SLAC NATIONAL ACCELERATOR LABORATORY

Emmanuel Schaan

Line Intensity Mapping

Enabling cross-correlations for robust cosmological detections

Doré+15

Great to be back!

What this talk is (not) about

This talk: Enabling LIM cross-correlations

LIM auto & cross modeling *Schaan White 21a, b*

Ly-α^2 x CMB lensing *Doux Schaan+16, La Posta Schaan 24*

CHIME^2 x CMB lensing, *Pinsonneault-Marotte+in prep*

CIB lensing *Schaan Ferraro Spergel 19*

LIM-pair lensing *Doux Schaan+16, Schaan+18, Maniyar Schaan Pullen 21*

Direct LIM x CMB lensing *Shen Kokron Schaan+25*

Astro colloquium next week: CMB secondary anisotropies

kSZ, tSZ, lensing, etc.

The Universe as a fundamental Physics laboratory

image credit: NAOJ

Years after the Big Bang

400 thousand | 0.1 billion | 1 billion | 4 billion | 8 billion | 13.8 billion

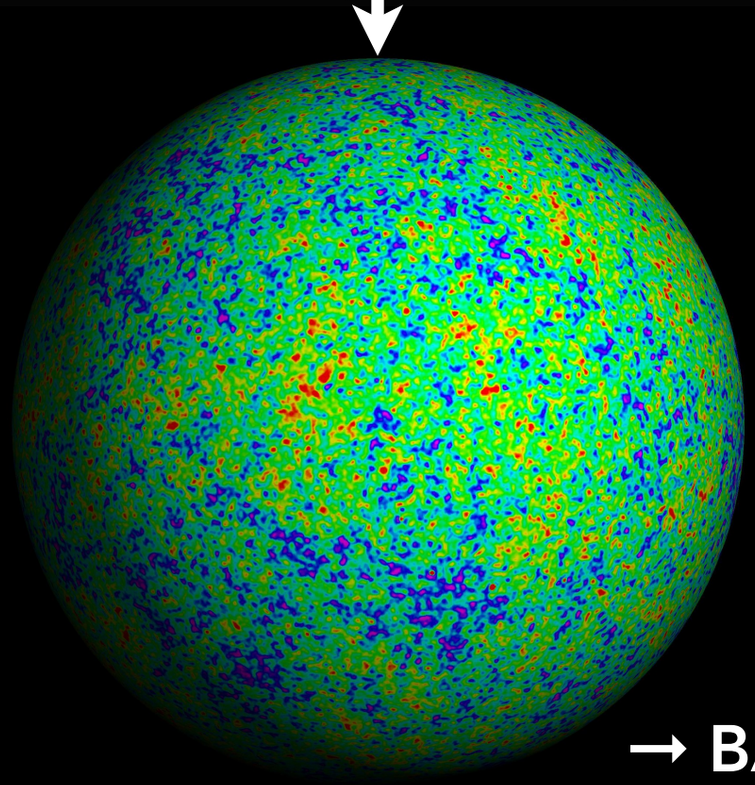
The Big Bang | Recombination | The Dark Ages | Formation of the first astronomical objects | Present day

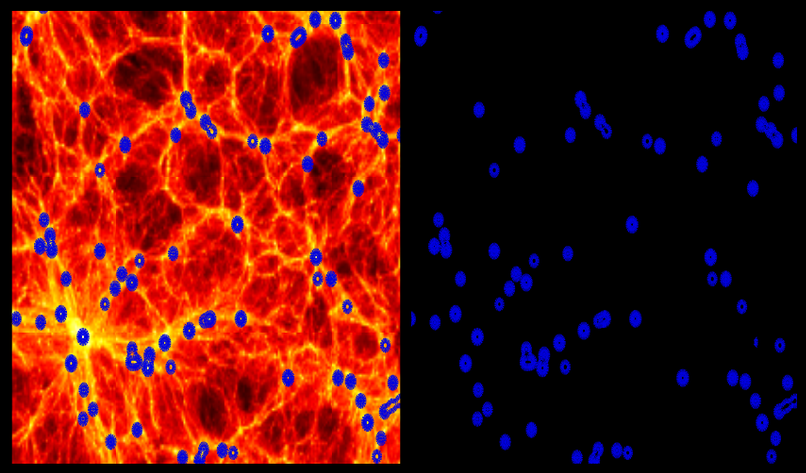
Fully ionised | Neutral | Reionisation | Fully ionised

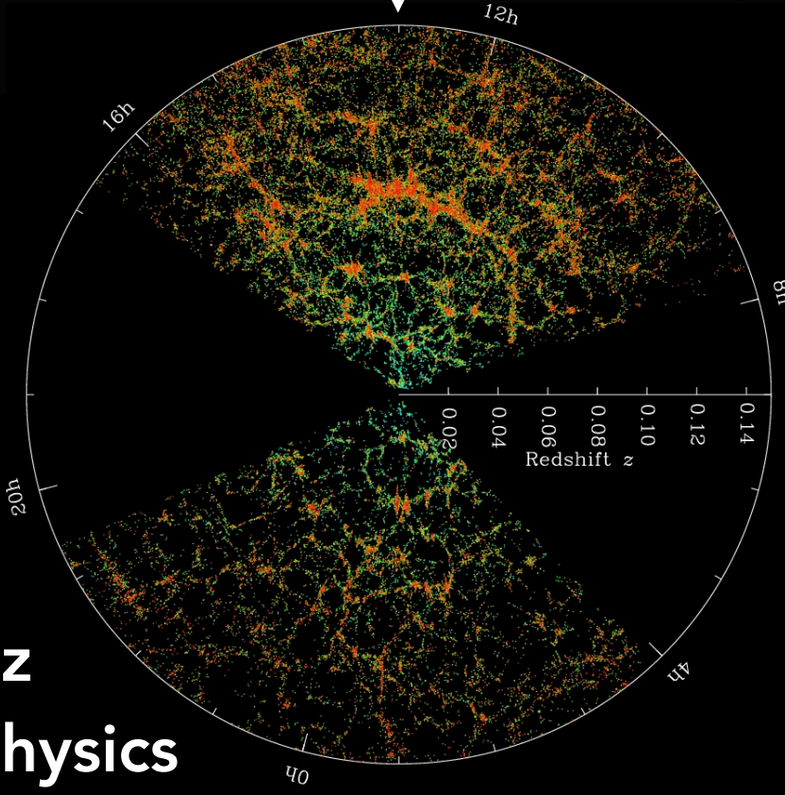
CMB | **~80% of volume uncharted!** | **Galaxy surveys**

1000 | 100 | 10 | 1

Redshift + 1







Intensity Mapping: 3D, high z

→ BAO, PNG, ν, early DE, Astrophysics

Tegmark, WMAP3 | *Doré+15, SPHEREx* | *Blanton, SDSS*

Intensity Mapping = Impressionism (pointillism)

Théo van Rysselberghe 1887

IM challenges: cross-correlations will be crucial

Avoid noise biases and continuum foregrounds

Beane Villaescusa-Navarro Lidz 19

Remove line interlopers with line-line cross-correlations

Cheng+20, Gong+20, Sun+21, ***Schaan White 21a***

Deproject any contaminant template (e.g., source catalog)

Furlanetto+07, Lidz+09, Visbal+10,11, and many more

Higher signal-to-noise in cross-correlation for first detections

Pen+08, Chang+10

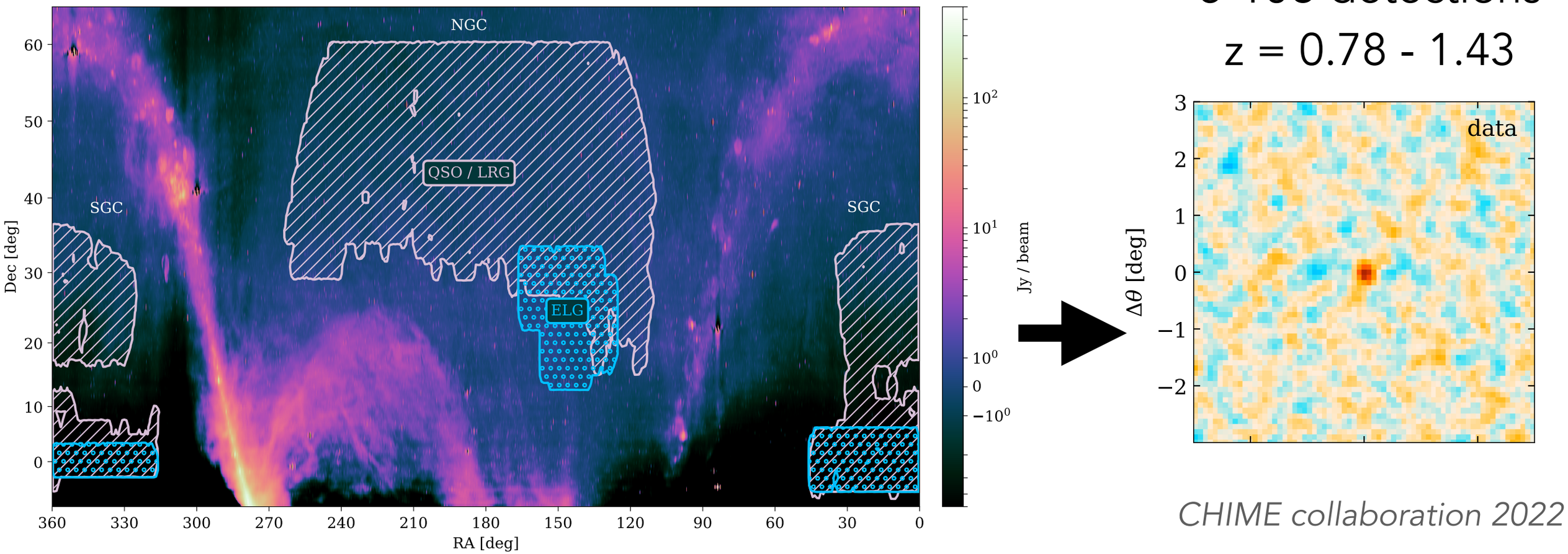
Test the matter-light relation

Doux Schaan+16, Schaan+18, Maniyar Schaan Pullen 21

(Need accurate model for cross-correlations)

Schaan White 21a, b

Evidence: CHIME x eBOSS results



5-10σ detections

z = 0.78 - 1.43

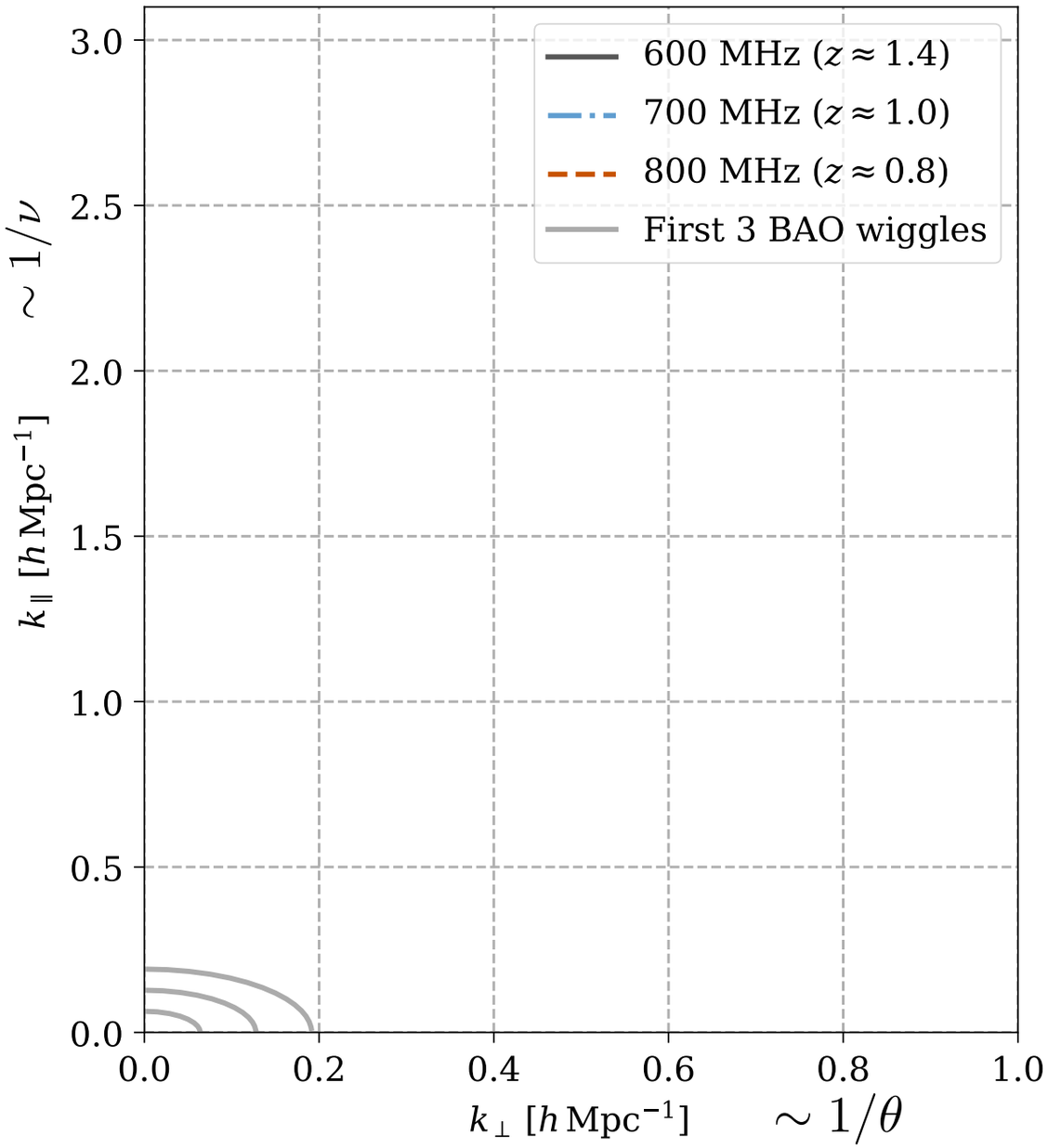
CHIME collaboration 2022

First interferometric cosmological 21cm detection!

But at higher z, spectroscopic samples may no longer be available…

→ Use photometric samples / CMB?

Missing modes hamper cross-correlations & hide cosmological signal



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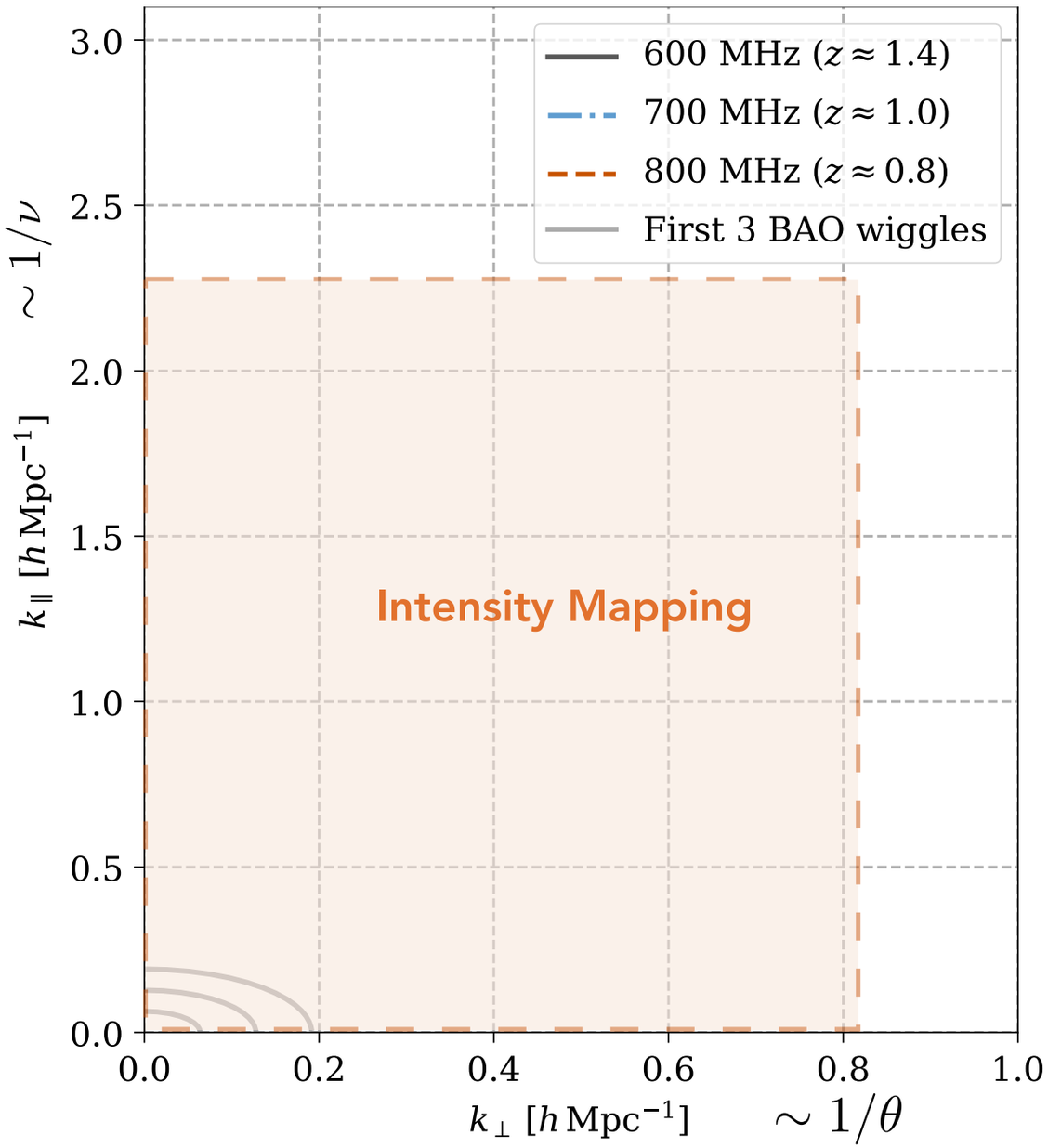

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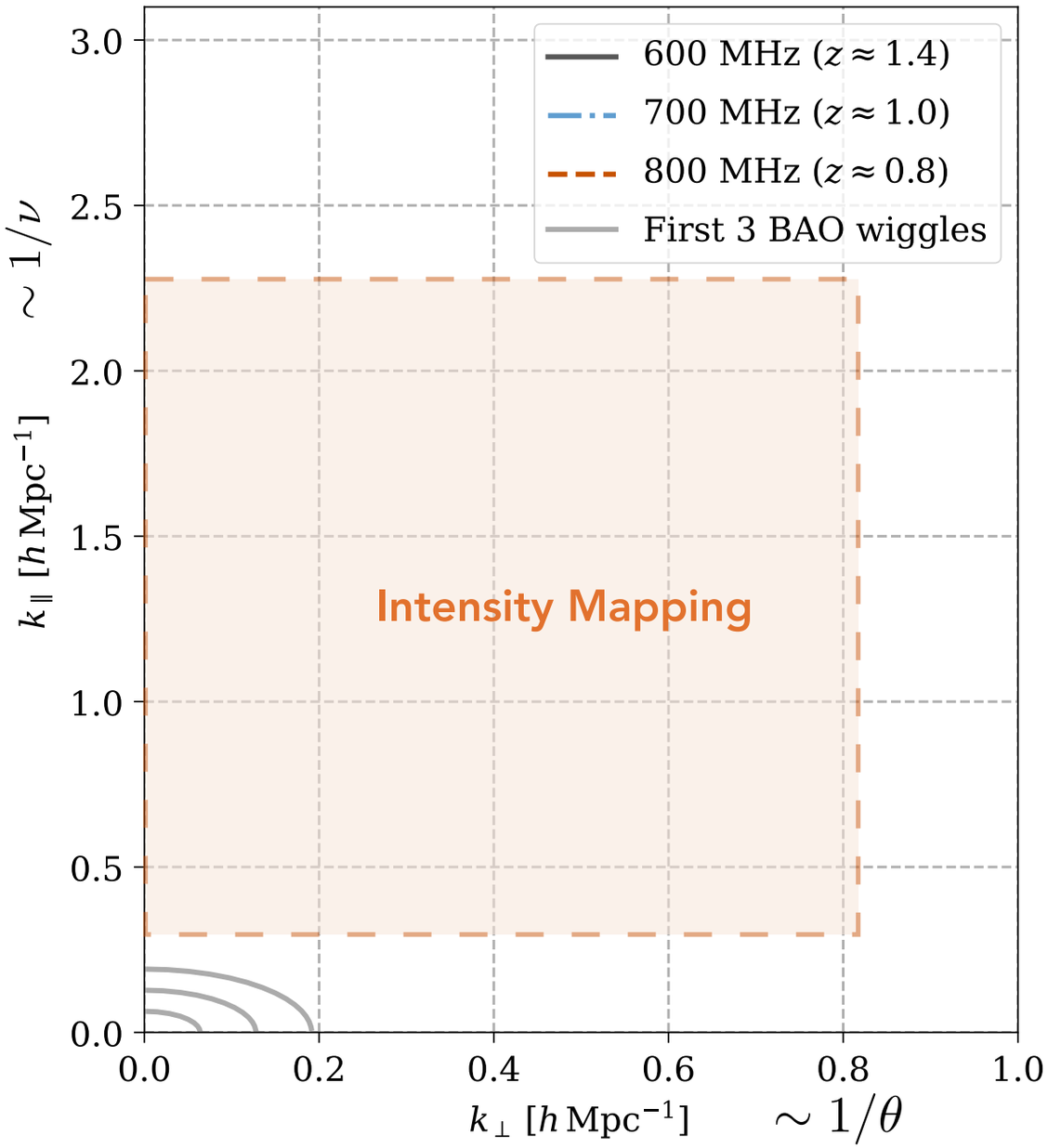
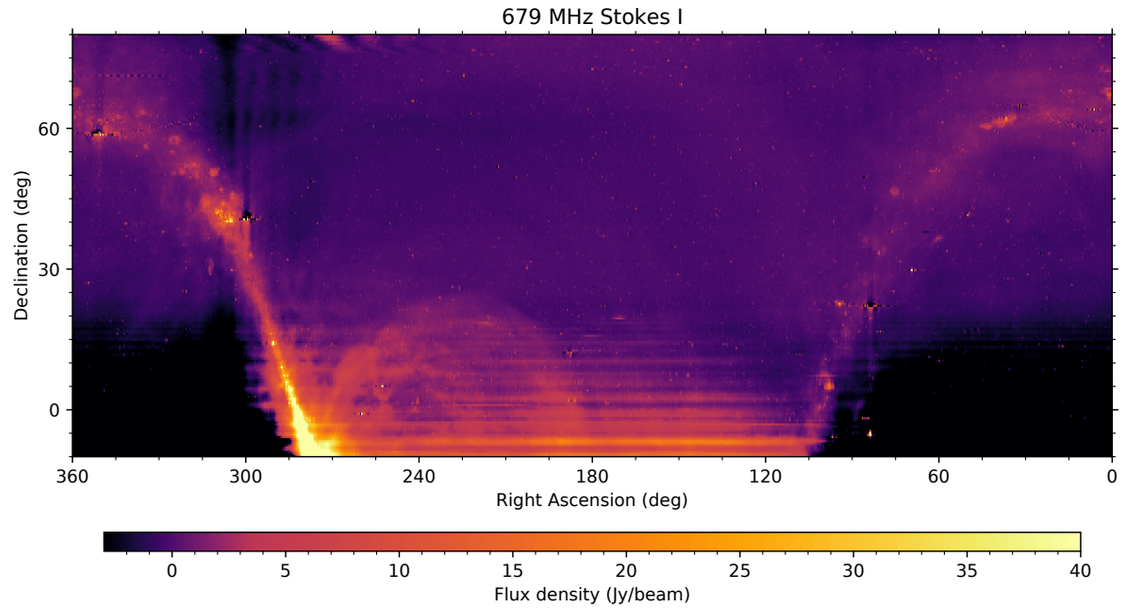


Dominant continuum foreground (Milky Way)

→ Missing low $k_\parallel$ modes



CHIME collaboration 2022

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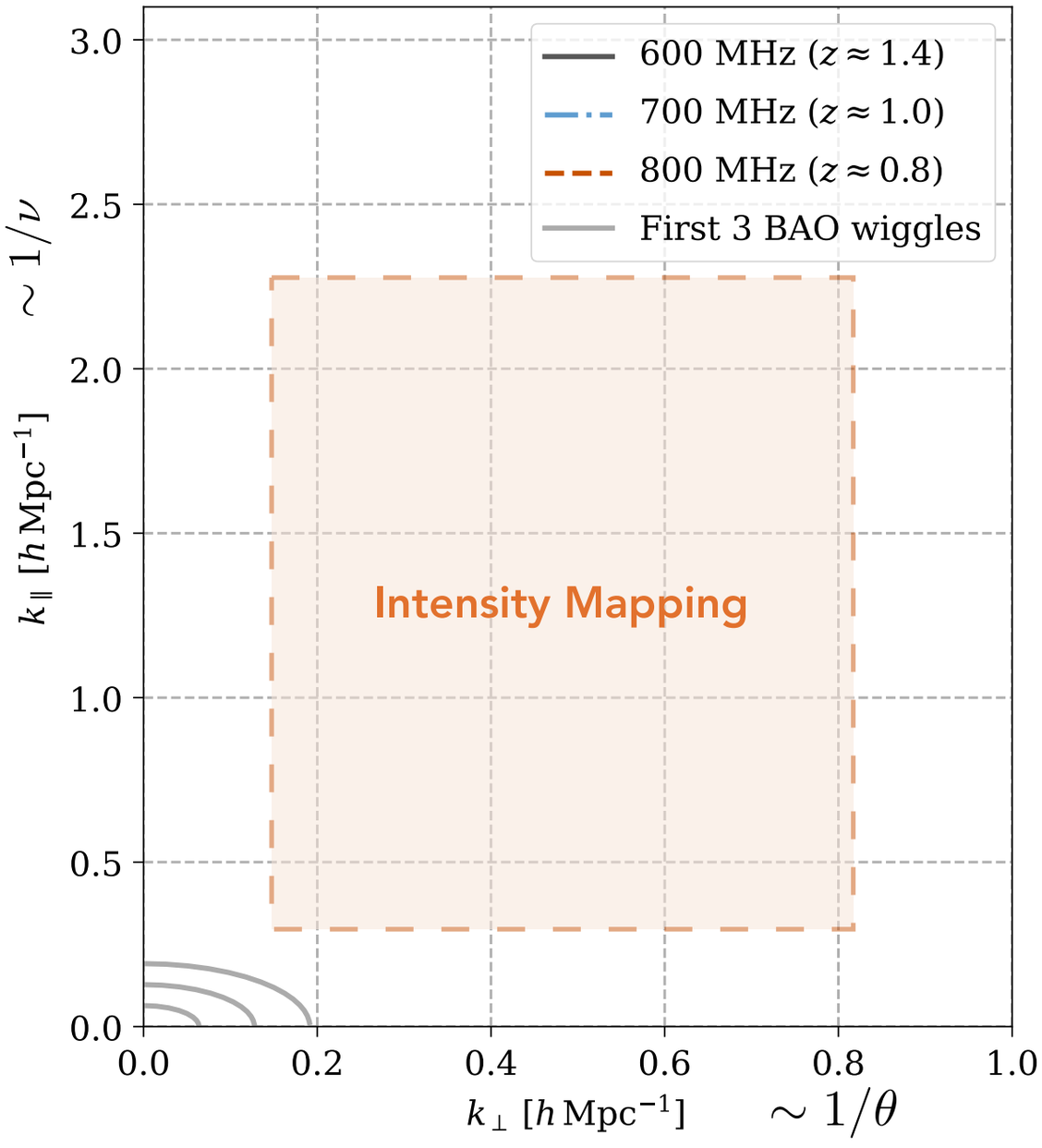
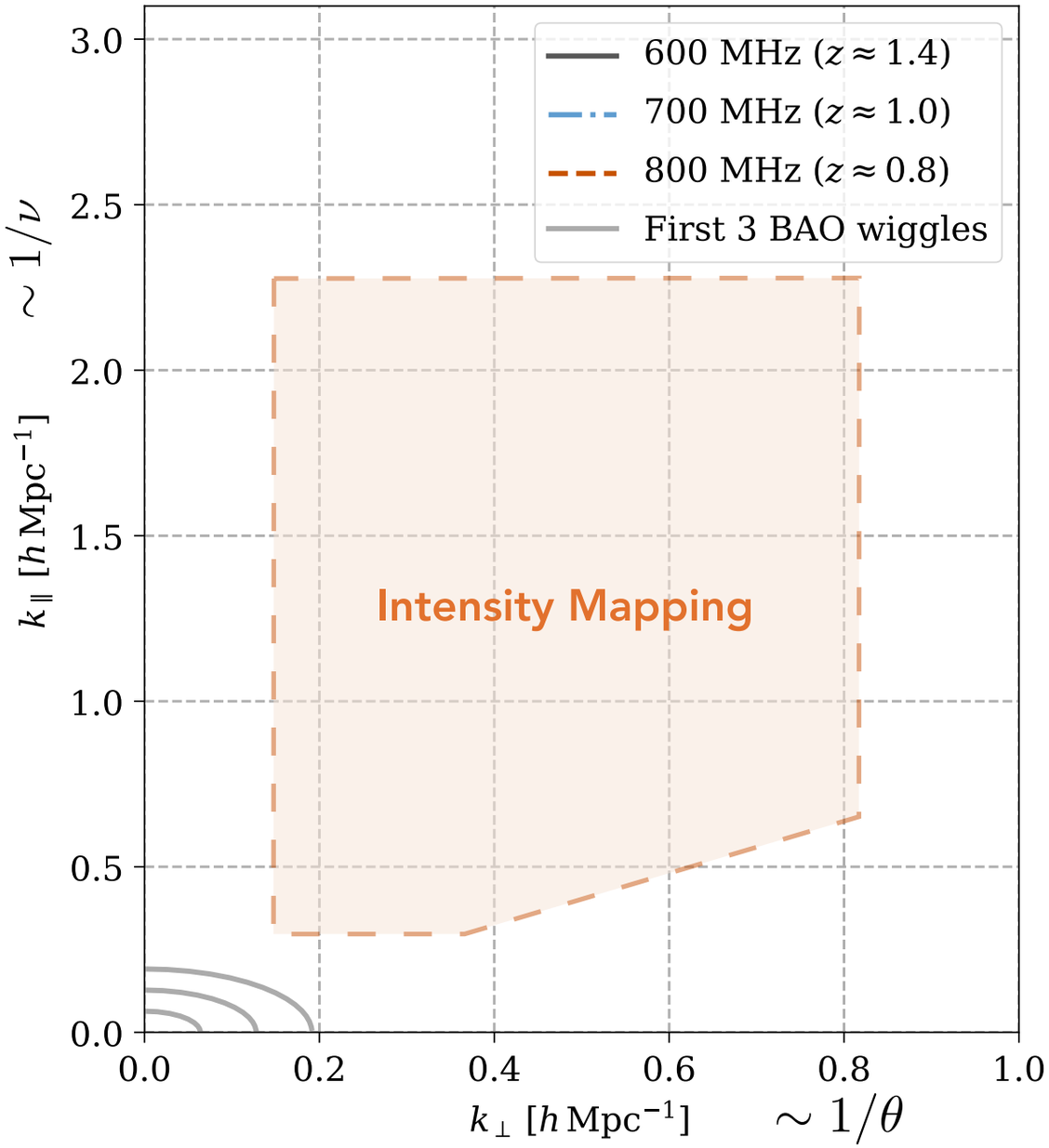


Dominant continuum foreground (Milky Way)
→ Missing low $k_\parallel$ modes

Interferometry with cross-talk
→ Missing low $k_\perp$ modes

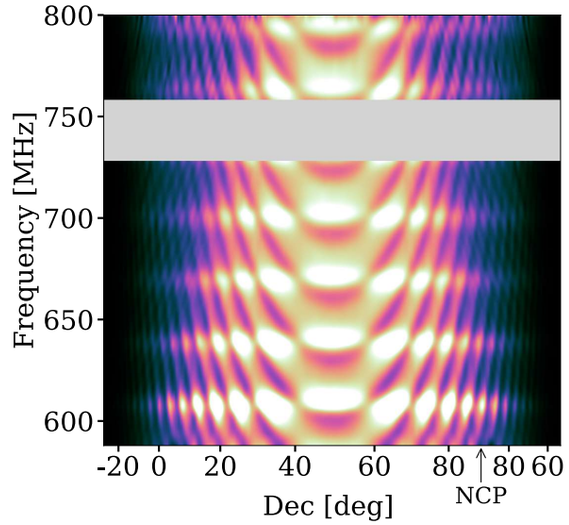
Missing modes hamper cross-correlations & hide cosmological signal



Dominant continuum foreground (Milky Way)
→ Missing low $k_\parallel$ modes

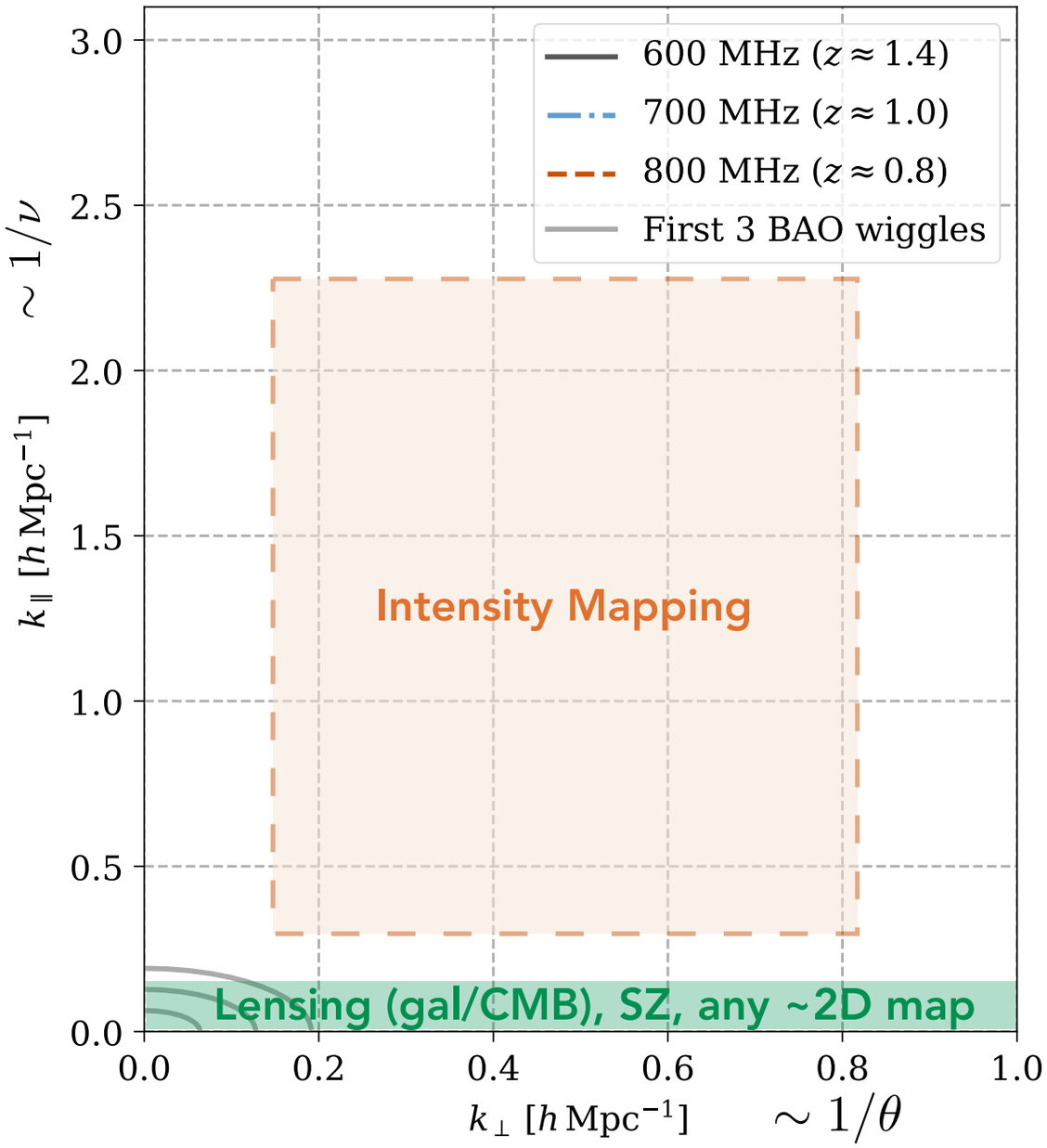
Interferometry with cross-talk
→ Missing low $k_\perp$ modes

Frequency-dependent beam
→ Missing "wedge"



CHIME collaboration 2022

Missing modes hamper cross-correlations & hide cosmological signal



Dominant continuum foreground (Milky Way)
→ Missing low $k_\parallel$ modes

Interferometry with cross-talk
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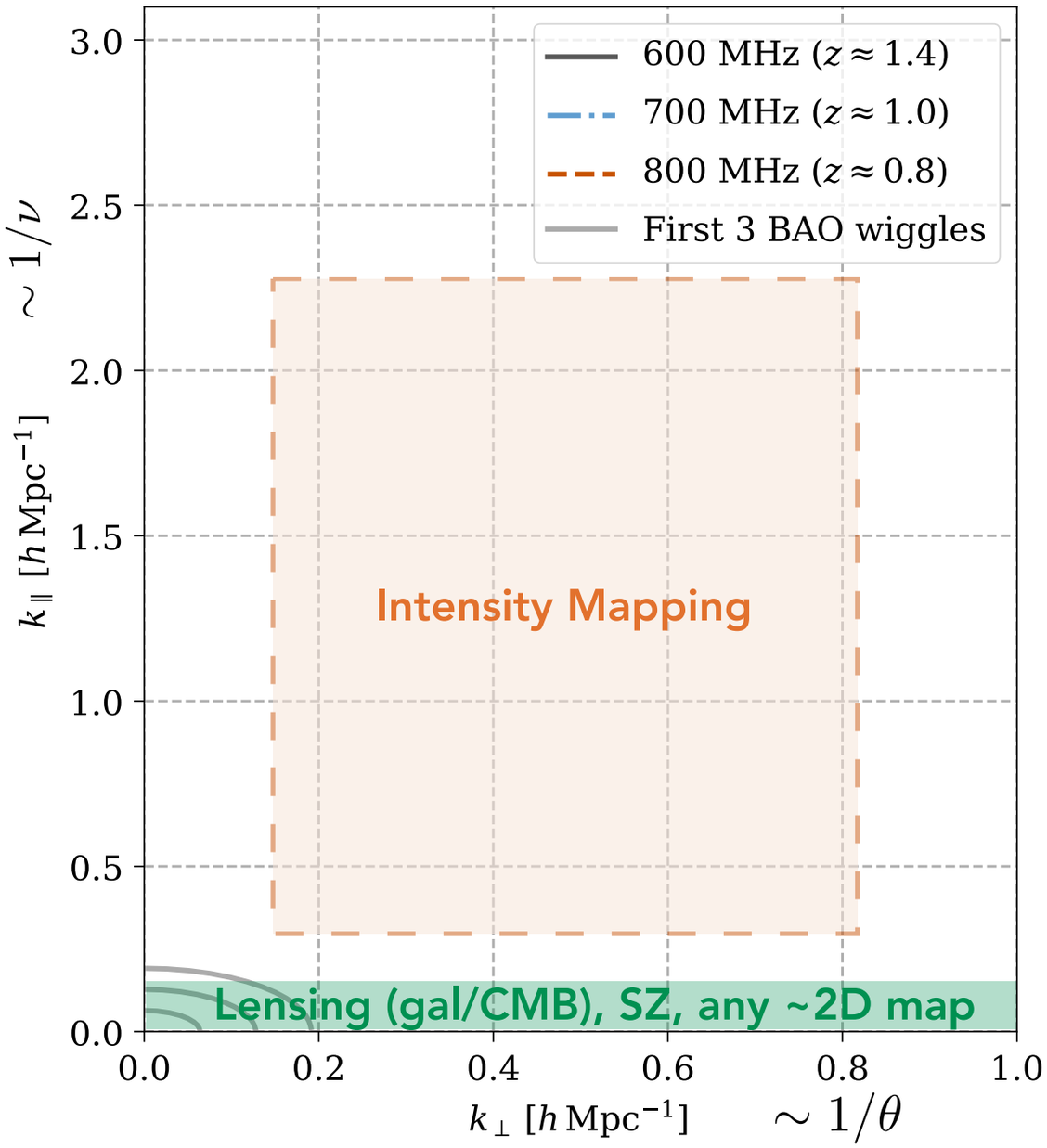
→ Apparently no mode overlap with ~2D datasets

Missing modes hamper cross-correlations & hide cosmological signal



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→ Missing low $k_\parallel$ modes

Interferometry with cross-talk
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Frequency-dependent beam
→ Missing "wedge"

→ Apparently no mode overlap with ~2D datasets

How to enable these cross-correlations?

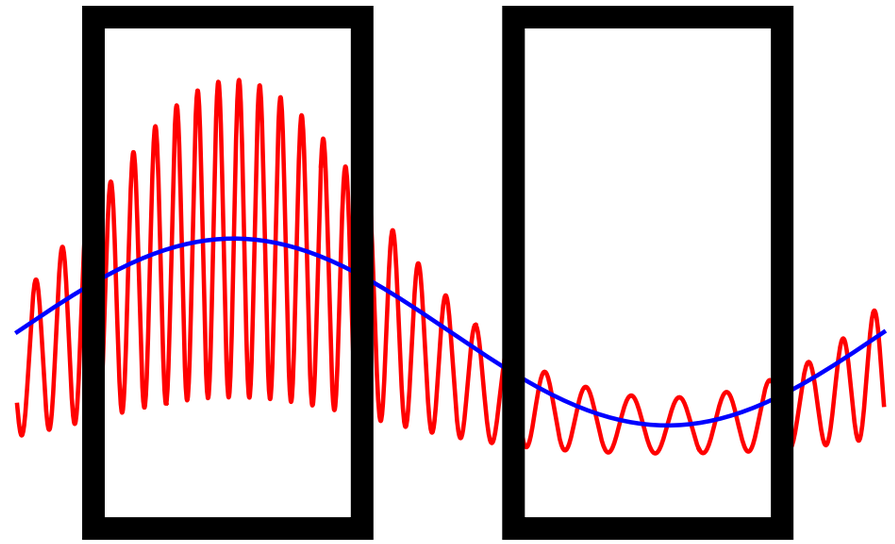
Non-Gaussian reconstruction of missing large scales from small scales

Reconstructing large scales: position-dependent power spectrum

Tidal reconstruction: growth & dilation from gravitational nonlinearities

Hamilton+06, Baldauf Seljak+11, de Putter+12, Sherwin+12, Li+14, Chiang+14, ***Schaan Takada Spergel 14, Doux Schaan+16****, Foreman+18,* ***La Posta Schaan 24***

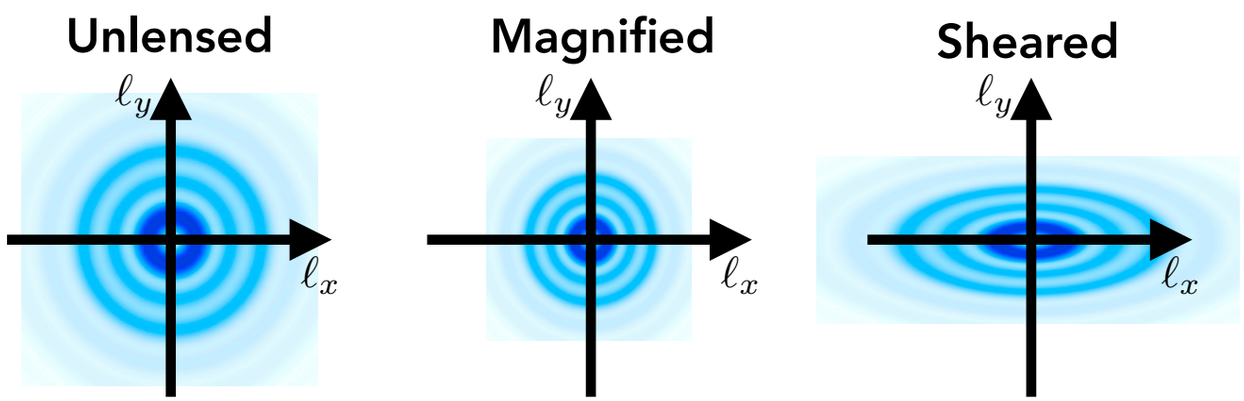
$$P(k) = \bar{P}(k)\,[1 + (\underbrace{\frac{68}{21}}_{\text{growth}} - \underbrace{\frac{1}{3}\frac{d\ln k^3\bar{P}}{d\ln k}}_{\text{dilation}})\delta_L]$$



Lensing reconstruction: magnification & shear

Pen 04, Cooray 04, Zhang+ 05,06,11, Zahn Zaldarriaga 06, Metcalf White 07, Lu Pen 07, Portsidou Metcalf 13, Croft+17, Metcalf+17, ***Schaan Ferraro Spergel 18****, Foreman+18, Chakraborty Pullen 19,* ***Schaan Ferraro 19, Maniyar Schaan Pullen 21***

$$C_{\boldsymbol{\ell}} = C^0_\ell \left[1 + \kappa \left\{ \underbrace{\frac{\partial \ln \ell^2 C^0_\ell}{\partial \ln \ell}}_{\text{Shear}} + \underbrace{\cos(2\theta_{\boldsymbol{\ell}})\frac{\partial \ln C^0_\ell}{\partial \ln \ell}}_{\text{Magnification}} \right\}\right]$$



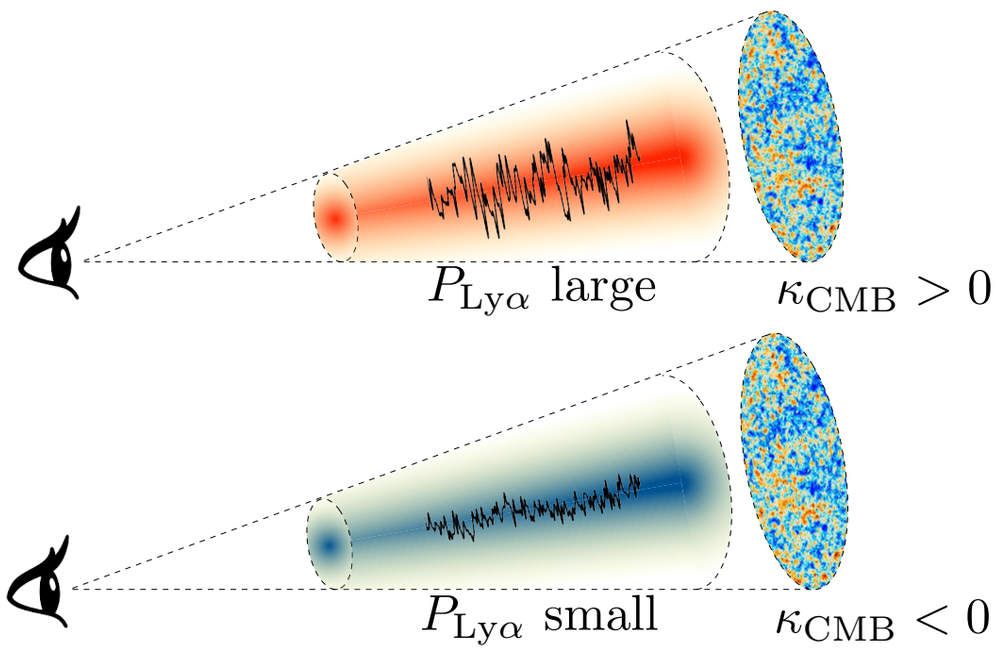
These methods are promising!

S/N on lensing or tidal reconstruction power spectra			
quantity / experiment	CMB S4	21-cm-S2, no wedge	21-cm-S2, with wedge
lensing x ~LSST g	367	676	358
lensing x ~LSST shear	178	367	173
lensing auto	353	216	8
tidal rec. auto	-	2240	266

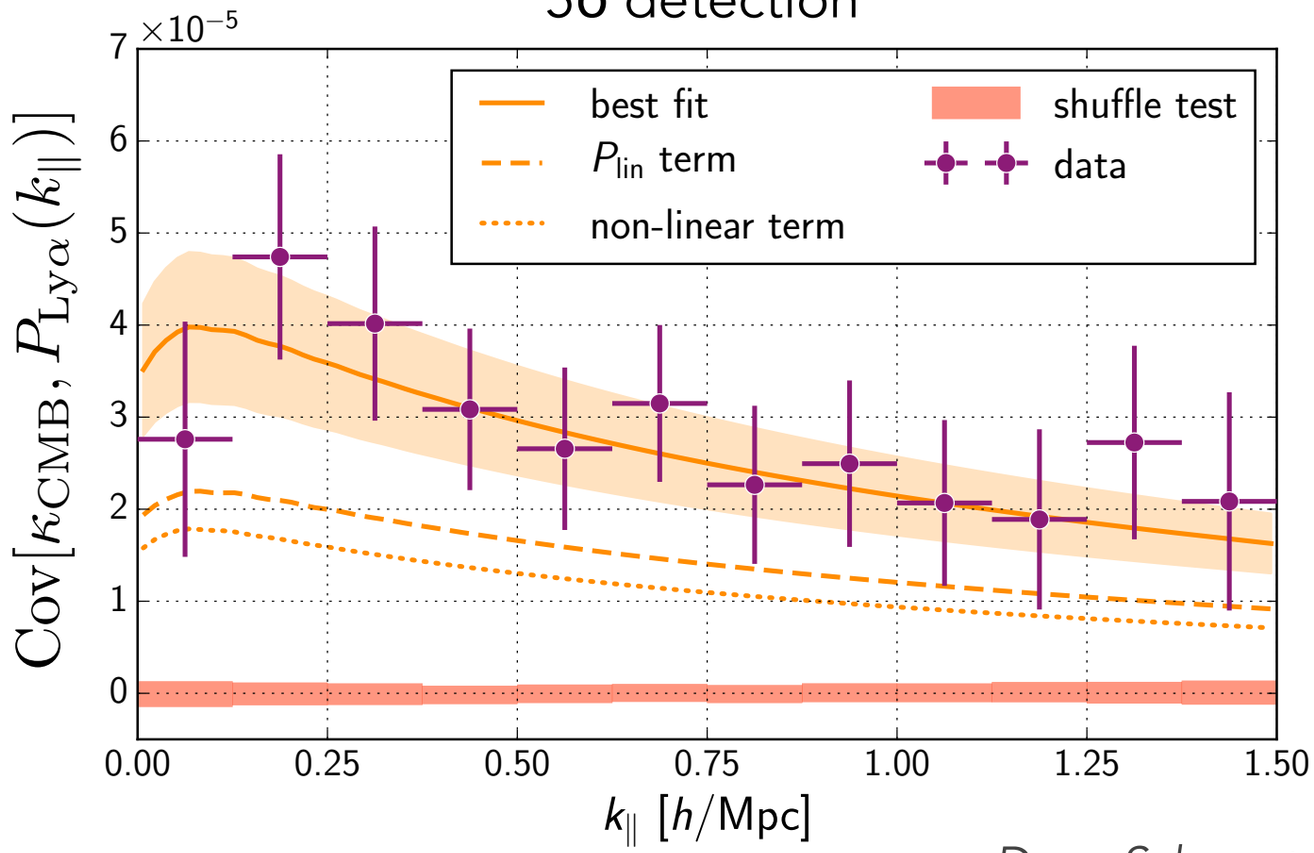
21cm-S2: $2 < z < 6$, 256 x 256 6m dishes, 5 years

Foreman+18, Ansari+19

Tidal reconstruction for Ly-α forest: Enabling cross-correlation with CMB lensing



5σ detection



Doux Schaan+16

First detection with BOSS & Planck

Generic method: correlate any IM with CMB lensing

(eg, 21cm x kSZ) *Li Zhu Pen 18, Foreman+18, Darwish+21*

Probe the halo - IM connection

Tidal reconstruction for Ly-α forest: Enabling cross-correlation with CMB lensing

Adrien La Posta

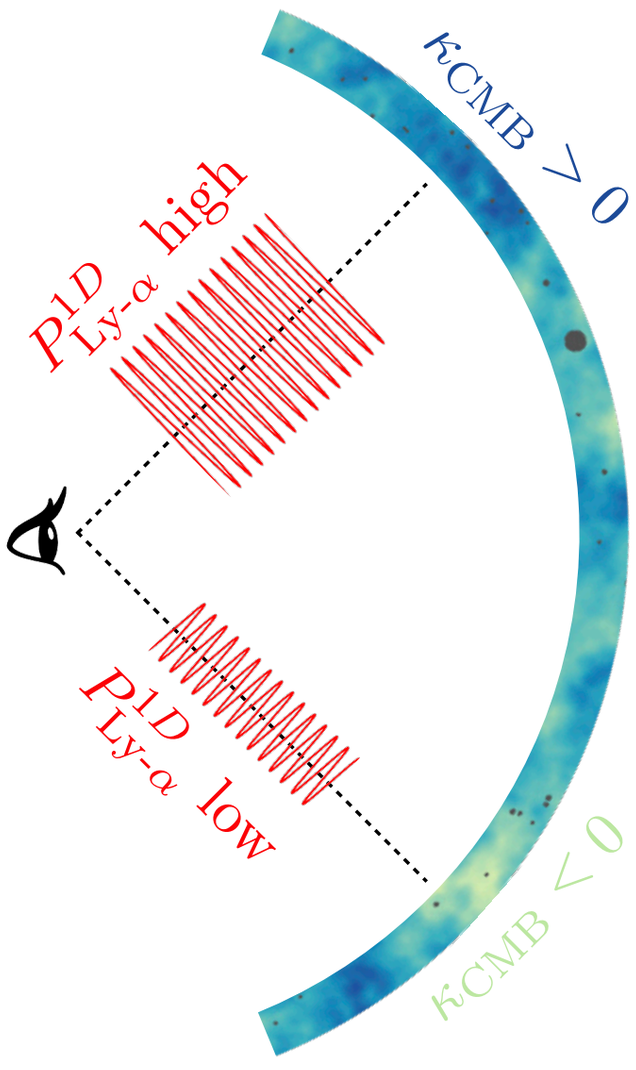
Forecast for DESI & ACT/SO/S4

	SNR					
Dataset	z_1	z_2	z_3	z_4	z_5	Combined
Planck+BOSS	1.9	2.2	2.0	2.2	1.5	**4.4**
ACT+DESI-Y1	2.4	2.8	2.6	2.8	1.9	**5.7**
ACT+DESI-Y5	4.5	5.1	4.8	5.1	3.5	**10.3**
SO+DESI-Y5	6.3	7.2	6.8	7.4	5.1	**14.8**
CMB-S4+DESI-Y5	8.5	9.8	9.3	10.2	7.1	**20.2**

DESI Y1 & Planck detected at 4.8σ

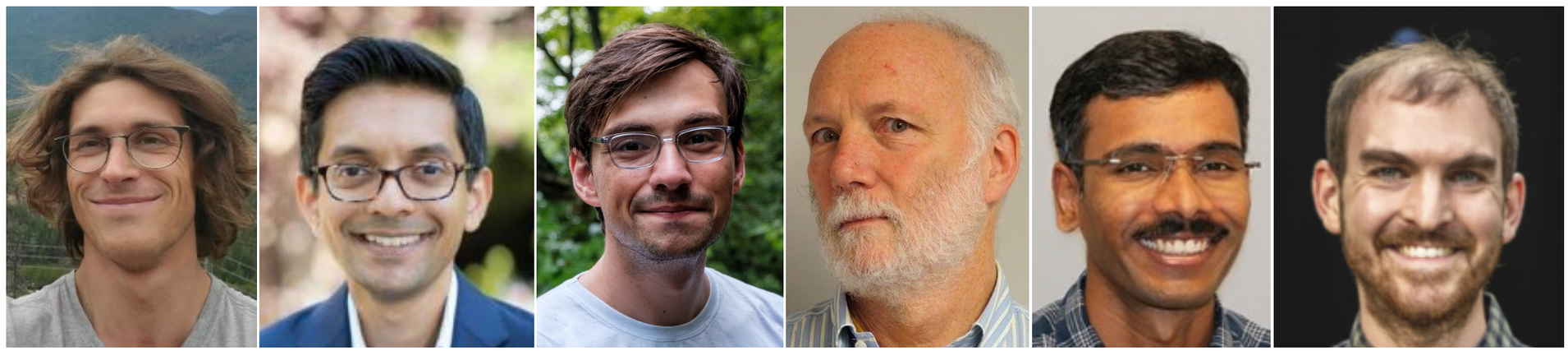
Göksel Karaçayli+24

Look forward to Belsunce+!



La Posta Schaan+16

CHIME² x Planck lensing bispectrum



+ CHIME

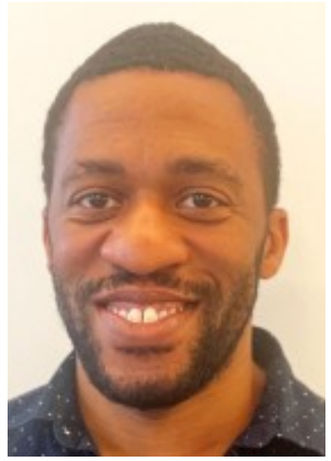
Tristan Pinsonneault-Marotte | *Zeeshan Ahmed* | *Nick Kokron* | *Mark Halpern* | *Shabbir Shaikh* | *Simon Foreman*

Configuration	S/N
Measured: CHIME x Planck	0.2
Simulated: CHIME x Planck	0.5
Simulated: CHIME 1000 nights x Planck	3
Simulated: CHIME 1000 nights x SO-like	5

Pinsonneault-Marottte+ & CHIME in prep (inc. Schaan)

Simulated signal from SkyLine *Sato-Polito Kokron Bernal 22*
Propagated through CHIME pipeline
Implemented estimator & applied it to CHIME x Planck lensing
→ **Marginal detection possible soon**

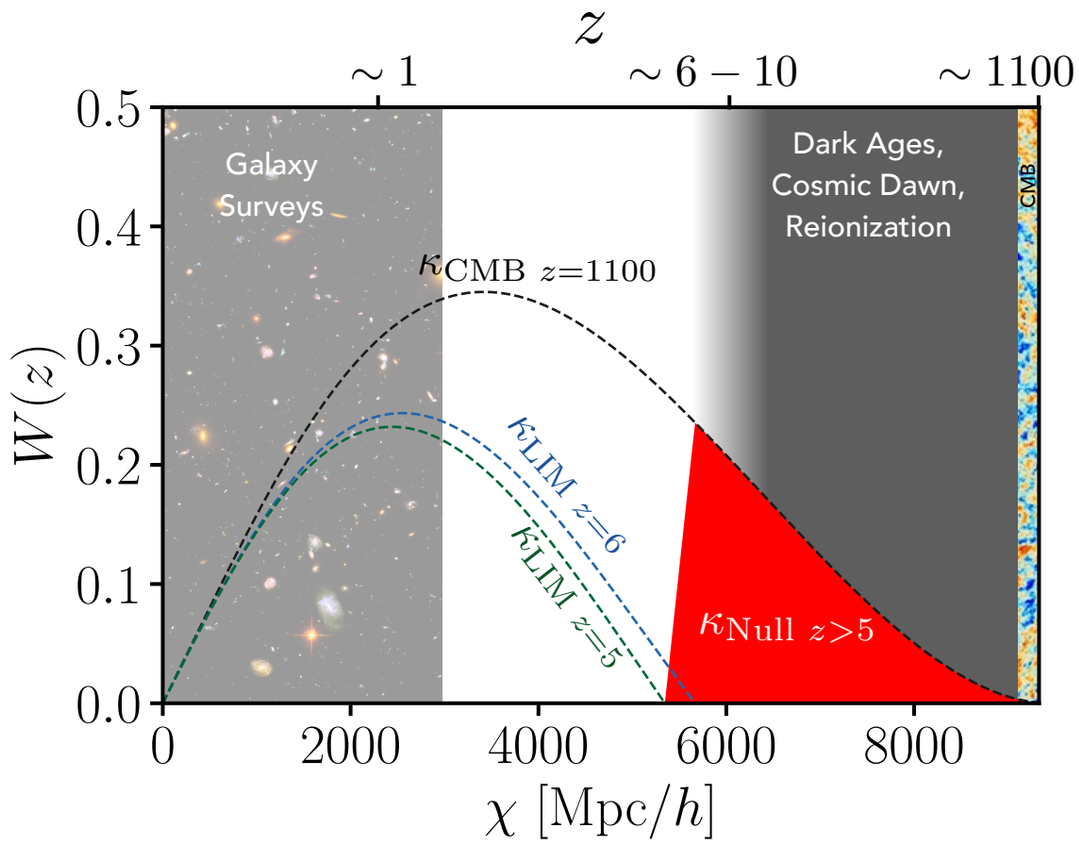
Multi-line IM lensing



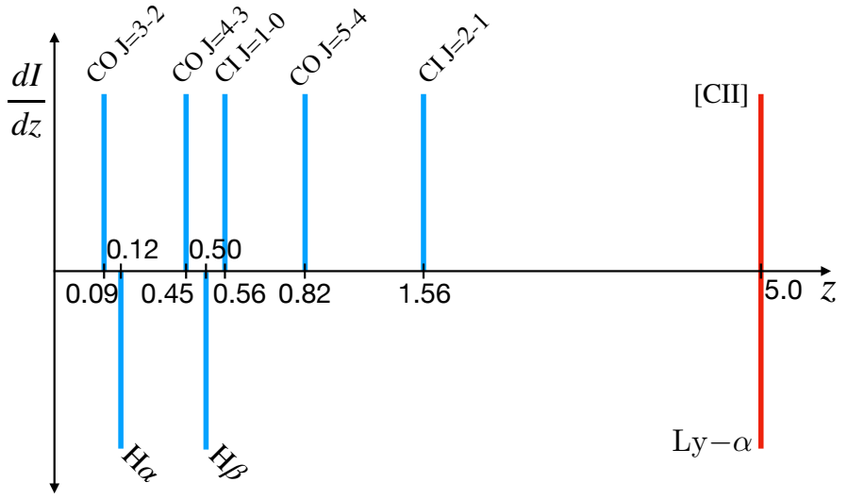
Abhi Maniyar *Anthony Pullen*

New source plane at high z

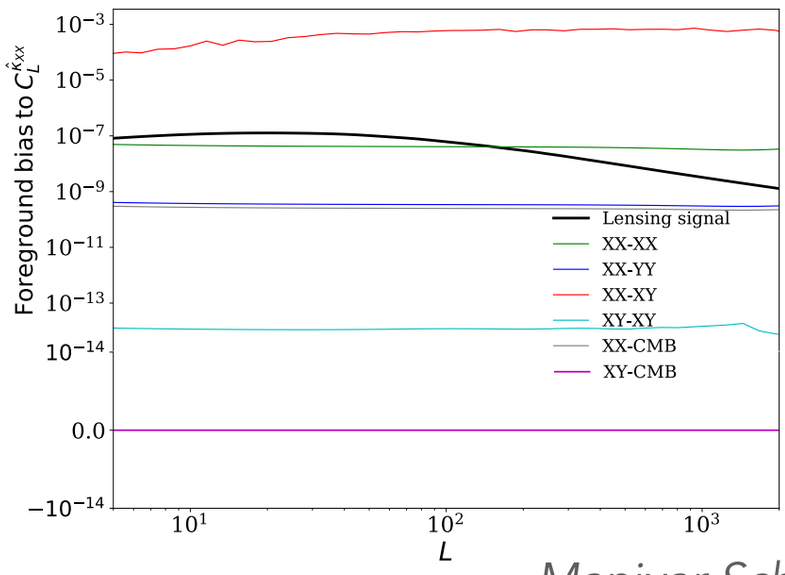
→ Nulling: isolate the *very*-high-z Universe



Using pair of lines at same z…



nulls the interloper bias!



Maniyar Schaan Pullen 21

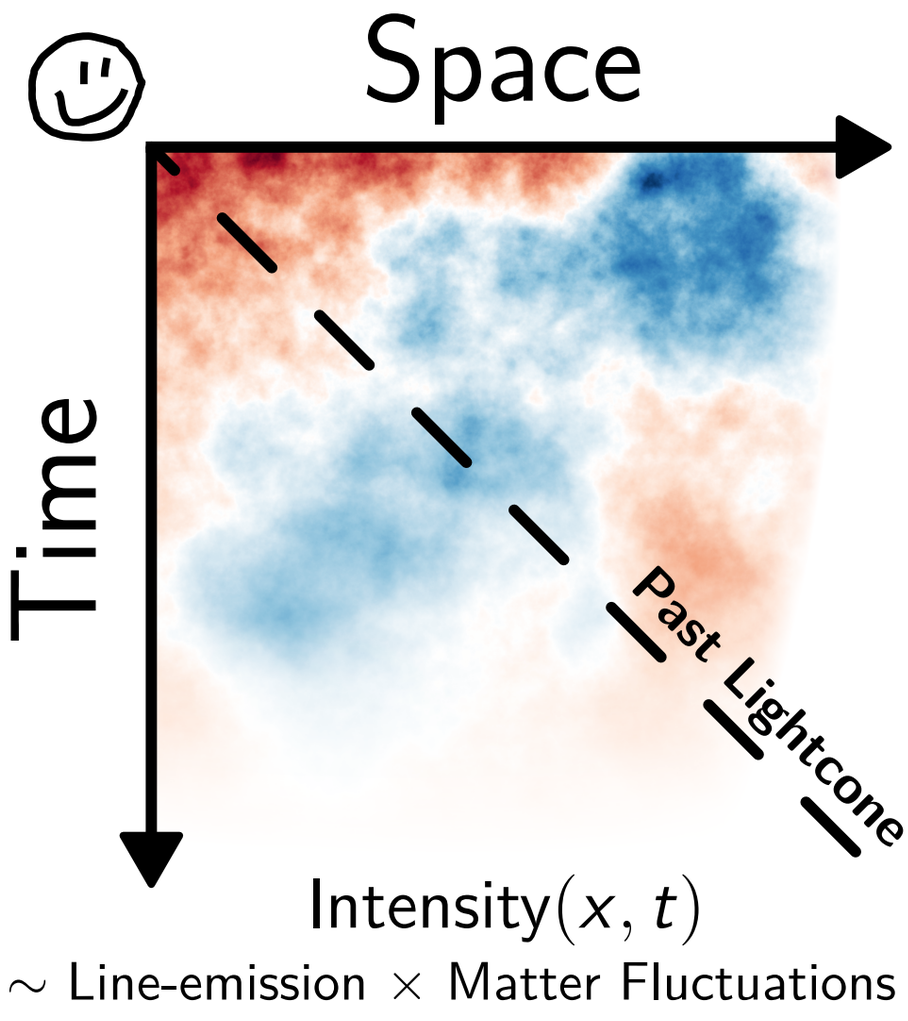
Leakage of large scales into small scales from time-evolution

Shen Kokron Schaan 25

Mode mixing from time evolution

Delon Shen

Nick Kokron



Credit: Delon Shen

Mode mixing from time evolution

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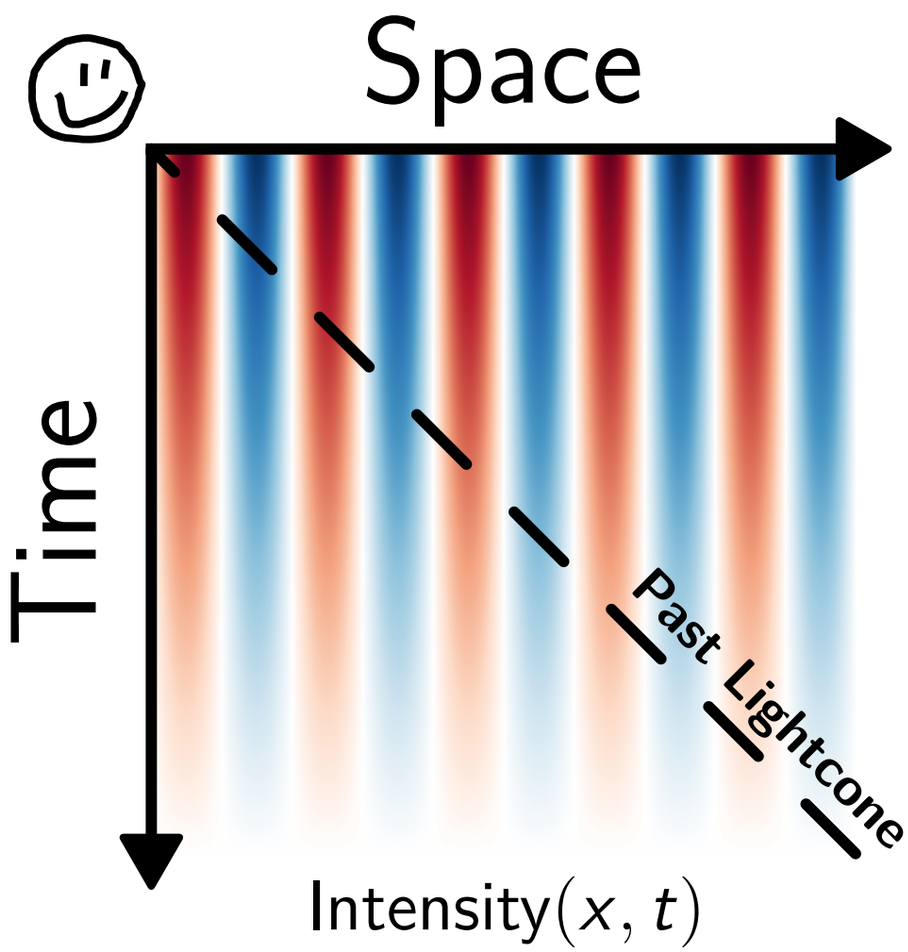

$\sim$ Line-emission $\times$ Matter Fluctuations

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

Credit: Delon Shen

Mode mixing from time evolution

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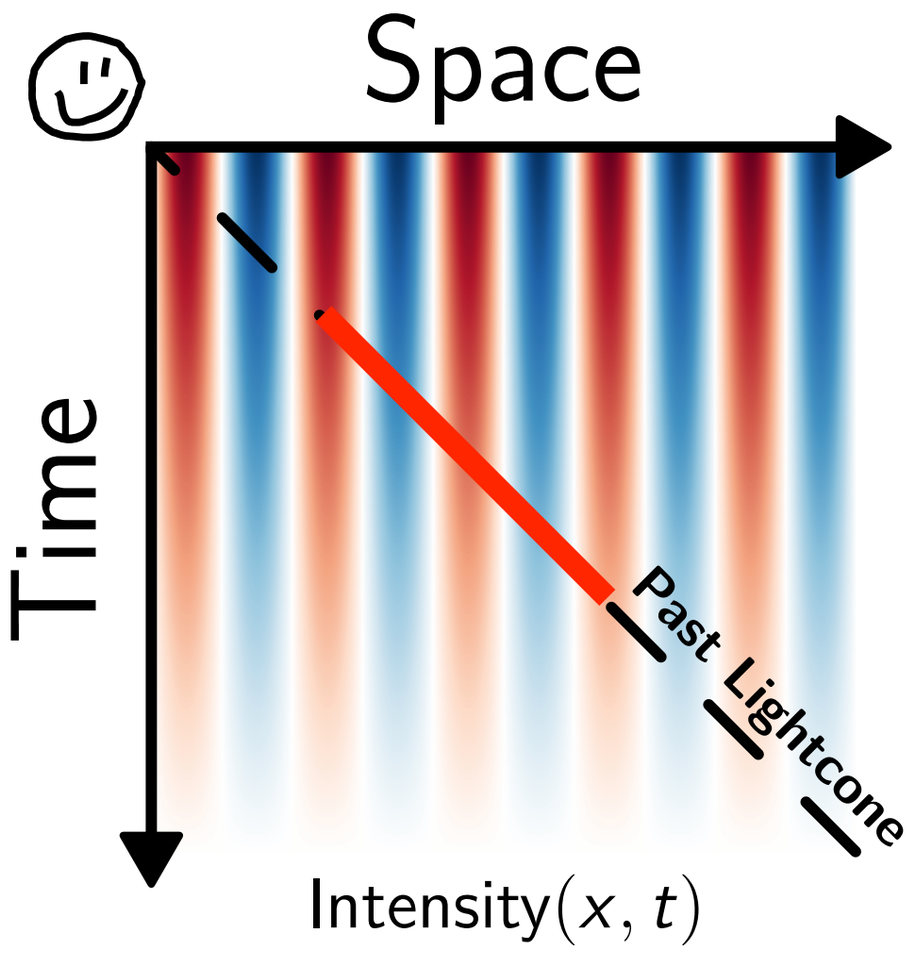

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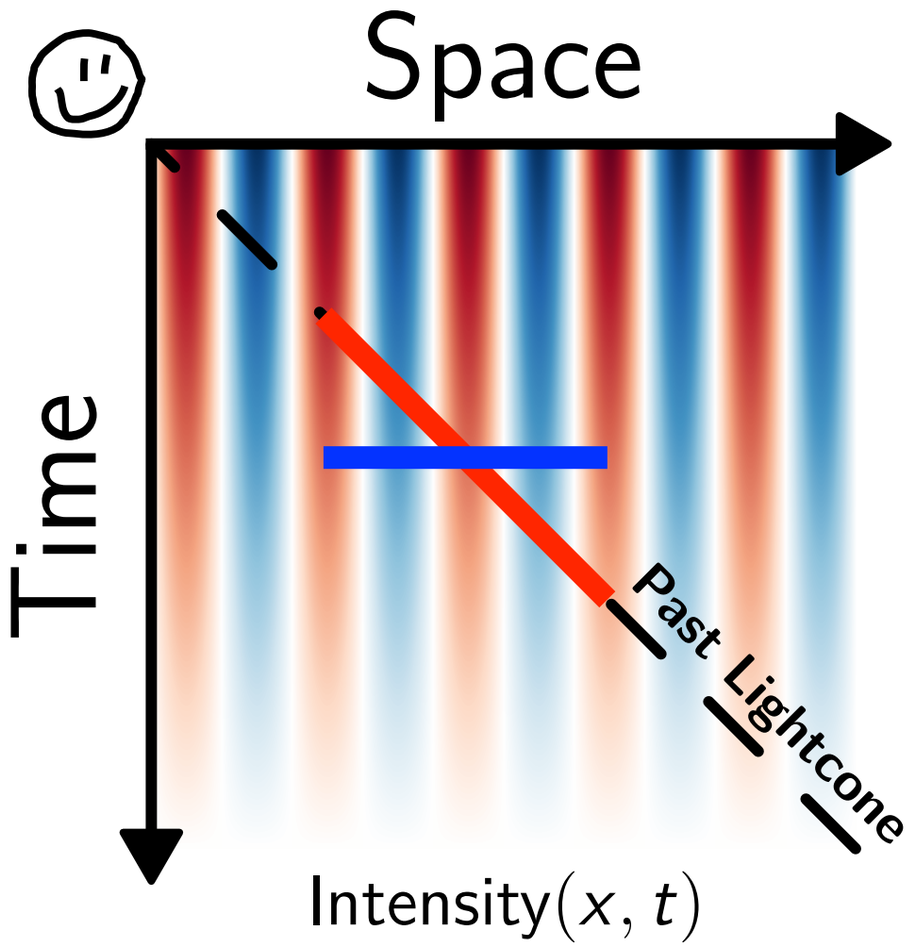

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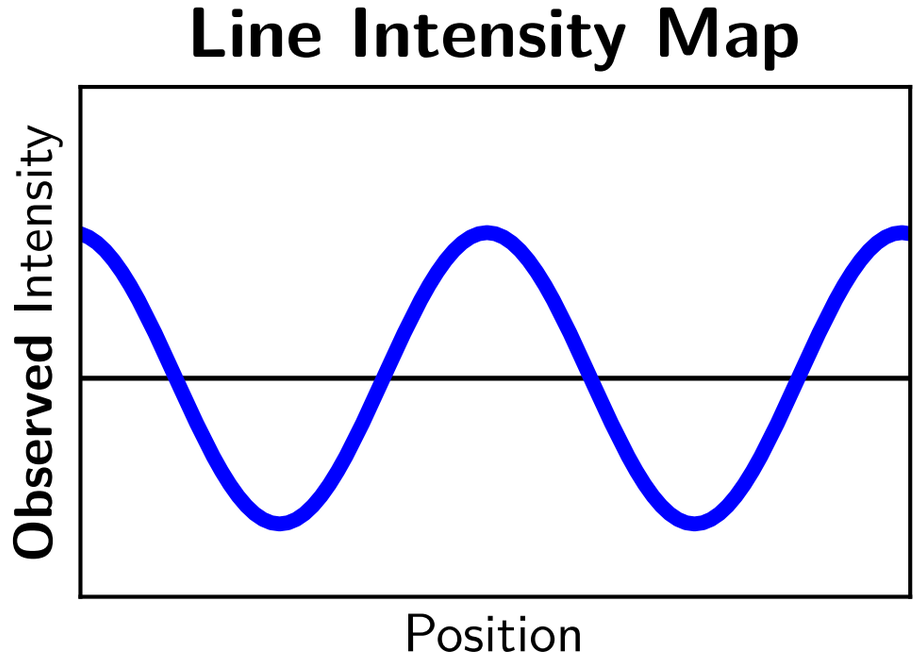


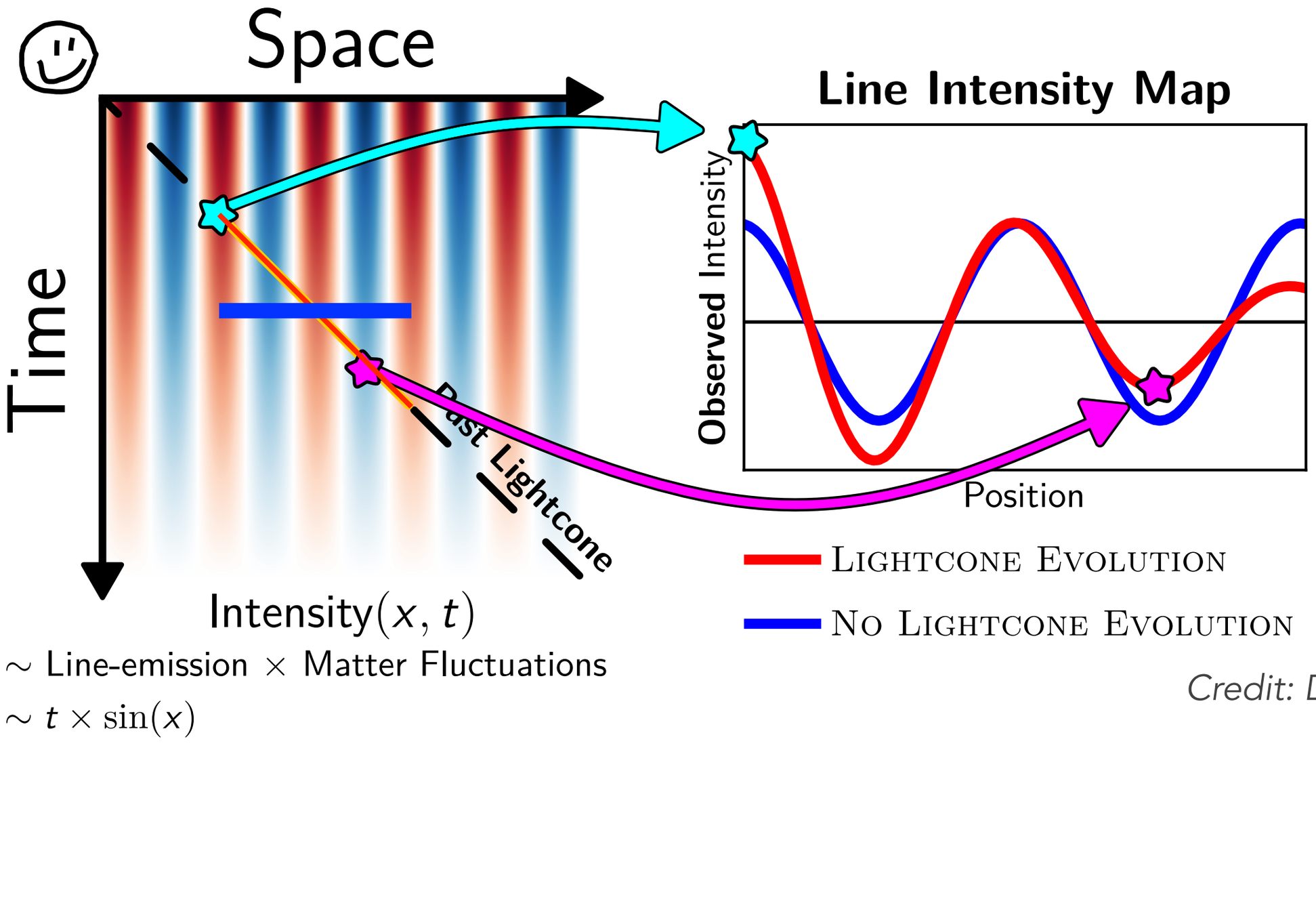
Credit: Delon Shen

LIM Fourier mode = matter density Fourier mode

Delon Shen

Nick Kokron

Mode mixing from time evolution



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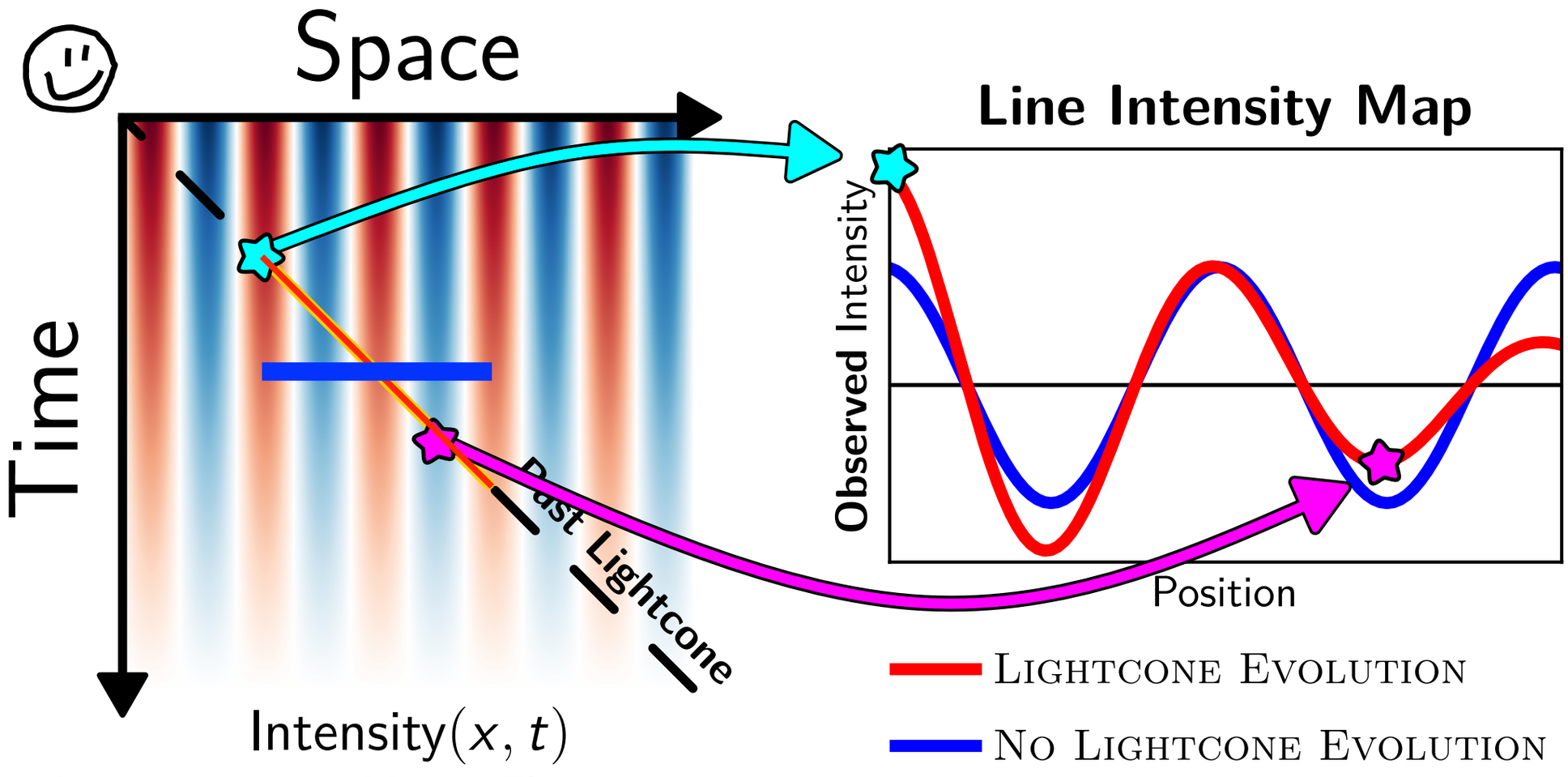
Credit: Delon Shen

Delon Shen

Nick Kokron

Mode mixing from time evolution



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

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

Credit: Delon Shen

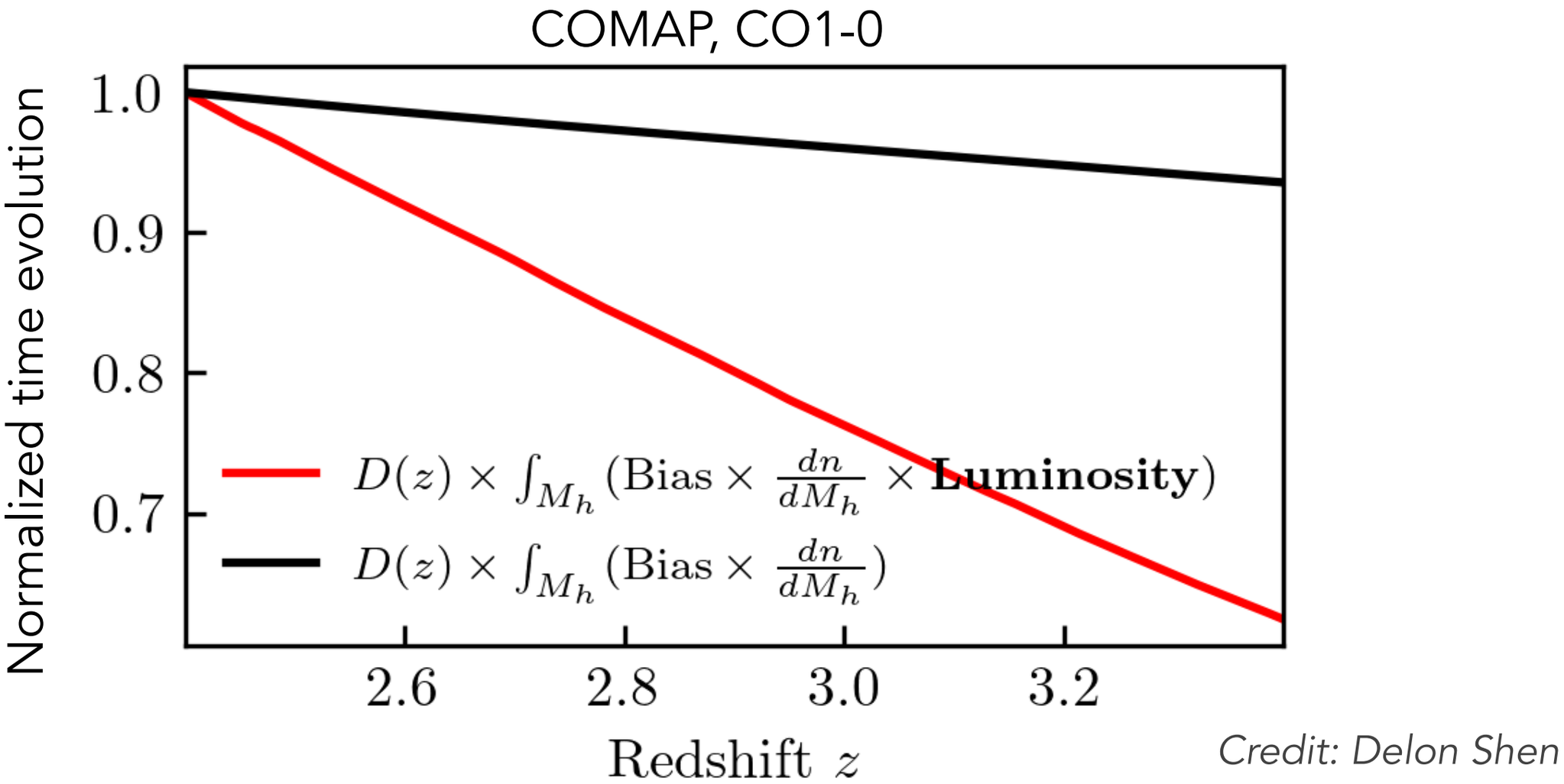
LIM Fourier mode $\supset$ all matter Fourier modes

True even in linear theory

$$I^{\rm obs}(\chi) \sim K_{\rm LIM}(\chi)\delta_m(\chi)$$

$$I^{\rm obs}(k) \sim \int_q K_{\rm LIM}(k-q)\delta_m(q)$$

Origin of the time evolution



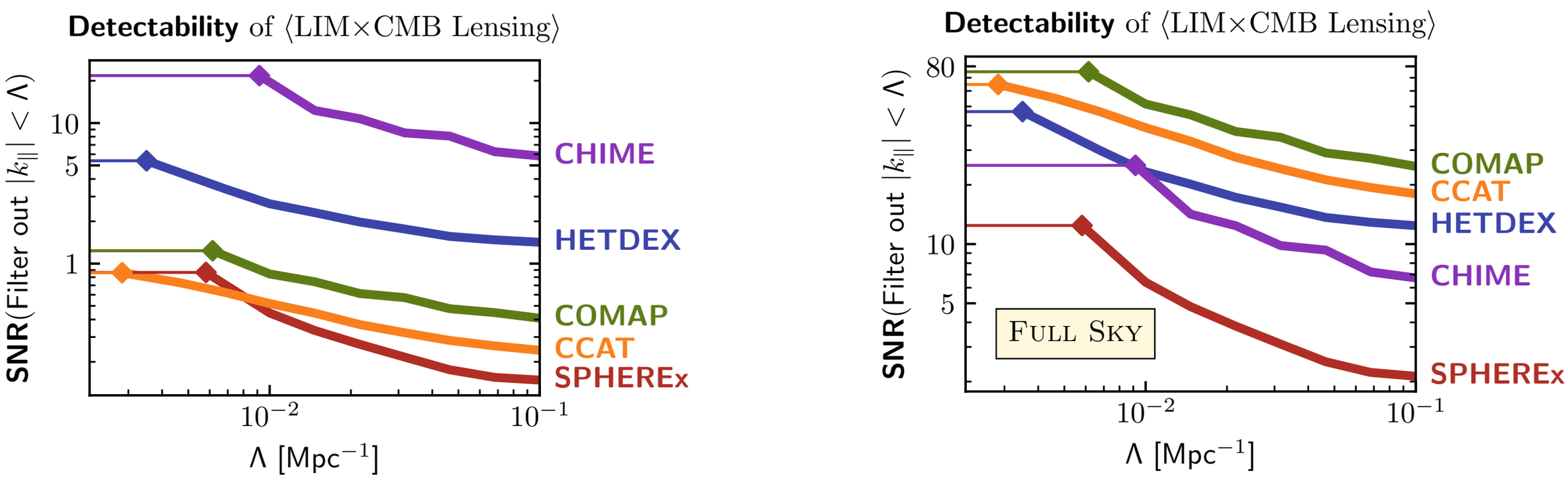
Credit: Delon Shen

Time evolution mostly due to halo luminosity evolution, not b.D

→ **Specific to LIM VS galaxy surveys**

Forecasting direct LIM x CMB lensing correlation

Current experiments → Future full-sky versions

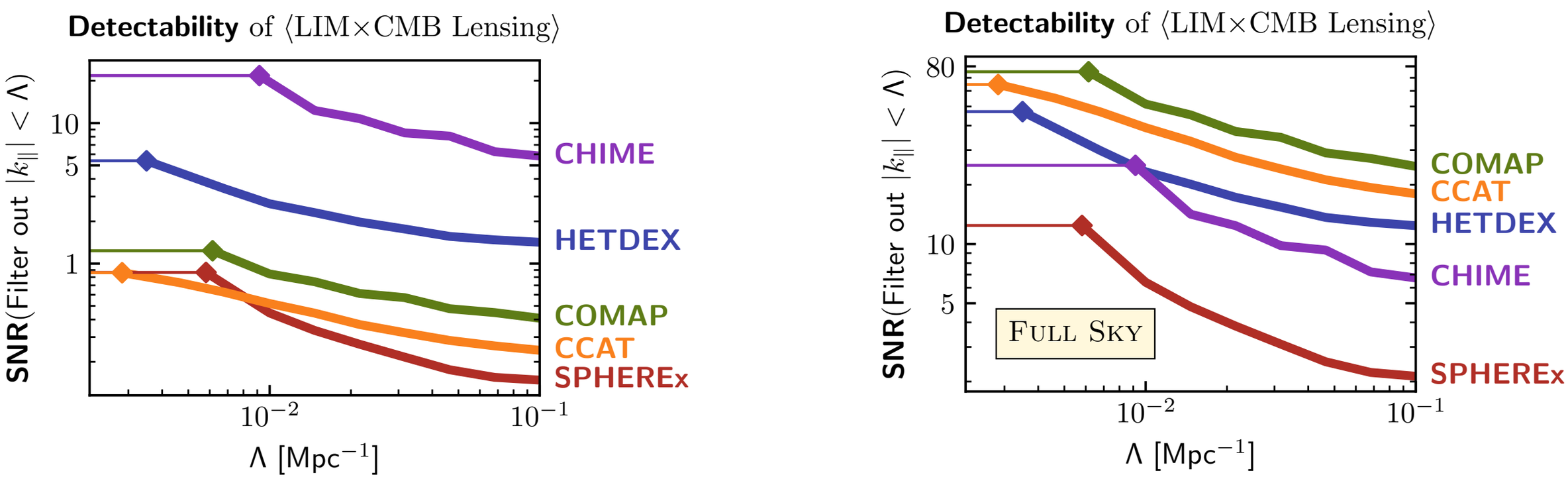


Shen Kokron Schaan 25

Direct cross-correlations LIM x 2D more promising than anticipated

Forecasting direct LIM x CMB lensing correlation

Current experiments → Future full-sky versions



Shen Kokron Schaan 25

Direct cross-correlations LIM x 2D more promising than anticipated

Mode coupling present even in linear theory
Motivates exploring other 2D fields (CIB, SZ, etc)
(Limber approximation inaccurate here)
(Delon unifies/clarifies signal & noise models for several LIM)

Conclusions

Cross-correlations with CMB / galaxy surveys are crucial
for IM at high z

Foregrounds → Missing large-scale Fourier modes

But the large-scales can be reconstructed from small scales
via tidal reconstruction and lensing reconstruction
Doux Schaan+16, Schaan Ferraro Spergel 19, Maniyar Schaan Pullen 21, La Posta Schaan 24, Pinsonneault-Marotte+in prep

Large-scales also leak into small-scales due to time evolution
Shen Kokron Schaan 25

Pairs of lines at same z avoid many interloper biases
Schaan White 21a, b, Maniyar Schaan Pullen 21