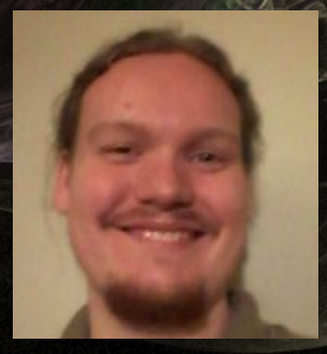
COSMO17, APC Paris, 30.08.2017

Dark Matter - Dark Radiation interactions, H_0 and σ_8

Based on

- Lesgourgues, Marques-Tavares, Schmaltz 2016 [JCAP]
- Buen-Abad, Schmaltz, Lesgourgues, Brinckmann 2017 [tomorrow?]





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H_0 and σ_8 tensions

High H_0 w.r.t Planck ΛCDM (2-3σ): SHoES, CCHP…

Low σ_8 w.r.t Planck ΛCDM (2-3σ):

- cluster counts (Planck SZ, …),
- weak lensing (CFHTLens, DES, KIDs)

No direct contradiction. Systematics or slightly wrong model.

Difficult to bring all data back to 1-2σ agreement. Doesn't work with simplest extensions (N_{eff}, m_ν, w, Ω_k, decaying DM…). Requires something less trivial:

- Interacting DM-DR of [Schmaltz et al. 2015, 2016, 2017]
- Extra relativistic species with non-standard interactions of active or sterile neutrinos [Archidiacono et al. 2016; Lancaster et al. 2017; Oldengott et al. 2017]
- Dynamical dark energy [Joudaki et al. 1610.04606]

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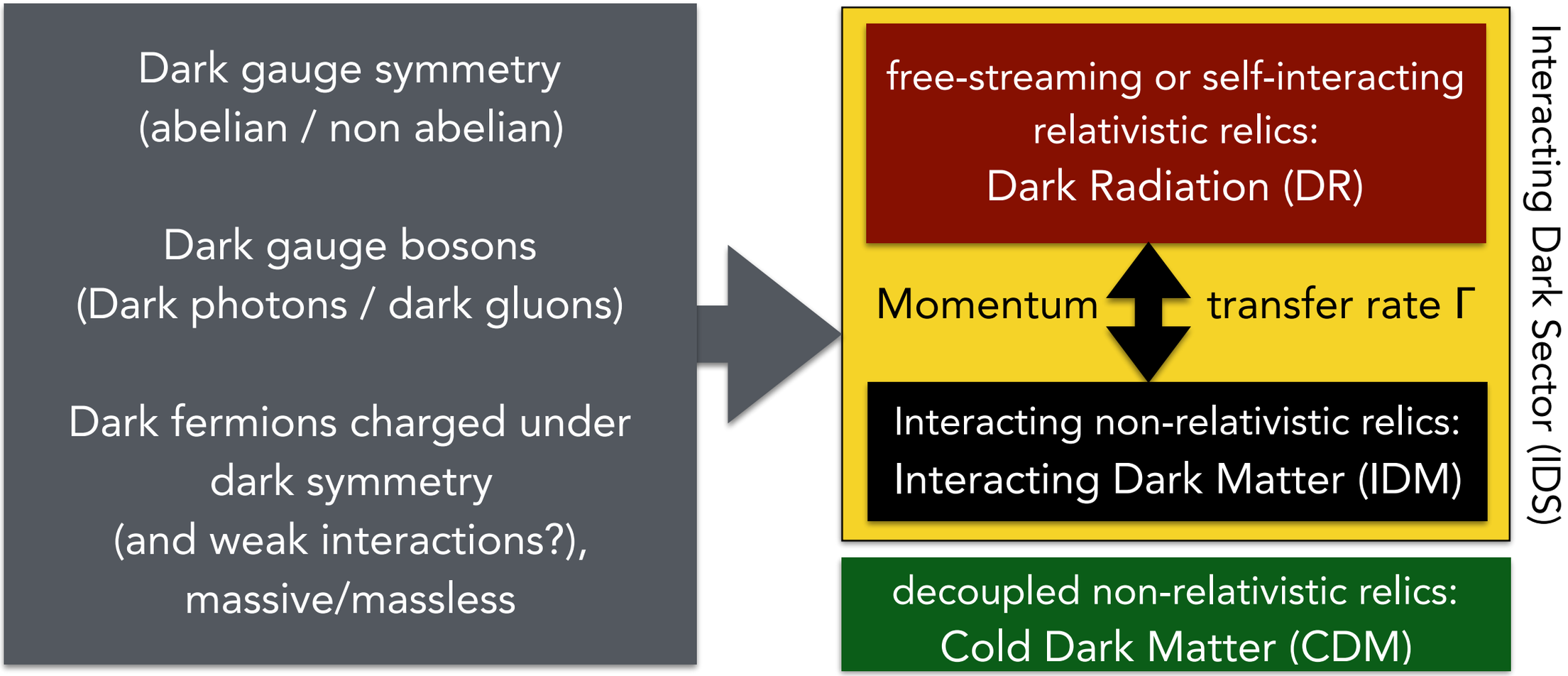
Interacting Dark Sector

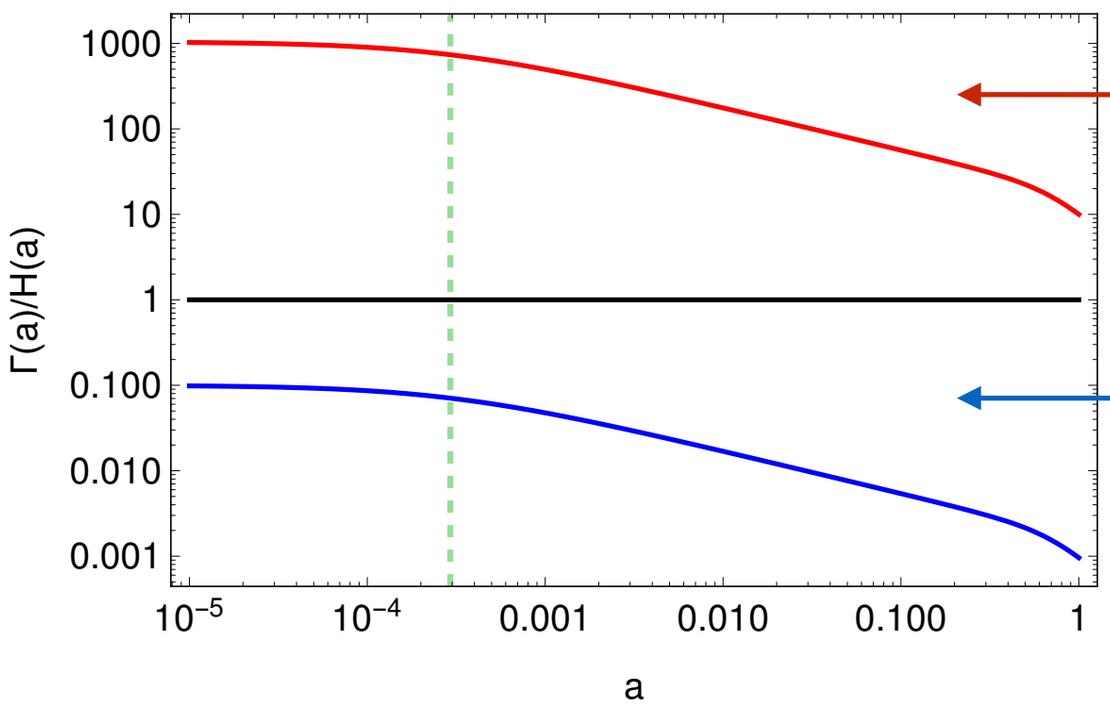


- Concrete examples [Buen-Abad et al. 2015, Cyr-Racine et al. 2015 (ETHOS), …]
- Specific predictions on, for instance, $\Gamma \sim T^n$, or ΔN_{eff}, or ΔN_{fluid}

Momentum exchange rate

- $\Gamma \sim T^n$ computed from first principles
- Many papers consider n=4, Γ/H increases, late time effects, needs N-body
- We are interested in n=2 (constant Γ/H during RD, linear scales)

- At most small departure of ΛCDM; possibilities:
  - all DM could be IDM in a Weakly Interacting (WI) limit
  - fraction f could be IDM in a Dark Plasma (DP) limit, (1-f) fraction = ordinary CDM



Dark Plasma limit
(always efficient)

Weakly Interacting limit
(small constant effect during RD)

Perturbation equations

- Coupling appears in Euler equations:

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

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

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

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

$$\mathcal{G} \equiv a\Gamma = a^{-1}\Gamma_0$$

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

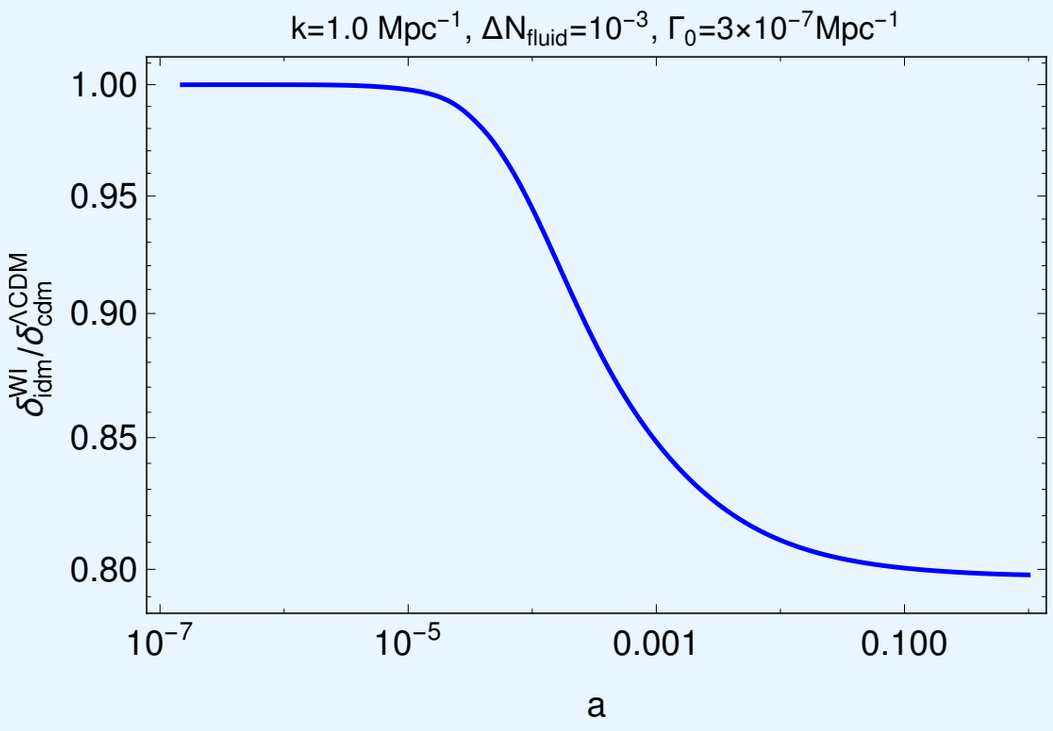
Interesting controversy on this factor
(may ask question or look at
appendix of tomorrow's paper)

- (Trivially) implemented in CLASS [http://class-code.net]

Modified Dark Matter growth

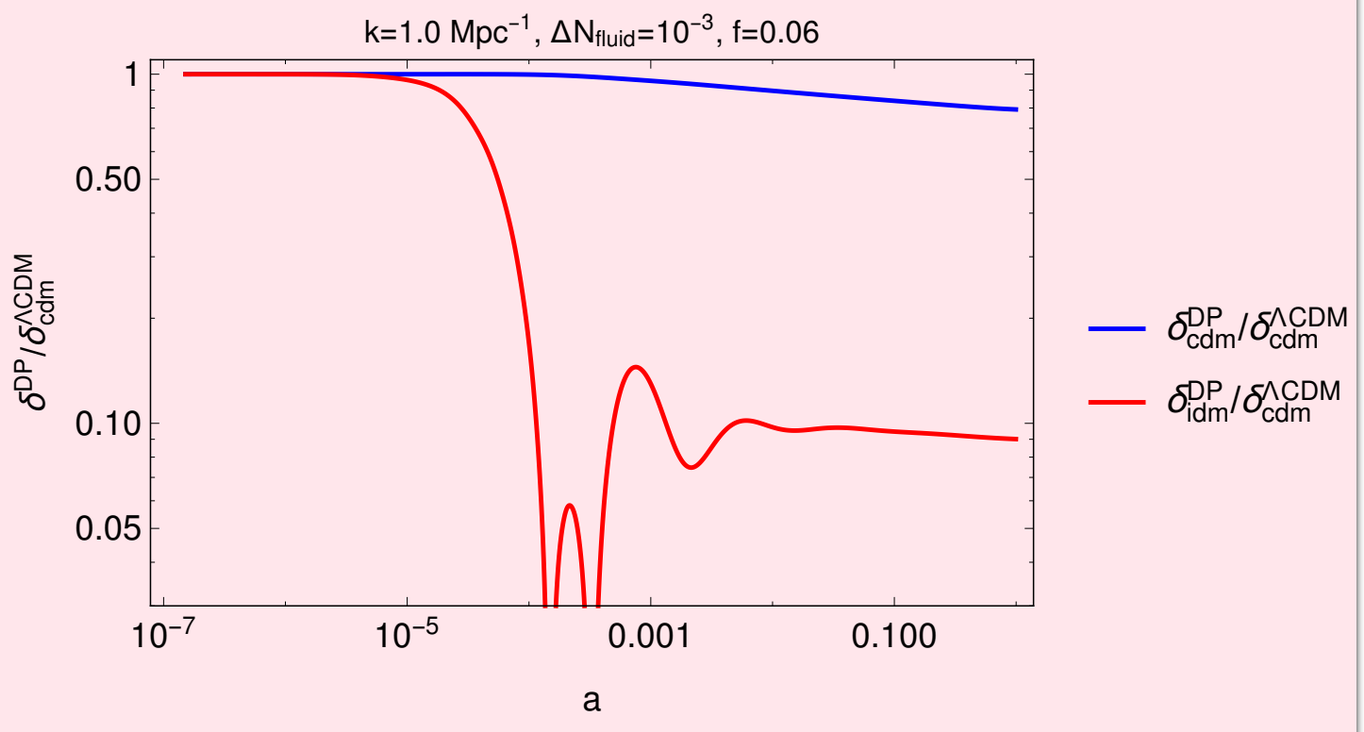
- Ratio of DM perturbation for (IDS model/standard ΛCDM), as a function of time, for fixed k:

Weakly Interacting model



if RD+sub-Hubble:
DR drag on DM,
IDM growth suppressed

Dark Plasma model

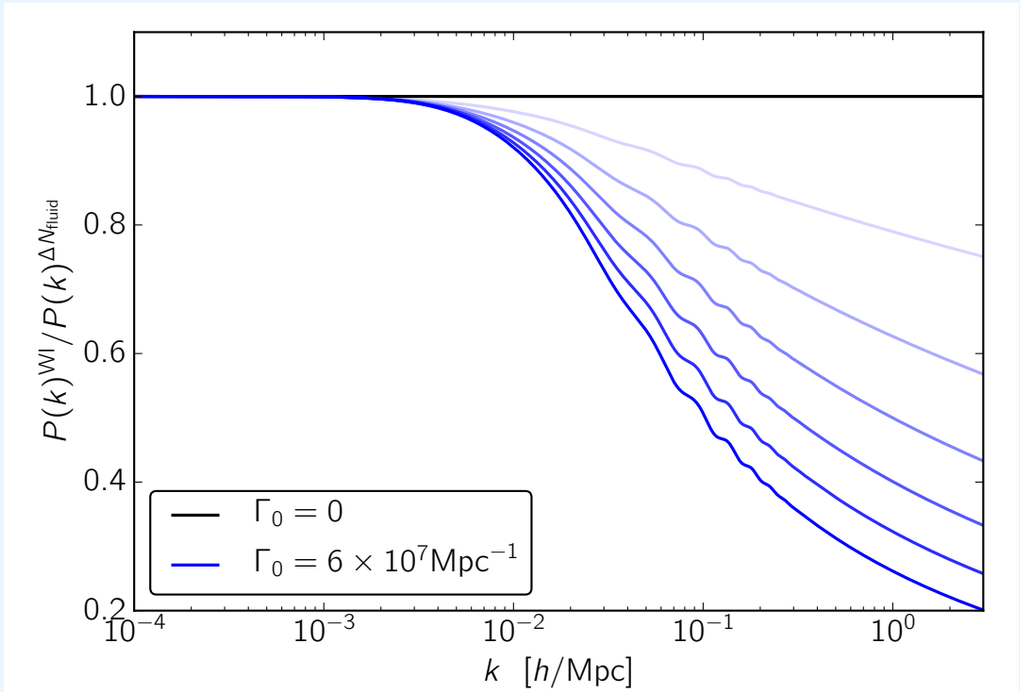


below Jeans length of Dark Plasma:
IDM suppressed like radiation
CDM growth suppressed
(analogy with massive νs)

Effects on Matter Power Spectrum

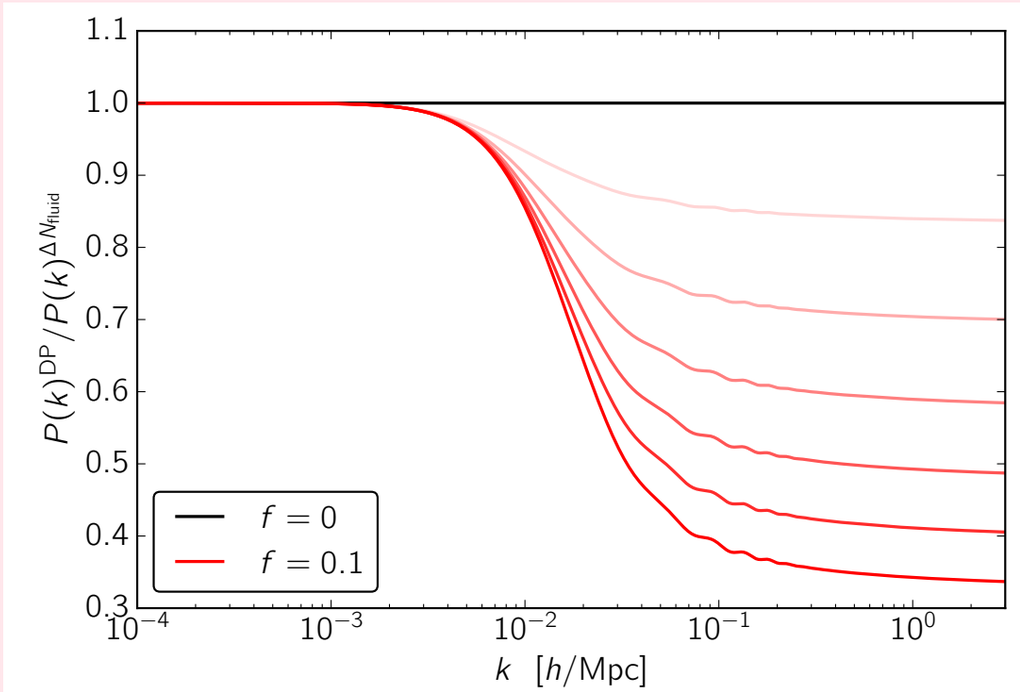
- Ratio of P(k,z=0) for IDS model/standard ΛCDM:

Weakly Interacting model
(increasing Γ)



(Very different from massive neutrinos)

Dark Plasma model
(increasing f)

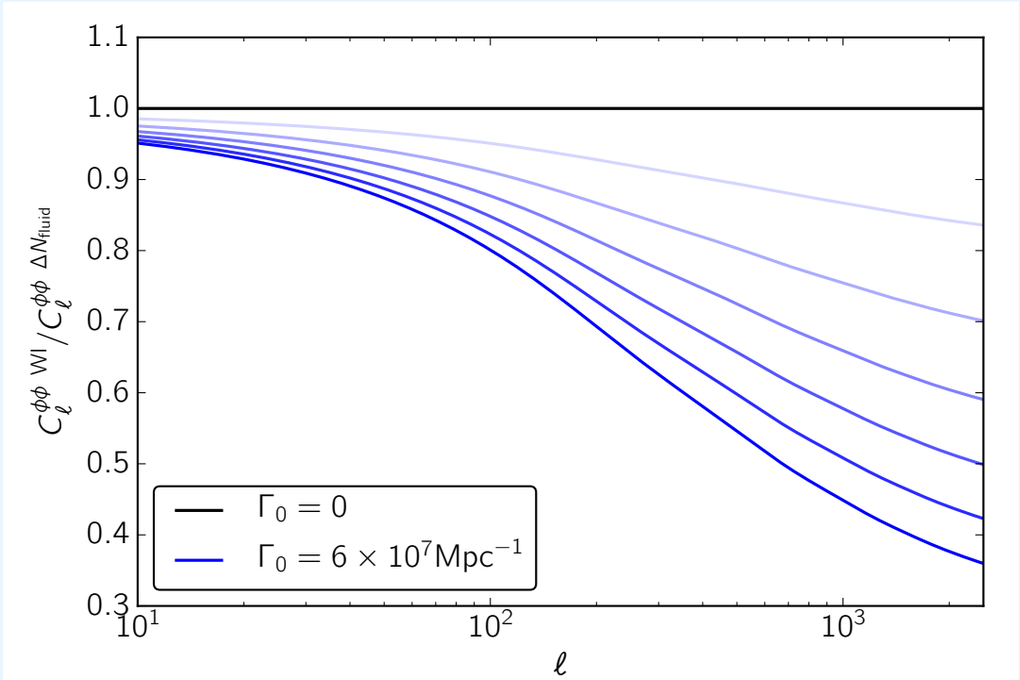


(more similar to massive neutrinos although different scales/times)

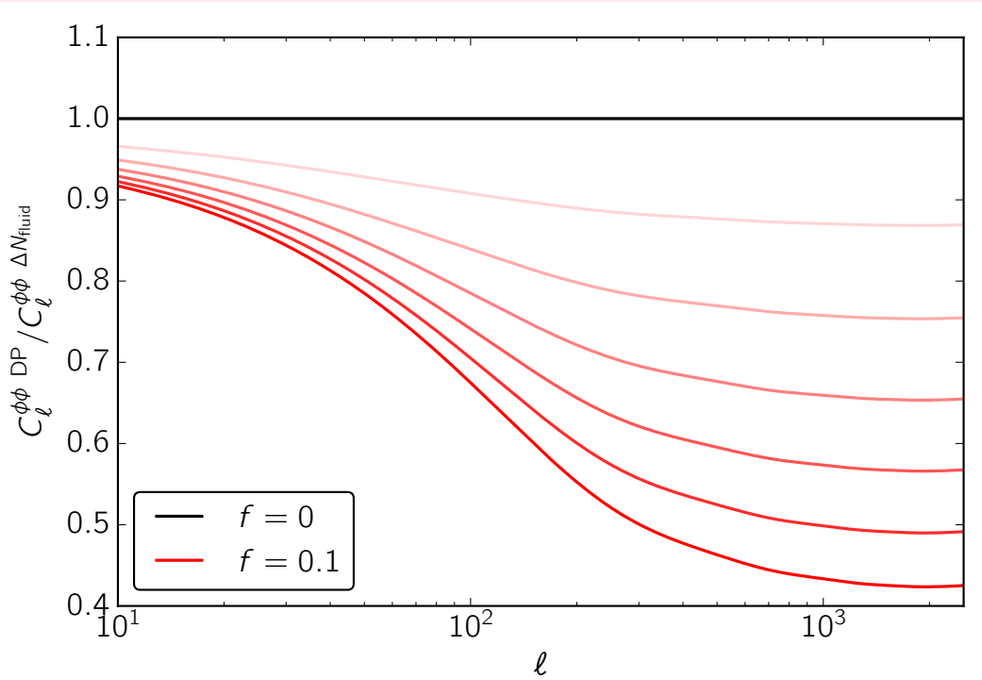
Effects on CMB Lensing spectrum

- Ratio of $C_l^{\Phi\Phi}$ for IDS model/standard ΛCDM:

Weakly Interacting model
(increasing Γ)



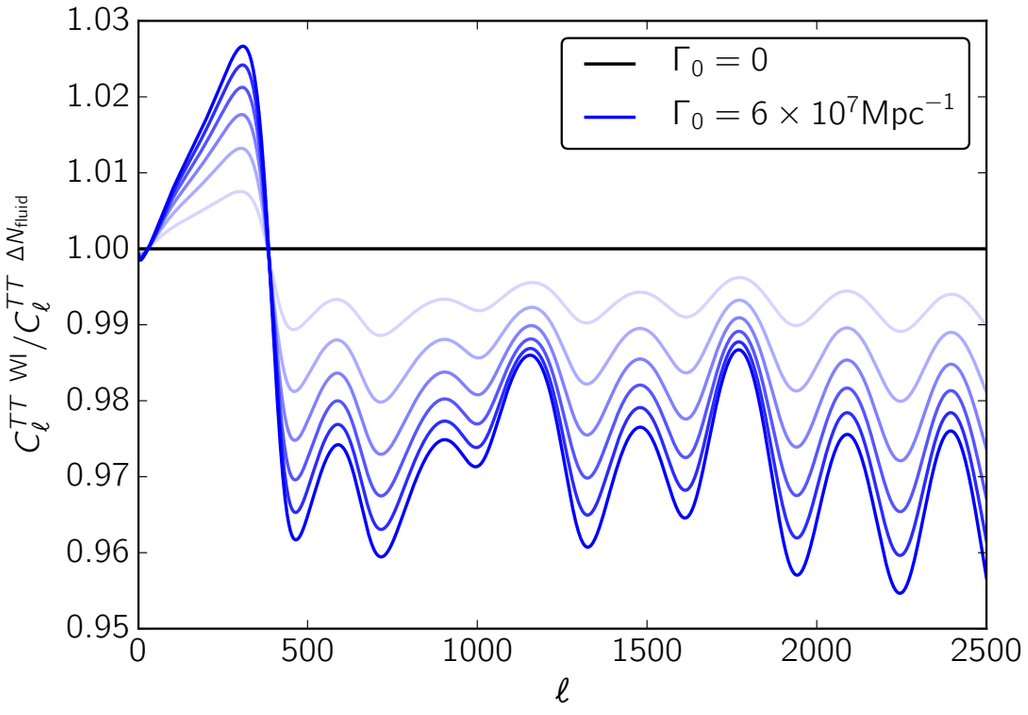
Dark Plasma model
(increasing f)



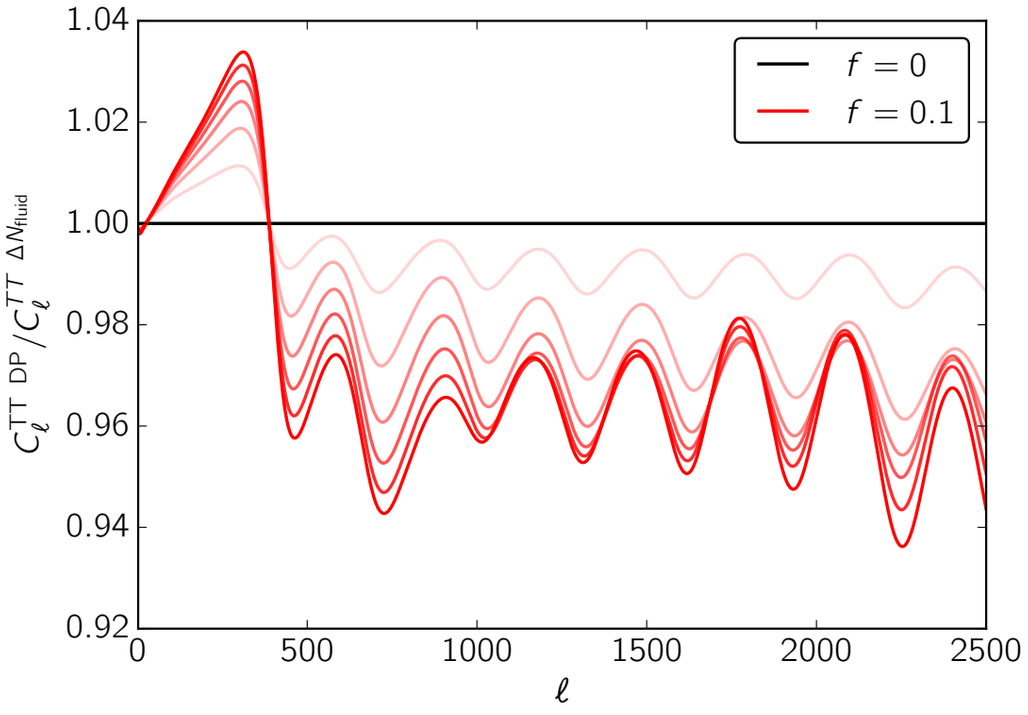
Effects on CMB temperature spectrum

- Ratio of Cl^{TT} for IDS model/standard ΛCDM:

Weakly Interacting model
(increasing Γ)



Dark Plasma model
(increasing f)



(Very different from effect massive neutrinos with comparable suppression of P(k); typically smaller; can suppress more P(k) while maintaining CMB agreement)

New dataset

Lesgourgues at al. 2016 [1507.04351]

- Planck 2015 high-l TT
- Planck 2015 low-l
- BAO 6dFGS, SDSS-MGS, BOSS-DR11
- Planck 2015 lensing
- Planck 2015 SZ as ($\sigma_8\,\Omega_m^{0.30}$) prior
- CFHTLens as ($\sigma_8\,\Omega_m^{0.30}$) prior
- H_0 of Riess et al. 2011

Buen-Abad et al. [1708.xxxxx]

- Planck 2015 high-l TTTEEE
- Planck 2016 τ_{reio} prior (from simlow)
- BAO 6dFGS, SDSS-MGS, BOSS-DR12
- Planck 2015 lensing
- Planck 2015 SZ as ($\sigma_8\,\Omega_m^{0.30}$) prior
- CFHTLens full correlation function
- Halo power spectrum from SDSS-DR7-LRG
- H_0 of Riess et al. 2016

New versions of IDS model

- non-abelian IDM model = Weakly Interacting + $\Delta N_{fluid} > 0.07$ (6 params + ΔN_{fluid}, Γ)

+ Dark Plasma model with $\Delta N_{fluid} > 0.07$ (6 params + ΔN_{fluid}, f)

+ WI and DP with $\Delta N_{fluid} > 0$ (6 params + ΔN_{fluid}, Γ or f)

+ full general IDS model with $\Delta N_{fluid} > 0$ (6 params + ΔN_{fluid}, Γ and f)

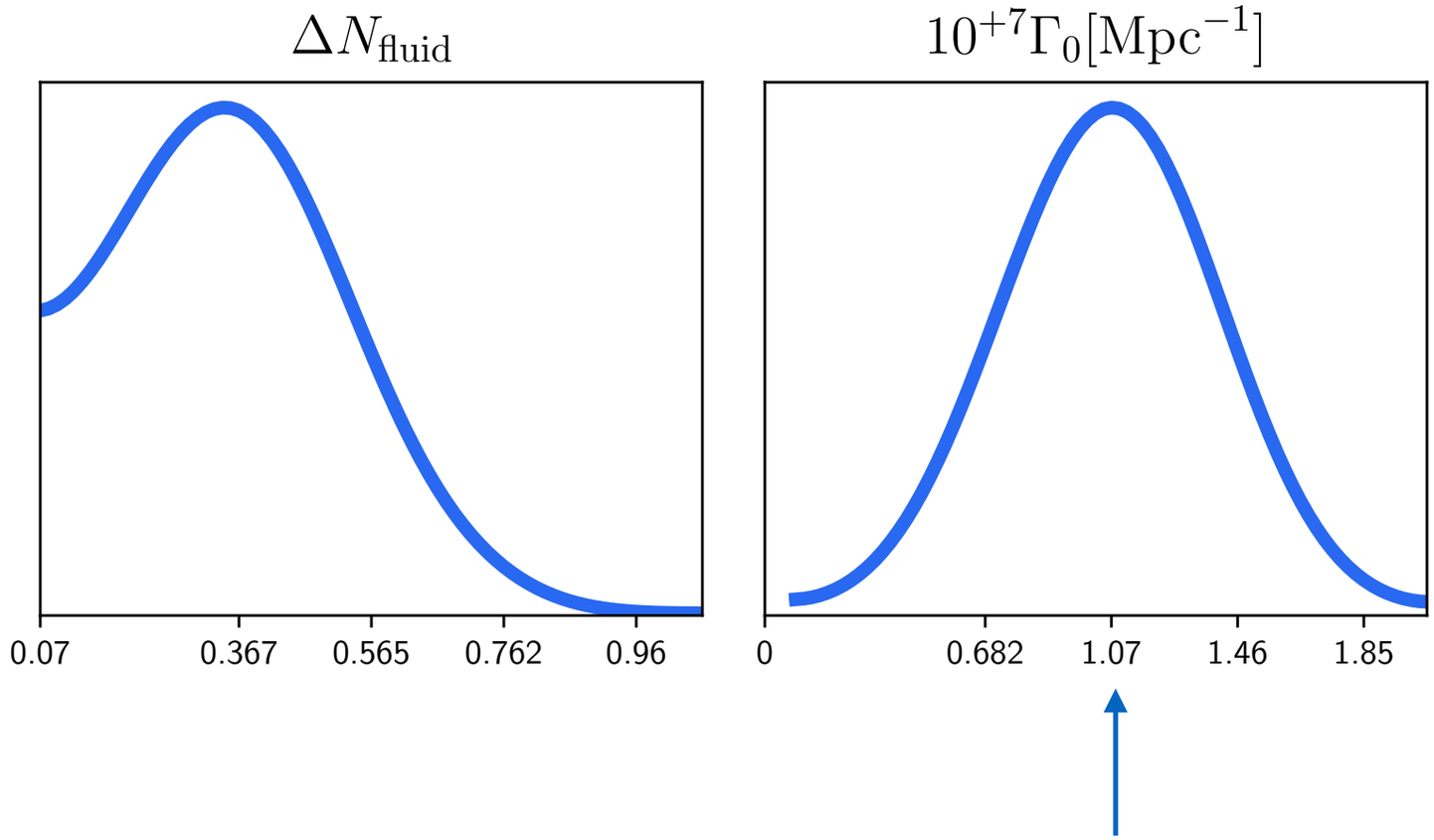
Weakly Interacting model with ΔN>0.07

Best fit model:

Data Sets	ΛCDM	WI $\Delta N_{\rm fluid}$ lin. Prior
high-ℓ TTTEEE	2452.6	2451.68
SimLow $\tau_{\rm reio}$	0.34	0.012
BAO	15.33	13.61
lensing	10.43	10.85
SDSS	45.43	46.13
CFHTLens	100.00	98.53
Planck SZ	15.50	5.20
H_0	7.80	4.08
TOTAL	2646.42	2630.09
$\Delta\chi^2_{\rm eff}$	0	−16.33

with 2 extra params: 3.6σ

Parameter posteriors



$\Gamma_0 \sim (1.1+-0.3)\ 10^{-21} s^{-1}$, > 0 at 4.1σ

Weakly Interacting model with ΔN>0.07

Best fit model:

Data Sets	ΛCDM	WI $\Delta N_{\rm fluid}$ lin. Prior
high-ℓ TTTEEE	2452.6	2451.68
SimLow $\tau_{\rm reio}$	0.34	0.012
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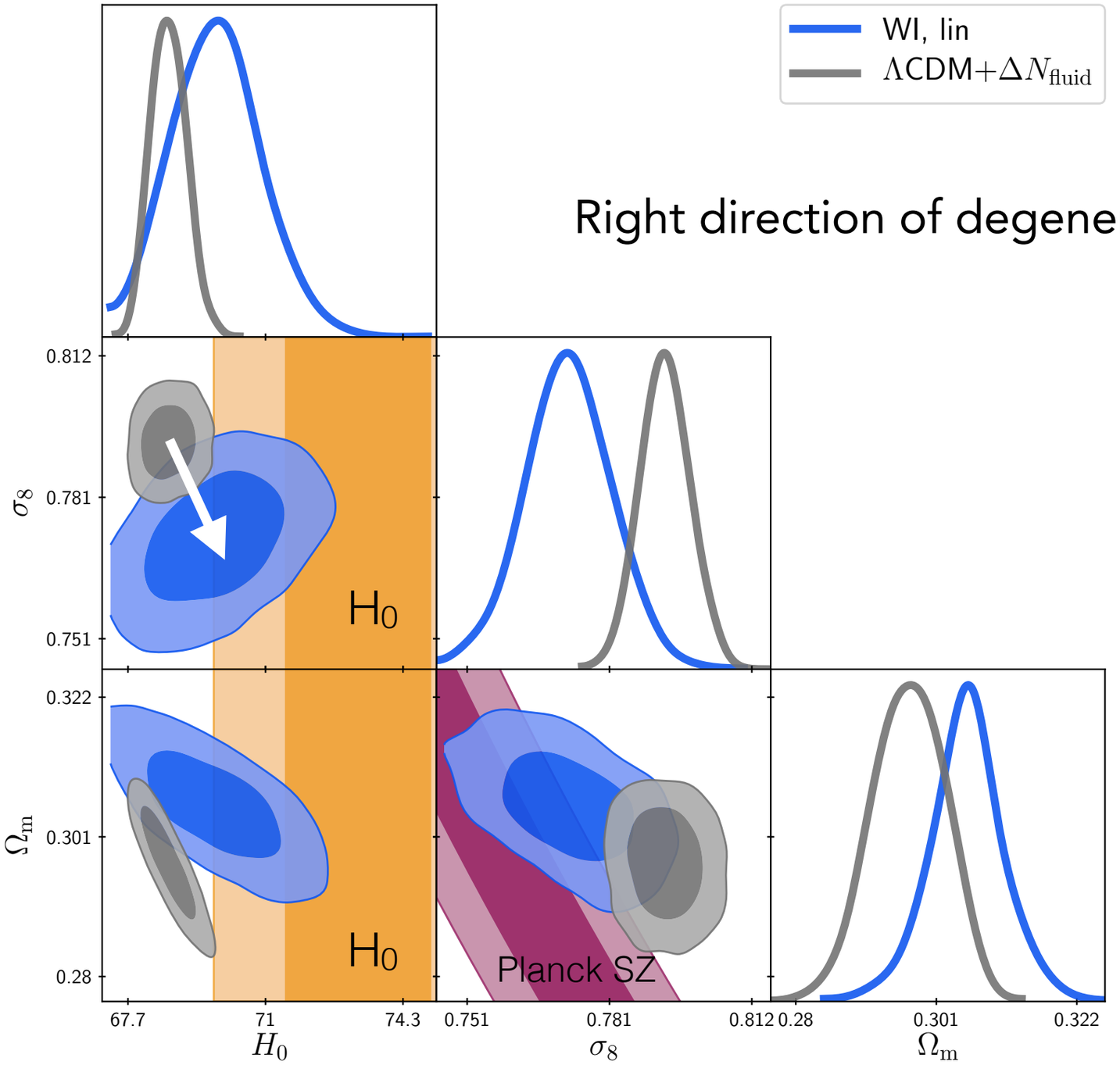


Right direction of degeneracy

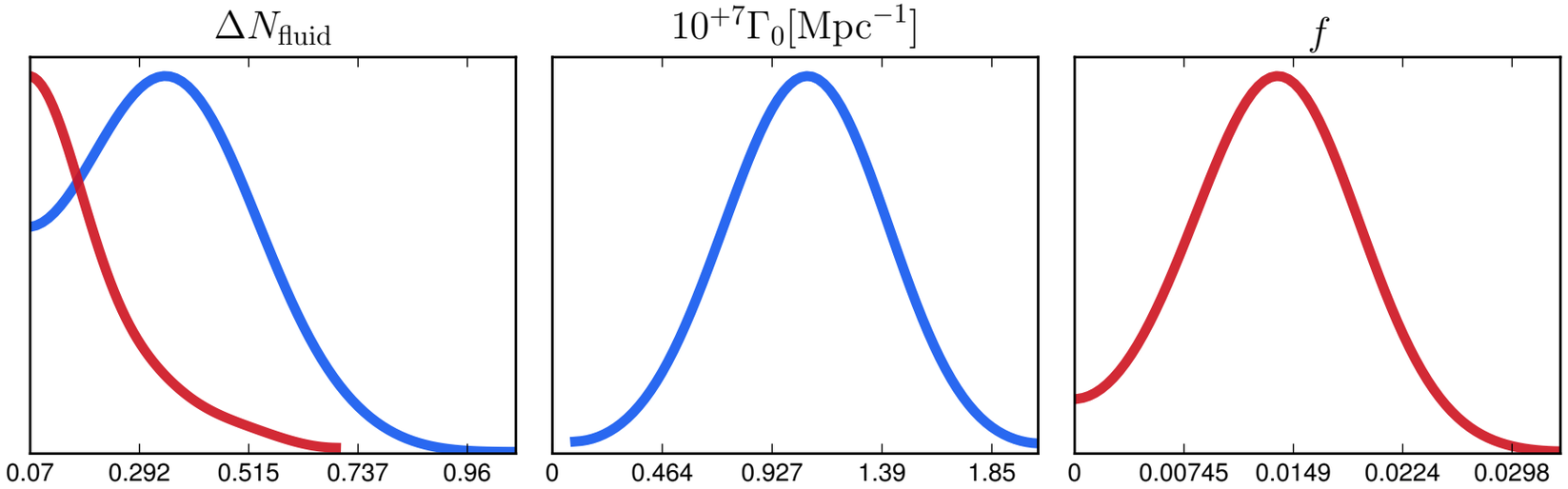
Dark Plasma model with ΔN>0.07

Best fit model:

Data Sets	ΛCDM	DP $\Delta N_{\rm fluid}$ lin. Prior
high-ℓ TTTEEE	2452.6	2454.76
SimLow $\tau_{\rm reio}$	0.34	0.26
BAO	15.33	14.91
lensing	10.43	12.03
SDSS	45.43	46.66
CFHTLens	100.00	98.17
Planck SZ	15.50	2.35
H_0	7.80	9.53
TOTAL	2646.42	2638.63
$\Delta\chi^2_{\rm eff}$	0	−7.79

with 2 extra params: 2.3σ

Parameter posteriors



f ~ 1.4%, > 0 at 2.8σ

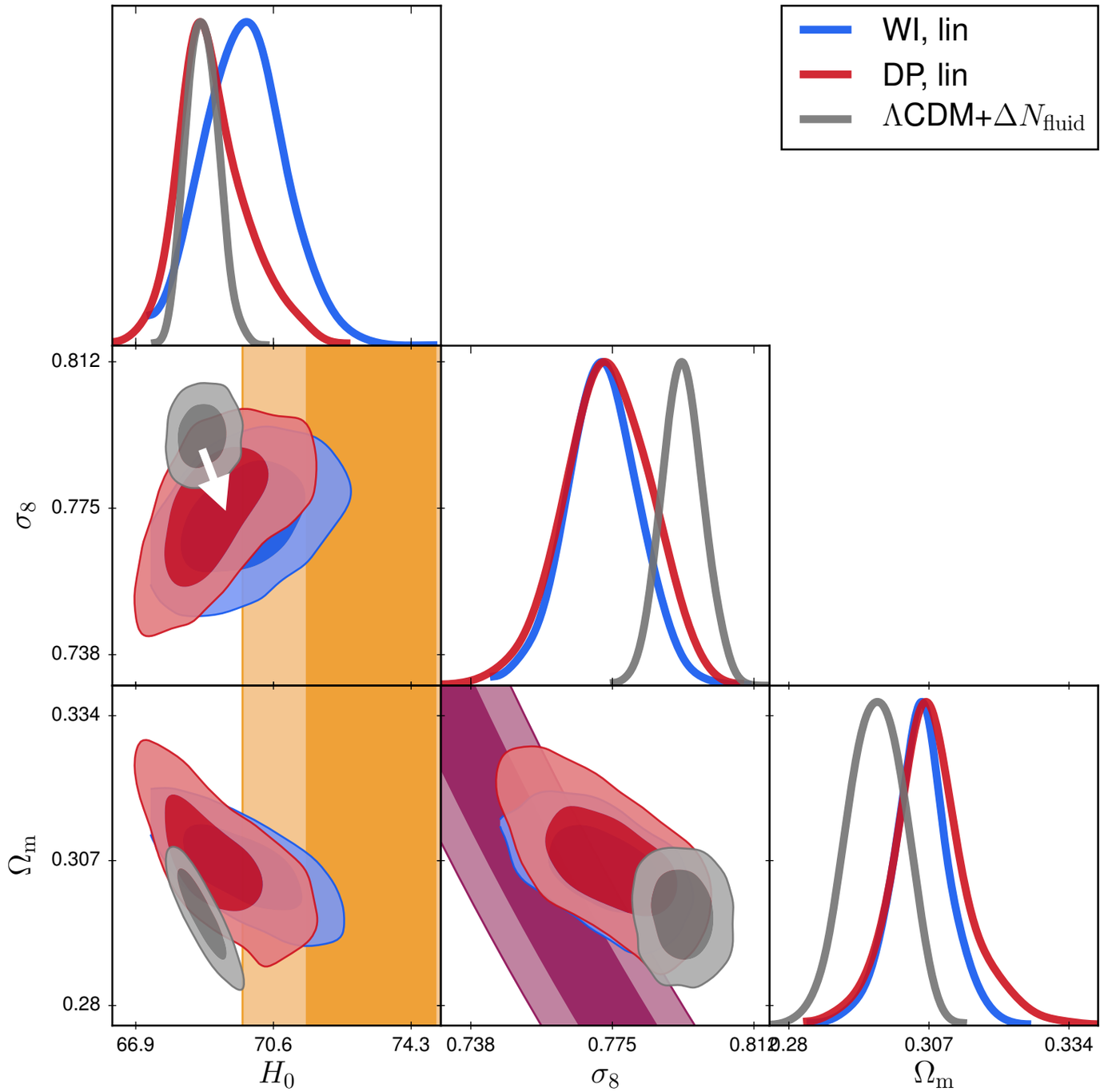
Dark Plasma model with ΔN>0.07

Best fit model:

Data Sets	ΛCDM	DP $\Delta N_{\rm fluid}$ lin. Prior
high-ℓ TTTEEE	2452.6	2454.76
SimLow $\tau_{\rm reio}$	0.34	0.26
BAO	15.33	14.91
lensing	10.43	12.03
SDSS	45.43	46.66
CFHTLens	100.00	98.17
Planck SZ	15.50	2.35
H_0	7.80	9.53
TOTAL	2646.42	2638.63
$\Delta\chi^2_{\rm eff}$	0	−7.79

with 2 extra params: 2.3σ

Parameter posteriors



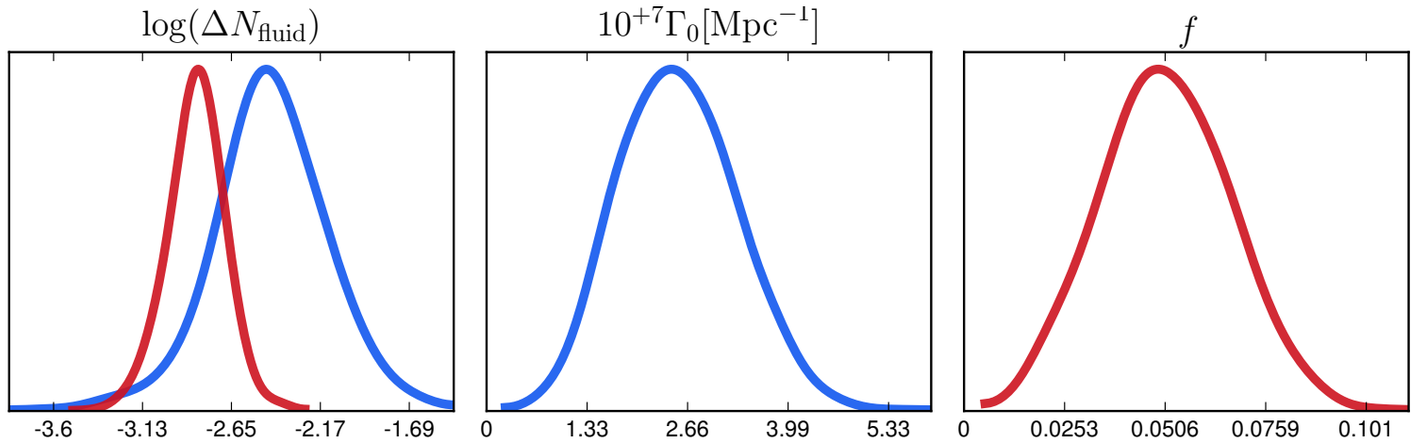
Relaxing lower bound on ΔN>0.07

Best fit model:

Data Sets	ΛCDM	WI $\Delta N_{\rm fluid}$ log Prior	DP $\Delta N_{\rm fluid}$ log Prior
high-ℓ TTTEEE	2452.6	2447.41	2447.91
SimLow $\tau_{\rm reio}$	0.34	0.07	0.04
BAO	15.33	13.37	13.90
lensing	10.43	9.37	9.65
SDSS	45.43	44.57	44.78
CFHTLens	100.00	101.35	100.90
Planck SZ	15.50	0.19	0.016
H_0	7.80	9.06	9.74
TOTAL	2646.42	2625.39	2626.94
$\Delta\chi^2_{\rm eff}$	0	−21.03	−19.48

with 2 extra params: 4.1σ / 4.0σ

Parameter posteriors



ΔN~0.0036, Γ_0 ~ 2.5 $10^{-21}s^{-1}$

ΔN~0.0015, f ~ 5%

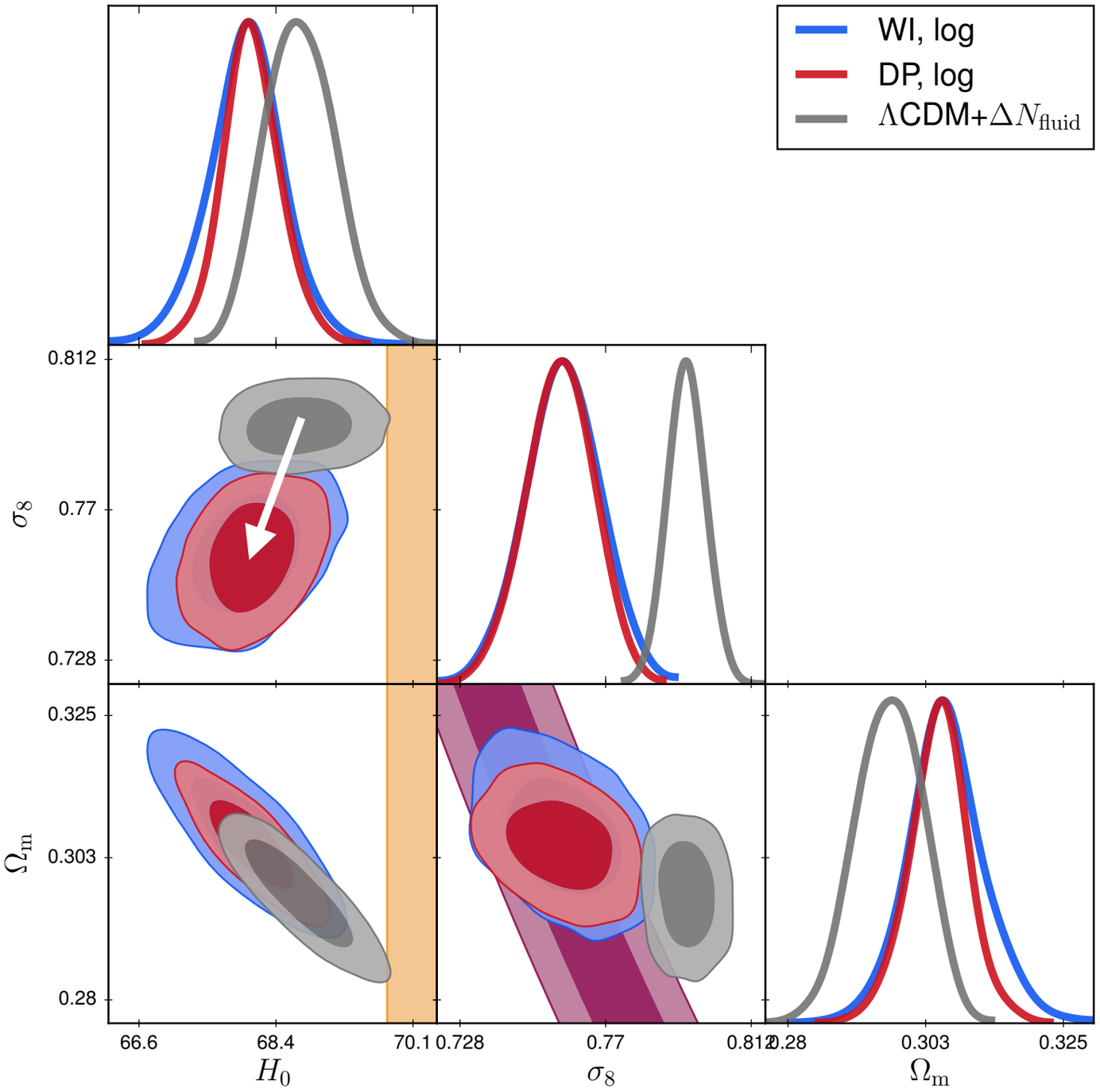
Relaxing lower bound on ΔN>0.07

Best fit model:

Data Sets	ΛCDM	WI $\Delta N_{\rm fluid}$ log Prior	DP $\Delta N_{\rm fluid}$ log Prior
high-ℓ TTTEEE	2452.6	2447.41	2447.91
SimLow $\tau_{\rm reio}$	0.34	0.07	0.04
BAO	15.33	13.37	13.90
lensing	10.43	9.37	9.65
SDSS	45.43	44.57	44.78
CFHTLens	100.00	101.35	100.90
Planck SZ	15.50	0.19	0.016
H_0	7.80	9.06	9.74
TOTAL	2646.42	2625.39	2626.94
$\Delta\chi^2_{\rm eff}$	0	−21.03	−19.48

with 2 extra params: 4.1σ / 4.0σ

Parameter posteriors



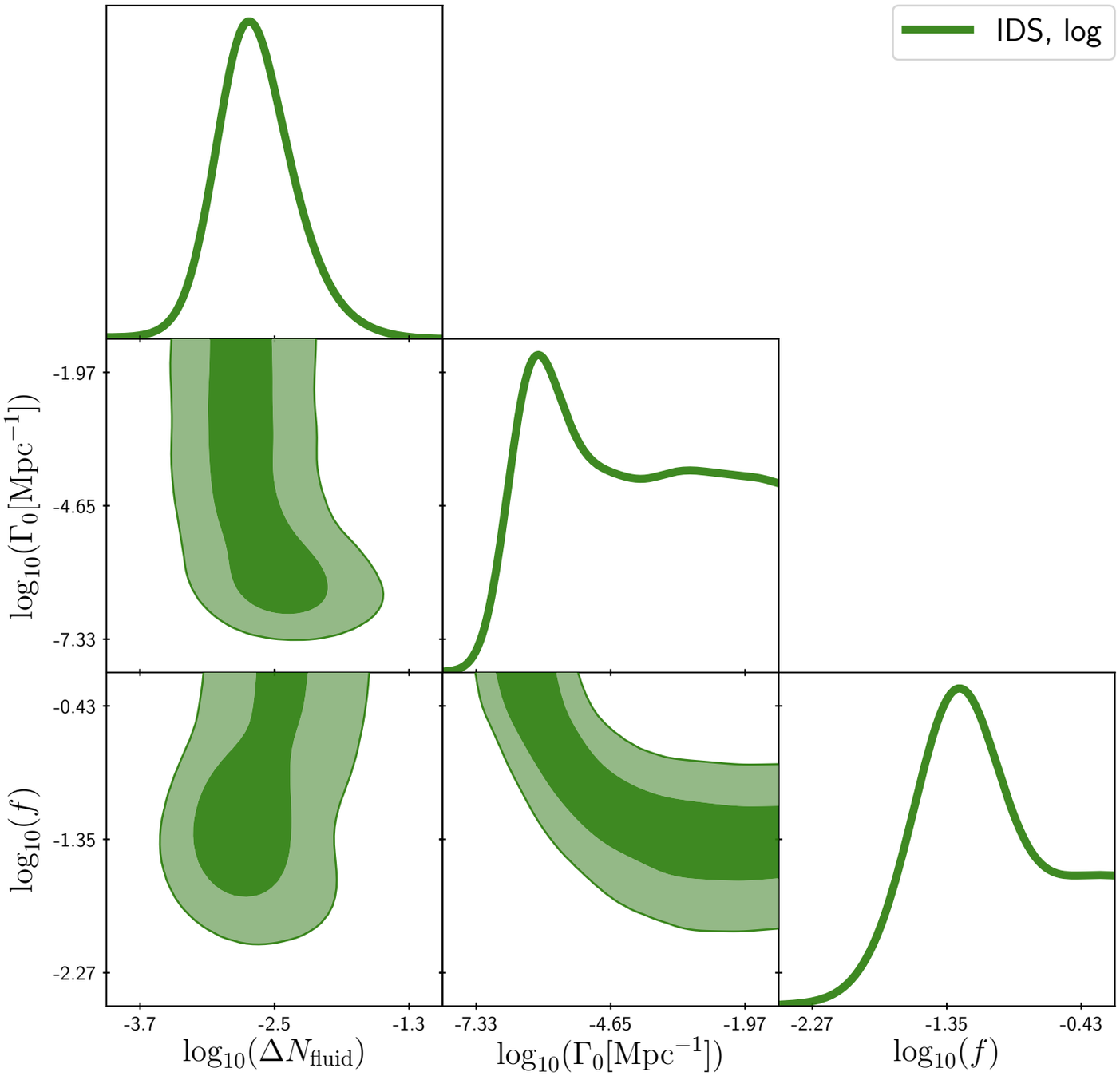
General Interacting Dark Sector model

Best fit model:

Data Sets	ΛCDM	IDS $\Delta N_{\rm fluid}$ 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

with 3 extra params: 3.8σ

Parameter posteriors



Short-term plans: include new data sets

- Full Planck SZ 2015 likelihood
- KIDs: will strengthen conclusions! From ($\sigma_8\,\Omega_m^{0.30}$) of Joudaki et al. [1707.06627] :
  - 2.6σ tension for ΛCDM (χ^2~6.7)
  - χ^2~0.37-1.33 for our IDS best fit models
- DES: same! χ^2~0.00-0.74 for our IDS best fit models
- Full P(k) from SDSS-DR12
- Lyman-α : tricky, new hydro simulation needed (specific linear growth rate).
  - Krall et al. 1705.08894 used $\chi^2(P(k_*), n_{eff}(k_*))$ from SDSS Ly-α of McDonald et al 2006: no significant χ^2 improvement (data has large σ_8).
  - Potentially different conclusions from recent BOSS Ly-α data of Palanque-Delabrouille et al. 2016, pushing not for high $\sigma_{8\,but}$ for small $n_{eff}(k_*)$!
- Planck 2017 polarisation, lensing, SZ !