Title: Kinetic decoupling and the matter distribution at high redshift

Speakers: Benjamin Lehmann

Collection: Dark Matter, First Light

Date: February 28, 2024 - 11:00 AM

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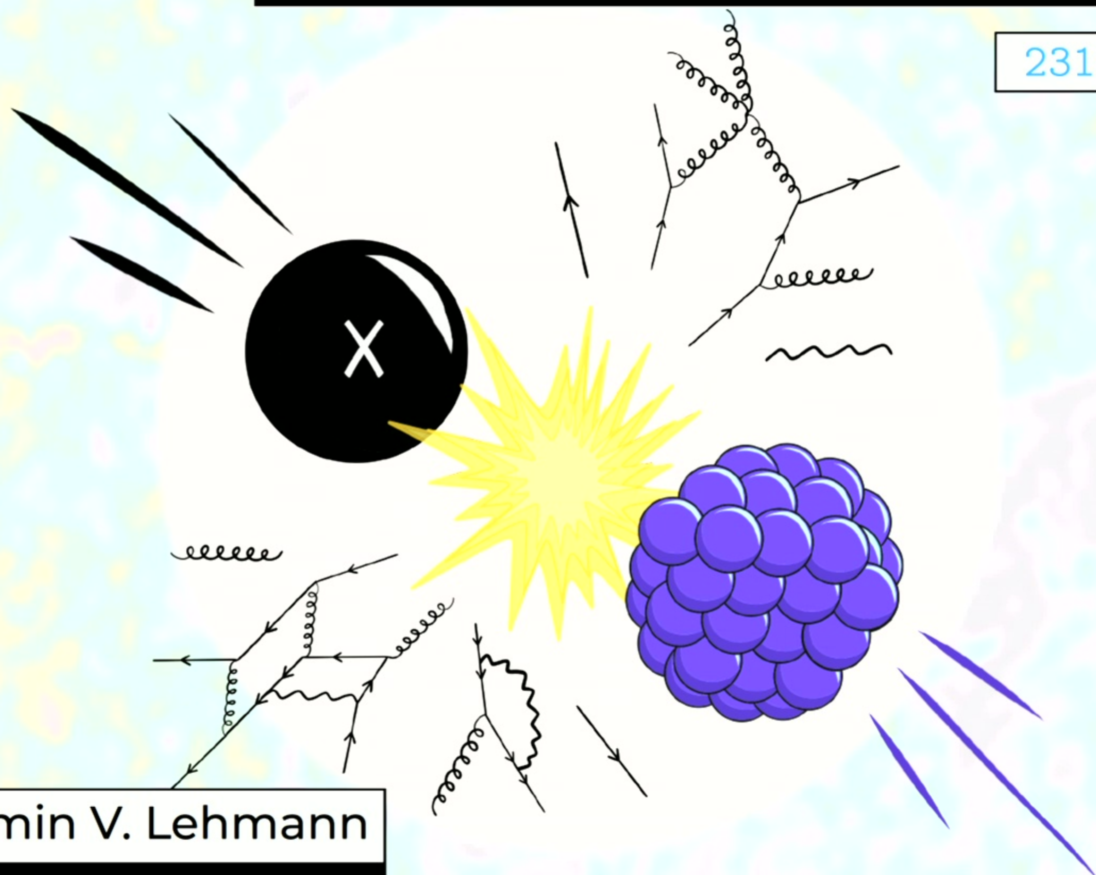
Kinetic recoupling of dark matter

2310.20513



Benjamin V. Lehmann

Massachusetts Institute of Technology

with Stefano Profumo, Nolan Smyth, & Logan Morrison


Kinetic recoupling of dark matter
2310.20513
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Benjamin V. Lehmann
Massachusetts Institute of Technology
→ Ciela Inst. ∈ Montreal!
with Stefano Profumo, Nolan Smyth, & Logan Morrison

This talk in one slide

1. A new thermal history

Kinetic decoupling? Kinetic recoupling!

3. Implementation

Possible origins for a kinetic recoupling

1

This talk in one slide

1. A new thermal history

Kinetic decoupling? Kinetic recoupling!

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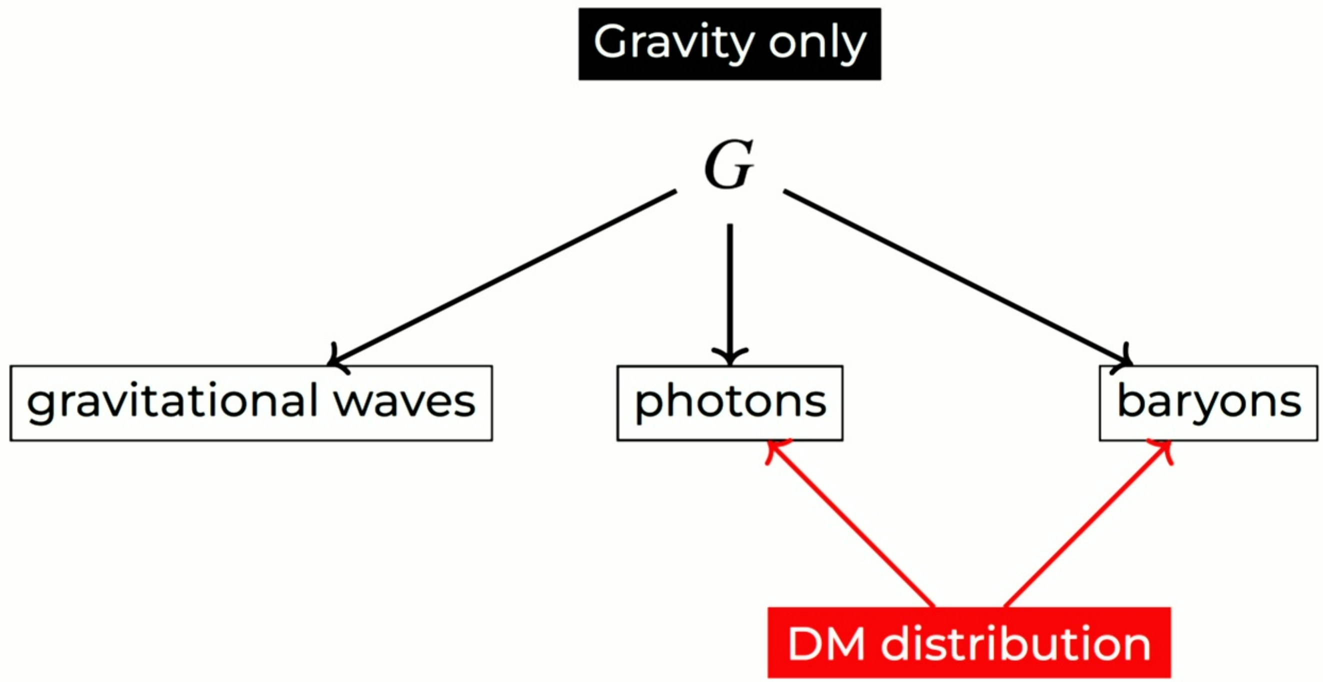
Possible origins for a kinetic recoupling

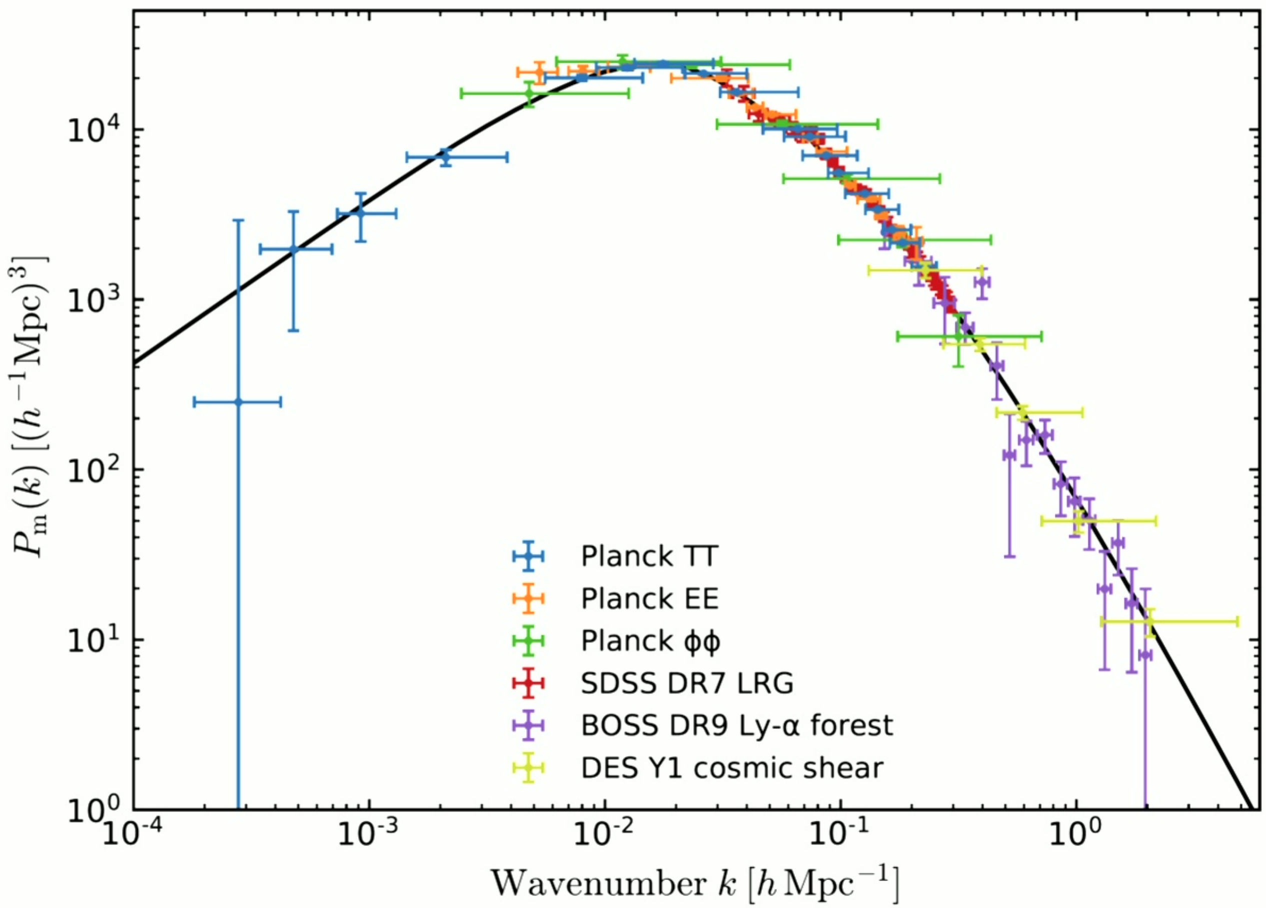
2. The DM distribution

Implications for the matter power spectrum

Probing sequestered dark sectors



Experimental progress



3 Planck Collaboration 2018

Small-scale power and 21 cm c.f. Rahul's talk

Suppression of small structure delays 21 cm evolution

Molecular cooling

No stars ⟷ Atomic cooling

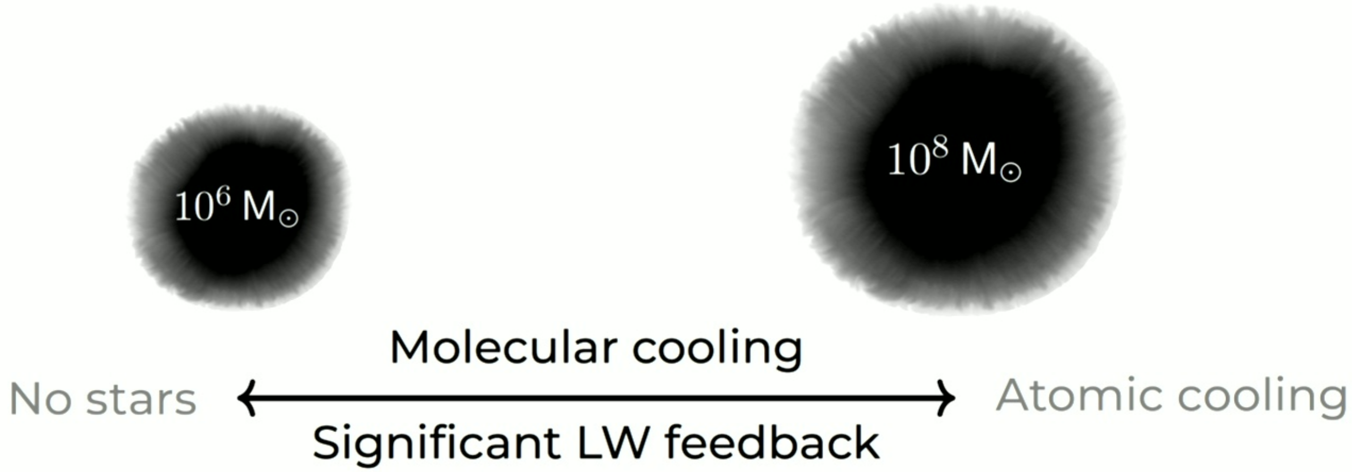
Significant LW feedback

SFR probes $40\,\mathrm{Mpc}^{-1} < k < 100\,\mathrm{Mpc}^{-1}$ **(**$12 < z < 15$**)**

Muñoz, Dvorkin, & Cyr-Racine 1911.11144

Small-scale power and 21 cm c.f. Rahul's talk

Suppression of small structure delays 21 cm evolution

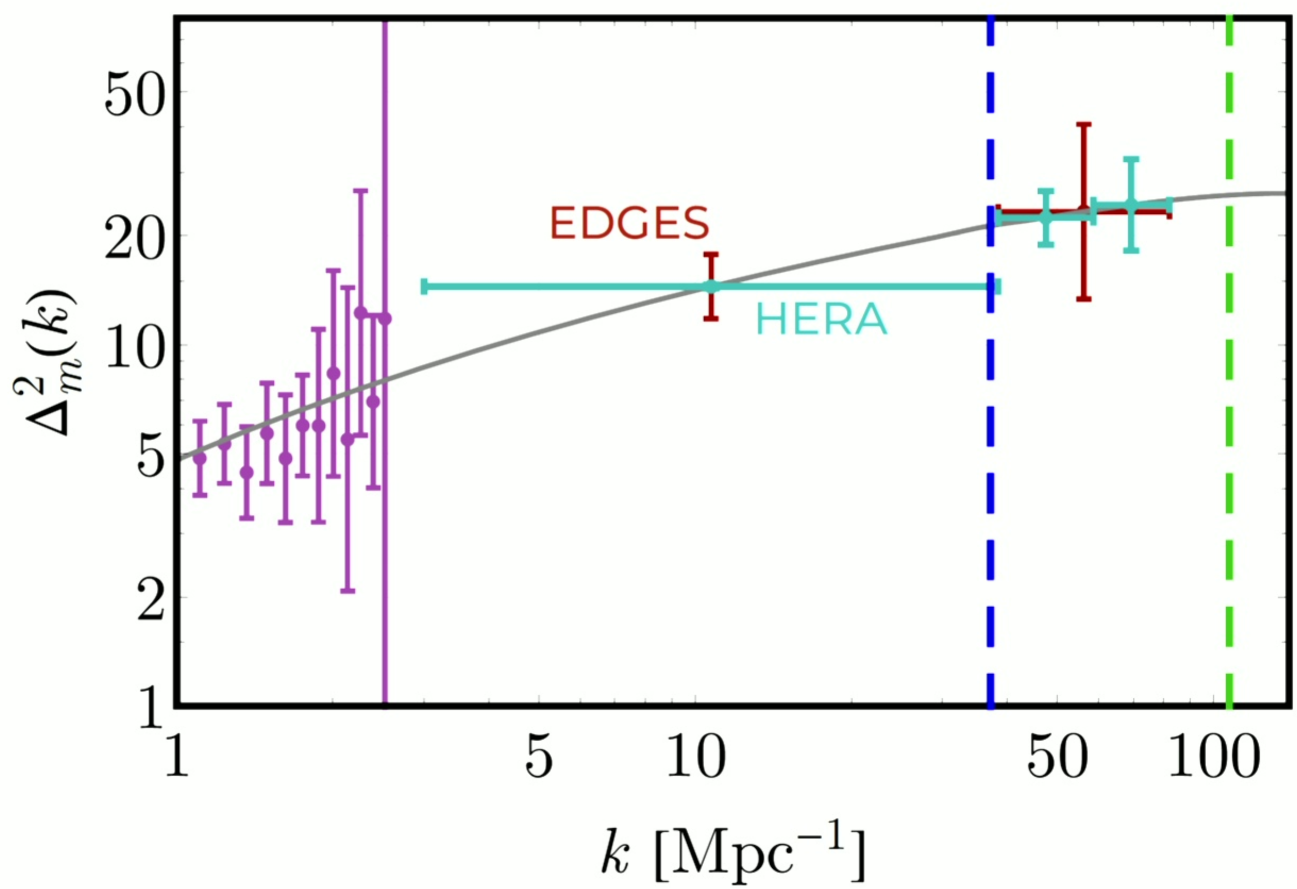


SFR probes $40\,\mathrm{Mpc}^{-1} < k < 100\,\mathrm{Mpc}^{-1}$ **(**$12 < z < 15$**)**

Caveats: baryons and nonlinearity

4 Muñoz, Dvorkin, & Cyr-Racine 1911.11144

21 cm forecasts



5 Muñoz, Dvorkin, & Cyr-Racine 1911.11144

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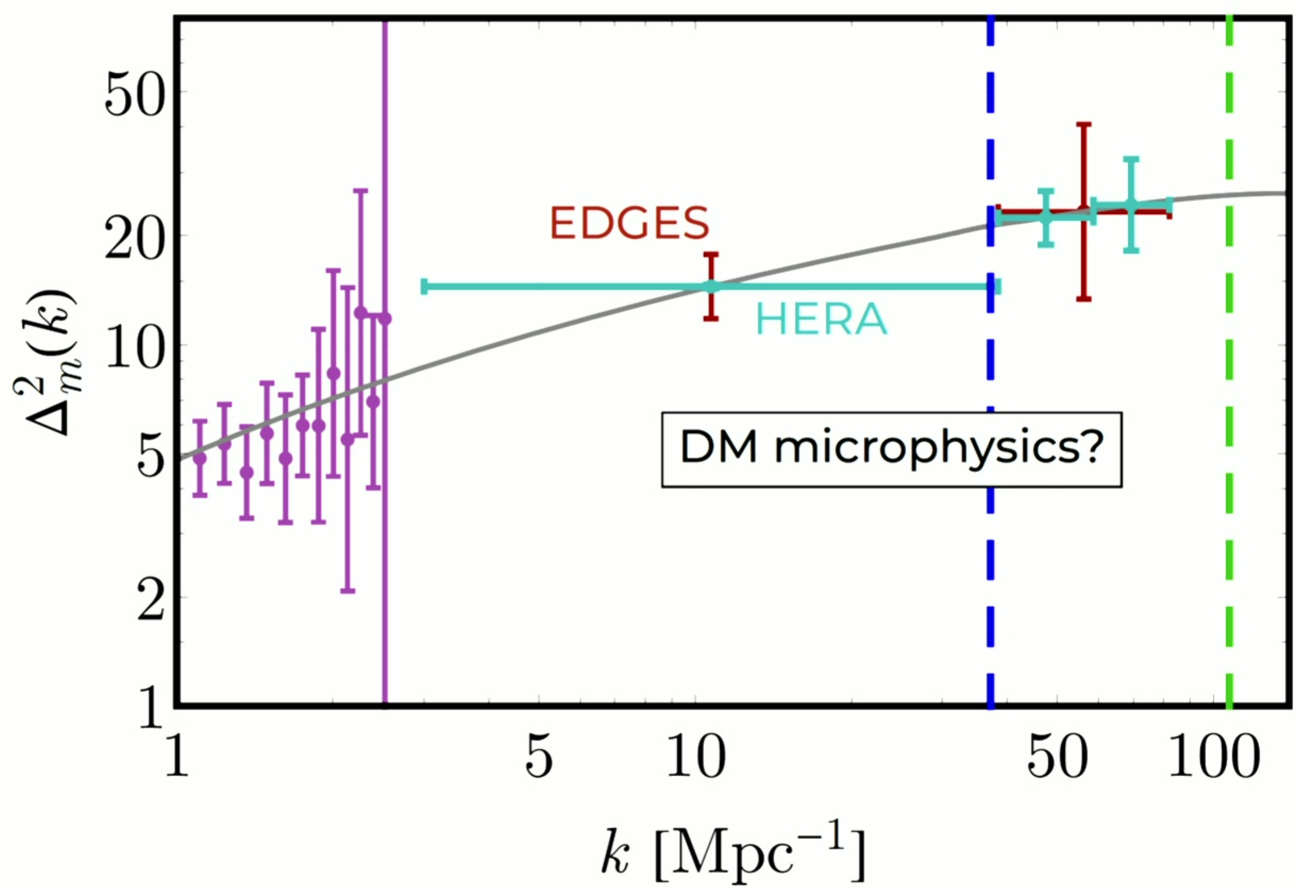
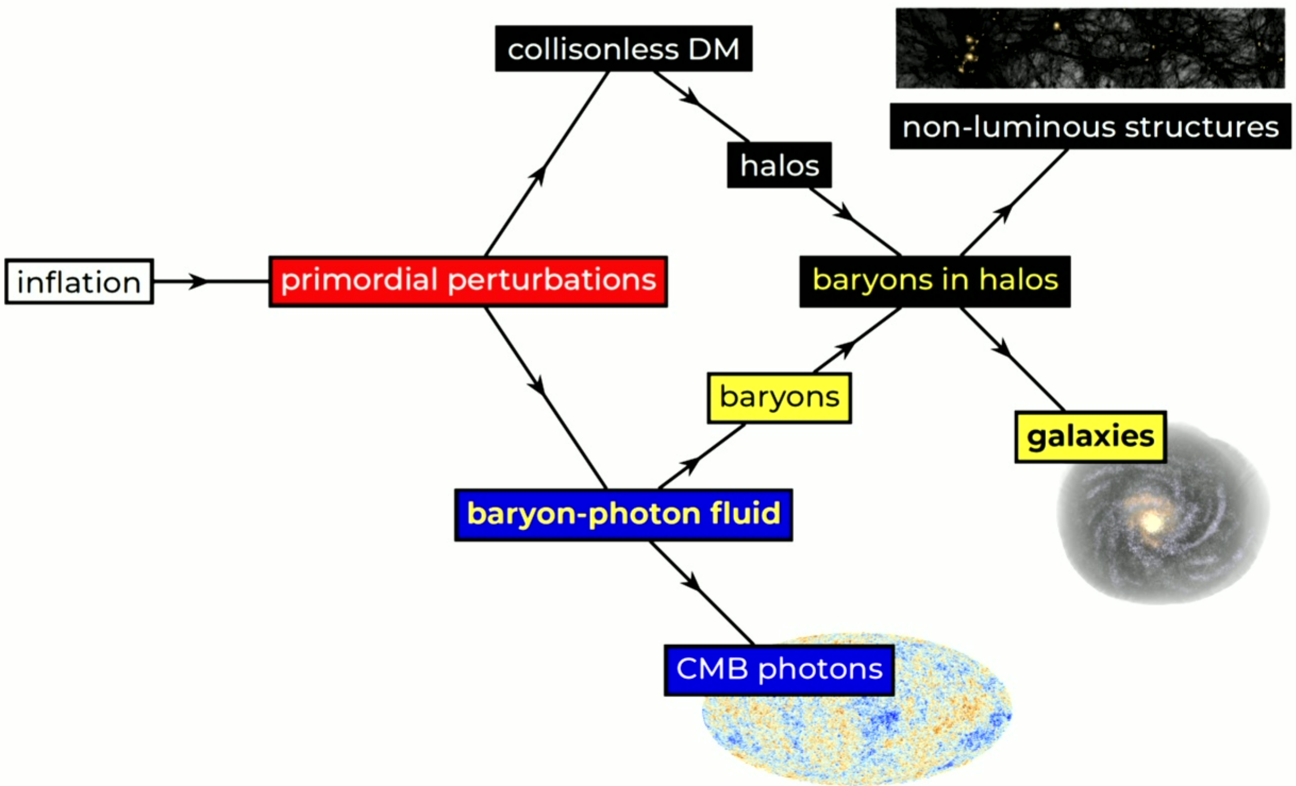


5 Muñoz, Dvorkin, & Cyr-Racine 1911.11144

The story of structure



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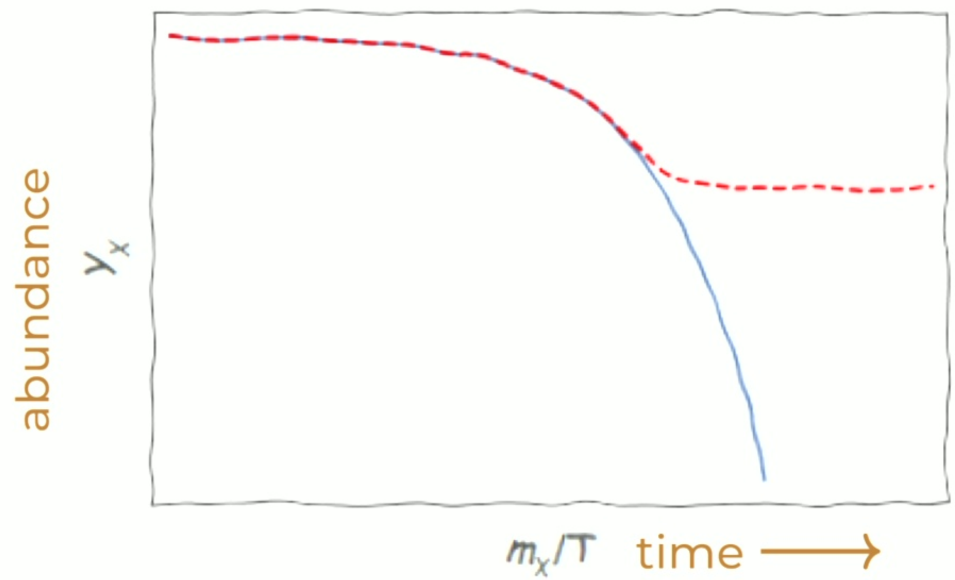
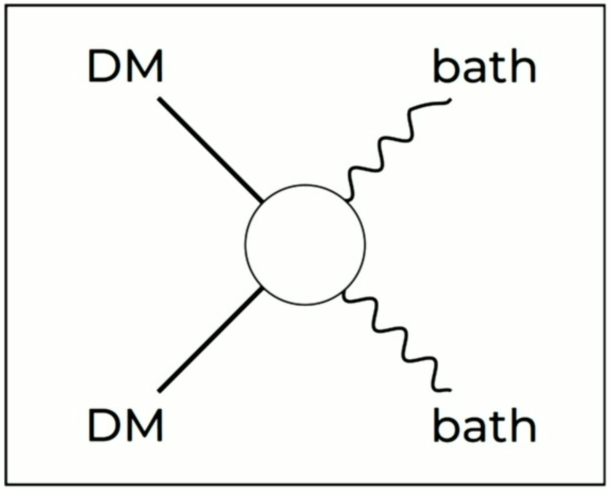
WIMPs and decoupling



Conditions set at **decoupling**

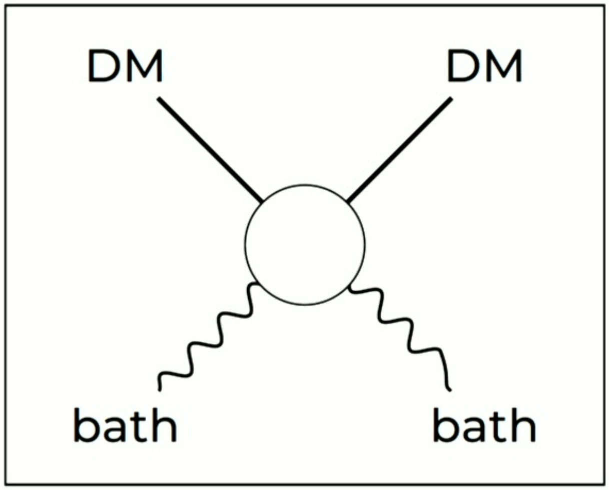
Decoupling: chemical vs. kinetic

Chemical equilibrium



Fast number-changing

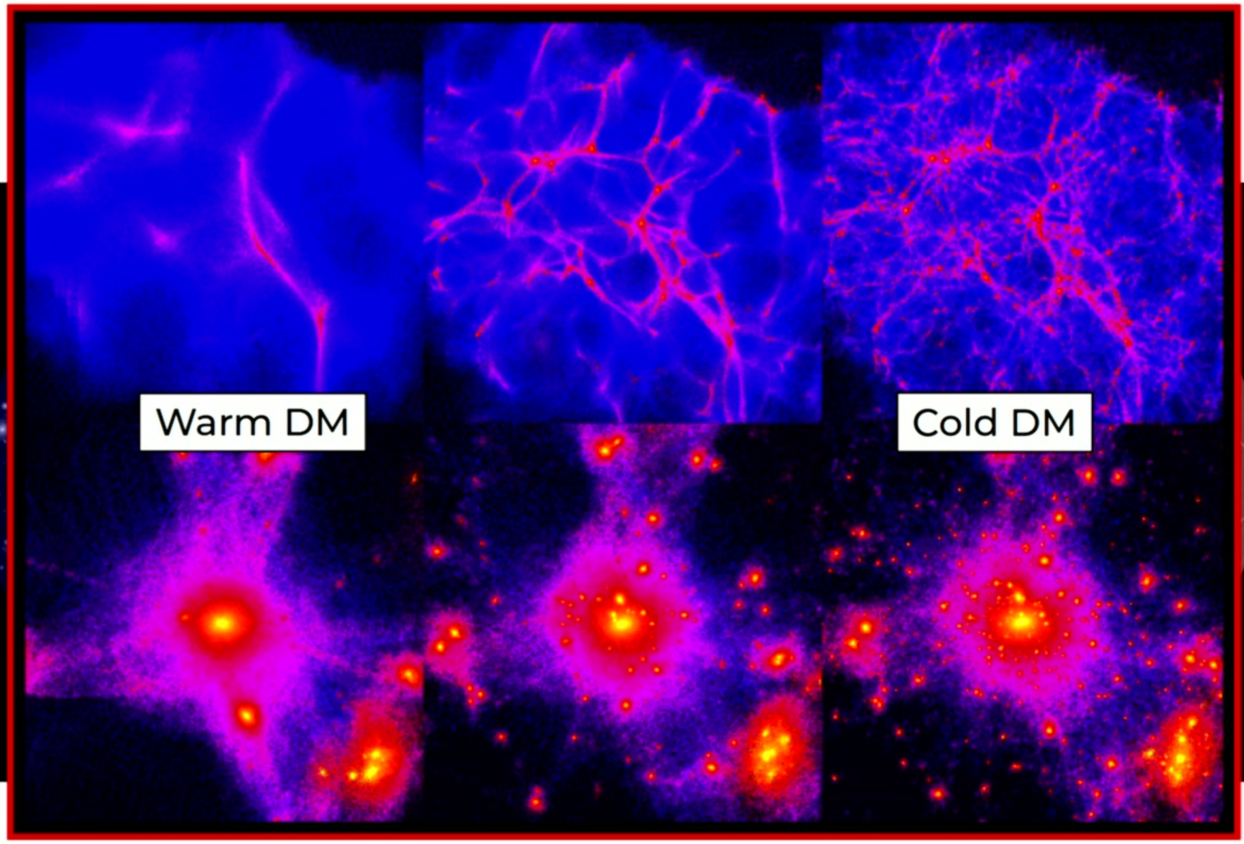
Kinetic equilibrium



Fast momentum-changing

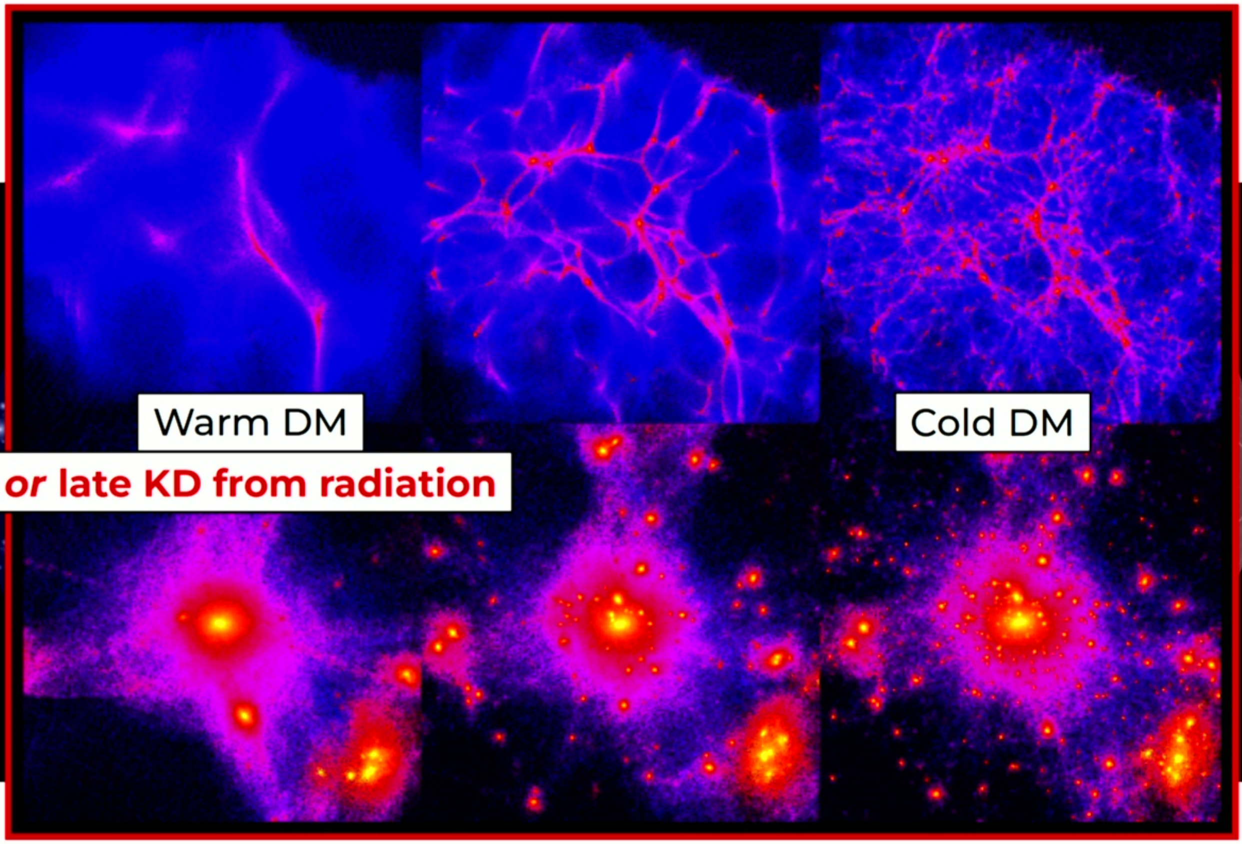
(Left diagram also maintains kinetic equilibrium!)

Nonminimal kinetic decoupling



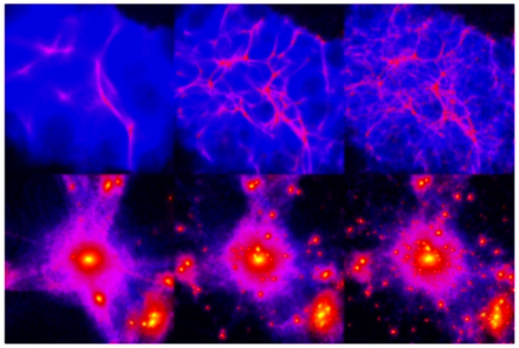
9 Bullock & Boylan-Kolchin 1707.04256

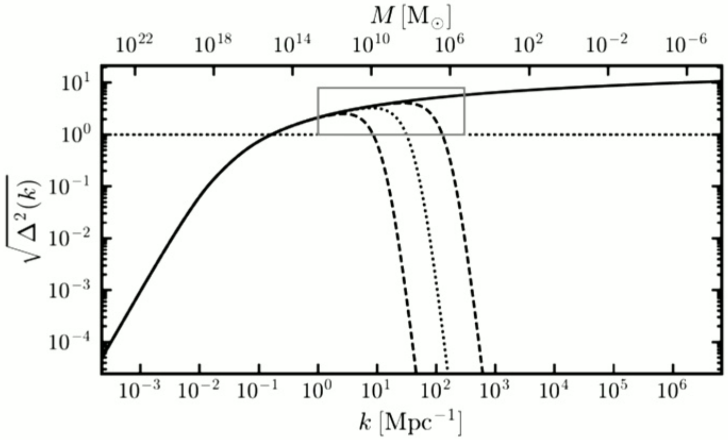
Nonminimal kinetic decoupling



9 Bullock & Boylan-Kolchin 1707.04256

Decoupling and the power spectrum





warm or *late* decoupling

Structured dark sectors $\longrightarrow$ complicated decoupling

Generic predictions

PHYSICAL REVIEW D **88,** 015027 (2013)

Kinetic decoupling and small-scale structure in effective theories of dark matter

Jonathan M. Cornell,[1,2,3,*] Stefano Profumo,[2,3,†] and William Shepherd[2,3,‡]

[1]*Department of Physics, Oskar Klein Centre for Cosmoparticle Physics, Stockholm University, SE-106 91 Stockholm, Sweden*
[2]*Department of Physics, University of California, 1156 High Street, Santa Cruz, California 95064, USA*
[3]*Santa Cruz Institute for Particle Physics, Santa Cruz, California 95064, USA*

(Received 20 May 2013; published 24 July 2013)

The size of the smallest dark matter collapsed structures, or protohalos, is set by the temperature at which dark matter particles fall out of kinetic equilibrium. The process of kinetic decoupling involves elastic scattering of dark matter off of Standard Model particles in the early universe, and the relevant cross section is thus closely related to the cross section for dark matter scattering off of nuclei (direct detection) but also, via crossing symmetries, for dark matter pair production at colliders and for pair annihilation. In this study, we employ an effective-field-theoretic approach to calculate constraints on the kinetic decoupling temperature, and thus on the size of the smallest protohalos, from a variety of direct, indirect and collider probes of particle dark matter.

Generic predictions

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elastic scattering of dar… iverse, and the relevant
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kinetic decoupling temp… from a variety of direct,
indirect and collider pro…

$$\mathcal{O}_S = \frac{m_f}{\Lambda_S^3}\bar{\chi}\chi\bar{f}f, \quad (1)$$

$$\mathcal{O}_P = \frac{m_f}{\Lambda_P^3}\bar{\chi}\gamma^5\chi\bar{f}\gamma^5 f, \quad (2)$$

$$\mathcal{O}_V = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma^\mu\chi\bar{f}\gamma_\mu f, \quad (3)$$

$$\mathcal{O}_A = \frac{1}{\Lambda_V^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{f}\gamma_\mu\gamma^5 f, \quad (4)$$

$$\mathcal{O}_T = \frac{m_f}{\Lambda_T^3}\bar{\chi}\sigma^{\mu\nu}\chi\bar{f}\sigma_{\mu\nu} f, \quad (5)$$

Generic predictions

PHYSICAL REVIEW D **93,** 123527 (2016)

ETHOS—an effective theory of structure formation: From dark particle physics to the matter distribution of the Universe

Francis-Yan Cyr-Racine,[1,2,*] Kris Sigurdson,[3,4] Jesús Zavala,[5] Torsten Bringmann,[6] Mark Vogelsberger,[7] and Christoph Pfrommer[8]

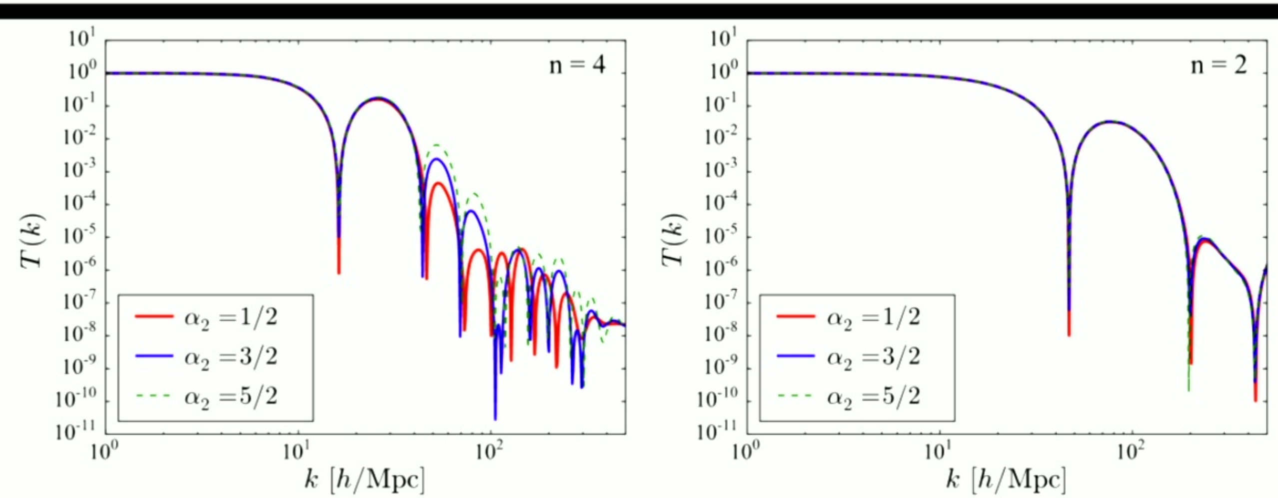
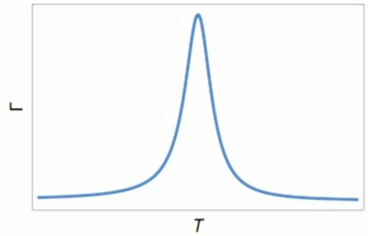
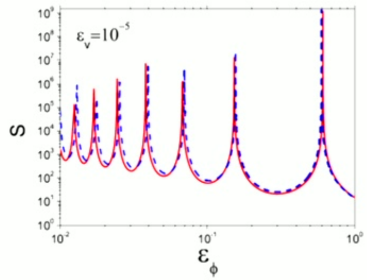


FIG. 2. Left panel: Transfer function for three different values of α_2 for a model characterized by a nonvanishing value of a_4. The

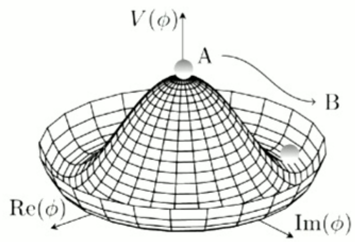
Nontrivial time dependence c.f. chemical decoupling



Resonant interaction



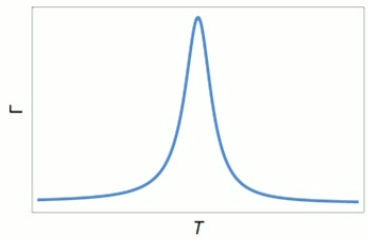
Sommerfeld enhancement



Phase transition

12 Feng+ 1005.4678

Nontrivial time dependence c.f. chemical decoupling



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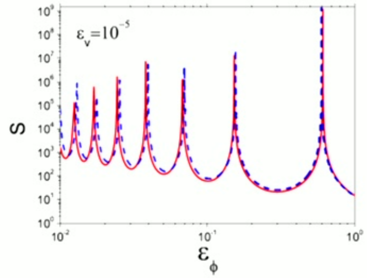
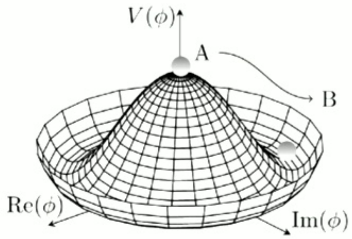


Sommerfeld enhancement



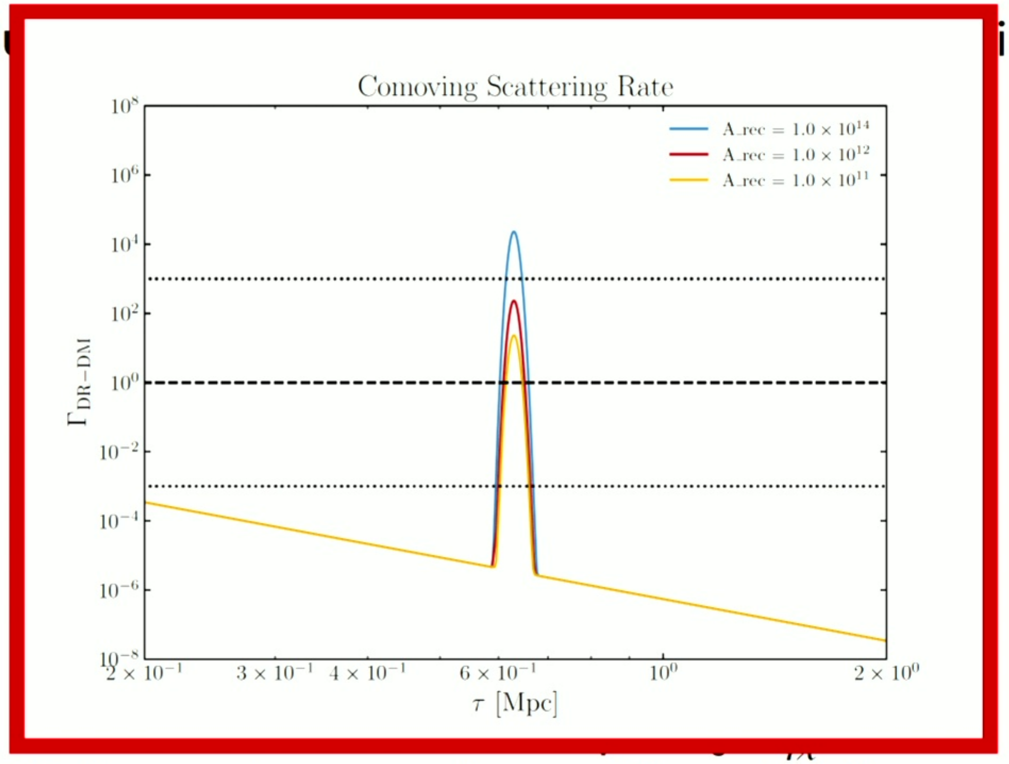
Phase transition

New possibility: **kinetic recoupling**

 Feng+ 1005.4678

Kinetic *re*coupling: basic picture

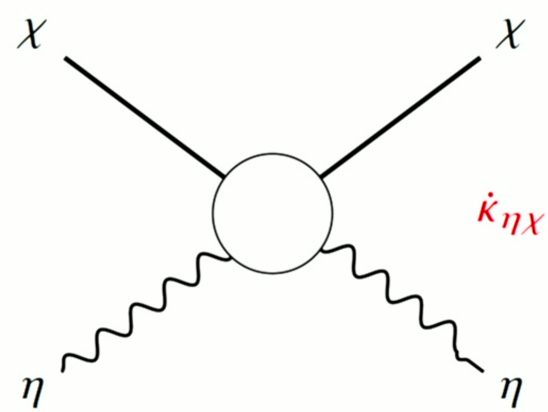
Secl … ion η



DM–DR decouple normally, and then briefly **recouple**

Kinetic *re*coupling: basic picture

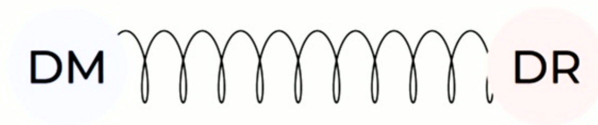
Secluded dark sector with matter χ and radiation η



Non-monotonic opacity $\dot{\kappa}_{\eta\chi}$
DM–DR decouple normally, and then briefly **recouple**

Kinetic decoupling and structure

Consider a coupled matter–radiation fluid



DM perturbations are damped by:

1. DM free-streaming
2. Collisional (acoustic) damping
3. Induced (Silk / diffusion) damping from DR

$$\ell_{\rm fs} \simeq \bar{v}_{\rm kd} a_{\rm kd} \int_{\tau_{\rm kd}}^{\tau} \frac{{\rm d}\tau'}{a(\tau')} \longrightarrow \left(\frac{m_\chi}{T_{\rm kd}}\right)^{1/2} \frac{a_{\rm eq}/a_{\rm kd}}{\log(4a_{\rm eq}/a_{\rm kd})} a_{\rm eq} H_{\rm eq}$$

Boehm+ astro-ph/0012504; Loeb+ astro-ph/0504112; Bertschinger astro-ph/0607319

Damping scales for kinetic recoupling

A *tight* recoupling introduces two new scales:

$$\Delta\tau_{\rm dec} = \tau_{\rm rec} - \tau_{\rm kd1}$$

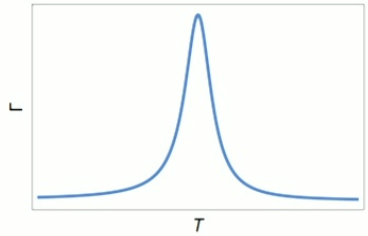
$$\Delta\tau_{\rm rec} = \tau_{\rm kd2} - \tau_{\rm rec}$$

Three differences for DM perturbations:

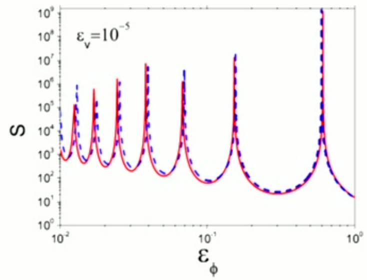
1. DM free-streaming is **interrupted** $\sim \Delta\tau_{\rm dec}$
2. Collisional damping on **smaller scale** $r_s^{\rm rec} \sim \Delta\tau_{\rm rec}$
3. Induced damping: **DR** perturbations **evolve** $\sim \Delta\tau_{\rm dec}$

Implementing kinetic recoupling

Implementation



Resonant interaction



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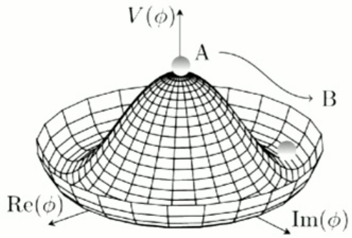
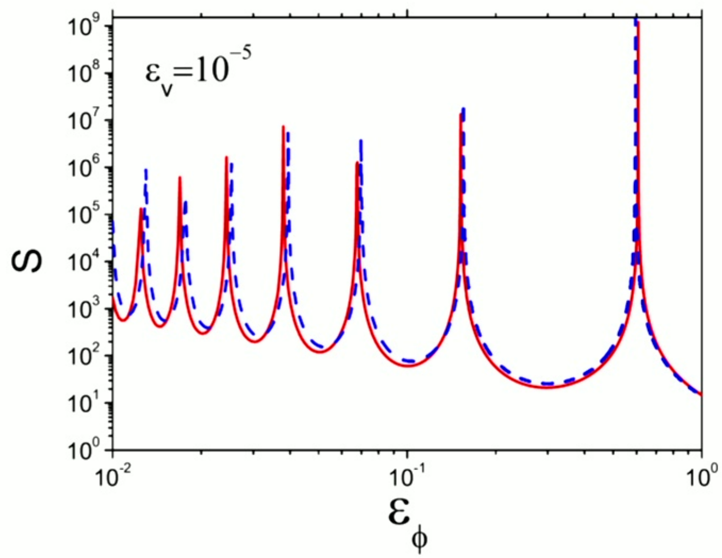


Phase transition

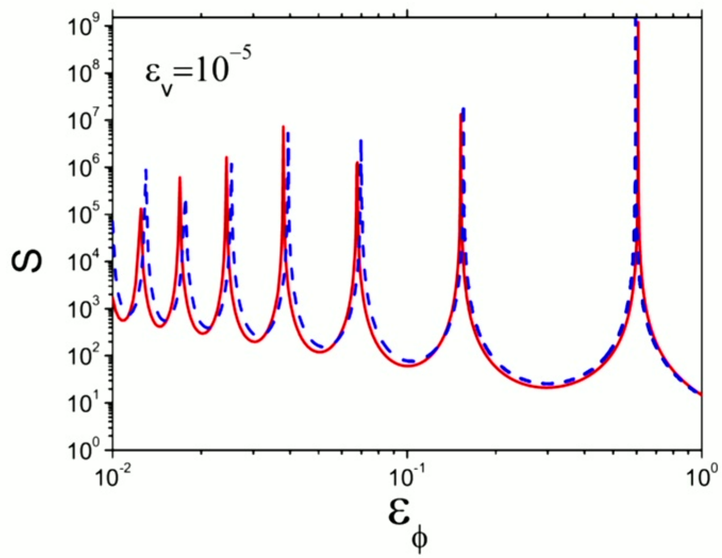
Sommerfeld enhancement



Intrinsically nonrelativistic

Feng+ 1005.4678

Sommerfeld enhancement

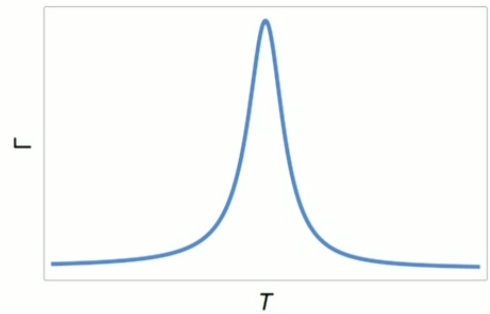


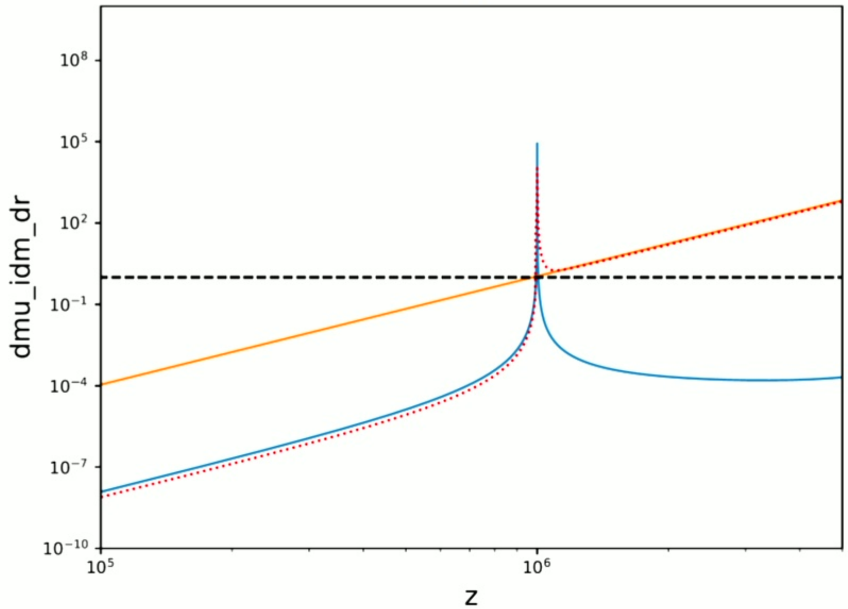
Intrinsically nonrelativistic

(Possible, but requires mediator bath)

 Feng+ 1005.4678

Resonance





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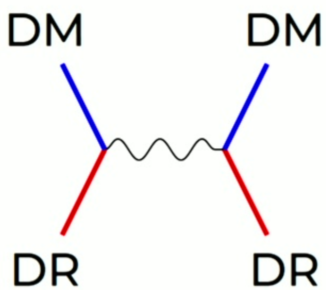
Do resonances recouple?



Near resonance; $M = m_\chi + \epsilon$

$$\mathcal{M} \simeq \frac{\mathcal{M}_s}{s - M^2 + iM\Gamma}$$
$$= -\frac{iM\Gamma}{(s-M^2)^2 + M^2\Gamma^2}\mathcal{M}_s + \mathcal{M}_{\text{regular}}$$

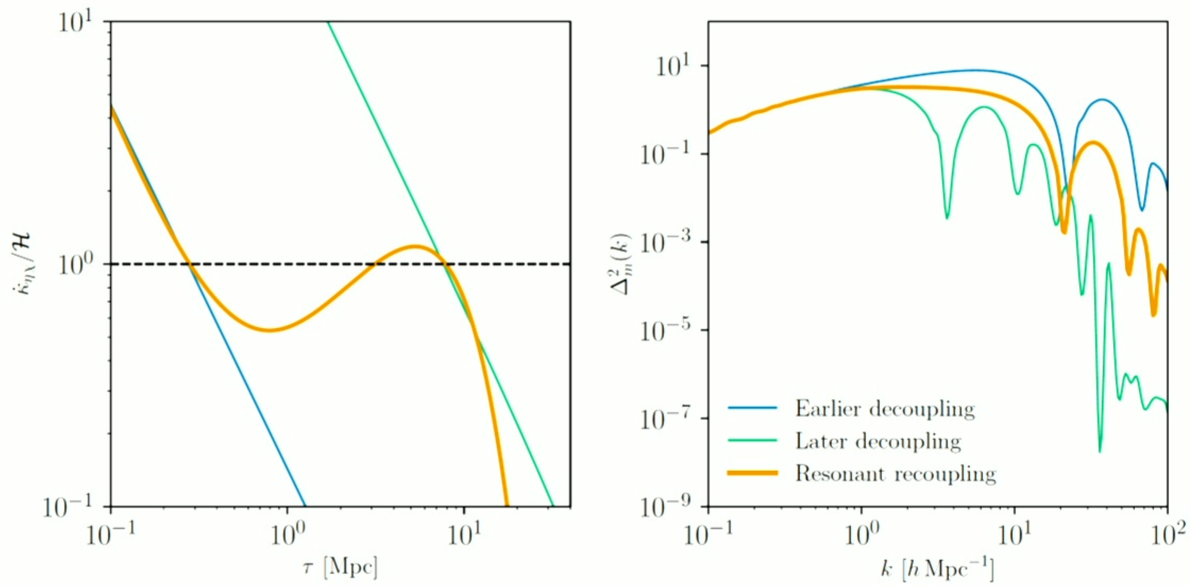
$$\frac{\dot{\kappa}^{\text{res}}_{\eta\chi}(T)}{\mathcal{H}} \sim \frac{1}{a}\int \frac{\mathrm{d}z}{2m_\chi}\frac{(M\Gamma)^2}{(z^2 + (M\Gamma))^2}\left(-k^4 \frac{\mathrm{d}f_\eta}{\mathrm{d}\omega}\left\langle |\mathcal{M}_s|^2 \right\rangle_t\right)$$

$$\sim \begin{cases} \begin{cases} e^{-\epsilon/T}, & T \ll \epsilon \\ 1, & T \gg \epsilon \end{cases} & \text{bosonic DR} \\ \begin{cases} e^{-\epsilon/T}, & T \ll \epsilon \\ \frac{4T^2}{\epsilon^2}, & T \gg \epsilon. \end{cases} & \text{fermionic DR} \end{cases}$$

Does the rate actually increase?

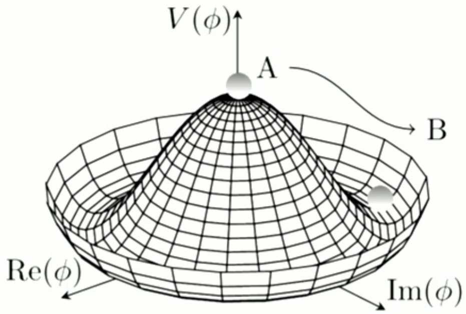
Recoupling through resonance

Does the rate actually increase?



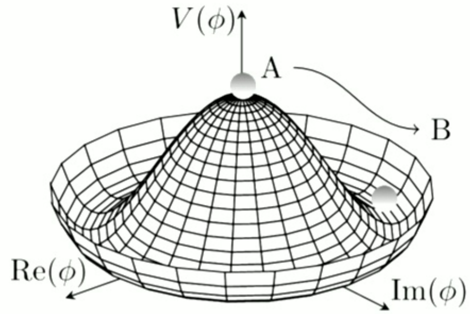
Yes, with tuning

Phase transition



e.g., $\mathcal{L} \supset g_1\chi\eta\varphi_1 + g_2\chi\eta\varphi_1\varphi_2$ acquiring large $\langle\varphi_2\rangle$

Phase transition



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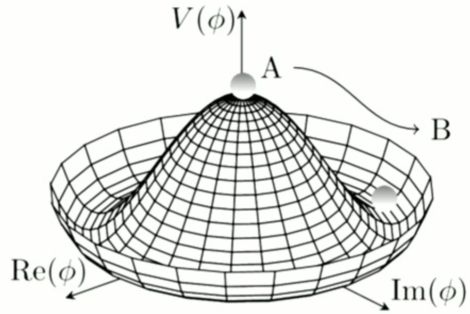

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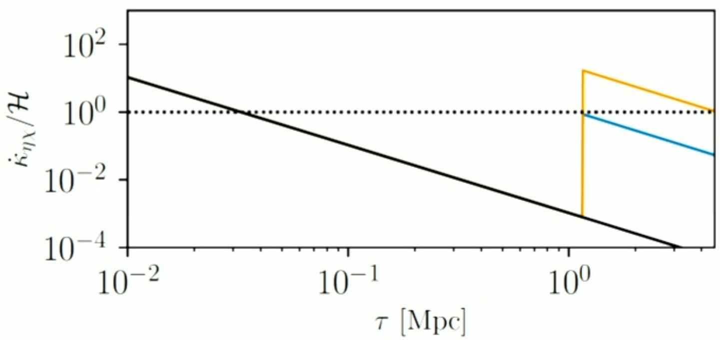

The power spectrum with kinetic recoupling

Coupled DM–DR perturbations

Linear evolution in conformal Newtonian gauge

DM perturbations: $\Delta\theta \equiv \theta_\eta - \theta_\chi,\ S \equiv \frac{4}{3}\frac{\rho_\chi}{\rho_\eta}$

$$\begin{cases} \dot{\delta}_\chi + \theta_\chi - 3\dot{\phi} = 0, \\ \dot{\theta}_\chi - c_\chi^2 k^2 \delta_\chi + \mathcal{H}\theta_\chi - k^2\psi = -S\dot{\kappa}_{\eta\chi}\Delta\theta \end{cases}$$

DR perturbations:

$$\begin{cases} \dot{\delta}_\eta + \frac{4}{3}\theta_\eta - 4\dot{\phi} = 0, \\ \dot{\theta}_\eta + k^2\left(\sigma_\eta - \frac{1}{4}\delta_\eta\right) - k^2\psi = \dot{\kappa}_{\eta\chi}\Delta\theta \end{cases}$$

$\theta \sim$ divergence of velocity field

$\phi \simeq \psi \sim$ total potential

Cyr-Racine+ 1512.05344; Ma & Bertschinger astro-ph/9506072

Perturbations in a tight recoupling

"Strong" recoupling ($\dot{\kappa}/\mathcal{H} \gg 1$) $\longrightarrow$ matter–radiation fluid

$$\theta_\chi \simeq \theta_\eta, \quad \delta_\chi \simeq \frac{3}{4}\delta_\eta, \quad \sigma_\eta \simeq c_\chi \simeq 0$$

Where do θ_χ, θ_η meet? Careful: $\dot{\kappa}_{\eta\chi}\Delta\theta$ is not small!

$$\delta_\eta(\tau) \equiv \tfrac{4}{3}\delta_\chi(\tau)\,[1+\epsilon(\tau)]\,, \quad \dot{\kappa}_{\eta\chi} \equiv \gamma(\tau)/\epsilon(\tau), \quad \Delta\theta \equiv \Omega(\tau)/\epsilon(\tau)$$

$$\boxed{\theta_\chi + \dot{\delta}_\chi - 3\dot{\phi} \simeq 0, \quad \dot{\theta}_\chi \simeq k^2\psi - \mathcal{H}\theta_\chi - \Omega S\gamma, \quad -\mathcal{H}\theta_\chi \simeq \tfrac{1}{3}k^2\delta_\chi + (1+S)\Omega\gamma}$$

Estimate θ after recoupling: linearize $\theta_i(\tau) = \theta_i(\tau_0) + \dot{\theta}_i(\tau_0)\Delta\tau$ after recoupling. Rapid evolution stops when $\Delta\theta = 0$.

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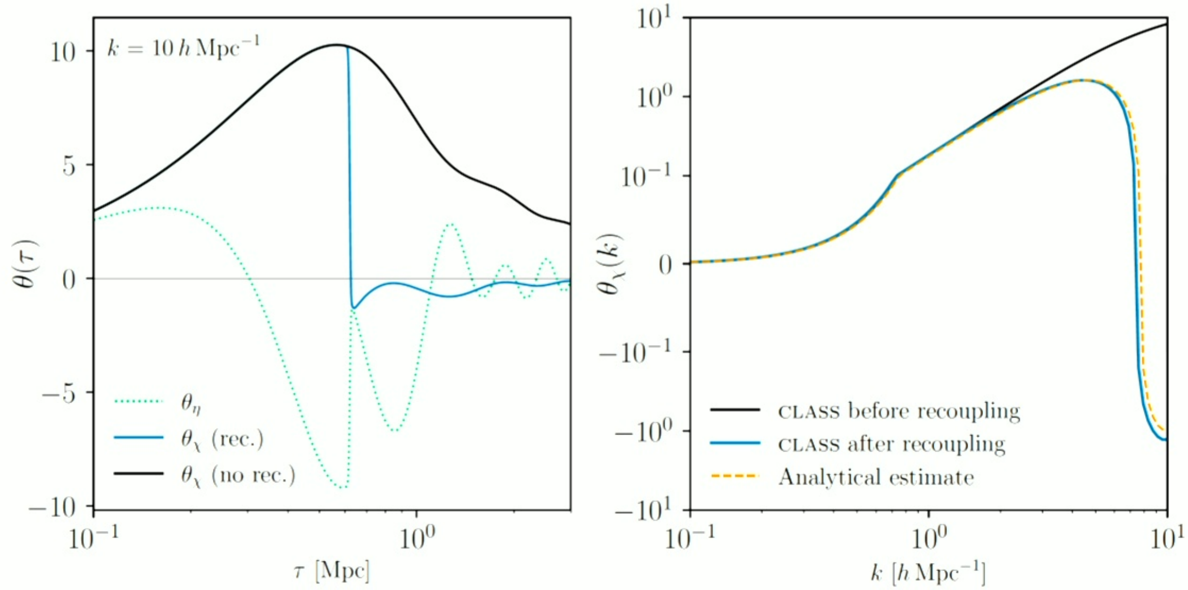
Expect a kick: a sudden change in $\dot{\delta}$

Check: brief recoupling in CLASS

$$\theta(\text{after}) \simeq \left. \frac{k^2\delta_\eta\theta_\chi - 4k^2\psi\,\Delta\theta + 4\mathcal{H}\theta_\chi\theta_\eta + 4\,\Delta\theta\,(\theta_\chi + S\theta_\eta)\dot{\kappa}_{\eta\chi}}{k^2\delta_\eta + 4\mathcal{H}\theta_\chi + 4(1+S)\,\Delta\theta\,\dot{\kappa}_{\eta\chi}} \right|_{\tau=\tau_0}$$



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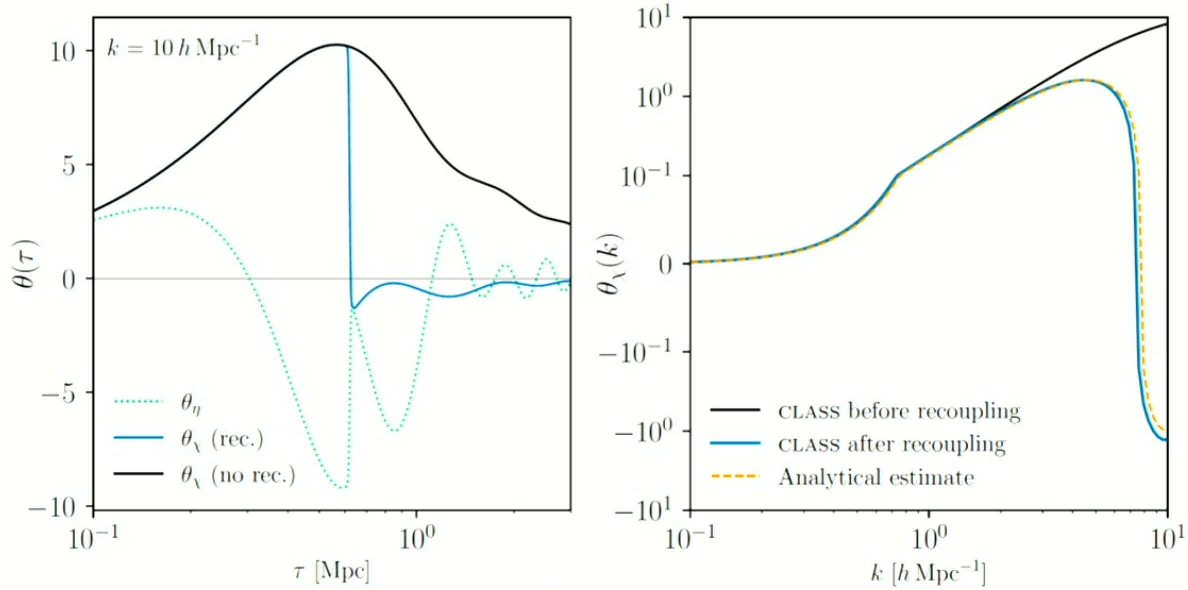
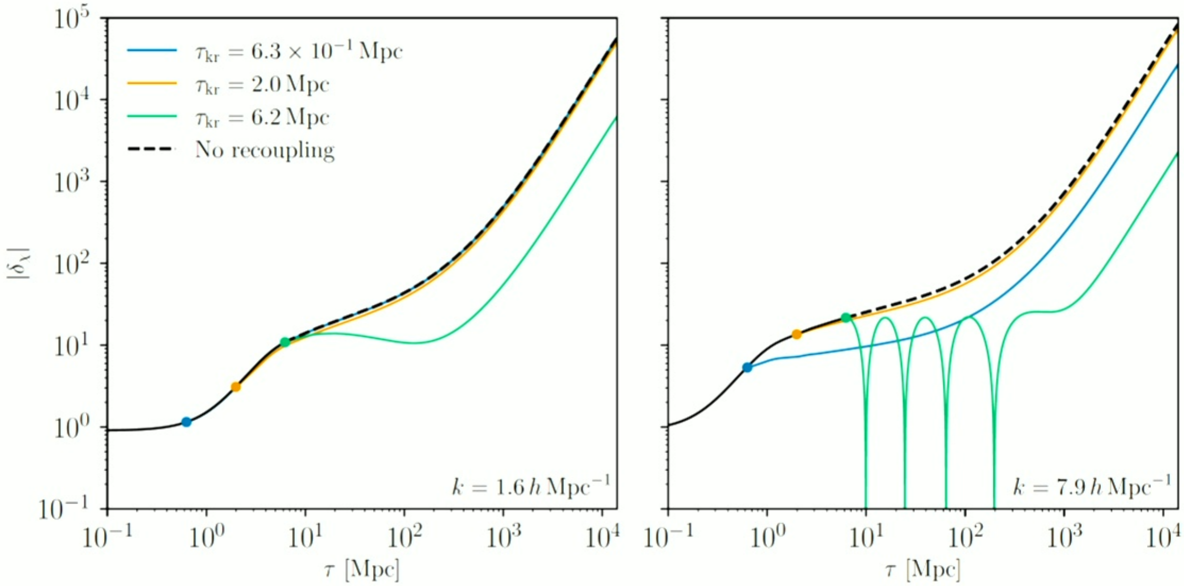
Check: brief recoupling in CLASS

$$\theta(\text{after}) \simeq \left.\frac{k^2\delta_\eta\theta_\chi - 4k^2\psi\,\Delta\theta + 4\mathcal{H}\theta_\chi\theta_\eta + 4\,\Delta\theta\,(\theta_\chi + S\theta_\eta)\dot{\kappa}_{\eta\chi}}{k^2\delta_\eta + 4\mathcal{H}\theta_\chi + 4(1+S)\,\Delta\theta\,\dot{\kappa}_{\eta\chi}}\right|_{\tau=\tau_0}$$



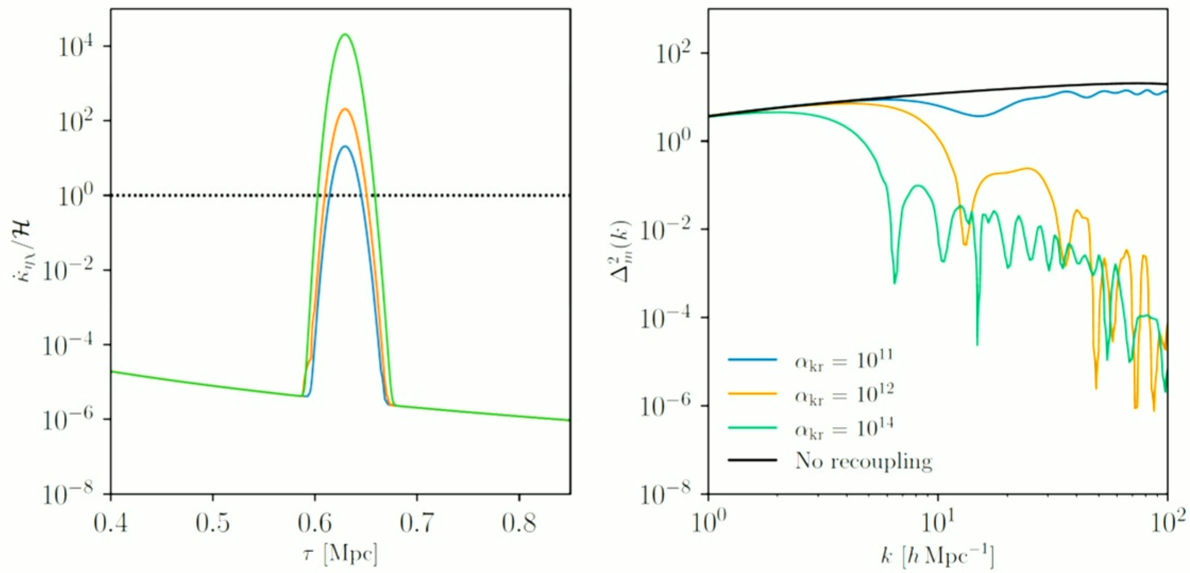
The kick is predictable

Understanding the kick

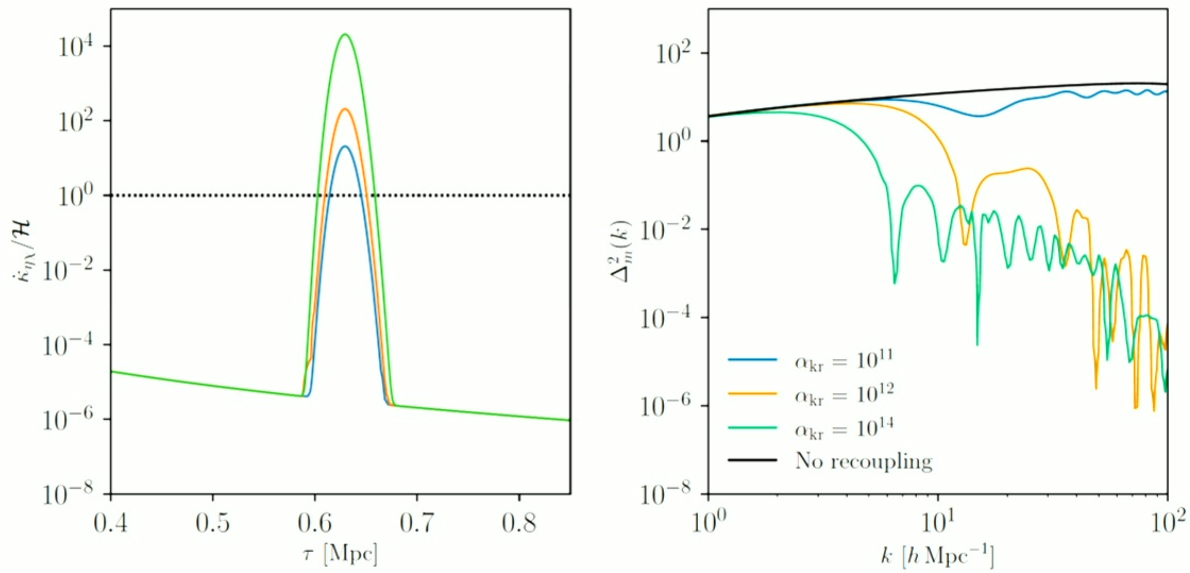


Scale-dependent delay to structure formation

The matter power spectrum



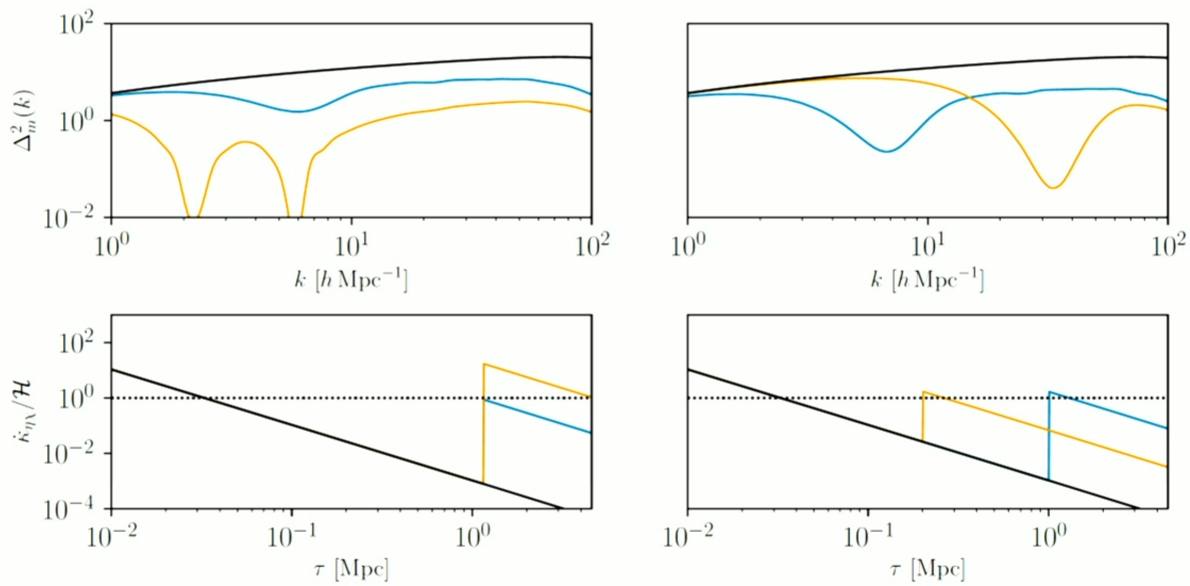
The matter power spectrum



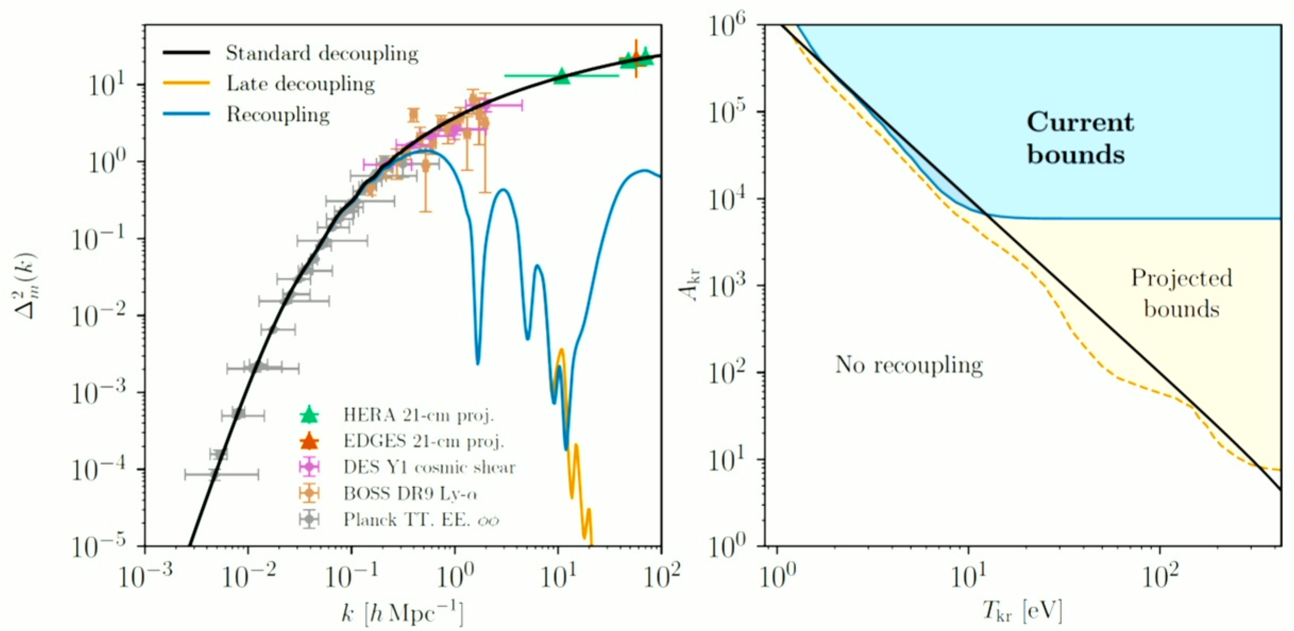
How can we interpret this?

Recoupling time and duration

Step-function enhancement (like phase transition)

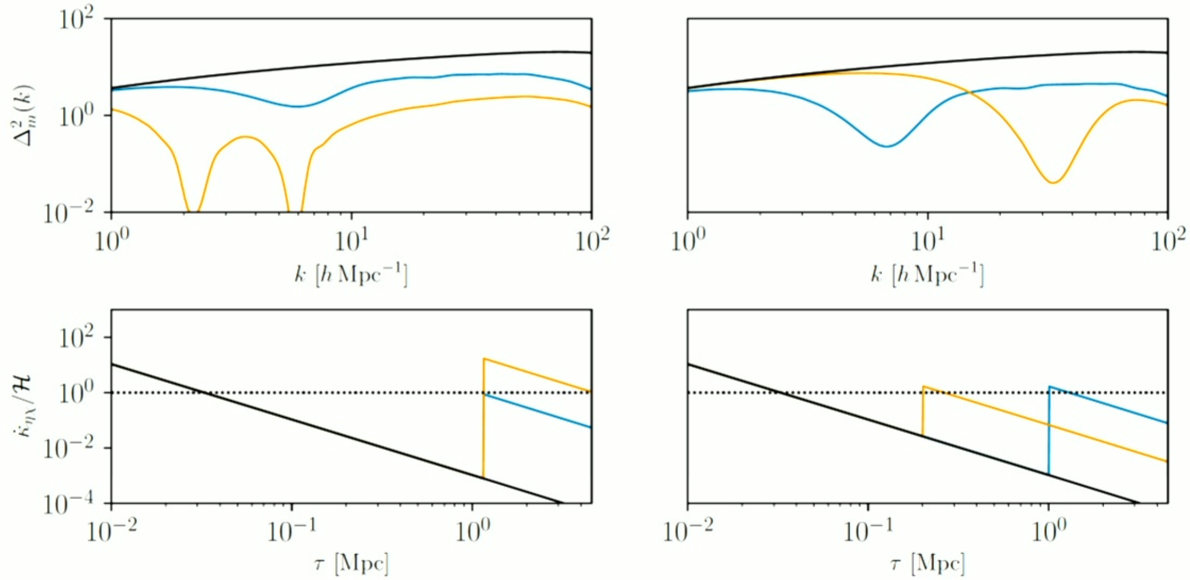


Interpretable constraints



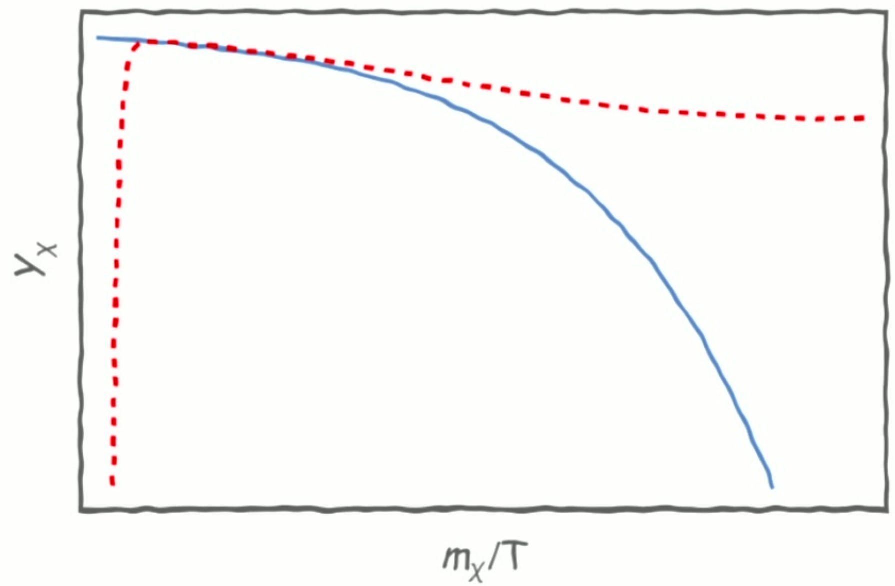
Recoupling time and duration

Step-function enhancement (like phase transition)



- Recoupling time ↔ feature scale
- Recoupling duration ↔ feature depth

Next: freeze-in!



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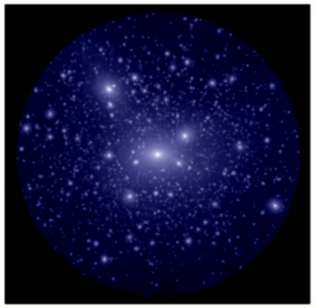
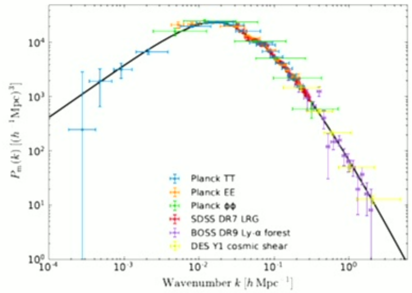
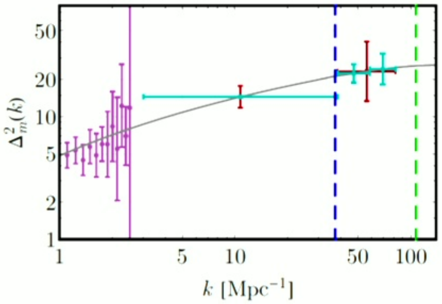
Conclusions

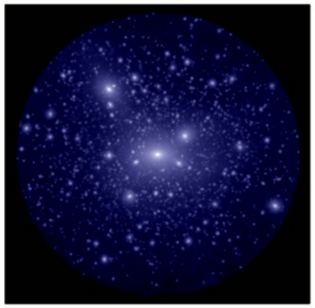


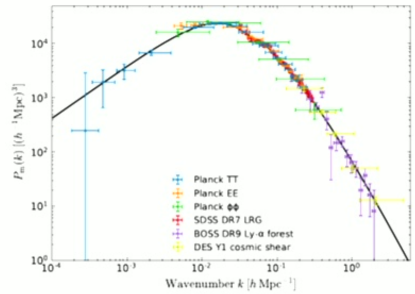


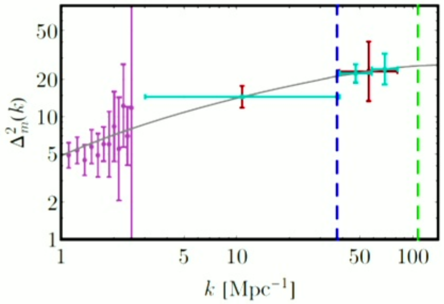


1. DM can kinetically *re*couple
2. Nontrivial time evolution in *kinetic* decoupling
3. Nonminimal observable for dark sectors

Conclusions



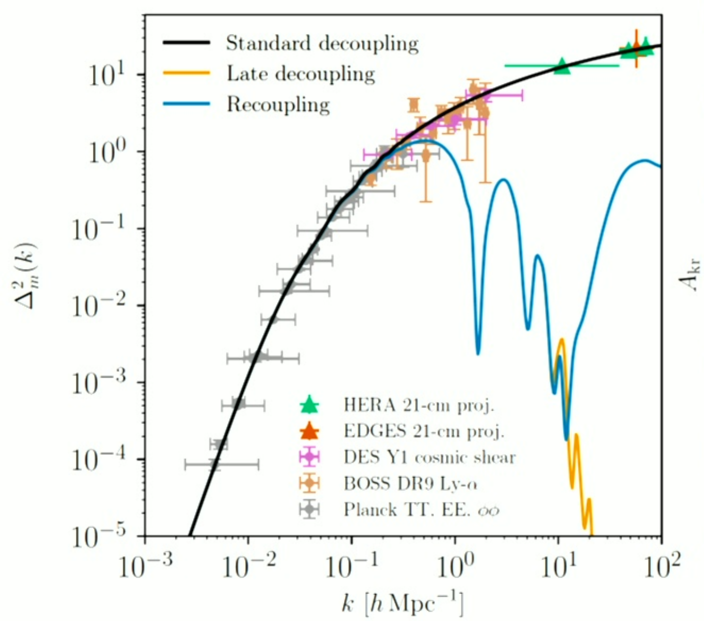


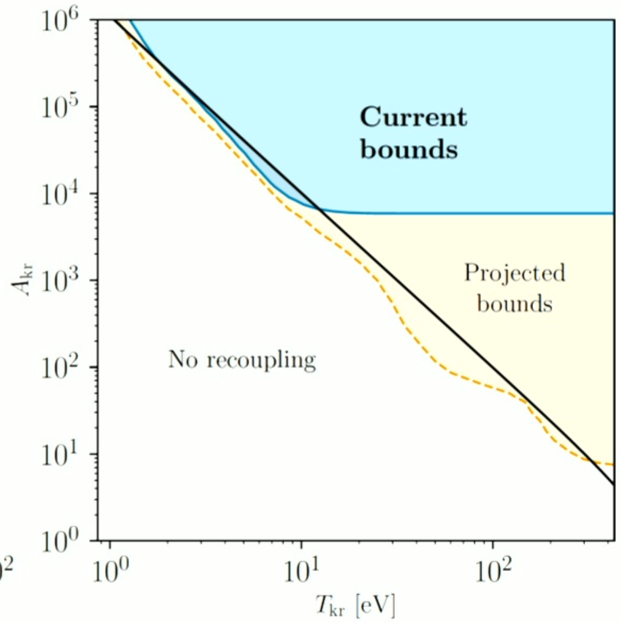


1. DM can kinetically *re*couple
2. Nontrivial time evolution in *kinetic* decoupling
3. Nonminimal observable for dark sectors

Goes beyond a cutoff in the power spectrum

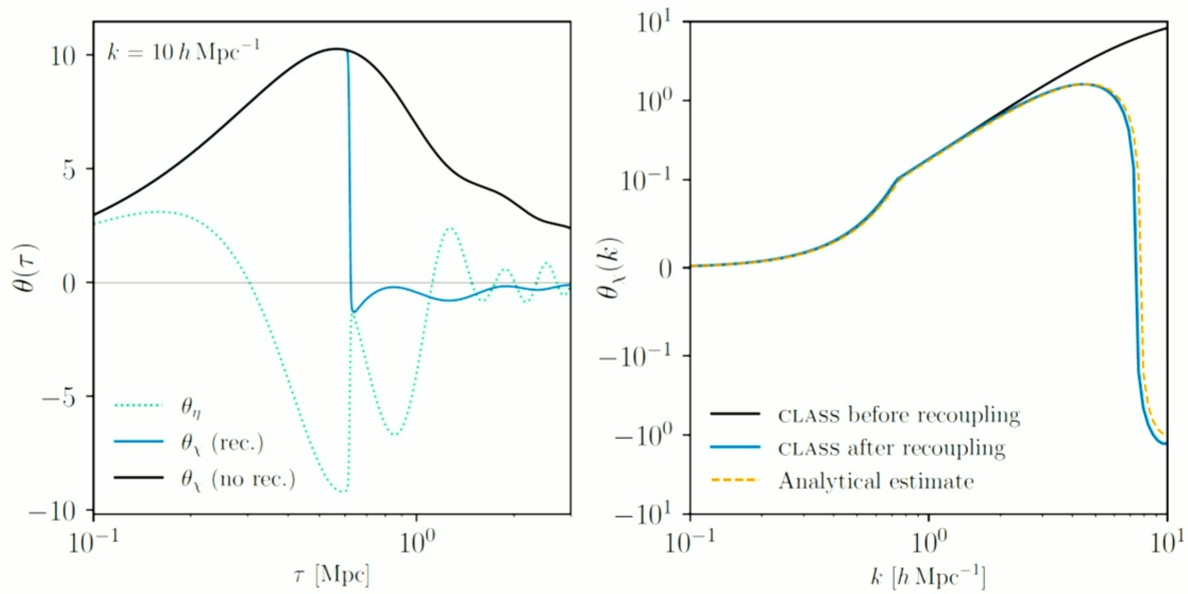
Interpretable constraints





Check: brief recoupling in CLASS

$$\theta(\text{after}) \simeq \left. \frac{k^2\delta_\eta\theta_\chi - 4k^2\psi\,\Delta\theta + 4\mathcal{H}\theta_\chi\theta_\eta + 4\,\Delta\theta\,(\theta_\chi + S\theta_\eta)\dot{\kappa}_{\eta\chi}}{k^2\delta_\eta + 4\mathcal{H}\theta_\chi + 4(1+S)\,\Delta\theta\,\dot{\kappa}_{\eta\chi}} \right|_{\tau=\tau_0}$$



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