New Era in Cosmology

Cora Dvorkin
Harvard University

PHENO Conference
May 2022

Hubble Space Telescope photo

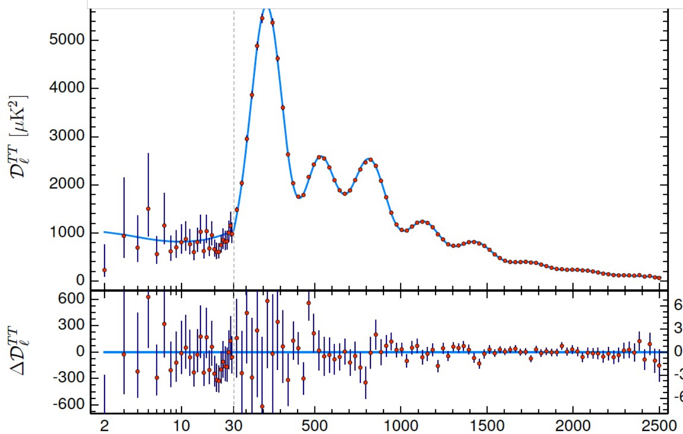
U.S. DEPARTMENT OF ENERGY

NSF

ΛCDM: our Standard Model of Cosmology

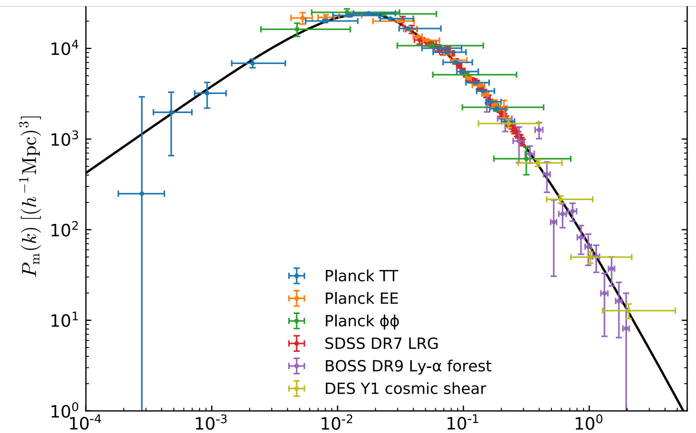
A simple model that is extremely successful on large cosmological scales.

Cosmic Microwave Background
temperature power spectrum



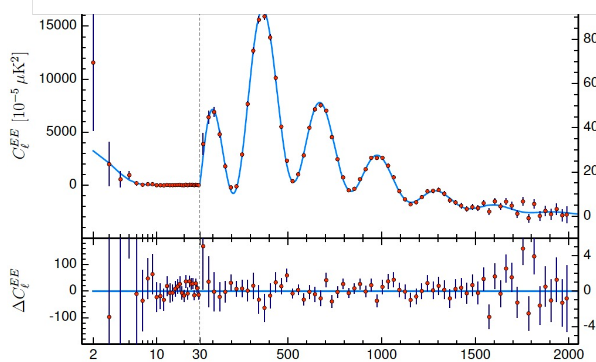
multipole moment

Matter power spectrum



wavenumber [h Mpc^{-1}]

Cosmic Microwave Background
polarization power spectrum

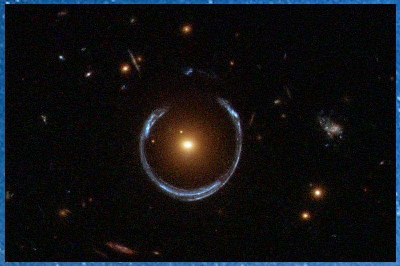


multipole moment

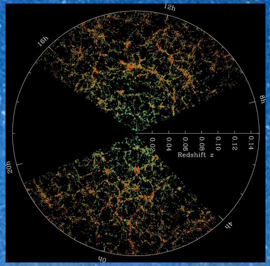
Planck collaboration (2019)

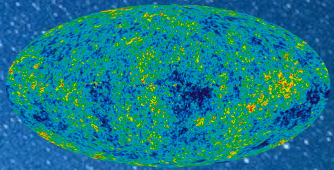
Discovering New Physics Beyond the Standard Model

From small scales



From large scales

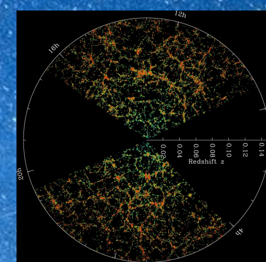


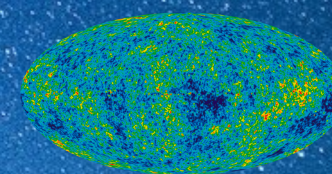


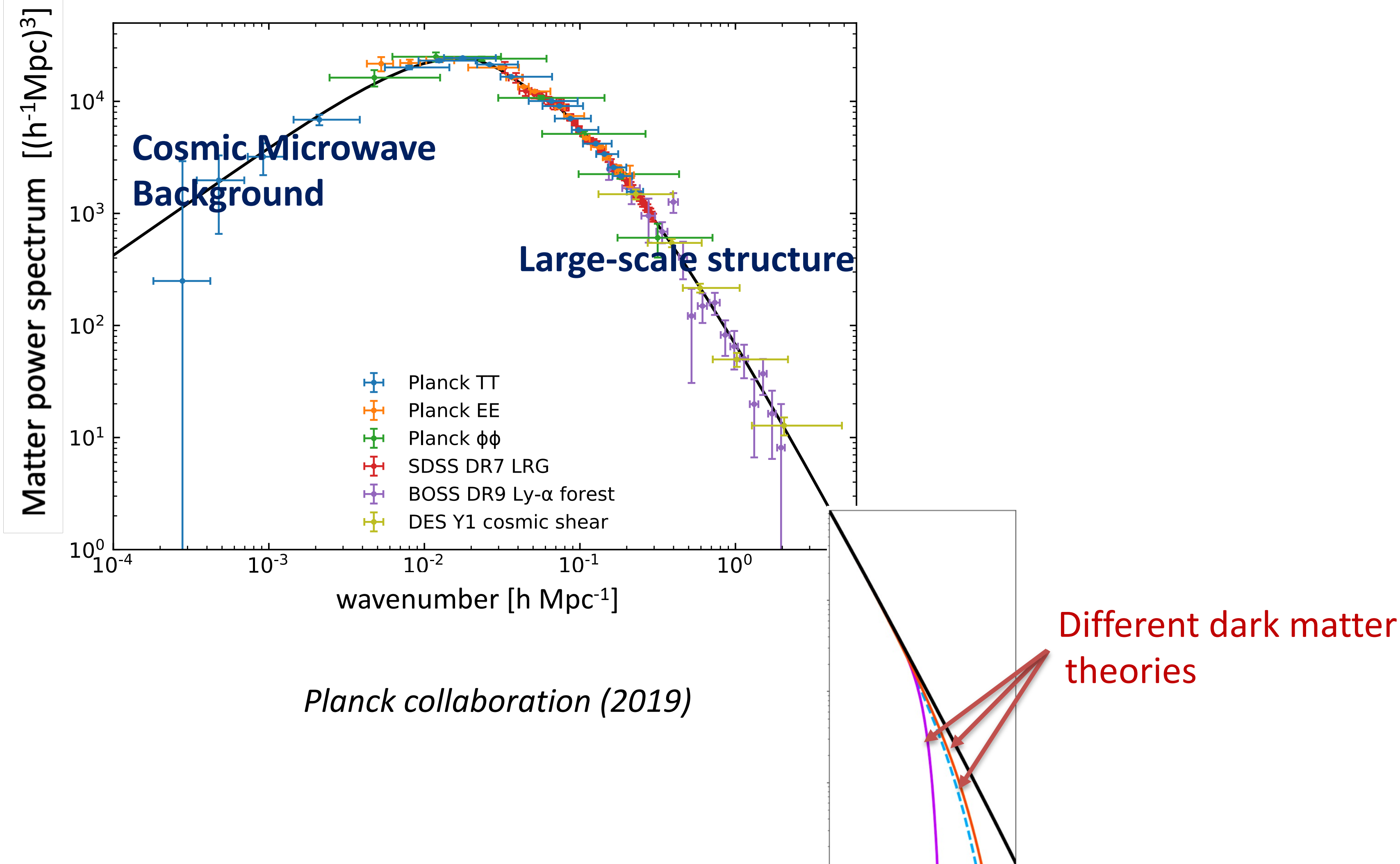
Discovering New Physics Beyond the Standard Model

From small scales

From large scales



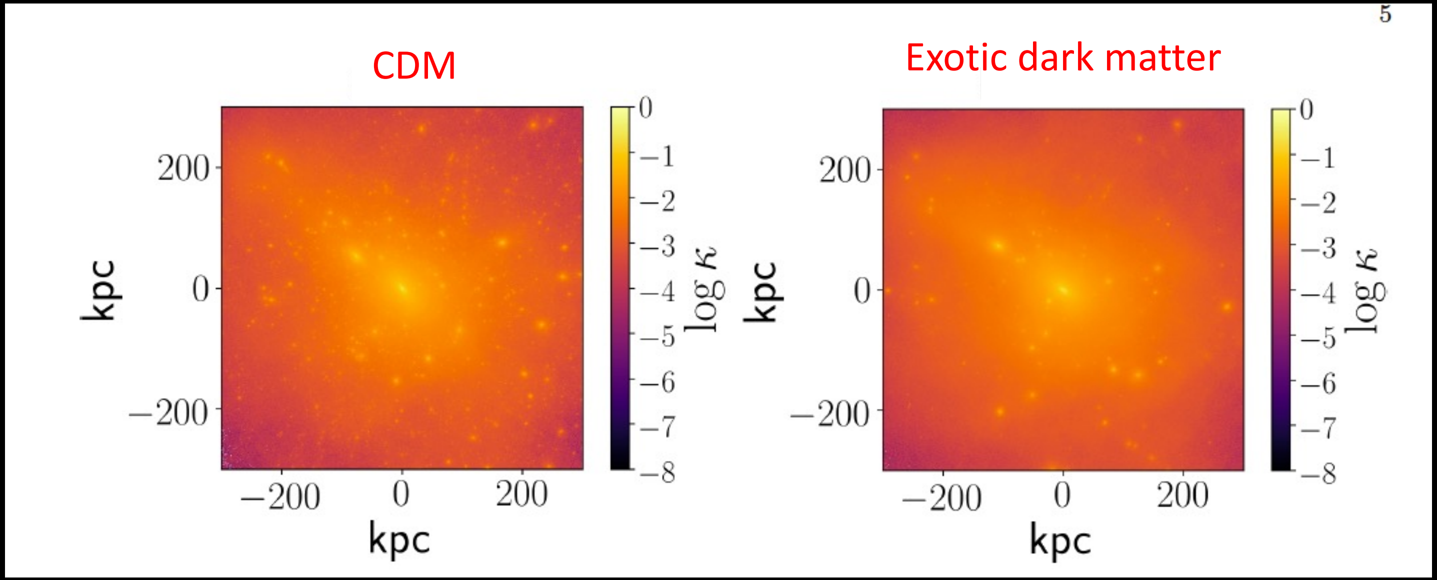




Planck collaboration (2019)

Small-scale structure: provides fertile grounds for testing different dark matter theories.

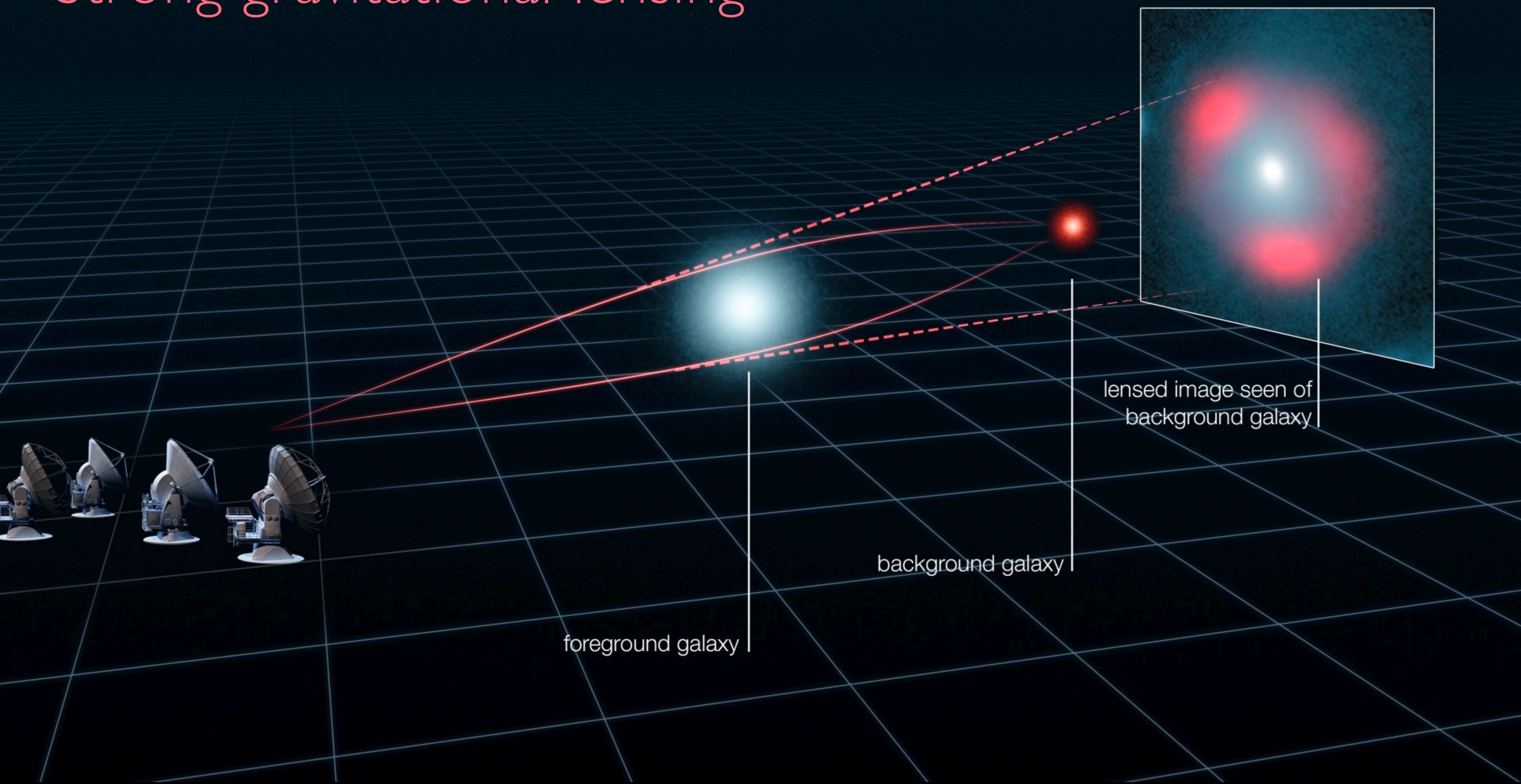
Dark Matter models:
effects on sub-galactic scales



Diaz Rivero, C. Dvorkin, et al., PRD (2018)

We will use these small scales to falsify/corroborate the Cold Dark Matter paradigm.

Strong gravitational lensing



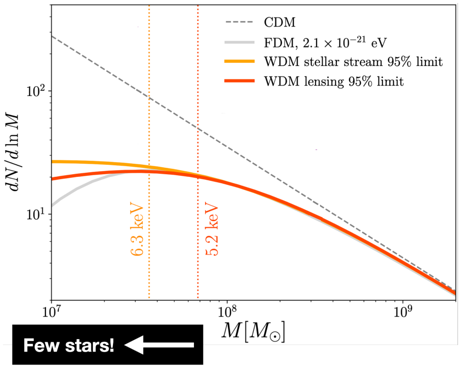
Credit: ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al.

Looking for dark subhalos

***Idea (Mao and Schneider, 1998)*: subhalos can locally perturb lensed images. By looking at the residual between the images predicted by modeling the lens as a smooth mass and what is actually observed we can infer the presence of subhalos.**

The advantage relative to other methods for detecting dark matter is that we do not need to assume a coupling between the Standard Model and dark matter: model-independent method.

The lowest-mass subhalos are largely devoid of stars: a gravitational technique is needed to detect them.



Schutz 2020, PRD 101, 123026
Fitts et al 2017, MNRAS 471 3

New roads to the small-scale universe

Direct detection: resolve individual, more massive perturbers and infer properties (mass, position). Requires postprocessing and combining many images to convert detections into dark matter constraints.

Diaz Rivero and Dvorkin, PRD (2019)
Ostdiek, Diaz Rivero, and Dvorkin (ApJ 2020a, A&A Lett 2020b)
Sengul, Dvorkin, Ostdiek, Tsang (2021)
[See also Hezaveh+(2016), Cyr-Racine+ (2016), etc]

Indirect/statistical detection: statistically detect the collective perturbations on images of a large number of unresolved low-mass structures (marginalizing over individual subhalo properties).

Diaz Rivero, Cyr-Racine, and Dvorkin, PRD (2017)
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[See also Vegetti+(2012), Hezaveh+(2016),Ritondale+(2019),Brehmer+(2019), Despali+(2021), etc]

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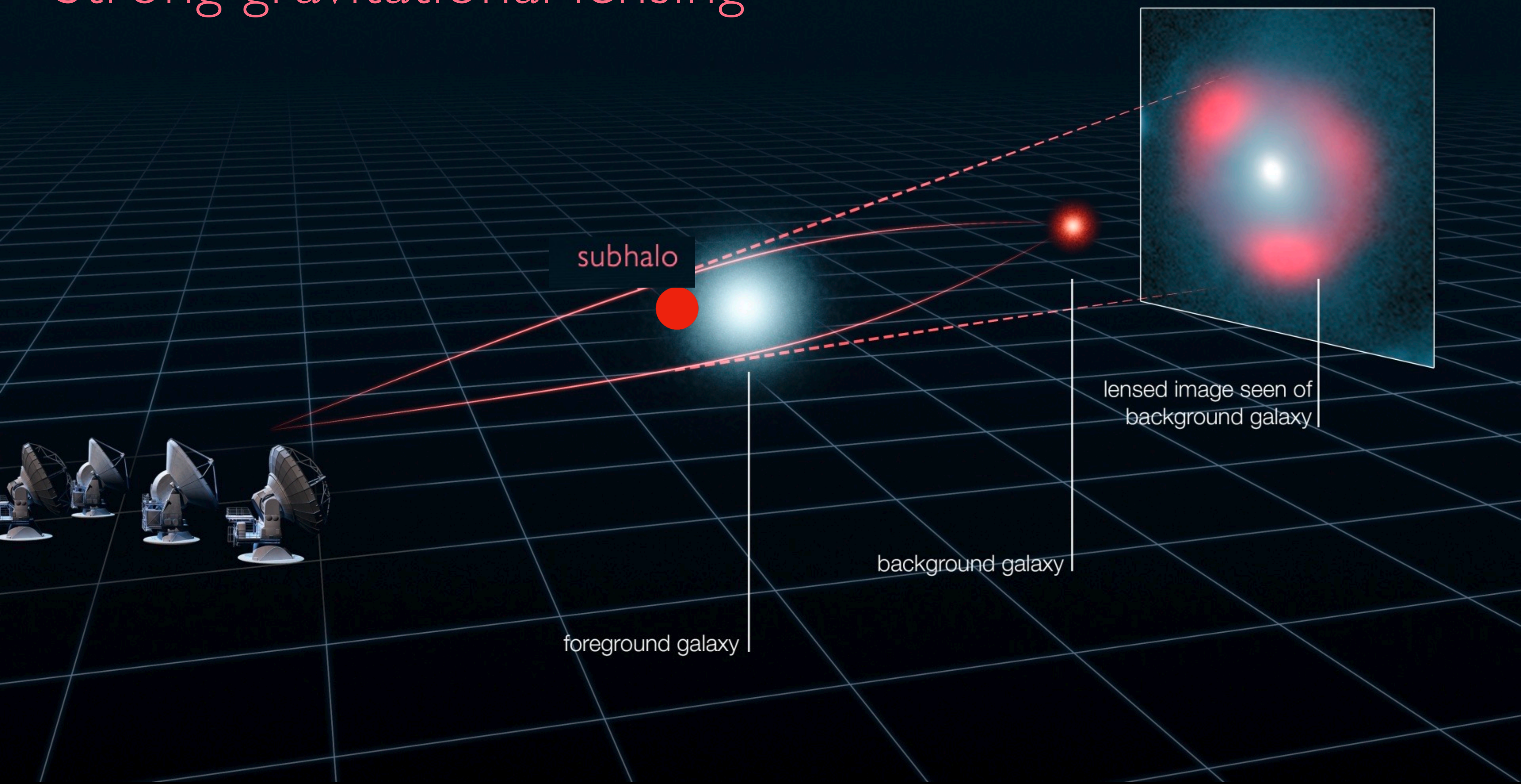
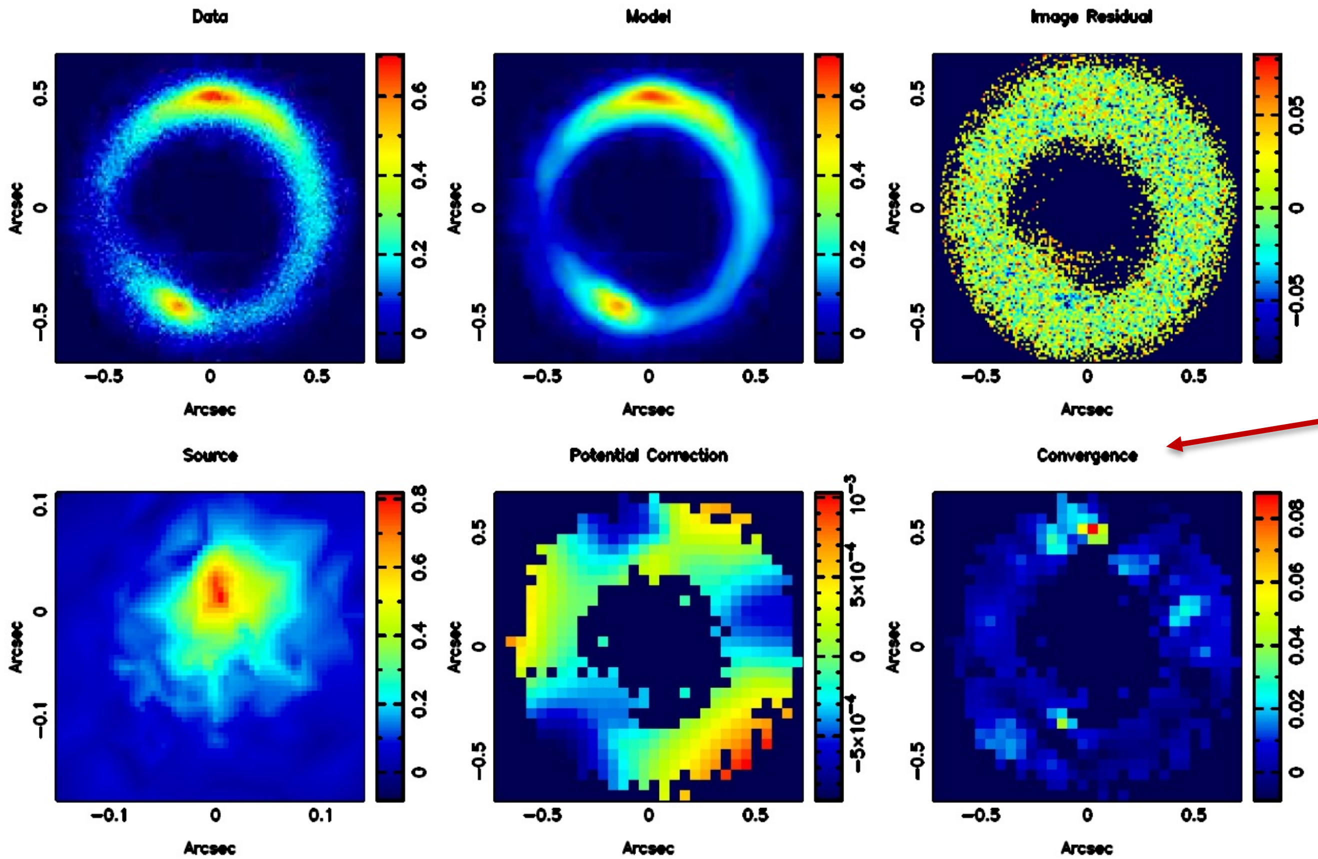
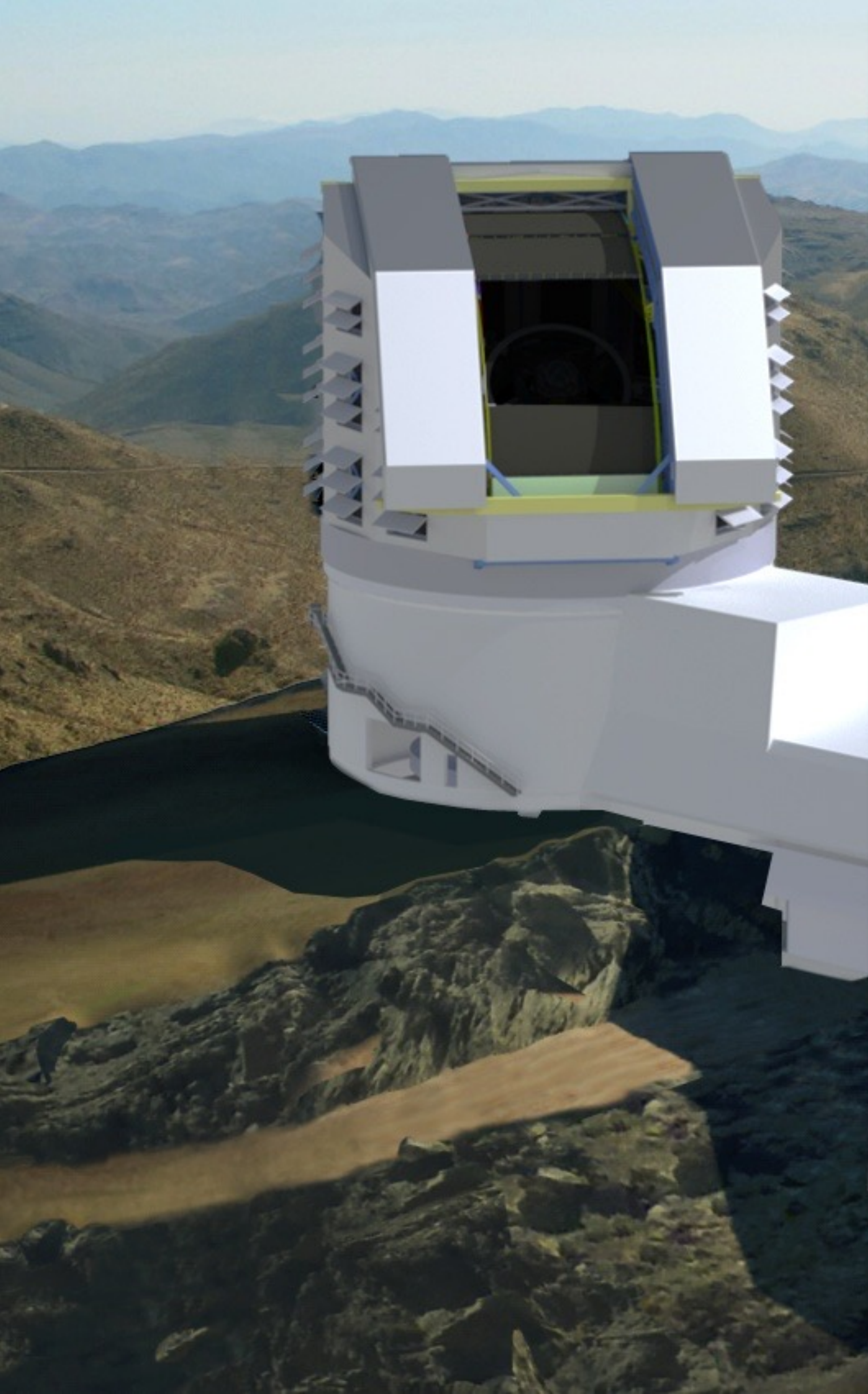


Direct detection: gravitational imaging



Reconstructed surface mass density

Vegetti et al., Nature (2012)



The Vera Rubin Observatory will discover tens of thousands of lensed galaxies in the coming decade.

This vast increase in sample sizes (in coordination with other facilities, e.g. HST, ELT, etc) will provide a leap in our understanding of dark matter.

"Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope"
(incl. C. Dvorkin, 2019) arXiv:1902.01055

The road ahead: machine learning to the rescue

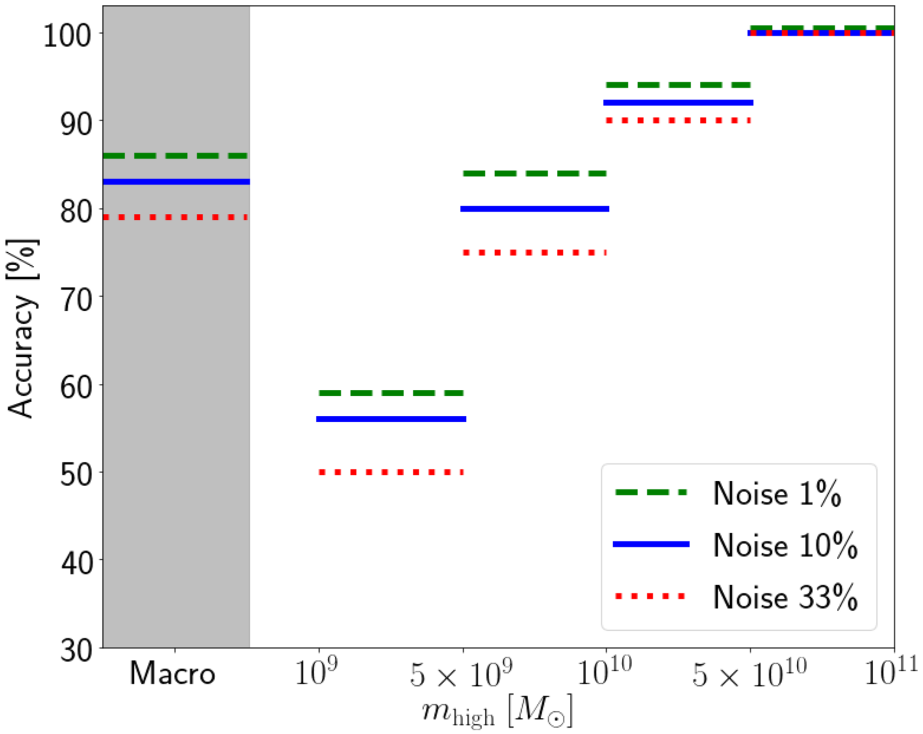
Ana Diaz Rivero

Direct detection of substructure is computationally very expensive.

Can we speed up the process of analyzing the huge number of lensed galaxies expected with near-future surveys?

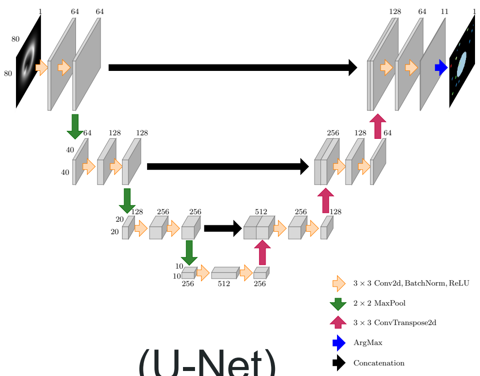
Direct detection of substructure with machine learning

Classification: binary output - is an image likely to contain substructure or not?



A. Diaz Rivero and C. Dvorkin, PRD (2019)

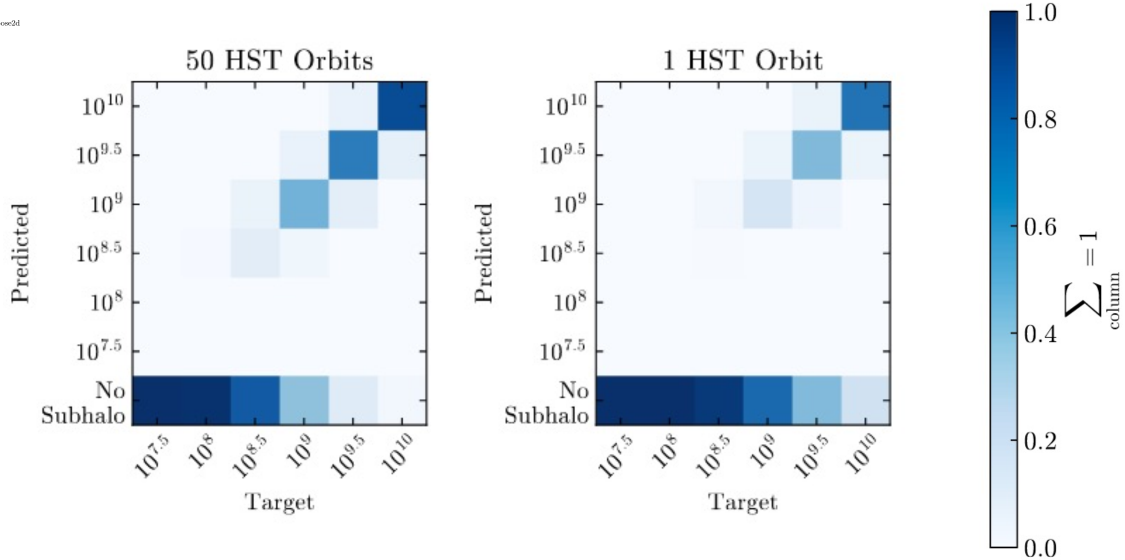
Direct detection of substructure with image segmentation



(U-Net)

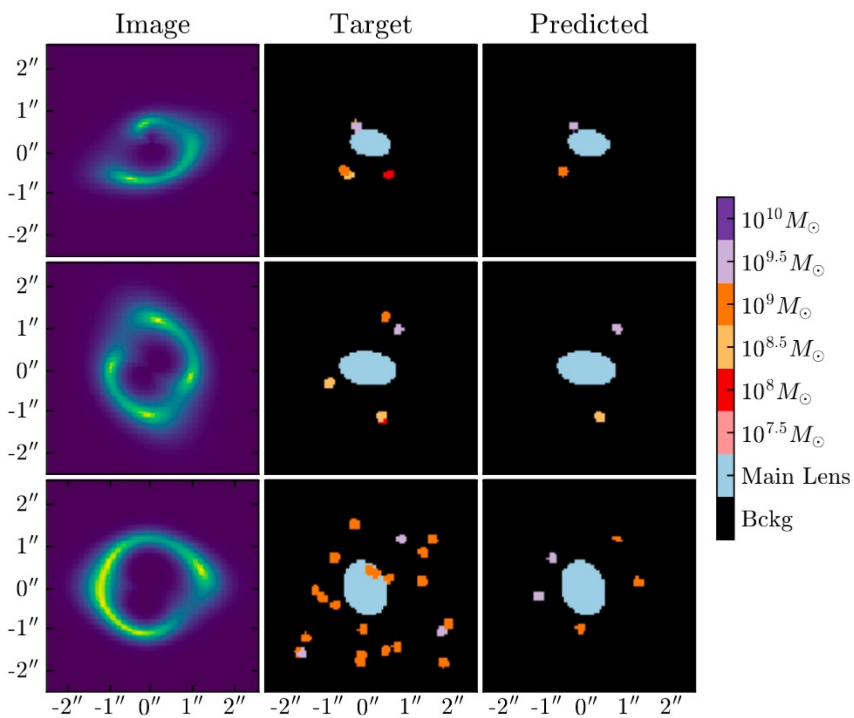
Bryan Ostdiek

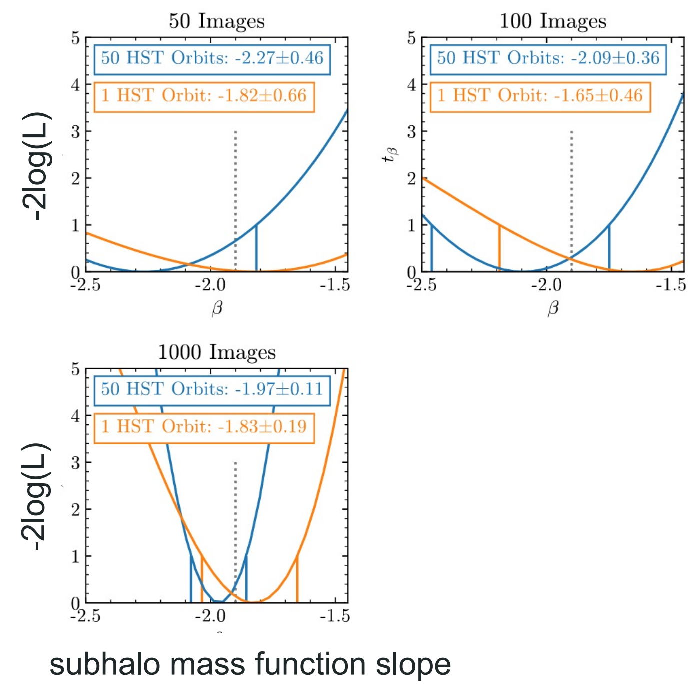
Ana Diaz Rivero



B. Ostdiek, A. Diaz Rivero and C. Dvorkin (ApJ, 2020, A&A Lett 2020)

Constraints on the subhalo mass function with image segmentation





B. Ostdiek, A. Diaz Rivero and C. Dvorkin (ApJ, 2020, A&A Lett 2020)

We have exciting years ahead…

The NSF AI Institute for Artificial Intelligence and Fundamental Interactions (IAIFI)

http://iaifi.org

arXiv:1902.10159 [pdf, ps, other] astro-ph.IM astro-ph.CO

The Role of Machine Learning in the Next Decade of Cosmology

Authors: Michelle Ntampaka, Camille Avestruz, Steven Boada, Joao Caldeira, Jessi Cisewski-Kehe, Rosanne Di Stefano, Cora Dvorkin, August E. Evrard, Arya Farahi, Doug Finkbeiner, Shy Genel, Alyssa Goodman, Andy Goulding, Shirley Ho, Arthur Kosowsky, Paul La Plante, Francois Lanusse, Michelle Lochner, Rachel Mandelbaum, Daisuke Nagai, Jeffrey A. Newman, Brian Nord, J. E. G. Peek, Austin Peel, Barnabas Poczos , et al. (5 additional authors not shown)

Abstract: In recent years, machine learning (ML) methods have remarkably improved how cosmologists can interpret data. The next decade will bring new opportunities for data-driven cosmological discovery, but will also present new challenges for adopting ML methodologies and understanding the results. ML could transform our field, but this transformation will require the astronomy community to both foster an… ▽ More

Submitted 14 January, 2021; **v1** submitted 26 February, 2019; **originally announced** February 2019.

Comments: Submitted to the Astro2020 call for science white papers

(Astro2020 Decadal Survey)
Ntampaka et al., 2020

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass White Paper: Machine Learning and Cosmology

Cora Dvorkin[1], Siddharth Mishra-Sharma[2,3,4,5], Brian Nord[6,7,8], and Ashley Villar[9]

(Snowmass 2021)
Dvorkin et al., 2022

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Direct detection: resolve individual, more massive perturbers and infer properties (mass, position). Requires postprocessing and combining many images to convert detections into dark matter constraints.

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Daylan, Cyr-Racine, Diaz Rivero, Dvorkin, Finkbeiner, ApJ (2018)
Sengul, Tsang, Diaz Rivero, Dvorkin, Zhu, and Seljak, PRD (2020)

A general framework for substructure statistics

- We developed a general formalism to study the N-point function of the convergence field from first principles, which can be easily applied to subhalo populations with different properties.

- We model the convergence field as a fluctuation field superimposed on the smoothly varying background density profile of the host:

$\kappa_{\rm tot}(\mathbf{r}) = \kappa_0(\mathbf{r}) + \kappa_{\rm sub}(\mathbf{r})$, where $\kappa = \frac{\Sigma}{\Sigma_{crit}}$ ($\Sigma_{crit} = \frac{c^2 D_{os}}{4\pi G D_{ol} D_{ls}}$).

$$\kappa_{\rm sub}(\mathbf{r}) = \sum_{i=1}^{N_{\rm sub}} \kappa_i(\mathbf{r} - \mathbf{r}_i, m_i, \mathbf{q}_i)$$

$\mathbf{q}_i$ are a set of parameters that represent the intrinsic properties of a subhalo.

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

A change of language

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

- Start from first principles to derive the lens plane-averaged convergence correlation function:

$$P_{\rm sub}(\mathbf{k}) = \int d^2\mathbf{r}\, e^{-i\mathbf{k}\cdot\mathbf{r}} \xi_{\rm sub}(\mathbf{r}) \quad ; \quad P_{\rm sub}(k) = P_{\rm 1sh}(k) + P_{\rm 2sh}(k)$$

- 1-subhalo term: arises from ensemble-averaging over the spatial distribution of a single subhalo.

$$P_{\rm 1sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\rm sub}}{\langle m \rangle \Sigma_{\rm crit}} \int dm\, d\mathbf{q}\, m^2\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times \left[\int dr\, r J_0(k\, r) \hat{\kappa}(r, \mathbf{q})\right]^2$$

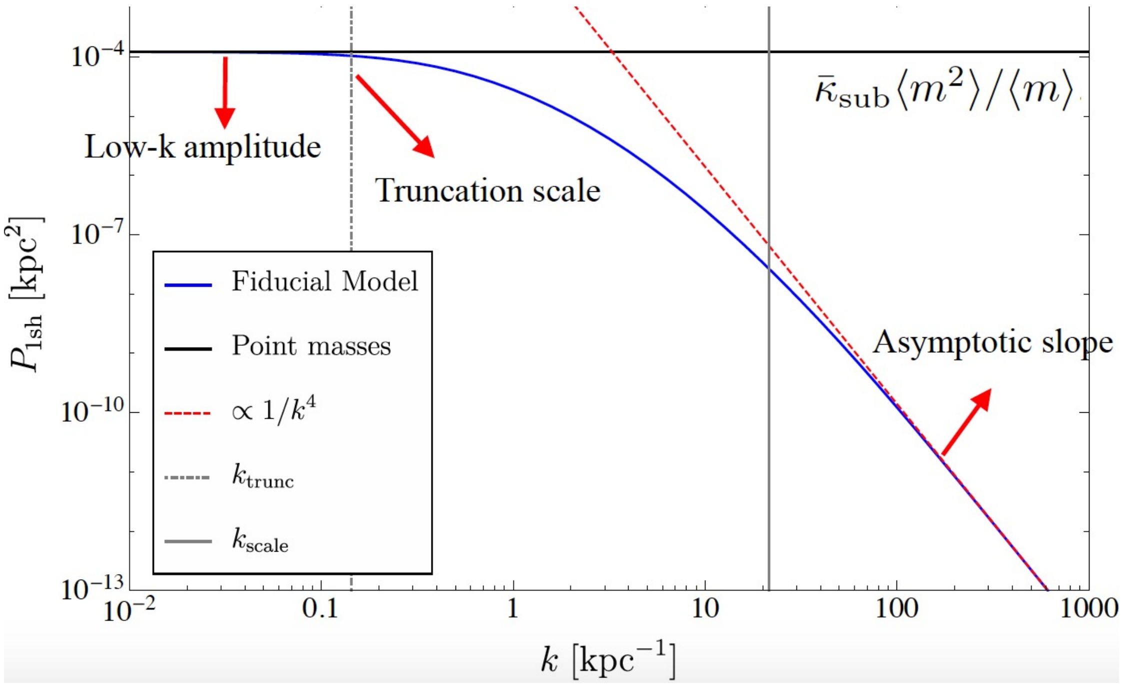
- 2-subhalo term: arises from averaging over pairs of distinct subhalos.

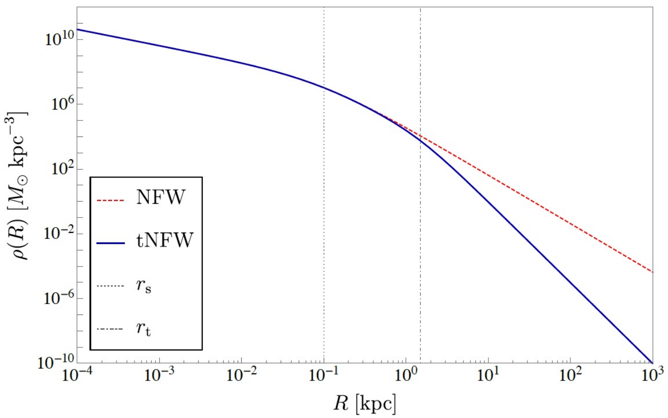
$$P_{\rm 2sh}(k) = \frac{(2\pi)^2 \bar{\kappa}_{\rm sub}^2}{\langle m \rangle^2} P_{\rm ss}(k) \left[\int dm\, d\mathbf{q}\, m\, \mathcal{P}_{\rm m}(m)\, \mathcal{P}_{\rm q}(\mathbf{q}|m) \times \int dr\, r J_0(k\, r) \hat{\kappa}(r, \mathbf{q})\right]^2$$

A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure convergence power spectrum

The power spectrum can be described mainly by three quantities:

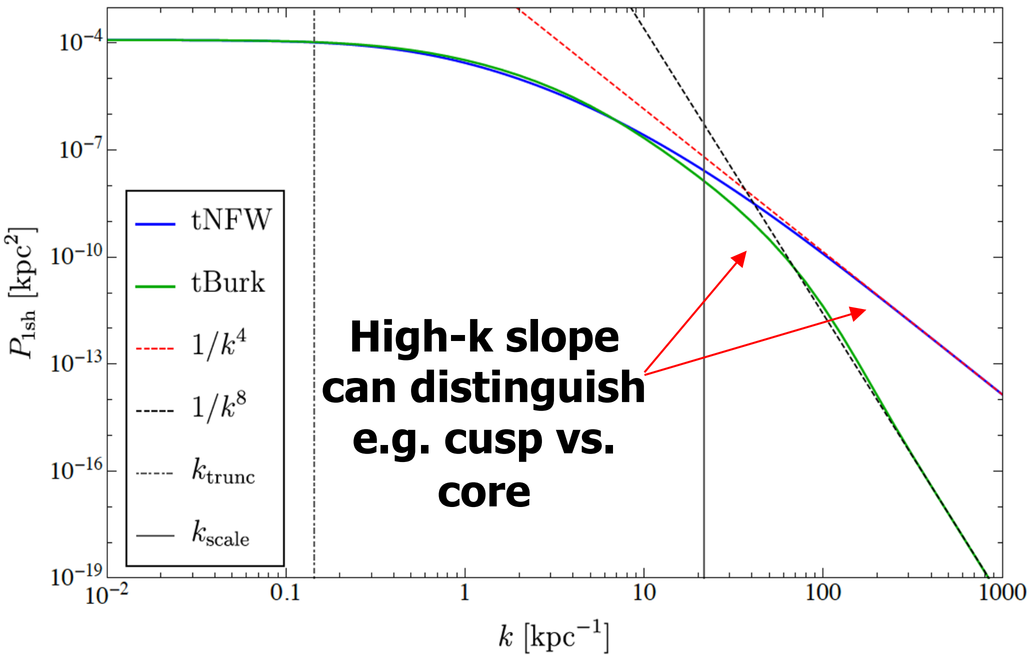


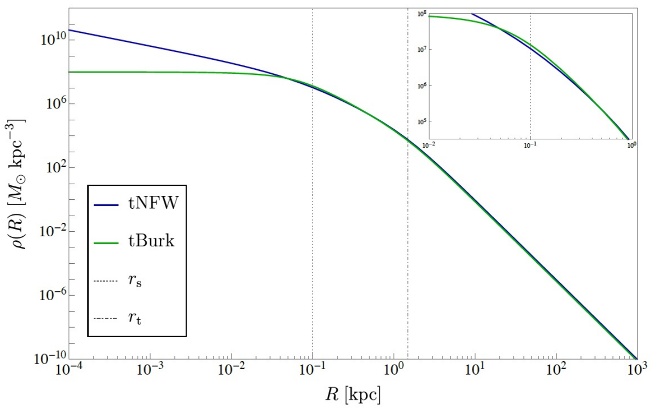


A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure convergence power spectrum

Key probe of the inner subhalo density profile: asymptotic slope.

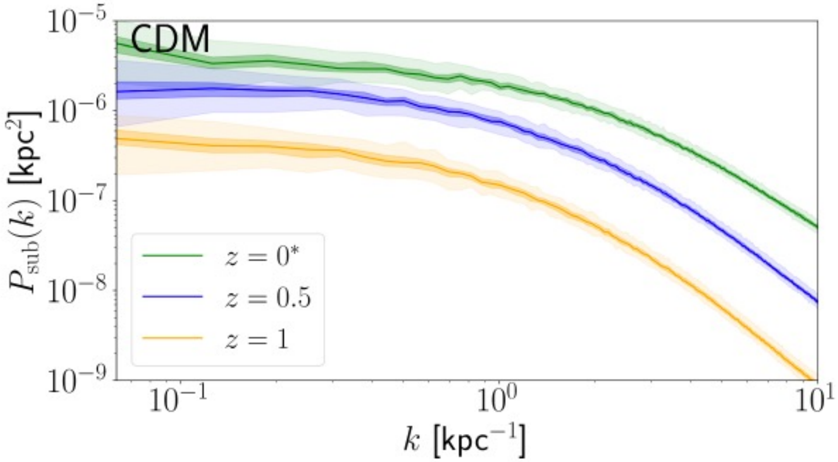




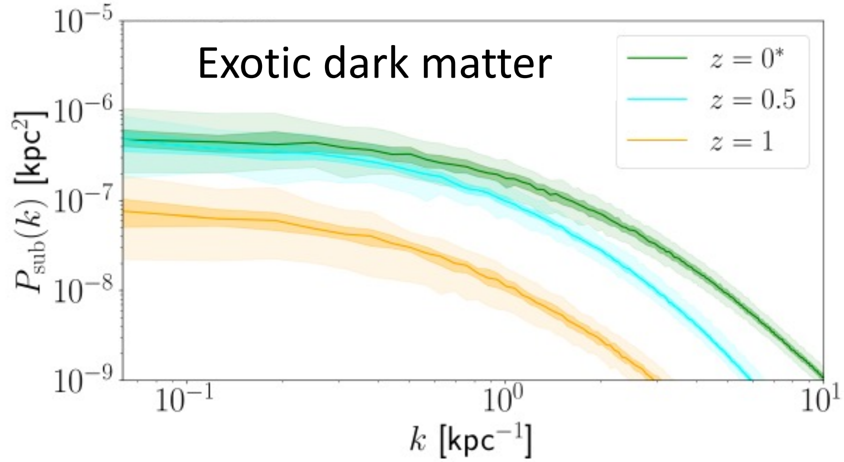
A. Diaz Rivero, F. Cyr-Racine, and C. Dvorkin, PRD (2017)

Substructure convergence power spectrum: redshift dependence

Comparing the amplitude and slope of the power spectrum on scales 0.1 kpc^{-1}<k<10 kpc^{-1} from lenses at different redshifts can help us distinguish between CDM and other DM scenarios.



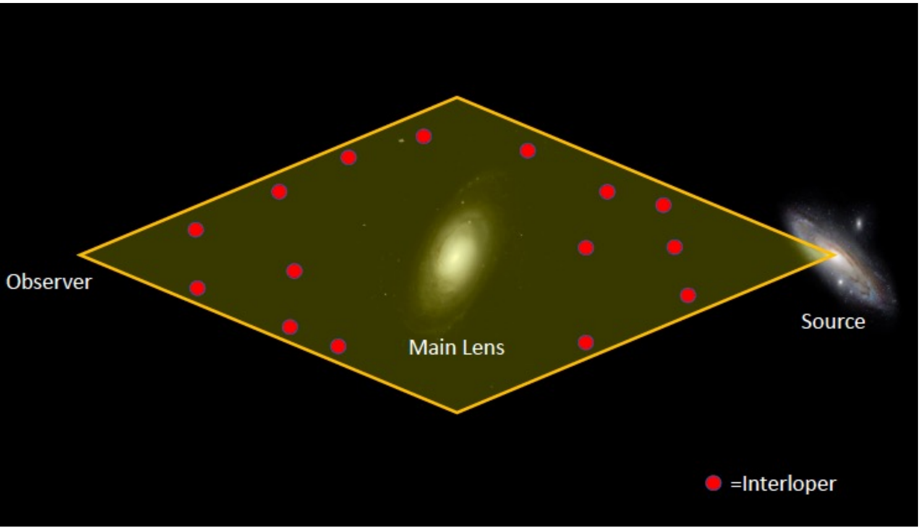
Exotic DM: low-mass cutoff+self-interactions

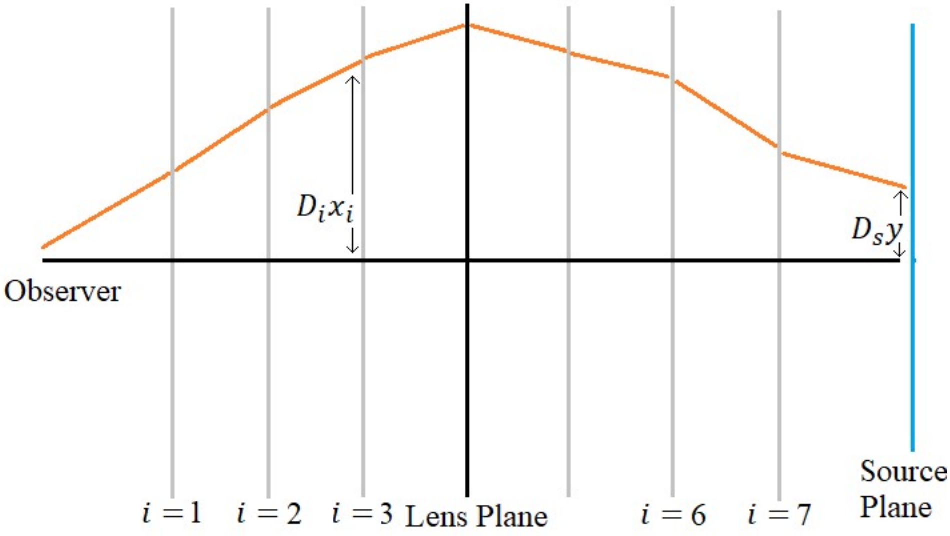


A. Diaz Rivero, C. Dvorkin, F. Cyr-Racine, J. Zavala, and M. Vogelsberger, PRD (2018)

Line-of-sight (LOS) halos


Cagan Sengul **Arthur Tsang**





$$\vec{y} = \vec{x}_1 - \sum_{i=1}^{N} \vec{\alpha}_i(\vec{x}_i)$$

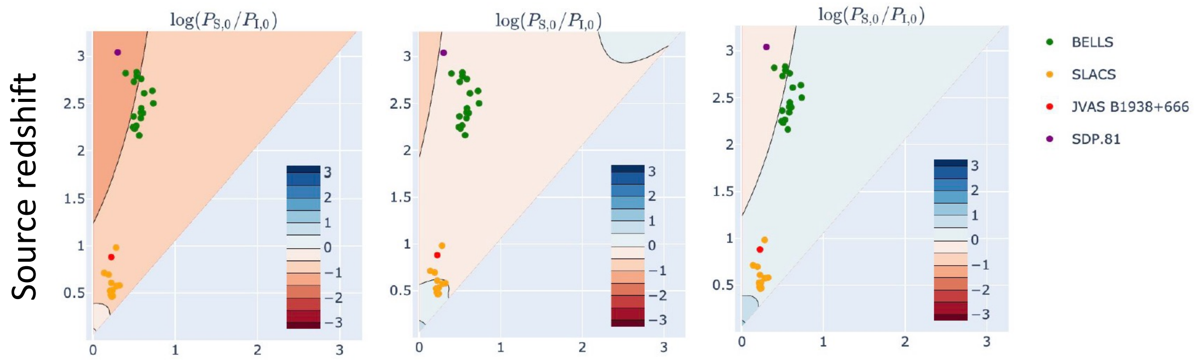
$$\vec{x}_j = \vec{x}_1 - \sum_{i=1}^{j-1} \beta_{ij} \vec{\alpha}_i(\vec{x}_i), \quad \text{where} \quad \beta_{ij} \equiv \frac{D_{ij} D_s}{D_j D_{is}}$$

C. Sengul, A. Tsang, A. Diaz Rivero, C. Dvorkin, H. Zhu and U. Seljak, PRD (2020)

[See also D'Aloisio and Natarajan (2010), Despali+(1017), Gilman+(2019), etc, for LOS-related works]

Line-of-sight (LOS) halos vs. subhalos

Ratio of substructure to LOS halos power spectrum amplitude:

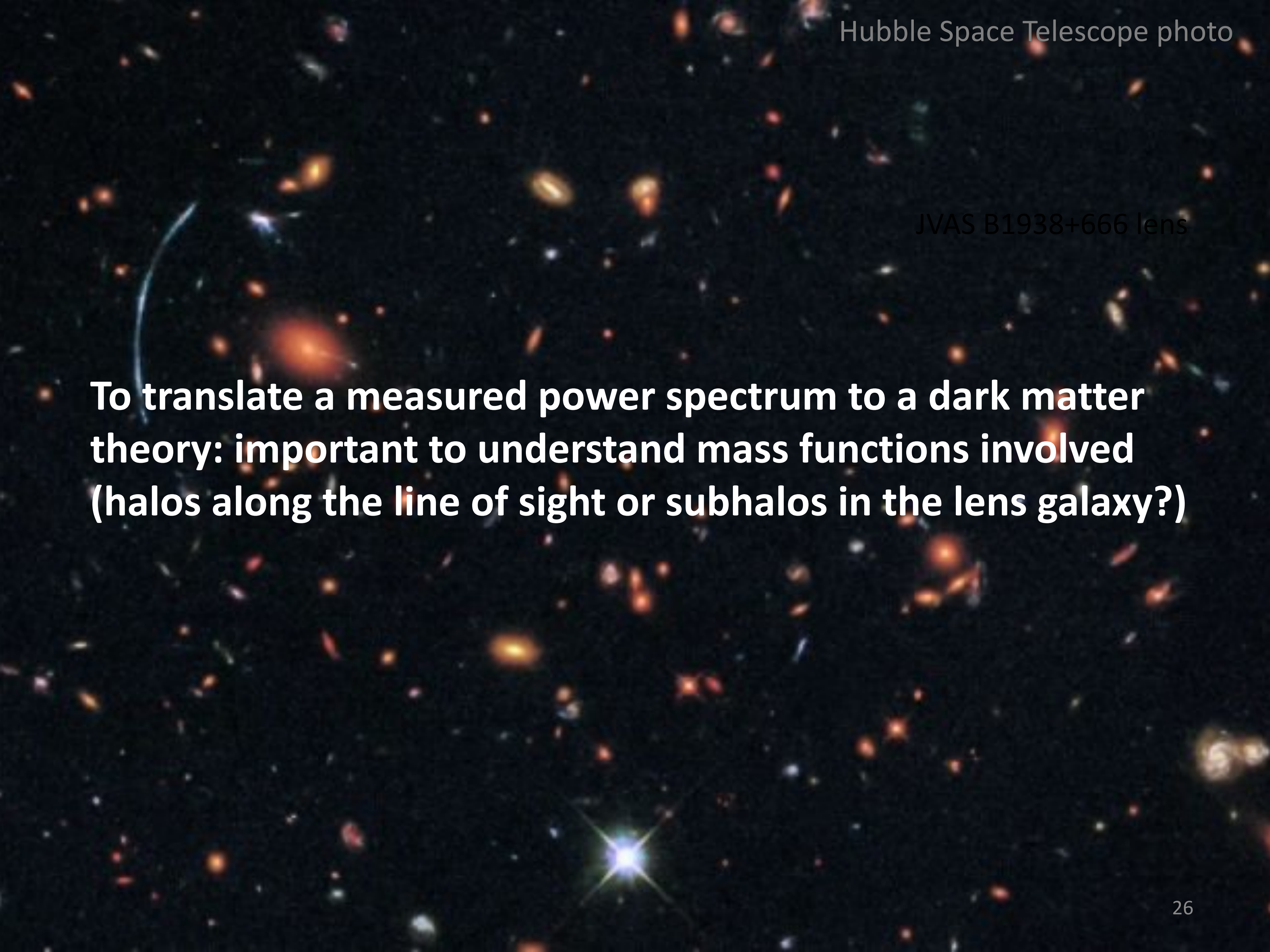


Lens redshift Lens redshift Lens redshift

f_{sub}= 0.4% f_{sub}= 2% f_{sub}= 4%

Fraction of dark matter halo mass in substructure (f_{sub}) →

C. Sengul, A. Tsang, A. Diaz Rivero, C. Dvorkin, H. Zhu and U. Seljak, PRD (2020)



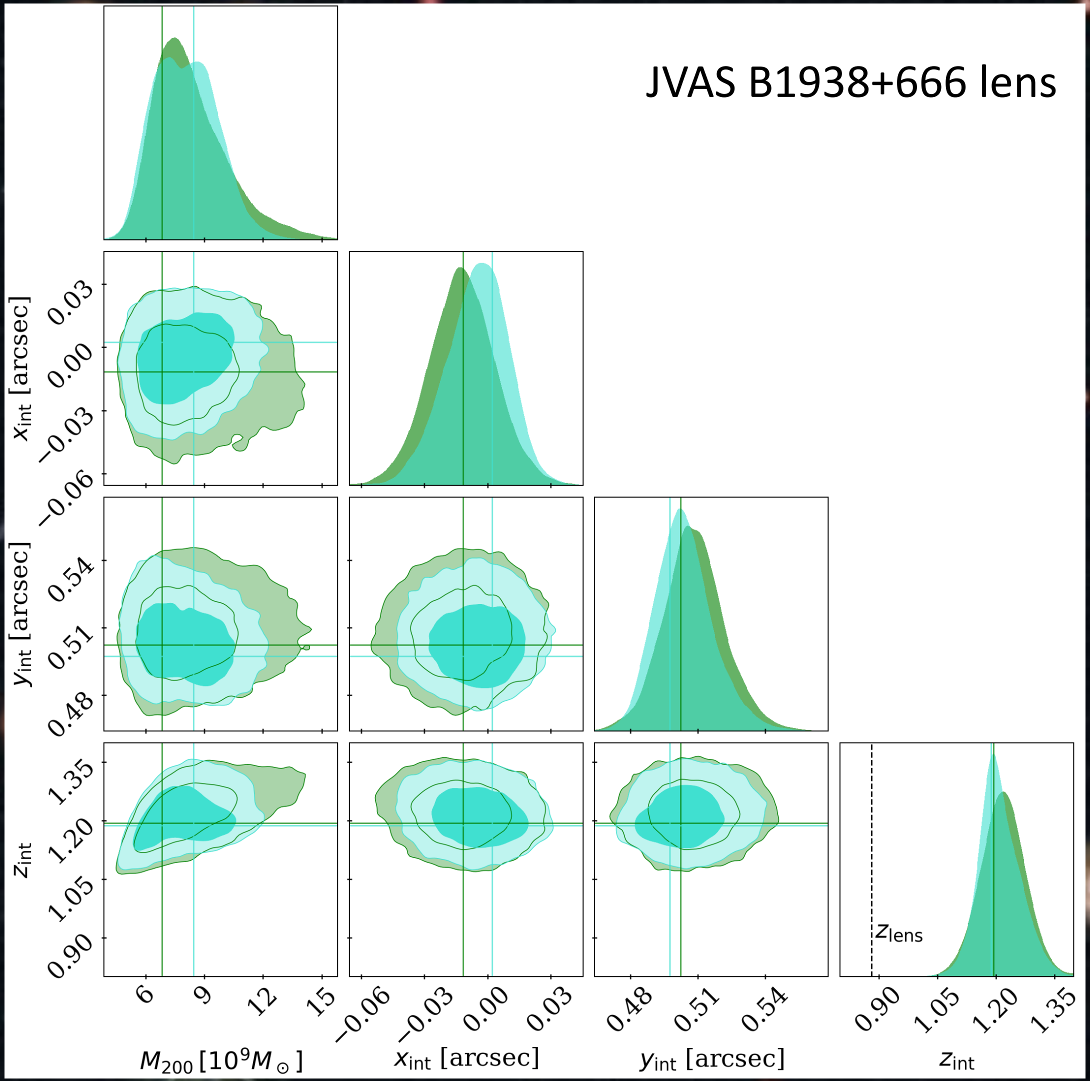
To translate a measured power spectrum to a dark matter theory: important to understand mass functions involved (halos along the line of sight or subhalos in the lens galaxy?)

Hubble Space Telescope photo

Substructure Detection Reanalyzed

We re-analyzed a system previously claimed as a subhalo and found it likely to be a line-of-sight halo.

Our analysis indicates that this structure is more massive than previously thought by an order of magnitude.



C. Sengul, C. Dvorkin, B. Ostdiek, A. Tsang (2021)

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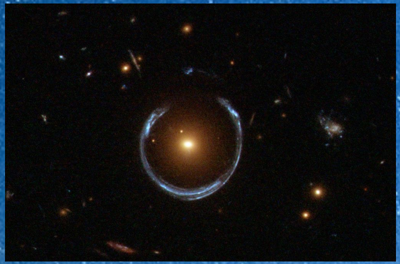
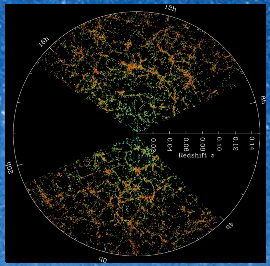
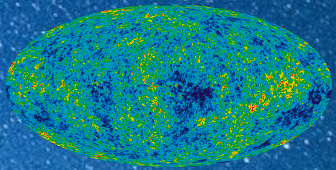
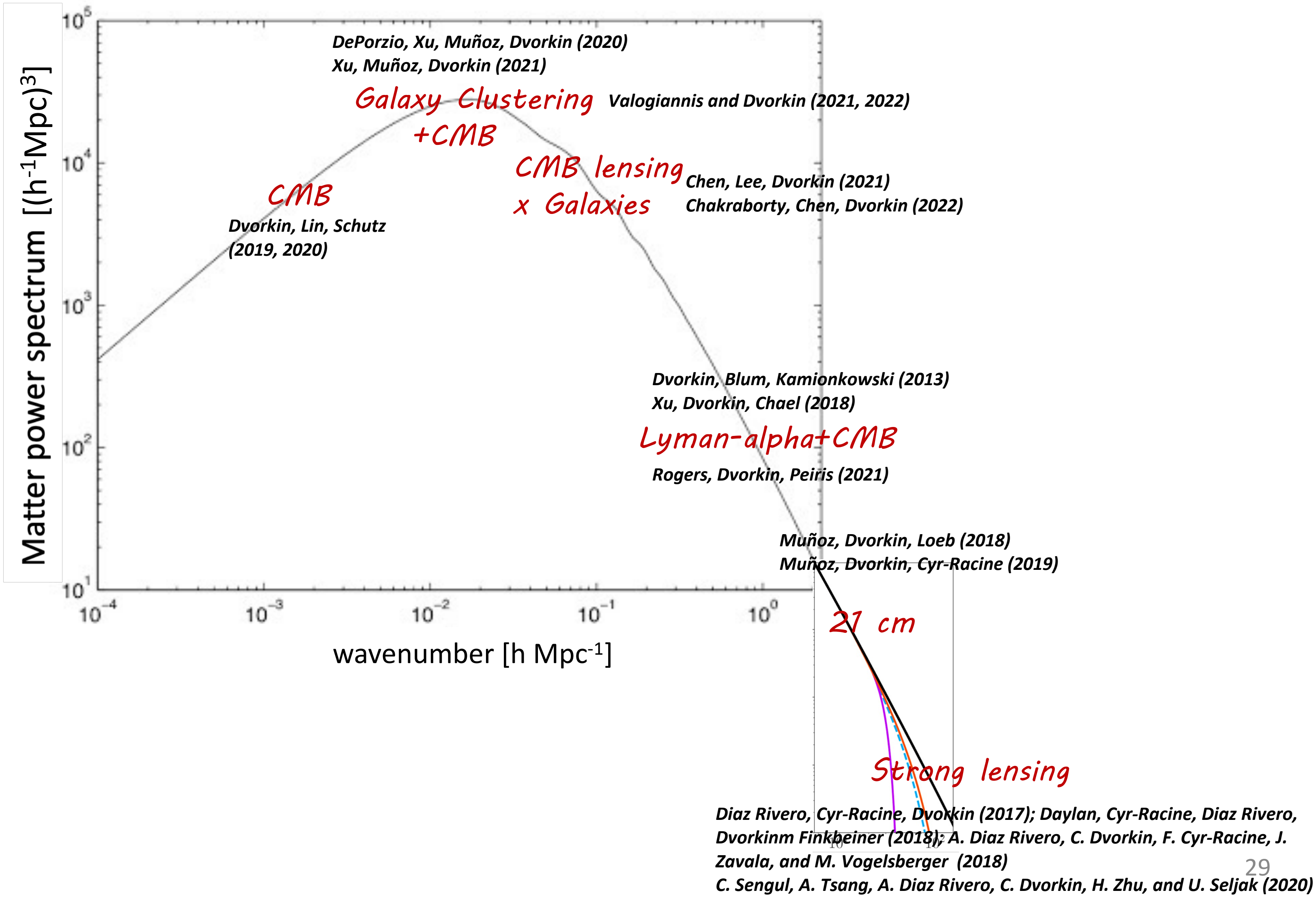


From large scales





Unveiling the nature of the dark sector using cosmology at large and small scales



Going Beyond the Power Spectrum: an analysis of BOSS Data with Wavelet Scattering Transform (Scrutinizing ΛCDM)

Input field

Family of wavelets:

Dilated by 2^{j1}
Rotated by l_1

$$S_0 \equiv \langle I_0 \rangle$$

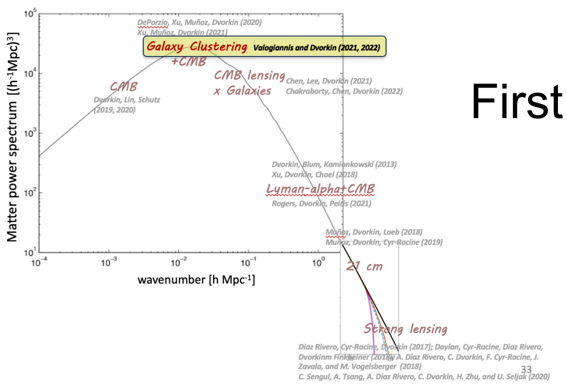
$$S_1^{j_1,l_1} \equiv \langle I_1^{j_1,l_1} \rangle = \langle \left| I_0 \star \psi^{j_1,l_1} \right| \rangle$$

$$S_2^{j_1,l_1,j_2,l_2} \equiv \langle I_2^{j_1,l_1,j_2,l_2} \rangle = \langle \left| |I_0 \star \psi^{j_1,l_1}| \star \psi^{j_2,l_2} \right| \rangle$$

Mallat (2012); Anden and Mallat (2011, 2014); Bruna and Mallat (2013); Cheng, Ting, Ménard, and Bruna (2020); Cheng and Ménard (2021); ***Valogiannis and Dvorkin (2021)***

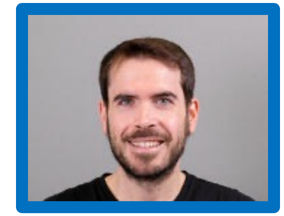
First application of WST
on 3D (simulated) cosmological fields

Going Beyond the Power Spectrum: an analysis of BOSS Data with Wavelet Scattering Transform (Scrutinizing ΛCDM)



↑

First application of WST on galaxy data



Georgios Valogiannis

BOSS with WST:

$$\sigma_8 = 0.695^{+0.024}_{-0.024}$$

$$H_0 = 68.31^{+0.42}_{-0.42} \text{ km/s/Mpc}$$

(0.6% measurement of H_0)

BOSS with P(k):

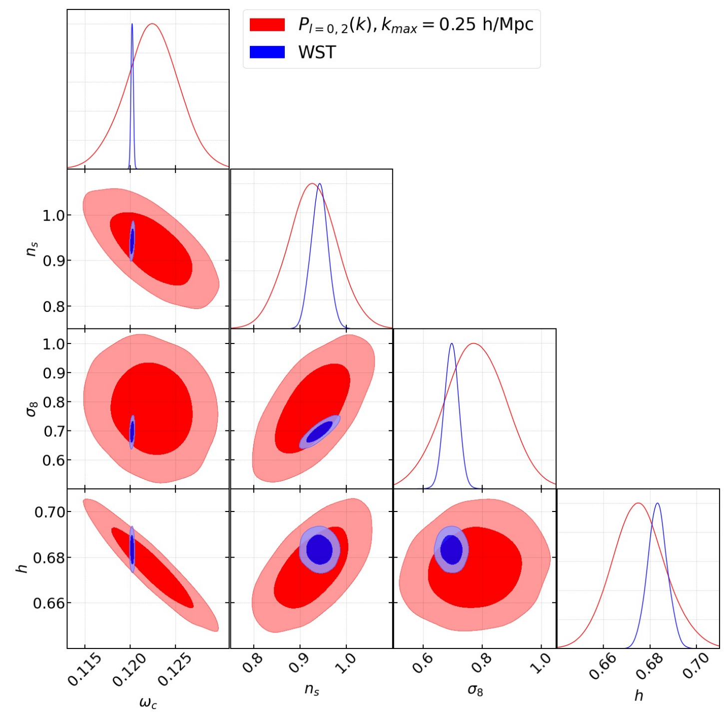
$$\sigma_8 = 0.77^{+0.14}_{-0.14}$$

$$H_0 = 67.6^{+1.0}_{-1.2} \text{ km/s/Mpc}$$

Planck results:

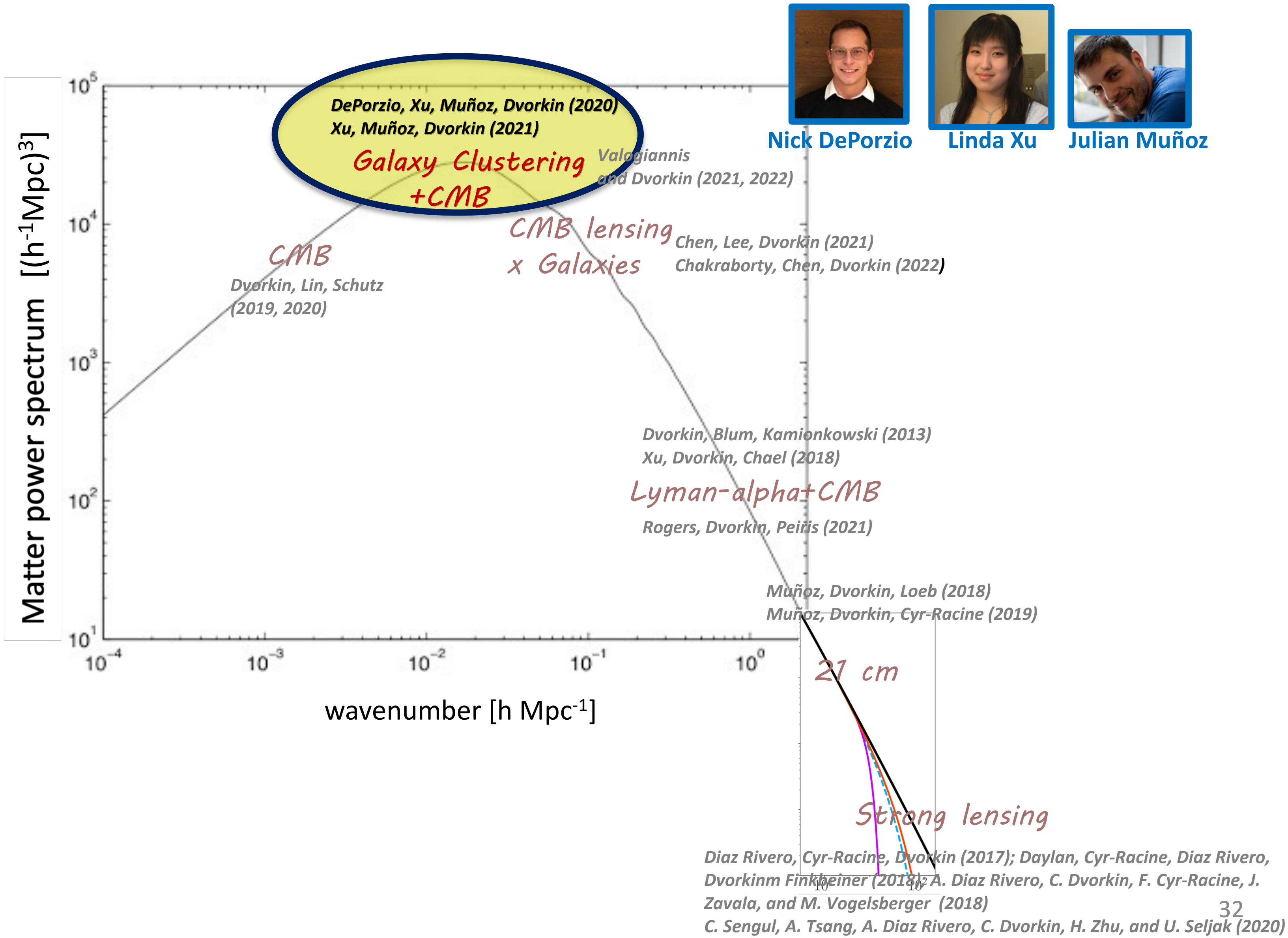
$$\sigma_8 = 0.811 \pm 0.006$$

$$H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$$

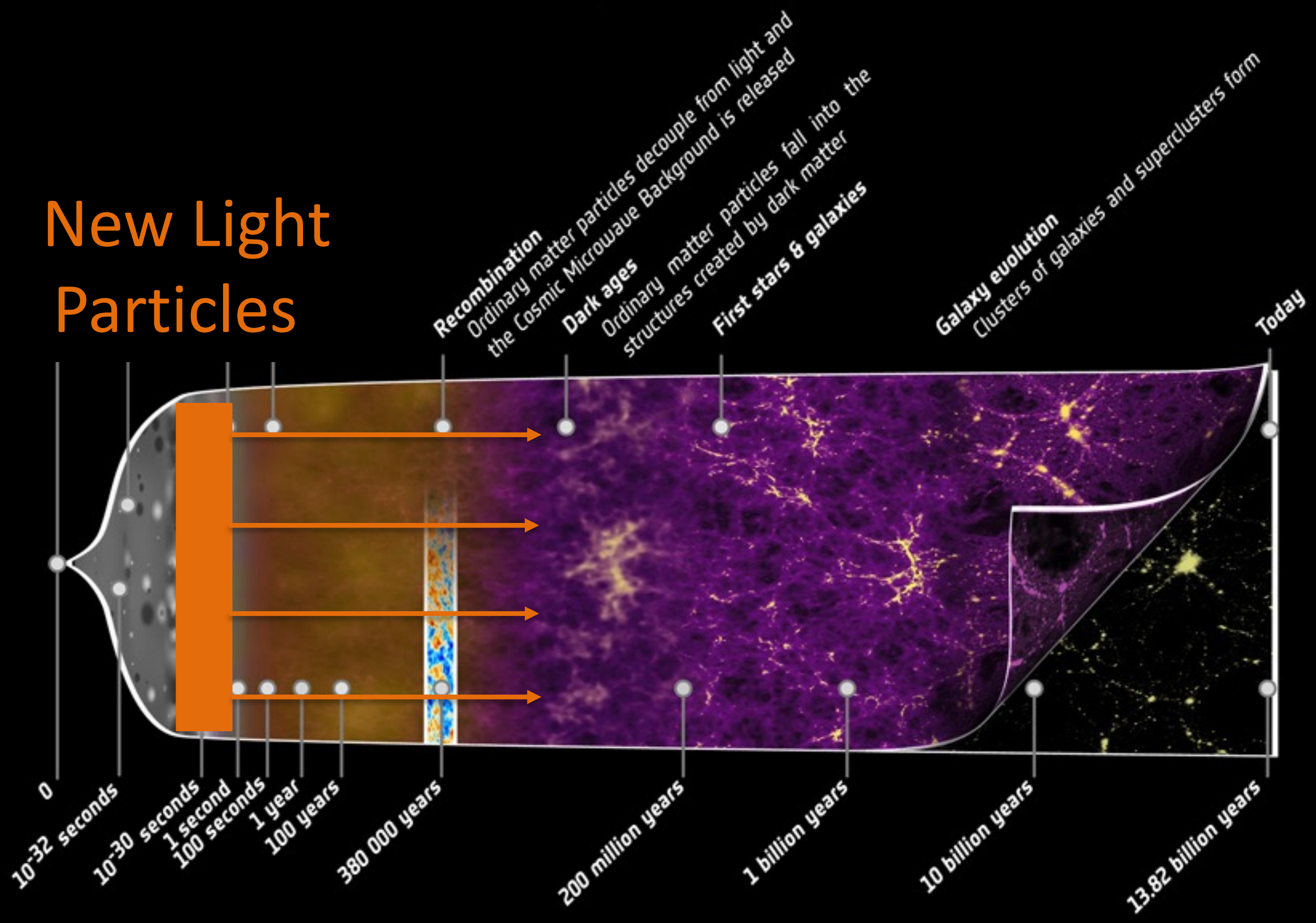


Valogiannis and Dvorkin (2022)

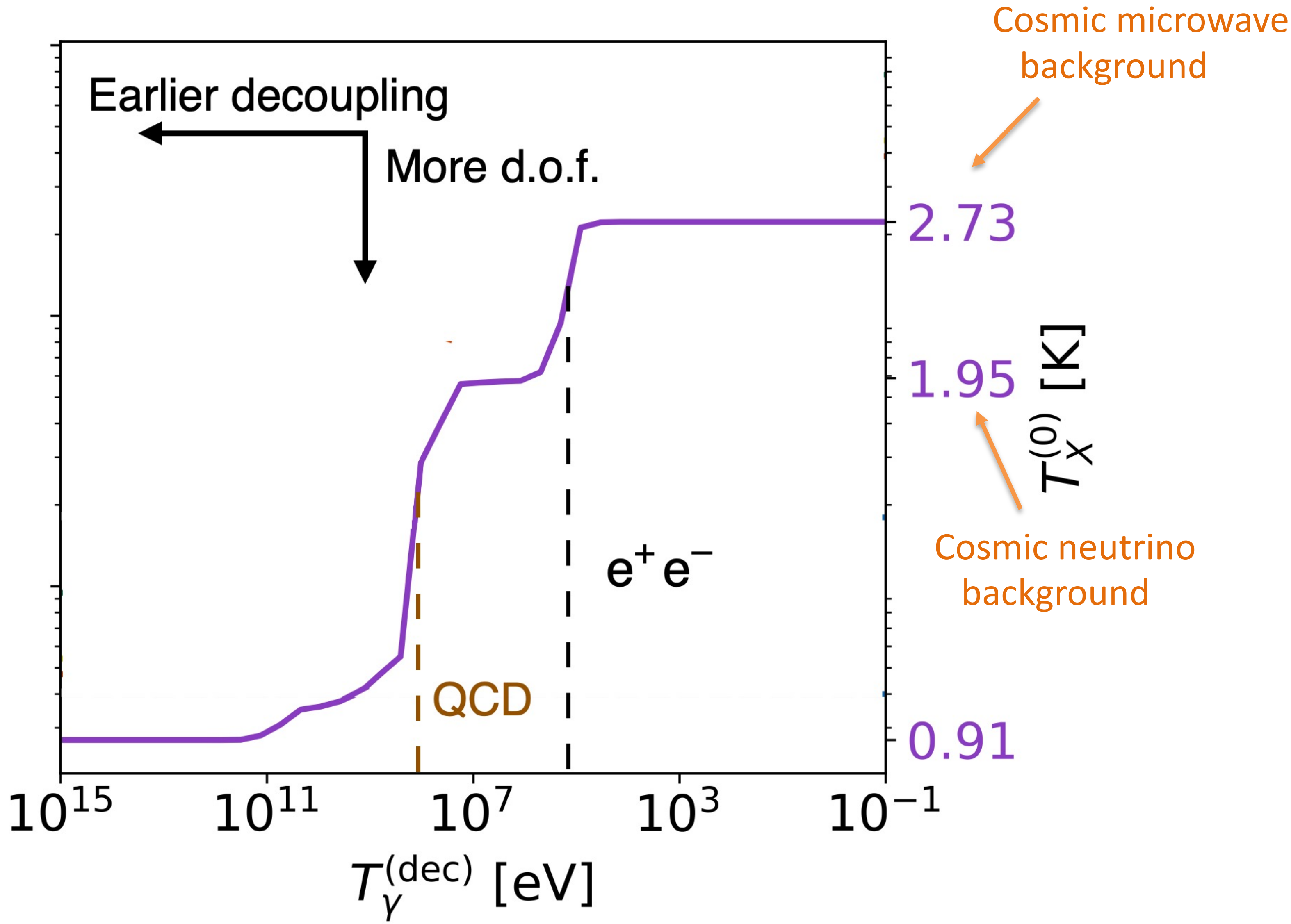
Looking for new particles beyond the Standard Model in the CMB and galaxy surveys



New Light Particles



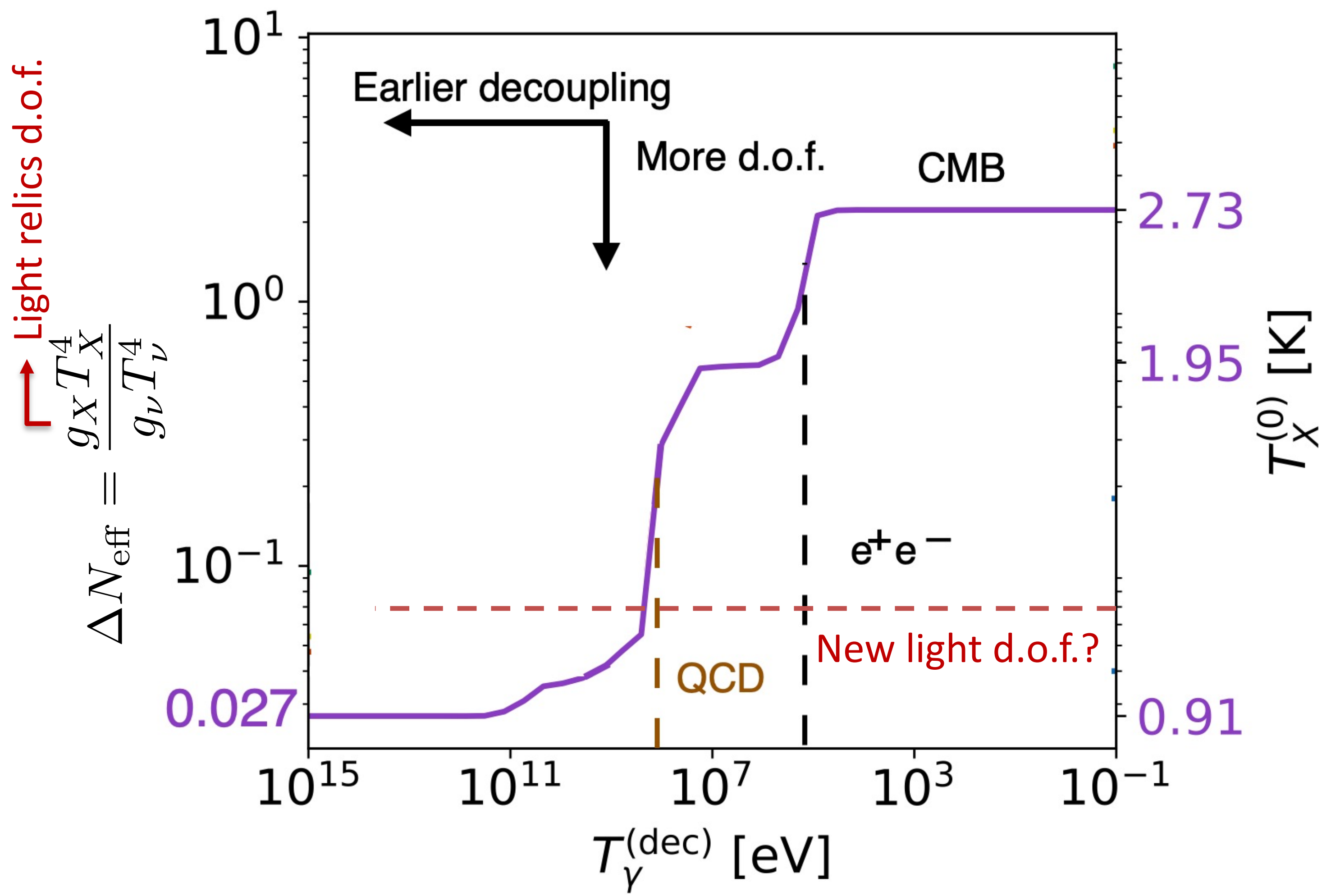
Cosmological Light Relics



DePorzio, Xu, Muñoz, Dvorkin (PRD, 2021)

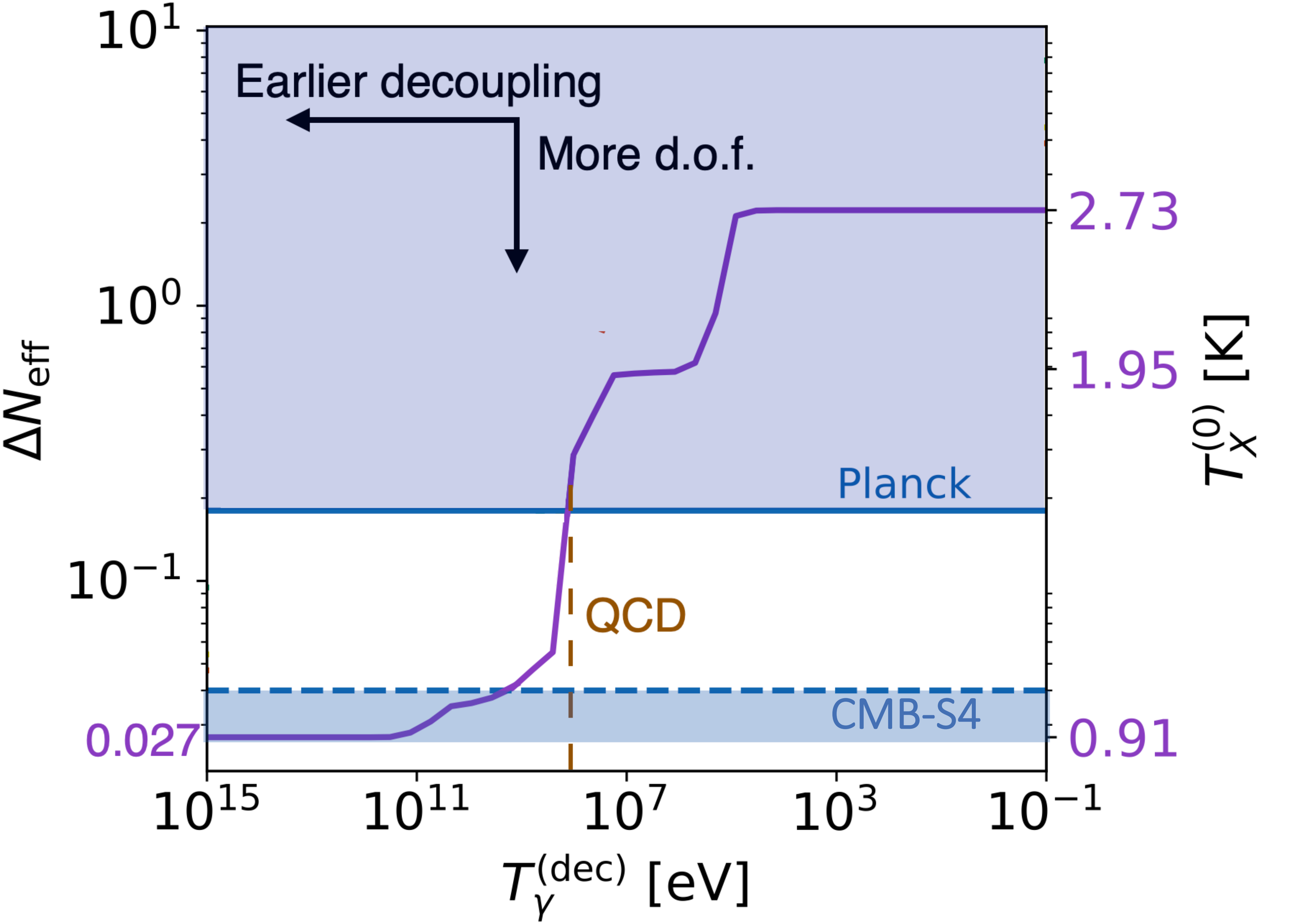
[Green et al. (2019);
Brust, Kaplan and Walters (2013)]

Contribution to the radiation energy density: $\rho_{\rm R} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$



DePorzio, Xu, Muñoz, Dvorkin (PRD, 2021)

[Green et al. (2019);
Brust, Kaplan and Walters (2013)]



Earlier decoupling
More d.o.f.
10^1
10^0
10^{-1}
0.027
ΔN_{eff}
2.73
1.95
0.91
$T_X^{(0)}$ [K]
Planck
QCD
CMB-S4
10^{15}
10^{11}
10^7
10^3
10^{-1}
$T_\gamma^{(\mathrm{dec})}$ [eV]

What happens if the relics aren't massless?

A search for light but Massive Relics (LiMRs)

- Light but massive relics (LiMRs): particles that were in thermal contact with the Standard Model in the early universe, relativistic at decoupling, but behave as matter today.

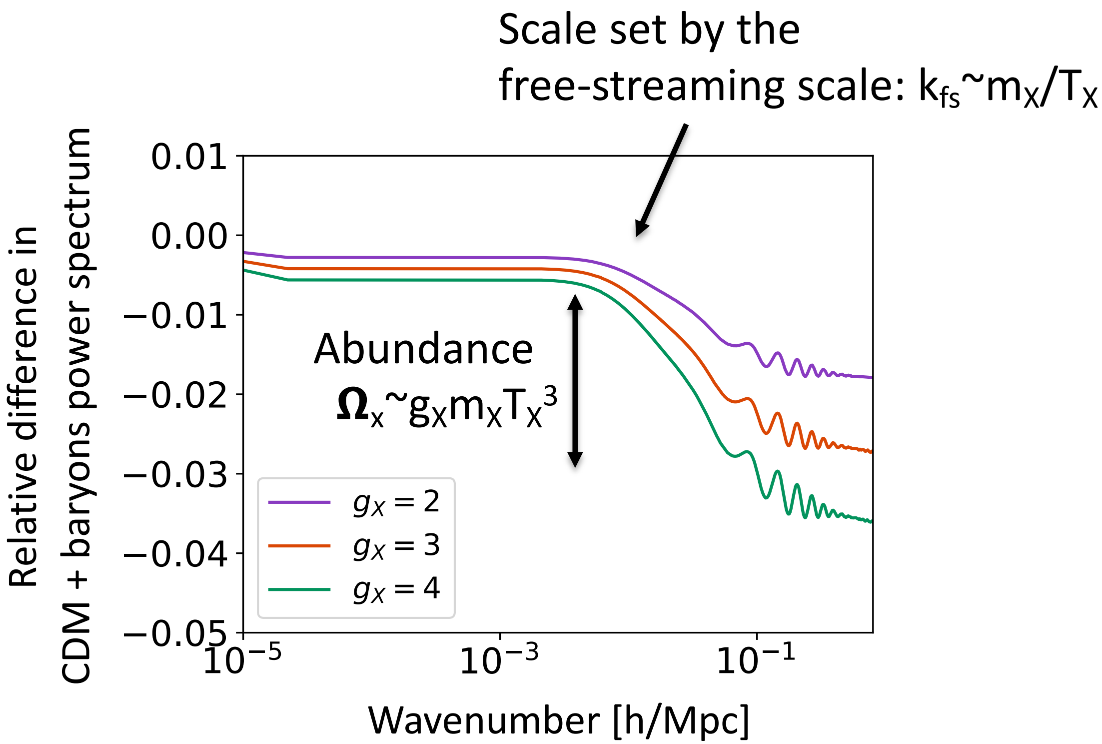
Fermionic

Bosonic

- We will use their unique imprints on the large-scale structure of the universe to look for them.

Slide credit: Linda Xu

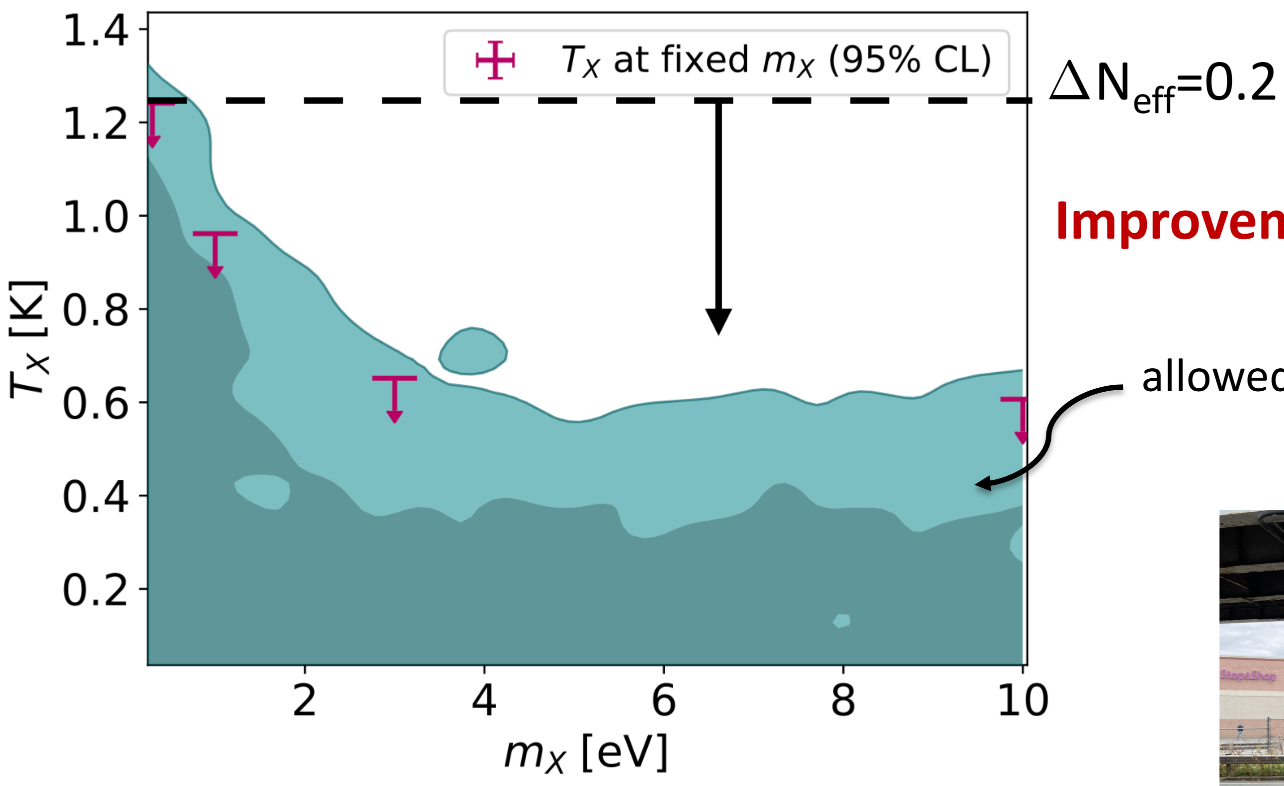
LiMRs and their imprints on the large-scale structure



N. DePorzio, W. L. Xu, J. Muñoz, C. Dvorkin (PRD, 2021)
[see also J. Muñoz and C. Dvorkin (PRD, 2018)]

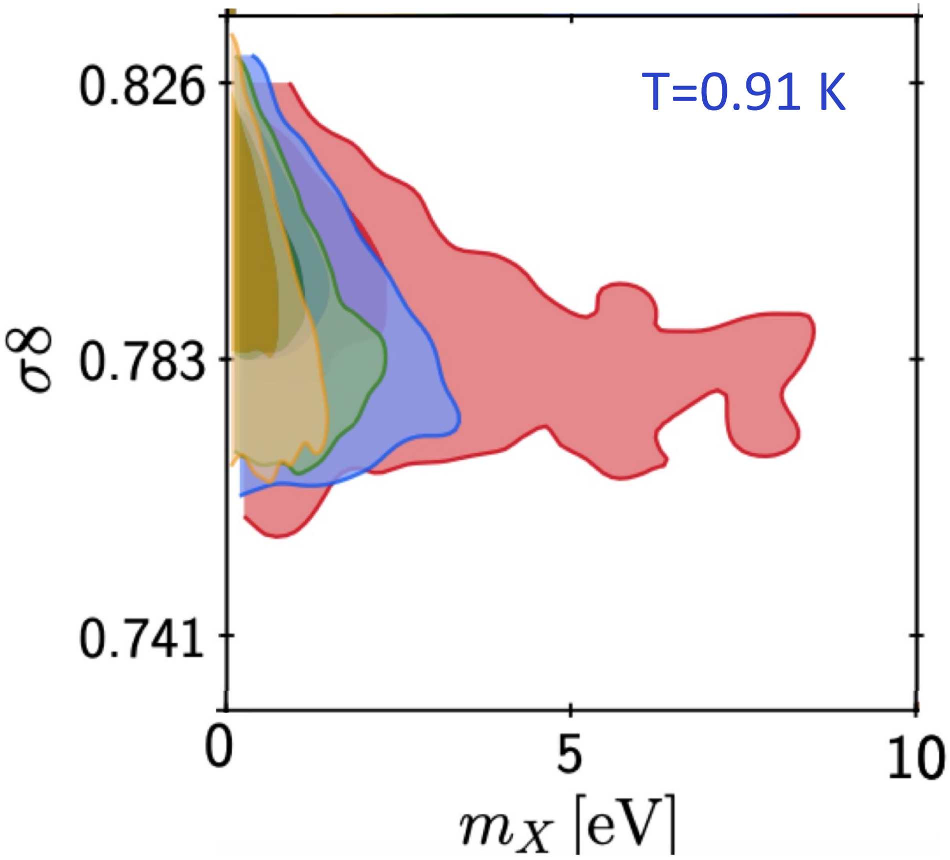
A search for Light but Massive Relics (LiMRs) in current CMB and galaxy data sets

(Marginalized over ΛCDM + M_ν + bias parameters)



W. L. Xu, J. Muñoz, C. Dvorkin (PRD, 2021)

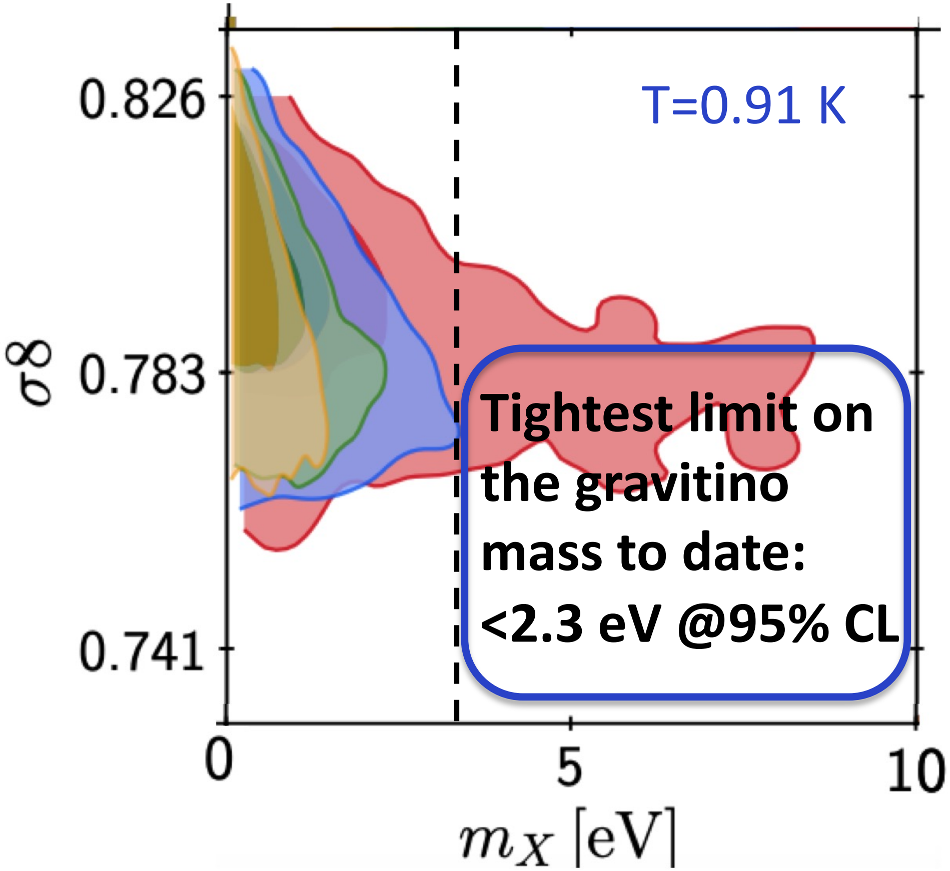
Limits on LiMRs at minimum temperature



Different LiMRs
scalar (eg axion),
vector (eg A'),
Weyl (eg gravitino, nu')
Dirac

W. L. Xu, J. Muñoz, C. Dvorkin (PRD, 2021)

Limits on LiMRs at minimum temperature



Different LiMRs
scalar (eg axion),
vector (eg A'),
Weyl (eg gravitino, nu')
Dirac

Ly-alpha:
<16 eV (Viel + 2005)

CMB:
< 5 eV (Osato+ 2016)

W. L. Xu, J. Muñoz, C. Dvorkin (PRD, 2021)

Concluding thoughts

- New roads to the small-scale universe (e.g., with strong gravitational lensing).

- Novel statistical techniques to accelerate discovery (e.g., with machine learning).

- Scrutinizing ΛCDM using its non-Gaussian information (e.g., Wavelet Scattering Transform analysis of BOSS data).

- Looking for new physics Beyond the Standard Model with cosmology (e.g., search for Light but Massive Relics - LiMRs).