Using Cosmological Data to study DM Interactions with SM particles

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arXiv:1309.7588

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Durham University

Outline

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3. Effect of DM interactions on the CMB

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Motivation

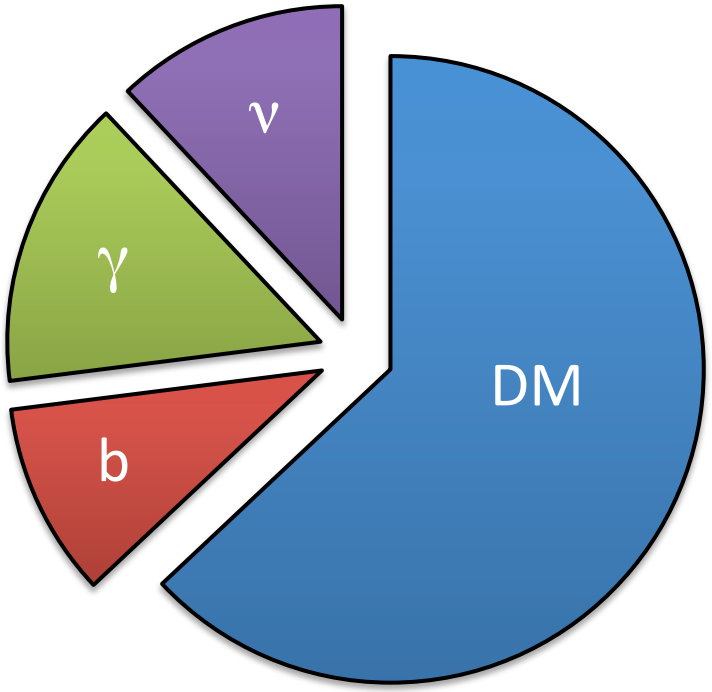
- We don't yet know the nature of DM.
- Detection methods generally assume:
  - Annihilations in our galaxy until late times
  - Interactions with quarks
- Instead, look for model-independent ways to study DM.
- DM interactions with SM particles suppress matter fluctuations, erasing ("damping") structures smaller than

$$l_{cd} \sim \pi \left(\frac{H}{\Gamma_i}\right)^{1/2} \left.\frac{v_i t}{a}\right|_{dec(DM-i)}$$

Largest for γ/ν

astro-ph/0012504, astro-ph/0410591 (Bœhm et al.)

Distribution of matter/energy in the Universe at CMB production:



- Can effectively use cosmological data to constrain the damping due to DM-photon and DM-neutrino interactions.
- Small interactions could help to solve problems with standard cold DM (CDM)…

Implementation

- Standard Euler equations for baryons, photons and DM:

$R \equiv (3/4)(\rho_b / \rho_\gamma)$

Ensures energy conservation

$$\dot{\theta}_b = k^2\psi - H\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot{\kappa}\left(\theta_b - \theta_\gamma\right)$$

$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\delta_\gamma/4 - \sigma_\gamma\right) - \dot{\kappa}\left(\theta_\gamma - \theta_b\right)$$

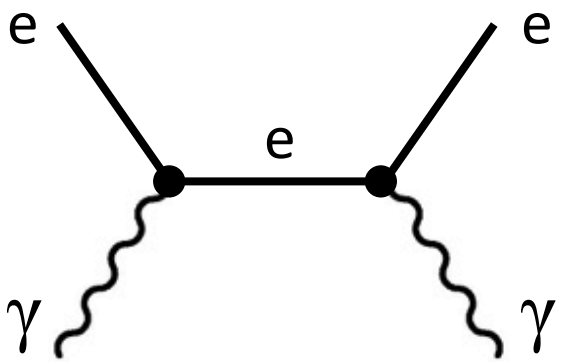
$$\dot{\theta}_{DM} = k^2\psi - H\theta_{DM}$$

(in the Newtonian gauge)

$\dot{\kappa} \equiv a\,\sigma_{Th}\,c\,n_b$

Thomson Scattering Rate

Thomson scattering:



θ_X	velocity divergence of X
k	wavenumber
ψ	gravitational potential
H	conformal Hubble parameter
c_s	sound speed
δ_X	density contrast of X ($\equiv \Delta\rho_X/\overline{\rho}_X$)
σ_γ	photon shear

Implementation

- For e.g. DM-γ interactions:

DM-γ Interaction Rate

$$\dot{\theta}_{\rm b} = k^2\psi - H\theta_{\rm b} + c_s^2 k^2 \delta_{\rm b} - R^{-1}\dot{\kappa}\left(\theta_{\rm b} - \theta_\gamma\right)$$

$$\dot{\theta}_\gamma = k^2\psi + k^2\left(\delta_\gamma/4 - \sigma_\gamma\right) - \dot{\kappa}\left(\theta_\gamma - \theta_{\rm b}\right) - \dot{\mu}\left(\theta_\gamma - \theta_{\rm DM}\right)$$

$$\dot{\theta}_{\rm DM} = k^2\psi - H\theta_{\rm DM} - S^{-1}\dot{\mu}\left(\theta_{\rm DM} - \theta_\gamma\right)$$

$$\dot{\mu} \equiv a\,\sigma_{\rm DM-\gamma}\,c\,n_{\rm DM}$$

Ensures energy conservation

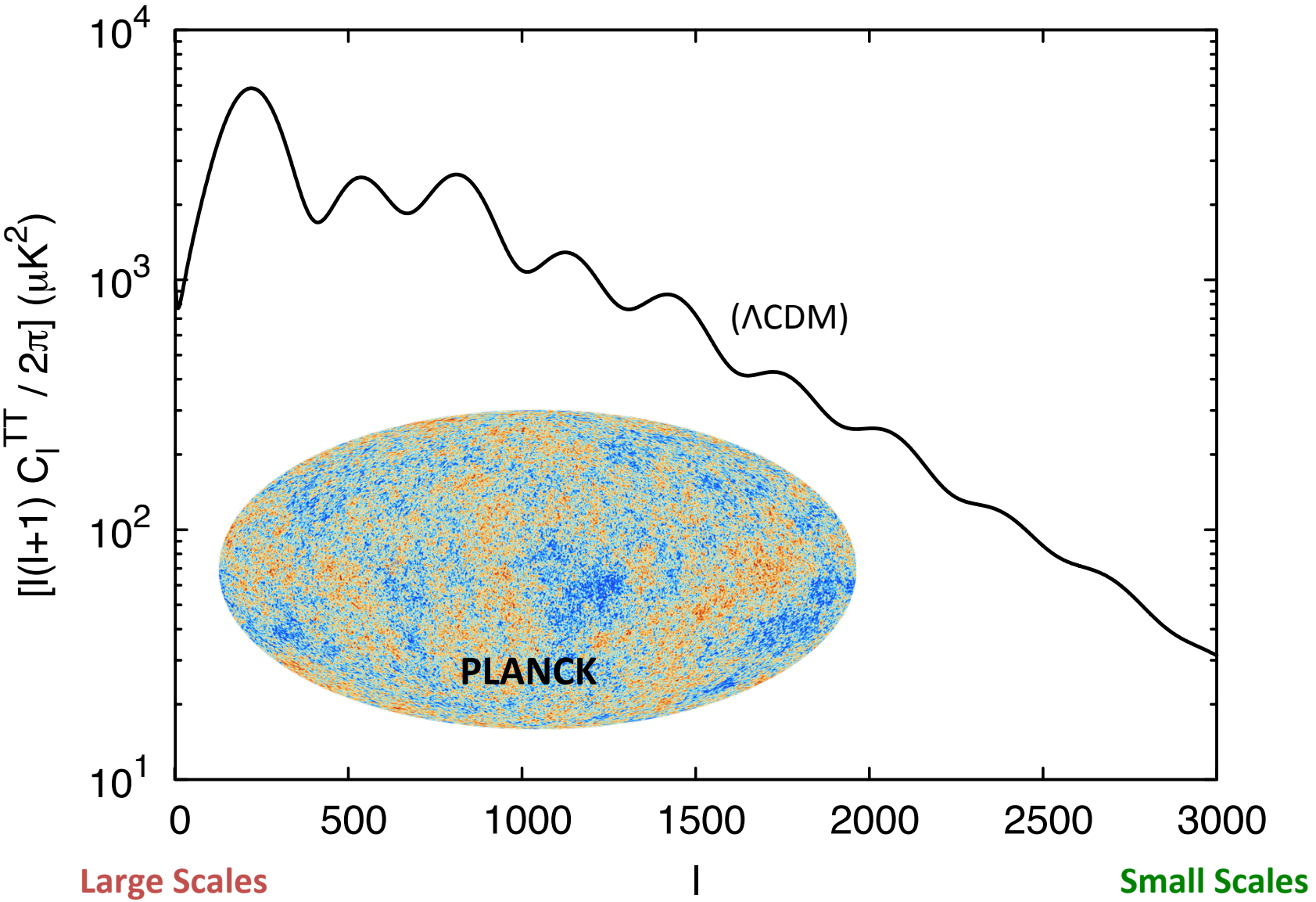
$$S \equiv (3/4)(\rho_{\rm DM}/\rho_\gamma)$$

- (Also need to modify photon temperature/polarisation – negligible effect).
- To quantify the effect on the CMB, we introduce:

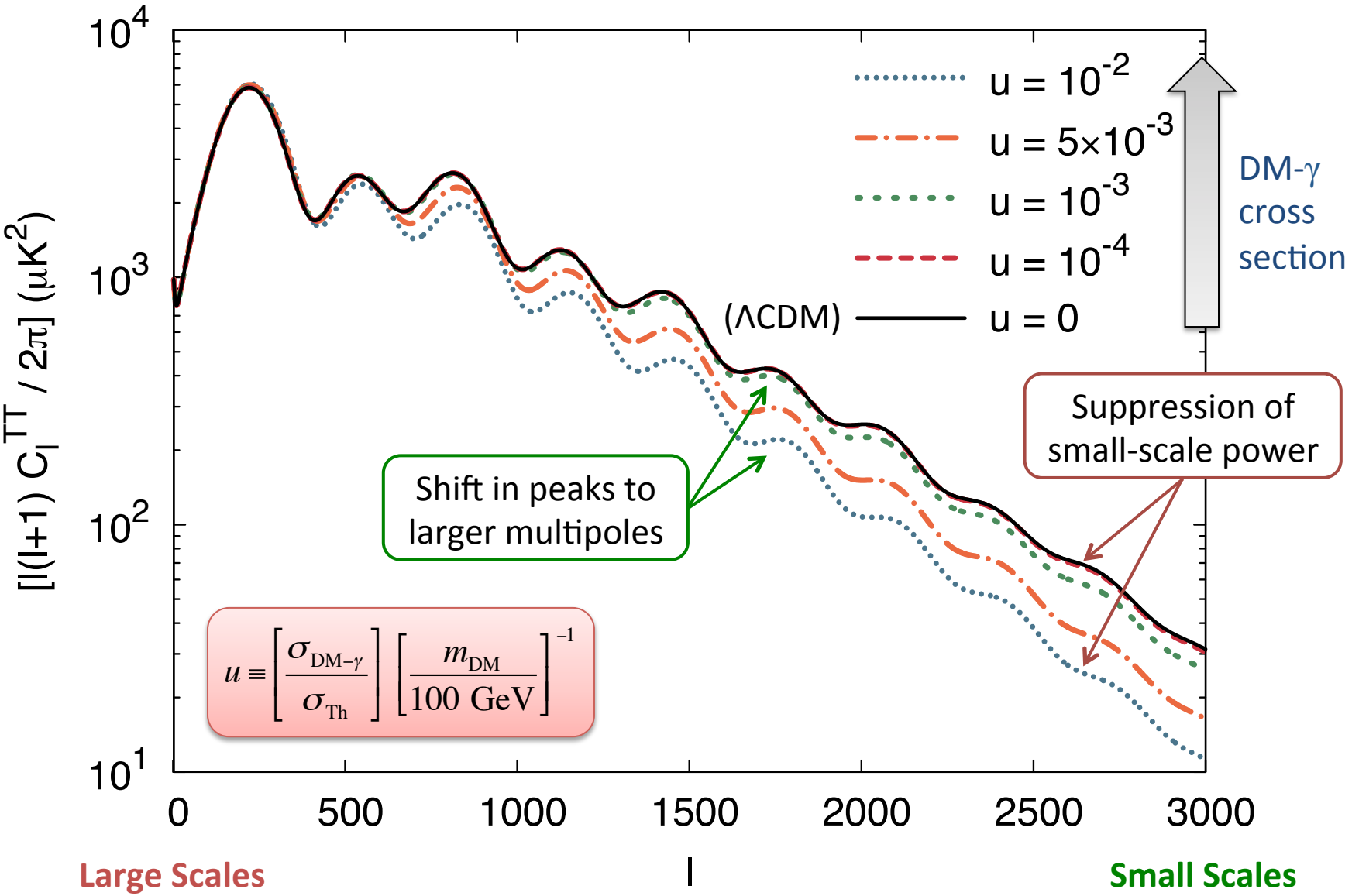
$$u \equiv \left[\frac{\sigma_{\rm DM-\gamma}}{\sigma_{\rm Th}}\right]\left[\frac{m_{\rm DM}}{100\ {\rm GeV}}\right]^{-1}$$

- We consider $\sigma_{\rm DM\text{-}\gamma}$ = constant and $\sigma_{\rm DM\text{-}\gamma} \propto T^2$.
- Made use of:
  - Boltzmann code *CLASS* *[class-code.net] arXiv:1104.2932 (Lesgourgues)*
  - Line-of-sight integral *astro-ph/9603033 (Seljak & Zaldarriaga)*

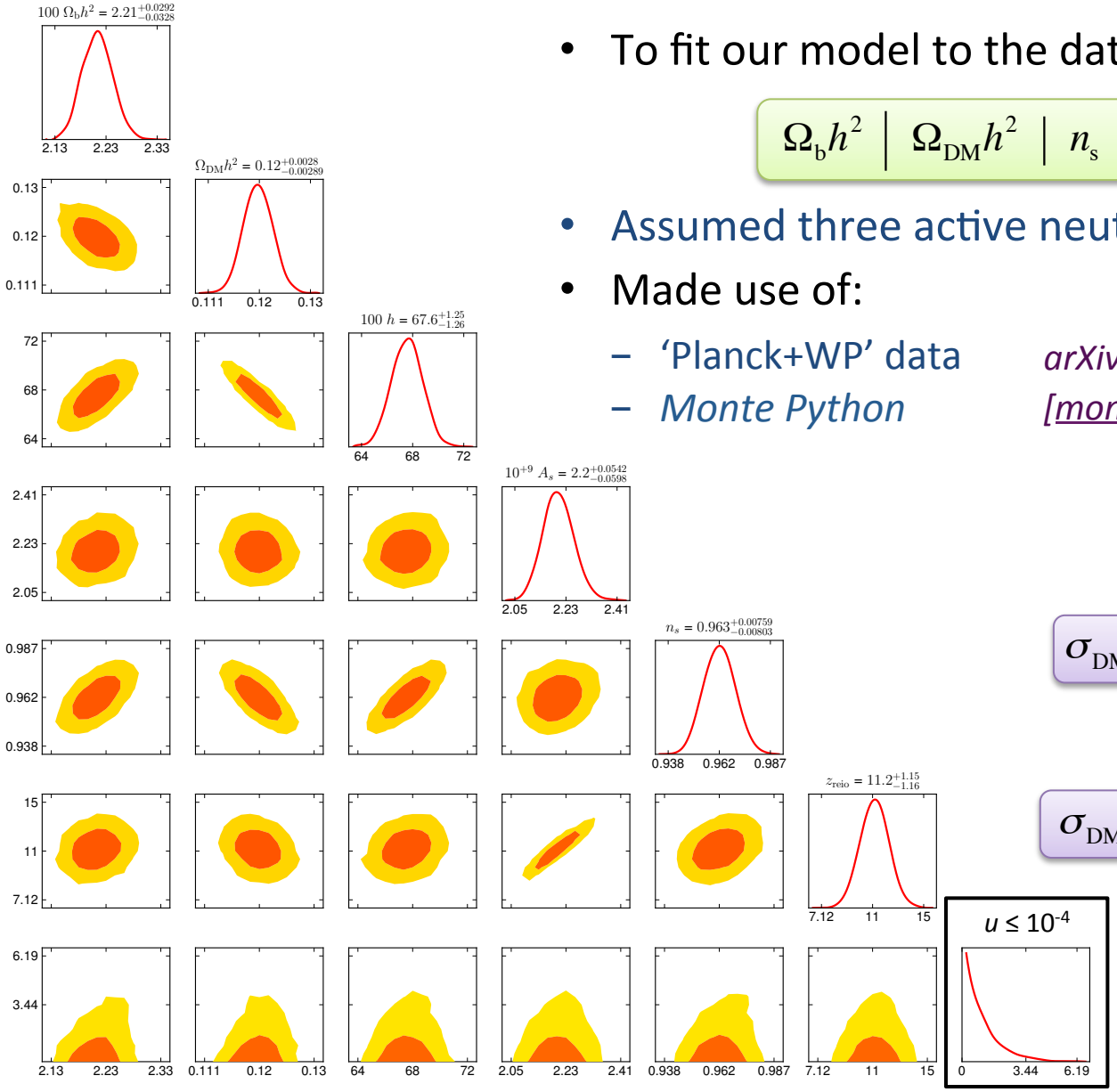
CMB Angular Power Spectrum



Effects on the CMB - Temperature



Constraints from Planck+WP



- To fit our model to the data, we varied:

$$\Omega_b h^2 \;|\; \Omega_{DM} h^2 \;|\; n_s \;|\; A_s \;|\; H_0 \;|\; z_{reio} \;|\; u$$

- Assumed three active neutrinos (with $\Sigma m_\nu = 0.06$ eV).
- Made use of:
  - 'Planck+WP' data — *arXiv:1303.5076 (Planck Collaboration)*
  - *Monte Python* — *[montepython.net] (Audren et al.)*

CMB constraints

$\sigma_{DM\text{-}\gamma}$ = constant

$$\sigma_{DM-\gamma} \leq 8 \times 10^{-34} (m_{DM} / \text{MeV})\ \text{cm}^2$$

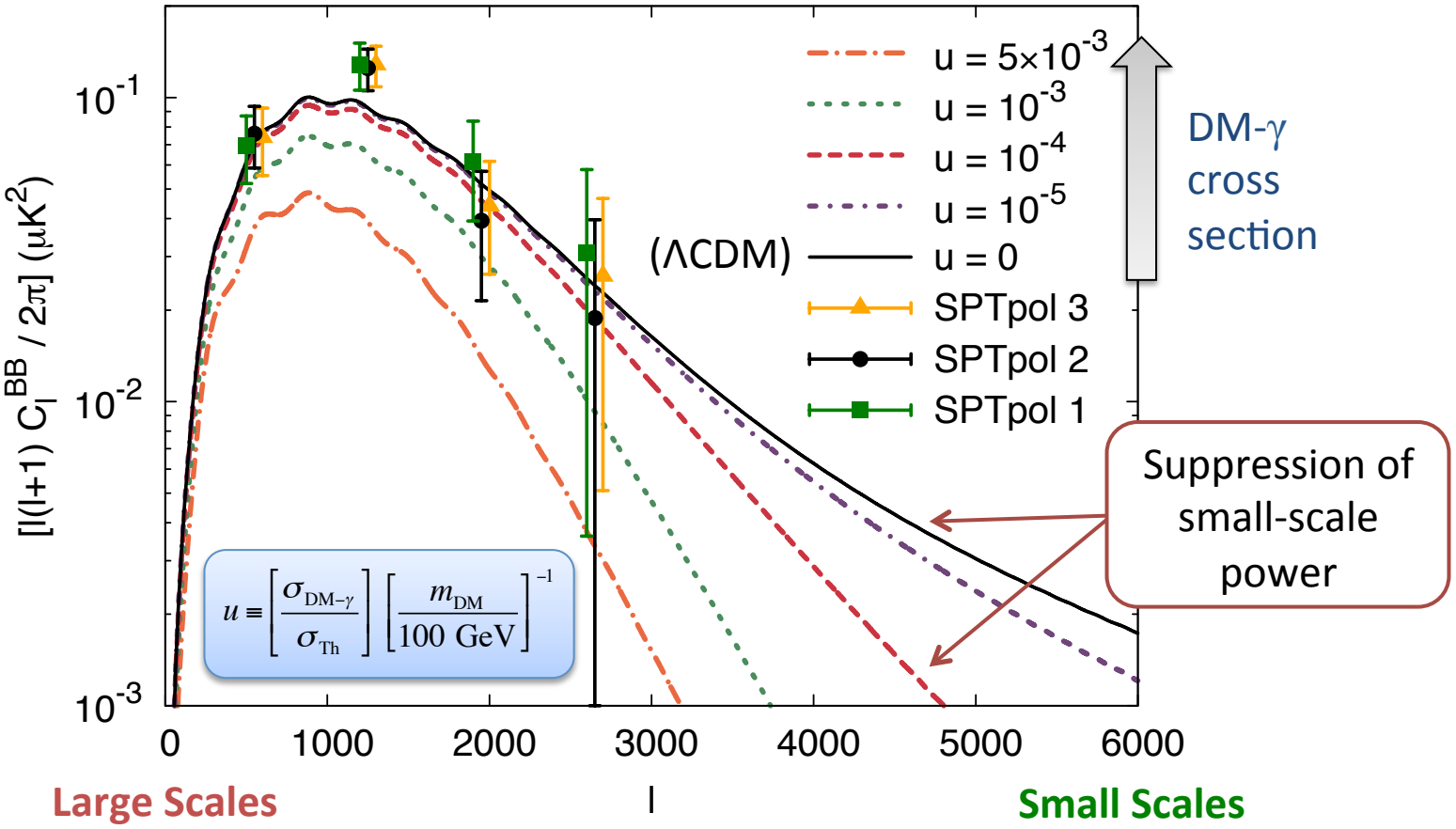
$\sigma_{DM\text{-}\gamma} \propto T^2$

$$\sigma_{DM-\gamma,0} \leq 6 \times 10^{-43} (m_{DM} / \text{MeV})\ \text{cm}^2$$

(at 68% CL)

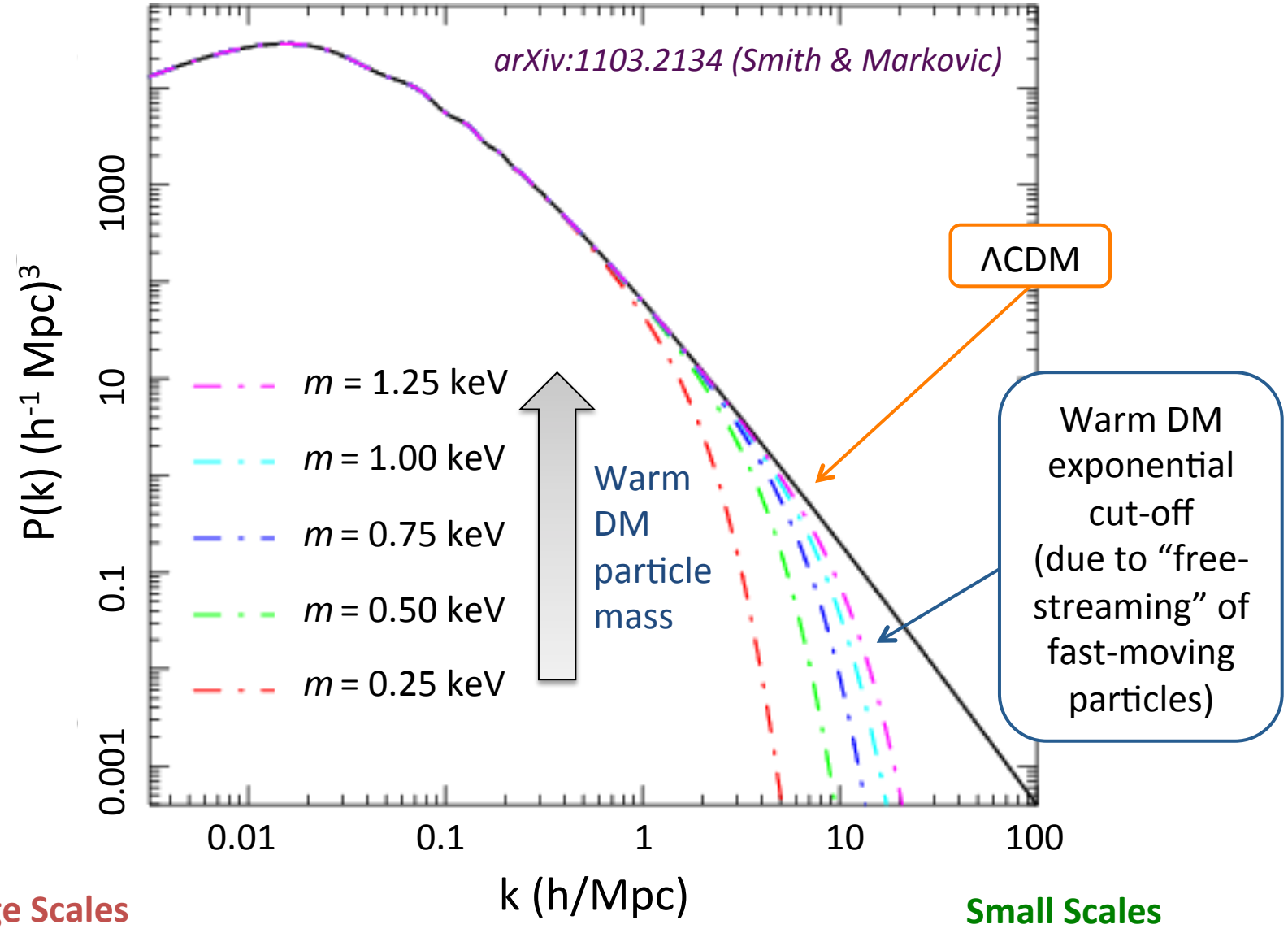
(arXiv:1309.7588)

Effects on the CMB - Polarisation

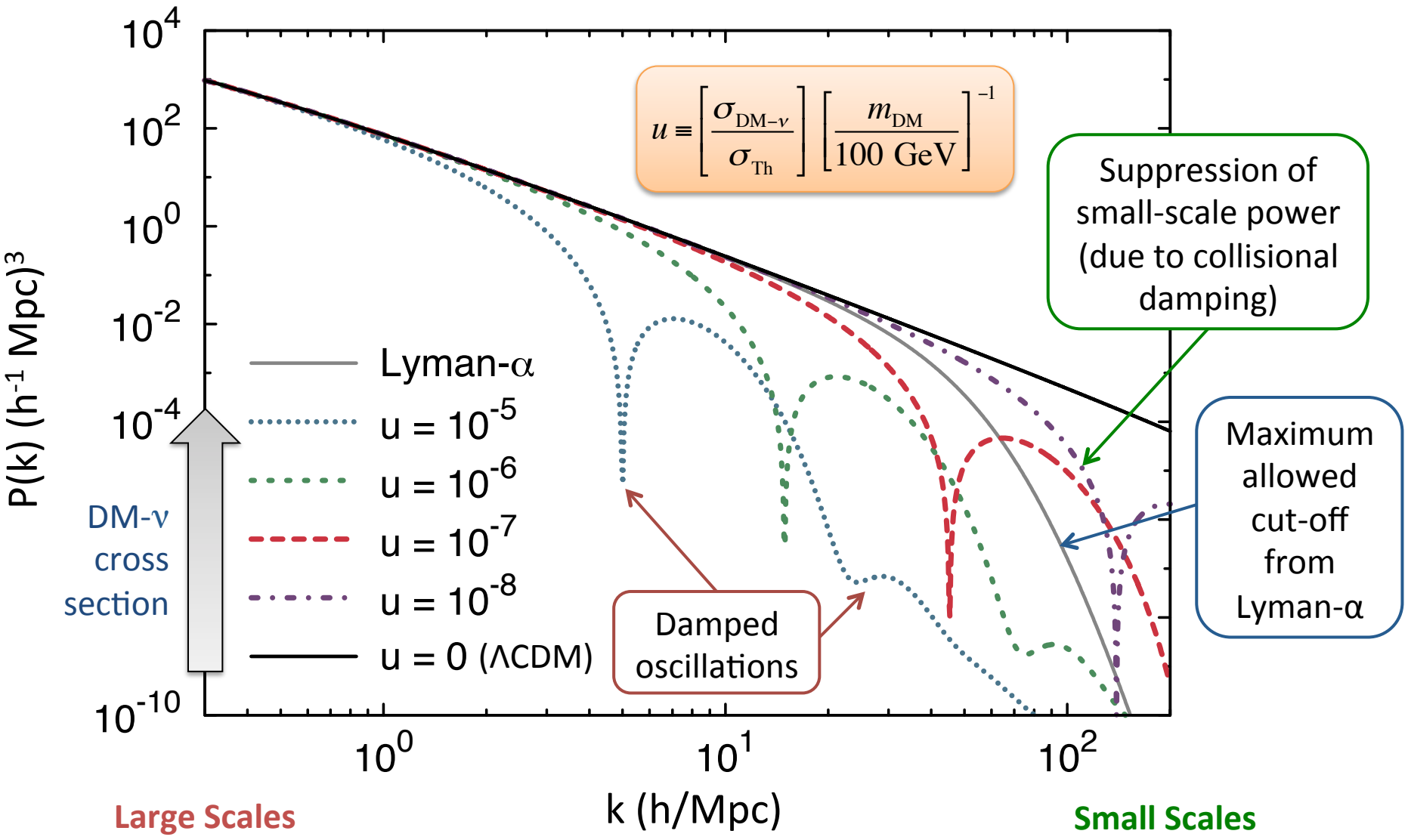


- First-season data from SPTpol ⇒ $\sigma_{DM\text{-}\gamma} \leq 10^{-32}\ (m_{DM}\ /\ \mathrm{MeV})\ \mathrm{cm}^2$.
- Future polarisation data from e.g. Planck, SPT and ACT could distinguish $\sigma_{DM\text{-}\gamma} \approx 10^{-33}\ (m_{DM}\ /\ \mathrm{MeV})\ \mathrm{cm}^2$ from ΛCDM.

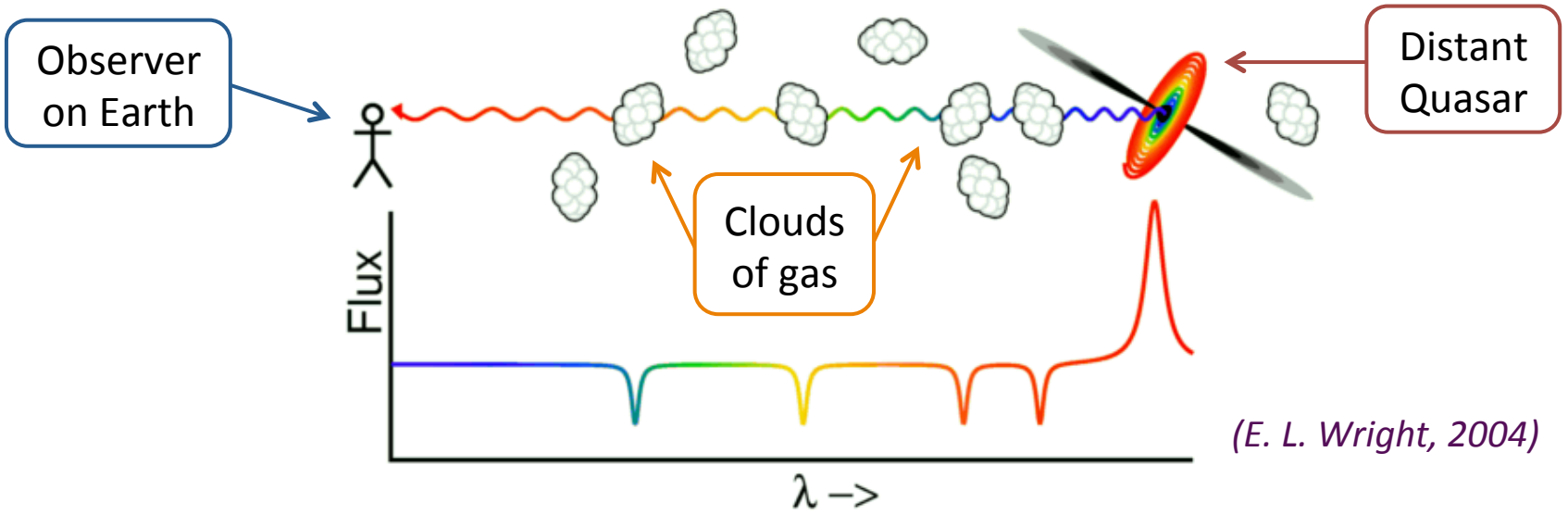
Matter Power Spectrum



Effects on the P(*k*)



Constraints from the Lyman-α Forest



(E. L. Wright, 2004)

- Most recent constraint on warm DM from Lyman-α: $m_{WDM} \geq 3.3$ keV. *arXiv:1306.2314 (Viel et al.)*
- We can compare the cut-off in the P(k) to our interacting DM models.
- Future LSS surveys: SDSS-III, Euclid etc.
- Deviation from ΛCDM on very small scales.
- To confirm our results, need to use high-resolution numerical simulations…

P(k) constraints

$\sigma_{DM\text{-}\nu}$ = constant

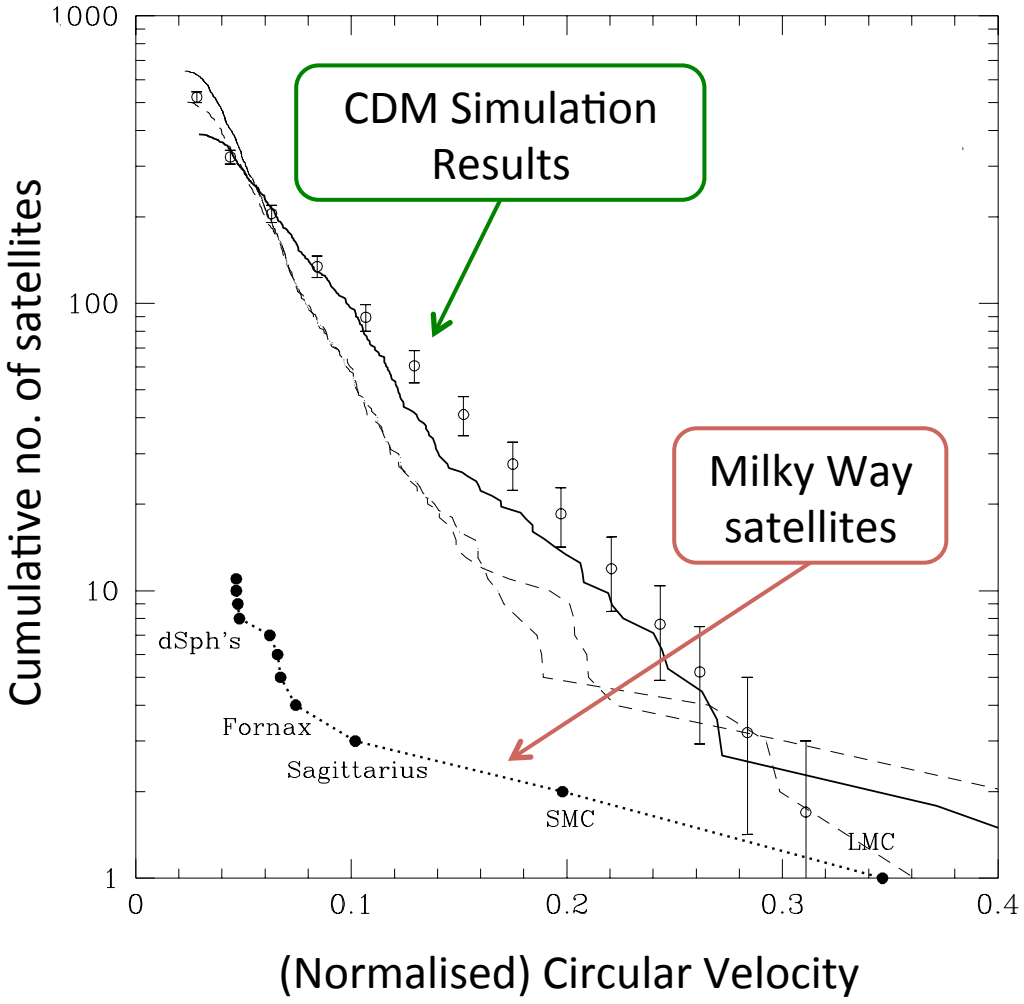
$$\sigma_{DM-\nu} \leq 10^{-36} (m_{DM} / \text{MeV}) \text{ cm}^2$$

$\sigma_{DM\text{-}\nu} \propto T^2$

$$\sigma_{DM-\nu,0} \leq 10^{-48} (m_{DM} / \text{MeV}) \text{ cm}^2$$

(arXiv:1401.7597)

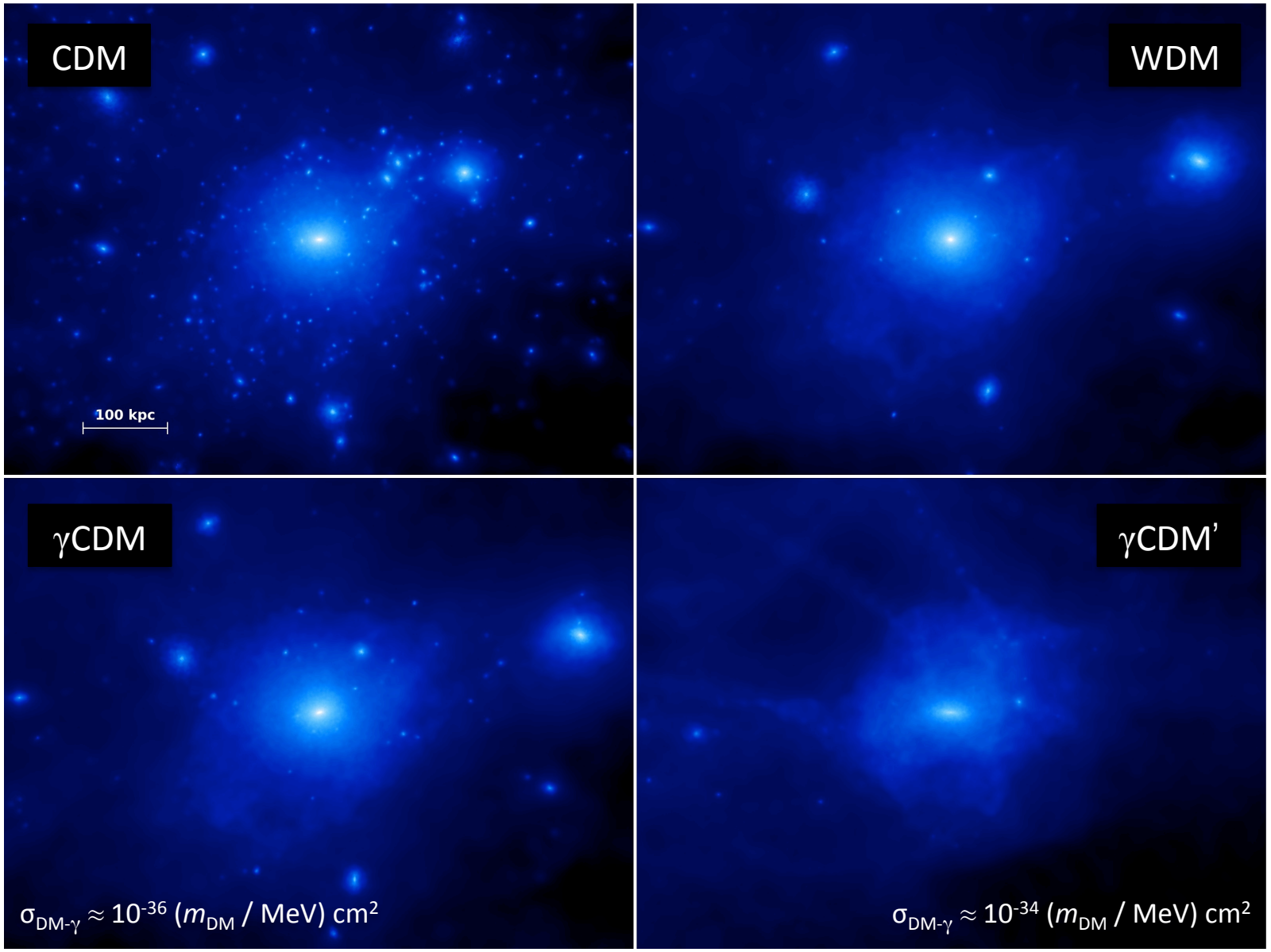
The Milky Way Satellite Problem



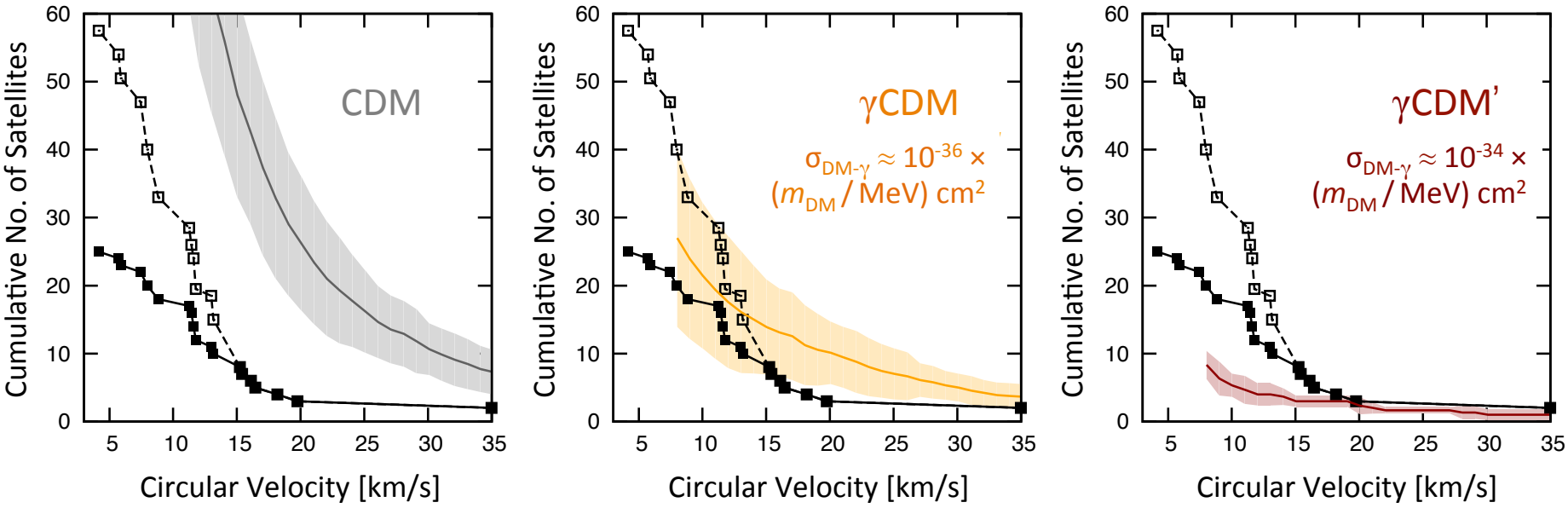
astro-ph/9907411 (Moore et al.)

- CDM agrees remarkably well with large-scale observations.
- However, discrepancy between the no. of "satellite" galaxies observed around the Milky Way and predicted in CDM simulations.
- Proposed solutions:
  - "Gastrophysics"
  - Warm DM
    (requires very light particles)
  - Self-interacting DM
    (very tightly constrained)
    arXiv:1208.3025 (Rocha et al.)
- Can we solve the problem using small DM interactions with photons/neutrinos? …

Simulation Results



Simulation Results



(Bœhm, Schewtschenko, RW, Baugh & Pascoli – in preparation)

- Small DM interactions with relativistic species can solve the satellite problem.
- Don't need to discard CDM, only need to take into account microphysics.
- By requiring a satisfactory number of satellites, can set strong constraints (similar magnitude to Lyman-α).
- Future work:
  - Simulations of νCDM.
  - Other small-scale problems of CDM: "too big to fail" and "cusp vs. core".

Conclusion

- We have studied the impact of DM interactions with relativistic particles on the CMB and large-scale structure of the Universe.
  - → Largest effect since neutrinos/photons are relativistic and abundant at early times.
  - → DM-baryon interactions would require much a larger cross section ⇒ less constraining.
- The strongest limits come from the large-scale structure data and numerical simulations.
  - → Imply cross sections $\leq 10^{-36}$ cm^2 for MeV DM.
- Importantly, one can use cosmological data to study DM interactions without having to impose a specific model.
- We have found that small DM interaction cross sections can provide a solution to the Milky Way satellite problem.
- Now need to check the other small-scale problems of CDM.

Thank you.

Additional Slides

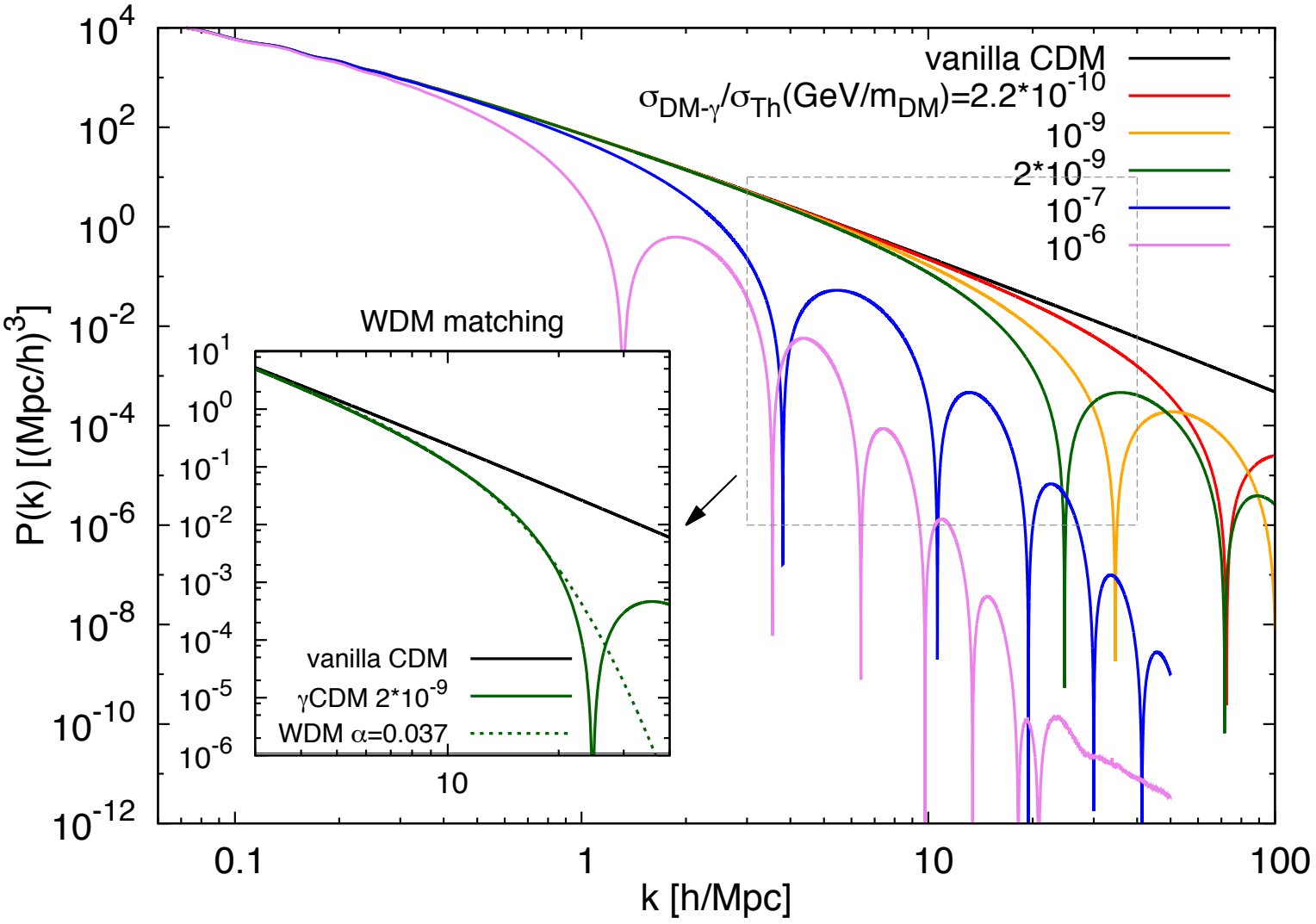
Simulation Information

- N-body simulations using the code GADGET-3.
- Best-fit LCDM parameters from Planck.
- Simulations begin at $z = 49$.
- ICs created with modified version of a 2nd order LPT code.
- Initial power spectra from modified version of CLASS.
- Box sizes: $(30\ \mathrm{Mpc/h})^3$ and $(100\ \mathrm{Mpc/h})^3$.
- Resolution: $(1024\ \mathrm{particles})^3$.

arXiv:1309.4293 (Piffl et al.)
arXiv:1210.6046 (Boylan-Kolchin et al.)

- Milky Way-like halo if:
  - $0.8 \times 10^{12}\ M_{sun} < M_{vir} < 2.7 \times 10^{12}\ M_{sun}$.
  - Sufficiently isolated (no object of similar size within 2 Mpc).

WDM Matching

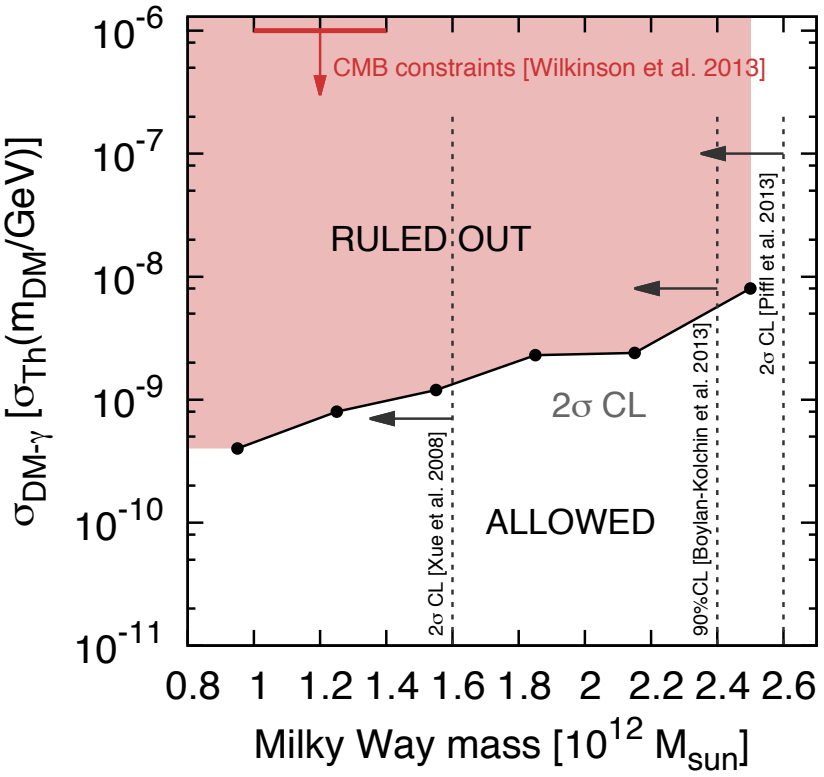


Milky Way Satellites

- List of the MW satellite galaxies and their stellar line-of-sight velocity dispersions, sorted by distance.
- Highlighted satellites have $V_{max} > 8$ km/s.

Classical (pre-SDSS)	
Name	$\sigma_\star$ (km/s)
Sagittarius	11.4 ± 0.7
LMC	≥ 20
SMC	≥ 20
Ursa Minor	9.3 ± 1.8
Draco	9.5 ± 1.6
Sculptor	6.6 ± 0.7
Sextans	6.6 ± 0.7
Carina	6.8 ± 1.6
Fornax	10.5 ± 1.5
Leo II	6.7 ± 1.1
Leo I	8.8 ± 0.9
Phoenix	8.9

SDSS discovered	
Name	$\sigma_\star$ (km/s)
Segue I	4.3 ± 1.2
Ursa Major II	6.7 ± 1.4
Segue II	3.4 ± 2.0
Willman I	4.3 ± 2
Coma Berenics	4.6 ± 0.8
Bootes II	–
Bootes I	6.5 ± 2.0
Pisces I	–
Ursa Major I	7.6 ± 1.0
Hercules	5.1 ± 0.9
Pisces II	–
Canes Venatici II	4.6 ± 1.0
LeoIV	3.3 ± 1.7
LeoV	2.4 ± 1.8
Canes Venatici I	7.6 ± 0.4
Leo T	7.5 ± 1.6

Constraints

- Constraints on the interaction cross section with respect to the MW halo mass.
- The CMB constraint and selected upper mass bounds for the MW halo are shown for comparison.