Interacting Dark Sectors and Precision Cosmology

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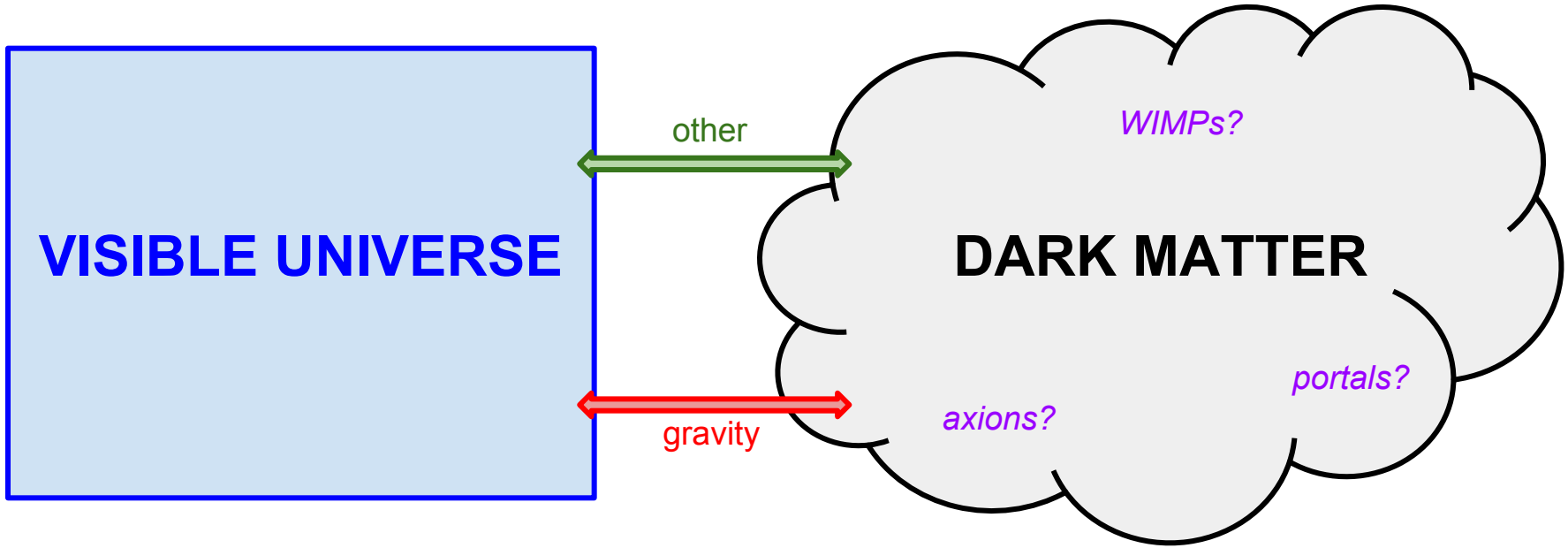
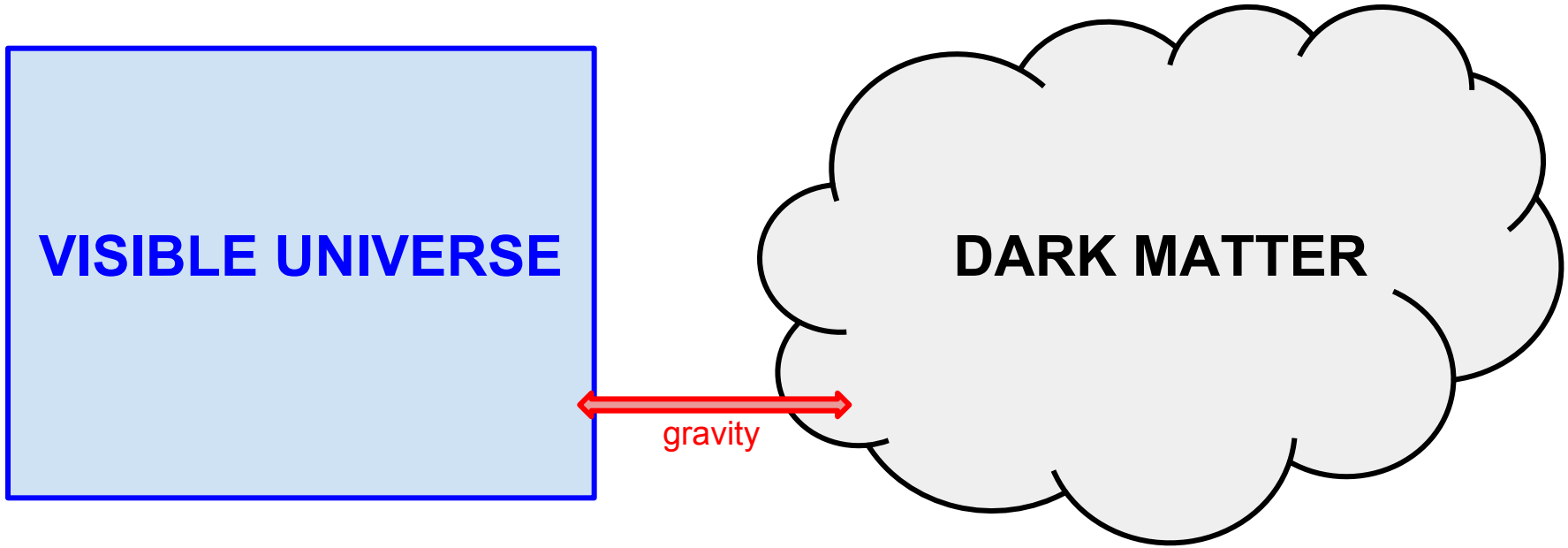
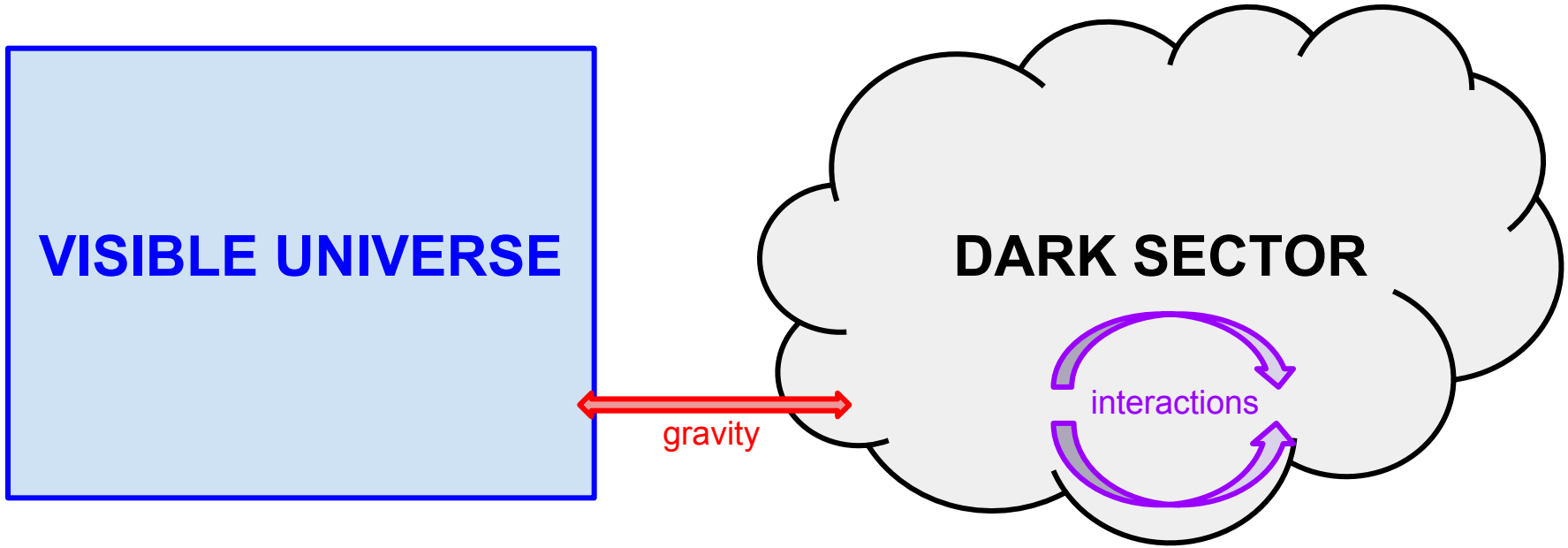
Brookhaven Forum 2017

BROOKHAVEN NATIONAL LABORATORY

70 YEARS OF DISCOVERY
A CENTURY OF SERVICE


VISIBLE UNIVERSE
other
gravity
DARK MATTER
WIMPs?
portals?
axions?


VISIBLE UNIVERSE
DARK MATTER
gravity



ETHOS: Cyr-Racine et al. 2016

Some hints (maybe?)

Not here: Small Scale Structure crisis:

- Core vs. cusp
- Missing satellites
- Too-big-to-fail

Highly non-linear, debate over baryon feedback...

This talk:

- Planck's H_0 **smaller** w.r.t. local measurements (3σ)
  - Riess et al. 2016
- Planck's σ_8 **larger** w.r.t. direct measurements (2-3σ)
  - Cluster counts (Planck SZ)
  - Weak lensing (CFHTLens, DES, KIDs)

Important: Planck's H_0 & σ_8 results **not** directly measured but **extrapolated** from best-fit to CMB data in ΛCDM framework.

Outline

I. The Model
II. Results
III. Conclusions

- **arXiv:1708.09406**
- arXiv:1507.04351
- arXiv:1505.03542

Work with:

- Martin Schmaltz (BU)
- Julien Lesgourgues (Aachen)
- Gustavo Marques-Tavares (Stanford)

I. The Model

ΛCDM

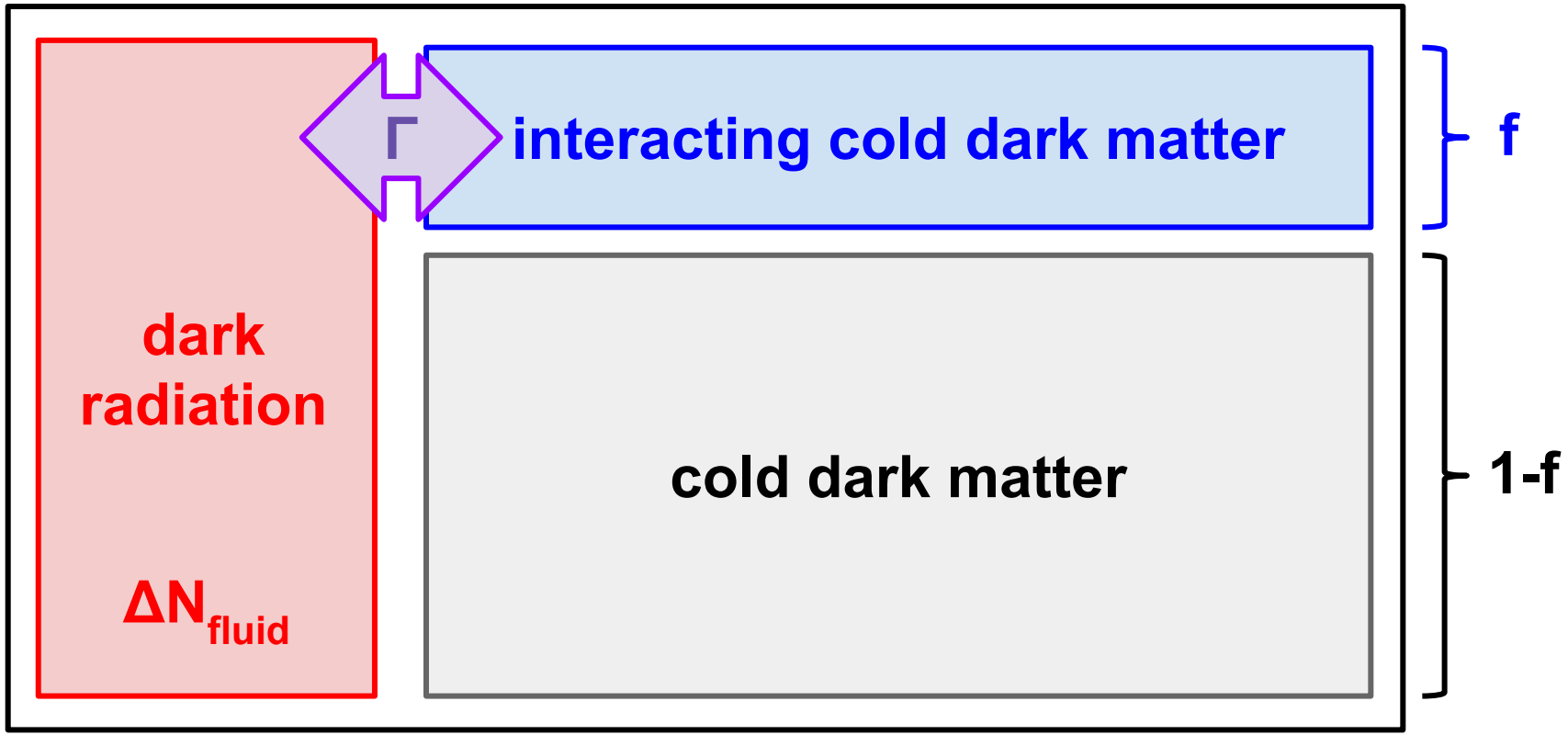
$$\rho_{tot} = \rho_{cdm} + \rho_b + \rho_\gamma + \rho_\nu + \rho_\Lambda$$

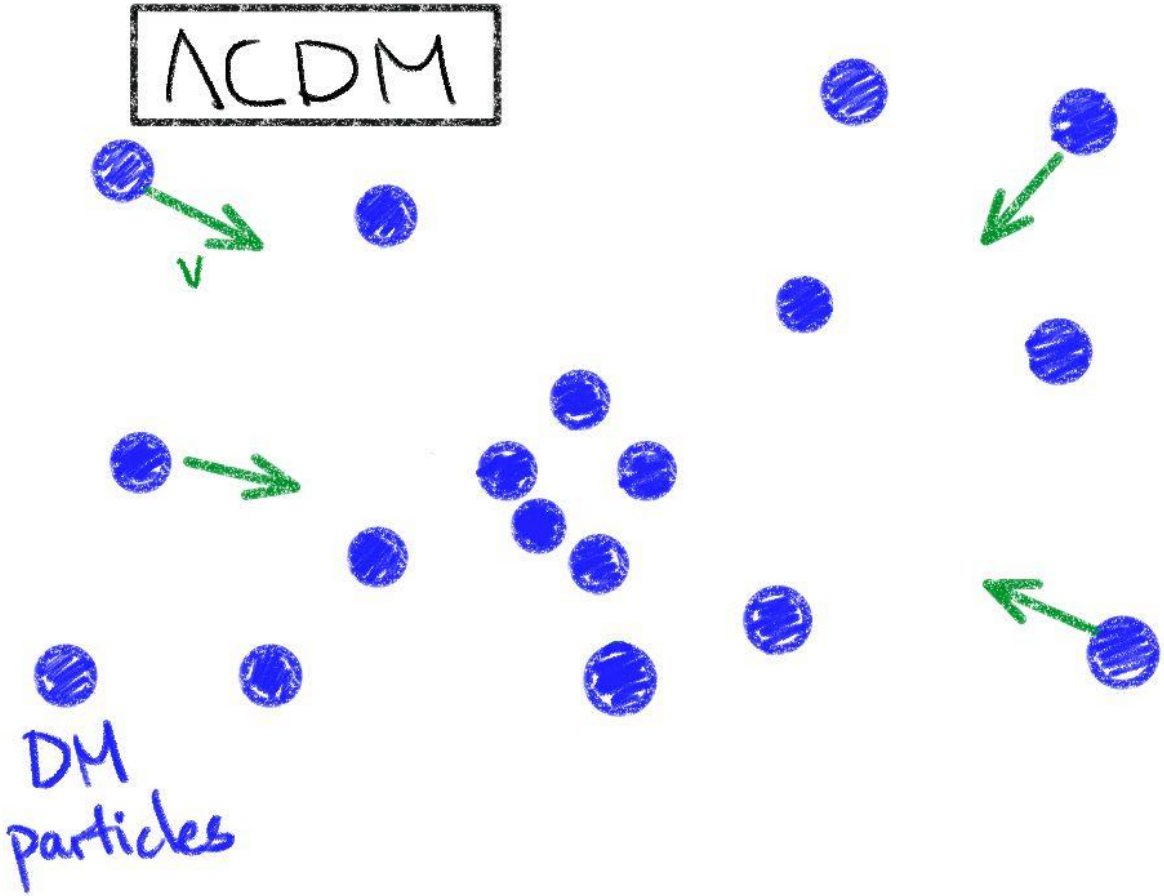
IDS

$$\rho_{tot} = \rho_{cdm} + \rho_b + \rho_\gamma + \rho_\nu + \rho_\Lambda + \rho_{dr} + \rho_{idm}$$

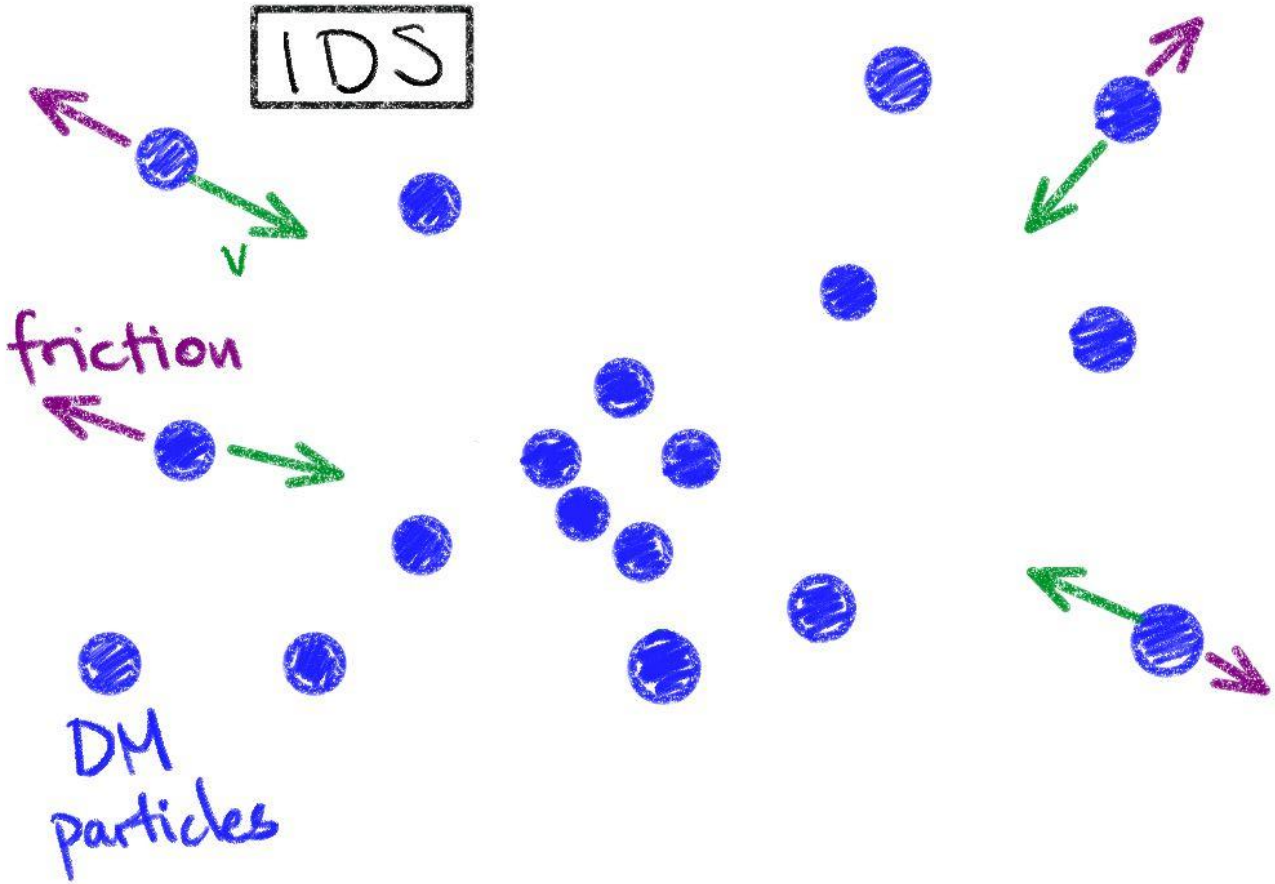
$\rho_{dr} + \rho_{idm} \rightarrow \Gamma$

Interacting Dark Sector (IDS)

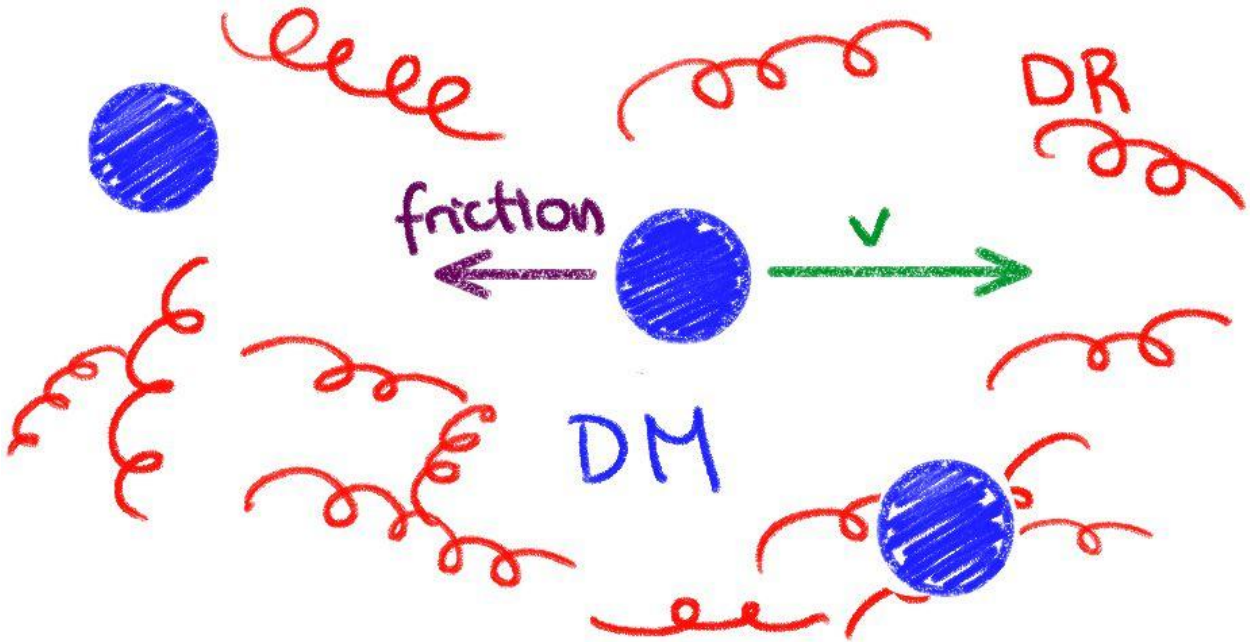




Structure Formation: Microscopic Picture

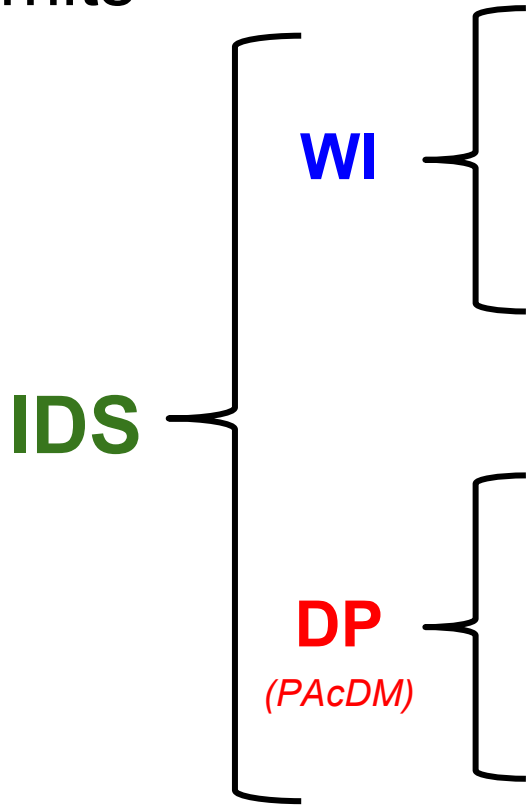


Structure Formation: Microscopic Picture



Friction

Two limits



f=1, Γ << H:

All DM is IDM and feels friction

f<<1, Γ >> H:

Part of DM is IDM w. large friction ⇒ tightly coupled to DR: Dark Plasma

Chacko et al. 2016

IDS lin. pert. eqns.

$$\dot{\delta}_{\rm idm} = -\theta_{\rm idm} + 3\dot{\phi}$$

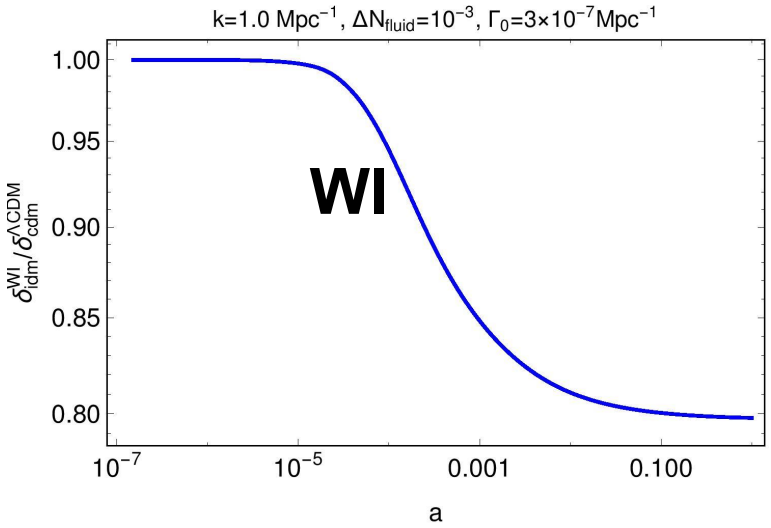
$$\dot{\theta}_{\rm idm} = -\mathcal{H}\theta_{\rm idm} + k^2\psi + a\Gamma(\theta_{\rm dr} - \theta_{\rm idm})$$

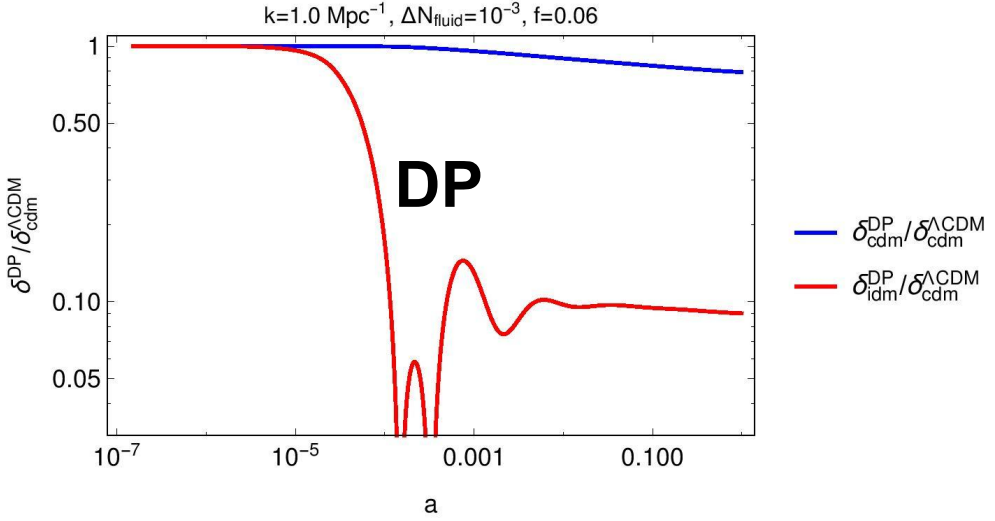
$$\dot{\delta}_{\rm dr} = -\frac{4}{3}\theta_{\rm dr} + 4\dot{\phi}$$

$$\dot{\theta}_{\rm dr} = k^2\left(\frac{\delta_{\rm dr}}{4} + \psi\right) - a\Gamma R(\theta_{\rm dr} - \theta_{\rm idm})$$

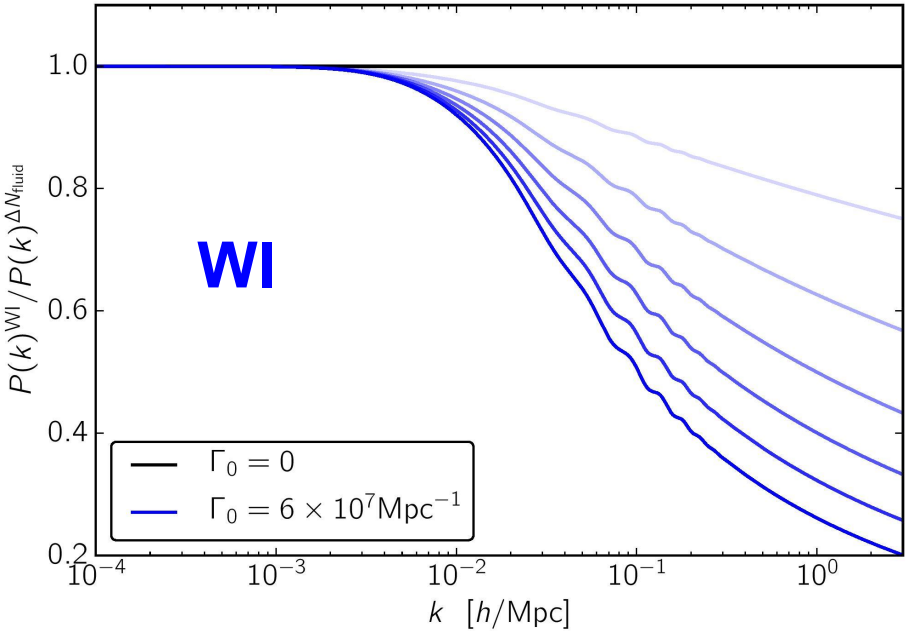
interesting controversy!

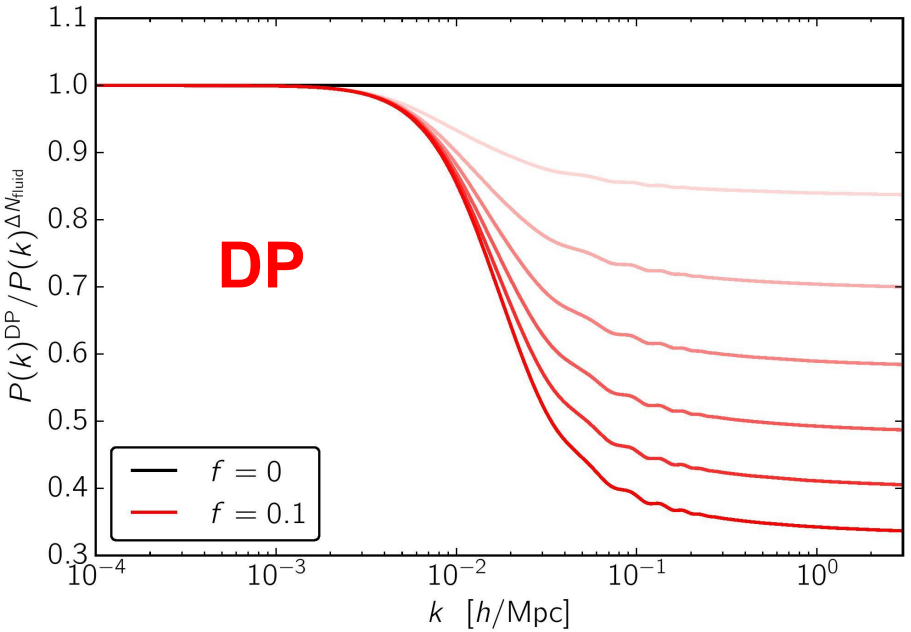
$$R \equiv \frac{3}{4}\frac{\rho_{\rm idm}}{\rho_{\rm dr}}$$





DM perturbations





$$\sim 1 - \left.\frac{\sqrt{2}\Gamma}{H}\right|_{\rm eq} \log k\eta_{\rm eq}$$

$$\sim (1-2f)\left(\frac{\eta_0}{\eta_{\rm eq}}\right)^{-\frac{12}{5}f}$$

Chacko et al. 2016

Matter Power Spectrum

II. Results

Codes & Data

- Boltzmann Code (cosmological eqns.):
  - CLASS
- Fit to data:
  - Montepython

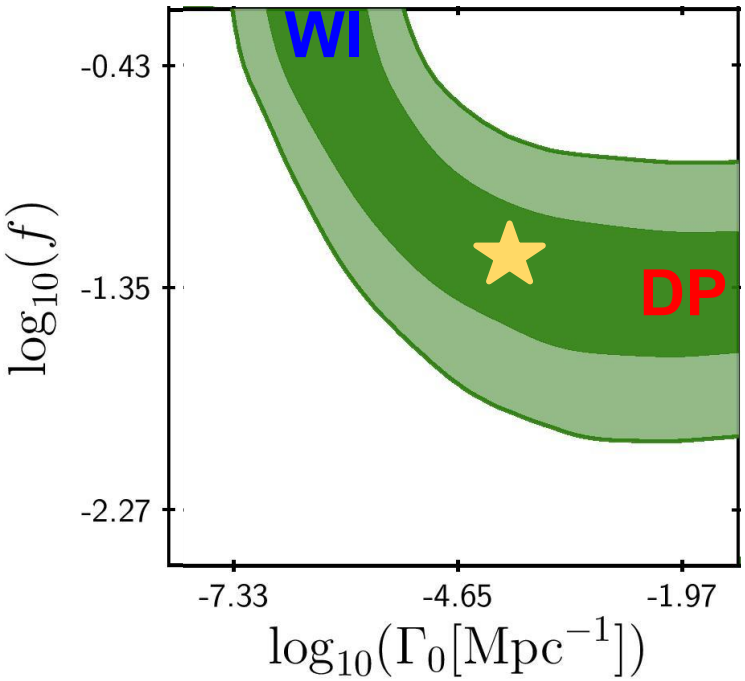
With minimal tweaking

- CMB (Planck 2015 & 2016)
- BAO (2011-2016)
- LSS (Planck 2015 lensing, Planck 2015 SZ prior, CFHTLens full spectrum, SDSS spectrum)
- H_0 (Riess et al. 2016)

	WI	DP	IDS
$\Delta\chi^2$	-22.2	-20.0	-24.0
σ	4.3σ	4.1σ	4.2σ

$\Delta\chi^2$ & σ

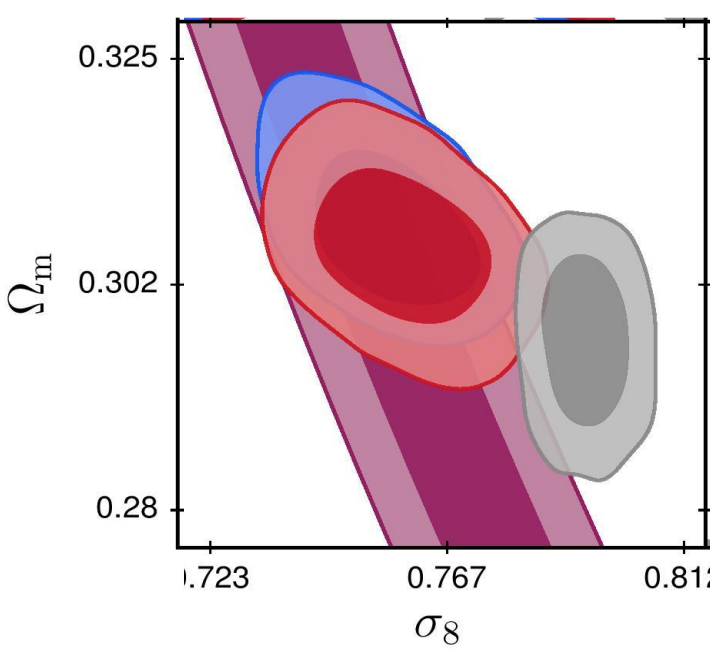
IDS



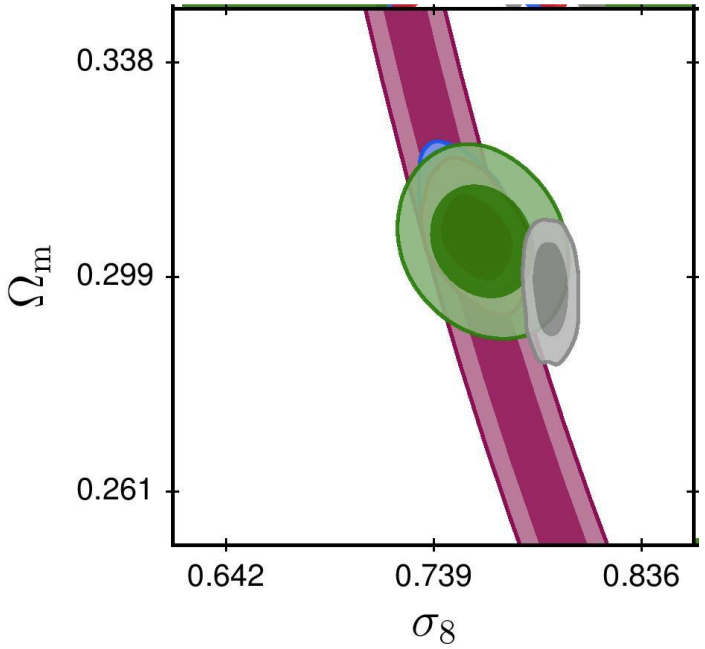
ΔN_{fluid} ~ few 10^{-3}

f vs. Γ_0

Planck SZ



ΛCDM
WI
DP
IDS



Ω_m vs. σ_8

III. Conclusions

Conclusions

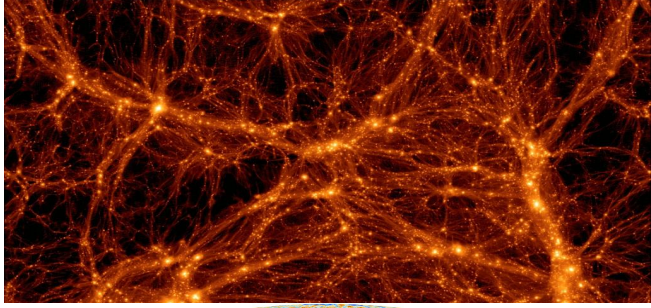
- **IDS model**: WI & DP as limits
- **New** data, included **LSS shape** info.
- IDS improves global fit by ~4σ, **solves** σ_8 problem.
- H_0 problem not solved by **global** best-fit but there is room for **easing tension**!
- LSS exps. not yet sensitive enough to shape: **family of models** give good fit (including WI & DP).

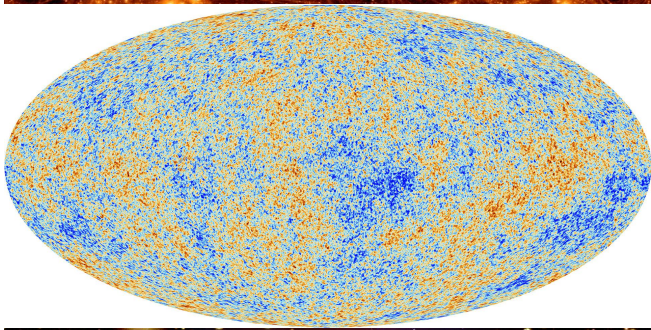
- More data:
  - KiDS, DES: expected to strengthen our conclusions
  - Full Planck SZ 2015 likelihood
  - Full P(k) from SDSS-DR12
- Future: 21 cm hydrogen line: P(k,**z**)!

BACKUP SLIDES

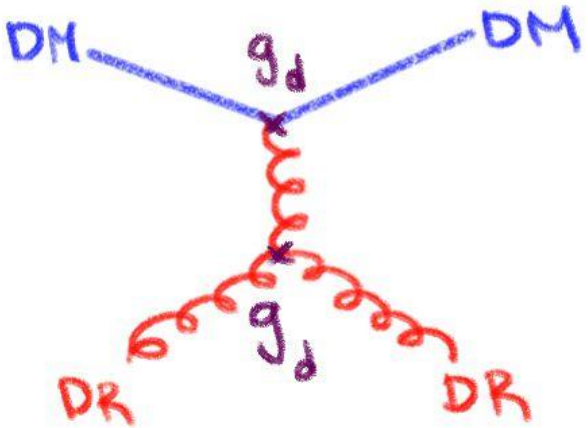
Dark Matter

- Galaxy rotation curves
- Bullet cluster
- Lensing
- Growth of structure (CMB, MPS)
- ...





Scattering

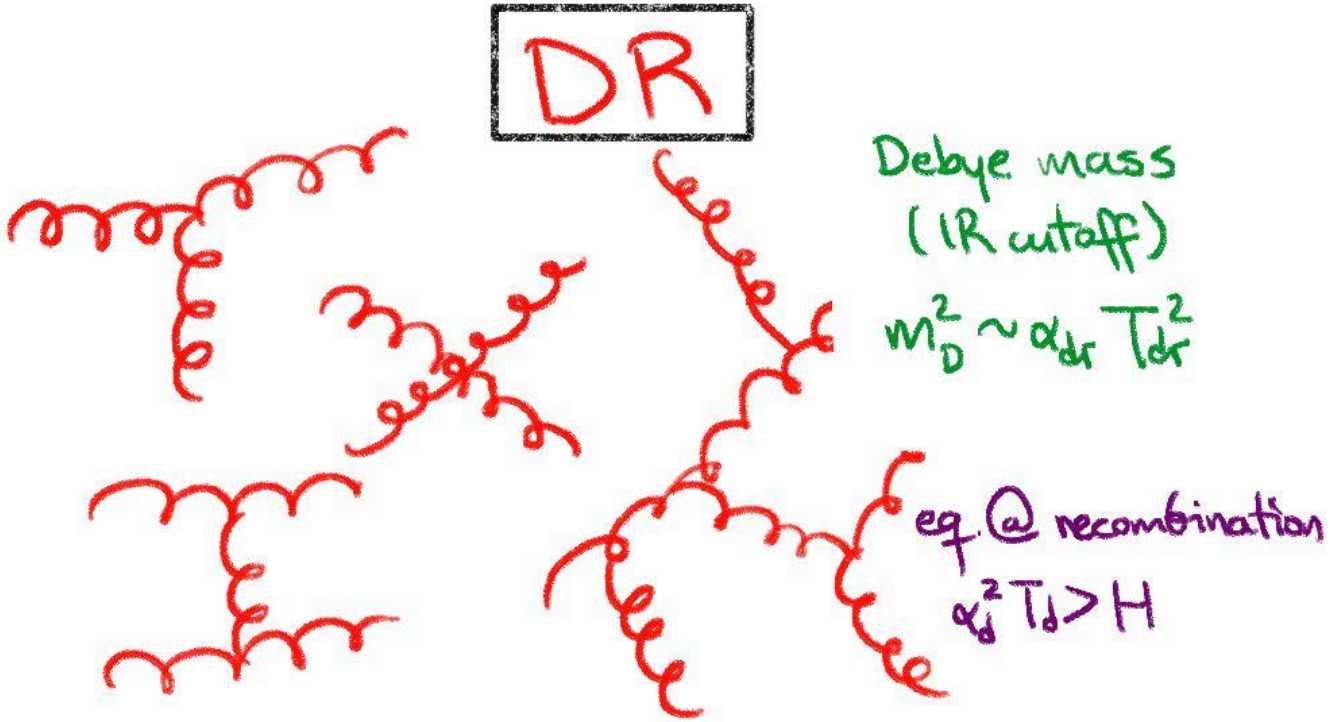


$$\sigma \sim \alpha_d^2 T_{dr}^{-2}$$

$\Rightarrow$ momentum loss rate

$$\Gamma \sim n_{dr} \langle \sigma v \rangle \frac{\Delta p}{p}$$

$$\therefore \Gamma \sim \alpha_d^2 \frac{T_{dr}^2}{M_{dm}} \propto a^{-2}$$



DR self interactions: perfect fluid ($\Pi = 0$)

$c_{eff}^2 = 1/3$, $c_{vis}^2 = 0$

IDS Model

DR: $SU(N)_d$, $\alpha_{dr} \ll 1$ $(\neq \Lambda_d \ll T_{dr,0})$

$$\Delta N_{eff} = \frac{8}{7}(N^2-1)(T_d/T_\nu)^4$$

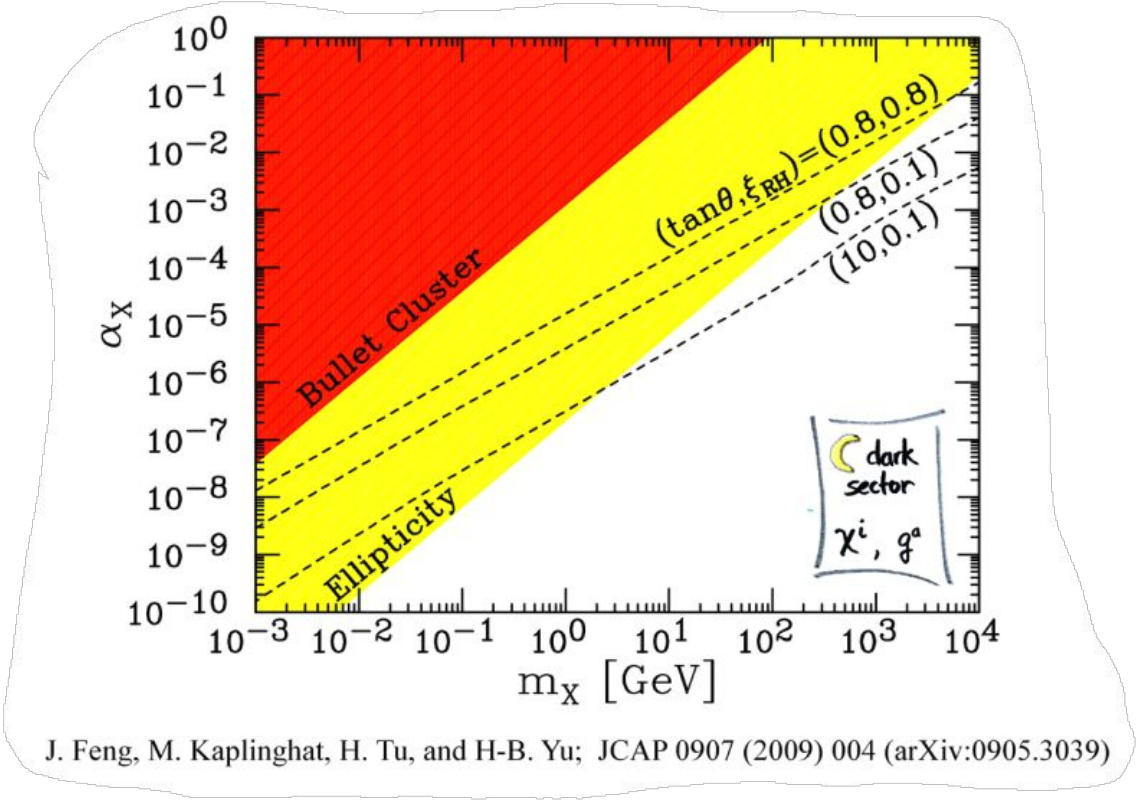
IDM: $N \sim SU(N)_d$; $\Gamma \equiv \Gamma_0 a^{-2}$;

$$\Gamma_0 = \frac{\pi^2}{9}(N^2-1)\alpha_d^2 \log \alpha_d^{-1} \frac{T_{dr}^2}{M_{idm}}$$

$H_0 \simeq 2.4 \times 10^{-4} M_{pl}^{-1}$ (L2: $\Gamma_0 \gg H_0 \Leftrightarrow \alpha_d > 10^{-7}$)

$$\Gamma \propto T^2$$

$$\Rightarrow \Gamma \equiv \Gamma_0 a^{-2}$$



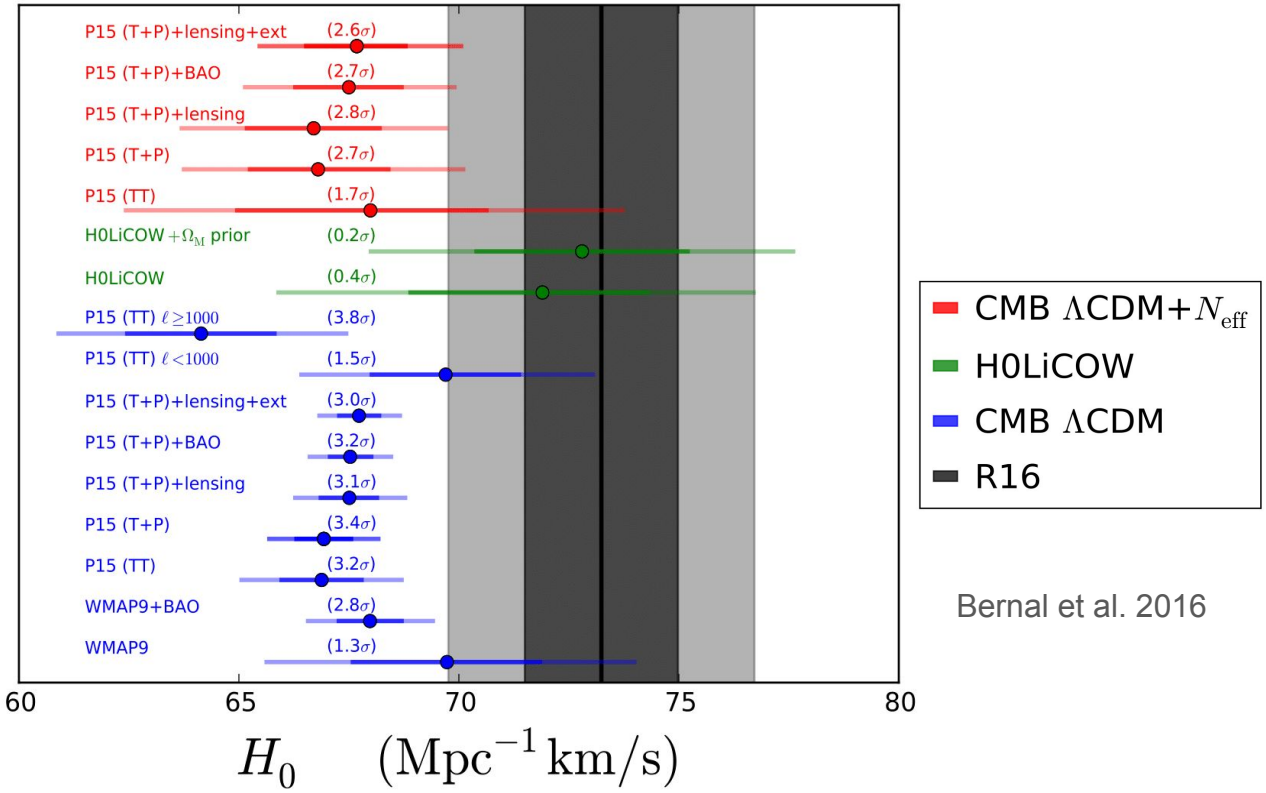
J. Feng, M. Kaplinghat, H. Tu, and H-B. Yu; JCAP 0907 (2009) 004 (arXiv:0905.3039)

DM interactions bounds

H_0: 3.2σ

- H_0 = 67.27 ± 0.66 Mpc^{-1} km/s (Planck 2015)
- H_0 = 73.24 ± 1.74 Mpc^{-1} km/s (Riess et al. 2016)

Solution? ΔN_{eff} or ΔN_{fluid}

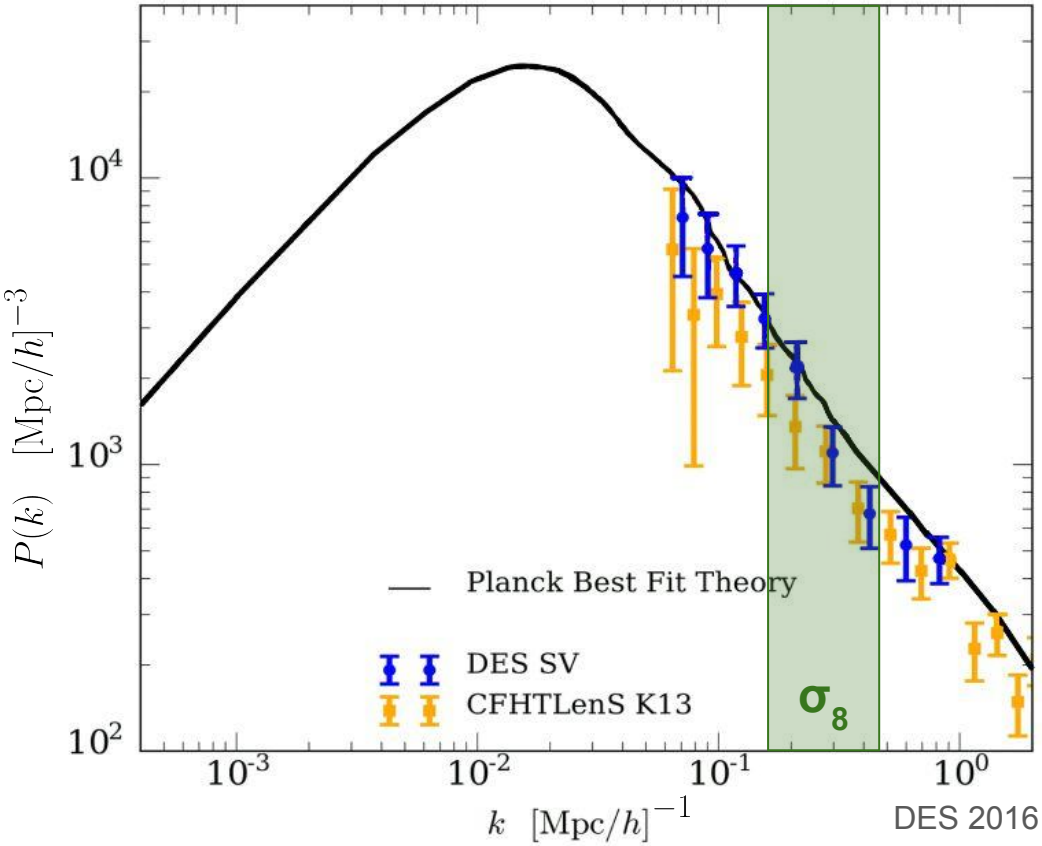


Bernal et al. 2016

σ_8: 2-3σ

- σ_8 = 0.831 ± 0.013 (Planck 2015)
- $\sigma_8 (\Omega_m/0.27)^{0.3}$ = 0.782 ± 0.010 (Planck SZ clusters)
- $\sigma_8 (\Omega_m/0.3)^{0.5}$ = 0.742 ± 0.035 (KiDS-450 + 2dFLenS)
- $\sigma_8 (\Omega_m/0.3)^{0.5} = 0.783^{+0.021}_{-0.025}$ (DES)
- $\sigma_8 (\Omega_m/0.27)^{0.48}$ = 0.768 ± 0.037 (CFHTLens, MacCrann et al.)

Solution? **Suppress MPS**



Data

CMB+BAO

- Planck 2015 high-l TT+TE+EE
- Planck 2016 $\tau_{reio} = 0.055 \pm 0.009$ prior (SimLow)
- BAO: 6dFGS, SDSS-MGS, BOSS-DR12

LSS

- Planck 2015 lensing
- Planck 2015 SZ: $\sigma_8 (\Omega_m/0.27)^{0.3} = 0.782 \pm 0.010$
- CFHTLens full correl. spectrum
- SDSS-DR7-LRG halo power spectrum
- $H_0 = 73.24 \pm 1.74$ Mpc^{-1} km/s (Riess et al. 2016)

The best-fit χ^2 per experiment of each model					
Data Sets	ΛCDM	WI limit		DP limit	
		$\Delta N_{\rm fluid}$ log Prior	$\Delta N_{\rm fluid}$ lin. Prior	$\Delta N_{\rm fluid}$ log Prior	$\Delta N_{\rm fluid}$ lin. Prior
high-ℓ TTTEEE	2452.6	2446.03	2455.22	2447.50	2450.54
SimLow $\tau_{\rm reio}$	0.34	0.03	0.07	0.12	0.67
BAO	15.33	13.69	13.45	13.50	14.21
lensing	10.43	9.53	11.50	9.35	10.34
SDSS	45.43	45.06	45.83	44.08	45.56
CFHTLens	100.00	100.41	98.41	101.46	98.76
Planck SZ	15.50	0.05	3.62	0.52	7.6
H_0	7.80	9.44	4.00	8.93	8.39
TOTAL	2646.42	2624.23	2632.09	2626.47	2636.08
$\Delta\chi^2_{\rm eff}$	0	−22.19	−14.33	−19.95	−10.34

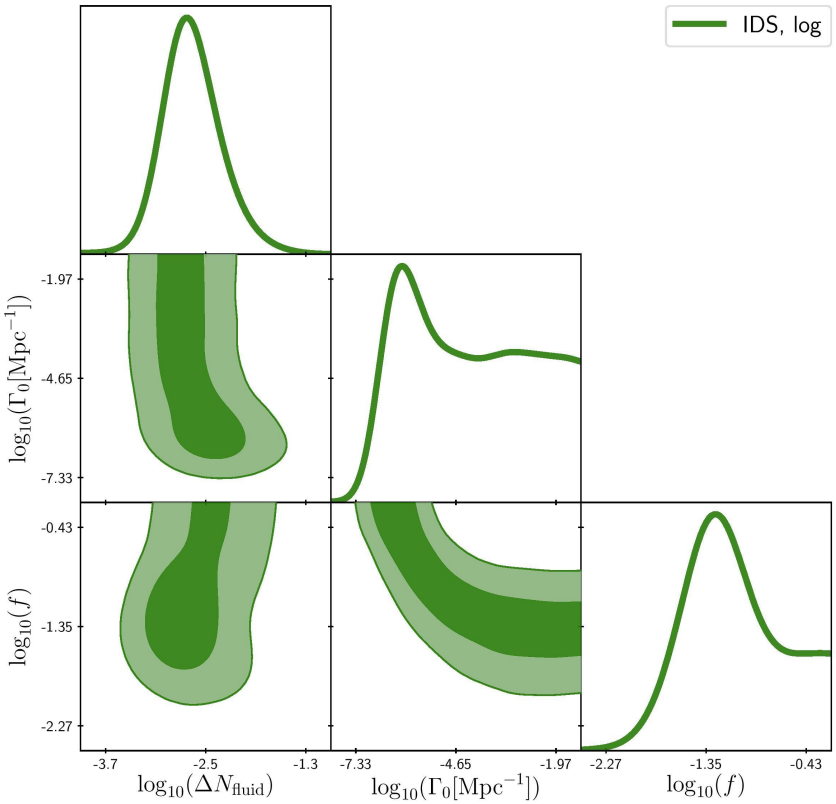
The best-fit χ^2 per experiment of each model		
Data Sets	ΛCDM	General IDS
		$\boldsymbol{\theta}_{\rm IDS}$ log Prior
TTTEEE lite	575.10	567.78
SimLow $\tau_{\rm reio}$	0.26	0.051
BAO	16.48	13.40
lensing	10.13	9.35
SDSS	45.77	44.02
CFHTLens	98.56	99.78
Planck SZ	13.68	0.19
H_0	7.00	8.74
TOTAL	766.98	743.32
$\Delta\chi^2_{\rm eff}$	0	−23.66

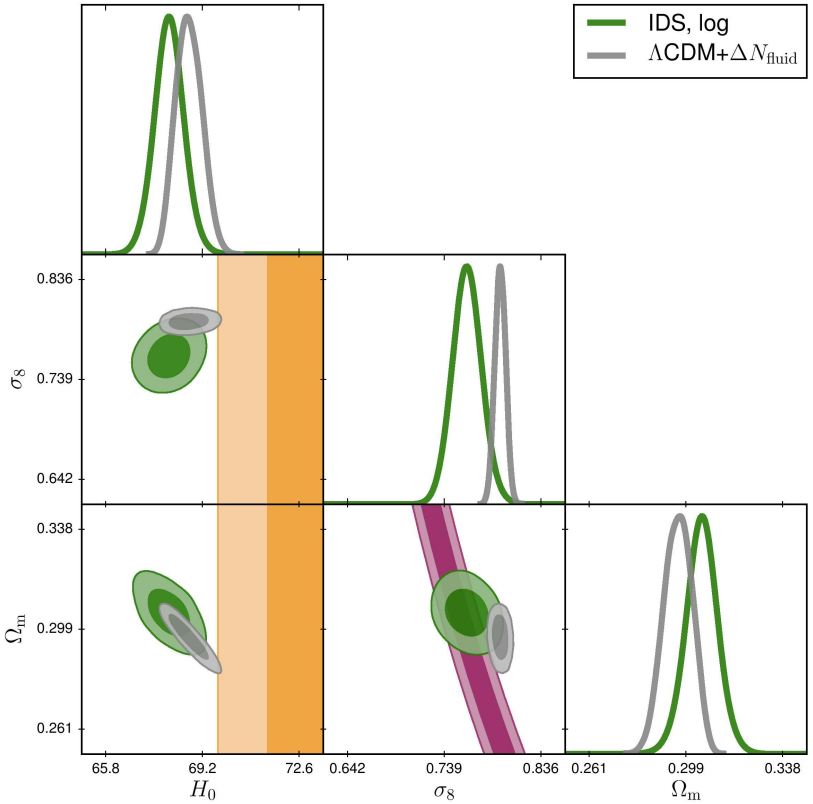
χ^2

Parameter mean values and 68%CL confidence interval, $\log \Delta N_{\rm fluid}$ prior				
Parameters	ΛCDM	WI limit $\log \Delta N_{\rm fluid}$ Prior	DP limit $\log \Delta N_{\rm fluid}$ Prior	General IDS $\log \Delta N_{\rm fluid}$, $\log \Gamma_0$, $\log f$ log Priors
$100\omega_{\rm b}$	$2.245^{+0.013}_{-0.014}$	$2.228^{+0.012}_{-0.012}$	$2.231^{+0.014}_{-0.014}$	$2.235^{+0.013}_{-0.013}$
$n_{\rm s}$	$0.9656^{+0.0038}_{-0.0037}$	$0.9625^{+0.0039}_{-0.0033}$	$0.9628^{+0.0035}_{-0.0035}$	$0.9670^{+0.0035}_{-0.0037}$
$\tau_{\rm reio}$	$0.04887^{+0.008}_{-0.008}$	$0.05815^{+0.0078}_{-0.0077}$	$0.05827^{+0.0082}_{-0.0082}$	$0.05835^{+0.0079}_{-0.0077}$
H_0	$68.67^{+0.41}_{-0.46}$	$67.84^{+0.42}_{-0.3}$	$67.98^{+0.35}_{-0.38}$	$68.06^{+0.39}_{-0.42}$
$\ln 10^{10} A_s$	$3.023^{+0.015}_{-0.015}$	$3.047^{+0.015}_{-0.016}$	$3.047^{+0.016}_{-0.016}$	$3.049^{+0.017}_{-0.016}$
$\omega_{\rm dm}^{\rm tot}$	$0.1168^{+0.001}_{-0.00089}$	$0.119^{+0.00065}_{-0.001}$	$0.1185^{+0.00084}_{-0.00081}$	$0.1184^{+0.00087}_{-0.00089}$
$\log_{10} \Delta N_{\rm fluid}$	–	$-2.309^{+0.25}_{-0.25}$	$-2.814^{+0.2}_{-0.19}$	$-2.67^{+0.27}_{-0.32}$
$10^7 \Gamma_0$	0	$2.272^{+0.61}_{-0.65}$	$\Gamma_0 \gg H_0$	$\log_{10} \Gamma_0 {\rm Mpc} > -7.1$ (95% CL)
f	0	1	$0.04785^{+0.016}_{-0.017}$	$\log_{10} f > -1.7$ (95% CL)
$100\theta_{\rm s}$	$1.042^{+0.00028}_{-0.0003}$	$1.042^{+0.00027}_{-0.00026}$	$1.042^{+0.00029}_{-0.00027}$	$1.0418^{+0.00042}_{-0.00041}$
σ_8	$0.7933^{+0.0052}_{-0.0054}$	$0.7565^{+0.01}_{-0.0092}$	$0.7588^{+0.0099}_{-0.011}$	$0.762^{+0.012}_{-0.012}$
$\Omega_{\rm m}$	$0.2968^{+0.0057}_{-0.0053}$	$0.3083^{+0.0039}_{-0.0057}$	$0.3062^{+0.0048}_{-0.0048}$	$0.305^{+0.0051}_{-0.0052}$

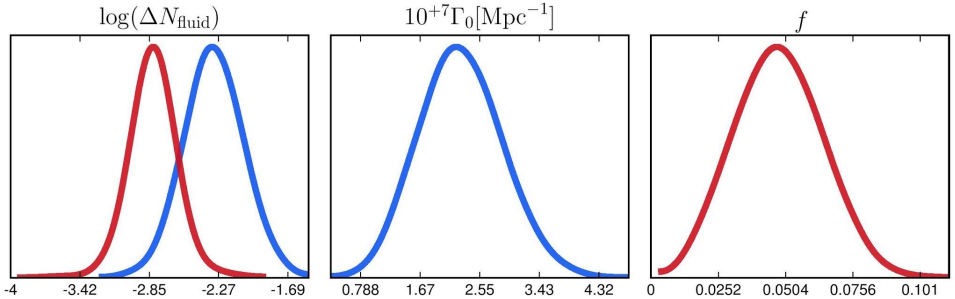
Parameter mean values and 68%CL confidence interval (or 95%CL upper limit), lin. priors			
Parameters	ΛCDM	WI limit	DP limit
$100\omega_{\rm b}$	$2.245^{+0.013}_{-0.014}$	$2.249^{+0.018}_{-0.019}$	$2.242^{+0.017}_{-0.019}$
$n_{\rm s}$	$0.9656^{+0.0038}_{-0.0037}$	$0.9708^{+0.0044}_{-0.0041}$	$0.9701^{+0.0038}_{-0.0042}$
$\tau_{\rm reio}$	$0.04887^{+0.008}_{-0.008}$	$0.05915^{+0.0082}_{-0.0078}$	$0.06118^{+0.0093}_{-0.0086}$
H_0	$68.67^{+0.41}_{-0.46}$	$70.01^{+1.1}_{-1.2}$ (95% CL: 72.21)	$69.13^{+0.76}_{-1.3}$ (95% CL: 71.32)
$\ln 10^{10} A_s$	$3.023^{+0.015}_{-0.015}$	$3.05^{+0.017}_{-0.017}$	$3.056^{+0.022}_{-0.019}$
$\omega_{\rm dm}^{\rm tot}$	$0.1168^{+0.001}_{-0.00089}$	$0.126^{+0.0032}_{-0.0039}$	$0.1235^{+0.0017}_{-0.0033}$
$\Delta N_{\rm fluid}$	0	$0.369^{+0.17}_{-0.19}$ (95% CL: ≤ 0.6657)	≤ 0.5064 (95% CL)
$10^7 \Gamma_0$	0	$1.097^{+0.32}_{-0.32}$	$\Gamma_0 \gg H_0$
f	0	1	$0.01387^{+0.0052}_{-0.0046}$
$100\theta_{\rm s}$	$1.042^{+0.00028}_{-0.0003}$	$1.043^{+0.00035}_{-0.00037}$	$1.043^{+0.00036}_{-0.00038}$
σ_8	$0.7933^{+0.0052}_{-0.0054}$	$0.7721^{+0.01}_{-0.01}$	$0.7734^{+0.011}_{-0.012}$
$\Omega_{\rm m}$	$0.2968^{+0.0057}_{-0.0053}$	$0.3043^{+0.0067}_{-0.0053}$	$0.3067^{+0.0074}_{-0.007}$

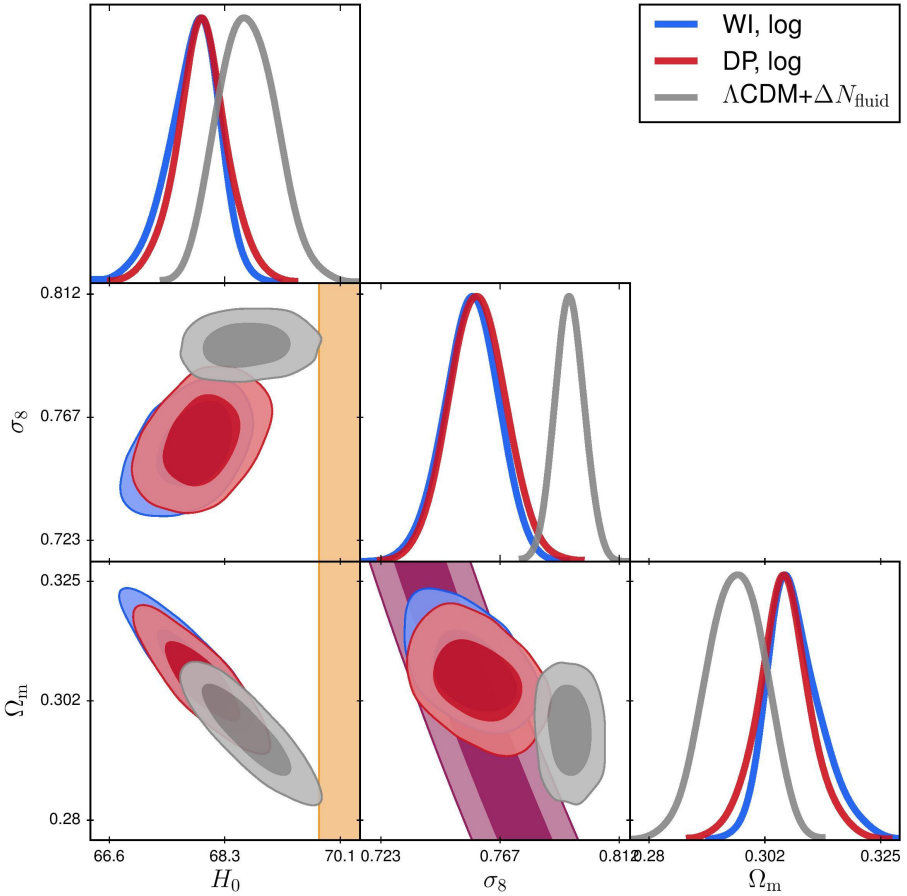
Parameters


IDS, log
-1.97
-4.65
-7.33
$\log_{10}(\Gamma_0[\mathrm{Mpc}^{-1}])$
-0.43
-1.35
-2.27
$\log_{10}(f)$
-3.7
-2.5
-1.3
$\log_{10}(\Delta N_{\mathrm{fluid}})$
-7.33
-4.65
-1.97
$\log_{10}(\Gamma_0[\mathrm{Mpc}^{-1}])$
-2.27
-1.35
-0.43
$\log_{10}(f)$

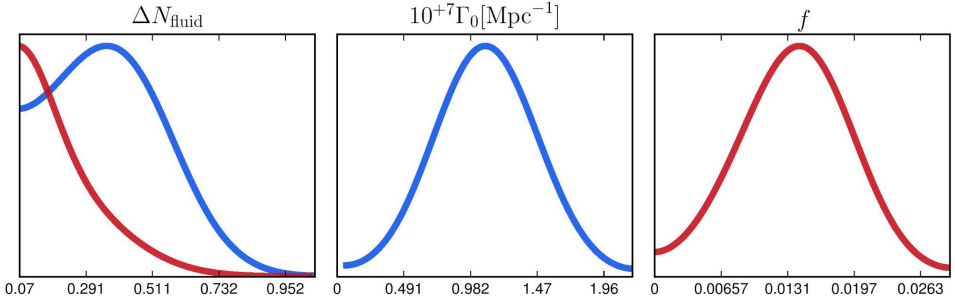

IDS, log
ΛCDM+$\Delta N_{\mathrm{fluid}}$
0.836
0.739
0.642
σ_8
0.338
0.299
0.261
Ω_{m}
65.8
69.2
72.6
H_0
0.642
0.739
0.836
σ_8
0.261
0.299
0.338
Ω_{m}

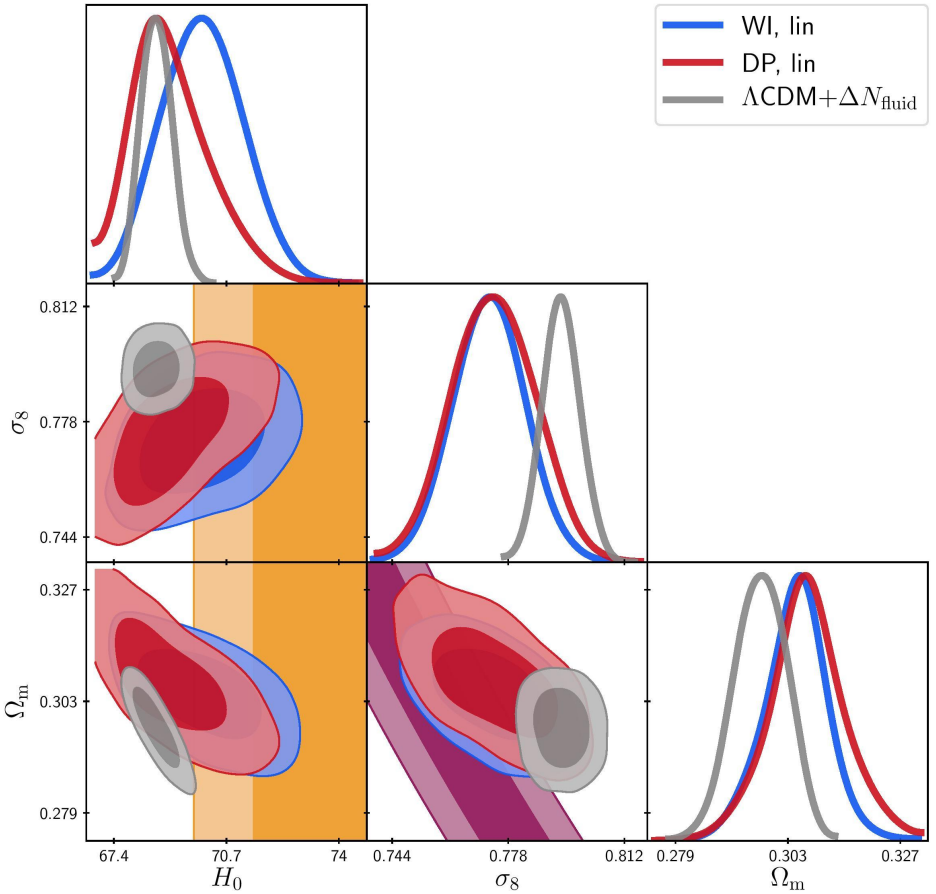
IDS


$\log(\Delta N_{\rm fluid})$
$10^{+7}\Gamma_0[{\rm Mpc}^{-1}]$
f
-4
-3.42
-2.85
-2.27
-1.69
0.788
1.67
2.55
3.43
4.32
0
0.0252
0.0504
0.0756
0.101


WI, log
DP, log
ΛCDM+$\Delta N_{\rm fluid}$
0.812
0.767
0.723
σ_8
0.325
0.302
0.28
$\Omega_{\rm m}$
66.6
68.3
70.1
H_0
0.723
0.767
0.812
σ_8
0.28
0.302
0.325
$\Omega_{\rm m}$

WI & DP, global





WI & DP, $\Delta N_{fluid} \geq 0.07$

$$S \equiv \frac{\delta_{\text{clumping DM}}}{\delta^{\Lambda\text{CDM}}_{\text{cdm}}}$$

$$\alpha^2 \delta''_{\text{idm}} + \left(\frac{1 + \frac{3}{2}\alpha}{1+\alpha} + \frac{g}{\sqrt{1+\alpha}} \right) \alpha \delta'_{\text{idm}} - \frac{\frac{3}{2}\alpha}{1+\alpha} \delta_{\text{idm}} \approx 0$$

$$g \equiv \left. \frac{\sqrt{2}\mathcal{G}}{\mathcal{H}} \right|_{\text{eq}} \approx \frac{h\Gamma_0}{\omega_{\text{r}}^{1/2} H_0} \approx 10^2 \frac{\Gamma_0}{H_0}$$

$$S(\alpha)_{\text{WI}} \xrightarrow{\alpha \gg 1} \frac{4 - 6g + 2g^2 - \left(\frac{0.36}{k\eta_{\text{eq}}}\right)^g (2+g) \cos(g\pi/2) \Gamma(3+g)}{g(4 - 5g^2 + g^4)(-1.9 + \log k\eta_{\text{eq}})}$$

$$S(\alpha \gg 1)_{\text{WI}} \sim 1 - \frac{g}{2} \log k\eta_{\text{eq}}$$

Analytic results: WI

$$\alpha^2\delta''_{\rm cdm} + \left(\frac{1+\frac{3}{2}\alpha}{1+\alpha}\right)\alpha\delta'_{\rm cdm} - (1-f)\frac{\frac{3}{2}\alpha}{1+\alpha}\delta_{\rm cdm} \approx 0$$

$$S(\alpha)_{\rm DP} \xrightarrow{\alpha\gg 1} \alpha^{-1-\beta_-}\left(0.38 \times \frac{2^{-2\beta_-}\Gamma(2\beta_-)\tan(2\pi\beta_-)}{\Gamma(2\beta_- + 1/2)}\right)\left(\frac{-0.05 + 2\Psi(1-2\beta_-) + \log k\eta_{\rm eq}}{-1.9 + \log k\eta_{\rm eq}}\right)$$

$$\beta_\pm \equiv \tfrac{1}{4}\left(1 \pm \sqrt{25-24f}\right)$$

$$S(\alpha \gg 1)_{\rm DP} \approx \alpha^{-\frac{3}{5}f}\left(1 + f\left(\frac{2.0 - 0.57\log k\eta_{\rm eq}}{-1.9 + \log k\eta_{\rm eq}}\right)\right)$$

Analytic results: DP

Lyman-α

- 2004 SDSS Ly-α (Krall et al. 170508894): WI goodness of fit reduced
  - σ_8 ~ 0.85
  - Hydrodynamic simulations based on ΛCDM
- BOSS Ly-α (Palanque-Delabrouille et al. 2016)
  - Lower σ_8
  - Lower n_s at large scales!