Baryons, Dark Matter, and Light Scalars

Takeshi Kobayashi (SISSA)

based on arXiv:1612.04824, 1708.00015
with A. De Simone, V. Iršič, S. Liberati, R. Murgia, M. Viel

YKIS 2018a, YITP

LIGHT SCALARS

- are ubiquitous in extensions of the Standard Model

e.g. QCD axion, string axiverse

Peccei, Quinn ’77 Weinberg ’78 Wilczek ’78

Svrcek, Witten ’06
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell ’09

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  may even solve the small-scale "crisis" of CDM,
  if ultralight (fuzzy) Hu, Barkana, Gruzinov '00

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Today's talk

- can generate the baryon asymmetry of the Universe

Cosmological Constraints on Ultralight Scalar DM

arXiv:1708.00015 TK, Murgia, De Simone, Iršič, Viel

PECULIAR FEATURE OF LIGHT SCALAR DM

Wave nature of the scalar field is prominent on small scales (< de Broglie wavelength).

Khlopov, Malomed, Zeldovich '85 Nambu, Sasaki '90 Ratra '91

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Klein-Gordon eq.

$$\nabla_\mu \nabla^\mu \phi = m^2 \phi$$

Einstein's eq.

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

Switching to a fluid description in a perturbed FRW universe,

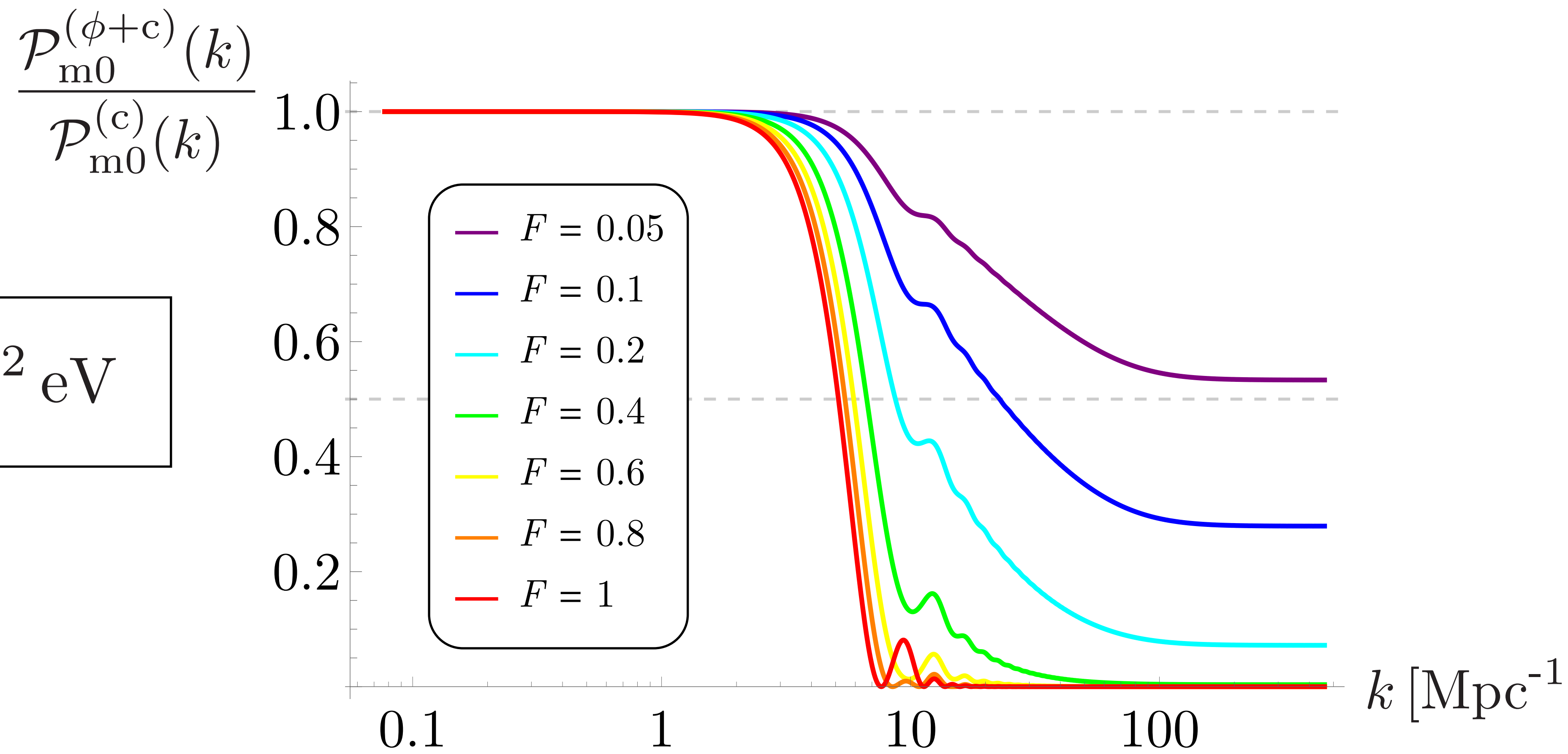
Euler eq. $$\dot{v}_i + H v_i + \frac{v_j \partial_j v_i}{a} = -\frac{\partial_i \Phi}{a} + \frac{1}{2a^3 m^2} \partial_i \left(\frac{\partial^2 \sqrt{\rho}}{\sqrt{\rho}} \right)$$

continuity eq. $$\dot{\rho} + 3H\rho + \frac{\partial_i (\rho v_i)}{a} = 0$$

Poisson eq. $$\frac{\partial^2 \Phi}{a^2} = 4\pi G \rho - \frac{3}{2} H^2$$

SUPPRESSION OF LINEAR MATTER POWER

$$m = 10^{-22}\,\mathrm{eV}$$



Ultralight scalar DM has been expected
to solve the small-scale "problems" of CDM
(e.g. missing-satellite, too-big-to-fail, core-cusp).

Hu, Barkana, Gruzinov '00 Hui, Ostriker, Tremaine, Witten '16

LYMAN-α FOREST

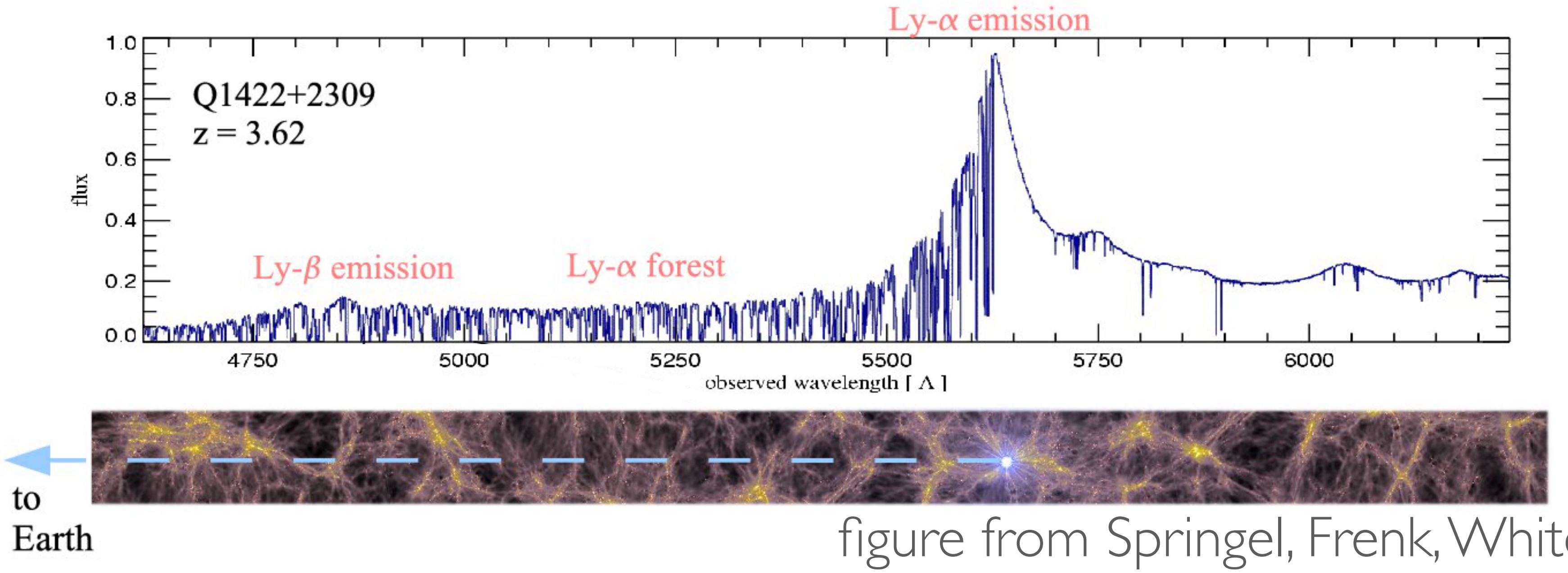


figure from Springel, Frenk, White astro-ph/0604561

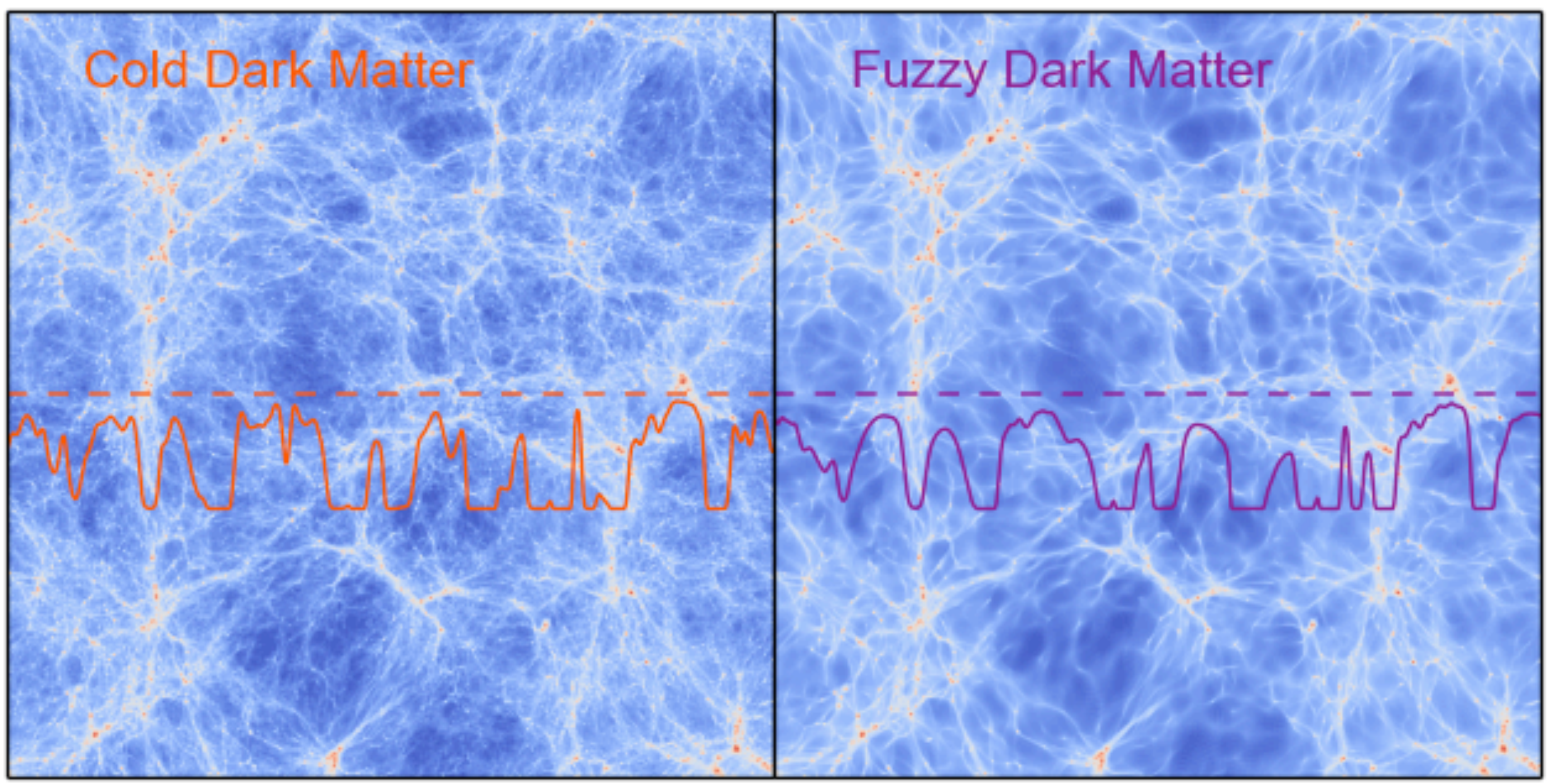
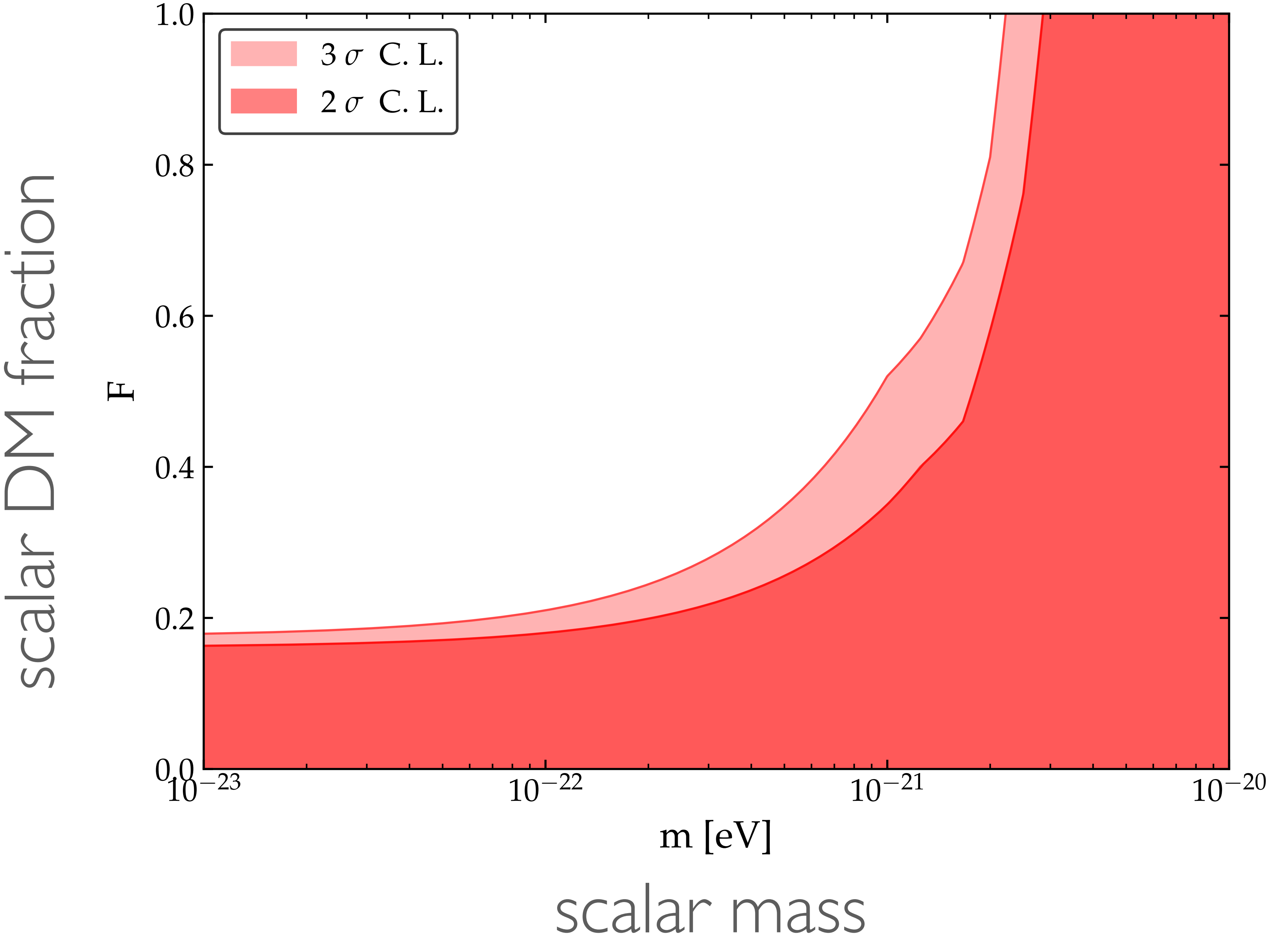


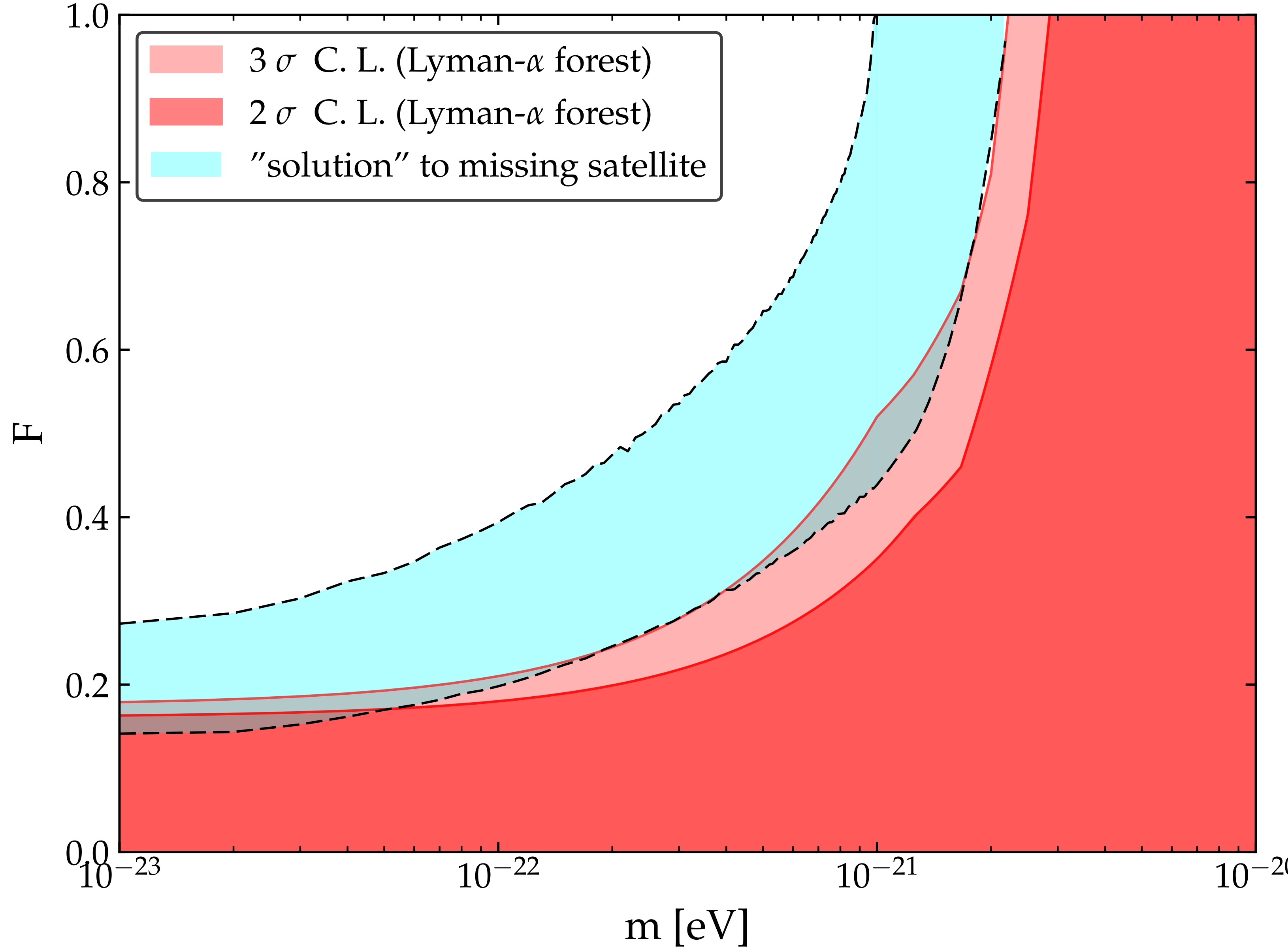
image courtesy of Vid Iršič

LYMAN-α CONSTRAINT



IMPLICATIONS FOR MISSING SATELLITES

Estimate of Milky Way satellites suggests



there is very little room for ultralight DM to solve the problem.

COMMENTS

- Further constraints from CMB and DM isocurvature perturbations

- The constraints apply to generic theories that contain ultralight scalar fields

Baryon Asymmetry from a Light Scalar: Geometric Baryogenesis

arXiv:1612.04824 Liberati, TK, De Simone

BASIC ASSUMPTIONS

- existence of a scalar with an (approximate) shift symmetry
- the scalar is allowed to couple to various fields through shift-symmetric operators

SHIFT-SYMMETRIC ACTION

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 + \phi \times \partial_\mu(\qquad) + \cdots$$

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(Gauss-Bonnet term $\mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$)

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Gravitational couplings are special in that they induce coherent effects to the scalar in an expanding universe.

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GEOMETRIC BARYOGENESIS

$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{2}(\partial\phi)^2 + \frac{\phi}{M}\mathcal{G} + \frac{\phi}{f}\nabla_\mu j^\mu_B + \underbrace{\cdots}$$

non-gravitational or mass dim. ≥ 6

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In a flat FRW universe

$$\mathcal{G} = 24(H^4 + H^2\dot{H}), \qquad \dot{\phi} = 8\frac{H^3}{M}, \qquad \frac{\phi}{f}\nabla_\mu j_B^\mu = -\frac{\dot{\phi}}{f}n_B$$

→ relative shift in baryon/antibaryon spectra

→ baryogenesis even in equilibrium
(due to CPT violation)

Cohen, Kaplan '87

$$\frac{n_B}{s} \sim \frac{T^5}{fMM_p^3}$$

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In a flat FRW universe

spontaneous breaking of Lorentz invariance due to cosmic expansion $\overset{\phi}{\dashrightarrow}$ baryon asymmetry

(due to CPT violation)

Cohen, Kaplan '87

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GEOMETRIC BARYOGENESIS WITH AN ULTRALIGHT SCALAR

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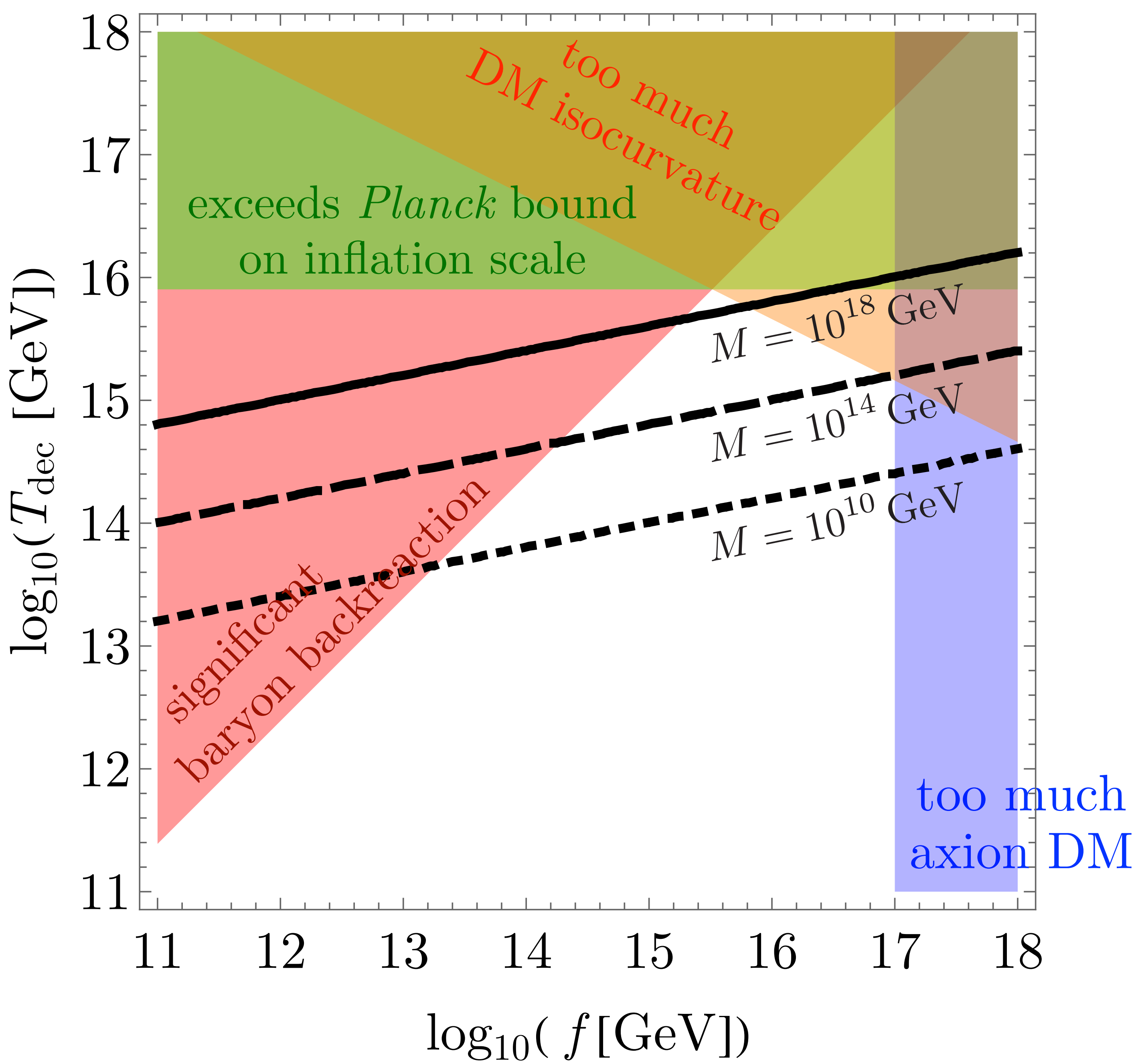

e.g., $m = 10^{-22}\,\mathrm{eV}$

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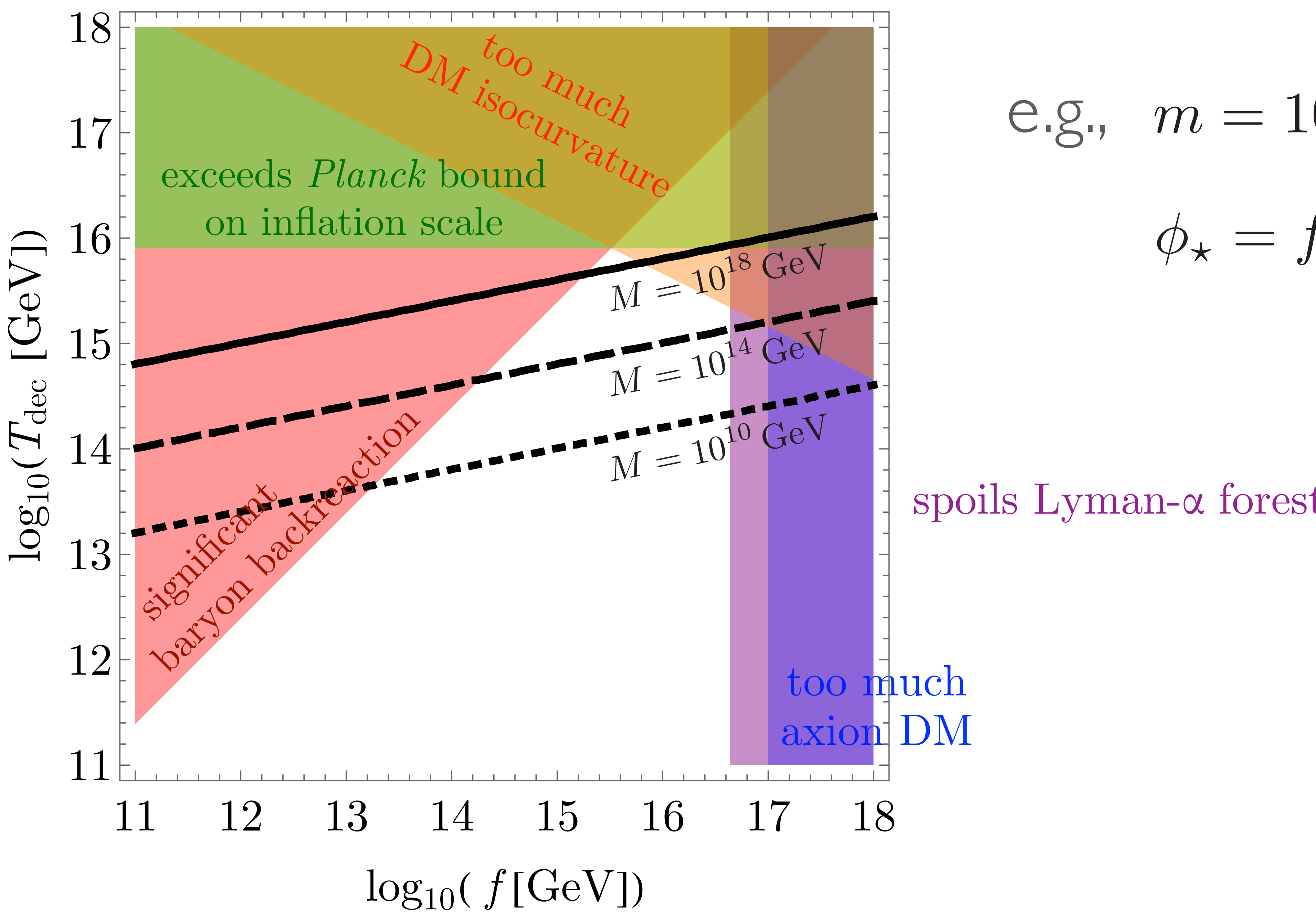

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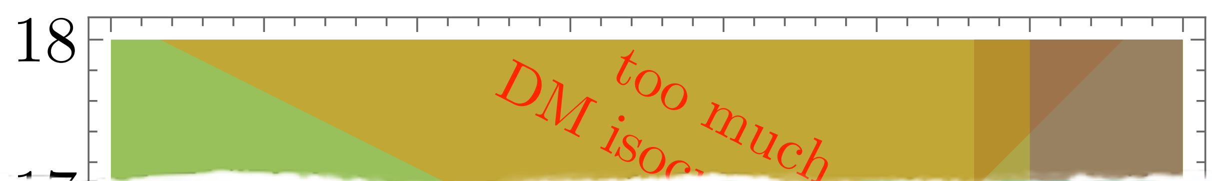

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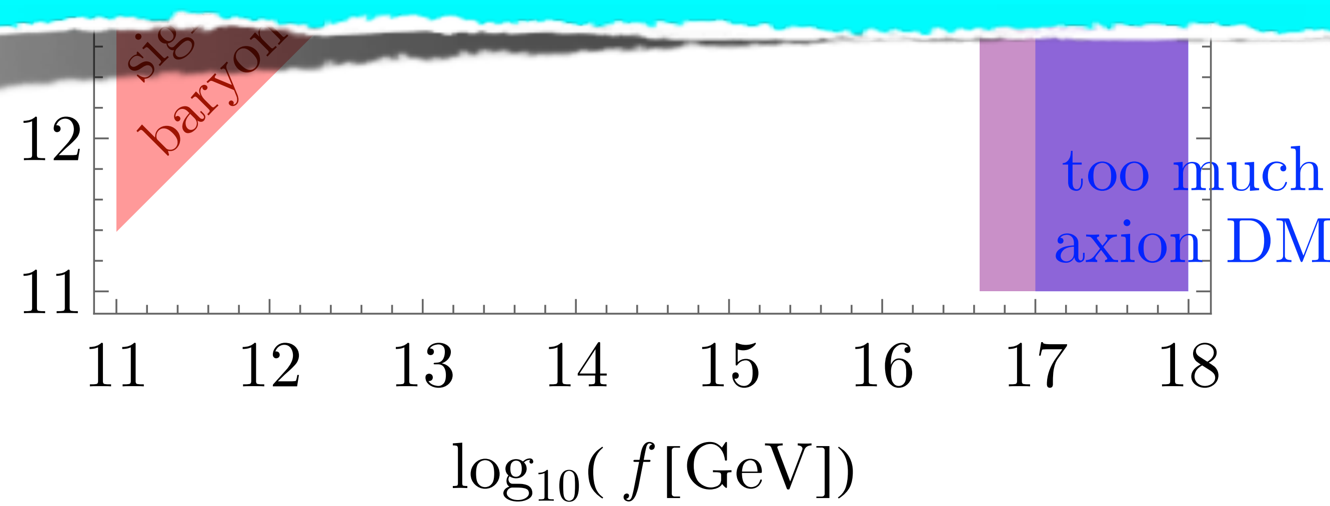
Alternatively, geometric baryogenesis can also be driven by the QCD axion!



SUMMARY

- Light scalars, if present in the theory, have significant impact in cosmology

- CANNOT solve the small-scale issues without spoiling the Lyman-α forest

- CAN generate the baryon asymmetry of our Universe!