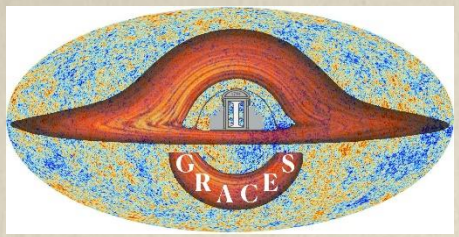
Fédération de Recherche Interactions Fondamentales (FRIF) Day



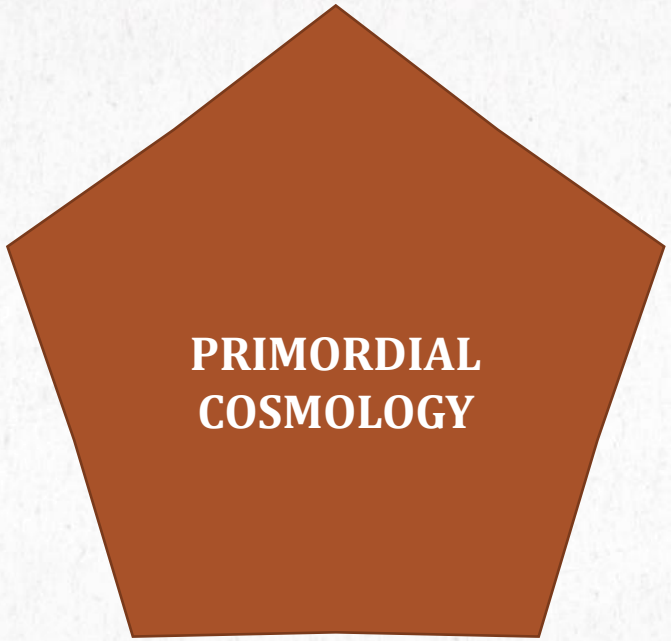
Lucas Pinol
CNRS researcher, LPENS, Paris

EARLY UNIVERSE COSMOLOGY

AT THE CROSSROADS

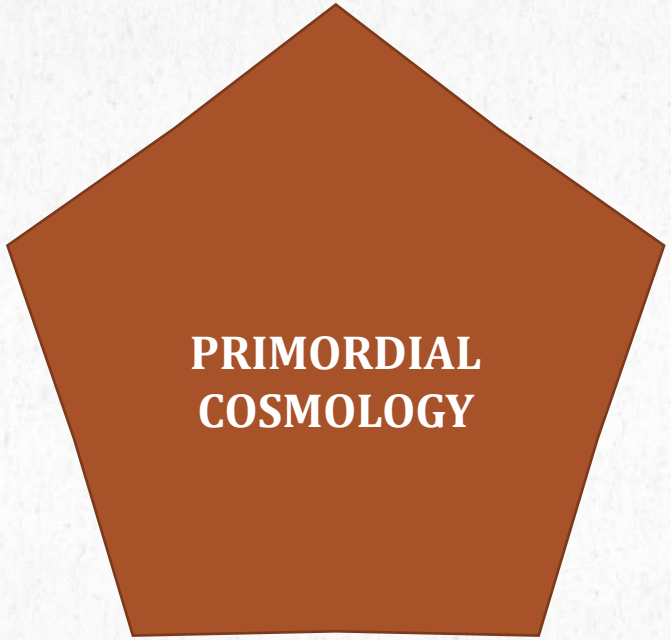
Why inviting a primordial cosmologist to the FRIF Day?

Fundamental Interactions



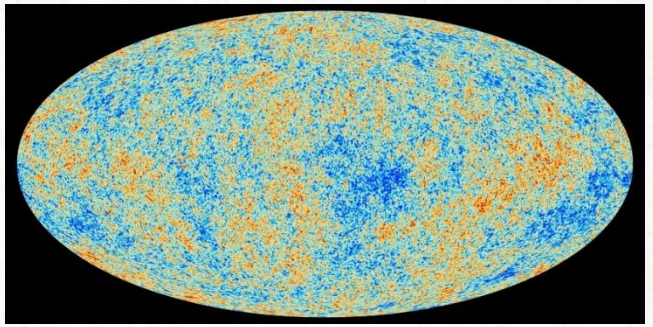
Why inviting a primordial cosmologist to the FRIF Day?

Gravity

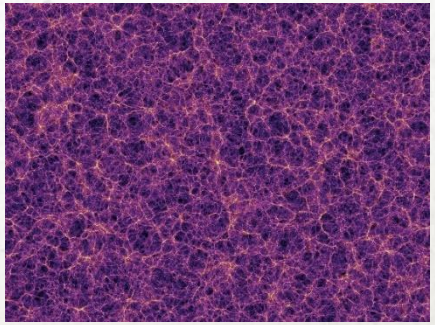


Fundamental Interactions

Primordial fluctuations undergo gravitational collapse into structures



Cosmic Microwave Background

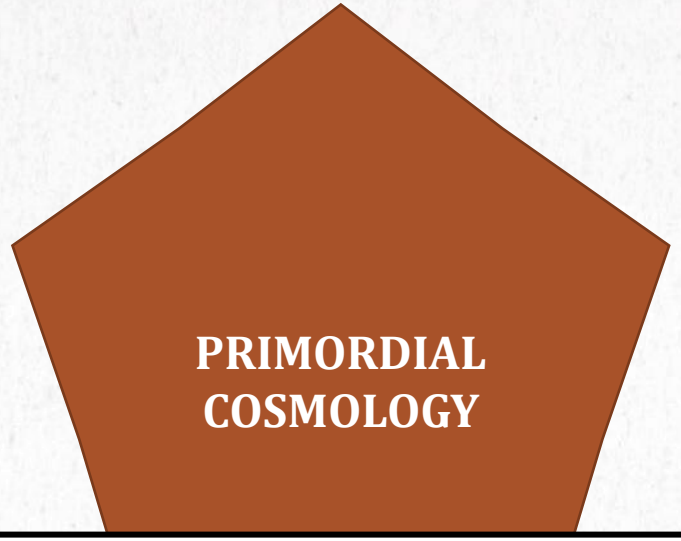


Large-scale distribution of galaxies

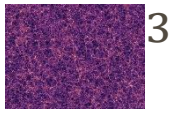
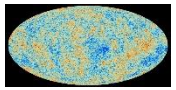
Why inviting a primordial cosmologist to the FRIF Day?

Fundamental Interactions

Gravity

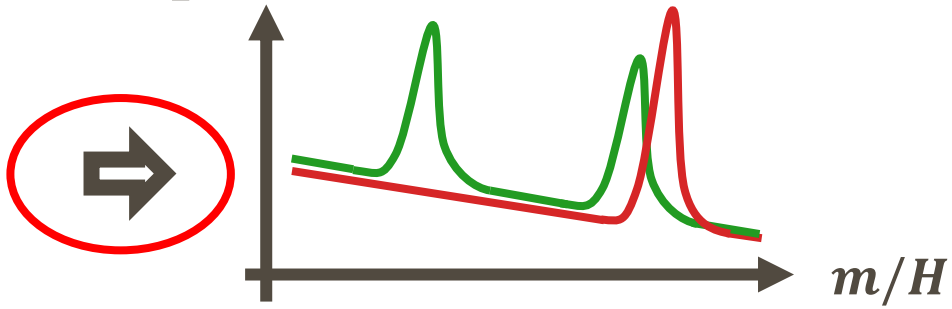


Particle physics

$\langle$  $^3\rangle + \langle$  $^3\rangle$ ⇨ $\langle\zeta^3\rangle$

ζ is the primordial curvature perturbation

Cosmic spectroscopy

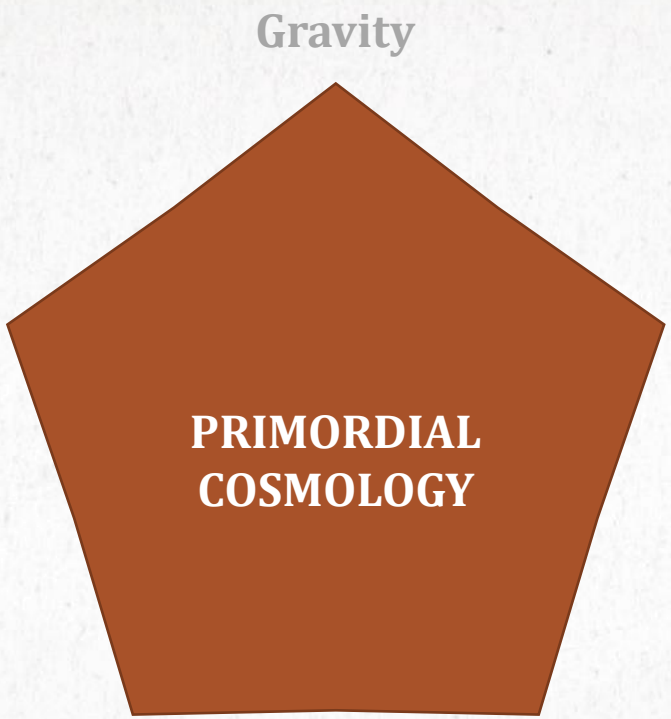


cosmological observations

initial conditions

particle content in the early universe

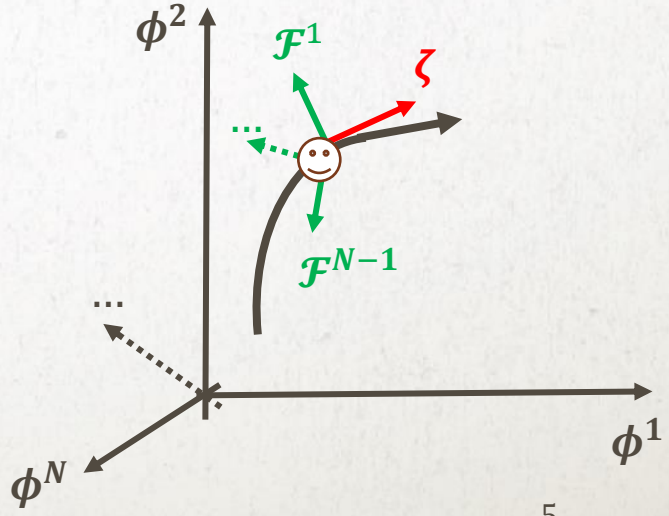
Why inviting a primordial cosmologist to the FRIF Day?



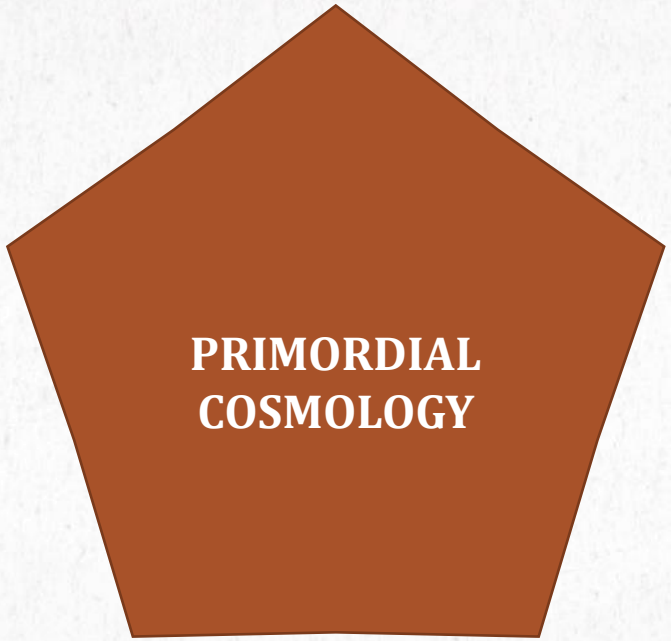
General Non-Linear Sigma Model and curved field space

$$\mathcal{L} = -\frac{1}{2}\sum_{A,B} g^{\mu\nu} \boldsymbol{G_{AB}}(\vec{\boldsymbol{\phi}})\partial_\mu \phi^A \partial_\nu \phi^B - \boldsymbol{V}(\vec{\boldsymbol{\phi}})$$

Axions, dilatons, moduli, …

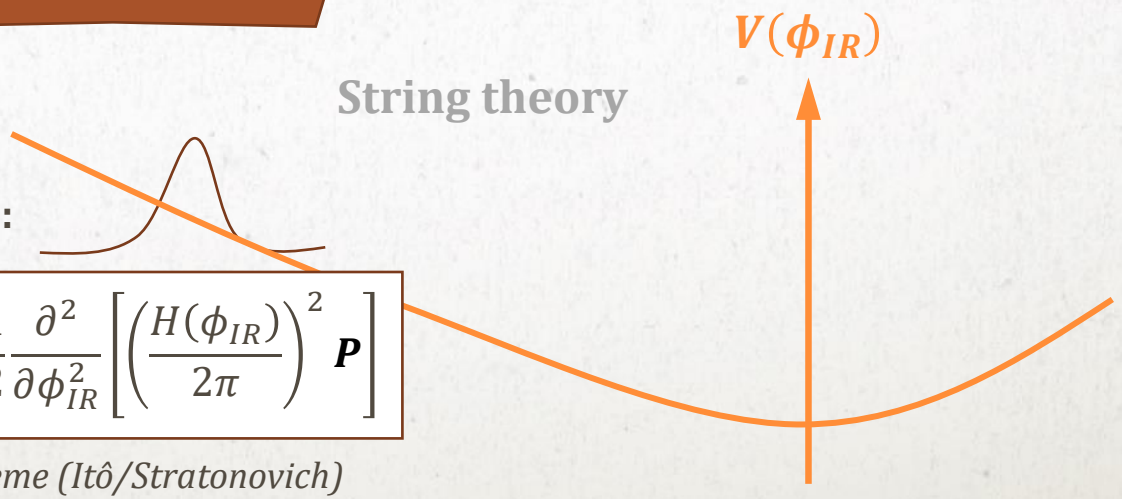


Why inviting a primordial cosmologist to the FRIF Day?



Stochastic inflation (coarse-graining):

$$\frac{\partial \boldsymbol{P}}{\partial N} = \frac{\partial}{\partial \phi_{IR}}\left[\left(\frac{V_{,\phi}(\phi_{IR})}{3H(\phi_{IR})^2} - \boldsymbol{\alpha}\frac{H(\phi_{IR})}{2\pi}\frac{\partial}{\partial \phi_{IR}}\frac{H(\phi_{IR})}{2\pi}\right)\boldsymbol{P}\right] + \frac{1}{2}\frac{\partial^2}{\partial \phi_{IR}^2}\left[\left(\frac{H(\phi_{IR})}{2\pi}\right)^2 \boldsymbol{P}\right]$$



$\boldsymbol{\alpha}$ *represents the discretization scheme (Itô/Stratonovich)*

Why inviting a primordial cosmologist to the FRIF Day?

Fundamental Interactions

Gravity

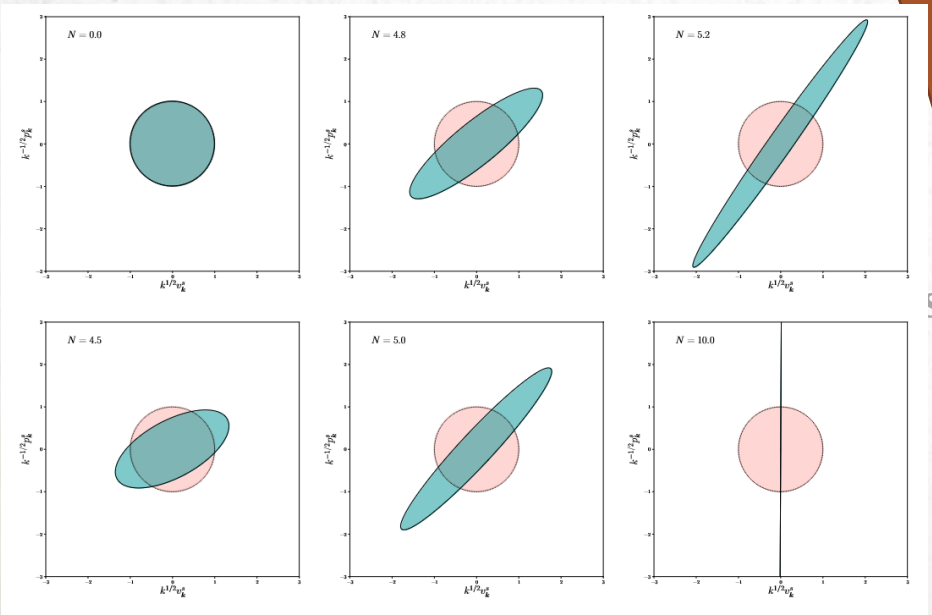
Quantum physics

Particle physics

PRIMORDIAL COSMOLOGY

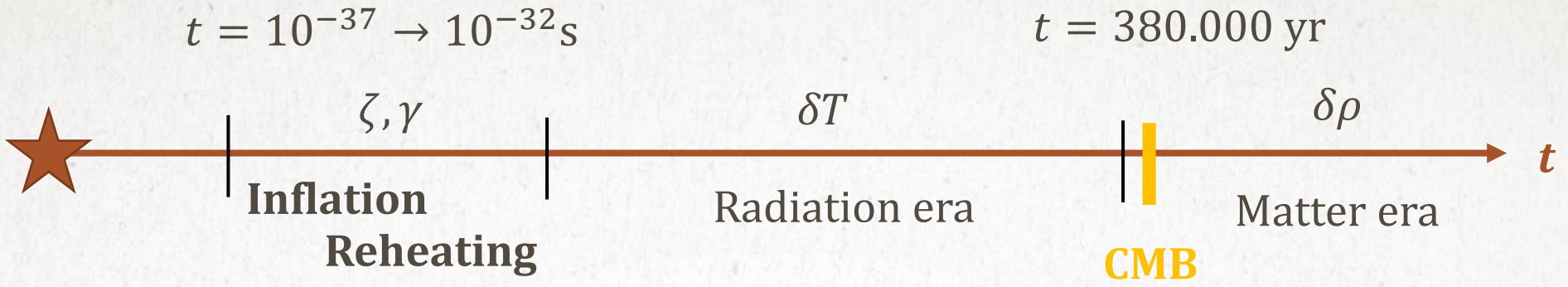
String theory

Inflationary two-mode squeezed states:



[Martin, Micheli, Vennin 2022]

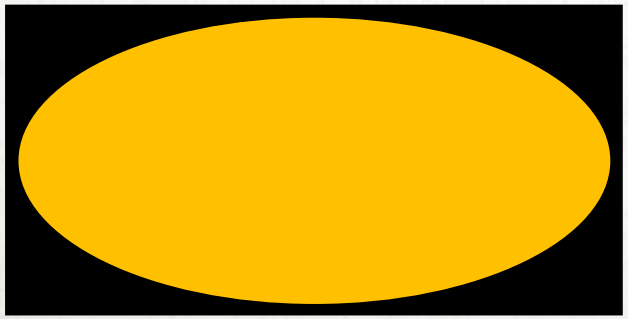
Early universe: the cosmological context



Scalar fluctuations ~ density fluctuations → $\zeta(t, \vec{x})$

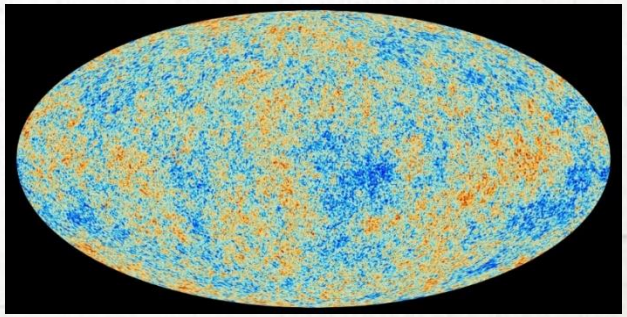
Tensor fluctuations ~ gravitational waves → $\gamma(t, \vec{x})$

Cosmic Microwave Background (CMB)



Penzias-Wilson (1964)

motivates → **Inflation** → predicts

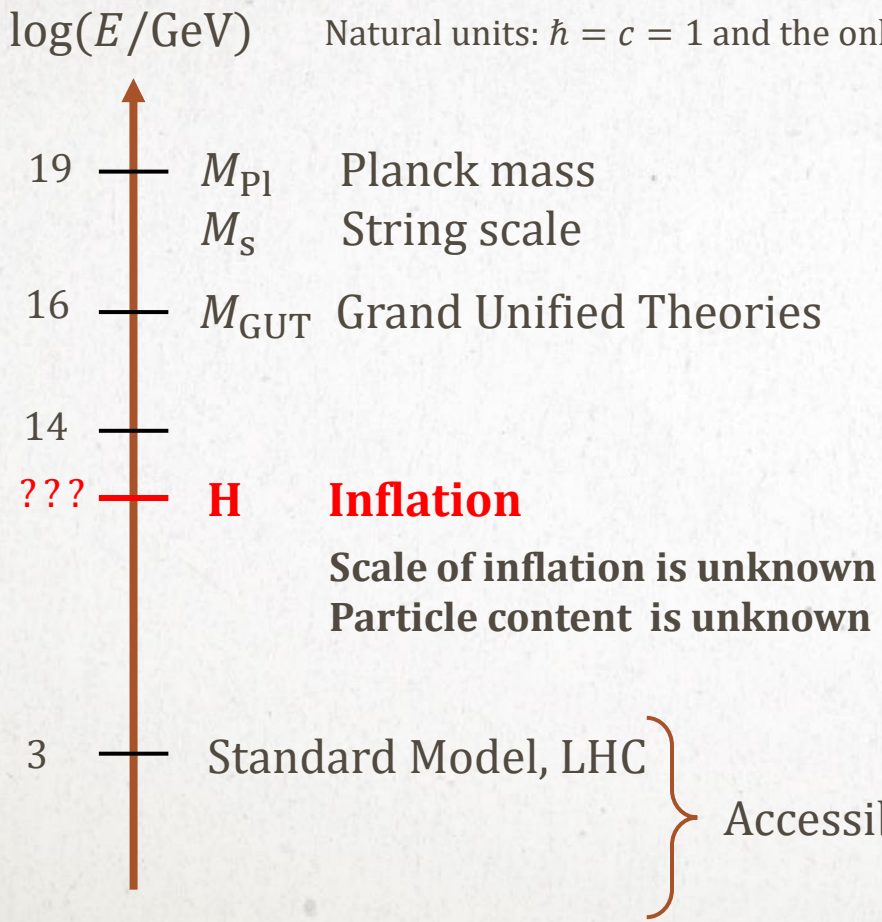


Planck (2013)

Early universe: the high-energy viewpoint

<u>Unique framework</u>: general relativity + quantum field theory + precision data

$$\text{CMB} \rightarrow \sqrt{\langle \zeta^2 \rangle} = (4.57 \pm \mathbf{0.02}) \times 10^{-5}$$



Inflation sensitive to high energies

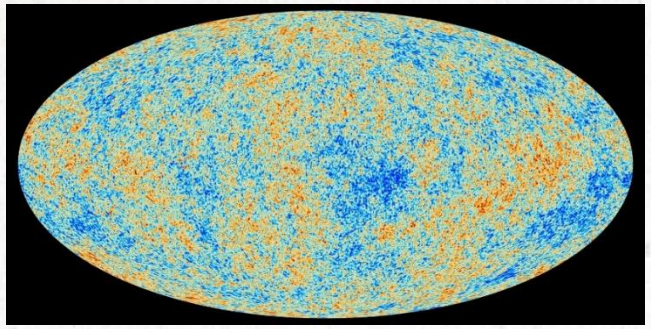
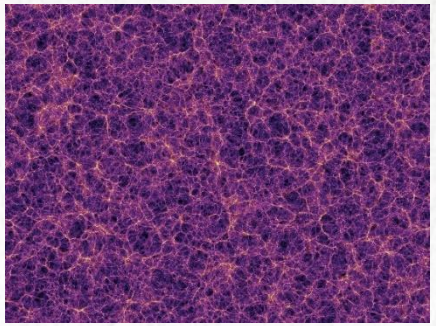
+

Precision data (current and future)

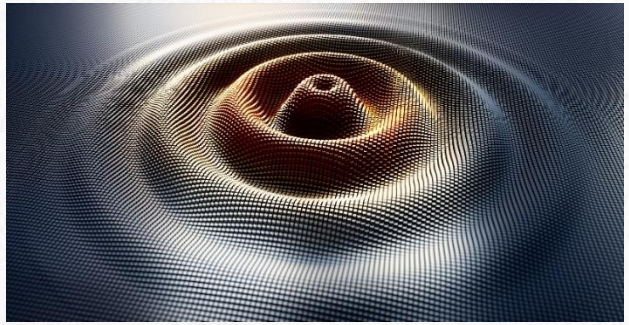
=

Formidable opportunity to test high-energy physics beyond the reach of terrestrial experiments

Early universe: the observational probes

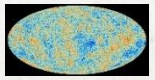
Current =  +  **(scalars)**

Cosmic Microwave Background **Large-Scale Structures**

Future =  **(tensors) ?**

Primordial Gravitational Waves

Objects of study = **primordial correlations functions**

e.g. $\langle \zeta^2 \rangle \rightarrow \left\langle \right.$  $^2 \left. \right\rangle$; $\langle \gamma^2 \rangle \rightarrow \left\langle \right.$  $^2 \left. \right\rangle$; $\langle \zeta^3 \rangle \rightarrow \left\langle \right.$  $^3 \left. \right\rangle$; etc.

EARLY UNIVERSE COSMOLOGY AT THE CROSSROADS

<u>Between gravity and particle physics</u>:
the cosmic spectroscopy = primordial non-Gaussianities in multifield inflation

[LP 2021]
[LP, Aoki, Renaux-Petel, Yamaguchi 2022]
[Aoki, LP, Sano, Yamaguchi, Zhu 2024]
[…]

COSMIC SPECTROSCOPY

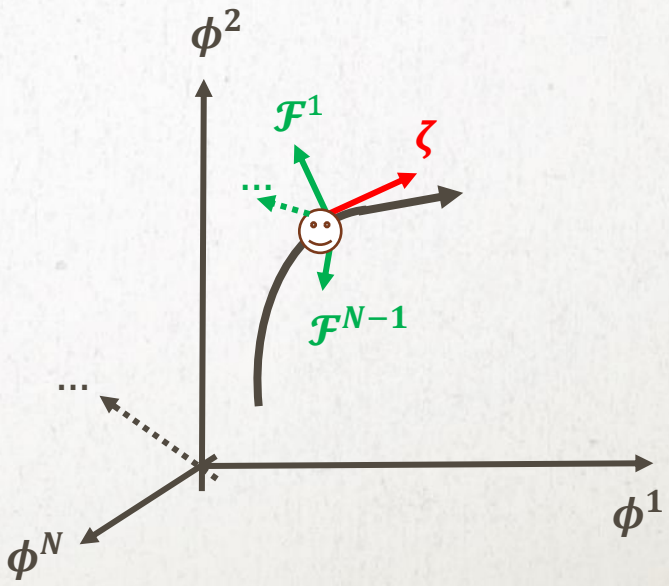
$$\mathcal{L} = -\frac{1}{2}\sum_{A,B} g^{\mu\nu} G_{AB}(\vec{\phi})\,\partial_\mu \phi^A \partial_\nu \phi^B - V(\vec{\phi})$$

From covariant models to the Lagrangian for fluctuations

- Multifield perturbation theory: $\phi^A(t,\vec{x}) = \bar{\phi}^A(t) + \delta\phi^A(t,\vec{x}) + \cdots$
- Identify covariant fluctuations: $Q^A = \delta\phi^A + \Gamma^A{}_{BC}\,\delta\phi^B\,\delta\phi^C/2 + \cdots$
- Define adiabatic and entropic fluctuations: $Q_\sigma = e_{\sigma A}\,Q^A \;;\; Q_s^\alpha = e_{sA}^\alpha\,Q^A$
- Fix the gauge freedom (comoving gauge): $Q_\sigma^{\rm com} = 0 \;;\; g_{ij}^{\rm com} = a^2 \exp[2\zeta]\,\delta_{ij}$

$$Q_s^{\alpha,{\rm com}} = \mathcal{F}^\alpha$$

Adiabatic-entropic basis



[LP 2021]

COSMIC SPECTROSCOPY

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- Fix the gauge freedom (comoving gauge): $Q_\sigma^{\rm com} = 0 \;;\; g_{ij}^{\rm com} = a^2\exp[2\zeta]\,\delta_{ij}$

$$Q_s^{\alpha,{\rm com}} = \mathcal{F}^\alpha$$

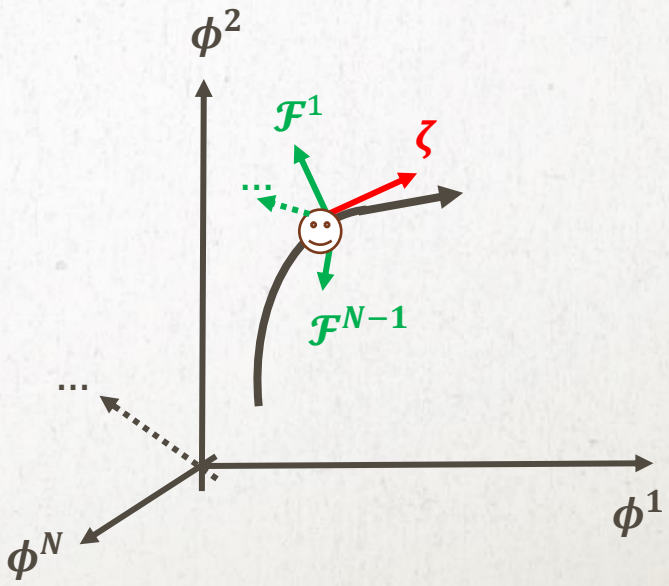
- Expand and simplify the action (up to cubic order for bispectrum calculations)

$$\mathcal{L}(\zeta,\mathcal{F}^\alpha) = \underbrace{\mathcal{L}^{(2)}(\zeta,\mathcal{F}^\alpha)}_{\text{Dictating the power spectrum}} + \underbrace{\mathcal{L}^{(3)}_{\rm Maldacena}(\zeta) + \mathcal{L}^{(3)}_{\rm new}(\zeta,\mathcal{F}^\alpha) + \mathcal{D}^{(3)}}_{\text{Dictating the bispectrum}}$$

Involve covariant derivatives of $V(\vec{\phi})$ and of $G_{AB}(\vec{\phi})$ (Field-space Riemann curvature etc.)

[LP 2021]

Adiabatic-entropic basis



COSMIC SPECTROSCOPY

[LP 2021]

Flavor and mass bases

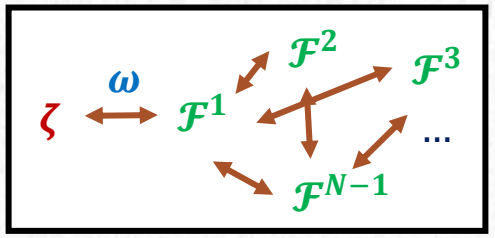
$$\mathcal{L}^{(2)} \supset -\sum_{\alpha,\beta} m^2_{\alpha\beta}\mathcal{F}^\alpha\mathcal{F}^\beta + \omega\,\mathcal{F}^1\dot{\zeta}$$

- **Non-trivial mass matrix mixing**
- **The first entropic field $\mathcal{F}^1$ is quadratically coupled to ζ**

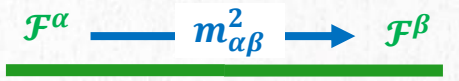
Flavor basis: interactions are specified

$\mathcal{F}^1$ *portal* to ζ

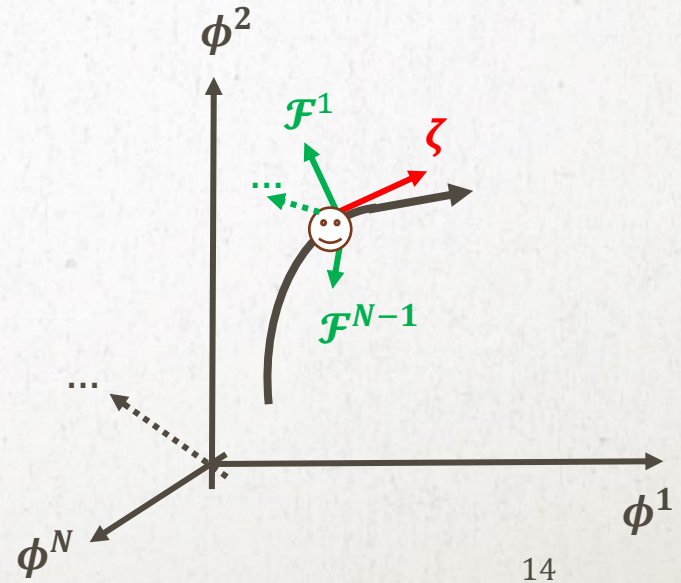
$\mathcal{F}^{2,\dots,N-1}$ *sterile* sector



perturbative mixing



non-perturbative mixing



ω *is the rate of turn of the background trajectory*

COSMIC SPECTROSCOPY

[LP 2021]

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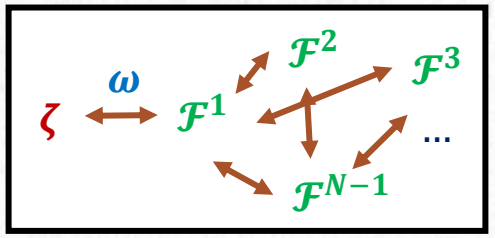
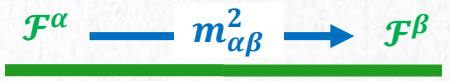


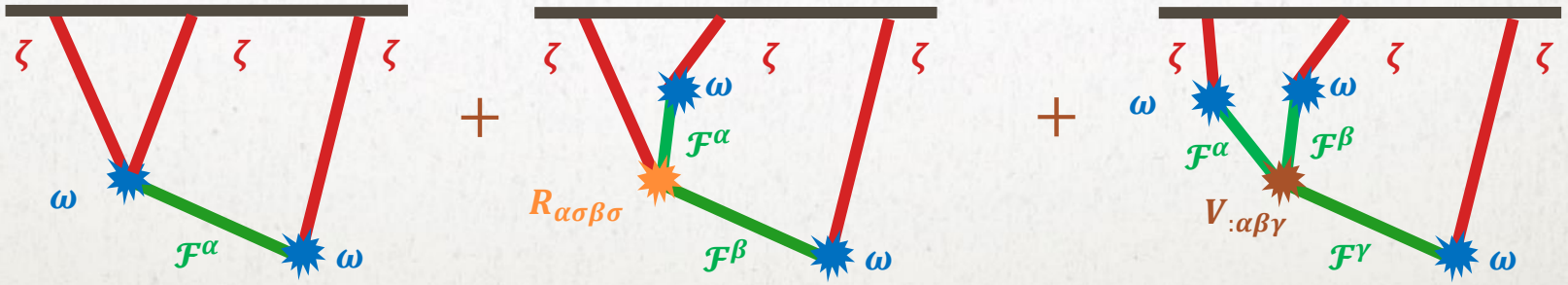
perturbative mixing



non-perturbative mixing

$$\mathcal{L}^{(3)} \supset \frac{\sqrt{2\epsilon}M_{\rm Pl}}{H}\omega\;\mathcal{F}^1\frac{(\partial\zeta)^2}{a^2} + 2\epsilon H^2 M_{\rm Pl}^2 R_{\alpha\sigma\beta\sigma}\dot{\zeta}\mathcal{F}^\alpha\mathcal{F}^\beta - \frac{1}{6}V_{;\alpha\beta\gamma}\mathcal{F}^\alpha\mathcal{F}^\beta\mathcal{F}^\gamma$$

$\langle\zeta^3\rangle =$



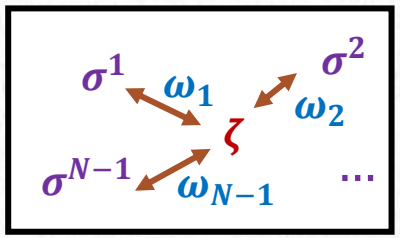
COSMIC SPECTROSCOPY

Flavor and mass bases

$$\mathcal{L}^{(2)} \supset -\sum_{\alpha,\beta} m^2_{\alpha\beta}\mathcal{F}^\alpha\mathcal{F}^\beta + \omega\,\mathcal{F}^1\dot{\zeta}$$

[LP 2021]

Diagonalization: $m^2_{\alpha\beta} = \left(O\,m\,O^T\right)_{\alpha\beta}$ **and** $\mathcal{F}^\alpha = O^\alpha{}_i\,\sigma^i$

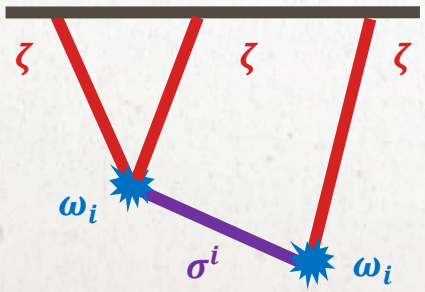


Mass basis:
masses are specified

All σ_i are coupled to ζ with ω_i

$$\mathcal{L}^{(2)}_{\text{mass}} \supset -\sum_i m_i^2\sigma_i^2 + \overbrace{\omega\,O^1}_{i}\,\sigma^i\dot{\zeta}$$

$$\langle\zeta^3\rangle = \sum_i$$



$+ \ \ldots$

[LP, Aoki, Renaux-Petel, Yamaguchi 2022]

COSMIC SPECTROSCOPY

Flavor and mass bases

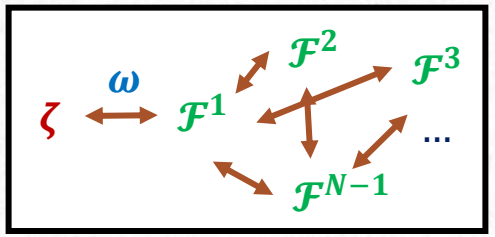
$$\mathcal{L}^{(2)}_{\text{flavor}} \supset -\sum_{\alpha,\beta} m^2_{\alpha\beta}\mathcal{F}^\alpha\mathcal{F}^\beta + \omega\,\mathcal{F}^1\dot{\zeta}$$

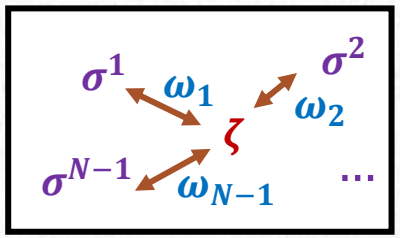
[LP 2021]

Flavor basis: interactions are specified

$\mathcal{F}^1$ *portal* to ζ

$\mathcal{F}^{2,\dots,N-1}$ *sterile* sector





Mass basis: masses are specified

All σ_i are coupled to ζ with ω_i

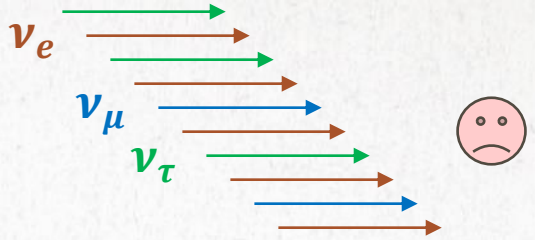
$$\mathcal{L}^{(2)}_{\text{mass}} \supset -\sum_i m_i^2\sigma_i^2 + \overbrace{\omega\, O^1}_{\;i}\,\sigma^i\dot{\zeta}$$

[LP, Aoki, Renaux-Petel, Yamaguchi 2022]

COSMIC SPECTROSCOPY

Analogy with neutrino oscillations

NO INTERACTIONS



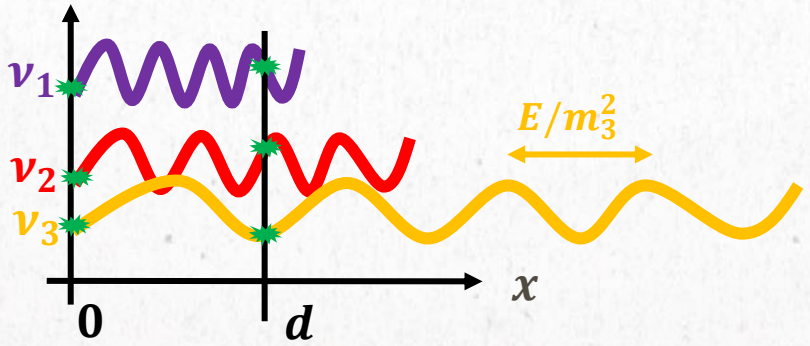
This is the Sun

It is emitting electronic neutrinos*

This is me

I am seeing many less electronic neutrinos

$$\nu_e = \sum_i U_{ei}\,\nu_i$$



*Entries of the PMNS** matrix: mixing angles, due to the mass matrix $M_{\alpha\beta}$ of neutrino flavors*

*also some ν_τ from MSW

**Pontecorvo-Maki-Nakagawa-Sakata

COSMIC SPECTROSCOPY

Analogy with neutrino oscillations

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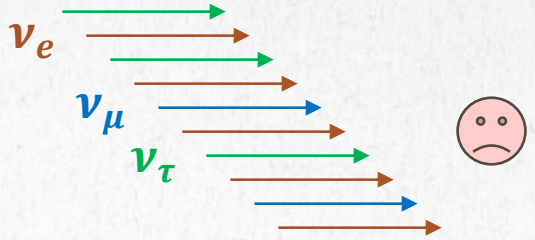
NO INTERACTIONS



This is me

I am seeing many less electronic neutrinos

ζ is the "detector"

$\mathcal{F}^\alpha$ are the flavor eigenstates and σ_i the freely propagating ones: the mass eigenstates

In particular: $\mathcal{F}^1 = \sum_i O^1{}_i \, \sigma_i$ with $O^1{}_i = [\cos(\theta_{12})\cos(\theta_{13}), \sin(\theta_{12})\cos(\theta_{13}), \sin(\theta_{13})]$

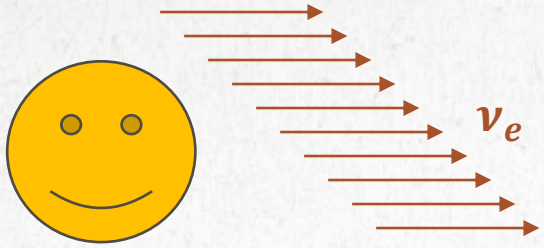
if $N_{flavor} = 3$ for example

Mixing angles

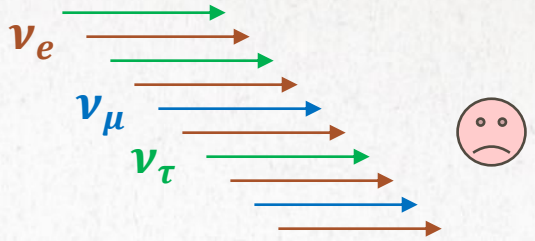
→ Inflationary flavor oscillations due to the misalignment between flavor and mass eigenstates

COSMIC SPECTROSCOPY

Analogy with neutrino oscillations



NO INTERACTIONS



This is the Sun

It is emitti

This is me

neutrinos

What process equivalent to the missing solar neutrinos may hint at inflationary flavor oscillations?

ζ is t

$\mathcal{F}^\alpha$ ar

In particular: $\mathcal{F}^1 = \sum_i$

$\ldots, \sin(\theta_{13})]$

if $N_{flavor} = 3$ for example

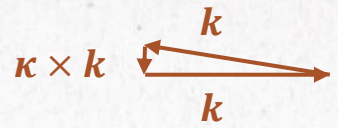
Mixing angles

→ Inflationary flavor oscillations due to the misalignment between flavor and mass eigenstates

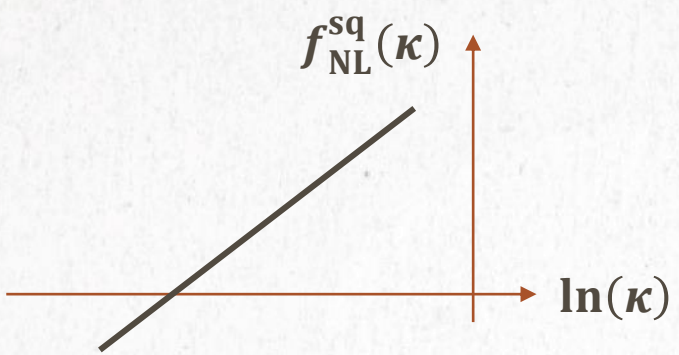
COSMIC SPECTROSCOPY

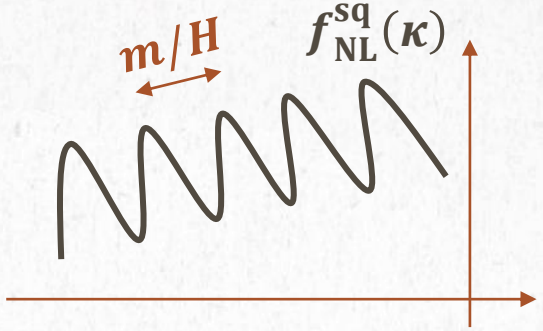
Inflationary flavor oscillations and the cosmic spectroscopy

Squeezed limit of the bispectrum: $\langle \zeta_k \zeta_k \zeta_{\kappa \times k} \rangle$



Squeezing: $\kappa = k_3/k_{1,2}$





<u>One entropic fluctuation</u>

Flavor basis = Mass basis

No mixing angle

No flavor oscillations

Single-field: $f_{\rm NL}^{\rm sq} \propto \kappa \ll 1$

Two-field: $f_{\rm NL}^{\rm sq} \propto \sqrt{\kappa} \cos\left(\frac{m}{H} \ln(\kappa) + \varphi\right)$

cosmological collider signal

[Maldacena 2003]
[Tanaka, Urakawa 2011]
[Pajer, Schmidt, Zaldarriaga 2013]

[Chen, Wang 2008]
[Noumi, Yamaguchi, Yokoyama 2013]
[Arkani-Hamed, Maldacena 2015]

COSMIC SPECTROSCOPY

Inflationary flavor oscillations and the cosmic spectroscopy

Single-field: $f_{\rm NL}^{\rm sq} \propto \kappa \ll 1$

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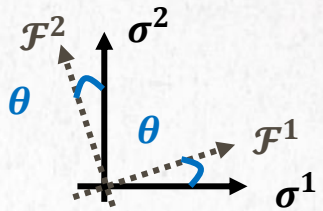
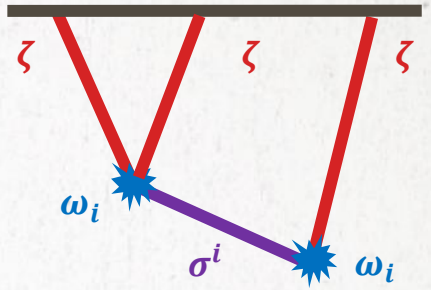
Squeezed limit of the bispectrum: $\langle \zeta_k \zeta_k \zeta_{\kappa\times k}\rangle$ $\quad \kappa \times k \;\overset{k}{\underset{k}{\rightleftarrows}}$ **Squeezing:** $\kappa = k_3/k_{1,2}$

Here we look at **3 fields** $=$ 2 flavors: $\{\zeta, \mathcal{F}^1, \mathcal{F}^2\} \leftrightarrow \{\zeta, \sigma^1, \sigma^2\}$





COSMIC SPECTROSCOPY

Inflationary flavor oscillations and the cosmic spectroscopy

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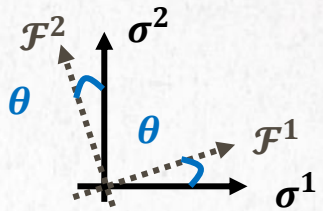
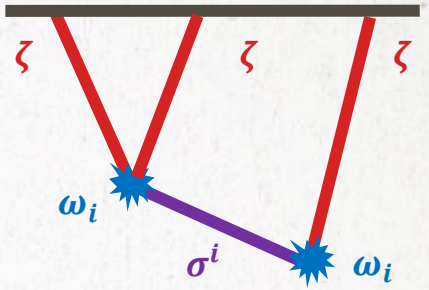
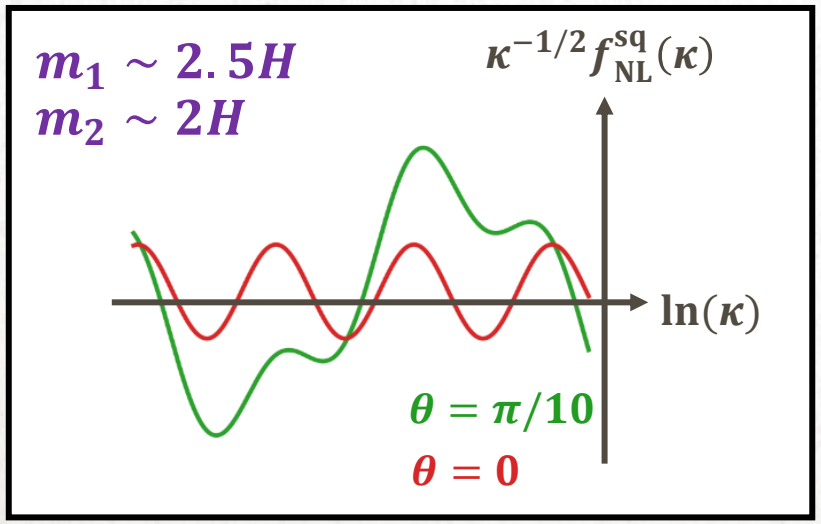
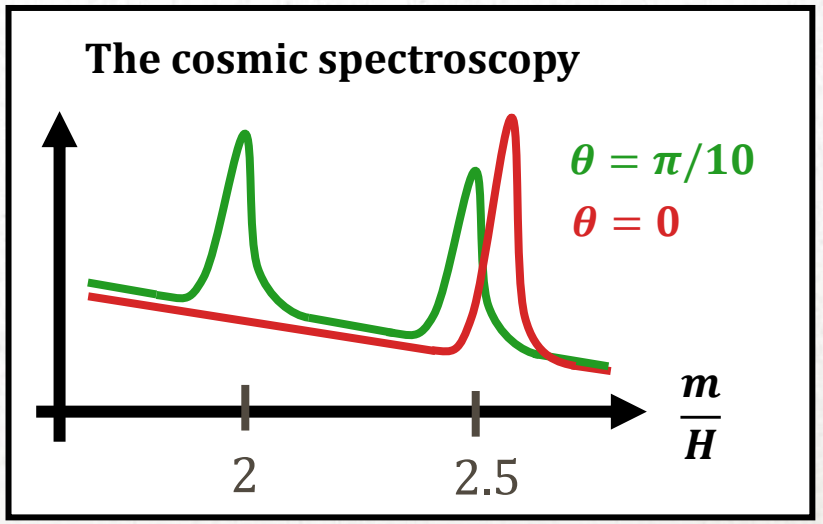




[LP, Aoki, Renaux-Petel, Yamaguchi 2022]



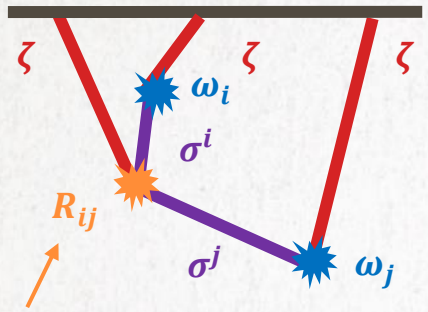


COSMIC SPECTROSCOPY

Other diagrams

- **[Aoki, LP, Sano, Yamaguchi, Zhu 2024]**

Recent calculation of double-exchange channel with bootstrap-inspired techniques



field-space curvature dependent coupling

differential operator in k-space

$$D \cdot I_{\text{double}} = I_{\text{simple}}$$

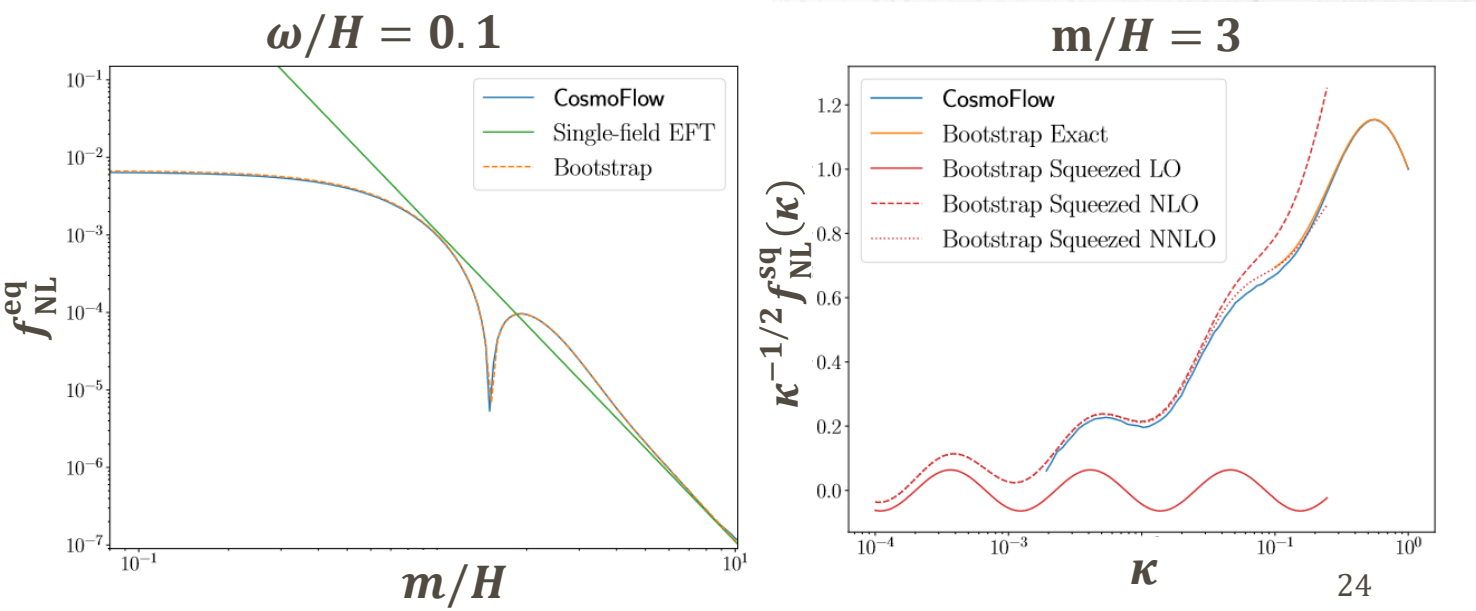
single-exchange « seed »

double-exchange « seed »

- **[Werth, LP, Renaux-Petel 2023]**
  [LP, Renaux-Petel, Werth 2023]
  [Werth, LP, Renaux-Petel 2024]

Systematic numerical evolution for any diagram
https://github.com/deniswerth/CosmoFlow

2nd Buchalter Cosmology Prize 2023



EARLY UNIVERSE COSMOLOGY AT THE CROSSROADS

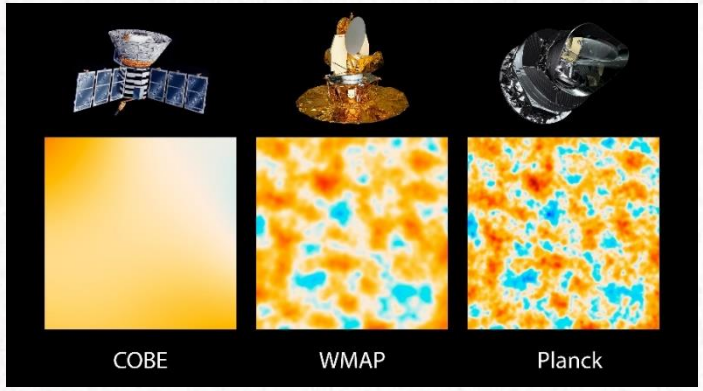
Towards a bright observational future

CMB

1964

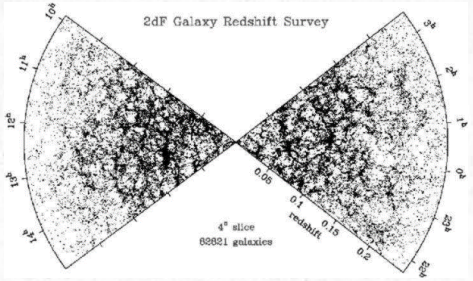
Penzias-Wilson

1992 2006 2018

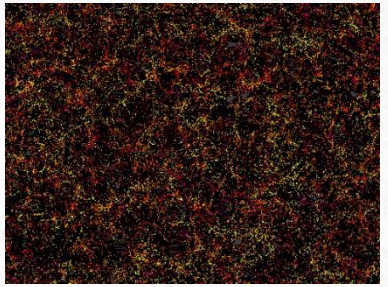


[credits: NASA]

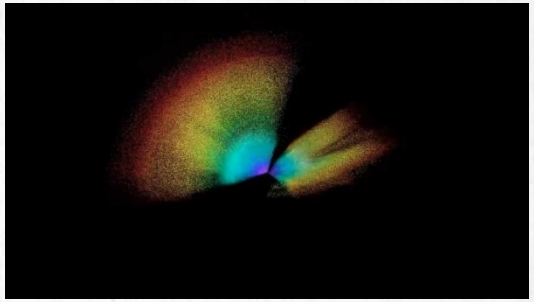
2-dFGRS (~2000)



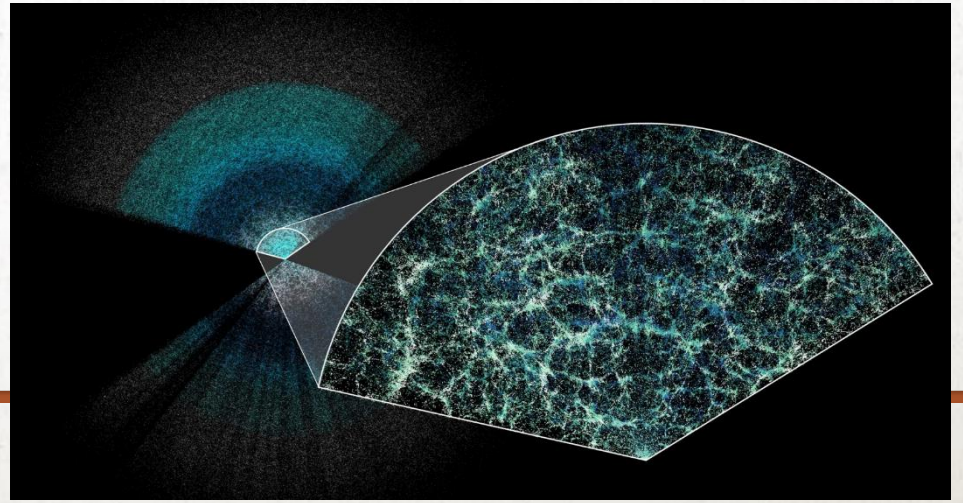
BOSS (2009-2014)



e-BOSS (2014-2020)

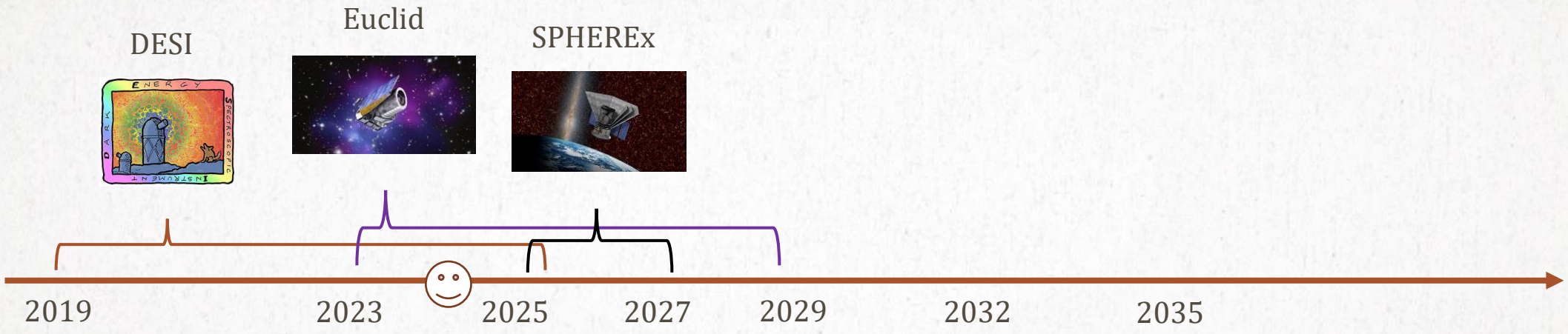


DESI (2020-?)



A BRIGHT FUTURE

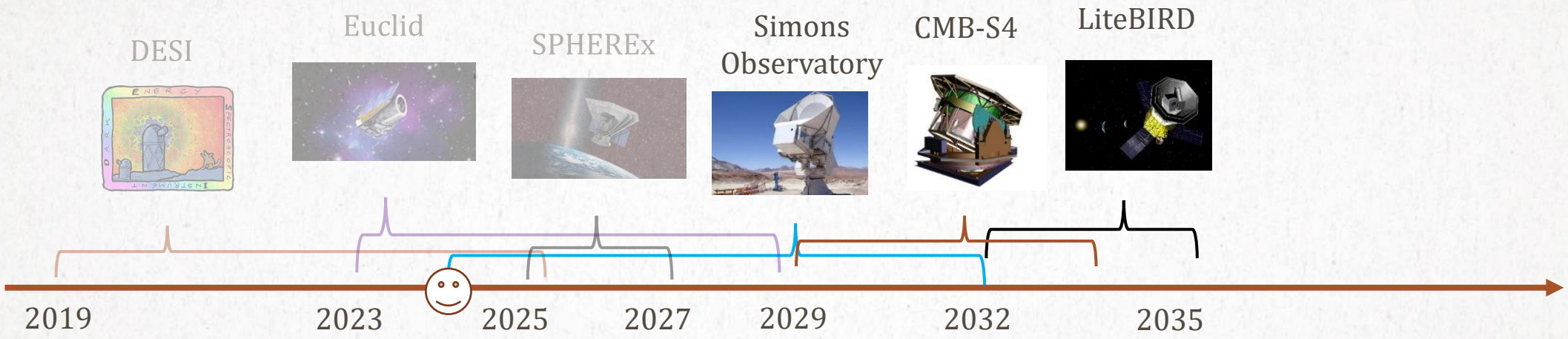
Primordial non-Gaussianities and large-scale structures



- ✓ Build **realistic** templates with all interactions and parameter space
- ✓ **Model-independent** tests of primordial particle content
- ✓ **Synergies** between analytical and numerical methods

A BRIGHT FUTURE

Extreme precision for linear fluctuations

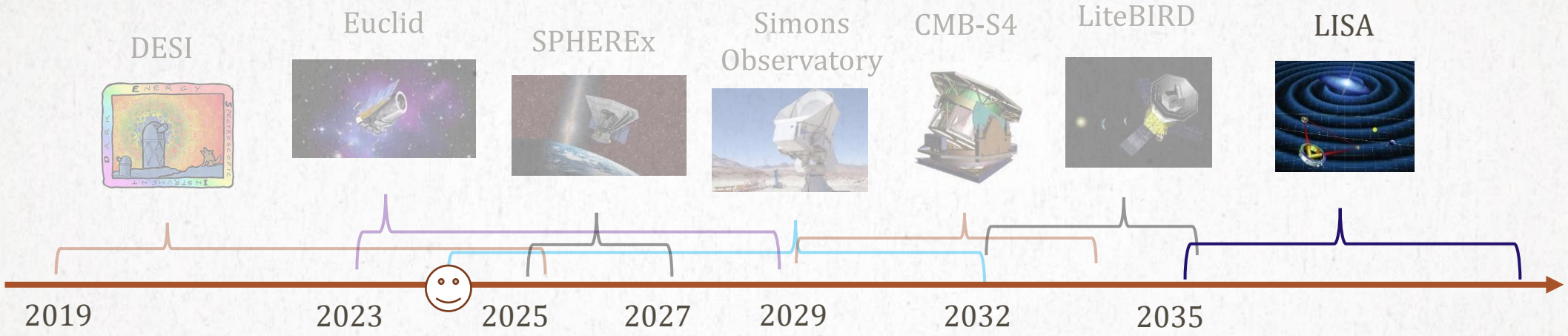


Primordial tensor modes: ✓ Scenarios **motivated** by high-energy physics, e.g. with gauge fields

Primordial features: ✓ Guaranteed information gain, **cross-checks** with galaxy surveys

A BRIGHT FUTURE

A new probe for the early universe in vastly different regimes



Primordial gravitational-wave background:

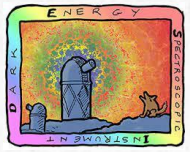
- ✓ Theoretical **"sanity checks" program** for a theoretically consistent phenomenology
- ✓ Remain open to **potential discoveries**, e.g. anisotropies of primordial origin

A BRIGHT FUTURE

Approximate budgets
Total ≃ 4 billions $

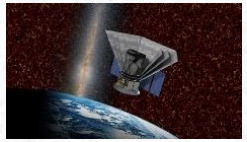
Towards a standard model of inflation

400M$
DESI



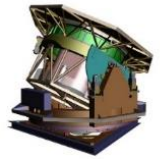
600M$
Euclid

400M$
SPHEREx

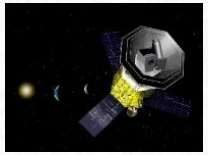


200M$
Simons Observatory

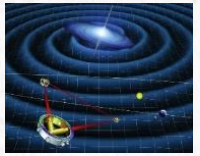
250M$
CMB-S4



500M$
LiteBIRD



1700M$
LISA



<u>Exciting era for primordial cosmology</u>

But discoveries = data + interpretation

EARLY UNIVERSE COSMOLOGY AT THE CROSSROADS

Conclusion

- Requires understanding of all fundamental interactions → **fun***
- Will enable to test fundamental physics with precision and numerous data → **promising**
- Many techniques could be imported from other fields and need of work force → **collaborative**

Personal subjects of interest dropping:

- Loop corrections and UV divergences in inflation
- Borel resumation of divergent time series in stochastic inflation
- Effective field theories for cosmological fluctuations and non-linearly realized symmetries
- Path integral representations of the in-in Schwinger-Keldysh formalism
- Primordial features beyond approximate scale invariance in string-inspired landscapes

*at least for a theoretical physicist

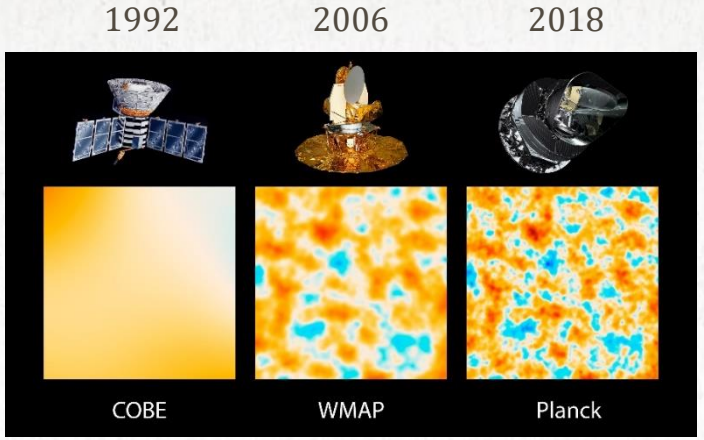
BACKUP SLIDES

Cosmic Microwave Background

CMB

1964

Penzias-Wilson

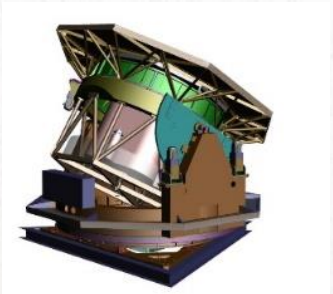


[credits: NASA]

Simons Observatory (2024-?)

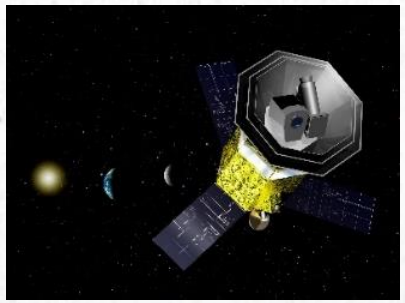
The coming one (Chile)

CMB-S4 (2029-?)

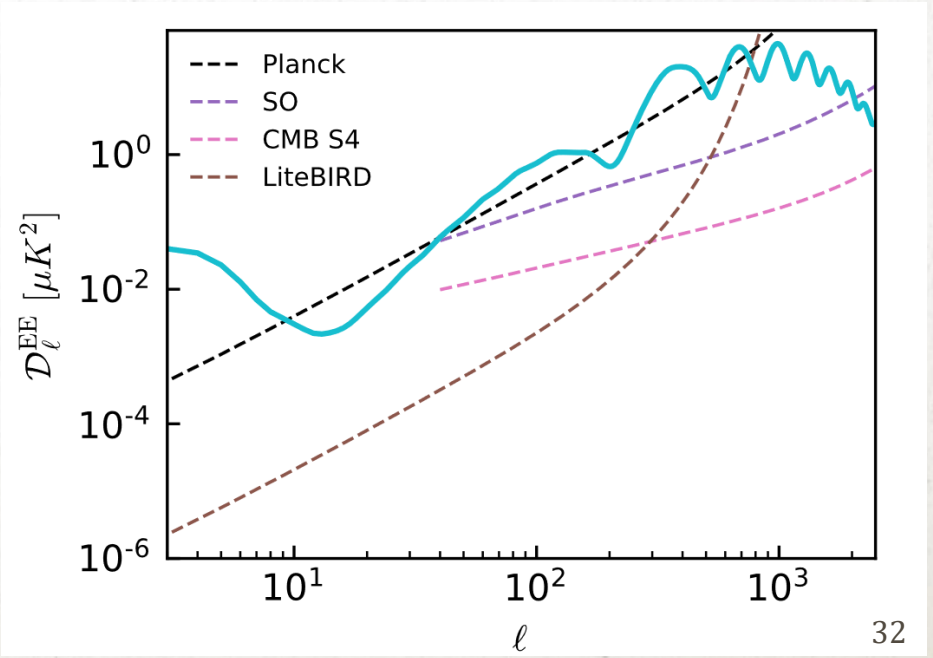


Multiple telescopes
Better foreground removal

LiteBIRD (2032-?)

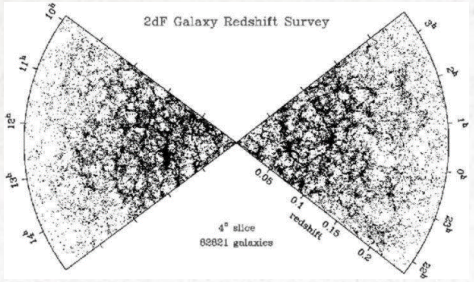


Satellite
Much better for low-ℓ

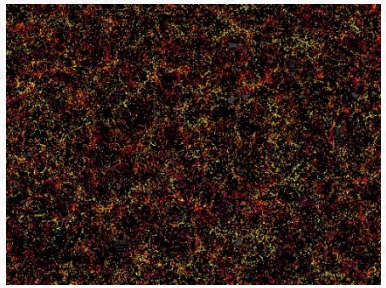


Large-Scale Structures

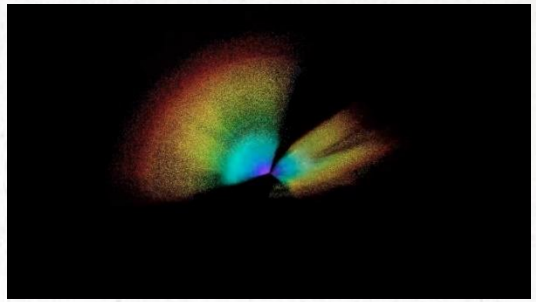
2-dFGRS (~2000)



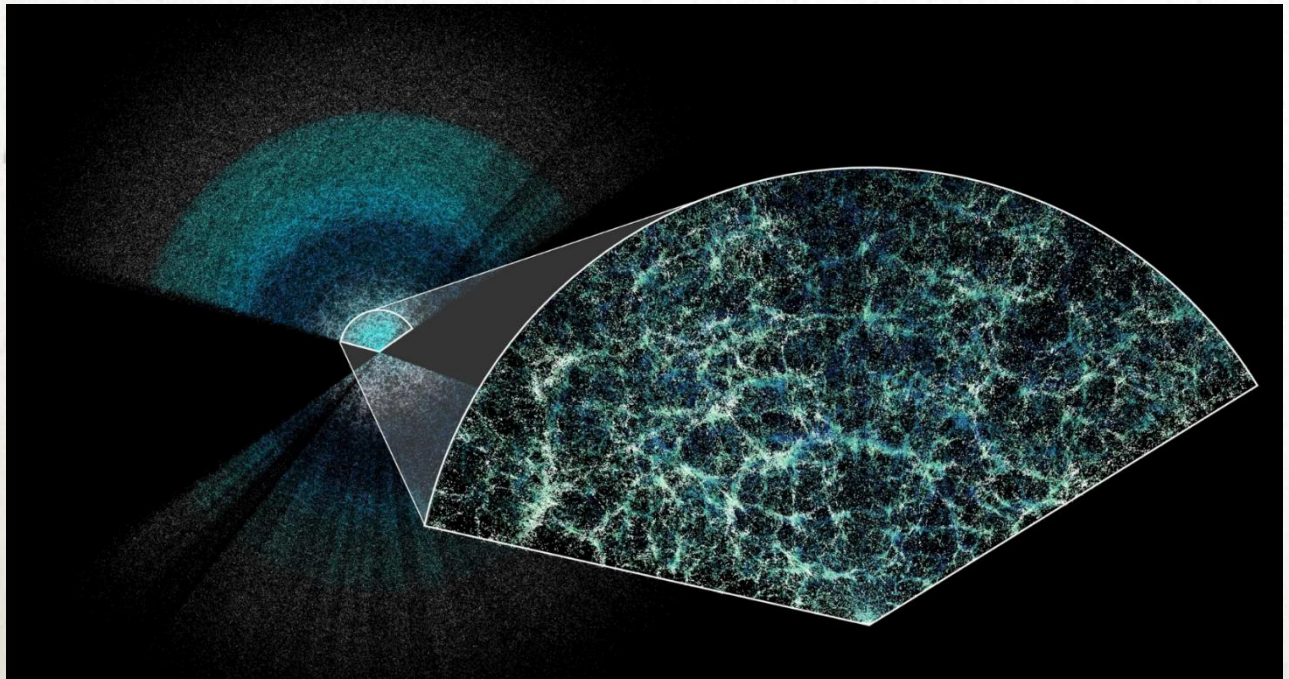
BOSS (2009-2014)



e-BOSS (2014-2020)

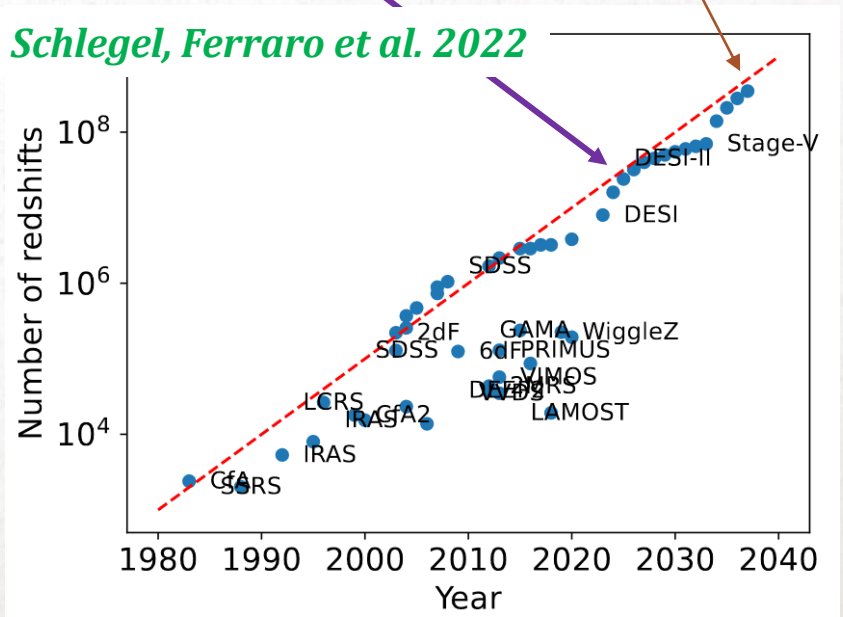


DESI (2020-?)



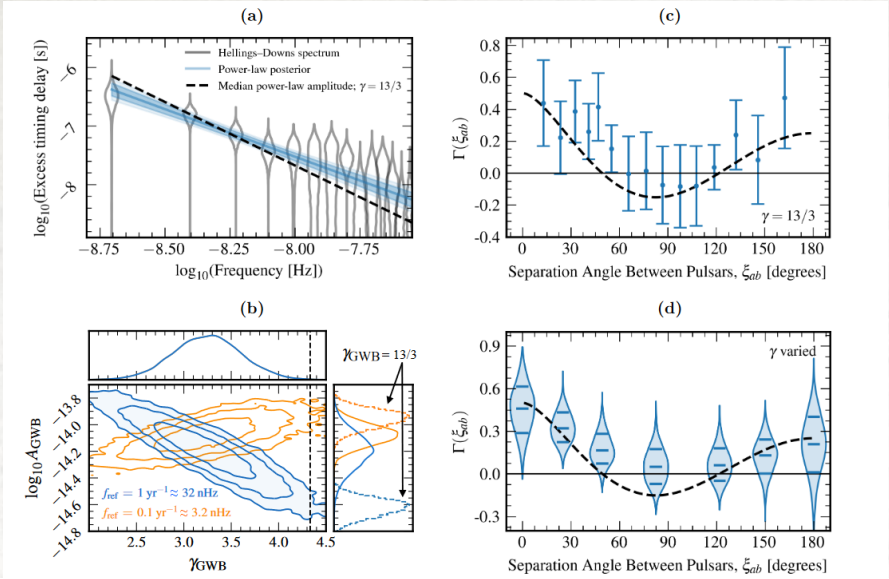
Euclid (2023-?)

PUMA, MegaMapper, ...

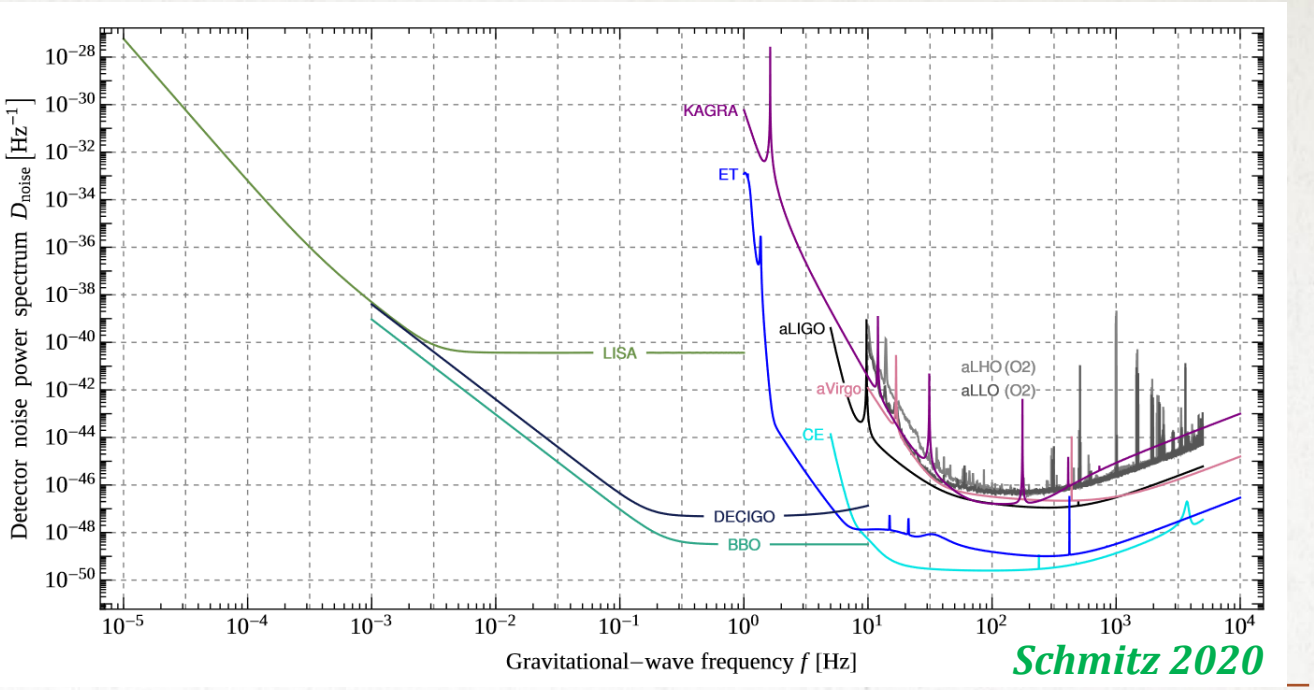


Gravitational-Wave Backgrounds

IPTA (2012-?)



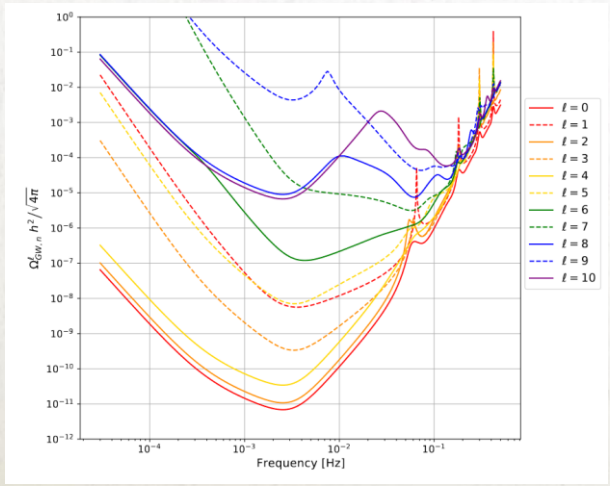
"No GW background" hypothesis is excluded at 3σ



Schmitz 2020

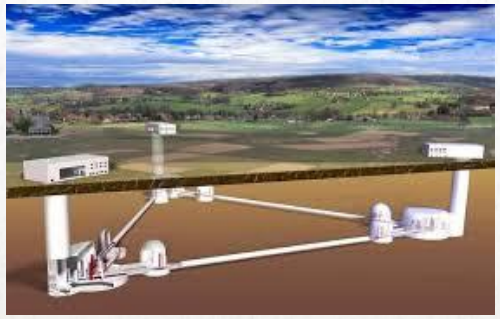
Europe

Anisotropies in LISA (2034-?)



Europe

Einstein Telescope



USA

Cosmic Explorer

Japan *USA+Europe*

DECIGO, BBO