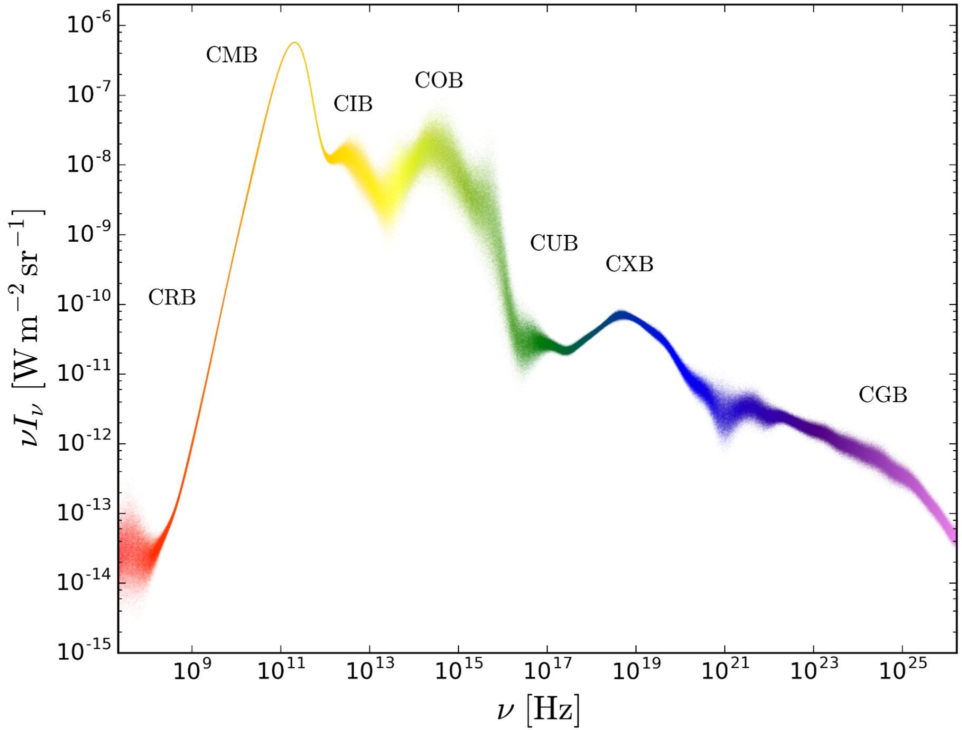
Cosmology and astrophysics with the extragalactic light: background and fluctuations

Gabriela Sato-Polito

Fall 2022

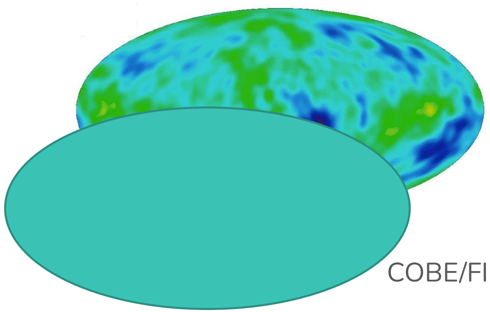
The cosmic background radiation



Hill et al. 2018

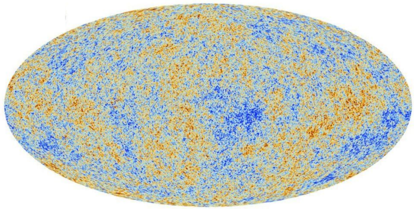
Cosmic Microwave Background (CMB)

Absolute Intensity

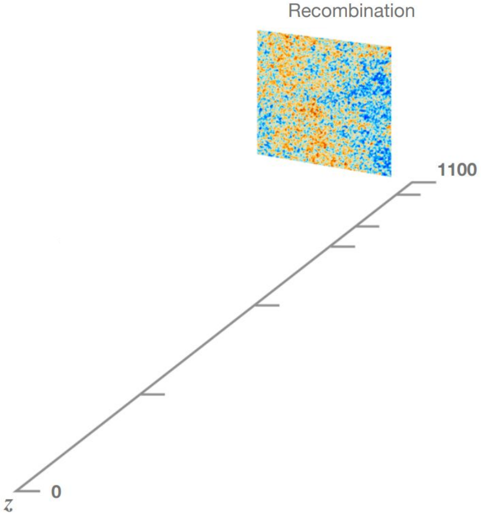


COBE/FIRAS

Intensity Fluctuations



Planck



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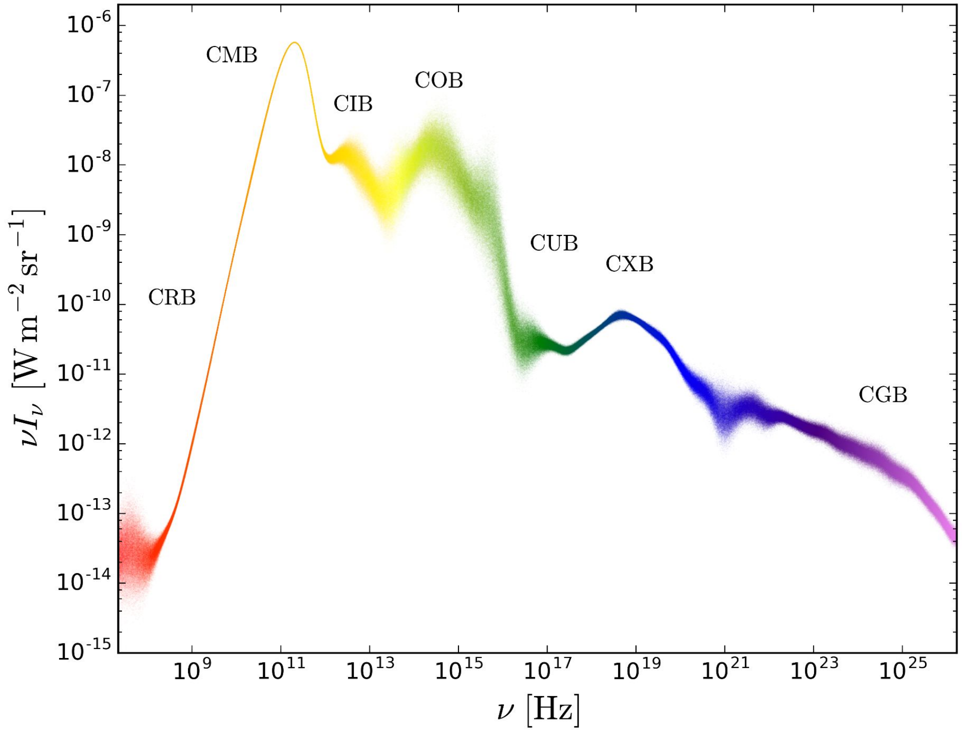
The cosmic background radiation



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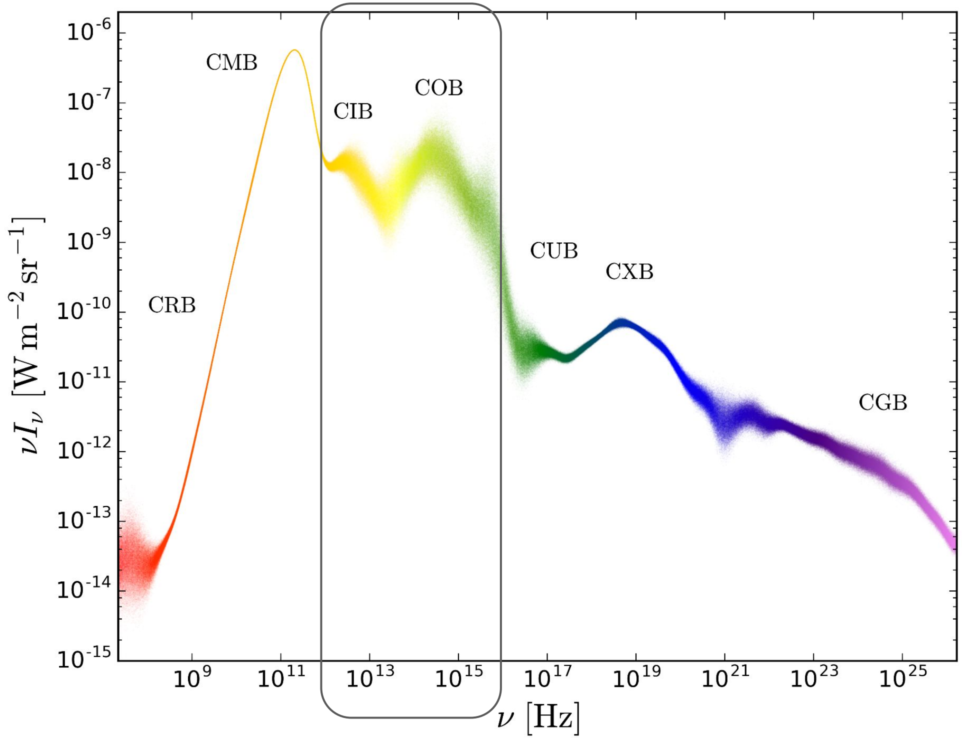
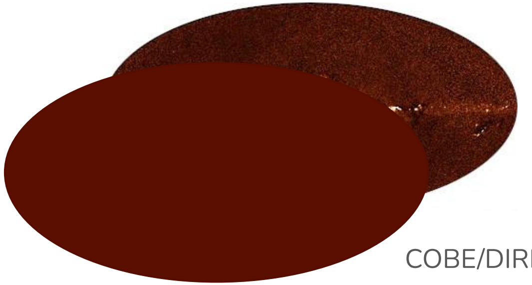


Hill et al. 2018

Mainly produced by **stellar nucleosynthesis** and reprocessing by **dust** within galaxies

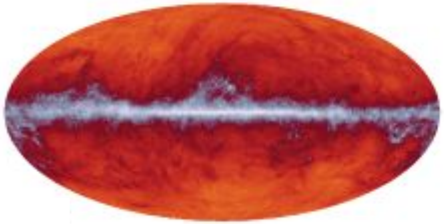
Cosmic Infrared Background (CIB)

Absolute Intensity

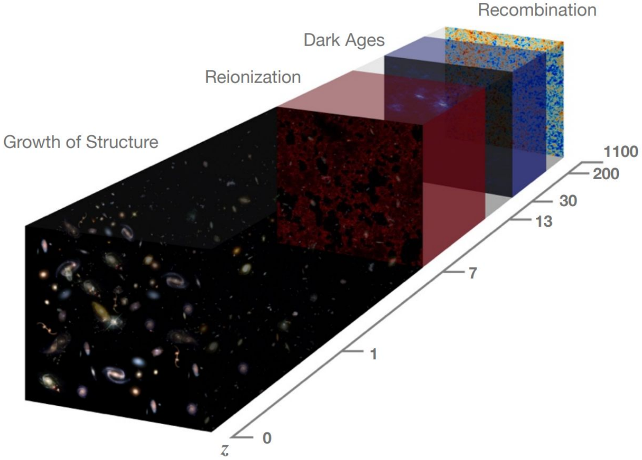


COBE/DIRBE

Intensity Fluctuations



Planck



Ely Kovetz

Sourced primarily by dusty star-forming galaxies

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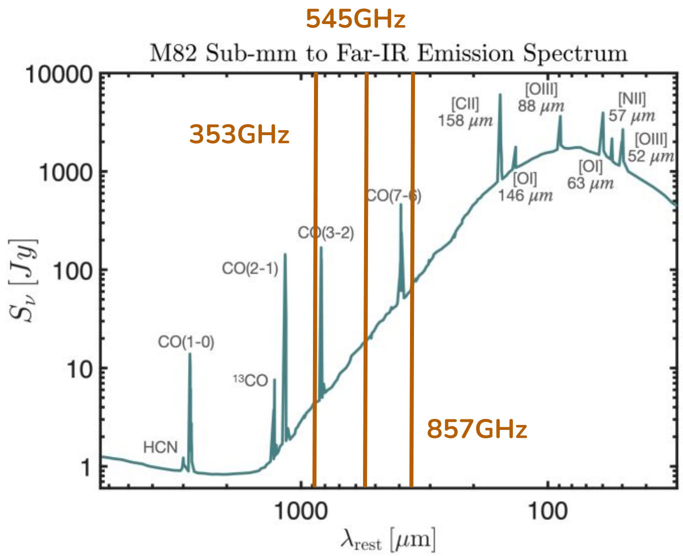
Galaxy emission at different wavelengths (SED)

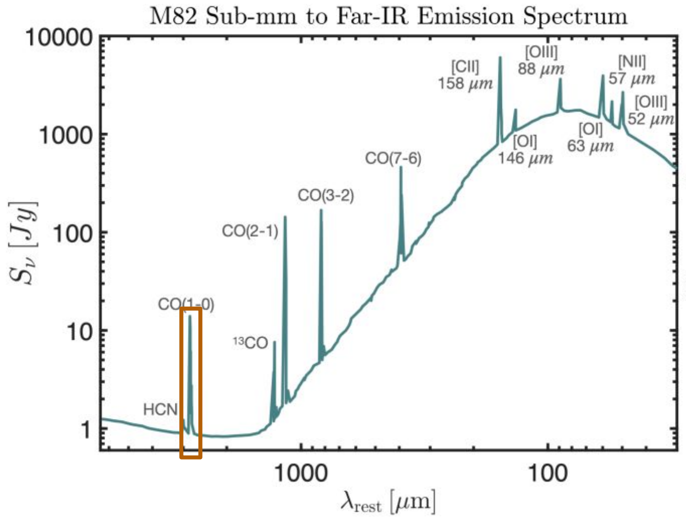


Bernal & Kovetz

CIB corresponds to the integrated emission of all sources at the highlighted frequencies

*Single galaxy SED as an example, but measurements of intensity capture all integrated sources

Galaxy emission at different wavelengths (SED)



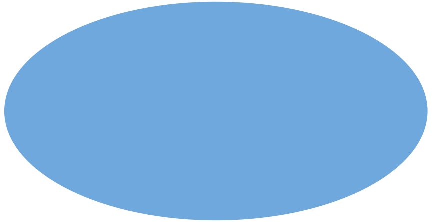
Bernal & Kovetz

Line-intensity mapping aims to build 3D maps of the Universe by targeting redshifted spectral lines

∗Single galaxy SED as an example, but measurements of intensity capture all integrated sources

Cosmic background in the sub-mm to UV

Absolute Intensity



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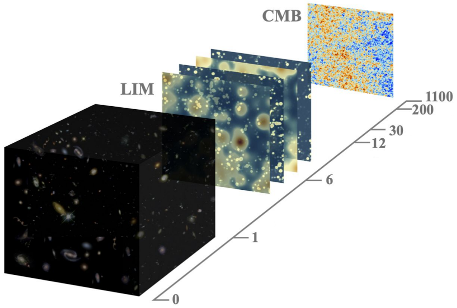

- Probe radiative processes across the Universe
- Captures light from both galaxies and diffuse sources

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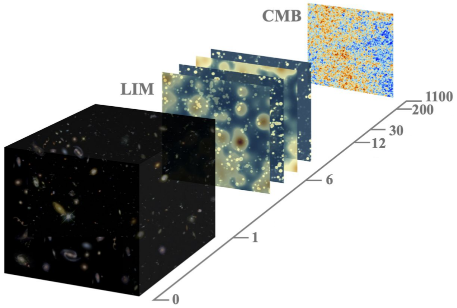
Cosmic background in the sub-mm to UV

Absolute Intensity   Intensity Fluctuations



- Probe radiative processes across the Universe
- Captures light from both galaxies and diffuse sources

  - Clustering of emitters
  - 3D map over wide redshift range
  - Quick mapping of large volumes

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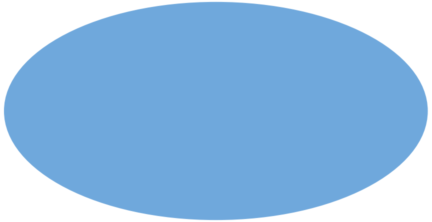
Outline

Absolute Intensity



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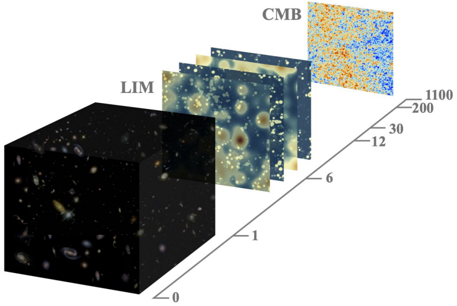

Cosmology

Dark matter
Dark energy
Early Universe
Neutrino properties

Astrophysics

Formation of first stars and galaxies
Process of reionization
Star formation history

- Probe radiative processes across the Universe
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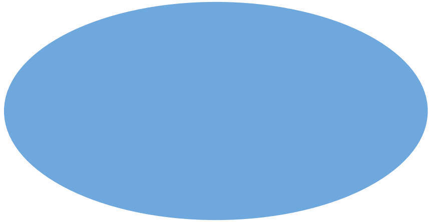

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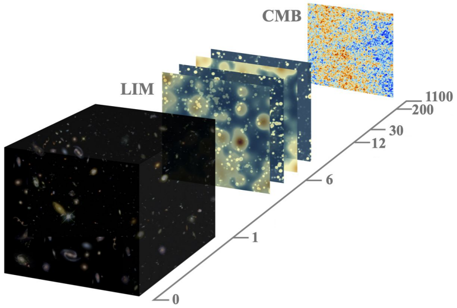

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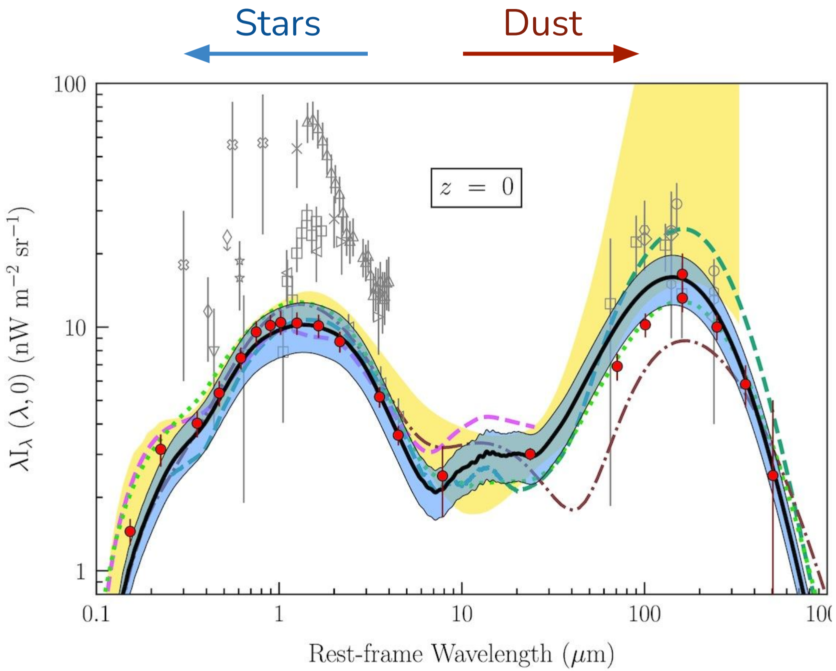
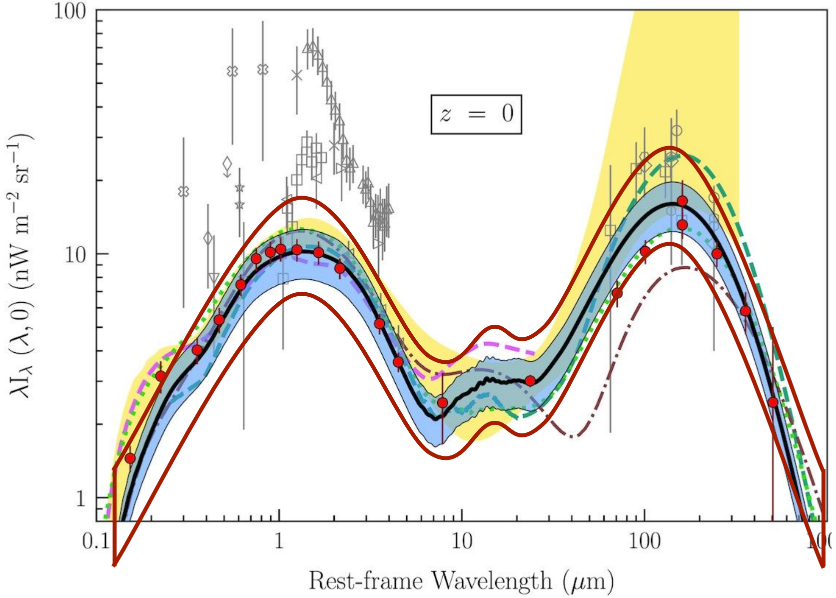


Saldana-Lopez et al. 2021

- Integrated galactic light
  - Mainly produced by stellar nucleosynthesis and reprocessing by dust within galaxies

Absolute intensity



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Determinations from galaxy counts

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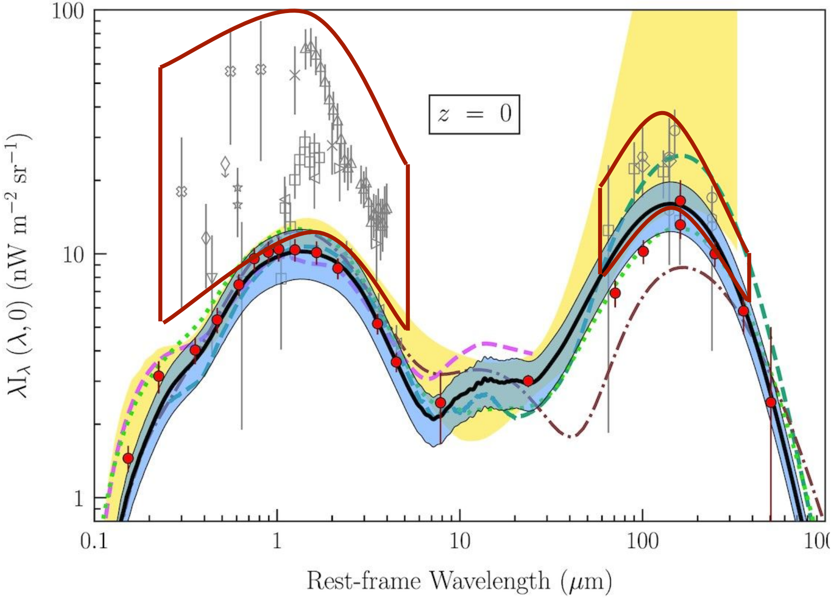
Absolute intensity



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Direct measurements

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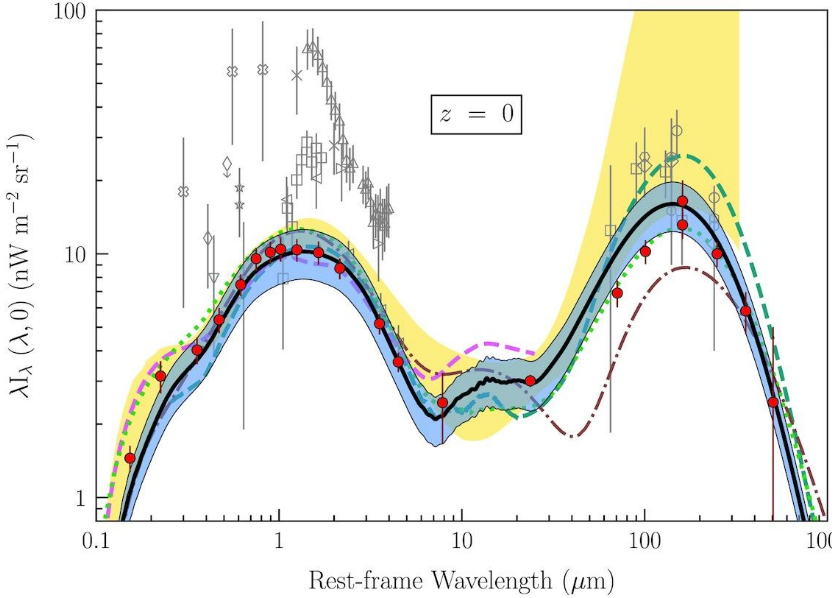
Absolute intensity



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- Stars and diffuse Milky Way components
- Solar system foregrounds (e.g. zodiacal light)
- Instrument noise (e.g. calibration error, dark current)

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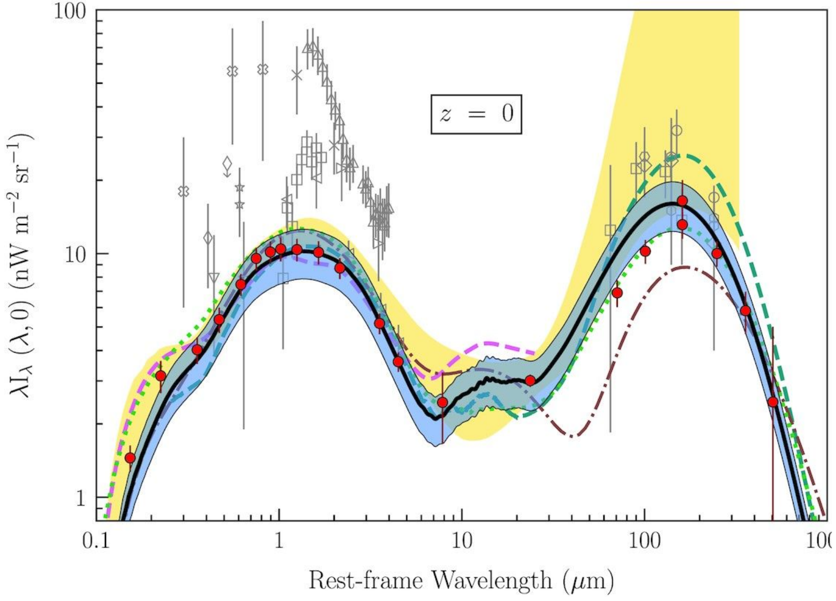

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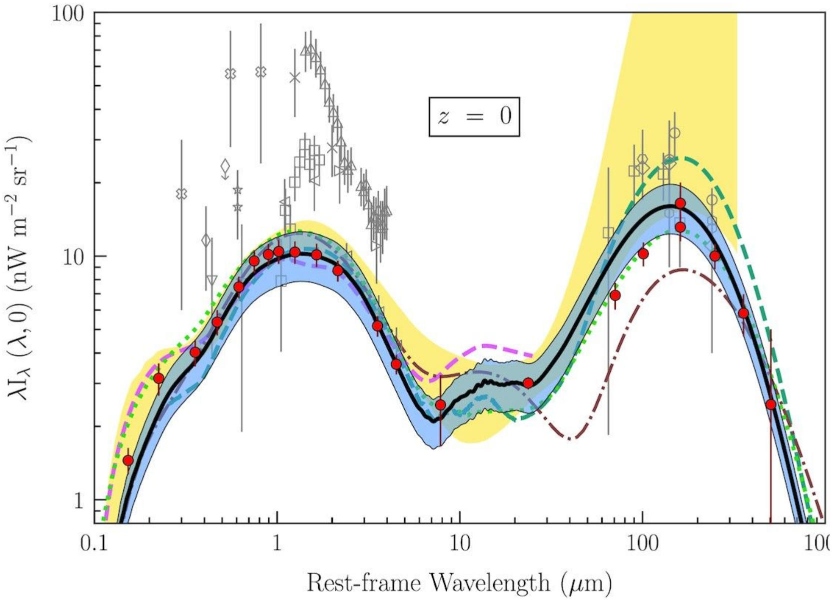
- Stars and diffuse Milky Way components
- Solar system foregrounds (e.g. zodiacal light)
- Instrument noise (e.g. calibration error, dark current)
- **Diffuse component?**
  - Intra-halo light (Cooray et al. 2012, Mitchell-Wynne et al. 2015)
  - Unresolved/high-redshift galaxies (z>6)
  - Direct collapse black holes (Yue et al. 2013)
  - Decaying dark matter

Absolute intensity



Saldana-Lopez et al. 2021

Broad-strokes integrated information from all emitters

Can be used as a consistency test of our understanding of the sources of radiation in the Universe:

“Did we count everything?”

Cosmic Optical Background (COB)

Most significant measurement to date made with New Horizons LORRI images

Wavelengths of $0.4 \leq \lambda \leq 0.9$ μm at 51.3 AU from the Sun

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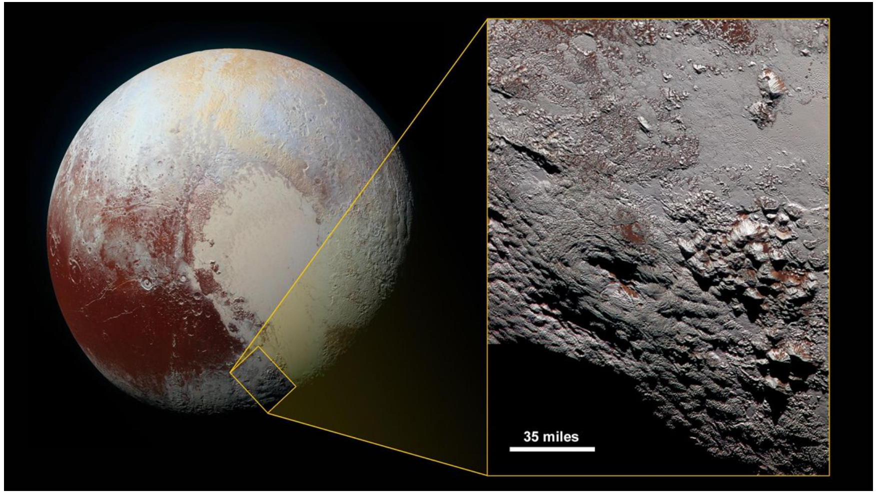

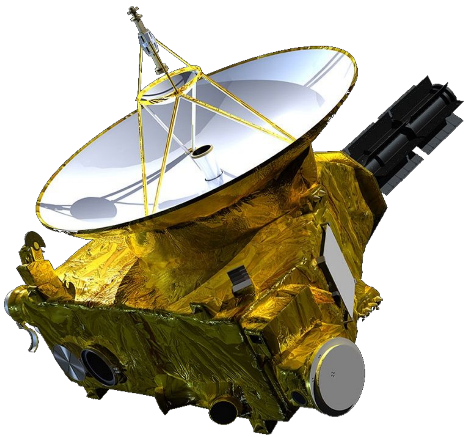

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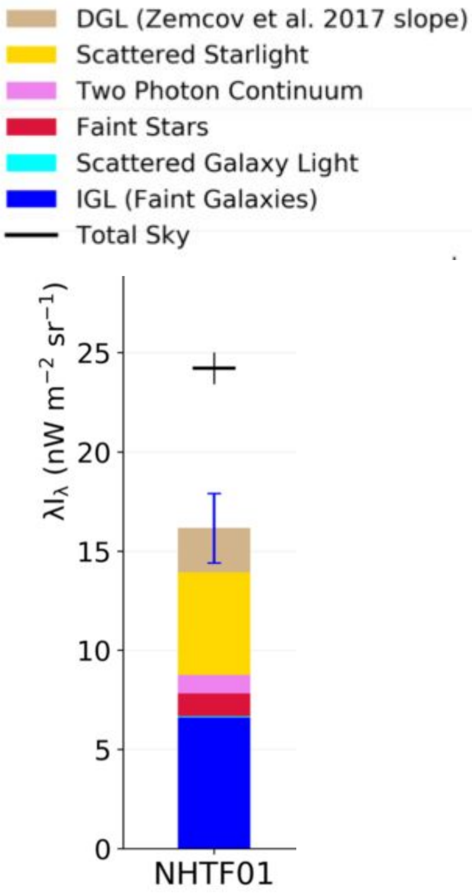
COB = 16.37±1.47

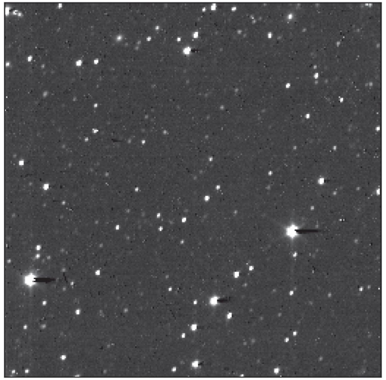
- IGL = 8.31 ± 1.24 nW m^{-2} sr^{-1}
- Anomalous = 8.06 ± 1.92 nW m^{-2} sr^{-1}



Lauer et al. 2022

Decaying dark matter?

Absolute photometry



Lauer et al. 2022

Evidence for excess of optical photons

Bernal, **GSP**, Kamionkowski 2022

ALP contribution to the COB

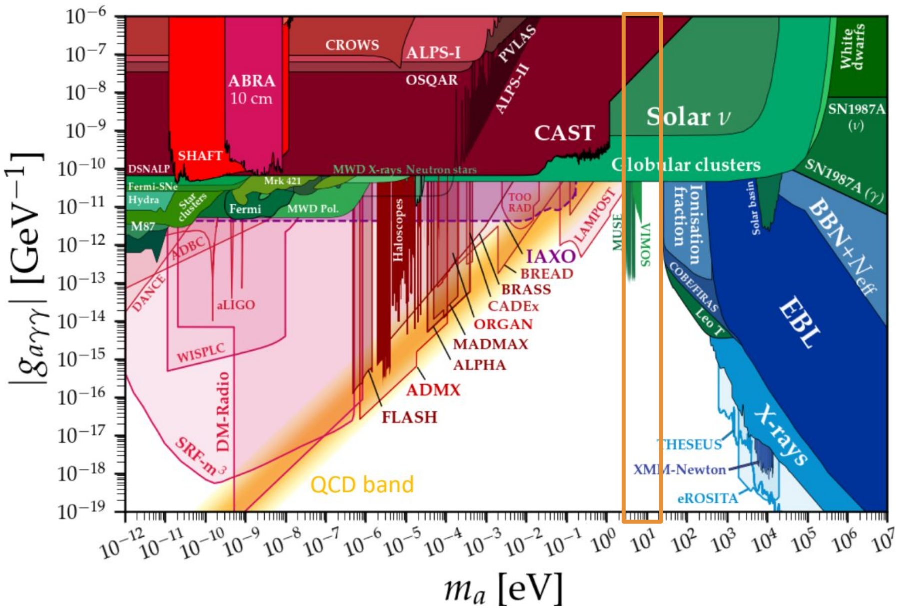
Axions: proposed as a solution to the strong CP problem

ALPs: generic pseudo-scalars (no coupling to gluons), but nevertheless arise in a variety of BSM theories

Coupling to photons can lead to two-photon decay a→γγ

$$\nu = \frac{m_a c^2}{2h} \qquad \Gamma_a = \frac{(m_a c^2)^3 g_{a\gamma\gamma}^2}{32h}$$

95% CL



ALP contribution to the COB

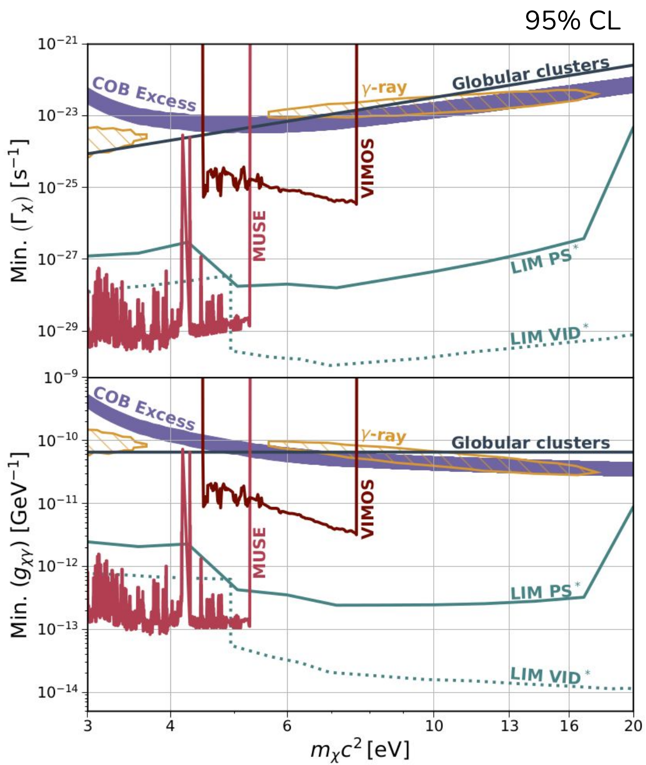
Line emission from ALP decay

$$I_\lambda \propto \frac{\Gamma_a}{\lambda_{\rm obs}(1+z_*)H(z_*)} \quad z_* = z \text{ of axion decay}$$

Can be explained by unconstrained region of parameter space

Overlaps with hint from γ-ray extinction (Korochkin et al. 2019)

Will be probed by upcoming LIM experiments (SPHEREx and HETDEX)



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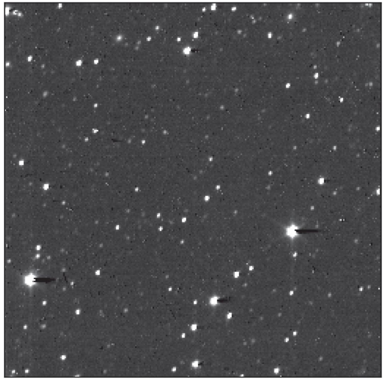

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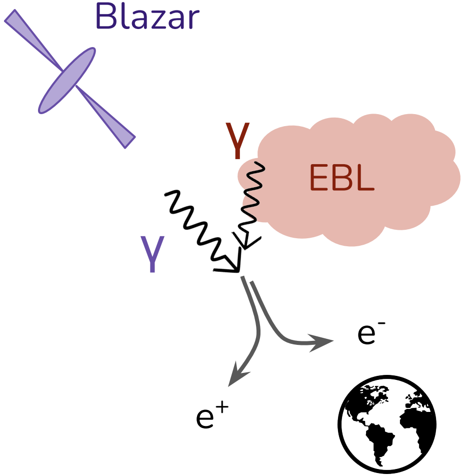
γ-ray attenuation

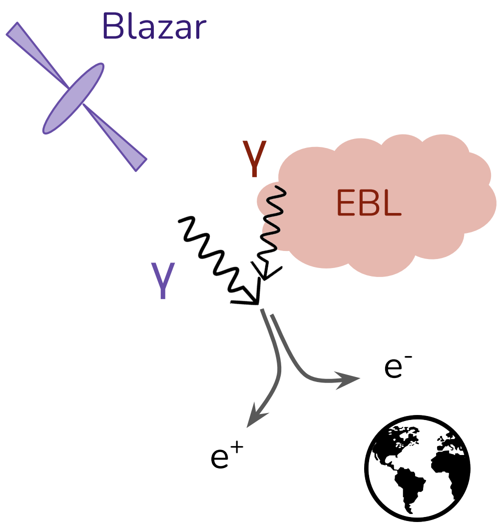


Bernal, Caputo, **GSP**, Mirocha, Kamionkowski 2022

γ-ray attenuation from ALPs

High-energy γ-rays are attenuated by IR-NUV photons through electron-positron pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$



Optical depth due to EBL photons

$$\tau = c \int_0^{z_s} dz \frac{l^{-1}}{H(1+z)} \qquad l^{-1} = \int_{\epsilon_{min}}^{\infty} d\epsilon \frac{dn}{d\epsilon} \int_{-1}^{1} d\mu \sigma_{\gamma\gamma}$$

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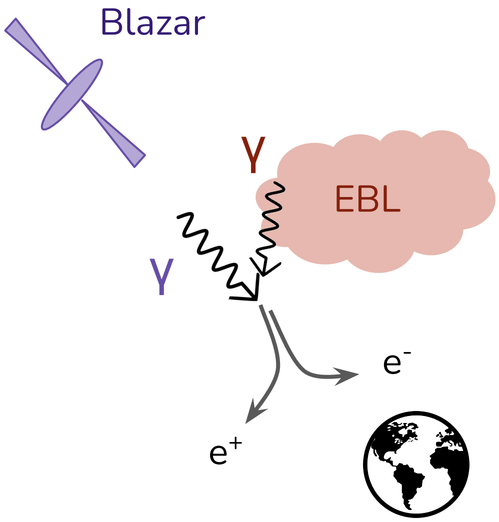
Measured from ~800 blazars by FermiLAT and Cherenkov Telescopes



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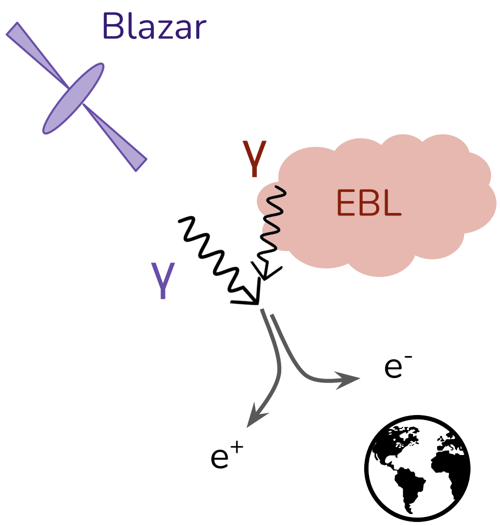

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EBL photons:

- Galaxies at z<6 (Saldana-Lopez et al 2021)
- Galaxies at z>6 (Mirocha 2014, Mirocha et al. 2017, Mirocha et al. 2018)
- Intra-halo light (Cooray et al. 2012, Mitchell-Wynne et al. 2015)
- Additional contribution? (Bernal, Caputo, **GSP**, Mirocha, Kamionkowski 2022)

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γ-ray attenuation from ALPs

Excess in the EBL:

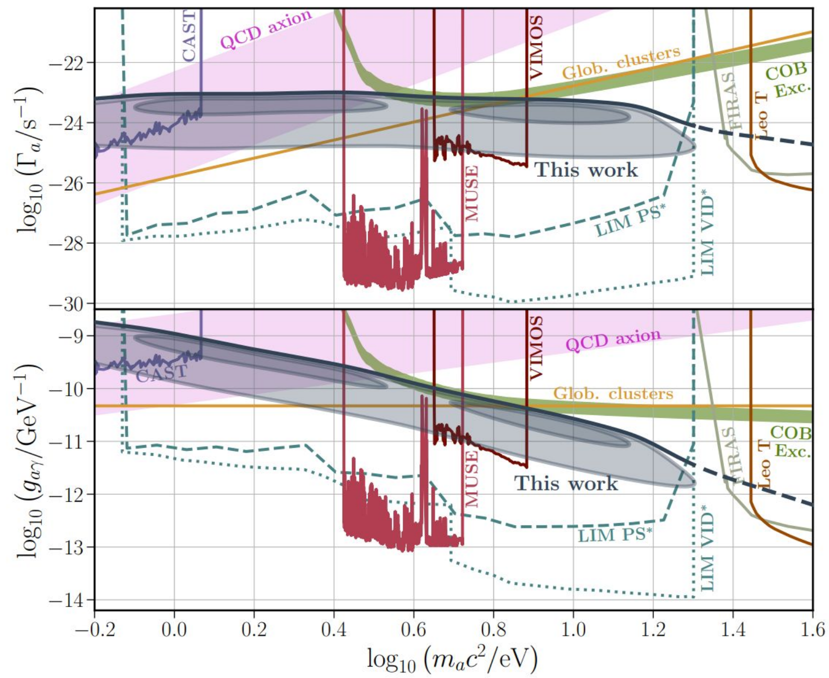
- ALP contribution: 2.1σ
- Boost known galaxies by $(1+F_{eEBL})$: 2.7 σ

- Unconstrained best-fit
- Overlaps with COB excess

But...

- ALP provides poor fit to local blazars
- Preference for boost of astrophysical contribution

95% CL



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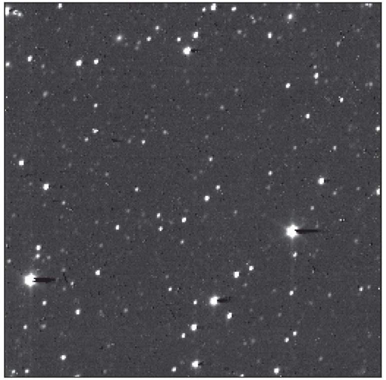

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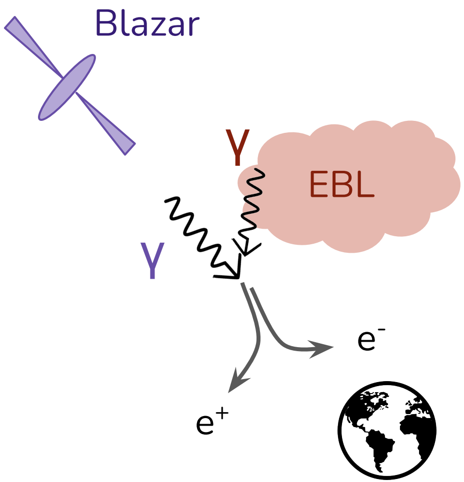

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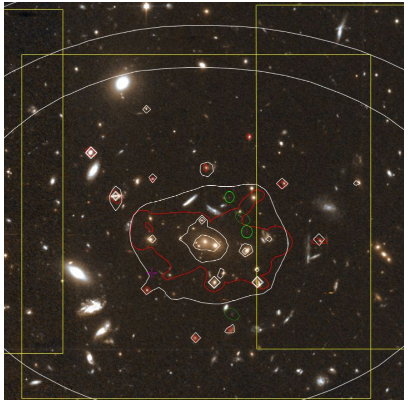
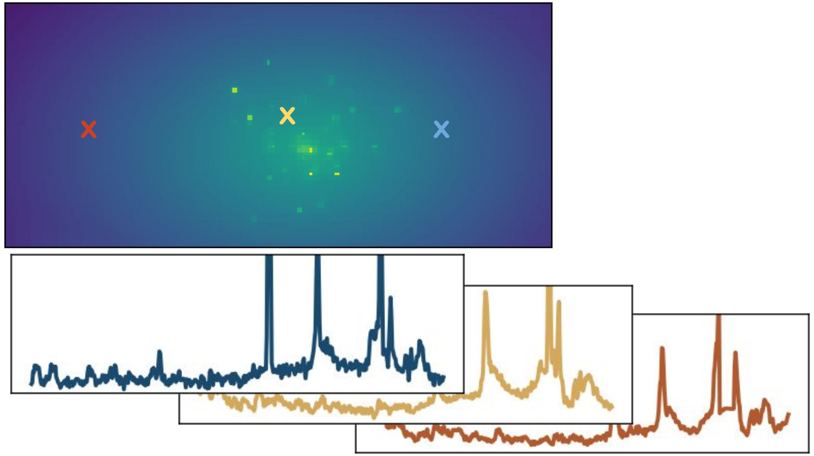
Telescope search



GSP, Grin, Kamionkowski in prep.

Ongoing exploration: Telescope search

ALP two-photon line can be searched directly from spectra of galaxy clusters (Grin et al. 2007)



Emission line correlated with matter distribution

$$I_{\lambda,i} = \left\langle \frac{I_\lambda}{\Sigma} \right\rangle \Sigma_i + b_\lambda$$

Galaxy cluster RDCS1252 (z=1.2) using VIMOS IFU at VLT + mass model from strong lensing observ.

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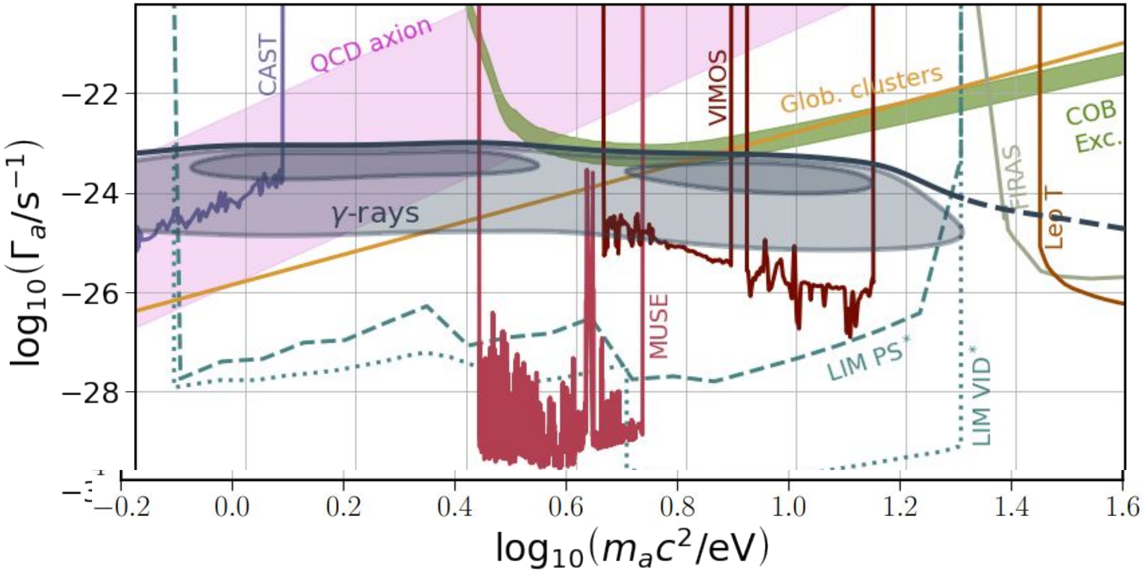

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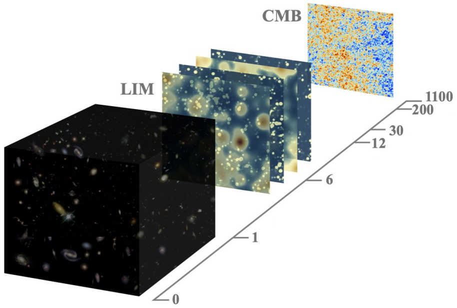

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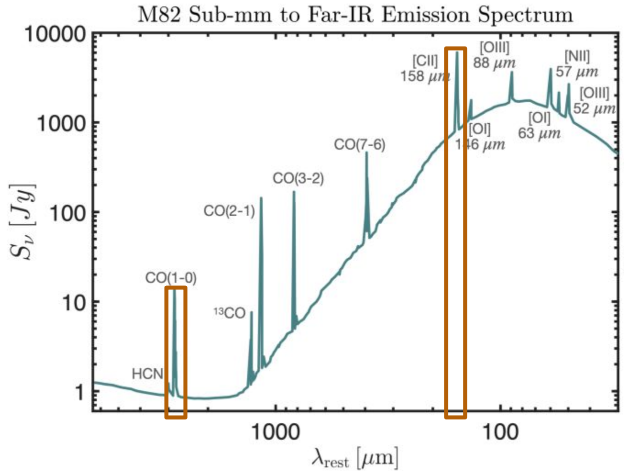
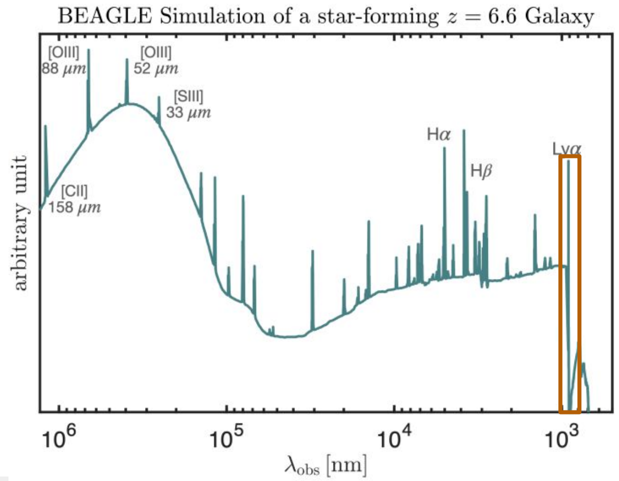
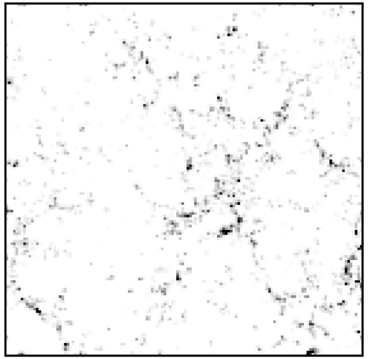
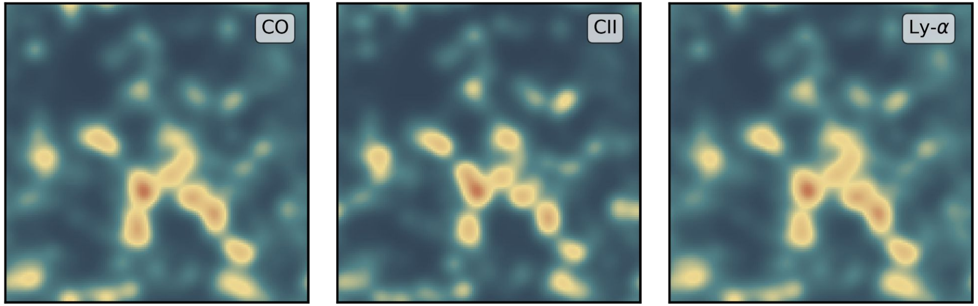


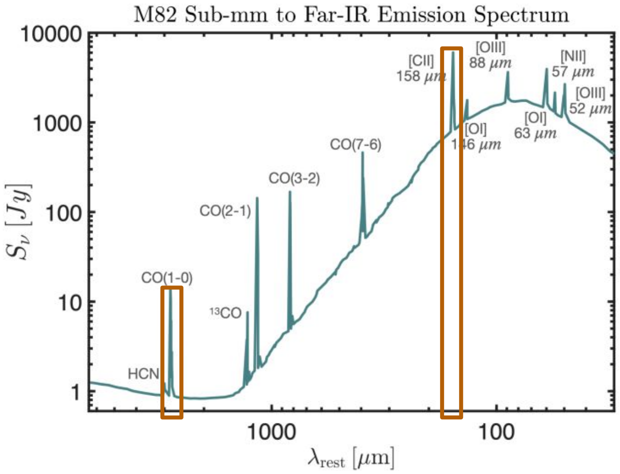


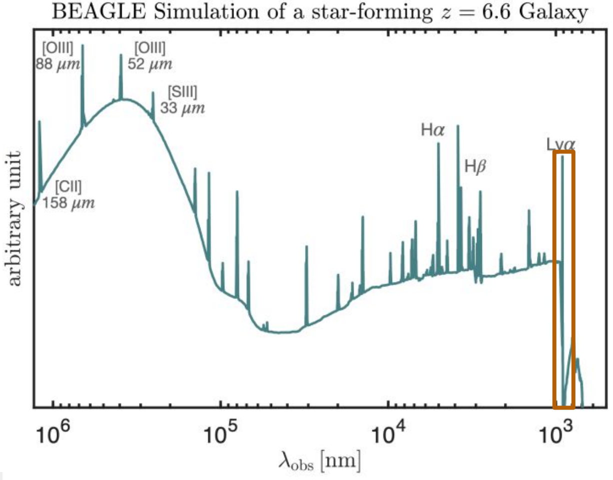
The Universe according to LIM



~1 deg^2 at z=2.5







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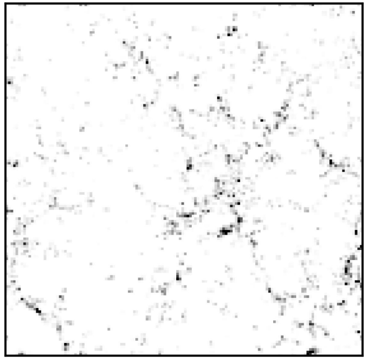
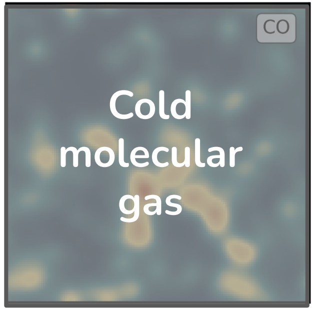
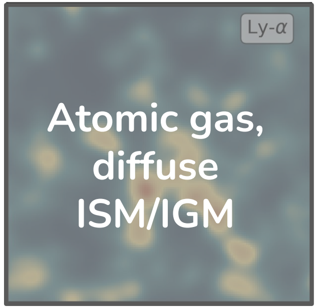


~1 deg² at z=2.5





Probe different phases of the ISM and IGM across the Universe

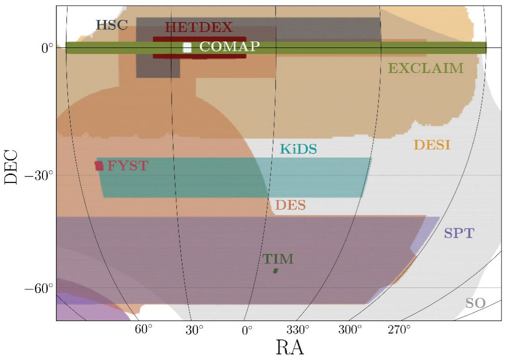
1. Complementarity in the signal from different lines

"To try to make a model of an atom by studying its spectrum is like trying to make a model of a grand piano by listening to the noise it makes when thrown downstairs." - Anonymous.
Therefore, making a model of a galaxy by studying its spectrum is like modelling an entire symphony orchestra from the noise it makes when falling downstairs. As we model galaxy spectra, it is crucial to understand the limitations of the models and the conditions where the models are invalid.

"Understanding Galaxy Evolution through Emission Lines", Kewley, Nicholls & Sutherland 2019

Outline

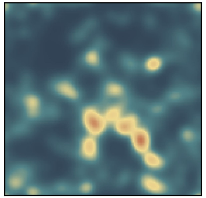
Observations



Bernal and Kovetz 2022

Models/Simulations

`Skyline`:multi-tracer lightcone catalogs



GSP, Kokron, Bernal in prep

→

Cosmology

Dark matter

Dark energy

Early Universe

Neutrino properties

Astrophysics

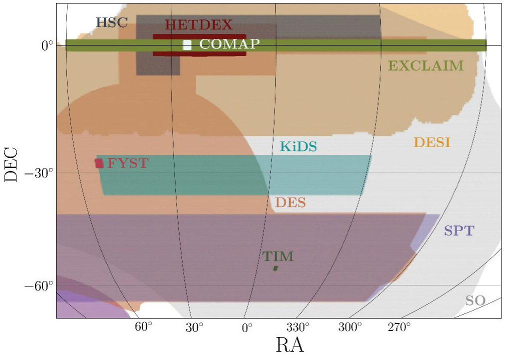
Formation of first stars and galaxies

Process of reionization

Star formation history

Outline

Observations



Bernal and Kovetz 2022

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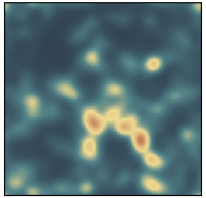

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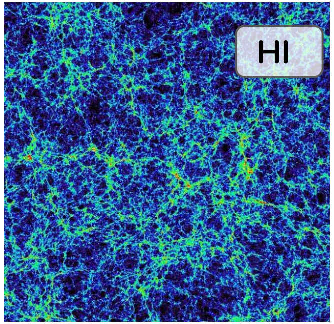
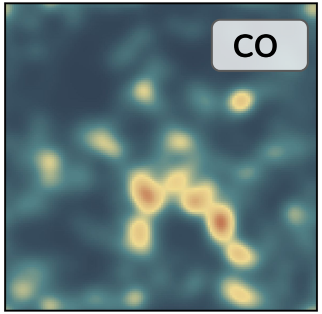
Epoch of reionization

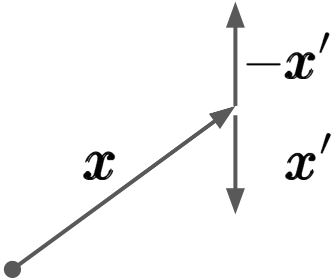
Mesinger et al. 2010





Antisymmetric cross-correlation captures the evolution of reionization

$$\langle \mathrm{CO}(\boldsymbol{x})\mathrm{HI}(\boldsymbol{x}+\boldsymbol{x}')\rangle - \langle \mathrm{CO}(\boldsymbol{x})\mathrm{HI}(\boldsymbol{x}-\boldsymbol{x}')\rangle$$



More information, more robust to foregrounds

GSP et al. 2020a

Outline

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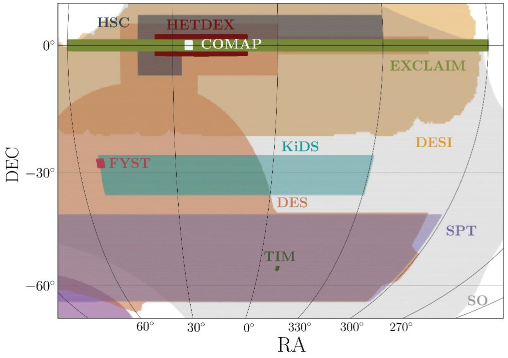

Bernal and Kovetz 2022

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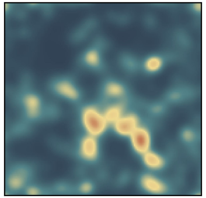

GSP, Kokron, Bernal in prep

→

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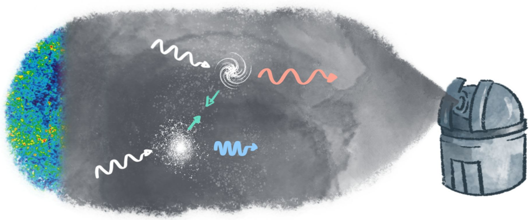
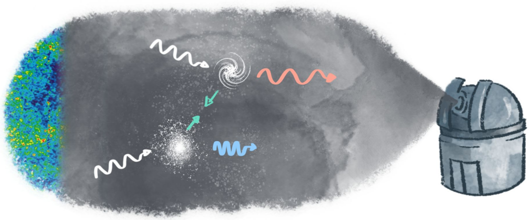
Kinetic Sunyaev-Zel'dovich (kSZ) effect

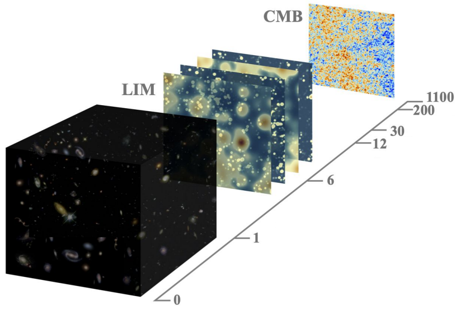


Scattering between **CMB** photons and **electrons** in moving structures induces temperature fluctuations

$$\frac{\Delta T}{T} \approx \sigma_T n_e v_r$$

kSZ + line-intensity mapping





Scattering between **CMB** photons and **electrons** in moving structures induces temperature fluctuations

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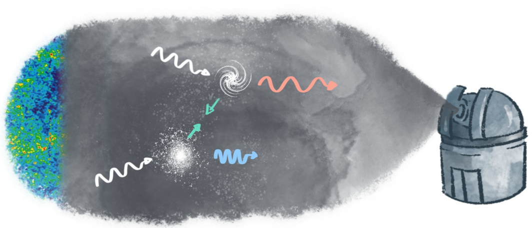
+

Direct probe of intervening large-scale structure up to z~5

GSP et al. 2020b

kSZ + line-intensity mapping



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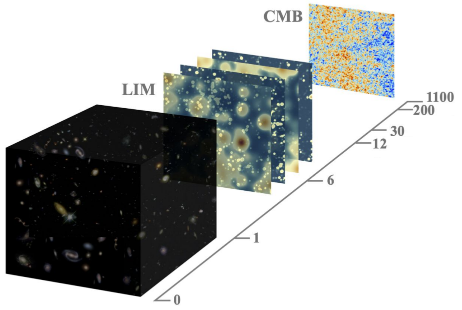


Direct probe of intervening large-scale structure up to z~5

GSP et al. 2020b

=

Primordial non-Gaussianity

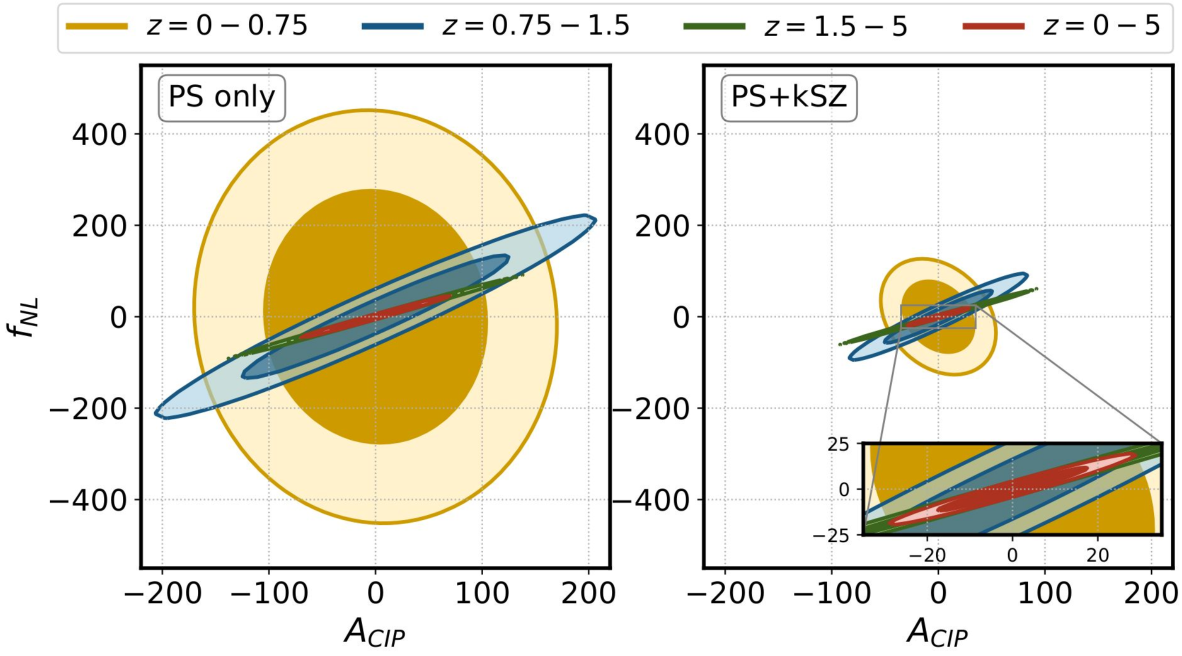
$$\Phi(\mathbf{x}) = \Phi_G + f_{NL}\left[\Phi_G^2(\mathbf{x}) - \langle\Phi_G^2(\mathbf{x})\rangle\right]$$

Compensated Isocurvature Perturbations

Baryon fluctuations compensated by dark matter fluctuations

$$A_{CIP} = \frac{\text{isocurvature}}{\text{adiabatic}}$$

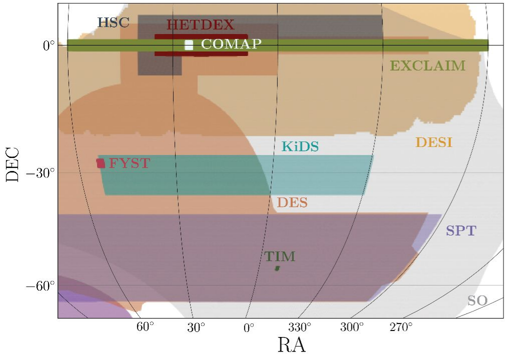
kSZ + line-intensity mapping



- ~3x improvement by including kSZ
- Distinguish different contributions from inflation
- Intensity mapping + kSZ can be a powerful probe of the early Universe!

Outline

Observations



Bernal and Kovetz 2022

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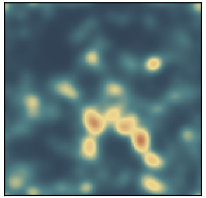

GSP, Kokron, Bernal in prep

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LIM with combined 1- and 2- point statistics

Power spectrum

Measures the degree of clustering of a map

$$P(k,z) \approx \langle T(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}$$

• gsatopo1@jhu.edu • Gabriela Sato-Polito • Johns Hopkins University •

LIM with combined 1- and 2- point statistics

Power spectrum

Measures the degree of clustering of a map

$$P(k,z) \approx \langle T(z)\rangle^2 b^2(z) \boxed{P_m(k,z)} + P_{\text{shot}}$$

Depends on **matter power spectrum** and 1^{st} and 2^{nd} moments of luminosity function

LIM with combined 1- and 2- point statistics

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Measures the degree of clustering of a map

$$P(k,z) \approx \langle T(z)\rangle^2 b^2(z) P_m(k,z) + P_{\rm shot}$$

$$\propto \int L\Phi(L)dL \qquad \propto \int L^2\Phi(L)dL$$

Depends on matter power spectrum and **1st and 2nd moments of luminosity function**

LIM with combined 1- and 2- point statistics

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Depends on matter power spectrum and 1^{st} and 2^{nd} moments of luminosity function

Voxel intensity distribution (VID)

Probability P(T) that a voxel has a temperature T

$$\mathcal{P}(T) = \sum_{N=0}^{\infty} \mathcal{P}_N(T)\mathcal{P}(N)$$

LIM with combined 1- and 2- point statistics

Power spectrum

Measures the degree of clustering of a map

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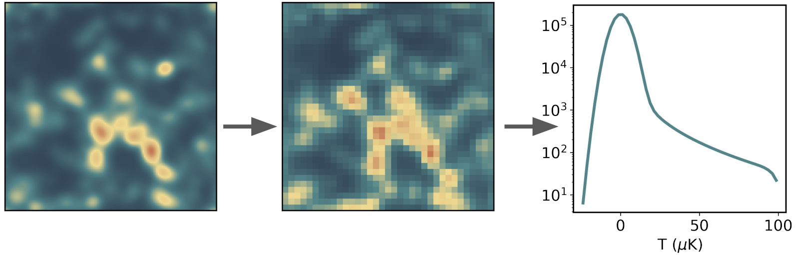

Depends on the luminosity function and matter PDF

LIM with combined 1- and 2- point statistics

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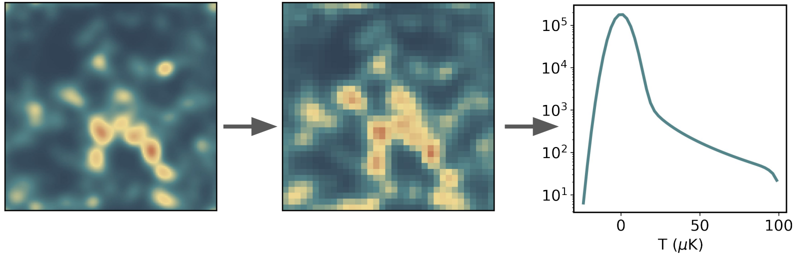


Depends on the luminosity function and matter PDF

GSP & Bernal 2022

• gsatopo1@jhu.edu • Gabriela Sato-Polito • Johns Hopkins University •

LIM with combined 1- and 2- point statistics

We derived the theoretical covariance for the first time:

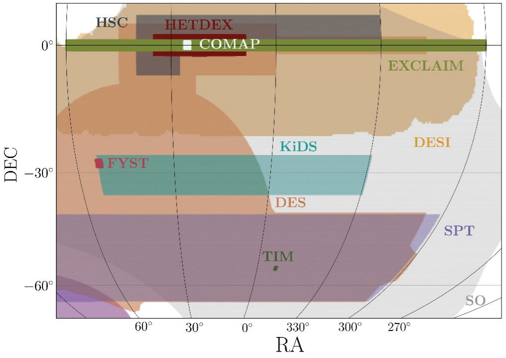
$$\mathrm{Cov}[\mathcal{B}_i, P(\boldsymbol{k}_j)] = \langle \mathcal{B}_i P(\boldsymbol{k}_j) \rangle - \langle \mathcal{B}_i \rangle \langle P(\boldsymbol{k}_j) \rangle$$
$$\propto \int \frac{d^3\boldsymbol{q}_1}{(2\pi)^3} \int \frac{d^3\boldsymbol{q}_2}{(2\pi)^3} B_{hTT}(-\boldsymbol{q}_1, \boldsymbol{k}_j - \boldsymbol{q}_2, -\boldsymbol{k}_j + \boldsymbol{q}_1 + \boldsymbol{q}_2)$$

In agreement with simulated covariance measurement! (Ihle et al. 2018)

GSP & Bernal 2022

Outline

Observations



Bernal and Kovetz 2022

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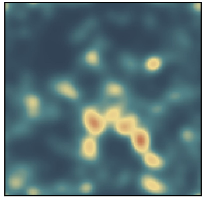

GSP, Kokron, Bernal in prep

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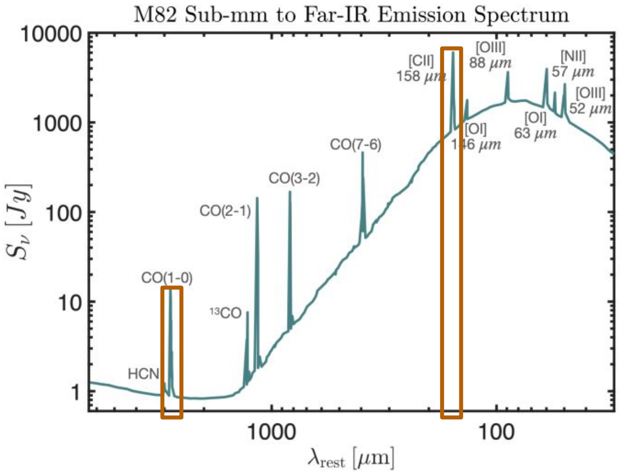
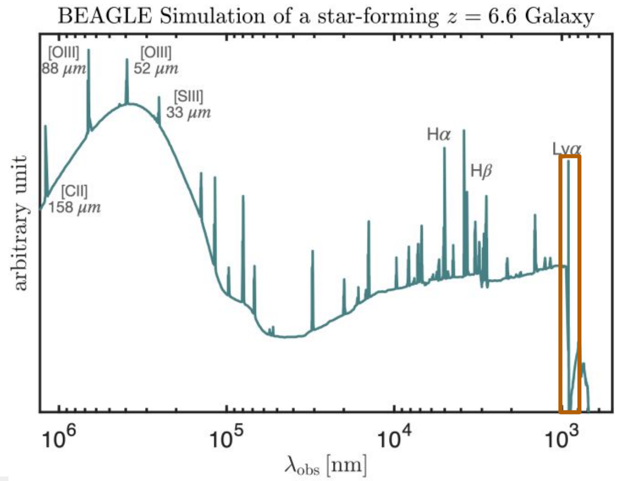
Total brightness

- Spectral line
- Line interlopers
- Continuum emission (correlated foreground)
- Milky Way (uncorrelated foreground)
- Instrument noise
- Other diffuse sources?





*Single galaxy SED as an example, but LIM will capture all integrated sources

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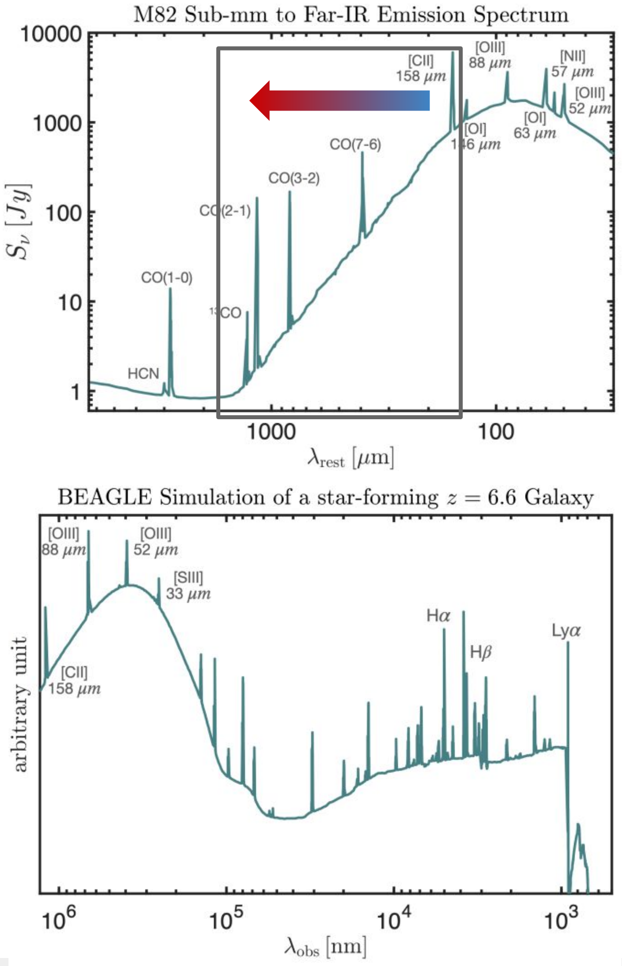

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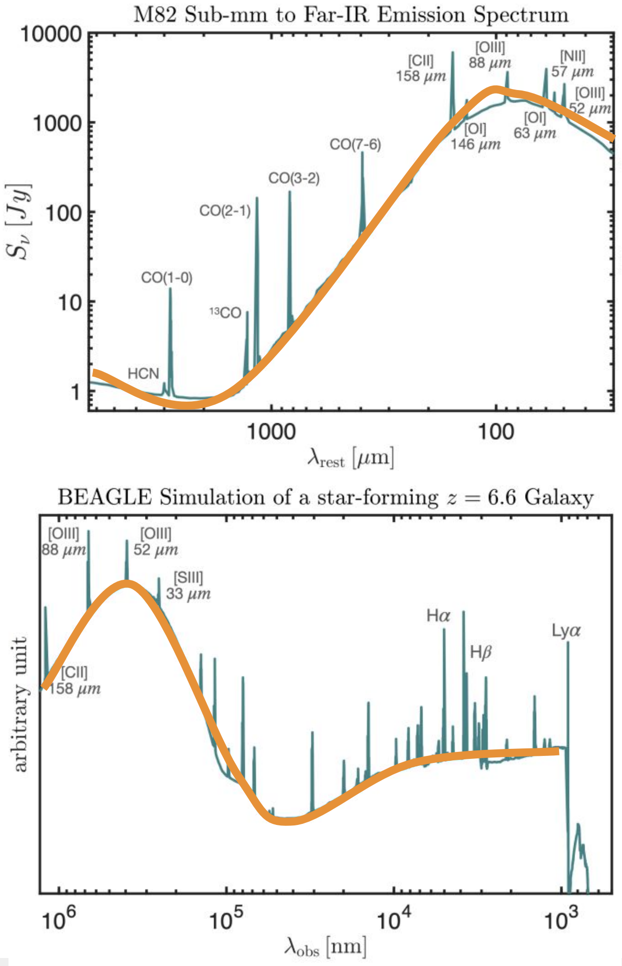

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1. Complementarity in the signal from different lines
2. Cross-correlations can help disentangle an integrated signal

Skyline

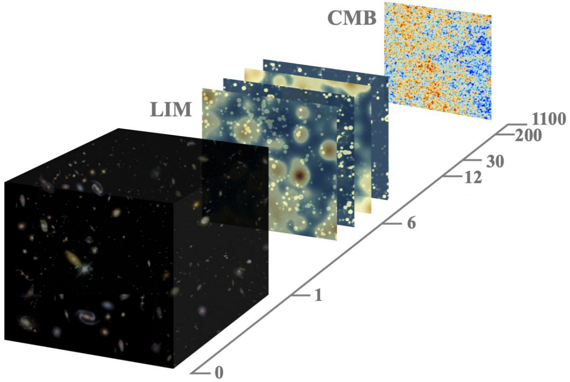
(**GSP**, Kokron, Bernal in prep.)

- Playground to realize realistic LIM mock observations
- First full-sky LIM lightcones from z=0–10, using UniverseMachine as the galaxy formation model
- Modular implementation of any spectral line sourced within halos
- Captures the effect of realistic observational contaminants and limitations
  (e.g., line interlopers, Milky Way foregrounds, continuum emission, instrument noise, limited volume and resolution)

*Please ask for more details about how we do this, if curious!

Galaxies and large-scale structure

LIM



Galaxies

Secondary CMB anisotropies

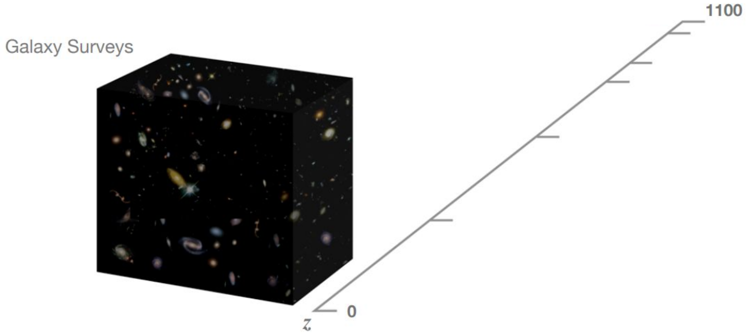
Galaxies and large-scale structure

LIM

Galaxies

Can be individually resolved, measured with spectroscopy/photometry

Many ongoing and future precision experiments: DES, DESI, VRO, Euclid...



Secondary CMB anisotropies

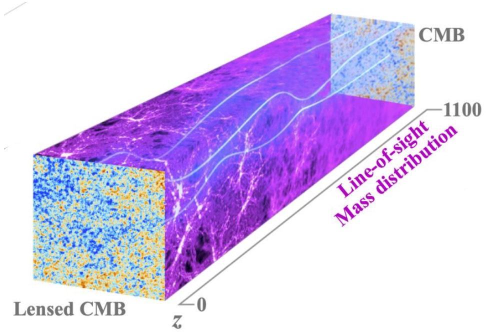
Galaxies and large-scale structure

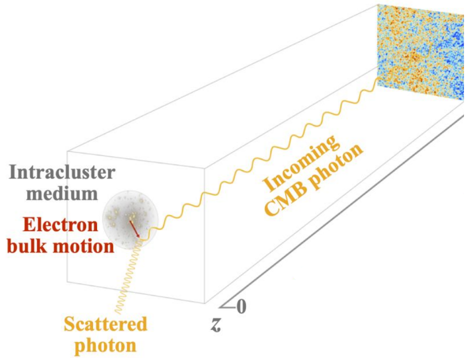
LIM

Galaxies

Secondary CMB anisotropies

Key target of next-generation CMB experiments, precise measurements expected with SO, CMB-S4





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Galaxies and large-scale structure

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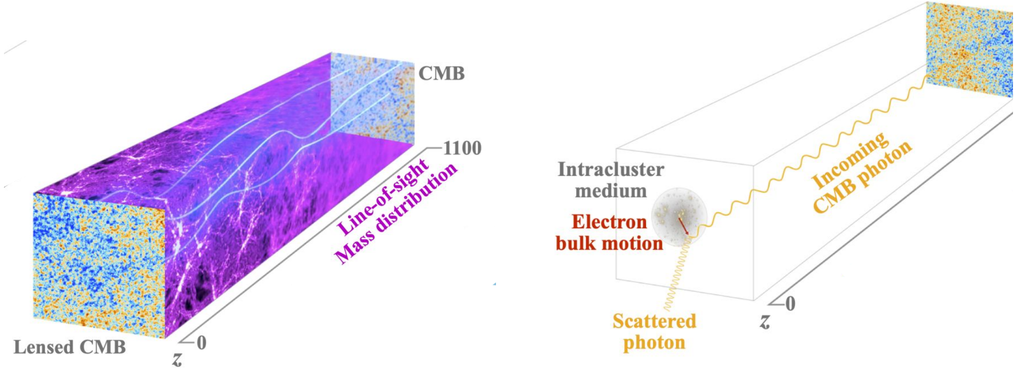


1. Complementarity in the signal from different lines
2. Cross-correlations can help disentangle an integrated signal
3. Complementarity between different tracers of large-scale structure

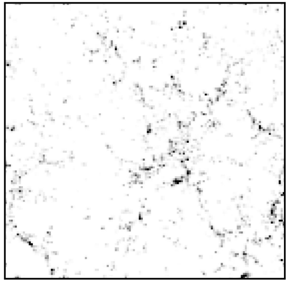
Skyline + MDPL2 Synthetic Skies

(**GSP**, Kokron, Bernal in prep.) (Omori in prep.)

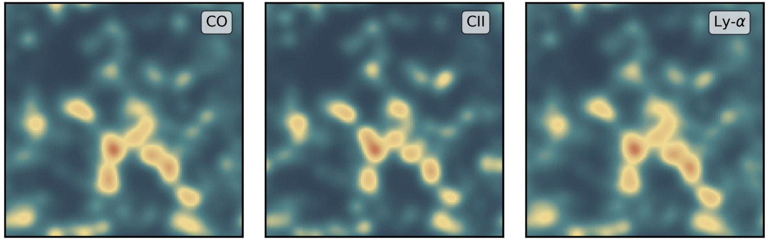
- Playground to realize realistic LIM mock observations
- First full-sky LIM simulation on a lightcone from z=0–10 using UniverseMachine galaxies
- Flexible implementation of any spectral line sourced within halos
- Captures the effect of realistic observational contaminants and limitations (e.g., line interlopers, Milky Way foregrounds, continuum emission, limited volume and resolution)
- Entirely consistent with SynSky maps of CMB secondaries and galaxy shear catalogs
  - CMB lensing, tSZ, kSZ, CIB, radio galaxies
  - Galaxy shear and convergence

Skyline + MDPL2 Synthetic Skies

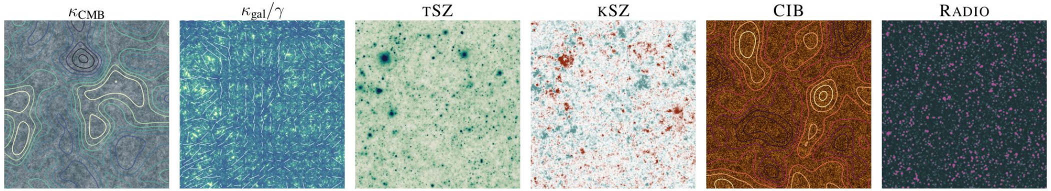
(**GSP**, Kokron, Bernal in prep.) (Omori in prep.)



Halos and galaxies



Gas properties



Extragalactic CMB foregrounds
and
galaxy weak lensing

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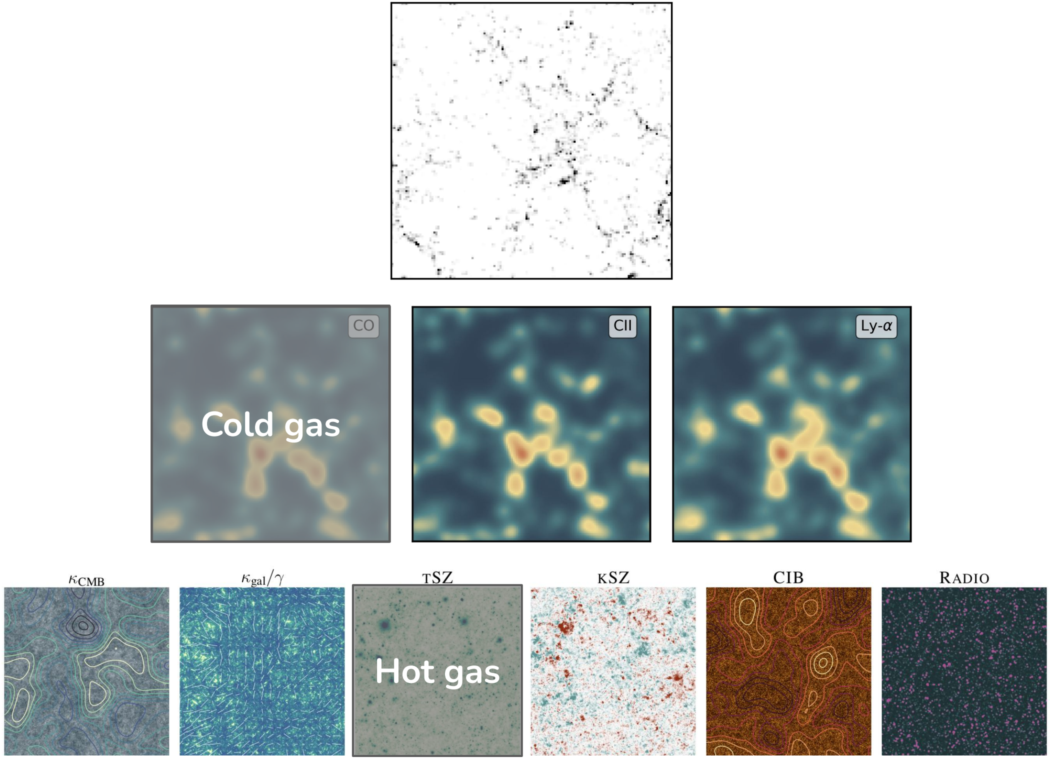
(**GSP**, Kokron, Bernal in prep.)

(Omori in prep.)



Halos and galaxies

Gas properties

Extragalactic CMB foregrounds and galaxy weak lensing

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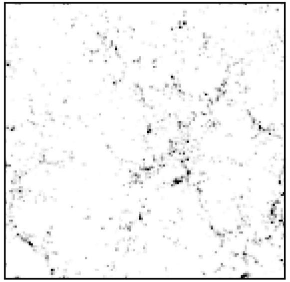

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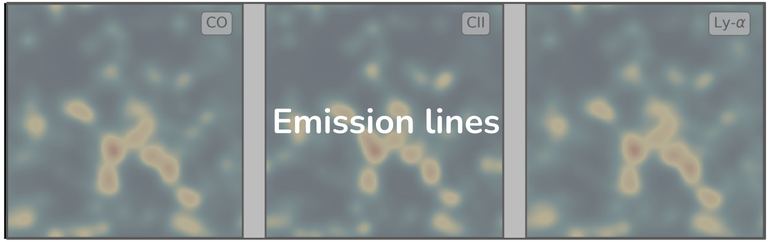

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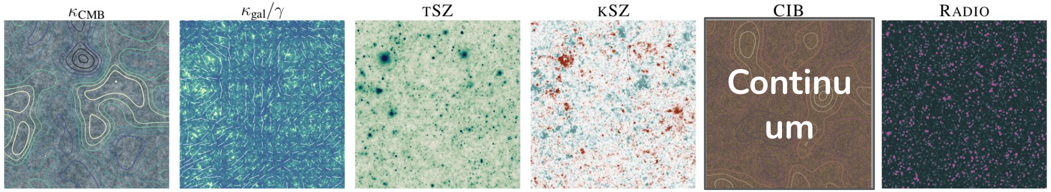

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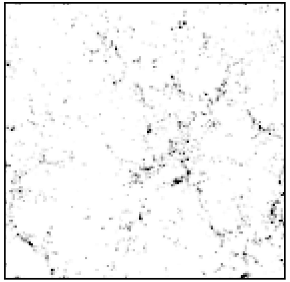
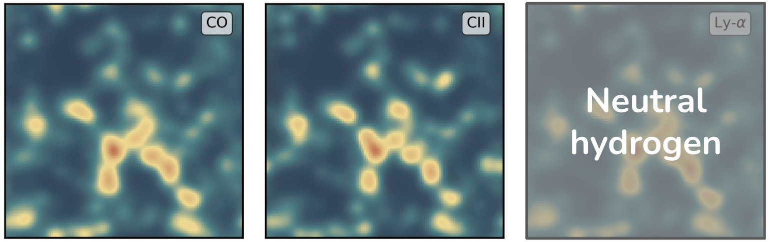


Halos and galaxies



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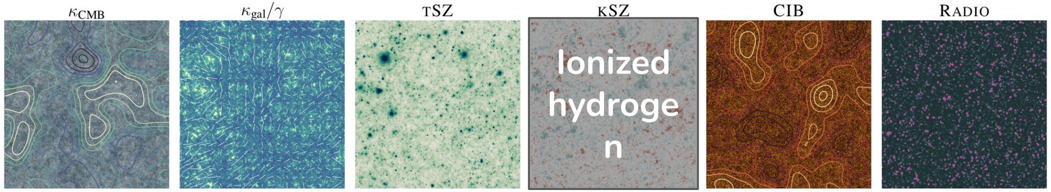


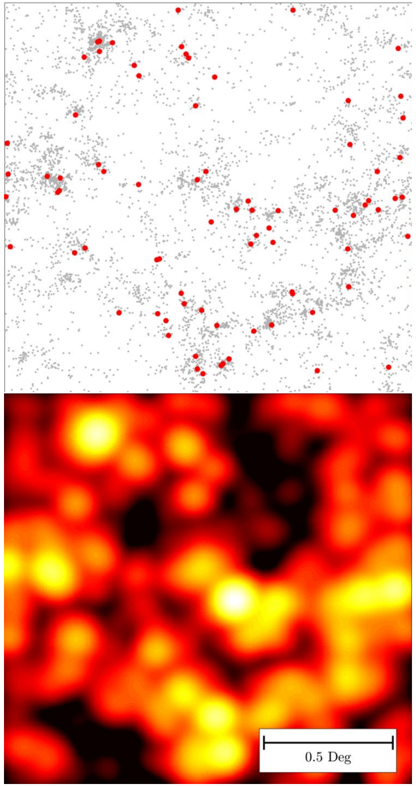
Extragalactic CMB foregrounds and galaxy weak lensing

Conclusions

- Measurements of the cosmic background in the sub-mm to UV range offer a distinct opportunity to probe radiative processes across the Universe
    - Capture diffuse, unresolved and/or high redshift sources
- Many synergies between LIM and other tracers of large-scale structure still to be explored
- `Skyline` will be an excellent tool to realize multi-tracer mock observations that include LIM!

*I also think about pulsar timing arrays and gravitational waves!

Galaxy/LIM comparison



2.5 deg^2

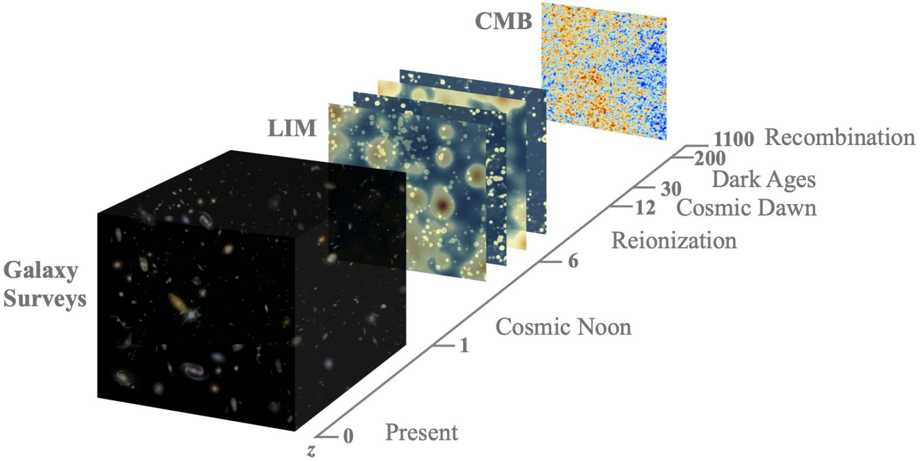
Very Large Array (VLA)

- advanced radio telescope with 27 dishes
- 4500 hours
- 1% of the total number of CO-emitting galaxies

CO intensity mapping instrument (COMAP)

- Pathfinder single-dish instrument
- 1500h
- Intensity fluctuations sensitive to emission throughout the field

Line-intensity mapping

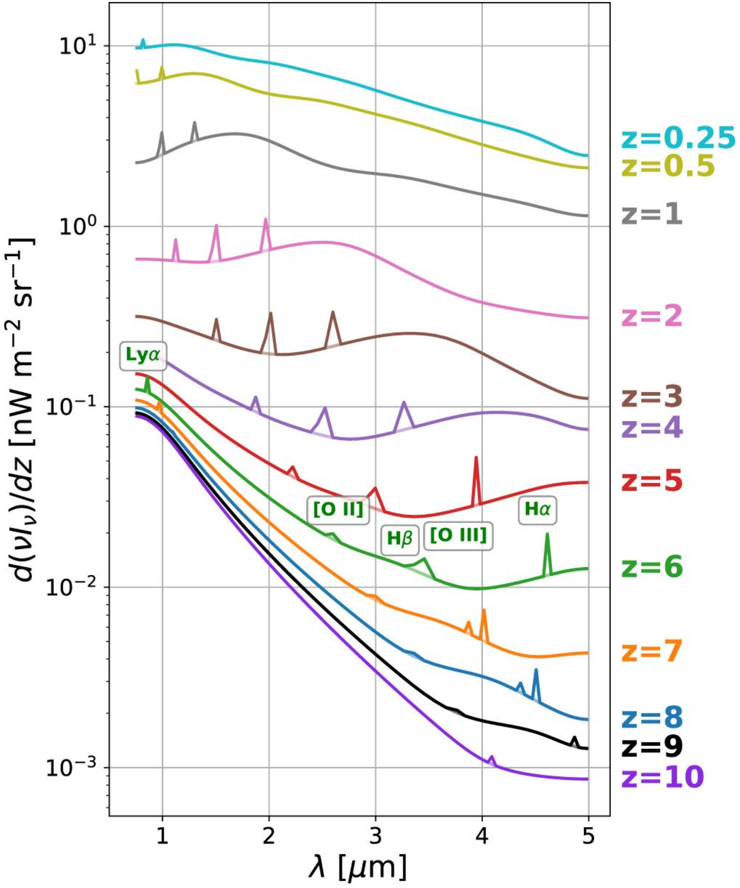


Bernal and Kovetz 2022

- Measures intensity fluctuations of atomic or molecular line transitions
  - Traces gas and the matter distribution
- Integrated signal from all sources
  - May include diffuse, unresolved sources
- Can map wide redshift range

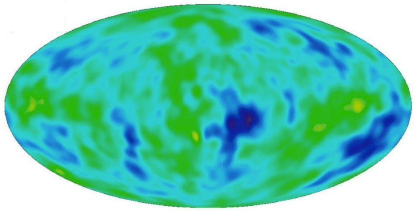
Total brightness

- Spectral line
- Line interlopers
- Continuum emission (correlated foreground)
- Milky Way (uncorrelated foreground)
- Instrument noise
- Other things?

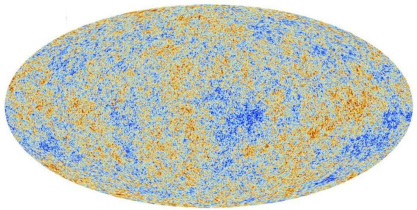


Cheng and Chang 2022

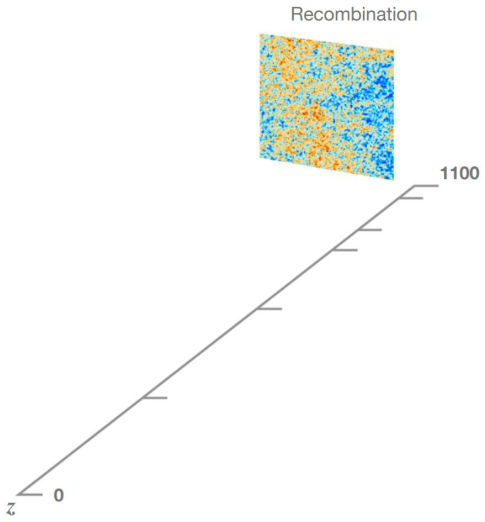
Cosmic Microwave Background (CMB)



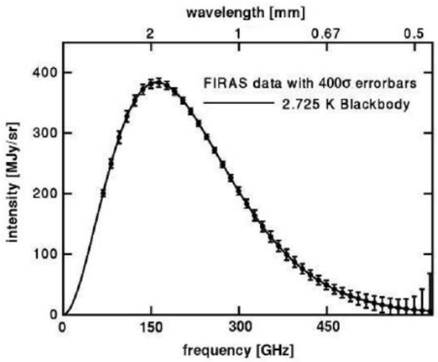
COBE/FIRAS



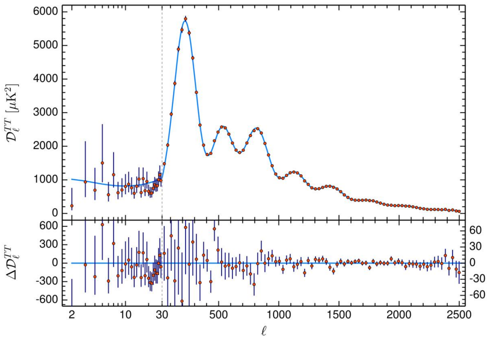
Planck



Absolute Intensity

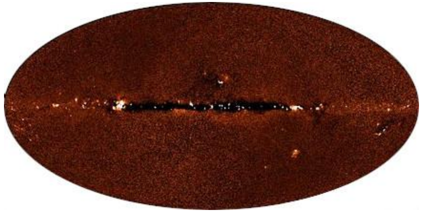


Intensity Fluctuations

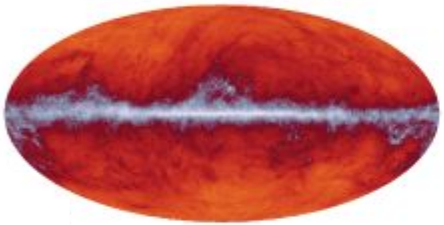


• gsatopo1@jhu.edu • Gabriela Sato-Polito • Johns Hopkins University •

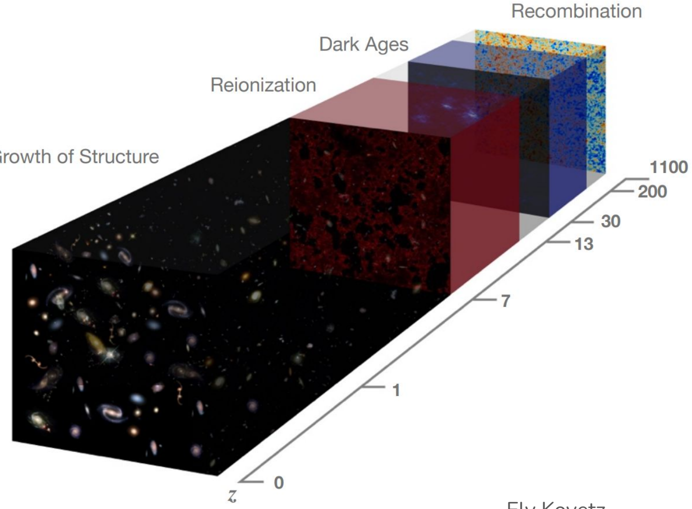
Cosmic Optical/Infrared Background (COB/CIB)



COBE/DIRBE

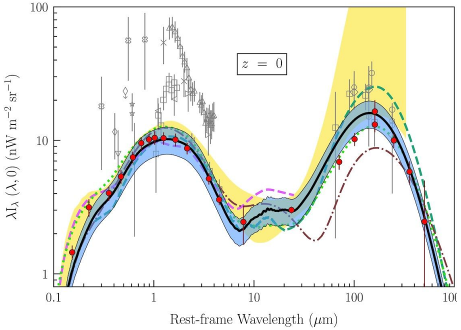


Planck



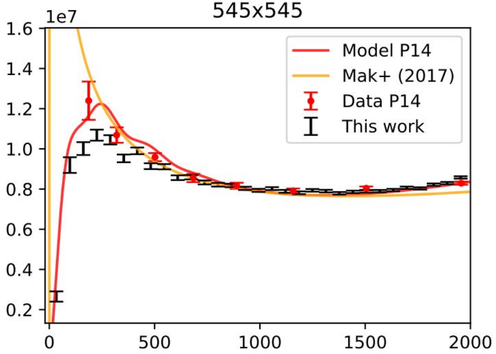
Ely Kovetz

Absolute Intensity



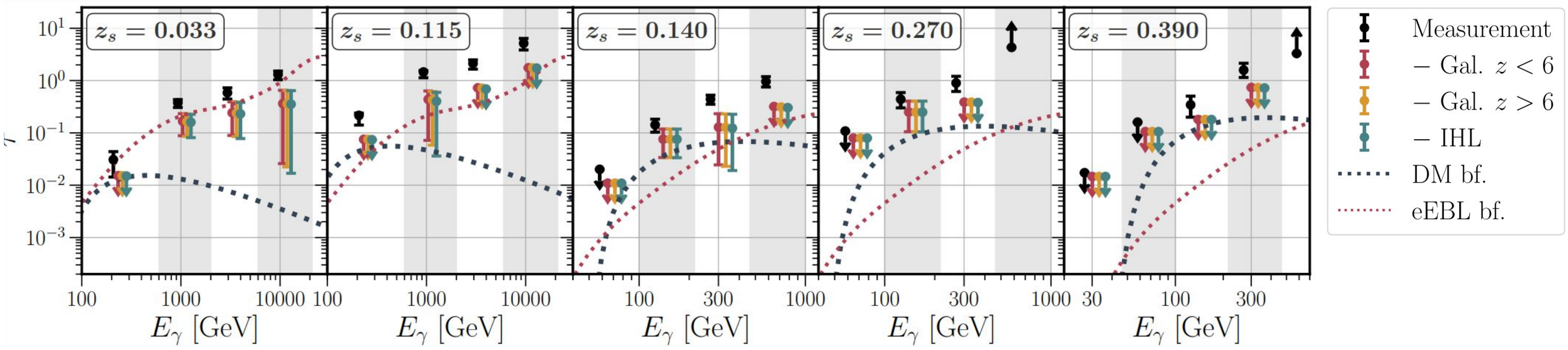
Saldana-Lopez et al. 2021

Intensity Fluctuations



Lenz et al. 2019

EBL budget vs measurement



Compare DM fit with a boost to the standard component from galaxies (z<6)

ALP contribution to optical depth: 2.1σ
Galaxy boost to optical depth: 2.7σ

Best fit: