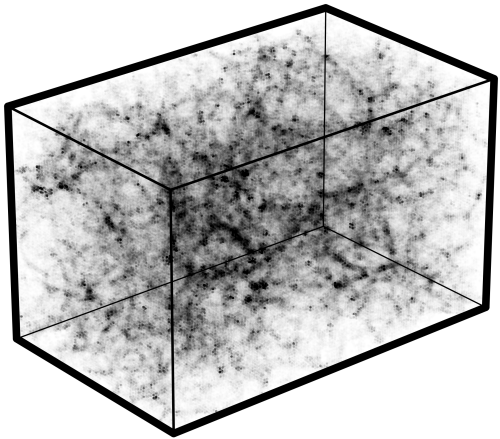
Probing the faint universe with line intensity mapping and CMB lensing

Delon Shen

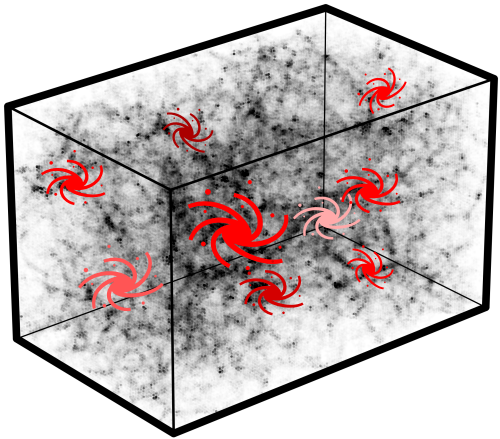
KIPAC Tea — August 12, 2025

arxiv:2507.17752 with Nick Kokron and Manu Schaan

Dark Matter



Galaxies trace **Dark Matter**



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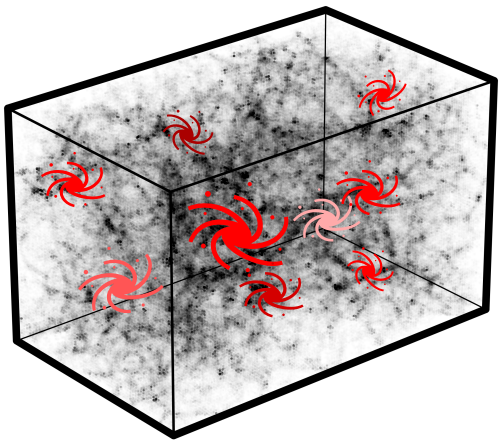
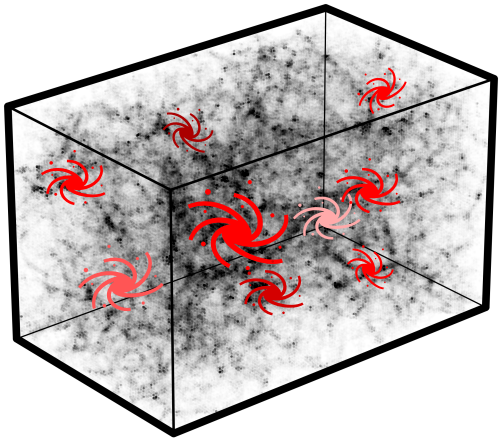


~~Faint Galaxies~~

(Hard to find but informative)

Galaxies trace **Dark Matter**



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~~High-redshift~~
(Not many galaxies have formed yet)

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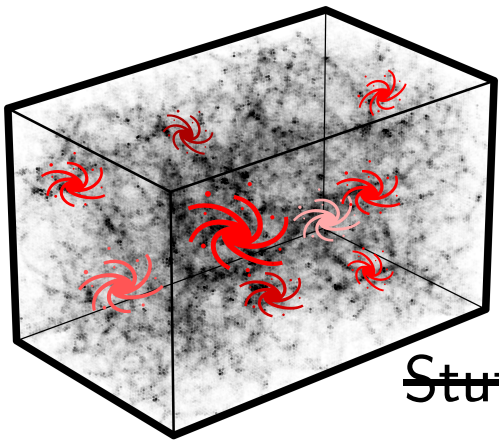
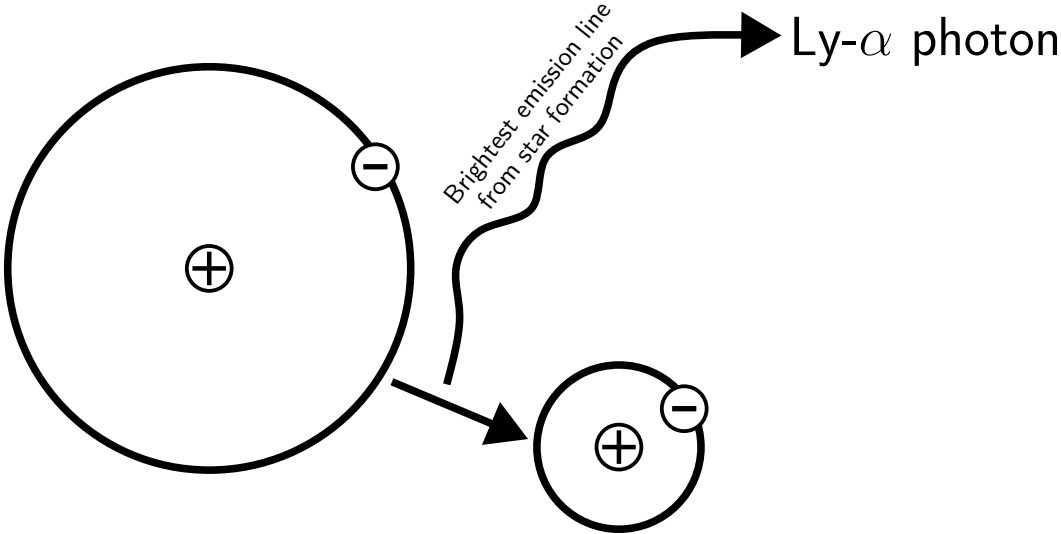


~~Faint Galaxies~~
(Hard to find but informative)

~~High-redshift~~
(Not many galaxies have formed yet)

~~Stuff outside of galaxies~~
(Where most of the matter resides)

Another way to map the universe?



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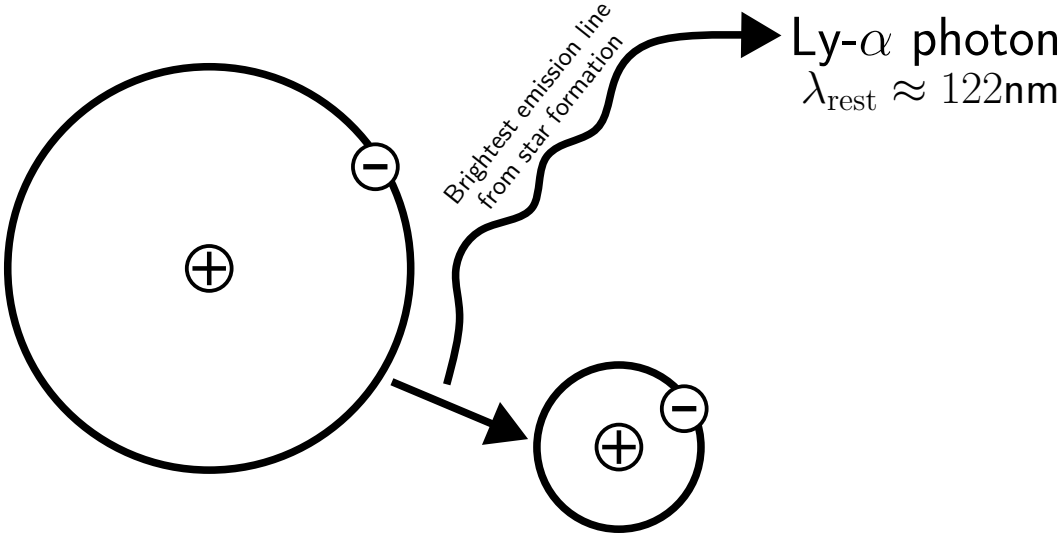

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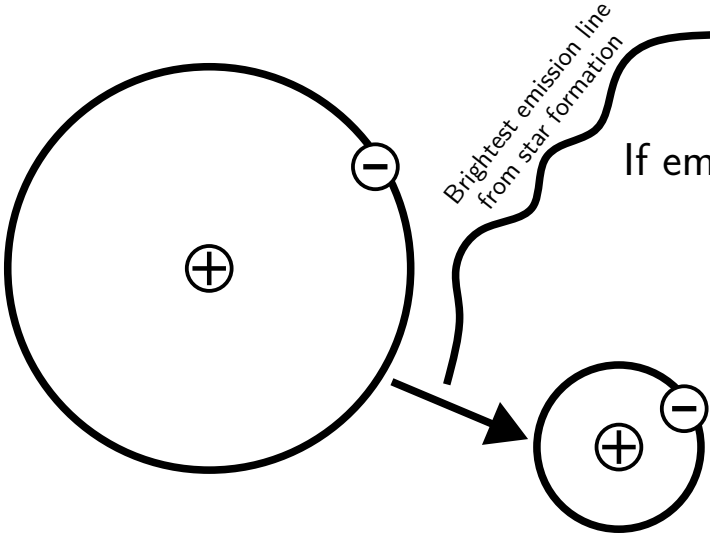


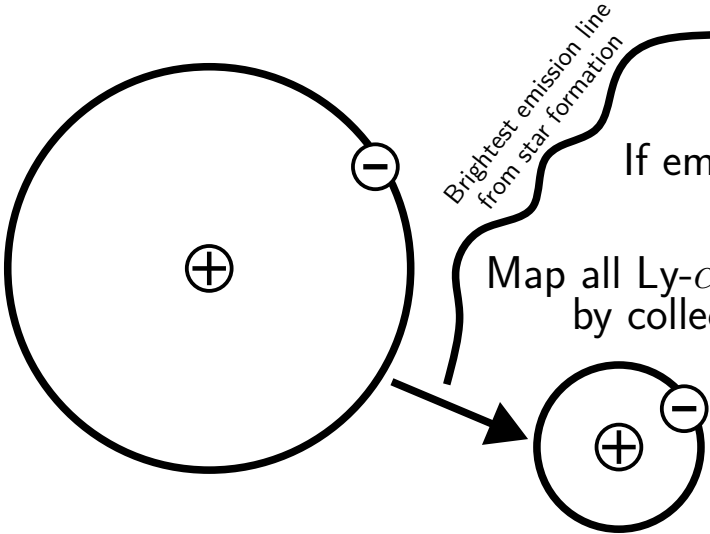
Ly-α photon

$\lambda_{\text{rest}} \approx 122\text{nm}$

If emitted at $z = 1$ then

$\lambda_{\text{obs}} \approx 244\text{nm}$

Another way to map the universe?



Ly-α photon
$\lambda_{\text{rest}} \approx 122$nm

If emitted at $z = 1$ then
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Map all Ly-α emission at $z = 1$
by collecting all 244nm γ's

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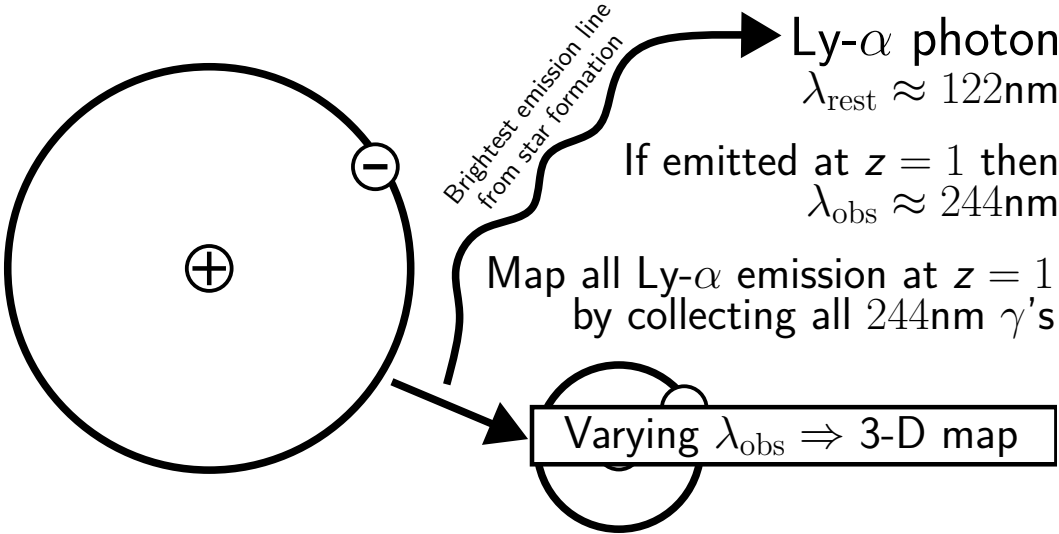
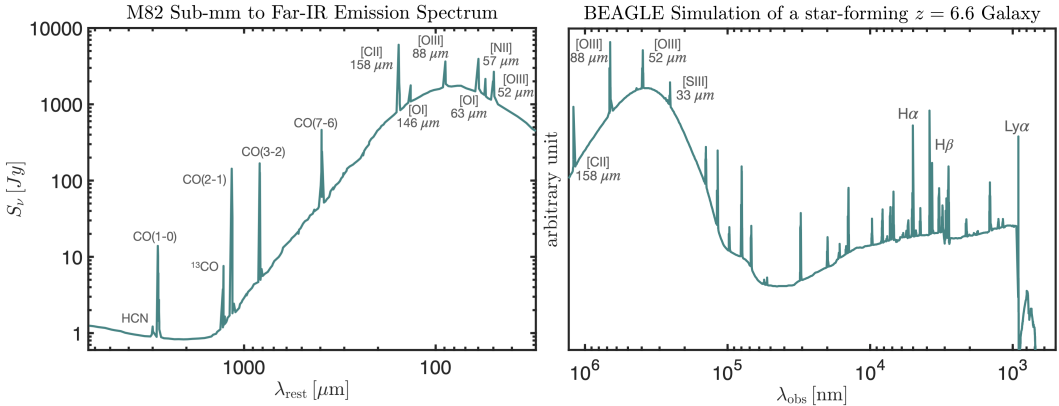
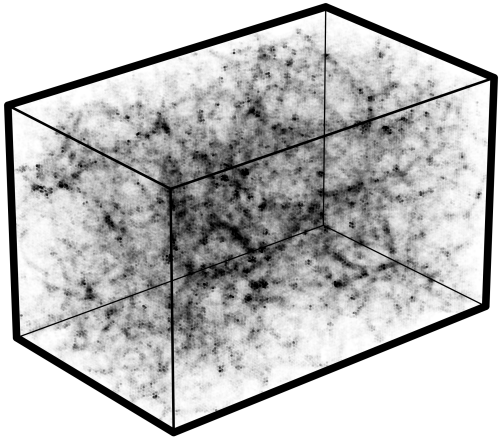


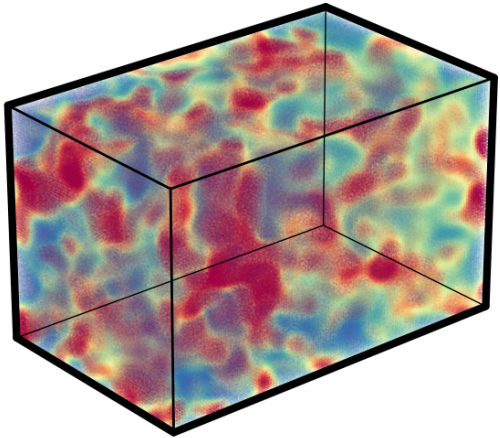
Many lines to choose from



Dark Matter



Line Intensity Map traces Dark Matter



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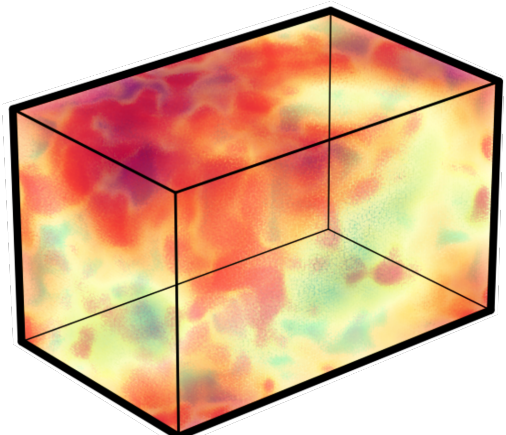
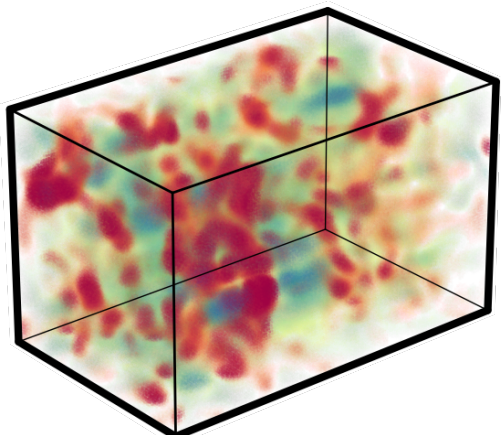


Contaminated by Galactic foregrounds

Spectrally smooth and bright free-free and synchrotron emission

Line Intensity Map traces Dark Matter



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Spectrally smooth and bright free-free and synchrotron emission

↓

(High-pass) filter out smoothly varying modes

Removes Galactic foregrounds and some cosmological line emission

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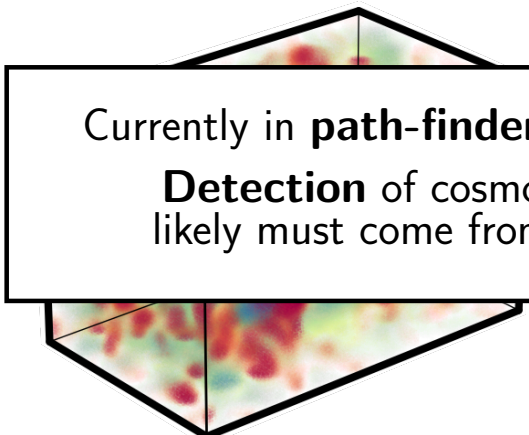


Contaminated by Galactic foregrounds

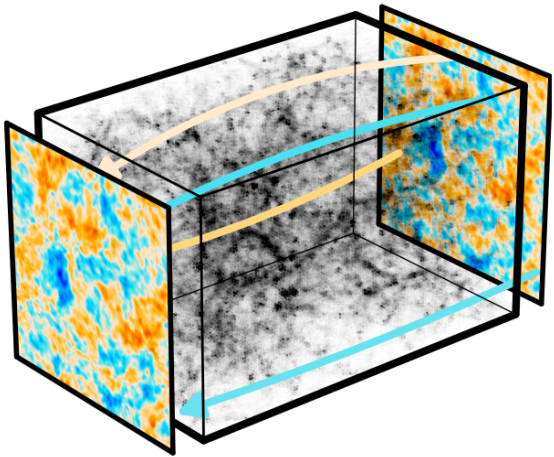
Currently in **path-finder** era of LIM experiments

Detection of cosmological line emission
likely must come from **cross-correlation**

(High-pass) filter out smoothly varying modes

Removes Galactic foregrounds and some cosmological line emission

CMB photons lensed by **Dark Matter**



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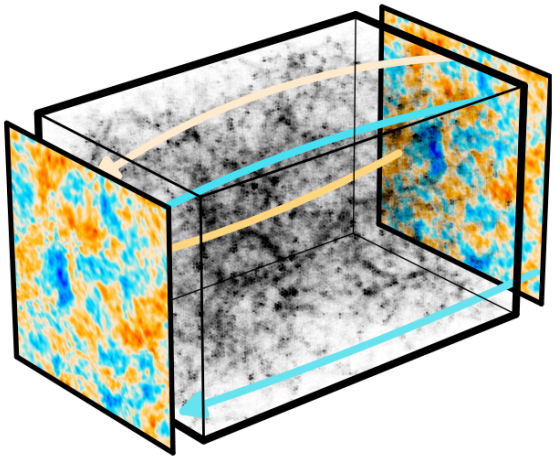
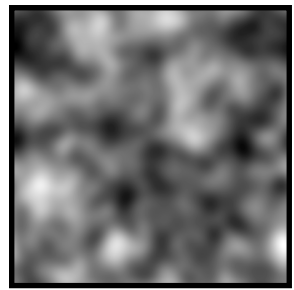
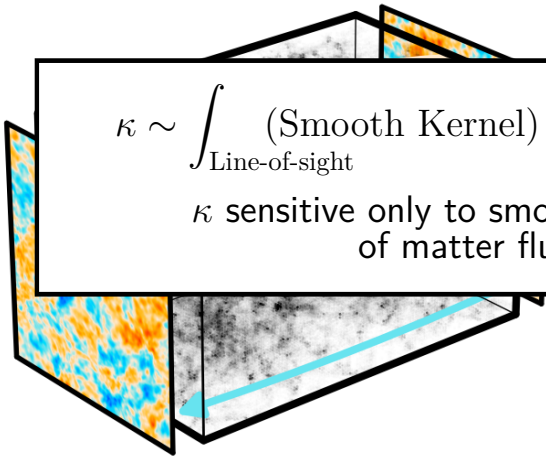




Reconstruct projection of matter fluctuations κ

CMB photons lensed by Dark Matter



$$\kappa \sim \int_{\text{Line-of-sight}} (\text{Smooth Kernel}) \times (\text{Matter Fluctuations})$$

κ sensitive only to smoothly varying modes of matter fluctuations

Reconstruct projection of matter fluctuations κ

LIM . . . . . **removes** smoothly varying modes

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CMB lensing . . . **only** smoothly varying modes

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CMB lensing . . . **only** smoothly varying modes

Symmetries of the universe make this
lack of overlap potentially **problematic**

Symmetries of background universe

Isotropic and Homogeneous

$$\rho_m(\boldsymbol{x}) = \overline{\rho}_m$$

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Symmetries of fluctuating universe

Statistically Isotropic and Homogeneous

$$\rho_m(\boldsymbol{x}) = \overline{\rho}_m(1 + \delta_m(\boldsymbol{x}))$$ (statistical field)

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Short-wavelength and **Long**-wavelength matter fluctuations are **uncorrelated**

Line Intesity Mapping
Loses *long-wavelength* fluctuations
because of Galactic foregrounds

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Loses *long-wavelength* fluctuations
because of Galactic foregrounds

CMB lensing
Loses *short-wavelength* fluctuations
because of the projection kernel

Line Intesity Ma

Loses *long*

s

Claim by previous works:
Direct **correlation** of
LIM with CMB lensing
is **hopeless**

fluctuations

of the projection kernel

Line Intesity Ma

Loses *long*

s

fluctuations

of the projection kernel

Claim by previous works:
Direct **correlation** of
LIM with **Any projected field**
is **hopeless**

Line Intesity Ma

Loses *long*

Claim by us

Direct **correlation** of
LIM with **Any projected field**
is **hopeless**

both fine and promising

of the projection kernel

Short and long wavelength **matter fluctuations** are uncorrelated

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Remove long-wavelength fluctuations from LIM

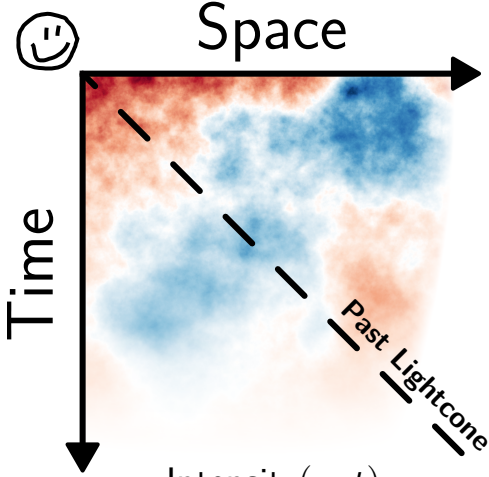
Remove long-wavelength matter fluctuations?

Short and long wavelength **matter fluctuations** are uncorrelated

Remove long-wavelength fluctuations from LIM

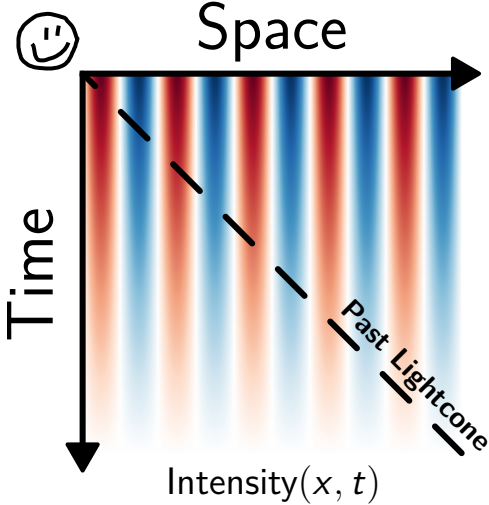
Remove long-wavelength matter fluctuations?

No, observations restricted to past lightcone



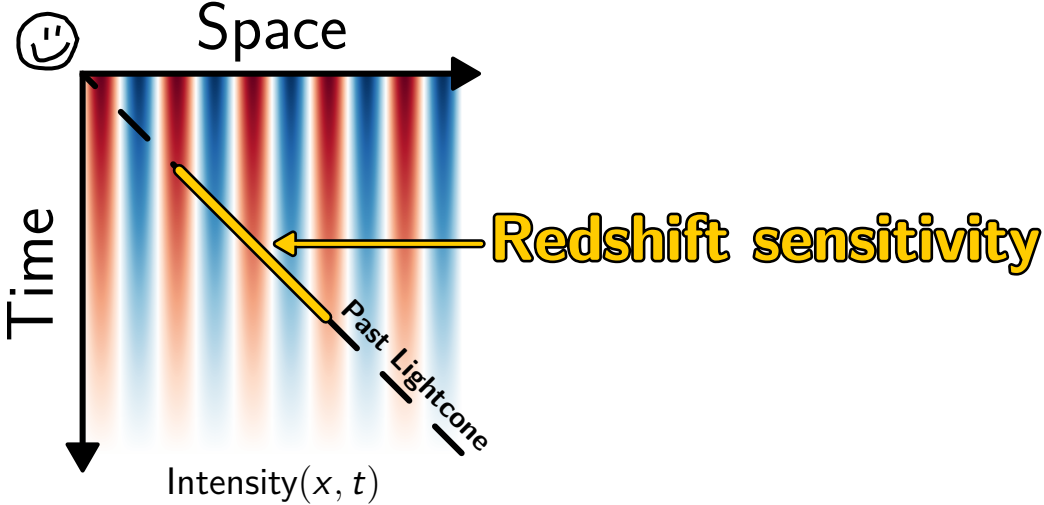
Intensity(x, t)

$\sim$ Line-emission $\times$ Matter Fluctuations



$\sim$ Line-emission $\times$ Matter Fluctuations

$\sim t \times \sin(x)$



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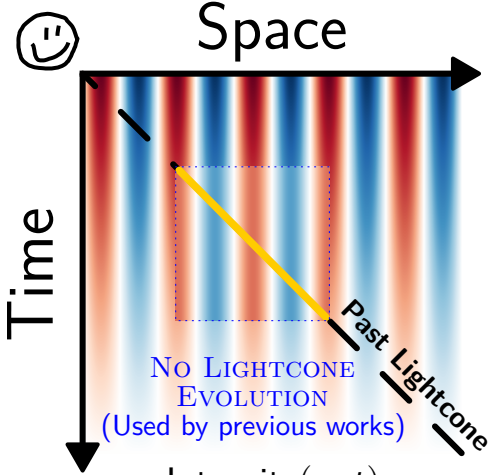
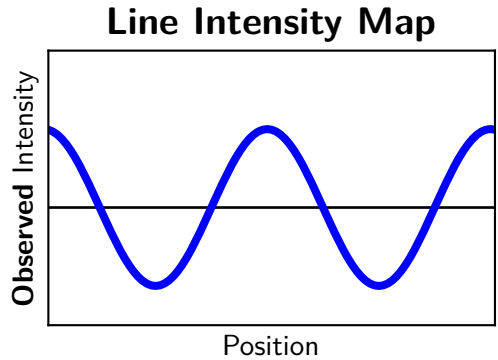
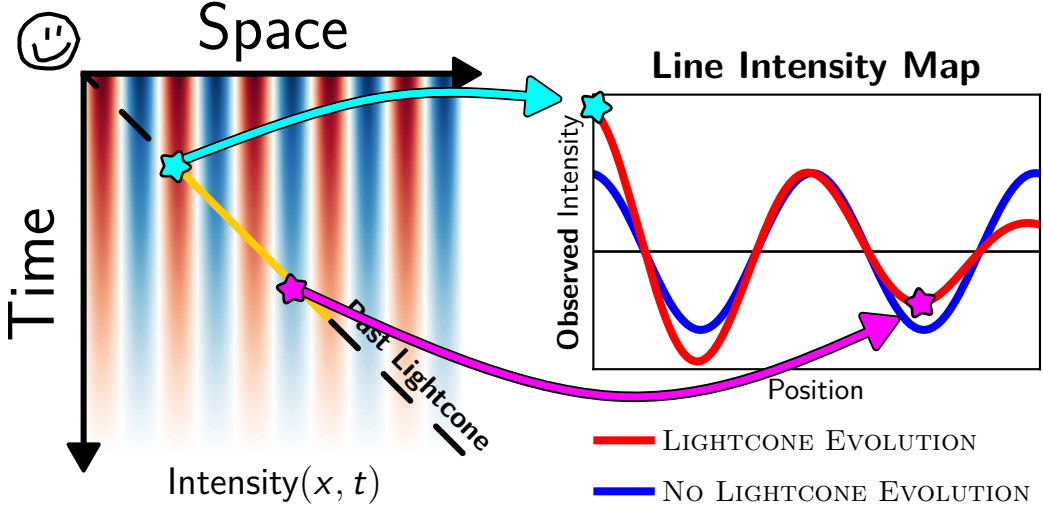


$\sim$ Line-emission $\times$ Matter Fluctuations

$\sim t \times \sin(x) \xrightarrow{\text{No Lightcone Evol.}} \bar{t} \sin(x)$





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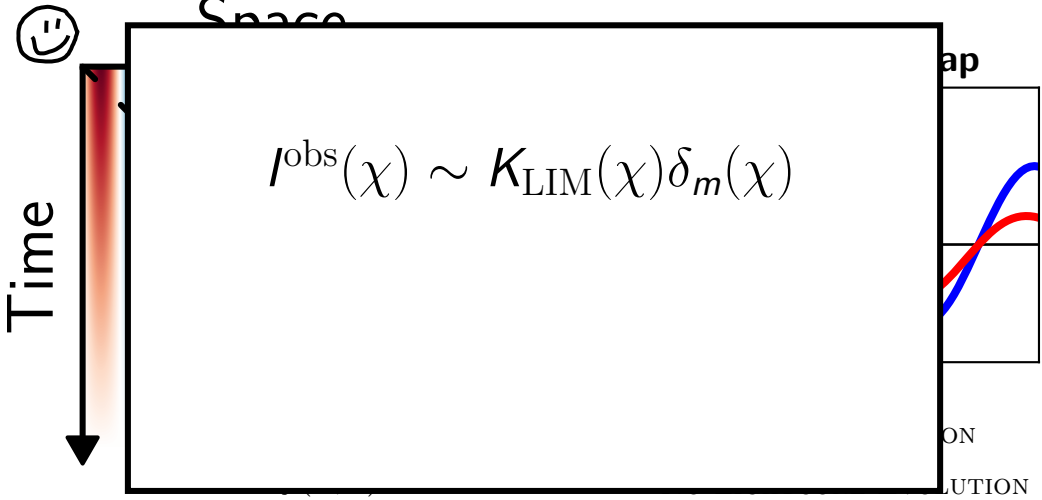

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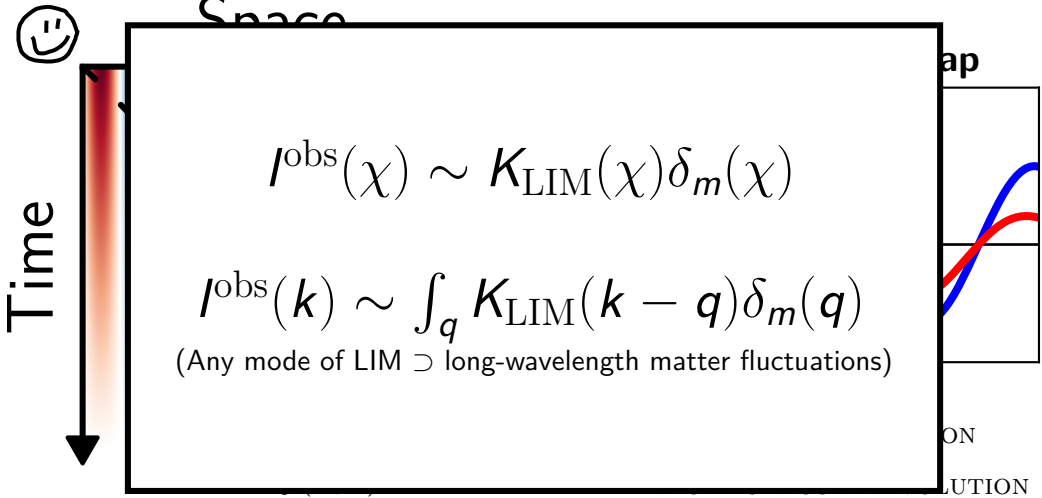

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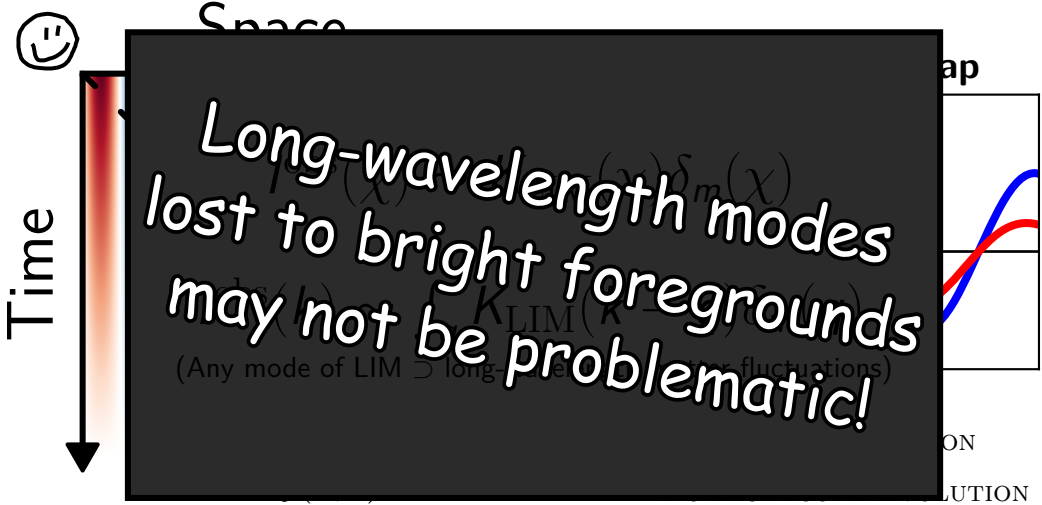

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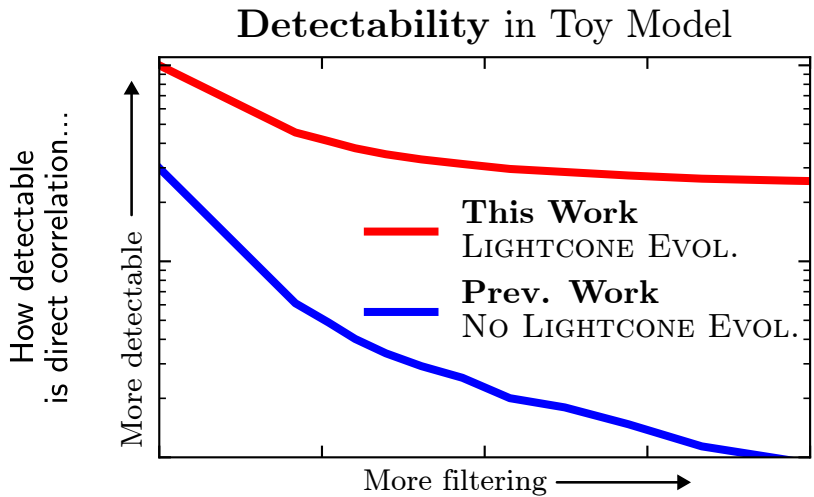
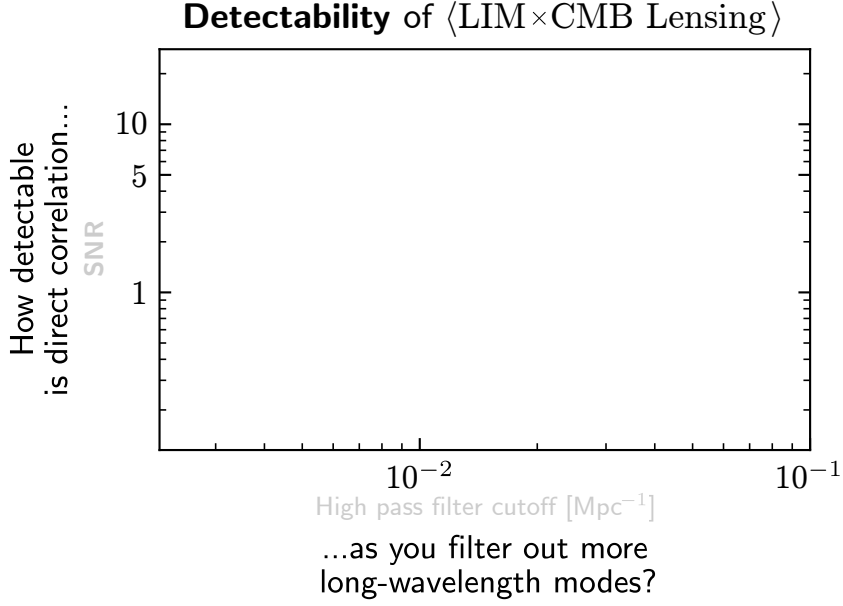
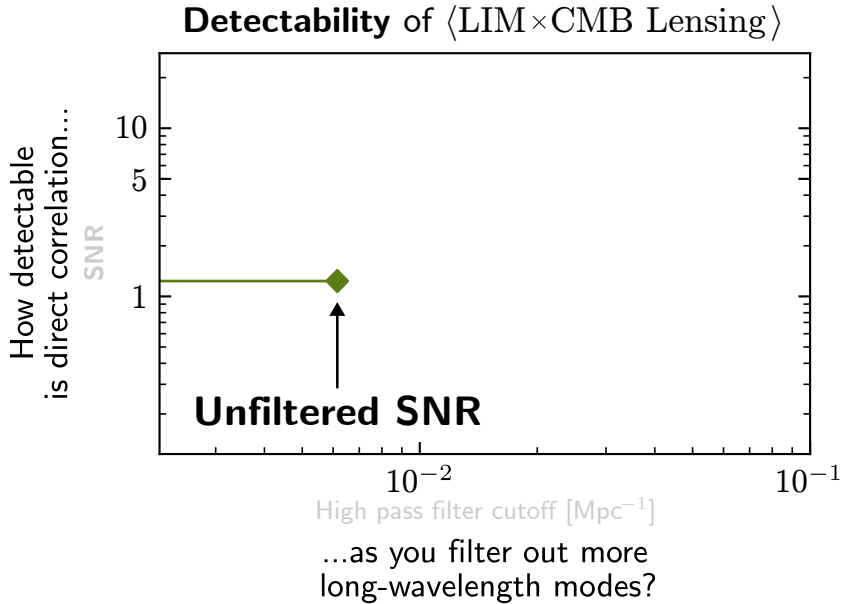
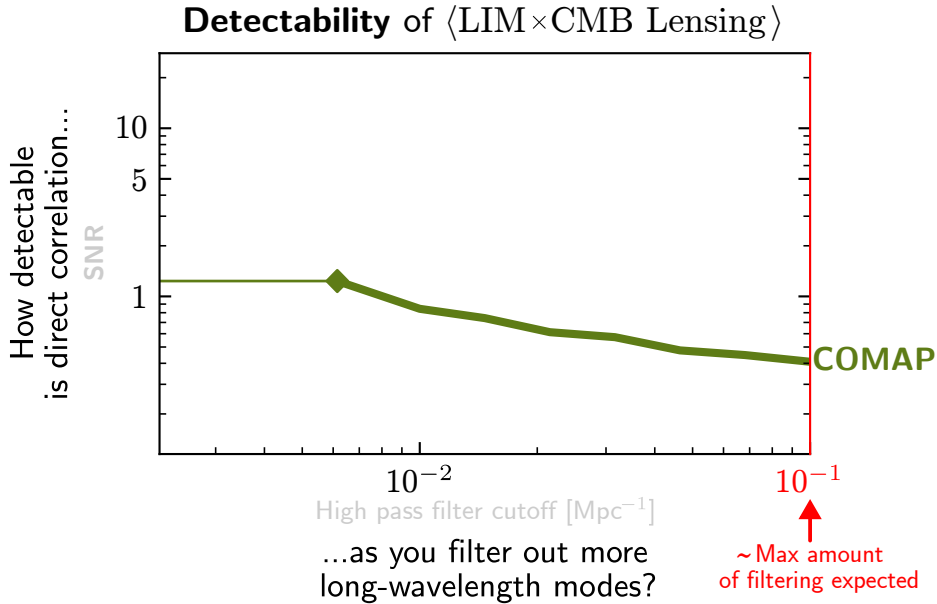
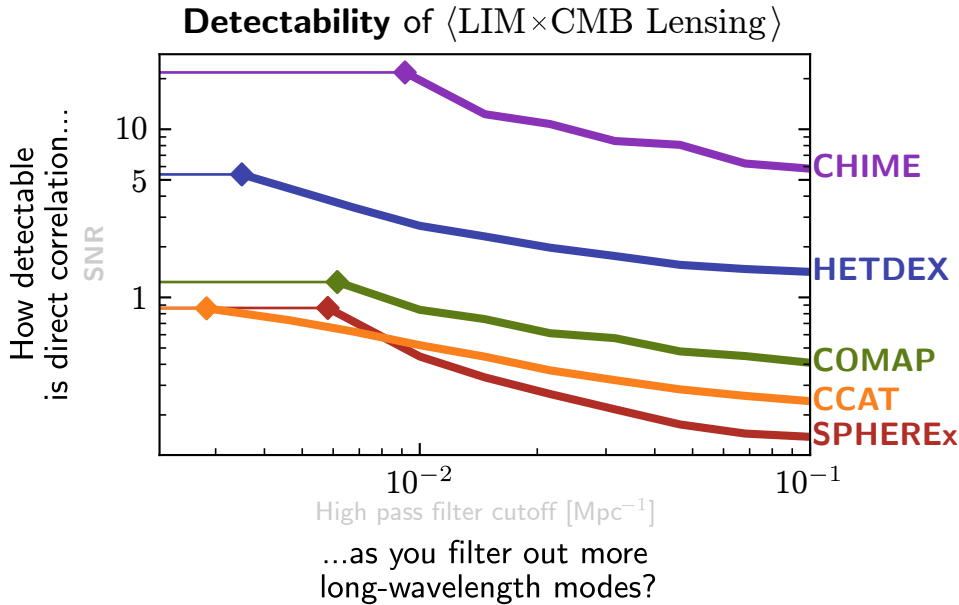

Detectability in Toy Model
How detectable is direct correlation...
More detectable
More filtering
This Work
Lightcone Evol.
Prev. Work
No Lightcone Evol.
...as you filter out more long-wavelength modes?

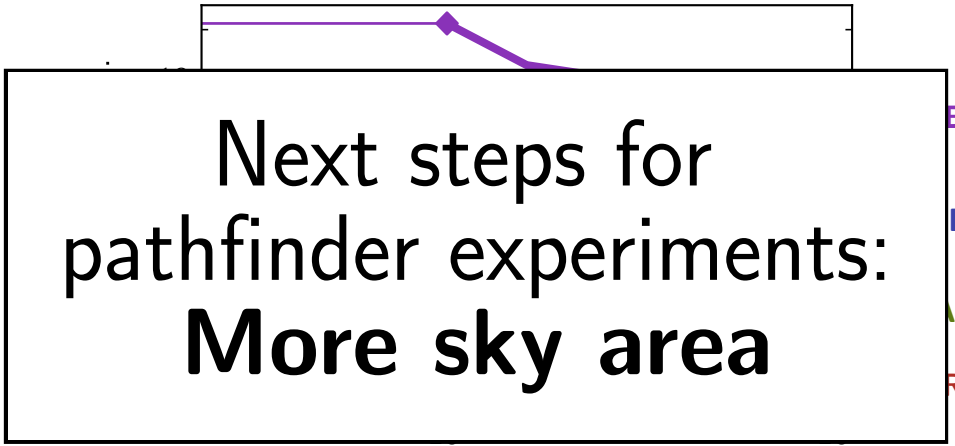

Detectability of ⟨LIM×CMB Lensing⟩
How detectable is direct correlation...
SNR
10
5
1
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
...as you filter out more long-wavelength modes?


Detectability of ⟨LIM×CMB Lensing⟩
How detectable is direct correlation...
SNR
10
5
1
Unfiltered SNR
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
...as you filter out more long-wavelength modes?


Detectability of ⟨LIM×CMB Lensing⟩
How detectable is direct correlation...
SNR
10
5
1
COMAP
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
...as you filter out more long-wavelength modes?
~Max amount of filtering expected

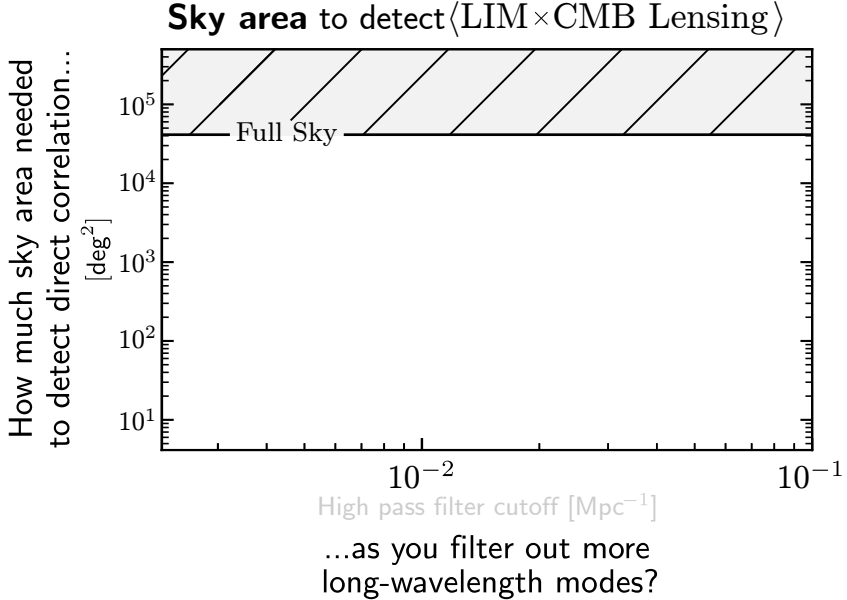

Detectability of ⟨LIM×CMB Lensing⟩
How detectable is direct correlation...
SNR
10
5
1
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
CHIME
HETDEX
COMAP
CCAT
SPHEREx
...as you filter out more long-wavelength modes?

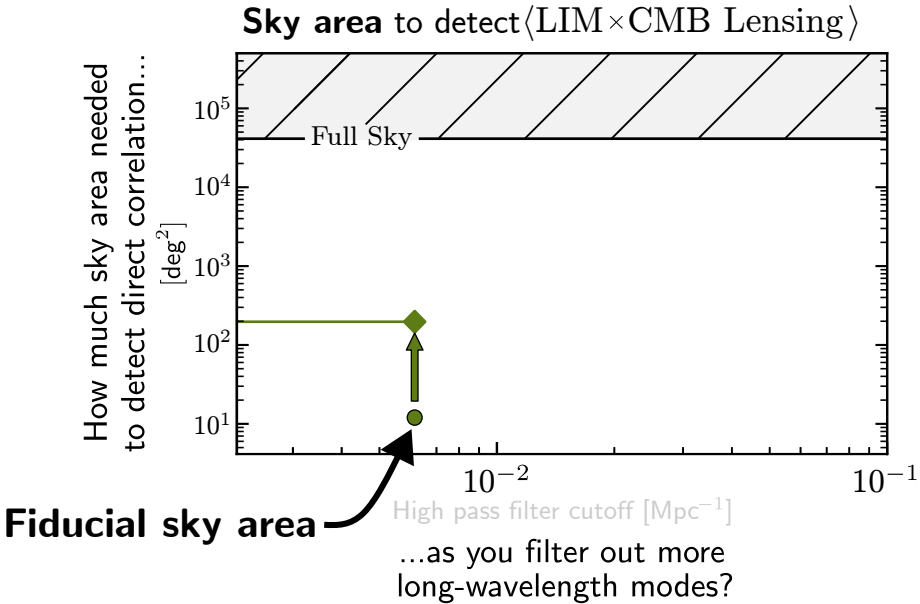
Detectability of $\langle \mathrm{LIM} \times \mathrm{CMB\ Lensing} \rangle$

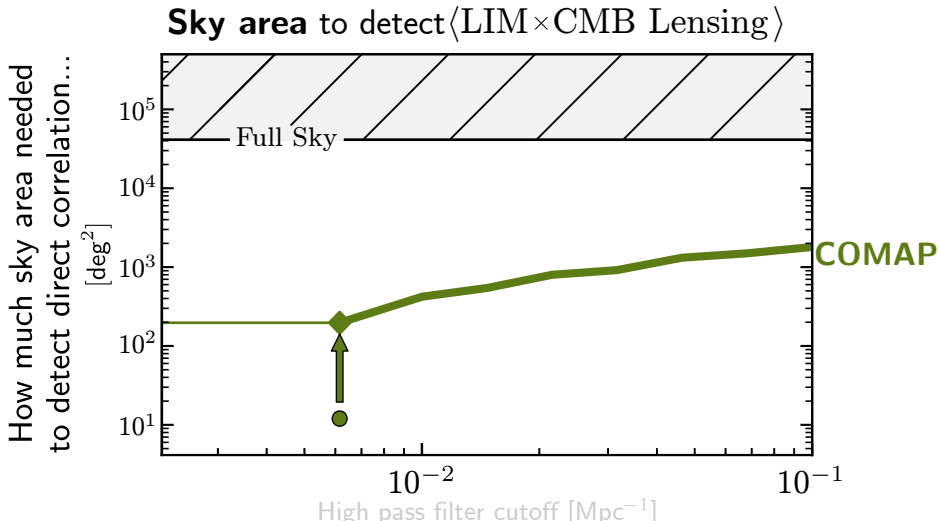


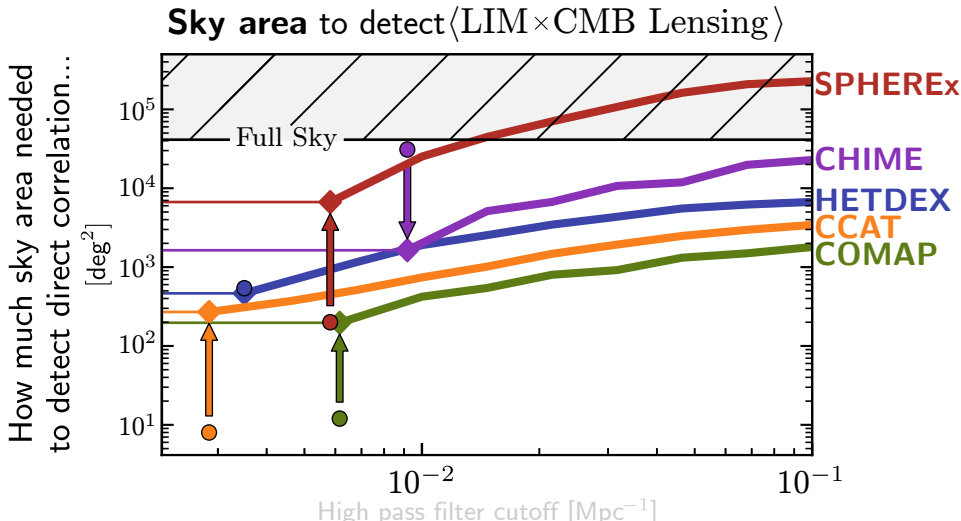
Next steps for pathfinder experiments: **More sky area**

...as you filter out more long-wavelength modes?


Sky area to detect ⟨LIM × CMB Lensing⟩
How much sky area needed to detect direct correlation... [deg^2]
10^5
10^4
10^3
10^2
10^1
Full Sky
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
...as you filter out more long-wavelength modes?


Sky area to detect ⟨LIM × CMB Lensing⟩
How much sky area needed to detect direct correlation...
[deg^2]
10^5
10^4
10^3
10^2
10^1
Full Sky
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
Fiducial sky area
...as you filter out more long-wavelength modes?


Sky area to detect ⟨LIM × CMB Lensing⟩
How much sky area needed to detect direct correlation...
[deg^2]
Full Sky
COMAP
10^5
10^4
10^3
10^2
10^1
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
...as you filter out more long-wavelength modes?


Sky area to detect ⟨LIM × CMB Lensing⟩
How much sky area needed to detect direct correlation...
[deg^2]
Full Sky
10^5
10^4
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10^2
10^1
10^{-2}
10^{-1}
High pass filter cutoff [Mpc^{-1}]
SPHEREx
CHIME
HETDEX
CCAT
COMAP
...as you filter out more long-wavelength modes?

Conclusion

1. Evolution along the lightcone enables LIM to be directly correlated with CMB lensing despite bright foregrounds.
   - ◇ We predict this direct correlation will be precisely measured by future LIM experiments like wider-sky versions of COMAP, CCAT, and HETDEX.
   - ◇ We also infer, based on conservative calculations for CHIME, that future 21cm experiments will also be able to precisely measure this direct correlation.
2. More generally, bright foregrounds do not kill

$$\langle \text{LIM} \times \textbf{[your favorite projected field]} \rangle,$$

reviving a lot of LIM science previously assumed hopeless.

Extra

We can estimate lensing potential since
lensing breaks symmetry of CMB

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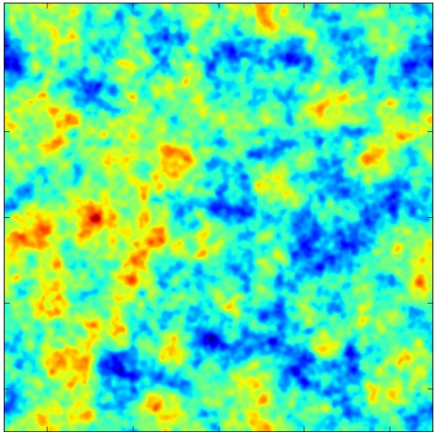
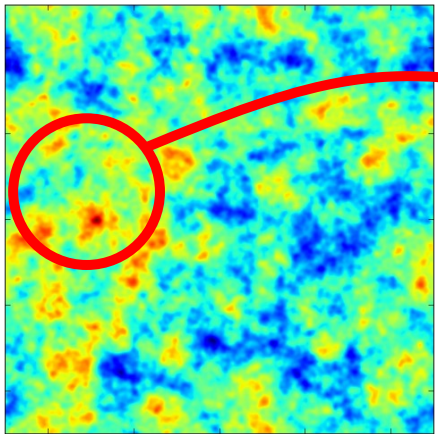
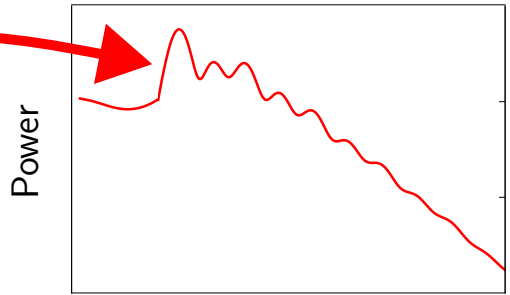


Unlensed CMB: **Statistically Homogeneous**

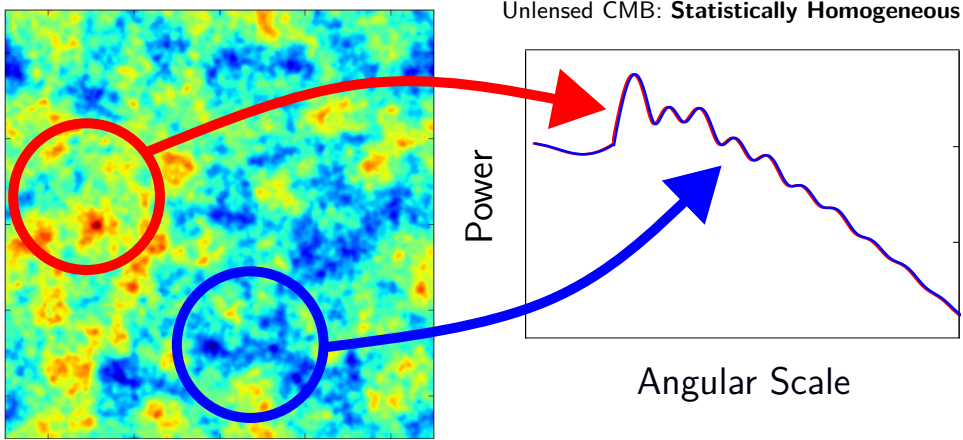
We can estimate lensing potential since
lensing breaks symmetry of CMB



Unlensed CMB: **Statistically Homogeneous**



We can estimate lensing potential since
lensing breaks symmetry of CMB



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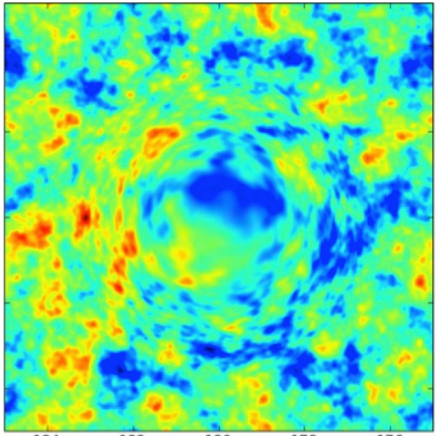
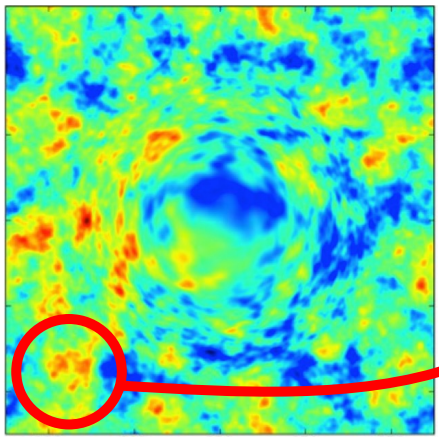
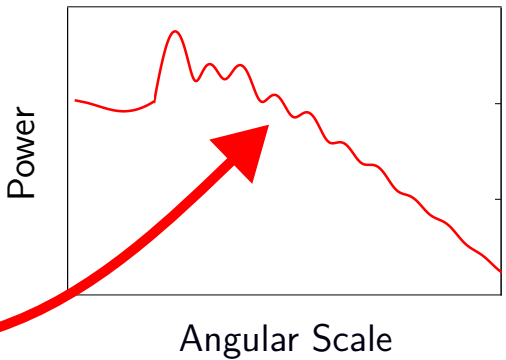


Lensed CMB: ~~**Statistically Homogeneous**~~

We can estimate lensing potential since
lensing breaks symmetry of CMB



Lensed CMB: ~~**Statistically Homogeneous**~~



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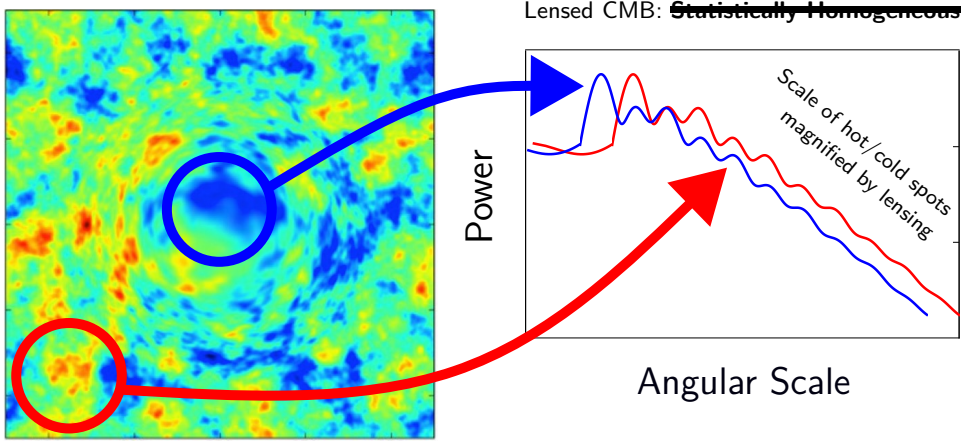

For a statistically **homogeneous** field like the unlensed CMB different Fourier modes are statistically independent:

$$\boxed{\langle T_{\boldsymbol{\ell}}^{\rm unlensed} T_{\boldsymbol{L}-\boldsymbol{\ell}}^{\rm unlensed} \rangle = 0}$$

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Lensing of the CMB breaks this symmetry by inducing correlations in our lensed CMB:

$$\boxed{\langle T_{\boldsymbol{\ell}} T_{\boldsymbol{L}-\boldsymbol{\ell}} \rangle \sim \kappa_{\boldsymbol{L}}}$$

$$(\kappa \equiv -\nabla^2(\text{Lensing Potential})/2)$$

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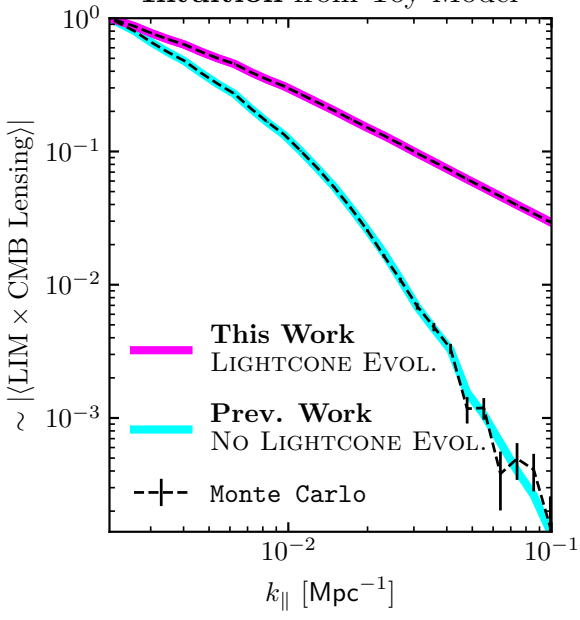
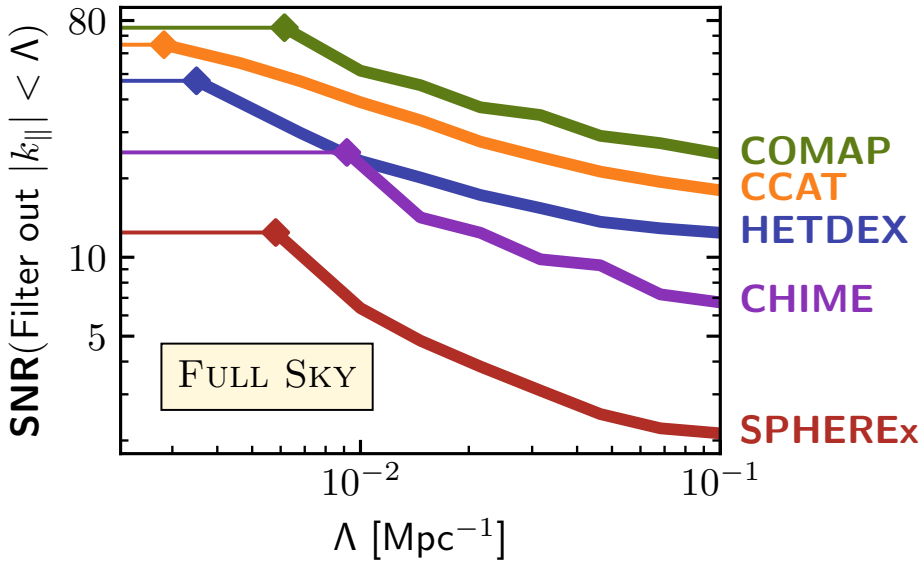
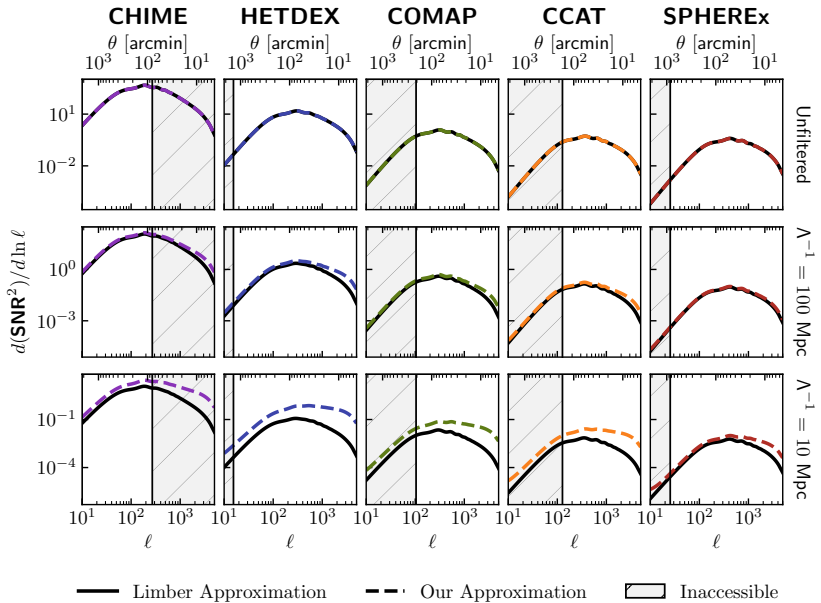
So correlations that we do see in our map give us information about the lensing allowing us to build an **quadratic estimator** (QE) of κ out of these correlations.

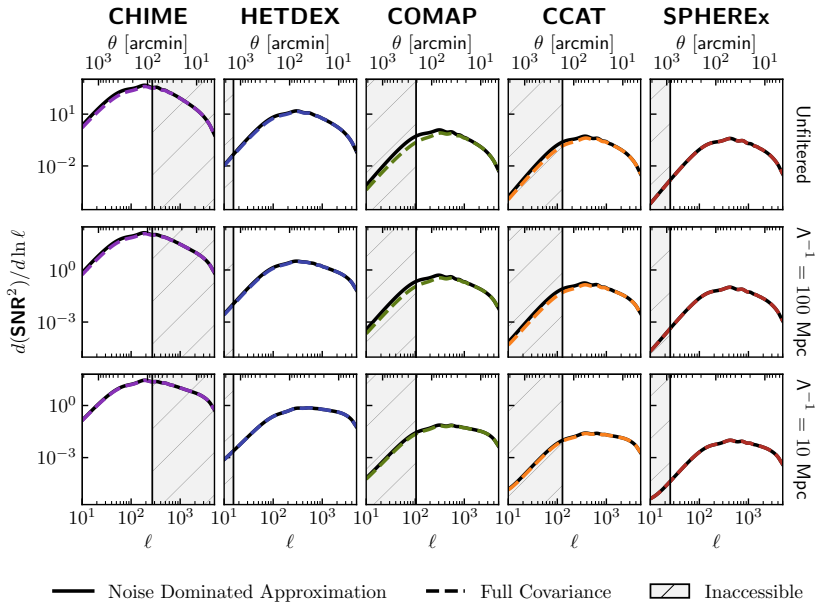
$$\boxed{\hat{\kappa}_{\boldsymbol{L}} \sim \int_{\ell} T_{\ell} T_{\boldsymbol{L}-\ell}}$$

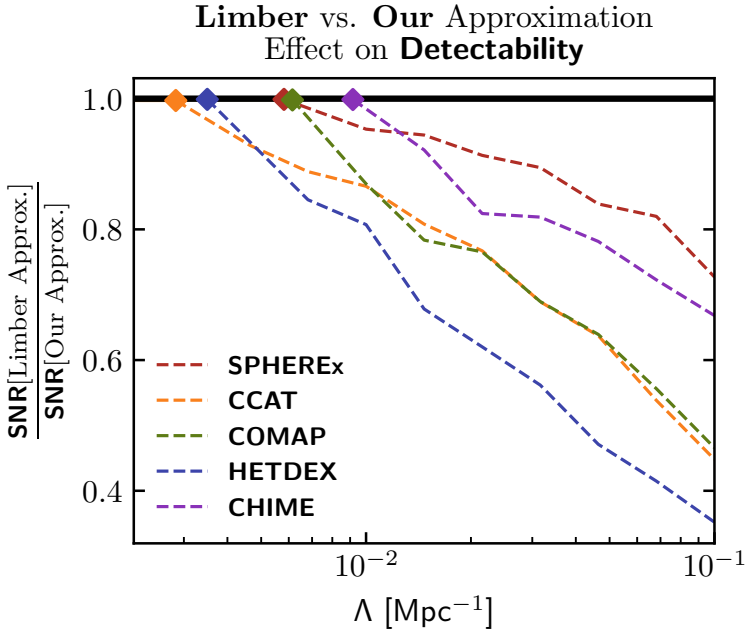
Experiment Line	**CHIME** HI(21cm)	**HETDEX** Ly-α	**COMAP** CO(1→0)	**CCAT** [CII]	**SPHEREx** Ly-α
$\nu_{\rm rest}$	1420.406 MHz	2456.43 THz	115.27 GHz	1900.5 GHz	2456.43 THz
$\nu_{\rm obs}$	617-710 MHz	545-857 THz	26-34 GHz	210-420 GHz	270-400 THz
$z_{\rm obs}$	1.0 - 1.3	1.9 - 3.5	2.4 - 3.4	3.5 - 8.1	5.2 - 8
$\mathcal{R}$	1700	800	800	100	41
$\Omega_{\rm field}$ $[\deg^2]$	31000	540	12	8	200
$\sqrt{\Omega_{\rm pixel}}$	$40'$	$3''$	$4.5'/\sqrt{8\ln 2}$	$30''/\sqrt{8\ln 2}$	$6''$

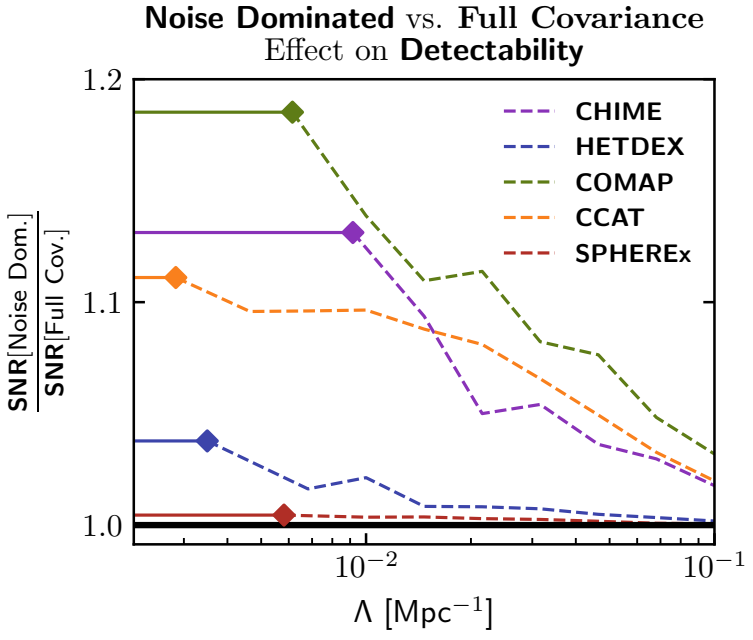

Intuition from Toy Model
10^0
10^{-1}
10^{-2}
10^{-3}
$\sim |\langle \mathrm{LIM} \times \mathrm{CMB\ Lensing} \rangle|$
This Work
Lightcone Evol.
Prev. Work
No Lightcone Evol.
Monte Carlo
10^{-2}
10^{-1}
$k_\parallel$ [Mpc^{-1}]

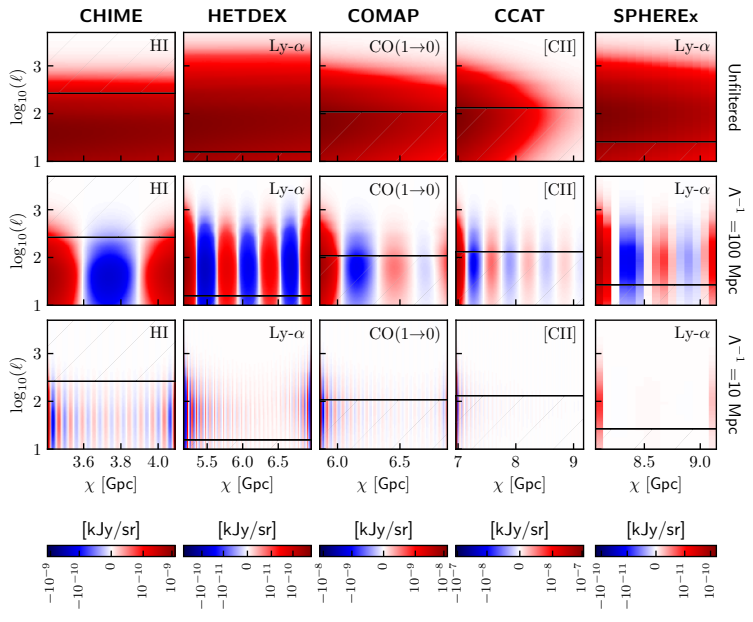

Detectability of ⟨LIM×CMB Lensing⟩
SNR(Filter out $|k_\parallel| < \Lambda$)
80
10
5
FULL SKY
10^{-2}
10^{-1}
Λ [Mpc^{-1}]
COMAP
CCAT
HETDEX
CHIME
SPHEREx

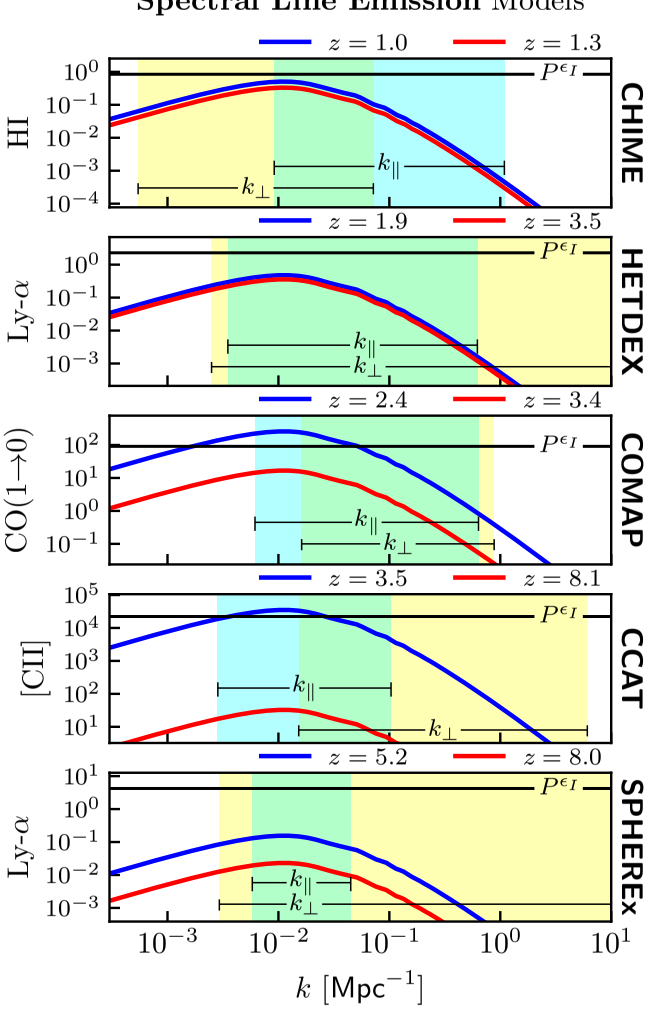

Limber vs. **Our** Approximation Effect on **Angular Distrbution** of **SNR**
CHIME
HETDEX
COMAP
CCAT
SPHEREx
θ [arcmin]
Unfiltered
Λ⁻¹ = 100 Mpc
Λ⁻¹ = 10 Mpc
d(SNR²)/d ln ℓ
ℓ
Limber Approximation
Our Approximation
Inaccessible

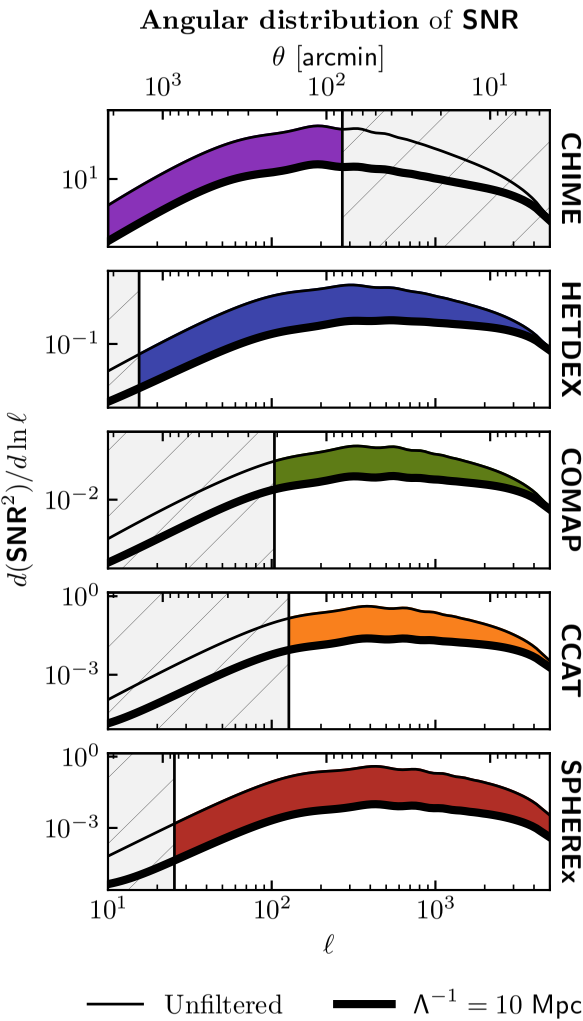

Noise Dominated vs. Full Covariance Effect on Angular Distrbution of SNR
CHIME
HETDEX
COMAP
CCAT
SPHEREx
θ [arcmin]
Unfiltered
Λ⁻¹ = 100 Mpc
Λ⁻¹ = 10 Mpc
d(SNR²)/d ln ℓ
ℓ
Noise Dominated Approximation
Full Covariance
Inaccessible


Limber vs. Our Approximation
Effect on Detectability
SNR[Limber Approx.] / SNR[Our Approx.]
1.0
0.8
0.6
0.4
SPHEREx
CCAT
COMAP
HETDEX
CHIME
10^{-2}
10^{-1}
Λ [Mpc^{-1}]


Noise Dominated vs. Full Covariance
Effect on Detectability
1.2
1.1
1.0
SNR[Noise Dom.] / SNR[Full Cov.]
CHIME
HETDEX
COMAP
CCAT
SPHEREx
10^{-2}
10^{-1}
Λ [Mpc^{-1}]


⟨Foreground Filtered LIM × CMB Lensing⟩
CHIME
HETDEX
COMAP
CCAT
SPHEREx
Unfiltered
Λ⁻¹ = 100 Mpc
Λ⁻¹ = 10 Mpc
HI
Ly-α
CO(1→0)
[CII]
log10(ℓ)
χ [Gpc]
[kJy/sr]


Spectral Line Emission Models
z = 1.0
z = 1.3
HI
CHIME
z = 1.9
z = 3.5
Ly-α
HETDEX
z = 2.4
z = 3.4
CO(1→0)
COMAP
z = 3.5
z = 8.1
[CII]
CCAT
z = 5.2
z = 8.0
Ly-α
SPHEREx
P^ϵI
k∥
k⊥
k [Mpc^−1]


Angular distribution of SNR
θ [arcmin]
10^3
10^2
10^1
CHIME
HETDEX
COMAP
CCAT
SPHEREx
10^1
10^-1
10^-2
10^0
10^-3
d(SNR^2)/d ln ℓ
10^1
10^2
10^3
ℓ
Unfiltered
Λ^-1 = 10 Mpc