# What if dark matter suddenly disappeared?

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Based on
**arXiv:1803.03644** in collaboration with Torsten Bringmann, Kai Schmidt-Hoberg and Parampreet Walia

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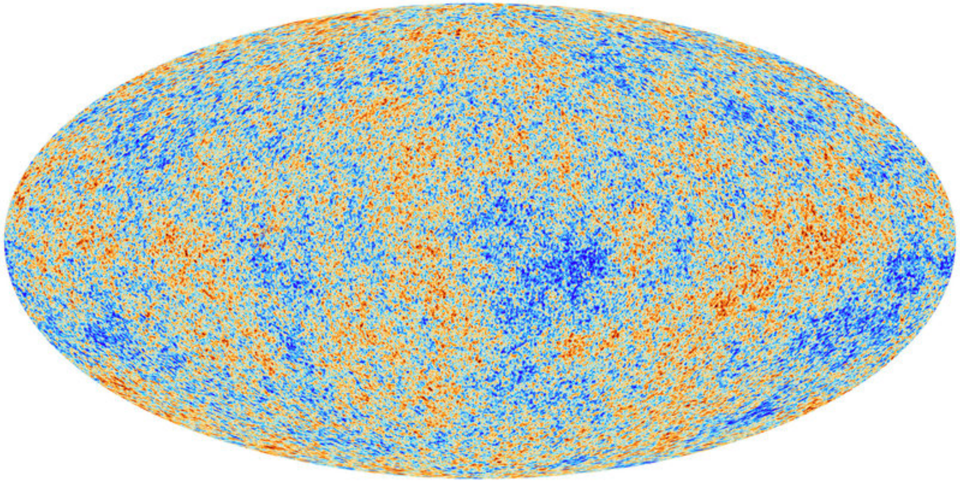
# Outline

- Part 1: Conversion of dark matter to dark radiation
  - Motivation for a model-independent approach
  - Constraints from the Cosmic Microwave Background
  - Intermezzo: Bayesian vs frequentist limits
  - Impact of low-redshift observables

- Part 2: Sommerfeld-enhanced dark matter annihilations
  - Dark matter models with light mediators
  - Cosmological constraints on late-time annihilations
  - Self-interactions and small-scale structure

# Describing dark matter in the early Universe

- Cosmological concordance model: Dark matter is a non-relativistic fluid with covariantly conserved number density
- Abundance of DM is set at some very high temperature (e.g. via thermal freeze-out) and then remains unchanged
- Fully described by a single parameter (e.g. the present-day energy density)
- Precisely measured by observations of the Cosmic Microwave Background

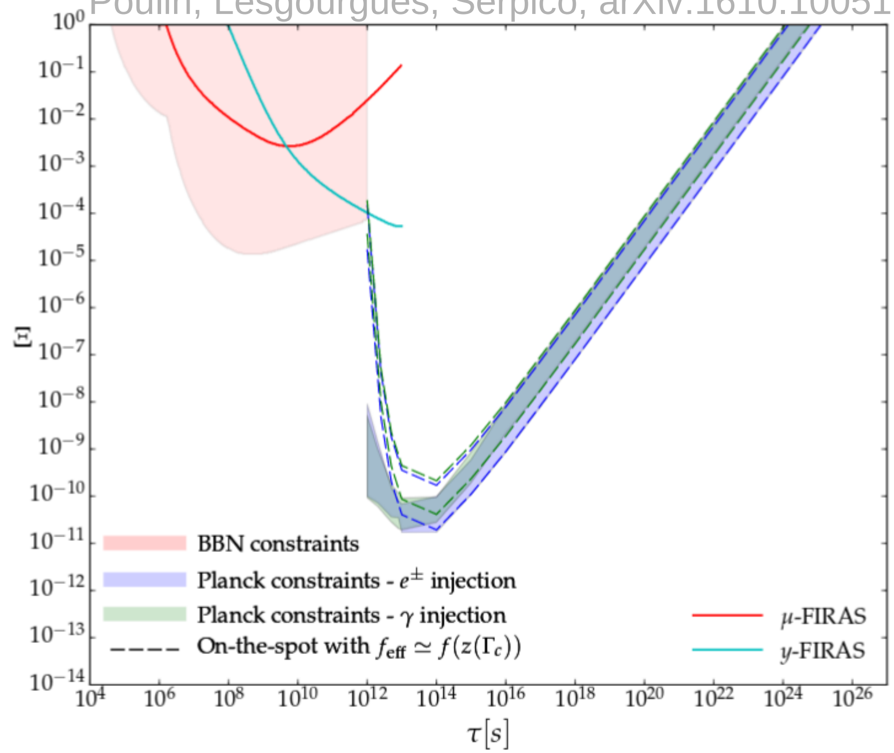


- Like any other assumption, this should be tested!
- How strong are constraints on alternative cosmologies, where the comoving DM density changes with time?

# Disappearing dark matter

- Of course, DM cannot simply disappear (apologies for the misleading title)!
- Energy conservation requires that any decrease in DM must be compensated by an increase in another form of matter or radiation
- Converting DM into SM particles is typically very strongly constrained
  - CMB bounds on exotic energy injection
  - Bounds on CMB spectral distortions
  - BBN constraints on energetic radiation
- But what if DM converted to something invisible (e.g. sterile neutrinos)?

Poulin, Lesgourgues, Serpico, arXiv:1610.10051



# Disappearing dark matter

- Simplest example: An unstable DM subcomponent — Lattanzi & Valle, arXiv:0705.2406
  - Unstable component "disappears" when its decay rate becomes comparable to Hubble rate
  - Simple model, but highly non-trivial effect on the expansion history of the Universe

Enqvist et al., arXiv:1505.05511

Berezhiani, Dolgov, Tkachev, arXiv:1505.03644

- Other possibilities
  - Late-time DM annihilations due to Sommerfeld enhancement (see 2nd half of talk)

van den Aarssen et al., arXiv:1202.5456

Binder et al., arXiv:1712.01246

  - Mergers of primordial black holes (conversion of dark matter into gravitational waves)

Raidal, Vaskonen, Veermäe, arXiv:1707.01480

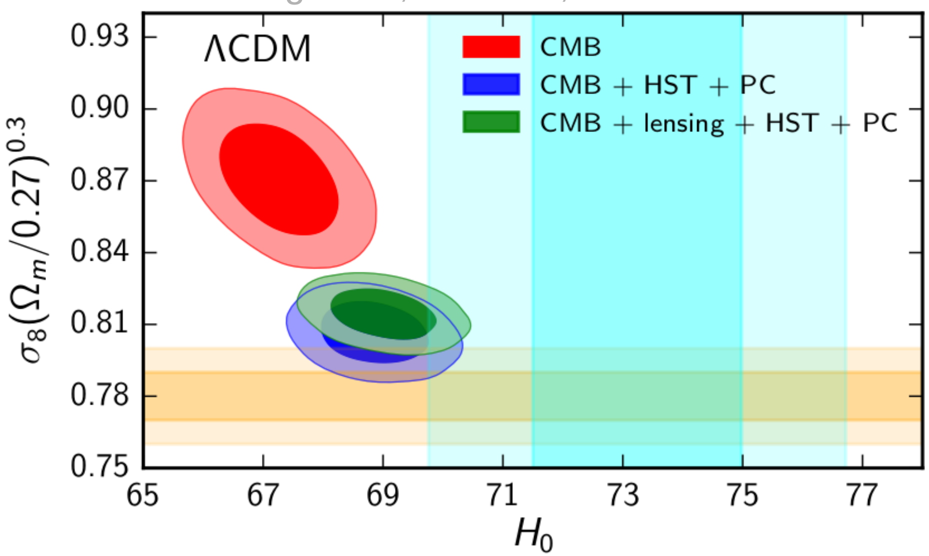
- Why is this interesting?
  - Various hints indicate that the concordance model may be incomplete!

# Crisis at large scales

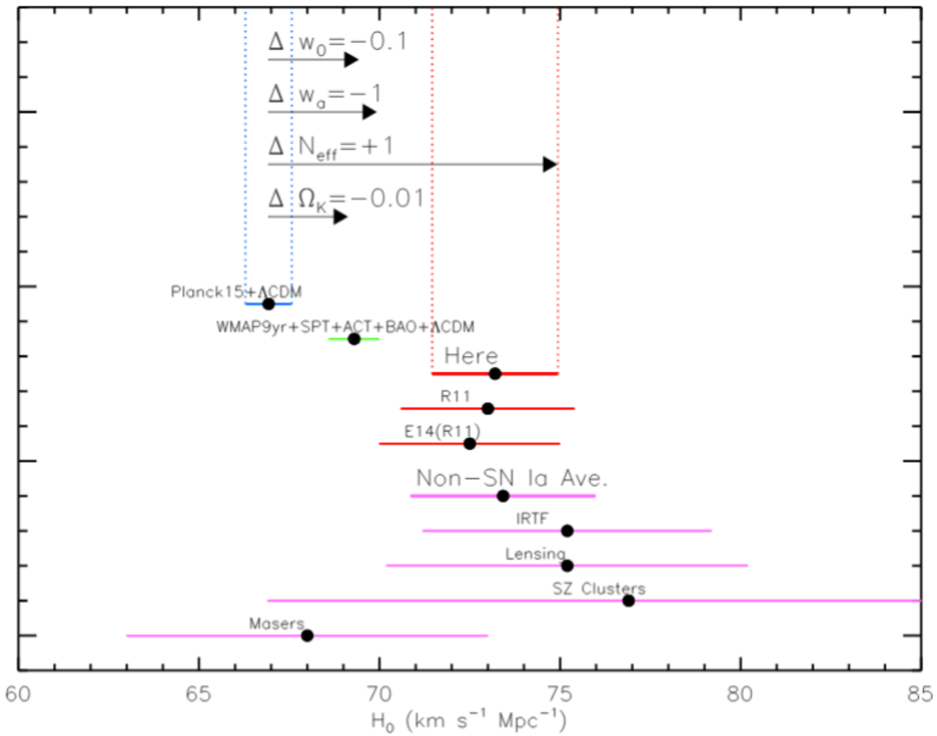
- Local (i.e. low-redshift) measurements of the expansion rate $H_0$ disagree with the value inferred from the CMB

- A similar discrepancy is found in local measurements of the amplitude of the matter power spectrum (parametrised by $\sigma_8$)

Bringmann, FK et al., arXiv:1803.03644



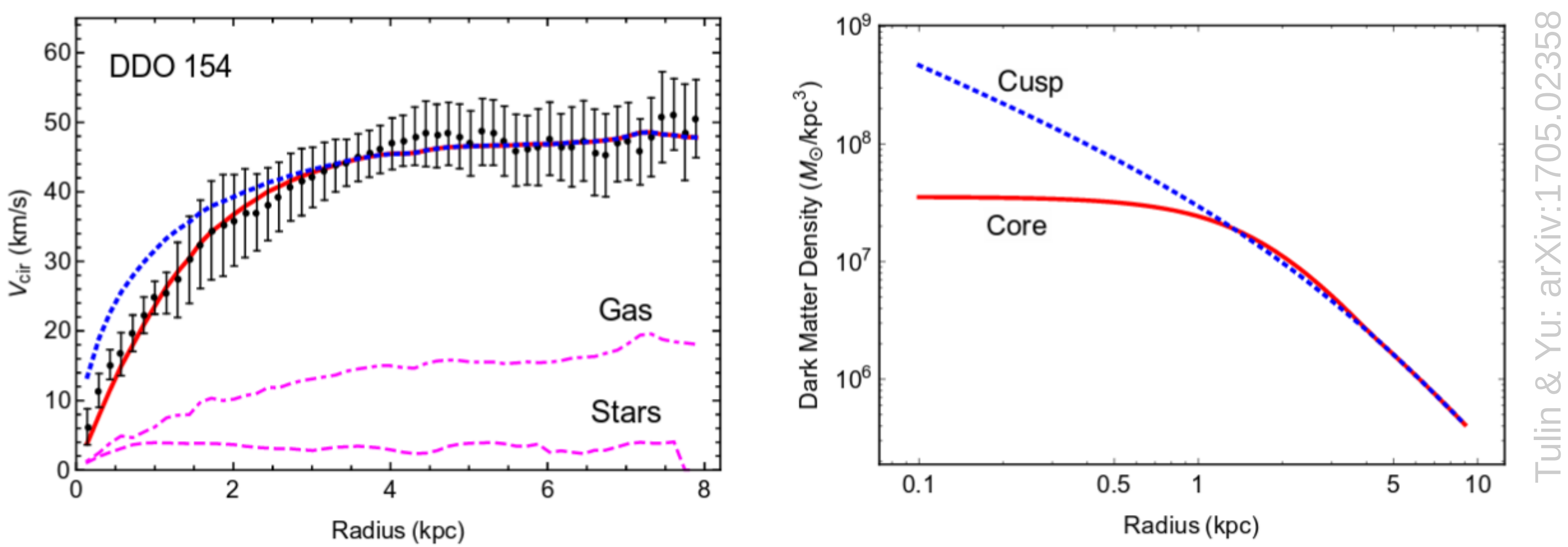

Riess et al., arXiv:1604.01424




- The tension between different data sets leads to a poor goodness-of-fit when performing a naive combination

# Crisis at small scales

- There are various discrepancies between N-body simulations of collisionless cold DM and astrophysical observations on galactic scales:
  - Too-big-to-fail problem — Boylan-Kolchin, Bullock, Kaplinghat: 1103.0007, 1111.2048
  - Missing-satellites problem — Klypin et al.: astro-ph/9901240; Moore et al.: astro-ph/9907411
  - Cusp-vs-core problem — Moore (1994); Flores, Primack: astro-ph/9402004
  - Diversity problem — Tulin & Yu: arXiv:1705.02358



# A simple question

Could (a fraction of) DM have been converted into some form of dark radiation* (DR) at some point during the cosmological evolution?

And if so, can this address the apparent shortcomings of the concordance model?

* By DR we mean new massless or very light states in the dark sector (e.g. sterile neutrinos), which are have negligible interactions with SM particles

# Describing DM-DR conversion

- Focus on scenarios where the conversion rate peaks at a specific point in time
- Adopt a model-independent approach, where the conversion is described by three parameters:
  - How much DM is converted into DR?
  - When does the conversion happen?
  - How quickly does the conversion happen?

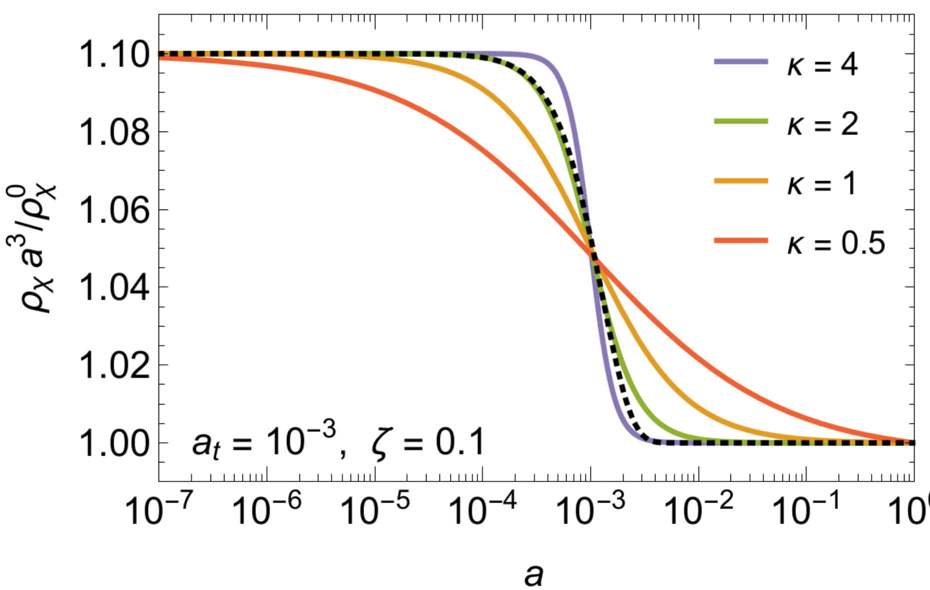
# Describing DM-DR conversion

- Focus on scenarios where the conversion rate peaks at a specific point in time

- Adopt a model-independent approach, where the conversion is described by three parameters:
  - How much DM is converted into DR? Fraction of converted DM: $\zeta$
  - When does the conversion happen? Scale factor at transition: $a_t$
  - How quickly does the conversion happen? Transition slope parameter: $\kappa$

$$\rho_\chi(a) = \frac{\rho_\chi^0}{a^3}\left[1 + \zeta \frac{1 - a^\kappa}{1 + (a/a_t)^\kappa}\right]$$

- $\rho_x$ : Dark matter energy density
- $a$ : Scale factor
- $\rho_x^0$ : Present-day dark matter density



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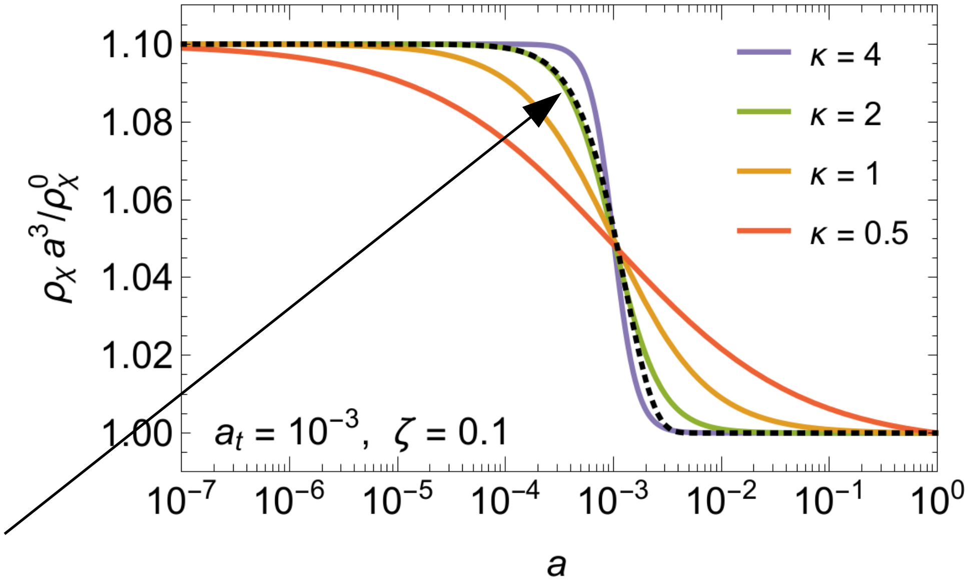
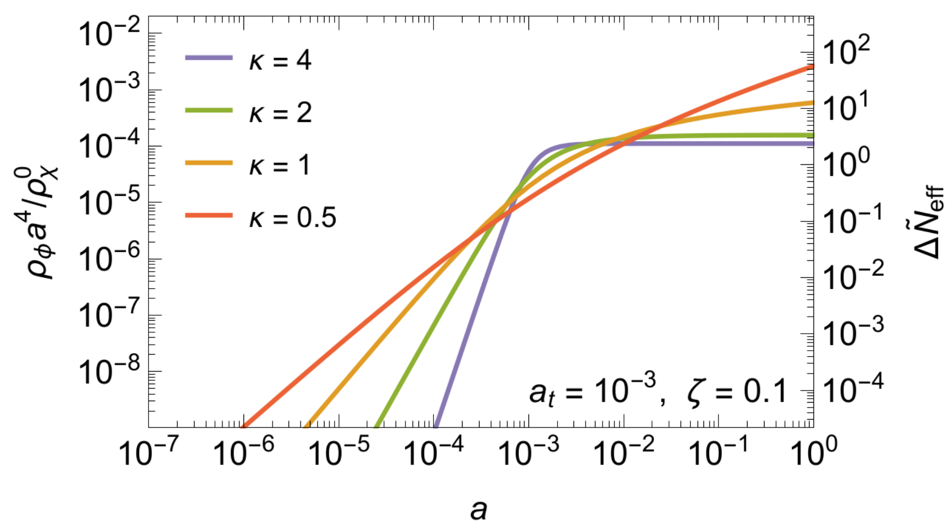
Decaying DM sub-component ($\kappa$ ~ 2)



# Evolution of dark radiation

- Any decrease in the DM density must be compensated by an increase in DR

$$\frac{1}{a^3}\frac{\mathrm{d}}{\mathrm{d}t}\left(a^3\rho_\chi\right) = -\frac{1}{a^4}\frac{\mathrm{d}}{\mathrm{d}t}\left(a^4\rho_\phi\right)$$




- Leads to a time-dependent effective number of additional neutrino species

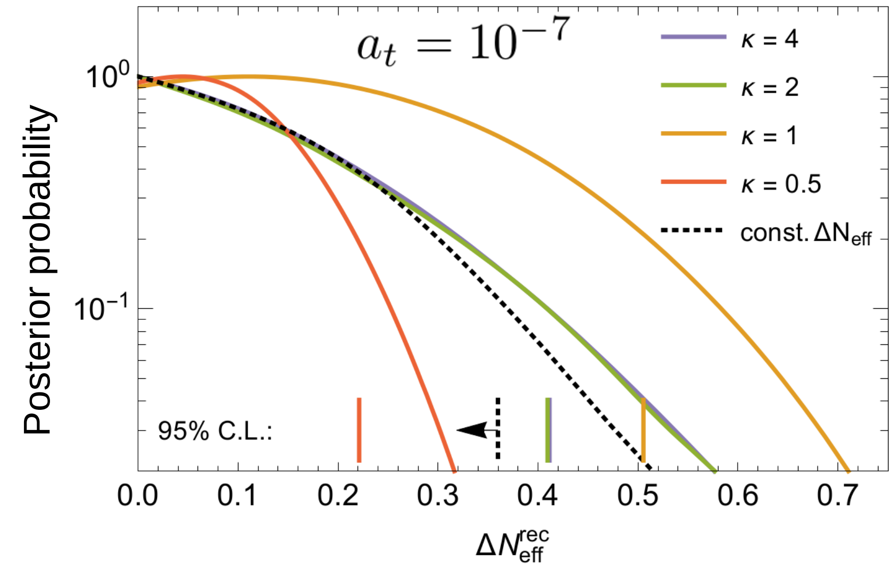
$$\Delta\tilde{N}_{\mathrm{eff}}(a) \equiv \frac{\rho_\phi(a)}{\rho_{1\nu}(a)} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\phi(a)}{\rho_\gamma(a)}$$

- Important subtlety: Evolution of background densities does not uniquely fix the evolution of perturbations
  - No completely model-independent treatment possible
  - We assume that perturbations arise only from volume expansion (as for decaying DM)
  - Alternative prescriptions do not significantly change results

# A few preliminary considerations

- For a quick transition (κ ≥ 2) the comoving DR density becomes constant for $a > a_t$

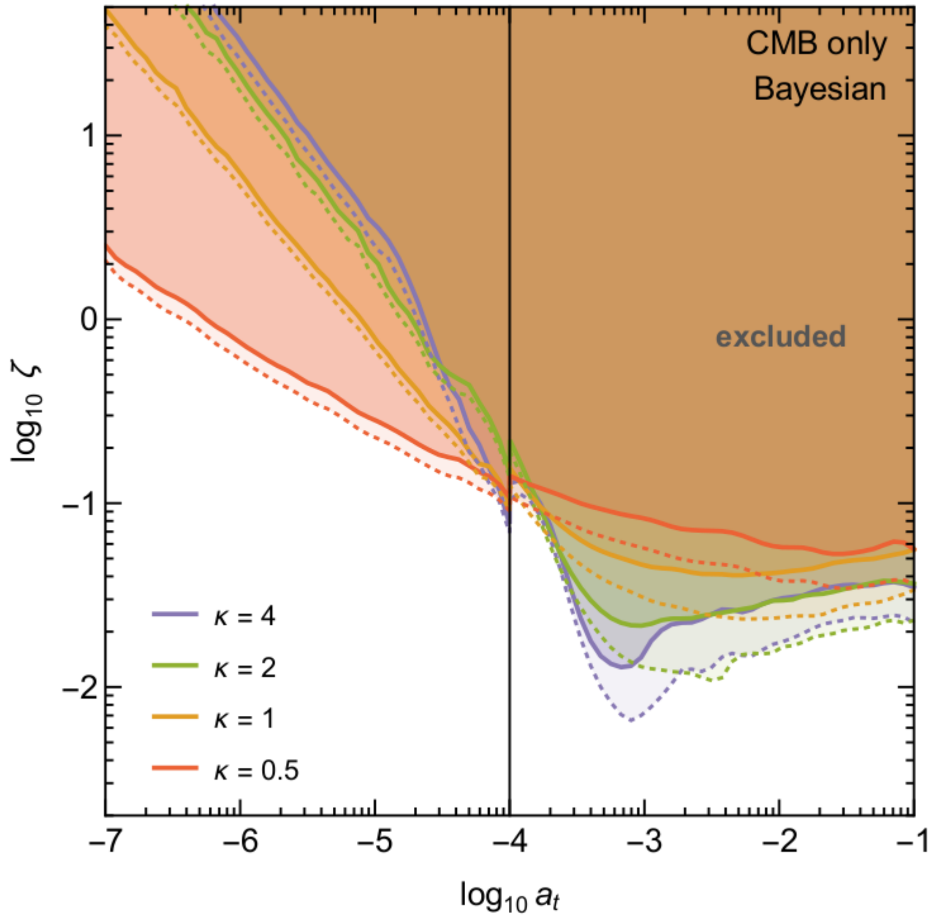
- If such a transition happens well before matter-radiation equality ($a_t < 10^{-4}$), our conversion scenario becomes equivalent to having a constant amount of DR
  - Recover ΛCDM + $\Delta N_{eff}$ cosmology



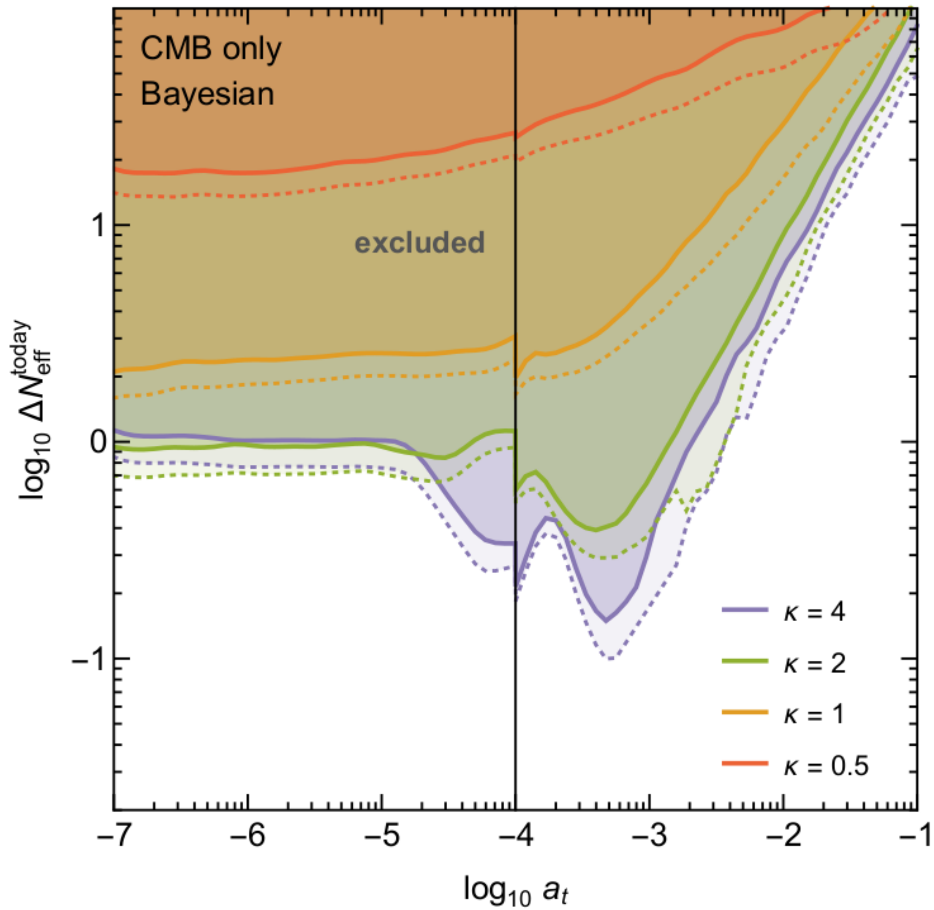

- If the transition happens more slowly (or peaks at later times), there is no simple way to estimate constraints
  - Need a full calculation of CMB observables using CosmoMC and CAMB, including all ΛCDM parameters as well as Planck nuisance parameters

# Results

Constraint on the fraction of converted DM




Constraint on the amount of produced DR



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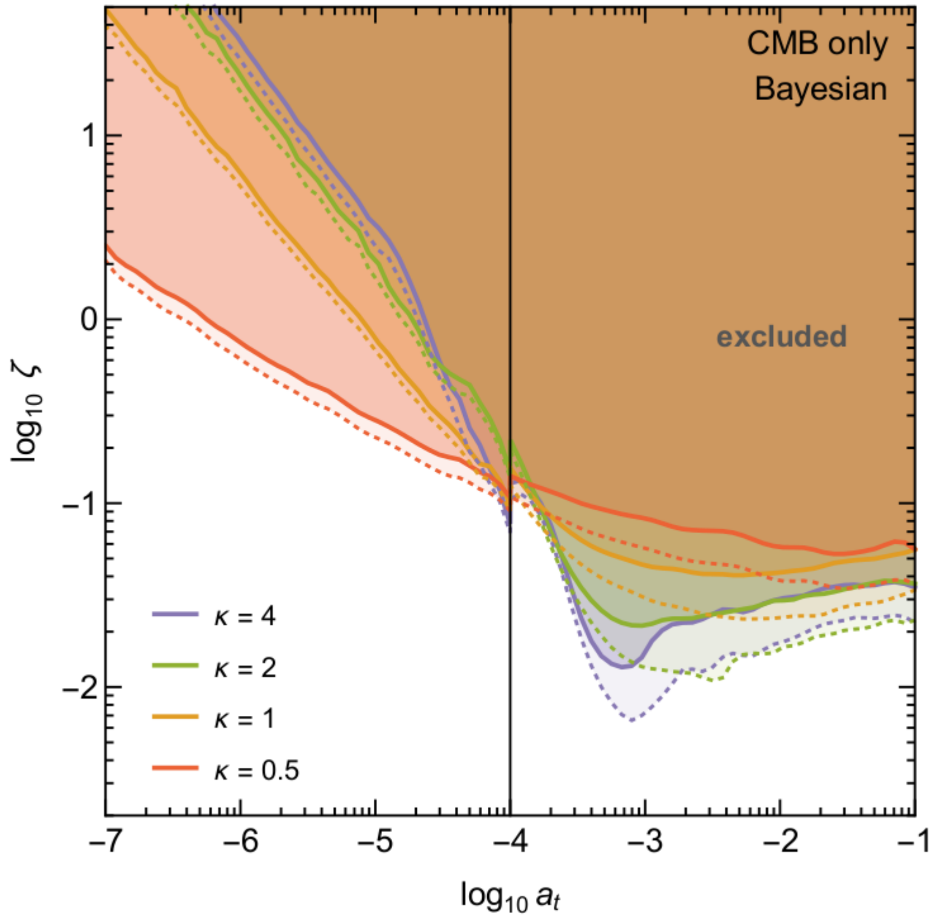
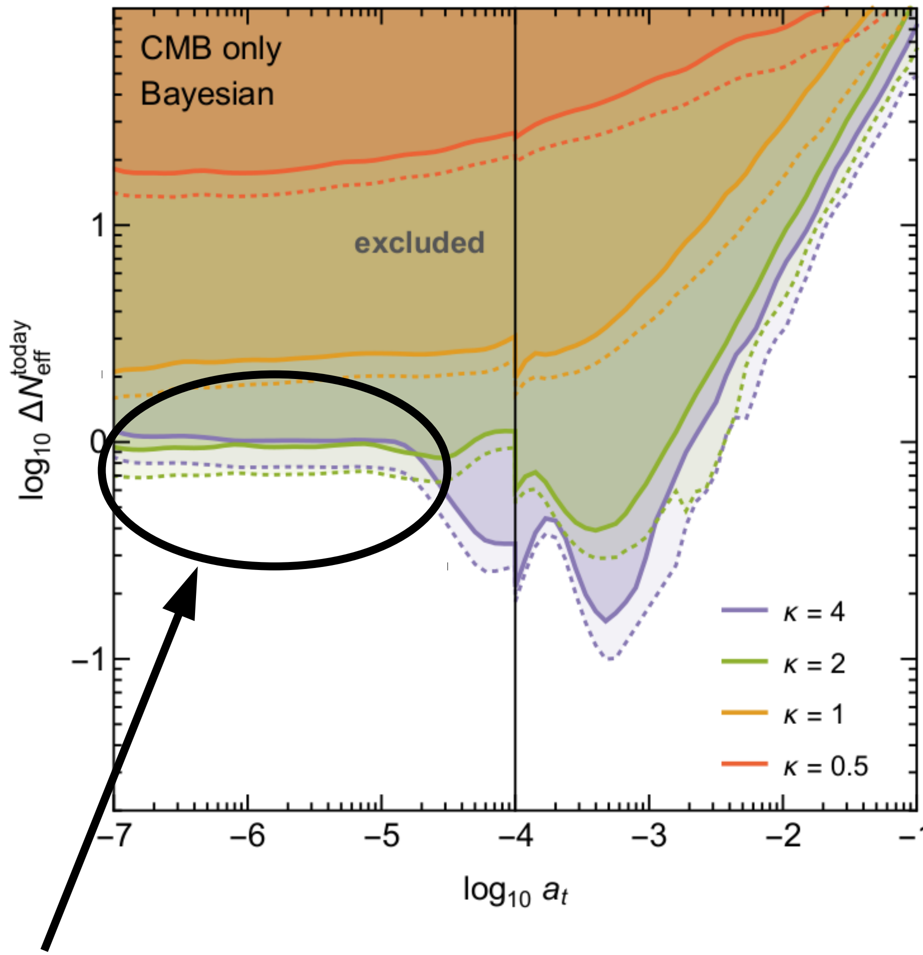
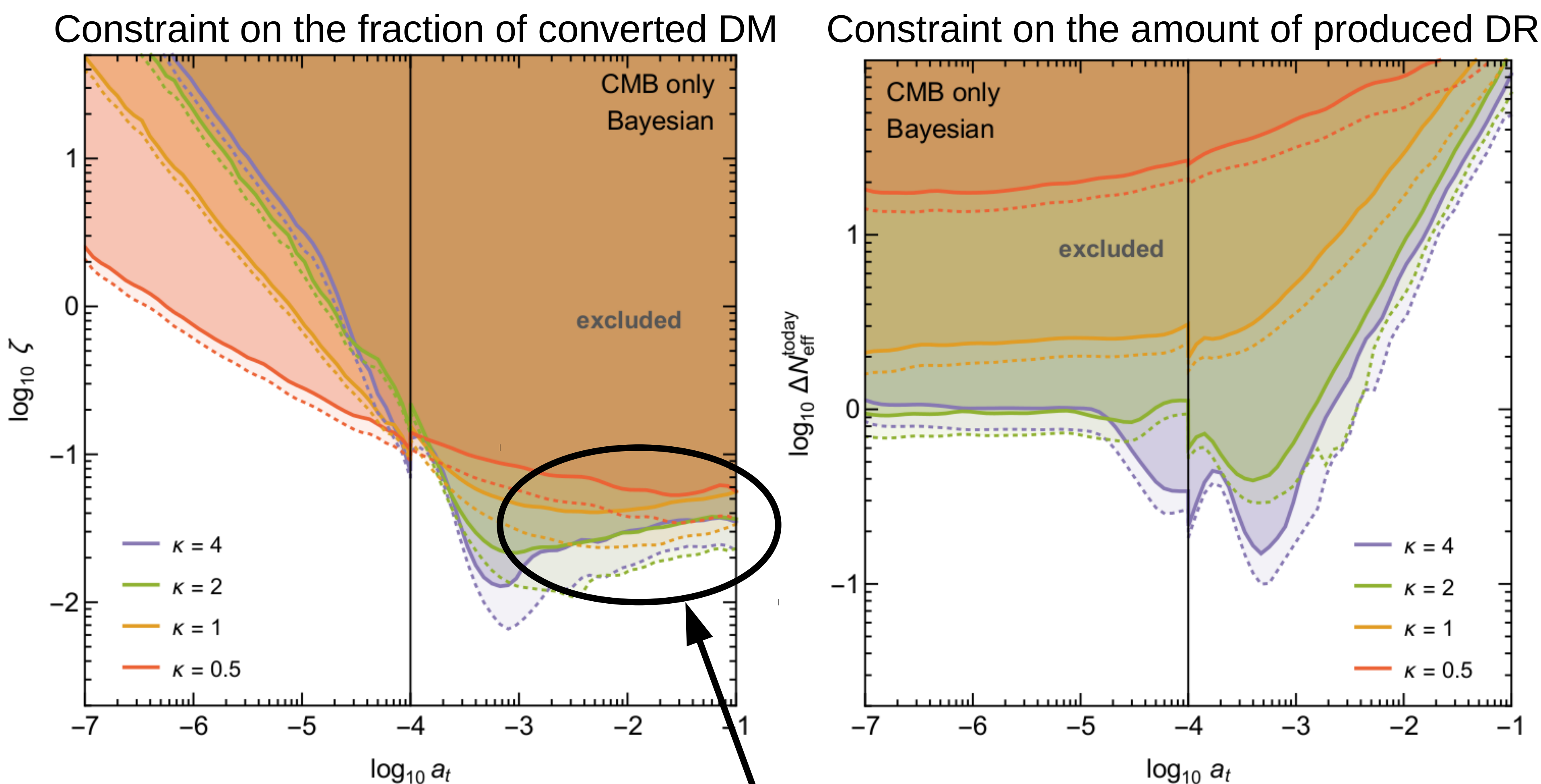



Constraint on the amount of produced DR




For a quick and early transition, constraints depend only on the total amount of DR produced

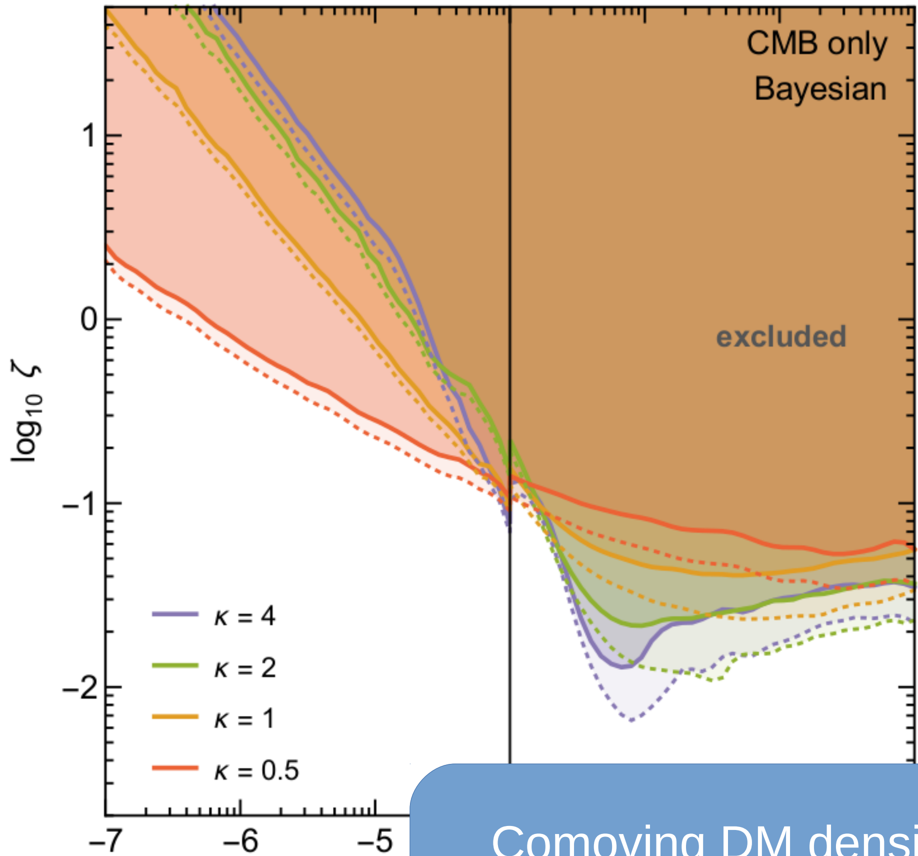
# Results



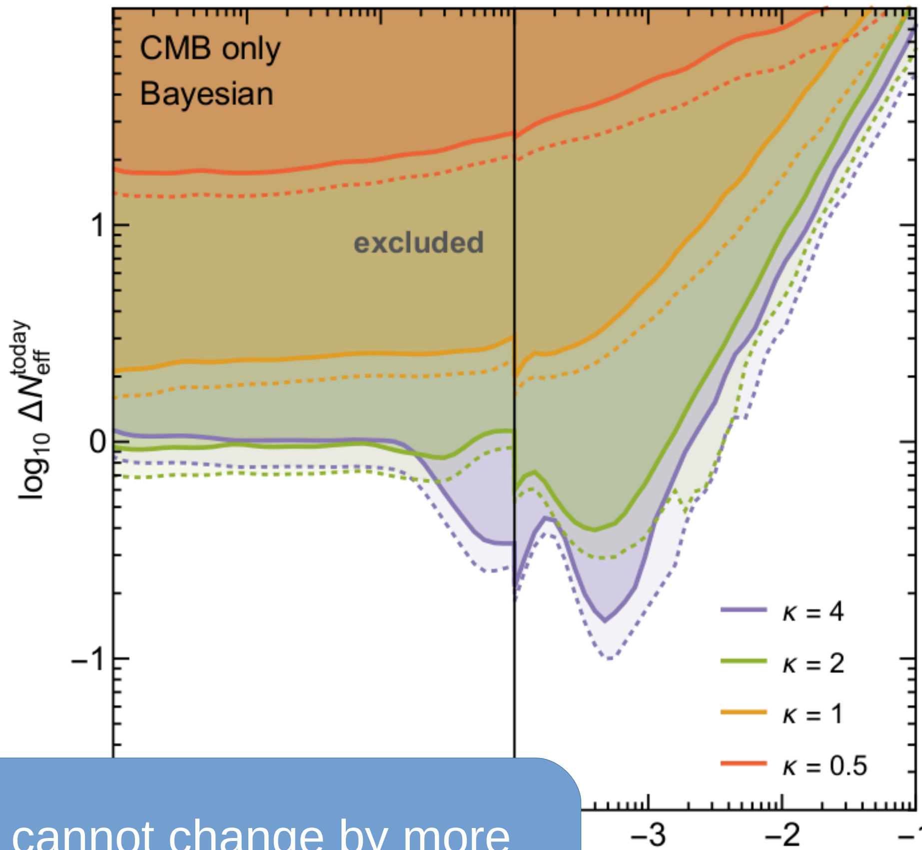

For a late transition (after recombination), constraints depend only on the total amount of "disappearing" DM

# Results

Constraint on the fraction of converted DM




Constraint on the amount of produced DR




Comoving DM density cannot change by more than a few percent after recombination, irrespective of the exact form of the conversion

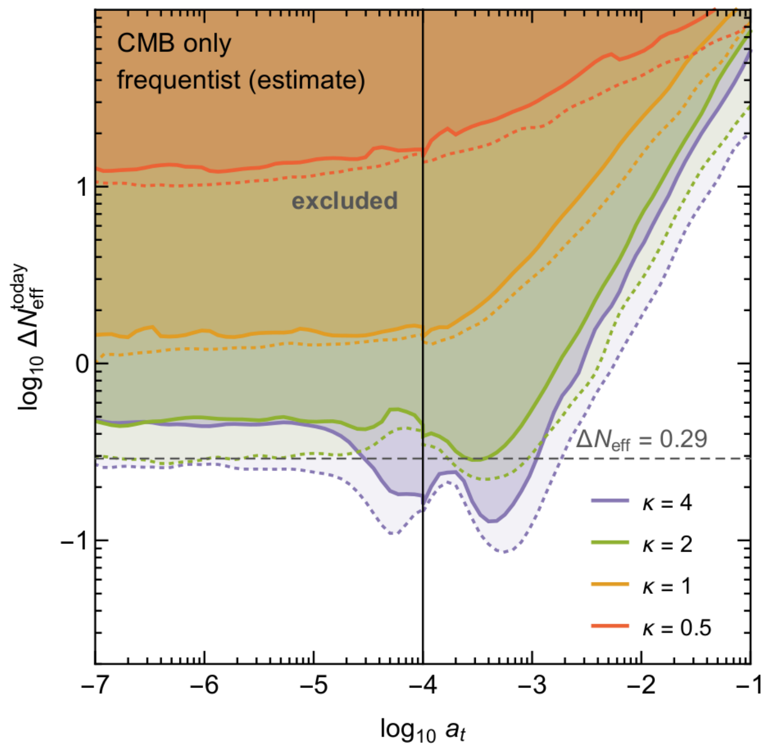
# Intermezzo: Bayesian vs frequentist bounds

- Standard approach in cosmology: Bayesian exclusion limits
  - Preferred parameter region calculated from marginalised posterior likelihoods and assumed priors
  - Works well for parameters that are tightly constrained by data
  - Huge prior dependence for unconstrained parameters
  - Highly undesirable for model-independent approach

- Construct approximate frequentist exclusion limits
  - Define likelihood ratio based on posterior probability:

$$t = -2\,\Delta \log \mathcal{L} \approx -2 \log \left[ \frac{p(\zeta, a_t)}{p(\zeta_\mathrm{best}, a_{t,\mathrm{best}})} \right]$$

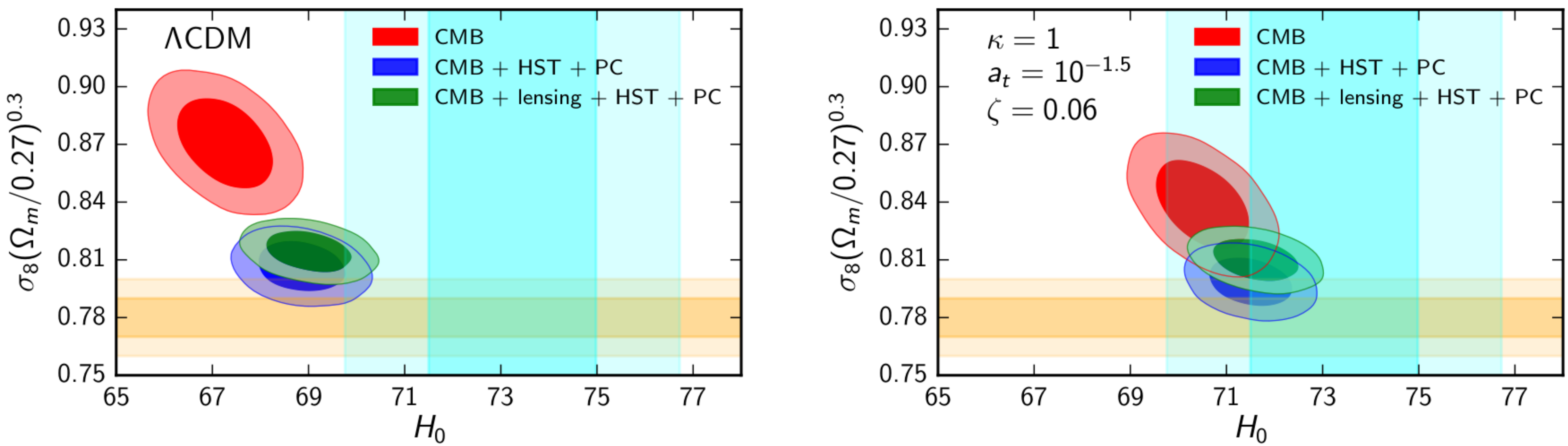
  - Assume $\chi^2$ distribution with 2 d.o.f. for $t$
  - $t > 5.99$ is excluded at 95% confidence level
  - Recover standard bound on $\Delta N_\mathrm{eff}$ from literature



# The plot thickens

- Constraints for late-time conversion of DM to DR stem mostly from modifications of the expansion rate and the matter power spectrum

- Can a DM-DR conversion scenario reduce the tension between CMB measurements and low-redshift observables?

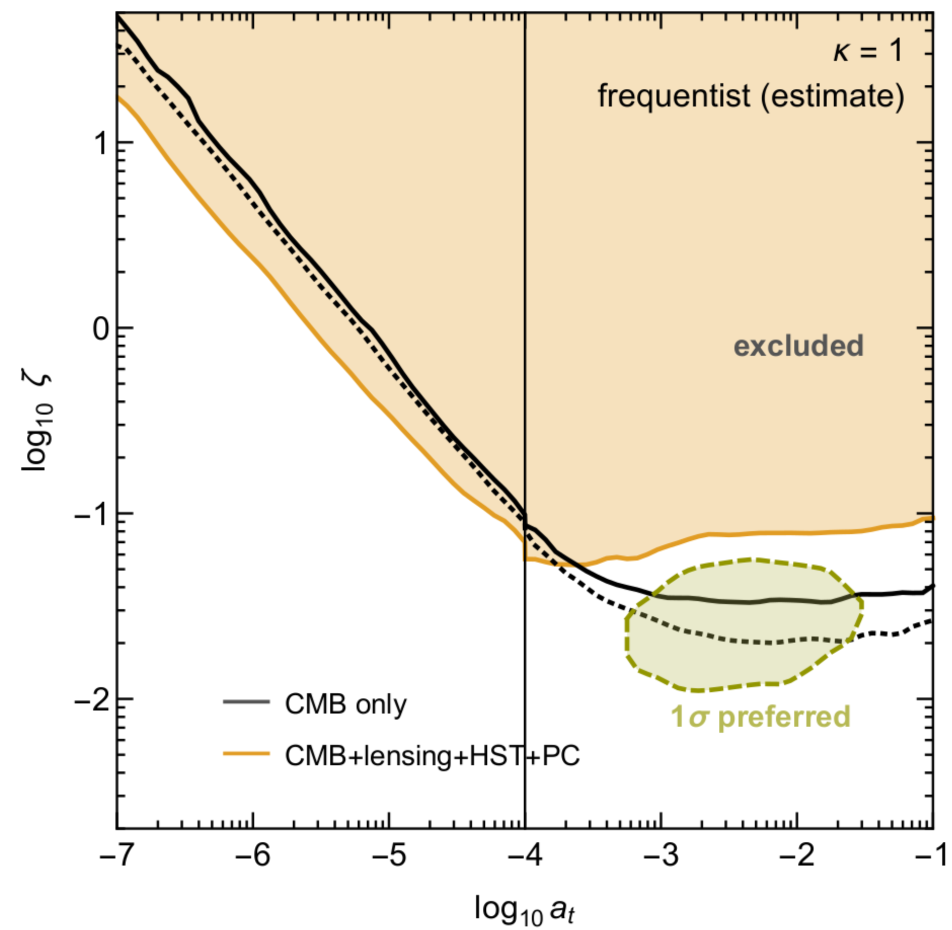



  - A decrease of $\Omega_x$ at late times must be compensated by increasing $H_0$ to keep $\Omega_x h^2$ constant

  - The decrease in $\Omega_m$ overcompensates for the increase in $\sigma_8$, reducing the tension further

# Constraints with low-redshift observables

- We combine Planck CMB data with
  - Lensing power spectrum reconstruction from Planck
  - Direct measurements of $H_0$ from HST (supernova data)
  - Direct measurements of $\sigma_8$ from Planck cluster counts
- Significant modification of results
  - Substantially weaker limit for late conversion (large $a_t$)
  - mild preference (~2σ) for DM-DR conversion
  - Not possible to fully resolve tension $H_0$-$\sigma_8$ tension



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- **Part 2: Sommerfeld-enhanced dark matter annihilations**
  - Dark matter models with light mediators
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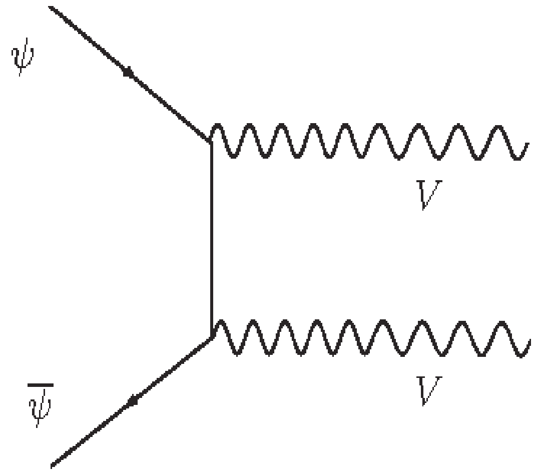
# Light mediators in the dark sector

- Consider a (fermionic) DM particle coupled to a light (vector) mediator:

$$\mathcal{L} \supset g_\chi \, \bar{\chi} \gamma^\mu \chi V_\mu$$




- Relic abundance set by annihilations into pairs of mediators: Dark sector freeze-out

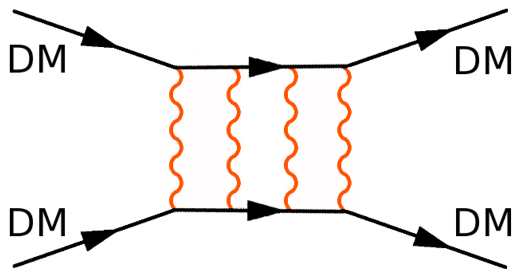
- Always possible to fix coupling $g_\chi$ such that observed relic abundance is reproduced

- To avoid overclosing the Universe, the mediator should ultimately decay

For an exception see Duerr et al., arXiv:1804.10385

# Self-interactions from a light mediator

- Non-perturbative effects due to multiple mediator exchange enhance DM self-interactions

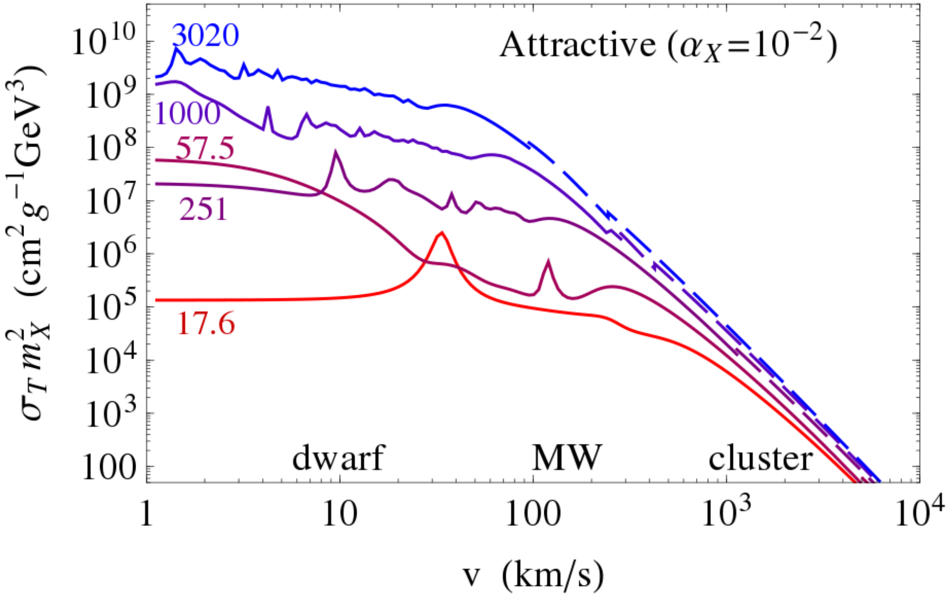



- Can be calculated by solving non-relativistic Schroedinger equation for Yukawa potential:

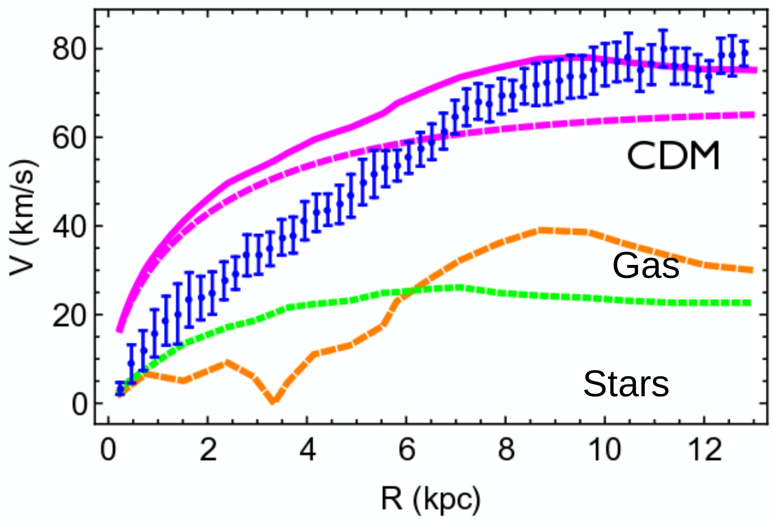
$$V(r) = \frac{\alpha\, e^{-r\, m_{\mathrm{med}}}}{r}$$

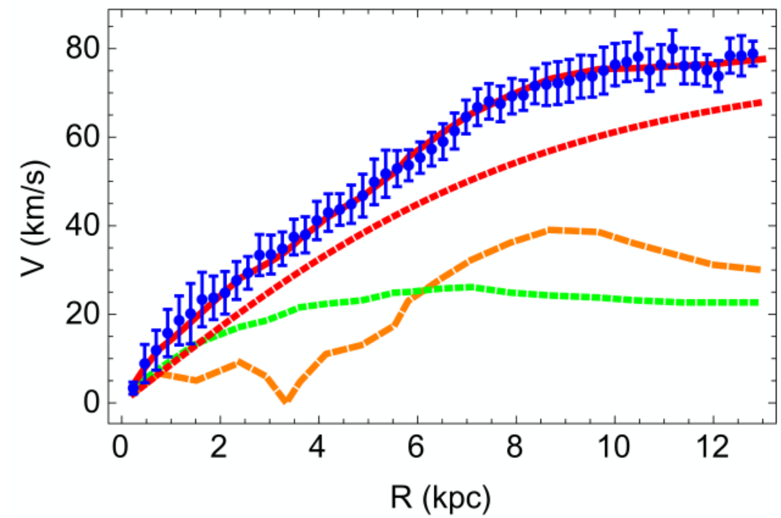
- For $\alpha_S m_\psi \gtrsim m_\phi$ resonances appear and modify results of tree-level calculation.
- Bonus: self-interactions depend on the relative velocity of the DM particles

Tulin et al., arXiv:1302.3898



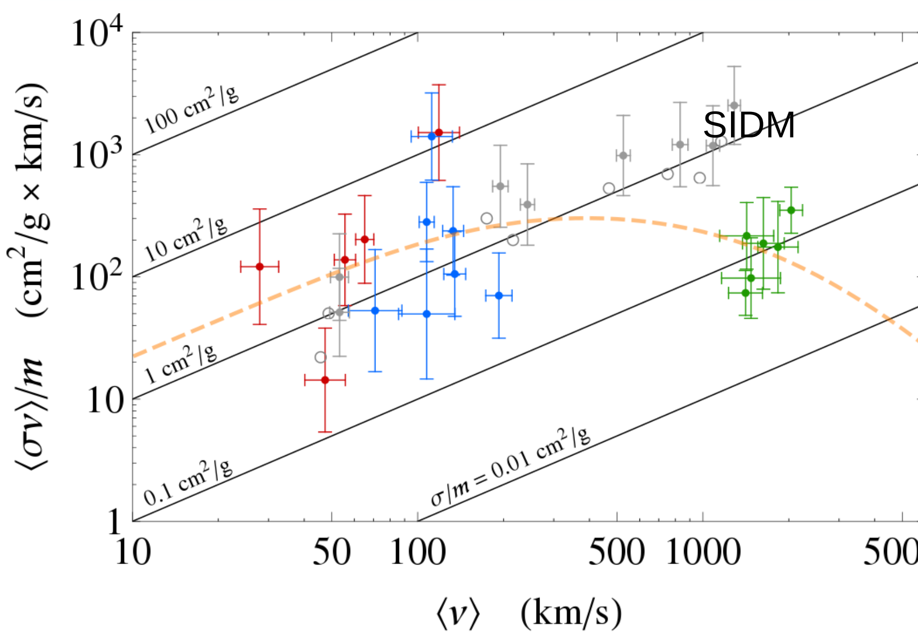
# Velocity-dependent self-interactions




Tulin & Yu: arXiv:1705.02358

- DM self-interactions lead to energy transfer between DM particles
- Creation of an isothermal core
- Resolution of cusp-core problem
- Need velocity dependence to explain observations at different scales




Kaplinghat et al., arXiv:1508.03339

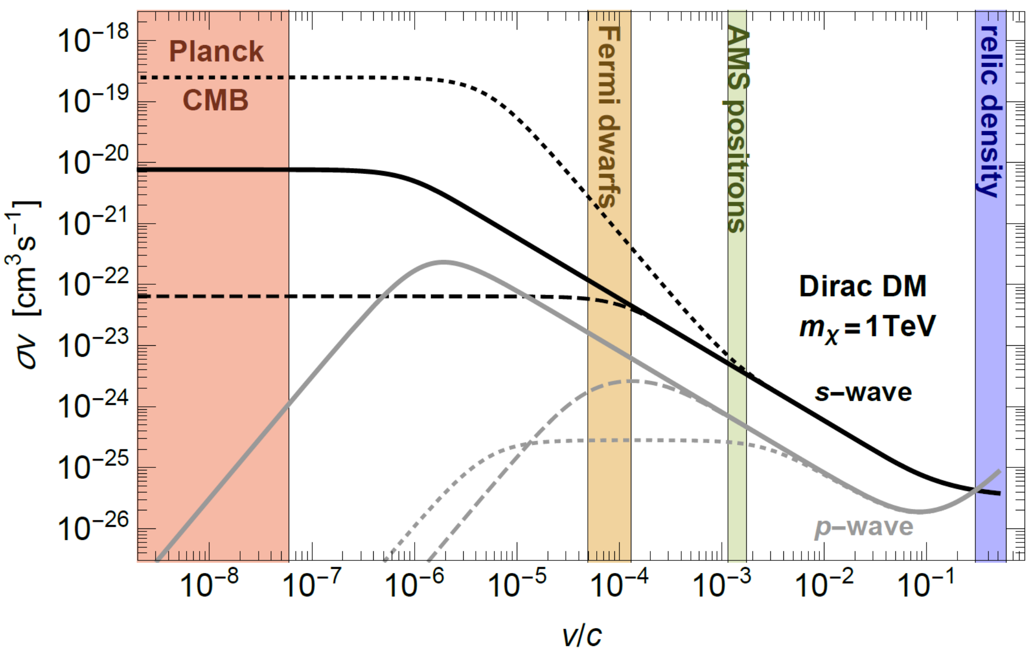
# Enhancement of DM annihilations

- The Yukawa potential from the light mediator exchange also modifies the wave-function of the annihilating DM pair (so-called Sommerfeld enhancement)

- Significant non-perturbative corrections to the tree-level annihilation rate

- Effects small during freeze-out, but increase with decreasing DM velocity

Bringmann, FK et al., arXiv:1612.00845



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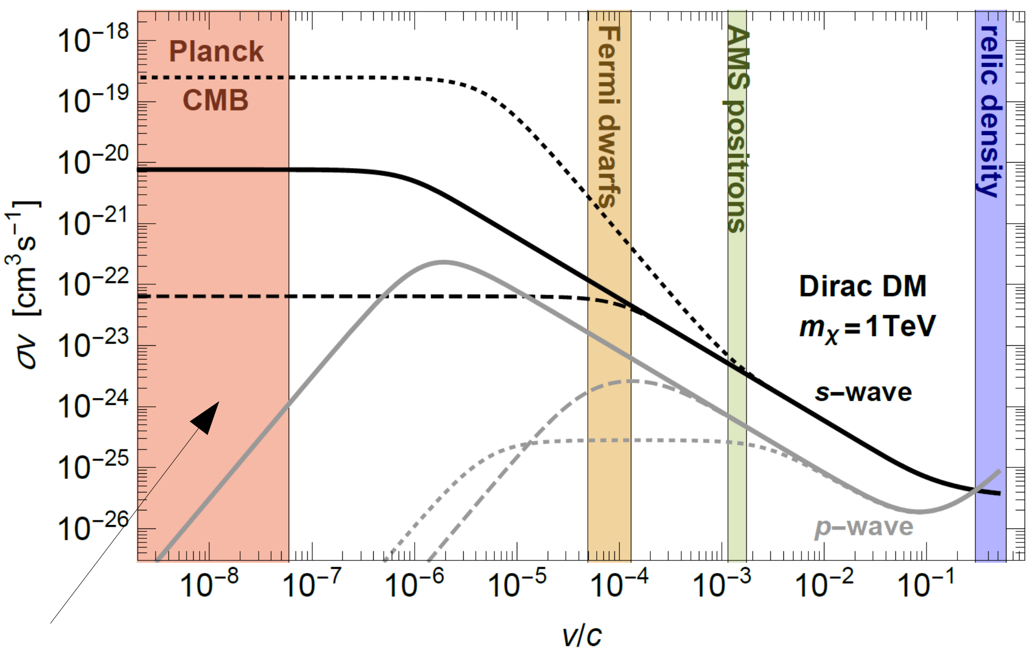
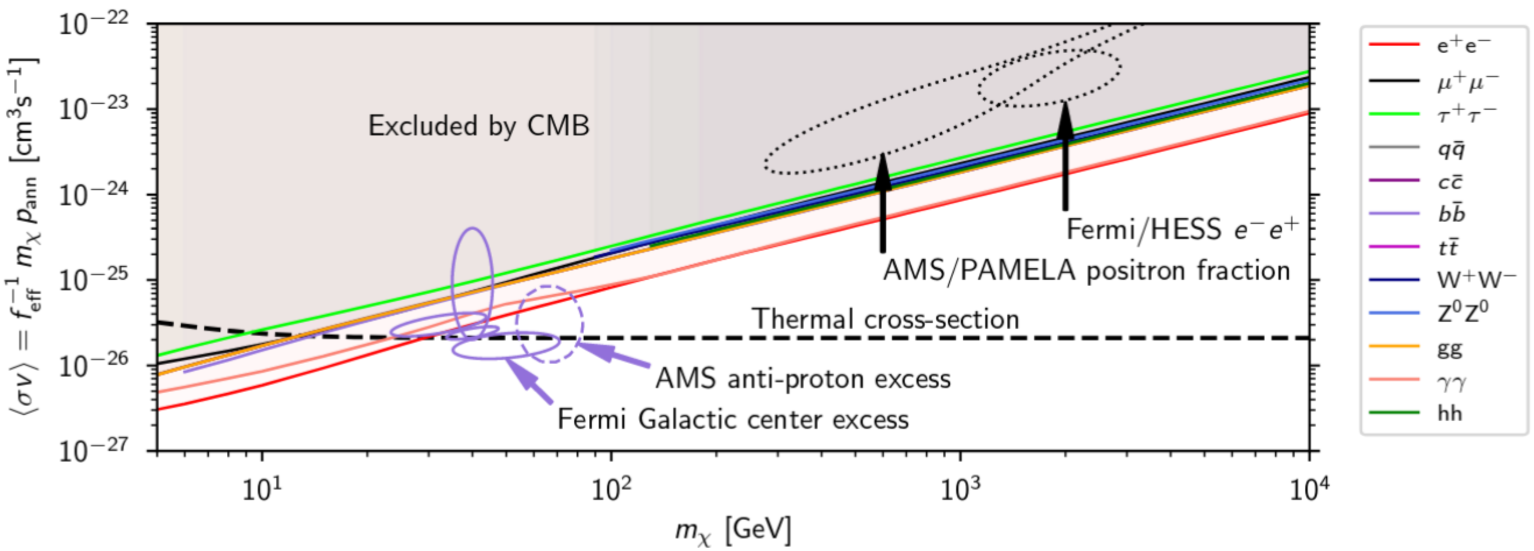




During recombination dark matter particles move at walking speed!

# CMB constraints on self-interacting DM

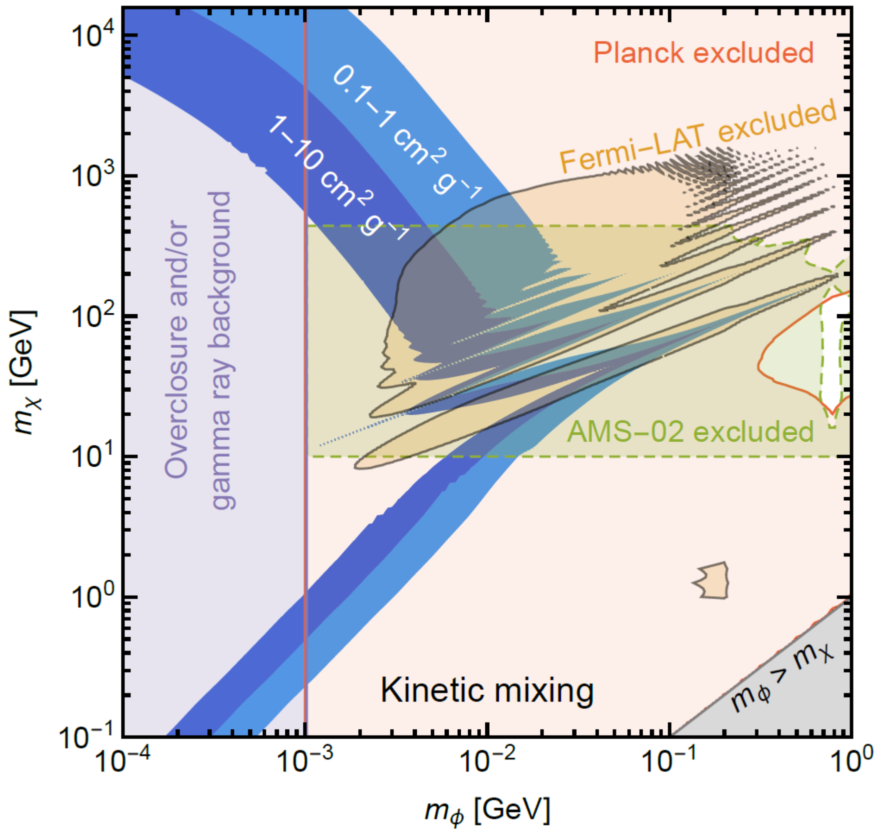
- DM annihilations during recombination, followed by mediator decays into SM particles, inject energetic electrons and photons into the plasma
- These energetic particles can re-ionize neutral atoms and thereby spoil the excellent agreement between predictions and measurements of the CMB



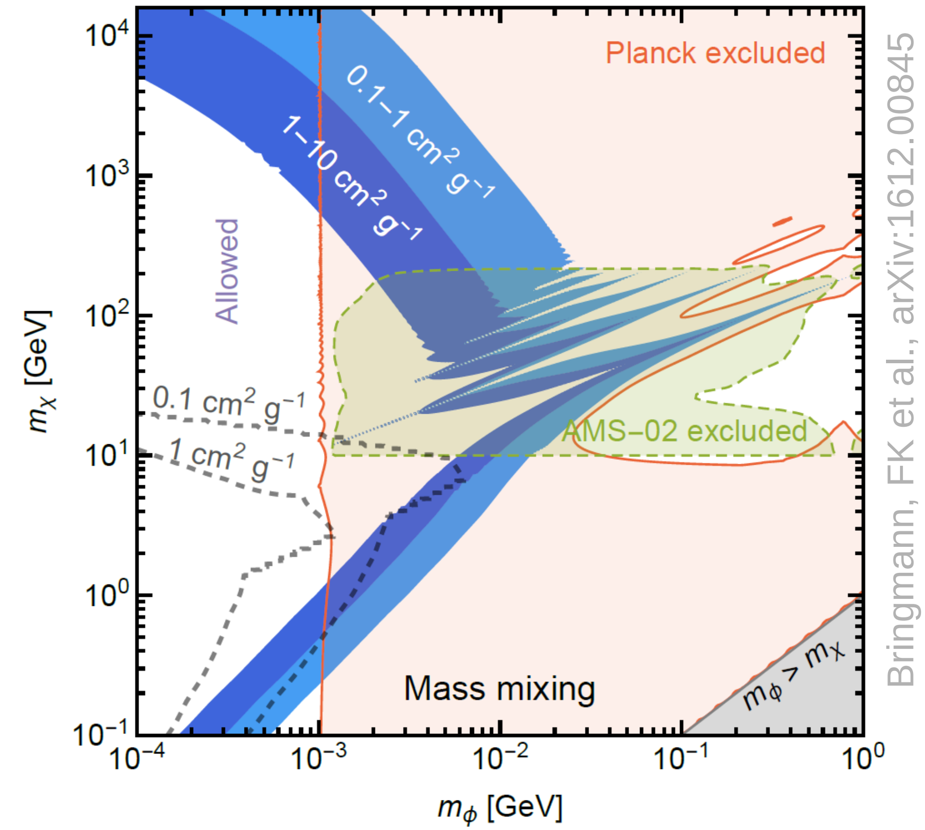

- Result: $$\frac{\langle\sigma v\rangle_{\rm rec}}{N_\chi} \lesssim 4\times10^{-25}\,{\rm cm}^3\,{\rm s}^{-1}\left(\frac{f_{\rm eff}}{0.1}\right)^{-1}\left(\frac{m_\chi}{100\,{\rm GeV}}\right)$$

# Constraints on vector mediators

- CMB and indirect detection constraints basically exclude the possibility that the mediator of large self-interactions decays into SM particles



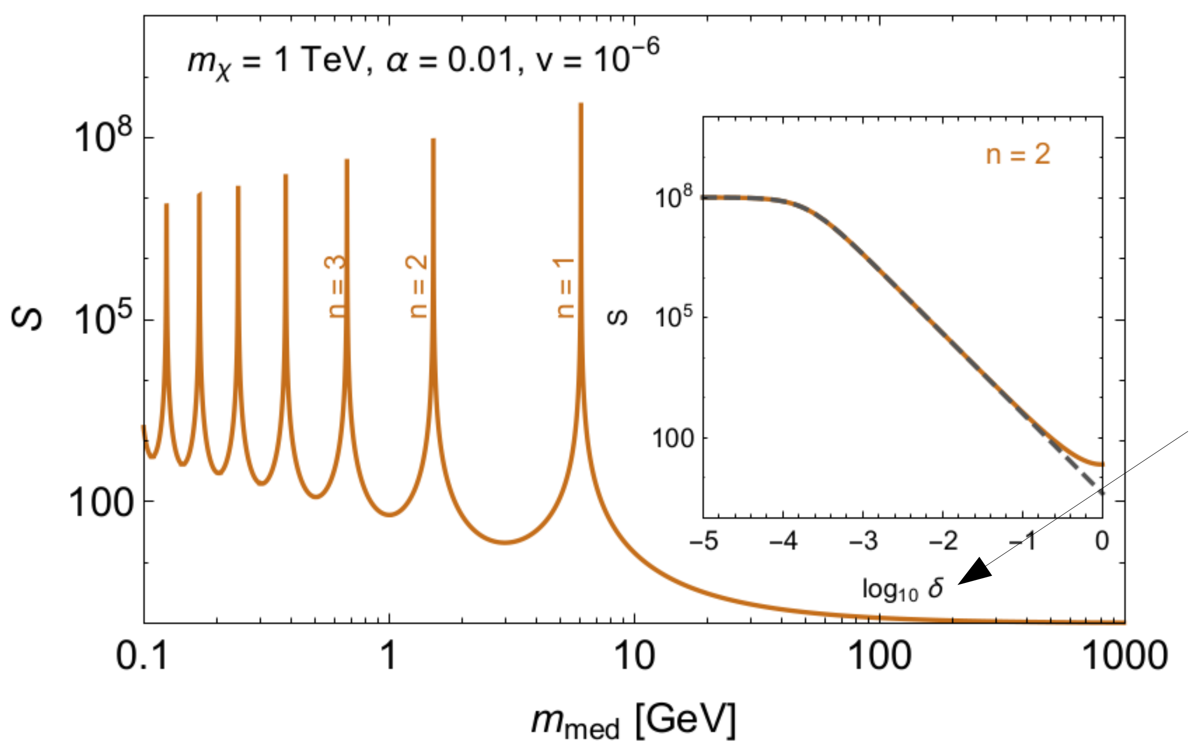

Mediator with photon-like couplings




Mediator with Z-like couplings

# What if the mediator decays to dark radiation?

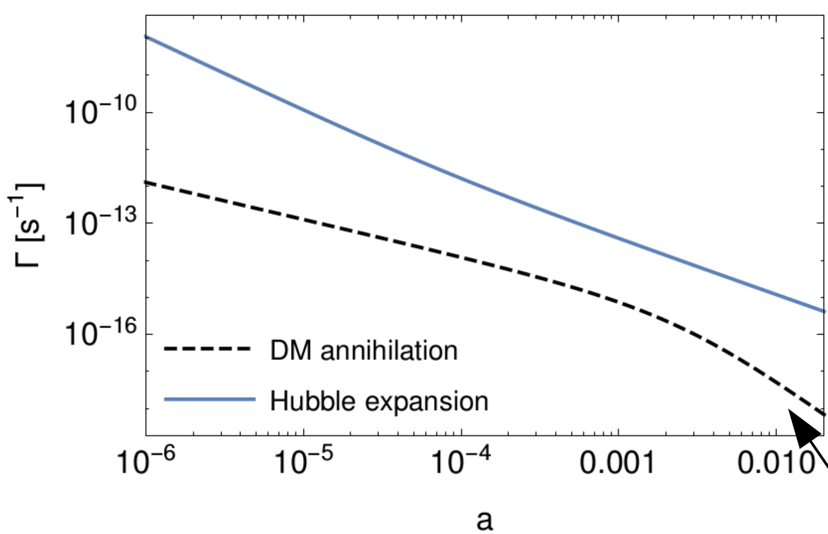
- No injection of electromagnetic energy into plasma → much weaker CMB constraints
- Back to the scenario of DM-DR conversion!
- There may still be relevant constraints if DM annihilations are resonantly enhanced

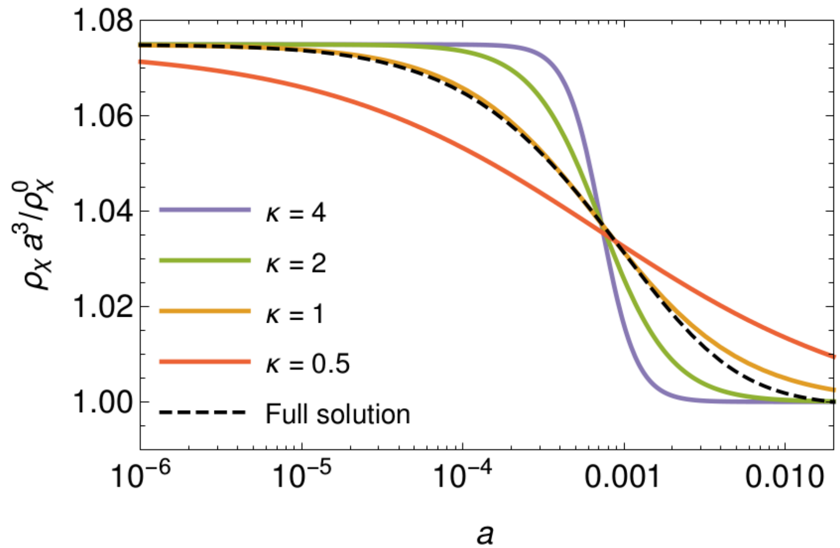



$$\delta \equiv \left| \frac{m_{\rm med} - m_{\rm med}^{(n)}}{m_{\rm med}^{(n)}} \right| \equiv \left| 1 - \frac{\pi^2 n^2\, m_{\rm med}}{6 m_\chi \alpha} \right|$$

# A second period of DM annihilation

- After kinetic decoupling DM velocity scales as $v \propto a^{-1}$
- Resonant Sommerfeld enhancement: $S(v) \propto v^{-2}$
- The DM number density scales as $\rho_\chi / m_\chi \propto a^{-3}$
- DM annihilation rate decreases more slowly than the Hubble rate: $\Gamma_{\text{ann}} \propto a^{-1}$
- DM annihilations can become important once again in the late Universe!




Saturation of Sommerfeld enhancement
prevents second freeze-out

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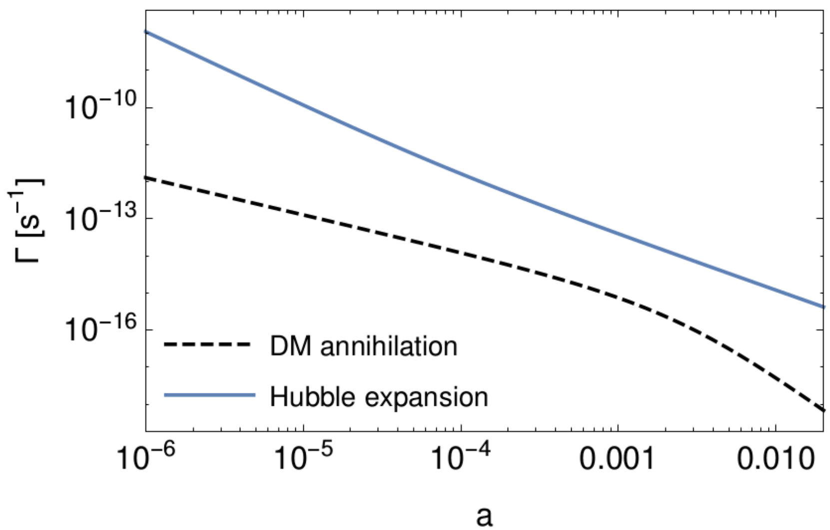
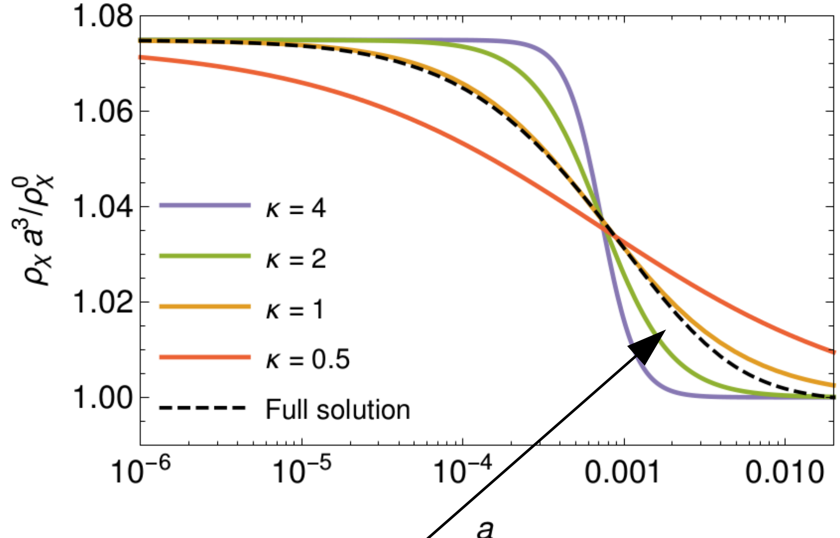



Scenario well-described by our model-independent bounds with $\kappa = 1$

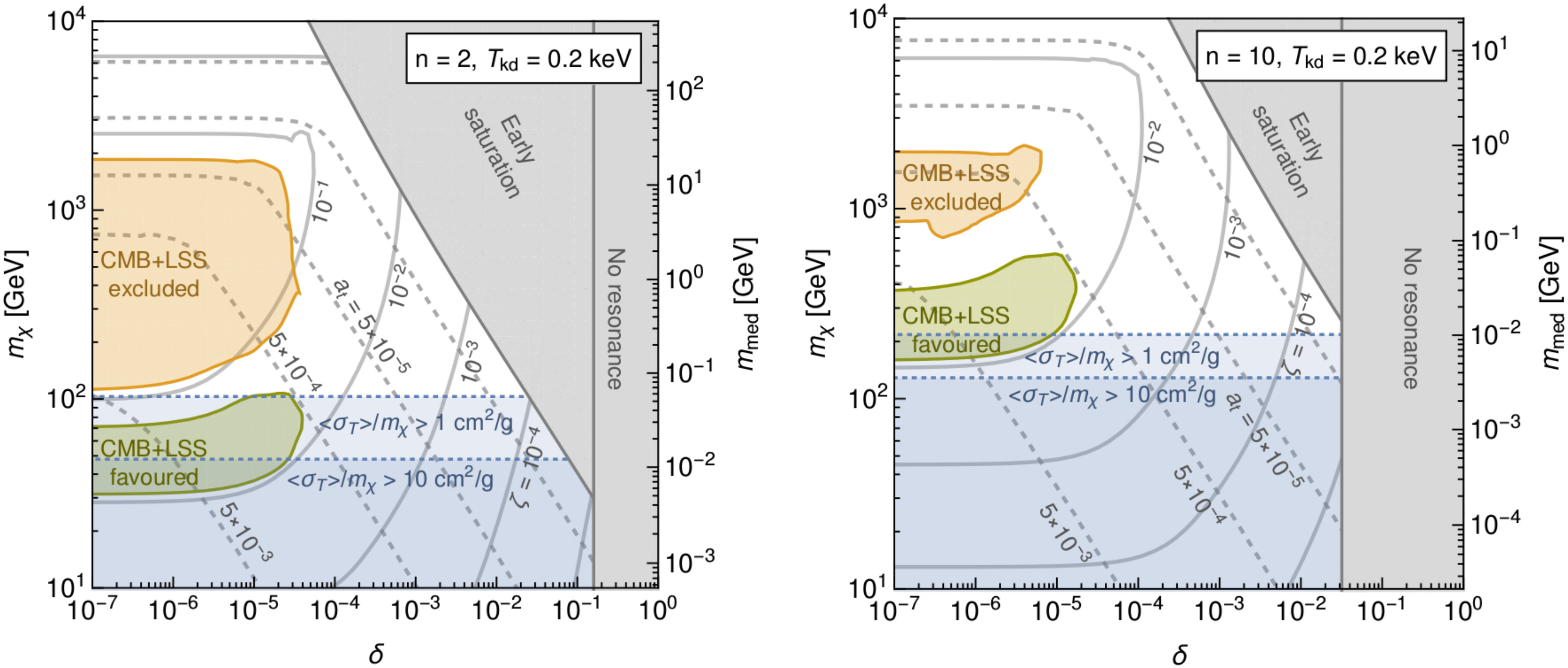
# CMB constraints on late-time DM annihilations

- For each set of particle physics parameters we solve the Boltzmann equation:

$$\frac{\mathrm{d}\rho_\chi}{\mathrm{d}z}(1+z)H(z) - 3\rho_\chi H(z) - \frac{1}{2}\langle\sigma v_{\mathrm{rel}}\rangle\frac{\rho_\chi^2}{m_\chi} = 0$$

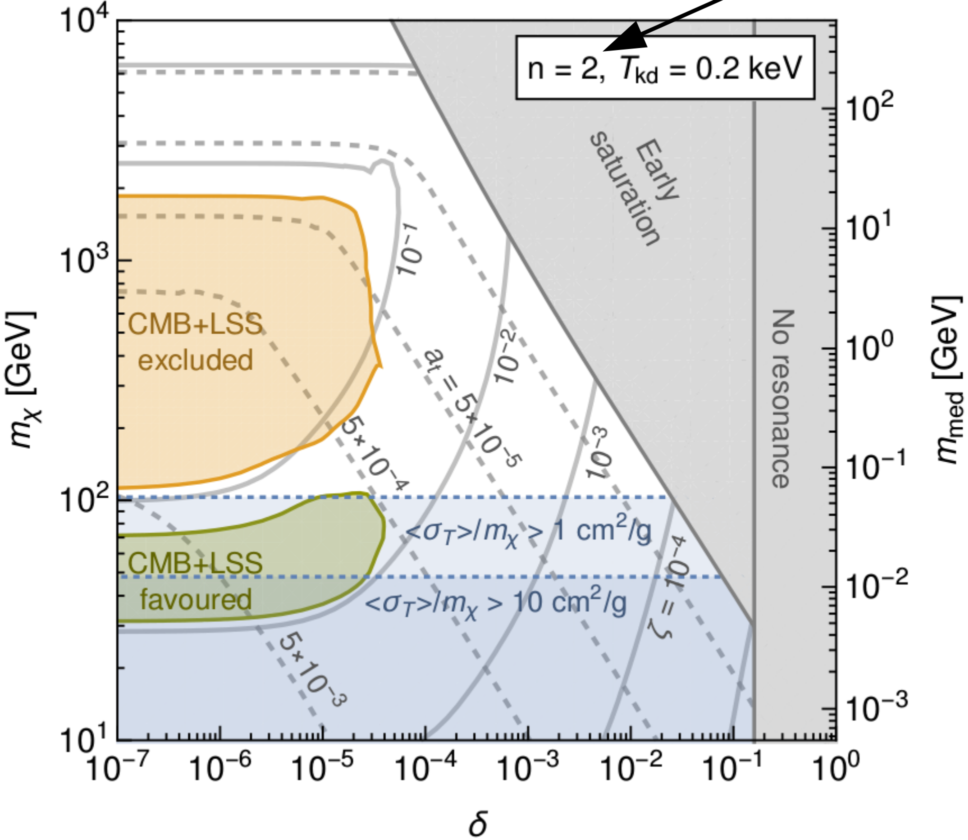
- We then determine the values of $\zeta$ and $a_t$ that give the best fit to the transition
  - Note: It is typically not possible to realize $a_t > 10^{-2}$ due to non-linear structure formation
- We can then use our model-independent results to determine whether the set of parameters is allowed or excluded (or even favoured by data)
  - Note: Since we obtained (approximate) frequentist bounds, there is no need to worry about transformation or priors

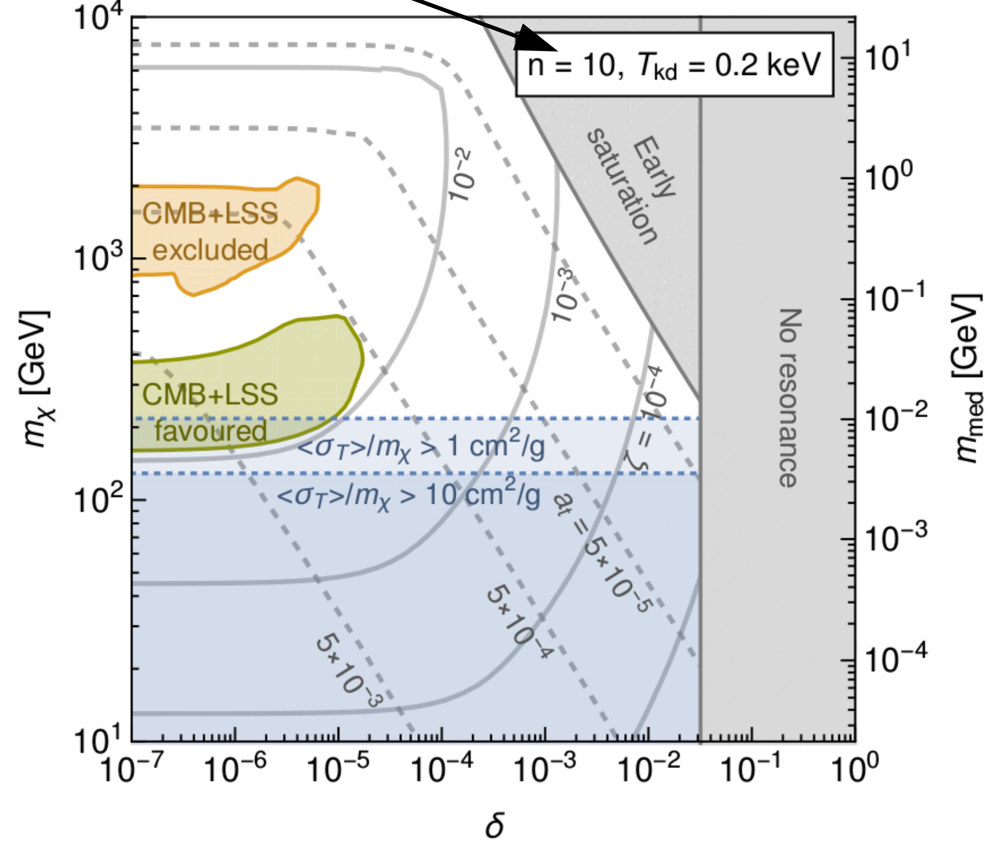
# Main results



# Main results

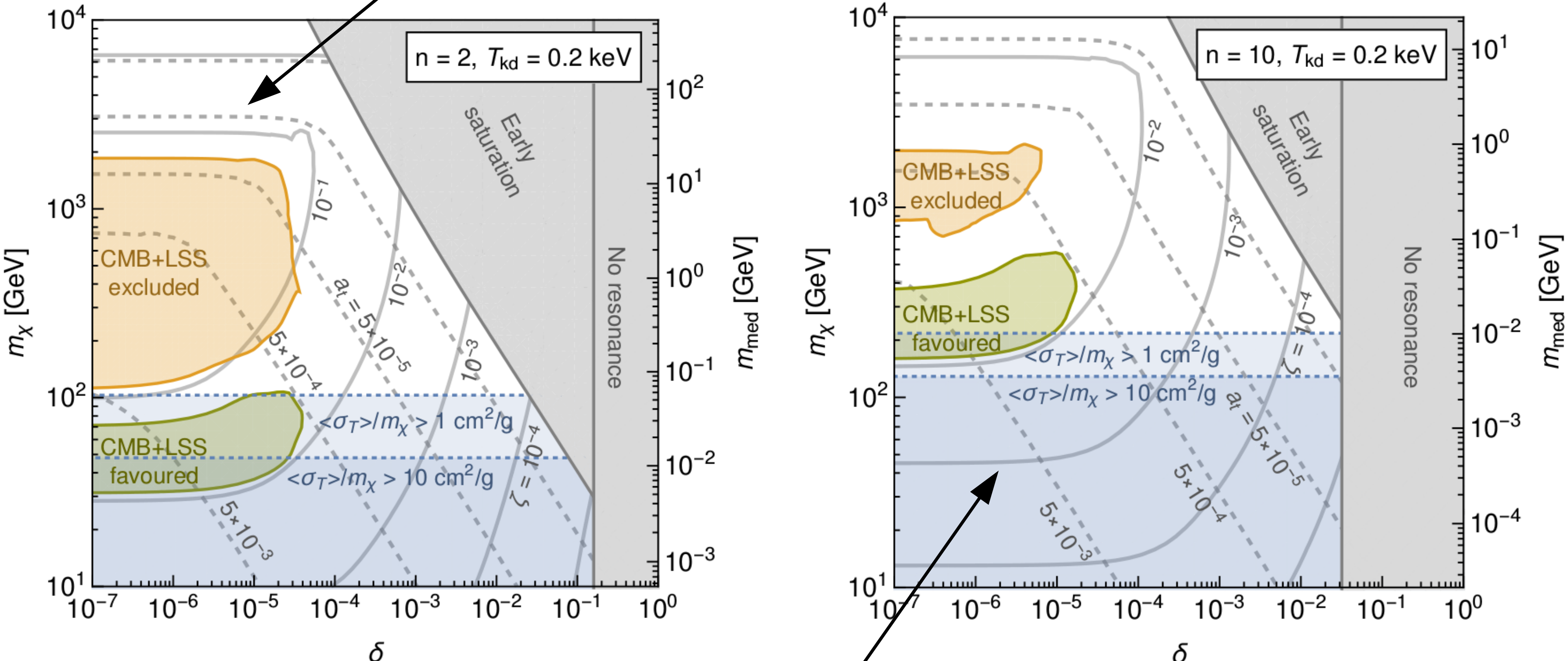
Different plots represent different resonances
→ changes the velocity when $S(v)$ saturates



# Main results

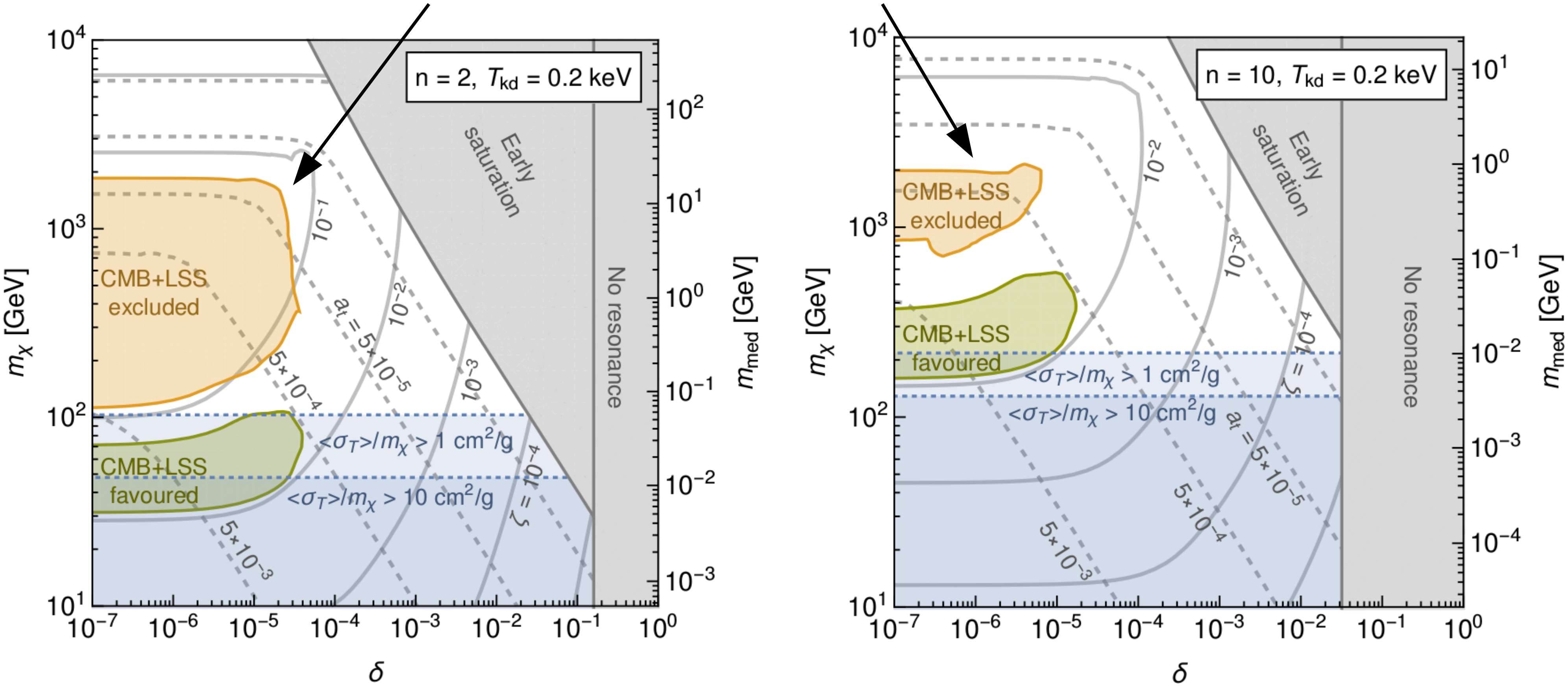
Dashed gray lines indicate when DM is converted to DR




Solid gray lines indicate how much DM is converted to DR

# Main results

CMB is more sensitive the larger the amount and the later the time of conversion



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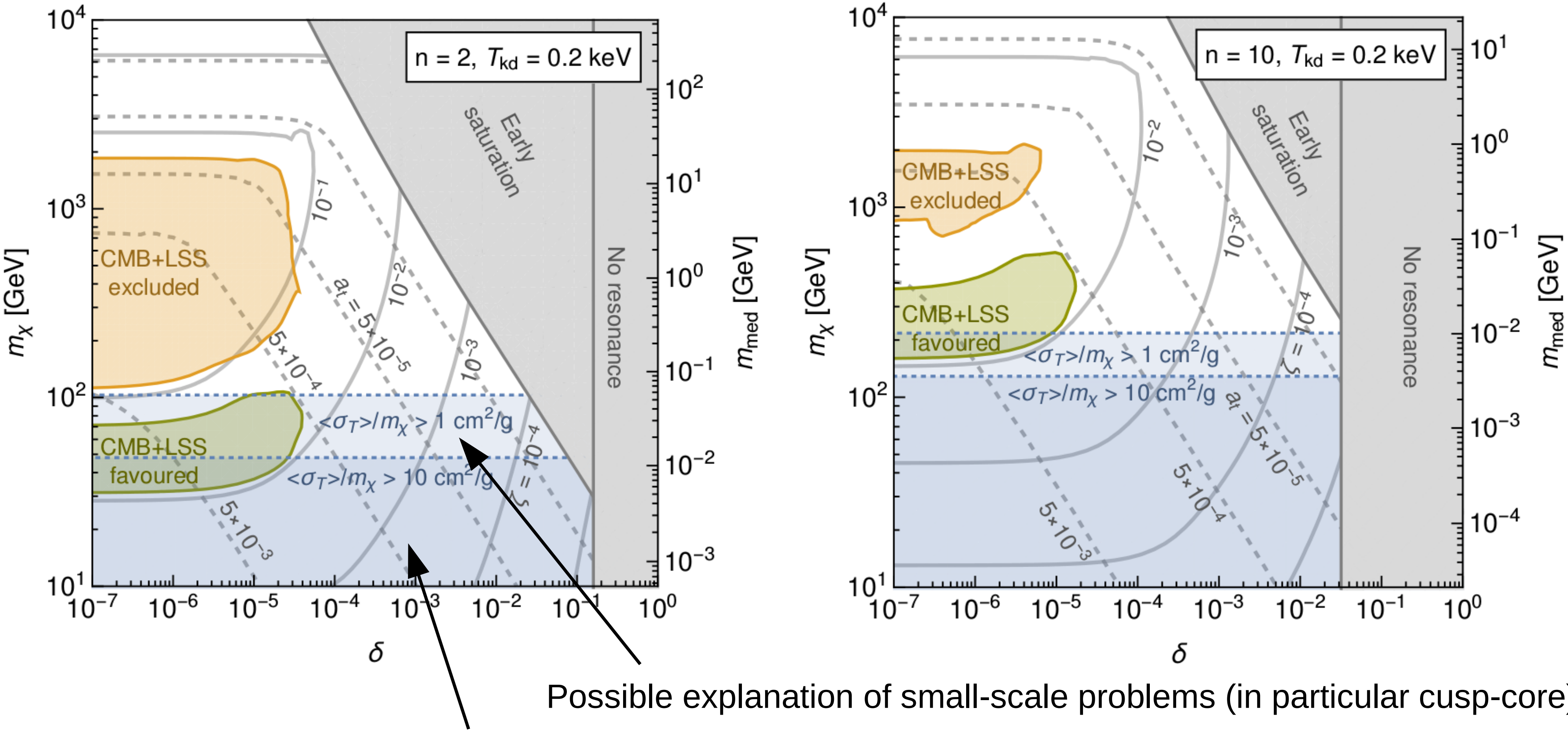


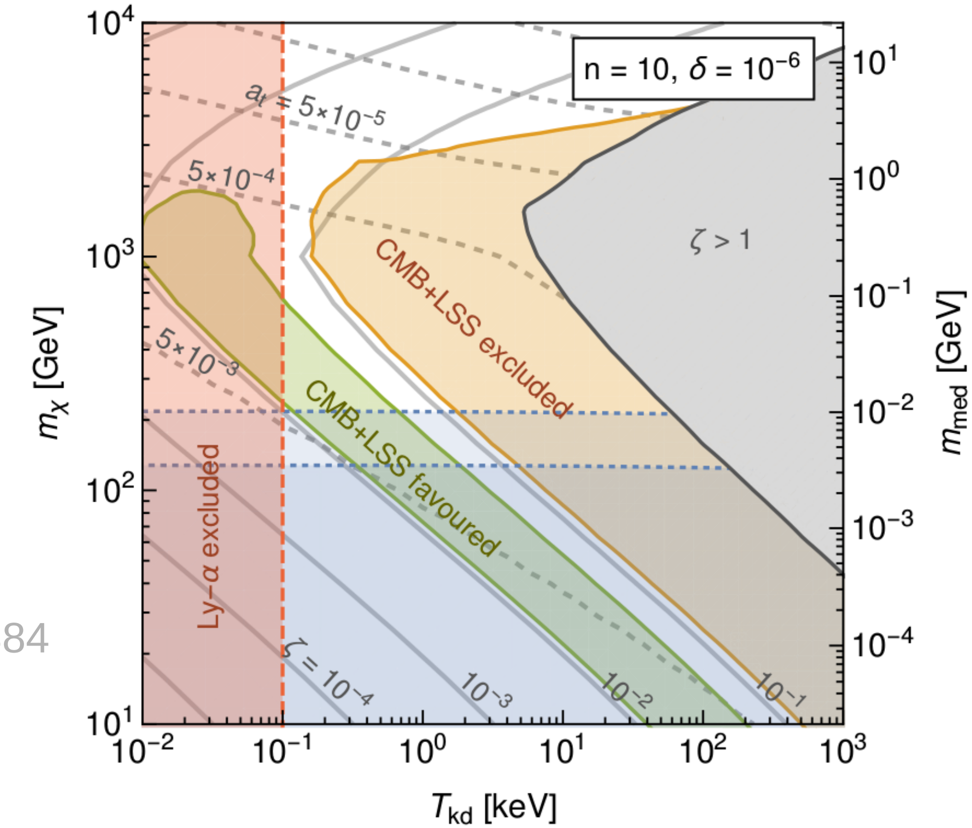

Possible explanation of small-scale problems (in particular cusp-core)

Robustly excluded by constraints on self-interacting dark matter

# Finally: late kinetic decoupling

- Kinetic decoupling temperature $T_{\rm kd}$ depends on coupling between mediator and DR
  - Determines the effective DM temperature: $T_{\rm eff} = T_{\rm kd} \dfrac{a_{\rm kd}^2}{a^2} = \dfrac{T_0^2}{T_{\rm kd}} a^{-2}$

- Very small values of $T_{\rm kd}$ are excluded by Lyman-$\alpha$ forest constraints
- Slightly larger values can lead to interesting effects on structure formation
  - Suppression of power on small scales (similar to warm DM)
  - Solution of the missing satellite problem




Bringmann et al., arXiv:1603.04884

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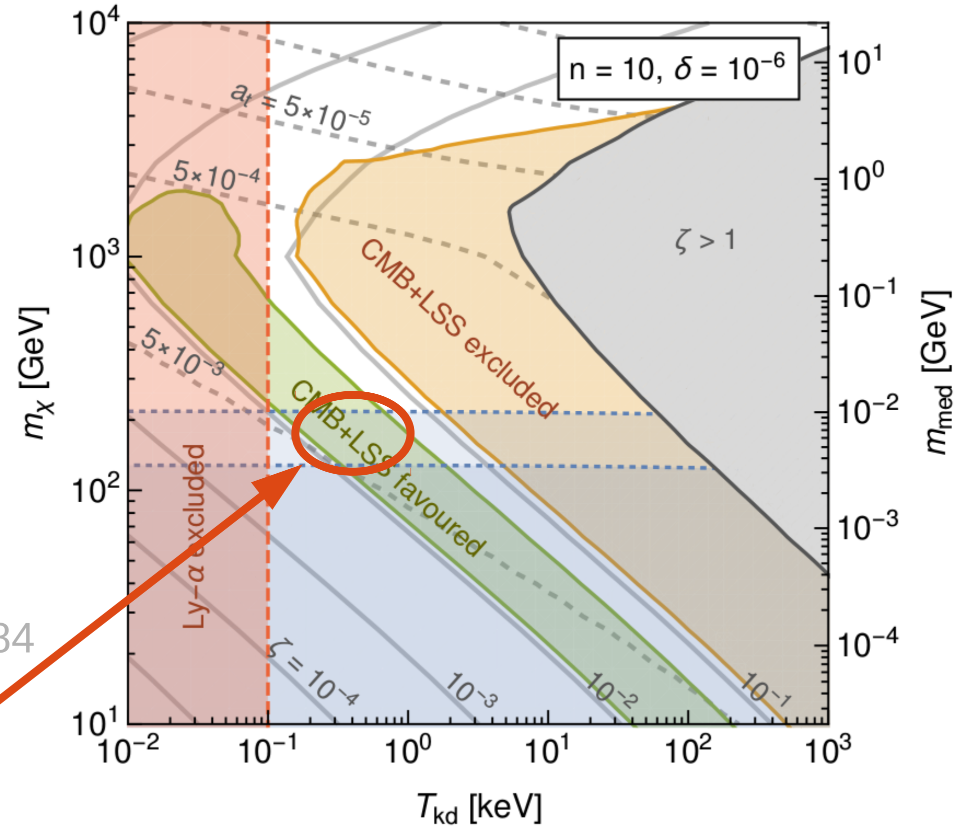



Bringmann et al., arXiv:1603.04884

Potential resolution of all small-scale and large-scale problems of ΛCDM!

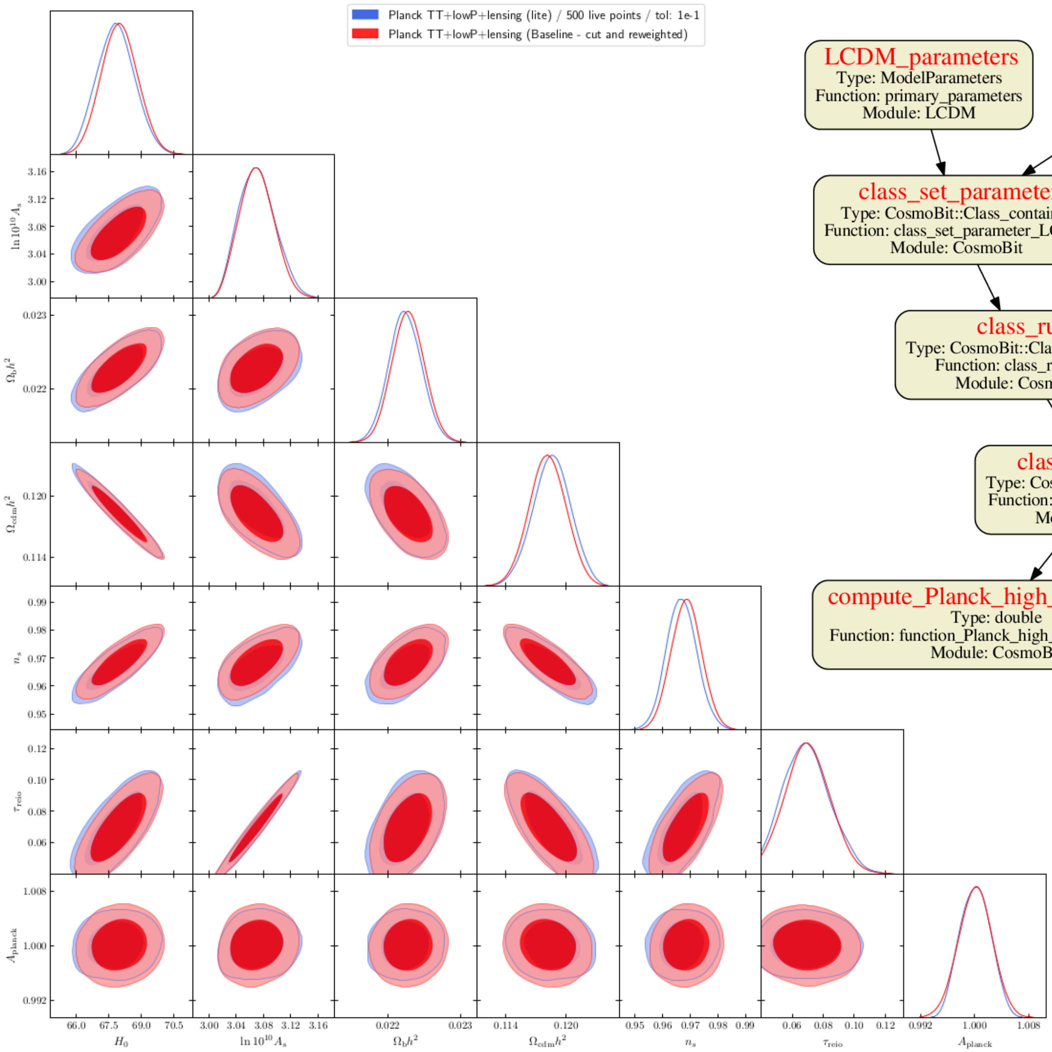
# What's next? CosmoBit!

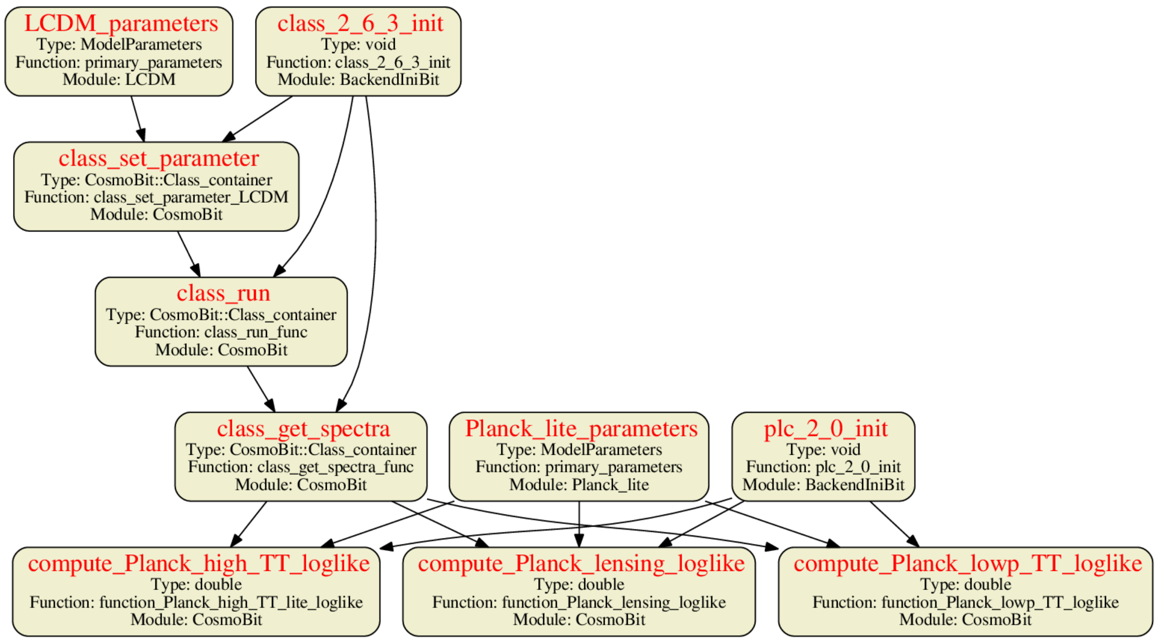
- Implementation of cosmological models and observables in the global fitting framework GAMBIT (The Global And Modular BSM Inference Tool)

- Interface for a range of cosmology codes and likelihoods
  - (Multi-field) inflation
  - BBN
  - CMB
  - Large-scale structure
  - Small-scale structure

- Implementation and analysis of a range of exciting models
  - Models of inflation
  - Warm, self-interacting or decaying dark matter
  - New light degrees of freedom ("dark radiation")
  - ...

# Example: Running CLASS with GAMBIT




Slide courtesy of Patrick Stöcker

# Conclusions

- Even models with a secluded dark sector annihilating into invisible dark radiation may actually be testable!
- CMB data is highly sensitive to the conversion of (even a small fraction of) DM to DR
- We would definitely notice if DM suddenly disappeared in the early Universe!
- Interesting scenario: Self-interacting WIMPs from light mediator exchange
- Simultaneous resolution of small-scale problems and large-scale tension possible
- By-product: Model-independent constraints on any type of DM-DR conversion

# Backup

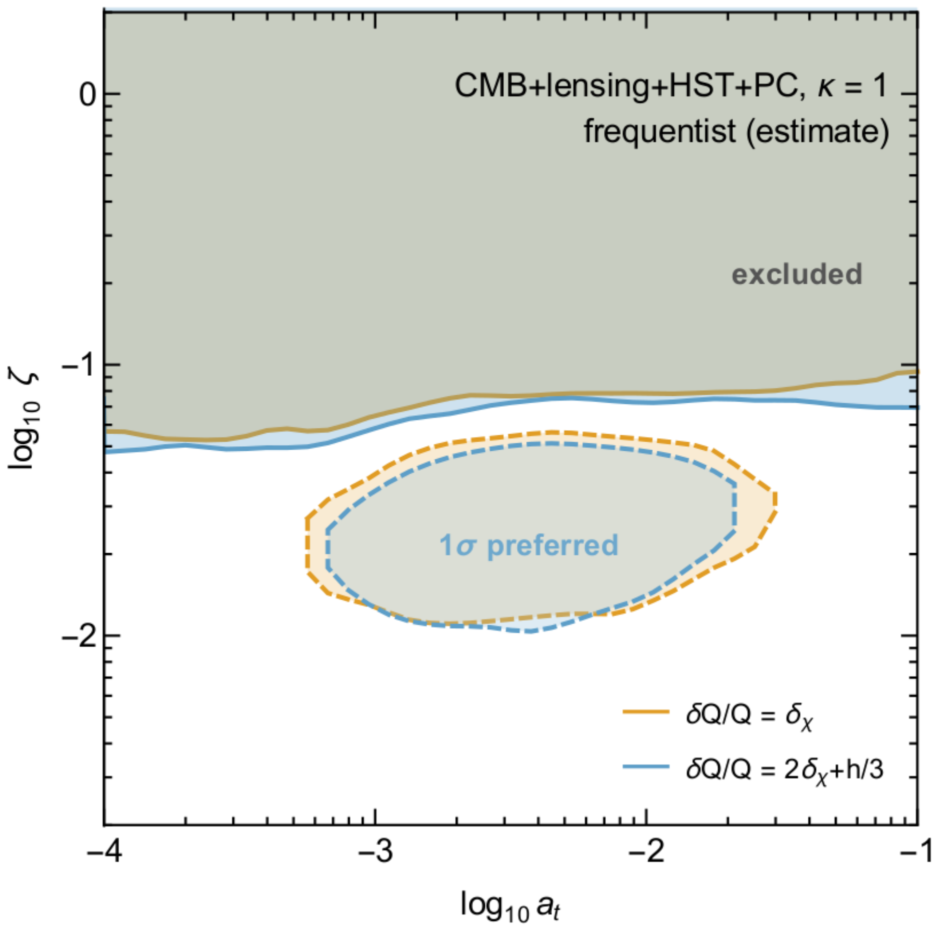
# Another look at perturbations

- Once we consider a specific particle physics realisation of DM-DR conversion, we can in principle calculate the evolution of perturbations self-consistently

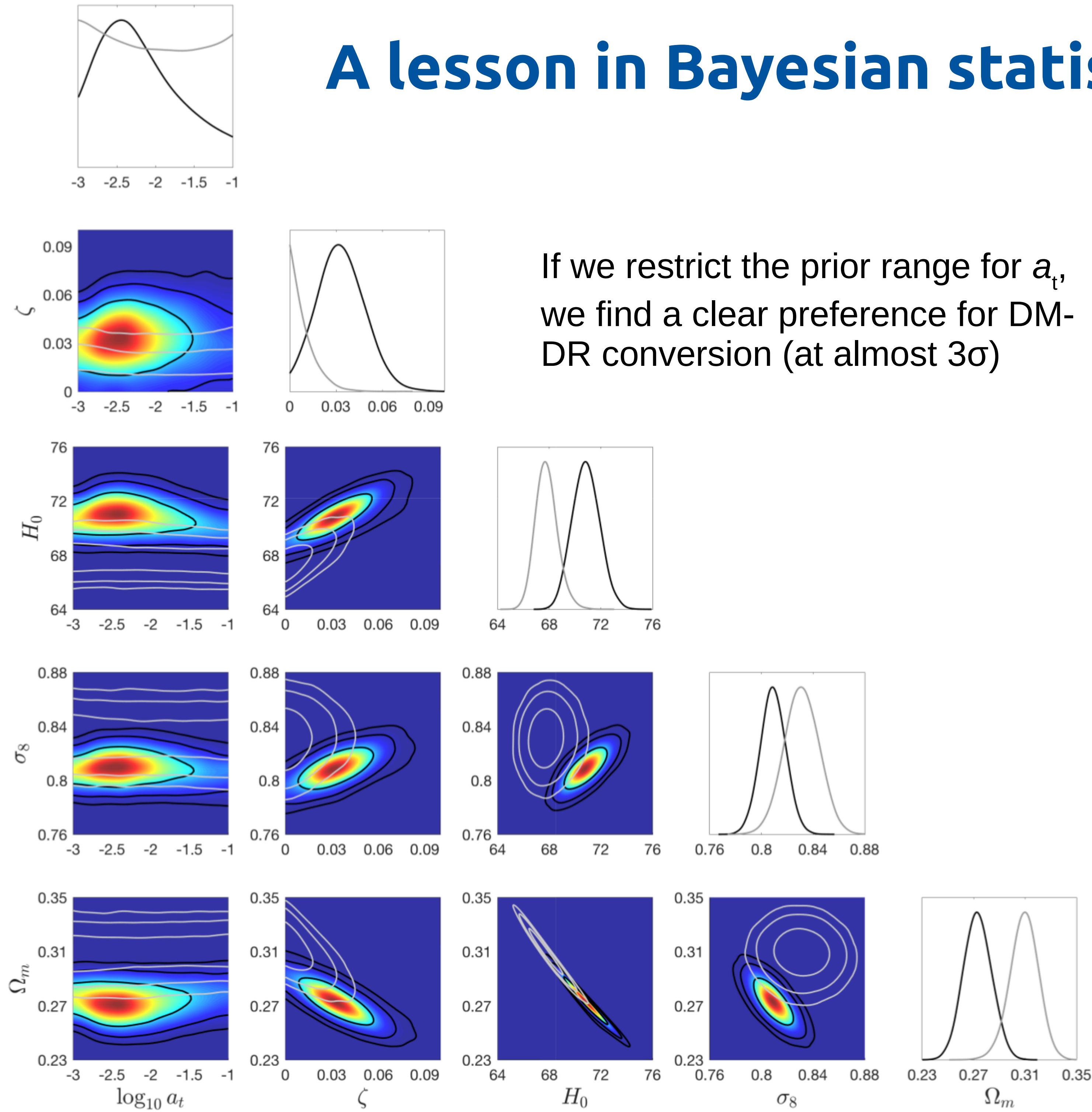
- For resonant Sommerfeld enhancement, we find

$$\delta Q/Q = \delta_\chi \to \frac{1}{3}h + 2\delta_\chi$$

- This gives basically no change relative to our previous description



# A lesson in Bayesian statistics




If we restrict the prior range for $a_t$, we find a clear preference for DM-DR conversion (at almost 3σ)