CERN, New physics from galaxy clustering

DM interaction with dark radiation + LSS + S8 tension

(or the EFT analysis of an effective theory)

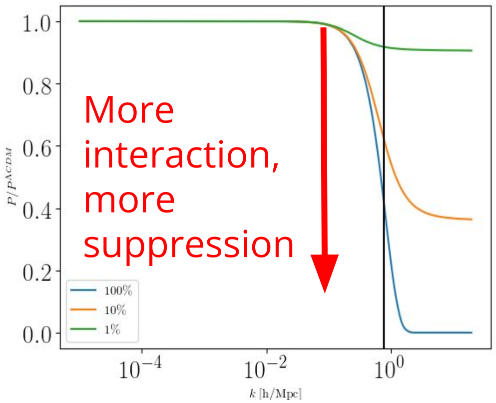
In collaboration with
Asmaa Mazoun and Mathias Garny

henrique.rubira@tum.de

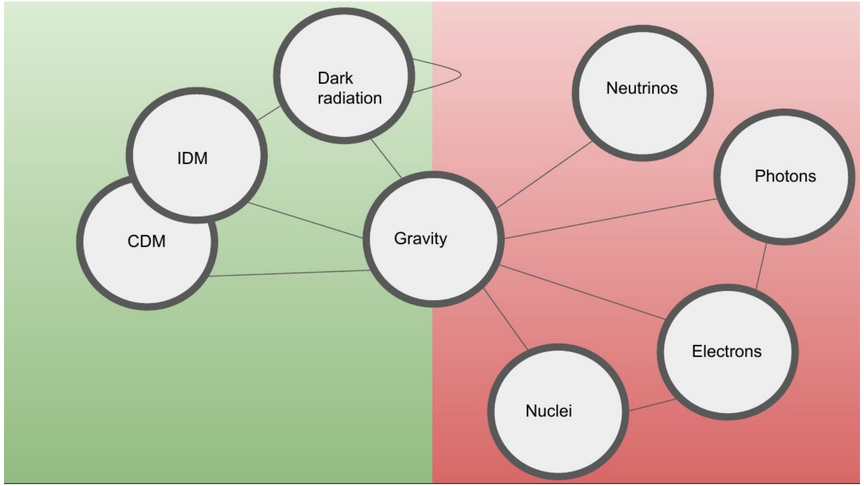
ArXiv: 2209.03974

Message to take home

Suppression of matter power spectrum by DM-DR interaction can address S8 tension (from ~2.5sigma to ~1sigma)



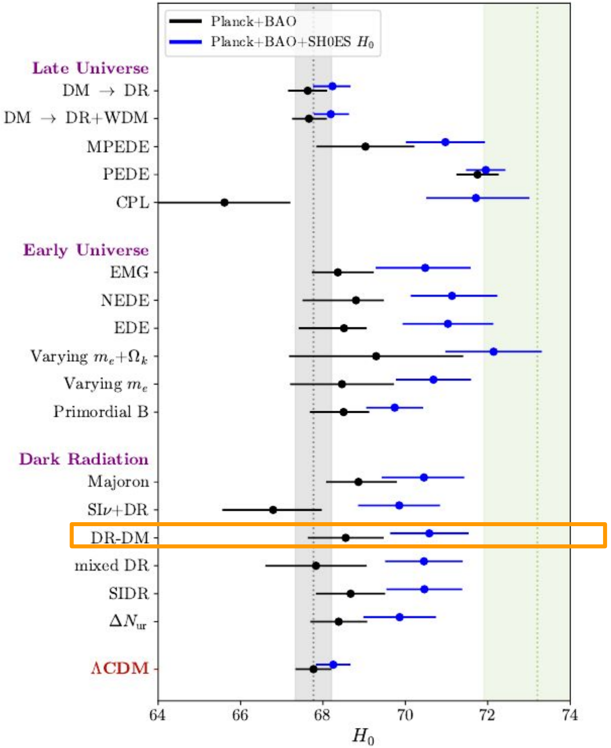
$$\sigma^2 = \frac{1}{2\pi^2}\int dk\, k^2 P(k,z)\, |W(kR)|^2$$



Using LSS to understand more about a dark sector

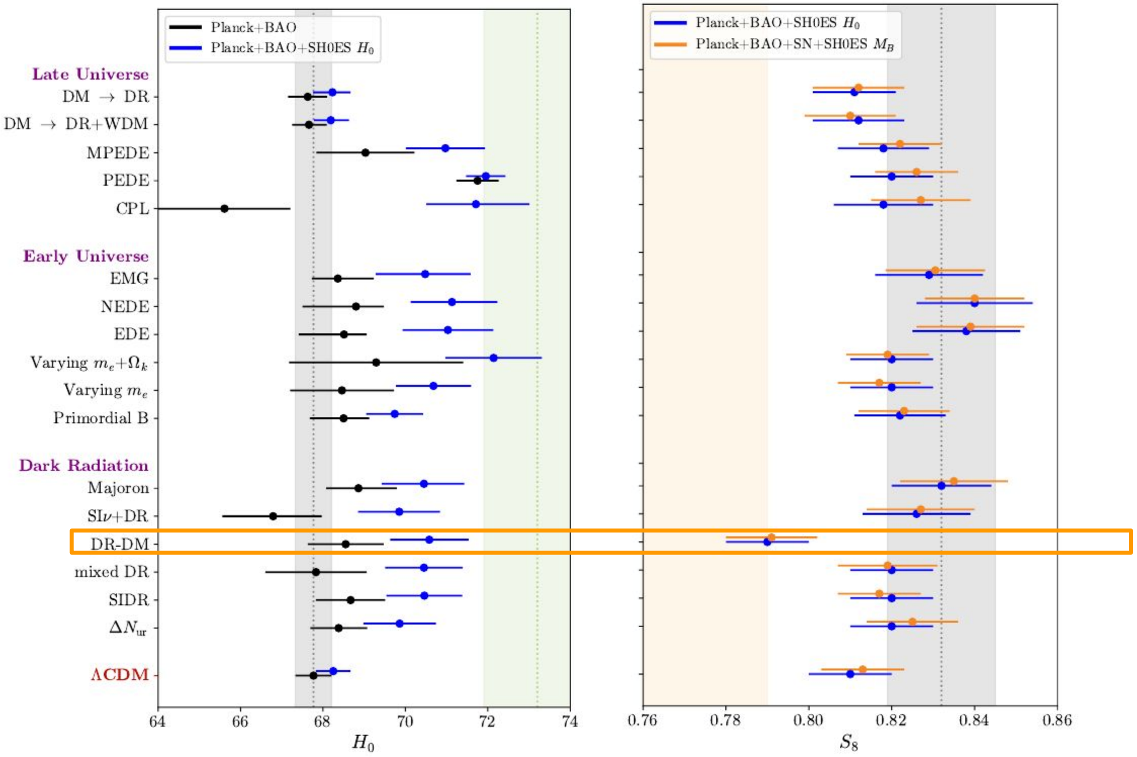
Motivation 1: Tensions in cosmology

H0 Olympics paper
(Schöneberg+)

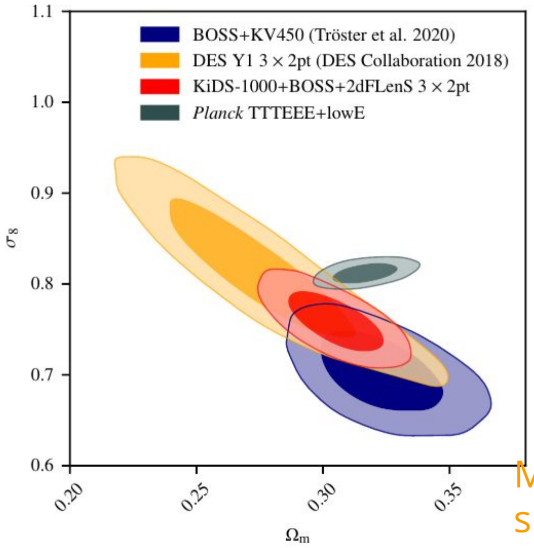


Motivation 1: Tensions in cosmology

H0 Olympics paper (Schöneberg+)



Motivation 1: on the S8 tension



Heymans, Tröster +, 20

Models that suppress P at scales of 8Mpc

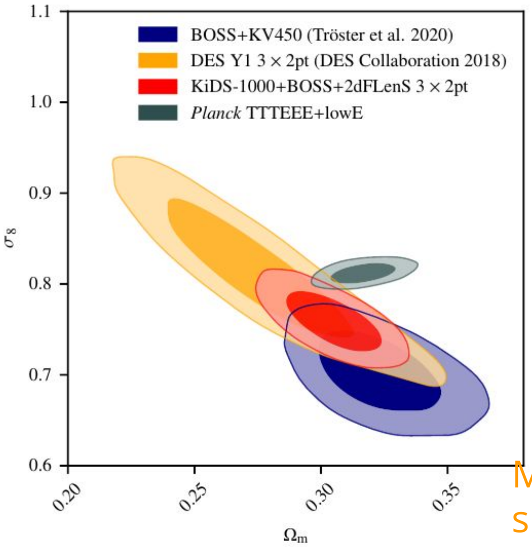
$$\sigma^2 = \frac{1}{2\pi^2}\int dk\, k^2 P(k,z)\, |W(kR)|^2$$

Play with this guy to reduce sigma for LSS/lensing

Henrique Rubira

Motivation 1: on the S8 tension

NOTICE THAT NOT ALL THOSE MEASUREMENTS ARE INDEPENDENT!!!



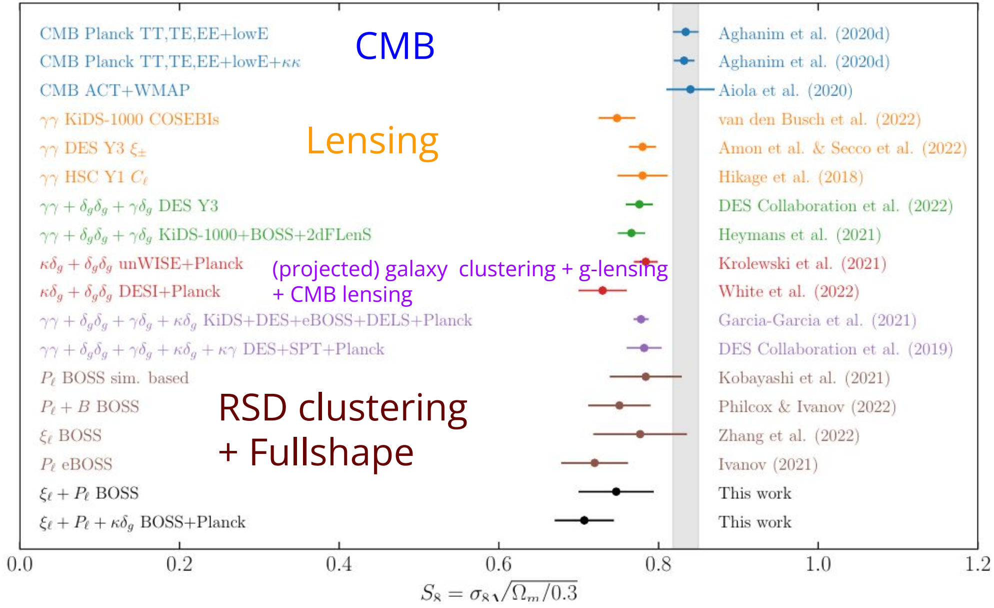
Heymans, Tröster +, 20

Models that suppress P at scales of 8Mpc

$$\sigma^2 = \frac{1}{2\pi^2}\int dk\, k^2 P(k,z)\, |W(kR)|^2$$

Play with this guy to reduce sigma for LSS/lensing

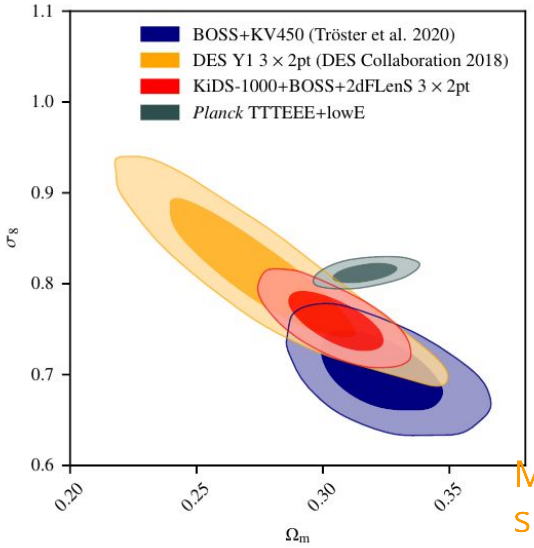
Chen, White, +, 22



Henrique Rubira

Motivation 1: on the S8 tension

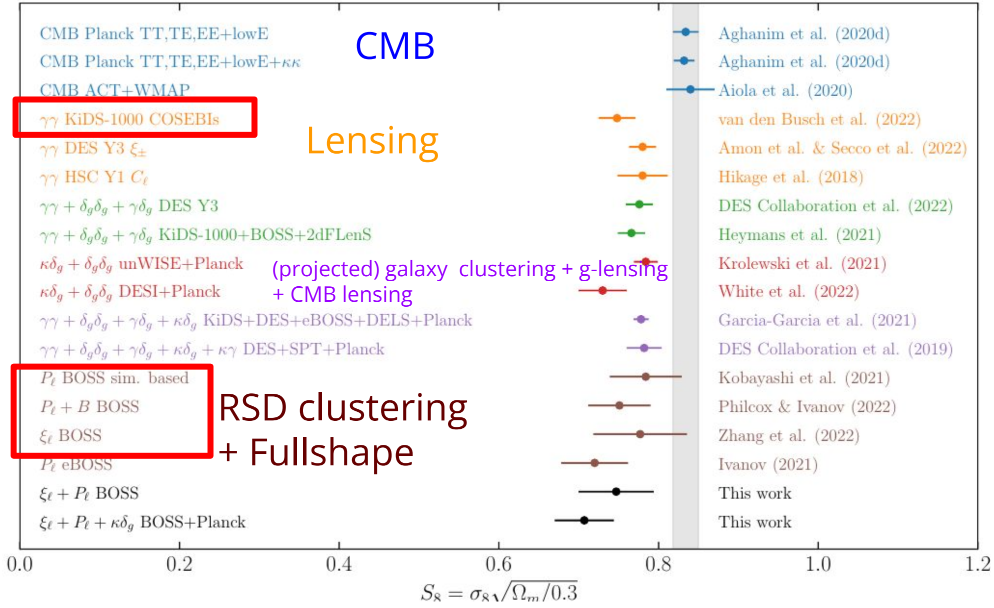
NOTICE THAT NOT ALL THOSE MEASUREMENTS ARE INDEPENDENT!!!



Heymans, Tröster +, 20

Important for this talk!

Chen, White, +, 22



Models that suppress P at scales of 8Mpc

$$\sigma^2 = \frac{1}{2\pi^2}\int dk\, k^2 P(k,z)\, |W(kR)|^2$$

Play with this guy to reduce sigma for LSS/lensing

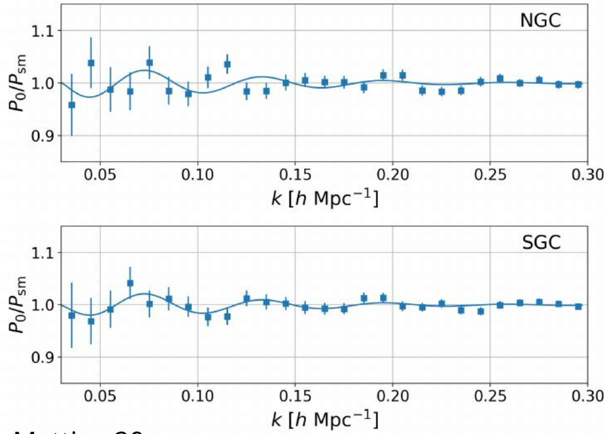
If you don't care about S8, shall you stop seeing this talk?

Henrique Rubira

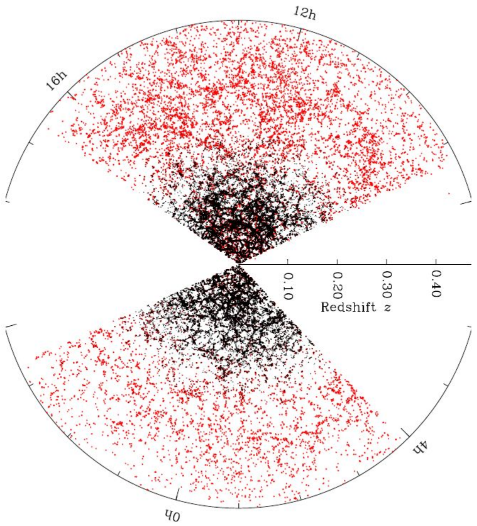
Motivation 2: on why (EFTof)LSS is so powerful

How we have been doing LSS
(and still relevant!!!)

Extracting BAO wiggles and
measure redshift-space distortions

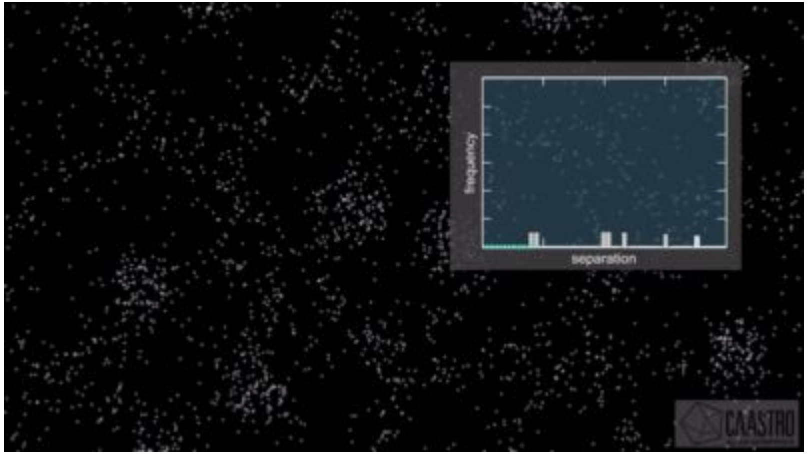


de Mattia+ 20



SDSS collaboration

CAASTRO

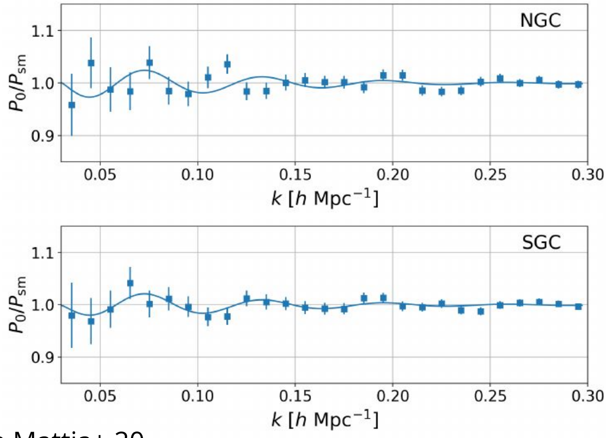


Motivation 2: on why (EFTof)LSS is so powerful

Henrique Rubira

How we have been doing LSS
(and still relevant!!!)

Extracting BAO wiggles and
measure redshift-space distortions



de Mattia+ 20

What we can do now

$$\delta_g(\boldsymbol{x},\tau) = \sum_{\mathcal{O}} b_{\mathcal{O}}(\tau)\mathcal{O}(\boldsymbol{x},\tau) + \epsilon(\boldsymbol{x},\tau) + \sum_{\mathcal{O}} \epsilon_{\mathcal{O}}(\boldsymbol{x},\tau)\mathcal{O}(\boldsymbol{x},\tau)$$

(Assassi+ 14; Desjacques, Jeong, Schmidt; 16)

Full-shape

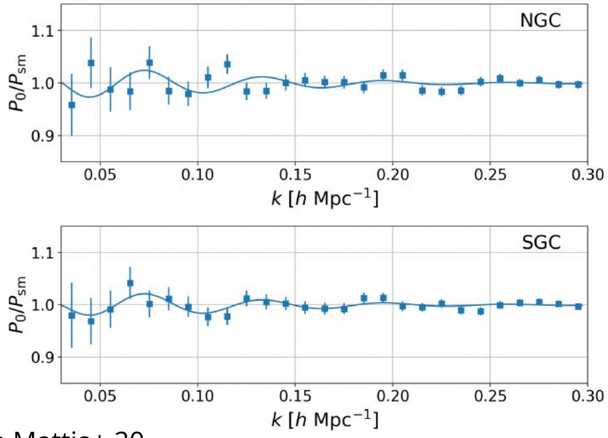
$$\begin{aligned} P^{gg}(z,k) = & (b_1)^2[P_{\rm lin}(z,k) + P_{\rm 1L}(z,k)] + b_1 b_2 \mathcal{I}_{\delta^2}(z,k) + 2b_1 b_{\mathcal{G}_2}\mathcal{I}_{\mathcal{G}_2}(z,k) \\ & + \left(2b_1 b_{\mathcal{G}_2} + \frac{4}{5} b_1 b_{\Gamma_3}\right)\mathcal{F}_{\mathcal{G}_2}(z,k) + \frac{1}{4}(b_2)^2 \mathcal{I}_{\delta^2\delta^2}(z,k) \\ & + (b_{\mathcal{G}_2})^2 \mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2 b_{\mathcal{G}_2}\mathcal{I}_{\delta^2\mathcal{G}_2}(z,k) + P_{\nabla^2\delta}(z,k) + P_{\varepsilon\varepsilon}(z,k)\,, \end{aligned}$$

Motivation 2: on why (EFTof)LSS is so powerful

Henrique Rubira

How we have been doing LSS
(and still relevant!!!)

Extracting BAO wiggles and
measure redshift-space distortions



de Mattia+ 20

What we can do now

$$\delta_g(\boldsymbol{x},\tau) = \sum_{\mathcal{O}} b_{\mathcal{O}}(\tau)\mathcal{O}(\boldsymbol{x},\tau) + \epsilon(\boldsymbol{x},\tau) + \sum_{\mathcal{O}} \epsilon_{\mathcal{O}}(\boldsymbol{x},\tau)\mathcal{O}(\boldsymbol{x},\tau)$$

(Assassi+ 14; Desjacques, Jeong, Schmidt; 16)

Full-shape

$$\boxed{\begin{aligned} P^{gg}(z,k) = & (b_1)^2 [P_{\rm lin}(z,k) + P_{\rm 1L}(z,k)] + b_1 b_2 \mathcal{I}_{\delta^2}(z,k) + 2b_1 b_{\mathcal{G}_2} \mathcal{I}_{\mathcal{G}_2}(z,k) \\ & + \left(2b_1 b_{\mathcal{G}_2} + \frac{4}{5} b_1 b_{\Gamma_3}\right) \mathcal{F}_{\mathcal{G}_2}(z,k) + \frac{1}{4}(b_2)^2 \mathcal{I}_{\delta^2\delta^2}(z,k) \\ & + (b_{\mathcal{G}_2})^2 \mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2 b_{\mathcal{G}_2} \mathcal{I}_{\delta^2\mathcal{G}_2}(z,k) + P_{\nabla^2\delta}(z,k) + P_{\varepsilon\varepsilon}(z,k)\,, \end{aligned}}$$

Cons: many free parameters

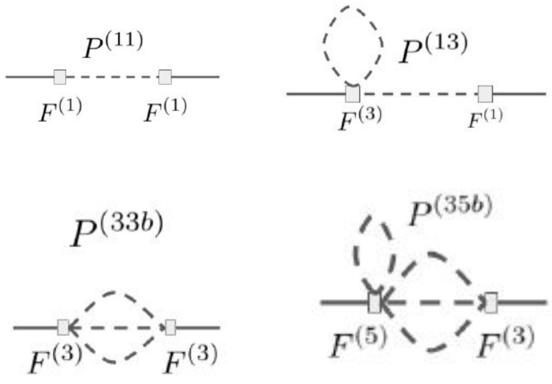
Pros:

- full (correct) non-linear parametrization
- trivially generalized to higher-order n-point function and other models

Motivation 2: on why (EFTof)LSS is so powerful

Full-shape

$$
\begin{aligned}
P^{gg}(z,k) = {} & (b_1)^2 \left[P_{\rm lin}(z,k) + P_{\rm 1L}(z,k)\right] + b_1 b_2\, \mathcal{I}_{\delta^2}(z,k) + 2 b_1 b_{\mathcal{G}_2}\, \mathcal{I}_{\mathcal{G}_2}(z,k) \\
& + \left(2 b_1 b_{\mathcal{G}_2} + \frac{4}{5} b_1 b_{\Gamma_3}\right) \mathcal{F}_{\mathcal{G}_2}(z,k) + \frac{1}{4}(b_2)^2\, \mathcal{I}_{\delta^2\delta^2}(z,k) \\
& + (b_{\mathcal{G}_2})^2\, \mathcal{I}_{\mathcal{G}_2\mathcal{G}_2}(z,k) + b_2 b_{\mathcal{G}_2}\, \mathcal{I}_{\delta^2\mathcal{G}_2}(z,k) + P_{\nabla^2\delta}(z,k) + P_{\varepsilon\varepsilon}(z,k)\,,
\end{aligned}
$$



Henrique Rubira

Effective Field Theory of LSS

1,2 and 3 loops P(k)

Carrasco, Hertzberg, Senatore; 12

Carrasco, Foreman, Green Senatore; 14

Konstandin, Porto, HR; 19

1 and 2 loops B(k)

Angulo, Foreman, Schmittfull, Senatore, 21

Baldauf, Garny, Taule, Steele; 21

Non-linear transformations

Philcox, Massara, Spergel; 20

HR, Voivodic; 20

Application to BOSS data

D'amico et al; 19

Ivanov, Simonović, Zaldarriaga; 19

Simon, Zhang, Poulin, 22

Bias Expansion

Assassi, Baumann, Green, Zaldarriaga; 15

Multi-tracer

Mergulhão, HR, Voivodic, Abramo, 21

Motivation 2: on why (EFTof)LSS is so powerful

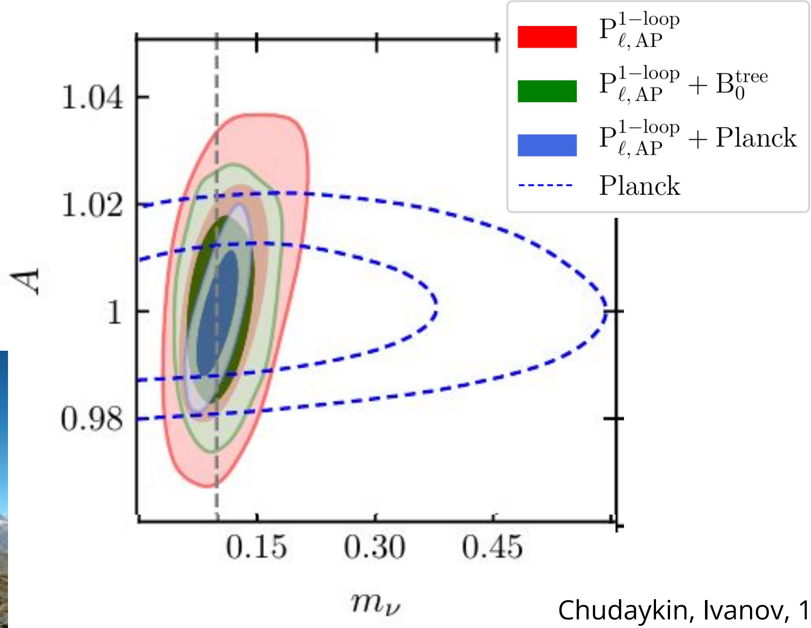
Henrique Rubira

The future is bright

Today: BOSS is amazing, DESI is taking data

Soon: EUCLID + DESI + LSST

EUCLID forecast for neutrinos



Chudaykin, Ivanov, 19

Motivation 2: on why (EFTof)LSS is so powerful

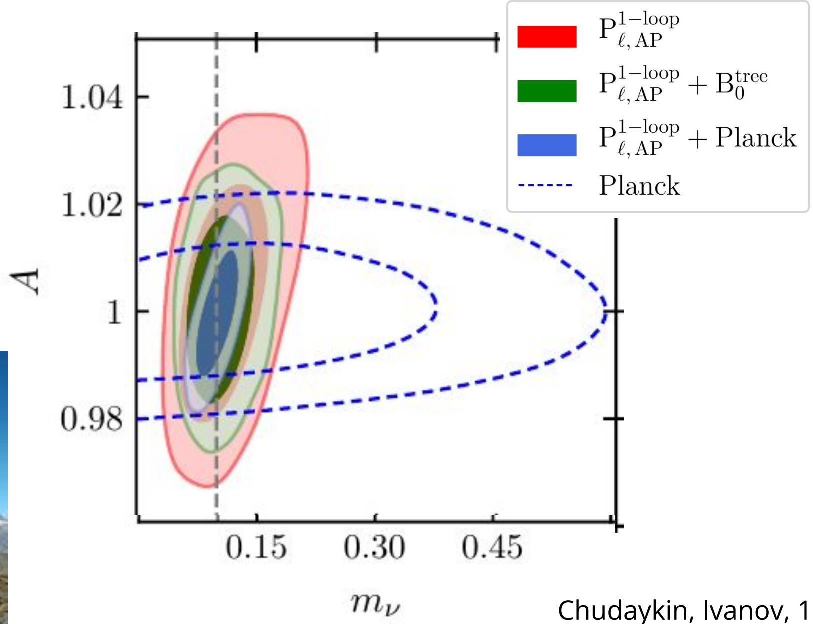
Henrique Rubira

The future is bright

Today: BOSS is amazing, DESI is taking data

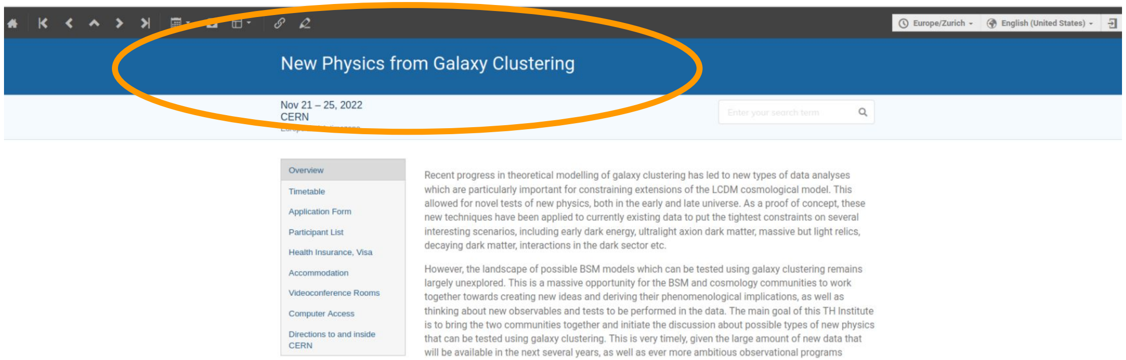
Soon: EUCLID + DESI + LSST

EUCLID forecast for neutrinos



Chudaykin, Ivanov, 19

Motivation 3



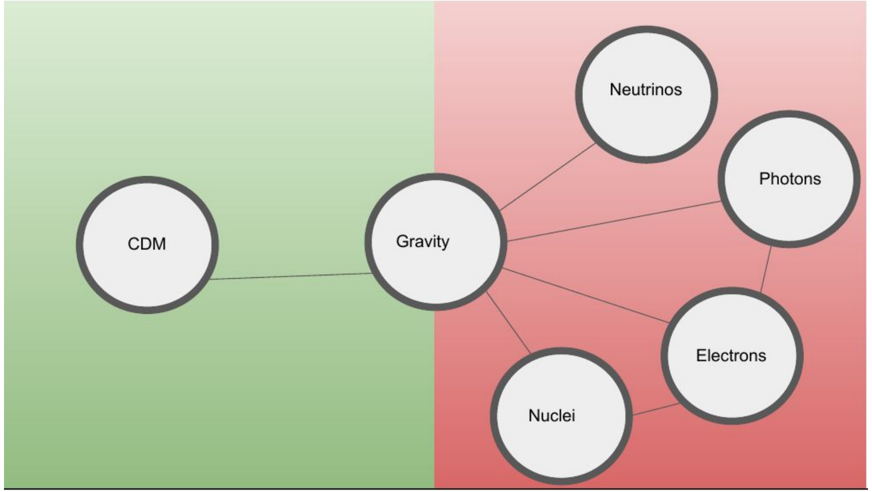
Outline of this talk

- Explain IDM-DR interaction and the ETHOS model

- Novel results from FS in light of the S8 tension

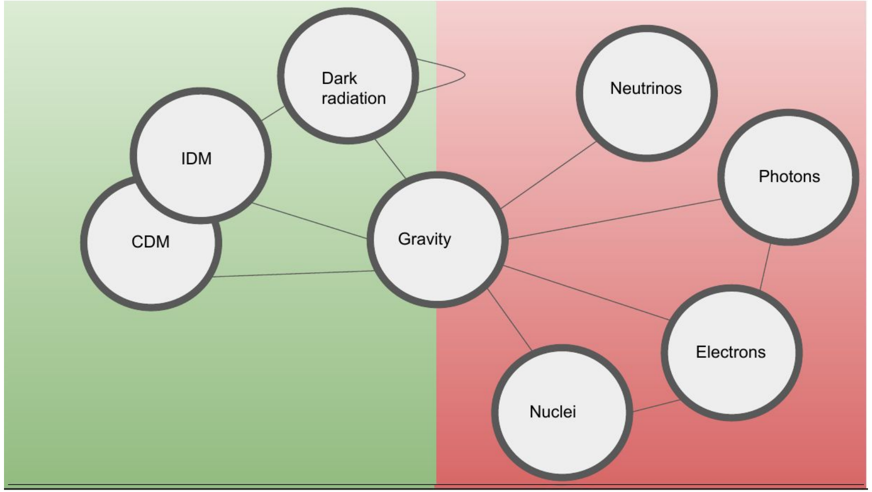
- What can we learn from that

Dark matter - dark radiation interaction



Dark matter - dark radiation interaction

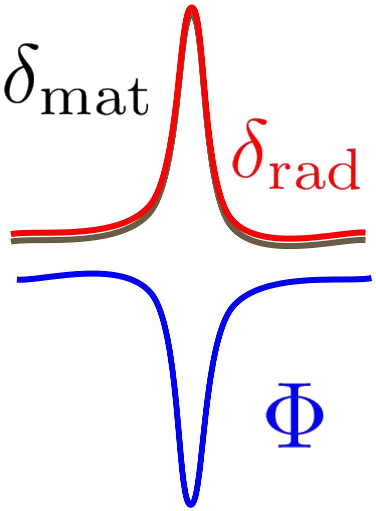
Henrique Rubira

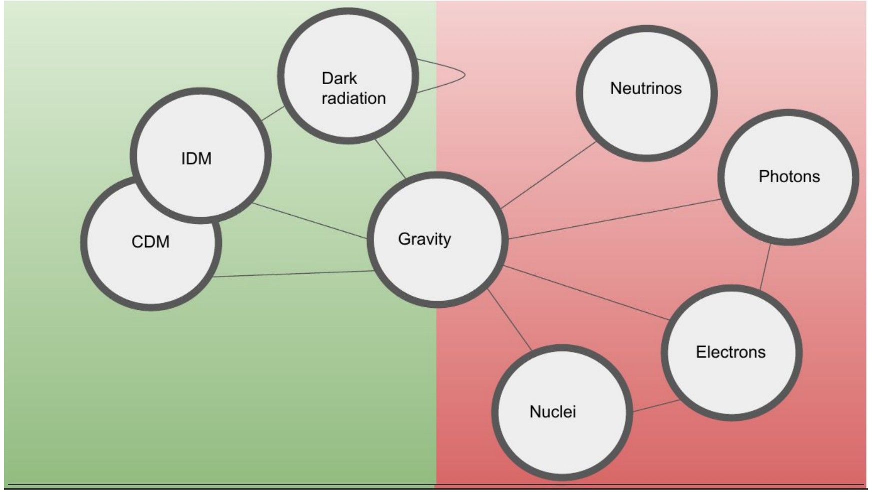


Dark matter - dark radiation interaction

What is the motivation to consider this model?

1) Radiation suppresses structure formation



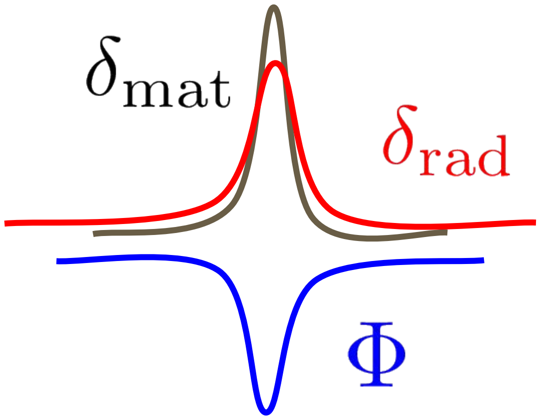


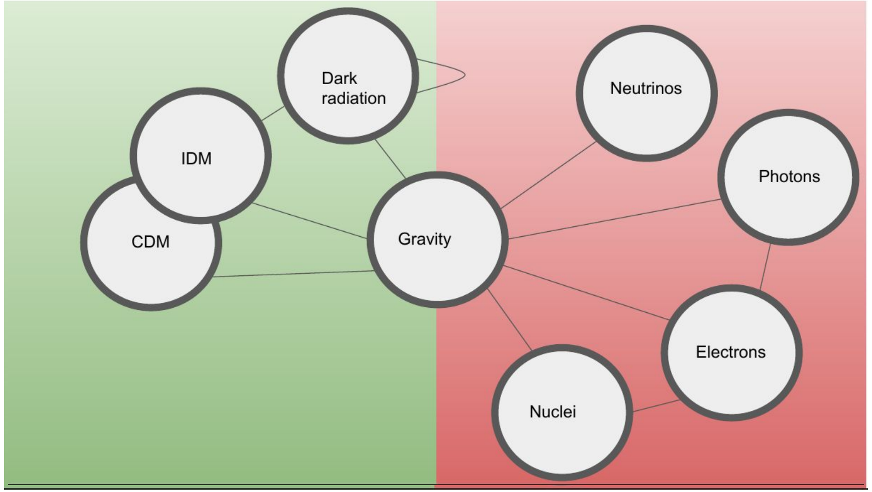
Dark matter - dark radiation interaction

Henrique Rubira

What is the motivation to consider this model?

1) Radiation suppresses structure formation



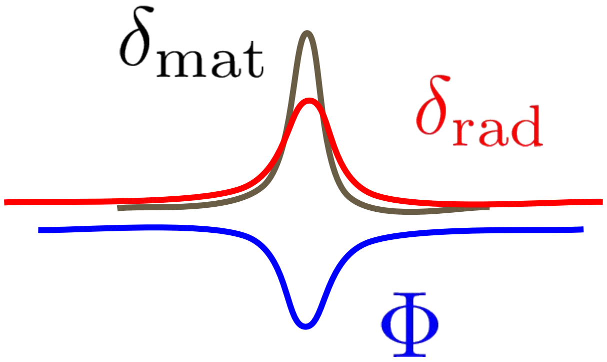


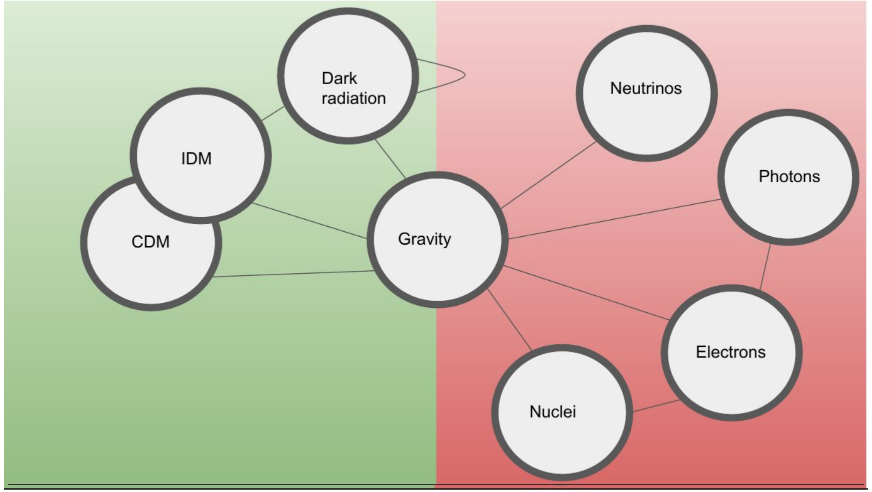
Dark matter - dark radiation interaction

Henrique Rubira

What is the motivation to consider this model?

1) Radiation suppresses structure formation





Dark matter - dark radiation interaction

Henrique Rubira

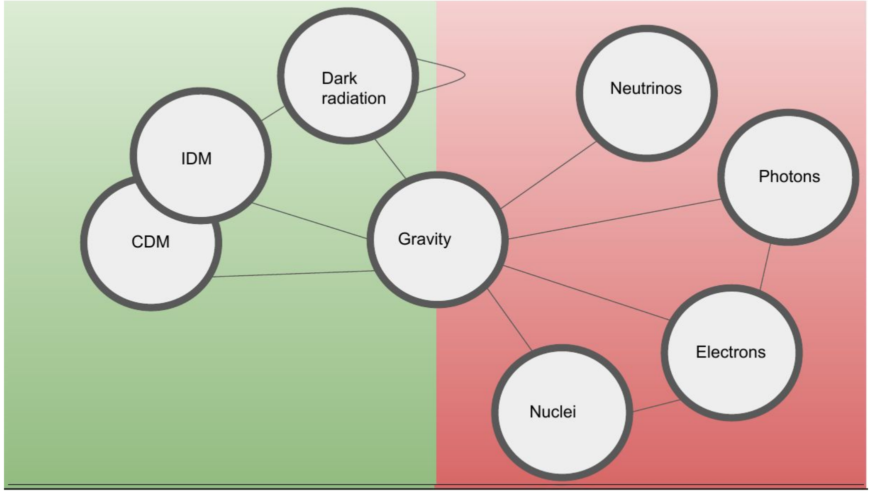
What is the motivation to consider this model?

1) Radiation suppresses structure formation

2) Considering a SU(N) dark is not that far from what we see in the Standard Model

$$\boxed{\mathcal{L}_{\rm SM}^{SU(3)\times SU(2)\times U(1)}}$$

$$\boxed{+\mathcal{L}_{\rm dark}^{SU(N)}}$$



Dark matter - dark radiation interaction

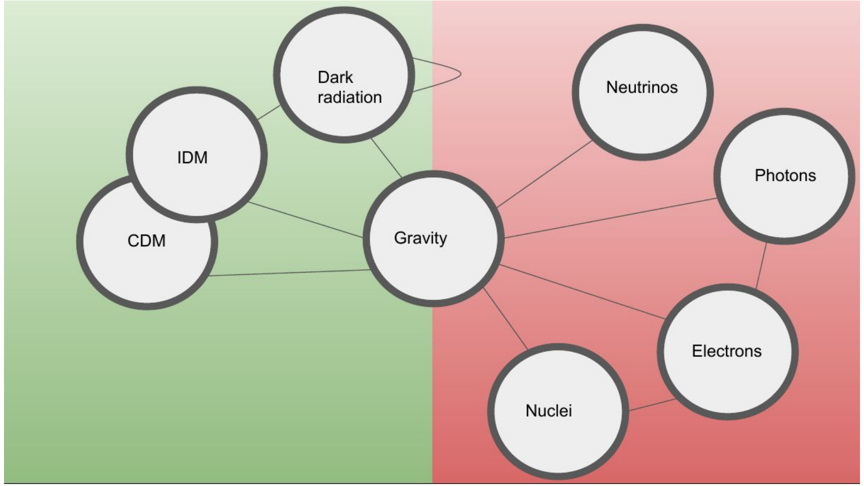
Henrique Rubira

$$\dot\delta_{\rm DR} + \frac{4}{3}\theta_{\rm DR} - 4\dot\phi_g = 0\,,$$
$$\dot\theta_{\rm DR} + k^2\left(\sigma^2_{\rm DR} - \frac{1}{4}\delta_{\rm DR}\right) - k^2\psi_g = \Gamma_{\rm DR-IDM}(\theta_{\rm DR} - \theta_{\rm IDM})\,,$$
$$\dot\Pi_{\rm DR,l} + \frac{k}{2l+1}\left[(l+1)\Pi_{\rm DR,l+1} - l\Pi_{\rm DR,l-1}\right] = (\alpha_l\Gamma_{\rm DR-IDM} + \beta_l\Gamma_{\rm DR-DR})\Pi_{\rm DR,l}\,,$$

Eqs. for DR

Eqs. for DM

$$\dot\delta_{\rm IDM} + \theta_{\rm IDM} - 3\dot\phi_g = 0\,,$$
$$\dot\theta_{\rm IDM} - c^2_{\rm IDM}k^2\delta_{\rm IDM} + \mathcal{H}\theta_{\rm IDM} - k^2\psi_g = \Gamma_{\rm IDM-DR}(\theta_{\rm IDM} - \theta_{\rm DR})$$



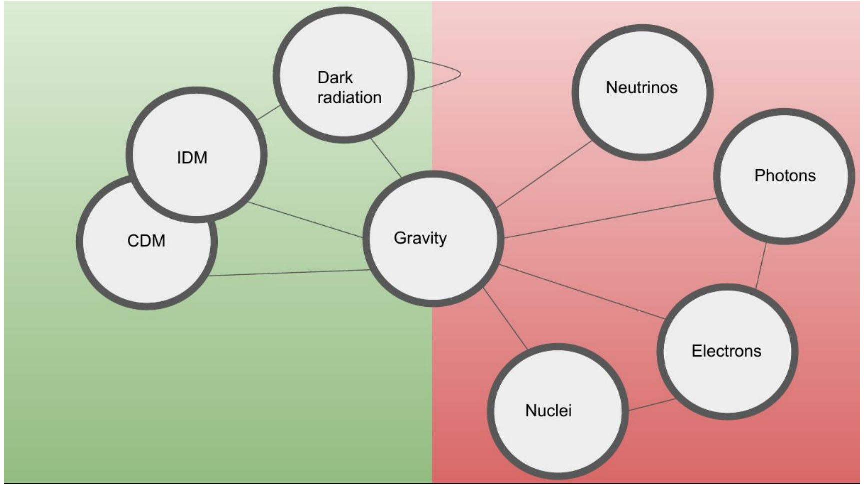
Dark matter - dark radiation interaction

$$\dot\delta_{\rm DR} + \frac{4}{3}\theta_{\rm DR} - 4\dot\phi_g = 0\,,$$
$$\dot\theta_{\rm DR} + k^2\left(\sigma^2_{\rm DR} - \frac{1}{4}\delta_{\rm DR}\right) - k^2\psi_g = \Gamma_{\rm DR-IDM}(\theta_{\rm DR} - \theta_{\rm IDM})\,,$$
$$\dot\Pi_{\rm DR,l} + \frac{k}{2l+1}\left[(l+1)\Pi_{\rm DR,l+1} - l\Pi_{\rm DR,l-1}\right] = (\alpha_l\Gamma_{\rm DR-IDM} + \beta_l\Gamma_{\rm DR-DR})\Pi_{\rm DR,l}\,,$$

Eqs. for DR

Eqs. for DM

$$\dot\delta_{\rm IDM} + \theta_{\rm IDM} - 3\dot\phi_g = 0\,,$$
$$\dot\theta_{\rm IDM} - c^2_{\rm IDM}k^2\delta_{\rm IDM} + \mathcal{H}\theta_{\rm IDM} - k^2\psi_g = \Gamma_{\rm IDM-DR}(\theta_{\rm IDM} - \theta_{\rm DR})$$



ETHOS (Effective theory of structure formation):

Cyr-Racine+ 1512.05344

Parametrize a broad range of UV models into a set of parameters that describe how they affect structure formation

Dark matter - dark radiation interaction

Henrique Rubira

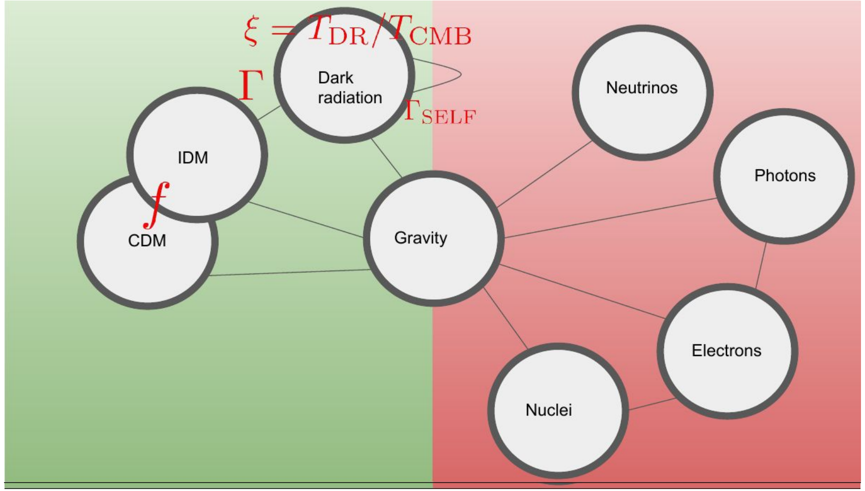
$$\dot{\delta}_{\rm DR} + \frac{4}{3}\theta_{\rm DR} - 4\dot{\phi}_g = 0\,,$$
$$\dot{\theta}_{\rm DR} + k^2\left(\sigma^2_{\rm DR} - \frac{1}{4}\delta_{\rm DR}\right) - k^2\psi_g = \Gamma_{\rm DR-IDM}(\theta_{\rm DR} - \theta_{\rm IDM})\,,$$
$$\dot{\Pi}_{\rm DR,l} + \frac{k}{2l+1}\left[(l+1)\Pi_{\rm DR,l+1} - l\Pi_{\rm DR,l-1}\right] = (\alpha_l\Gamma_{\rm DR-IDM} + \beta_l\Gamma_{\rm DR-DR})\Pi_{\rm DR,l}\,,$$

Eqs. for DR

Eqs. for DM

$$\dot{\delta}_{\rm IDM} + \theta_{\rm IDM} - 3\dot{\phi}_g = 0\,,$$
$$\dot{\theta}_{\rm IDM} - c^2_{\rm IDM}k^2\delta_{\rm IDM} + \mathcal{H}\theta_{\rm IDM} - k^2\psi_g = \Gamma_{\rm IDM-DR}(\theta_{\rm IDM} - \theta_{\rm DR})$$

ETHOS (Effective theory of structure formation):
Cyr-Racine+ 1512.05344



Parametrize a broad range of UV models into a set of parameters that describe how they affect structure formation

$$f \equiv \frac{\Omega_{\rm IDM}}{\Omega_{\rm CDM} + \Omega_{\rm IDM}}$$

$$\xi \equiv \left.\frac{T_{\rm DR}}{T_{\rm CMB}}\right|_{z=0}$$ (gives the amount of DR)

$$\Gamma \propto a_n(1+z)^n$$

Henrique Rubira

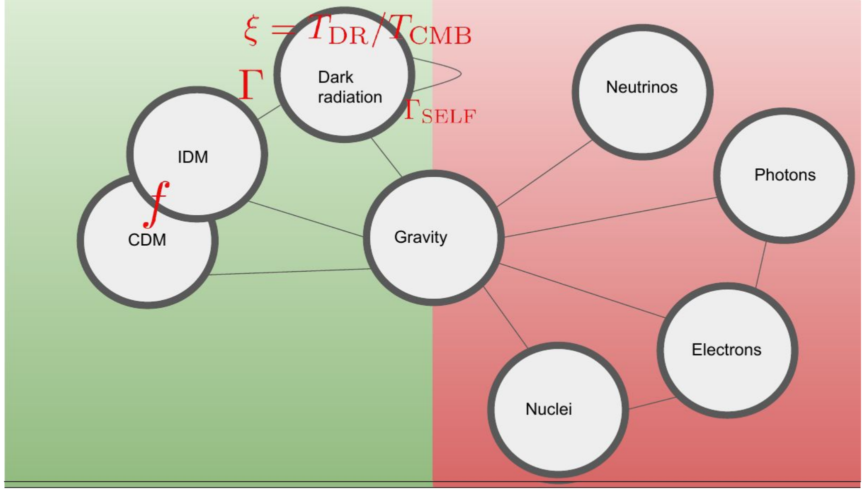
Dark matter - dark radiation interaction

$$\dot{\delta}_{\mathrm{DR}} + \frac{4}{3}\theta_{\mathrm{DR}} - 4\dot{\phi}_g = 0\,,$$
$$\dot{\theta}_{\mathrm{DR}} + k^2\left(\sigma_{\mathrm{DR}}^2 - \frac{1}{4}\delta_{\mathrm{DR}}\right) - k^2\psi_g = \Gamma_{\mathrm{DR-IDM}}(\theta_{\mathrm{DR}} - \theta_{\mathrm{IDM}})\,,$$
$$\dot{\Pi}_{\mathrm{DR},l} + \frac{k}{2l+1}\left[(l+1)\Pi_{\mathrm{DR},l+1} - l\Pi_{\mathrm{DR},l-1}\right] = (\alpha_l\Gamma_{\mathrm{DR-IDM}} + \beta_l\Gamma_{\mathrm{DR-DR}})\Pi_{\mathrm{DR},l}\,,$$

Eqs. for DR

Eqs. for DM

$$\dot{\delta}_{\mathrm{IDM}} + \theta_{\mathrm{IDM}} - 3\dot{\phi}_g = 0\,,$$
$$\dot{\theta}_{\mathrm{IDM}} - c_{\mathrm{IDM}}^2 k^2\delta_{\mathrm{IDM}} + \mathcal{H}\theta_{\mathrm{IDM}} - k^2\psi_g = \Gamma_{\mathrm{IDM-DR}}(\theta_{\mathrm{IDM}} - \theta_{\mathrm{DR}})$$



ETHOS (Effective theory of structure formation):

Cyr-Racine+ 1512.05344

Parametrize a broad range of UV models into a set of parameters that describe how they affect structure formation

$$f \equiv \frac{\Omega_{\mathrm{IDM}}}{\Omega_{\mathrm{CDM}} + \Omega_{\mathrm{IDM}}}$$

$$\xi \equiv \left.\frac{T_{\mathrm{DR}}}{T_{\mathrm{CMB}}}\right|_{z=0}$$ (gives the amount of DR)

$$\Gamma \propto a_n(1+z)^n$$

The z-dependence of the DM-DR scattering is model dependent

Some examples

From Cyr-Racine+, 15

$$\Gamma \propto a_n(1+z)^n$$

Henrique Rubira

The z-dependence of the DM-DR scattering is model dependent

Some examples

Henrique Rubira

$$\Gamma \propto a_n (1+z)^n$$

The z-dependence of the DM-DR scattering is model dependent

From Cyr-Racine+, 15

$\boxed{n = 4}$ **Massive mediator**

e.g., DR is sterile neutrino ν_s interacts with DM via broken U(1) with massive vector boson ϕ_μ

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_s \gamma^\mu \nu_s - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

Some examples

$$\Gamma \propto a_n (1+z)^n$$

Henrique Rubira

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n=4}$ **Massive mediator**

e.g., DR is sterile neutrino ν_s interacts with DM via broken U(1) with massive vector boson ϕ_μ

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_s \gamma^\mu \nu_s - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

$\boxed{n=2}$ **Hidden-charged scalar DM**

e.g., DR the gauge boson of a dark unbroken U(1)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$

Some examples

Henrique Rubira

$$\Gamma \propto a_n (1+z)^n$$

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n=4}$ **Massive mediator**

e.g., DR is sterile neutrino $\nu_{\rm s}$ interacts with DM via broken U(1) with massive vector boson ϕ_μ

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_{\rm s}\gamma^\mu \nu_{\rm s} - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

$\boxed{n=2}$ **Hidden-charged scalar DM**

e.g., DR the gauge boson of a dark unbroken U(1)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$

$\boxed{n=0}$ **Non-abelian DR**

e.g., DR the gauge boson of a dark SU(N)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_{\rm d} T^a \tilde{A}^a_\mu$$

Some examples

$$\Gamma \propto a_n (1+z)^n$$

Henrique Rubira

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n = 4}$ **Massive mediator**

DR free streams

e.g., DR is sterile neutrino ν_s interacts with DM via broken U(1) with massive vector boson ϕ_μ

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi} \gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_s \gamma^\mu \nu_s - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi} \chi,$$

$\boxed{n = 2}$ **Hidden-charged scalar DM**

e.g., DR the gauge boson of a dark unbroken U(1)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$

$\boxed{n = 0}$ **Non-abelian DR**

DR behaves as a fluid

e.g., DR the gauge boson of a dark SU(N)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_{\rm d} T^a \tilde{A}^a_\mu$$

Henrique Rubira

Some examples

$$\Gamma \propto a_n (1+z)^n$$

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n=4}$ **Massive mediator**

DR free streams

e.g., DR is sterile neutrino $\nu_{\rm s}$ interacts with DM via broken U(1) with massive vector boson ϕ_μ

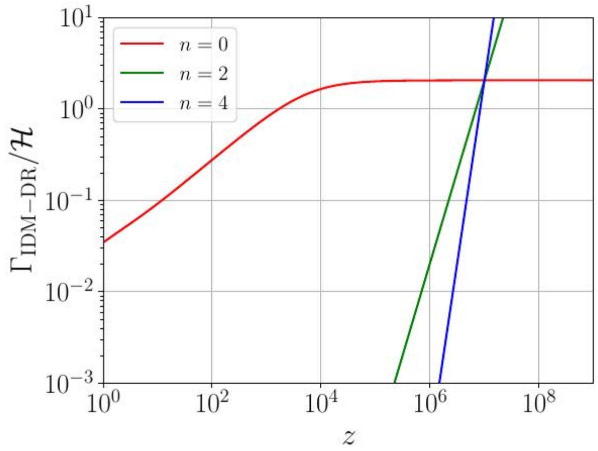
$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_{\rm s} \gamma^\mu \nu_{\rm s} - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

This scaling will set how (and when) this interaction will be relevant

$\boxed{n=2}$ **Hidden-charged scalar DM**

e.g., DR the gauge boson of a dark unbroken U(1)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$



$\boxed{n=0}$ **Non-abelian DR**

DR behaves as a fluid

e.g., DR the gauge boson of a dark SU(N)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_{\rm d} T^a \tilde{A}^a_\mu$$

Some examples

Henrique Rubira

$$\Gamma \propto a_n (1+z)^n$$

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n = 4}$ **Massive mediator**

DR free streams

e.g., DR is sterile neutrino $\nu_{\rm s}$ interacts with DM via broken U(1) with massive vector boson ϕ_μ

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_{\rm s} \gamma^\mu \nu_{\rm s} - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

This scaling will set how (and when) this interaction will be relevant

$\boxed{n = 2}$ **Hidden-charged scalar DM**

e.g., DR the gauge boson of a dark unbroken U(1)

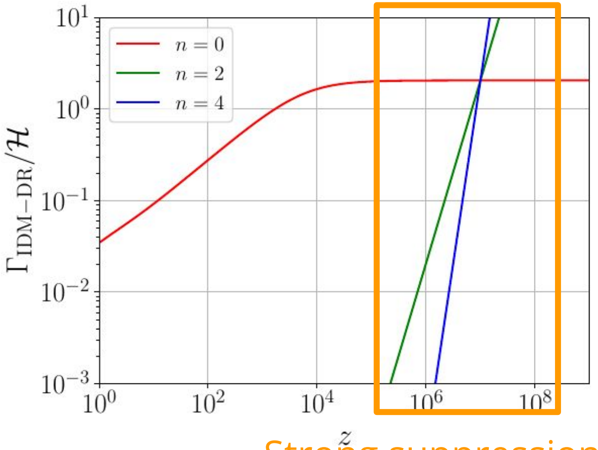
$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$

$\boxed{n = 0}$ **Non-abelian DR**

DR behaves as a fluid

e.g., DR the gauge boson of a dark SU(N)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_{\rm d} T^a \tilde{A}^a_\mu$$



Strong suppression of modes that enter the horizon

Some examples

$$\Gamma \propto a_n (1+z)^n$$

From Cyr-Racine+, 15

The z-dependence of the DM-DR scattering is model dependent

$\boxed{n=4}$ **Massive mediator**

DR free streams

e.g., DR is sterile neutrino ν_s interacts with DM via broken U(1) with massive vector boson ϕ_μ

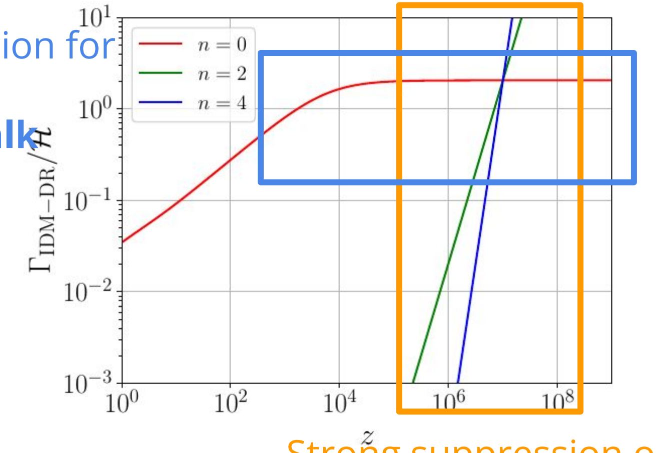
This scaling will set how (and when) this interaction will be relevant

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi}\gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_s \gamma^\mu \nu_s - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi}\chi,$$

$\boxed{n=2}$ **Hidden-charged scalar DM**

Milder suppression for longer times

Focus of this talk



e.g., DR the gauge boson of a dark unbroken U(1)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu$$

$\boxed{n=0}$ **Non-abelian DR**

DR behaves as a fluid

e.g., DR the gauge boson of a dark SU(N)

$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi \qquad D_\mu = \partial_\mu - i g_{\rm d} T^a \tilde{A}^a_\mu$$

Strong suppression of modes that enter the horizon

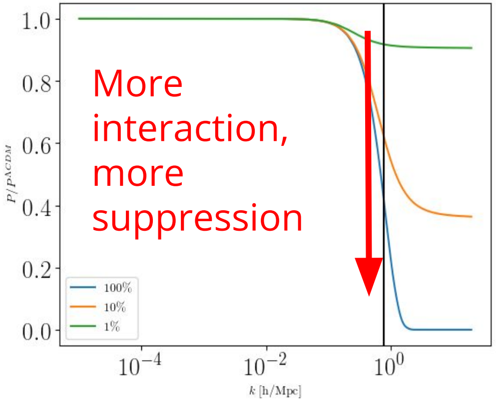
Let's relax for 1 minute... do you have any question?

The effect of each parameter on structure formation

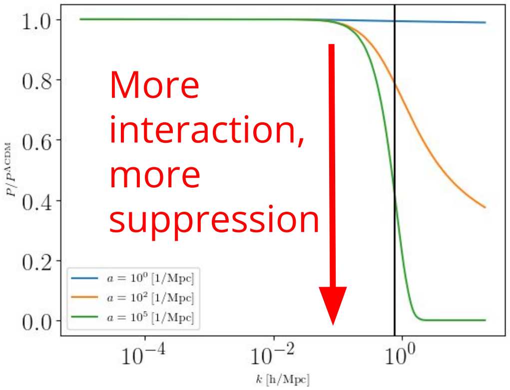
Henrique Rubira

The effect of each parameter on structure formation

$$f \equiv \frac{\Omega_{\rm IDM}}{\Omega_{\rm CDM} + \Omega_{\rm IDM}}$$



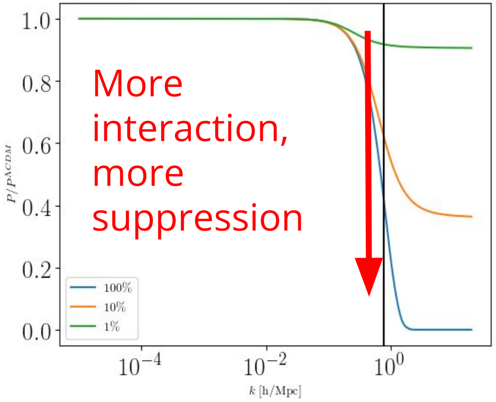
$$\Gamma \propto a_n (1+z)^n$$



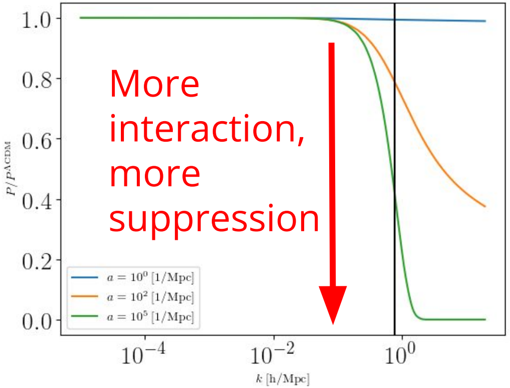
Henrique Rubira

The effect of each parameter on structure formation

$$f \equiv \frac{\Omega_{\rm IDM}}{\Omega_{\rm CDM} + \Omega_{\rm IDM}}$$

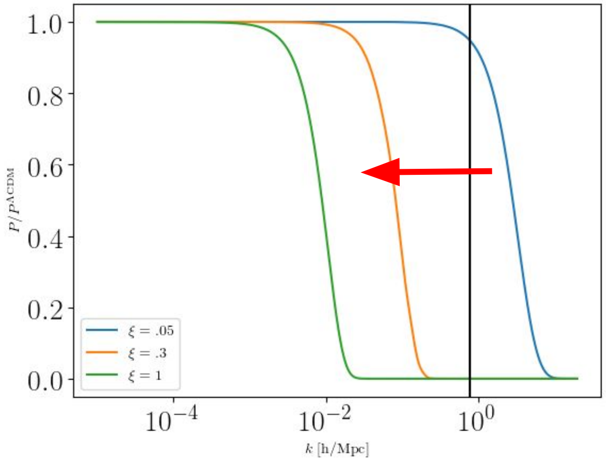


$$\Gamma \propto a_n (1+z)^n$$



$$\xi \equiv \left.\frac{T_{\rm DR}}{T_{\rm CMB}}\right|_{z=0}$$

More DR,
equality postponed
Larger scales suppressed



Dataset and first results

Henrique Rubira

We vary: cosmo + IDM-DR parameters together

$$\{\boxed{\omega_b,\ \omega_{\rm cdm},\ \log\left(10^{10}A_s\right),\ n_s,\ \tau_{\rm reio},\ H_0},\ \boxed{\xi,\ a_{\rm dark}}\}$$

Dataset and first results

- $\boxed{\textit{Planck} + \text{BAO} + \text{RSD}}$

- $\boxed{\textit{Planck} + \text{BAO} + \text{FS}}$

Compare to see how much info we gain from FS

We vary: cosmo + IDM-DR parameters together

$$\{\boxed{\omega_b,\ \omega_{\rm cdm},\ \log\left(10^{10}A_s\right),\ n_s,\ \tau_{\rm reio},\ H_0}\ \boxed{\xi,\ a_{\rm dark}}\}$$

Dataset and first results

Henrique Rubira

- $\boxed{\textit{Planck} + \text{BAO} + \text{RSD}}$
- $\boxed{\textit{Planck} + \text{BAO} + \text{FS}}$
- $\boxed{\textit{Planck} + \text{BAO} + \text{FS} + \text{KiDS}}$

Compare to see how much info we gain from FS

Compare those to see how models accommodate S8

We vary: cosmo + IDM-DR parameters together

$$\boxed{\{\omega_b,\ \omega_{\rm cdm},\ \log\left(10^{10}A_s\right),\ n_s,\ \tau_{\rm reio},\ H_0}\ \boxed{\xi,\ a_{\rm dark}\}}$$

Dataset and first results

Henrique Rubira

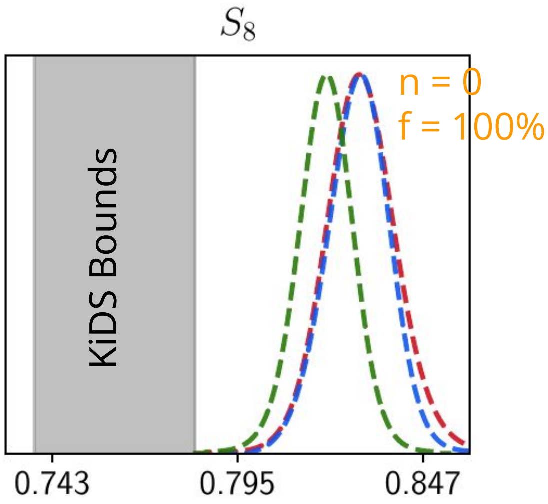
- *Planck* + BAO + RSD

- *Planck* + BAO + FS

- *Planck* + BAO + FS + KiDS

Compare to see how much info we gain from FS

Compare those to see how models accommodate S8



Results for LCDM:

Adding FS (blue) doesn't change much

Adding KiDS is not even allowed… those data disagree completely

Even if you do, it does not change much S8

We vary: cosmo + IDM-DR parameters together

$$\boxed{\{\omega_b,\ \omega_{\rm cdm},\ \log\left(10^{10}A_s\right),\ n_s,\ \tau_{\rm reio},\ H_0} \boxed{\xi,\ a_{\rm dark}\}}$$

Dataset and first results

Henrique Rubira

Now look IDM (solid lines):

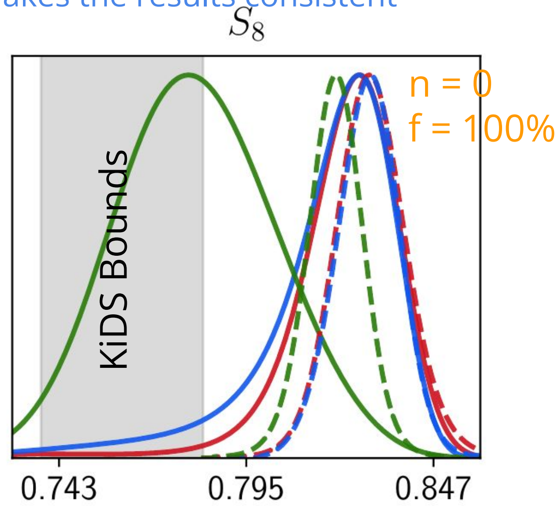
Planck + BAO + FS allow a smaller S8

Combining with KiDS makes the results consistent

- $Planck$ + BAO + RSD
- $Planck$ + BAO + FS
- $Planck$ + BAO + FS + KiDS

Compare to see how much info we gain from FS

Compare those to see how models accommodate S8



Results for LCDM:

Adding FS (blue) doesn't change much

Adding KiDS is not even allowed… those data disagree completely

Even if you do, it does not change much S8

We vary: cosmo + IDM-DR parameters together

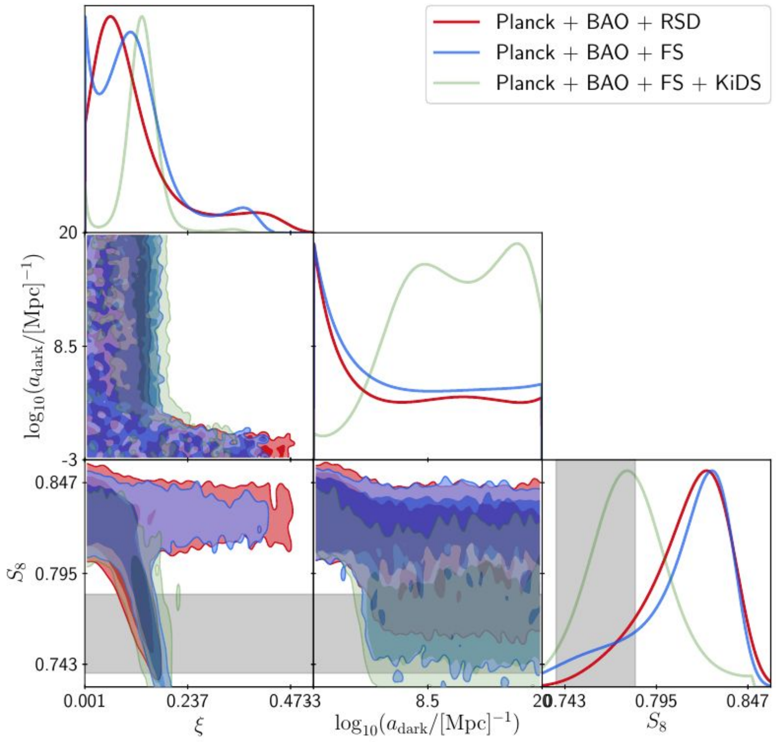
$$\{\omega_b,\, \omega_{\rm cdm},\, \log\left(10^{10}A_s\right),\, n_s,\, \tau_{\rm reio},\, H_0\,\, \xi,\, a_{\rm dark}\}$$

What is the reason why IDM-DR lifts S8?

Henrique Rubira

MCMC result for f = 10%

$$n = 0$$



What is the reason why IDM-DR lifts S8?

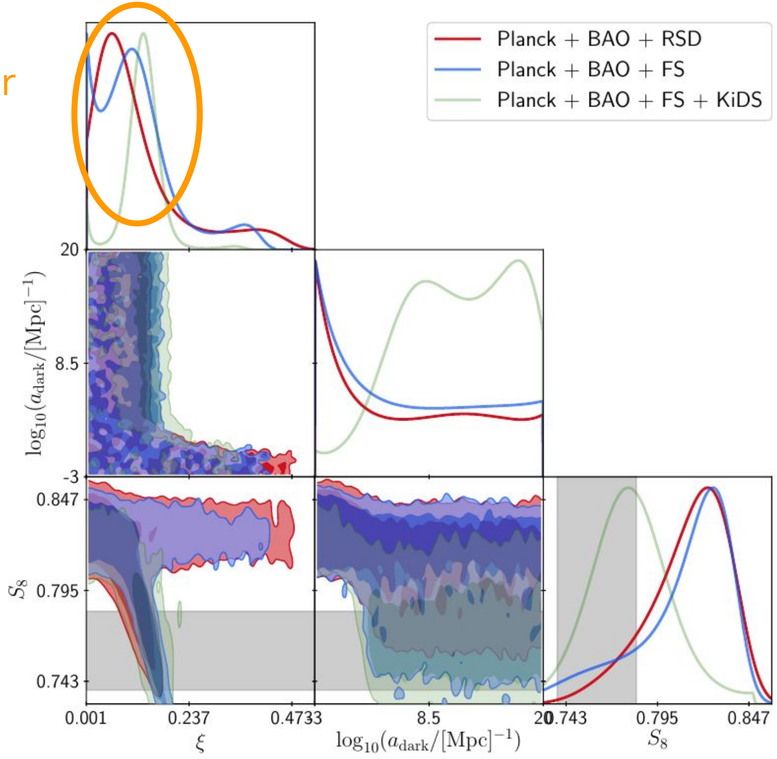
Henrique Rubira

MCMC result for f = 10%

Notice this preference for

$$\xi \sim 0.1$$

$$n = 0$$



What is the reason why IDM-DR lifts S8?

Henrique Rubira

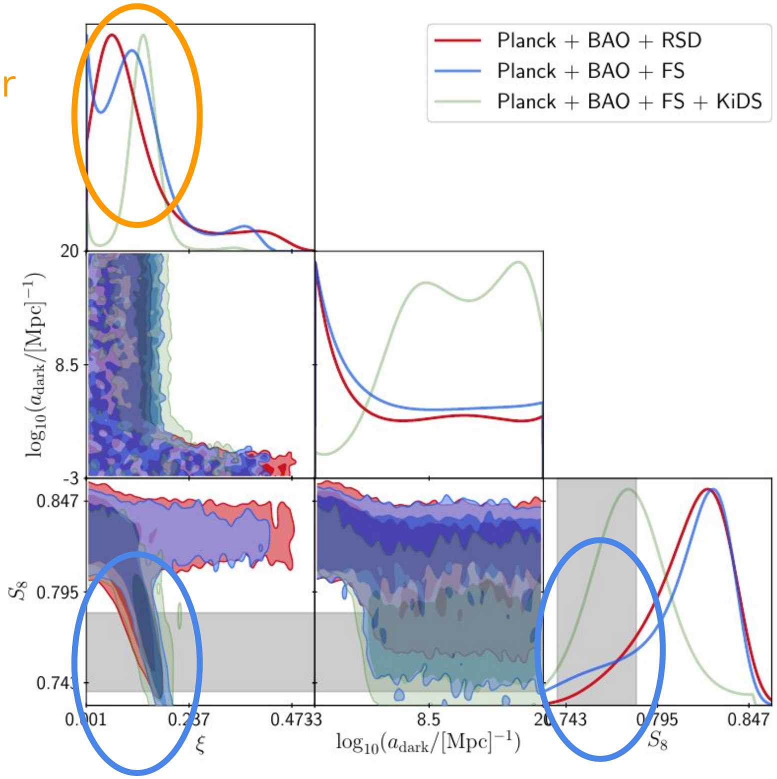
MCMC result for f = 10%

Notice this preference for

$$\xi \sim 0.1$$

This feature in the MCMC shows one parameter direction that addresses S8!

$$n = 0$$



What is the reason why IDM-DR lifts S8?

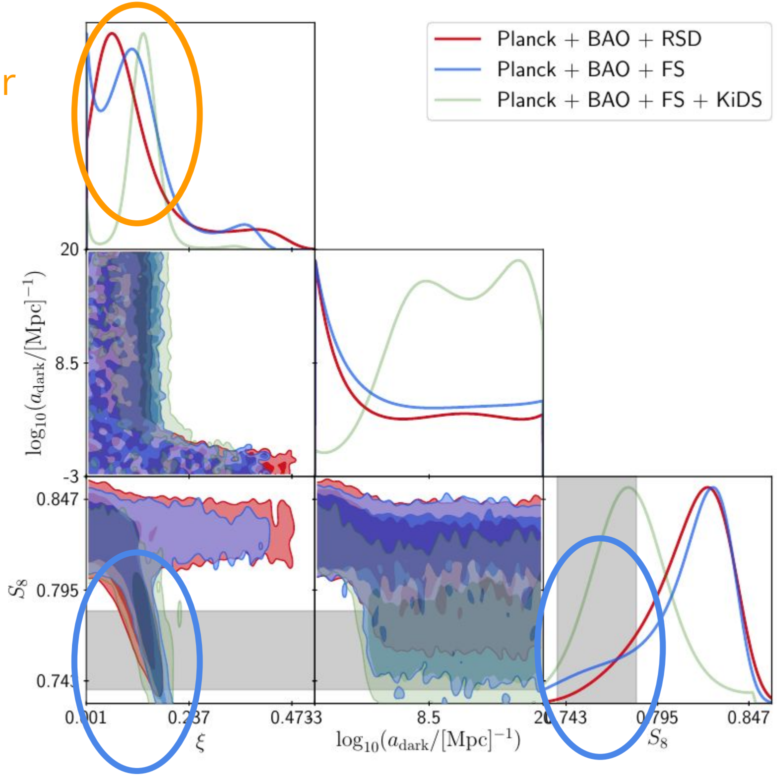
Henrique Rubira

MCMC result for f = 10%

$$n = 0$$

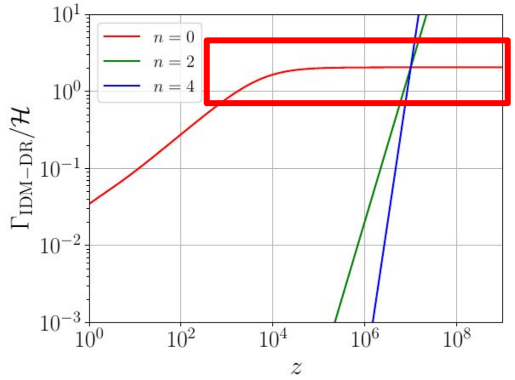
Notice this preference for

$$\xi \sim 0.1$$



This feature in the MCMC shows one parameter direction that addresses S8!

Milder suppression for longer times



What is the reason why IDM-DR lifts S8?

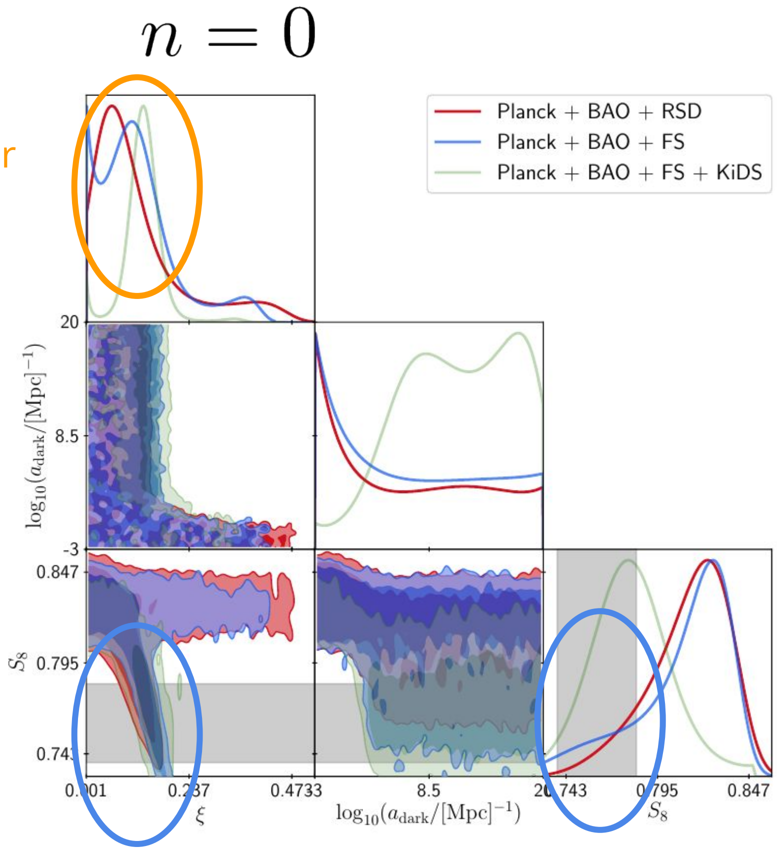
Henrique Rubira

MCMC result for f = 10%

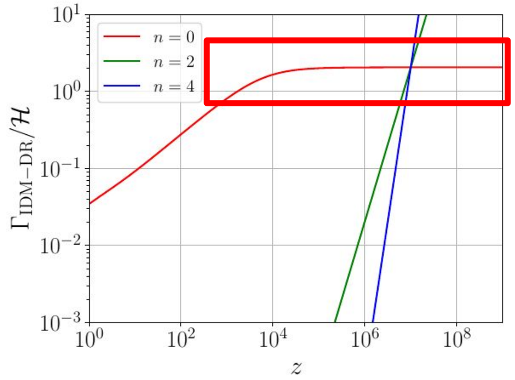
Notice this preference for

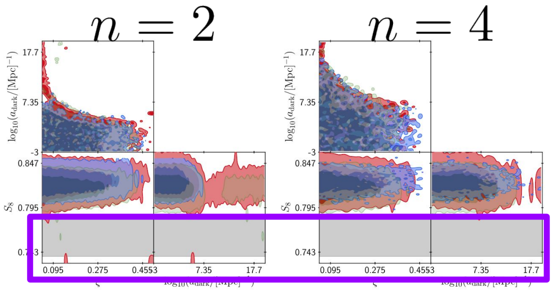
$$\xi \sim 0.1$$

This feature in the MCMC shows one parameter direction that addresses S8!



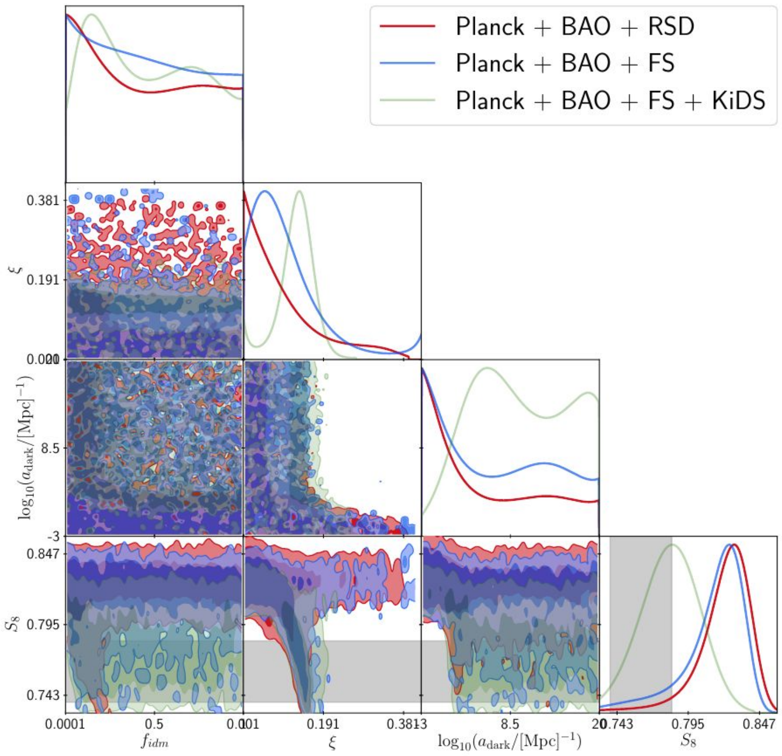
Milder suppression for longer times





No solution to S8

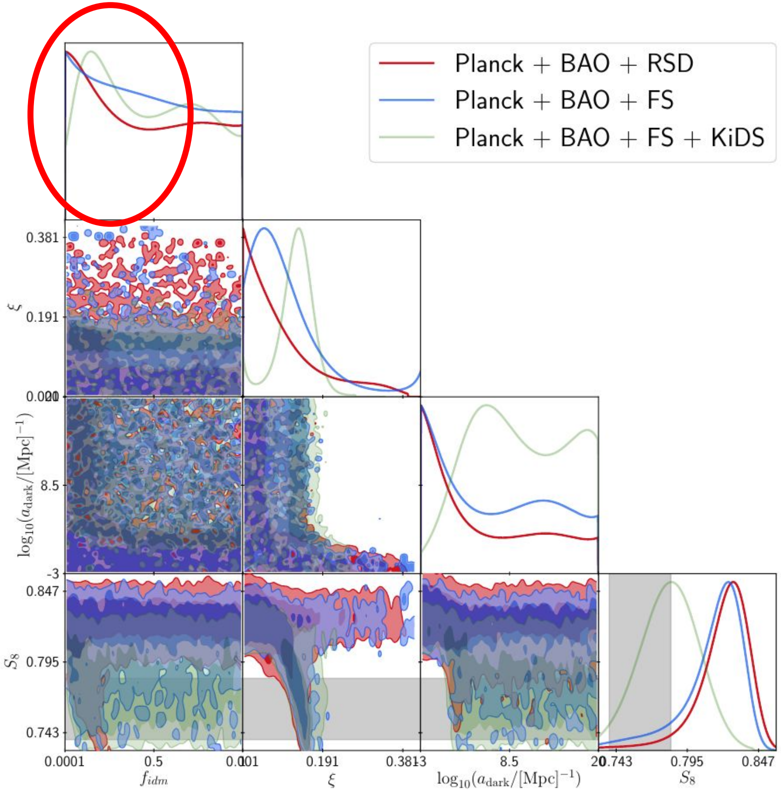
Free IDM fraction



Free IDM fraction

If you want to solve S8, you need $f \gtrsim 10\%$

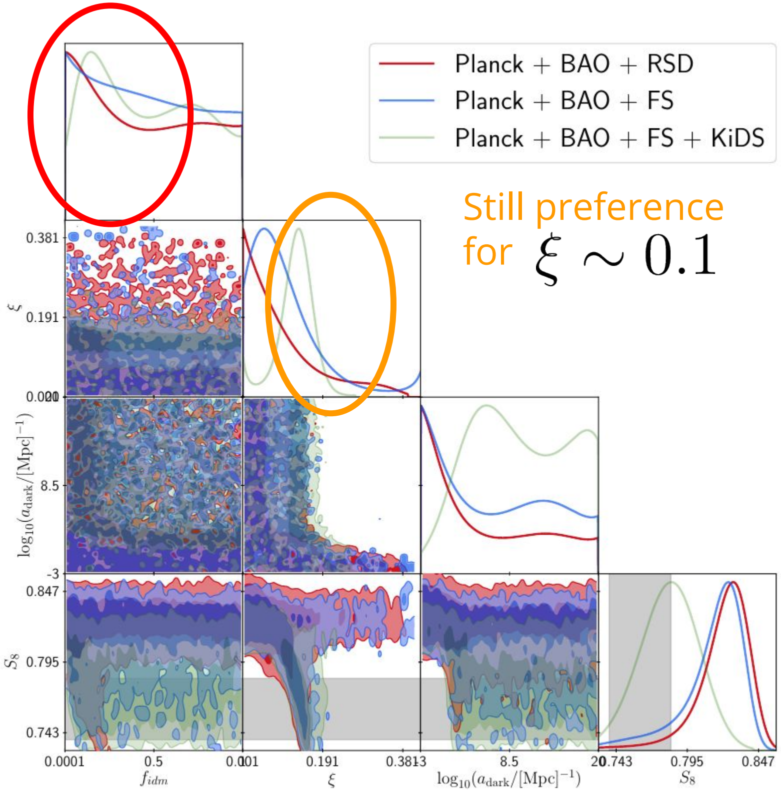
Remember that
$$f = 0$$
resembles extra DR



Free IDM fraction

If you want to solve S8, you need $f \gtrsim 10\%$

Remember that
$$f = 0$$
resembles extra DR



Still preference for $\xi \sim 0.1$

A bit of statistics...

How can we quantify the preference for a model?

A bit of statistics...

How can we quantify the preference for a model?

$$\Delta\chi^2_{\mathcal{M},\mathrm{data}} = \chi^2_{\mathrm{min},\mathcal{M},\mathrm{data}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM},\mathrm{data}}$$

But that is too simple...
No penalty for extra parameters

A bit of statistics...

How can we quantify the preference for a model?

$$\Delta\chi^2_{\mathcal{M},\mathrm{data}} = \chi^2_{\mathrm{min},\mathcal{M},\mathrm{data}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM},\mathrm{data}}$$

But that is too simple...
No penalty for extra parameters

$$\Delta\mathrm{AIC}_{\mathcal{M},\mathrm{data}} = \Delta\chi^2_{\mathcal{M},\mathrm{data}} + 2(N_{\mathcal{M}} - N_{\Lambda\mathrm{CDM}})$$

Occam's razor factor

A bit of statistics...

How can we quantify the preference for a model?

$$\Delta\chi^2_{\mathcal{M},\mathrm{data}} = \chi^2_{\mathrm{min},\mathcal{M},\mathrm{data}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM},\mathrm{data}}$$

But that is too simple...
No penalty for extra parameters

$$\Delta\mathrm{AIC}_{\mathcal{M},\mathrm{data}} = \Delta\chi^2_{\mathcal{M},\mathrm{data}} + 2(N_{\mathcal{M}} - N_{\Lambda\mathrm{CDM}})$$

Occam's razor factor

How can we quantify S8 tension with KiDS?

A bit of statistics...

How can we quantify the preference for a model?

$$\Delta\chi^2_{\mathcal{M},\mathrm{data}} = \chi^2_{\mathrm{min},\mathcal{M},\mathrm{data}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM},\mathrm{data}}$$

But that is too simple...
No penalty for extra parameters

$$\Delta\mathrm{AIC}_{\mathcal{M},\mathrm{data}} = \Delta\chi^2_{\mathcal{M},\mathrm{data}} + 2(N_{\mathcal{M}} - N_{\Lambda\mathrm{CDM}})$$

Occam's razor factor

How can we quantify S8 tension with KiDS?

$$Q_{\mathrm{DMAP}}^{\mathcal{M},\mathrm{data}} = \chi^2_{\mathrm{min},\mathcal{M}}(\mathrm{w/\ data}) - \chi^2_{\mathrm{min},\mathcal{M}}(\mathrm{w/o\ data})$$

How much does $\chi^2_{\mathrm{min},\mathcal{M}}$ change by adding one dataset within a model ?

Some numbers

The three dataset described before

	Planck + BAO			+ FS			+ FS + KiDS			$\sqrt{Q^{\text{KiDS}}_{\text{DMAP}}}$
	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM										
Fluid:										
Fiducial										
$f = 0.1$										
$f = 0.01$										
f free										
Free-streaming:										
$n = 0$										
$n = 2$										
$n = 4$										

Models

Some numbers

	Planck + BAO			+ FS			+ FS + KiDS			$\sqrt{Q_{\rm DMAP}^{\rm KiDS}}$
	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM	2791.6	-	-							
Fluid:										
Fiducial	2790.3	-1.3	2.7							
$f=0.1$	2789.5	-2.1	1.9							
$f=0.01$	2791.1	-0.5	3.5							
f free	2790.3	-1.3	4.7							
Free-streaming:										
$n=0$	2790.2	-1.4	2.6							
$n=2$	2790.0	-1.6	2.4							
$n=4$	2790.7	-0.9	3.1							

All positive:
no preference for IDM

Henrique Rubira

Conclusions:
1: FS drives preference towards IDM, but pretty mildly

Some numbers

	Planck + BAO			+ FS			+ FS + KiDS			$\sqrt{Q_{\rm DMAP}^{\rm KiDS}}$
	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM	2791.6	-	-	3563.1	-	-				
Fluid:										
Fiducial	2790.3	-1.3	2.7	3557.7	-5.5	-1.5				
$f = 0.1$	2789.5	-2.1	1.9	3560.4	-2.7	1.3				
$f = 0.01$	2791.1	-0.5	3.5	3561.5	-1.6	2.4				
f free	2790.3	-1.3	4.7	3558.0	-5.2	0.8				
Free-streaming:										
$n = 0$	2790.2	-1.4	2.6	3559.0	-4.1	-0.1				
$n = 2$	2790.0	-1.6	2.4	3560.7	-2.4	1.6				
$n = 4$	2790.7	-0.9	3.1	3559.9	-3.2	0.8				

Slight preference for IDM
for some scenarios

Henrique Rubira

Some numbers

Conclusions:
1: FS drives preference towards IDM, but pretty mildly
2: KiDS substantially prefers IDM (for some scenarios)

	Planck + BAO			+ FS			+ FS + KiDS			$\sqrt{Q^{\rm KiDS}_{\rm DMAP}}$
	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM	2791.6	-	-	3563.1	-	-	3571.6	-	-	
Fluid:										
Fiducial	2790.3	-1.3	2.7	3557.7	-5.5	-1.5	3559.9	-11.7	-7.7	
$f = 0.1$	2789.5	-2.1	1.9	3560.4	-2.7	1.3	3562.0	-9.6	-5.6	
$f = 0.01$	2791.1	-0.5	3.5	3561.5	-1.6	2.4	3566.9	-4.7	-0.7	
f free	2790.3	-1.3	4.7	3558.0	-5.2	0.8	3561.4	-10.2	-4.2	
Free-streaming:										
$n = 0$	2790.2	-1.4	2.6	3559.0	-4.1	-0.1	3559.7	-11.9	-7.9	
$n = 2$	2790.0	-1.6	2.4	3560.7	-2.4	1.6	3567.7	-3.9	0.1	
$n = 4$	2790.7	-0.9	3.1	3559.9	-3.2	0.8	3568.0	-3.6	0.4	

Preference for IDM for some scenarios

Some numbers

Henrique Rubira

Conclusions:
1: FS drives preference towards IDM, but pretty mildly
2: KiDS substantially prefers IDM (for some scenarios)
3: S8 tension is alleviated within IDM

	Planck + BAO			+ FS			+ FS + KiDS			$\sqrt{Q_{\mathrm{DMAP}}^{\mathrm{KiDS}}}$
	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	χ^2	$\Delta\chi^2$	ΔAIC	
ΛCDM	2791.6	-	-	3563.1	-	-	3571.6	-	-	2.9σ
Fluid:										
Fiducial	2790.3	-1.3	2.7	3557.7	-5.5	-1.5	3559.9	-11.7	-7.7	1.5σ
$f = 0.1$	2789.5	-2.1	1.9	3560.4	-2.7	1.3	3562.0	-9.6	-5.6	1.3σ
$f = 0.01$	2791.1	-0.5	3.5	3561.5	-1.6	2.4	3566.9	-4.7	-0.7	2.3σ
f free	2790.3	-1.3	4.7	3558.0	-5.2	0.8	3561.4	-10.2	-4.2	1.9σ
Free-streaming:										
$n = 0$	2790.2	-1.4	2.6	3559.0	-4.1	-0.1	3559.7	-11.9	-7.9	0.8σ
$n = 2$	2790.0	-1.6	2.4	3560.7	-2.4	1.6	3567.7	-3.9	0.1	2.6σ
$n = 4$	2790.7	-0.9	3.1	3559.9	-3.2	0.8	3568.0	-3.6	0.4	2.8σ

Tension on S8 is alleviated!

More numbers...

Which data is driving χ^2 **?**

More numbers...

Which data is driving χ^2 ?

	ΛCDM	Fiducial	$f = 0.1$
Planck High ℓ			
Planck Low ℓ EE			
Planck Low ℓ TT			
Planck lensing			
BAO			
FS			
KIDS			
Total			

More numbers...

Which data is driving χ^2 **?**

	ΛCDM		Fiducial	$f = 0.1$
	+FS	+FS+KiDS		
Planck High ℓ	2354.3	2352.7		
Planck Low ℓ EE	395.8	396.5		
Planck Low ℓ TT	22.8	23.1		
Planck lensing	9.0	8.9		
BAO	9.8	9.8		
FS	771.3	772.7		
KIDS	-	7.9		
Total	3563.1	3571.6		

More numbers...

Which data is driving χ^2 **?**

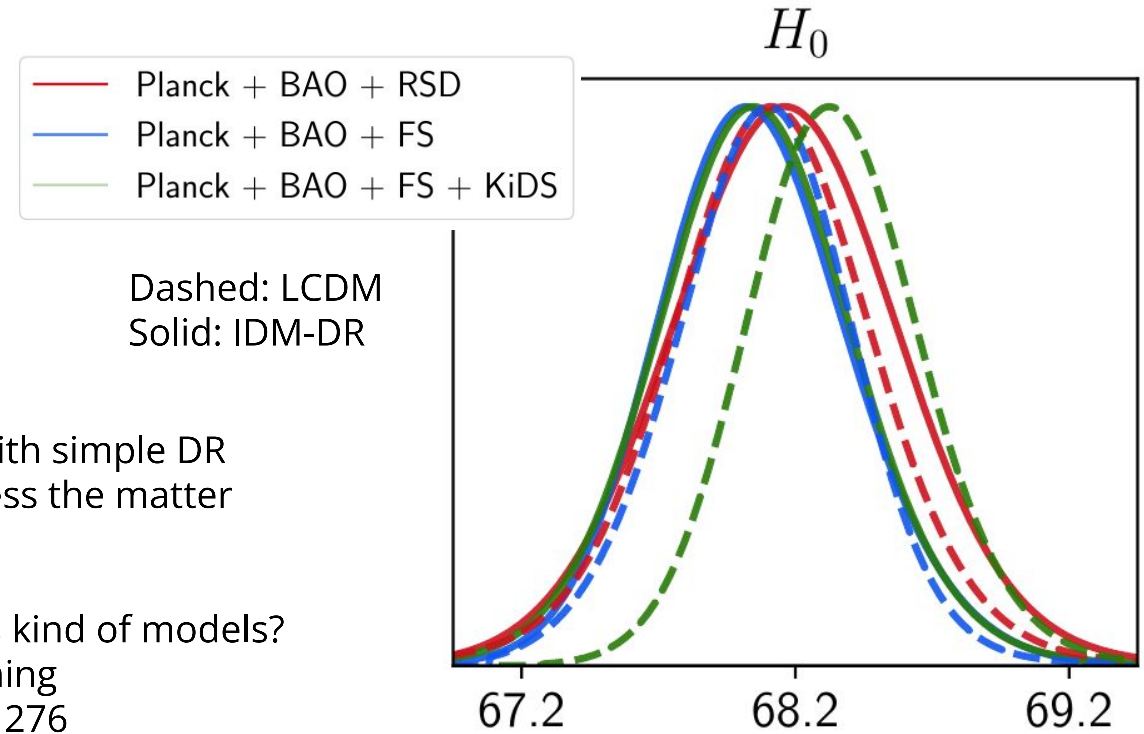
	ΛCDM		Fiducial		$f = 0.1$
	+FS	+FS+KiDS	+FS	+FS+KiDS	
Planck High ℓ	2354.3	2352.7	2348.0	2351.6	
Planck Low ℓ EE	395.8	396.5	396.1	396.2	
Planck Low ℓ TT	22.8	23.1	23.0	23.4	
Planck lensing	9.0	8.9	9.2	8.7	
BAO	9.8	9.8	10.0	9.9	
FS	771.3	772.7	771.4	769.5	
KIDS	-	7.9	-	0.4	
Total	3563.1	3571.6	3557.7	3559.9	

More numbers...

Which data is driving χ^2 ?

	ΛCDM		Fiducial		$f = 0.1$	
	+FS	+FS+KiDS	+FS	+FS+KiDS	+FS	+FS+KiDS
Planck High ℓ	2354.3	2352.7	2348.0	2351.6	2348.7	2355.8
Planck Low ℓ EE	395.8	396.5	396.1	396.2	396.8	395.9
Planck Low ℓ TT	22.8	23.1	23.0	23.4	23.3	23.5
Planck lensing	9.0	8.9	9.2	8.7	9.4	9.5
BAO	9.8	9.8	10.0	9.9	9.8	10.9
FS	771.3	772.7	771.4	769.5	772.5	766.4
KIDS	-	7.9	-	0.4	-	0.0
Total	3563.1	3571.6	3557.7	3559.9	3560.4	3562.0

Can we address both H0 and S8?



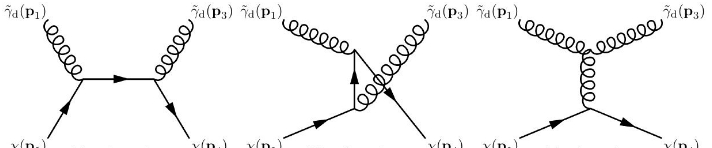
Dashed: LCDM
Solid: IDM-DR

Problem: H0 cannot be solved with simple DR (also extra DR would oversuppress the matter clustering)

Is it the end for H0-S8 within this kind of models?
Not really… new models are coming
See e.g. 2207.03500 and 2206.11276

A short rest for your eyes...

Corrections to IDM-DR interaction



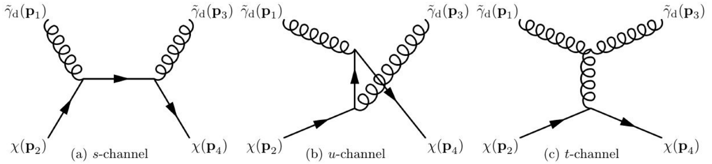
(a) s-channel (b) u-channel (c) t-channel

Temperature dependence of DR-DM interaction leads to n = 0 case

$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

*one can add massive fields that transform trivially with respect to this extra SU(N) to account for extra CDM

Corrections to IDM-DR interaction



Temperature dependence of DR-DM interaction leads to n = 0 case

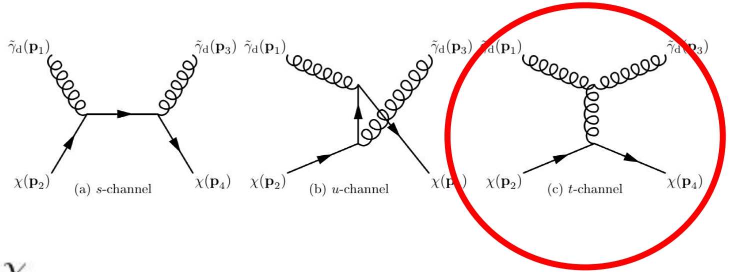
$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

Non-relativistic limit $T_{\rm DR} \ll m_\chi$

Weak coupling limit $g_d \ll 1$

*one can add massive fields that transform trivially with respect to this extra SU(N) to account for extra CDM

Corrections to IDM-DR interaction



Temperature dependence of DR-DM interaction leads to n = 0 case

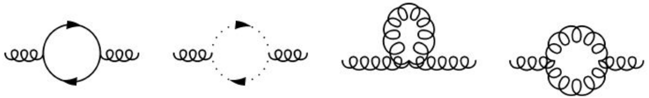
$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

t-diagram introduce a log-divergence

Non-relativistic limit $T_{\mathrm{DR}} \ll m_\chi$

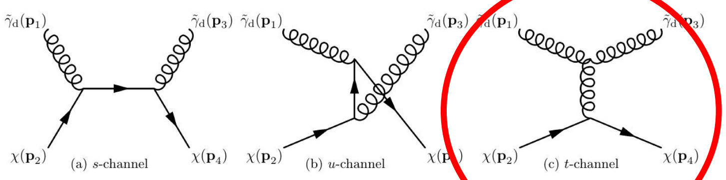
Weak coupling limit $g_d \ll 1$

Those divergences can be regulated by replacing propagator to hard thermal loop resummed prop $t^{-1} \to (t - \Pi_{L,T})^{-1}$



*one can add massive fields that transform trivially with respect to this extra SU(N) to account for extra CDM

Corrections to IDM-DR interaction



Temperature dependence of DR-DM interaction leads to n = 0 case

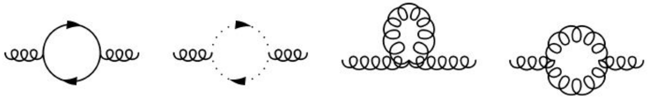
$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\chi}(i\gamma^\mu D_\mu - m_\chi)\chi$$

t-diagram introduce a log-divergence

Non-relativistic limit $T_{\mathrm{DR}} \ll m_\chi$

Weak coupling limit $g_d \ll 1$

Those divergences can be regulated by replacing propagator to hard thermal loop resummed prop $t^{-1} \to (t - \Pi_{L,T})^{-1}$

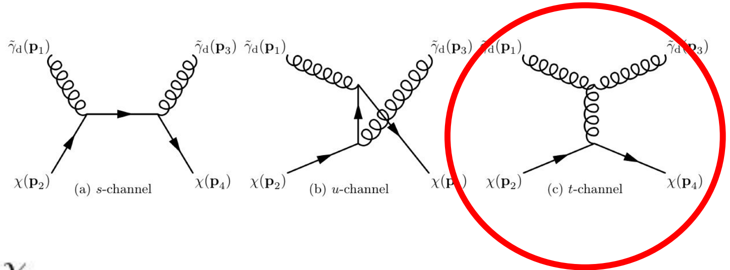


Thermal prop. includes Debye mass corrections:

$$m_D^2 = \frac{1}{3}g_d^2 T_{\mathrm{DR}}^2 (C_A + \frac{1}{2}N_f)$$

*one can add massive fields that transform trivially with respect to this extra SU(N) to account for extra CDM

Corrections to IDM-DR interaction



Temperature dependence of DR-DM interaction leads to n = 0 case

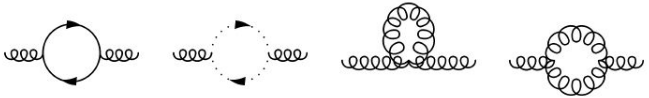
$$\mathcal{L} = -\frac{1}{2}\mathrm{tr}(F_{\mu\nu}F^{\mu\nu}) + \bar{\chi}(i\gamma^{\mu}D_{\mu} - m_{\chi})\chi$$

t-diagram introduce a log-divergence

Non-relativistic limit $T_{\mathrm{DR}} \ll m_{\chi}$

Weak coupling limit $g_d \ll 1$

Those divergences can be regulated by replacing propagator to hard thermal loop resummed prop $t^{-1} \to (t - \Pi_{L,T})^{-1}$



Thermal prop. includes Debye mass corrections:

$$m_D^2 = \frac{1}{3}g_d^2 T_{\mathrm{DR}}^2\left(C_A + \frac{1}{2}N_f\right)$$

Final result:

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

For the first time those contributions were calculated in that context

*one can add massive fields that transform trivially with respect to this extra SU(N) to account for extra CDM

Henrique Rubira

Mapping those constraints onto SU(N) model

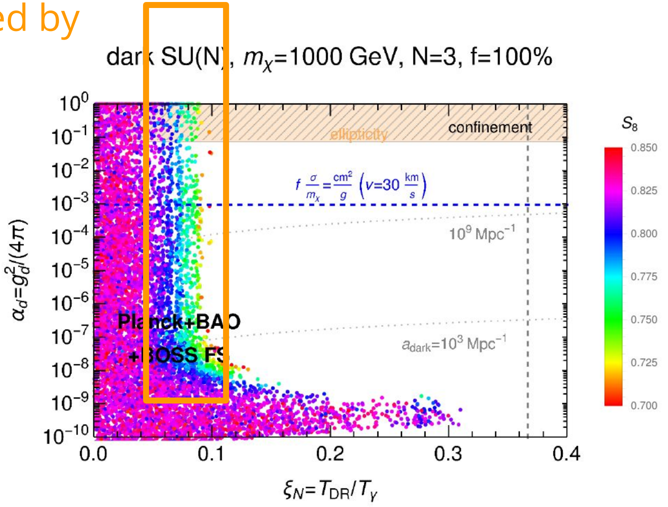
$$a_{\rm dark} = \frac{\pi}{12}\frac{\alpha_d^2}{m_\chi}\frac{1}{\xi_N^2}\frac{T_{\gamma,0}^2}{\Omega_\gamma h^2}\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] = 0.91\cdot 10^9 {\rm Mpc}^{-1}\left(\frac{\alpha_d}{10^{-4}}\right)^2\left(\frac{100\,{\rm GeV}}{m_\chi}\right)\left(\frac{0.1}{\xi_N}\right)^2\left[\ln\alpha_d^{-1} - (0.84 + \ln N) + 0.413\sqrt{N} g_d\right]\ ,$$

Mapping those constraints onto SU(N) model

Henrique Rubira

$$a_{\rm dark} = \frac{\pi}{12}\frac{\alpha_d^2}{m_\chi}\frac{1}{\xi_N^2}\frac{T_{\gamma,0}^2}{\Omega_\gamma h^2}\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] = 0.91\cdot 10^9 {\rm Mpc}^{-1}\left(\frac{\alpha_d}{10^{-4}}\right)^2\left(\frac{100\,{\rm GeV}}{m_\chi}\right)\left(\frac{0.1}{\xi_N}\right)^2\left[\ln\alpha_d^{-1} - (0.84+\ln N) + 0.413\sqrt{N}g_d\right],$$

Favored by KiDS



Mapping those constraints onto SU(N) model

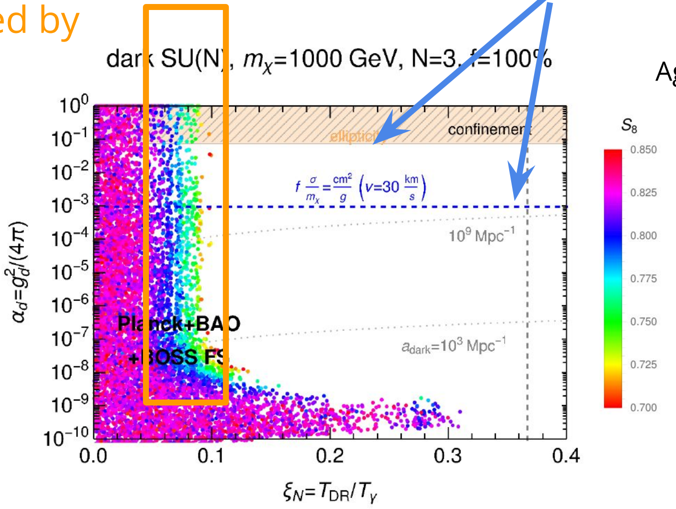
Henrique Rubira

$$a_{\rm dark} = \frac{\pi}{12}\frac{\alpha_d^2}{m_\chi}\frac{1}{\xi_N^2}\frac{T_{\gamma,0}^2}{\Omega_\gamma h^2}\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] = 0.91\cdot 10^9\,{\rm Mpc}^{-1}\left(\frac{\alpha_d}{10^{-4}}\right)^2\left(\frac{100\,{\rm GeV}}{m_\chi}\right)\left(\frac{0.1}{\xi_N}\right)^2\left[\ln\alpha_d^{-1} - (0.84+\ln N) + 0.413\sqrt{N}g_d\right],$$

Upper bound from galaxy ellip. $\sqrt{\frac{1}{2}C_F\alpha_d} \lesssim 0.01\frac{1}{\sqrt{f}}\left(\frac{m_\chi}{300\,{\rm GeV}}\right)^{3/2}$

Consistent with self-interaction typical values...

Favored by KiDS



Agrawal+, 16

Henrique Rubira

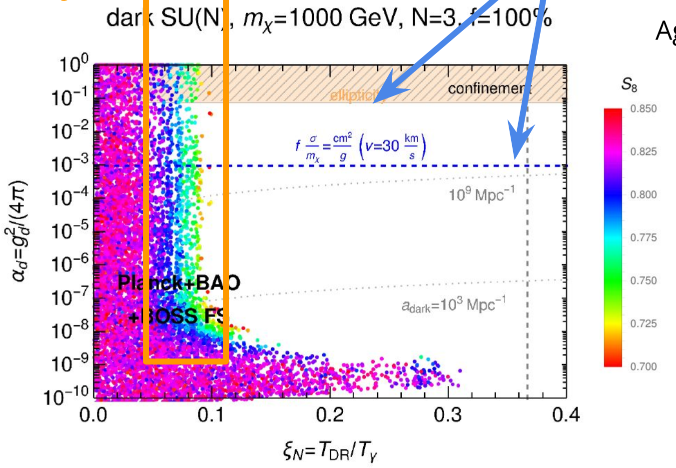
Mapping those constraints onto SU(N) model

$$a_{\rm dark} = \frac{\pi}{12}\frac{\alpha_d^2}{m_\chi}\frac{1}{\xi_N^2}\frac{T_{\gamma,0}^2}{\Omega_\gamma h^2}\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] = 0.91\cdot 10^9 {\rm Mpc}^{-1}\left(\frac{\alpha_d}{10^{-4}}\right)^2\left(\frac{100\,{\rm GeV}}{m_\chi}\right)\left(\frac{0.1}{\xi_N}\right)^2\left[\ln\alpha_d^{-1} - (0.84+\ln N) + 0.413\sqrt{N}g_d\right],$$

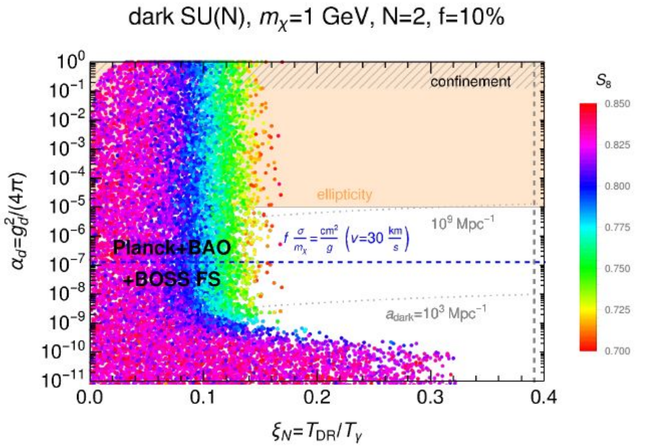
Upper bound from galaxy ellip. $\sqrt{\frac{1}{2}C_F\alpha_d} \lesssim 0.01\frac{1}{\sqrt{f}}\left(\frac{m_\chi}{300\,{\rm GeV}}\right)^{3/2}$

Consistent with self-interaction typical values…

Favored by KiDS



Agrawal+, 16



Henrique Rubira

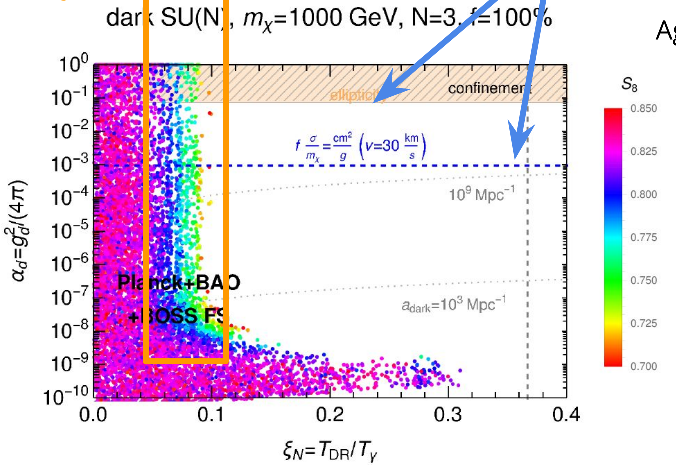
Mapping those constraints onto SU(N) model

$$a_{\rm dark} = \frac{\pi}{12}\frac{\alpha_d^2}{m_\chi}\frac{1}{\xi_N^2}\frac{T_{\gamma,0}^2}{\Omega_\gamma h^2}\left[\ln\alpha_d^{-1} + c_0 + c_1 g_d + \mathcal{O}(g_d^2)\right] = 0.91\cdot 10^9 \mathrm{Mpc}^{-1}\left(\frac{\alpha_d}{10^{-4}}\right)^2\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{0.1}{\xi_N}\right)^2\left[\ln\alpha_d^{-1} - (0.84+\ln N) + 0.413\sqrt{N}g_d\right],$$

Upper bound from galaxy ellip. $\sqrt{\frac{1}{2}C_F\alpha_d} \lesssim 0.01\frac{1}{\sqrt{f}}\left(\frac{m_\chi}{300\,\mathrm{GeV}}\right)^{3/2}$

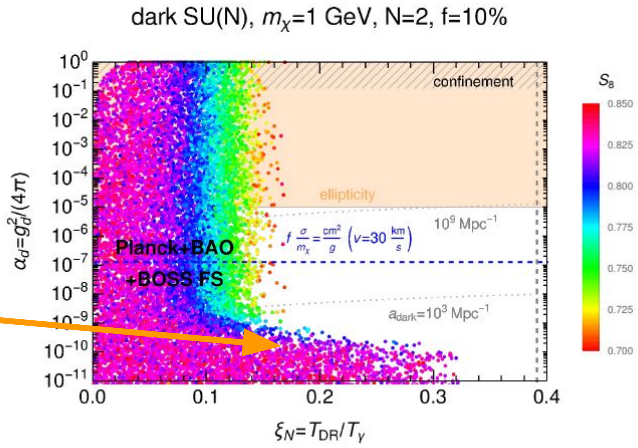
Consistent with self-interaction typical values...

Favored by KiDS



Agrawal+, 16

Bounded from below if we want it compatible with KiDS



$\boxed{\alpha_d \gtrsim 10^{-8}}$

Solution to S8

$\boxed{\alpha_d \gtrsim 10^{-9}}$

Conclusion and challenges for the future

LSS is great:

- It constraints and indicate interesting parameter directions on very well motivated BSM scenarios

Interacting DM-DR can address the S8 tension with $\xi \equiv \left.\frac{T_{\mathrm{DR}}}{T_{\mathrm{CMB}}}\right|_{z=0} \sim 0.1$ as long as $f \gtrsim 10\%$

The tension in that case is reduced from $\sim 2.5\sigma$ to $\sim 1\sigma$

We calculate corrections due to Debye screening

We map those novel Planck + LSS constraints on SU(N) interacting DM

Thanks a lot!