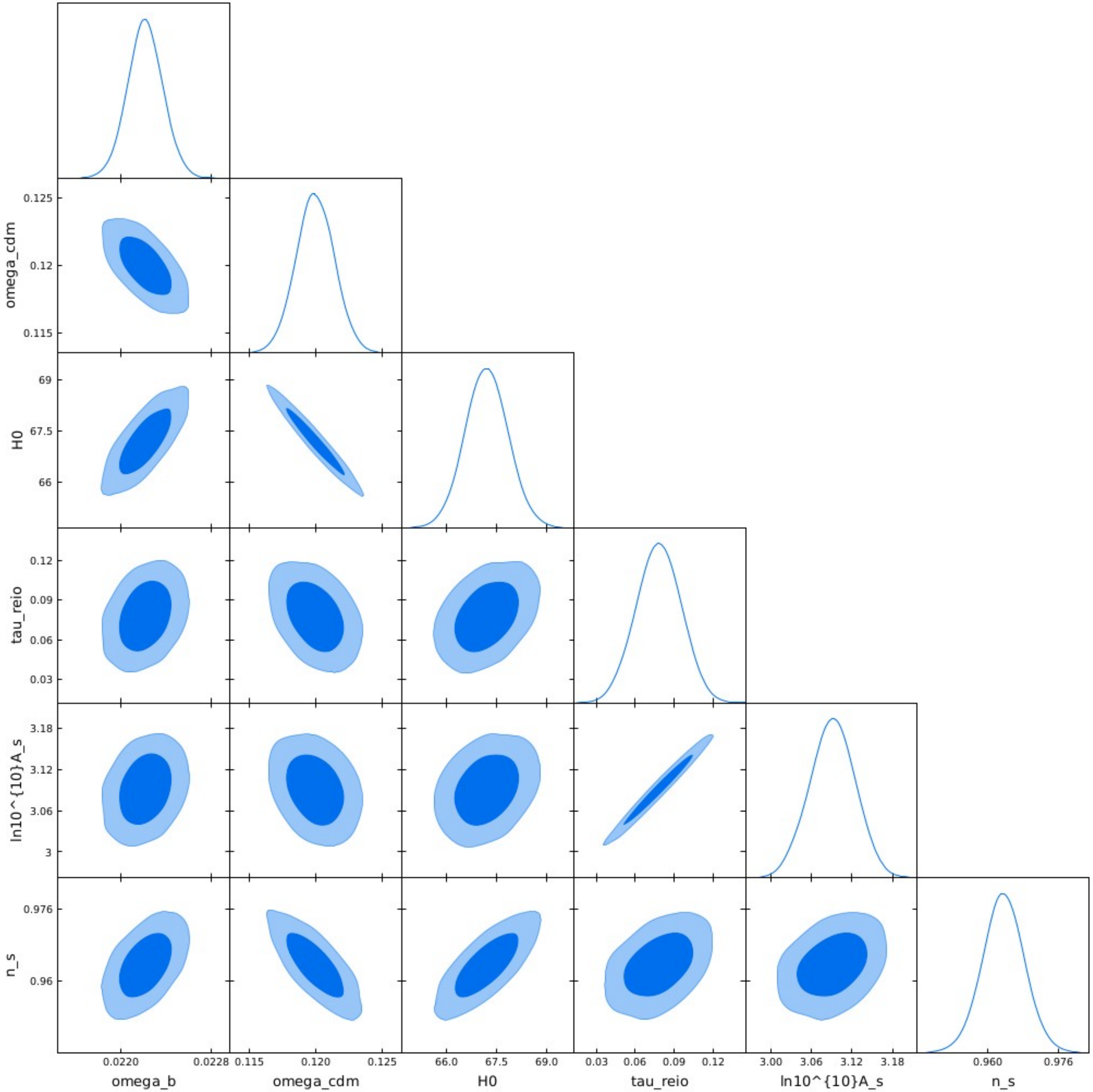
Contour plots



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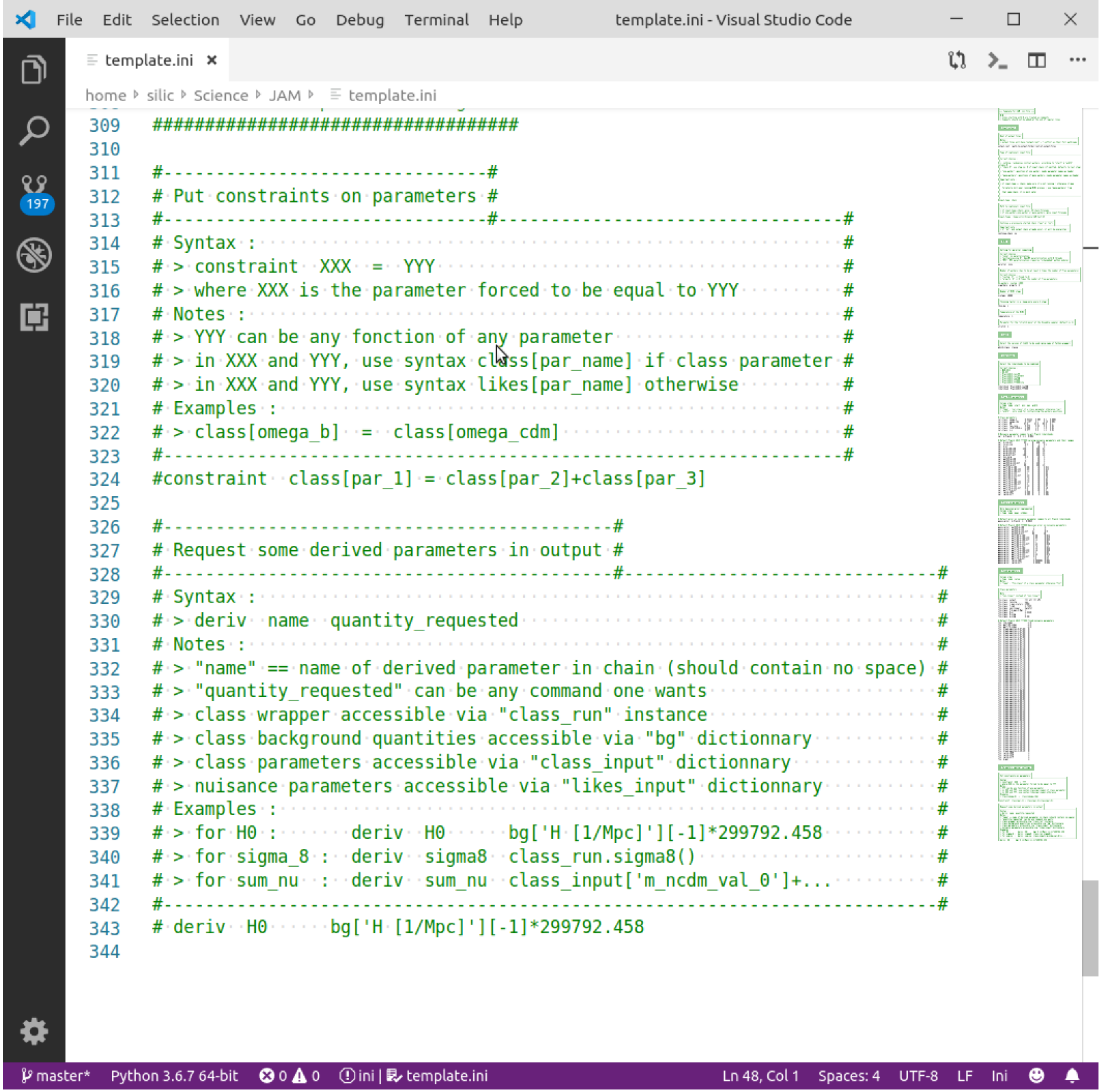
ECLAIR parsing features



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- Robust minimizer combining simulated annealing & ensemble sampling

Minimizing with ECLAIR

$$\mathcal{L} \longrightarrow \mathcal{L}^{1/T}$$

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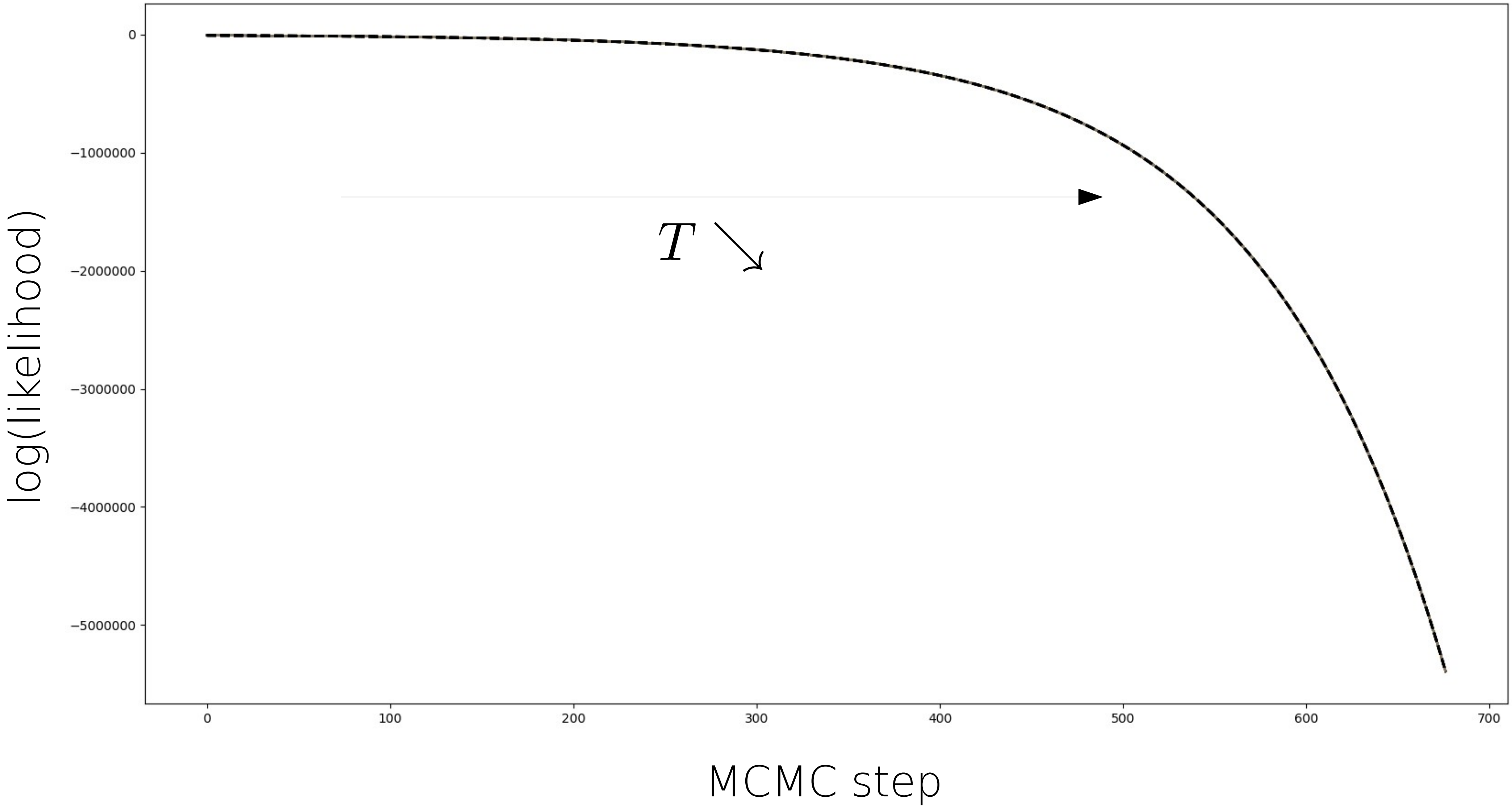
$$\mathcal{L} \longrightarrow \mathcal{L}^{1/T}$$



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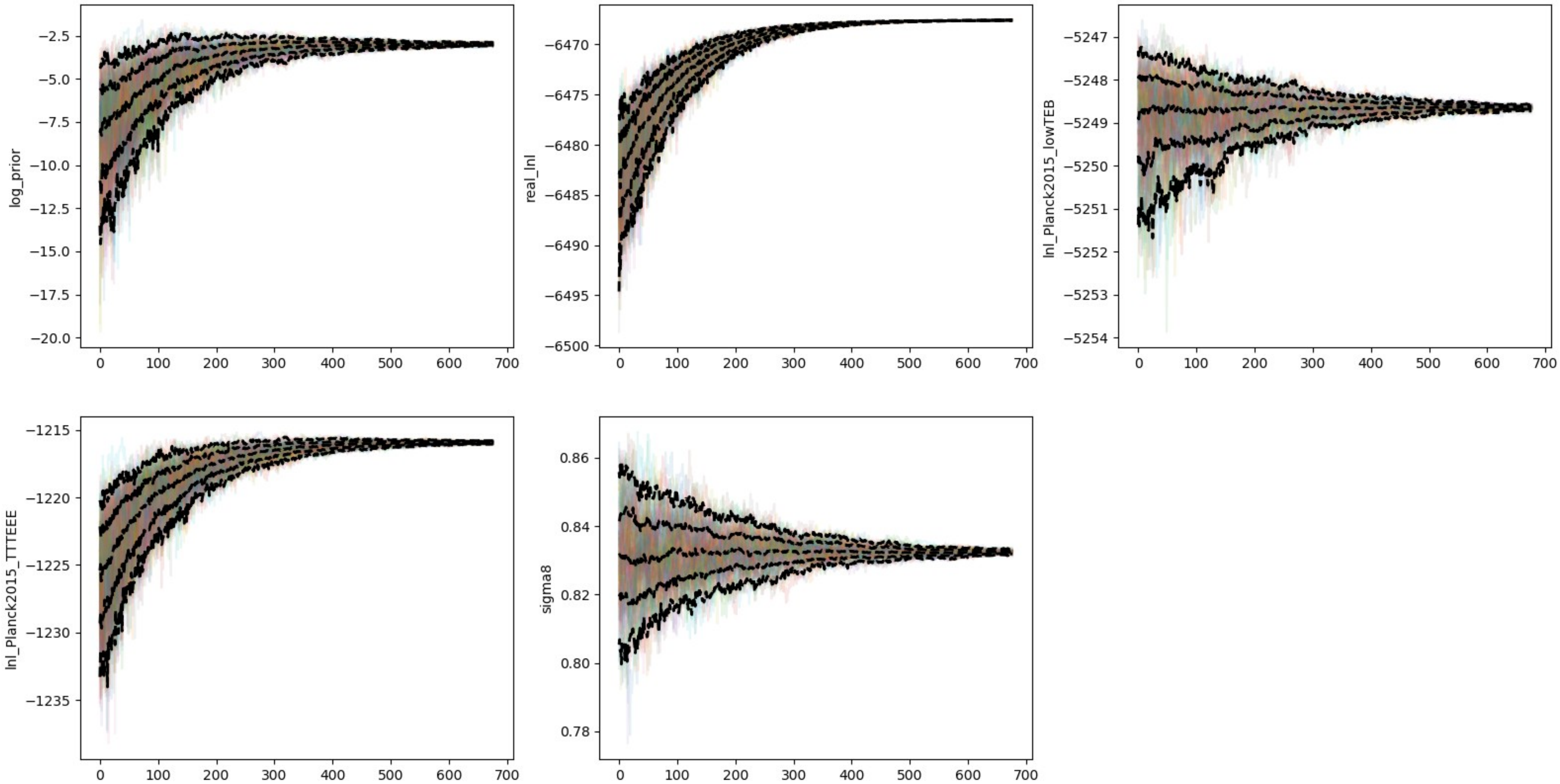

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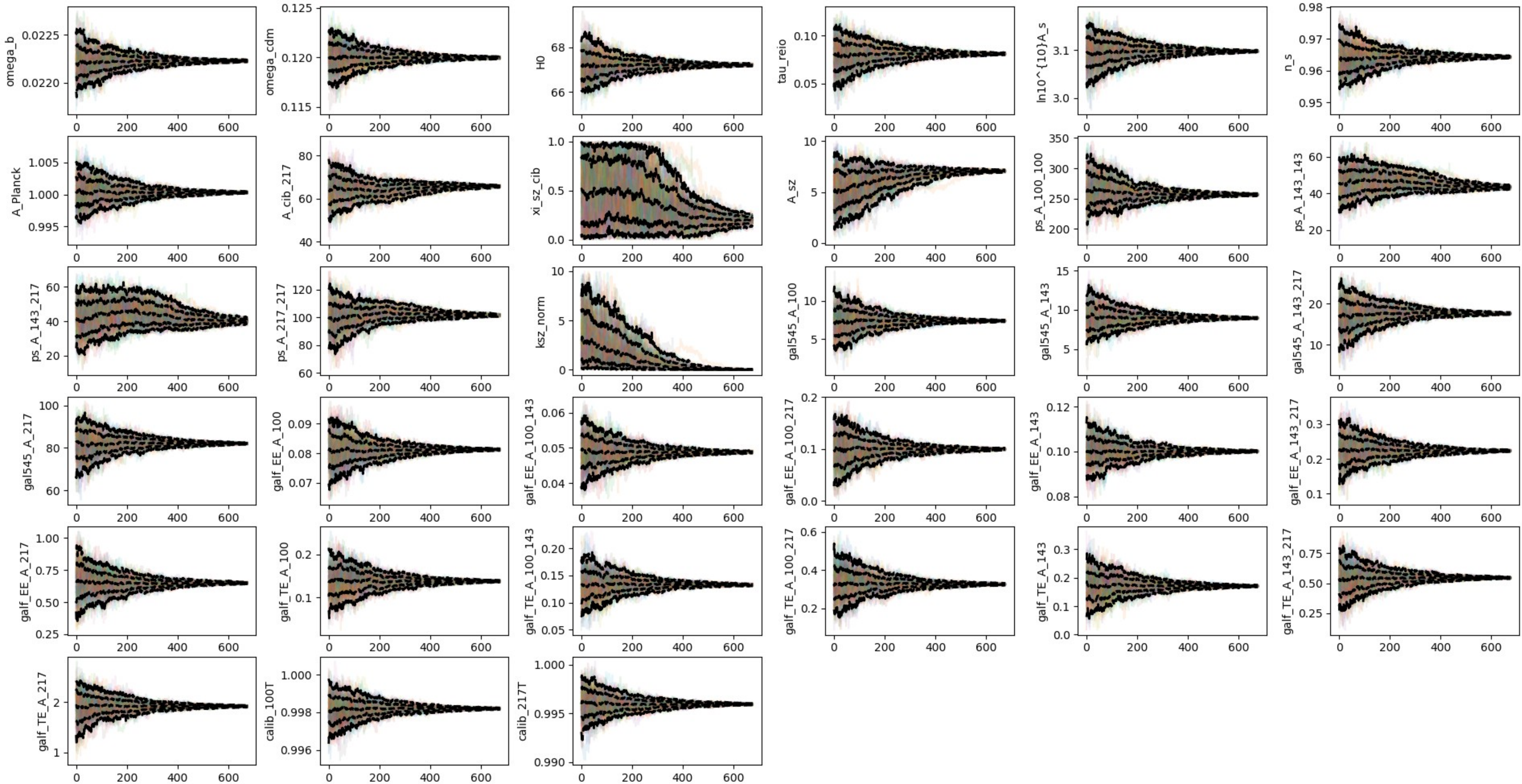

Identifying prior effects with ECLAIR

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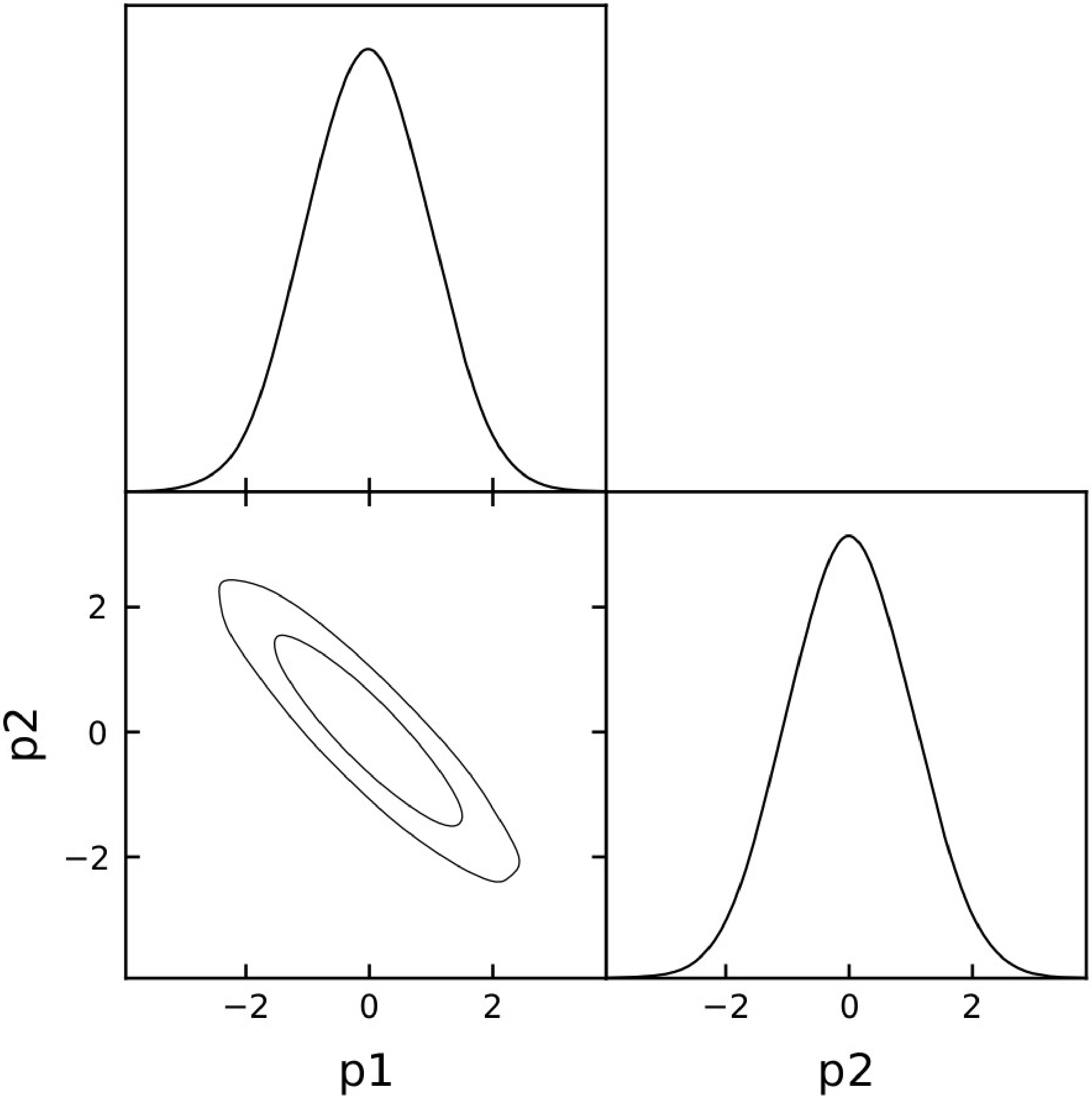

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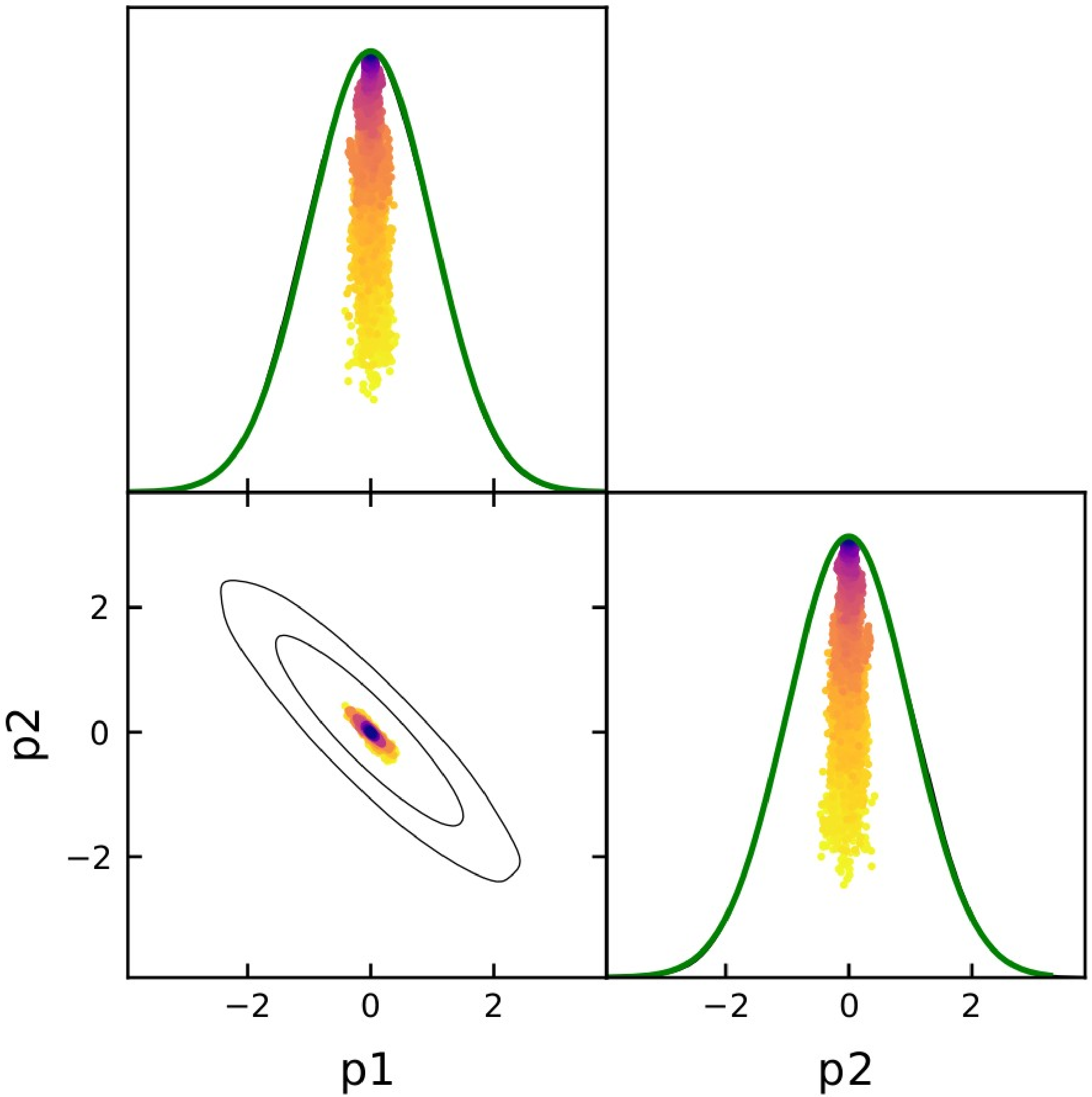

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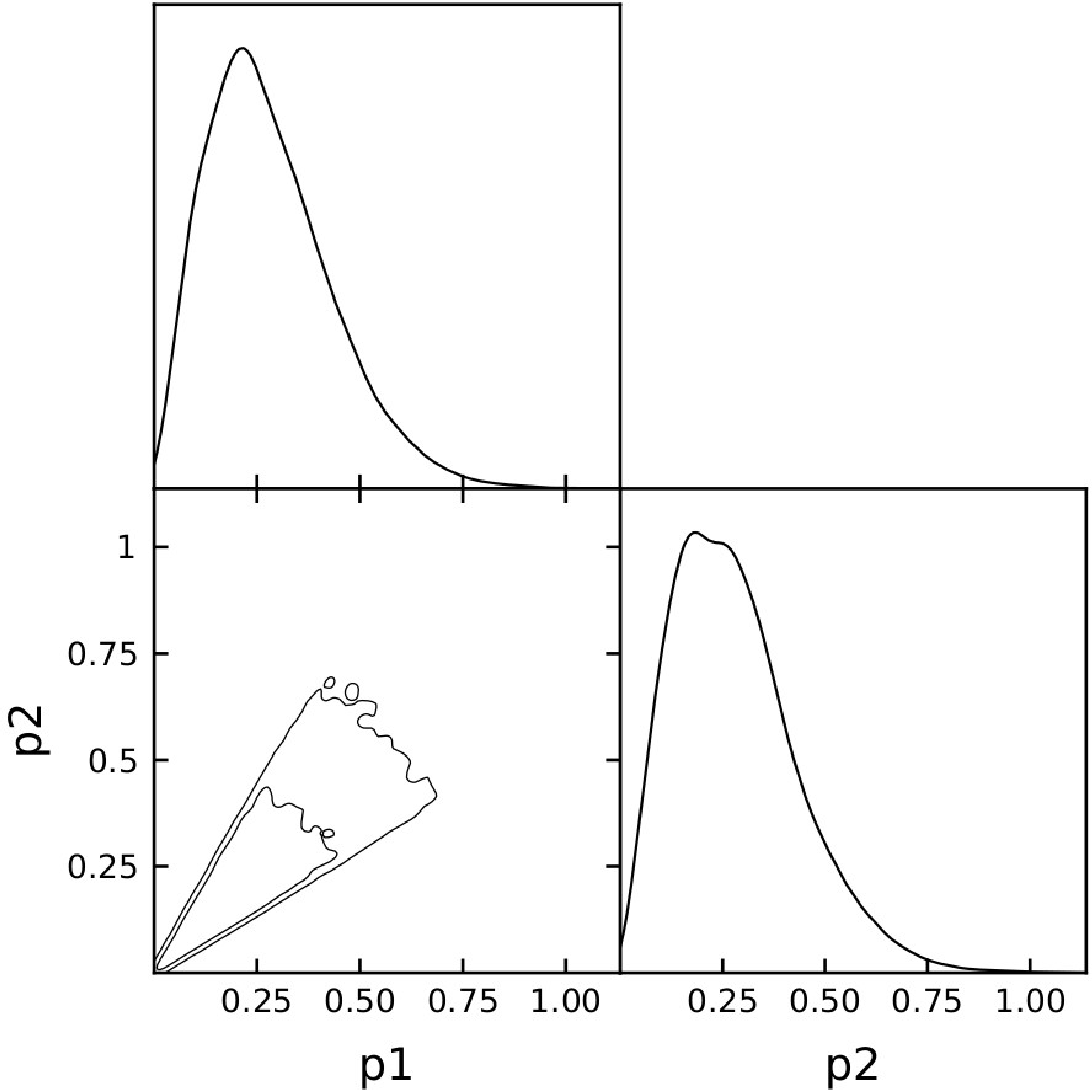

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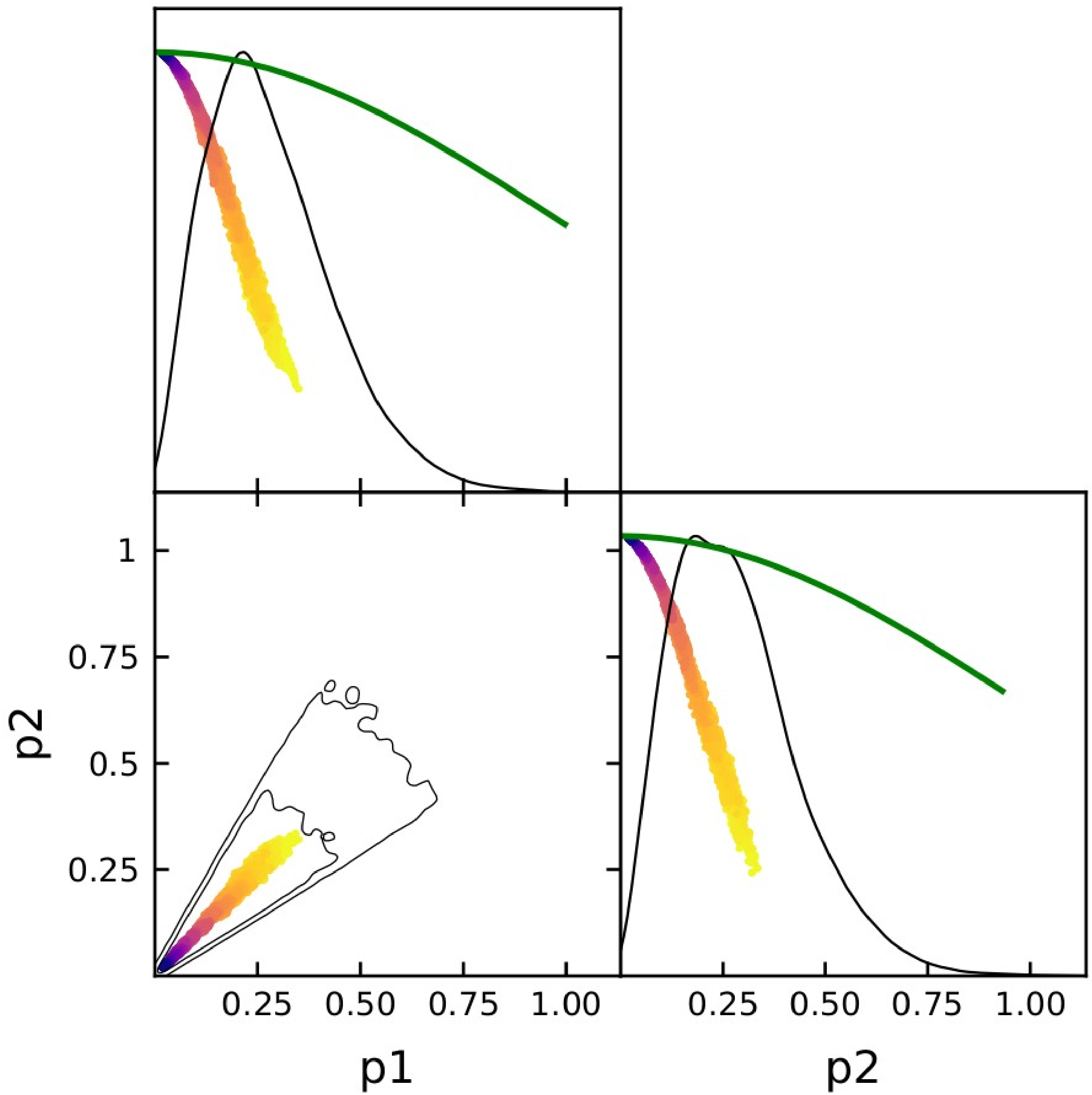

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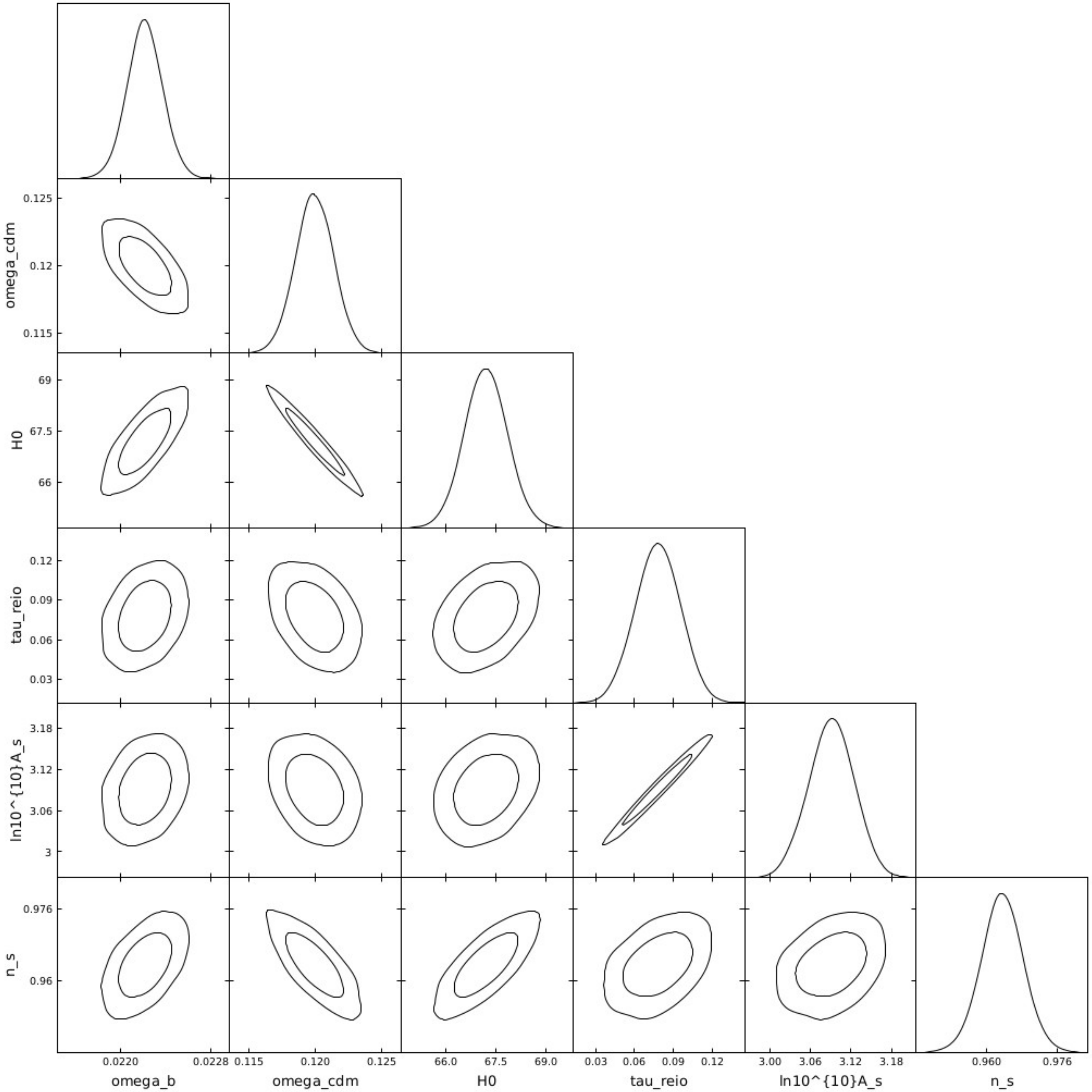

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