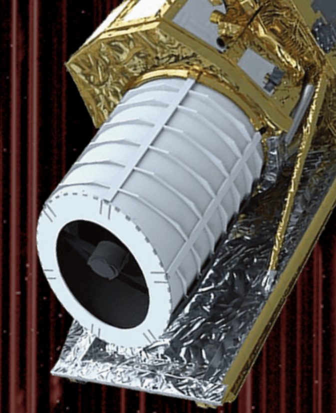
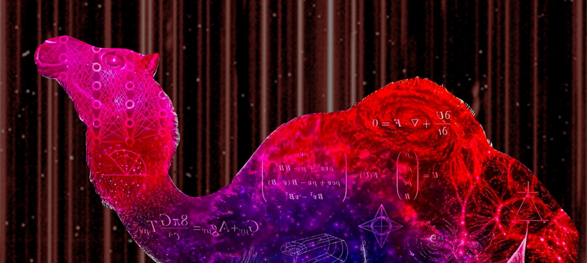


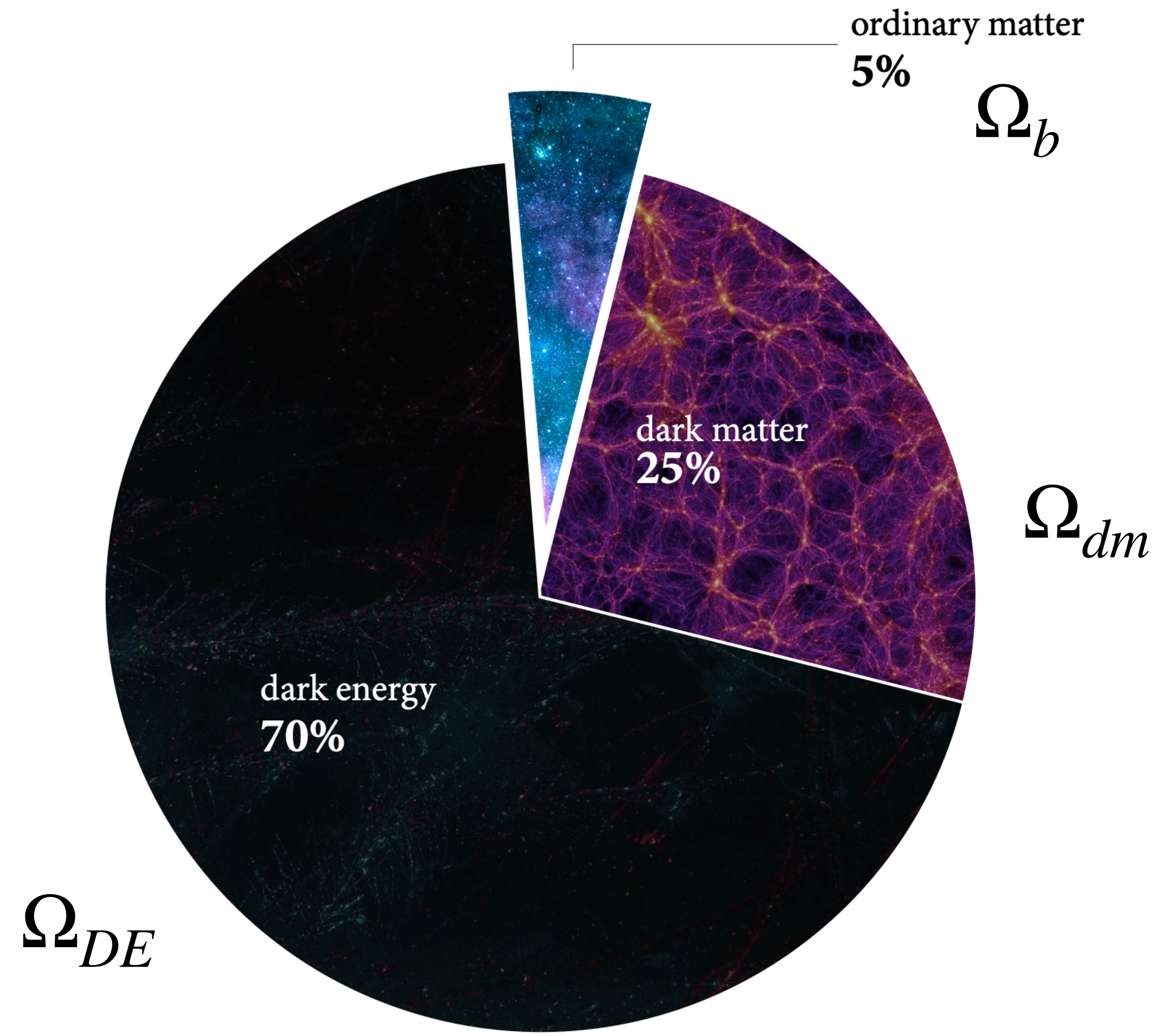
COSMOLOGY AND ASTROPHYSICS WITH OLD AND NEW PROBES

GIULIO FABBIAN

INSTITUT D'ASTROPHYSIQUE SPATIALE

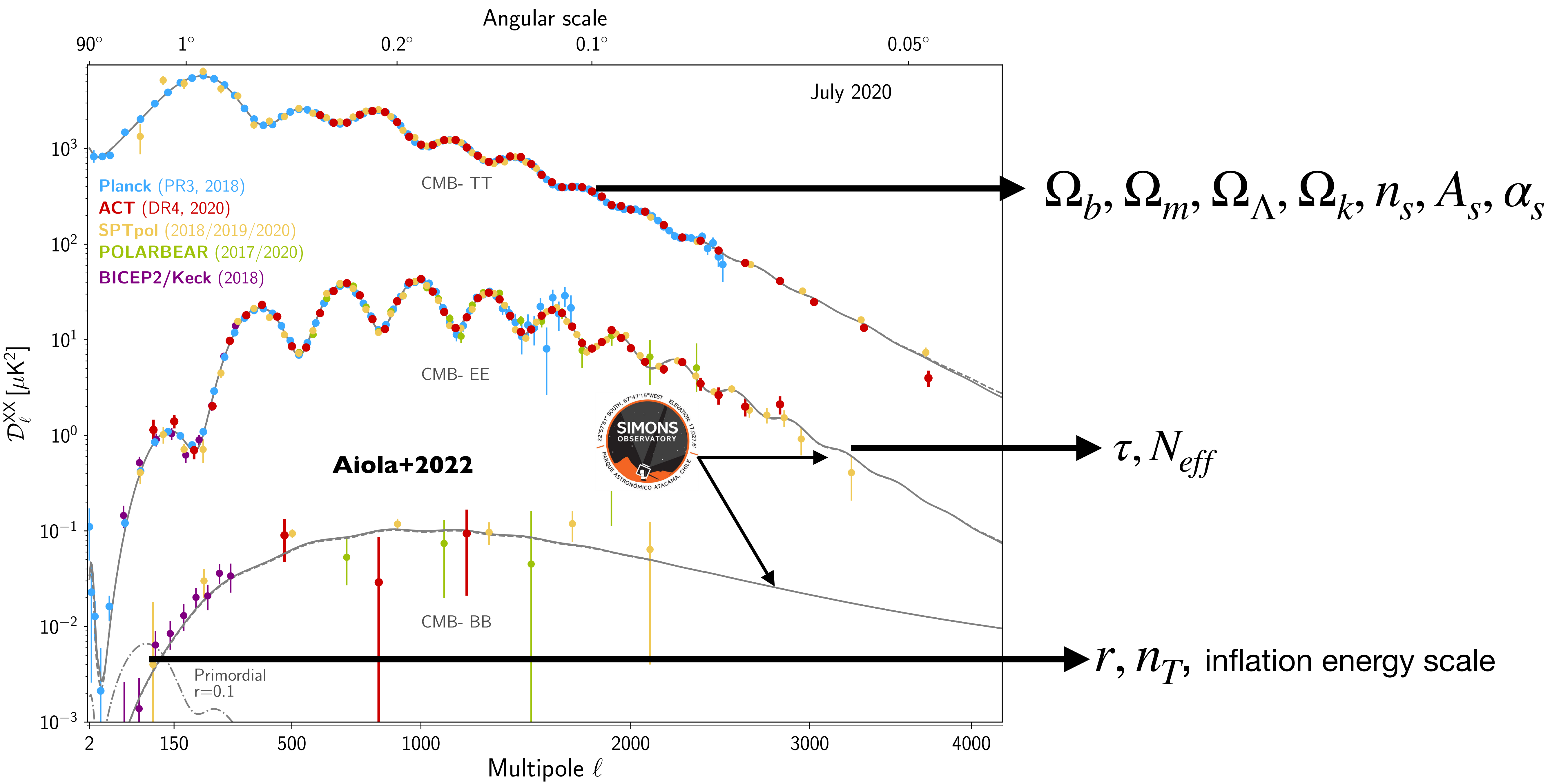


Open questions in cosmology as of 2026



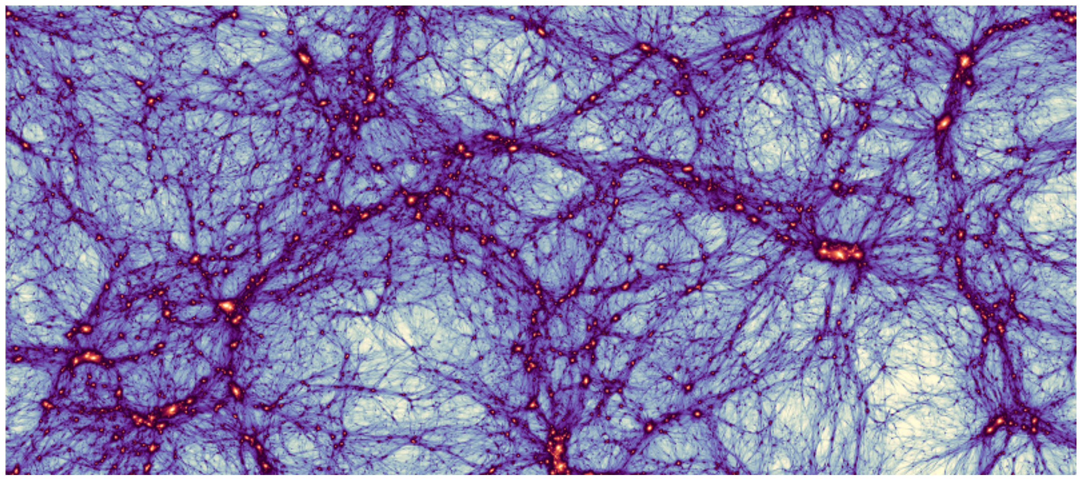
- What is dark matter? Do **massive neutrinos** contribute?
- What is the nature of **dark energy**?
- Which mechanism driving primordial **inflation**?

Cosmological probes: CMB

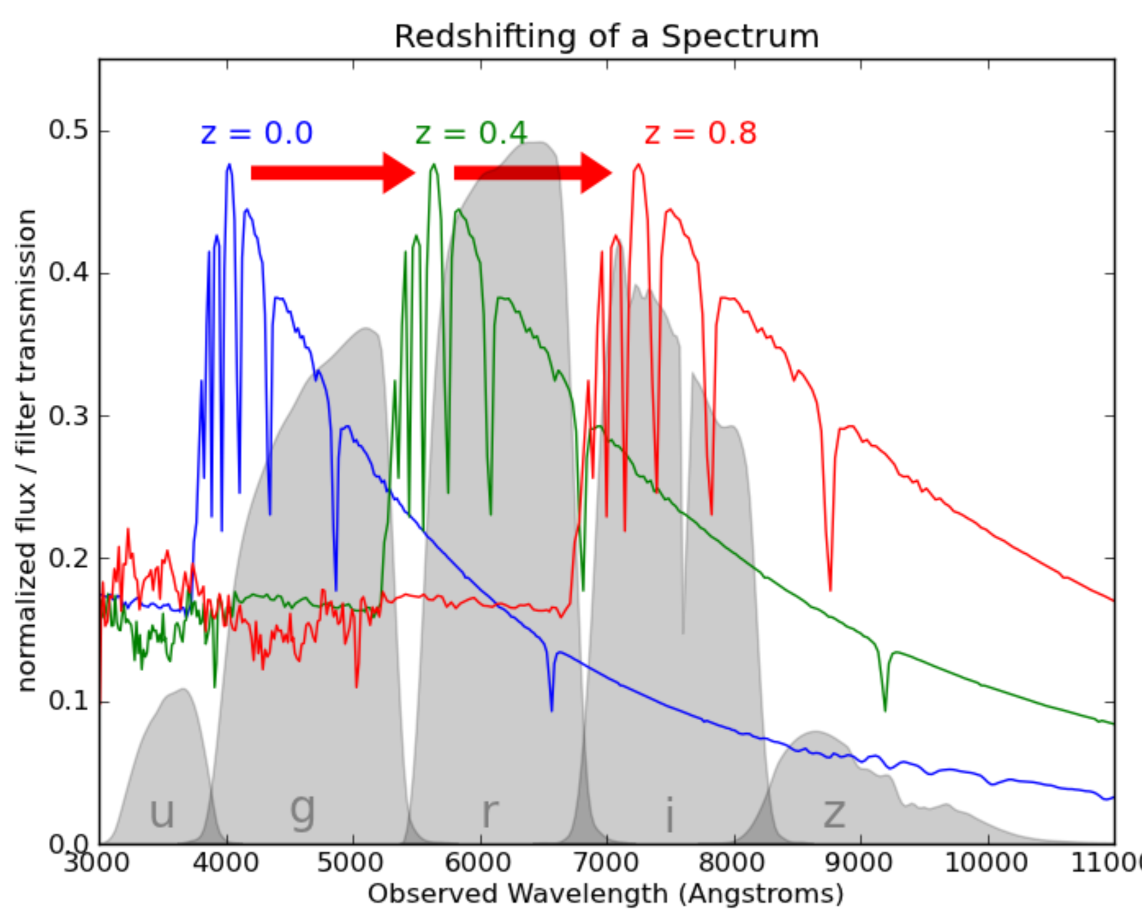


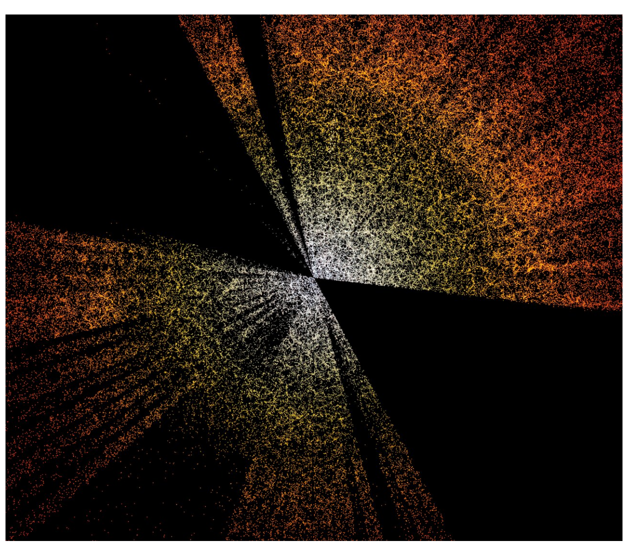
- CMB temperature information almost saturated by Planck
- Major improvements on $\sum m_\nu$ from new polarization measurements.

Beyond CMB observations



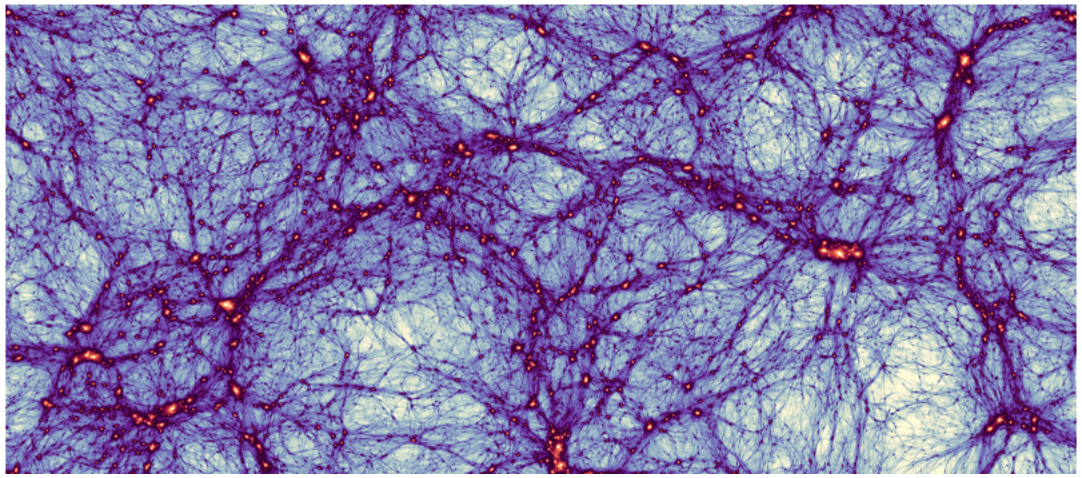
$f[\delta_m]$





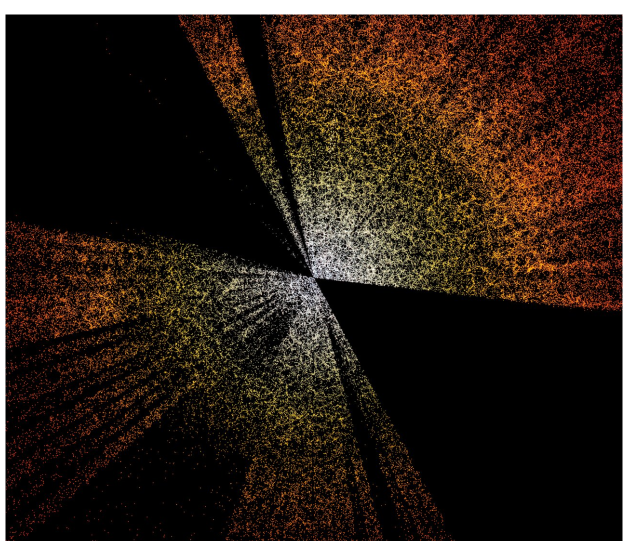
Beyond CMB observations

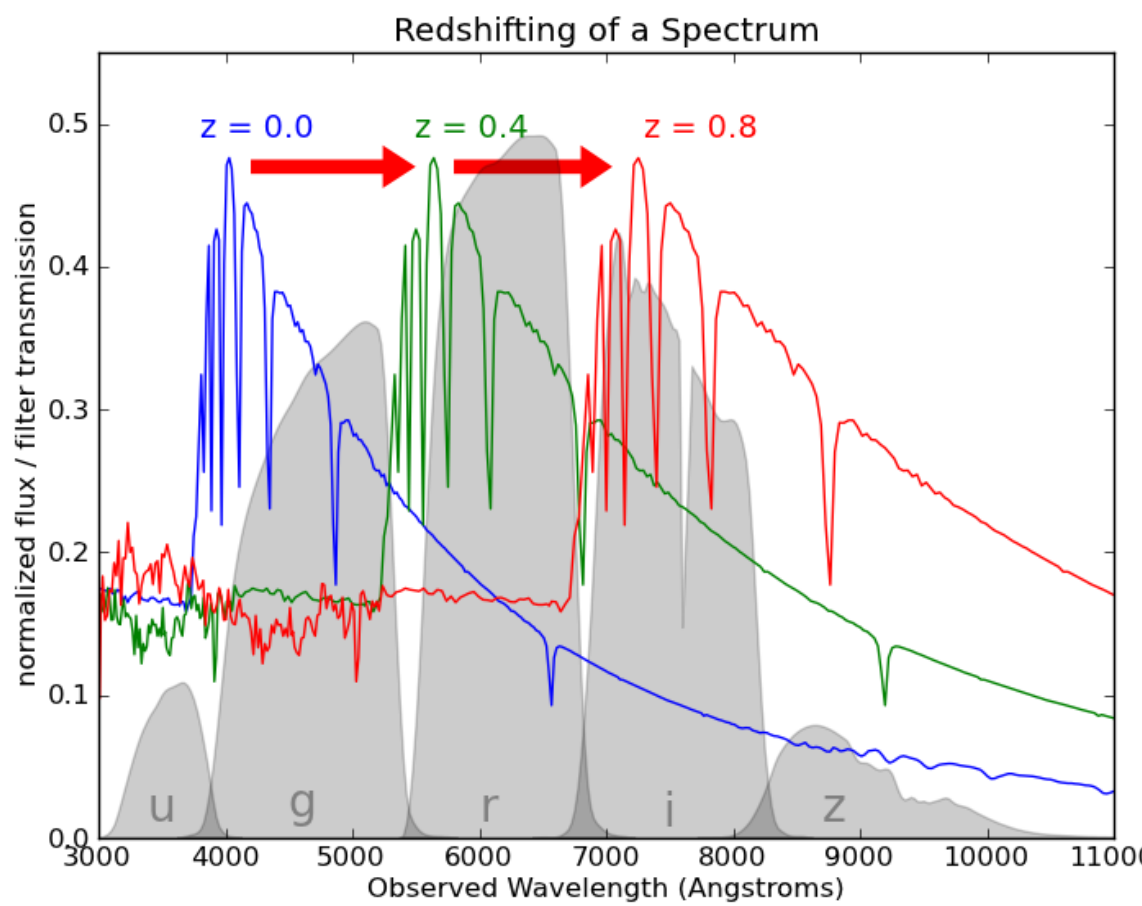
- Observing matter distributions as it grows: we need proxies



$$f[\delta_m]$$

- Spectroscopic surveys (e.g. DESI)

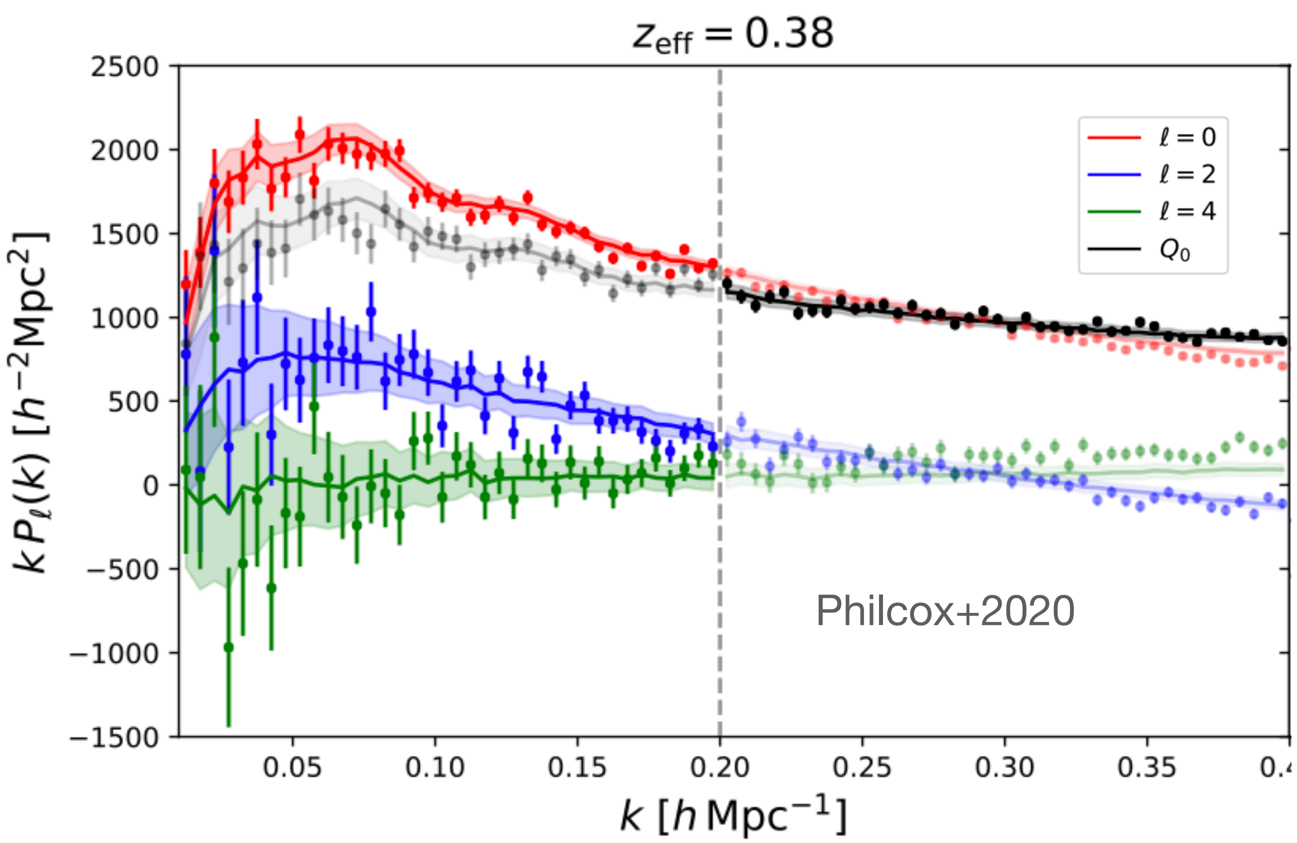


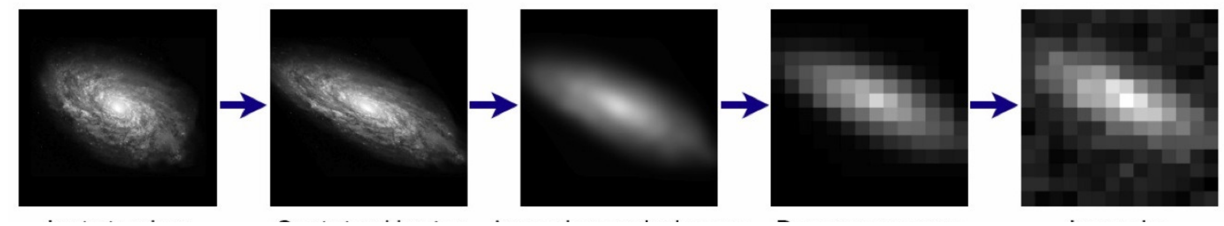


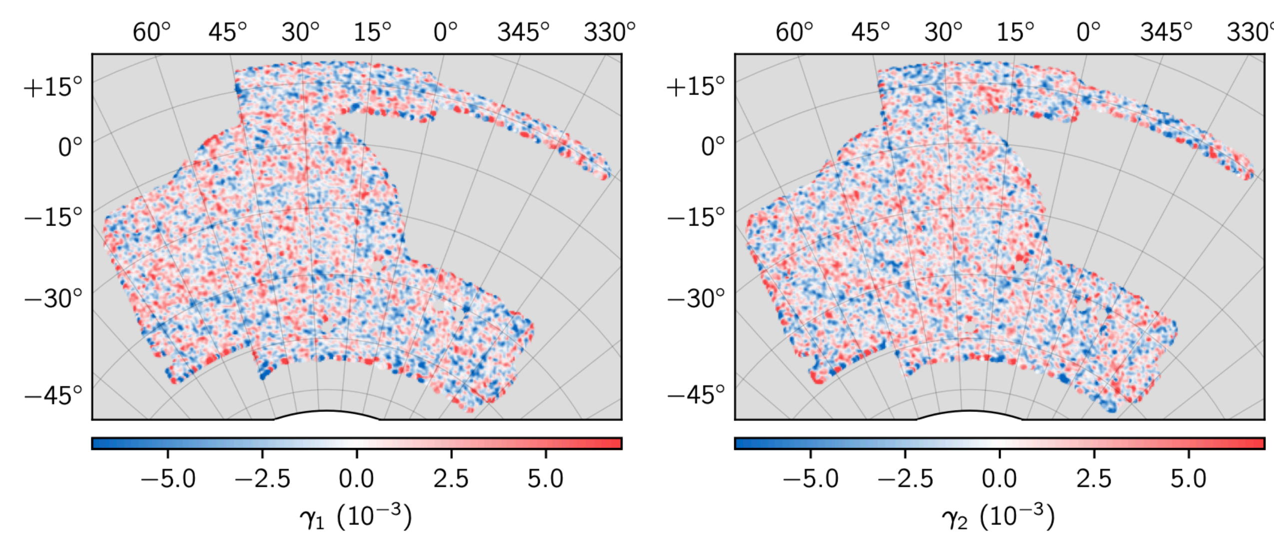
- Photometric surveys (e.g. Rubin)

Cosmological probes: galaxy clustering + shear

- CMB alone is weakly sensitive to e.g. dark energy: we need (tomographic) LSS!







- Galaxy clustering: P(k), BAO, RSD, voids are sensitive to the growth rate and amplitude of fluctuations

- Biased tracers…

$$P_{gg}(k,z) \approx b^2(z,k) P_{mm}(k,z)$$

- Galaxy lensing: sensitive to amplitude of fluctuations and geometry

$$C^{\gamma\gamma}_{z_i} \approx P_m(k,z_i) \frac{\chi - \chi_{z_i}}{\chi \chi_{z_i}} \frac{dN}{dz} j_\ell(k\chi)$$

- Unbiased but very hard: needs good z, many galaxies, systematics control.

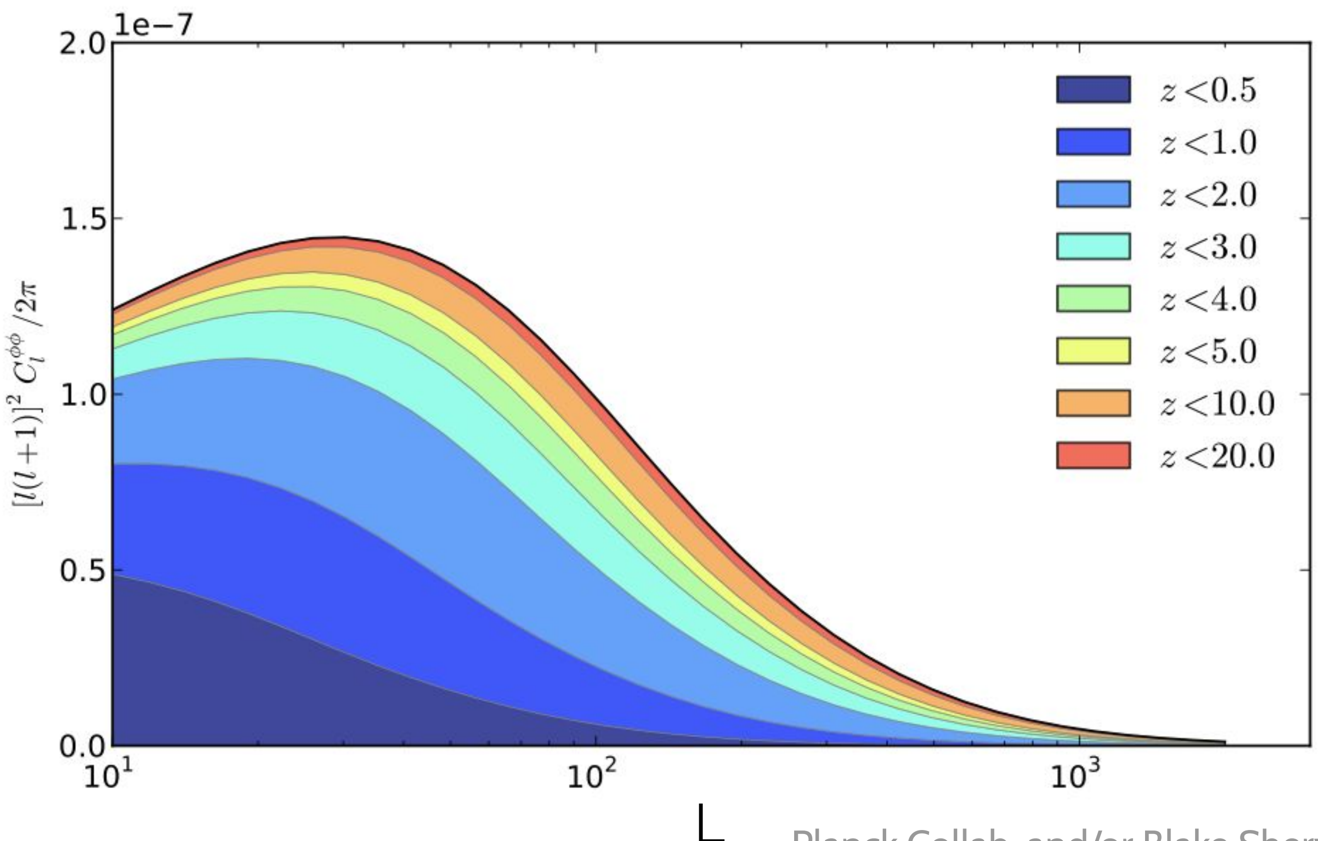
The CMB lensing potential

- Unbiased tracers of the whole integrated matter distribution along the line of sight.

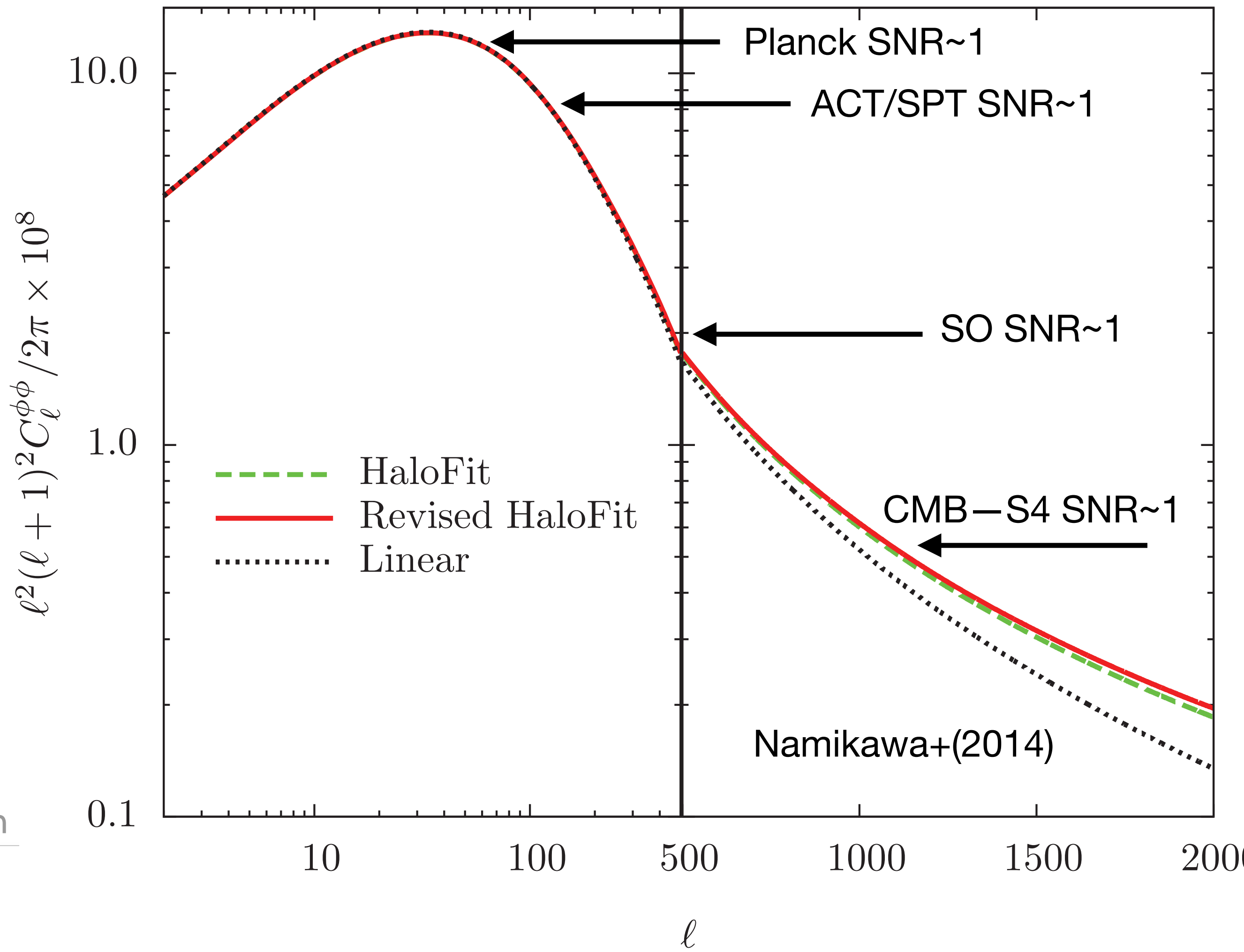
$$\phi(\boldsymbol{\theta}) = -2 \int_0^{\chi_s} \frac{D_A(\chi_s - \chi')}{D_A(\chi_s) D_A(\chi')} \Psi\left(\boldsymbol{\theta}, \chi'\right) \mathrm{d}\chi' \qquad \kappa \propto -\nabla^2\phi \rightarrow \delta$$

Notation Warning!

- Sensitive to total matter distribution $\sigma_8 \Omega_m^{0.25}$ at z~0.6-5 on mildly non-linear scales.

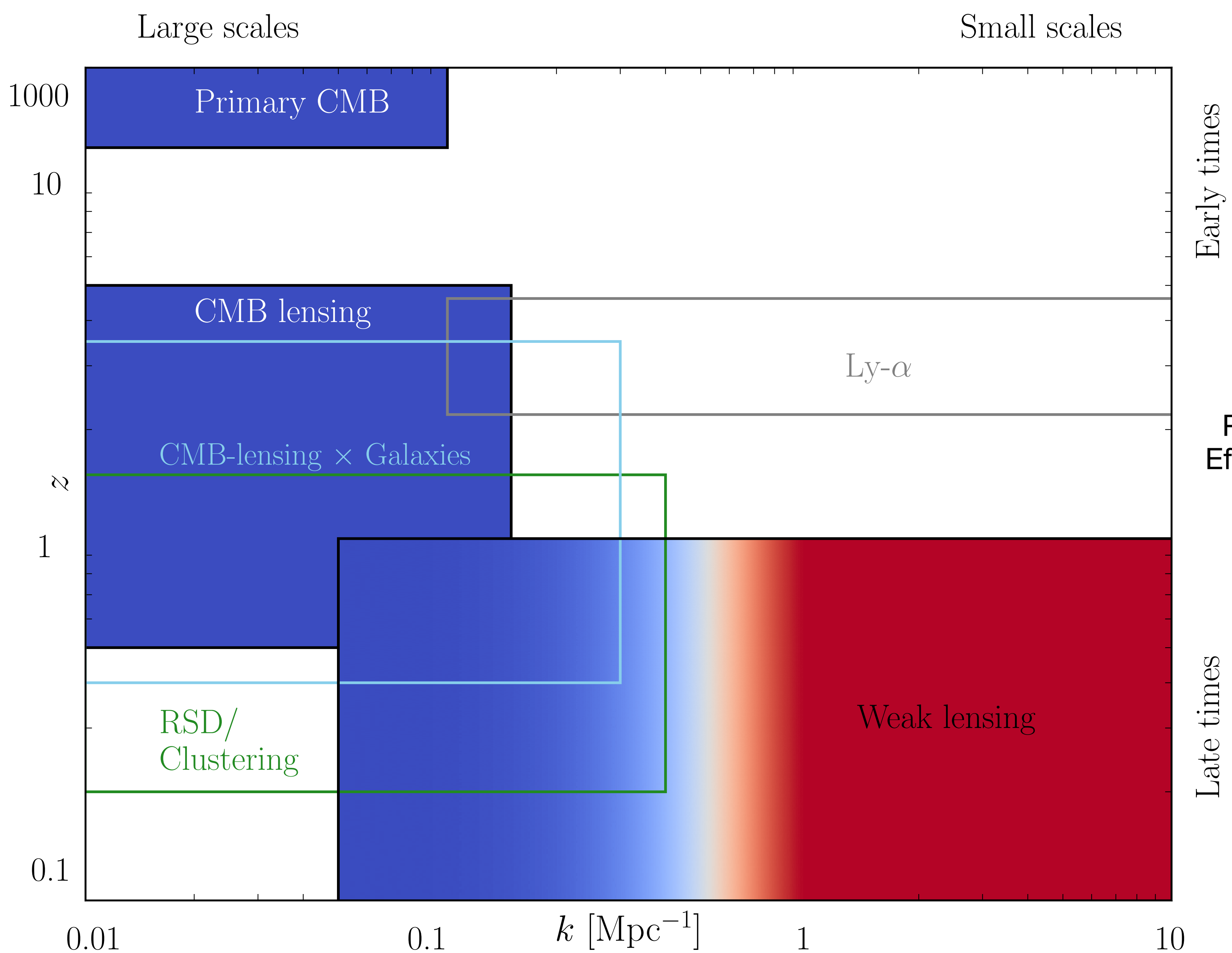


Planck Collab. and/or Blake Sherwin



Cosmological probes and cross-correlations

- Different probes test different scales and redshift (and different systematics).
- Need to assess if growth tension is real or effect of non-linear physics.



Preston, Amon, Efsthathiou (2023)

EUCLID

LAUNCH

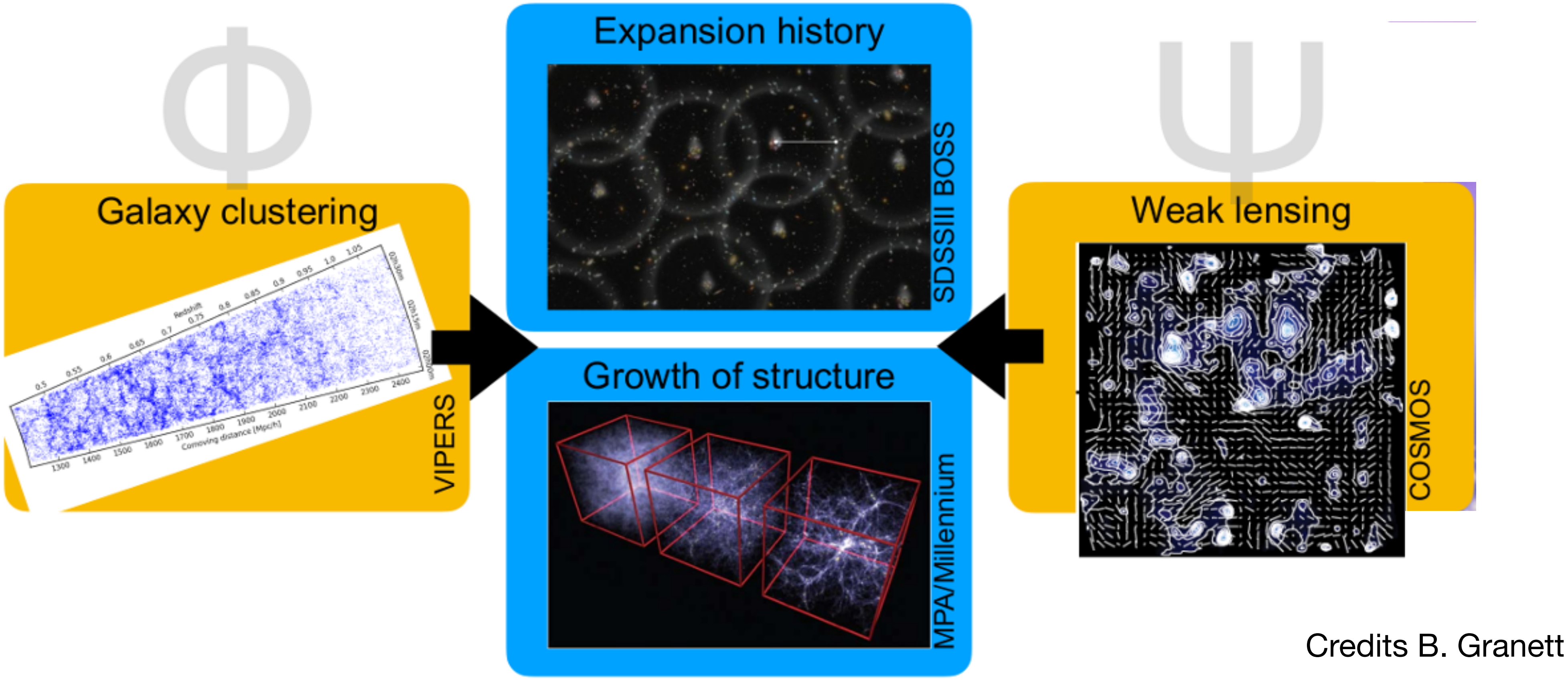
Euclid **launched on 1st July 2023** from Florida aboard a Falcon 9 launcher.

Euclid mission

- 14 European countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, the Netherlands, Norway, Portugal, Romania, Spain, Switzerland, UK) + USA, Canada, Japan.

- 2600 members, 200 institutes covering cosmology, astrophysics, particle physics

Euclid concept and targets



Clusters

CMB cross-correlations

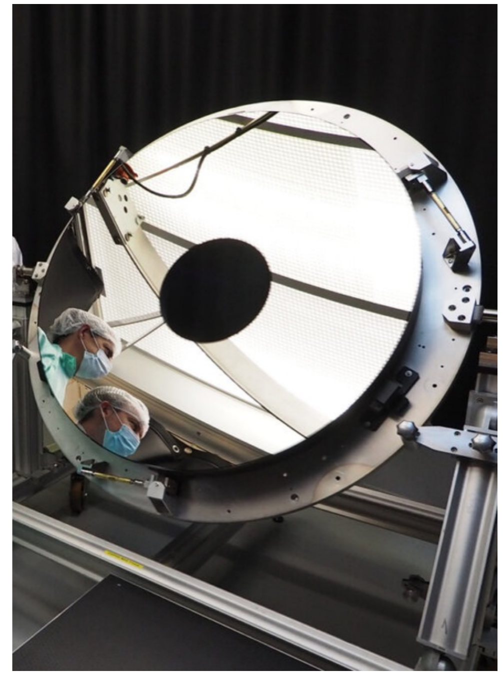
Strong lensing

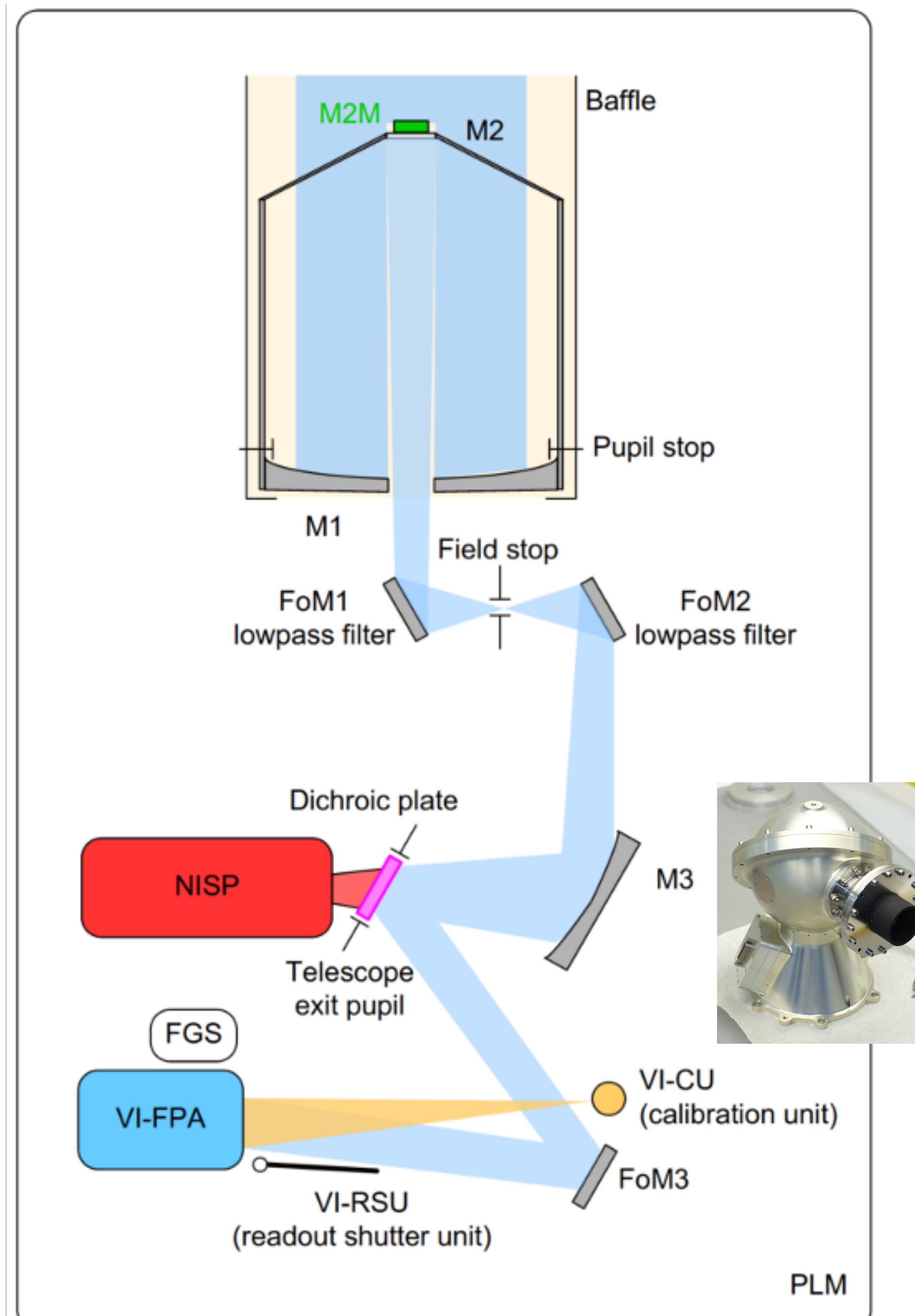
... and more

- Probe dark energy EOS $w(a) = w_0 + w_a(1-a) \quad \sigma(w_0) = 0.02,\ \sigma(w_a) = 0.1$
- Test gravity $f \approx \Omega_m^\gamma \quad \sigma(\gamma) = 0.02, \quad \sigma(f) \approx 0.02 \quad 0.9 < z < 1.9$
- Probe dark mater and IC: $\sigma(\sigma_8) = 0.01,\ \sigma\left(\sum m_\nu\right) = 0.03eV$, 2x better n_s, α_s

The Euclid instrument

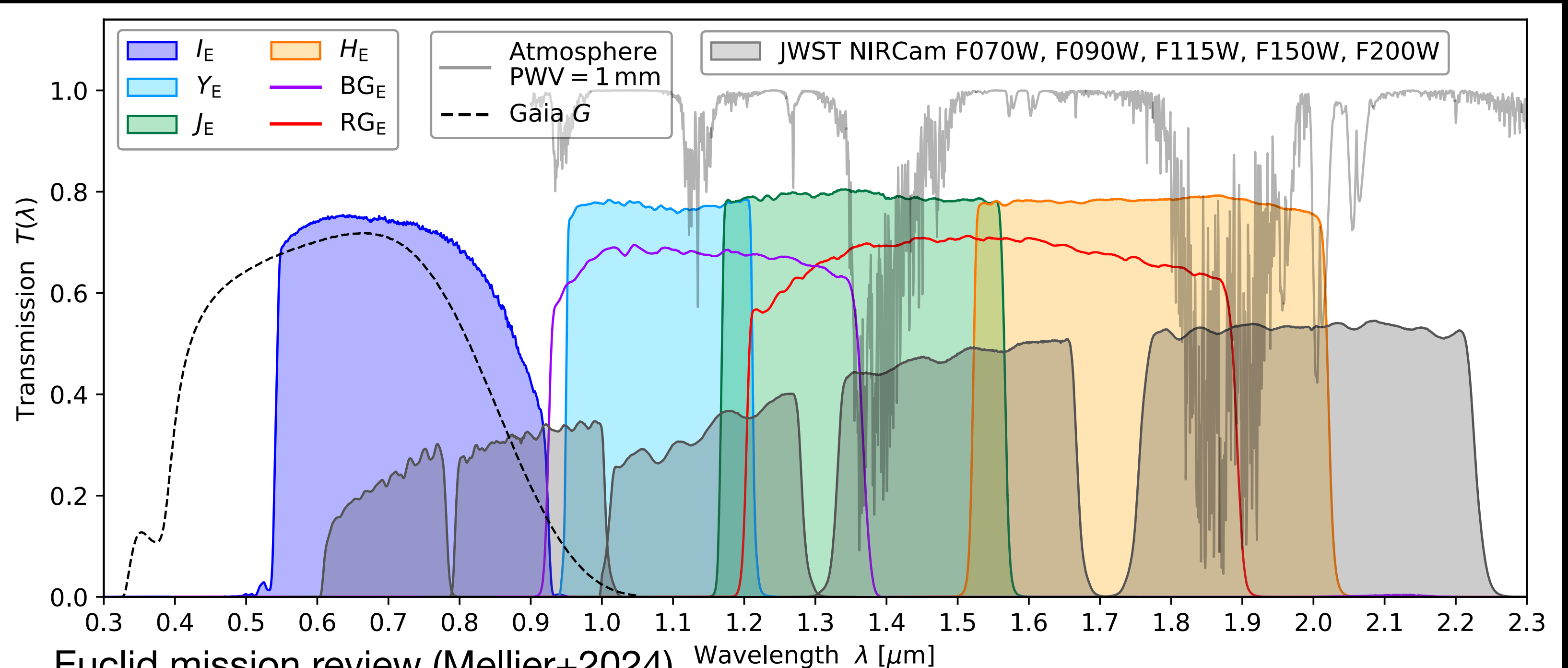
- 2100 kg
- 1.2 m mirror cooled <130K
- 3 mirror in SiCO
- FoV ~ 0.57 deg2
- 2 set of instrument working simultaneously:
  - VIS: visible band, 25 AB mag. limit at SNR~10
  - NISP: near IR, 24.5 AB mag. limit at SNR~5, spectra with R~400.



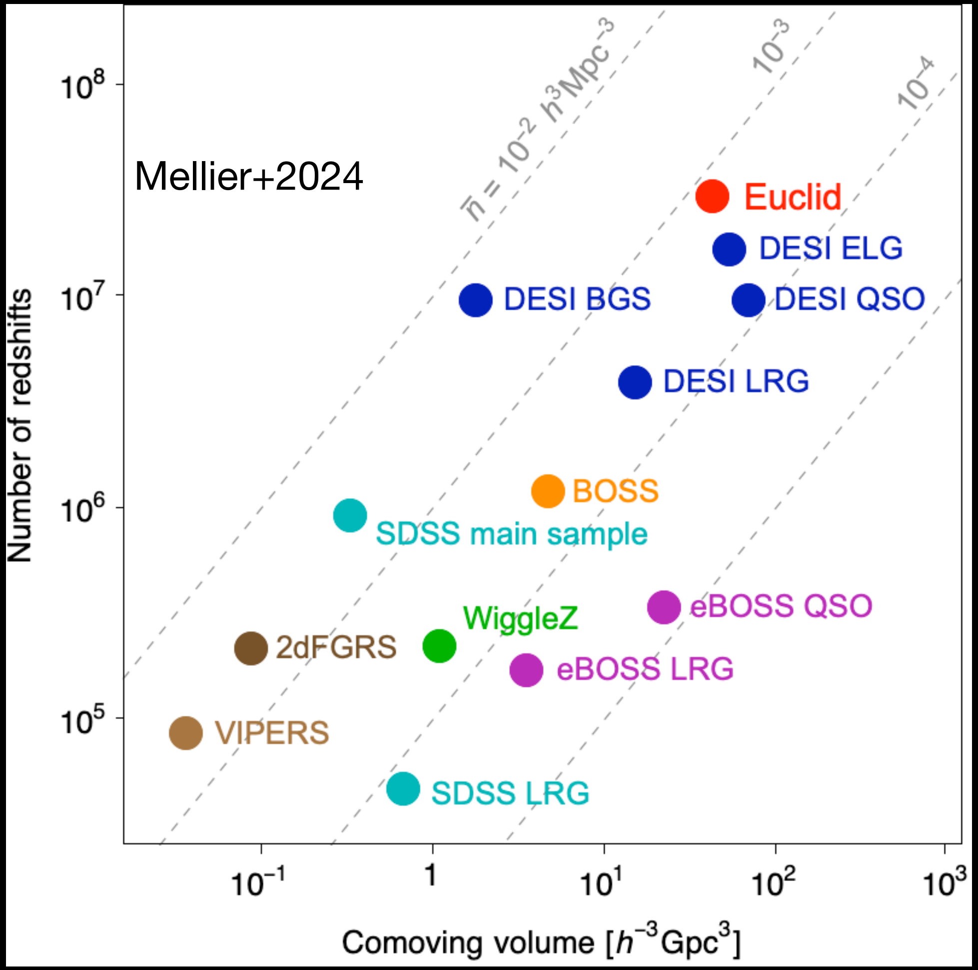


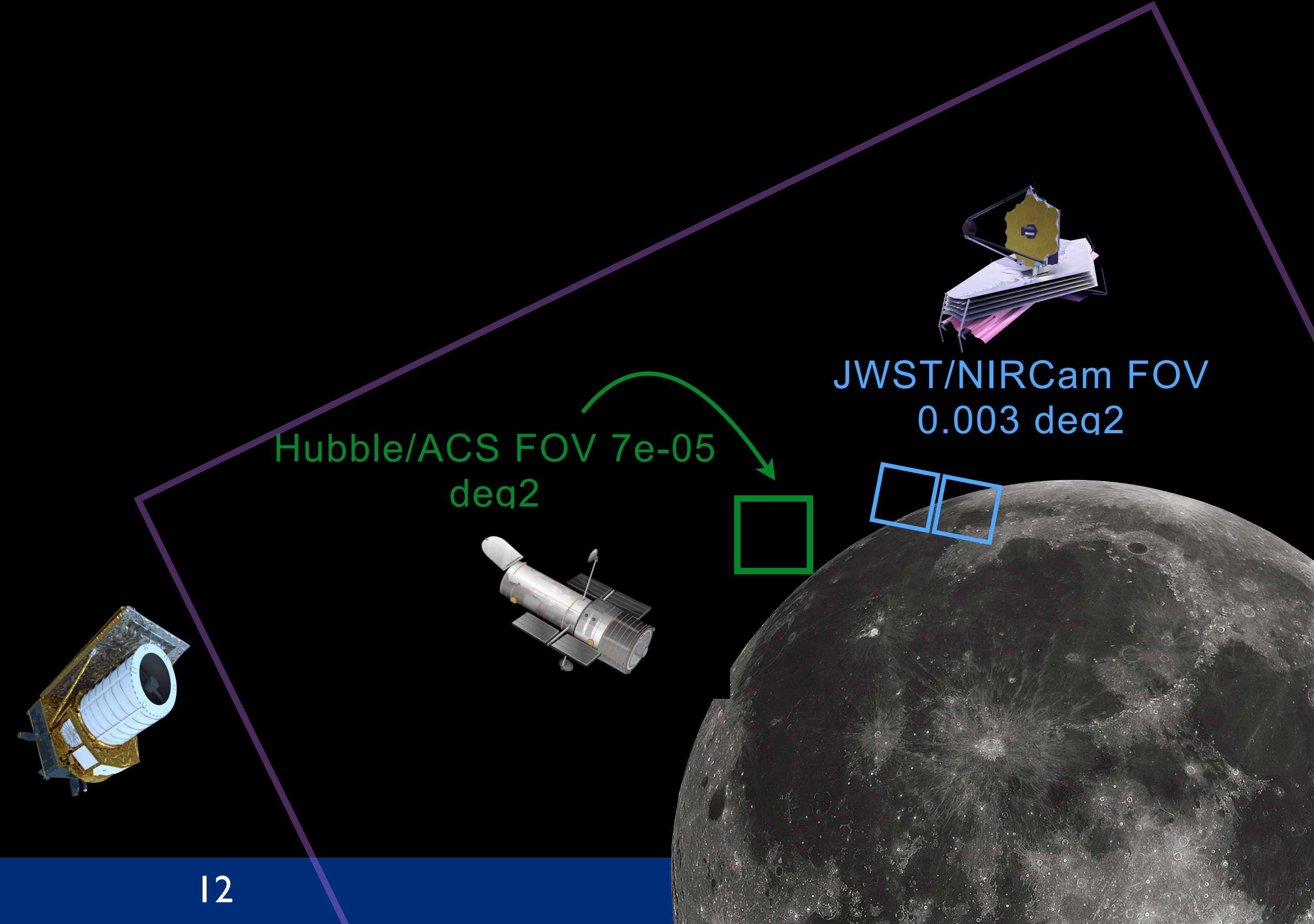
Performances

- Euclid covers 30 years of Hubble operation every ~5 days.
- Euclid FOV ~ 3x the moon size.
- Complements others facilities from space and ground (e.g. DESI, LSST).



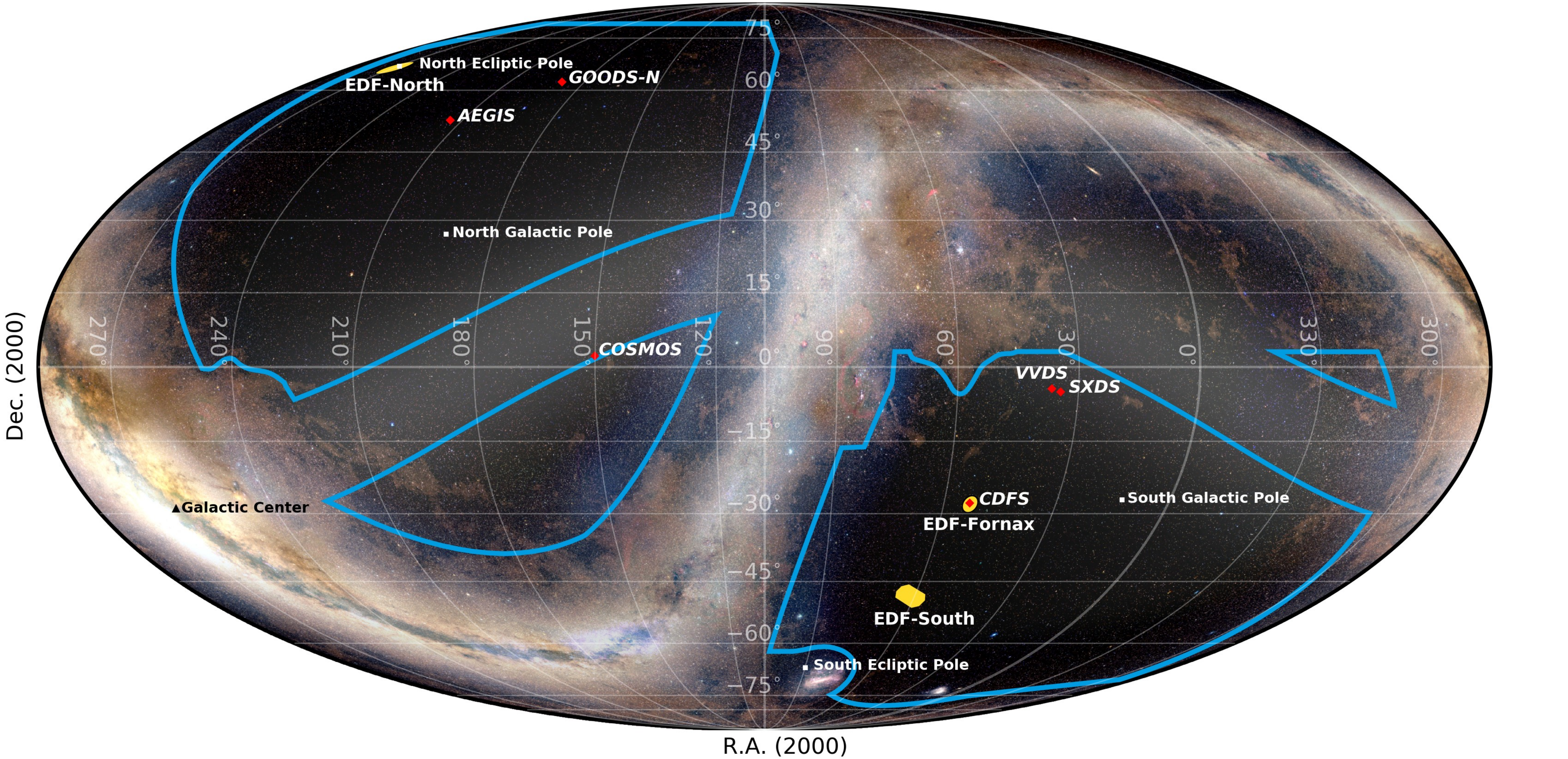
Euclid mission review (Mellier+2024)





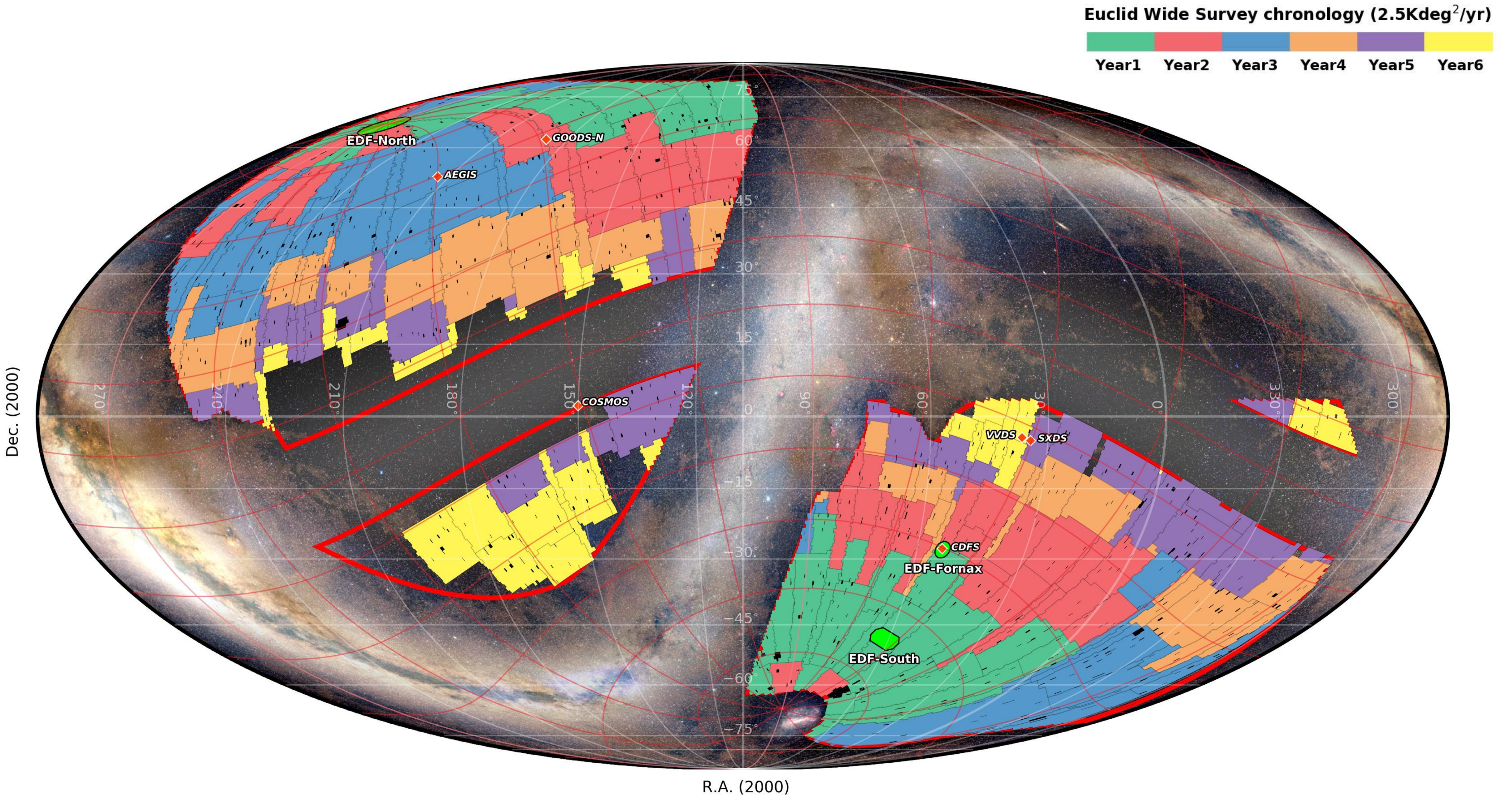
WIDE survey

- 15000 deg2 covered over 6 years of data acquisition. 4 visits with ~700s exposure.
- Optimized for low background (1/100 of Zodiacal + Galactic background).



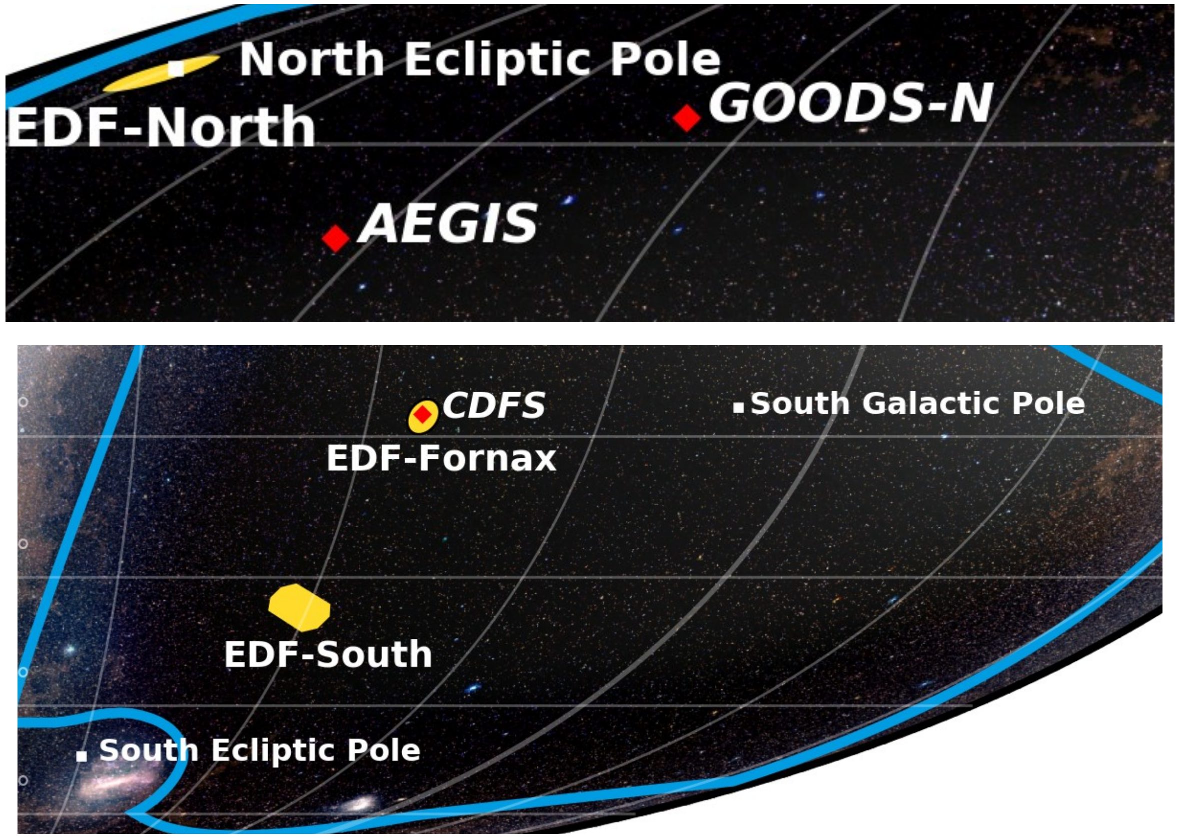
WIDE survey

- 15000 deg2 covered over 6 years of data acquisition. 4 visits with ~700s exposure.
- Optimized for low background (1/100 of Zodiacal + Galactic background).

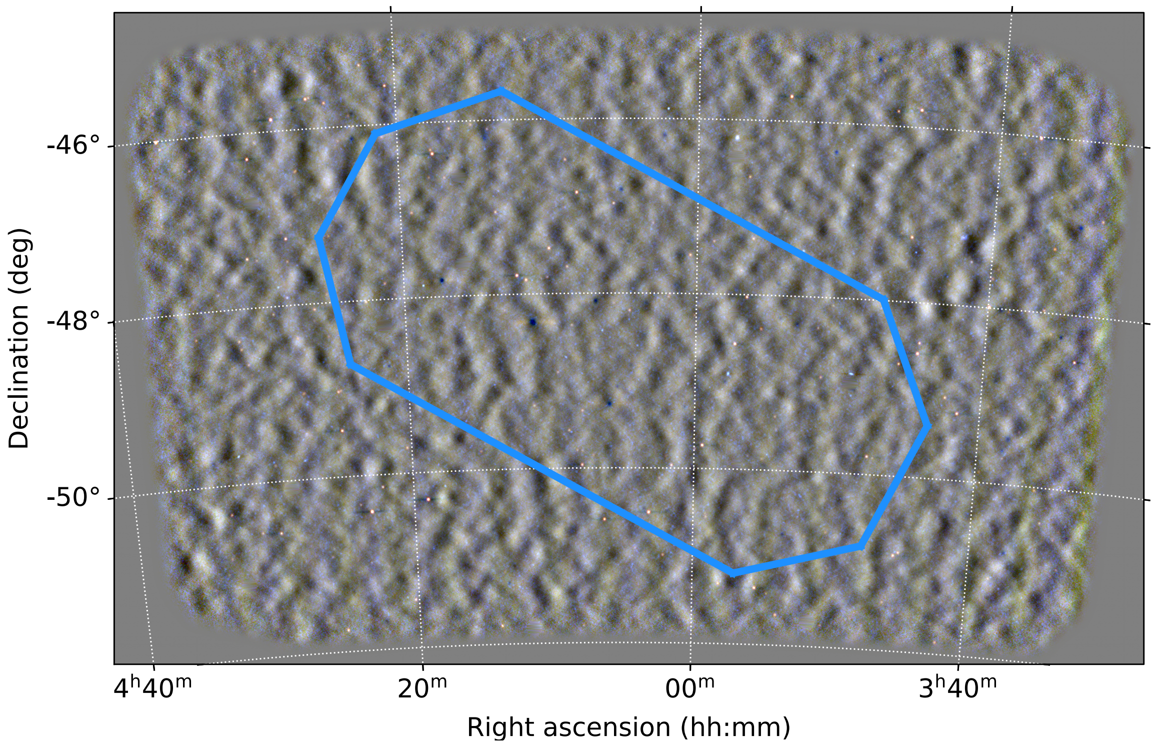


Deep fields

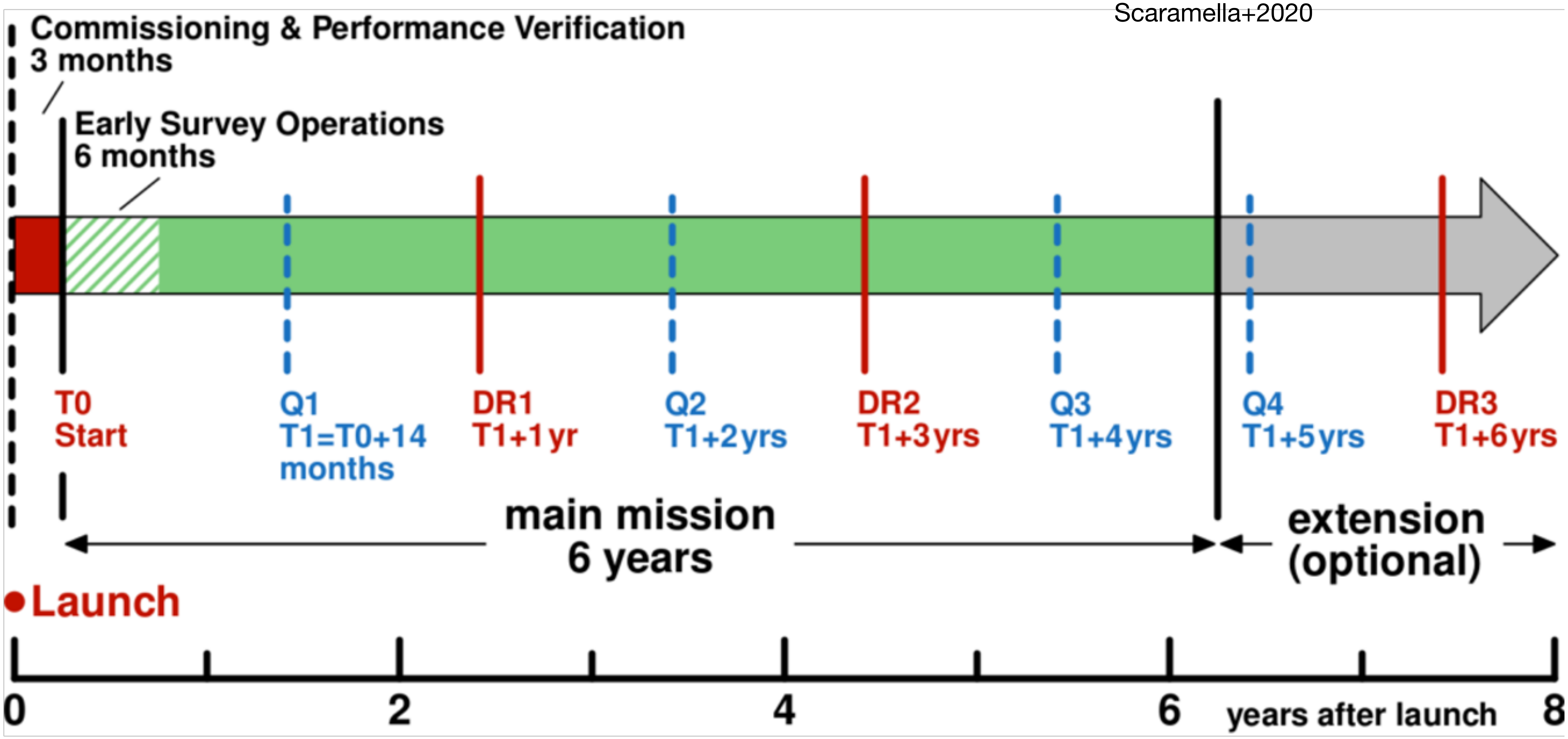
- 53 deg2 + auxiliary fields (e.g. COSMOS)
- Revisited multiple times across the survey time
- 2x magnitude deeper will be used for
  - Calibration, selection function, legacy science…
- Ground based synergies with DES, HSC, UNIONS for photometric redshift.
  - None of them will match the Euclid specs until… Rubin.
- Follow-up with mm-wave instruments, e.g. SPT.



SPT coll: Archipley+(2025)

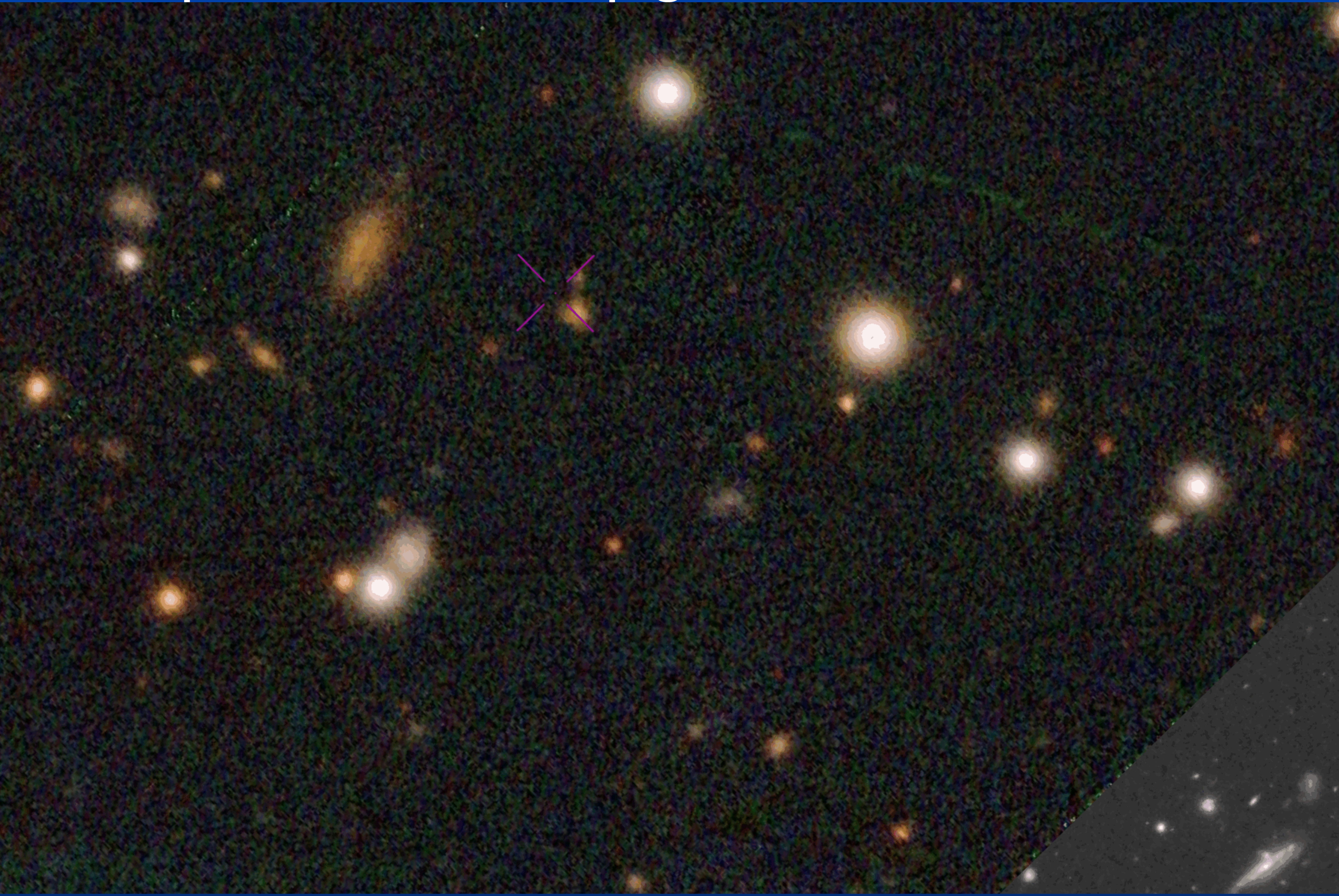


Status and timeline



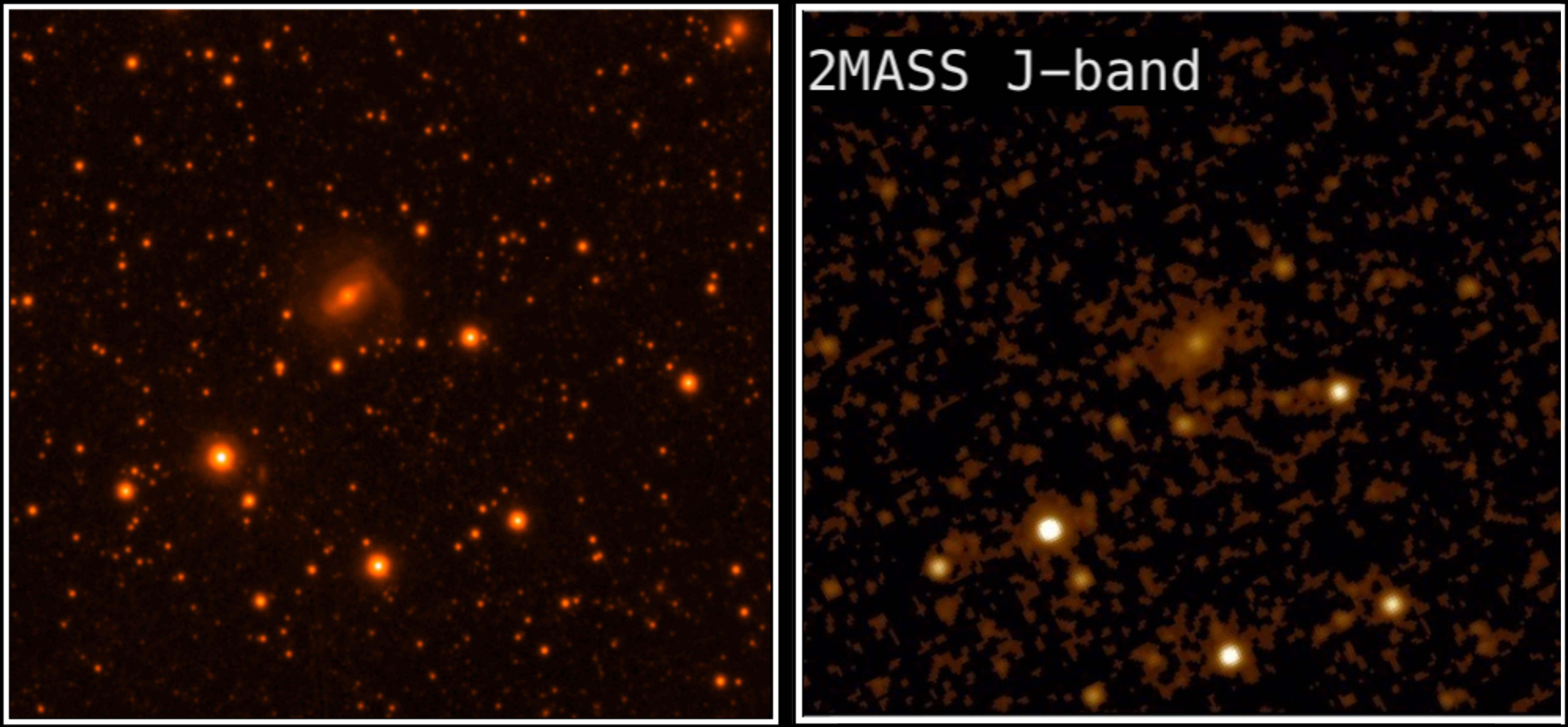
- Commissioning ongoing, focusing and mechanical tests all successful.
- Few problems identified and solved (e.g. ice, solar flares…)
- 1st public release 2025 (Q1). Internal DR1 release imminent.

A comparison with deep ground-based data…



EUCLID

RESULTS SO FAR

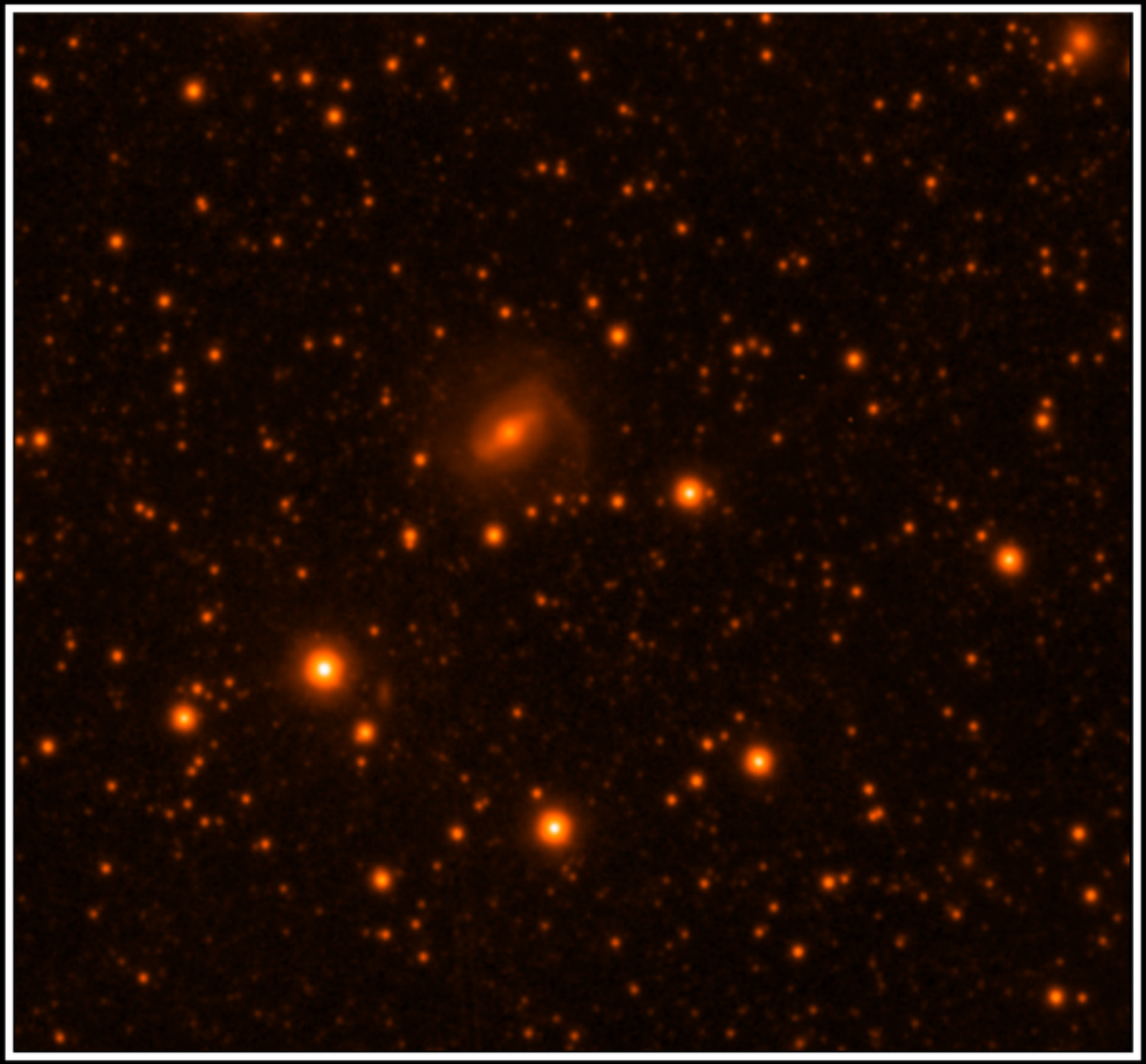


VISTA VMC J–band

Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

EUCLID

RESULTS SO FAR



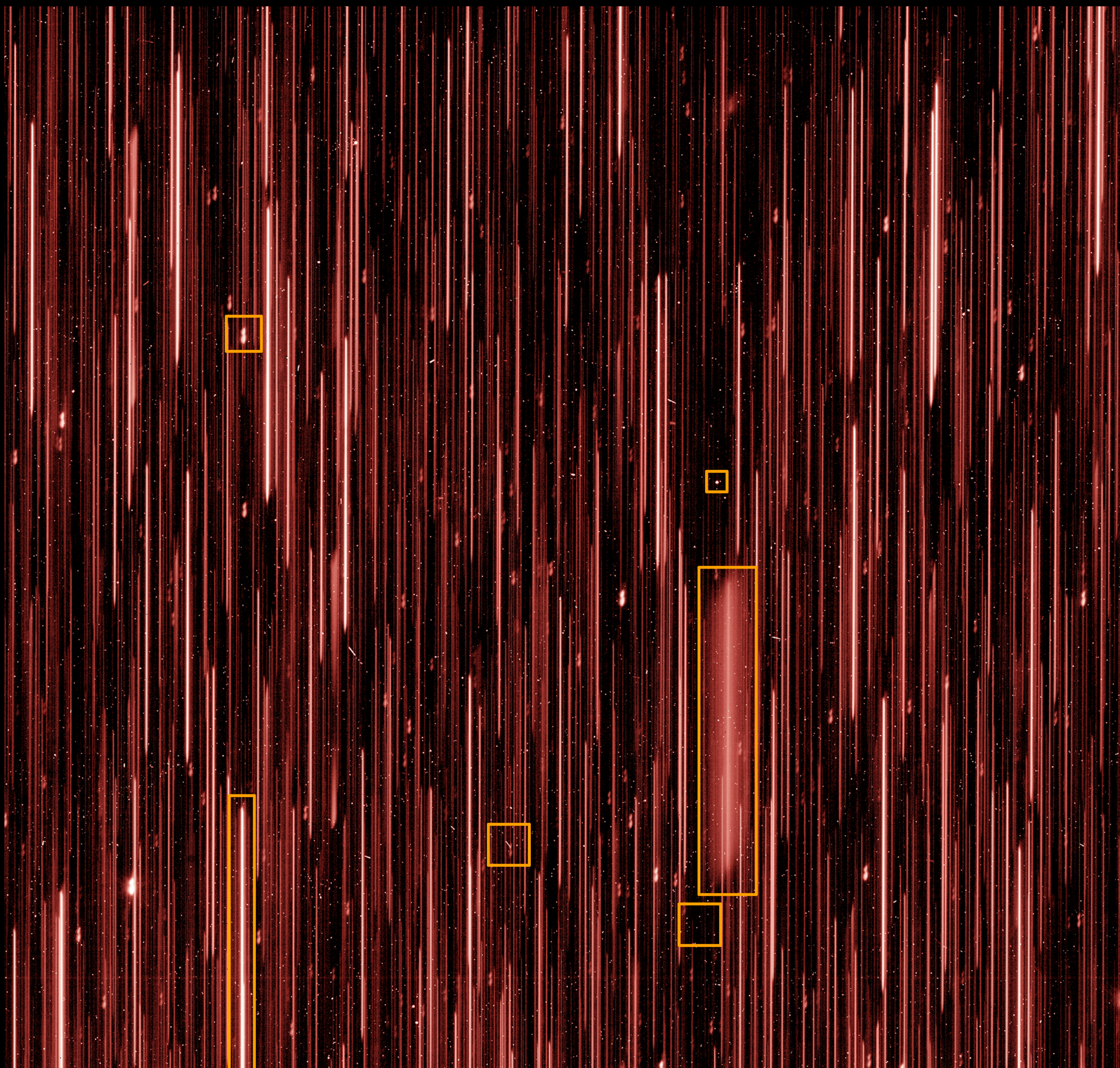
VISTA VMC J-band

Euclid NISP Test Image

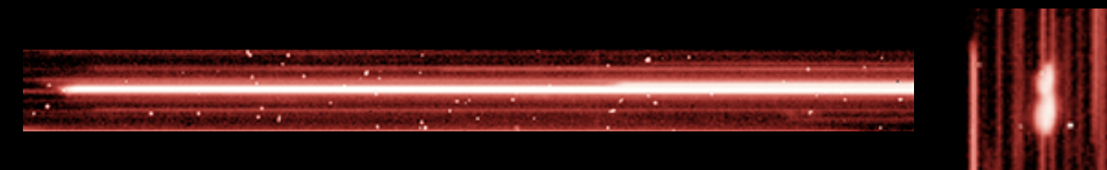
Credit: Ralf Bender & Ross Collins using public data from Euclid and VISTA

EUCLID

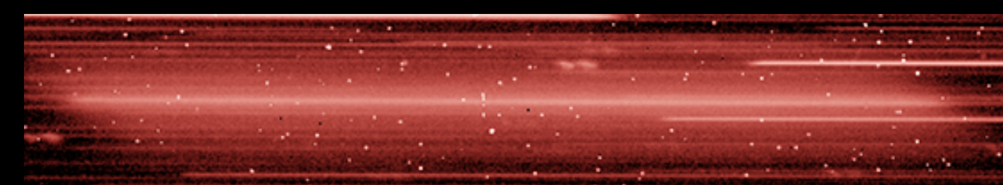
RESULTS SO FAR



Early commissioning test image, NISP instrument (grism mode)

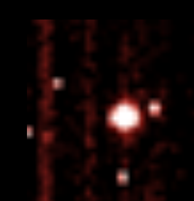


Stars



Galaxy

Cosmic ray / artifacts



Snowball / muon

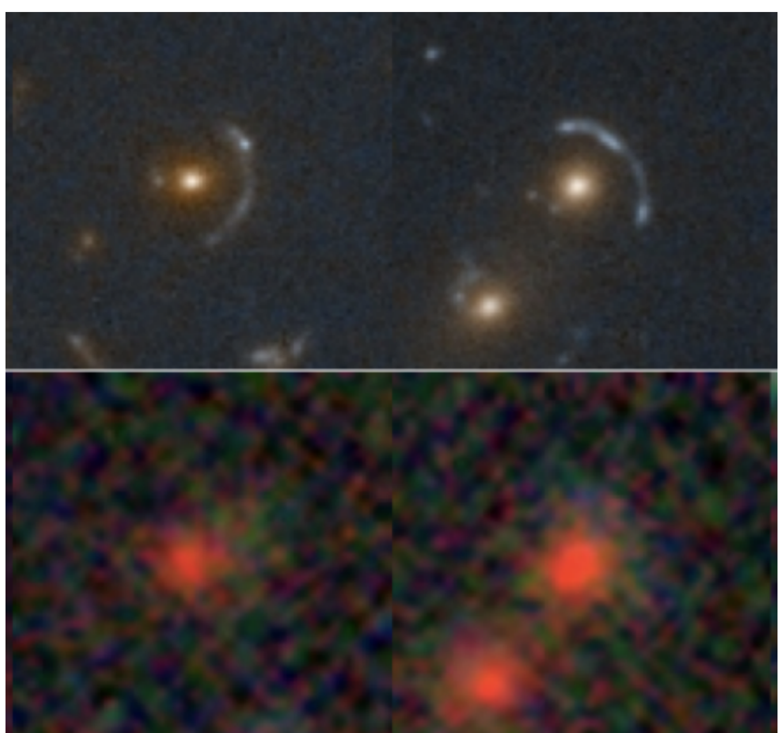
Credit: ESA/Euclid/Euclid Consortium/NASA

What to expect: synergies between surveys.

Euclid Early Release Observation image

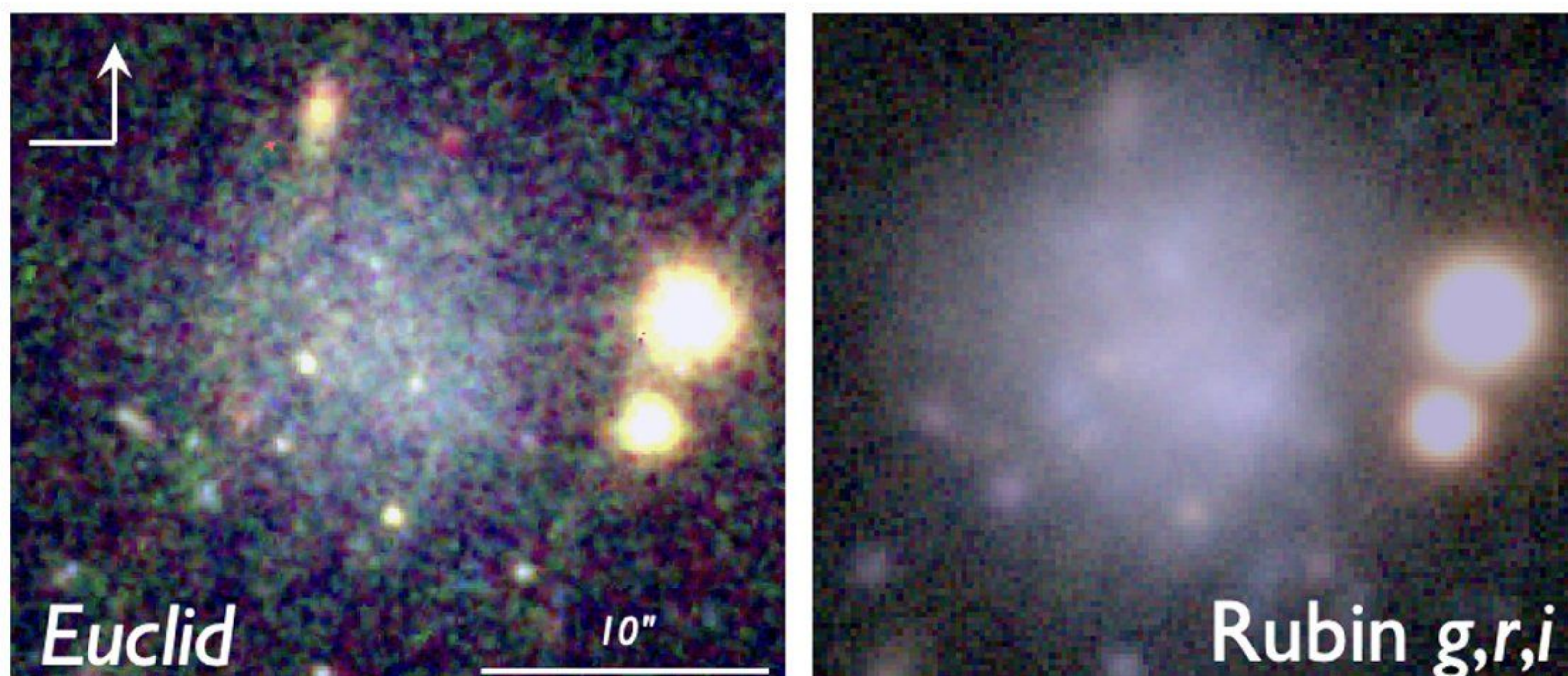
Rubin 1st wide image

Euclid Q1 release



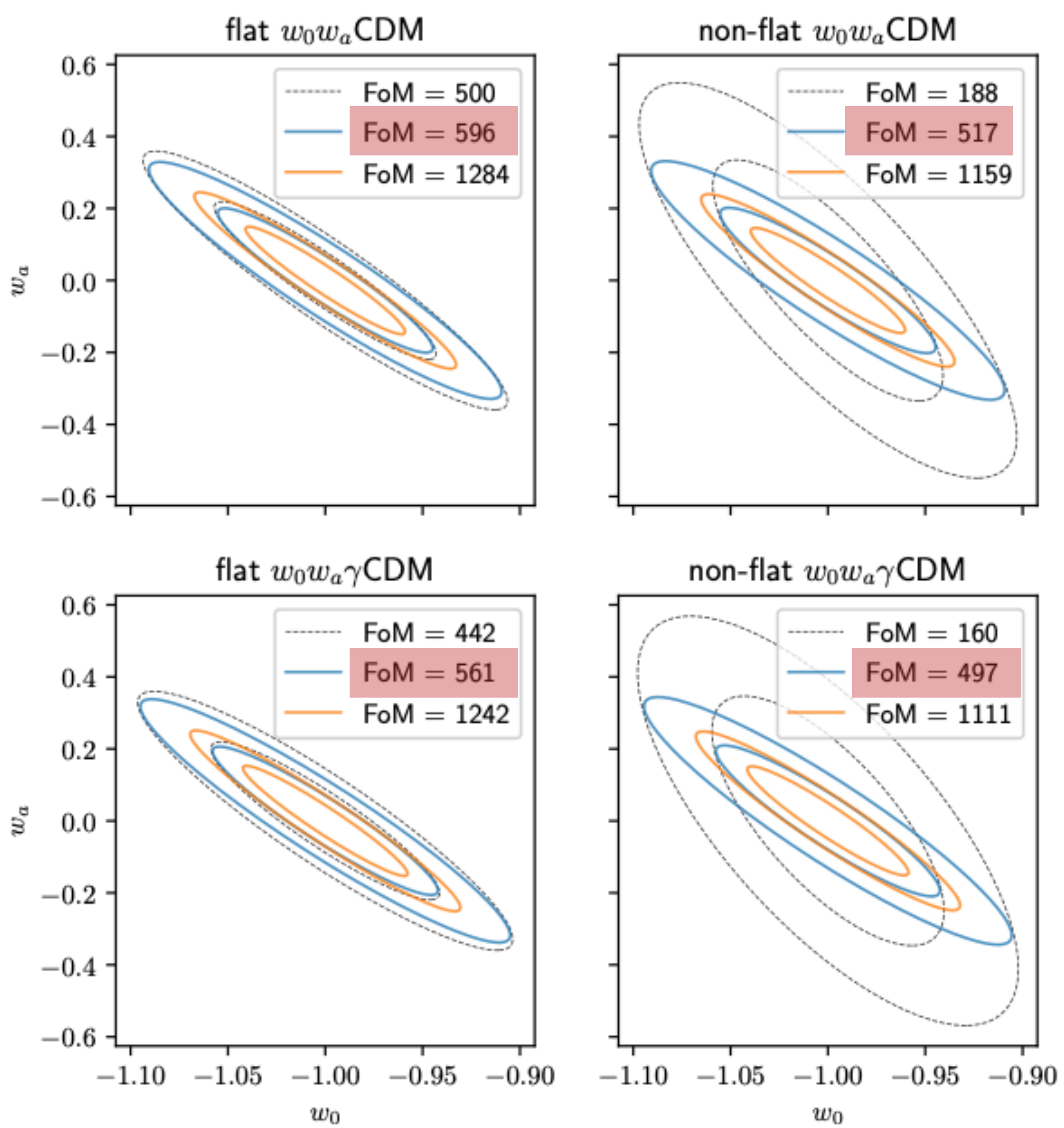
DESI Legacy Imaging Survey

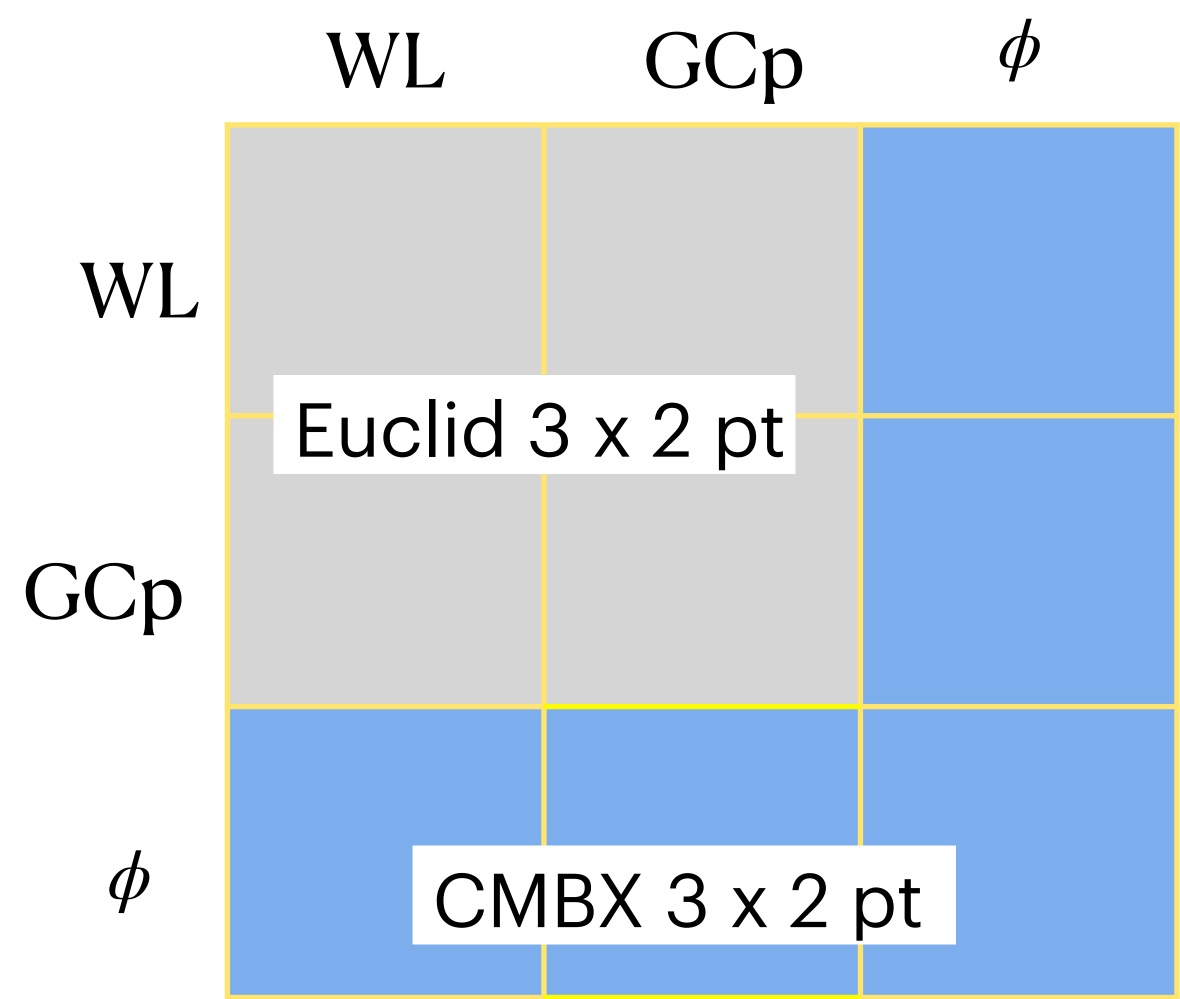
Romanowsky+(2025)



Forecast for 6x2pt analysis

- Pessimistic setup in ~5 tomographic redshift bins and WL, zmax=1 and SO-like baseline sensitivity (conservative)
  - 4-10x improvements in dark energy / modified gravity parameters!



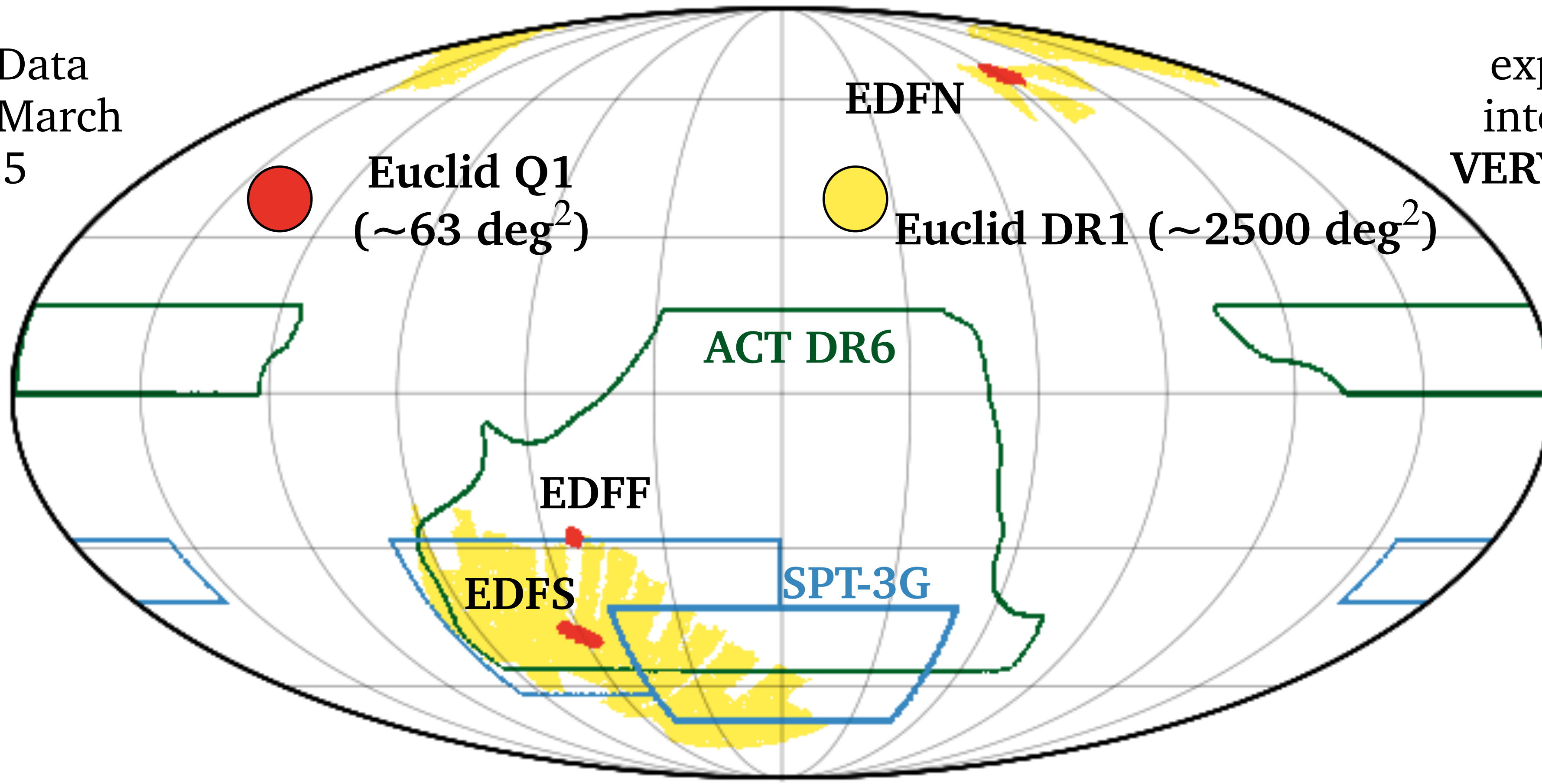


Euclid collab. (Blanchard+19)

Euclid collab. w/ CMBX SWG (Ilic+21)

Towards DR1: the Q1 data release

Quick Data Release March 2025

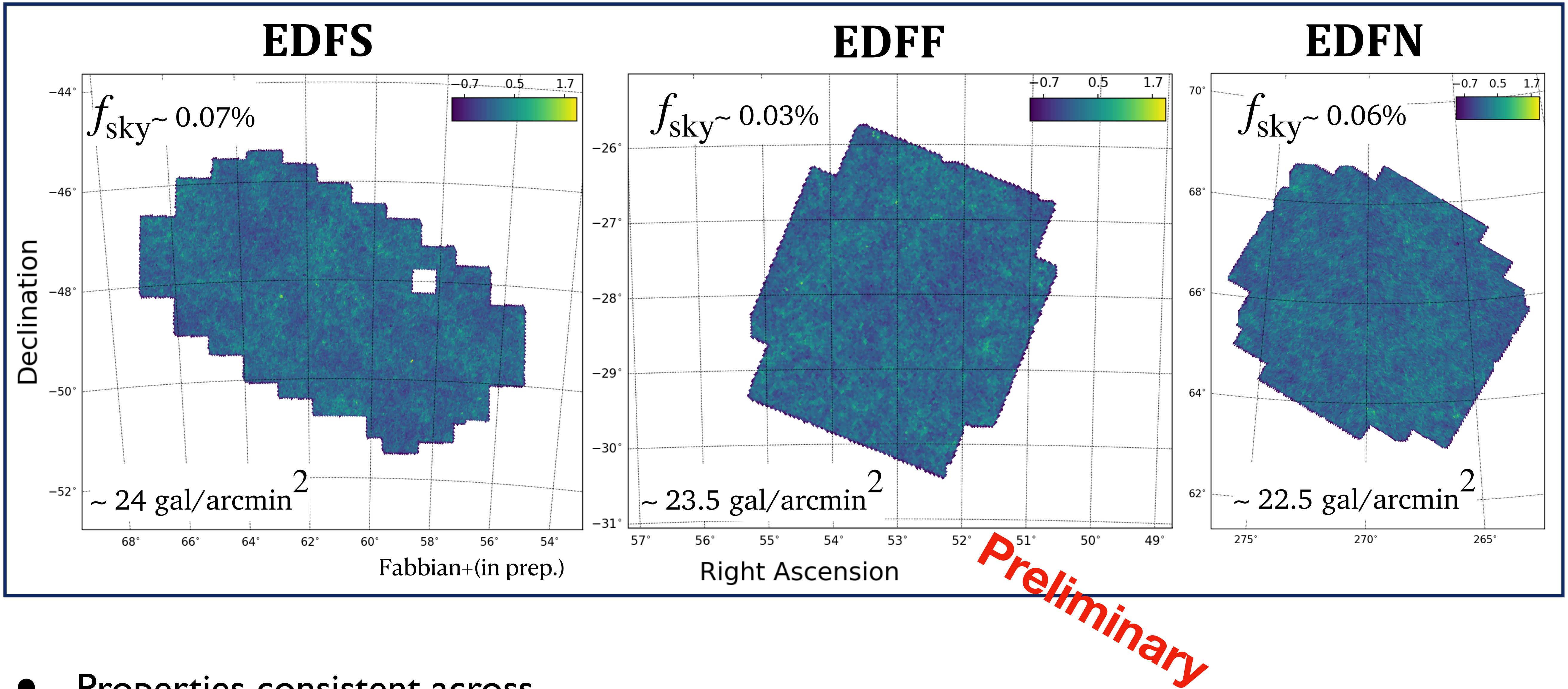


expected internally **VERY SOON**

- Preliminary release with 1st quarter of data (Q1) ~63 deg2 with "pre-launch" pipeline.
  - Ideal for cross-correlation!

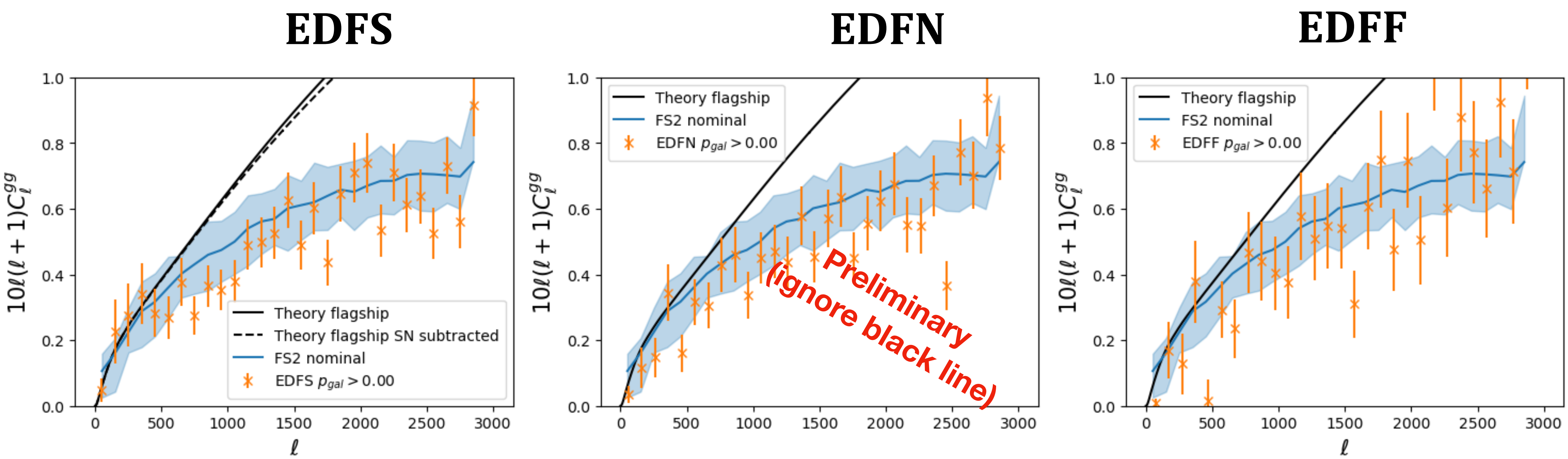
    Fabbian, Legrand, Pagano, Lembo, Piccirilli, Kou, Hartley, Tessore+(in prep.)
  - Planck for the EDFN, ACT for the EDFF and EDFS patches
- DR1 analysis: Planck for the north, both ACT and SPT in the south patch

Towards DR1: the Q1 data release



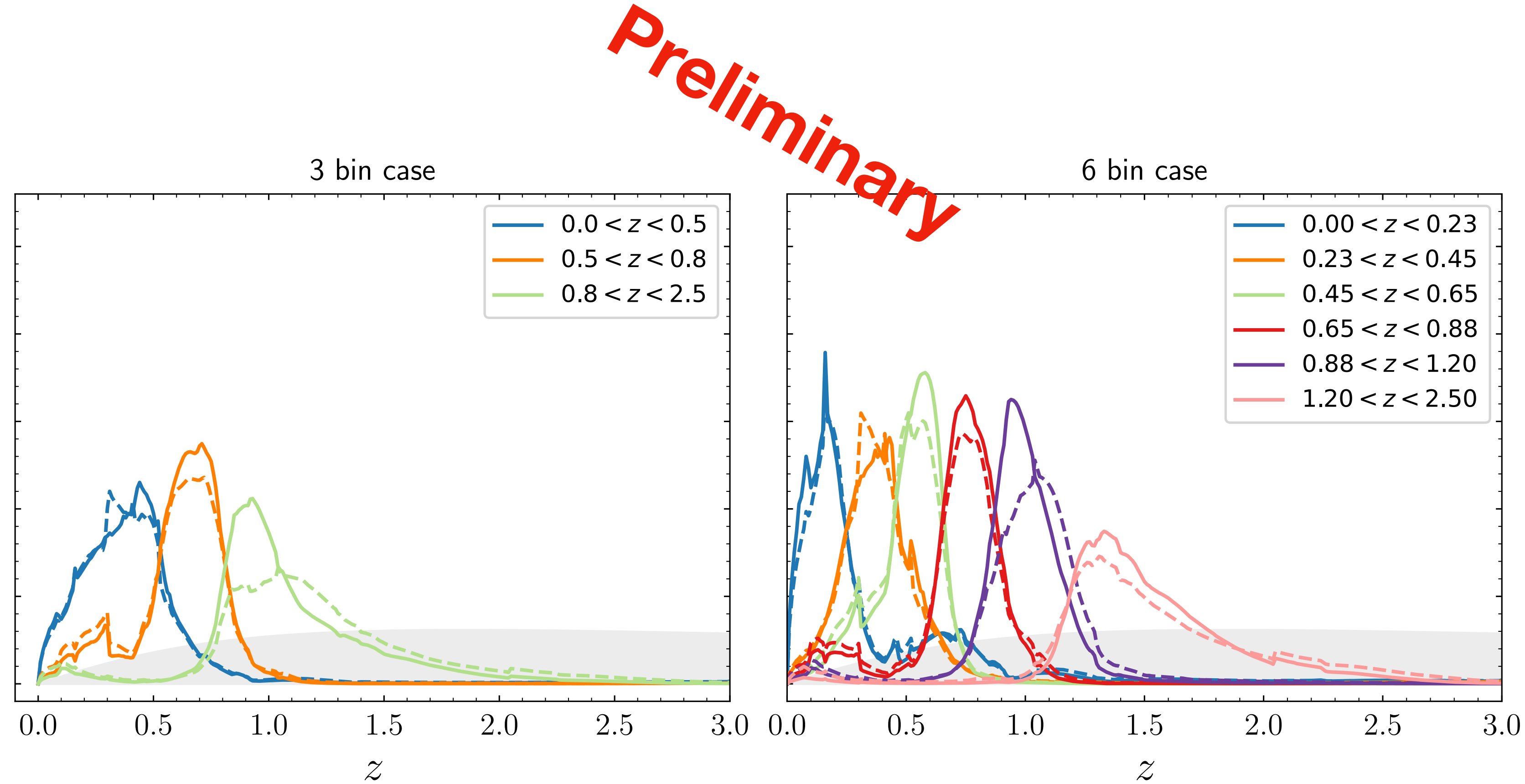
- Properties consistent across fields
- Agreement with Flagship simulation predictions "uncalibrated"!!!!!

Towards DR1: the Q1 data release

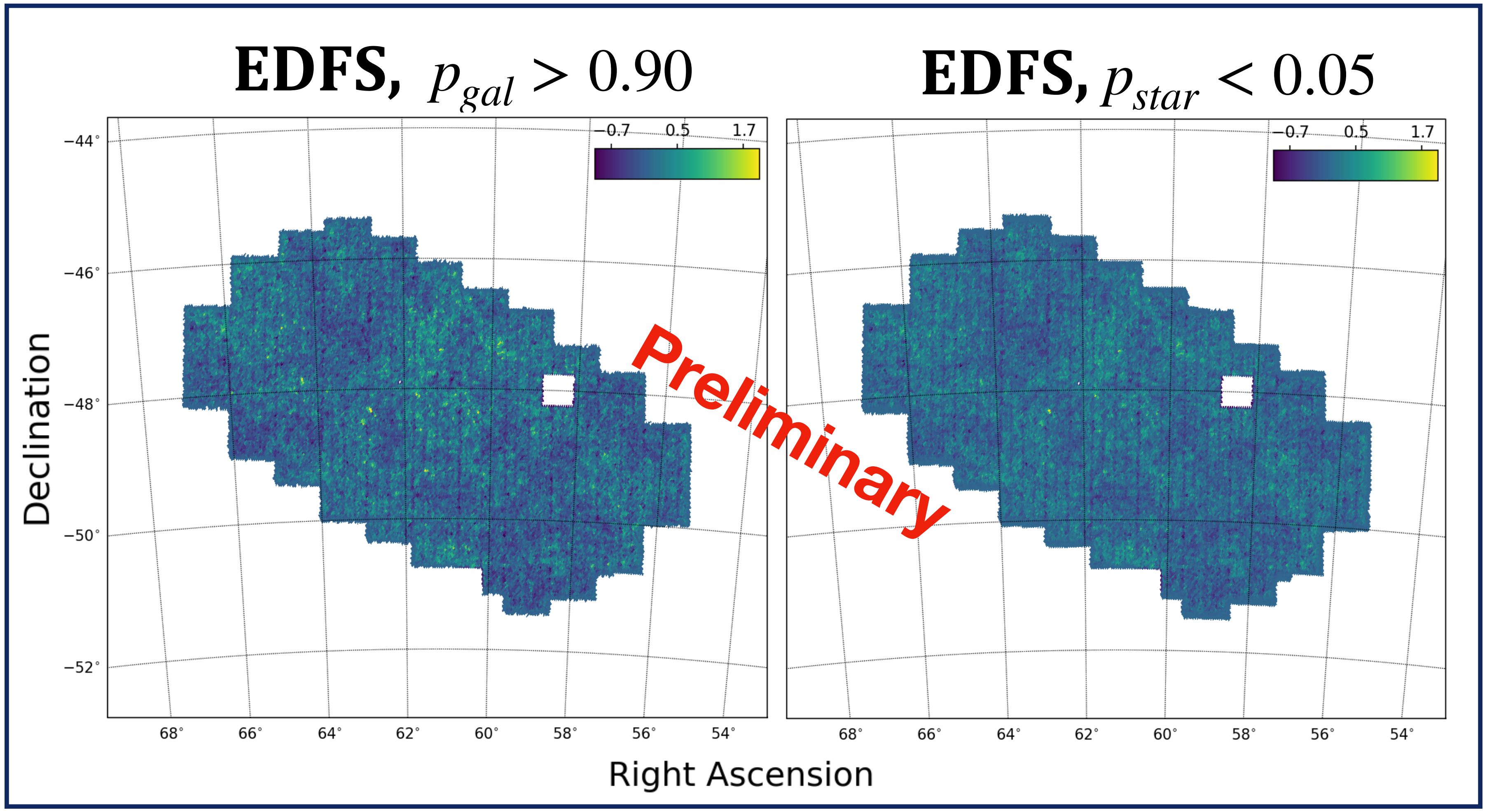


Fabbian+(in prep.)

- Properties consistent across fields
- Agreement with Flagship simulation predictions "uncalibrated"!!!!!



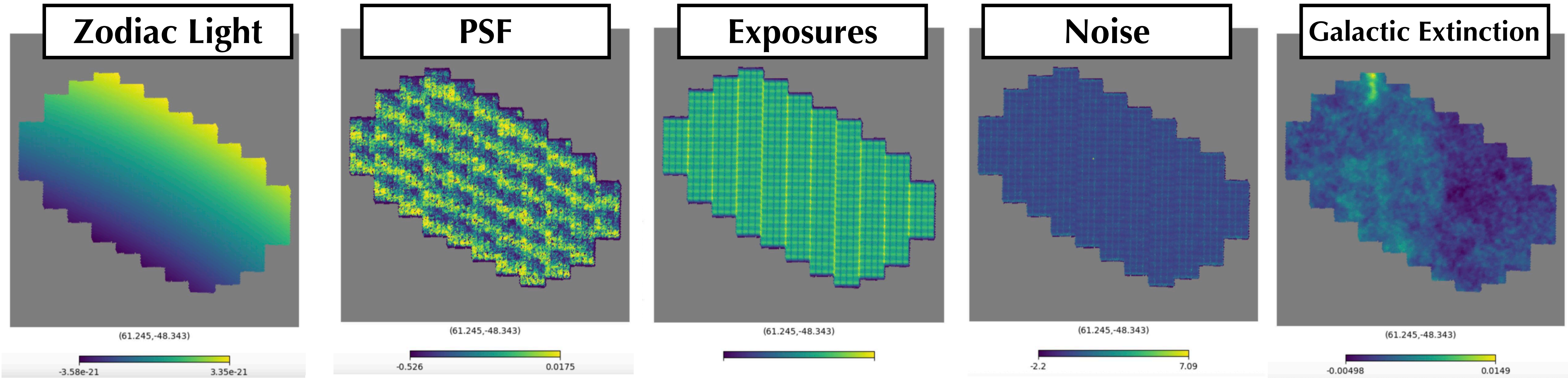
Towards DR1: the Q1 data release

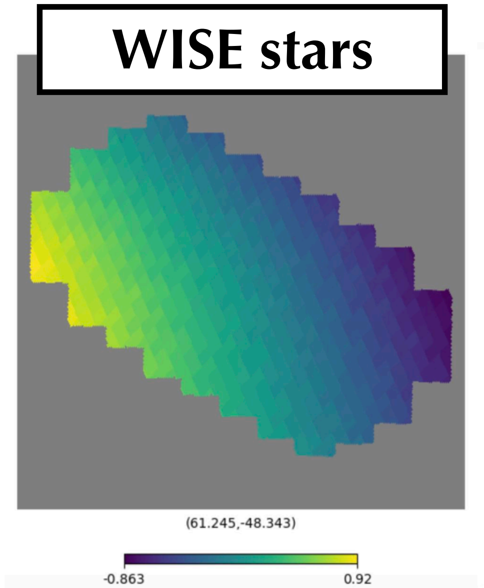


- Two different sample selection based on purity of galaxy classification or star rejection.
- The two cuts deliver samples with with different redshift limits:
  - Pgal ~11 gal/arcmin^2, z_{max}~1.2.
  - Pstar ~ 21 gal/arcmin^2,z_{max}~2.5.
  - DES gold clustering sample 0.8 gal/arcmin^2.

Zooming in on systematics

- Systematics deprojection needed due to lack of deep external data and no full visibility masks (minimal effects in science band).

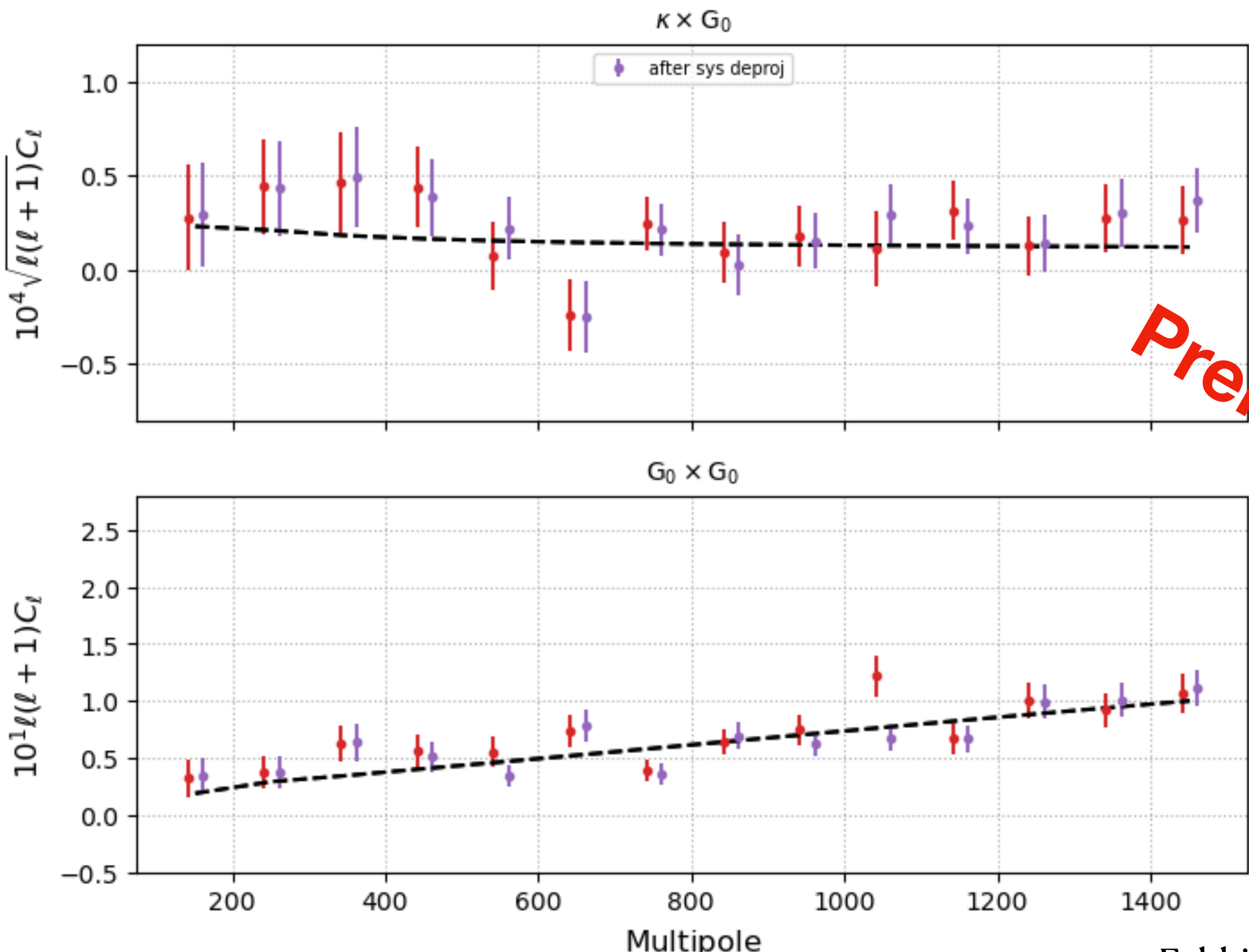




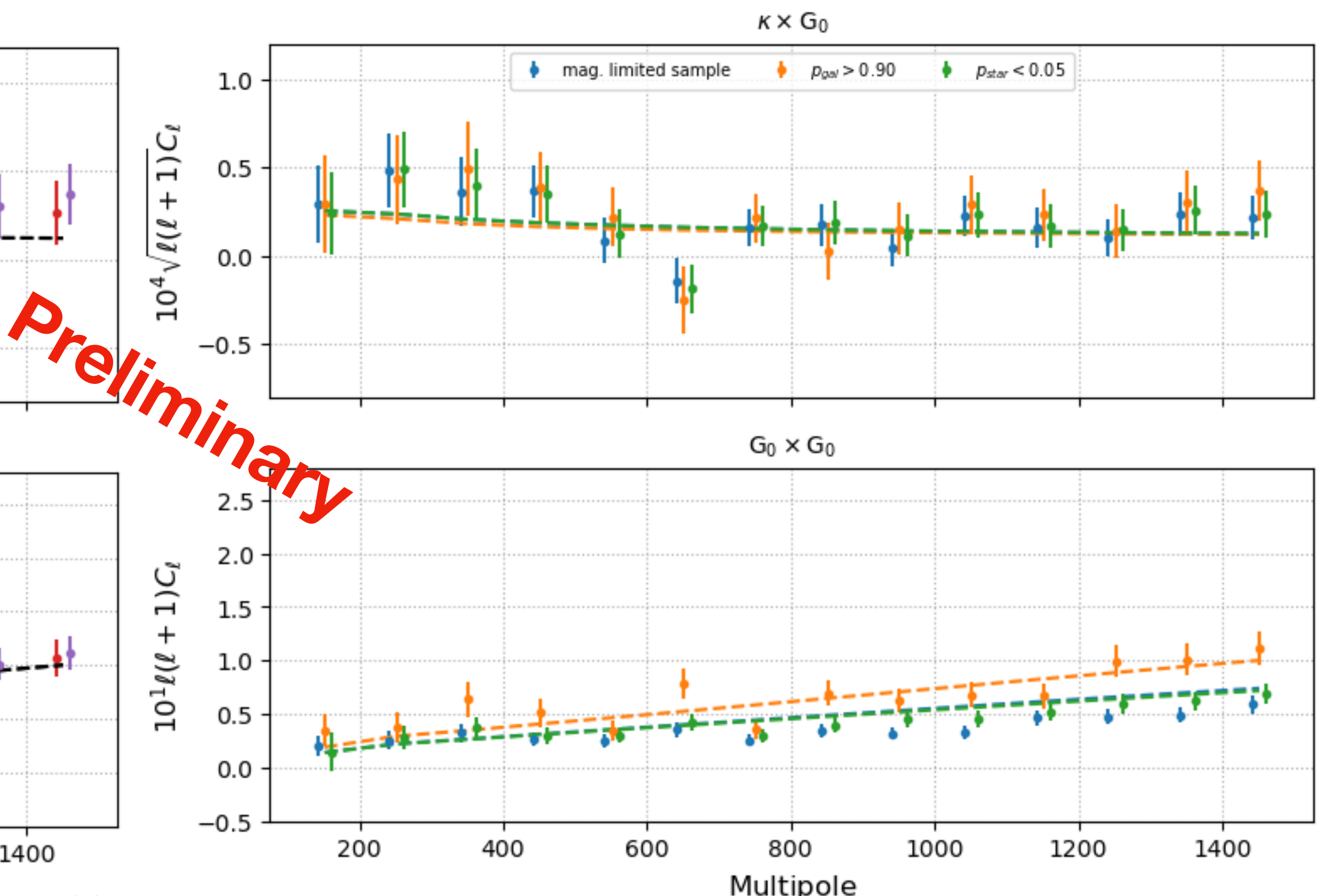
- In addition solar aspect angle, scanning strategy parameters, external data set depth…

Preliminary results: single bin

w vs /wo systematics deproj



Different sample selections

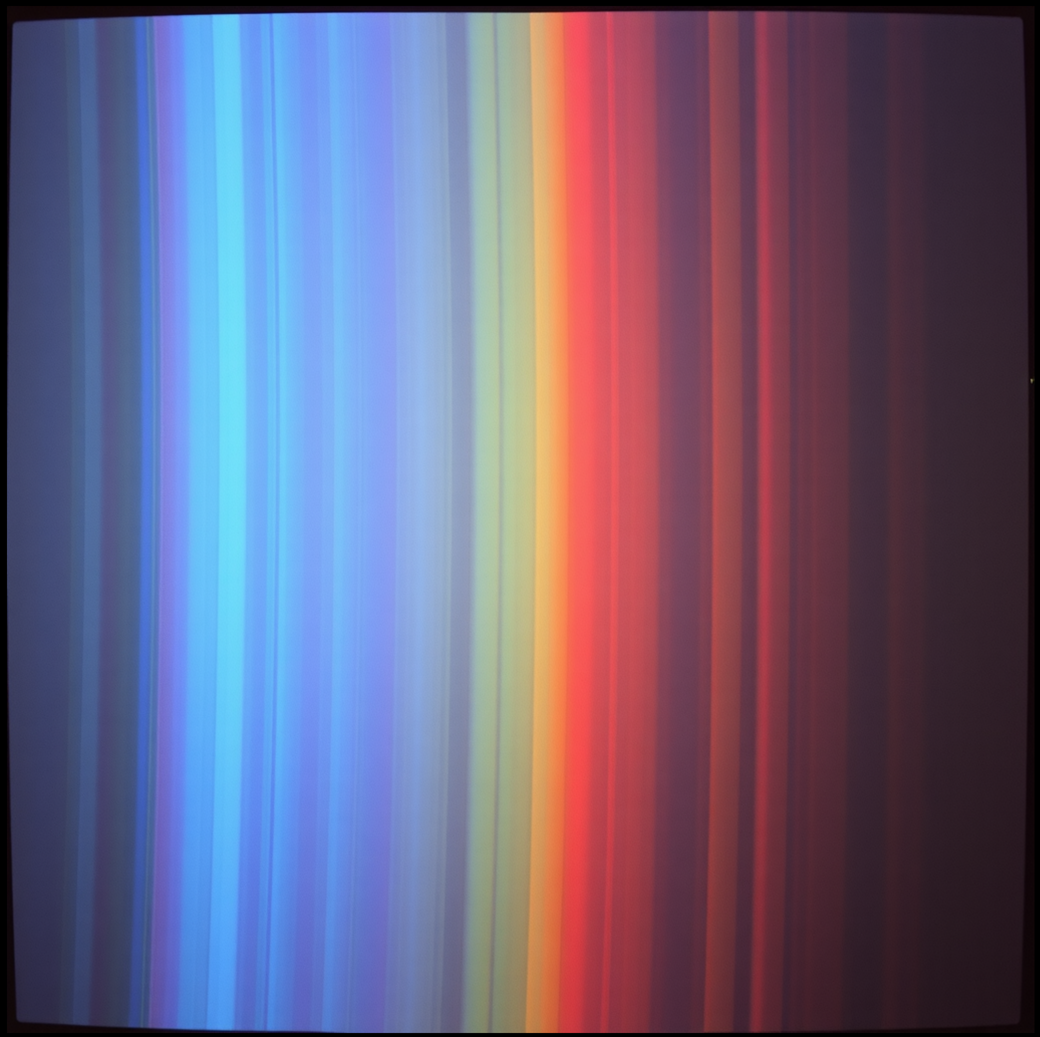


Fabbian+(in prep.)

- WARNING: theory lines are not fits!
    - Planck 2018 + estimated N(z) + fiducial Flagship calibrated galaxy bias model.
    - **TLDR**: good $\tilde{\chi}^2$ (w/ RSD, magnification bias matching expectations)
- Cross-correlation extremely stable and robust to any systematics deprojection!

SWITCHING GEARS INTO CMB SPECTRAL DISTORTIONS…

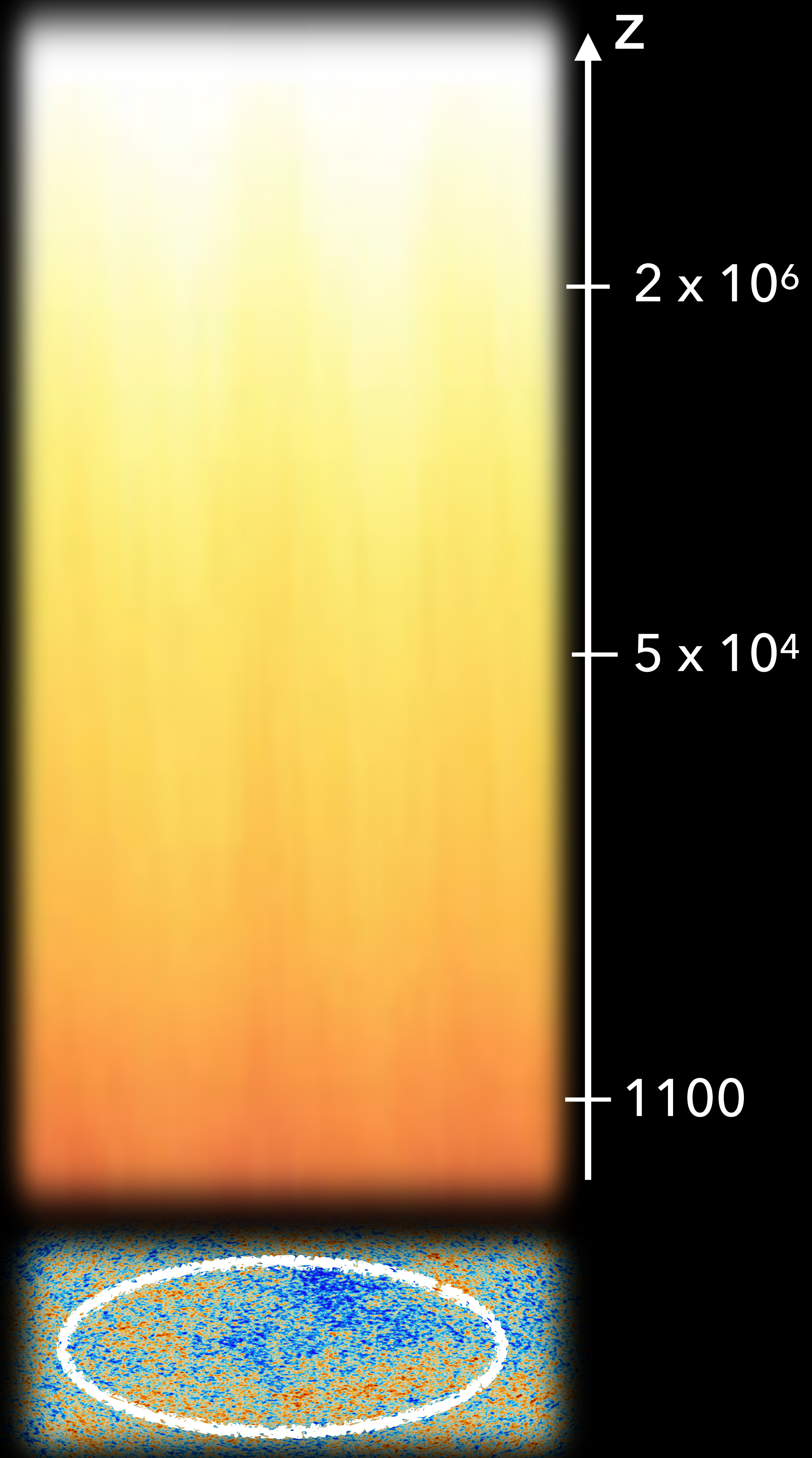
AI



HUMAN

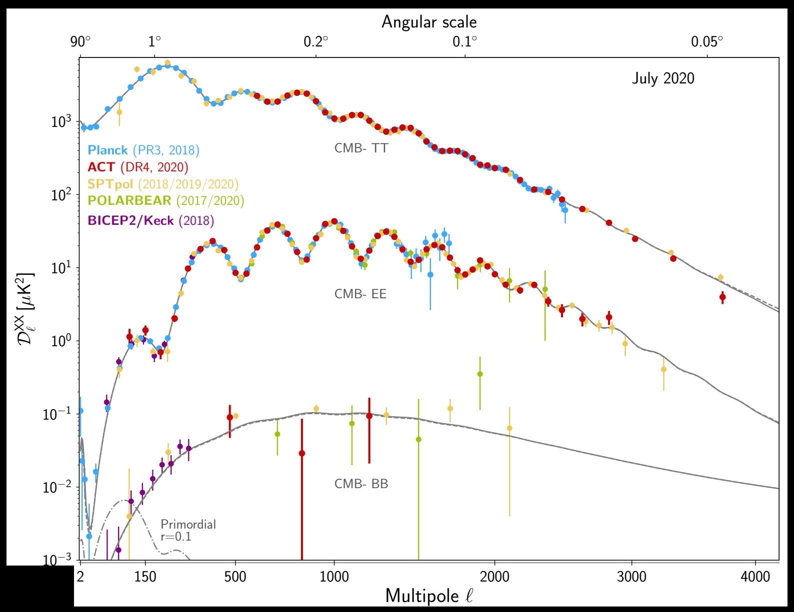
BASED ON ASTRO-PH:
2206.02762,
2508.04593,
2512.03038

A brief (thermal) history of the Universe



Accurate measurements of the CMB temperature and polarization anisotropies give us a snapshot of the Universe at the time of recombination but…

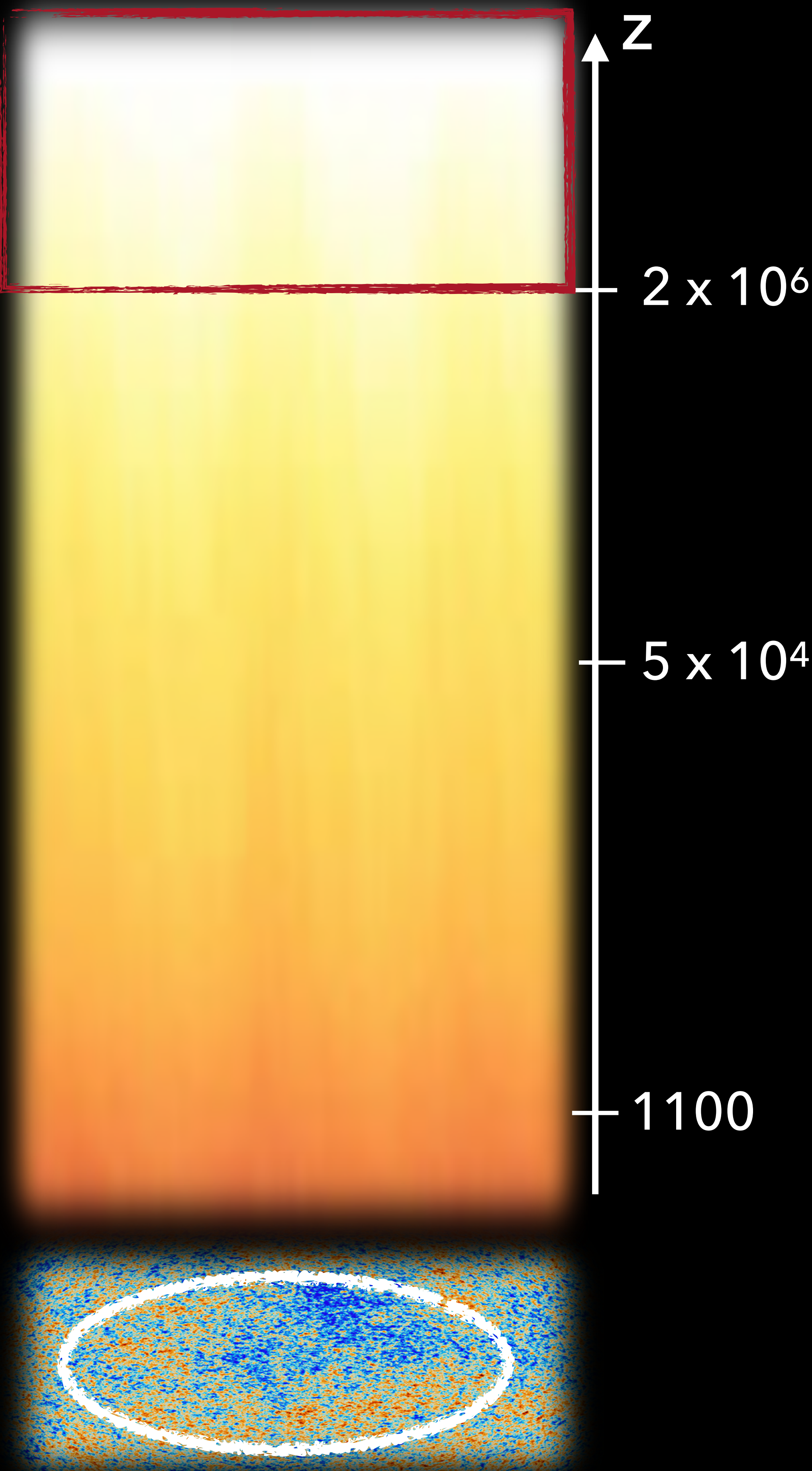
$$\frac{\Delta T}{T}(\hat{n})$$



…wealth of info is encoded in the CMB spectral energy distribution (and its departure from a blackbody spectrum)!

$$I_\nu$$

A brief (thermal) history of the Universe

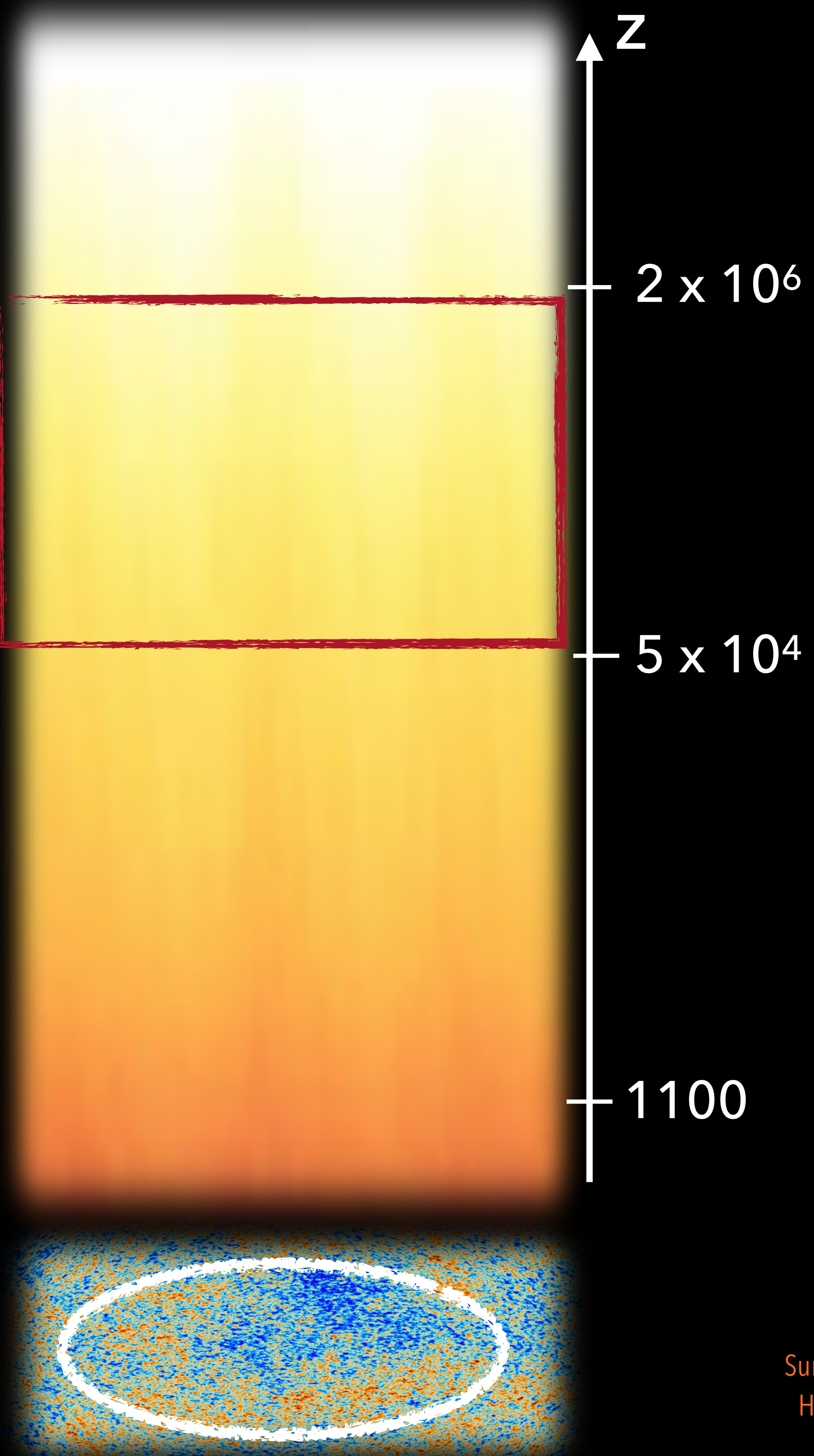


- Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma$
- Double Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma + \gamma$
- Bremsstrahlung: $e^- + X \rightarrow e^- + X + \gamma$

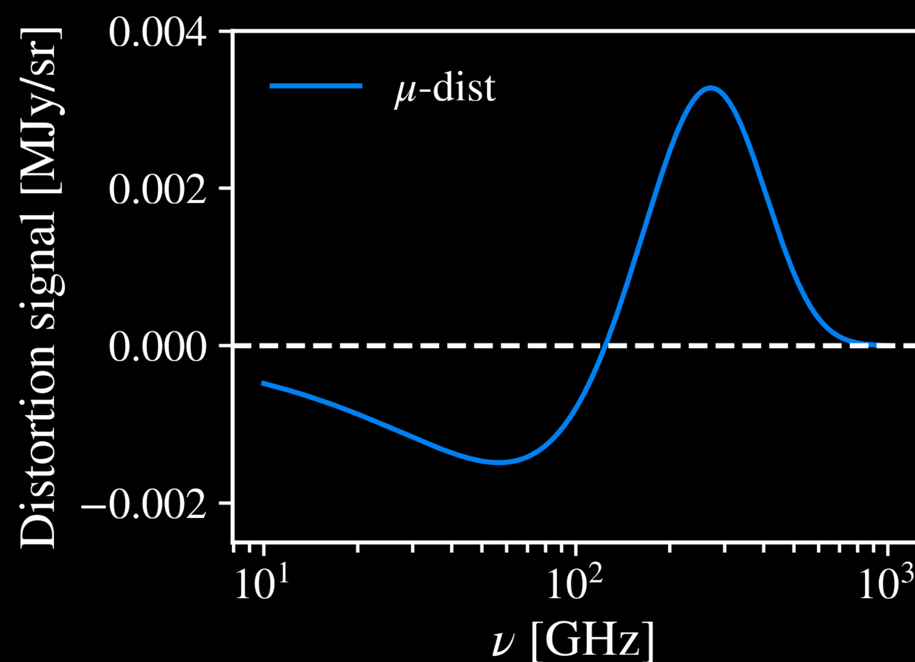
The creation/destruction and scattering of photons allows to establish **thermodynamic** (= **chemical** + **kinetic**) equilibrium

Blackbody spectrum is achieved!

A brief (thermal) history of the Universe



- Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma$
- Double Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma + \gamma$
- Bremsstrahlung: $e^- + X \rightarrow e^- + X + \gamma$



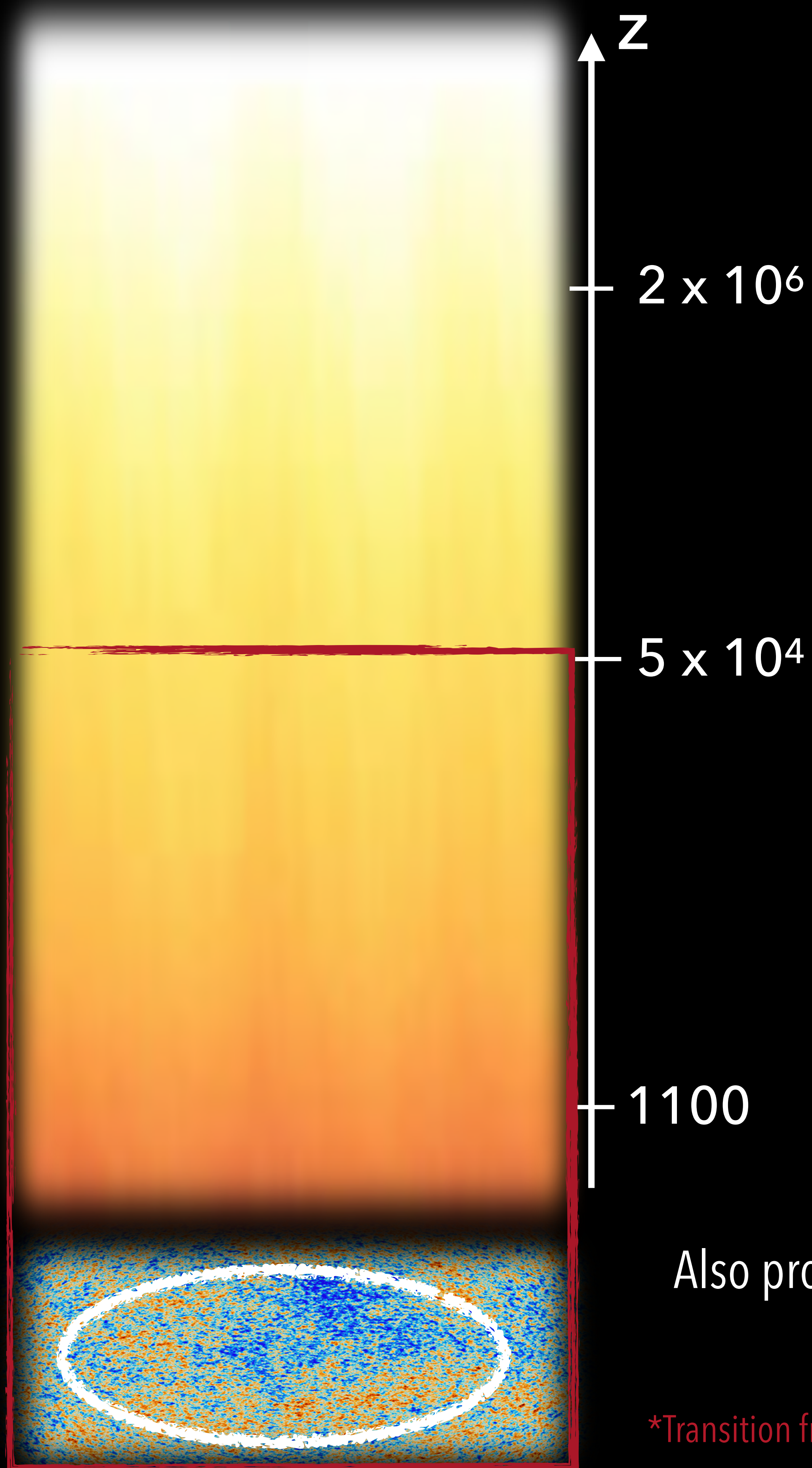
# of CMB photons is **frozen**

energy injections in primordial plasma will distort the BB spectrum

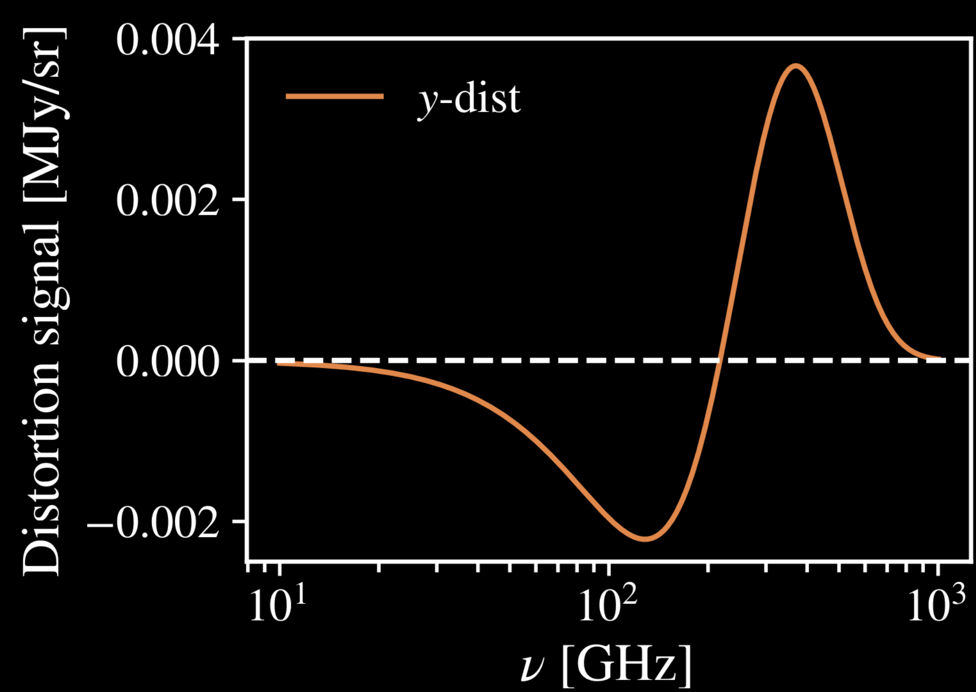
$$\mu \simeq 1.4 \left. \frac{\Delta\rho_\gamma}{\rho_\gamma} \right|_\mu$$

Sunyaev, Zel'dovich, 1970; Danese, de Zotti, 1982; Burigana, Danese, de Zotti, 1991
Hu, Silk, 1994; Chluba, Sunyaev, 2011; Kathri, Sunyaev, 2012; Chluba, 2016,++

A brief (thermal) history of the Universe



- Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma$
- Double Compton scattering: $e^- + \gamma \rightarrow e^- + \gamma + \gamma$
- Bremsstrahlung: $e^- + X \rightarrow e^- + X + \gamma$



No photon energy redistributions / thermal equilibrium

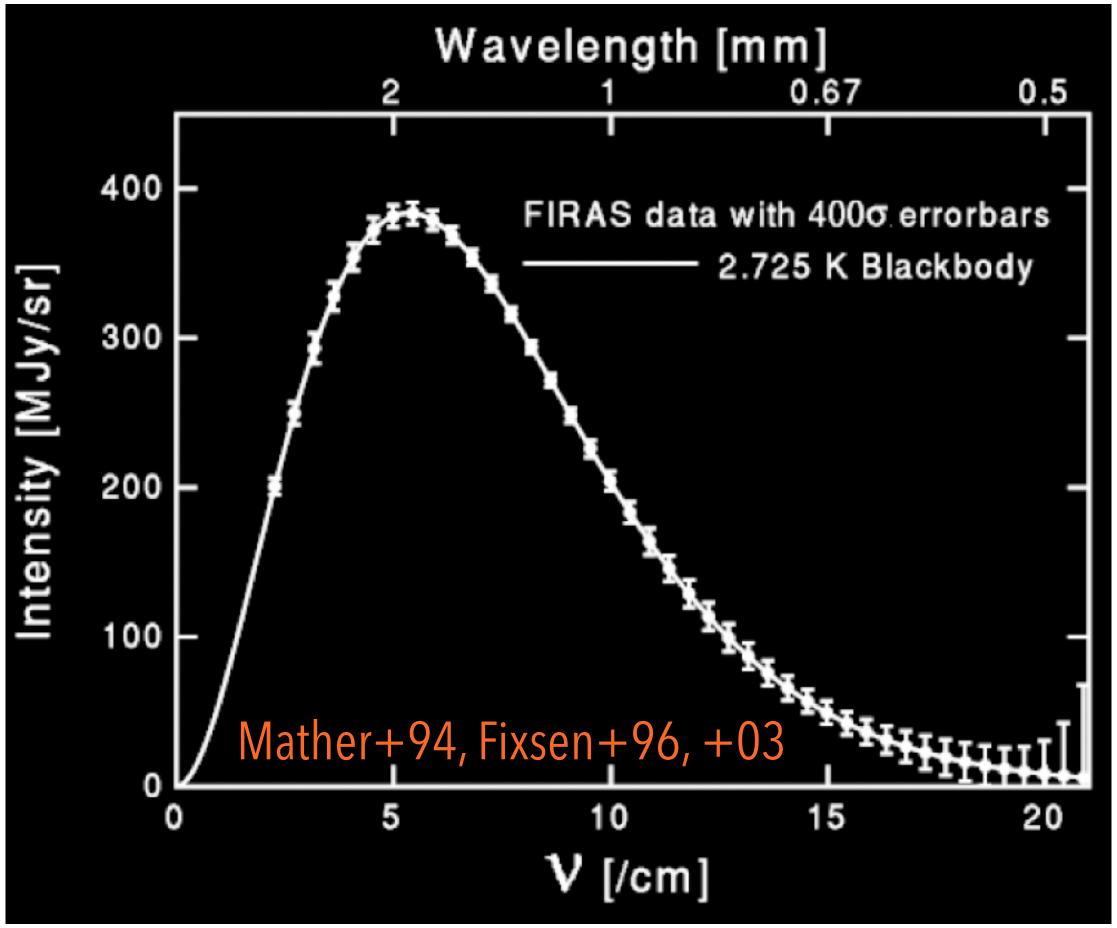
energy injections in primordial plasma will distort the BB spectrum

Also probe of late time physics (e.g SZ / reionization)

$$y \simeq \frac{1}{4} \left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

*Transition from μ to y is gradual, generation of residual distortions not described by μ + y

Constraints on distortions



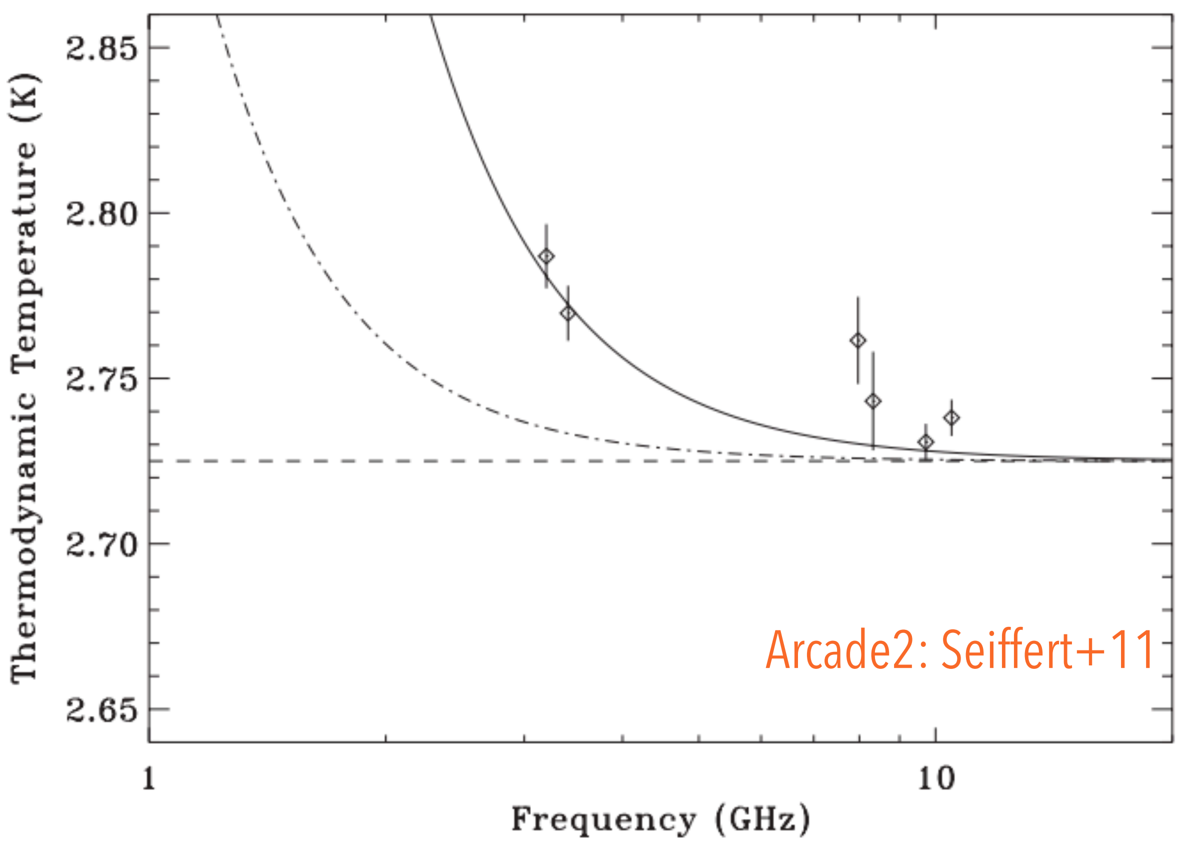
- Limited improvements after FIRAS

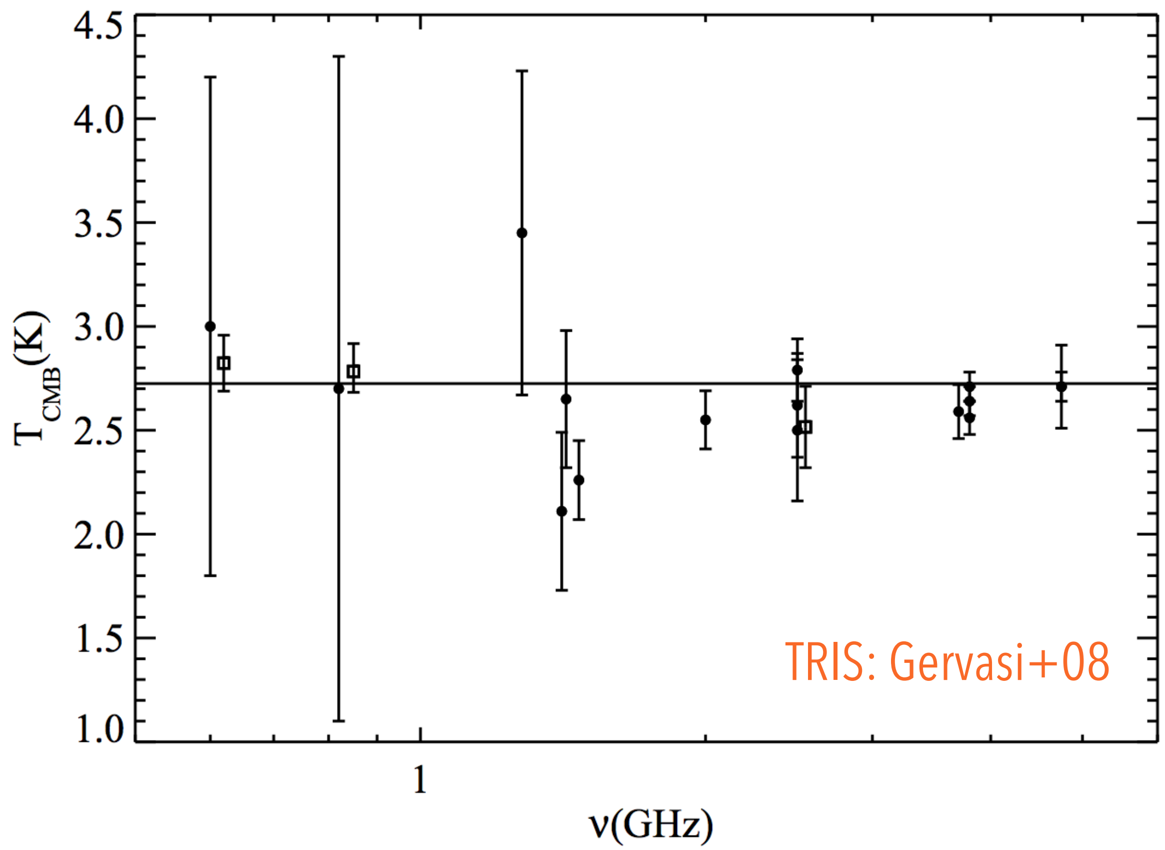
$$|\langle \mu \rangle| \lesssim 90 \times 10^{-6}$$

$$|\langle y \rangle| \lesssim 15 \times 10^{-6} \rightarrow (-1 \pm 6 \times 10^{-6} \text{ stat.}) \times 10^{-6}$$

- ARCADE, TRIS: improved at $\nu \lesssim 10$ GHz, questions on foreground/systematics remain.

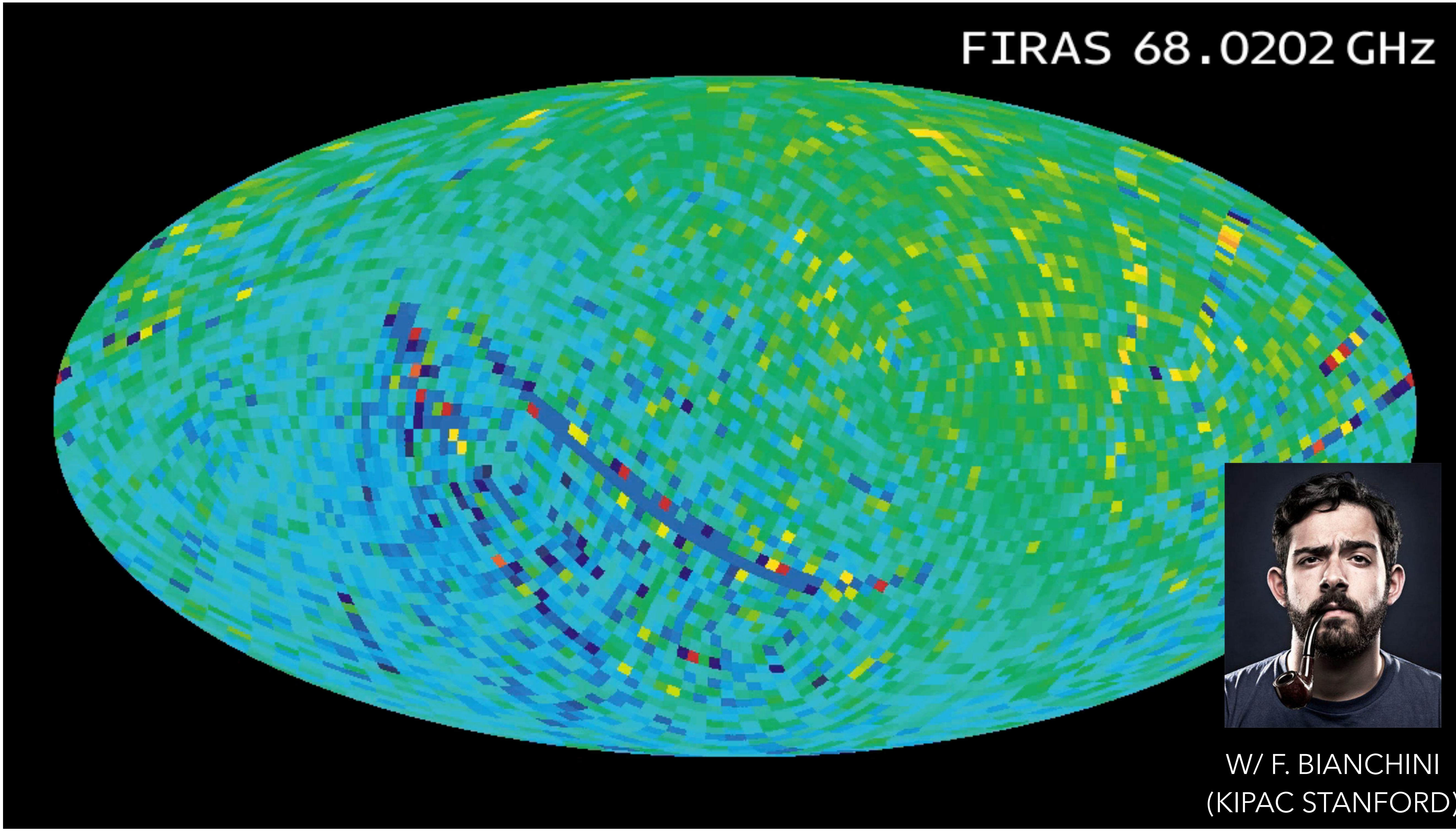
- Nothing in Decadal survey despite effort (PIXIE, Prism, Bisous, Cosmo etc)





FIRAS data are more than a spectrum

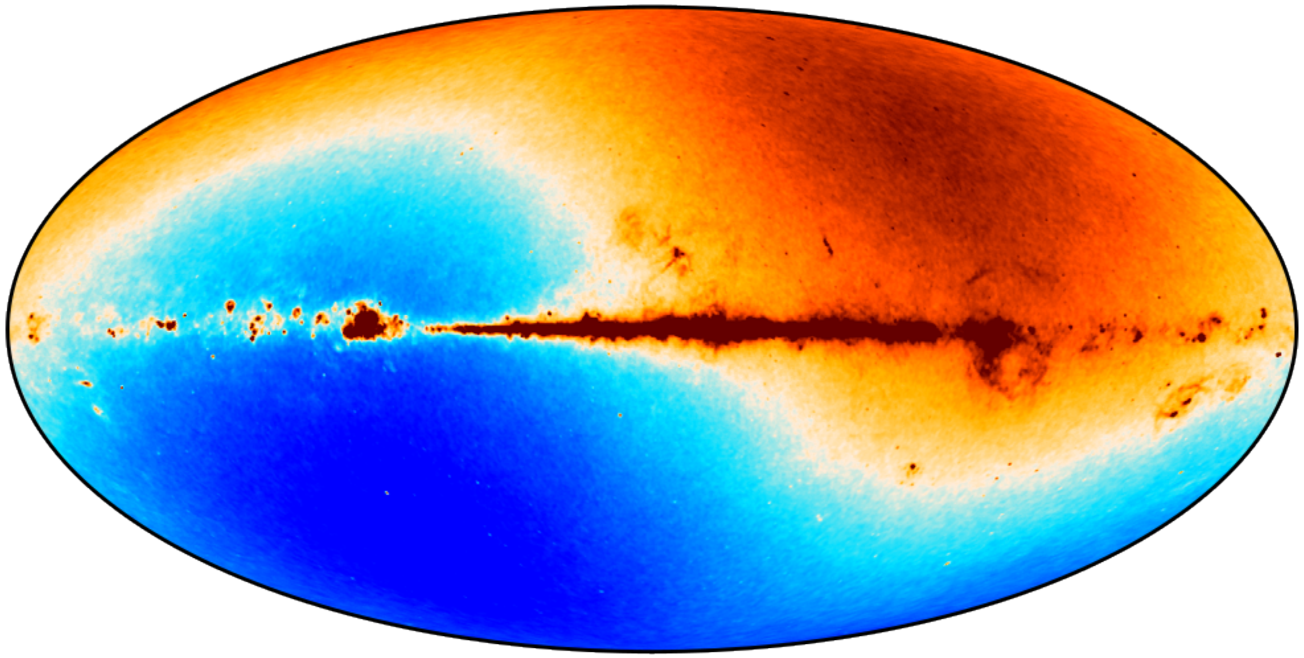
- 170 frequency channels maps. Can we do a better analysis based on modern techniques and what we have learned in the meantime?



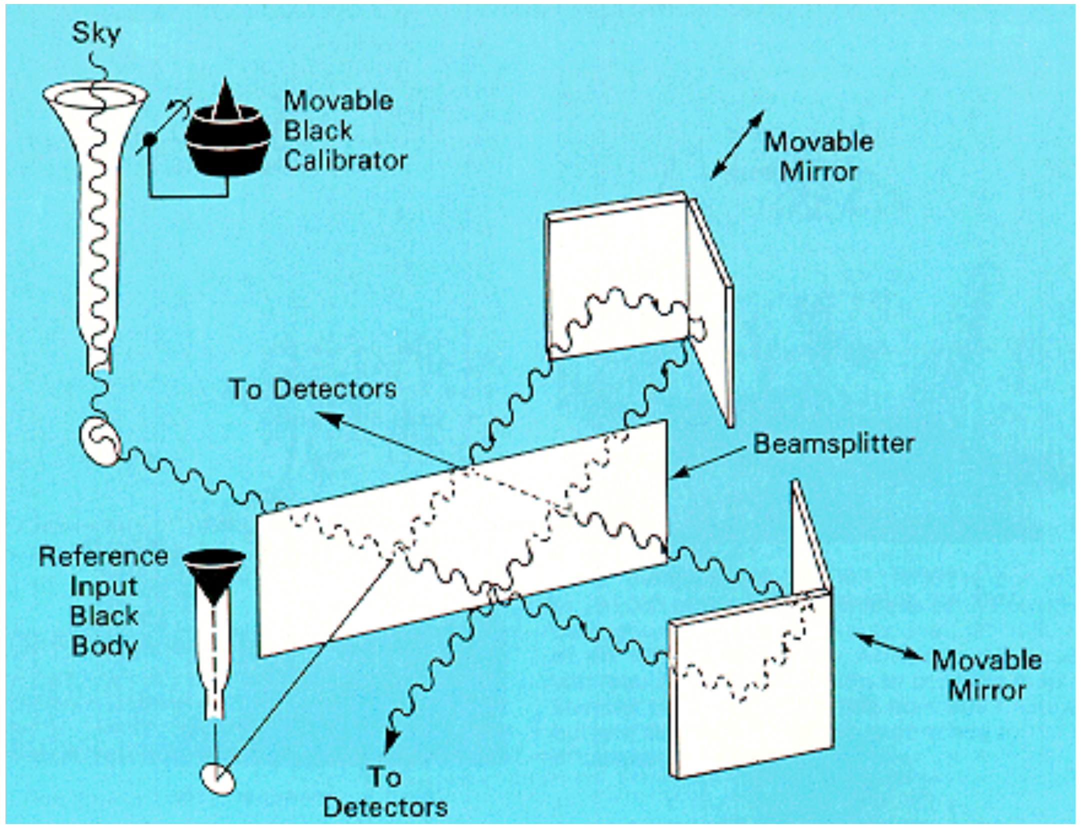
W/ F. BIANCHINI
(KIPAC STANFORD)

Why FIRAS is unique

Planck



FIRAS



- Uses motion of satellite to calibrate

$$T(\hat{\mathbf{n}}') = \frac{T(\hat{\mathbf{n}})}{\gamma(1 - \boldsymbol{\beta} \cdot \hat{\mathbf{n}}')}$$

- Assumes T0 (from… FIRAS)

- Fourier Transform Spectrometer

- Absolutely calibrated experiment, gives true brightness temperature

FIRAS: a fully correlated data set

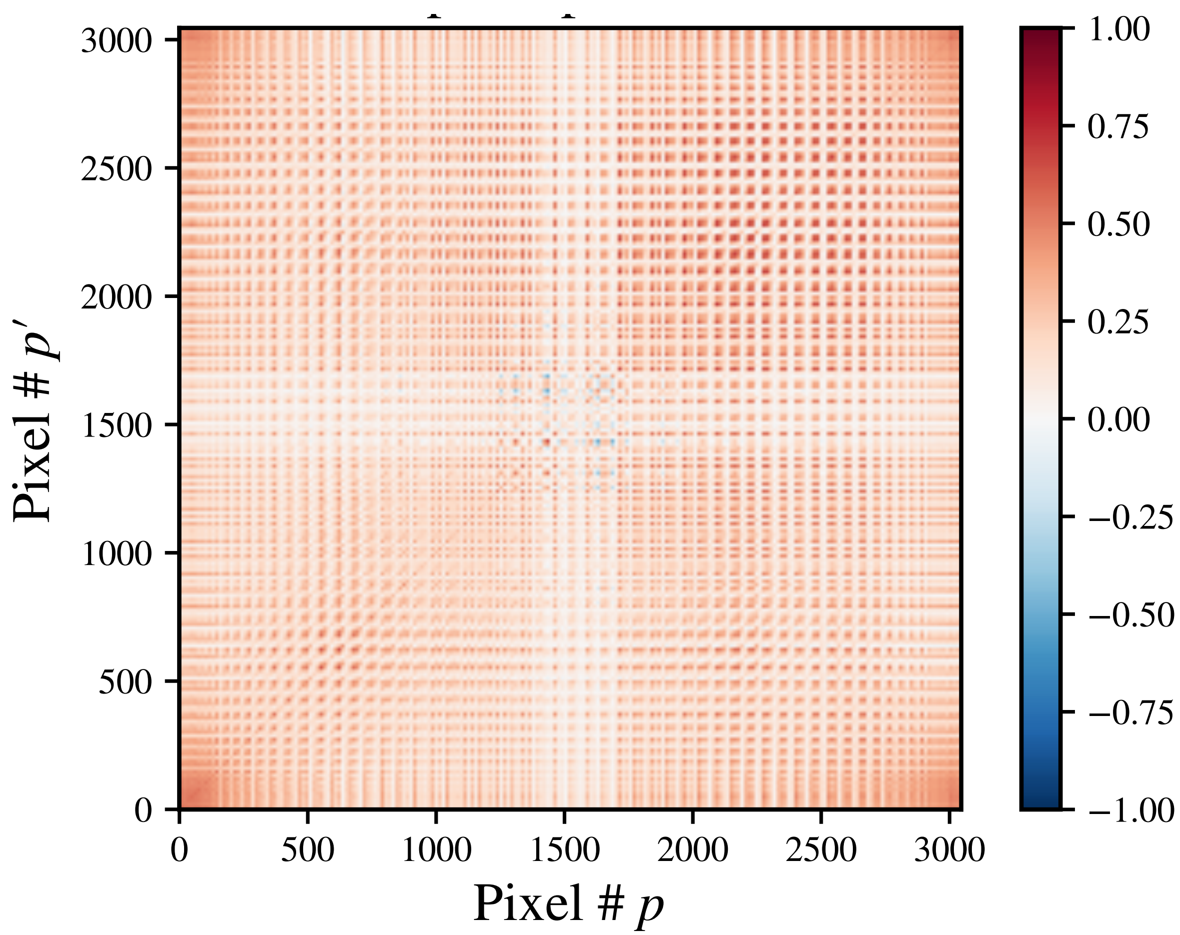
- Measurements correlated in pixel and frequency space (“unusual" regime)

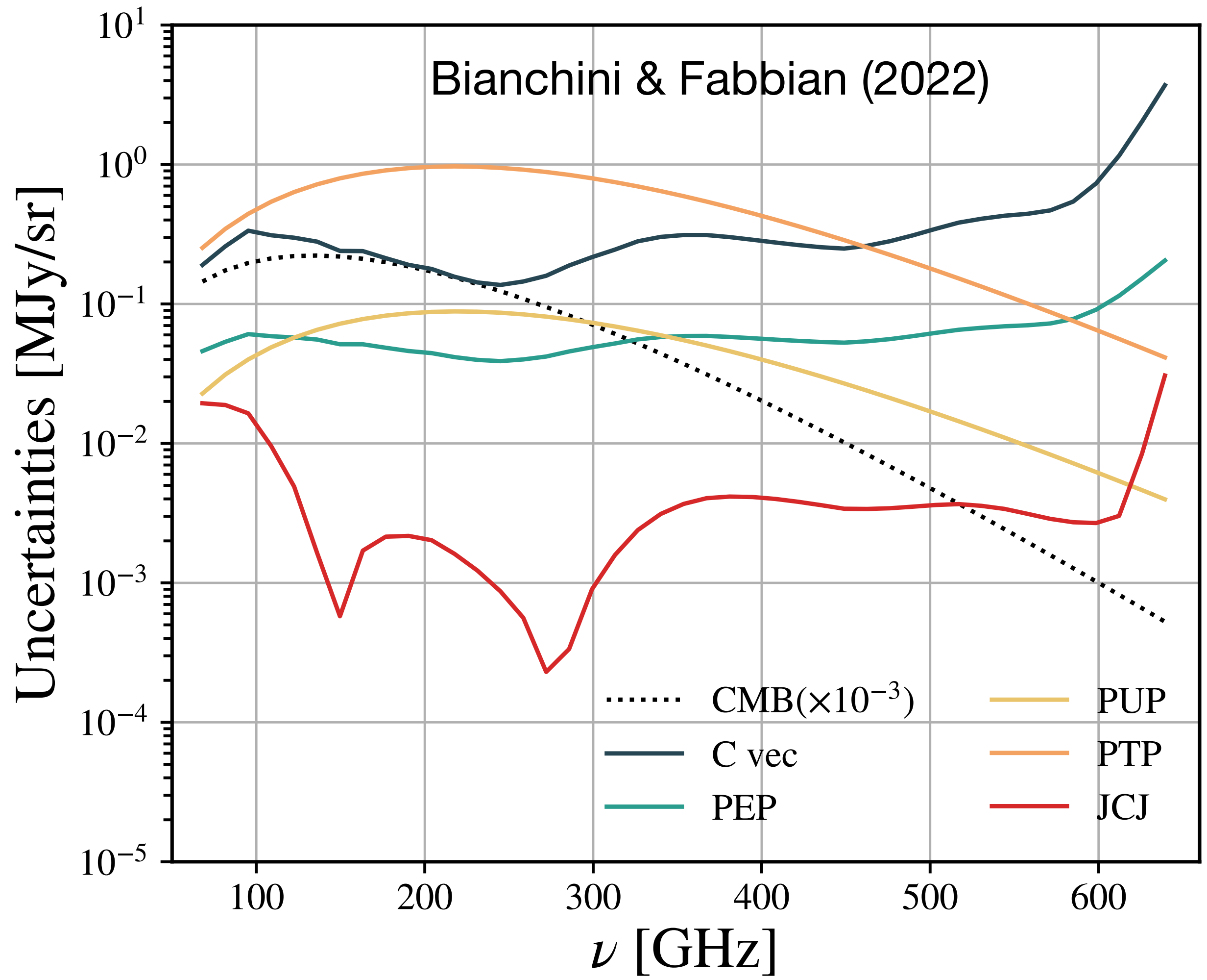
Noise correlation — **Sky variation** — **Calibrator emissivity**

$$\mathbb{C}^{FIRAS}_{\nu p \nu' p'} = C_{\nu\nu'} P_{pp'} + S_{p\nu} S_{p'\nu'} \left(J_\nu J_{\nu'} + G_\nu G_\nu \delta_{\nu\nu'} \right) + \partial_T B_\nu \partial_T B_{\nu'} \left(U^2 \delta_{pp'}/N_p + T^2 \right) .$$

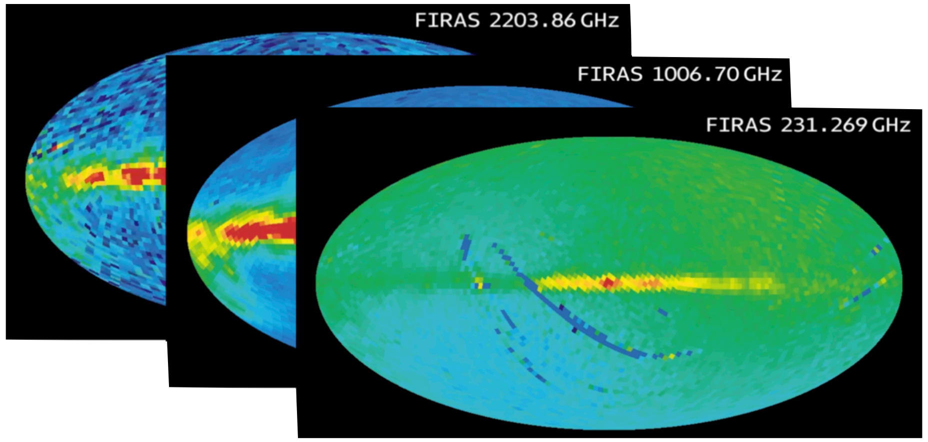
FFT — **Destriping** — **Calibration errors** — **Calibrator systematics**

$$P_{pp'} \equiv \delta_{pp'}/N_p + \beta^p_k \beta_{p'k} + 0.04^2,$$





Analyzing the FIRAS data cube



Original FIRAS Fixsen+ (1996)

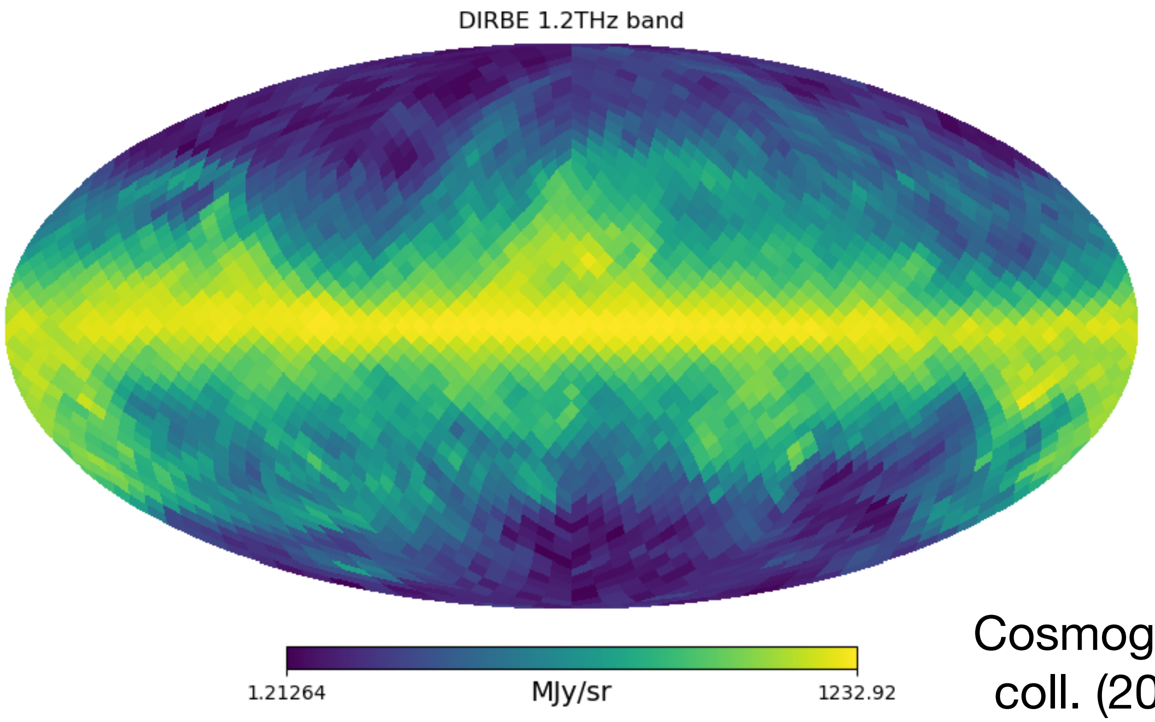
For each frequency $\nu \lesssim 600$ GHz

$$I_\nu(\hat{\mathbf{n}}) = B_\nu + D_\nu \hat{\boldsymbol{\beta}} \cdot \hat{\mathbf{n}} + \sum_i A_\nu^{FG,i} I^{FG,i}(\hat{\mathbf{n}})$$

Least-square fitting

$$B_\nu = B_\nu(T_0) + \Delta T \frac{\partial B_\nu}{\partial T} + \mu \frac{\partial B_\nu}{\partial \mu}\bigg|_{\mu=0} + G_0 g(\nu)$$

- Re-analysis has to address the shortcomings
  - Template fitting foreground cleaning: sensitive to systematics, noise, template reliability.
  - DIRBE @ Cosmoglobe: Zodiacal light residuals

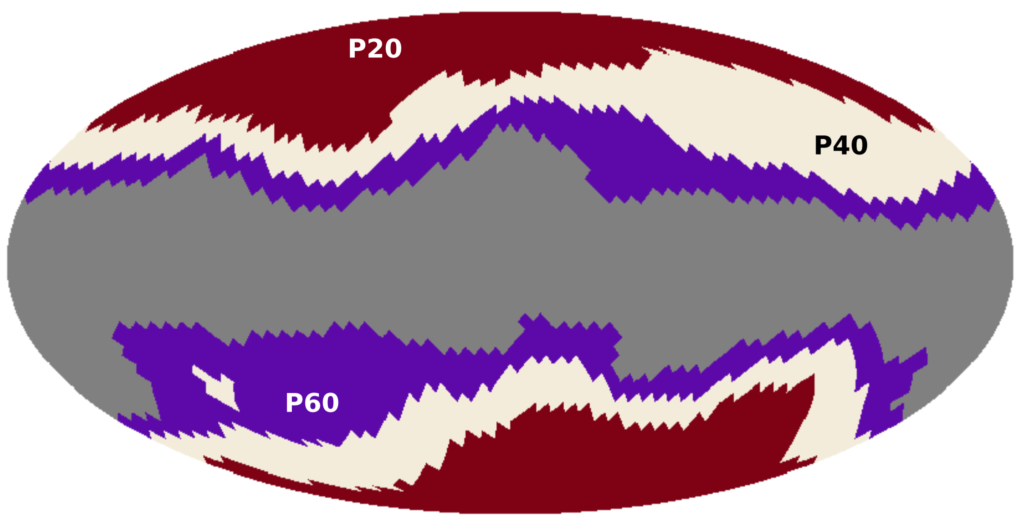


Cosmoglobe coll. (2024)

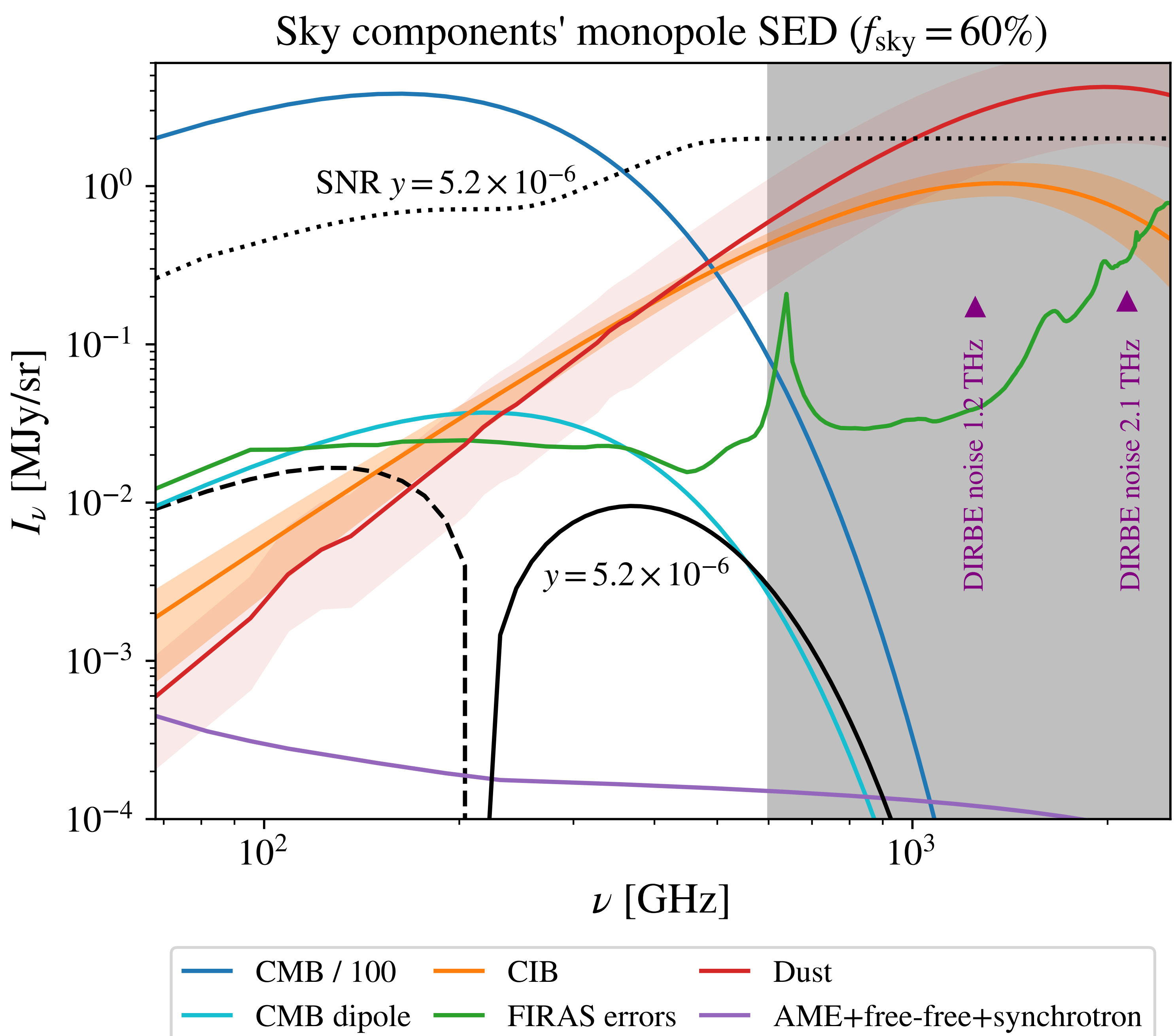
  - Foreground extrapolation from high freqs…
- Linearized distortion nearly fully degenerate with other parameters.

The foreground challenge

- Spectral distortions are weak and foregrounds are ~100x brighter even on clean sky regions.
  - DIRBE noise ~= FIRAS: correlated noise introduced by template fitting cleaning leading to sensitivity loss.



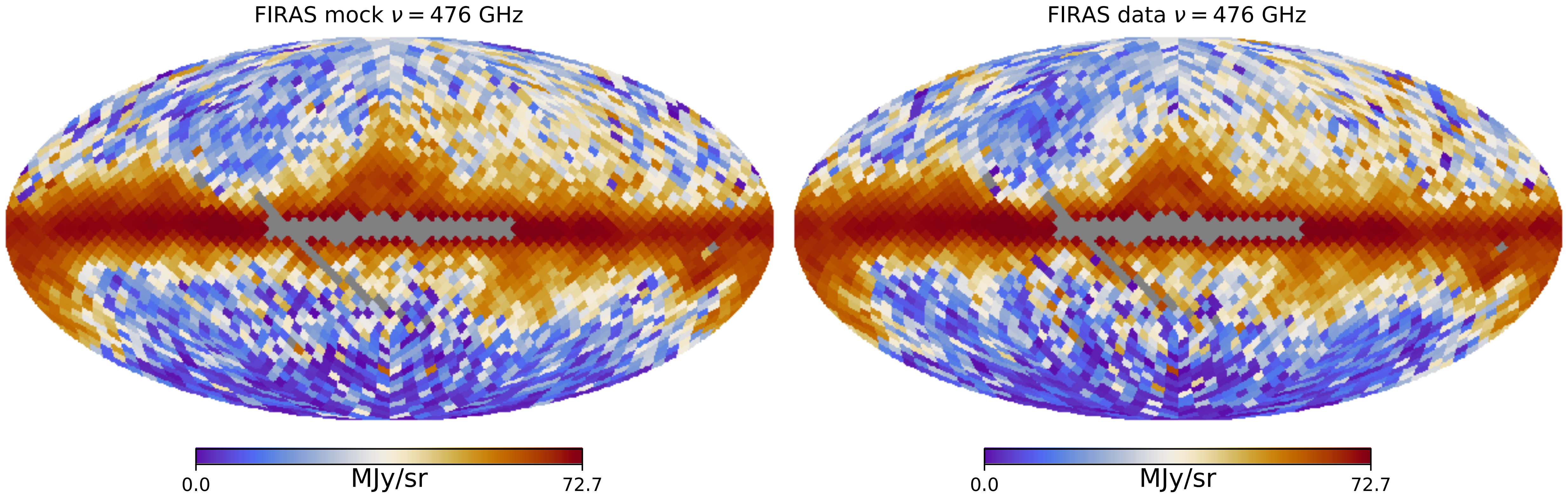
Sabyr+ (2025)
Fabbian+(2025)
Bianchini & Fabbian (2022)



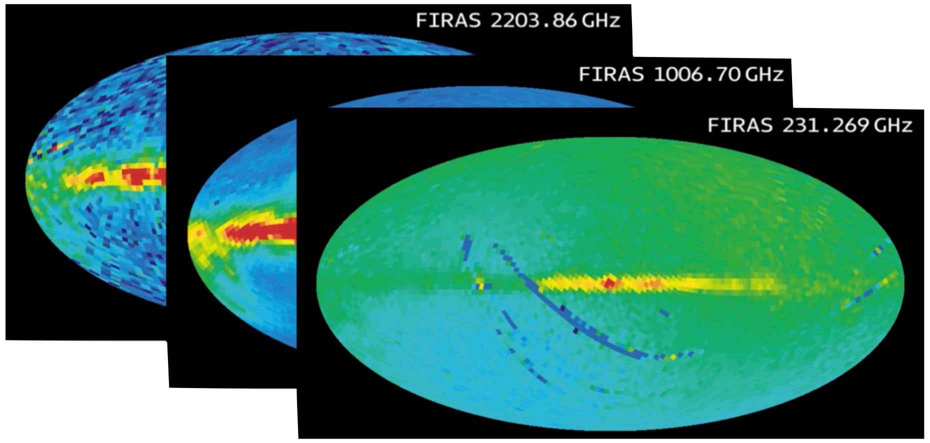
Robustness of component separation methods

- What is the best, most robust way to measure <y>?
  - CIB needs great care (spectral degeneracy with dust, spatial correlation with SZ…)
- Idea: realistic mocks based on state of the art sky models to compare approaches.
- Find best tradeoff between foreground complexity and and FIRAS frequency coverage.

A. Sabyr, GF, C. Hill, F. Bianchini (2025)



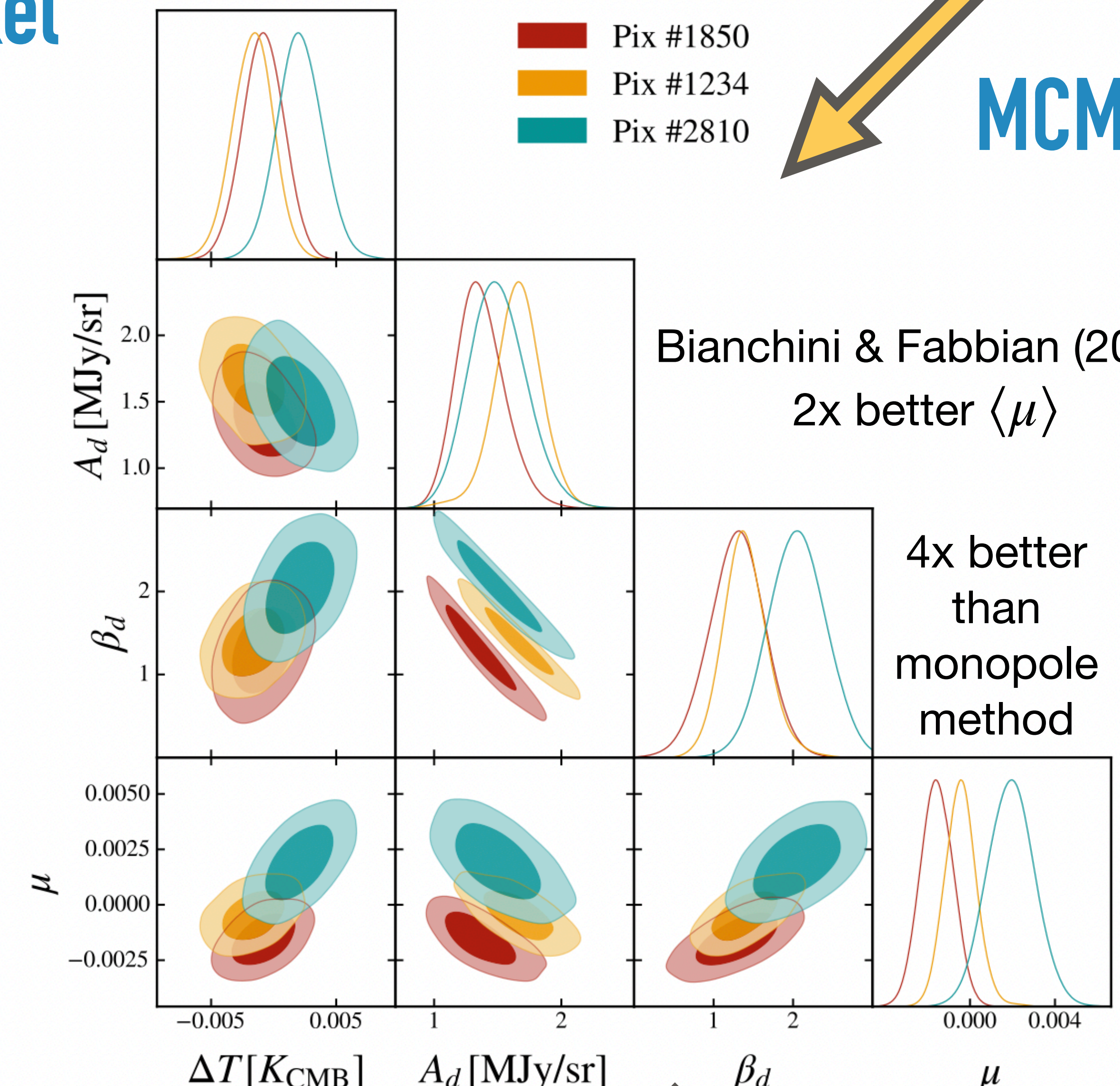
Analyzing the FIRAS data cube: our approacheS



Pixel-by-pixel

$$I_\nu(\hat{\mathbf{n}}) = B_\nu(T_0, \mu(\hat{\mathbf{n}})) + \Delta T(\hat{\mathbf{n}}) \frac{\partial B}{\partial T}\bigg|_{T_0} + I^{FG}(\boldsymbol{\theta}^{FG}, \hat{\mathbf{n}})$$

MCMC



Bianchini & Fabbian (2022)
2x better $\langle \mu \rangle$

4x better than monopole method

Parameters' maps → $\{\langle \mu \rangle, \langle y \rangle, \ldots\}$

Monopole modeling

Spatial mean

$$\langle I_\nu \rangle = B_\nu(T_0) + \langle \Delta T \rangle \frac{\partial B}{\partial T} + \langle I_\nu^{SD} \rangle + \sum_i \langle I^{FG,i} \rangle$$

MCMC

$$\boldsymbol{\theta} = \{\langle \Delta T \rangle, \langle y \rangle, \langle \mu \rangle, \ldots\}$$

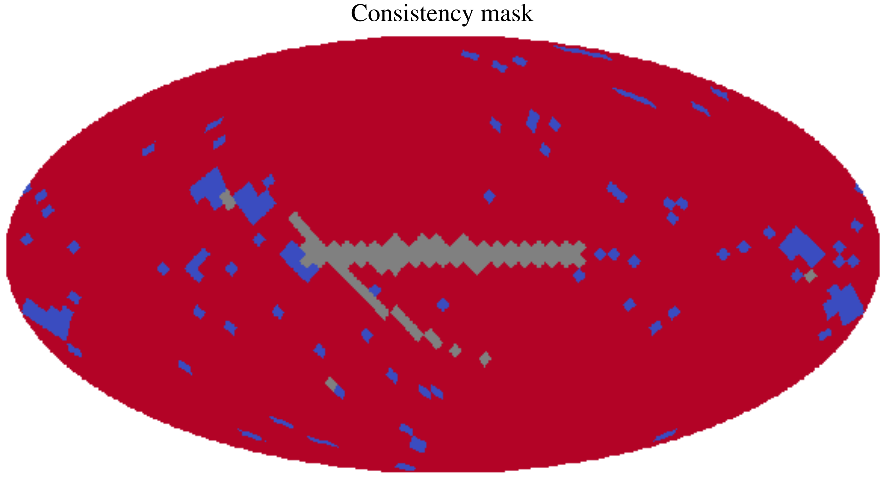
Reference forecasting tool Abitbol+ (2017)

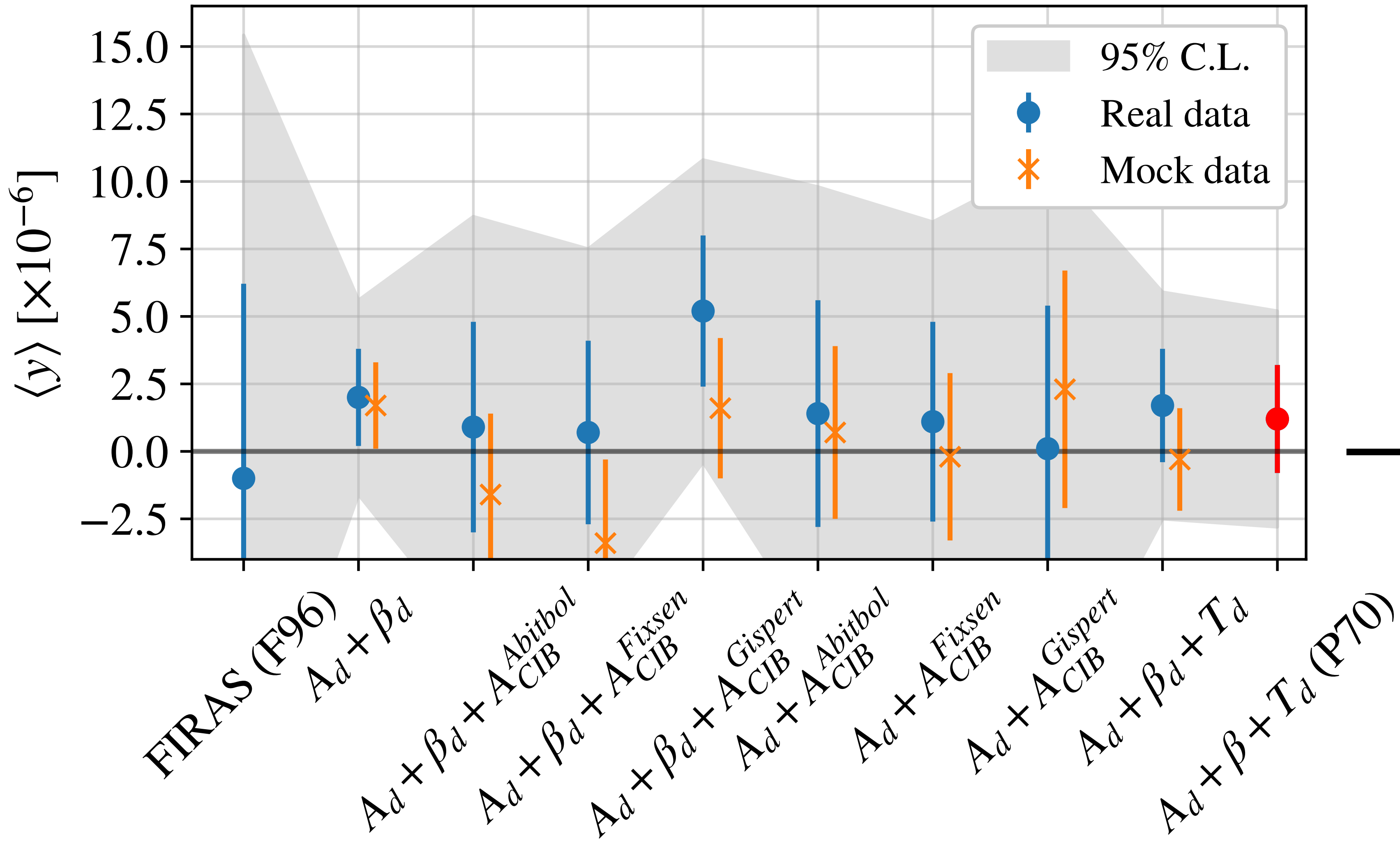
<y> measurements results

- Use only pixels consistent across foreground models for robustness and P60 galactic mask

Gratton & Challinor (2019)

$$\frac{\left|\langle y\rangle_1 - \langle y\rangle_2\right|}{\sqrt{\left|\sigma^2_{\langle y\rangle,1} - \sigma^2_{\langle y\rangle,2}\right|}} \lesssim 2$$





3x better upper limit

$$\langle y\rangle \sim (1.0 \pm 2.1) \times 10^{-6}$$

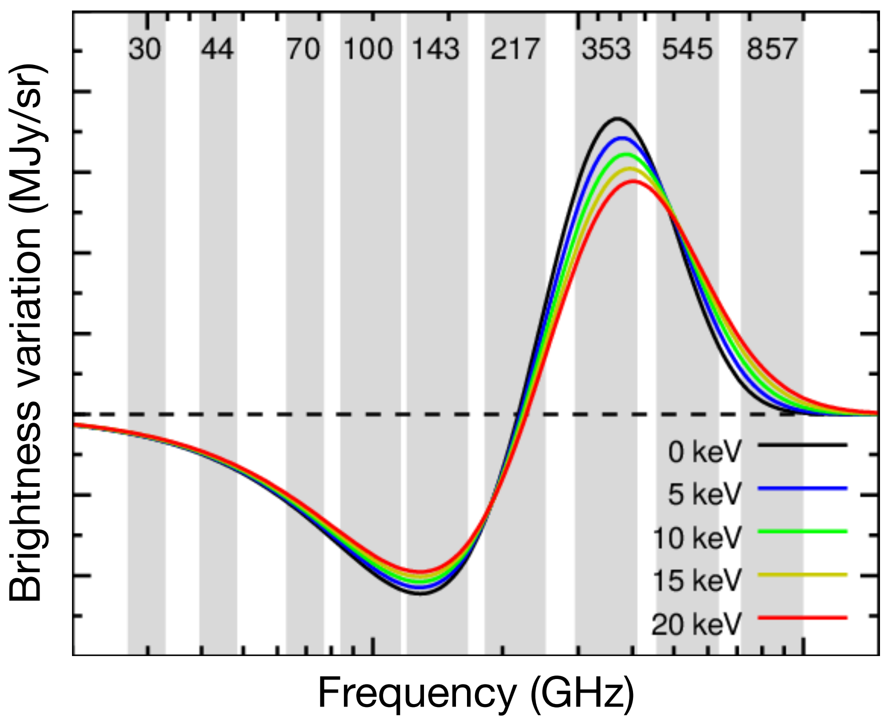
Fabbian+ (2025)

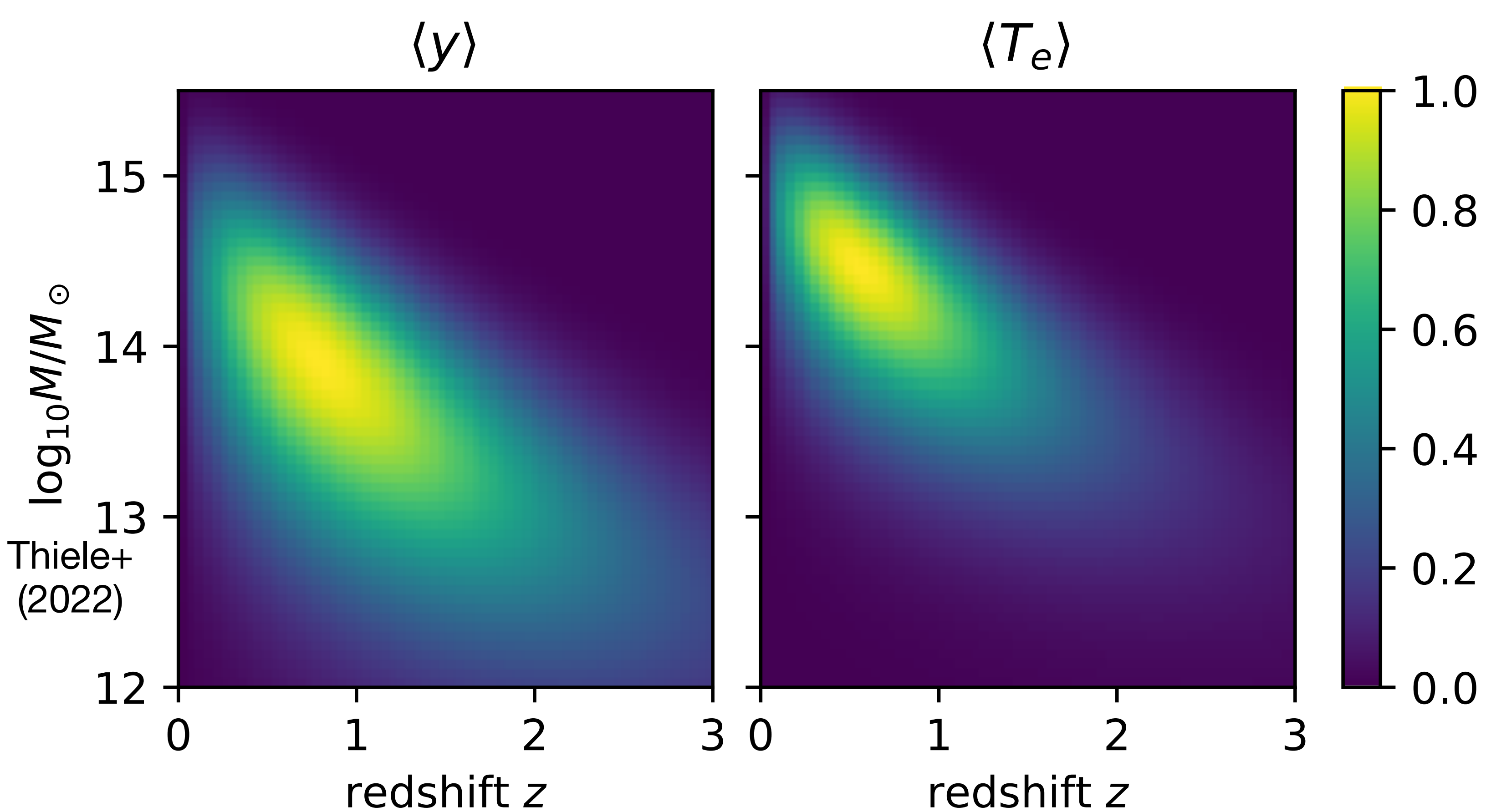
Why do we care?

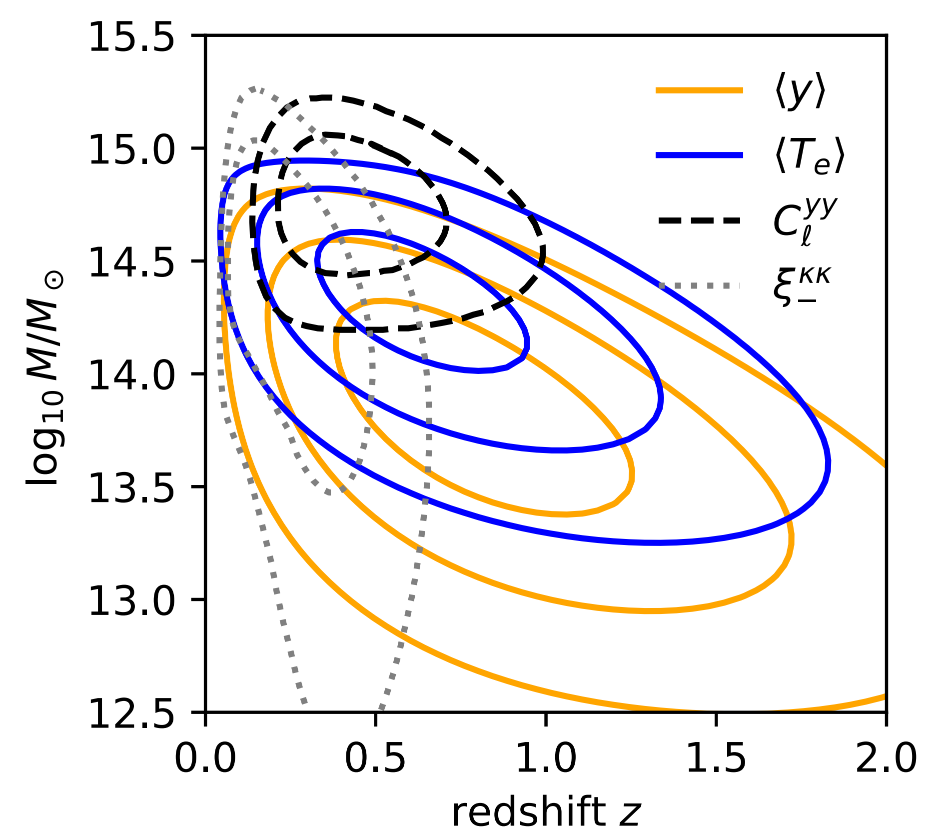
- y distortions are dominated by late time gas physics: unique probe of feedback.

$$\langle y \rangle \equiv \langle y(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int P_e(\hat{\mathbf{n}}, l) dl$$

$$\langle T_e \rangle \equiv \langle T_e(\hat{\mathbf{n}}) \rangle_{\hat{\mathbf{n}}} = \langle y \rangle^{-1} \int \frac{d\hat{n}}{4\pi} \frac{\sigma_T}{m_e} \int \left[T_e P_e\right](\hat{\mathbf{n}}, l) dl$$





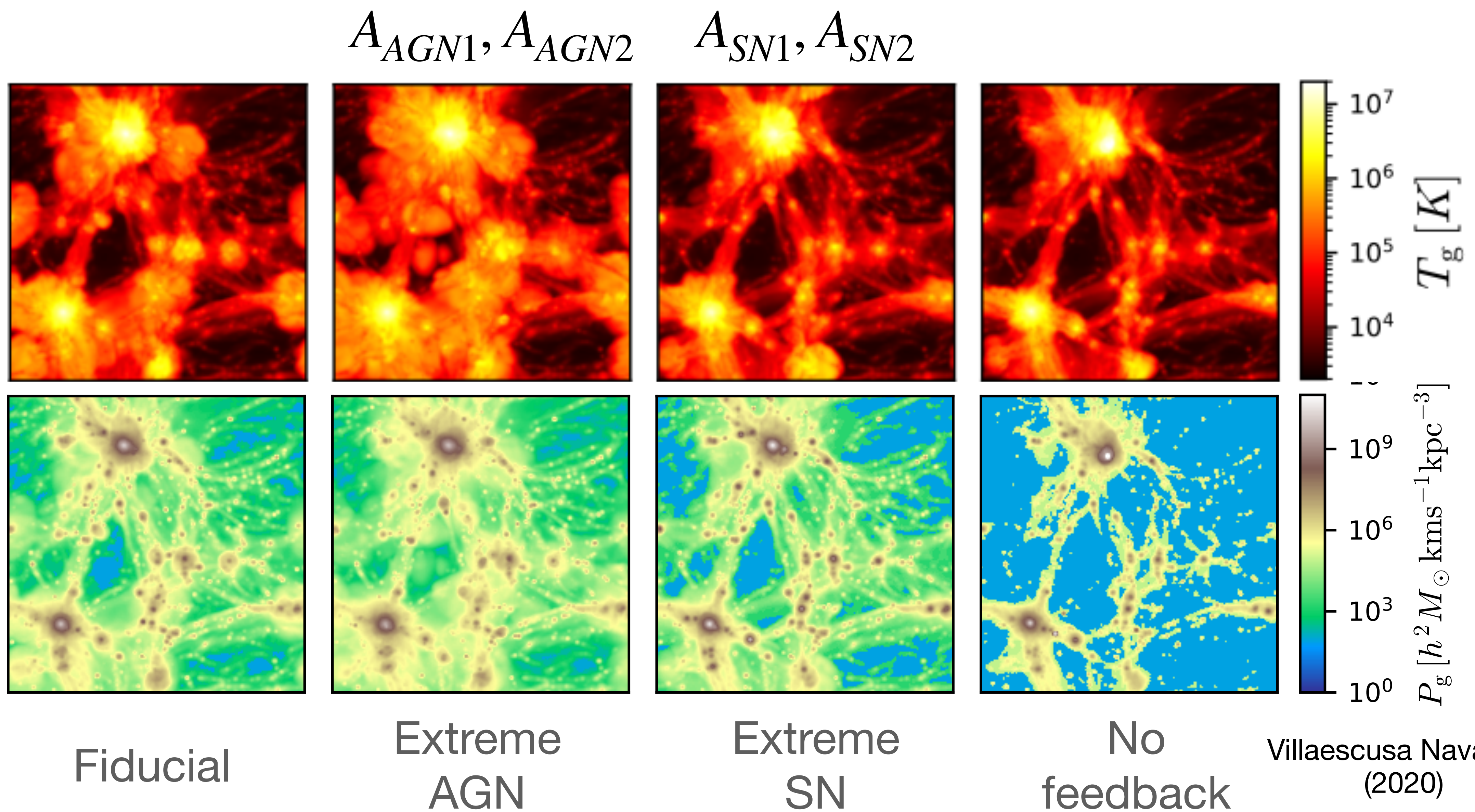


Modeling <y> in hydrodynamical simulations

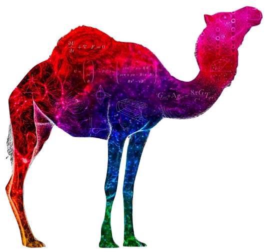
- CAMELS: over 8k hydro simulations varying cosmology, feedback recipes, codes…
- 25 Mpc/h, 2x 256^3 particles: need to address volume and cosmic variance effects

$$x_i \sim f_i^c(\sigma_8, \Omega_m, ...) f_i^b(\{A_j\}) f_i^{\mathrm{CV}}(\delta)$$

Thiele+(2022)

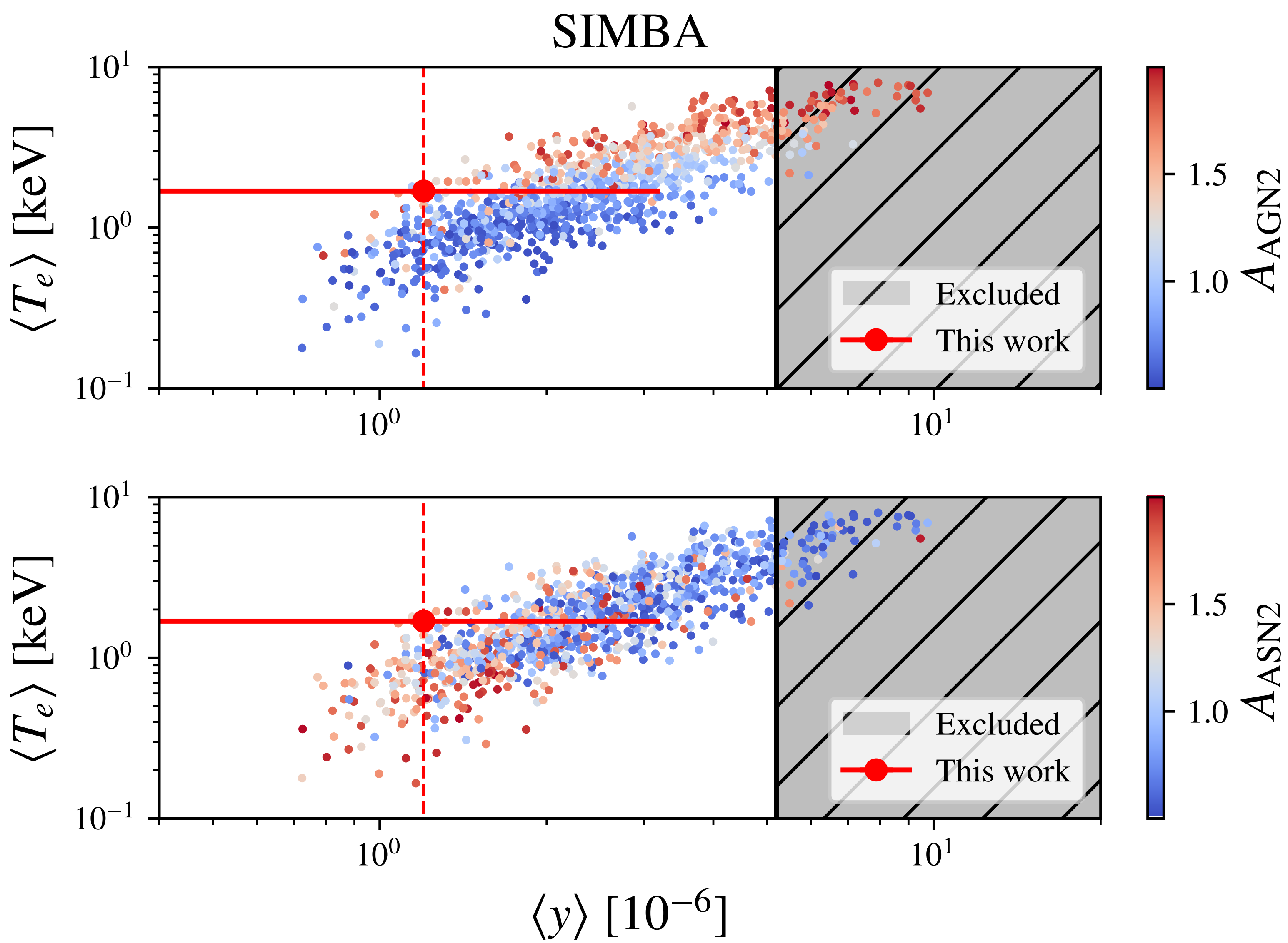


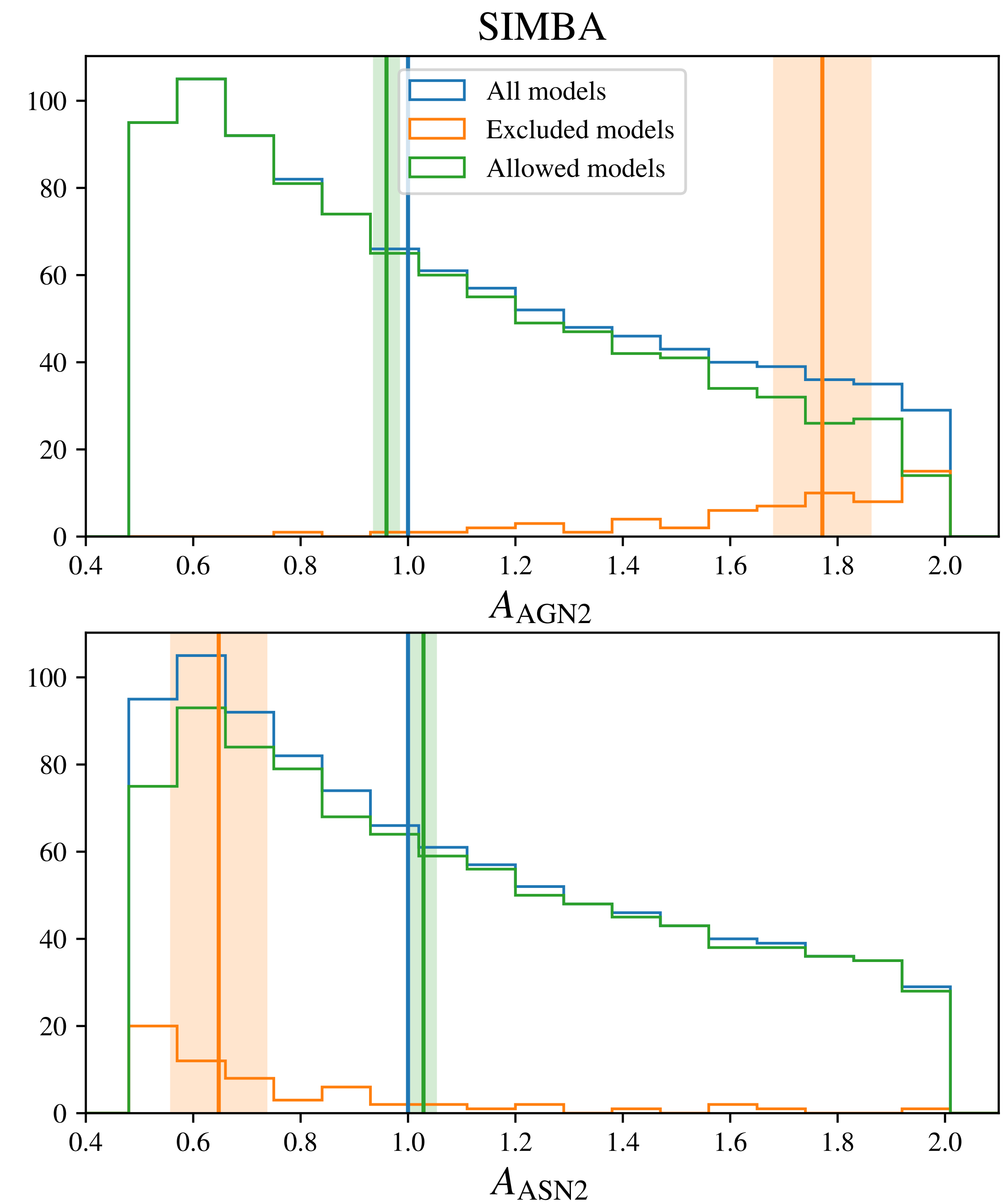
Villaescusa Navarro+ (2020)



Constraining galaxy formation models

- SIMBA stronger feedback model with directional AGN jets.
- Some models start to be ruled out but large degeneracies remains.
  - Direct constraints are weak but not hopeless: likelihood-free inference?

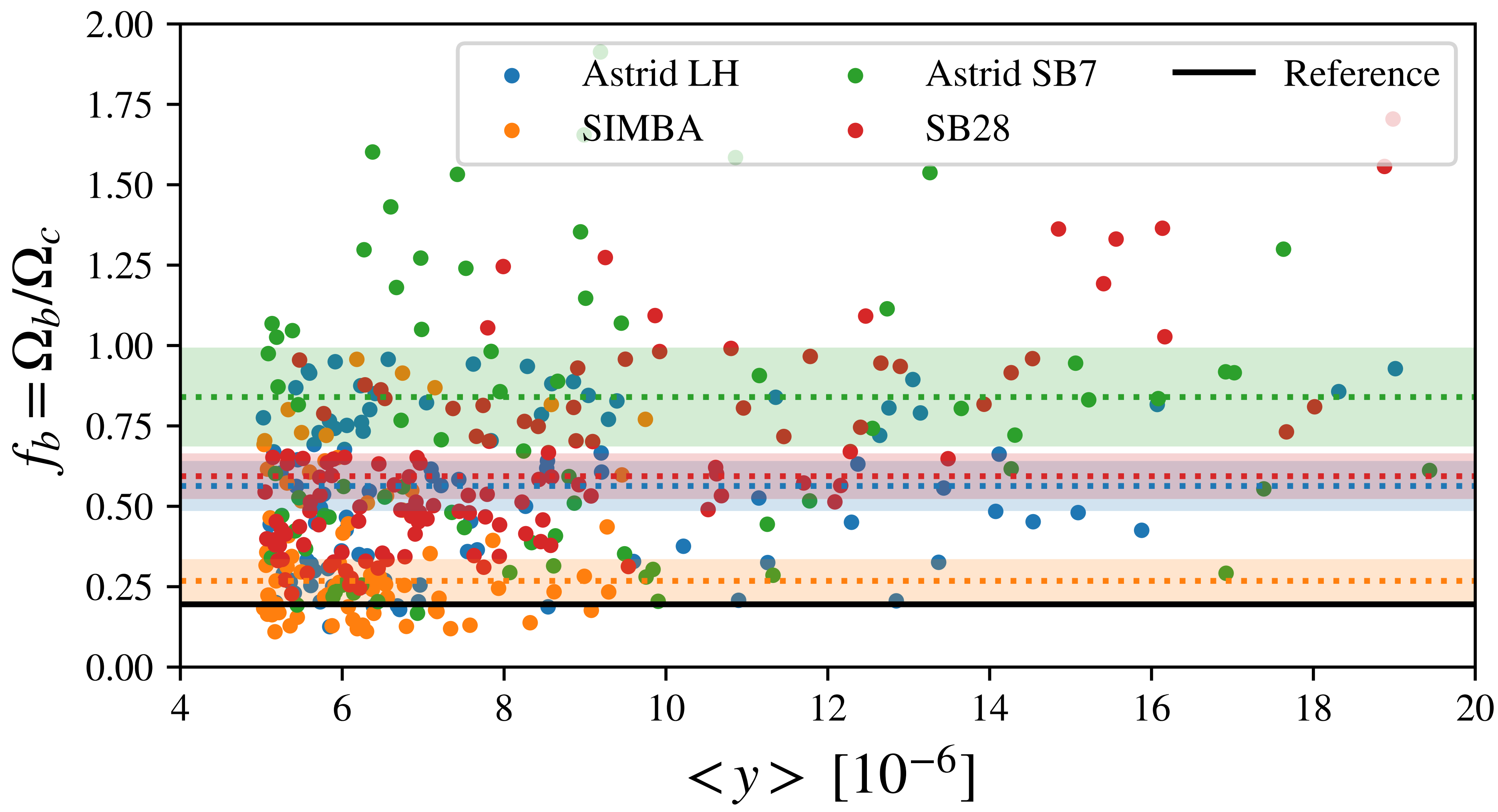




Fabbian+(2025)

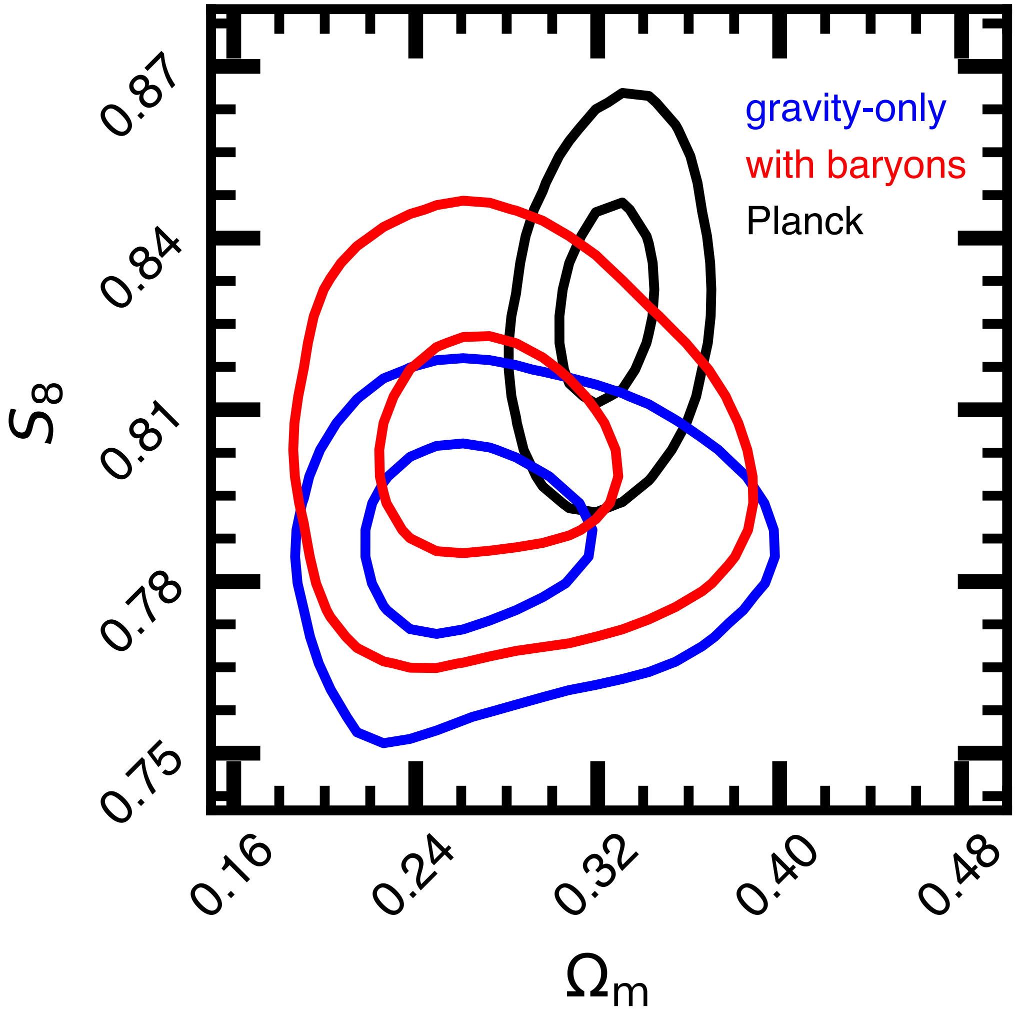
<y> interpretation robustness

- Feedback strength usually dependent/coupled to baryon fraction $f_b = \Omega_b/\Omega_c$
- We checked that the ruled-out models in Simba do not have anomalous f_b
- It's not the same for low feedback models…

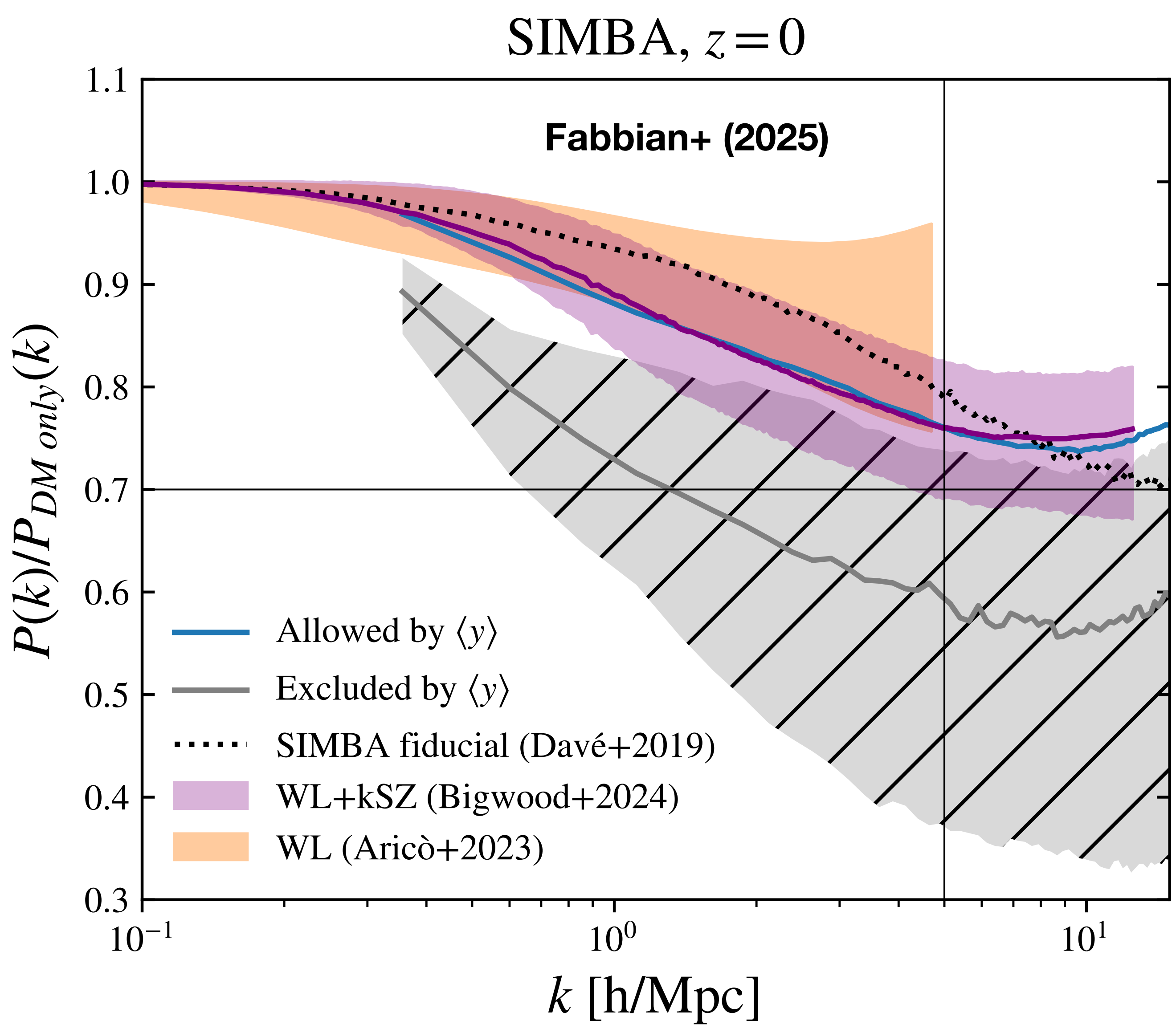


Implications for S8 / galaxy lensing / LSS probes

- Galaxy lensing drives the S8 tension: large uncertainties on matter distribution at small scales.
  - Weak lensing + kSZ : can reconcile current measurements with (extreme) feedback.
  - <y> constraints on baryon suppression in the ballpark of current analyses, informative probe for consistency tests!

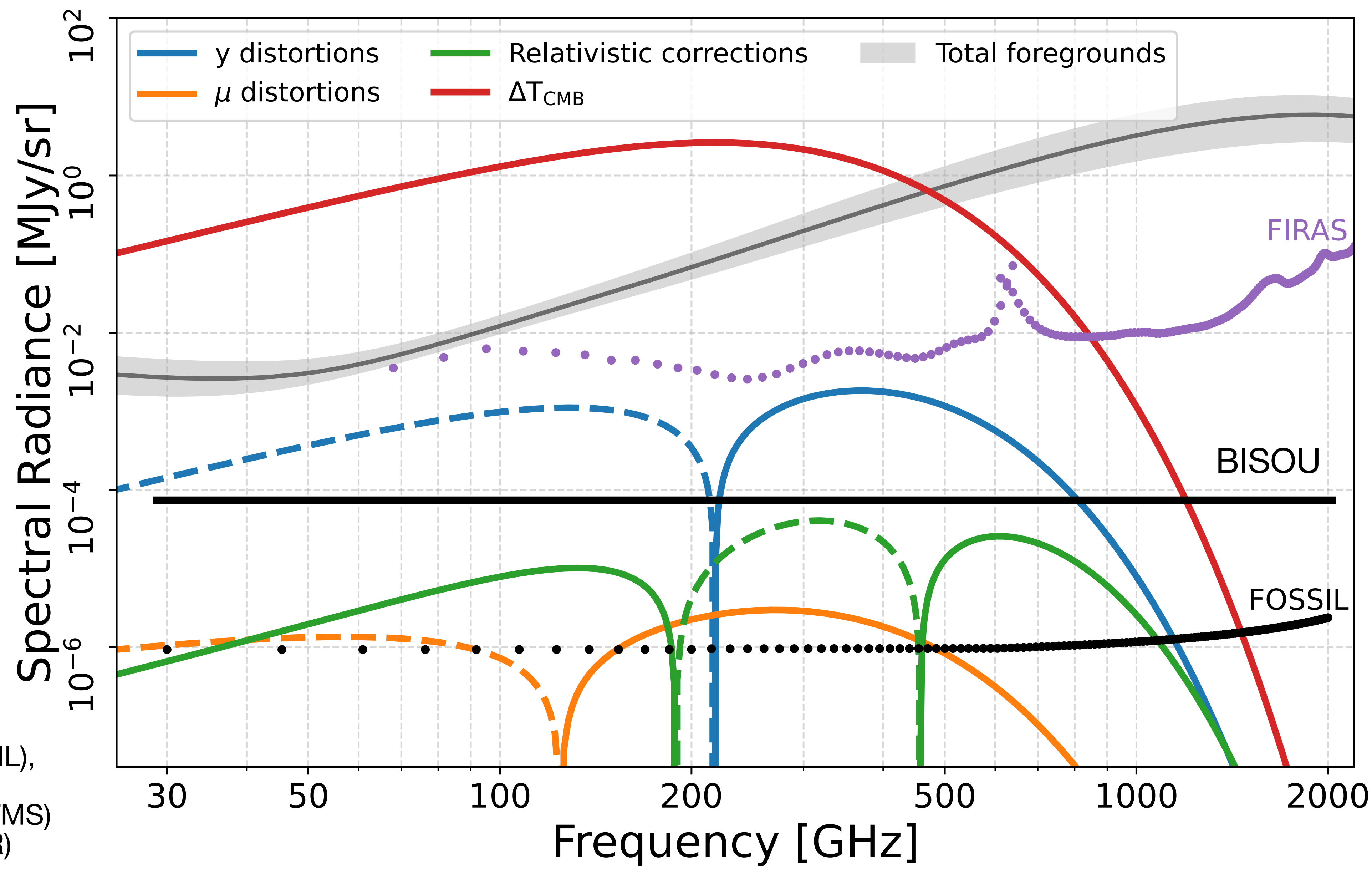


Aricò+ (2023)



Experimental prospects

- Several instruments are being built, deployed or in phase A: transformational potential!
- **FOSSIL ESA M8 mission pre-selected** (P.I. N. Aghanim, B. Maffei @ IAS)
- Forecasts for 16 foreground parameters: potential 5σ detection for BISOU, >200σ for FOSSIL!



Maffei+ (2021, BISOU),
Aghanim+ (2025, FOSSIL),
Masi+(2021, COSMO),
Rubiño-Martin+(2020, TMS)
Sabyr+(2024, SPECTER)

Conclusions

- **Euclid: instrument is working very well.**
  - Promising benchmark from photometric probes x CMB lensing…
  - but not without challenges: **A TON OF SALT** needed.
  - CMB lensing cross-correlation can recover constraining power.
  - Results coming soon, **stay tuned**! (Or ask me more later).

- **CMB spectral distortions are alive and well**
  - We showed you can get feedback constraints with 30 years old data, competitive with current measurements.
  - There is an experimental path forward (TMS, COSMO, BISOU…)
  - FOSSIL could constrain feedback models!