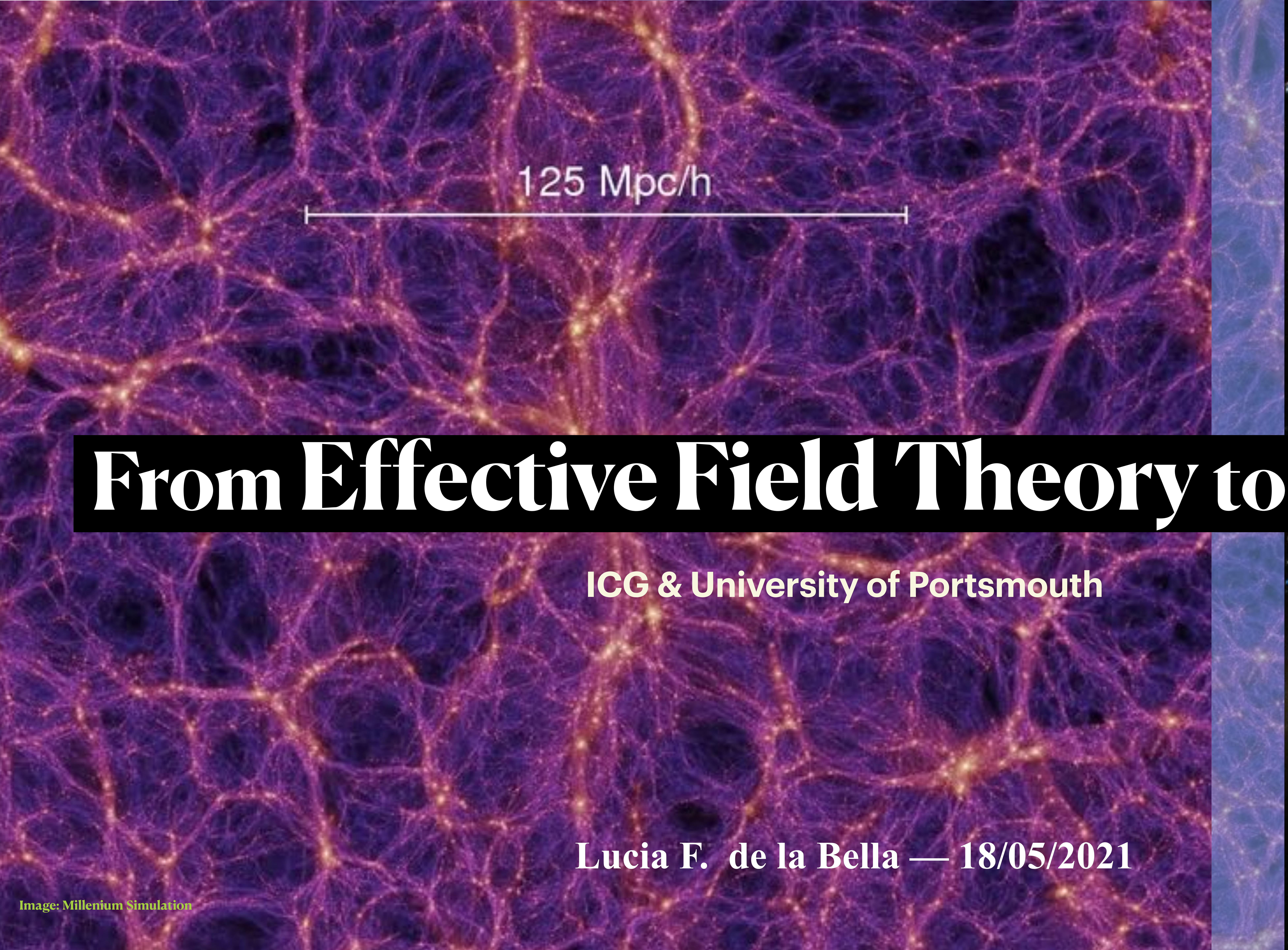


Image: Millenium Simulation

From Effective Field Theory to lensing

ICG & University of Portsmouth

Lucia F. de la Bella — 18/05/2021

https://howtoreachthecosmos.jimdofree.com

Lucia F. de la Bella

- I'm Spanish
- I have a twin sister
- Craft hobbies
- Love nature & hiking
- Gospel Choir

UNIVERSIDAD COMPLUTENSE MADRID

B.Sc

Quantum Cosmology

2008-2013

Aix*Marseille université

M.Sc

EFToDE

2013-2014

US University of Sussex

PhD

EFToLSS
RSDs
Halo bias

2014-2018

Teaching

2018-2019

MANCHESTER 1824
The University of Manchester

PDRA

2019-2021

Weak Lensing

Unequal-time correlators

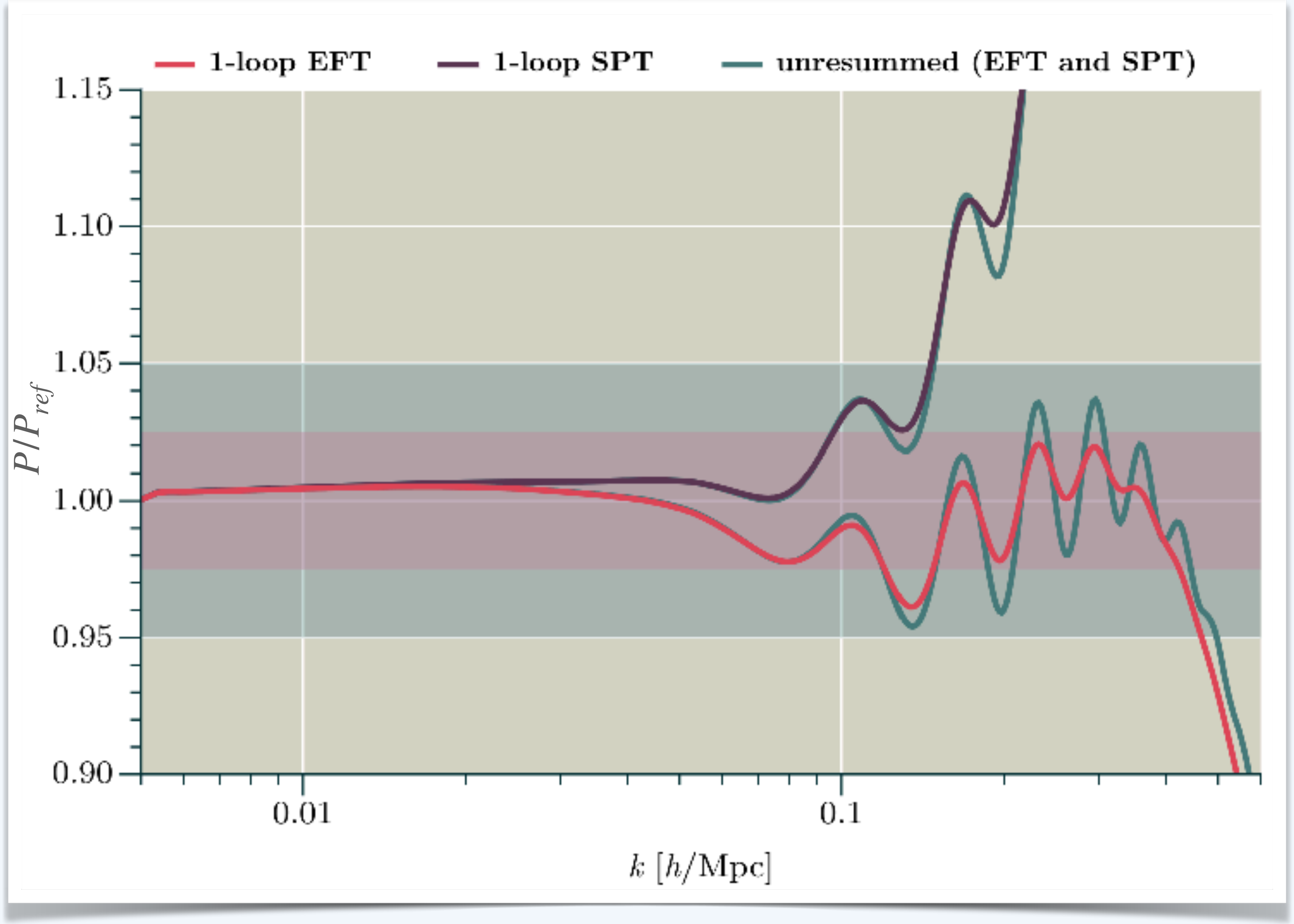
ICG Portsmouth

Effective Field Theory of Large Scale Structure

de la Bella et al. 2017
de la Bella et al. 2018

Linear regime SPT works.
Mild non-linear regime SPT breaks down.
Non-linear regime unknown description.

$$P_{EFT} = P_{SPT} - \underset{\text{counterterm}}{c^2 k^2 P_{11}}$$



Traditionally

- One-loop power spectrum in standard perturbation theory
- Einstein-de Sitter approximation for growth functions
- Divergences from small-scale physics

New

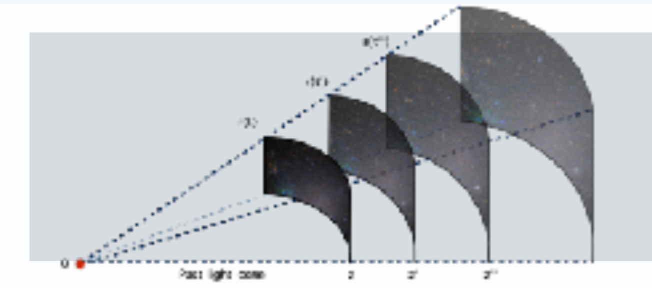
- One-loop power spectrum in redshift space
- Most general bias model
- Full time dependence non-linear growth functions
- Novel analytical methods:
  - Split tensor and scalar loop integrals
  - Fabrikant's procedure for Bessel functions
- Counterterms:
  - Uniform notation and language
- Applied the Vlah et al. IR-resummation scheme in redshift space.

Application

- Redshift-space distortions
- Halo bias and WIZCOLA sims

Impact

- Accuracy on smaller scales!



Unequal-time correlators

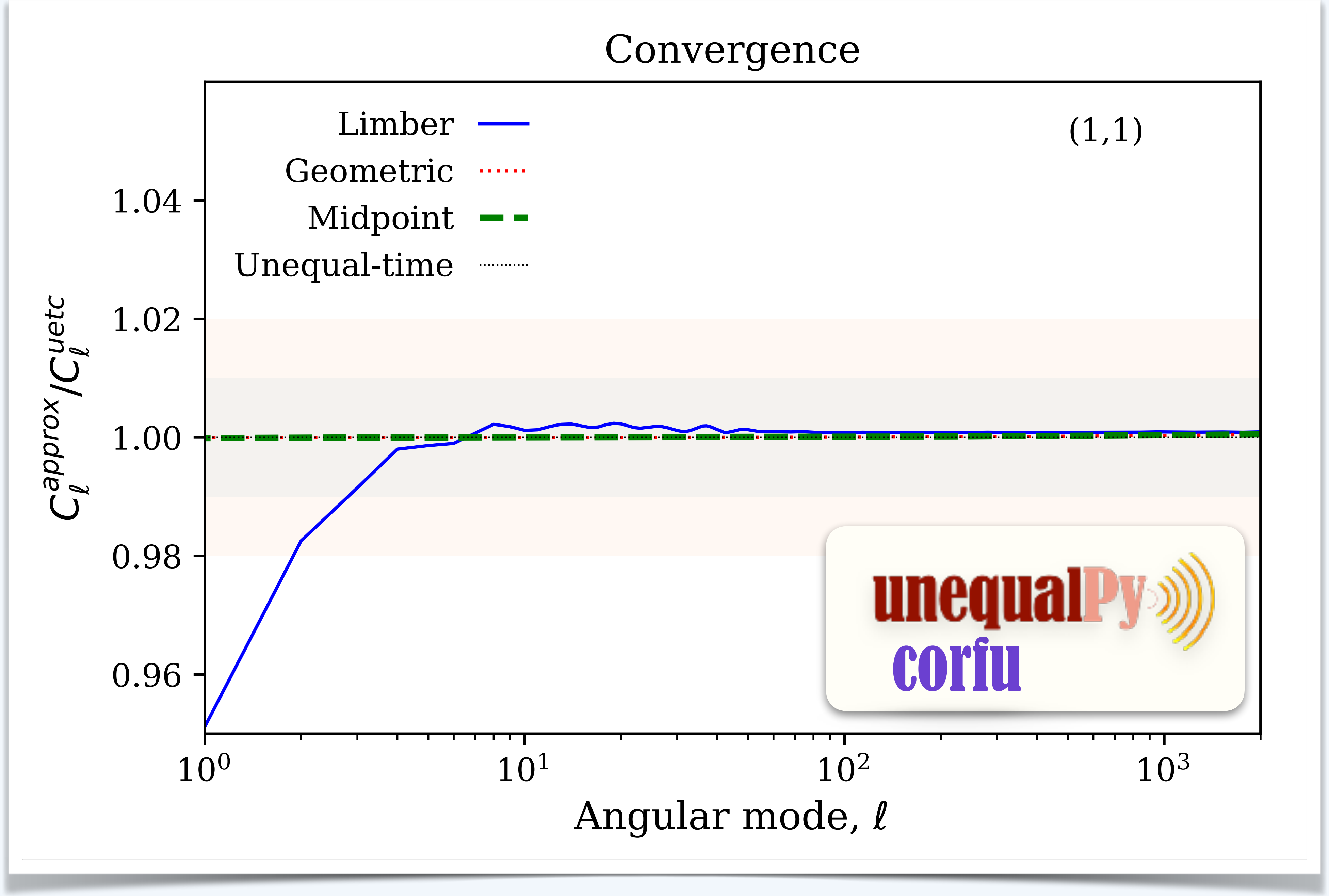
de la Bella et al. (2020)
Tessore, de la Bella (in prep)

Correlations between fields

- Same time slice: *equal-time correlators*
- Different time slices: *unequal-time correlators*

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, f_1(x_1) f_2(x_2)\, \xi(r_{12}; t_1, t_2)$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\;\, f_1(x_1) f_2(x_2) j_\ell(kx_1) j_\ell(kx_2) \boxed{P(k; t_1, t_2)}$$



Traditionally

- Limber's approximation and equal-time power spectrum
- Only good for linear theory and small-angle separations

New

- **Exact** angular power spectrum at all angular scales
- Flexibility to include equal and **unequal-time** correlators

- Unequal-time correlator:
  - One-loop SPT and EFToLSS
  - First fitting formula for counterterms
  - New midpoint approximation
  - Open-source software: **unequalpy**
- Exact angular correlations:
  - FFTLog methods
  - Avoid highly-oscillatory Bessel functions.
  - Open-source software: **corfu**

Application

- Cosmic convergence
- Galaxy clustering
- Galaxy-galaxy lensing
- DES Y1 & LSST Y10

Impact

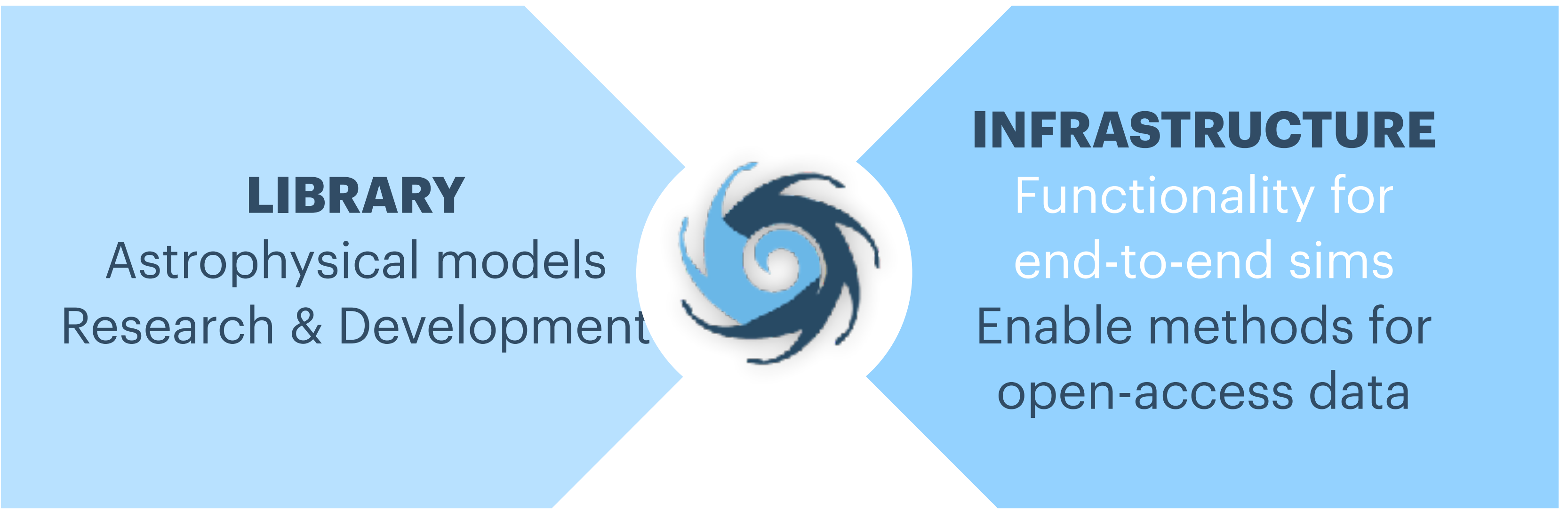
- Drop Limber's approximation
- Relevant even for DES Y1

The SkyPy Project

SkyPy v0.4

COMMUNITY PACKAGE

- **Open-source** off-project
- High-quality **Python** package



LIBRARY
Astrophysical models
Research & Development

INFRASTRUCTURE
Functionality for
end-to-end sims
Enable methods for
open-access data

- **GitHub** organisation
- Unit tests & high-quality documentation
- Code review & Infrastructure team

```
pip install skypy or
conda install -c conda-forge skypy or
git clone https://github.com/skypyproject/skypy.git
import skypy
```

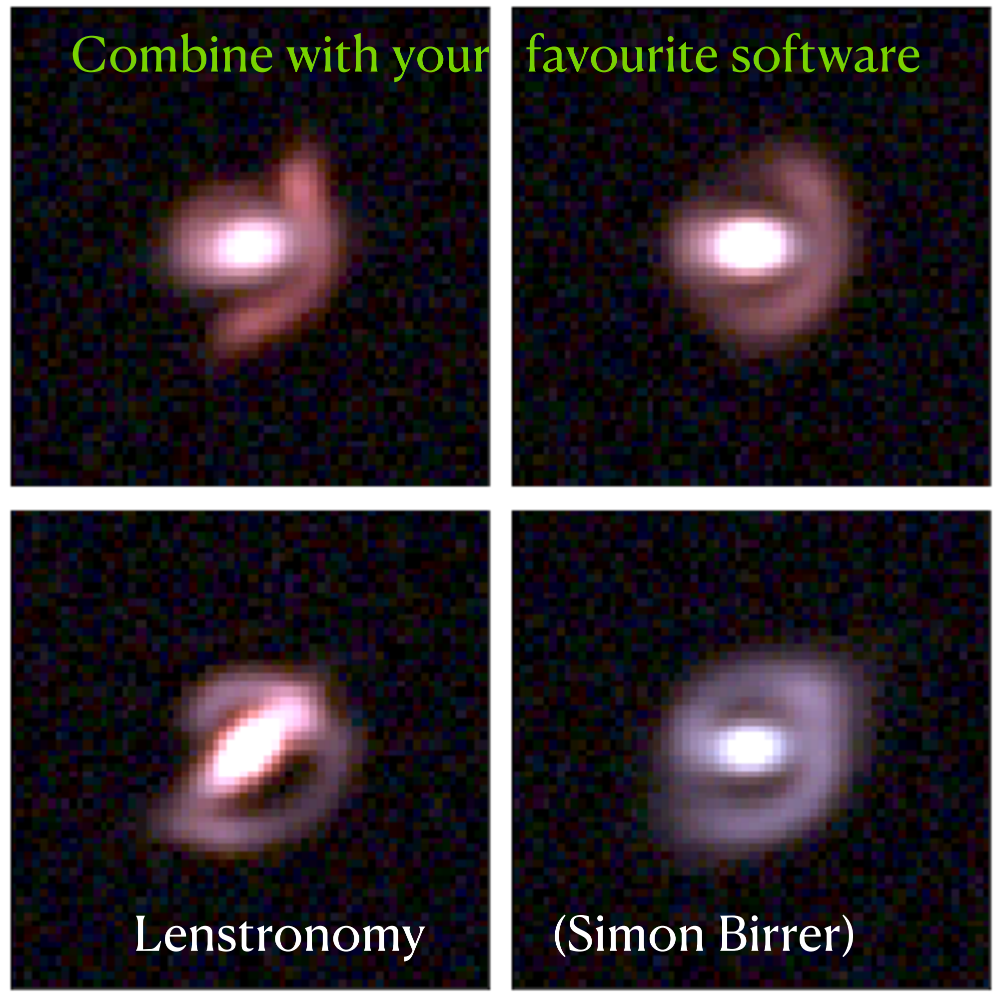
https://github.com/skypyproject/skypy.git

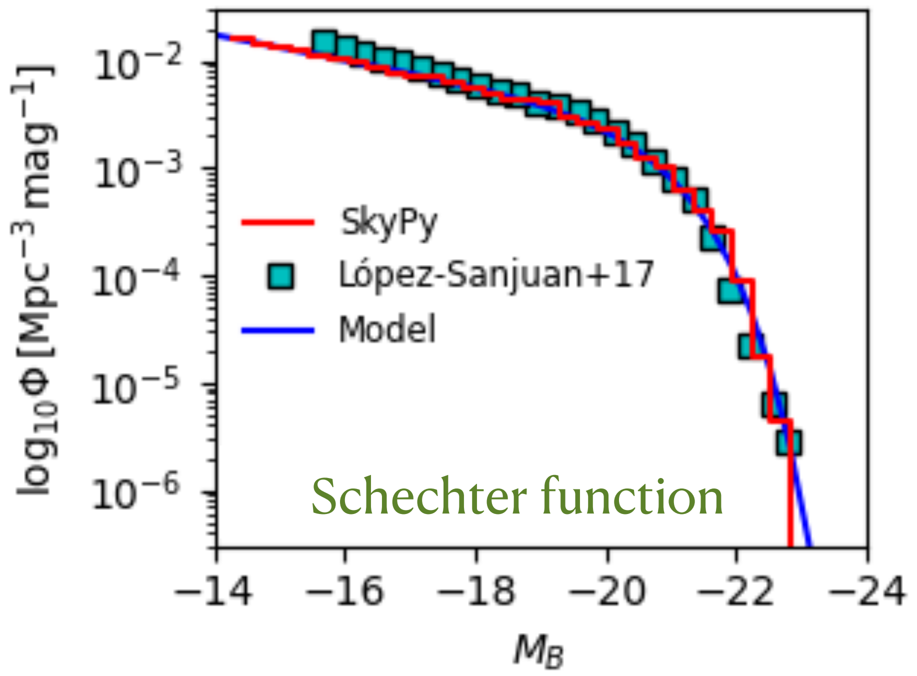
https://skypyproject.org

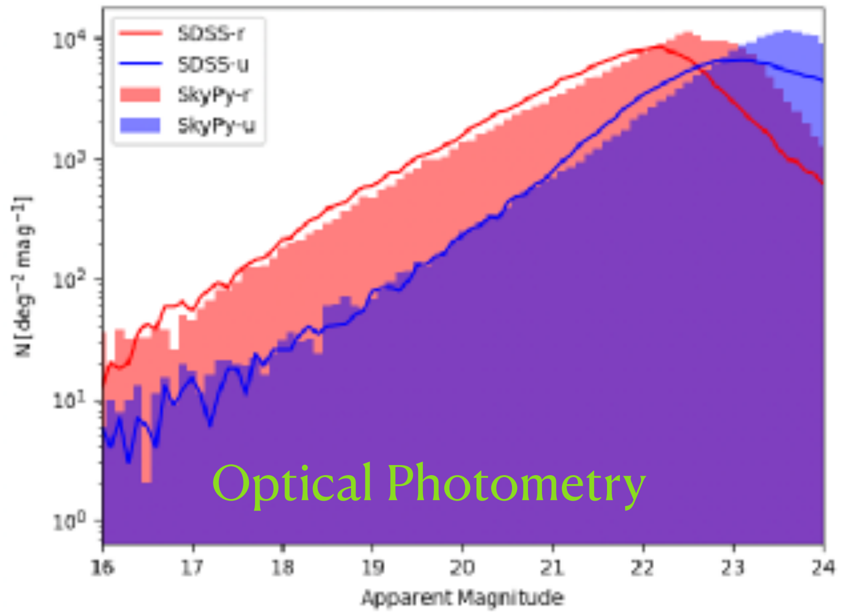
SIMULATION PIPELINES

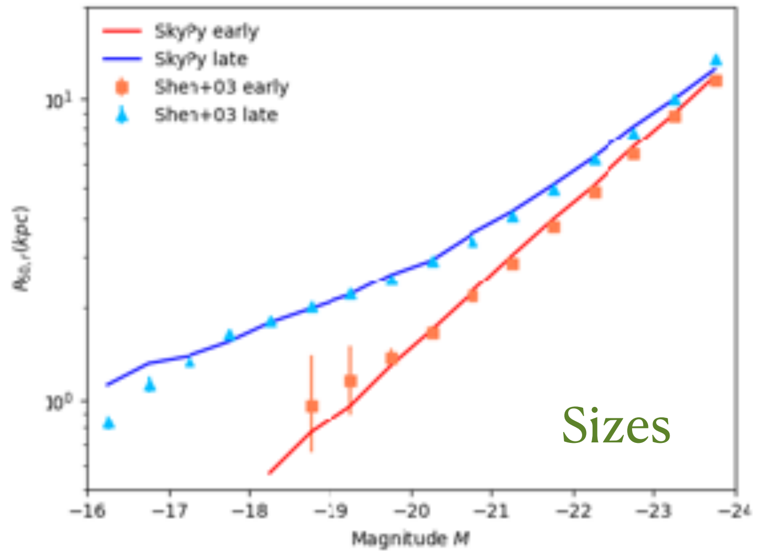
- YAML-based config files
- The **SkyPy Driver** runs end-to-end **pipelines**
- **Total flexibility**!

- SkyPy Pipeline
- **KEY: you** can write your own **pipelines!**









https://skypy.readthedocs.io/en/latest/examples/index.html

Work in progress...

Eftpy

Idea

- **Screening** phenomena
- Merge **EFToLSS** and **EFToDE**
- Make use of counterterms

Traditionally

- Linear power spectrum for dark energy and modified gravity theories

New

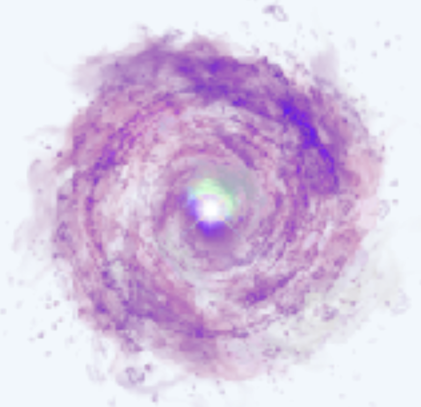
- First **library** for non-linear power spectrum within EFToDE
  - Parametrisation of screening
  - Determination of screening scale
  - Open-source software: **eftPy**

Application

- Covariance Galileons
- Simulations

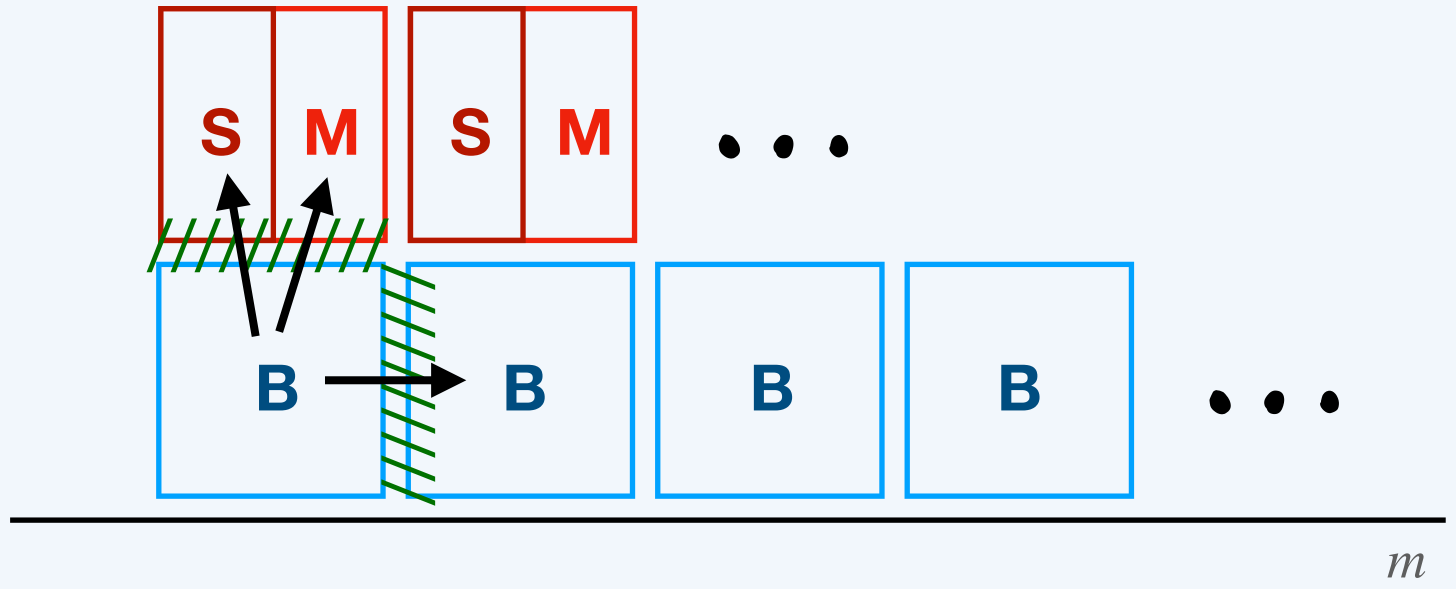
Impact

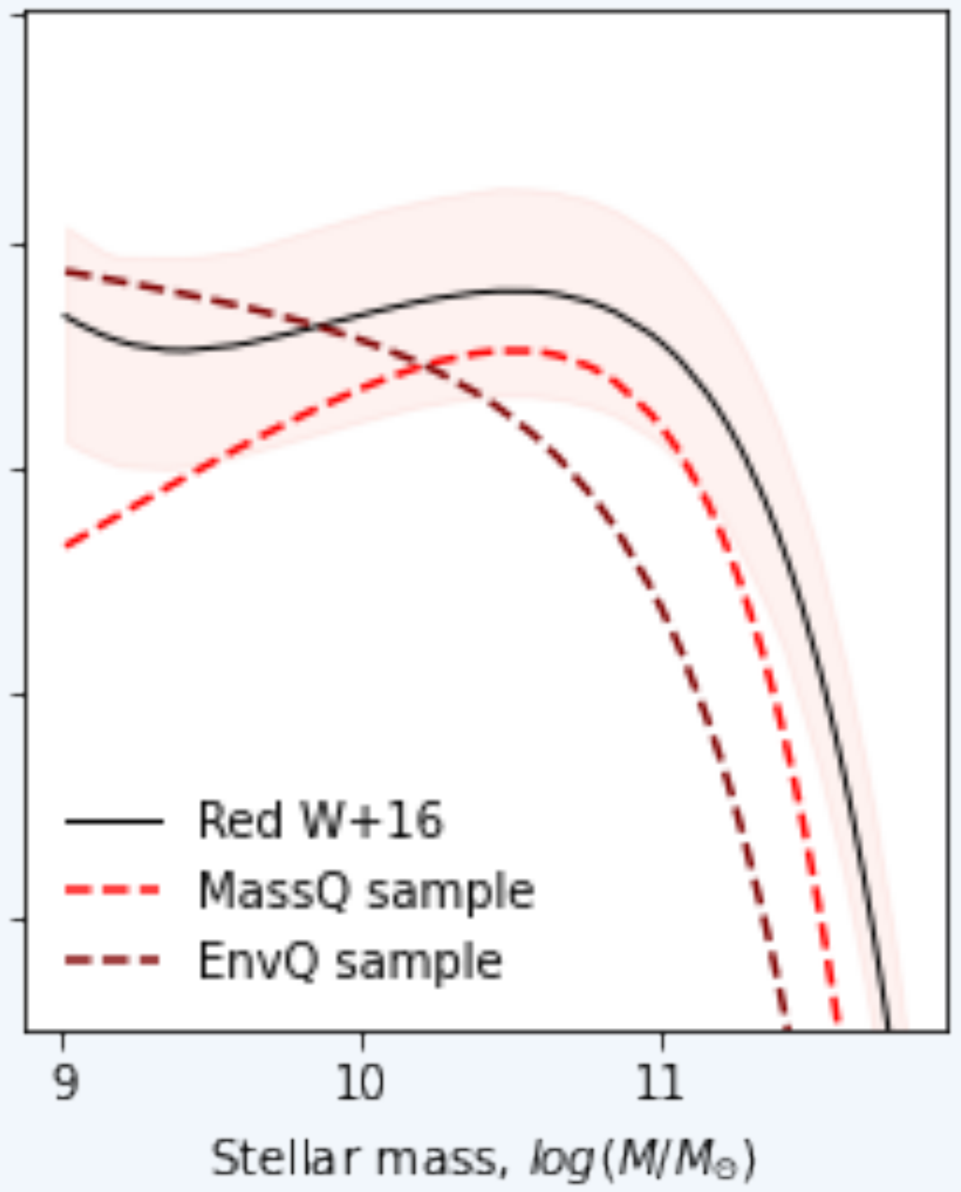
- Crucial to truly compare with observations



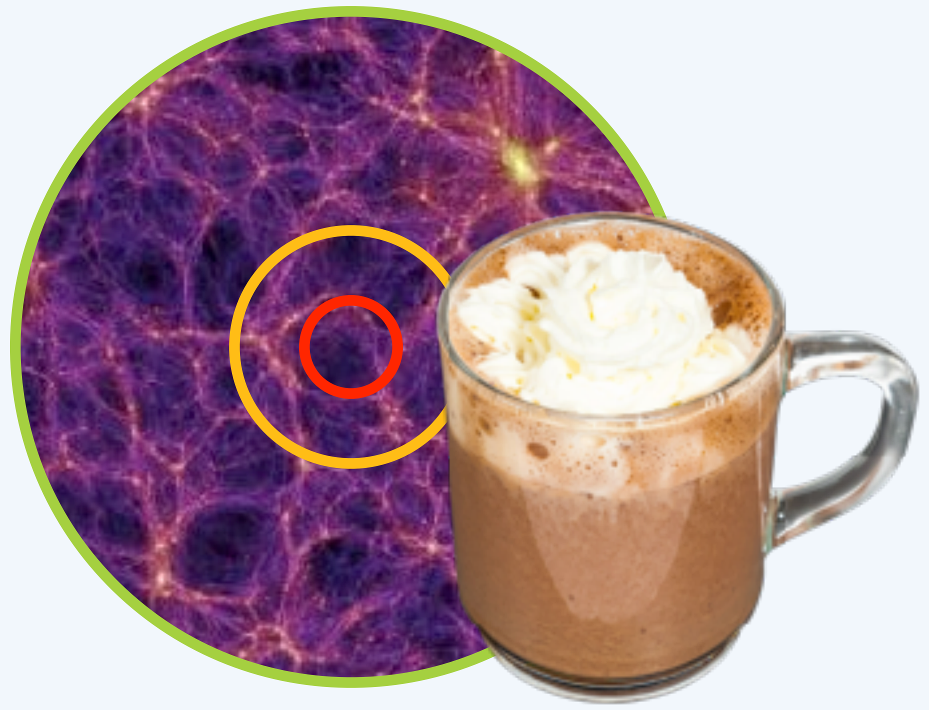
Quenched galaxies

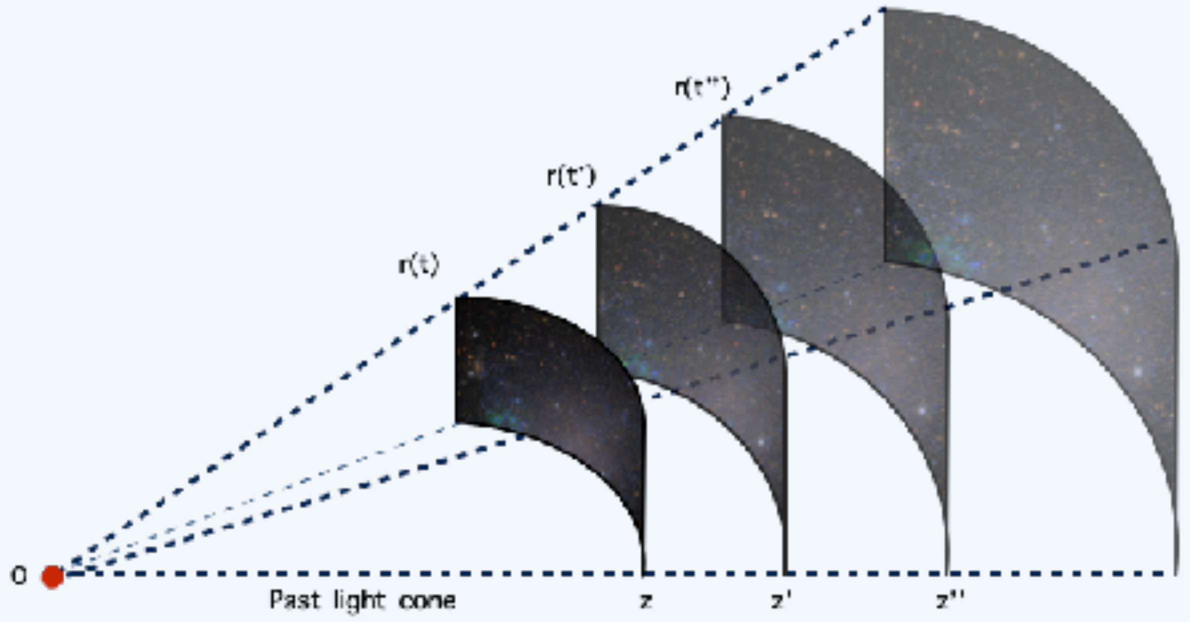
- Star-forming galaxies $\{\phi_b^*, \alpha_b, m_b^*\}$
- Satellite-quenched g. $\{\phi_\rho^*, \alpha_\rho, m_\rho^*\}$
- Mass-quenched g. $\{\phi_m^*, \alpha_m, m_m^*\}$





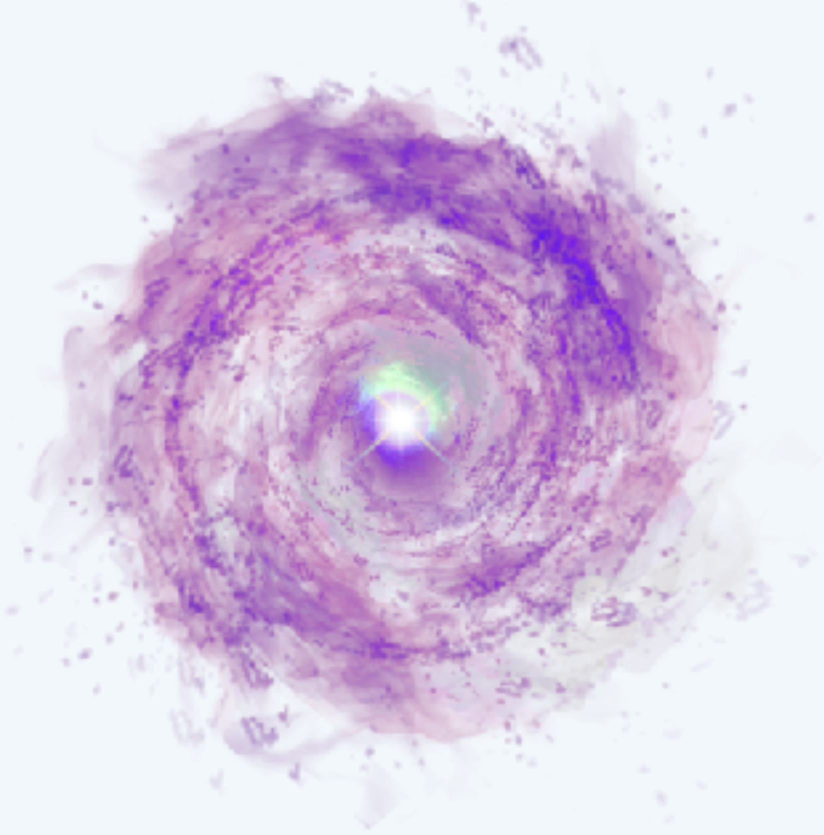
SkyPy v0.4

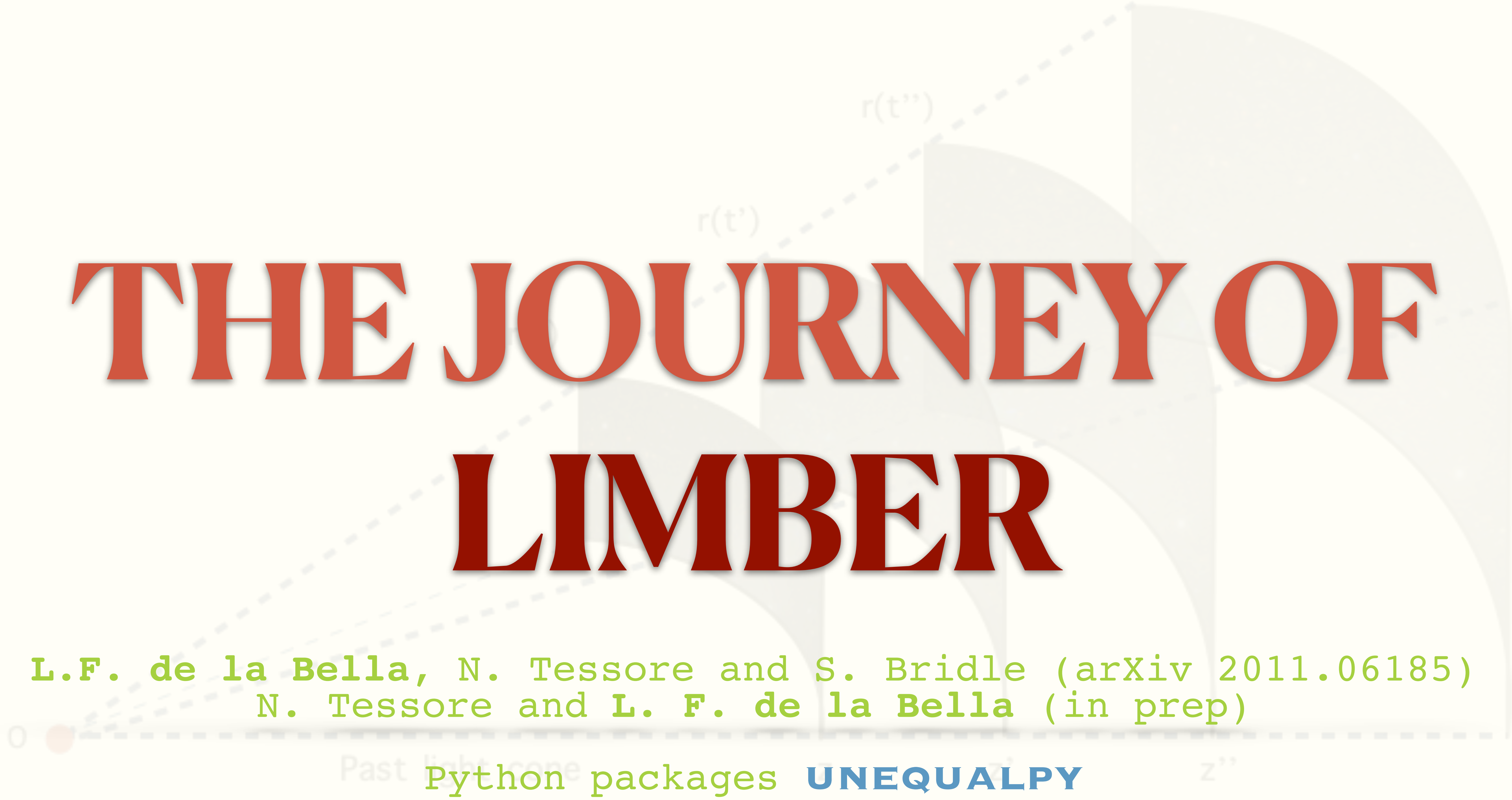




Interested in these topics?
Happy to chat!

Eftpy

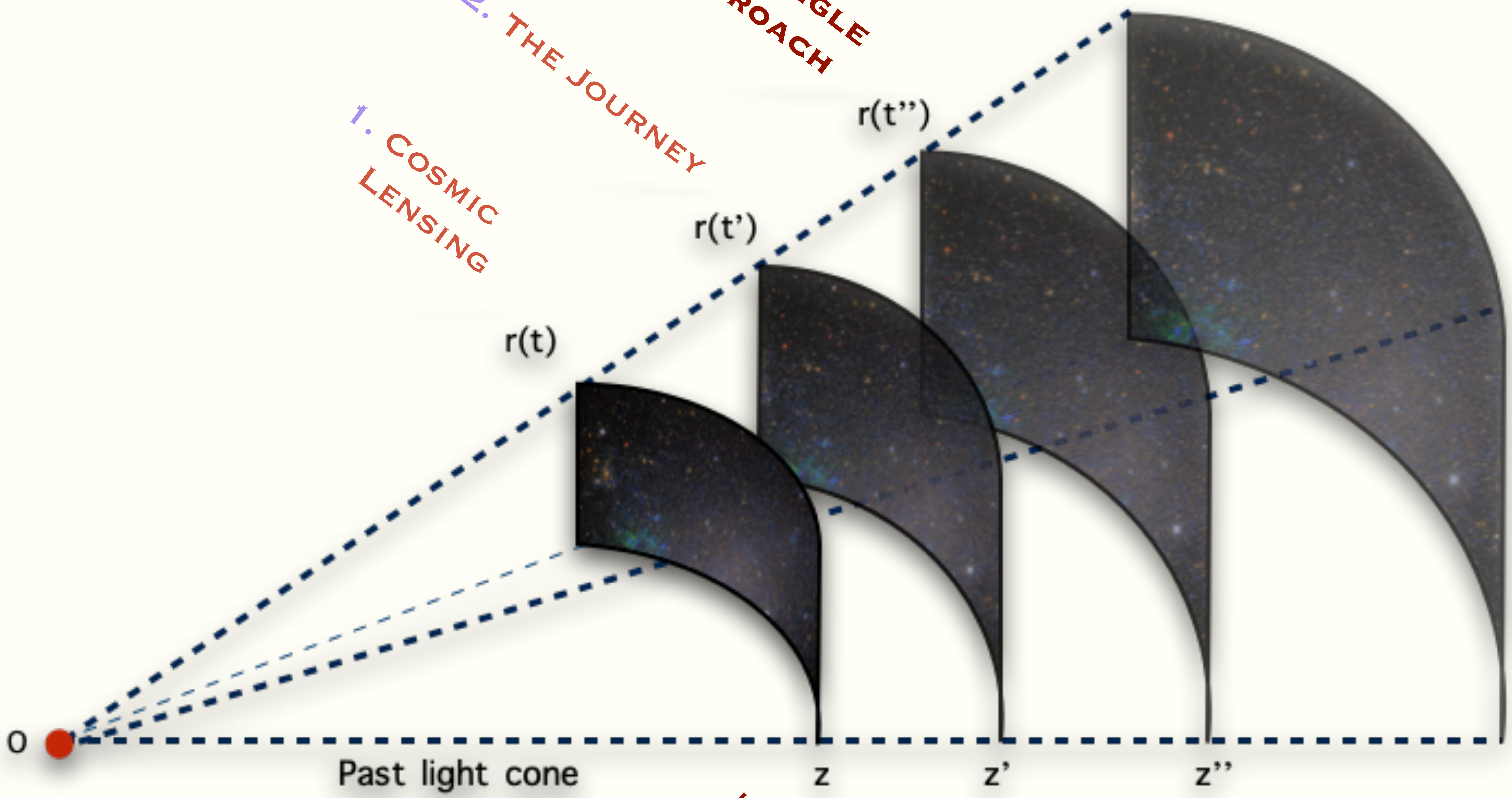




THE JOURNEY OF LIMBER

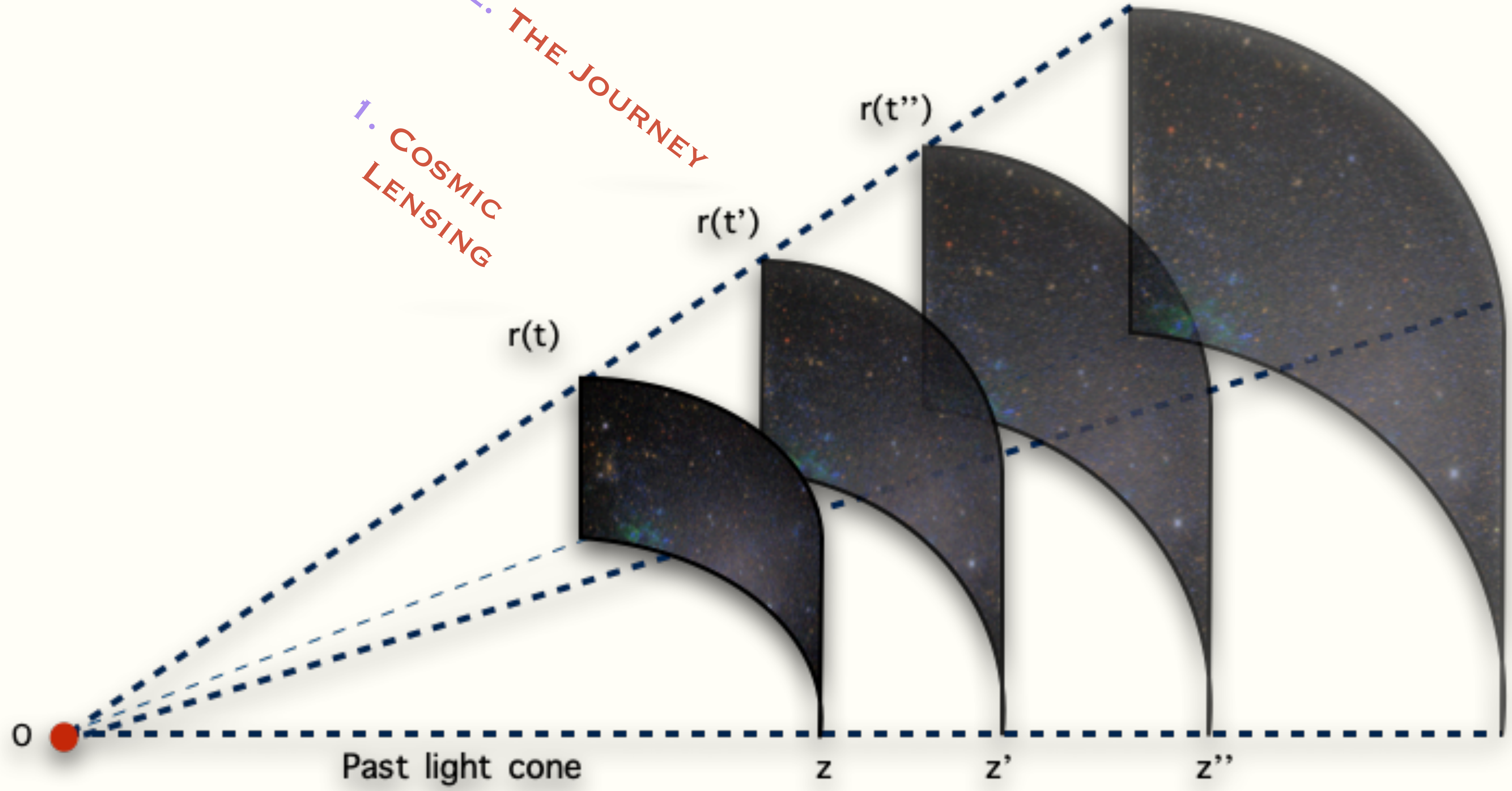
L.F. de la Bella, N. Tessore and S. Bridle (arXiv 2011.06185)
N. Tessore and **L. F. de la Bella** (in prep)

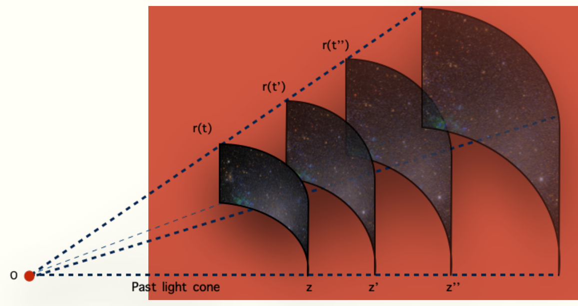
Python packages **UNEQUALPY**
CORFU


r(t)
r(t')
r(t'')
O
Past light cone
z
z'
z''

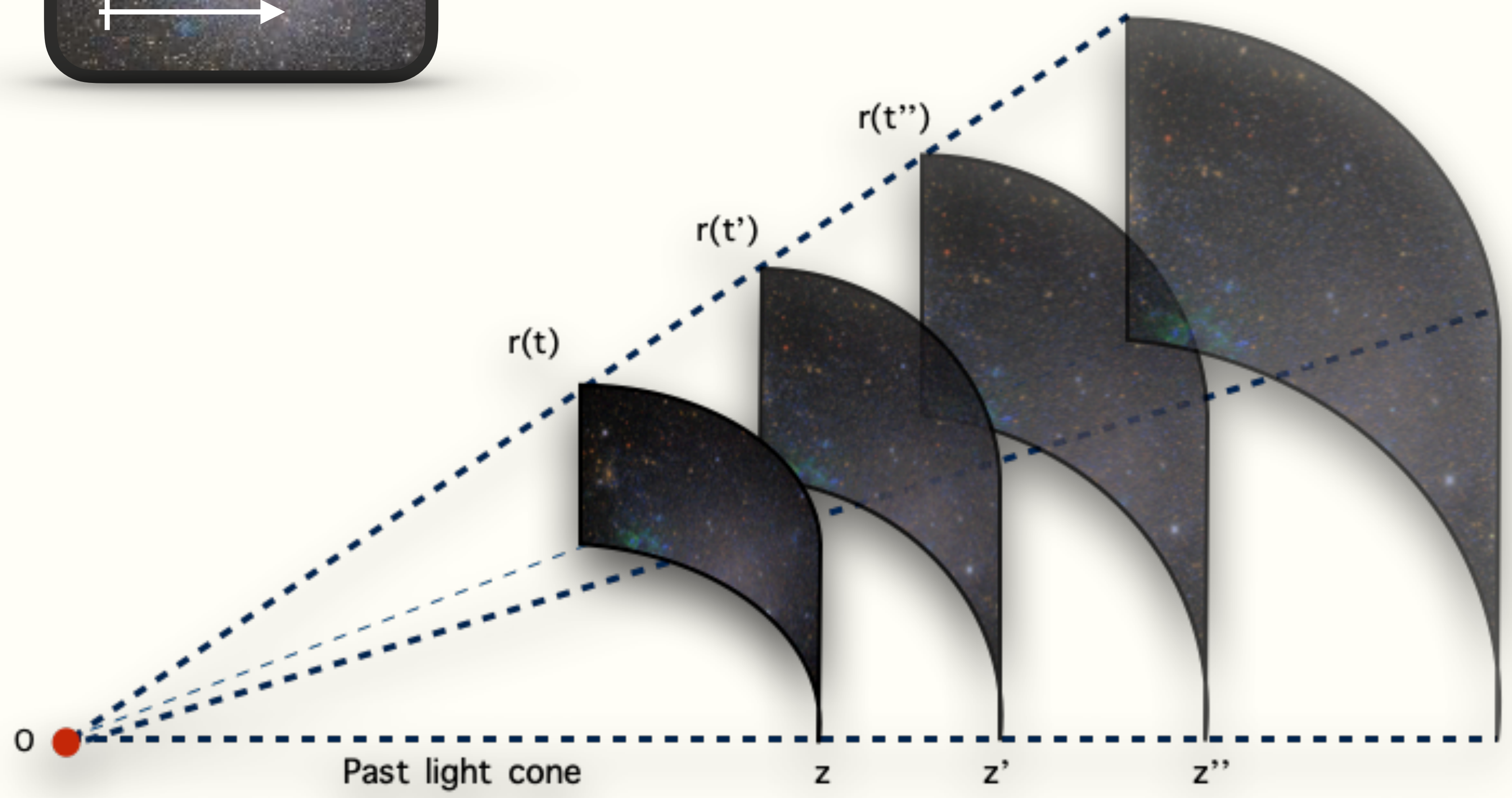
1. COSMIC LENSING

2. THE JOURNEY





1. Cosmic Lensing



Correlations between fields

- Same time slice: *equal-time correlators*
- Different time slices: *unequal-time correlators*

Examples of fields:

Matter, convergence, cosmic shear

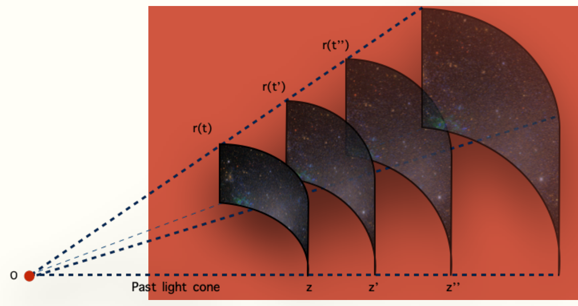
Angular correlation function

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, \underbrace{f_1(x_1) f_2(x_2)}_{\text{Filters}}\, \underbrace{\xi(r_{12}; t_1, t_2)}_{\text{Unequal-time correlation function}}$$

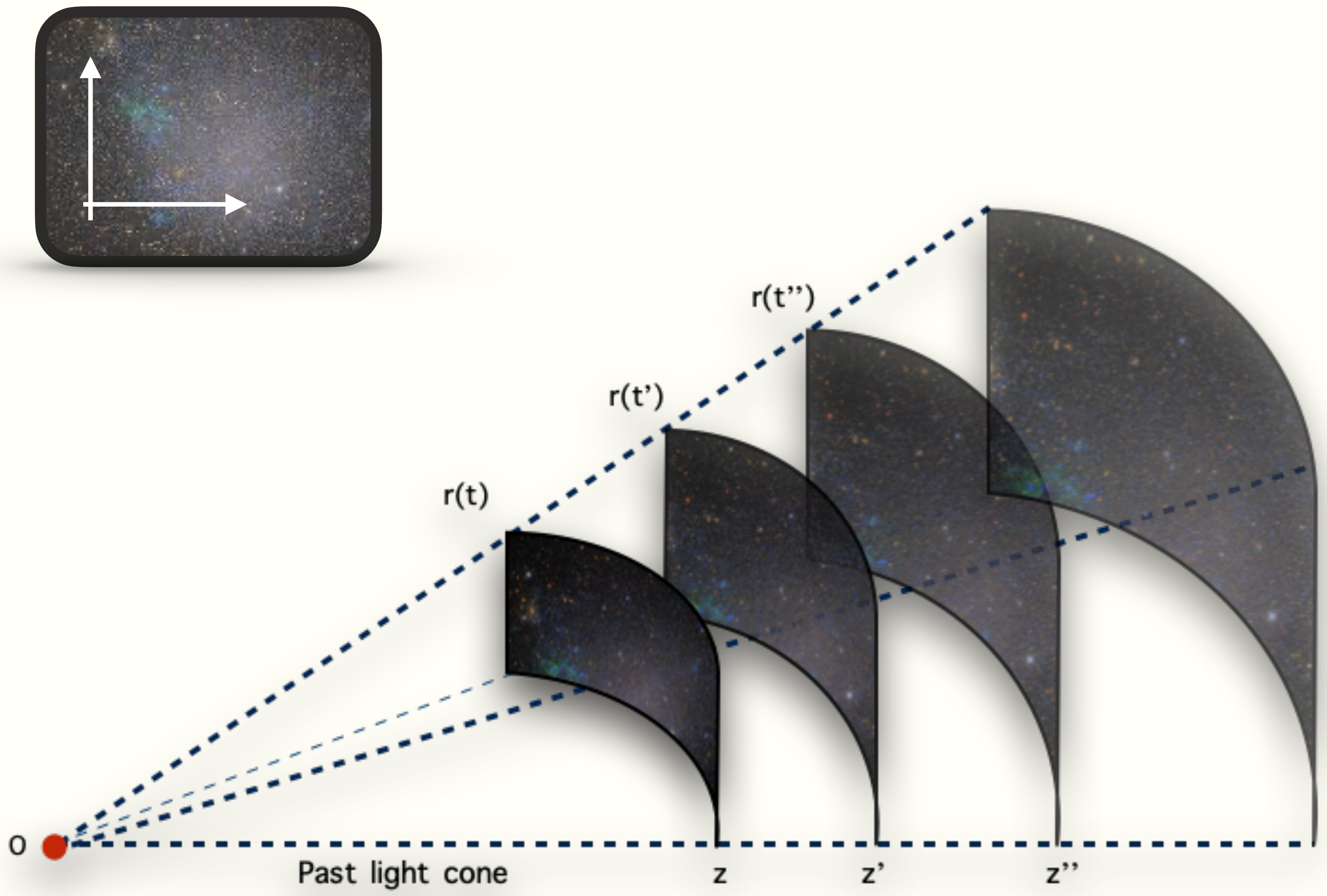
Angular power spectrum

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\, f_1(x_1) f_2(x_2) \underbrace{j_\ell(kx_1)\, j_\ell(kx_2)}_{\text{Bessel functions}}\, \underbrace{P(k; t_1, t_2)}_{\text{Unequal-time Power spectrum}}$$

Note: lookback time = redshift = co-moving distance



1. Cosmic Lensing



Correlations between fields

- Same time slice: *equal-time correlators*
- Different time slices: *unequal-time correlators*

Examples of fields:

Matter, convergence, cosmic shear

Angular correlation function

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, \underbrace{f_1(x_1)\, f_2(x_2)}_{\text{FILTERS}}\, \underbrace{\xi(r_{12}; t_1, t_2)}_{\text{UNEQUAL-TIME CORRELATION FUNCTION}}$$

HARD TO COMPUTE

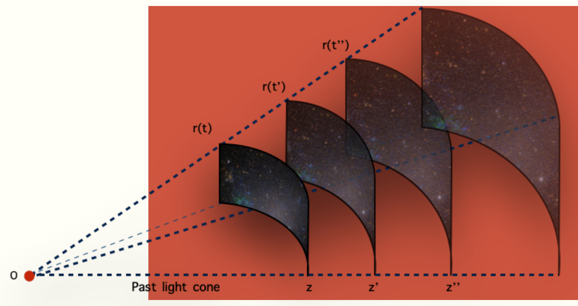
Angular power spectrum

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\, f_1(x_1)\, f_2(x_2)\, \underbrace{j_\ell(kx_1)\, j_\ell(kx_2)}_{\text{BESSEL FUNCTIONS}}\, \underbrace{P(k; t_1, t_2)}_{\text{UNEQUAL-TIME POWER SPECTRUM}}$$

EVEN HARDER TO COMPUTE

This work

Note: lookback time = redshift = co-moving distance

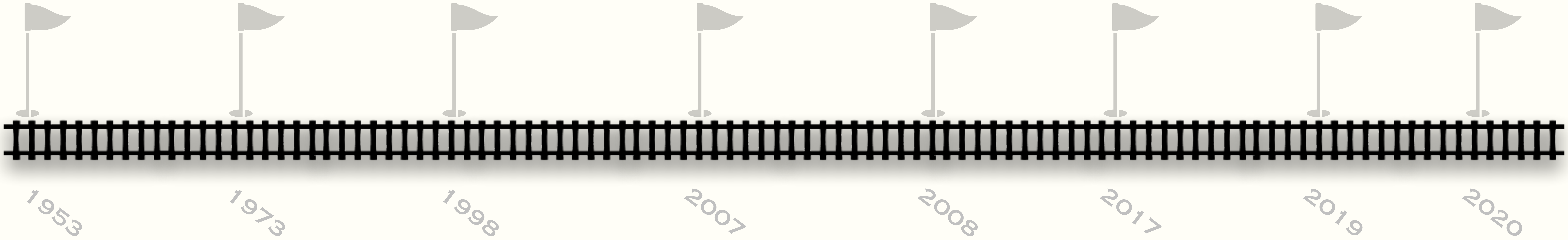


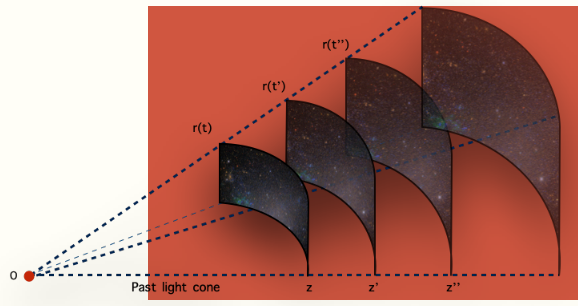
2. The Journey

$$w(\theta) = \iint_0^\infty dx_1\, dx_2 \boxed{f_1(x_1) f_2(x_2)} \boxed{\xi(r_{12}; t_1, t_2)}$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2 \boxed{f_1(x_1) f_2(x_2)} \boxed{j_\ell(kx_1)\, j_\ell(kx_2)} \boxed{P(k; t_1, t_2)}$$

- Filters
- Bessel functions
- Unequal-time correlators





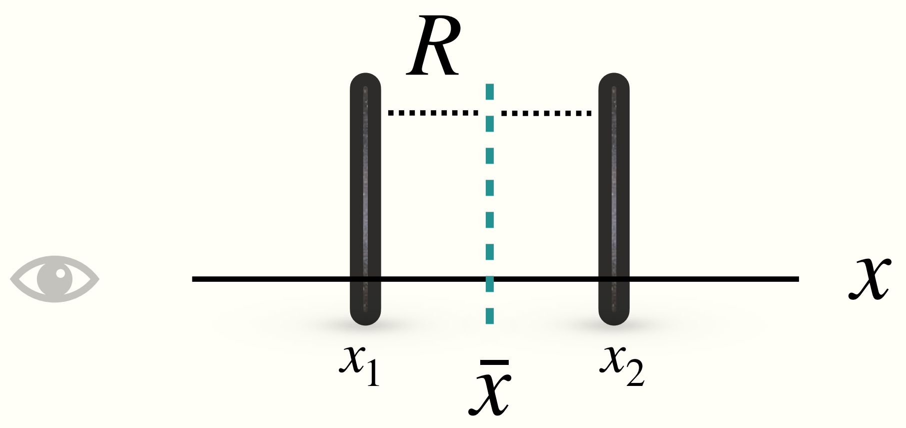
2. The Journey

$$w(\theta) = \iint_0^\infty dx_1\, dx_2 \boxed{f_1(x_1) f_2(x_2)} \boxed{\xi(r_{12}; t_1, t_2)}$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\ f_1(x_1) f_2(x_2) j_\ell(kx_1) j_\ell(kx_2)\, P(k; t_1, t_2)$$

Assumptions:

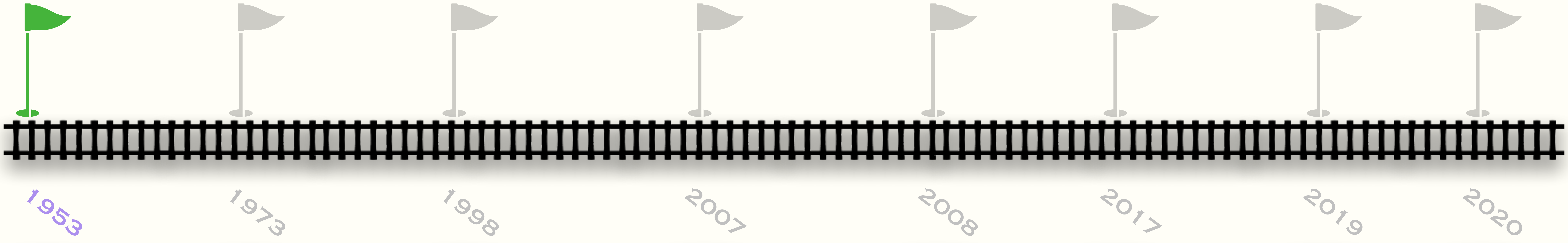
i) Smooth filters
ii) Correlation falls off fast
iii) Small angle separation

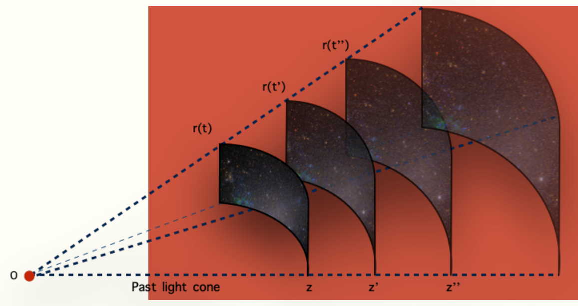


$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\, f_1(\bar{x}) f_2(\bar{x})\, \xi(r_{12}; \bar{t})$$

i) Filters
ii) Mid point

LIMBER





2. The Journey

$$w(\theta) = \iint_0^\infty dx_1\, dx_2 \boxed{f_1(x_1) f_2(x_2)} \boxed{\xi(r_{12}; t_1, t_2)}$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\;\; f_1(x_1) f_2(x_2)\, j_\ell(kx_1)\, j_\ell(kx_2)\, P(k; t_1, t_2)$$

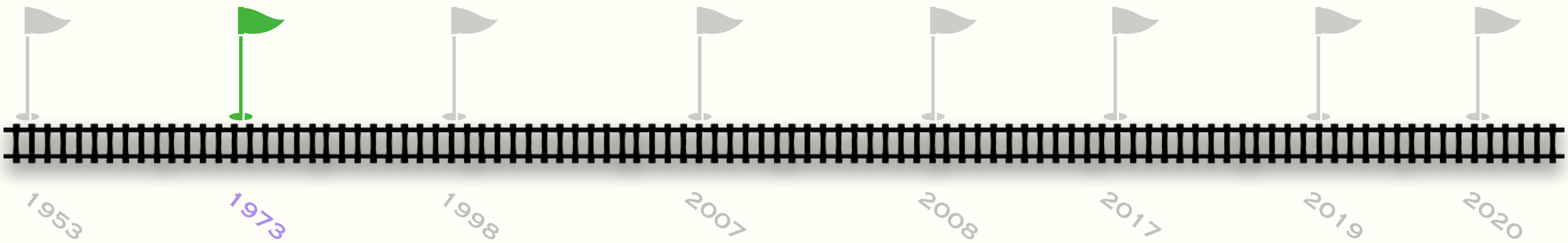
$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\, f_1(\bar{x})\, f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

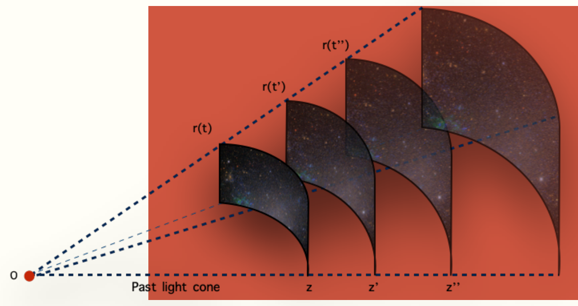
i) Filters
ii) Mid point

i) Sphere
ii) Discrete case

LIMBER

PEEBLES





2. The Journey

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, \boxed{f_1(x_1) f_2(x_2)}\, \xi(r_{12}; t_1, t_2)$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\, \boxed{f_1(x_1) f_2(x_2)}\, j_\ell(kx_1)\, j_\ell(kx_2)\, P(k; t_1, t_2)$$

$$C(\ell) = \int d^2\vec{\theta}\, w(\theta) \mathrm{e}^{-i\vec{\ell}\cdot\vec{\theta}}$$

$$\approx \int dx \frac{f_1(x) f_2(x)}{x^2} P(\ell/x; t)$$

Fourier space
Delta functions

$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\, f_1(\bar{x})\, f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

i) Filters
ii) Mid point

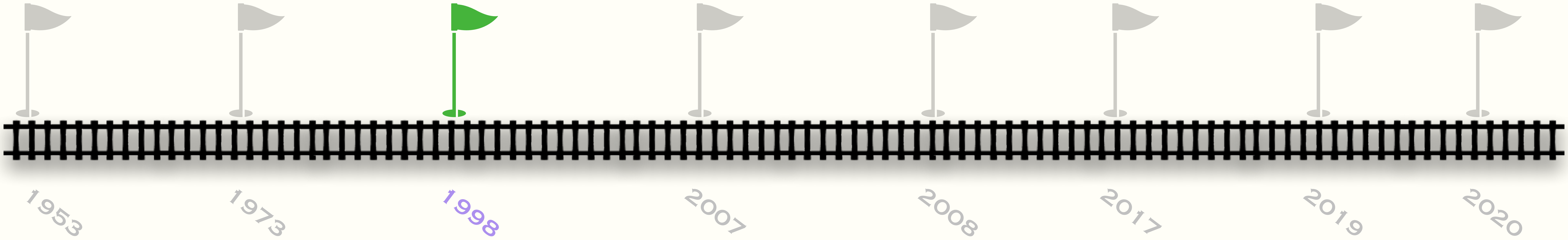
LIMBER

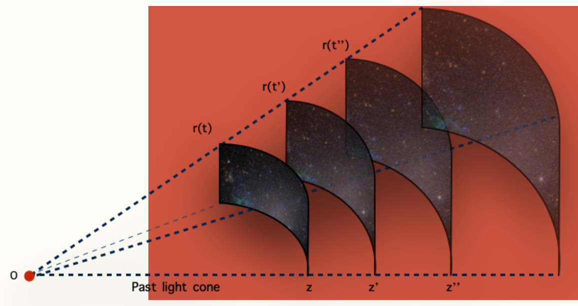
i) Sphere
ii) Discrete case

PEEBLES

i) Flat sky
ii) Curved universe
iii) Dirac delta

KAISER





2. The Journey

$$w\boxed{\theta} = \iint_0^\infty dx_1\, dx_2\, f_1(x_1) f_2(x_2)\, \xi(\boxed{r_{12}}; t_1, t_2)$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\;\; f_1(x_1) f_2(x_2)\, j_\ell(kx_1)\, j_\ell(kx_2)\, P(k; t_1, t_2)$$

Accuracy of Limber:

- Small angles: Limber
- Large angles: Thin-layer approximation

- Compares Limber's vs "exact"
- Applies small-angle to "exact"

$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\, f_1(\bar{x})\, f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

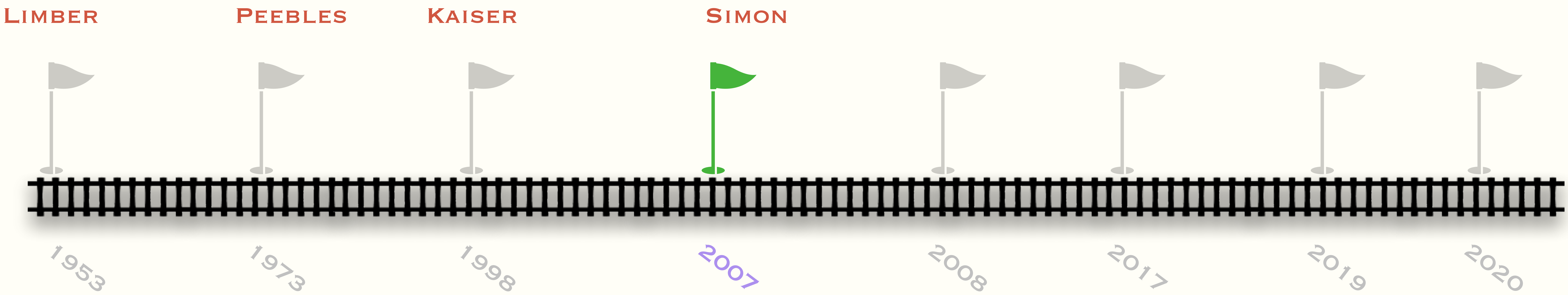
i) Filters
ii) Mid point

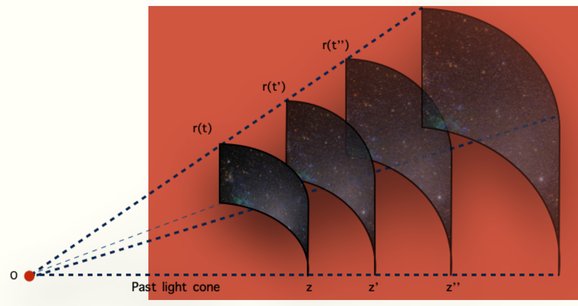
i) Sphere
ii) Discrete case

$$C(\ell\,) \approx \int dx \frac{f_1(x) f_2(x)}{x^2} P(\ell/x; t)$$

i) Flat sky
ii) Curved universe
iii) Dirac delta

i) Small and large angles
ii) Thin-layer approx.
iii) **Limber's inaccurate**





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$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\; f_1(x_1) f_2(x_2) \boxed{j_\ell(kx_1)\, j_\ell(kx_2)} P(k; t_1, t_2)$$

Dirac delta version:

$$j_\ell(kx) \approx \sqrt{\frac{\pi}{2\nu}}\delta_D(kx - \nu)$$

Series expansion in $1/\nu$

$$\nu = \ell + 1/2$$

$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\; f_1(\bar{x}) f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

- i) Filters
- ii) Mid point

- i) Sphere
- ii) Discrete case

$$C(\ell) \approx \int dx \frac{f_1(x) f_2(x)}{x^2} P(\ell/x; t)$$

- i) Flat sky
- ii) Curved universe
- iii) Dirac delta

- i) Small and large angles
- ii) Thin-layer approx.
- iii) **Limber's inaccurate**

- i) Post-Limber
- ii) Divergence small ℓ

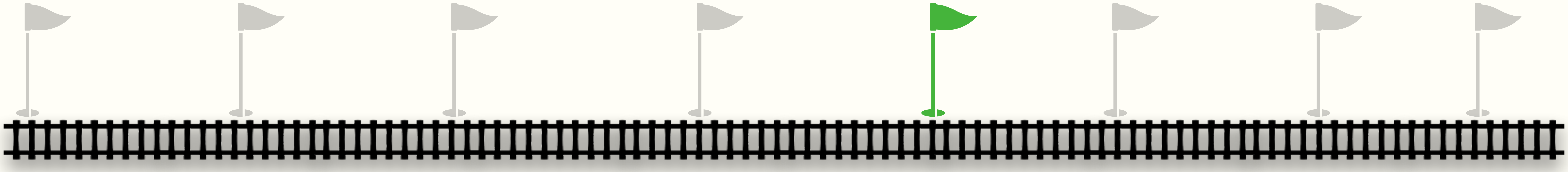
LIMBER

PEEBLES

KAISER

SIMON

LOVERDE
ET AL



1953

1973

1998

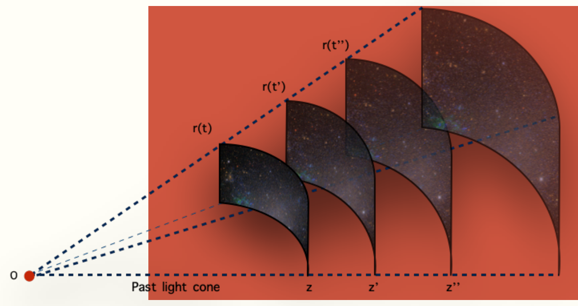
2007

2008

2017

2019

2020



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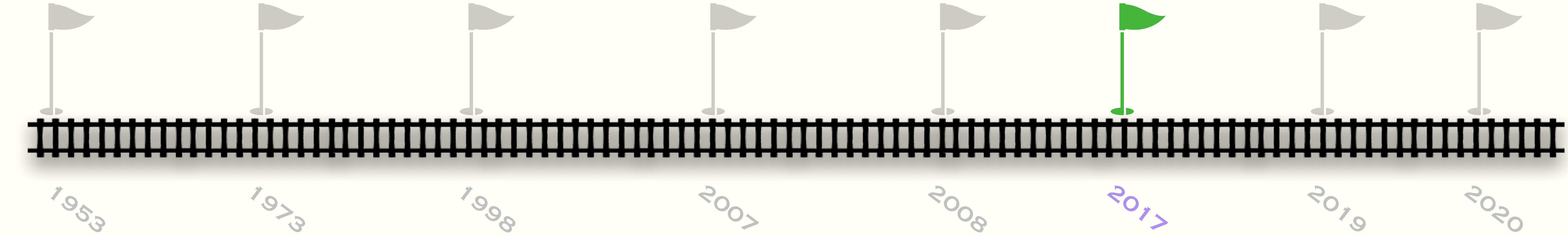
$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\;\; f_1(x_1) f_2(x_2) \boxed{j_\ell(kx_1)\, j_\ell(kx_2)} \boxed{P(k; t_1, t_2)}$$

Geometric approximation (large scales)

$$P(k; t_1, t_2) \approx \sqrt{P(k, t_1) P(k, t_2)}$$

$$C(\ell) \approx \frac{\pi}{2\nu} \int \frac{dk}{k^2} f_1(\nu/k) f_2(\nu/k) P(k, \nu/k)$$

$$j_\ell(kx) \approx \sqrt{\frac{\pi}{2\nu}}\, \delta_D(kx - \nu)$$



$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\; f_1(\bar{x})\, f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

i) Filters
ii) Mid point

LIMBER

1953

i) Sphere
ii) Discrete case

PEEBLES

1973

$$C(\ell) \approx \int dx \frac{f_1(x) f_2(x)}{x^2} P(\ell/x; t)$$

i) Flat sky
ii) Curved universe
iii) Dirac delta

KAISER

1998

i) Small and large angles
ii) Thin-layer approx.
iii) **Limber's inaccurate**

SIMON

2007

Expansion $1/\nu$

i) Post-Limber
ii) **Divergence small ℓ**

LOVERDE ET AL

2008

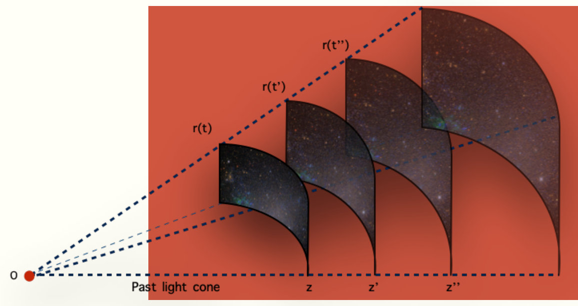
i) Geometric
ii) Dirac delta
iii) **Valid large ℓ**
iv) **Valid small k**

LEMOS ET AL

2017

2019

2020



2. The Journey

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, f_1(x_1) f_2(x_2)\, \xi(r_{12}; t_1, t_2)$$

$$C(\ell) = \boxed{\int_0^\infty} \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\;\; f_1(x_1) f_2(x_2) \boxed{j_\ell(kx_1)\, j_\ell(kx_2)} \boxed{P(k; t_1, t_2)}$$

Linear

Non-linear

$$C(\ell) \approx \int_0^\infty \frac{dk}{k^2}(\ldots)\, P_{lin}(k; t_1, t_2) + \int_0^\infty \frac{dk}{k^2}(\ldots)\, P_{Nl}(k; t_1, t_2)$$

Exact

$$P(k; t_1, t_2) \equiv \sqrt{P(k, t_1) P(k, t_2)}$$

No unequal-time

Dirac delta $\ell >> 1$

Geometric $k << 1$?

NL Physics?

$$w(\theta) \approx \int_0^\infty d\bar{x} \int_{-2\bar{x}}^{2\bar{x}} dR\; f_1(\bar{x}) f_2(\bar{x})\, \xi(r_{12}; \bar{t}\,)$$

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- i) Geometric
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LEMOS ET AL

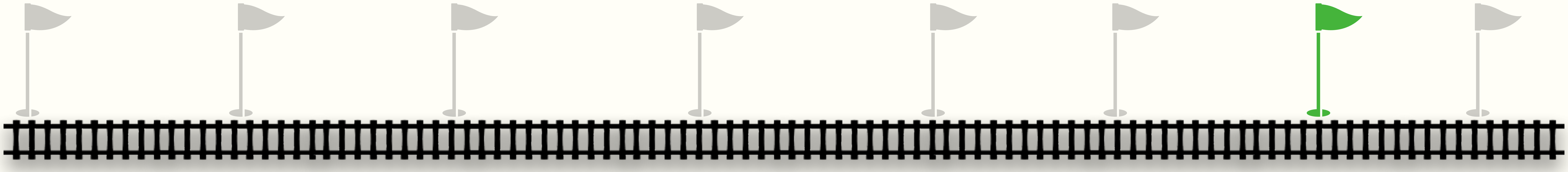
2017

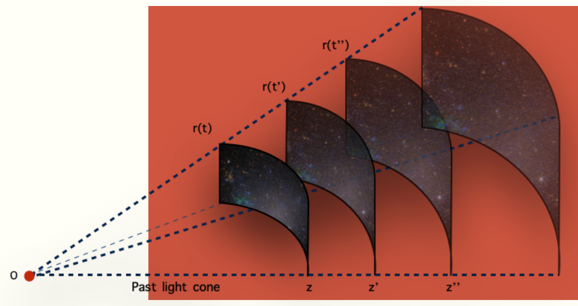
- i) FFTLog
- ii) Split regimes
- iii) **Limber Inaccurate**
- iv) **Accuracy large k?**

FANG ET AL

2019

2020





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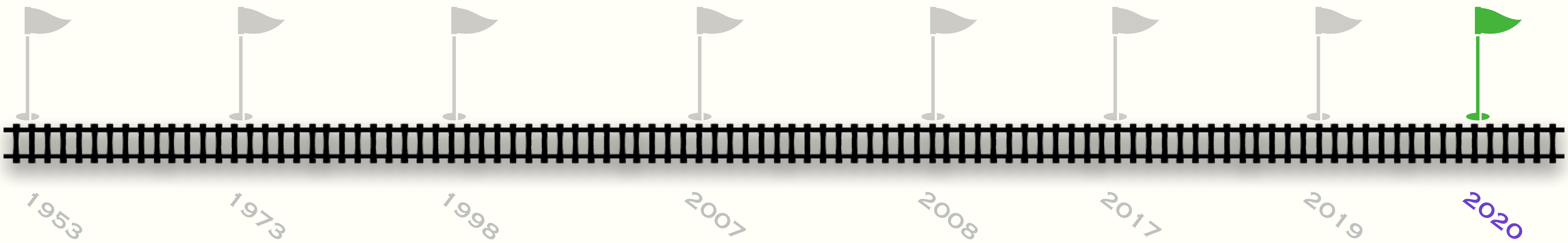
Issues

- Limber's accuracy
- Divergence on large angles
- Geometric app good on large scales
- Accuracy of non-linear physics

Need

- ☆ Unequal-time correlators
- ☆ All-angle calculations



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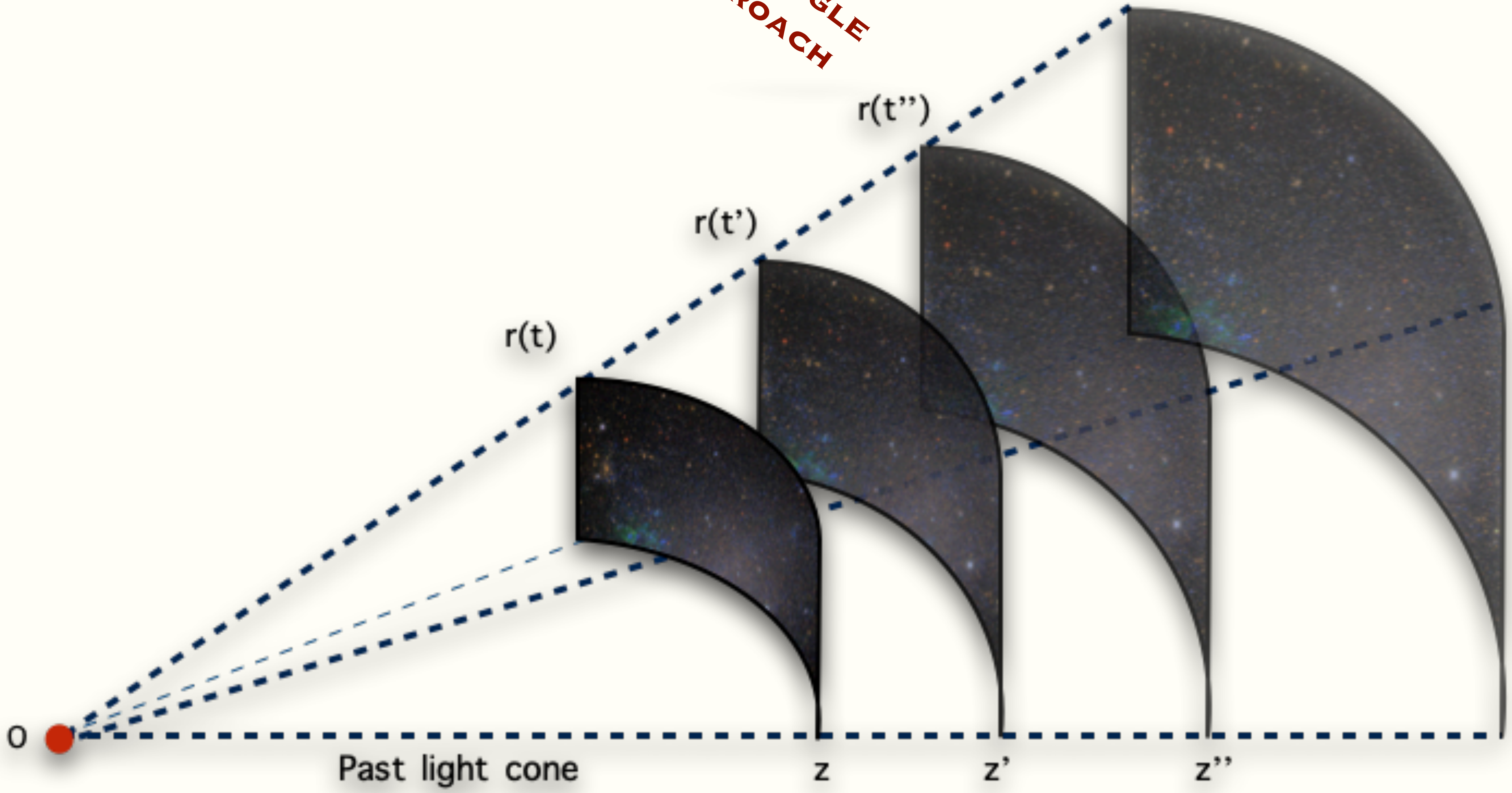
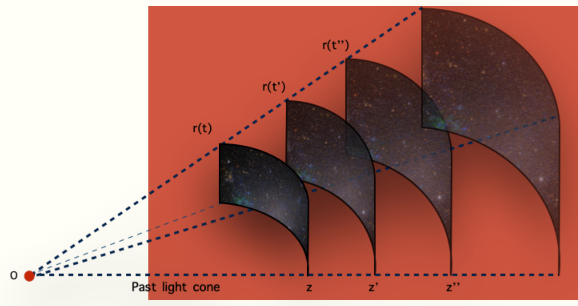
FANG ET AL 2019

This work 2020

N. Tessore, L. F. de la Bella (in prep)
Python package **CORFU**

3. ALL-ANGLE APPROACH





3. All-angle approach

$$w(\theta) = \iint_0^\infty dx_1\, dx_2\, f_1(x_1) f_2(x_2)\, \xi(r_{12}; t_1, t_2)$$

$$C(\ell) = \int_0^\infty \frac{dk}{k^2} \iint_0^\infty dx_1\, dx_2\; f_1(x_1) f_2(x_2) j_\ell(kx_1) j_\ell(kx_2) \boxed{P(k; t_1, t_2)}$$

- Need accurate unequal-time power spectrum
- Deal with non-linear physics (one-loop, EFT)
- Impact on weak lensing. How?
    - Midpoint approximation ★
    - Compare with geometric approx.
- Analyse regimes of validity
- Drop approximations
- Python package **UNEQUALPY**

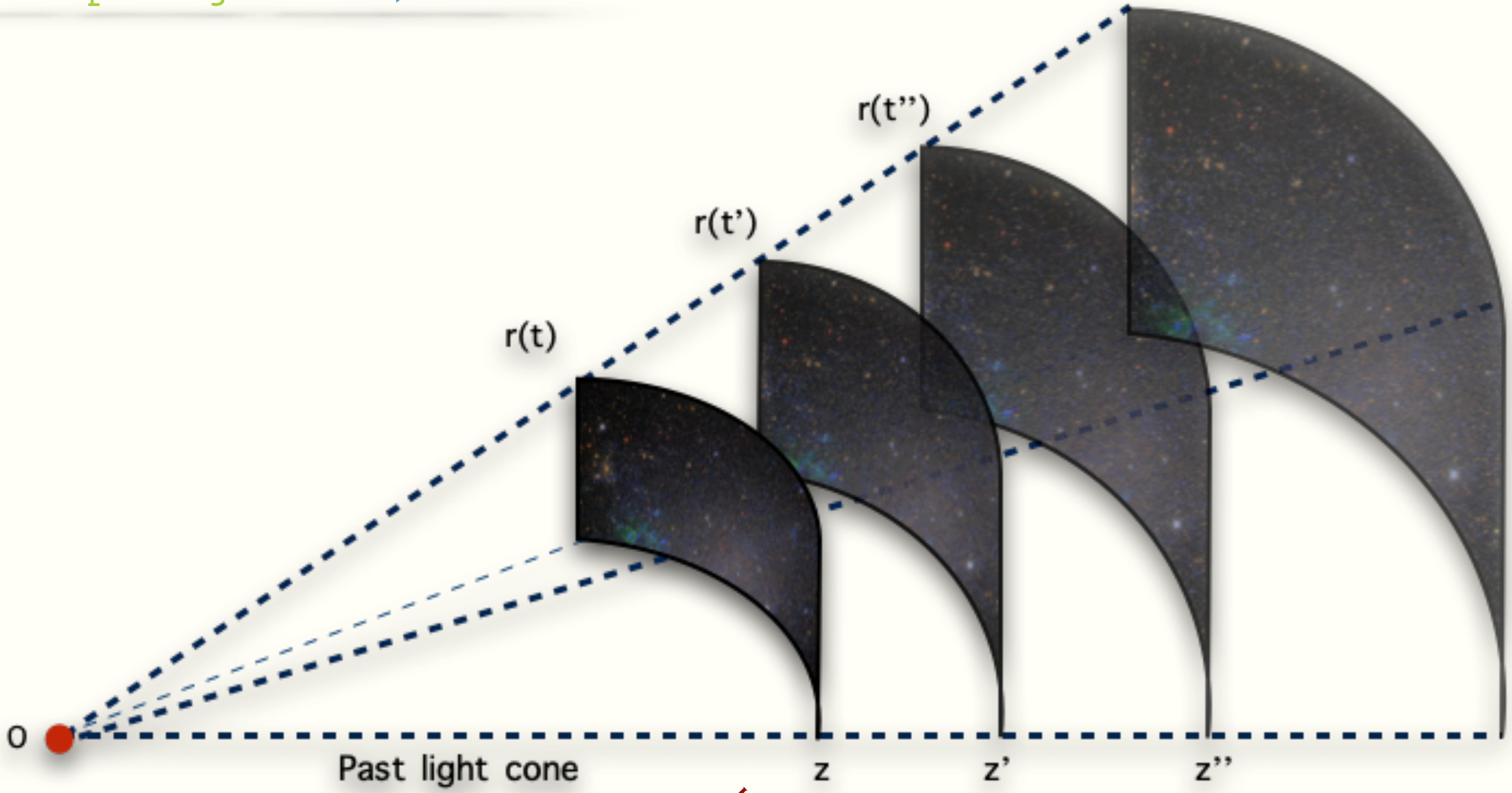
- Need exact calculation at all angular scales
- Python package **CORFU**
    - FFTLog methods
    - Inverse Fourier transform

$$P(k; t_1, t_2) \longrightarrow \xi(r; t_1, t_2)$$

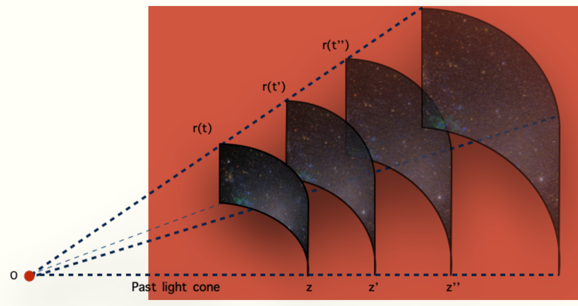
    - Legendre polynomials

$$w(\theta) \longrightarrow C(\ell)$$

L. F. de la Bella, N. Tessore and
S. L. Bridle (arXiv 2011.06185)
Python package **UNEQUALPY**



4. UNEQUAL-TIME CORRELATORS



4. Unequal-time Correlators

2point functions

Homogeneous
Isotropic

- EQUAL-TIME POWER SPECTRUM

  `Same time slice`

$$(2\pi)^3\delta_D(\mathbf{k}_1+\mathbf{k}_2)P(k,z) := \langle \delta(\mathbf{k}_1,z)\delta^*(\mathbf{k}_2,z)\rangle$$

- UNEQUAL-TIME POWER SPECTRUM

  `Different time slices`

$$(2\pi)^3\delta_D(\mathbf{k}_1+\mathbf{k}_2)P(k,z_1,z_2) := \langle \delta(\mathbf{k}_1,z_1)\delta^*(\mathbf{k}_2,z_2)\rangle$$

LINEAR THEORY

$$P(k,z) = D(z)^2 P_{11}(k)$$

$$P(k,z_1,z_2) = D(z_1)D(z_2)P_{11}(k)$$

@ $z_1 = z_2$

$$P(k,z,z) = P(k,z)$$

Non-linear

ONE-LOOP THEORY

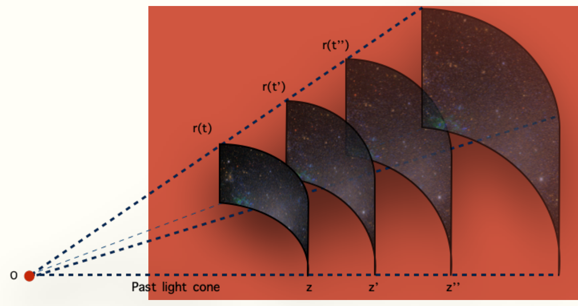
$$P(k,z_1,z_2) = P_{11}(k,z_1,z_2) + P_{22}(k,z_1,z_2) + P_{13}(k,z_1,z_2)$$

i) STANDARD PERTURBATION THEORY
ii) EFFECTIVE FIELD THEORY

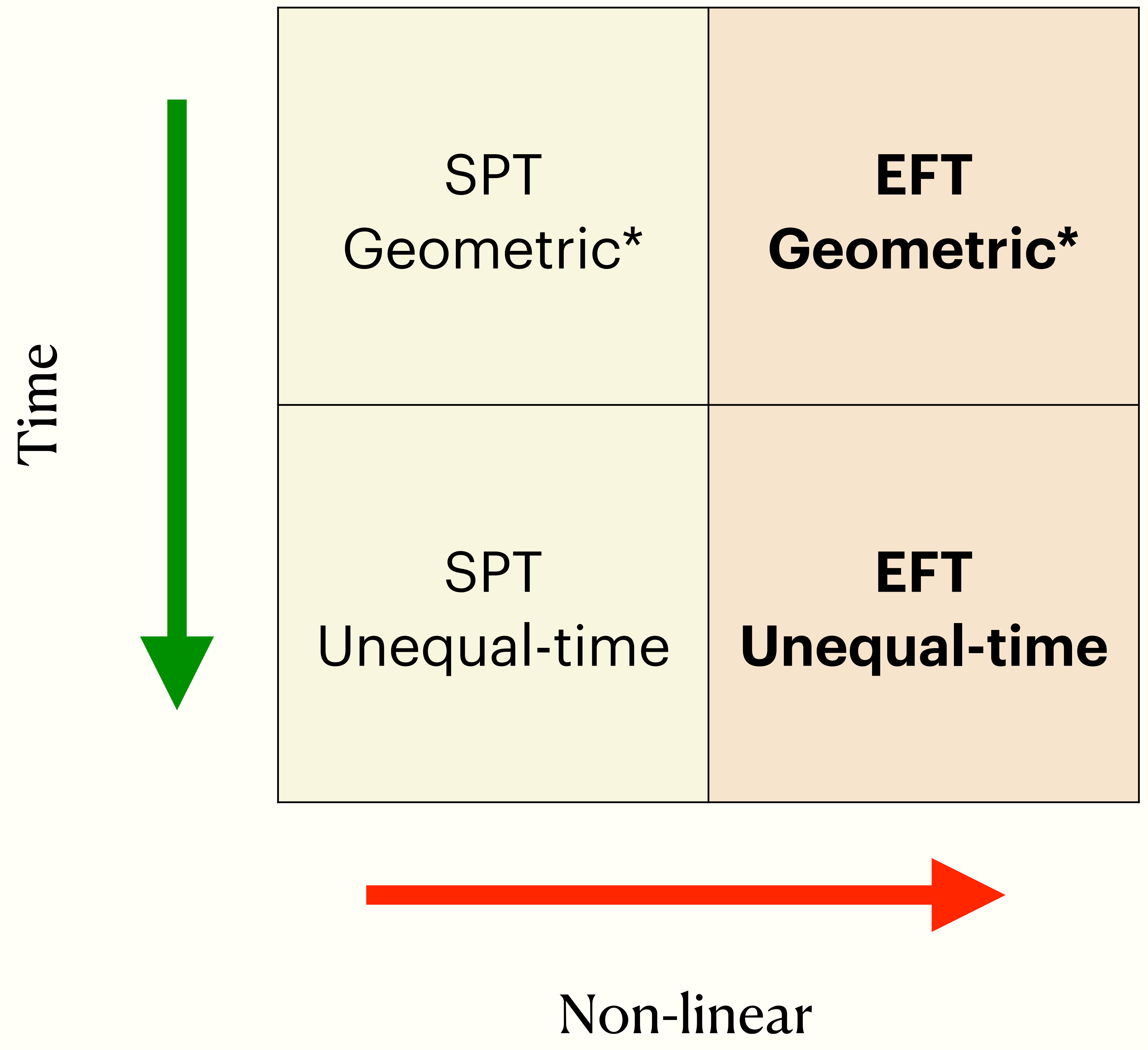
`NL physics → counterterms`

$$P_{EFT} = P_{SPT} - c^2k^2P_{11}$$

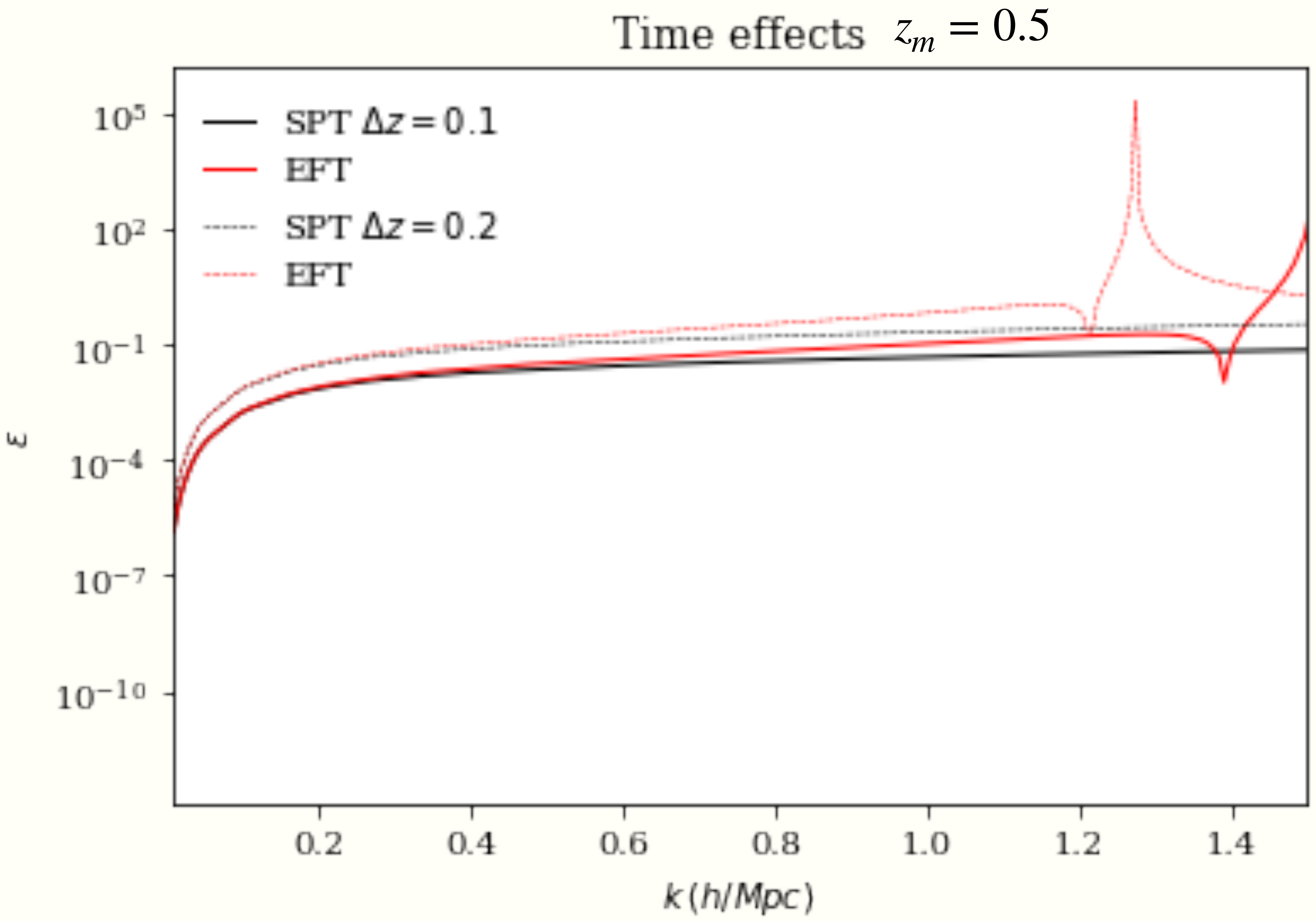
- This work shows unequal-time EFT breaks
- New idea: **the midpoint approximation!**



4.1. Time and non-linear effects

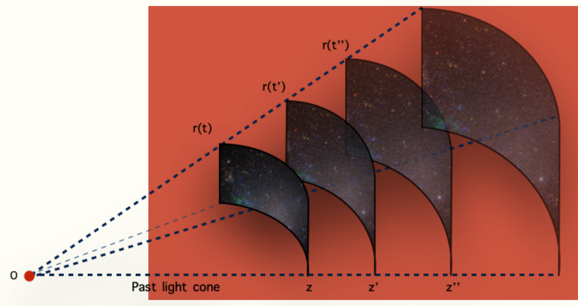


Time	SPT Geometric*	**EFT** **Geometric***
	SPT Unequal-time	**EFT** **Unequal-time**
	Non-linear	



$$* \quad P(k; t_1, t_2) \approx \sqrt{P(k, t_1)P(k, t_2)}$$

$$\frac{\Delta P}{P^2} = \frac{|P_{theory}(k, z_1)P_{theory}(k, z_2) - P_{theory}(k; z_1, z_2)^2|}{P_{theory}(k; z_1, z_2)^2}$$



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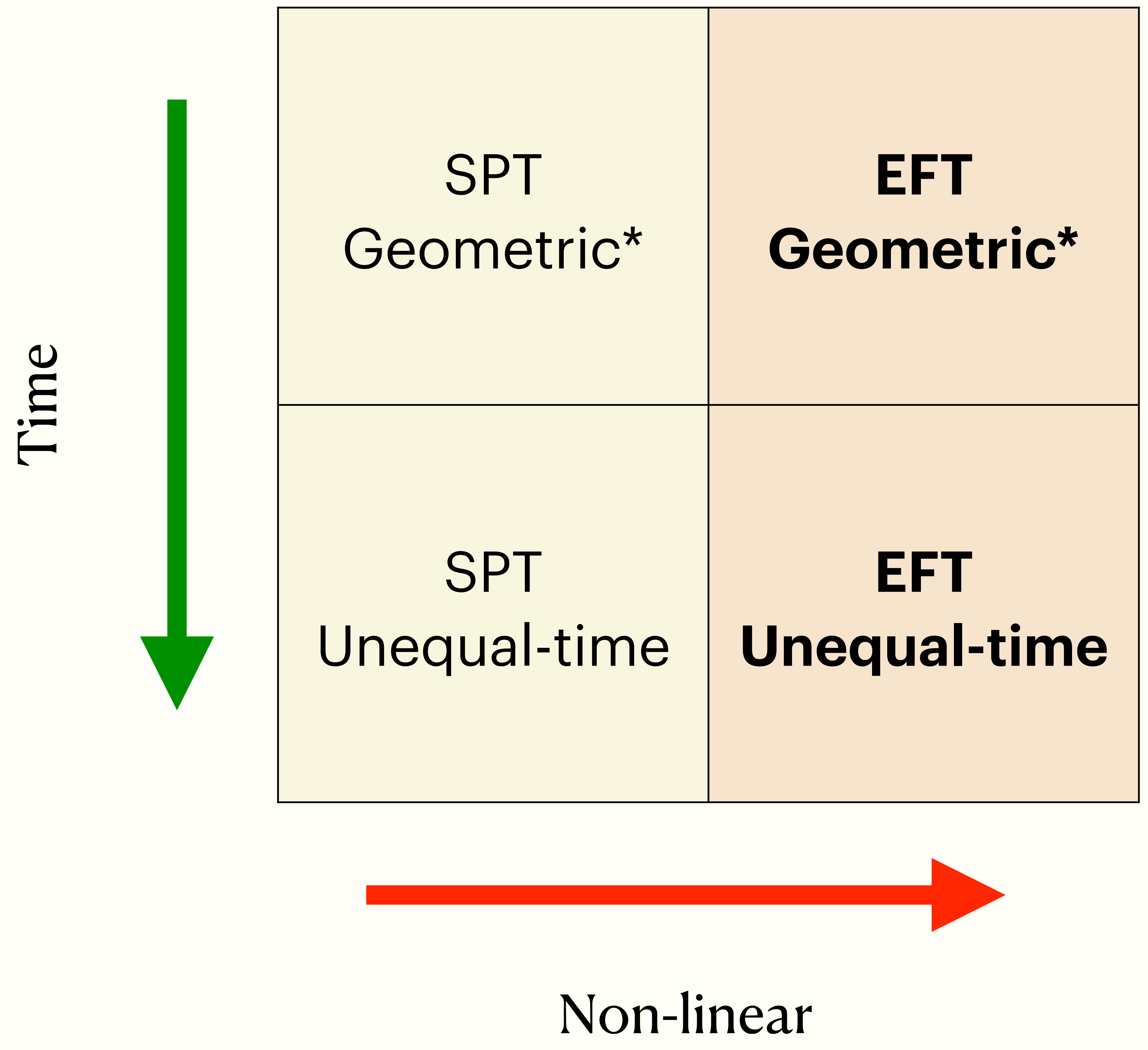
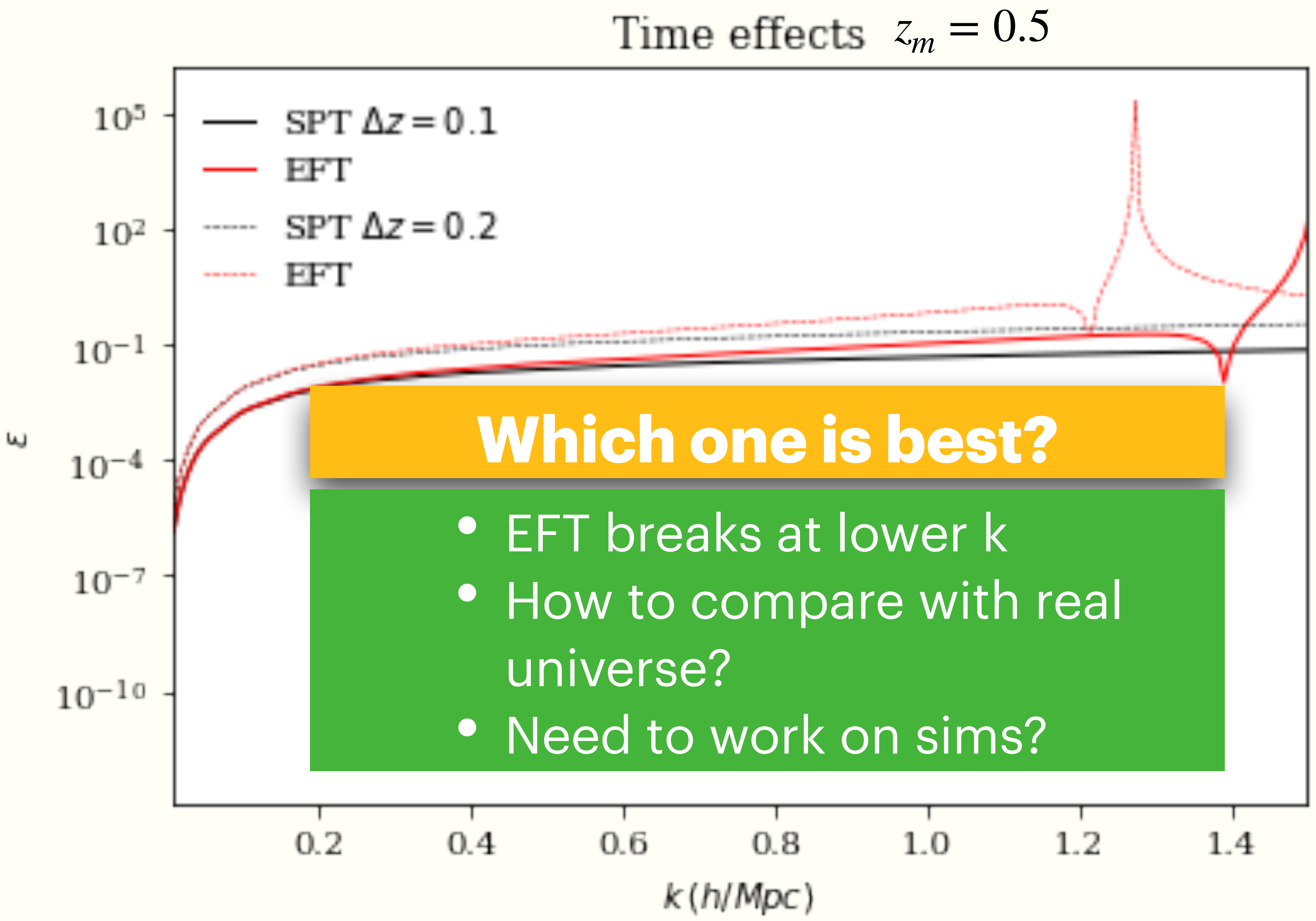


SPT Geometric*	**EFT** **Geometric***
SPT Unequal-time	**EFT** **Unequal-time**

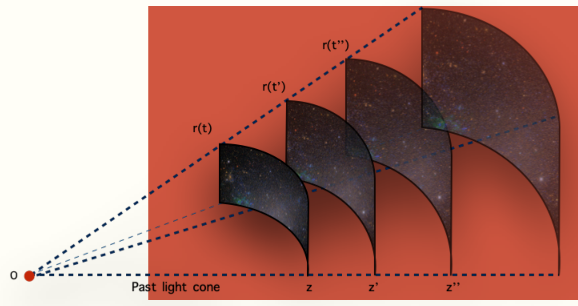


Which one is best?

- EFT breaks at lower k
- How to compare with real universe?
- Need to work on sims?

$$* \quad P(k; t_1, t_2) \approx \sqrt{P(k, t_1)P(k, t_2)}$$

$$\frac{\Delta P}{P^2} = \frac{|P_{theory}(k, z_1)P_{theory}(k, z_2) - P_{theory}(k; z_1, z_2)^2|}{P_{theory}(k; z_1, z_2)^2}$$



4.2. Midpoint approximation

- Unequal-time power spectrum

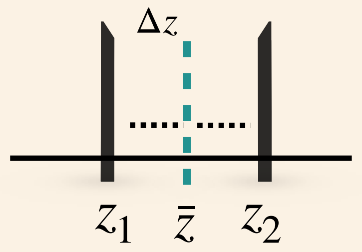
$$P(k; z_1, z_2)$$

- Geometric approximation

$$\sqrt{P(k, z_1)P(k, z_2)}$$

- Midpoint approximation

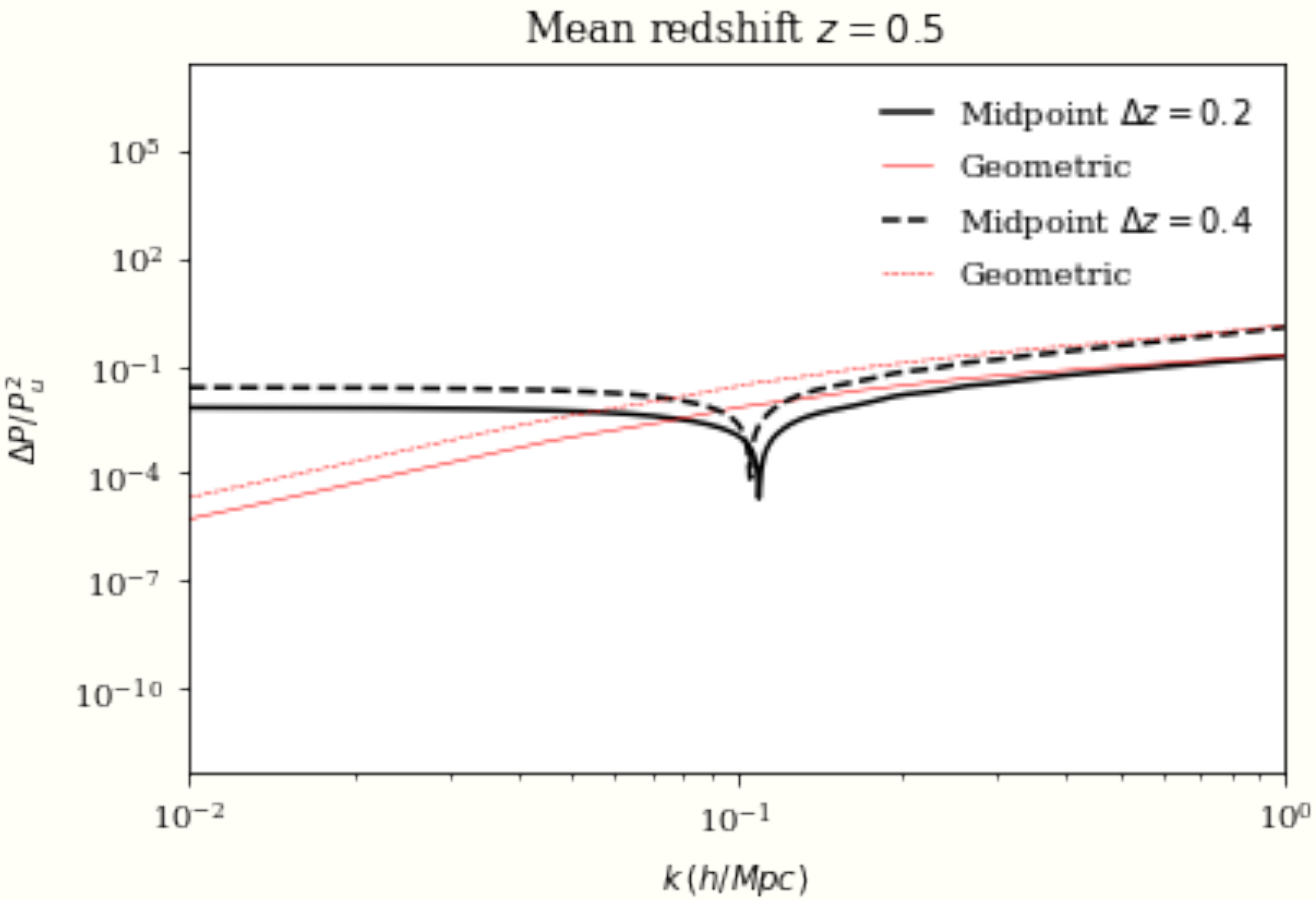
★ $P(k; z_m)$

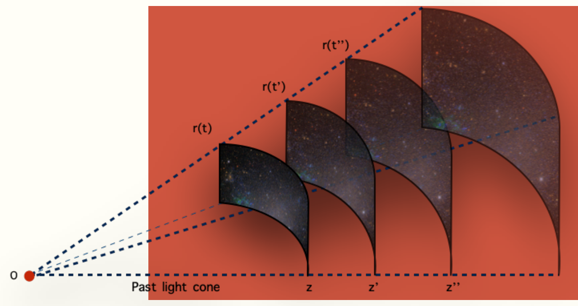


- More accurate for small separation
- Geometric approximation
  - Good on very large scales
  - Error increases on smaller scales

- Midpoint approximation
  - Not perfect on large scales
  - Error much more stable
  - Better prediction on small scales

- EFT does not improve SPT





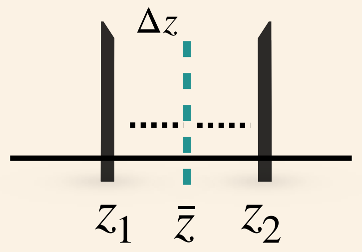
4.2. Midpoint approximation

- Unequal-time power spectrum

$$P(k; z_1, z_2)$$

- Geometric approximation

$$\sqrt{P(k, z_1)P(k, z_2)}$$



- Midpoint approximation

★ $P(k; z_m)$

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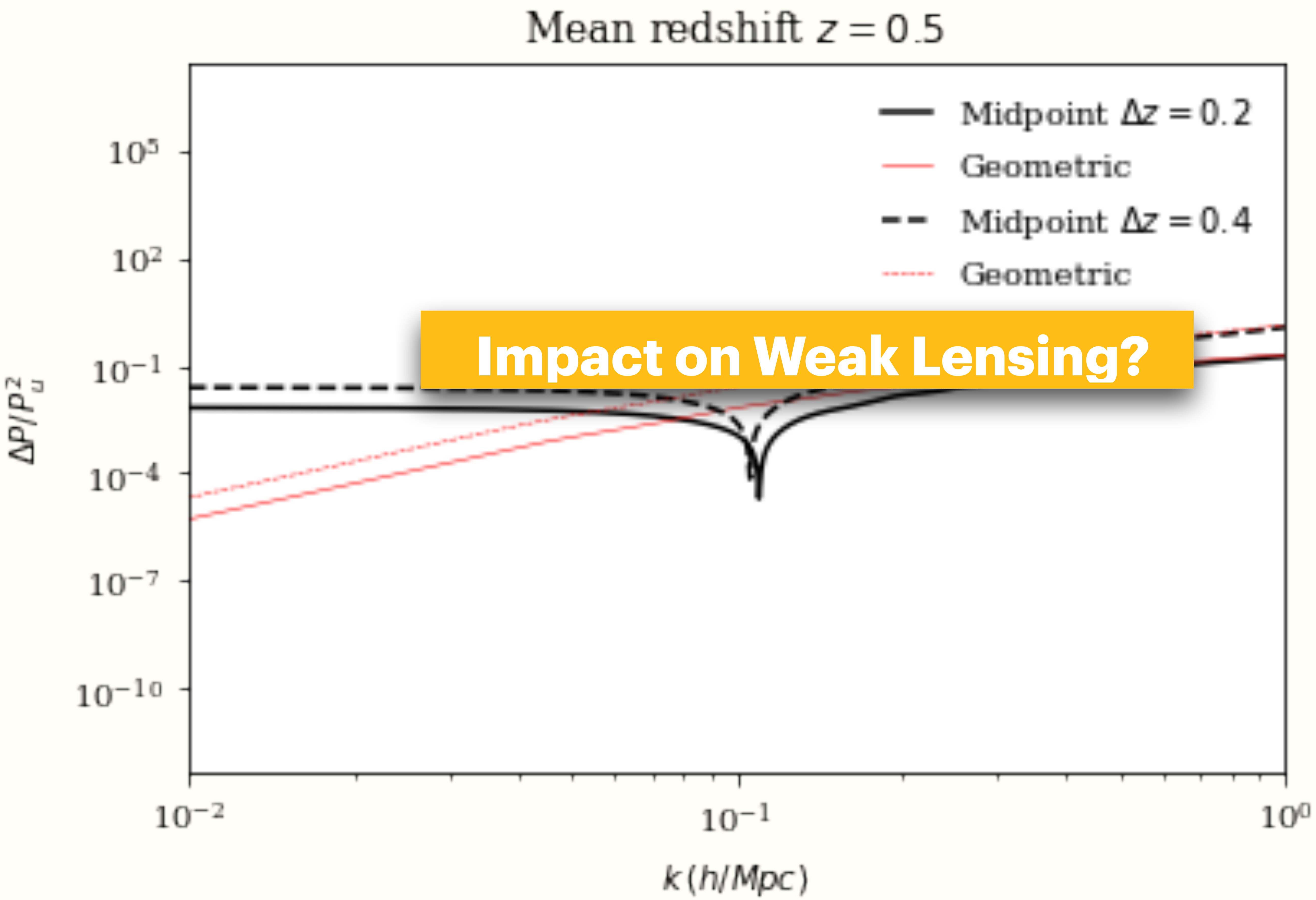
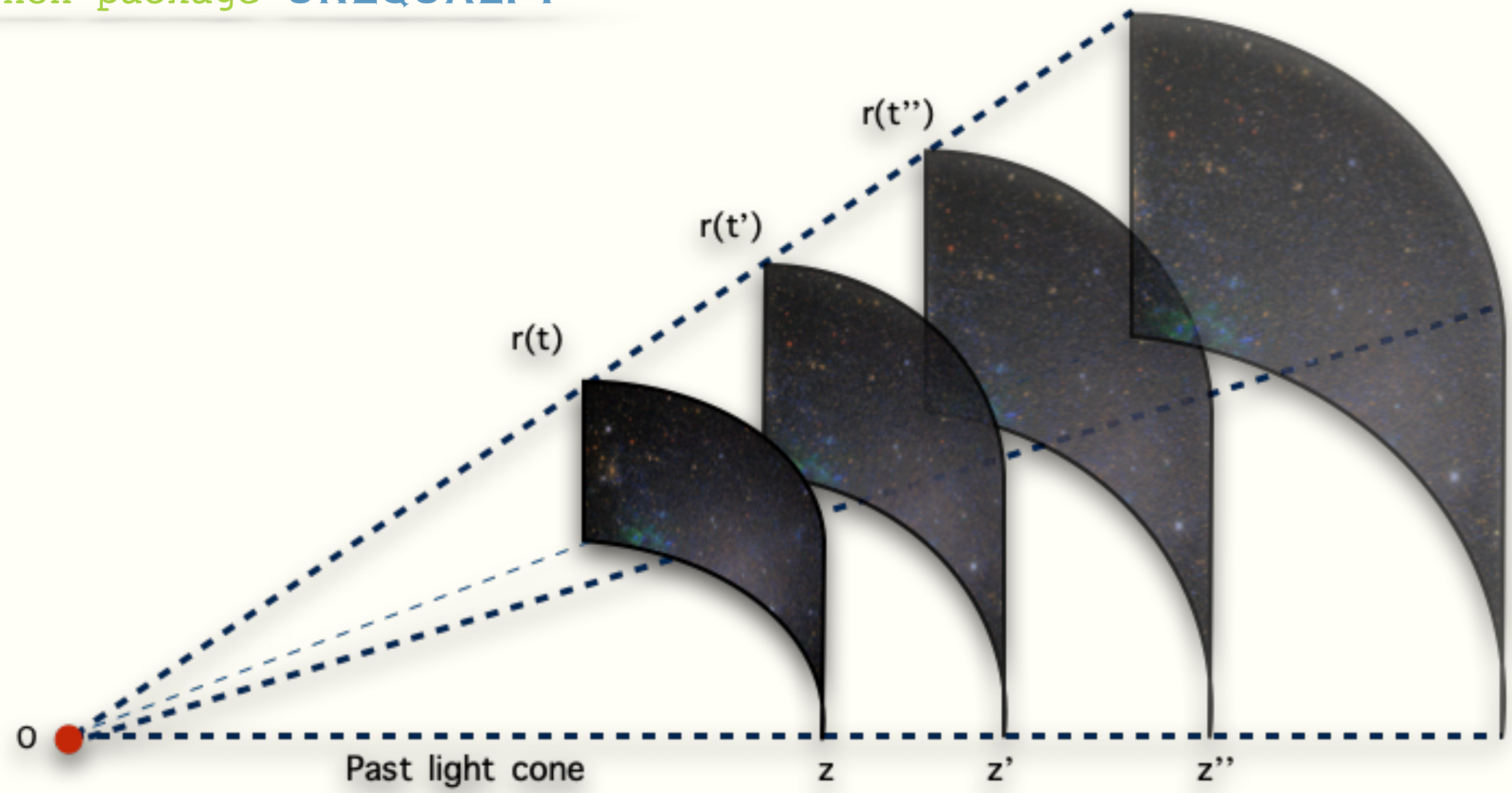


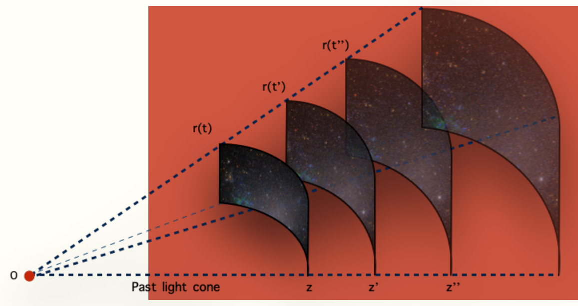
Impact on Weak Lensing?

L. F. de la Bella, N. Tessore and
S. L. Bridle (arXiv 2011.06185)
Python package **UNEQUALPY**



5. RESULTS
6. SUMMARY

5. Results



Exact

$$C_{ab}^{(i,j)}(\ell) = \frac{2}{\pi}\int_0^\infty dk k^2 \iint_0^\infty dx_1\, dx_2\;\, f_a^i(x_1) f_b^j(x_2)\, j_\ell(kx_1)\, j_\ell(kx_2)\, P(k; t_1, t_2)$$

CORFU

$P(k; t_1, t_2) \longrightarrow \xi(r; t_1, t_2)$

$w(\theta) \longrightarrow C(\ell)$

Limber

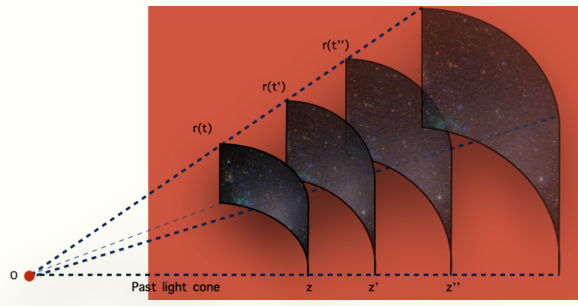
$$C_{ab}^{(i,j)}(\ell) \approx \frac{1}{\nu}\int_0^\infty dk k^2 f_a^i(\nu/k) f_b^j(\nu/k) P(k; \nu/k)$$

Geometric

$$C_{ab}^{(i,j)}(\ell) \approx \frac{2}{\pi}\int_0^\infty dk k^2 \int_0^\infty dx_1\, f_a^i(x_1) j_\ell(kx_1)\sqrt{P(k; x_1)} \int_0^\infty dx_2 f_b^j(x_2) j_\ell(kx_2)\sqrt{P(k; x_2)}$$

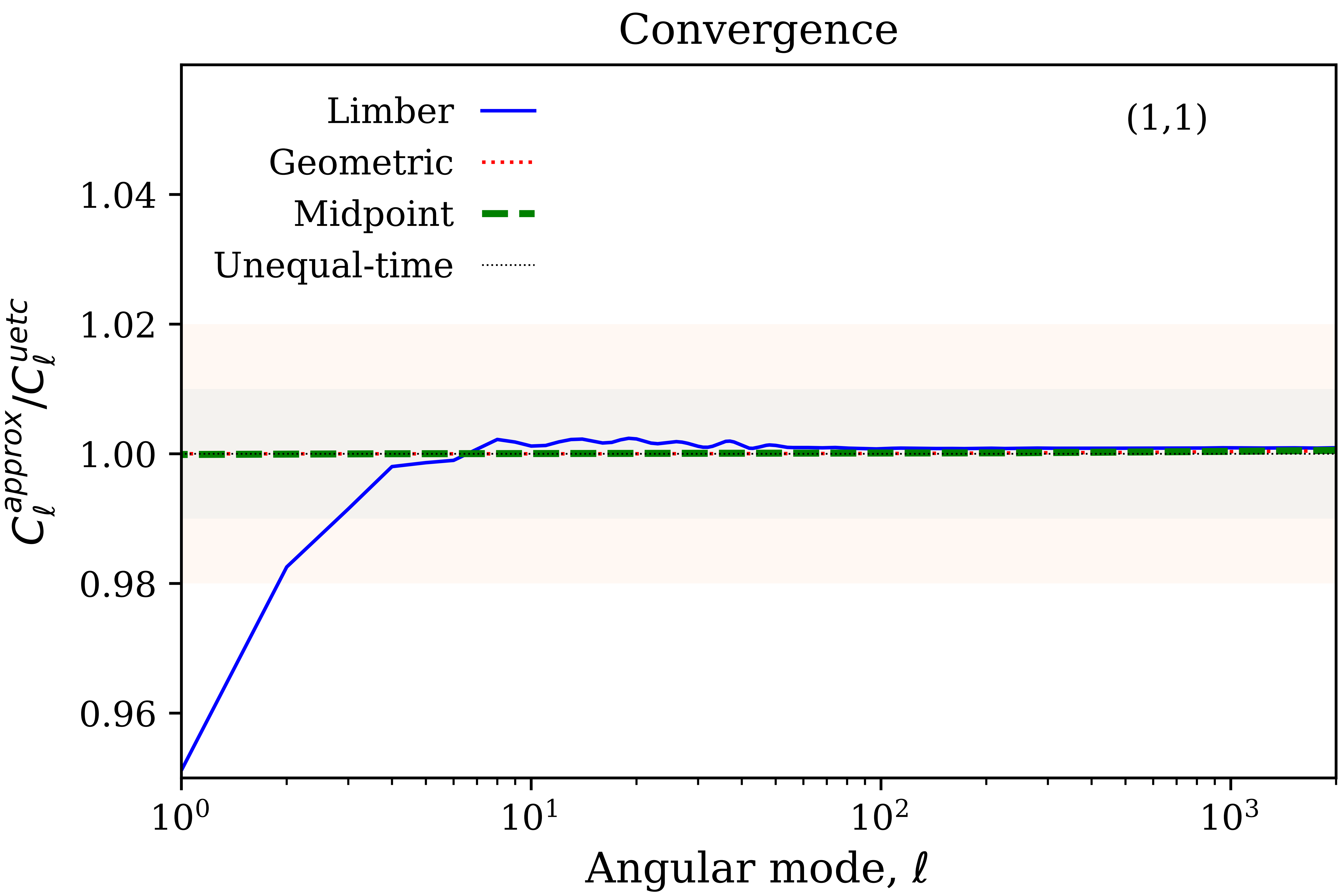
Midpoint

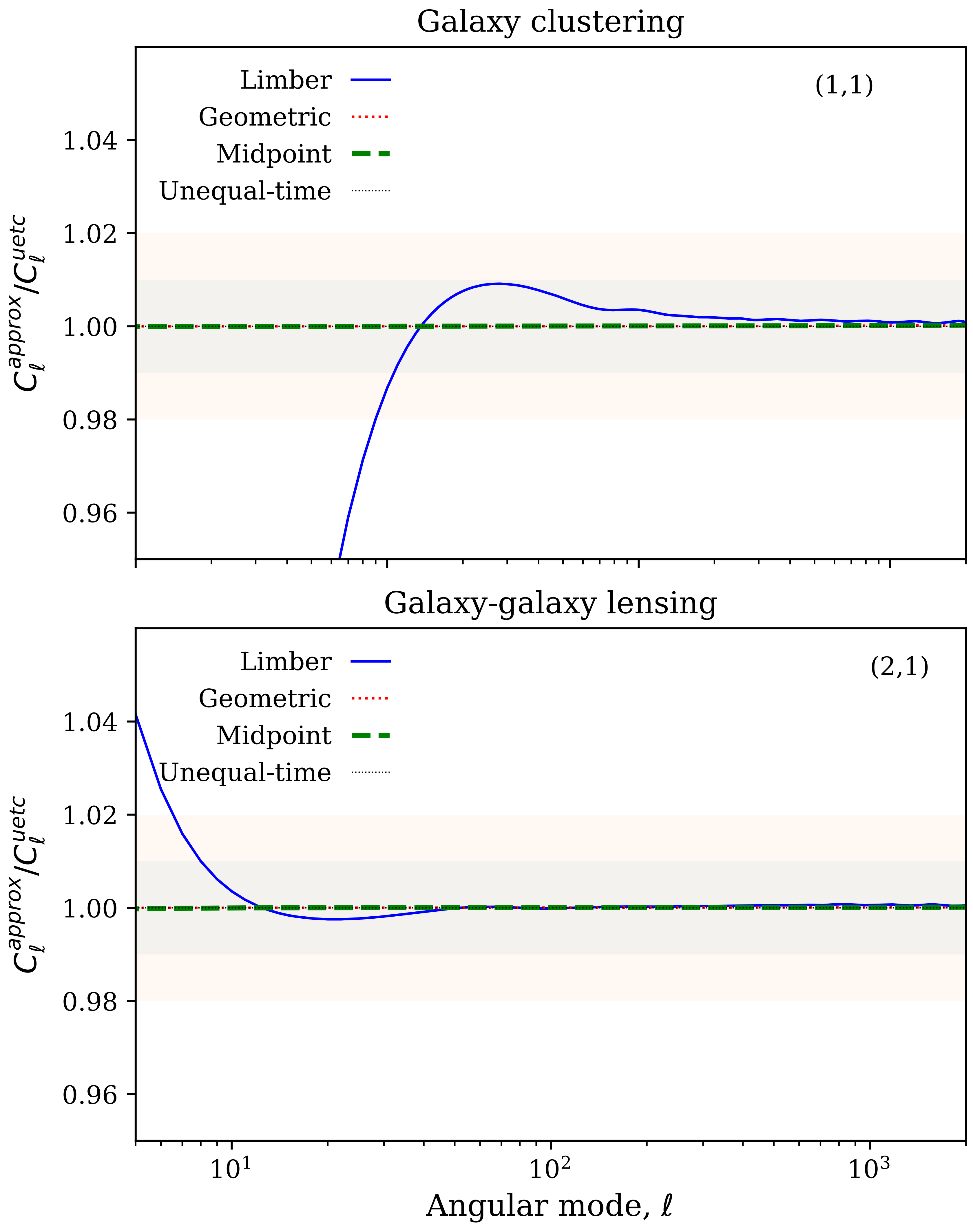
$$C_{ab}^{(i,j)}(\ell) \approx \frac{2}{\pi}\int_0^\infty dk k^2 \iint_0^\infty dx_1\, dx_2\;\, f_a^i(x_1) f_b^j(x_2)\, j_\ell(kx_1)\, j_\ell(kx_2)\, P\left(k; \frac{x_1 + x_2}{2}\right)$$

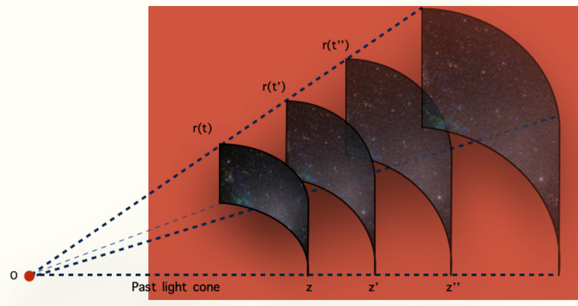


5. Results

DES-Y1 DATA

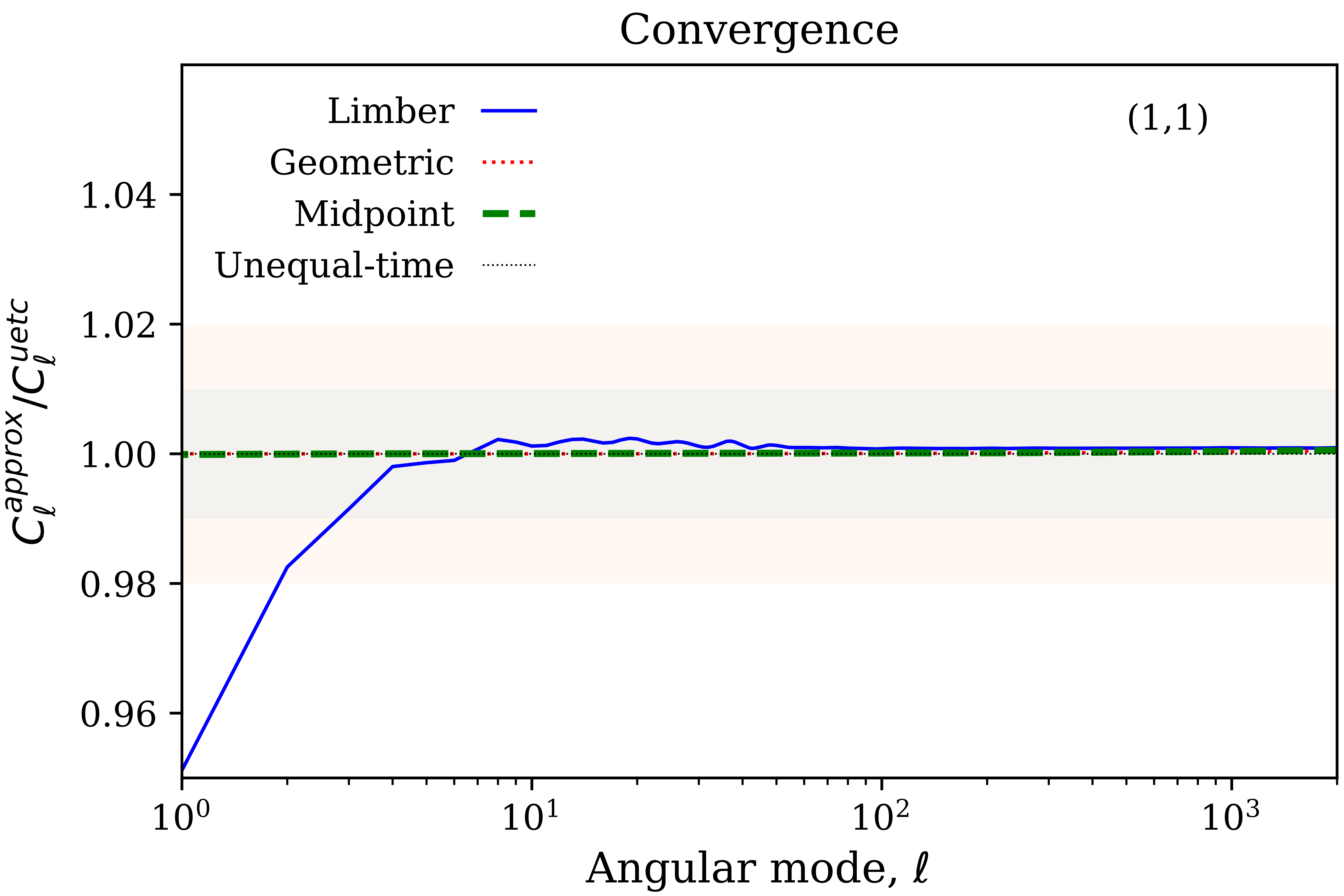


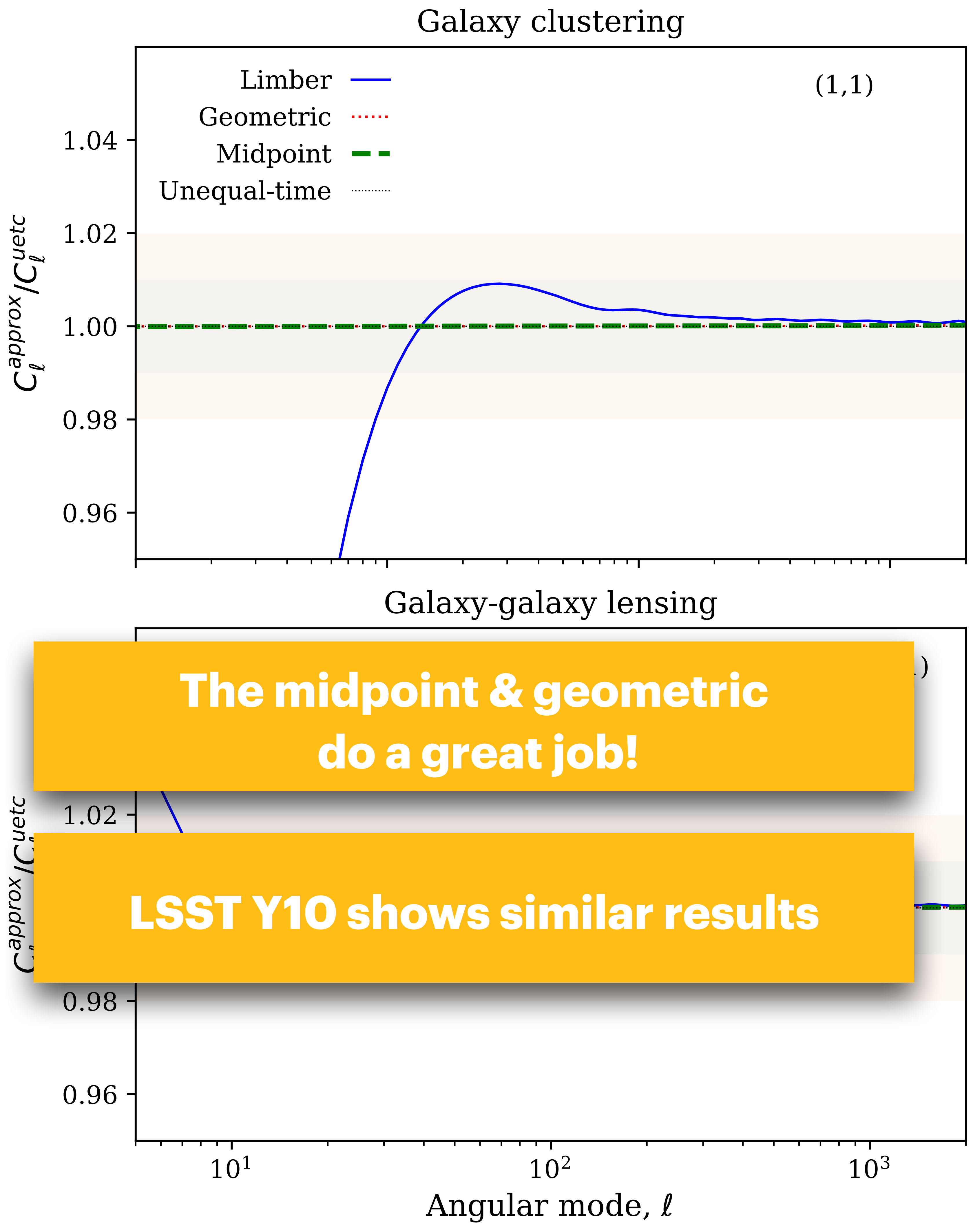




5. Results

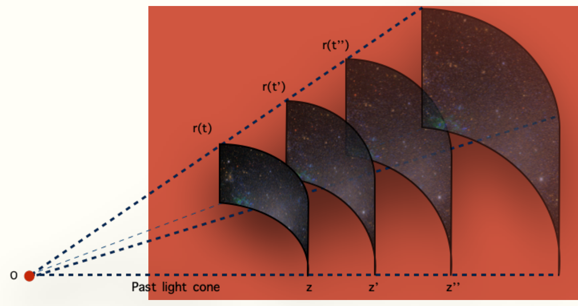
DES-Y1 DATA





The midpoint & geometric do a great job!

LSST Y10 shows similar results



6. Summary

Summary

- Angular correlations functions are very hard to compute
- Limber is the most widely used approximation
- List of issues: accuracy and validity of approximations
- Need for unequal-time correlators and all-angle computations
- Unequal-time EFT does not improve the prediction
- Midpoint approximation better on non-linear scales

Coming next!

- **Numeric paper (in prep)**
  - All angular scale computations
  - Equal and unequal-time correlators
  - Phyton package **CORFU**
- **Science paper (arXiv 2011.06185)**
  - Unequal-time matter power spectrum at one-loop
  - Phyton package **UNEQUALPY**
  - Analysis of all approximations and validity regimes
  - **Midpoint and Geometric** best to mimic unequal-time features!
  - **Beyond Limber** relevant for **galaxy clustering** and **galaxy-galaxy lensing**.

QUESTIONS?