Combinations of cosmic microwave background and large-scale structure cosmological probes

Two studies with Planck and SDSS-III/BOSS data

… and some ideas for LSST

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LSST Webinar | November 20th 2017

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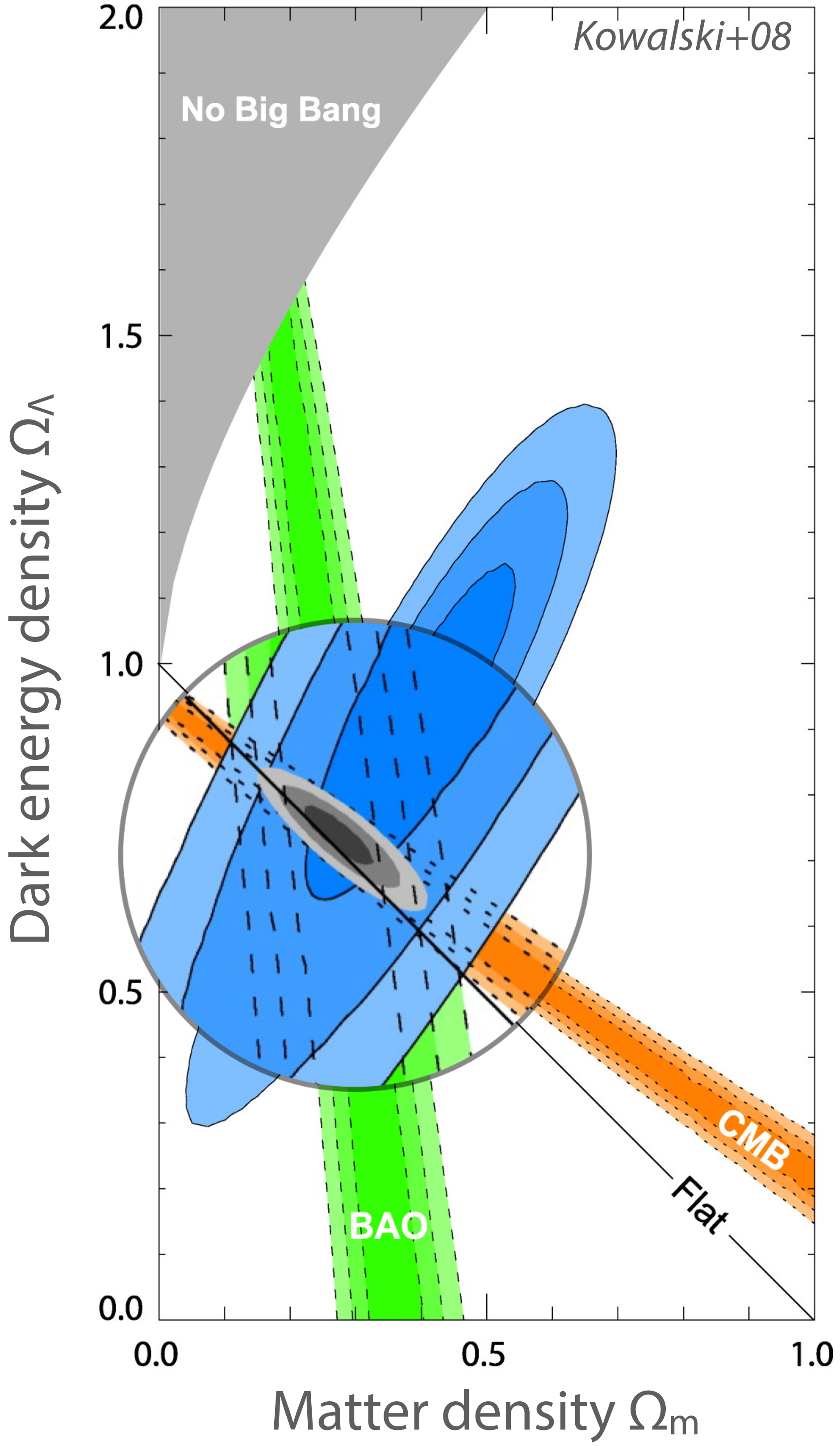
Outline

- **INTRODUCTION**
  - ⟶ Why and how combine cosmological probes?
- **JOINT ANALYSIS OF PLANCK & BOSS DATA**
  - ⟶ Planck and BOSS
  - ⟶ Methodology
  - ⟶ Results
- **LY-A FOREST × CMB LENSING BISPECTRUM**
- **THESIS CONCLUSIONS**
- **LOW-LEVEL COMBINATION OF WEAK LENSING SURVEYS**

Independent probes



Combination of independent probes

- breaks degeneracies
- shows that the Universe is **flat ΛCDM**

However it involves some unknowns:

- dark energy?
- dark matter?
- inflation?

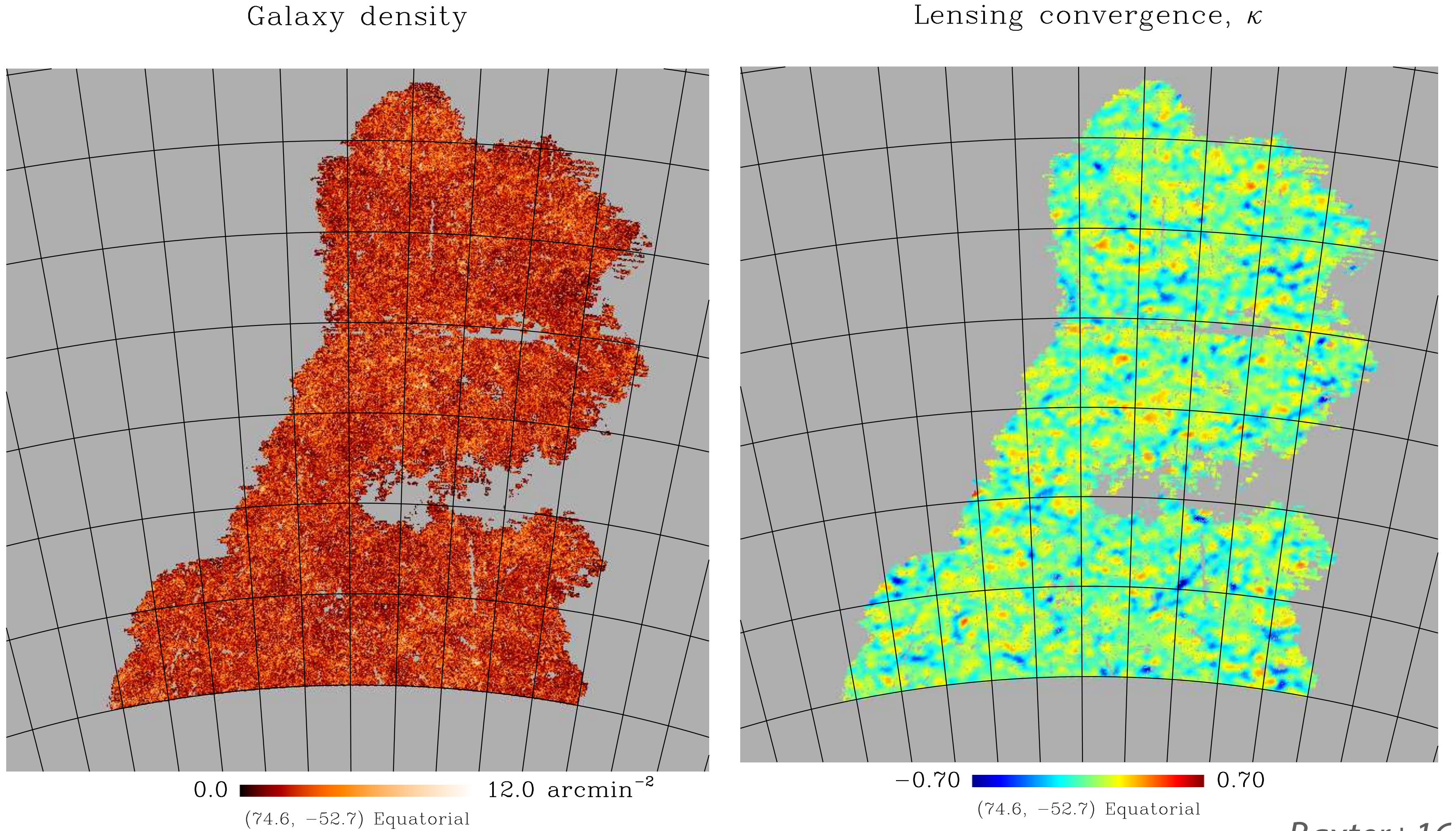
⇒ we need to track more *information/data*

- new experiments: LSST, Euclid, WFIRST, CMB-S4, DESI

AND

- **exploiting cross-correlations**

Correlated cosmological probes

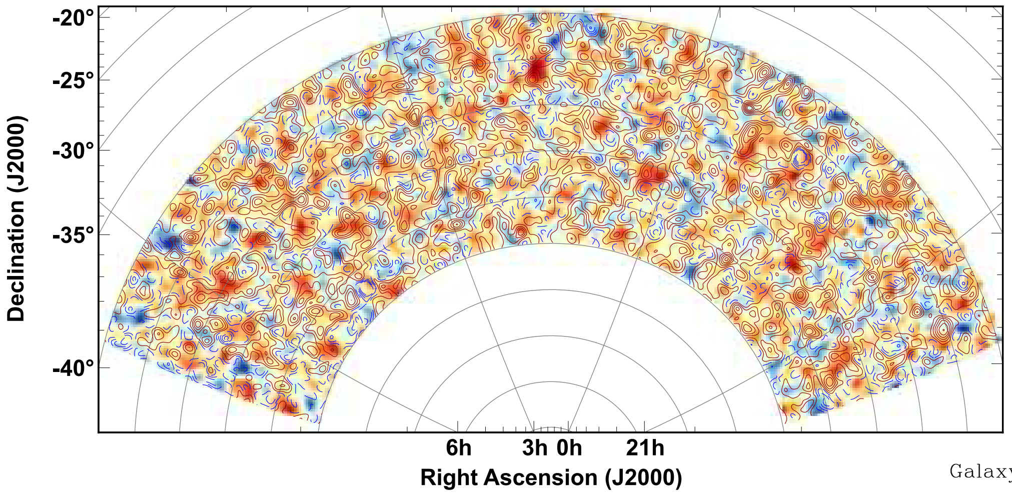


Baxter+16

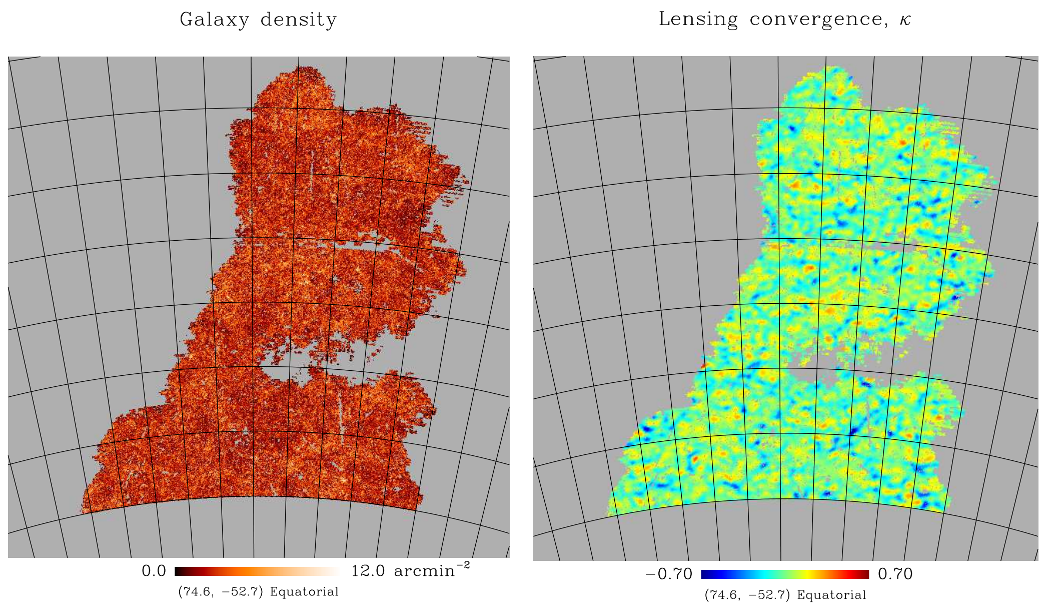
- **cosmic probes** mapping the *same* ***matter volume*** are correlated
  - ⟶ ex: galaxy density/velocities, CMB/galaxy lensing, 2nd CMB anisotropies
- cross-correlations hold *extra information*

$$\Delta S = S_{\mathcal{L}(X,Y)} - S_{\mathcal{L}(X)\mathcal{L}(Y)} = \ln \sqrt{1 - \frac{\mathrm{cov}(X,Y)^2}{\sigma_X^2 \sigma_Y^2}} < 0$$

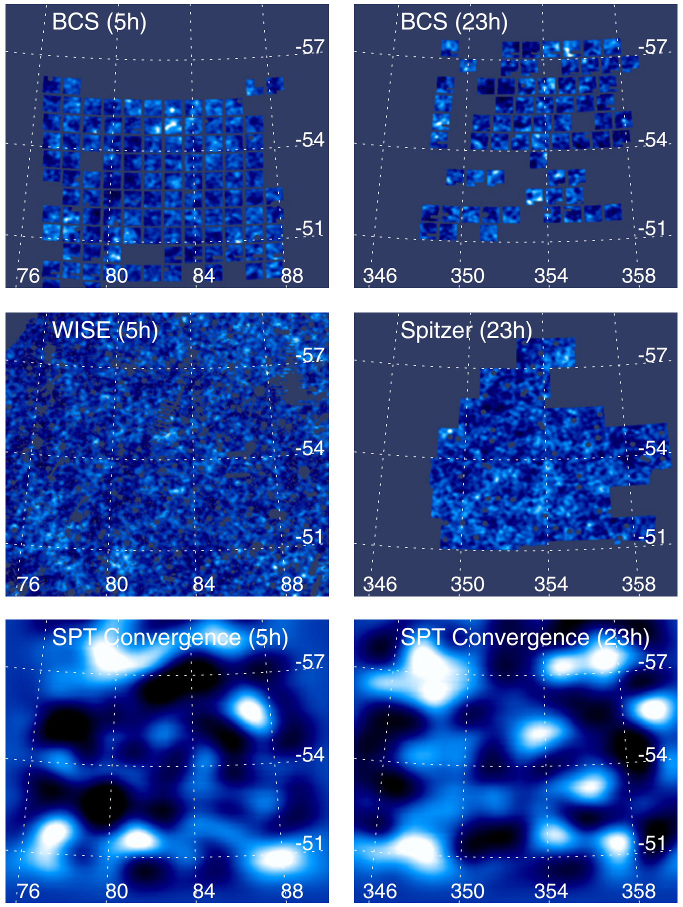
CMB lensing × LSS tracers



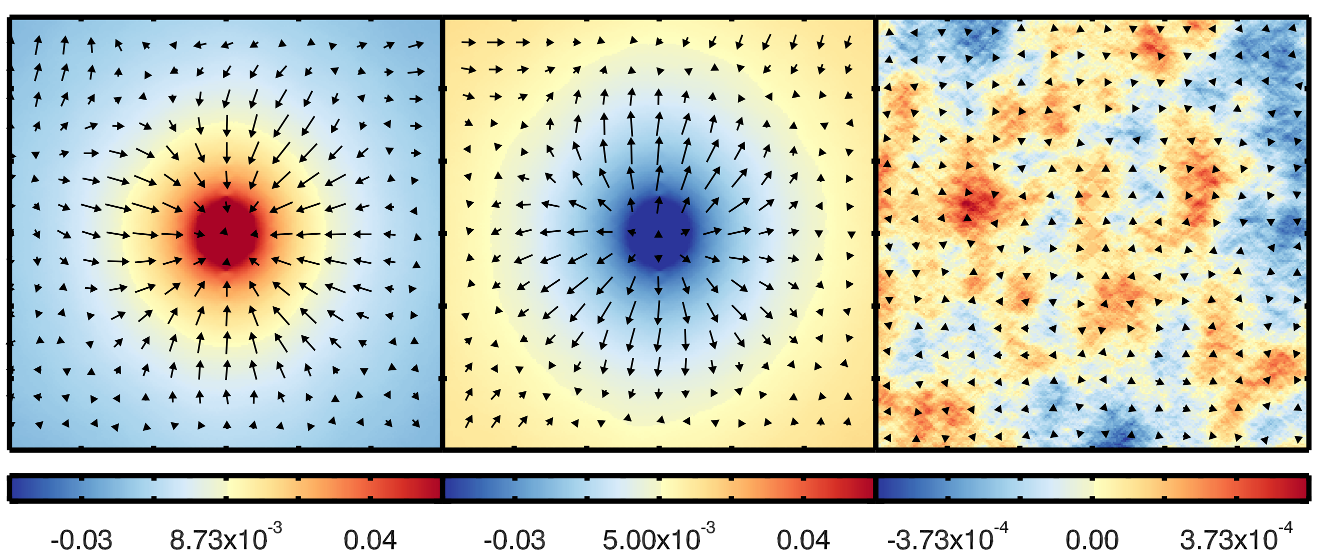
Geach+13 : SPT x WISE



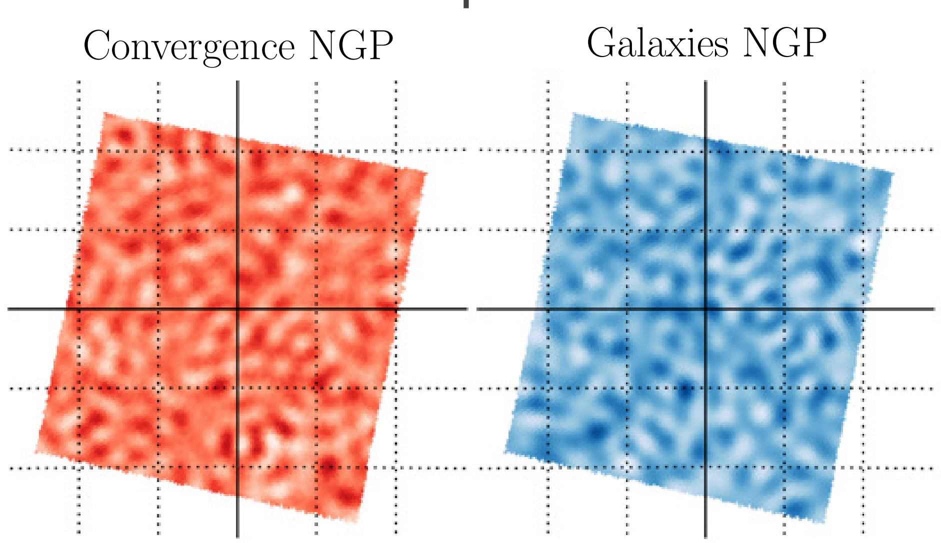
Baxter+16 : DES SV x SPT



Bleem+12 : SPT x WISE & Spitzer

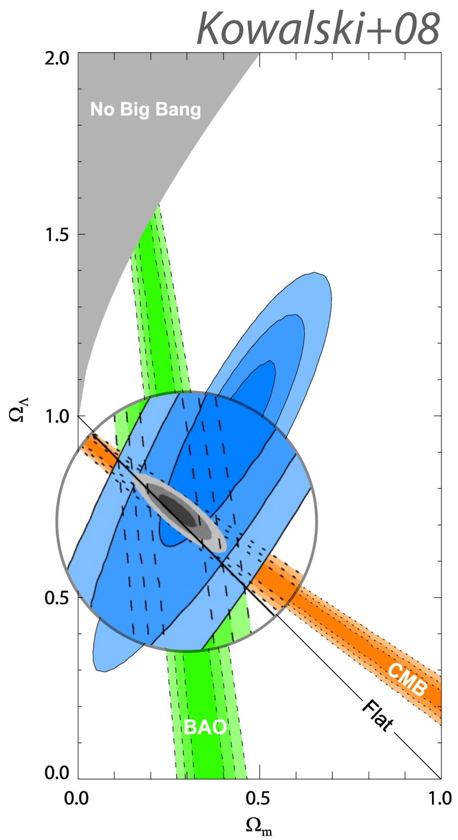


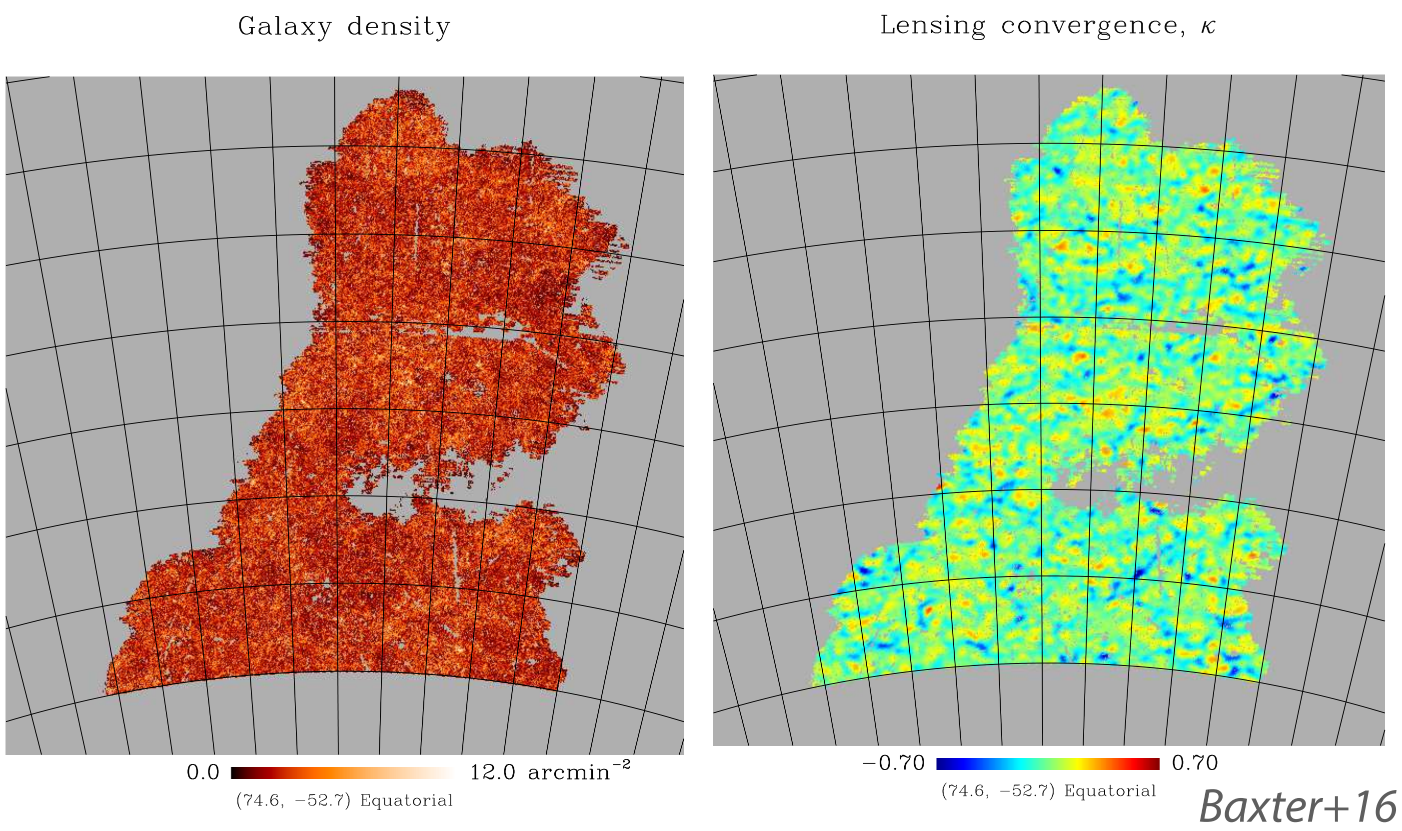
Planck13 : CIB x lensing



Bianchini+15 : Herschel x Planck

Exploiting combinations of probes





MOTIVATIONS

- **Combinations of probes** ⇒ break degeneracies
- **Cross-correlations** of *correlated* probes
  - ⟶ contain *free extra information* ⇒ sharper constraints
  - ⟶ they are less prone to systematics (noise uncorrelated)

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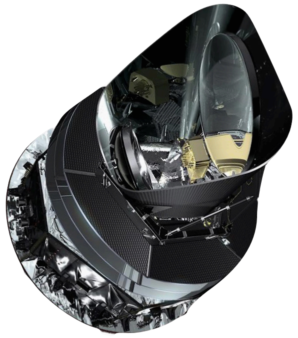
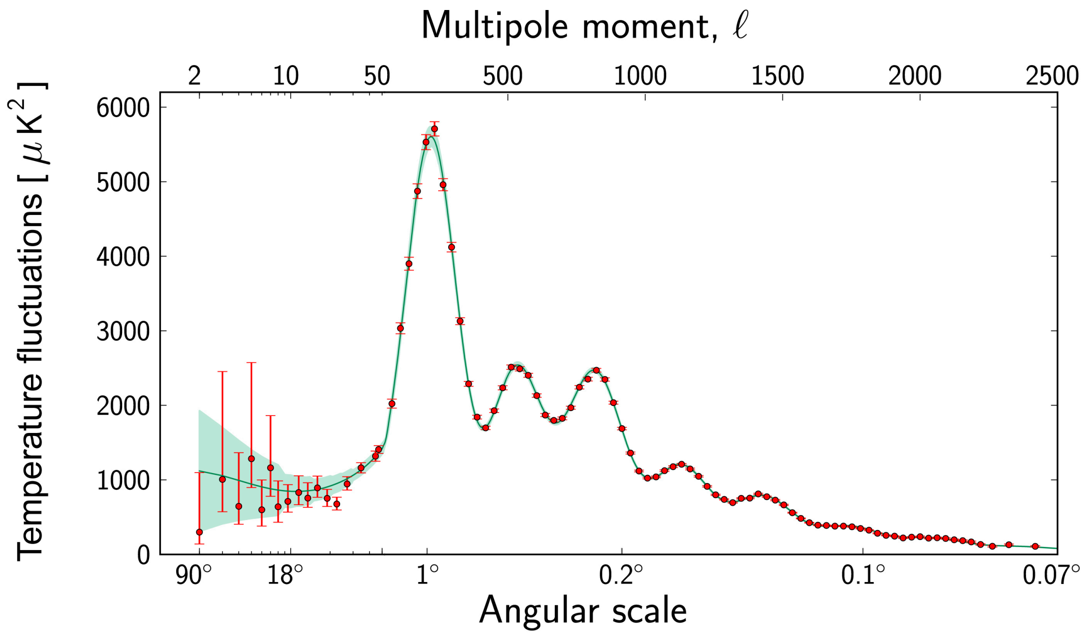
Planck

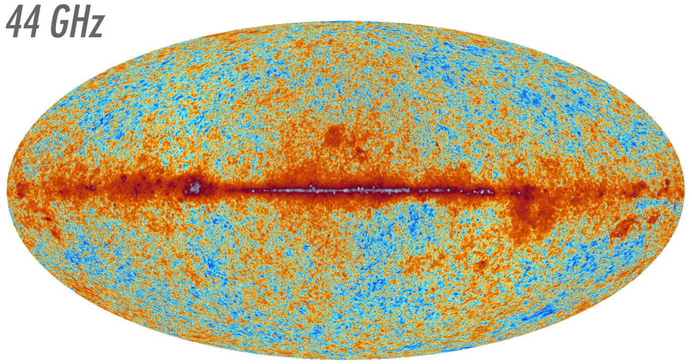
- esa full sky CMB satellite, launched in 2009, orbiting at L2
- two instruments on board :
  - **LFI** (30, 44, 77 GHz)
  - **HFI** (100, 143, 217, 353, 545, 857 GHz)



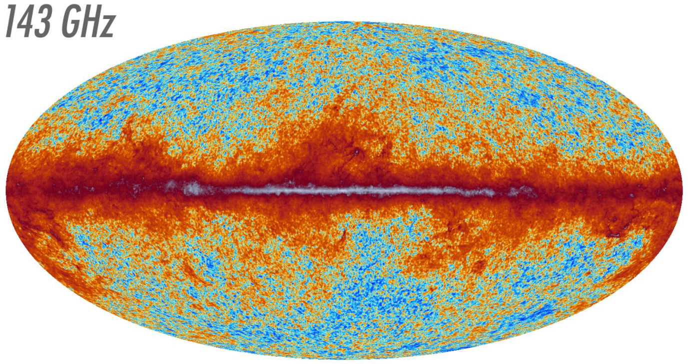
- **CMB maps** : `SMICA`
- C_ℓ^{TT} **likelihood** : low-ℓ (`commander`) + high-ℓ (`Plik`)
- **CMB lensing map**, SZ clusters, foreground maps, polarization, dust, magnetic field…



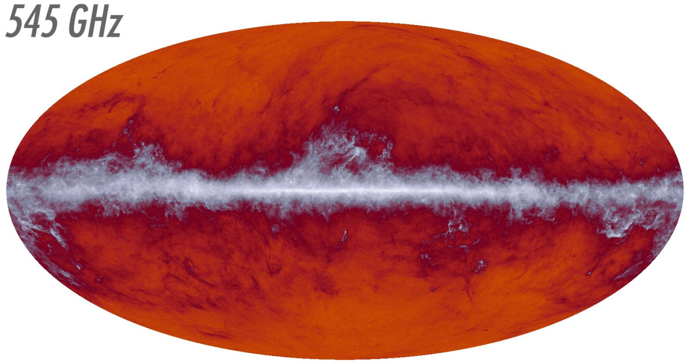
44 GHz

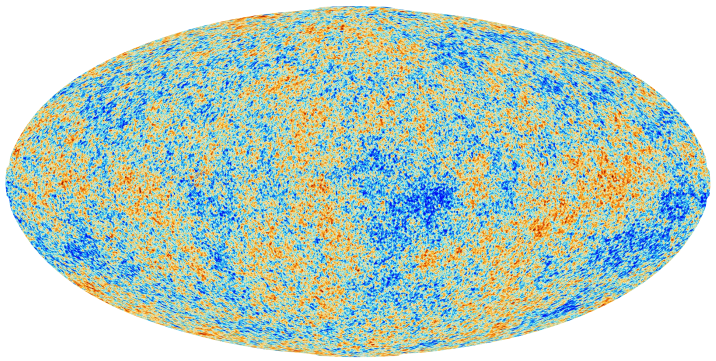


143 GHz



545 GHz





CMB lensing

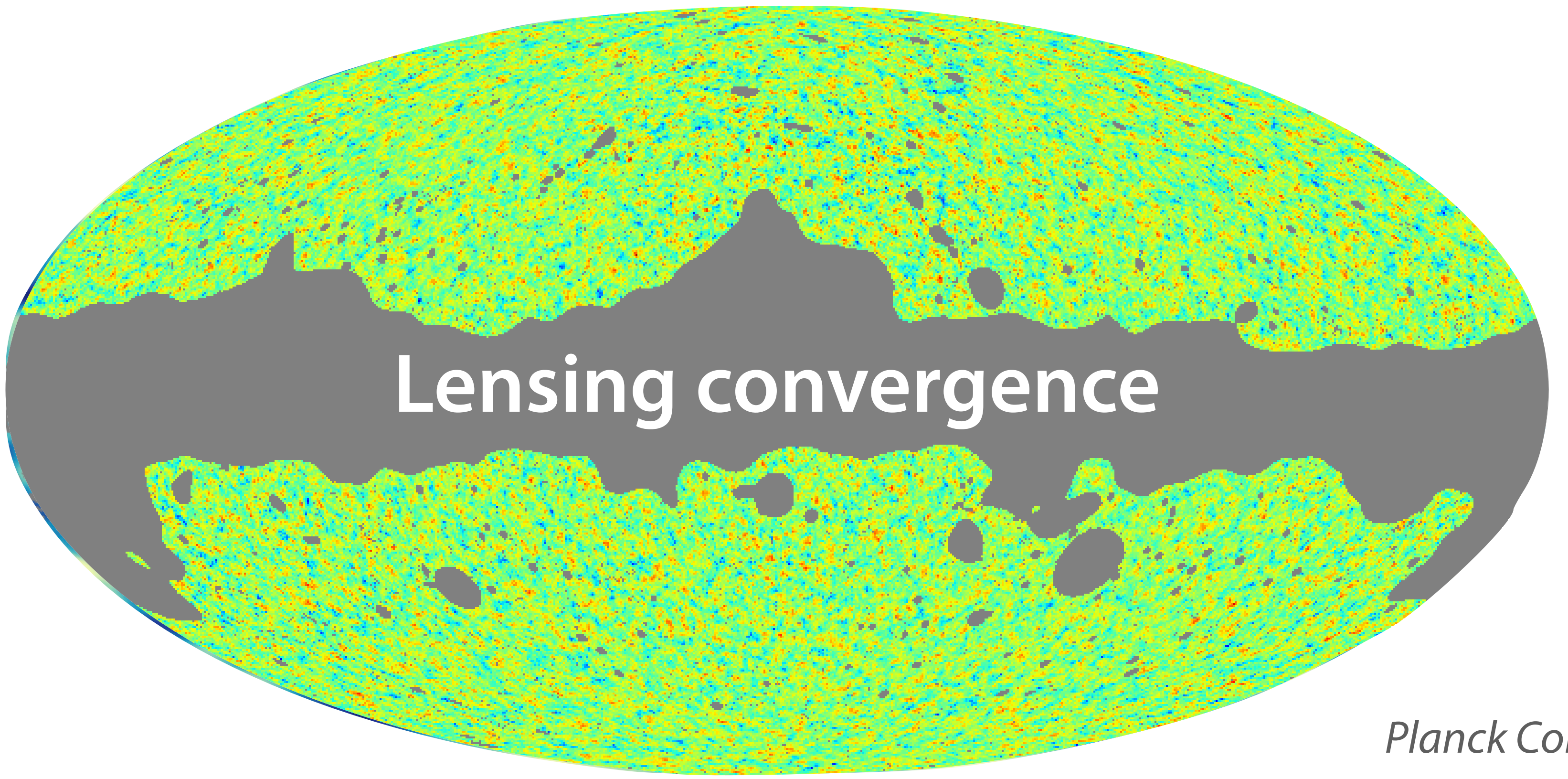
- **Remapping** of CMB (2′ deflection, coherent on patches 2°) :

$$T_{\text{obs}}(\hat{n}) = T(\hat{n} + \nabla\phi(\hat{n}))$$

- Lensing potential and **convergence** :

$$\kappa_{\text{CMB}} = -\frac{1}{2}\nabla^2\phi$$

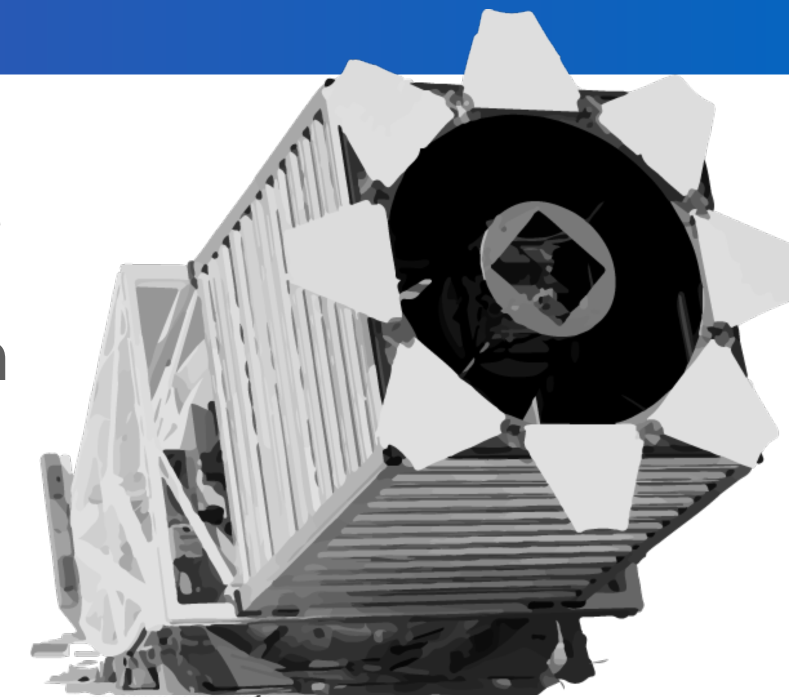
- *κ_{CMB} weighs matter along the l.o.s.* ⇒ **correlated with LSS tracers**



Planck Collaboration, 2013

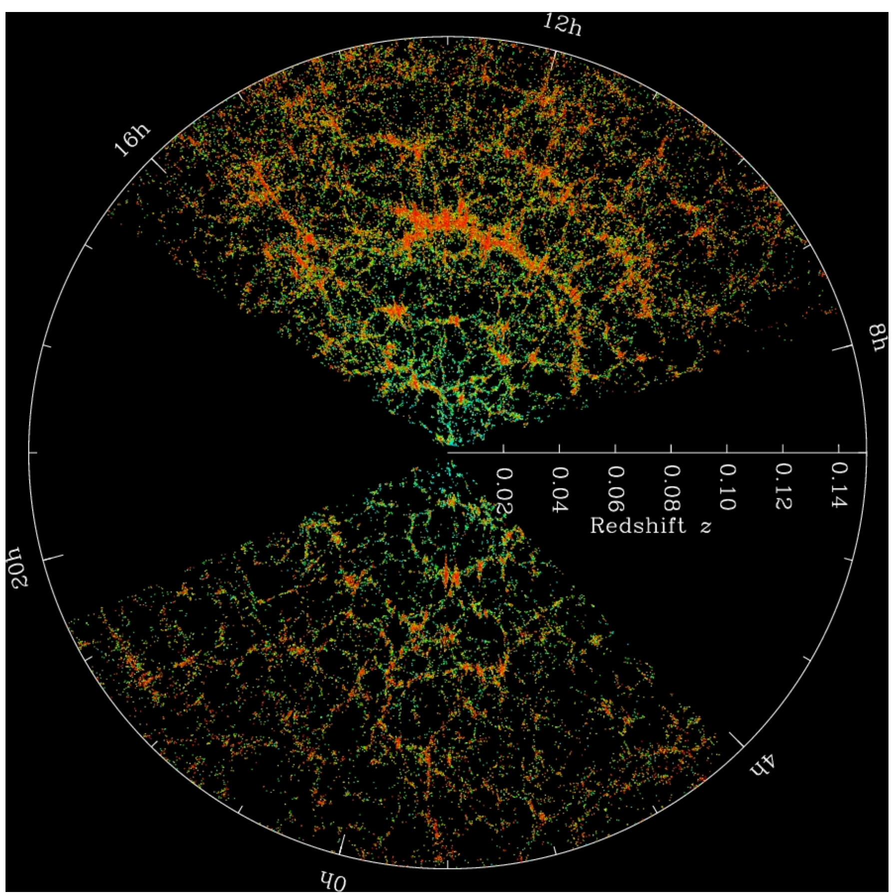
SDSS-III/BOSS

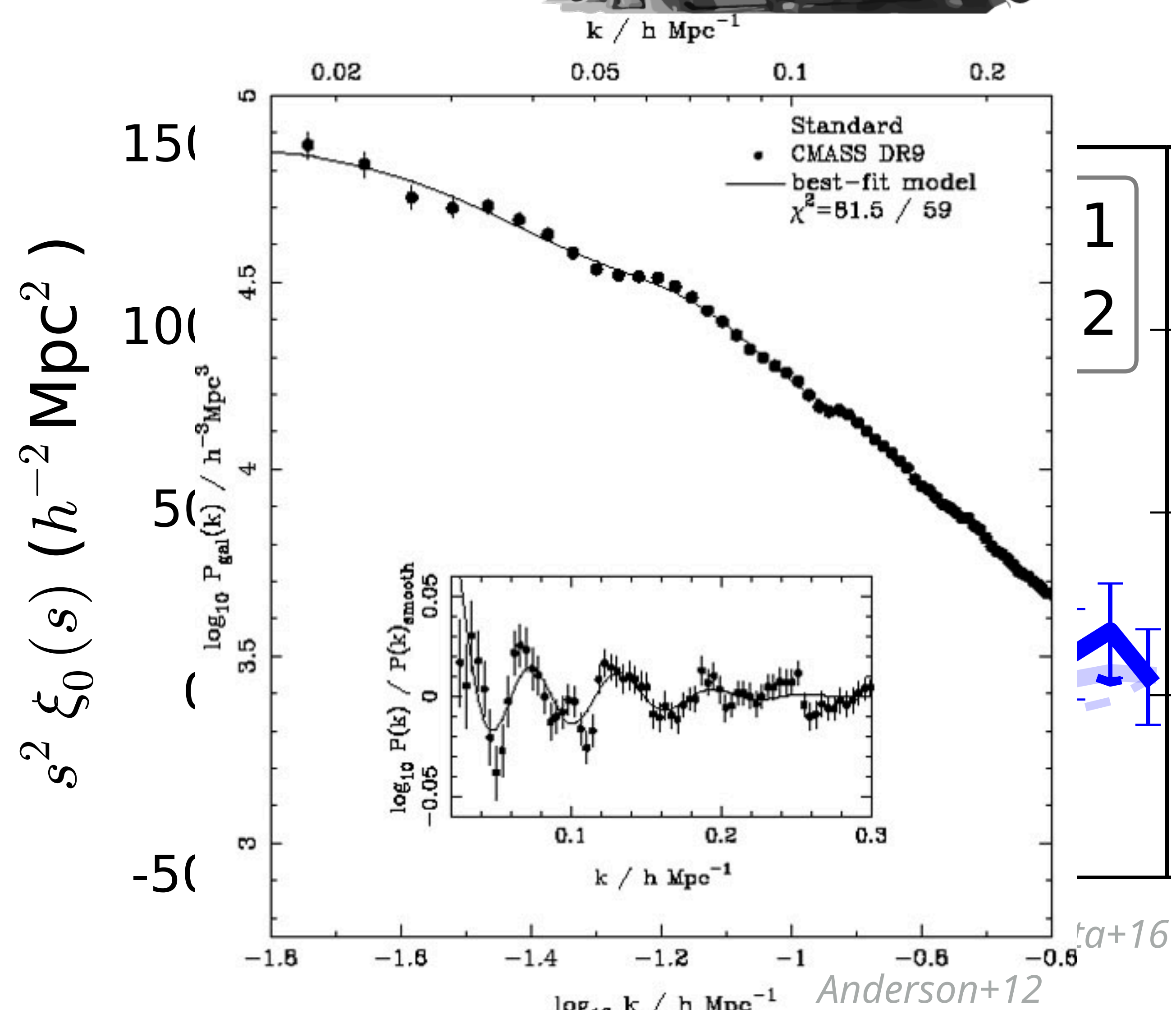
SDSS ∅=2.5m telescope at Apache Point Observatory, NM



BOSS = 1,000-fiber spectrograph, *R*~2000, λ=360-1100 nm

- 1M galaxies (LRGs), 200k quasars (with **Lyα forest**)
- large-scale structure : *P*(*k*), BAO, RSD, etc.





Spectroscopic samples

- **3 samples**

Redshift z

LOWZ

$0 \leq z \leq 0.4$, $N_{gal} = 392432$

- LRG in massive haloes $\langle M_{halo} \rangle \simeq 5.2 \times 10^{13}\ h^{-1}\ M_\odot$
- almost constant number density

CMASS

$0.4 \leq z \leq 0.8$, $N_{gal} = 811194$

- massive LRG with old stellar pop°, $M_{stellar} > 10^{13}\ M_\odot$
- close to (stellar) mass-limited sample

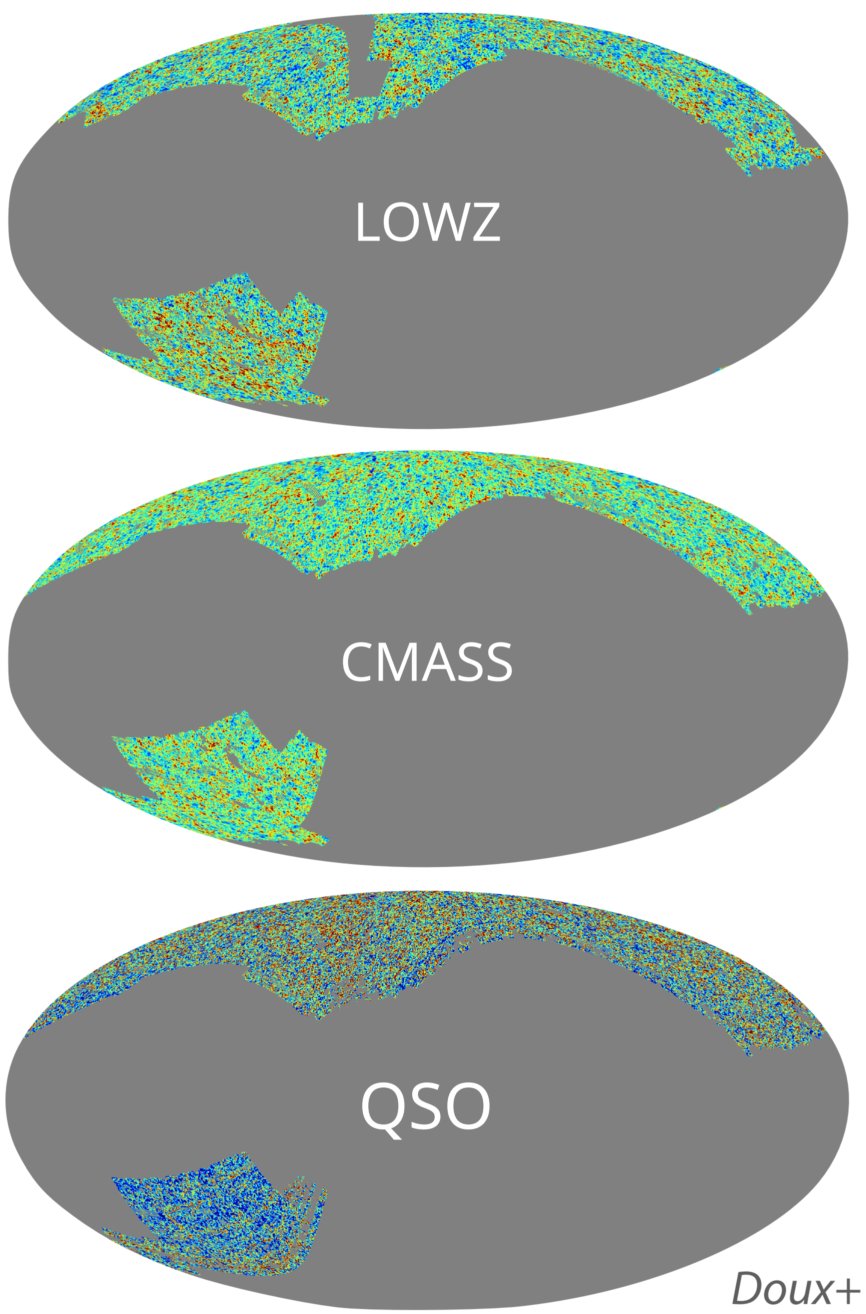
QSO

$2.15 \leq z \leq 3.5$, $N_{QSO} = 94971$

- "CORE" sample, uniformly selected by XDQSO
- high shot-noise

- **Projected overdensity**

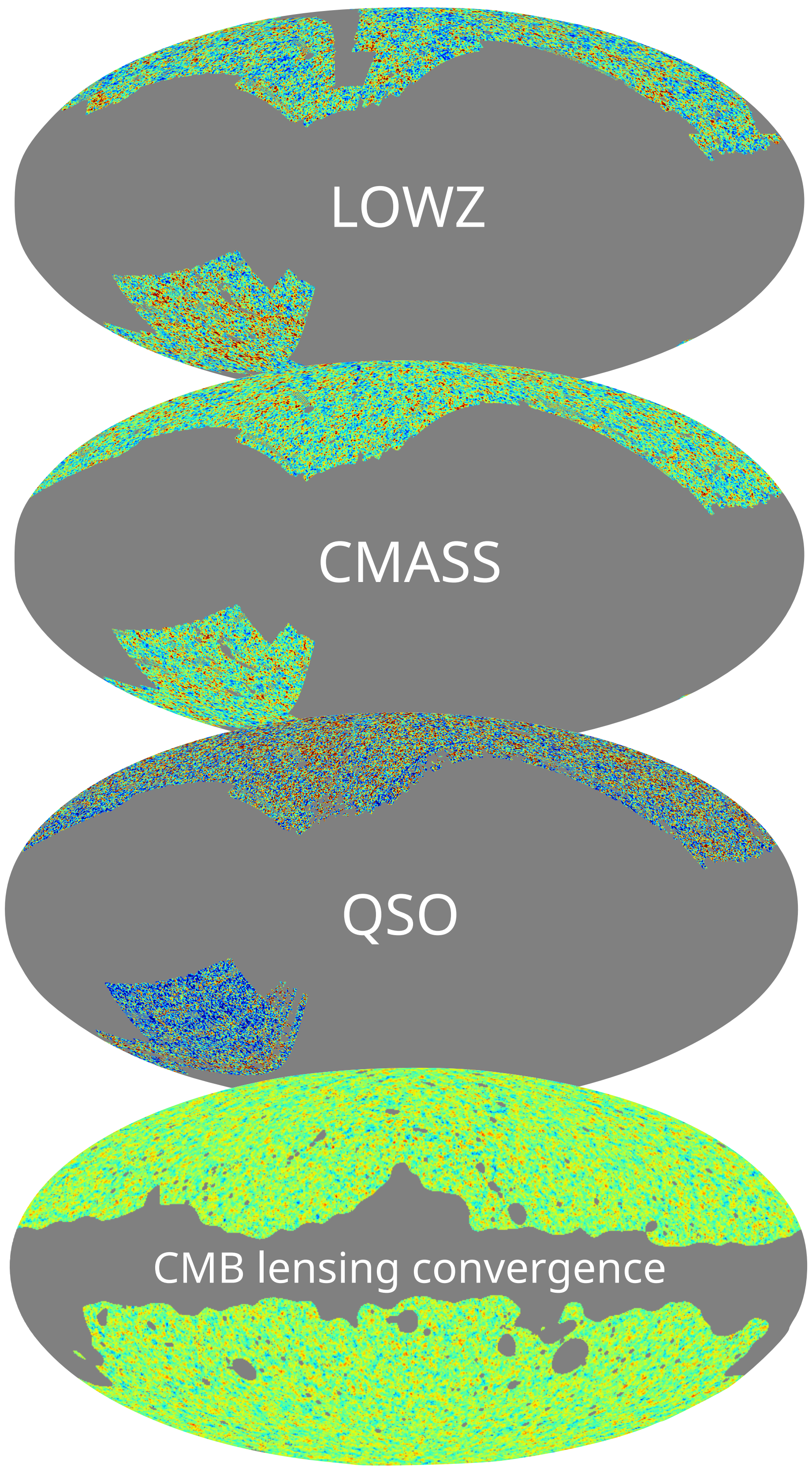
$$\delta(\theta) = \frac{\rho(\theta)}{\bar{\rho}} - 1$$



Doux+17

Why Planck × BOSS ?

- **AREA**
  - ⟶ large area: f_{sky}(Planck)=67% f_{sky}(BOSS)=25%
  - ⟶ largest spectroscopic sample available
  - ⟶ ~ full overlap
- **S/N of κ_{CMB} × BOSS tracers**
  - ⟶ 4.6σ, 13σ, 9.5σ for κ × LOWZ, CMASS, QSO
- **Complementarity**
  - ⟶ CMB ⇒ primordial Universe
  - ⟶ CMB lensing ⇒ weighs l.o.s. DM
  - ⟶ galaxies/quasar at z~0.25, 0.57, 2.2
    - redshift distribution perfectly known



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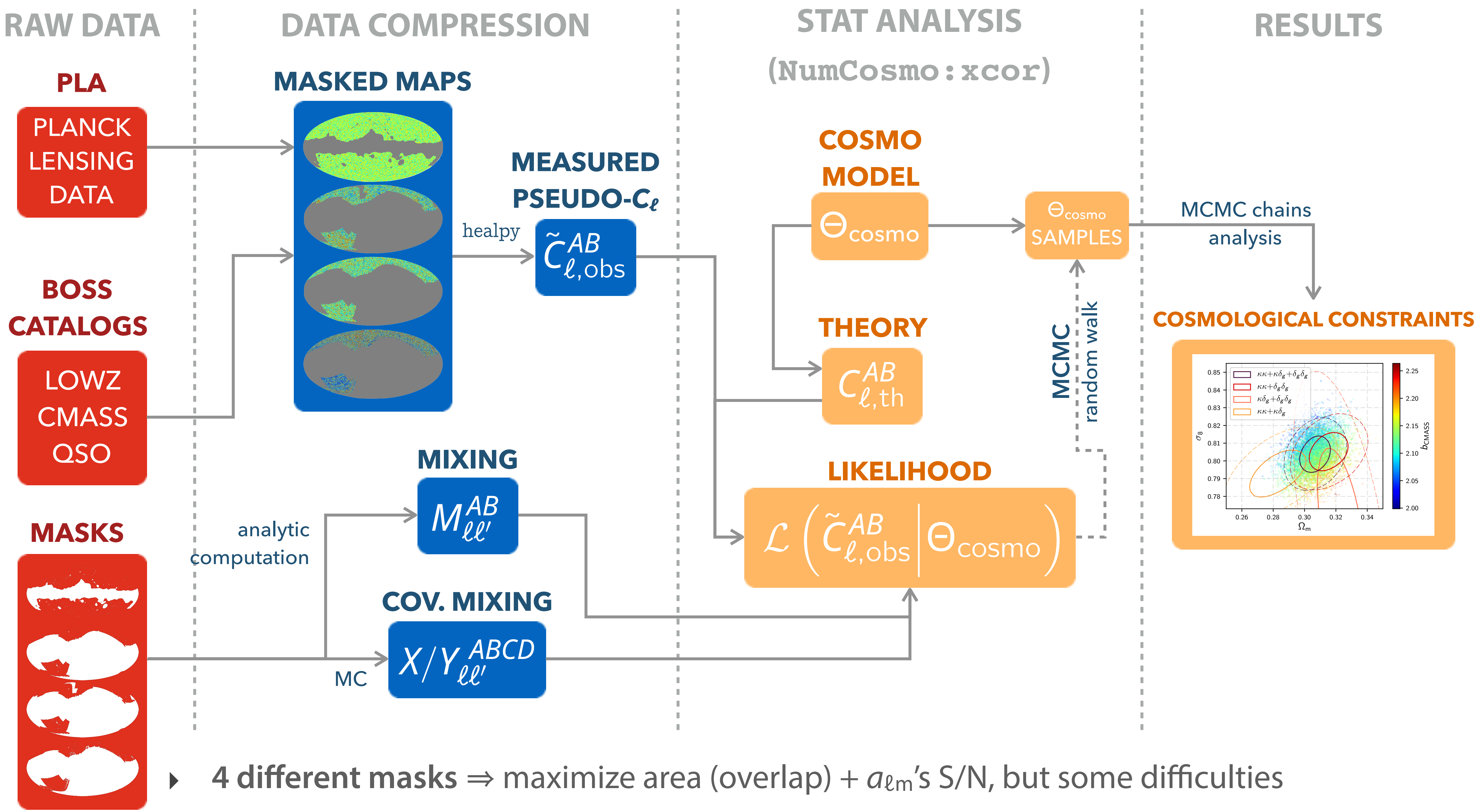
Pipeline



- **4 different masks** ⇒ maximize area (overlap) + $a_{\ell m}$'s S/N, but some difficulties
- **NumCosmo** `xcor` module: general framework for joint analyses of multiple probes

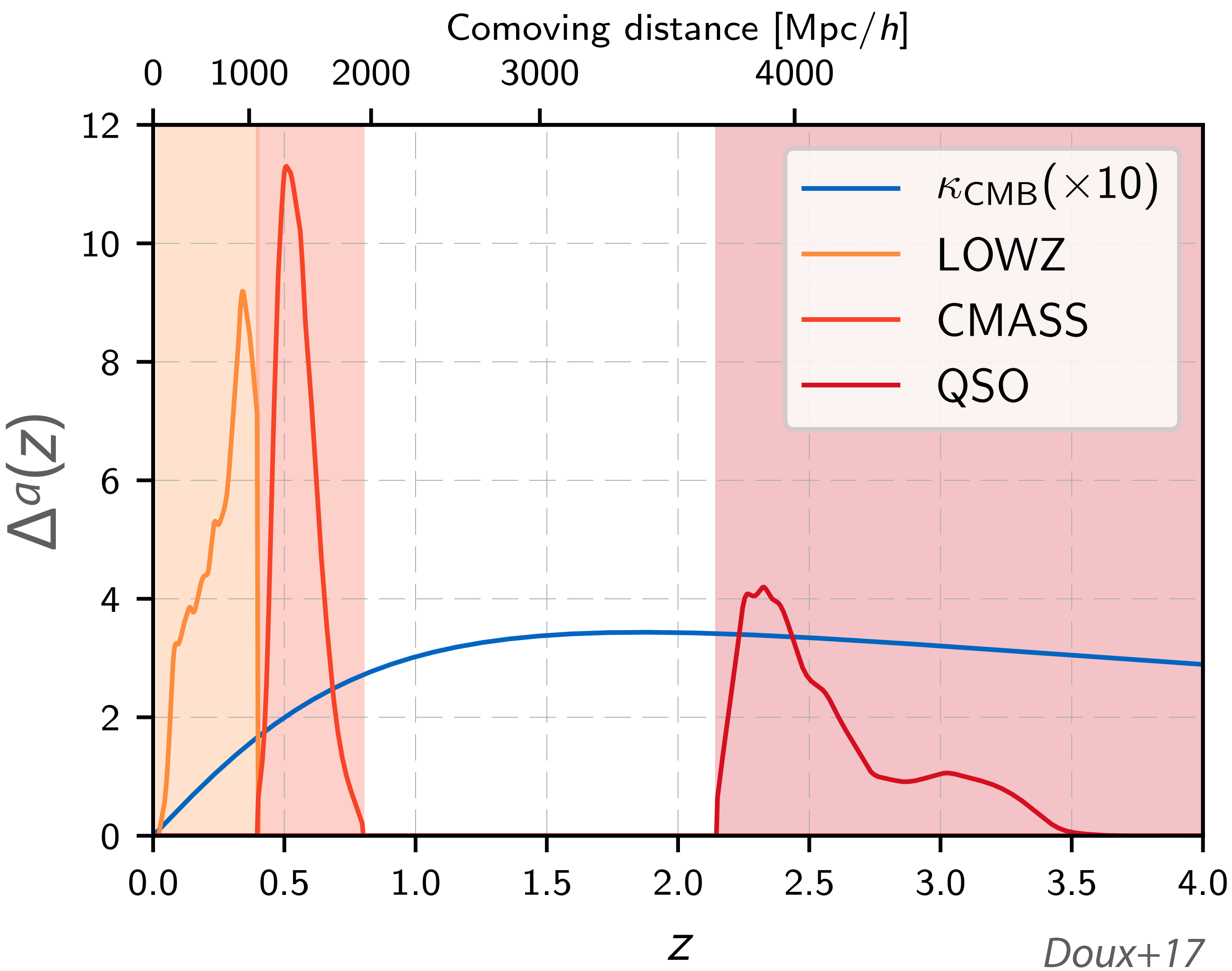
  @ numcosmo.github.io

Angular power spectrum: theory

Angular power-spectrum of *projected* observables *a* and *b* (Limber approx):

$$C_\ell^{ab} = \langle a_{\ell m} b_{\ell m}^* \rangle = \int_0^{z_*} dz \frac{H(z)}{c} \frac{1}{\chi(z)^2} \Delta_\ell^a(z) \Delta_\ell^b(z) P\left(k = \frac{\ell + 1/2}{\chi(z)}, z\right) + \mathcal{O}\left(\frac{1}{\ell^2}\right)$$

comoving distance — kernels — matter power spectrum



$$\Delta^\kappa(z) = \frac{3\Omega_m}{2} \frac{H_0^2}{H(z)} (1+z)\chi(z) \frac{\chi_* - \chi(z)}{\chi_*}$$

$$\Delta_\ell^g(z) = b(z) \frac{dn}{dz}$$ (+ lensing effects)

bias — redshift distribution

Angular power spectrum: estimators

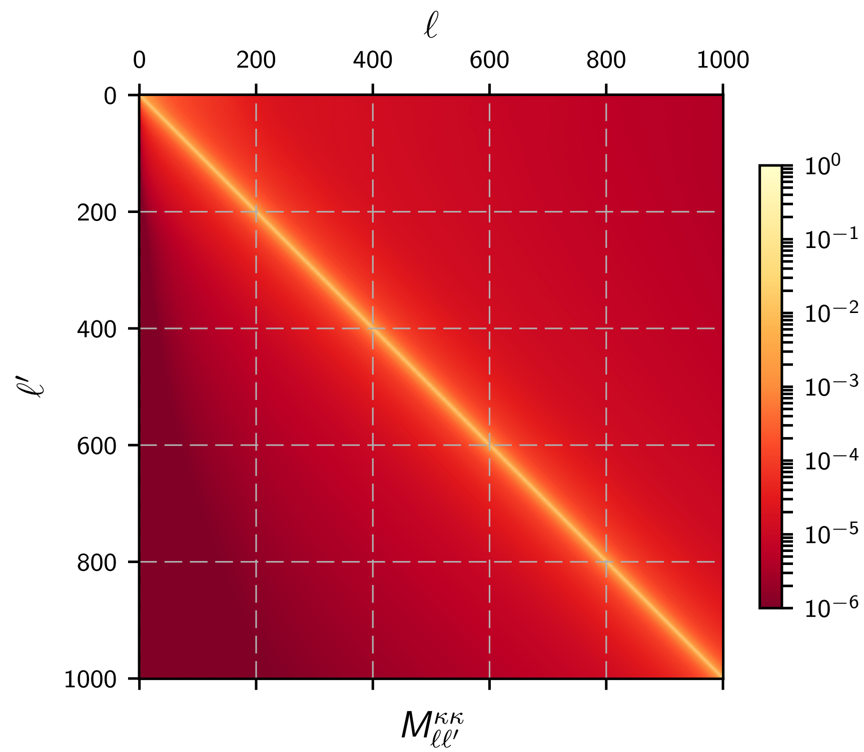
- **Partial sky** ⇒ *pseudo* angular power spectra :

$$\tilde{C}_\ell^{\rm th} = \sum_{\ell'} M_{\ell\ell'} C_{\ell'}$$

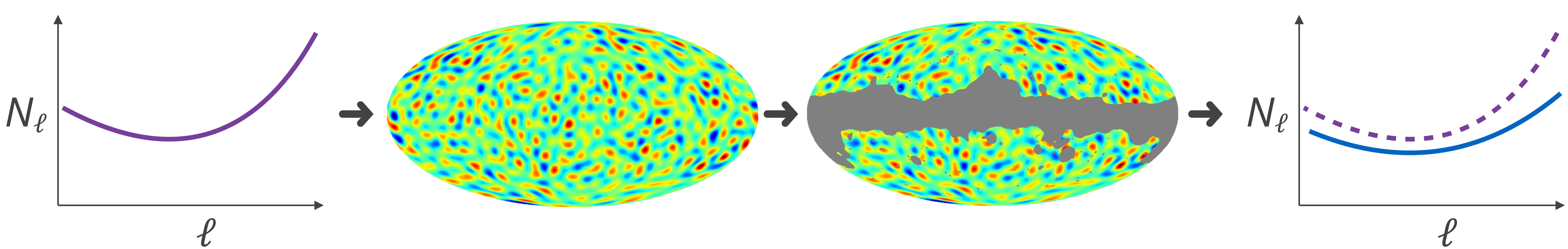
- **Estimator** :

$$\widehat{\tilde{C}_\ell^{\rm obs}} = \tilde{C}_\ell^{\rm map} - \langle \tilde{N}_\ell \rangle_{\rm MC}$$

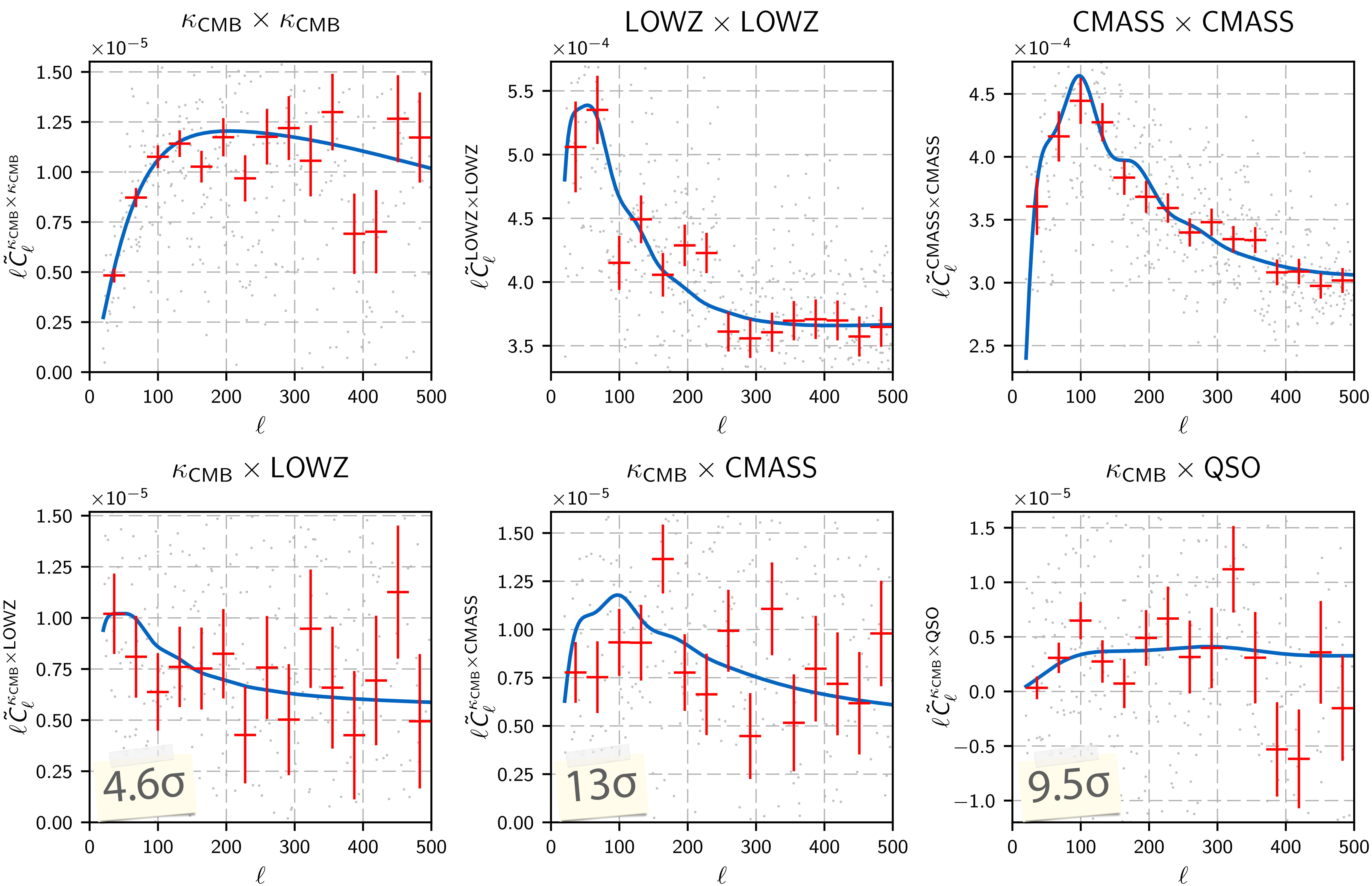
data = S + N pseudo-noise



- **Noise pseudo-spectrum**
  - For cross-spectra, noise is *uncorrelated*, so $\tilde{N}_\ell = 0$
  - For auto-spectra, $\tilde{N}_\ell$ estimated from **MC simulations**
    - Galaxies : shot-noise (pure Poisson) realizations with $N_\ell = 1/\bar{n}$
    - Lensing : Planck's 100 reconstruction simulations for κ



Auto- & cross-power spectra



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Likelihood

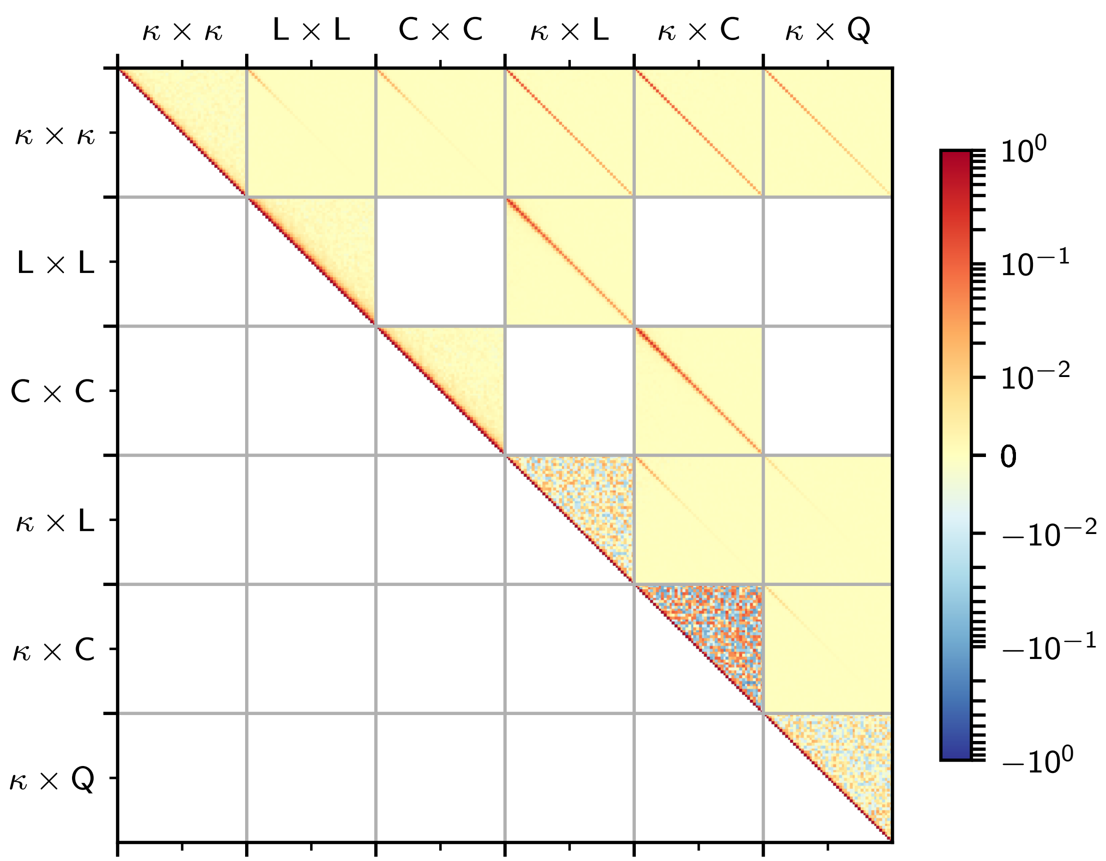
- Gaussian likelihood :

$$\mathcal{L}\left(\tilde{C}_\ell^{\rm obs}|b_g,\Theta_{\rm cosmo}\right) = \frac{1}{(2\pi)^{n/2}|\mathbf{Cov}|^{1/2}}\exp\left[-\frac{1}{2}\left(\tilde{C}_\ell^{\rm obs}-\mathbf{M}_{\ell\ell'}C_{\ell'}^{\rm th}\right)^{\rm T}\mathbf{Cov}^{-1}\left(\tilde{C}_\ell^{\rm obs}-\mathbf{M}_{\ell\ell'}C_{\ell'}^{\rm th}\right)\right]$$

- Semi-analytical covariance (Efstathiou's approx., see Brown+05) :

$$\mathrm{Cov}\left(\tilde{C}_\ell^{ab},\tilde{C}_{\ell'}^{cd}\right) = \sqrt{D_\ell^{ad}D_{\ell'}^{ad}D_\ell^{bc}D_{\ell'}^{bc}}\,\mathbf{X}_{\ell\ell'}^{abcd} + \sqrt{D_\ell^{ac}D_{\ell'}^{ac}D_\ell^{bd}D_{\ell'}^{bd}}\,\mathbf{Y}_{\ell\ell'}^{abcd}$$

where $D_\ell^{ab} = C_\ell^{ab} + \delta_{ab}N_\ell^a$

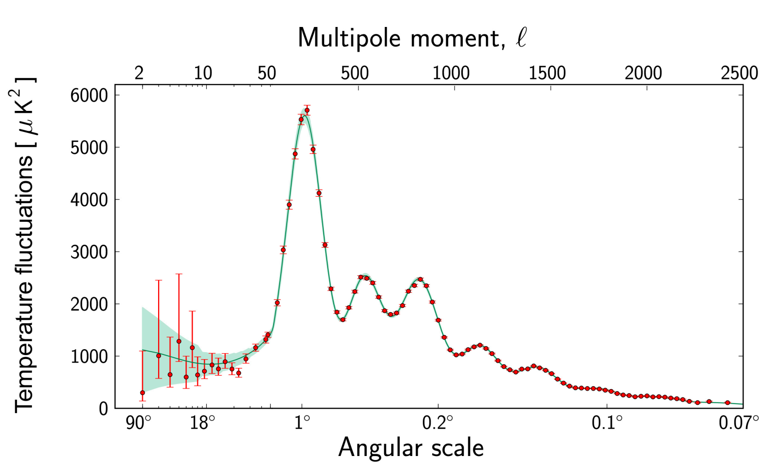


⟶ covariance of stacked $\tilde{C}_\ell^{ab}$

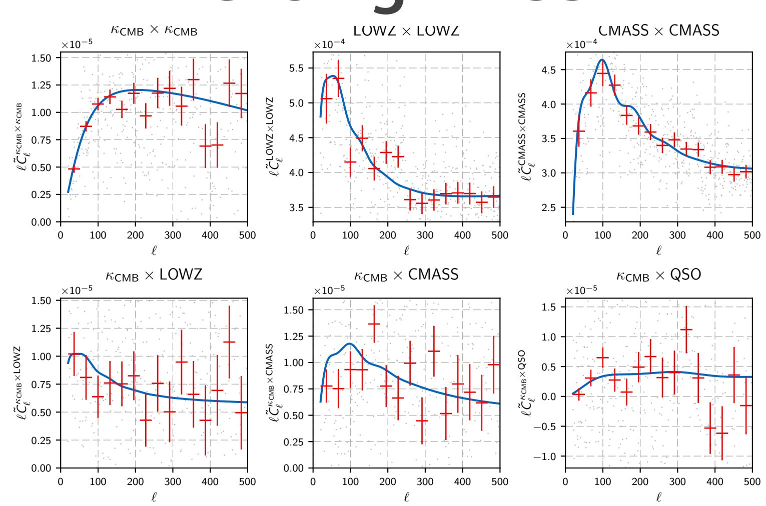
Wrapping up

- **Parameters**
  - ⟶ **Cosmology**: flat ΛCDM, 6 base params H_0, ω_b, ω_c, A_s, n_s, z_{re}, then m_ν and w
  - ⟶ **BOSS samples**: 3 biases + 2 nuisance params (shot noise)
- **Computations**
  - ⟶ **`NumCosmo:xcor`** module: free object-oriented C library (with GObject), on GitHub
  - ⟶ Power spectrum from **`CLASS`** + **halofit** (reimplemented)
- **Data**
  - ⟶ "**Planck *TT***" = Planck CMB temperature C_ℓ^{TT} (high + low ℓ)
  - ⟶ "**Planck *TT* + lensing**" = Planck *TT* + Planck $\kappa_{\rm CMB}$ $\tilde{C}_\ell$
  - ⟶ "**Planck *TT* + lensing ⊗ LSS**" = Planck *TT* + (Planck $\kappa_{\rm CMB}$⊗BOSS samples) $\tilde{C}_\ell^{ab}$ **= Joint analysis**

"Planck *TT*"



"lensing ⊗ LSS"



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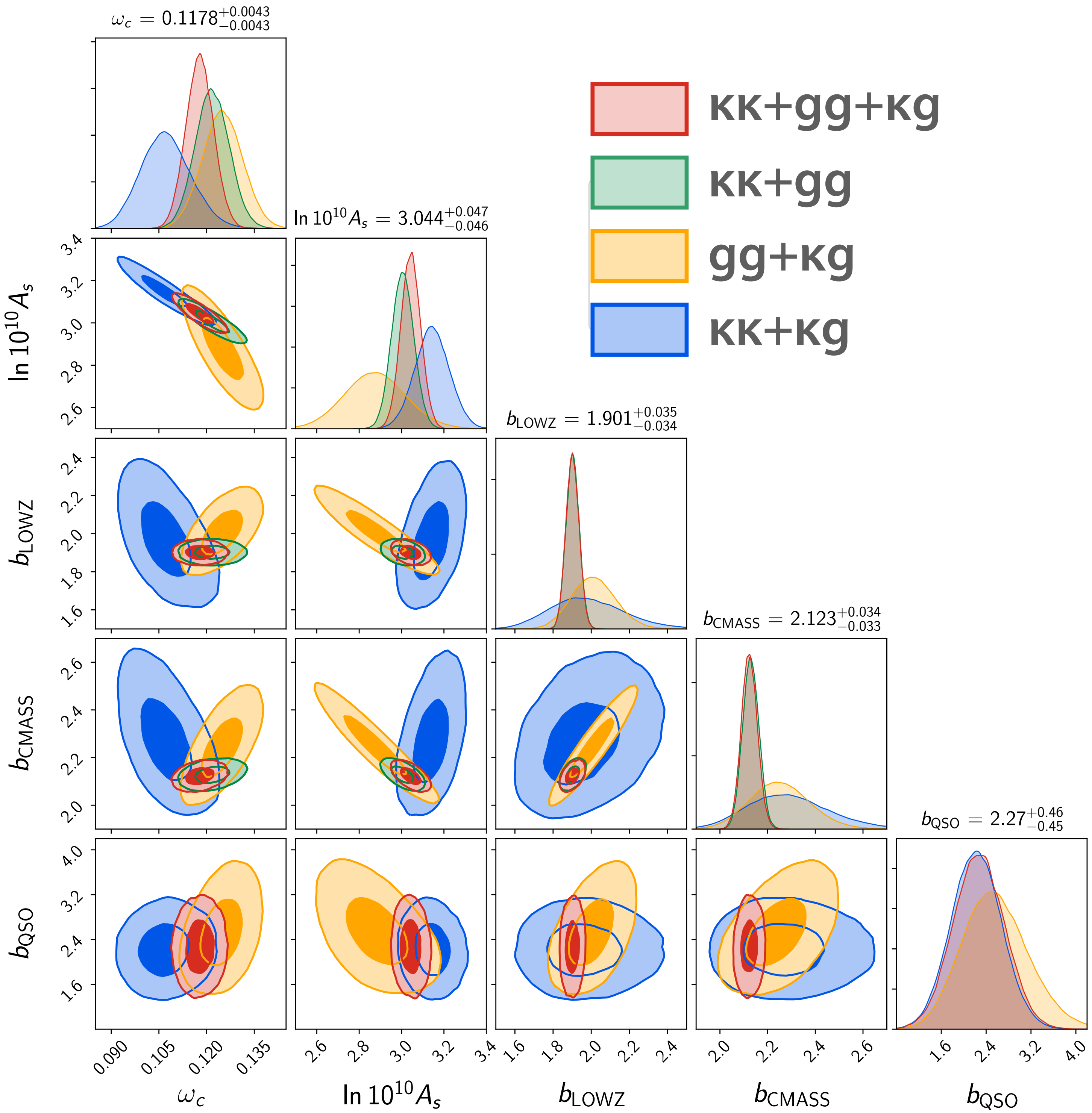
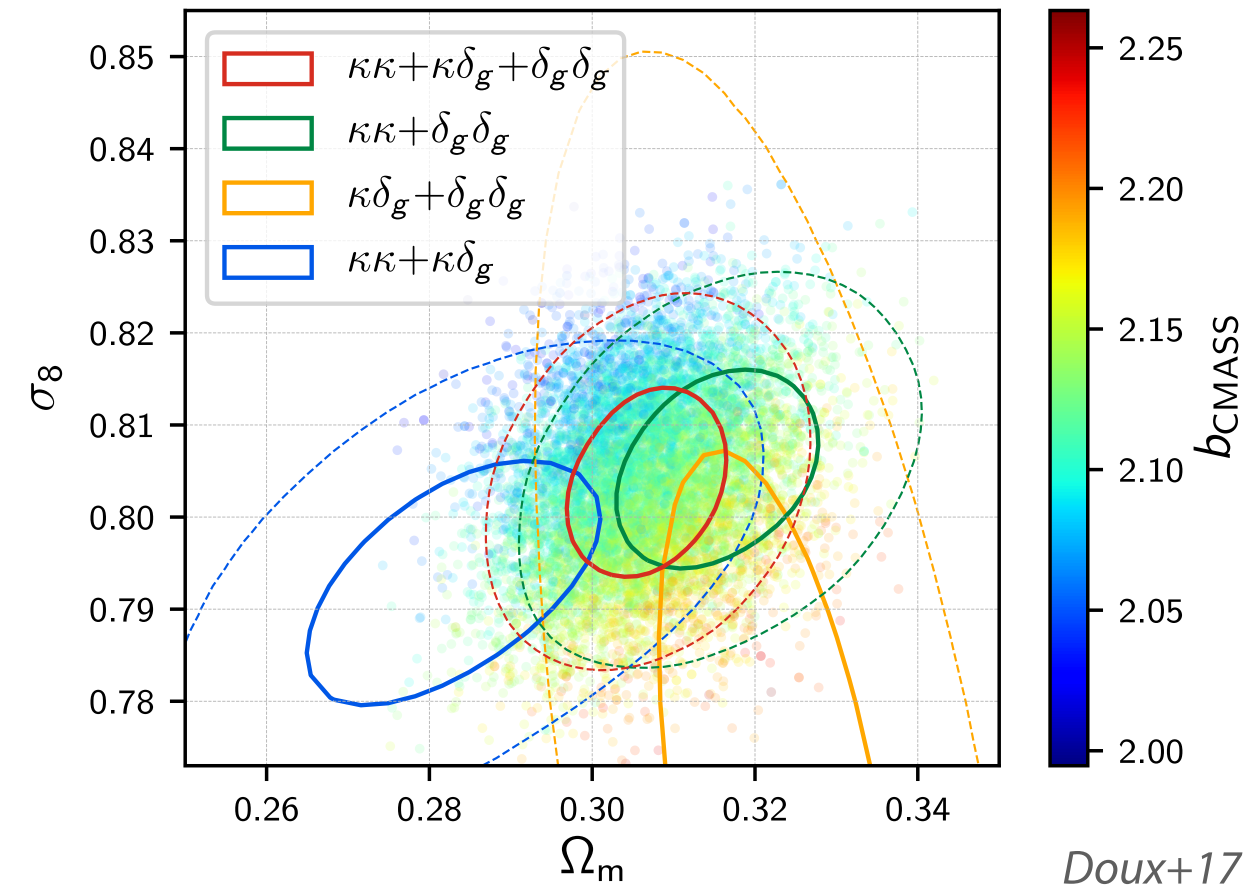
Contraints from lensing⊗LSS only





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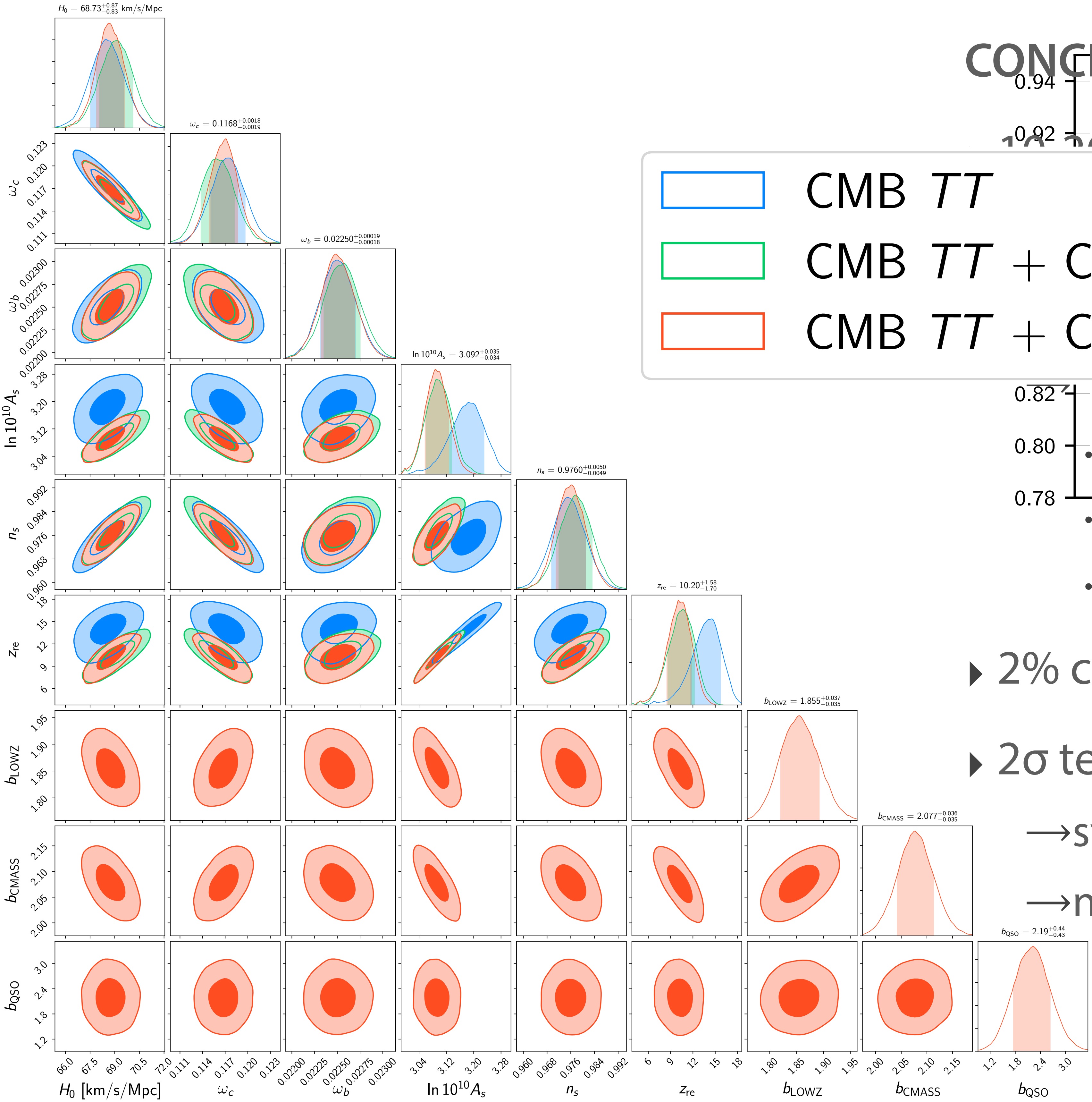
$$C_\ell^{\kappa\kappa} \propto \Omega_m^2 A_s$$

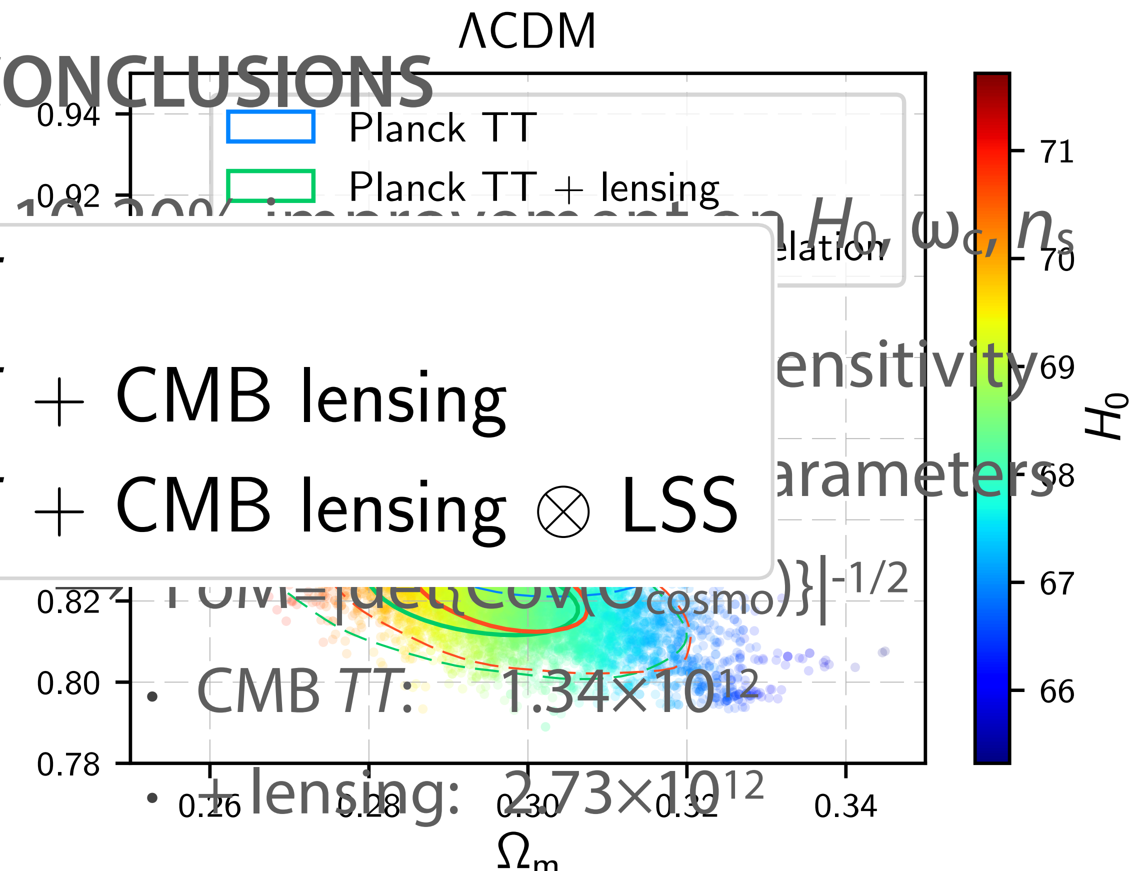
$$C_\ell^{\kappa g} \propto \Omega_m b A_s$$

$$C_\ell^{gg} \propto b^2 A_s$$

- **Multiple probes** to break degeneracies
- **Cross-correlations** improve constraints by 10-20%

Constraints on ΛCDM



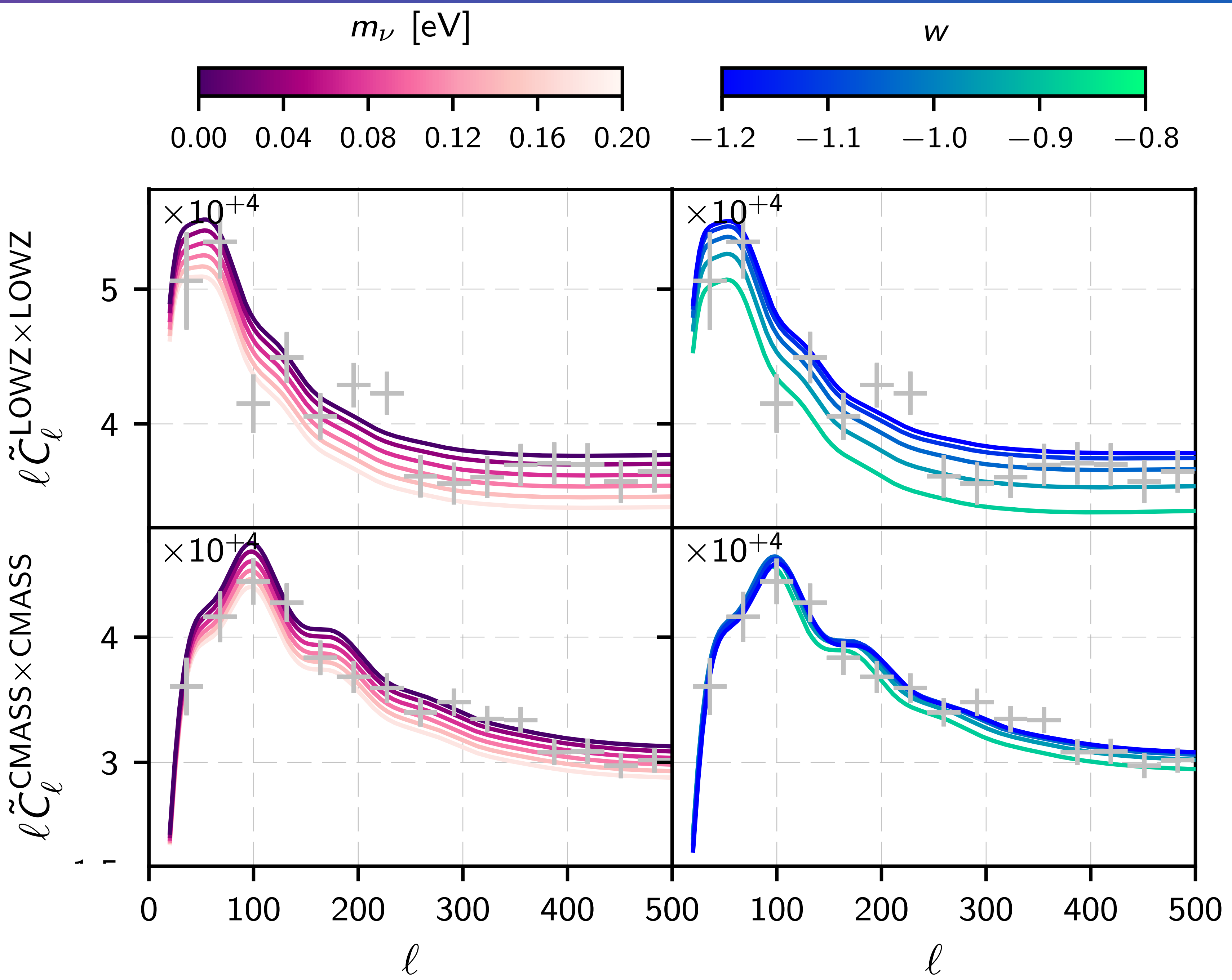


CONCLUSIONS

- 10-20% improvement on H_0, ω_c, n_s
- ...correlation
- ...sensitivity
- ...parameters
- FoM=[det(Cov(O_{cosmo}))]$^{-1/2}$
  - CMB *TT*: 1.34×10^{12}
  - + lensing: 2.73×10^{12}
  - ⊗ LSS: 3.89×10^{12}

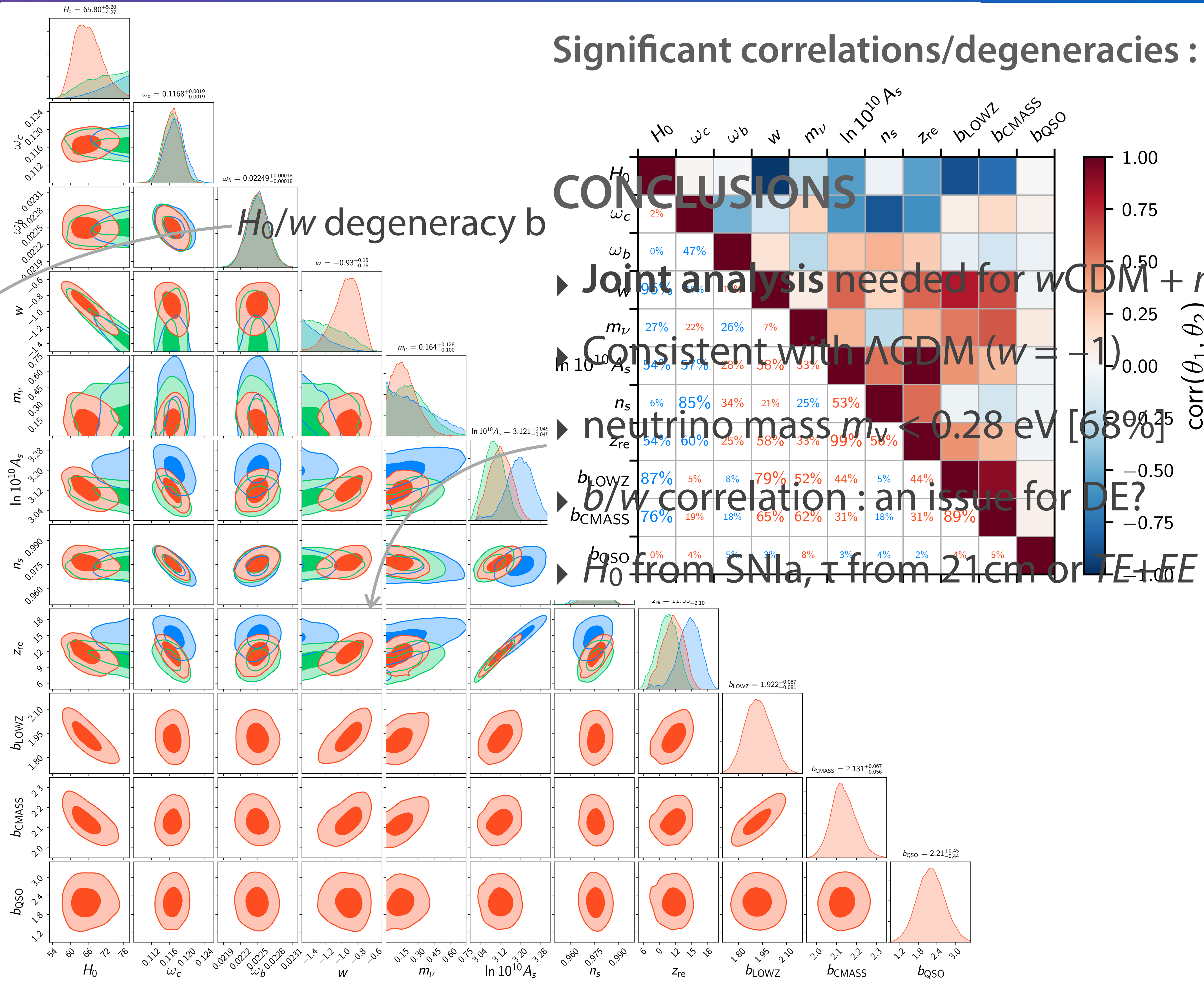
- 2% constraints on biases
- 2σ tension in σ_8-Ω_m CMB *vs* LSS
  - →systematics?
  - →new physics?

Constraints on *w*CDM + m_ν



- Galaxies trace z~0.2-0.8 ⇒ sensitive to w
- Small-scale clustering affected by m_ν

Constraints on wCDM + m_ν



H_0/w degeneracy b

Significant correlations/degeneracies :

CONCLUSIONS

- **Joint analysis** needed for wCDM + m_ν
- Consistent with ΛCDM ($w = -1$)
- neutrino mass $m_\nu < 0.28$ eV [68%]
- b/w correlation : an issue for DE?
- H_0 from SNIa, τ from 21cm or TE+EE

Conclusion I

Results

- Method + code for joint statistical analysis of CMB, LSS tracers & weak lensing
- Significant improvement on H_0, w, ω_c and m_ν (depends on small scales)
- Constraints on 8-params model wCDM + m_ν + biases ⟶ impossible independently !

Conclusion I

In the future

- Likelihood/covariance
  - ⟶ covariance noisy and expensive (size ~ $\ell_{max} \times N_{obs}^4/4$) but takes care of masks
  - ⟶ non-gaussianities (bi- & tri-spectrum terms) or super-sample variance
- Theory
  - ⟶ non-linear power spectrum, neutrinos, baryons ?
  - ⟶ Limber approximation (`Angpow`), relativistic effects (lensing & RSD mostly)

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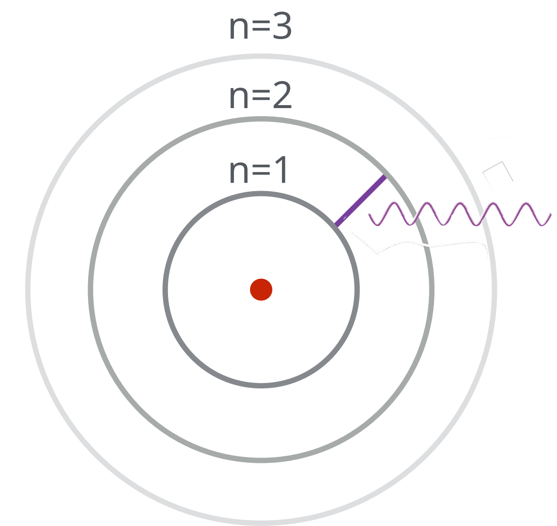
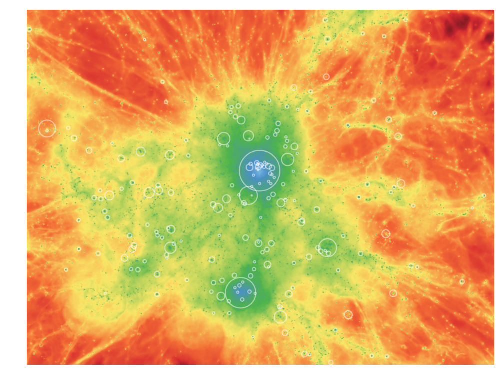
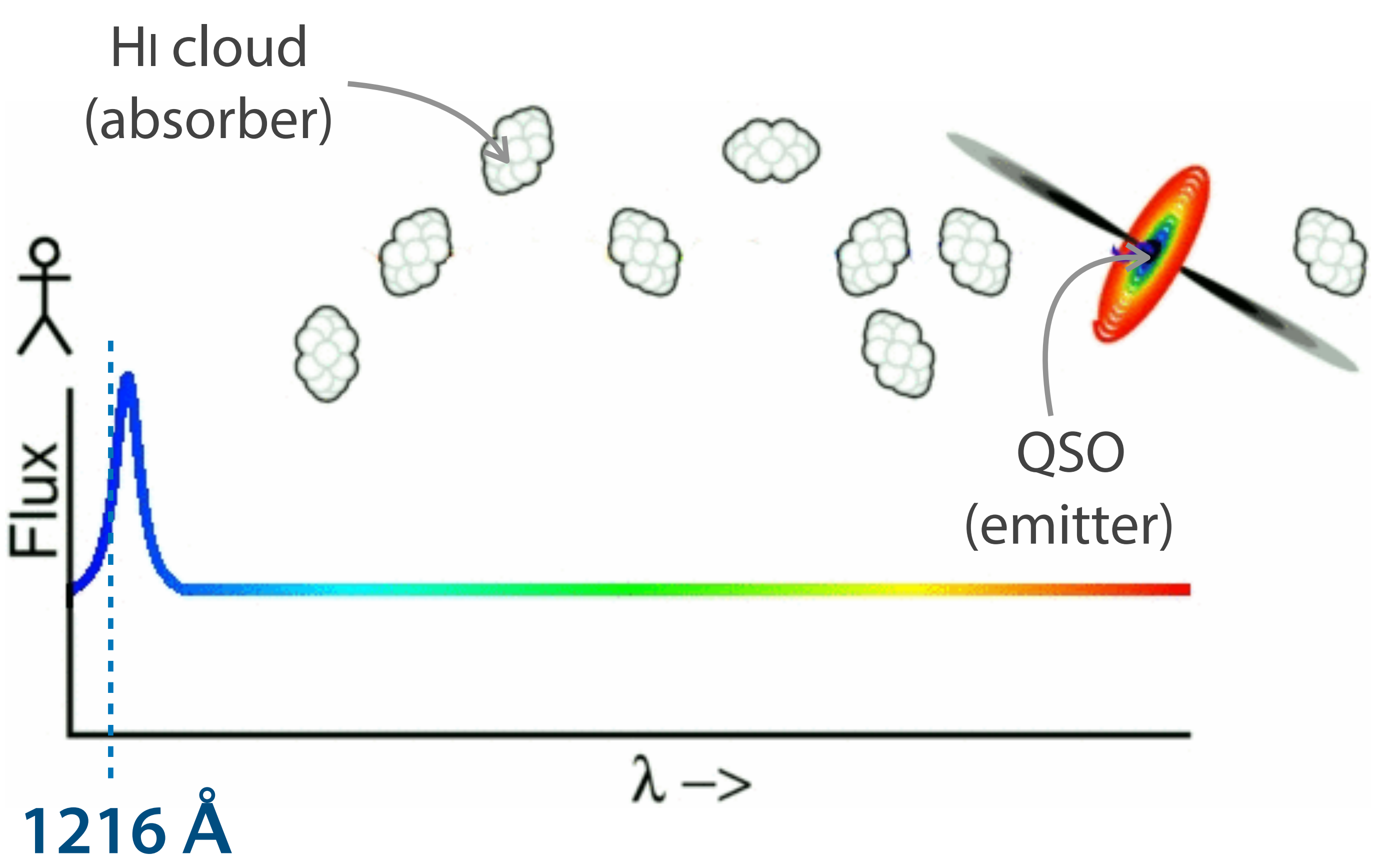
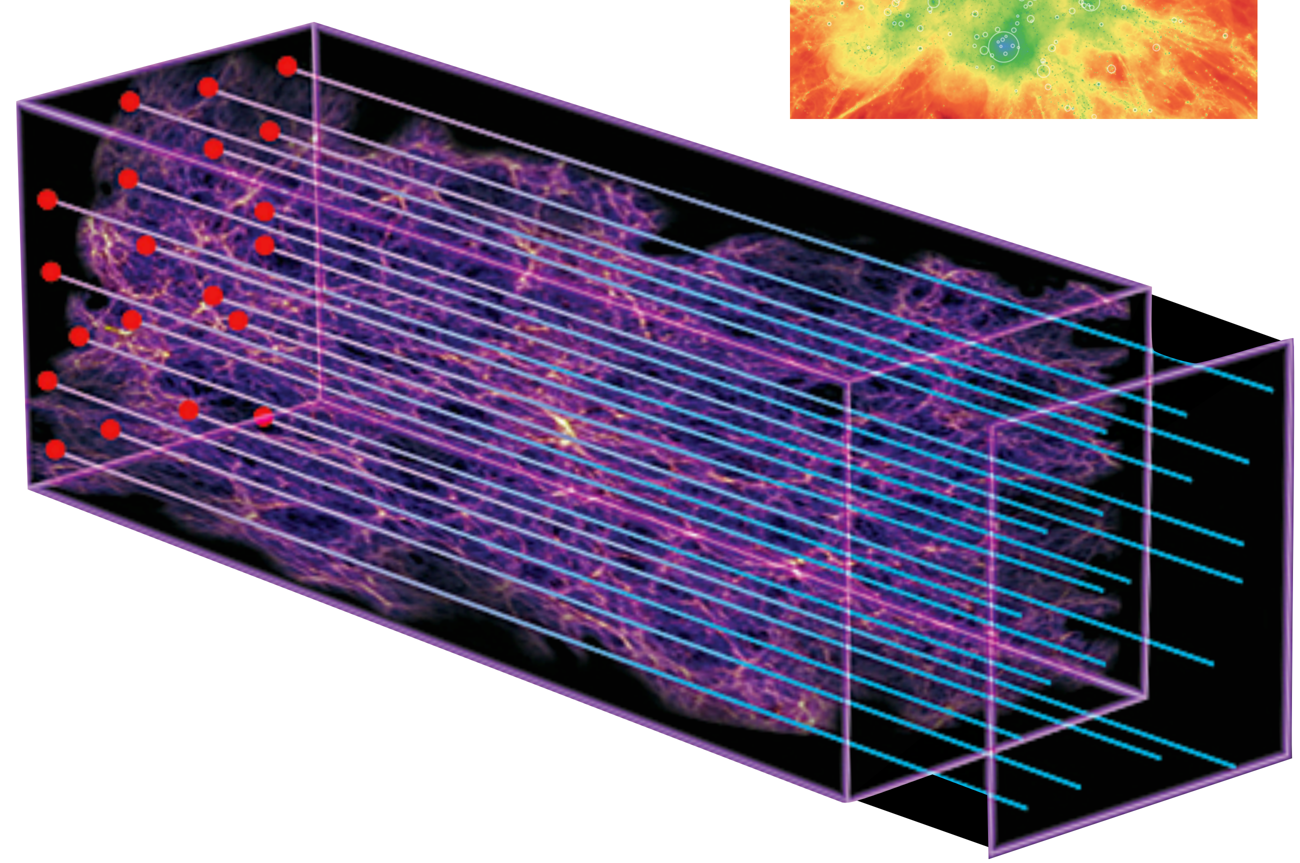
Lyman-α forest

- **neutral hydrogen HI** Ly-α transition, λ=1216 Å
- **spectra of quasars** carved by many HI absorption lines
  - ⟶ Ly-α forest = a *core sample* probing **HI in IGM** at z~2-4
  - ⟶ used as a *tracer* of the large-scale structure ⇒ BAO, *P*(*k*)

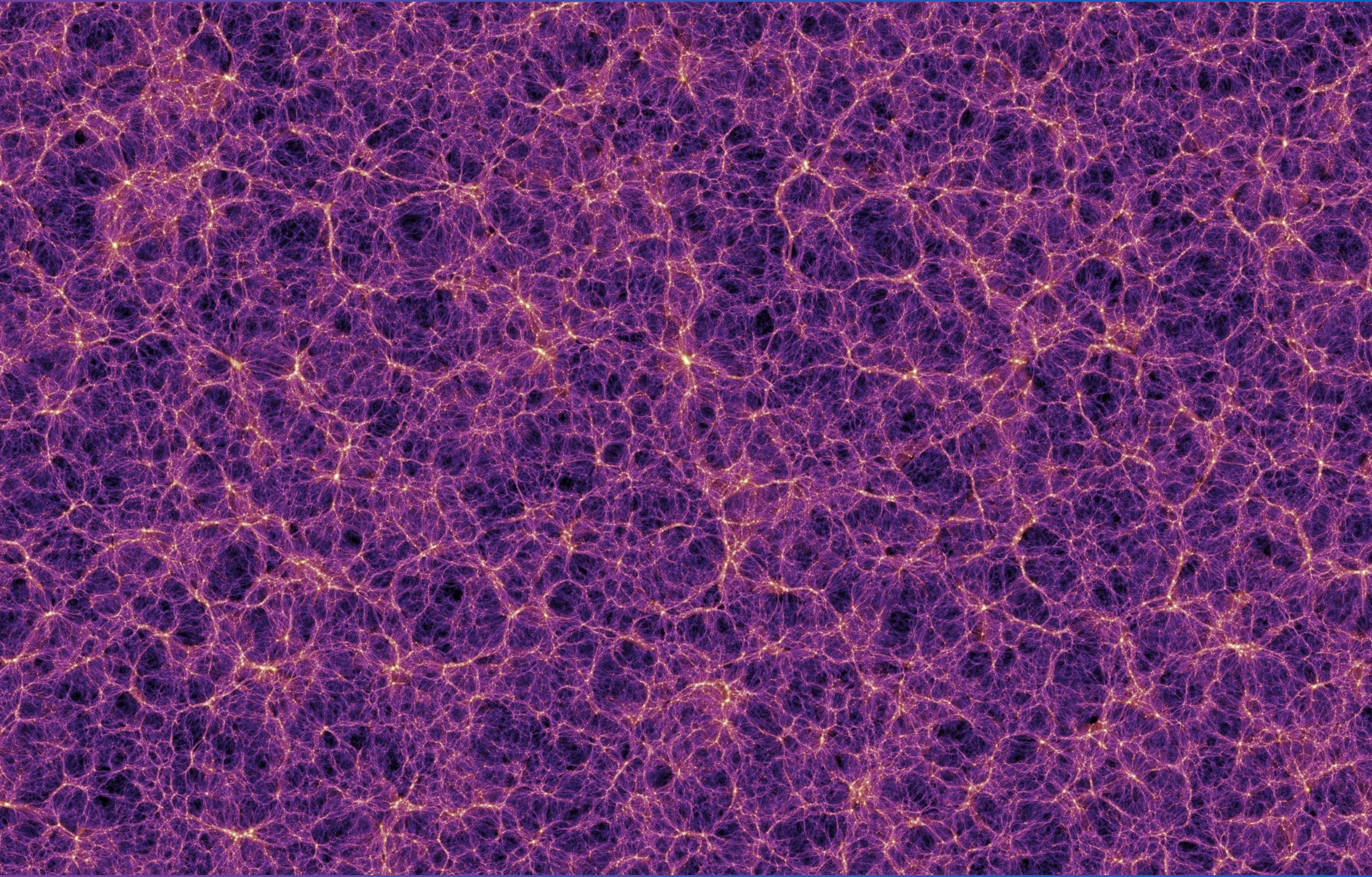








Position-dependent power spectrum



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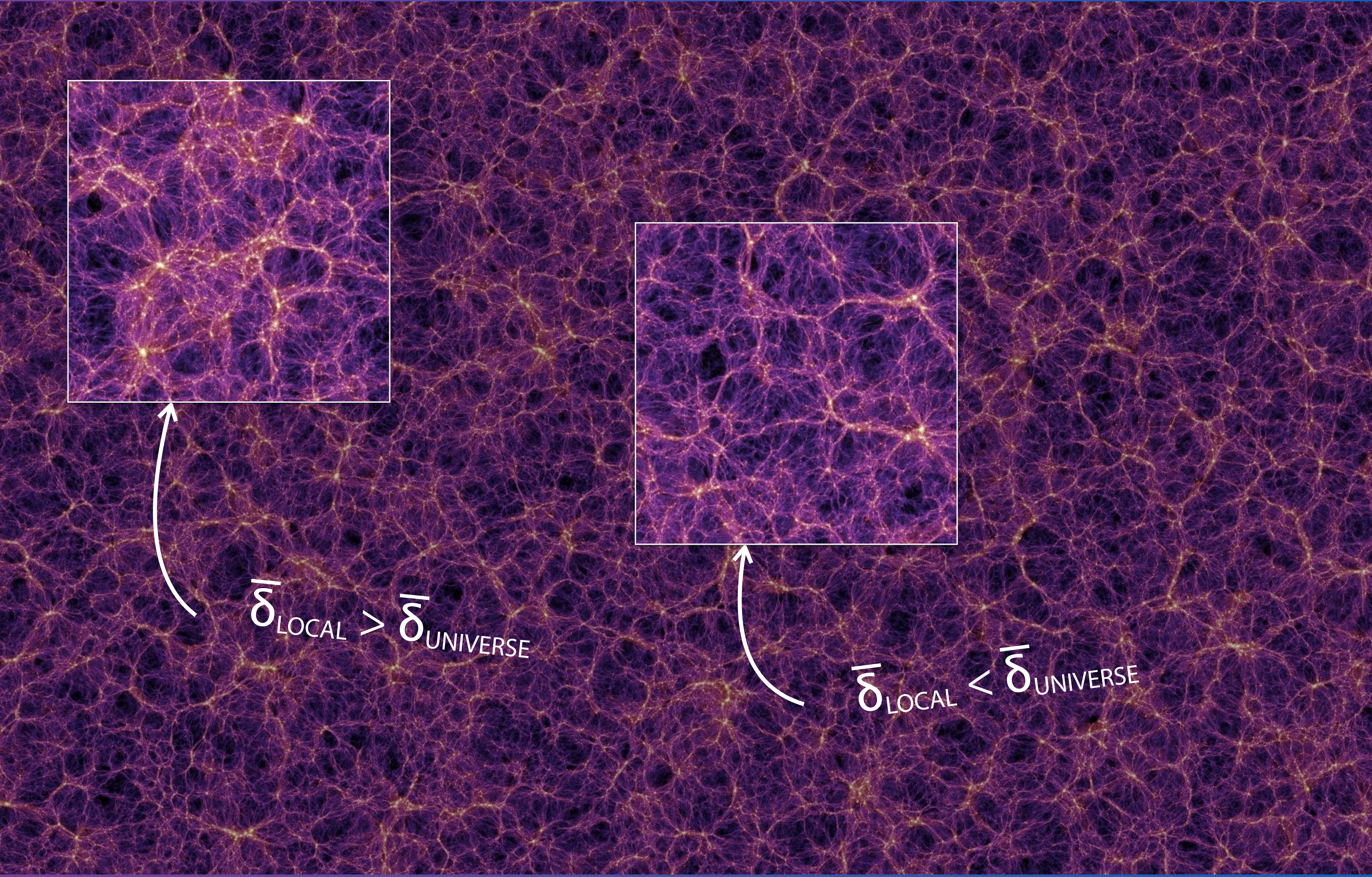
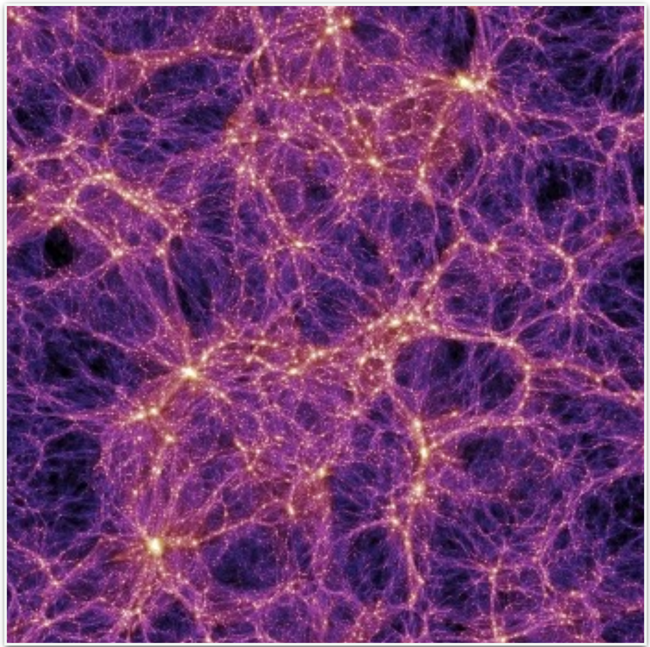
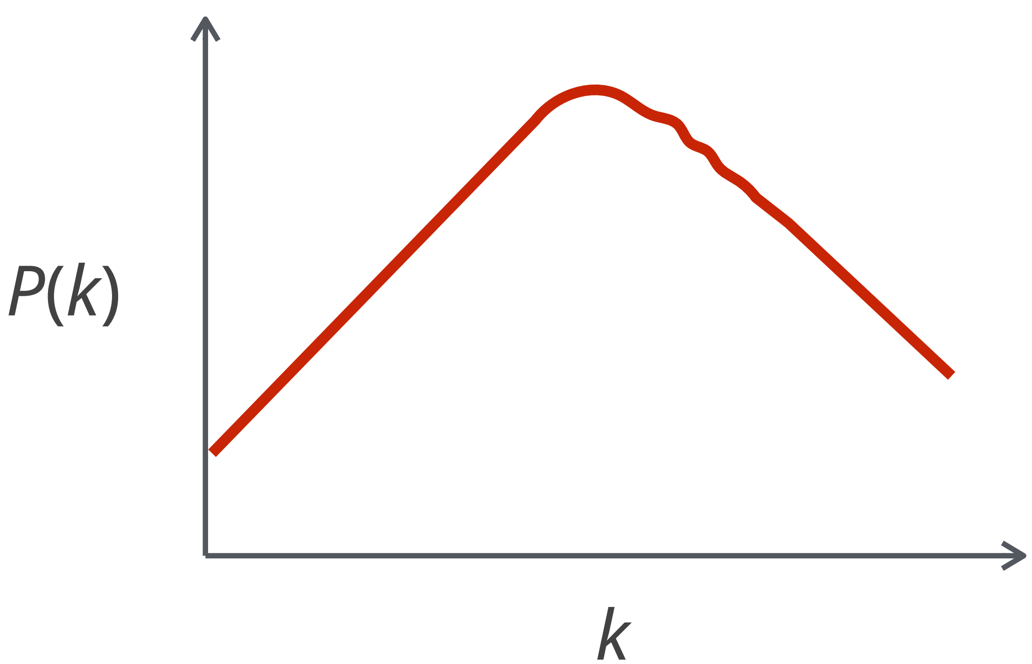
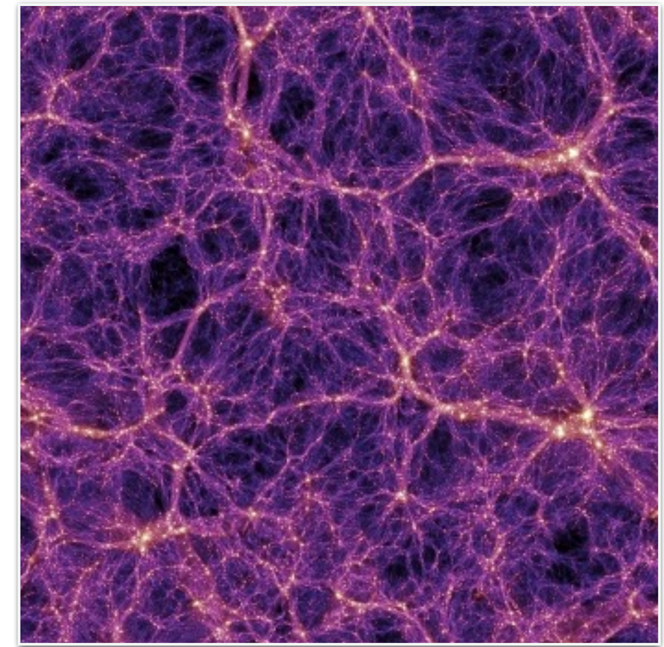


Position-dependent power spectrum



$\bar{\delta}_{\mathrm{LOCAL}} > \bar{\delta}_{\mathrm{UNIVERSE}}$





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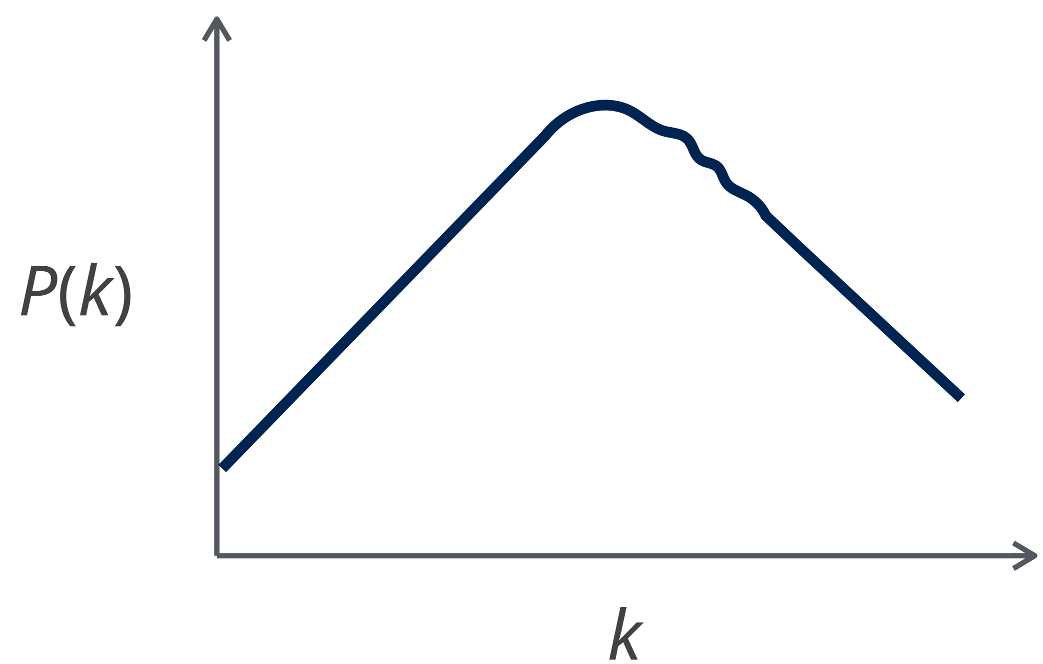
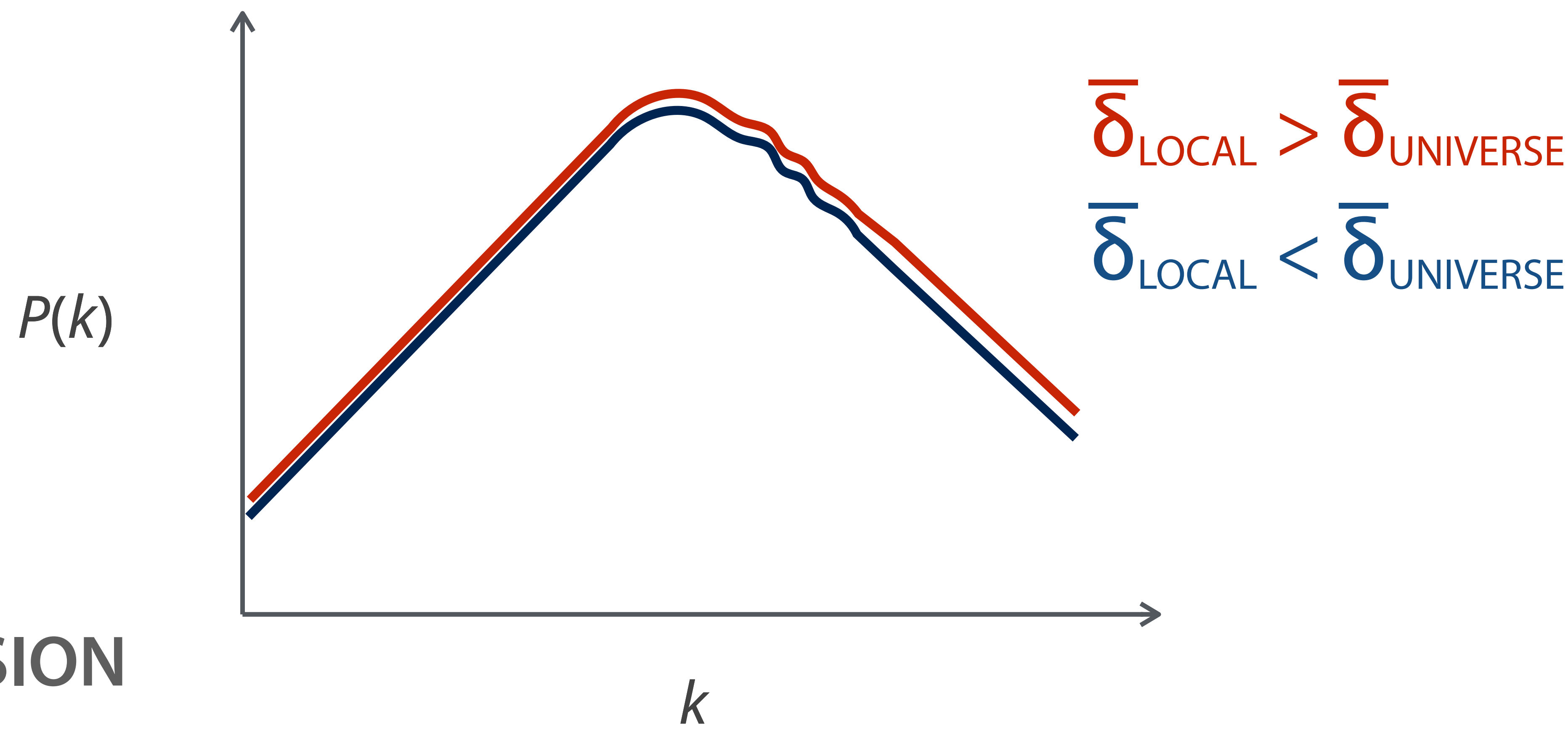


Position-dependent power spectrum



CONCLUSION

- **measured** $P(k)$ depends on the local mean density $\bar{\delta}$!
- **denser** regions have **more fluctuations**, i.e.

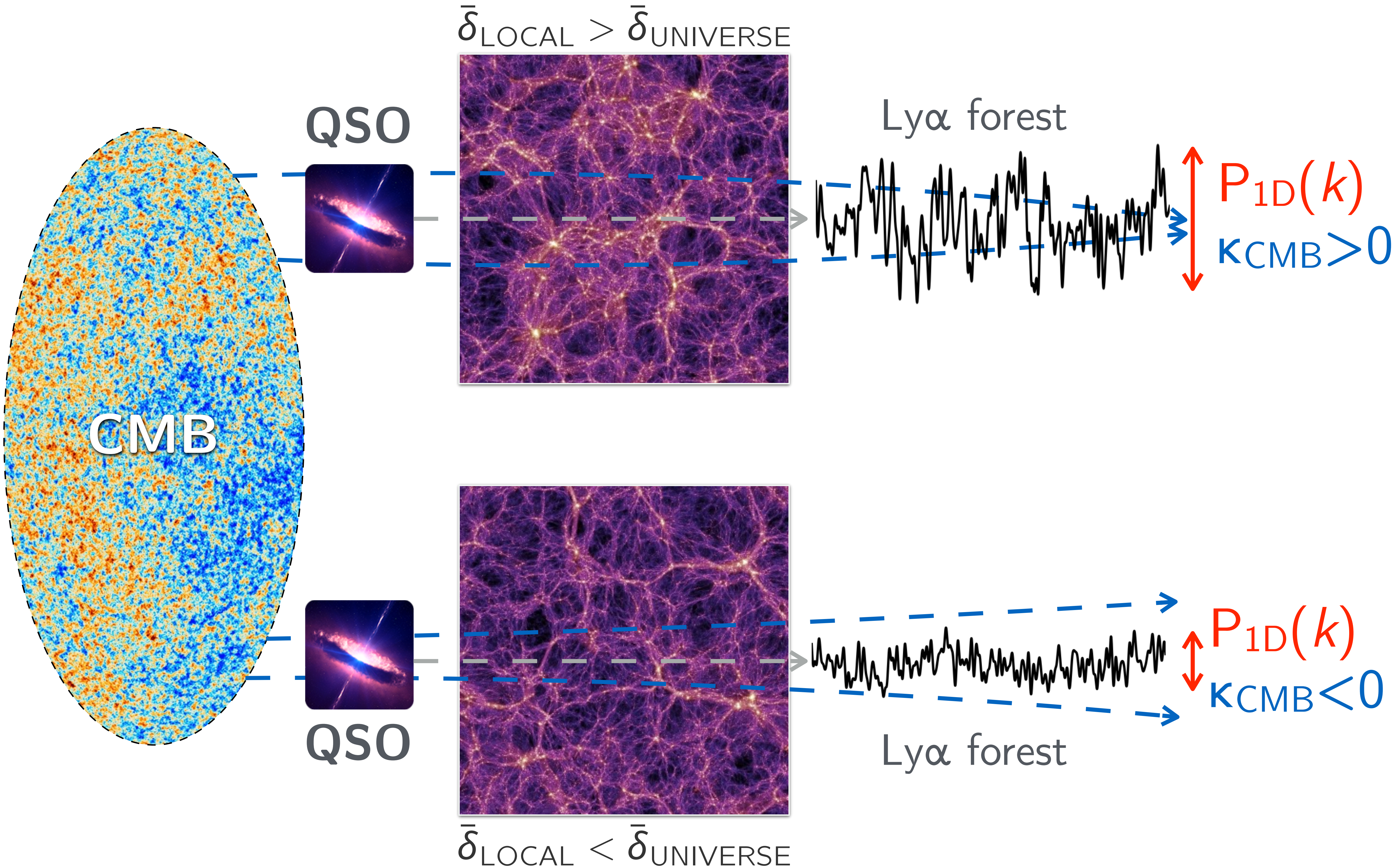
$$\frac{\partial P(k)}{\partial \bar{\delta}} > 0$$

small-scale modes

LARGE-scale mode : $\bar{\delta} = \delta(k \approx 0)$

- fully **non-linear** process

Ly-α × CMB lensing



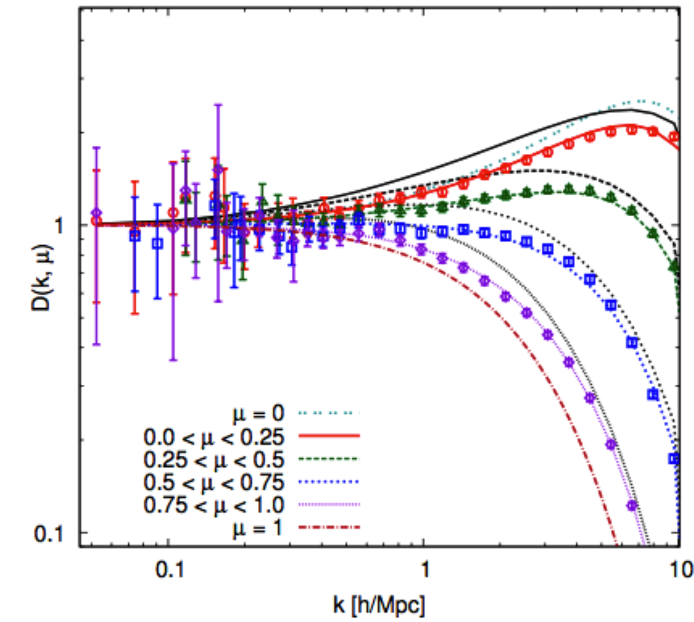
Theoretical bispectrum

$$\rightarrow \quad B_{\kappa,\mathrm{Ly}\alpha}(k_\parallel) \;\hat{=}\; \mathrm{Cov}\left[\kappa, P^{1\mathrm{d}}_{\mathrm{Ly}\alpha}(k_\parallel)\right] \qquad \kappa = \int d\chi W_\kappa(\chi)\delta(\chi)$$

$$= \frac{1}{\Delta\chi}\int d\chi W_\kappa(\chi)\frac{\partial P^{1\mathrm{d}}_{\mathrm{Ly}\alpha}(k_\parallel,\chi)}{\partial\delta}\sigma^2(\chi)$$

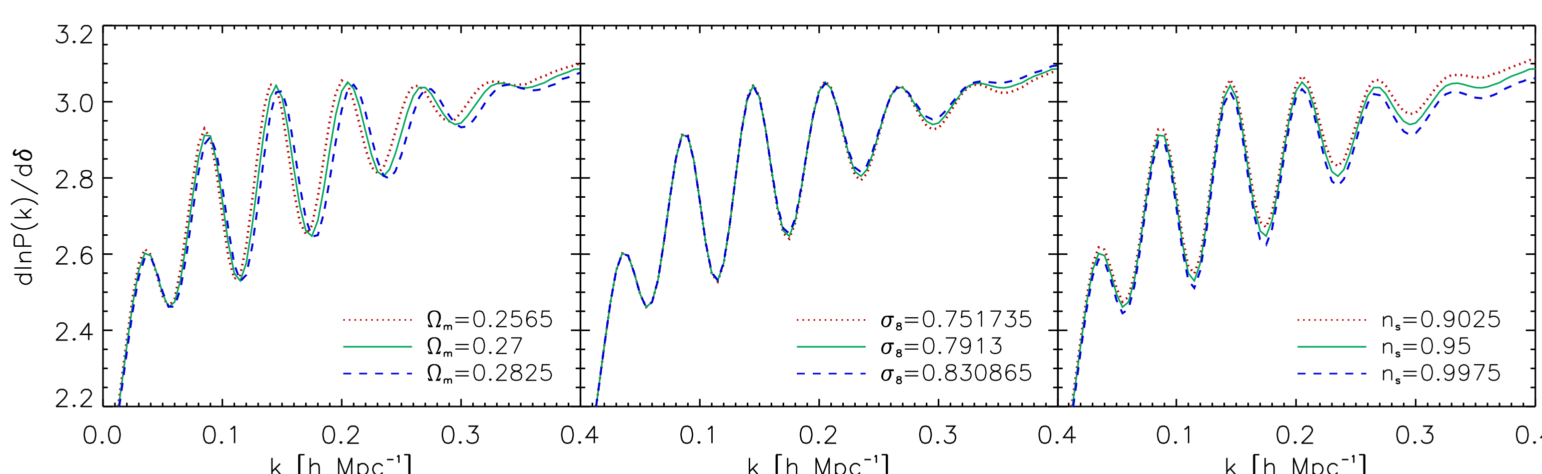
$$\rightarrow \quad P^{3d}_{\mathrm{Ly}\alpha}(k_\parallel,\vec{k}_\perp) = b_1^2\left(1+\beta\mu^2\right)^2 D(k,\mu)P_{\mathrm{lin}}(k)$$

① linear bias ② RSD ③ baryons & grav. non-linearities



Arinyo-i-Prats+15

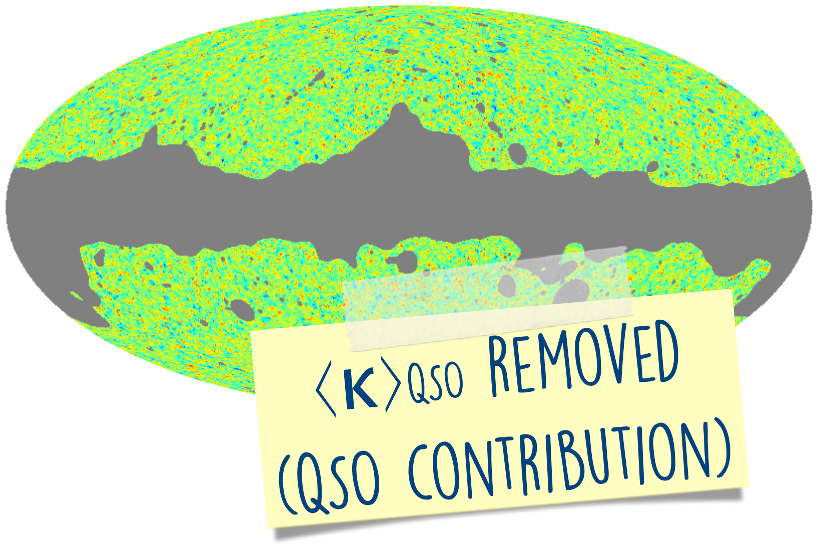
$$\rightarrow \quad \frac{\partial P^{1\mathrm{d}}_{\mathrm{Ly}\alpha}(k_\parallel)}{\partial\delta} = \int \frac{d^2\vec{k}_\perp}{(2\pi)^2}\, P^{3d}_{\mathrm{Ly}\alpha}(\vec{k})\left(\frac{\partial \ln P_{\mathrm{lin}}}{\partial\delta} + b_2^{\mathrm{eff}}(k,\mu)\right)$$

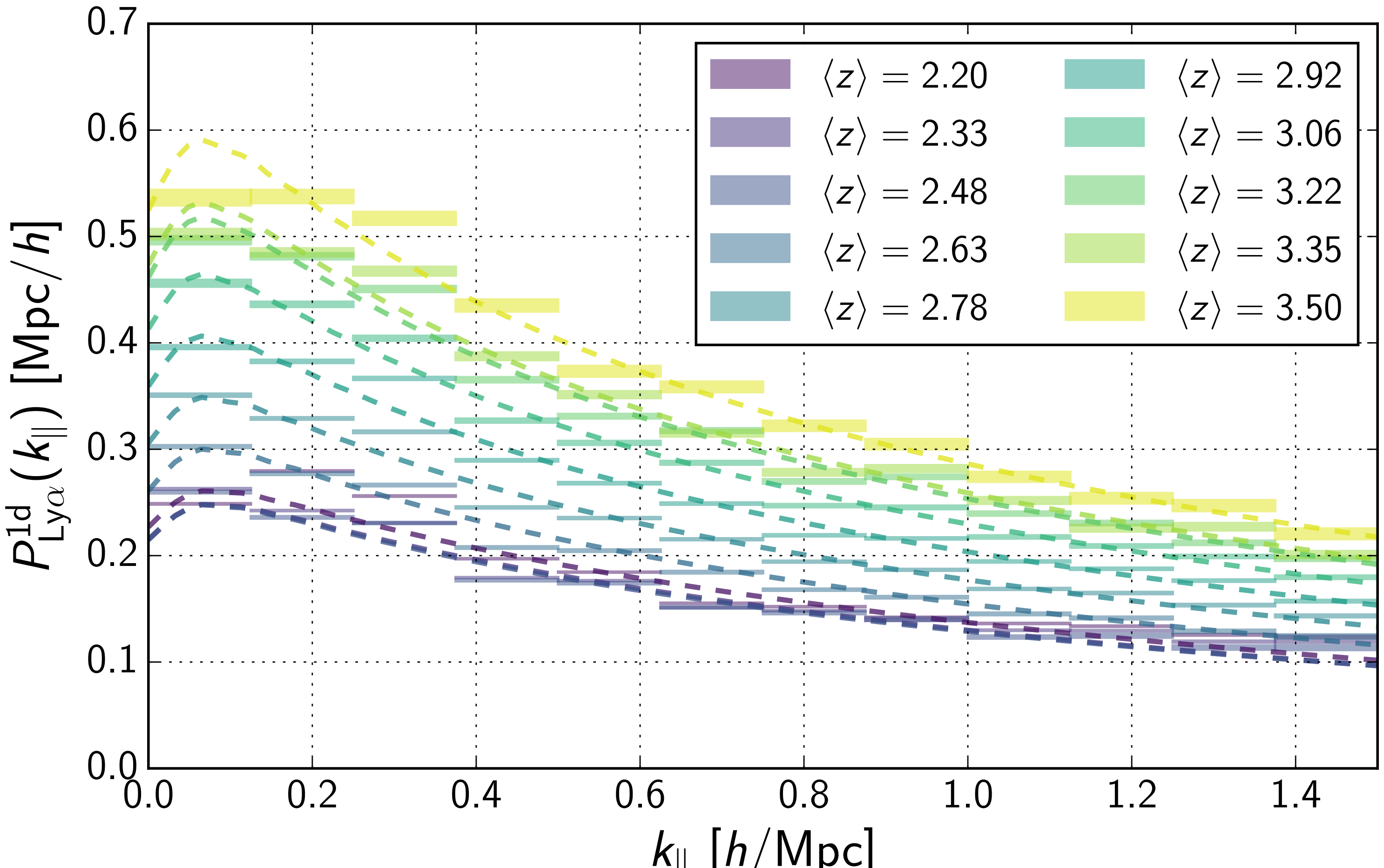


Chiang+15

Analysis method

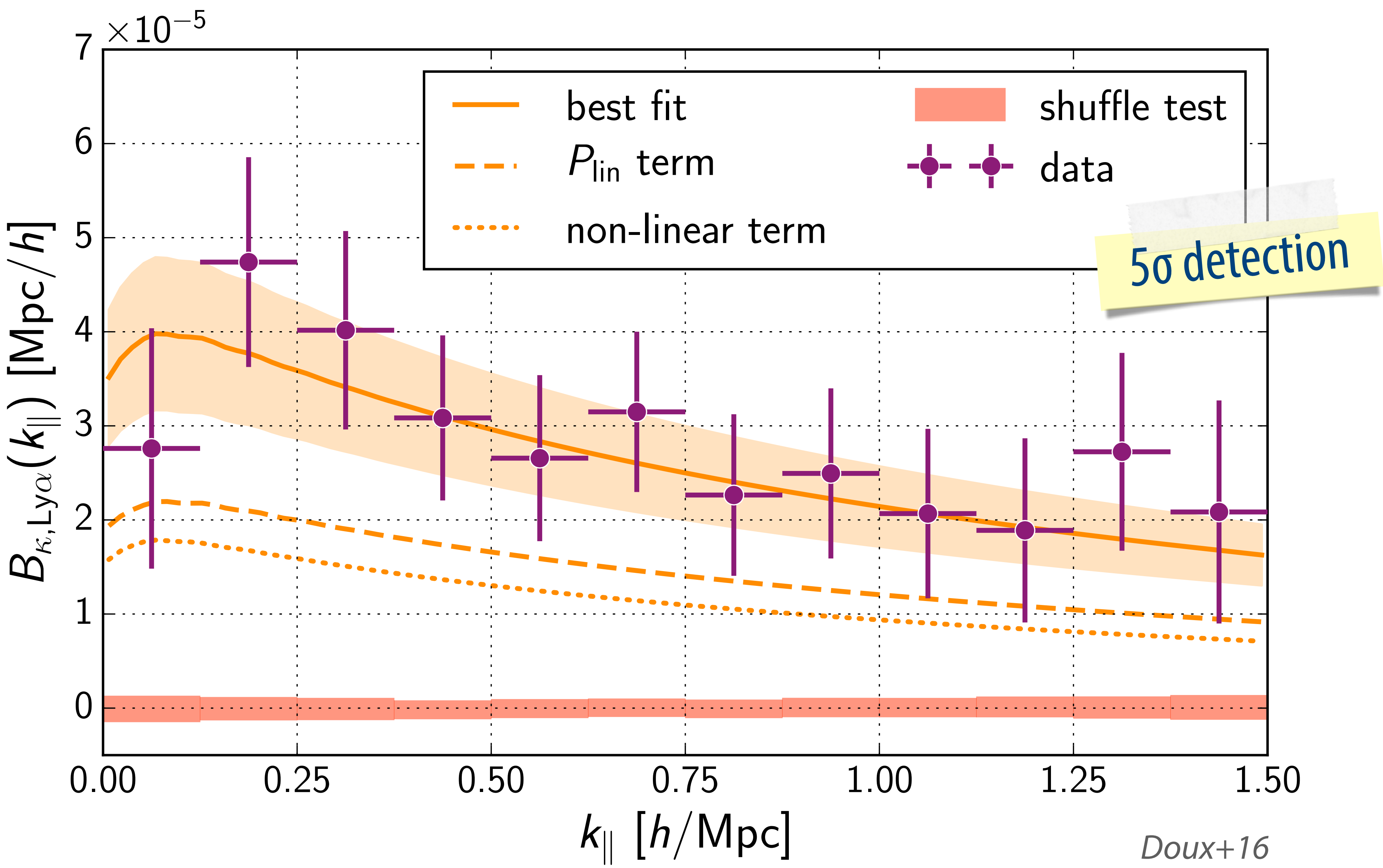
- for each Ly-α forest, measure:
  - κ_{CMB} in the direction of the quasar ($-\langle\kappa\rangle_{QSO}$)
  - $\hat{P}^{1d}_{Ly\alpha}(k,z) = \frac{\hat{P}^{raw}_i(k) - P^{noise}_i}{W^2_{spectro}(k, R_i)}$
- measure linear bias $b_1(z)$





Ly-α × CMB lensing bispectrum

- bispectrum $B_{\kappa,\mathrm{Ly}\alpha}(k_\parallel)$ = response of linear PS + non-linear
- linear bias measured from $P_{\mathrm{Ly}\alpha}(k_\parallel)$
- effective non-linear bias b_2 measured from $B_{\kappa,\mathrm{Ly}\alpha}(k_\parallel)$



Doux+16

Conclusion II

Results

- First correlation of Ly-α and CMB lensing
- Denser regions ($\kappa_{CMB} > 0$) $\Longrightarrow$ higher $P_{\text{Ly-}\alpha}(k)$ = more fluctuations

Beyond

- Calibration of hydrodynamical simulations (Chiang+17 agrees)
- Similar correlation found with the CIB-545 GHz map (CIB-CMB lensing xcor)

Conclusion II

In the future

- eBOSS and DESI will have more data : observe redshift dependence ?
- Better resolution with CMB-S3/4 : angular dependence ?
- Probe of small-scale power spectrum : neutrino masses, dark matter models, baryons ?

Outline

- INTRODUCTION
  - → Why and how combine cosmological probes?
- JOINT ANALYSIS OF PLANCK & BOSS DATA
  - → Planck and BOSS
  - → Methodology
  - → Results
- LY-A FOREST × CMB LENSING BISPECTRUM
- THESIS CONCLUSIONS
- LOW-LEVEL COMBINATION OF WEAK LENSING SURVEYS

Thesis conclusions

- **Combinations of cosmological probes** can
  1. reveal new physical phenomenon
  2. improve cosmological constraints
  3. calibrate astrophysical uncertainties (*e.g.*, biases) and instrumental systematics

- **Results**

  ⟶ General framework in `NumCosmo` for joint statistical analyses

  ⟶ Constraints on wCDM + m_ν + biases at once

  ⟶ Detection Ly-α forest × CMB lensing ⟶ indep. test + hydro sim calibration

Thesis conclusions

- **Joint analysis of future surveys**

⟶ combinations of probes *and* experiments to **boost science impact**

⟶ full ***multi-probe, multi-survey* analysis** + cross-calibration

⟶ **radial decomposition** adapted to spectro/photo survey + 2D fields

⟶ going further: **low-level data** combination, e.g., *multi-band*, *multi-resolution* image analysis for weak lensing surveys (LSST, Euclid, WFIRST)

Outline

- **INTRODUCTION**
  - → Why and how combine cosmological probes?
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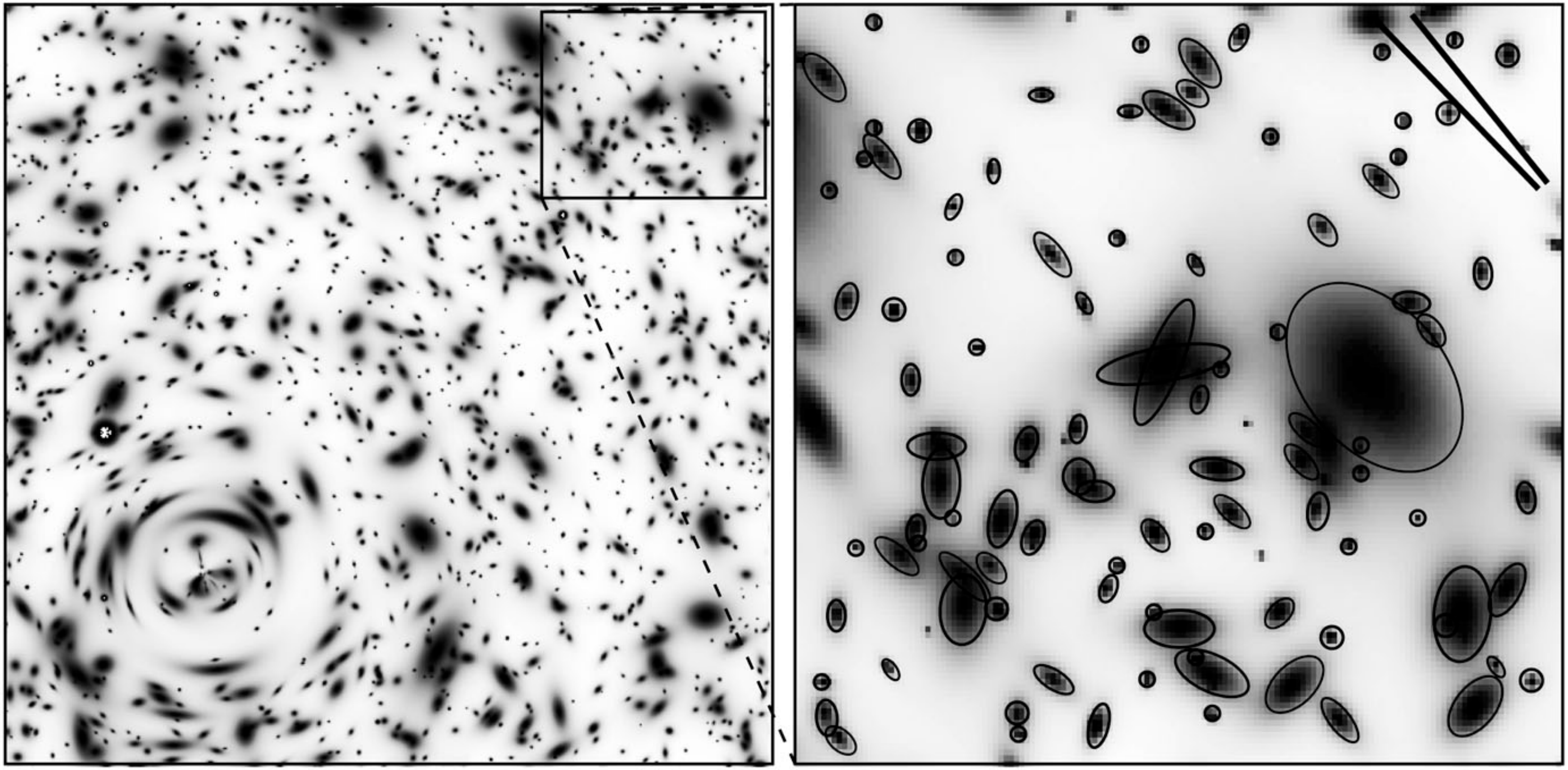
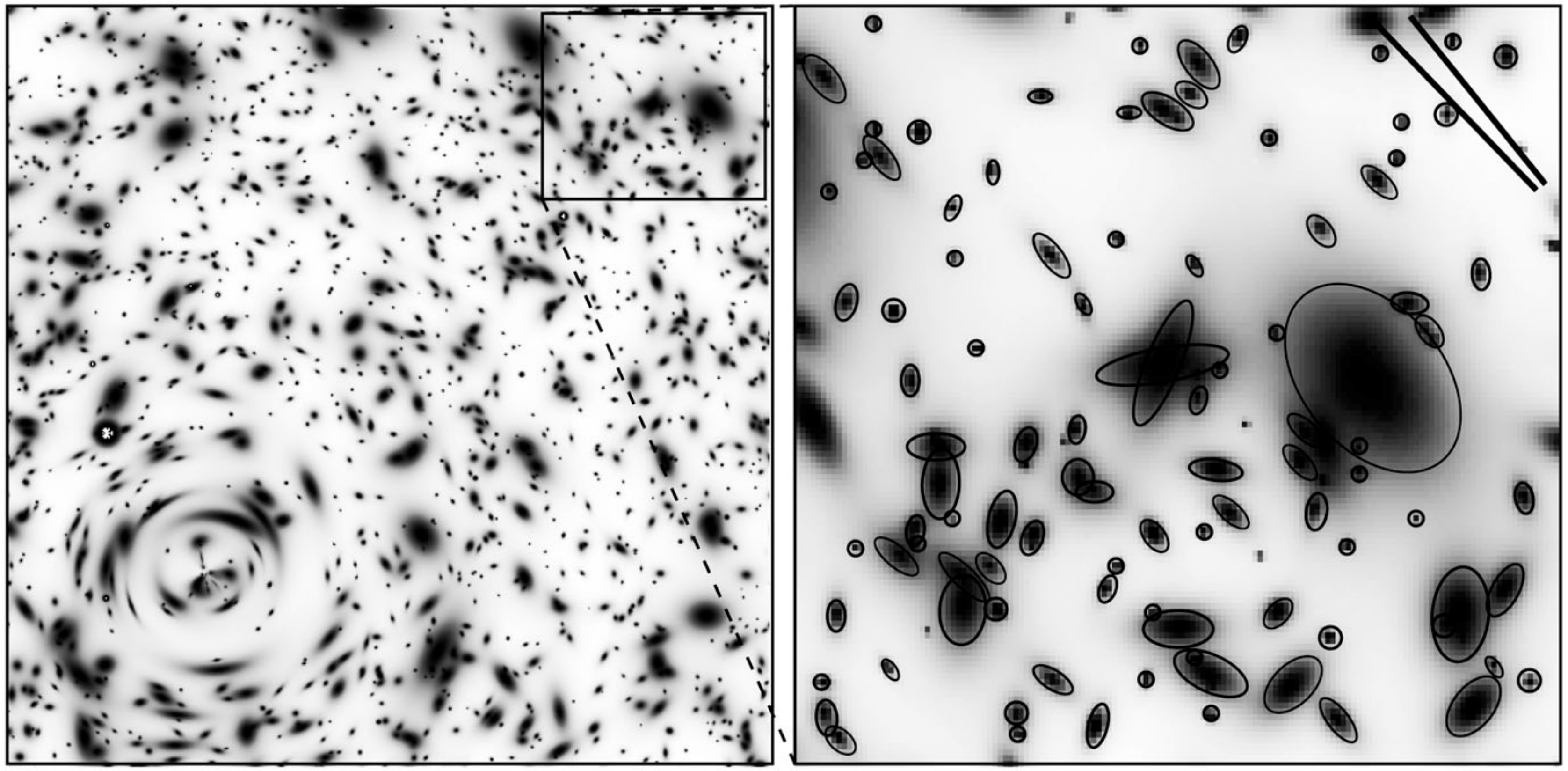
- **THESIS CONCLUSIONS**
- **LOW-LEVEL COMBINATION OF WEAK LENSING SURVEYS**

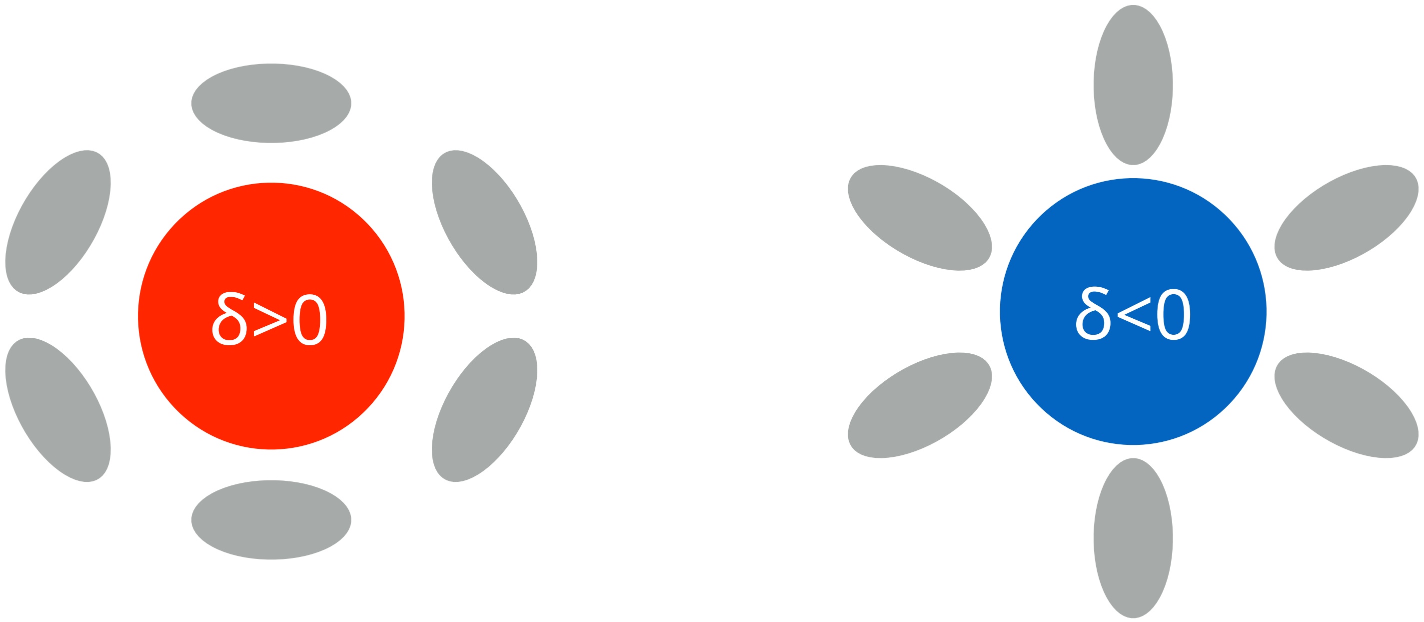
Weak lensing 101



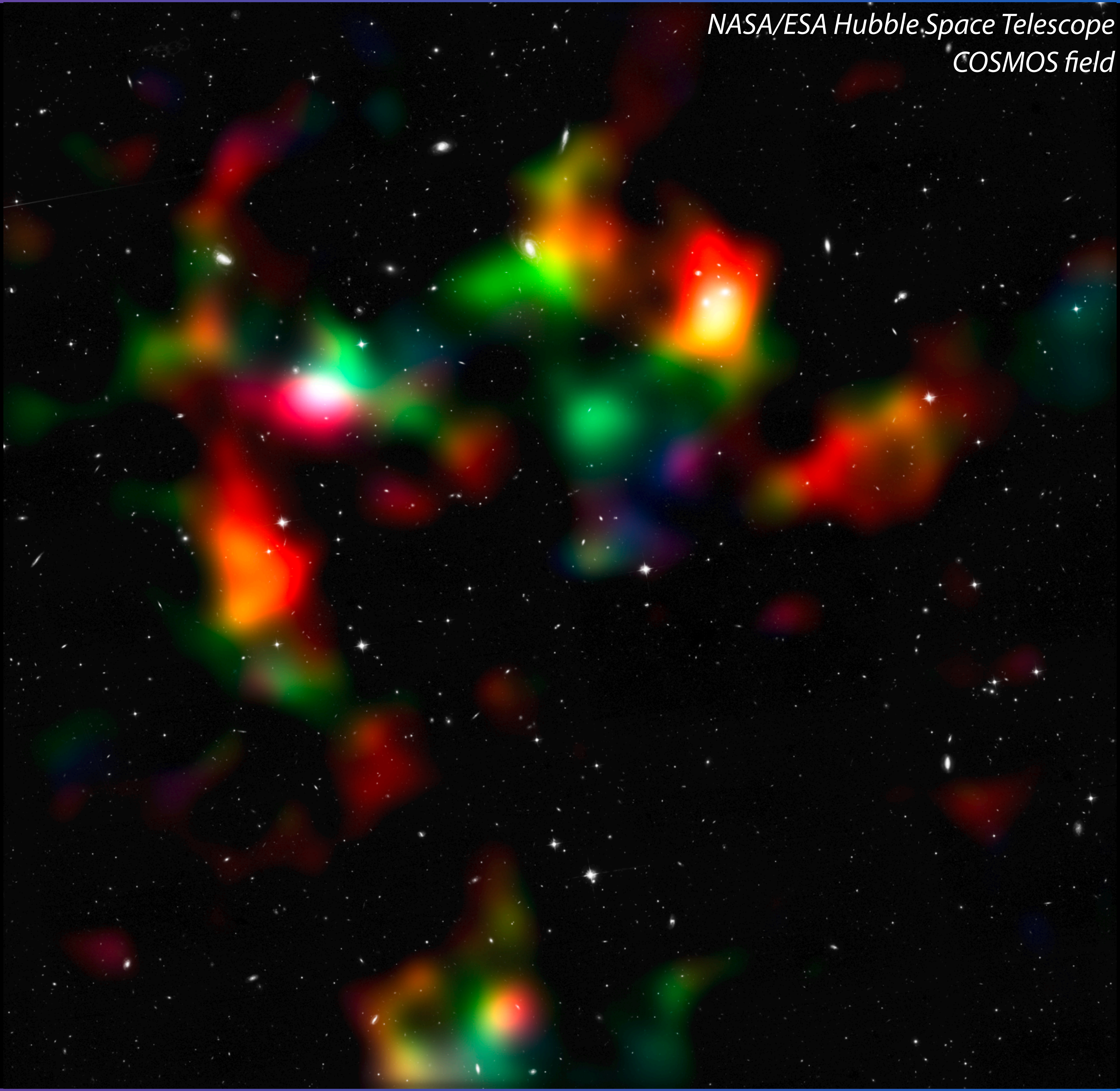
Weak lensing 101



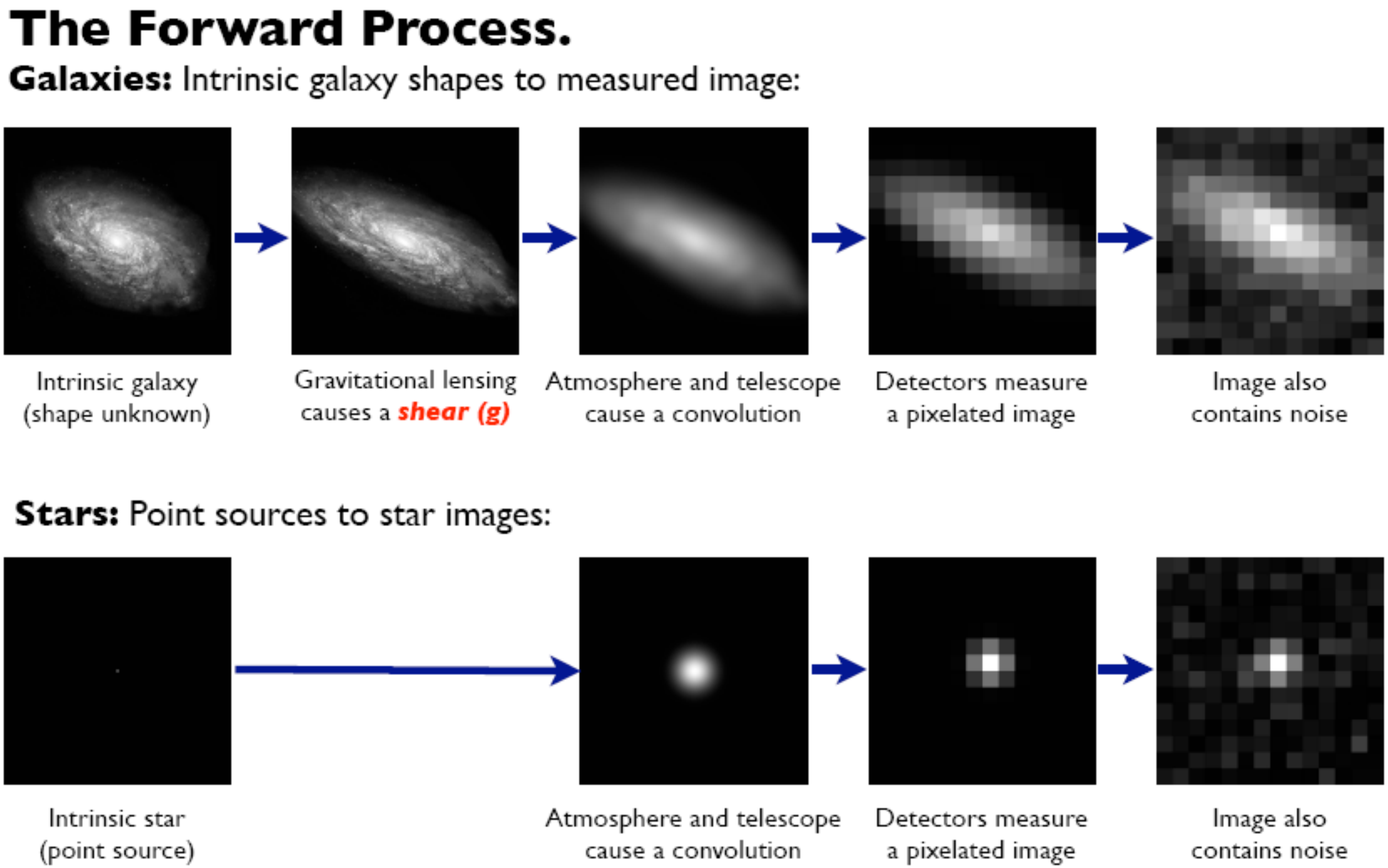
SHAPES ⟶ MASS :



Mass mapping



The forward process

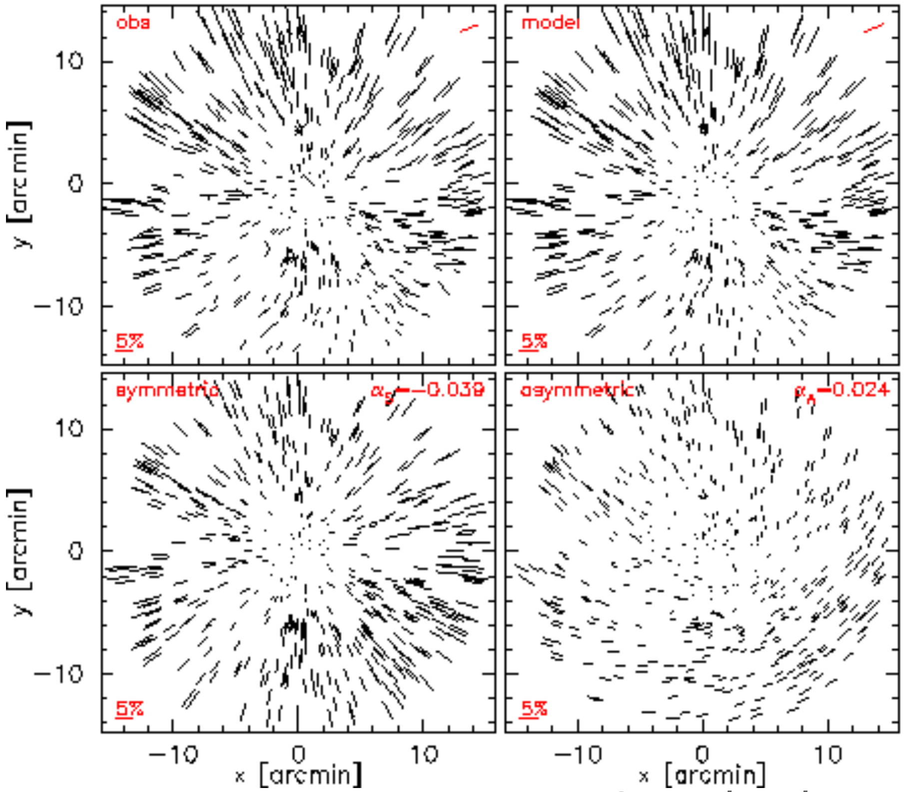


Bridle+09

- **IDEA** : same galaxy observed with different **PSFs** (no atmosphere in space!) and color filters

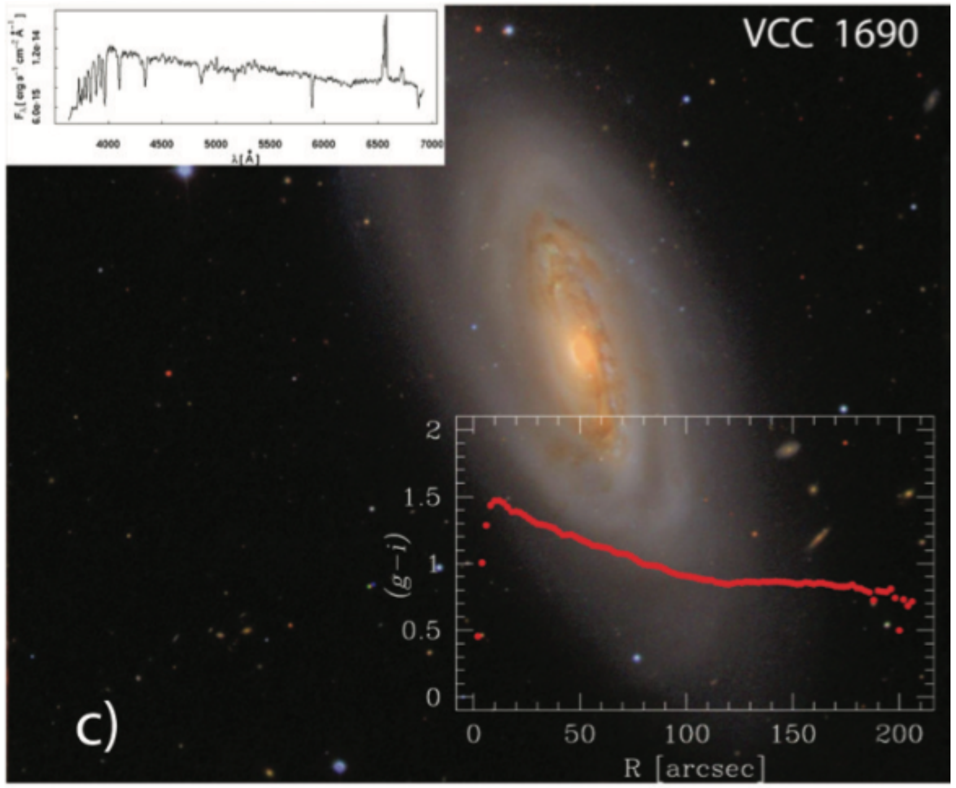
Astrophysical/instrumental uncertainties

- PSF anisotropies



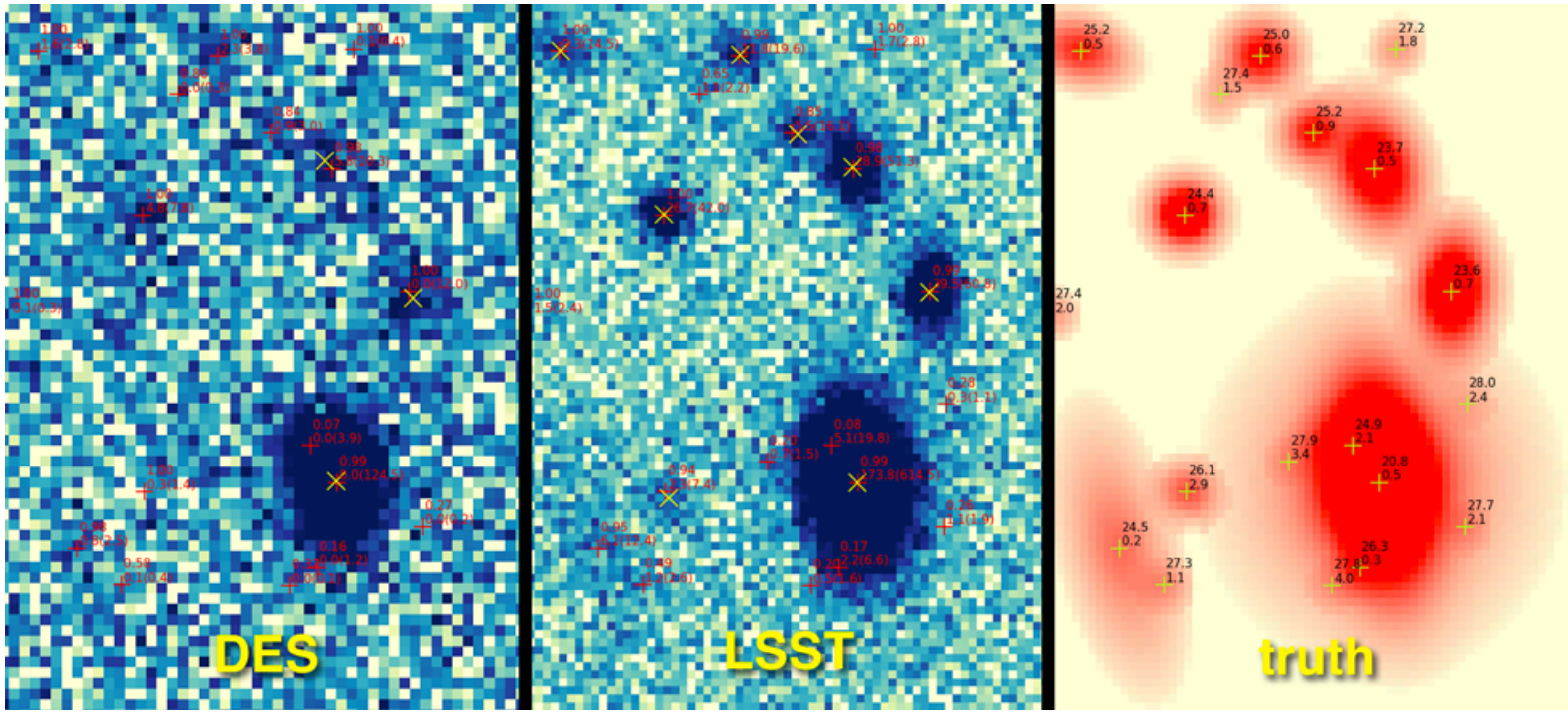
Consolandi+16

- color gradients



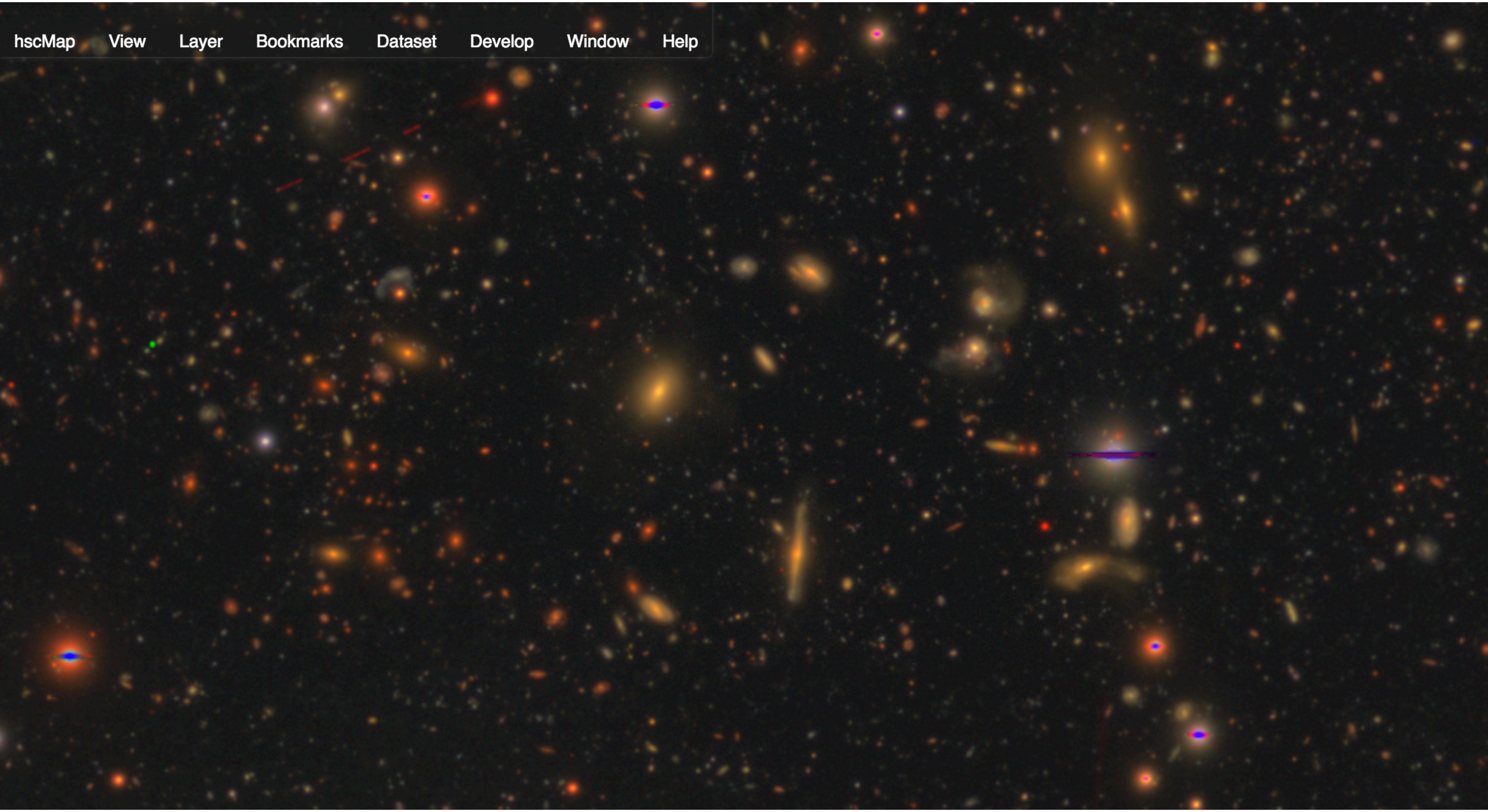
Dawson+16

- blending



What will LSST data look like?

A lot like HSC data (hsc-release.mtk.nao.ac.jp/hscMap2/) !



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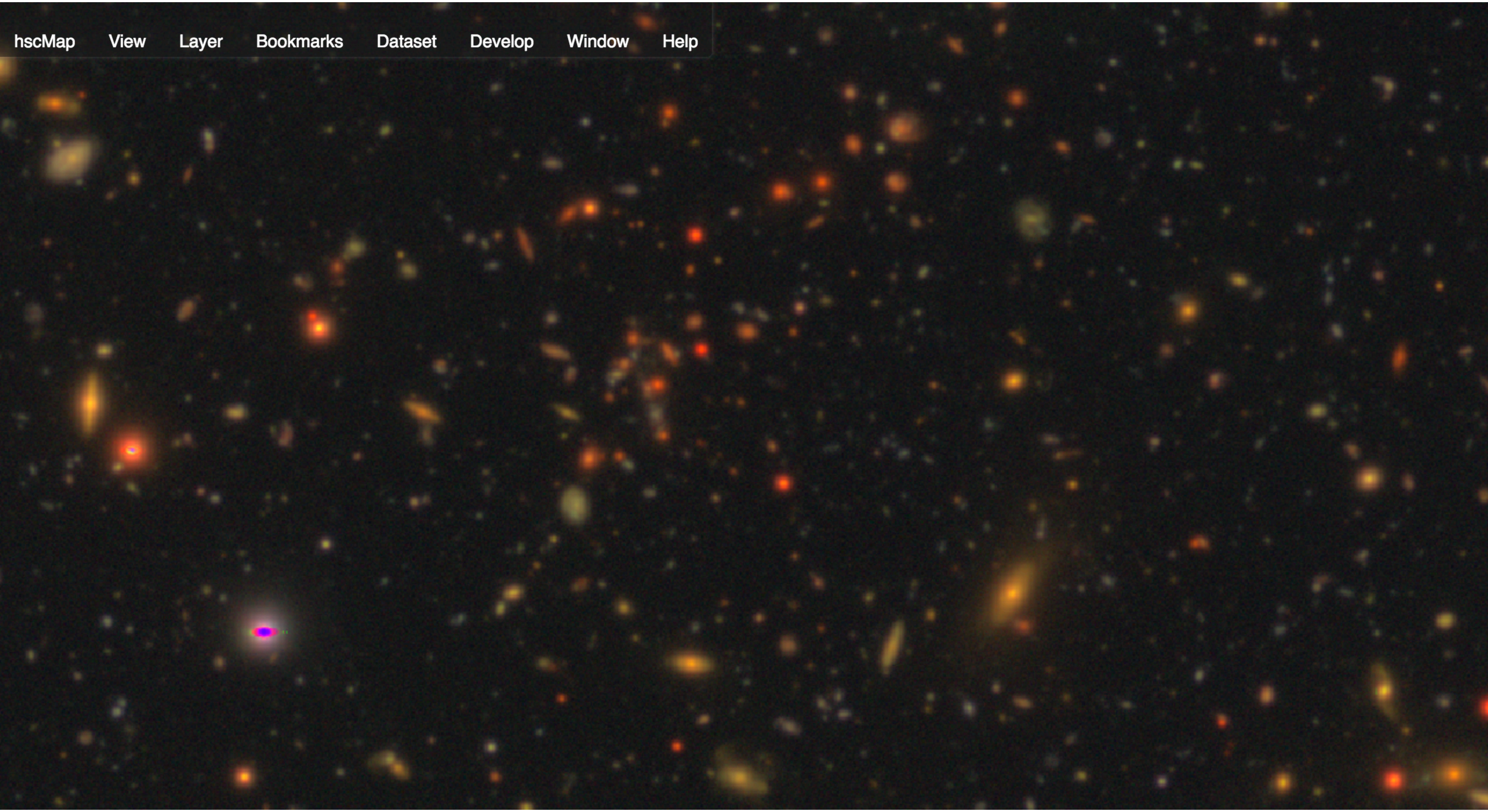

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The deblending problem

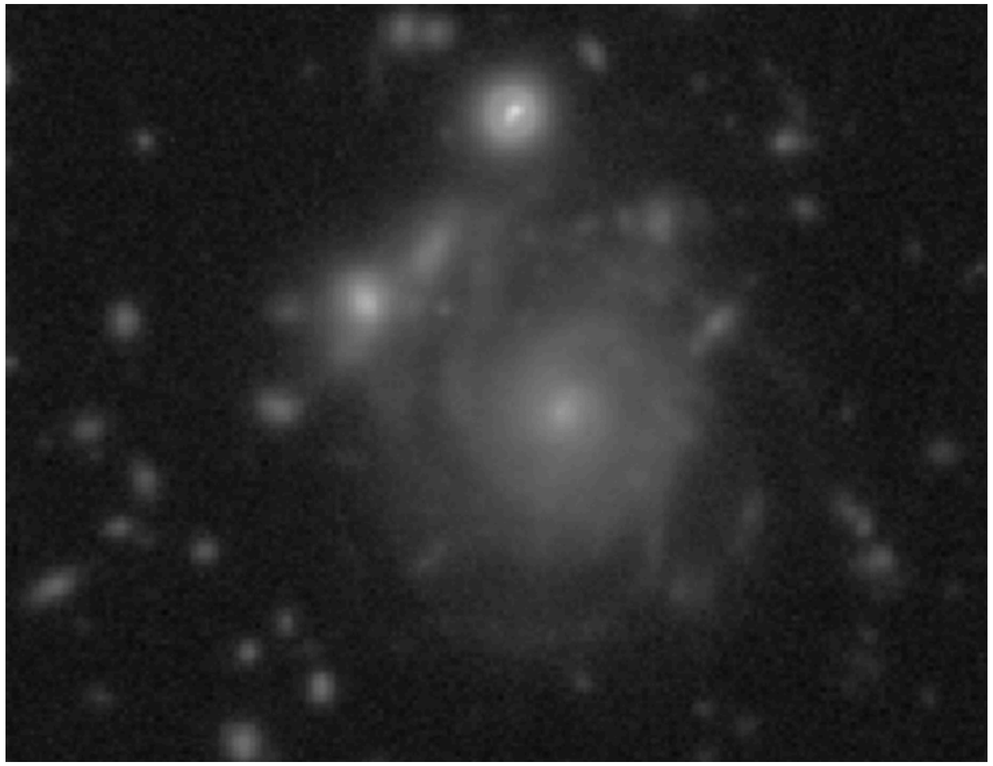
- **Is it an issue ?**
  - → Yes !
  - → *deep* survey: maybe up to 40% of blended objects (so says R. Lupton !)
  - → depends on your definition of "*blended*"

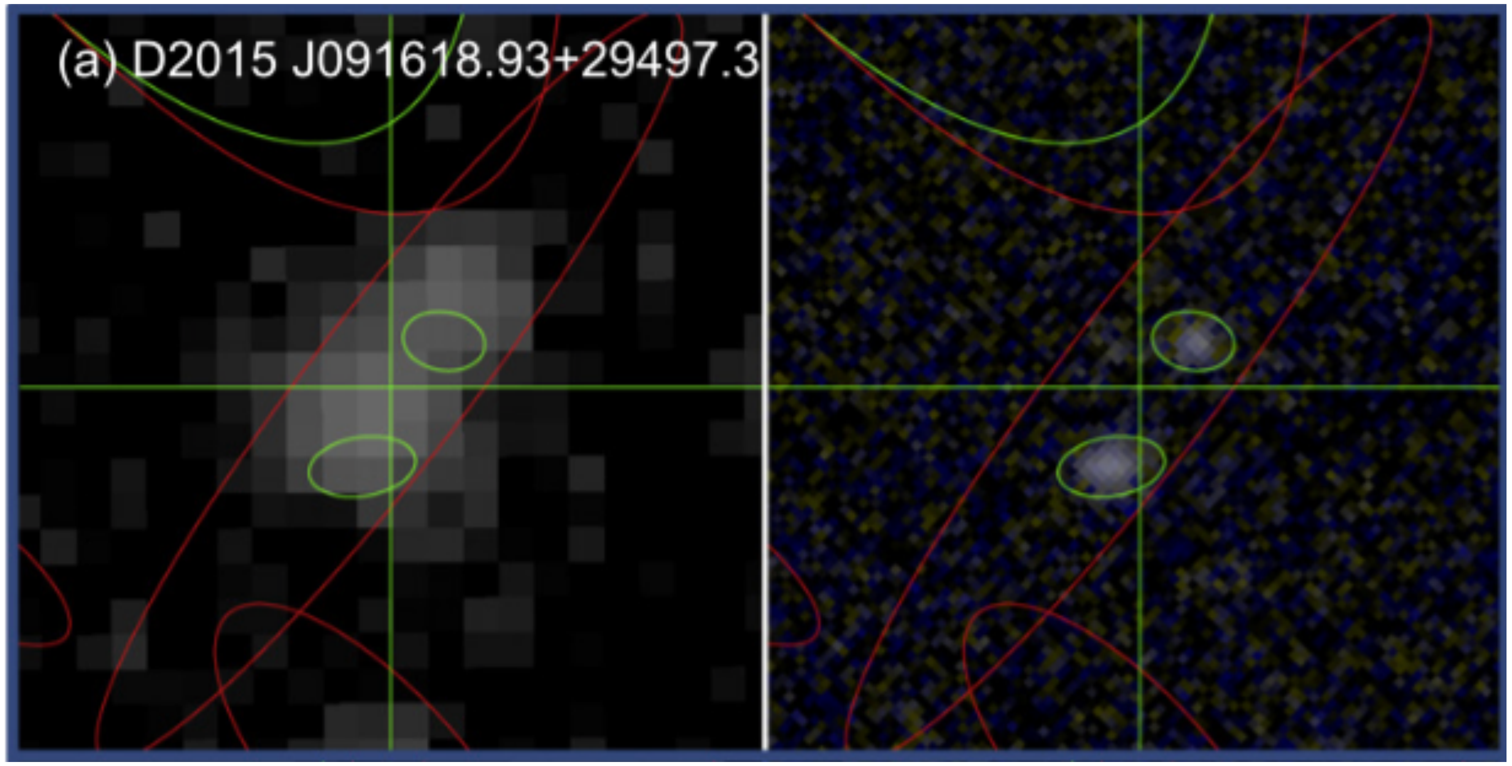
- **Why ?**
  - → it affects all measurements :
    - fluxes of extended objects per band > colors > redshift
    - shapes > cosmic shear
    - morphology
    - …

What can you do about it?

- Use **colors** (*ugrizy* bands)
- Use **space** observations (Euclid, WFIRST !) ⇒ diffraction-limited PSF
- Learn what *real* galaxies look like *vs* symmetries

→ *neural networks can do that very well!*





Ground : HSC Space : HST

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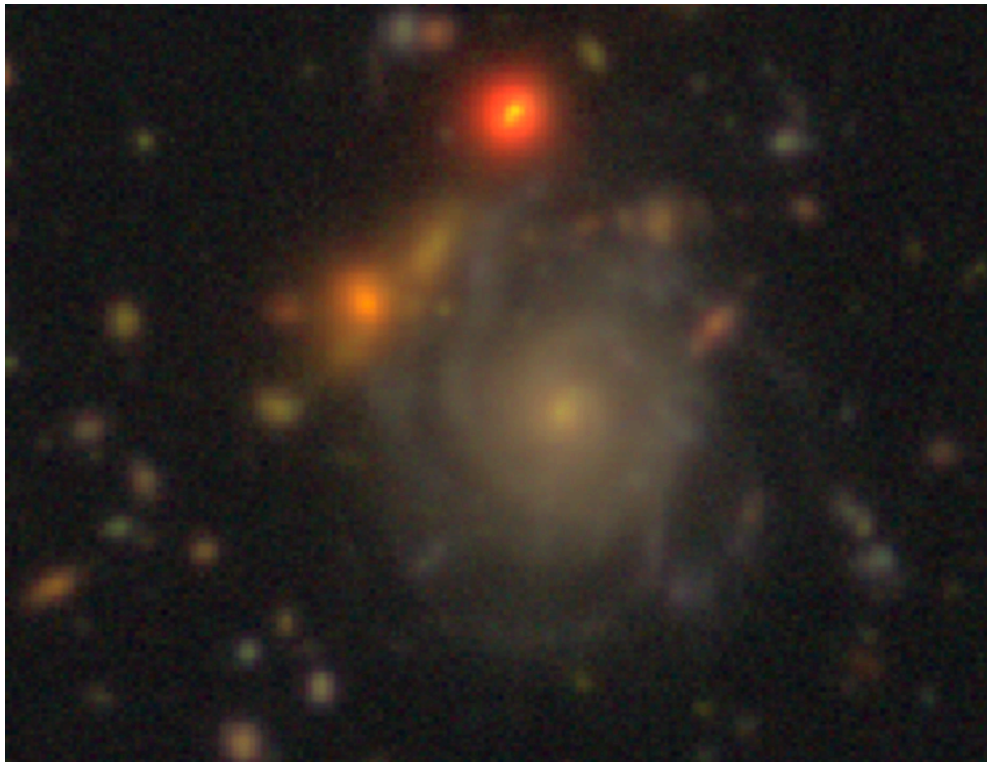
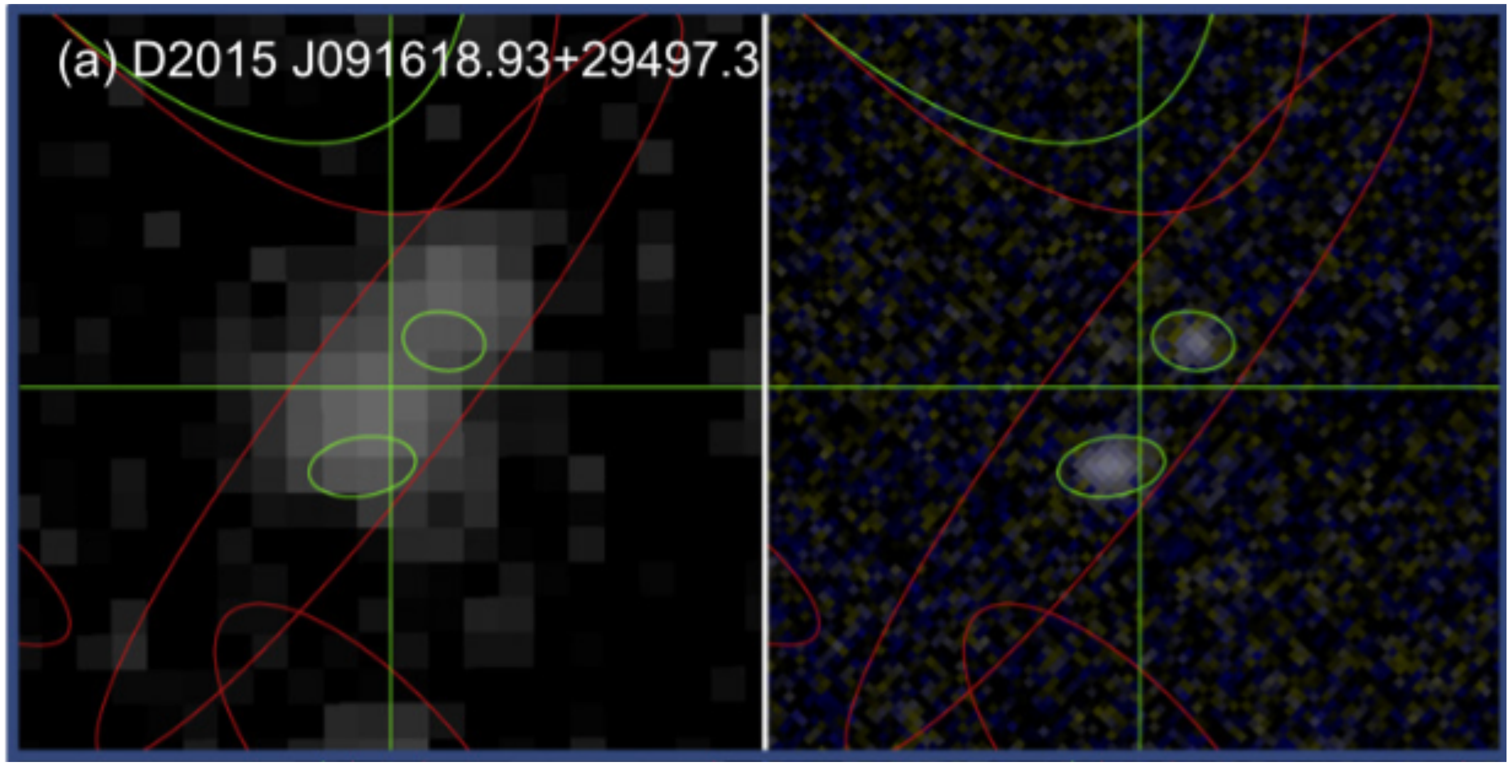
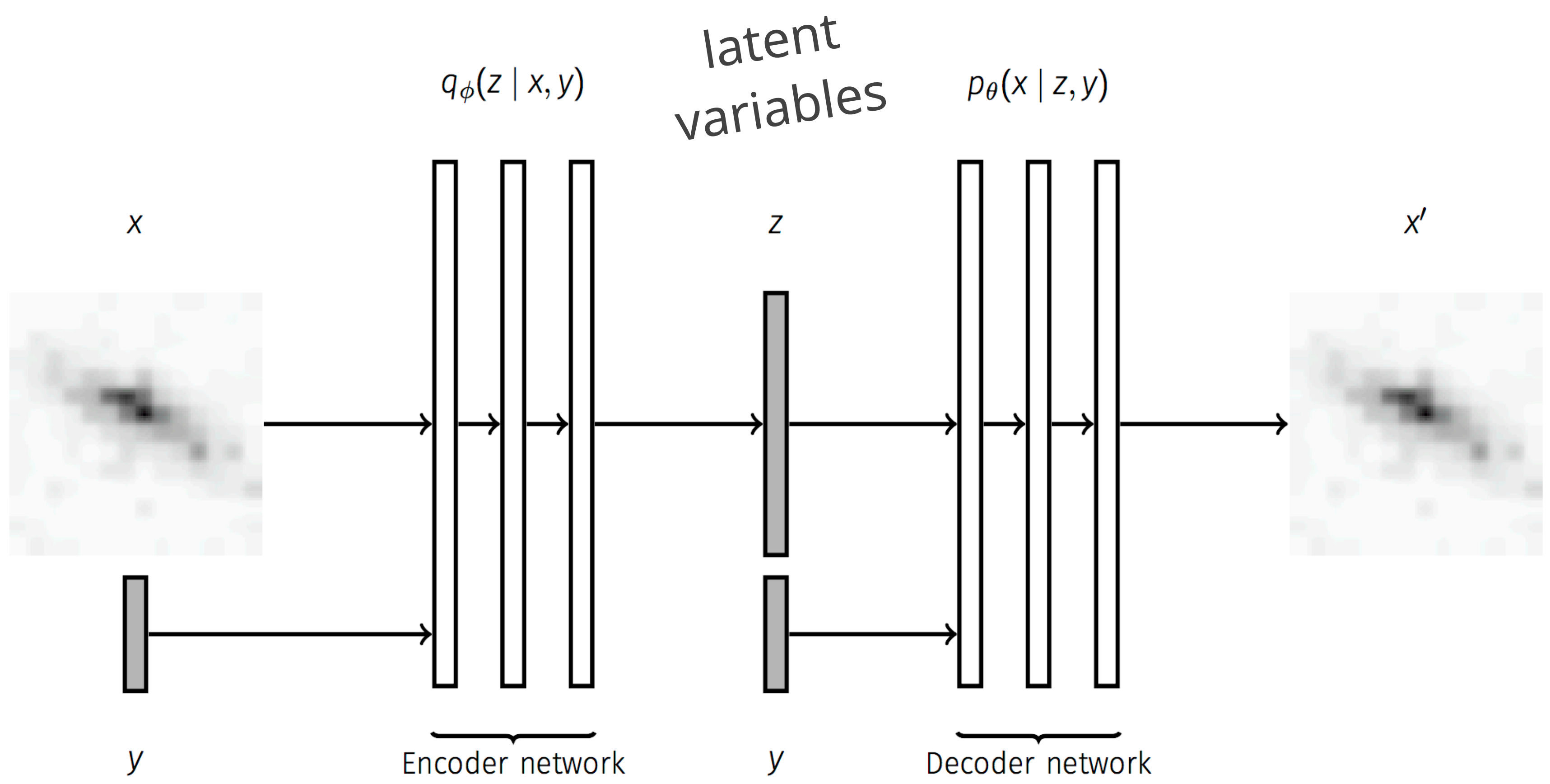




Ground : HSC Space : HST

GENERATING REALISTIC GALAXY IMAGES

→ learn what real galaxies look like : (conditional) variational auto encoders



$$\log(p_\theta(x \mid y)) \geq -\underbrace{\mathbb{D}_{\mathrm{KL}}(q_\phi(z \mid x, y) \| p_\theta(z \mid y))}_{\text{Code regularisation}} + \underbrace{\mathbb{E}_{z \sim q_\phi(\cdot \mid x, y)}[\log p_\theta(x \mid z, y)]}_{\text{Reconstruction error}}$$

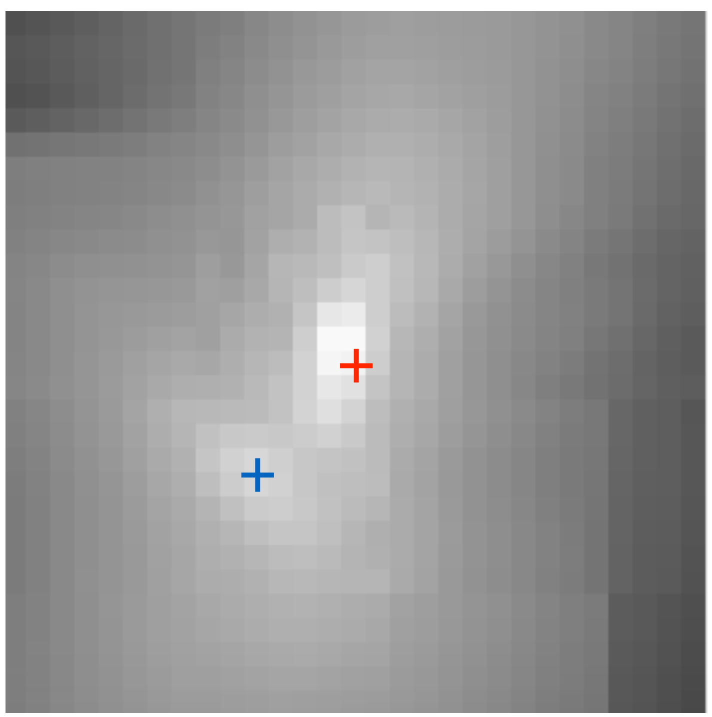
©François Lanusse

→ draw z~$\mathcal{N}(0,\mathbb{1})$ to produce new realistic images

Deblending galaxies

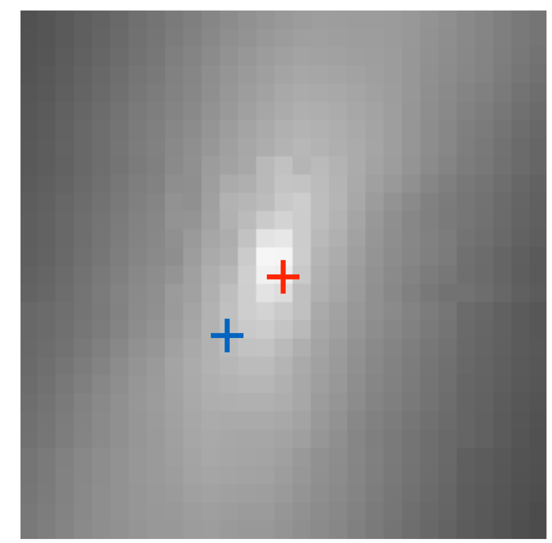
deep neural networks to perform deblending

- adapted VAE-type networks ? preliminary work : monochromatic, shape only
- hierarchical networks using pre-trained encoders ?
- use latent variables encoding shear ?

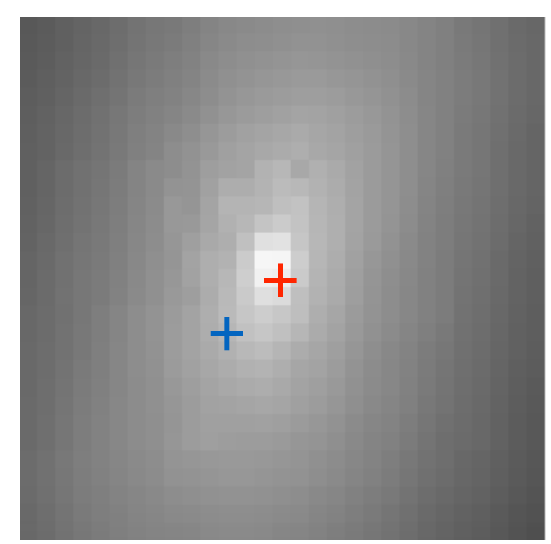


input
(blended)

desired output
(deblended)



output
(deblended)



The case for ground × space


DES data - deliberately stolen from Peter Melchior’s slides

The case for ground × space

CLASH WFC3/IR data - deliberately stolen from Peter Melchior's slides

Asking the good questions

- Deblending is a *necessity*, not a *purpose*
- **Scientific goal(s)** sets the deblending *score*
  - shape
  - colors/redshift
  - morphology
  - ?

  cosmic shear needs both!
- **How to proceed ?**

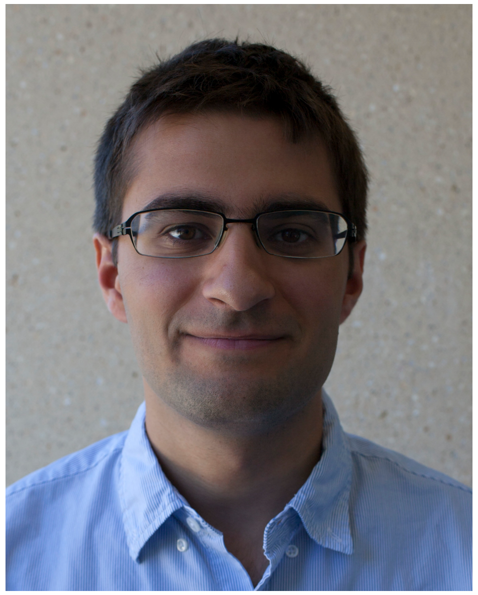
⟶ define the question: what task should NN learn?

  - do you care about single objects ? or statistical measurements ?
  - where can they outperform good ol' algorithmic? see Alpha Go

⟶ build a test data base (COSMOS field?)

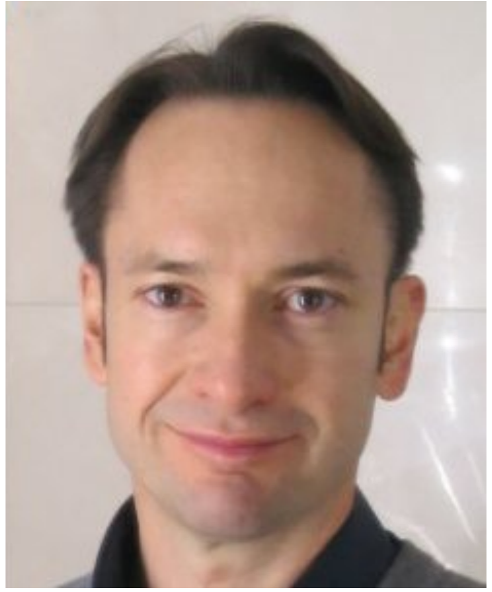
⟶ test algorithms for different scores (RAMP ?)

Main collaborators


Emmanuel Schaan
Princeton/Berkeley


Mariana Penna-Lima
LAL, Annecy


Sandro Vitenti
CBPF & Univ. Louvain


Julien Tréguer
APC, Paris


Éric Aubourg
APC, Paris


Ken Ganga
APC, Paris


David Spergel
Princeton

Research products

Publications

1. **Doux, C.** et al. *First detection of cosmic microwave background lensing and Lyman-a forest bispectrum*. Phys. Rev. D 94, 103506 (2016). + synopsis in APS's Physics
2. **Doux, C.** et al. *Cosmological constraints from a joint analysis of cosmic microwave background and large-scale structure*. arXiv.org 1706, arXiv:1706.04583 (2017).
3. Vitenti, S. D. P., Penna-Lima, M. & **Doux, C.** NumCosmo: Numerical Cosmology library.

Code

- NumCosmo library: `xcor` module on numcosmo.github.io

General conclusion

THANK YOU!