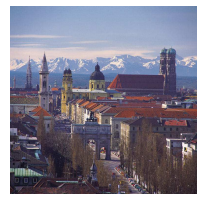
Probing interacting dark sectors with cosmology

Mathias Garny (TUM Munich)

TECHNISCHE UNIVERSITÄT MÜNCHEN



Seminar on particle physics, University of Vienna, 21.01.25

Dark Matter

- Galactic (rotation curves) [kpc]

  Freeman, Rubin, Ford,. . . 1970s

  e.g. Genzel et al Nature 543 (2017) 397

- Galaxy clusters [Mpc]

  Fritz Zwicky 1933

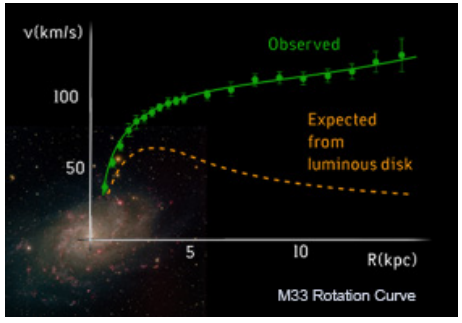
  Bullet Cluster, Clowe et al AJ 648 (2006) L109

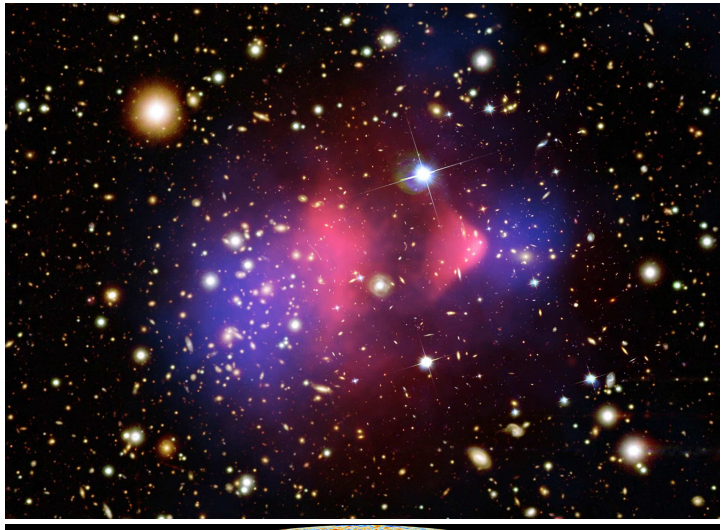
- Cosmic microwave background (CMB)/large-scale structure (LSS) [100 Mpc – Gpc]

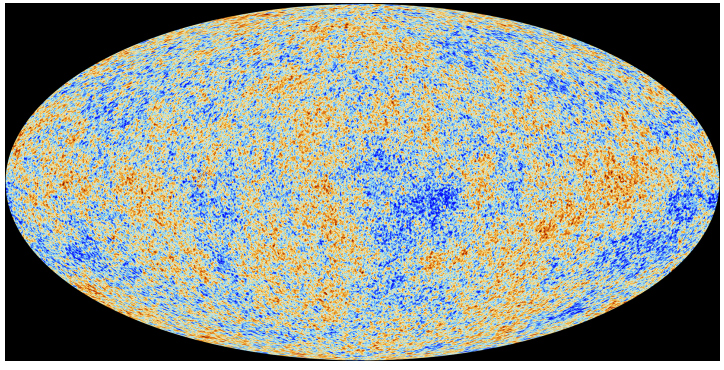
$$\Omega_{DM} h^2 = \frac{\rho_{DM}}{10.50\,\mathrm{GeV/m^3}} = 0.120 \pm 0.001$$

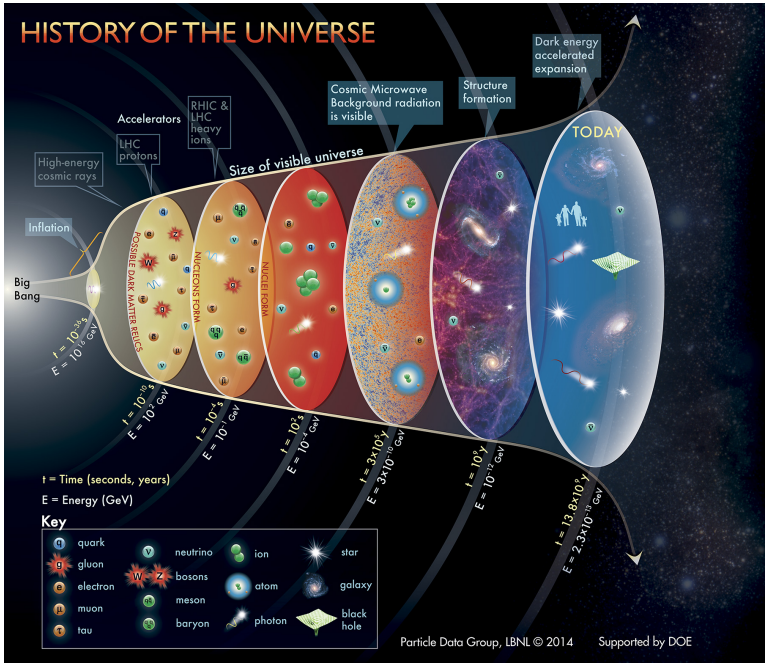
Planck Mission (ESA) 1807.06209

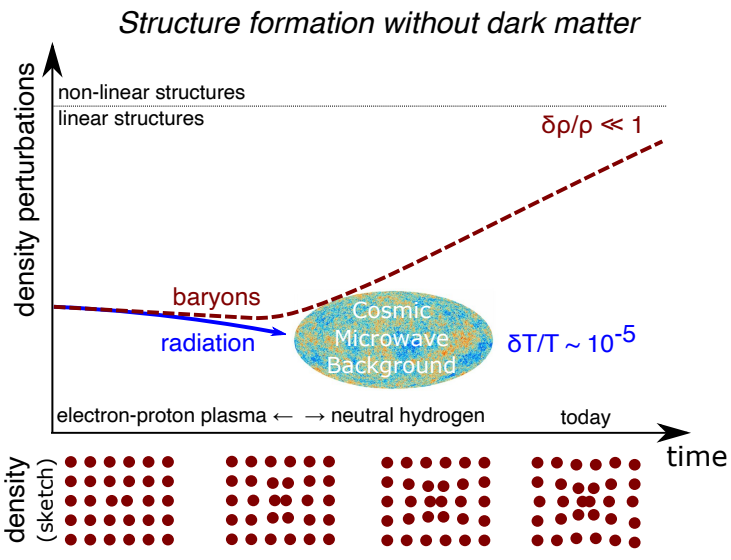
SDSS/BOSS 1909.11006, DESI 2404.03002 2411.12022

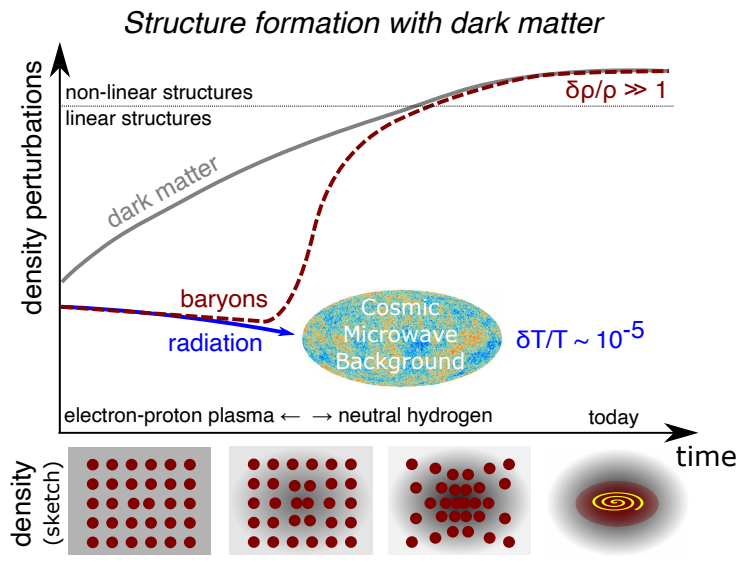








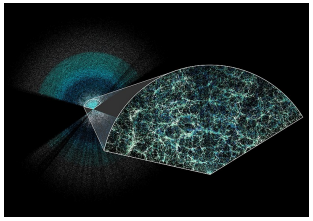


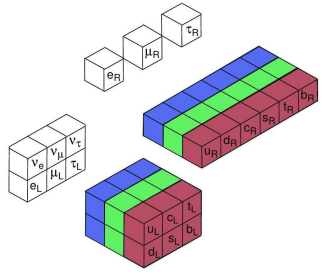


Balazs et al 2411.05062

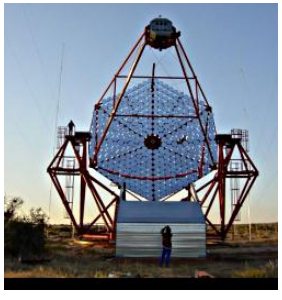
Particle
HEP/lab

Cosmo
CMB/LSS



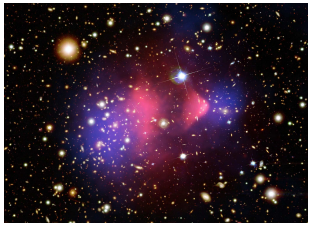


$+ \; ?$



Astroparticle

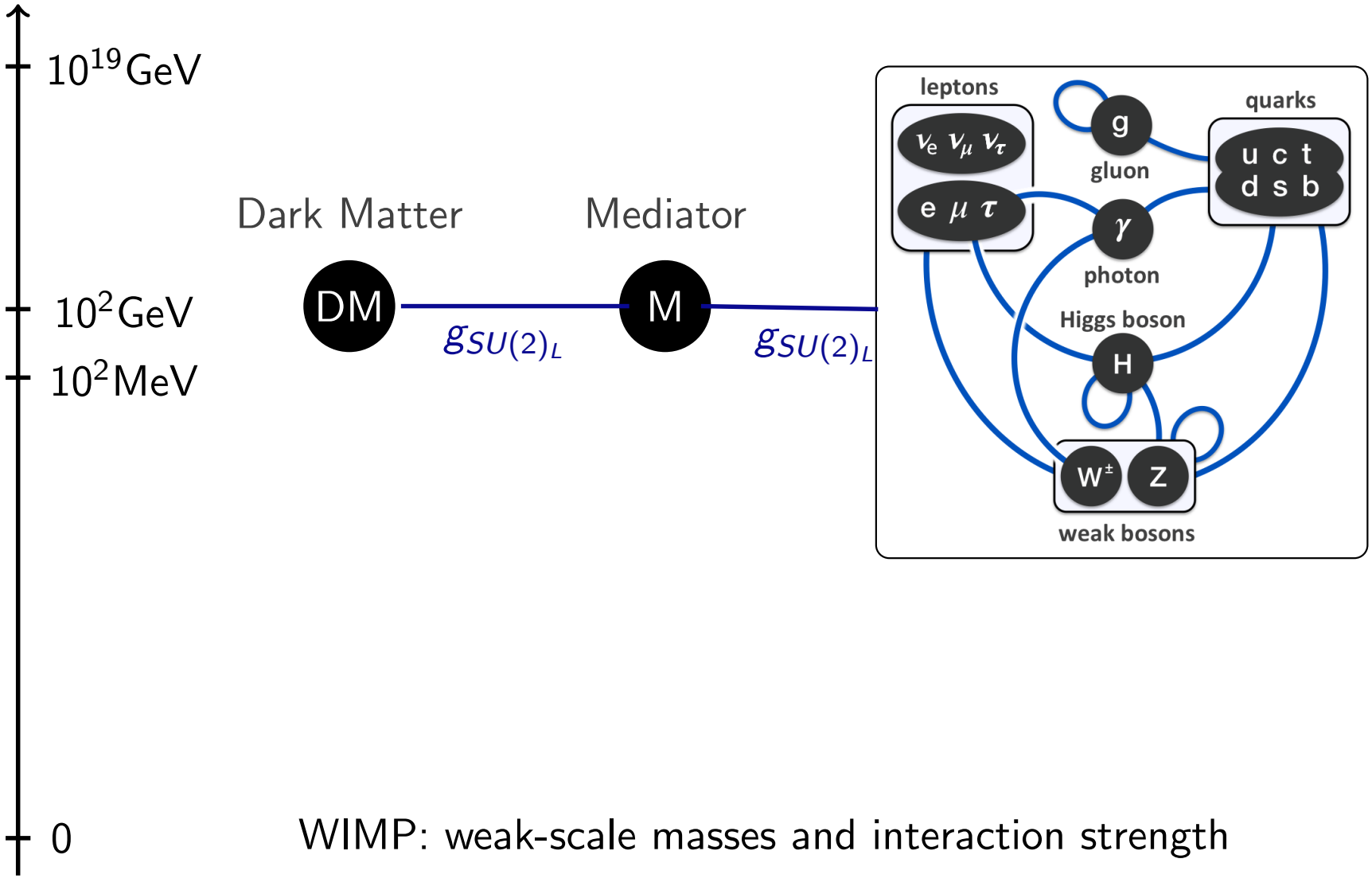
Astro
"small-scale"



DM-SM connection
Production mechanism?

Dark Sector
Is DM cold and collisionless?

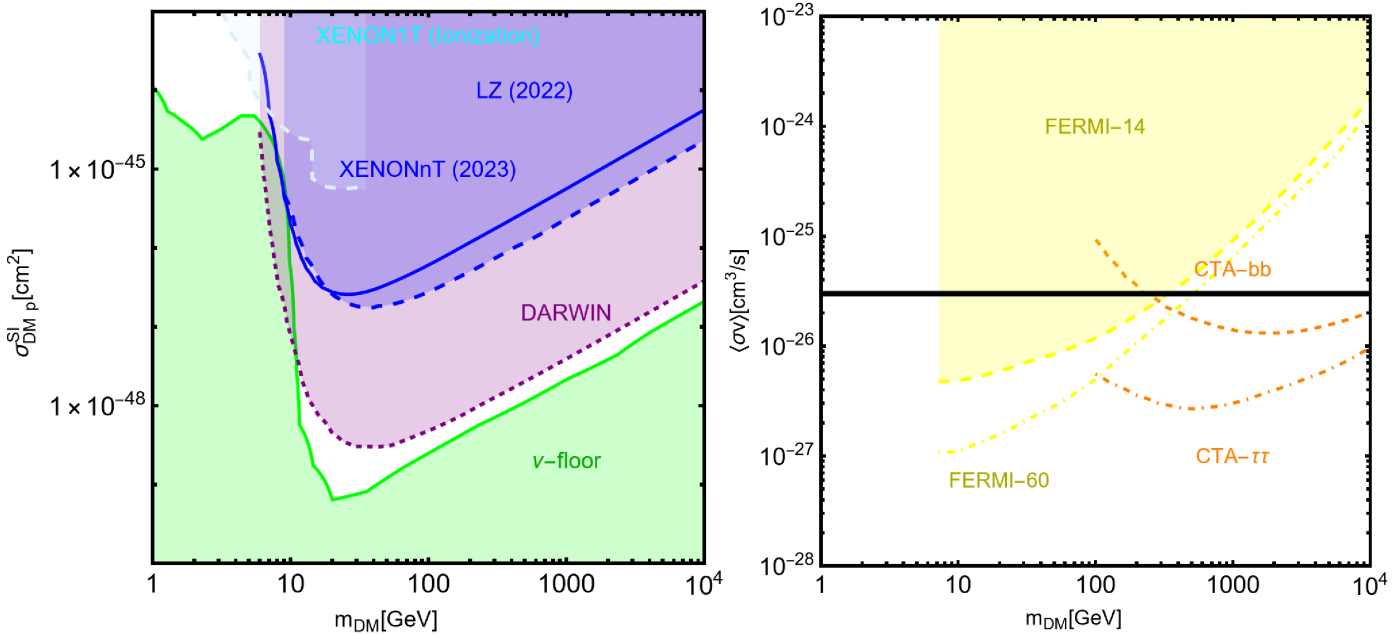
What is the Dark Sector?



WIMP: weak-scale masses and interaction strength

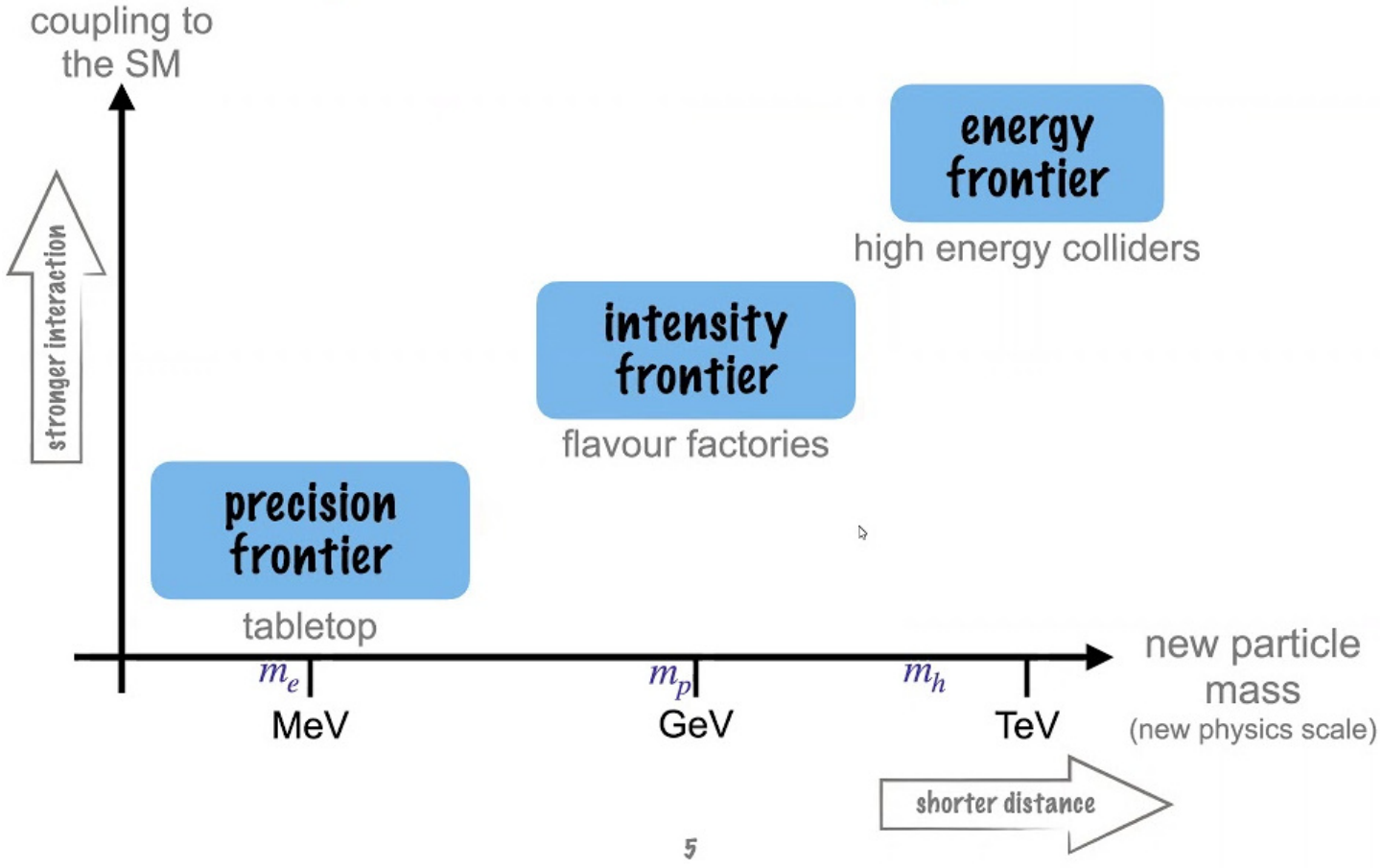
The Waning of the WIMP: Endgame?

Giorgio Arcadi[a,1,2], **David Cabo-Almeida**[b,1,2,3], **Maíra Dutra**[c,4,5], **Pradipta Ghosh**[d,6], **Manfred Lindner**[e,7], **Yann Mambrini**[f,8], **Jacinto P. Neto**[g,1,9,10], **Mathias Pierre**[h,11], **Stefano Profumo**[i,12,13], **Farinaldo S. Queiroz**[j,9,10,14]



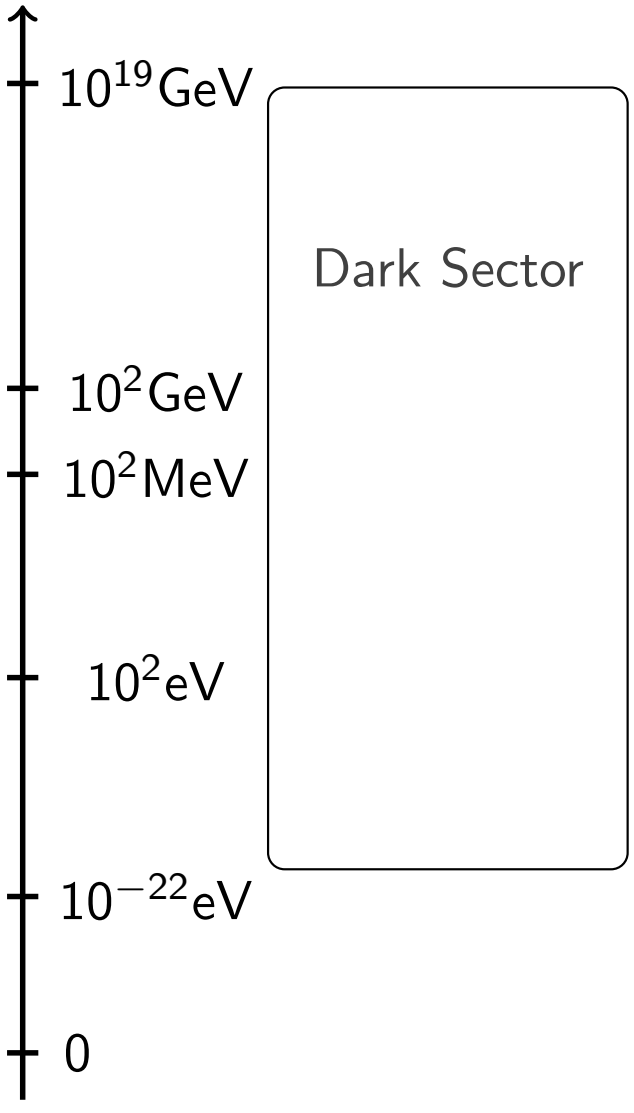
2403.15860

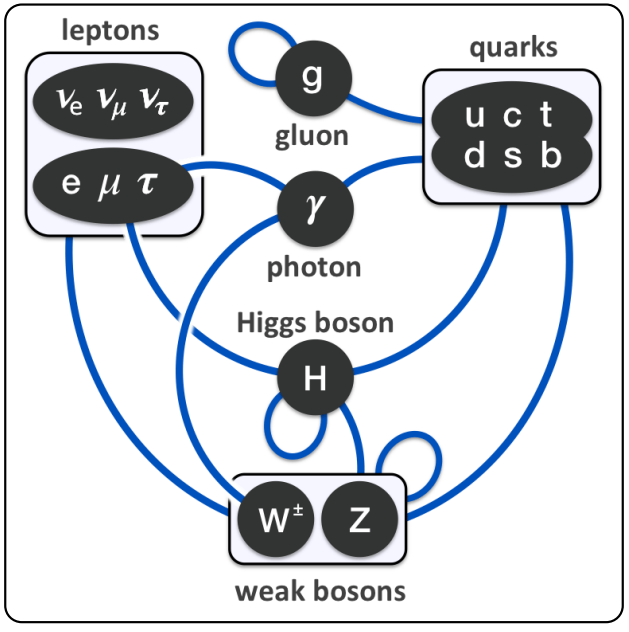
the quest for new physics



slide from Yotam Soreq

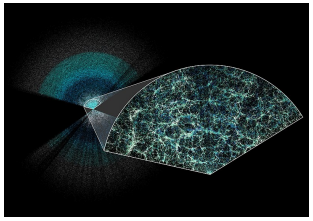
New Physics in the Dark Sector?

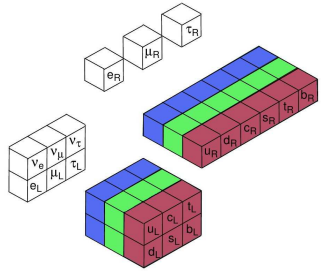




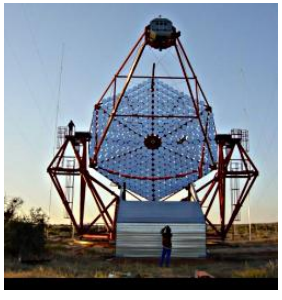
Particle
HEP/lab

Cosmo
CMB/LSS





$+ \; ?$



Astroparticle

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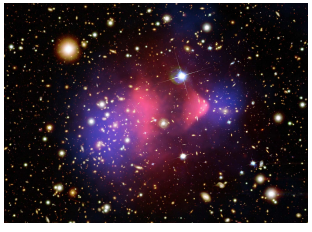

DM-SM connection
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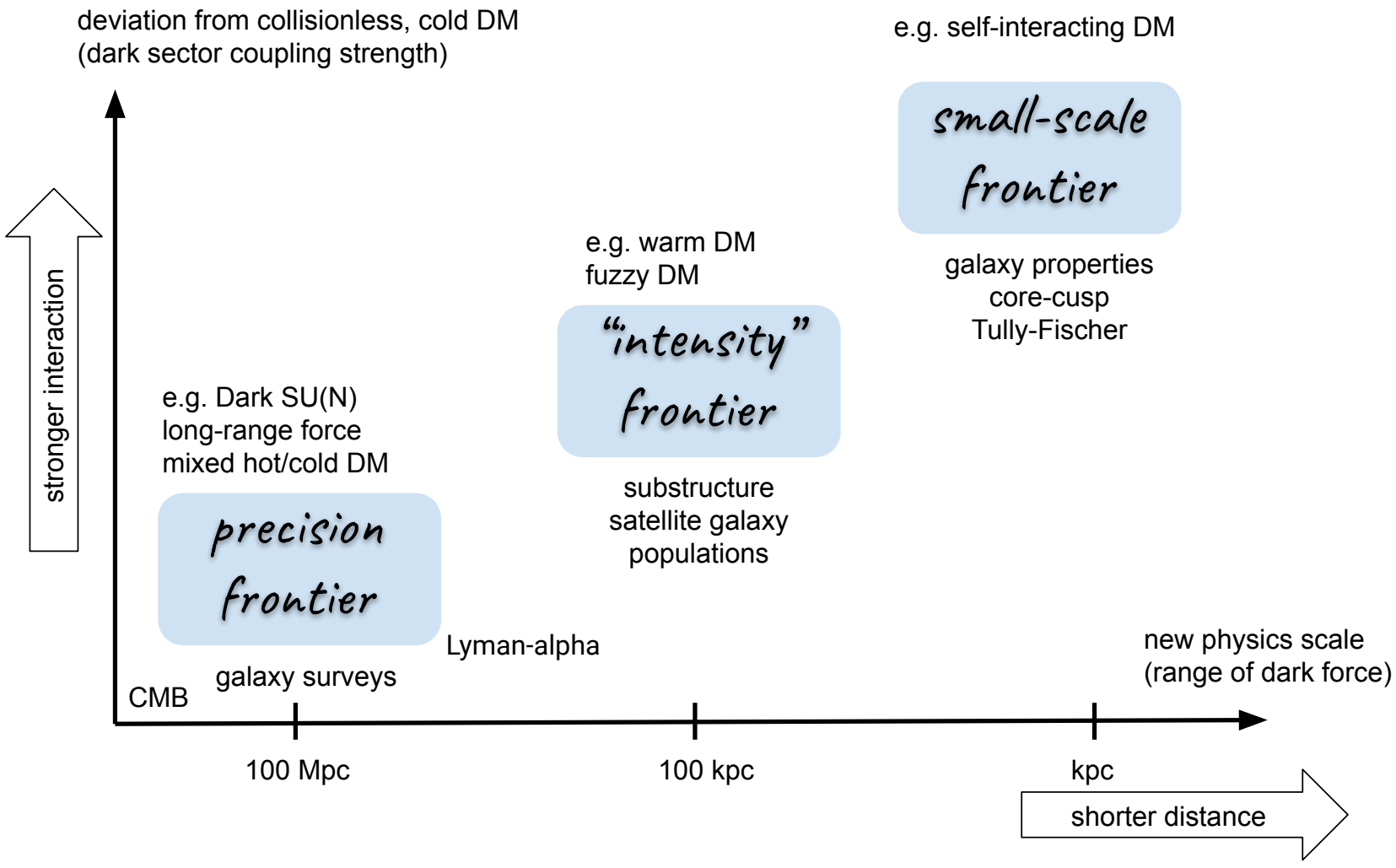
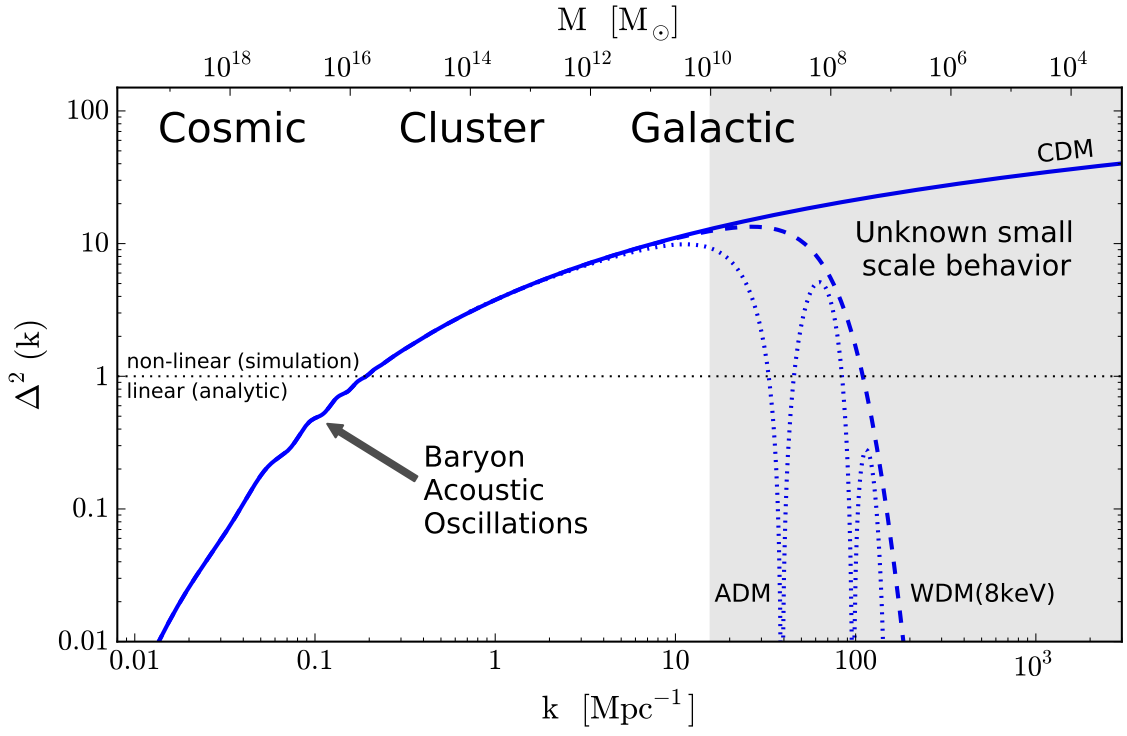
the quest for new physics



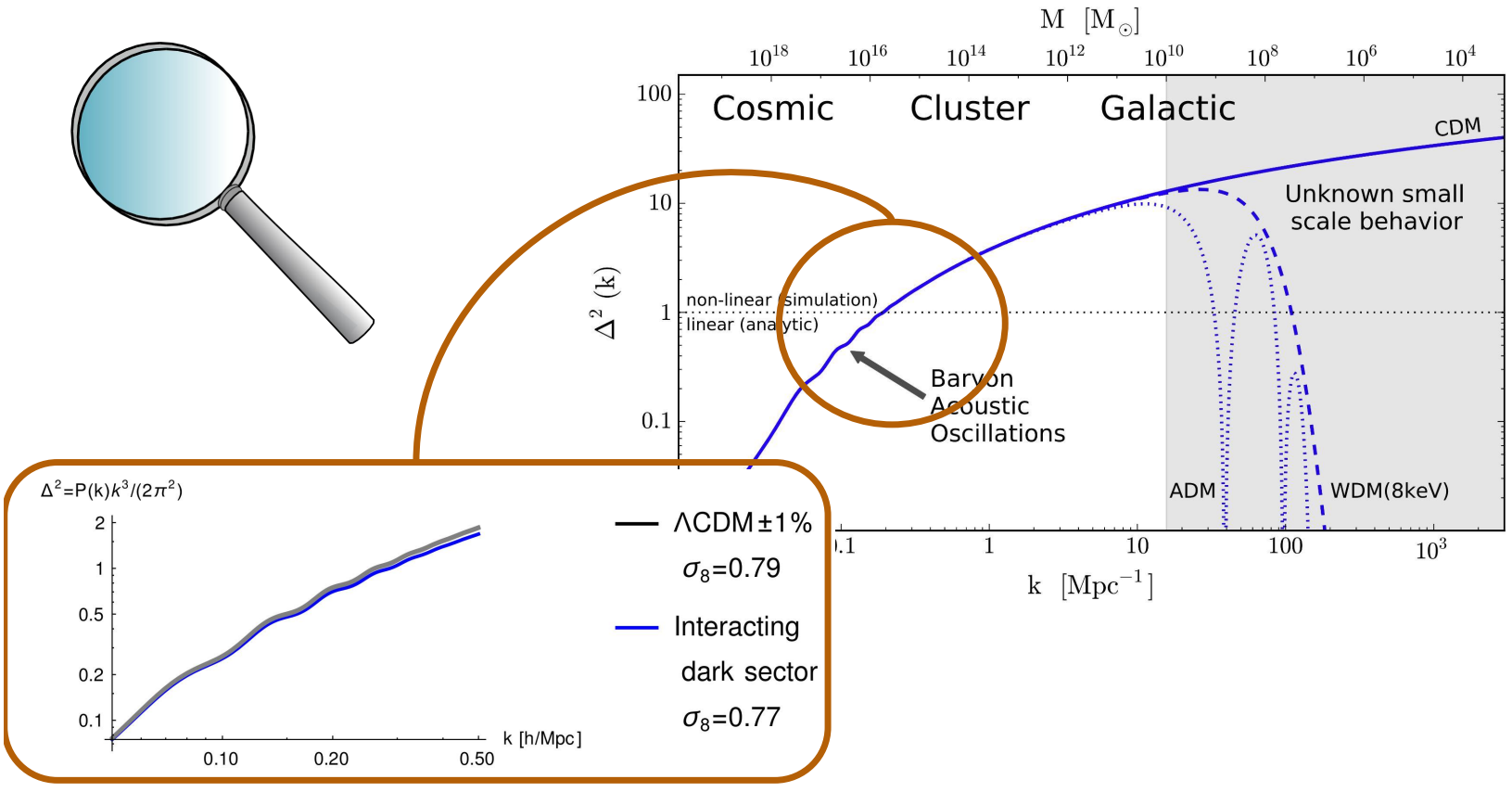


Kuhlen, Vogelsberger, Angulo 1209.5745

$$\delta(\mathbf{x}, z) = \rho(\mathbf{x}, z)/\bar{\rho}(z) - 1$$

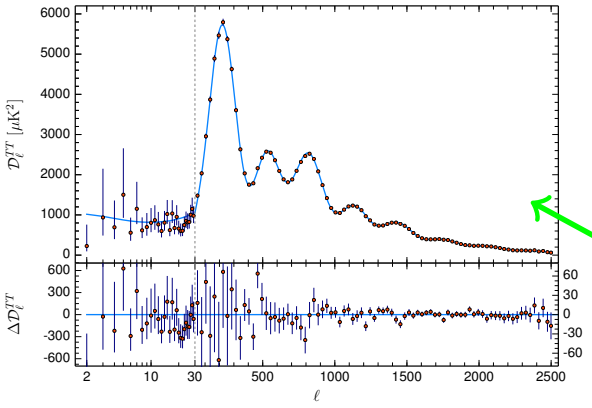
$$\langle \delta(\mathbf{k}, z)\delta(\mathbf{k}', z)\rangle = \delta_D(\mathbf{k} + \mathbf{k}')P(k, z)$$

$$\Delta^2(k, z) = 4\pi k^3 P(k, z)$$


M [M⊙]
10^18 10^16 10^14 10^12 10^10 10^8 10^6 10^4
Cosmic
Cluster
Galactic
CDM
Unknown small scale behavior
non-linear (simulation)
linear (analytic)
Δ² (k)
Baryon Acoustic Oscillations
ADM
WDM(8keV)
k [Mpc⁻¹]
Δ²=P(k)k³/(2π²)
ΛCDM ±1%
σ8=0.79
Interacting dark sector
σ8=0.77
k [h/Mpc]

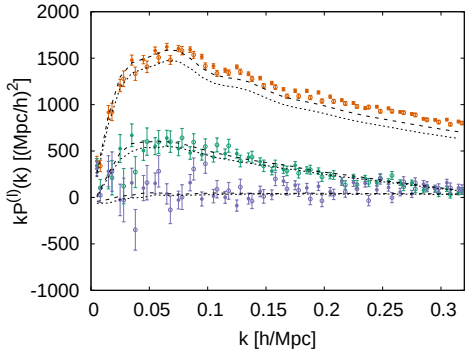
Large-scale structure

CMB ($z \sim 10^3$)

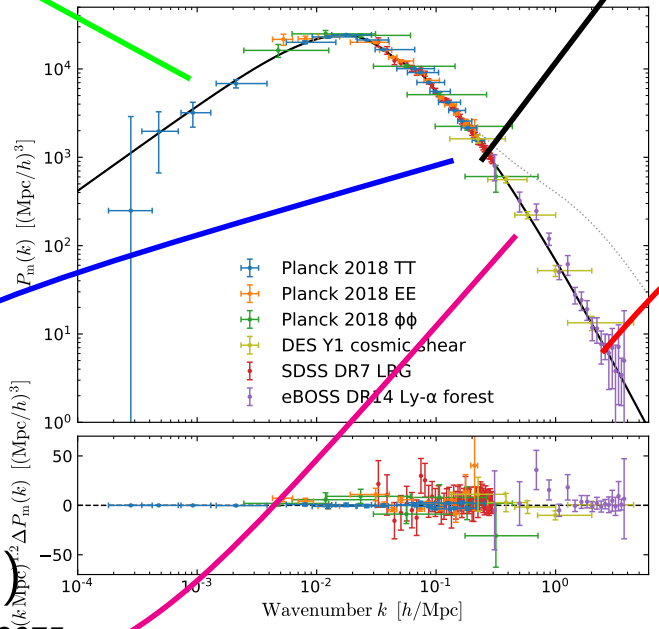


Planck 2007.04997, ACT 2007.07288,...

Galaxy surveys ($z \lesssim 2$)

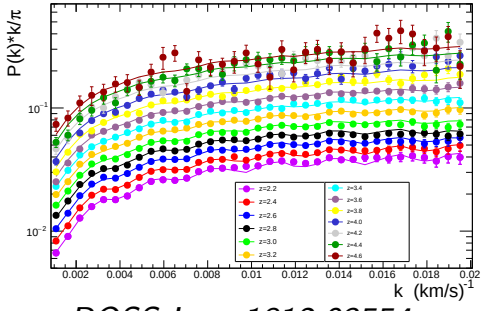


BOSS DR16 2007.08994
DESI 2404.03002, 2411.12022



1905.08103

Lyα forest ($z \sim 2-4$)



BOSS Lyα 1812.03554
DESI early Lyα 2405.03447

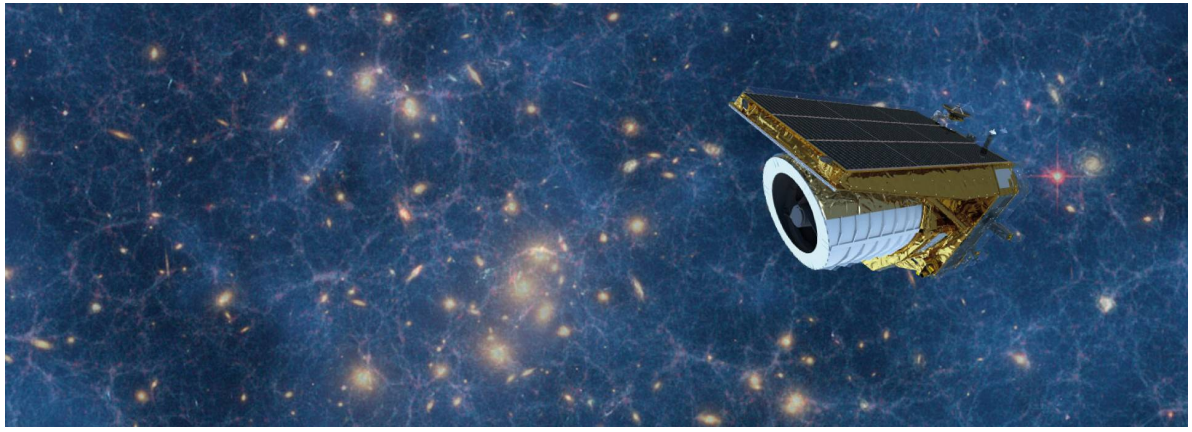
Galaxy cluster counts ($z \lesssim 2$)

Planck/SPT/ACT/DES SZ 2009.11043,2401.02075

Weak lensing ($z \lesssim 2$)

DES 2107.04646
KiDS-1000 2007.15632
KiDS+DES 2305.17173

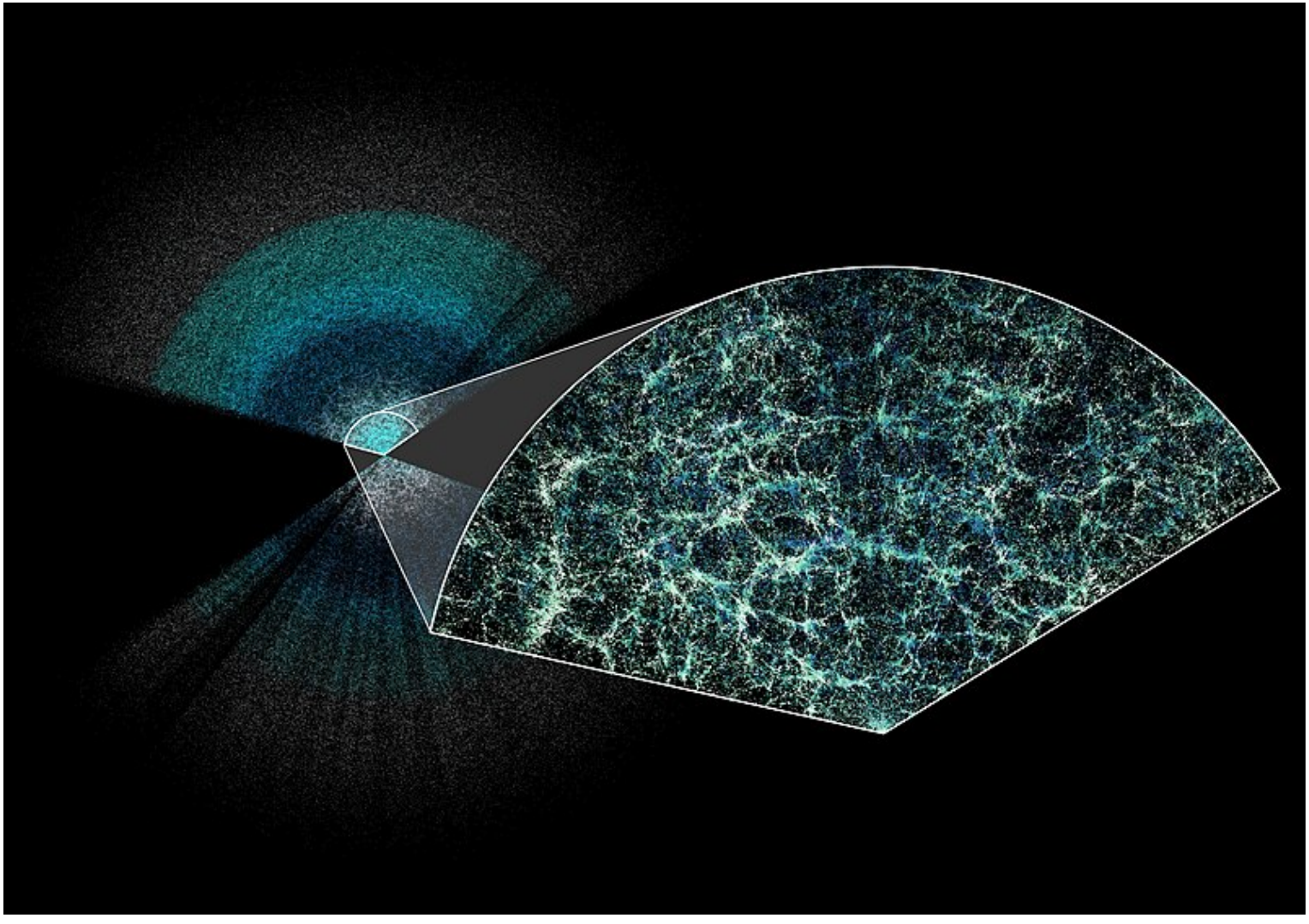
Large-scale structure



Euclid satellite (ESA, launched 2023)

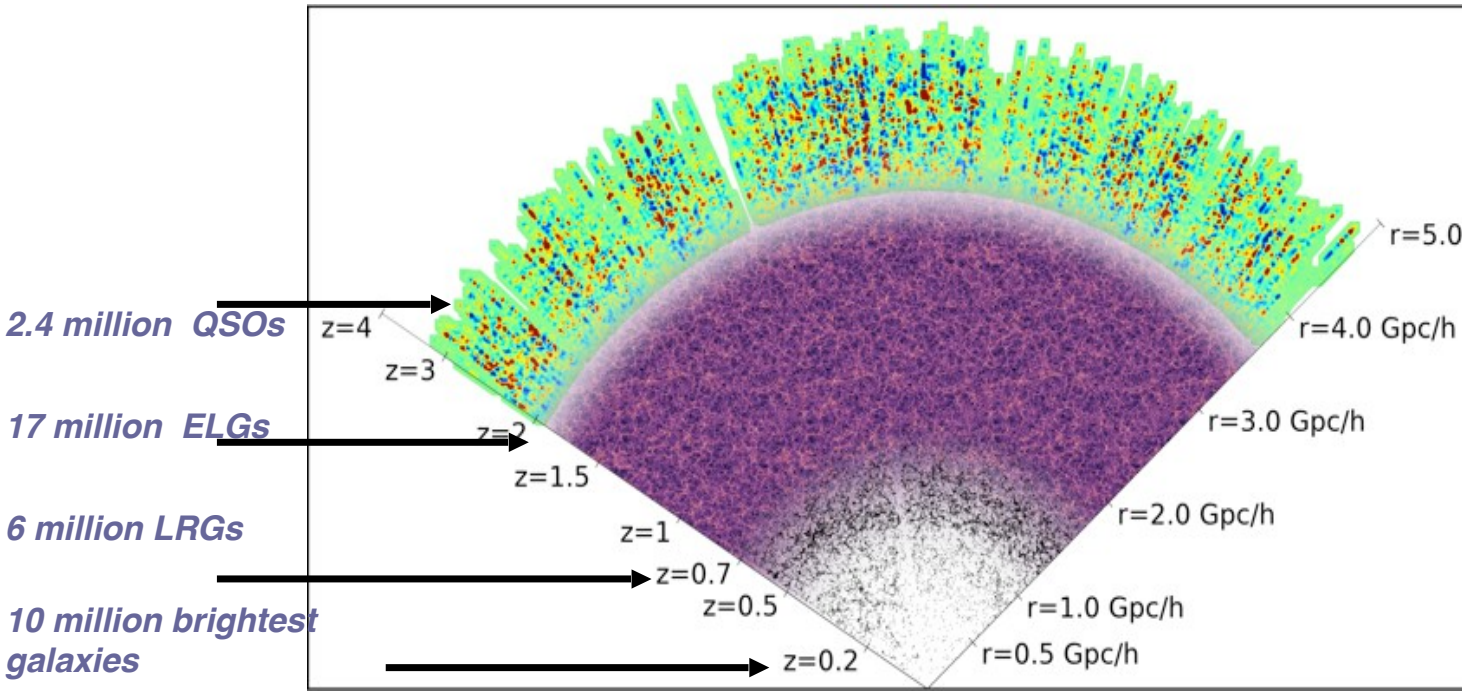
DESI Arizona (yr1 results 2024)

Large-scale structure



DESI one-year data 2404.03002

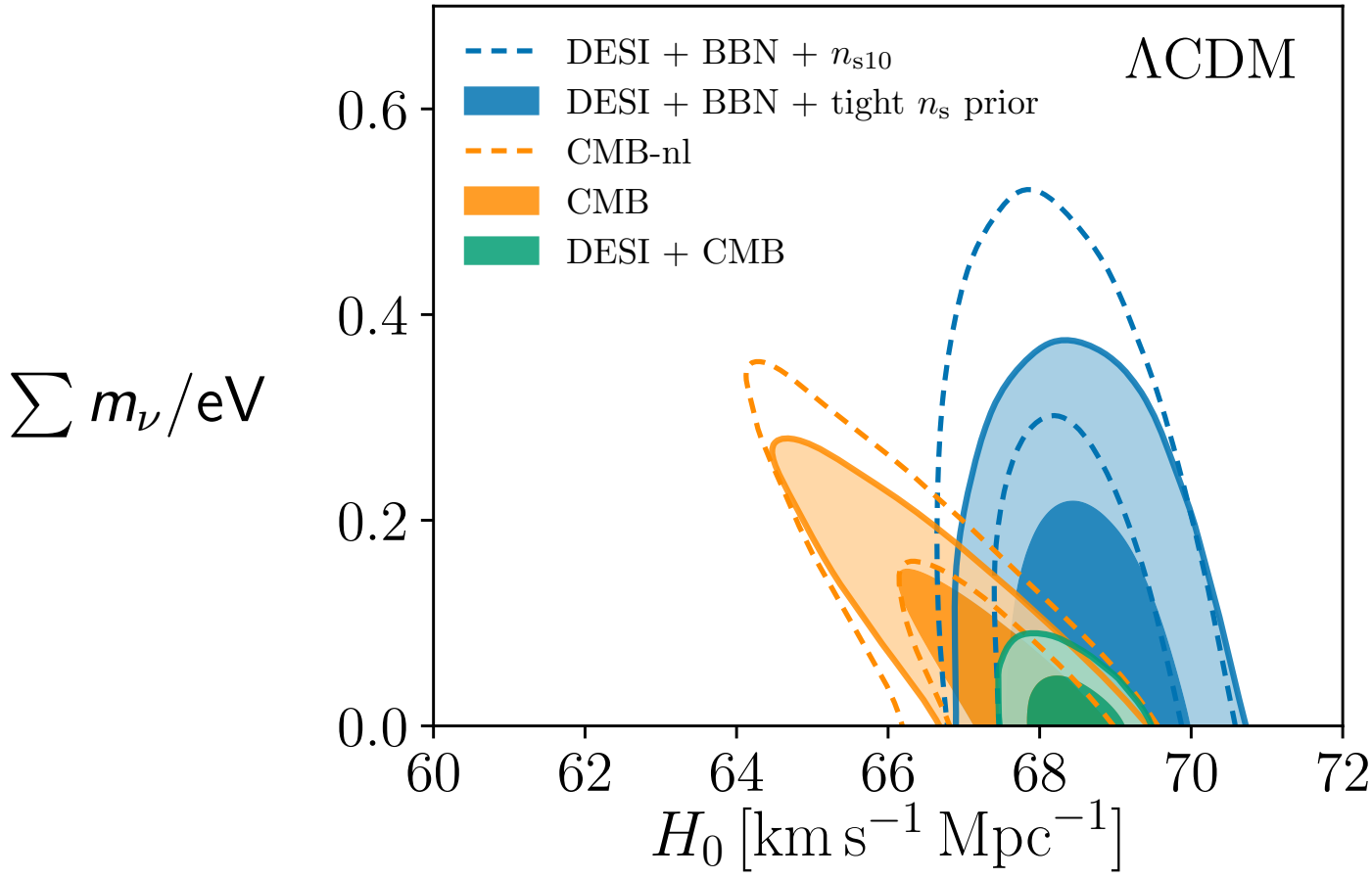
Large-scale structure



DESI, from O. Lahav

DESI 2024 VII: Cosmological Constraints from the Full-Shape Modeling of Clustering Measurements

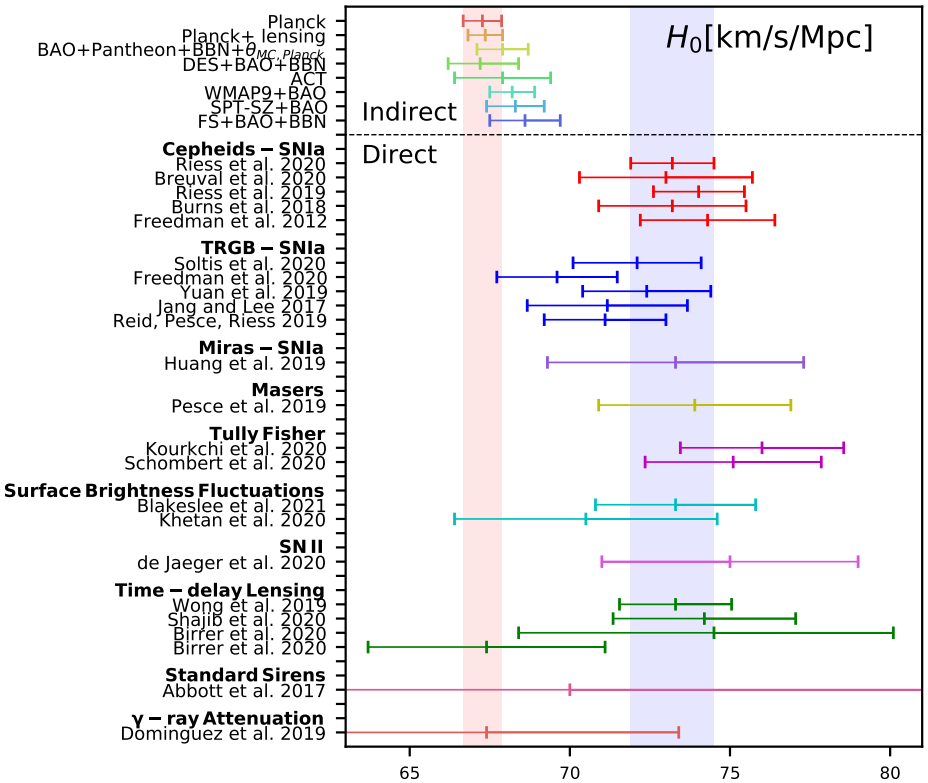
arXiv:2411.12022

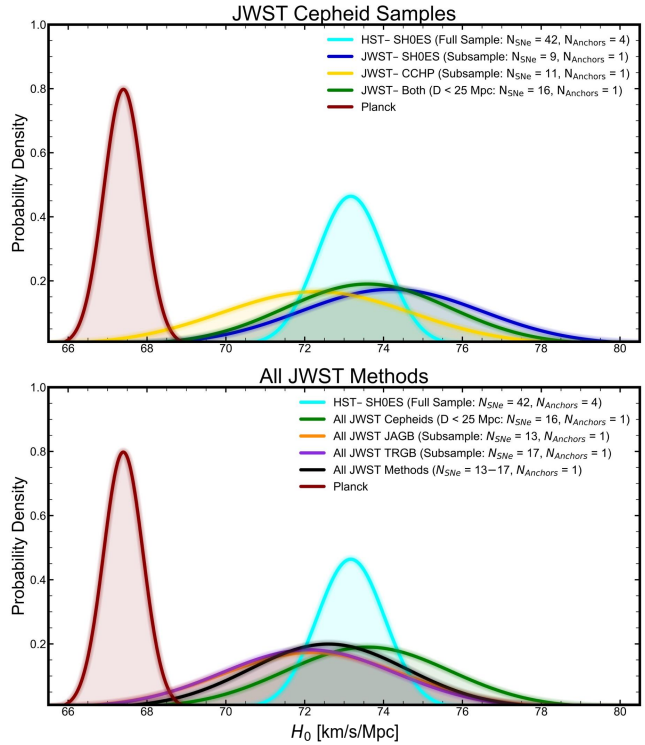


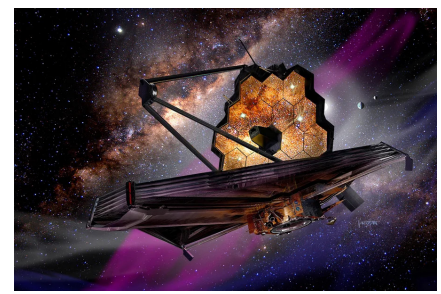
$\sum m_\nu < 0.409\,\mathrm{eV}$ (95 %, DESI (FS+BAO)+BBN+n_{s10}).

$\sum m_\nu < 0.071\,\mathrm{eV}$ (95 %, DESI (FS+BAO)+CMB).

H_0?







Di Valentino et al 2011.0024

Riess et al 2408.11770

Freedman et al 2408.06153

Sytematics or Beyond-ΛCDM Physics?

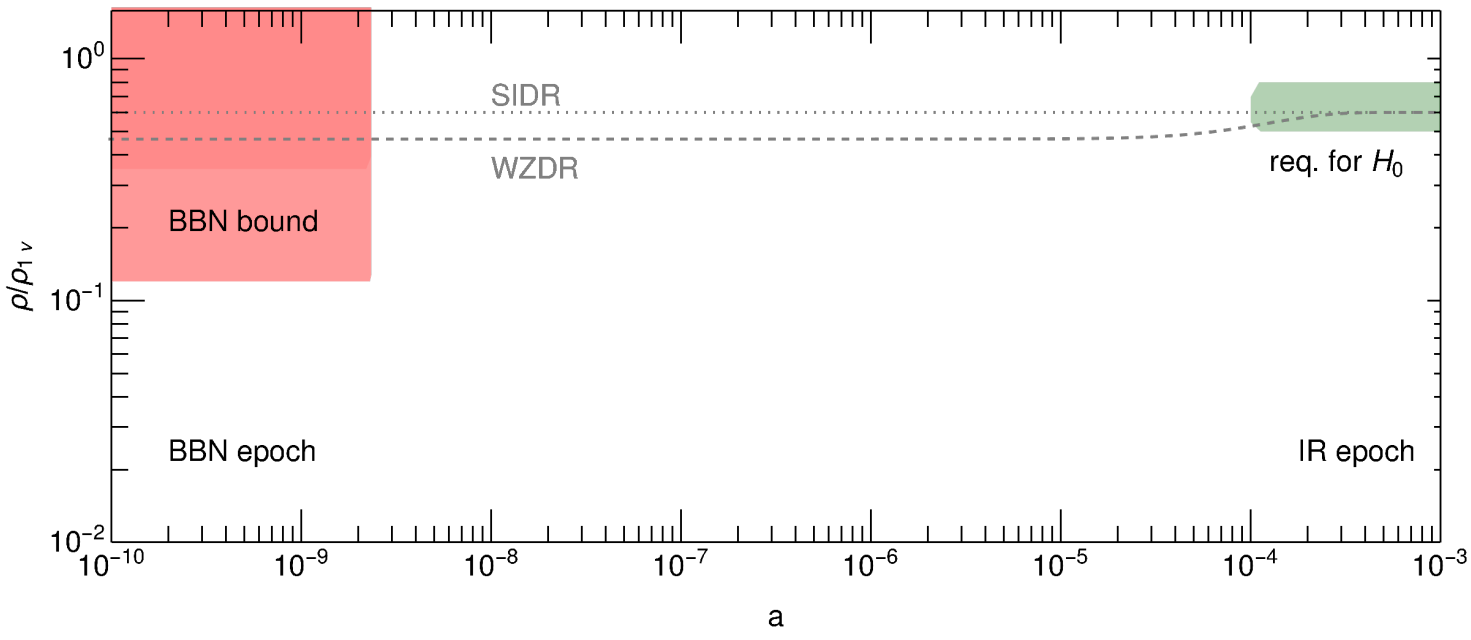
- Indirect measurements set by the ratio of the sound horizon at recombination, and the angular diameter distance

$$
\begin{aligned}
r_s(z_{rec}) &= \int_{z_{rec}}^{\infty} dz' \frac{c_s(z')}{H(z')} \propto 1/\sqrt{\rho_{\text{total}}(z \sim z_{rec})}\,, \\
d_A(z_{obs}) &= \int_{0}^{z_{obs}} dz' \frac{1}{H(z')} \propto 1/H_0
\end{aligned}
$$

- Increasing the inferred value of H_0 from CMB and galaxy surveys (BAO) requires to lower the sound horizon, e.g. via additional (dark sector) energy around recombination

[.. and changing ω_m, ..., see e.g. Poulin et al 2407.18292]

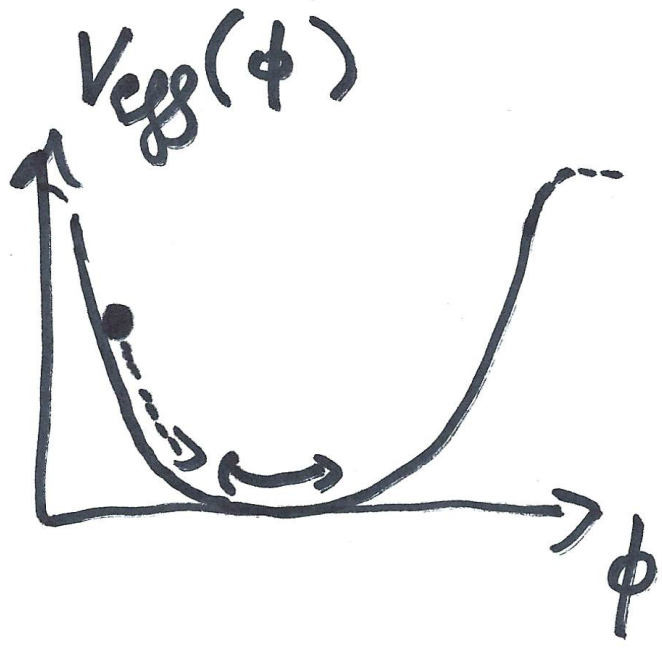
Extra (self-interacting) dark radiation?



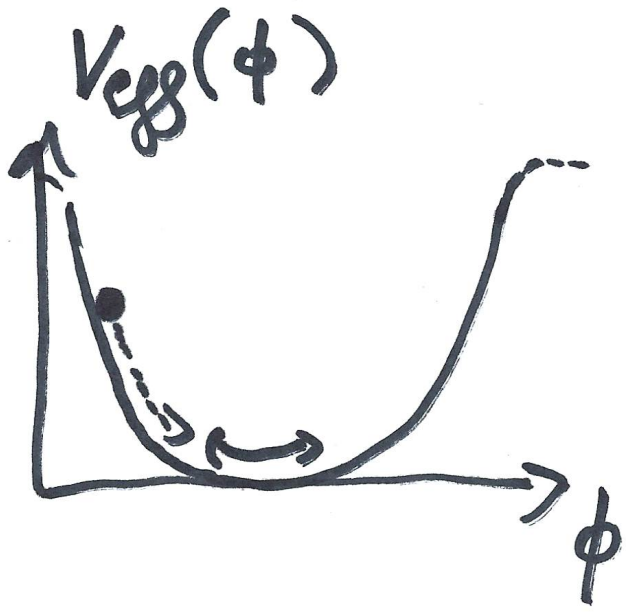
e.g. Schmaltz, Weiner, Joseph, Aloni, Allali

Rompineve, Hertzberg, Poulin, Simon, Schöneberg ...

Extra (early) dark energy?

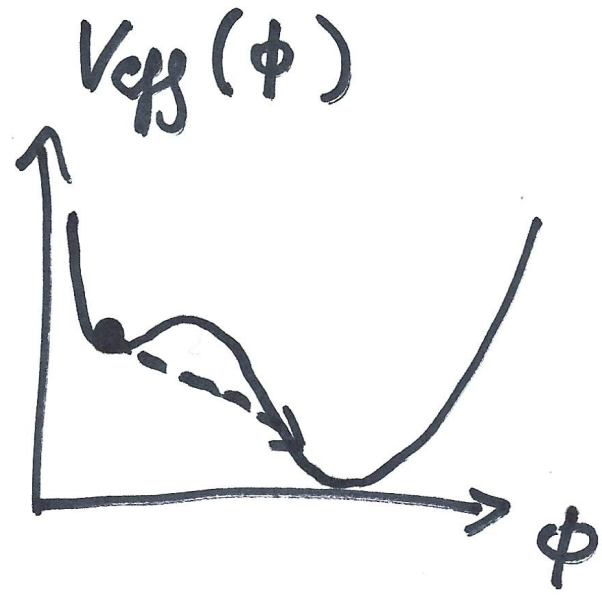


Poulin, Smith, Karwal, Kamionkowski 18,...



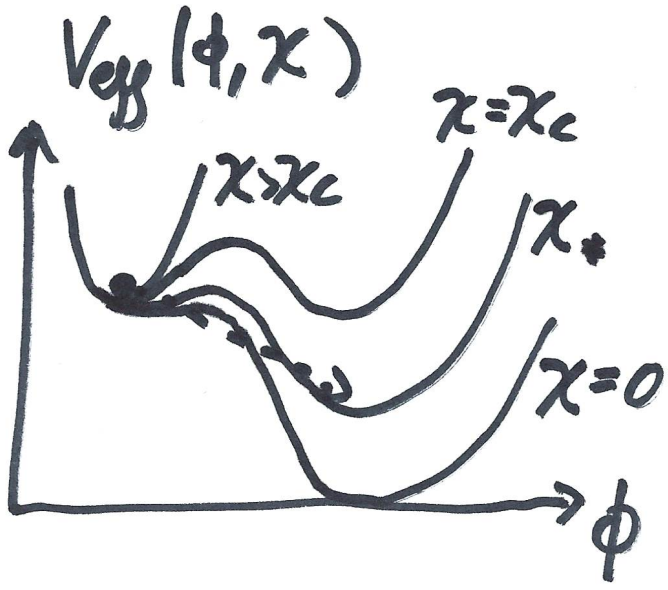
EDE

Poulin, Smith, Karwal, Kamionkowski 18



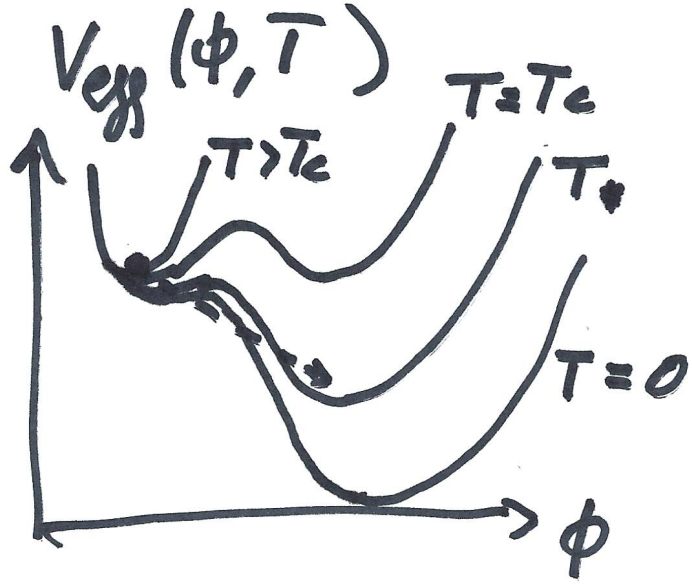
NEDE

Niedermann, Sloth 19



cold NEDE

Niedermann, Sloth 19+

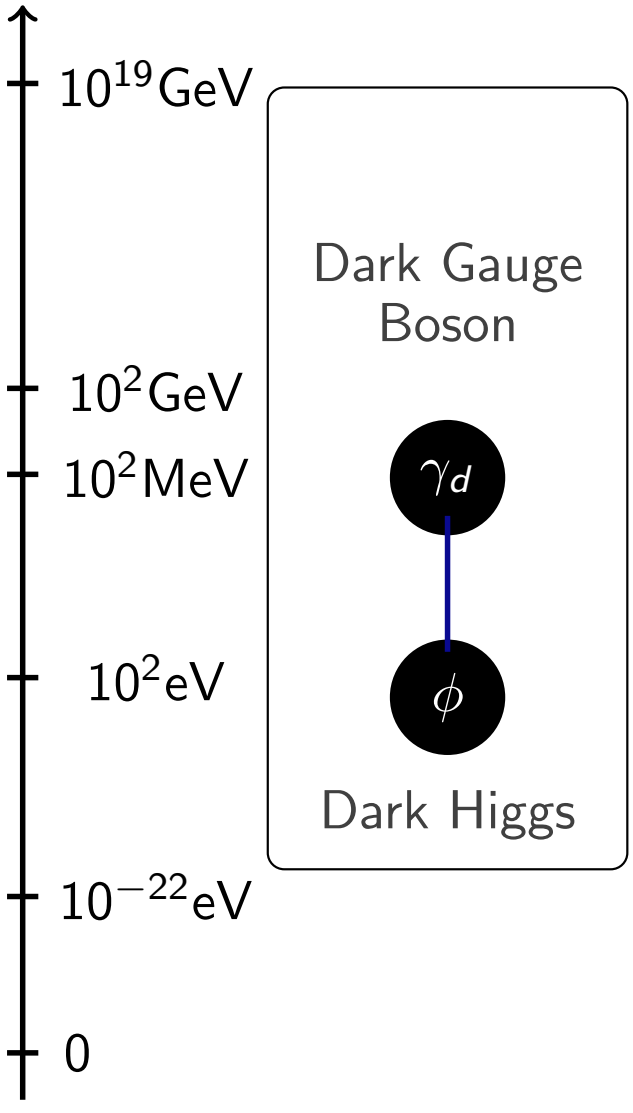


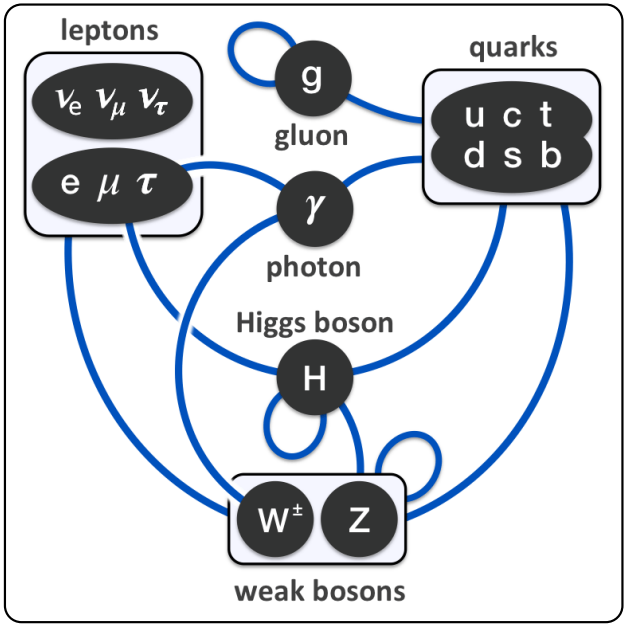
hot NEDE
(this talk)

Niedermann, Sloth 21

MG, Niedermann, Rubira, Sloth 24

New Physics in the Dark Sector?





Dark $SU(N)$ + Higgs mechansim

Example: weakly coupled non-Abelian gauge symmetry with dark Higgs

$$\mathcal{L} = \mathcal{L}_{SM} + (D_\mu \phi)^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \frac{\lambda}{4}(\phi^\dagger \phi)^2 - \frac{1}{4} F_a^{\mu\nu} F^a_{\mu\nu}$$

- Dark gauge bosons A_a^μ = dark radiation DR
- Dark Higgs $\phi = (\phi_1, \ldots, \phi_N)^T$ leads to spont. symmetry breaking

$$\boxed{SU(N) \to SU(N-1)}$$

Parameters: $\alpha_d \equiv \frac{g_d^2}{4\pi}, \mu^2, \lambda, \xi \equiv \frac{T_{DR}}{T_{SM}}$

Assume Debye length $\sim 1/(g_d T_{DR}) \ll$ confinement length scale $1/\Lambda_c \propto e^{-1/g^2}$

(similar to quark-gluon plasma phase in QCD at high-T)

Dark $SU(N)$ + Higgs mechansim

Coleman-Weinberg mechanism for classically scale-inv. theory with VEV $\langle\phi\rangle = (0, .., 0, v)^T$ generated by dimensional transmutation

$$\lambda(\mu_{\overline{MS}} = v) = \mathcal{O}(g_d^4)$$

Light Higgs compared to dark gauge bosons that acquire mass $m_A \sim g_d v$

$$\frac{m_\phi}{m_A} \sim \mathcal{O}(g_d)$$

Coleman, E. Weinberg 73

Dark $SU(N)$ + Higgs mechansim

Can allow for soft breaking of class. scale inv. by mass term in Higgs potential as long as

$$\gamma \equiv \frac{|\mu^2|}{g_d^4 v^2} \ll 1$$

$\Rightarrow$ Parameters: $\alpha_d \equiv \frac{g_d^2}{4\pi}, v^2, \gamma, \xi \equiv \frac{T_{DR}}{T_{SM}}$

Dark $SU(N)$ + Higgs mechansim

Symm. breaking via supercooled phase transition at $z = z_*$

$$\Delta V = V_{CW}(0) - V_{CW}(v) \sim g_d^4 v^4 \gg T_{DR}(z_*)^4$$

Witten 1981

Transition temperature* (unless for exp. small γ)

$$T_{DR}(z_*) \sim \sqrt{\gamma} g_d v$$

(*) small negative μ^2-term; barrier in eff. pot. vanishes at z_*

Dark $SU(N)$ + Higgs mechansim = hot NEDE

$z > z_*$ Vacuum energy ΔV = "early dark energy"

$z < z_*$ Thermalization heats dark sector (DR = remaining massless $SU(N-1)$ gauge bosons and light Higgs)

$$\Rightarrow \text{increase of } \Delta N_{\text{eff}} \propto \Delta V \quad \text{at } z = z_*$$

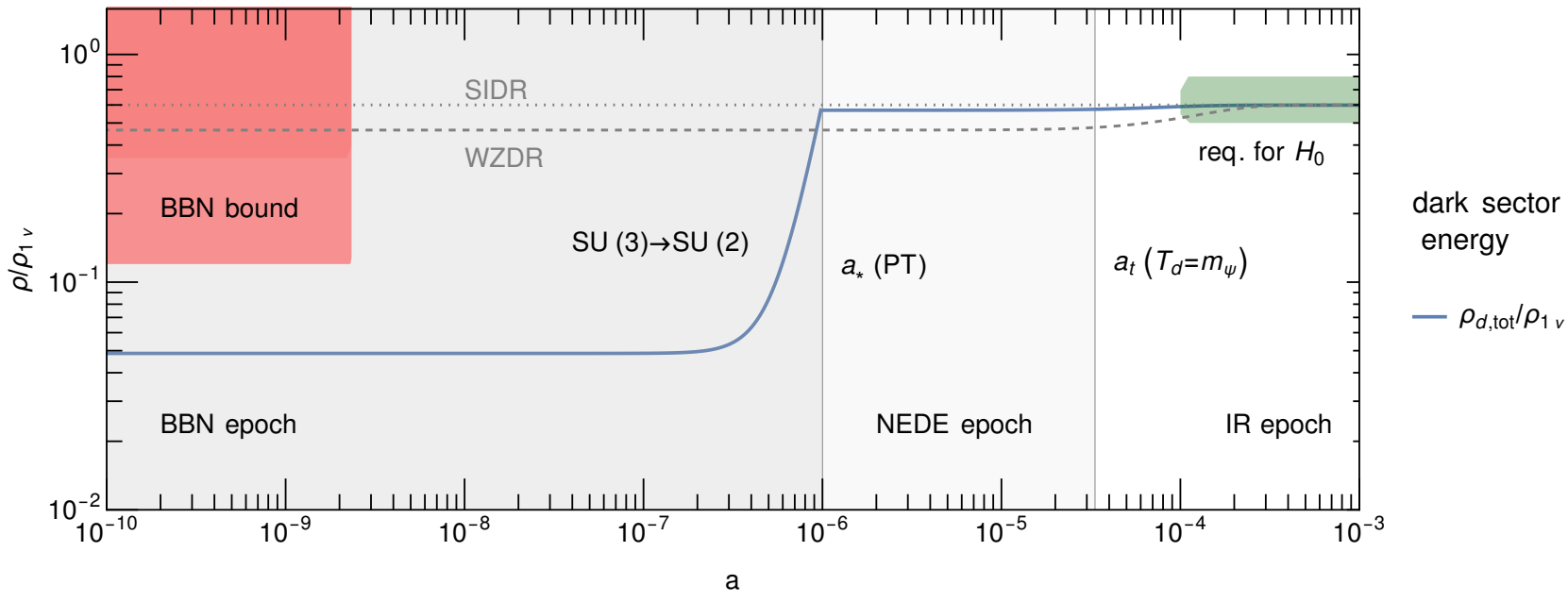
$z < z_t$ Mass threshold of light Higgs leads to further (small) increase at

$$z_t \sim z_* \frac{m_\phi}{m_A} \sim g_d z_*$$

analogous to step model, see Schmaltz, Weiner, Joseph, Aloni, Allali Rompineve, Hertzberg, Poulin, Simon, Schöneberg ...

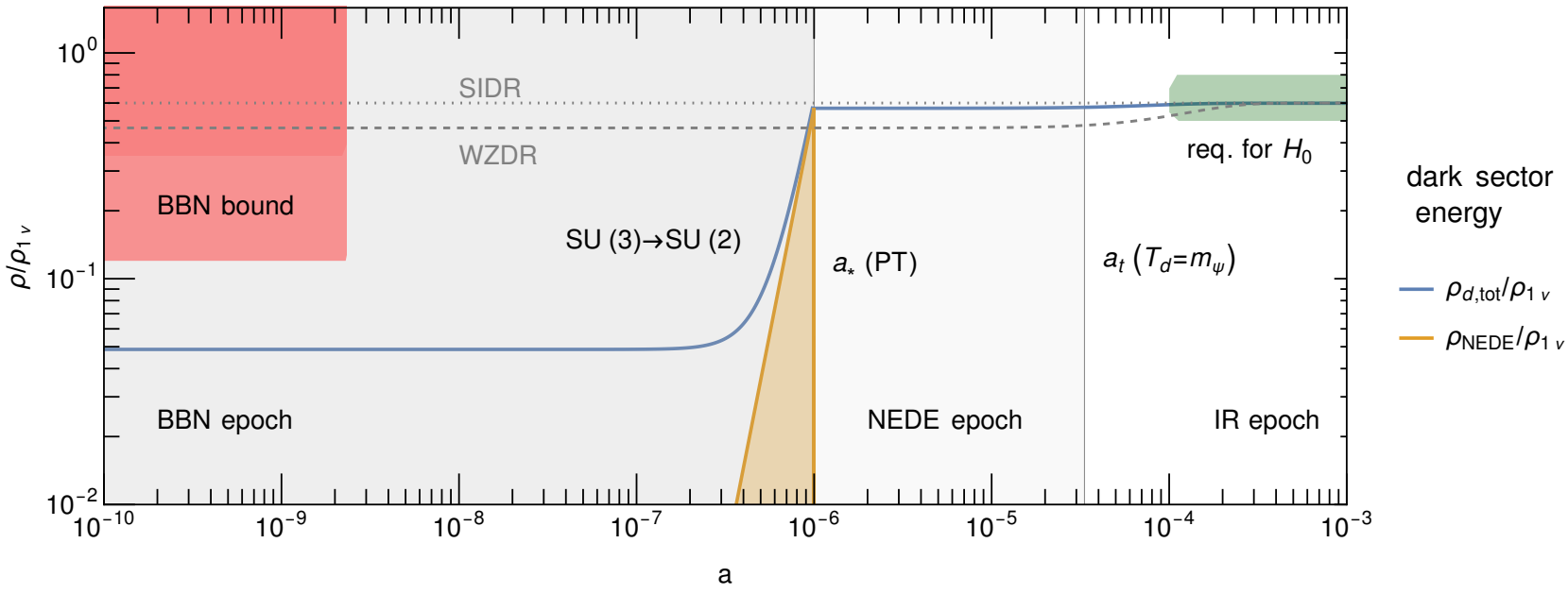
In summary: two "steps" in ΔN_{eff} at z_* and $z_t \sim g_d z_*$

Dark $SU(N)$ + Higgs mechansim = hot NEDE



MG, Niedermann, Rubira, Sloth 2404.07256

Dark $SU(N)$ + Higgs mechansim = hot NEDE



MG, Niedermann, Rubira, Sloth 2404.07256

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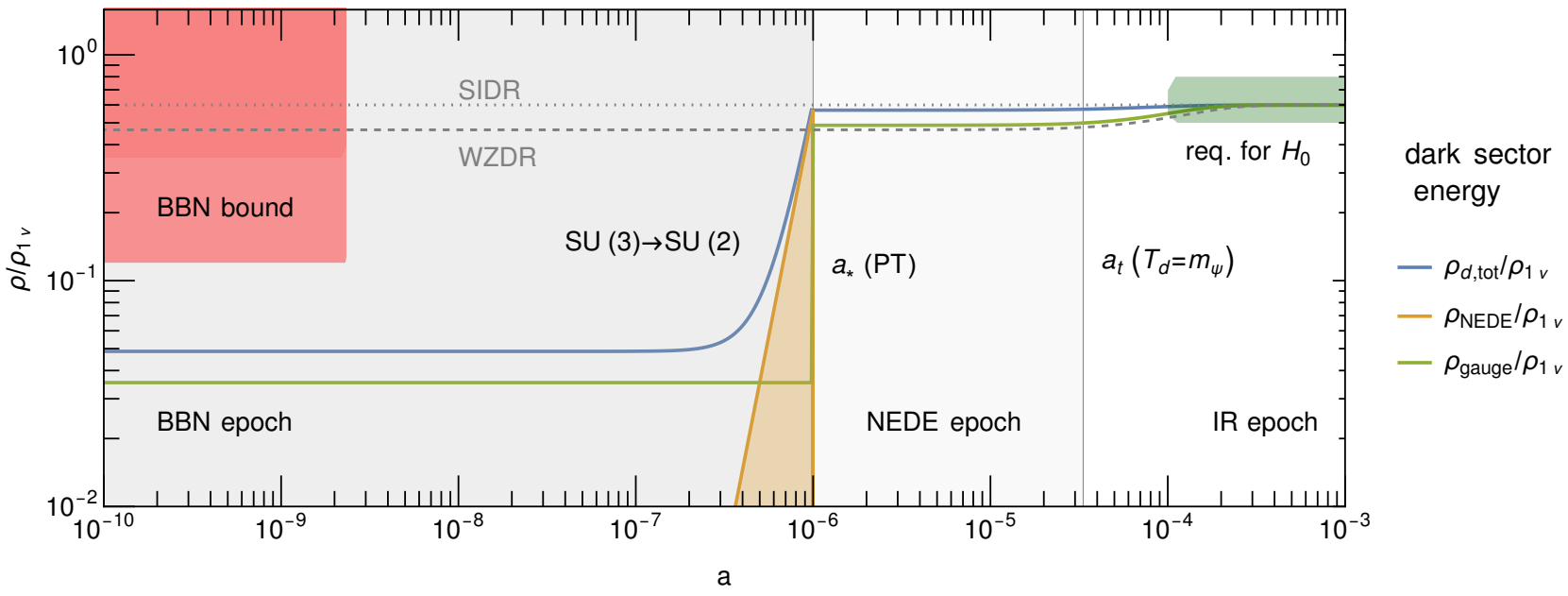

MG, Niedermann, Rubira, Sloth 2404.07256

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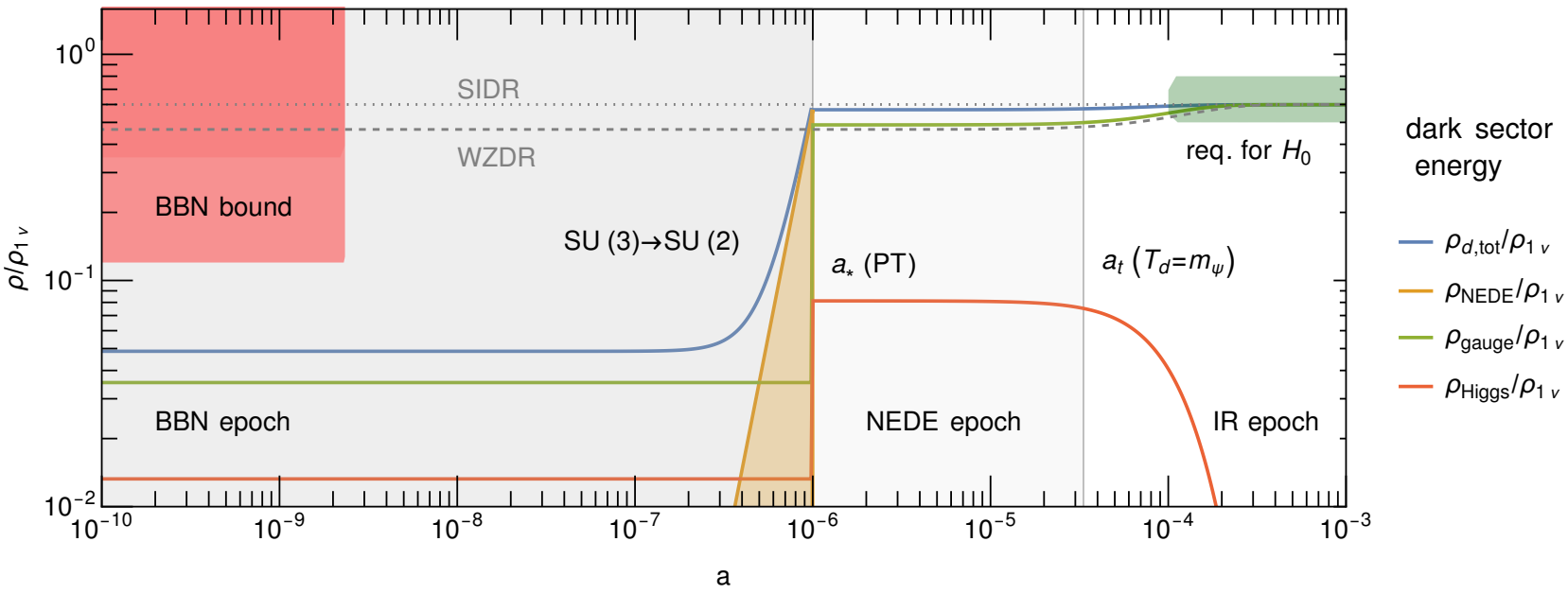
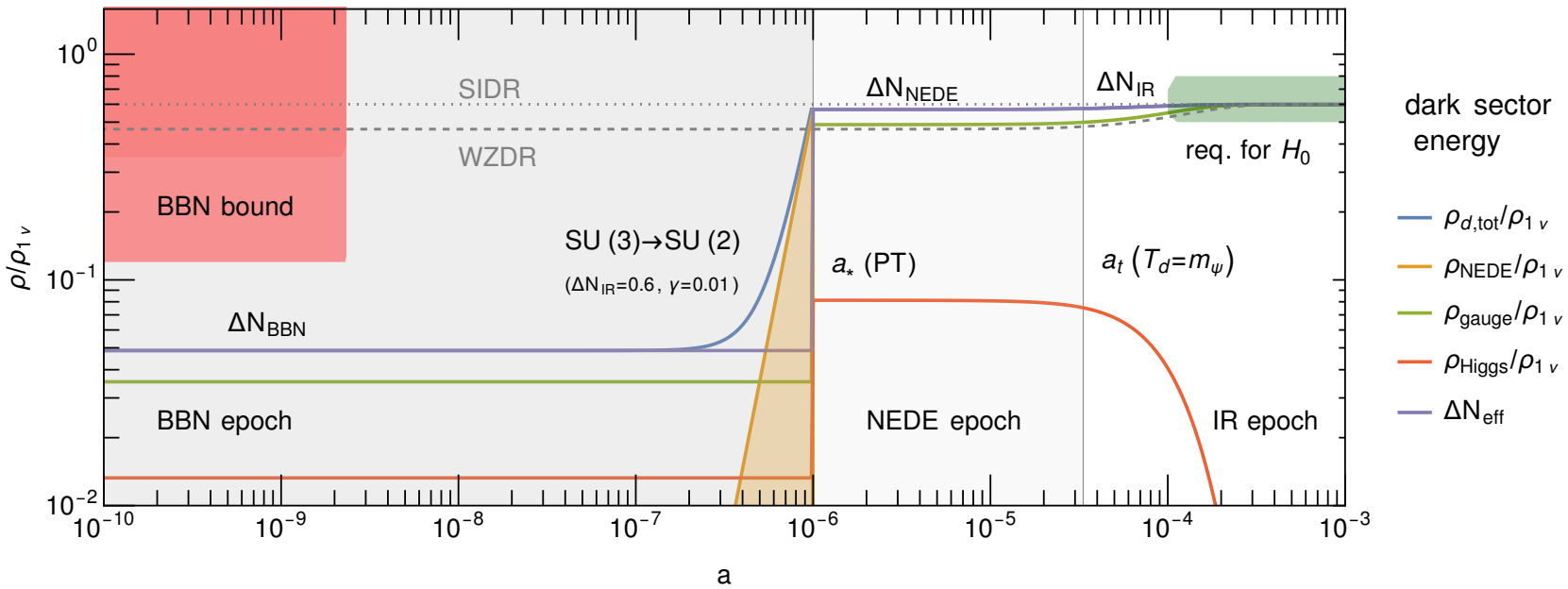


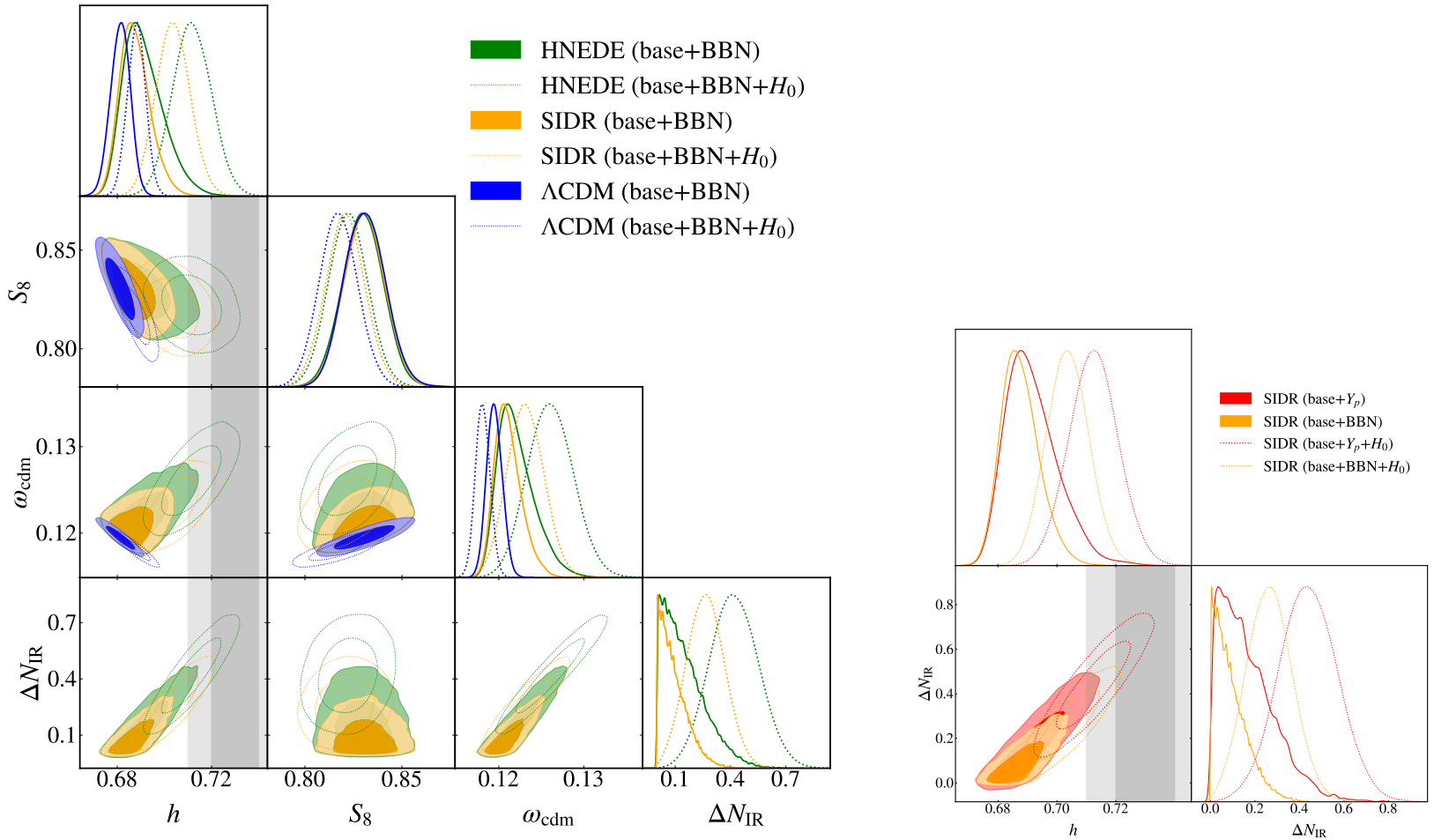
MG, Niedermann, Rubira, Sloth 2404.07256

Dark $SU(N)$ + Higgs mechansim = hot NEDE



MG, Niedermann, Rubira, Sloth 2404.07256

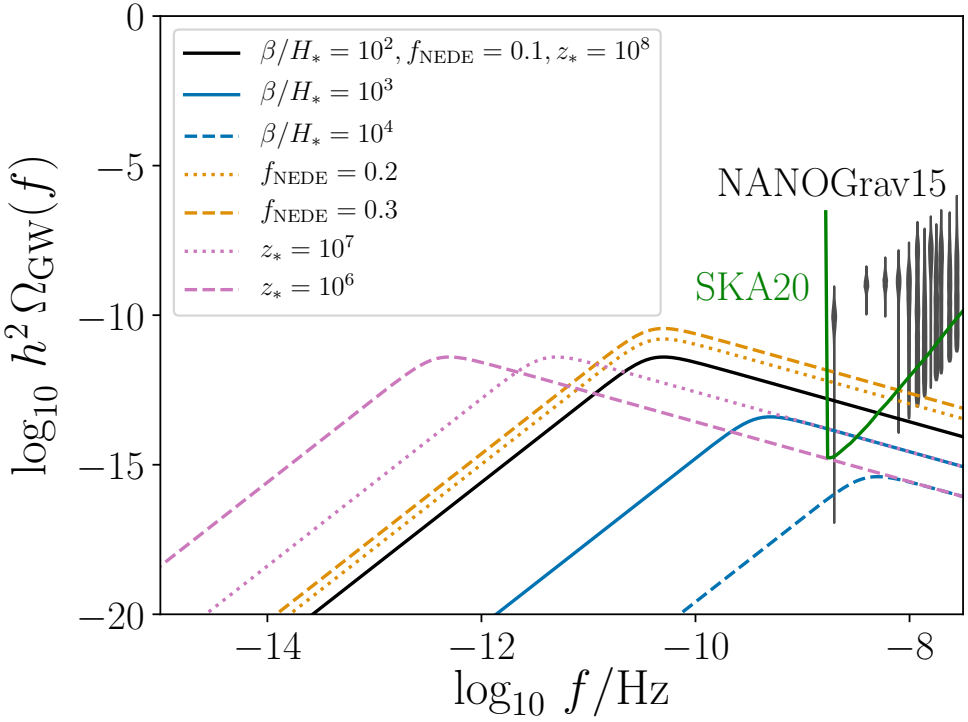
Dark $SU(N)$ + Higgs mechansim = hot NEDE

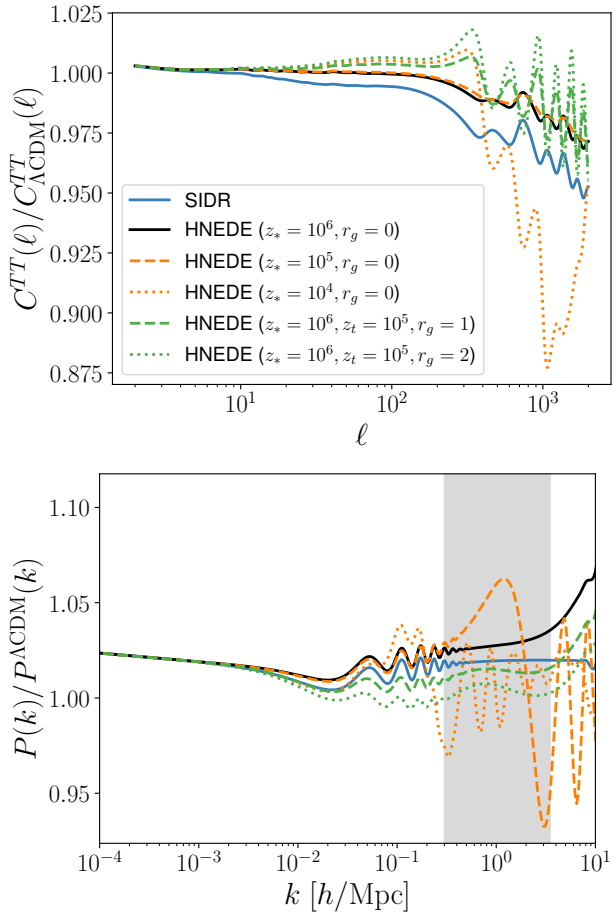


	Base + BBN					+ H_0					$\sqrt{Q^{H_0}_{\rm DMAP}}$
	H_0	$\Delta N_{\rm IR}$	χ^2	$\Delta\chi^2$	ΔAIC	H_0	$\Delta N_{\rm IR}$	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM	68.13 ± 0.42	-	3810.5	-	-	68.81 ± 0.39	-	3829.7	-	-	4.3σ
SIDR	$68.77^{+0.52}_{-0.73}$	$0.094^{+0.024}_{-0.093}$	3810.5[a]	0.0	2.0	70.37 ± 0.72	0.27 ± 0.10	3825.7	-4.0	-2.0	3.9σ
Hot NEDE	$69.13^{+0.62}_{-1.0}$	$0.151^{+0.041}_{-0.15}$	3810.4	-0.1	1.9	71.17 ± 0.83	0.42 ± 0.13	3818.3	-11.4	-9.4	2.8σ

MG, Niedermann, Rubira, Sloth 2404.07256

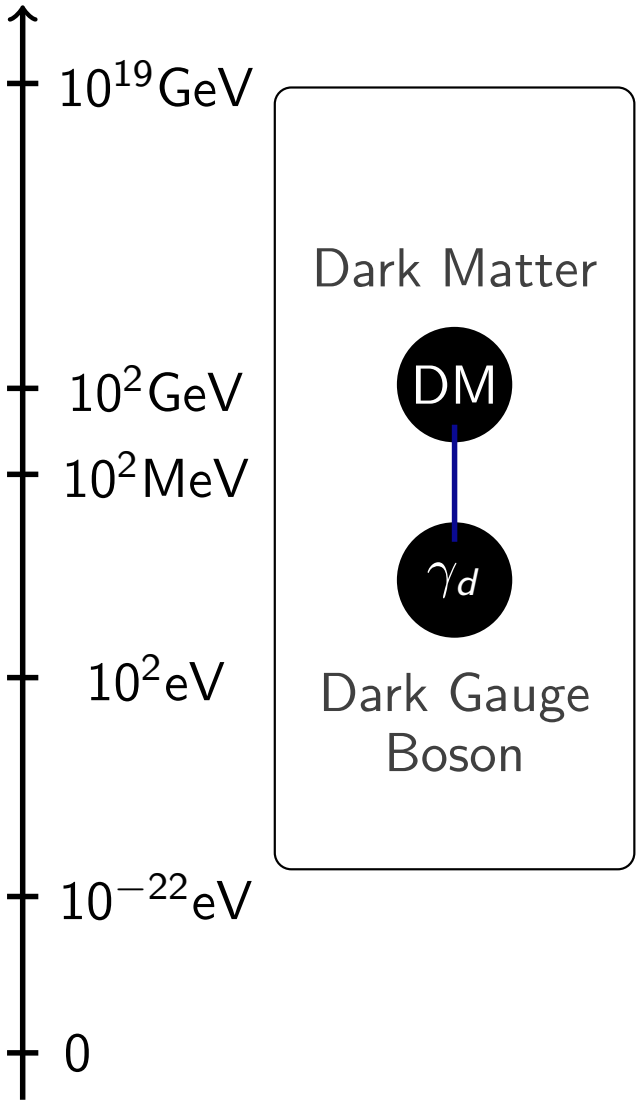
Dark $SU(N)$ + Higgs mechansim = hot NEDE

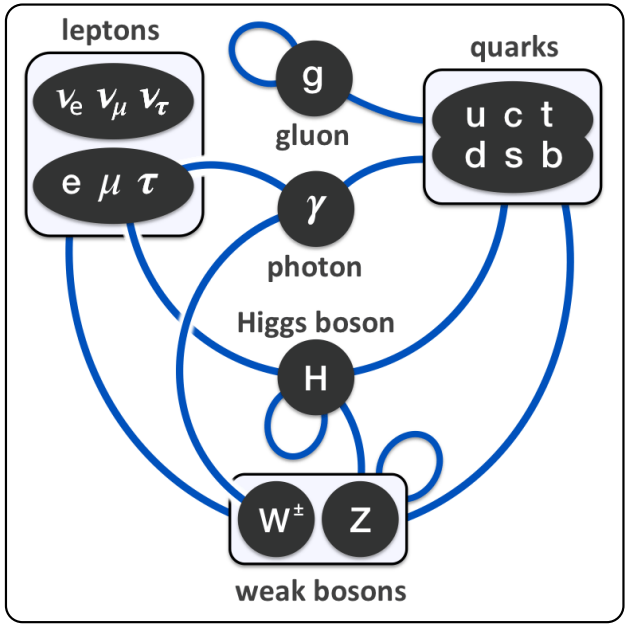




MG, Niedermann, Rubira, Sloth 2404.07256

Dark $SU(N)$ + DM


10^{19}GeV
10^{2}GeV
10^{2}MeV
10^{2}eV
10^{-22}eV
0
Dark Matter
DM
γ_d
Dark Gauge Boson


leptons
ν_e ν_μ ν_τ
e μ τ
g
gluon
quarks
u c t
d s b
γ
photon
Higgs boson
H
$W^\pm$
Z
weak bosons

Dark $SU(N)$ + DM

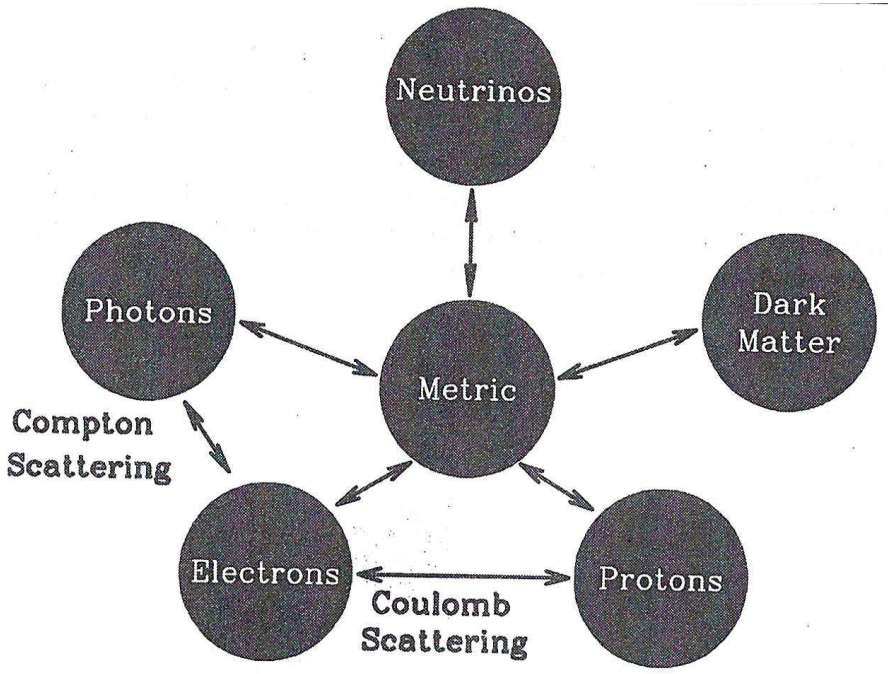


image: Dodelson, Modern Cosmology

Dark $SU(N)$ + DM

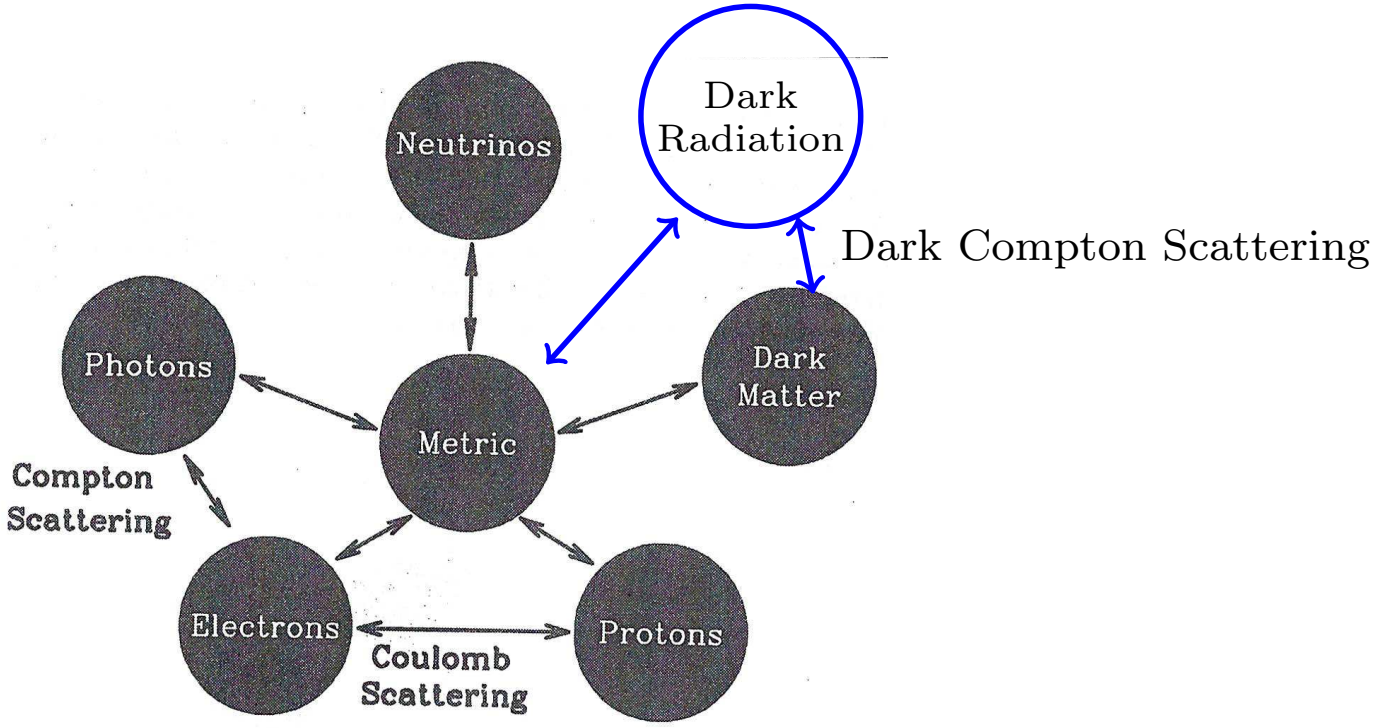
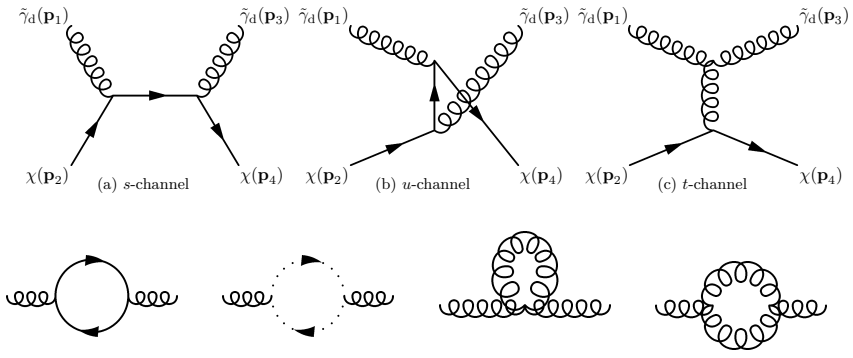


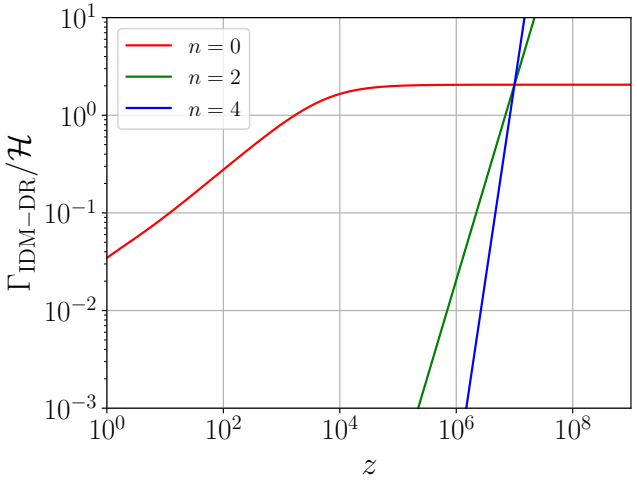
image: Dodelson, Modern Cosmology

Dark $SU(N)$ + DM



$$\Gamma_{\rm IDM-DR} = -a\frac{\pi}{18}\frac{\alpha_d^2}{m_\chi}\eta_{\rm DR}\left\{T_{\rm DR}^2\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] + \mathcal{O}\left(\frac{T_{\rm DR}^4}{m_\chi^2}\right)\right\},$$

$$c_0 = 1 + \ln\left(\frac{6}{2N+N_f}\right) + \ln(4\pi) - 24\ln(A), \quad \text{and} \quad c_1 = \frac{3\sqrt{2N+N_f}}{4\pi}\sqrt{\frac{3}{2}},$$



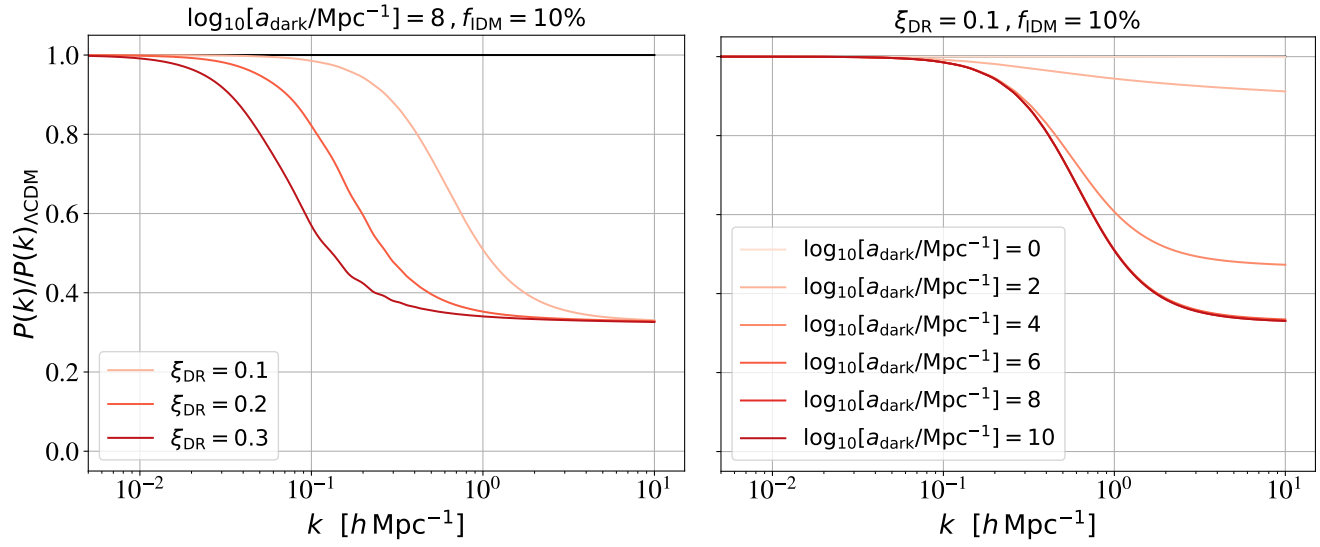
$\Rightarrow$ suppression of $P(k)$ over wide range of scales (ETHOS $n = 0$)

(note: different for Abelian (dark photon) or contact interaction)

Moore, Teaney hep-ph/0412346; Buen-Abad, Lesgourgues, Marquez-Tavarez, Schmaltz 1505.03542, 1507.04351;

Cyr-Racine, Sigurdson, Zavala, Bringmann, Vogelsberger 1512.05344; ...; Rubira, Mazoun, MG 2209.03974

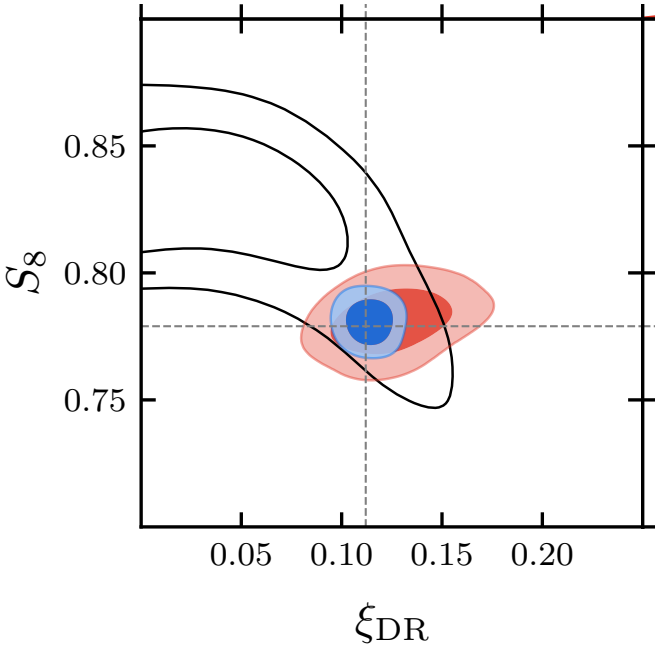
Dark $SU(N)$ + DM



- Dark sector temperature $\xi = T_{DR}/T_\gamma$: scale of suppression
- DM+DR interaction strength: amount of suppression

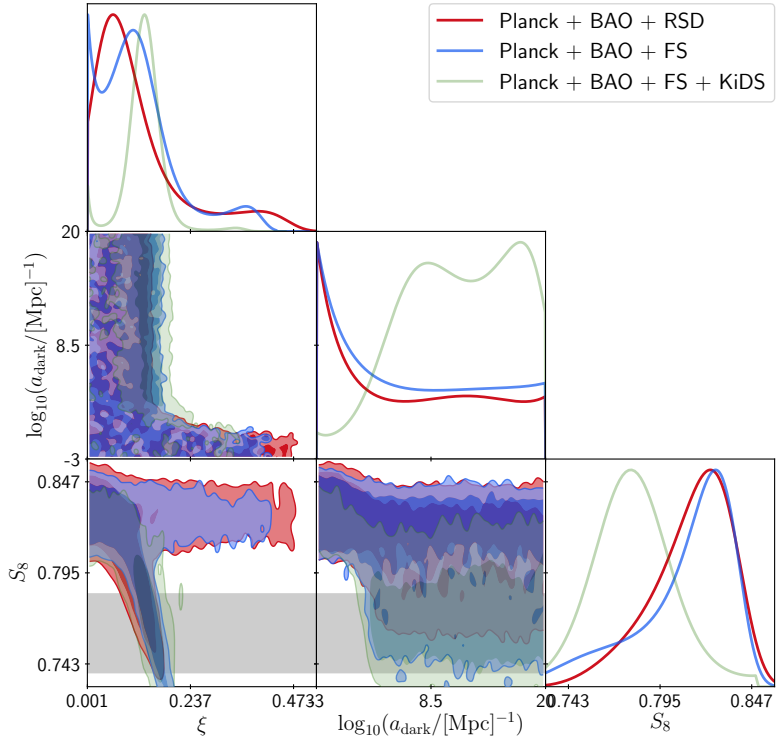
fig. from Mazoun, Bocquet, MG, Mohr, Rubira, Vogt 2312.17622

Dark $SU(N)$ + DM



Planck
CMB-S4×ngWL
Planck+CMB-S4×ngWL

$$\xi = \frac{T_{\rm DR}}{T_\gamma}$$



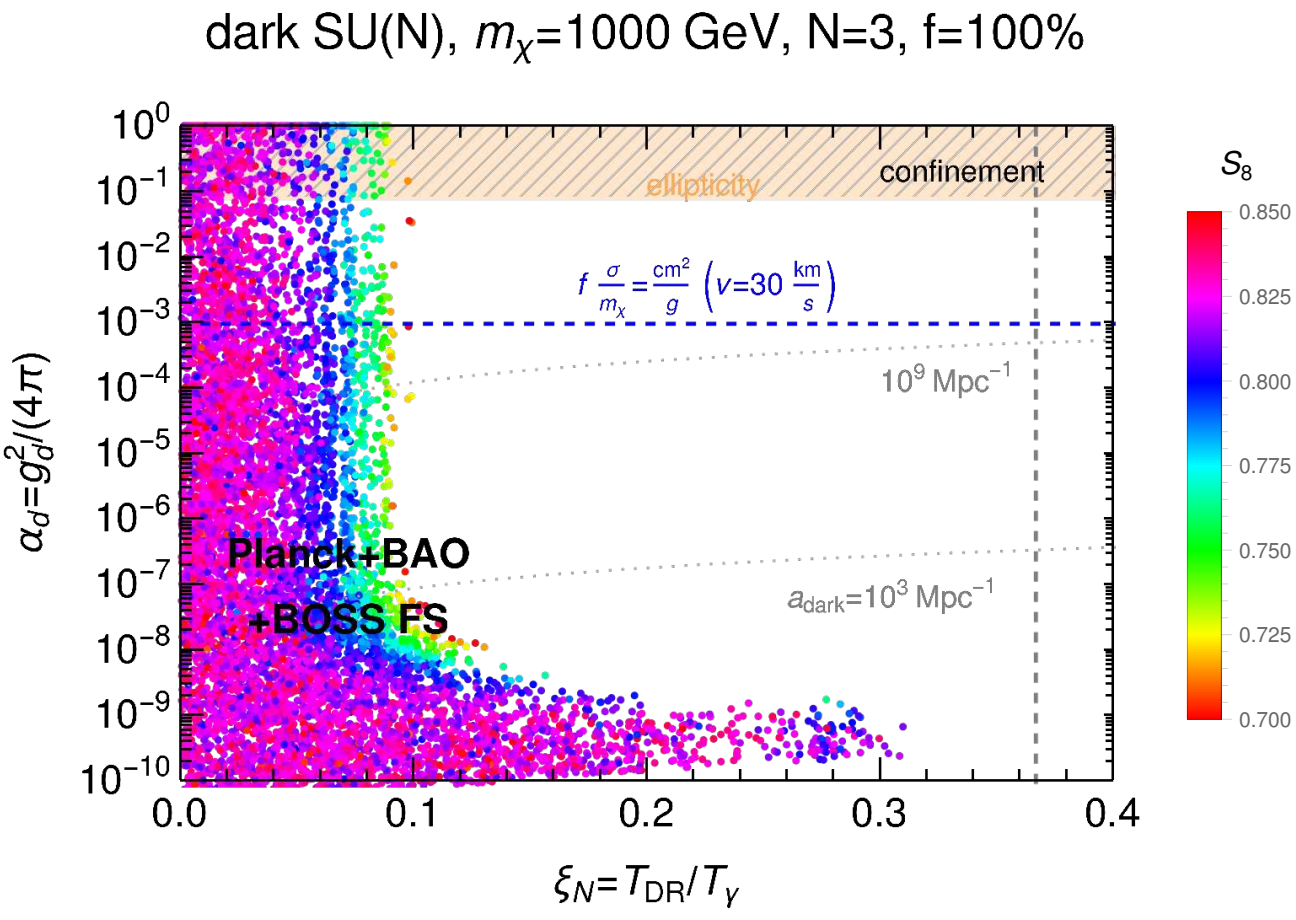
Forecast for CMBS4-SZ cluster counts + masses via Euclid weak lens
Mazoun, Bocquet, MG, Mohr, Rubira, Vogt 2312.17622

BOSS-DR12 (1-loop EFT CLASS-PT)
Rubira, Mazoun, MG 2209.03974

cf. also Euclid weak lensing shear forecast *Euclid coll. 2406.18274* *Simon++, Joseph++*

21cm forecast *Plombat, Simon, Flitter, Poulin 2410.01486* *Chacko++, Rompineve+*

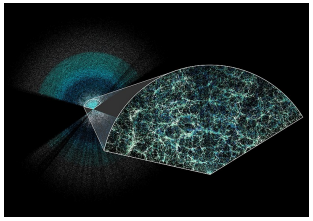
Dark $SU(N)$ + DM

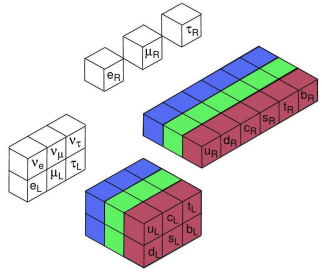


Rubira, Mazoun, MG 2209.03974

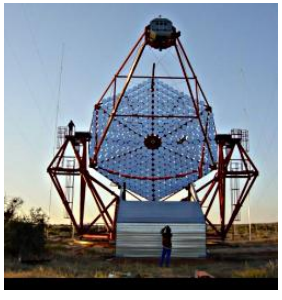
Particle
HEP/lab

Cosmo
CMB/LSS



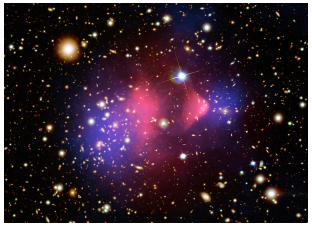


$+ \; ?$



Astroparticle

Astro
"small-scale"



DM-SM connection
Production mechanism?

Dark Sector
Is DM cold and collisionless?