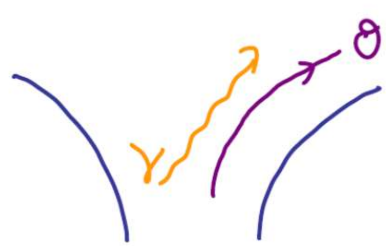
Cosmology at the Theory Frontier

State of the super-horizon perturbations seeding structure

(Micro-)states of spacetime

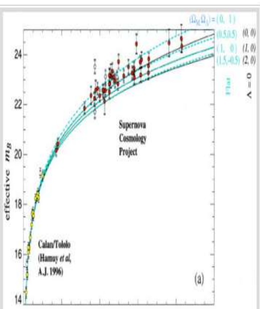
White paper for TF01 & TF09 in progress with Flauger, Gorbenko, Joyce, McAllister, Shiu

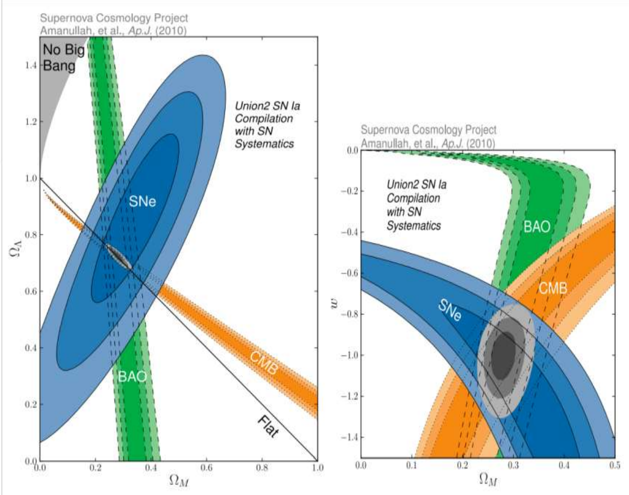


Accelerated expansion

Observationally:

(1) Late Universe





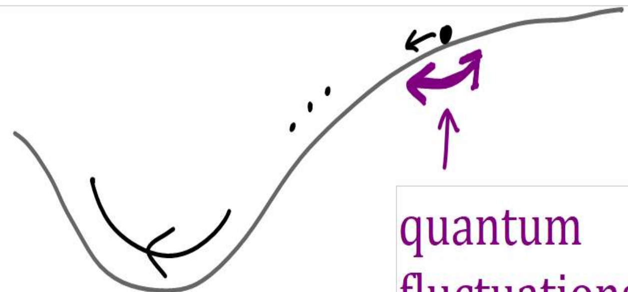
Independent measures of expansion history agree on new parameter Λ

$$\Lambda \sim H^2 \sim 10^{-120} M_P^2$$

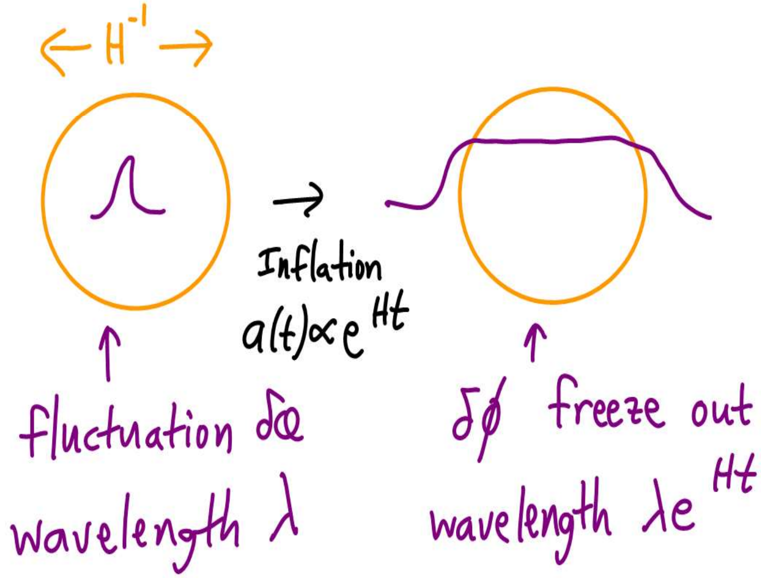
$$M_P \sim 10^{18} GeV \sim 1/\sqrt{G_{Newton}}$$

Strong coupling scale of gravity

(2) Early Universe: leading theory is Inflation, accelerated expansion e.g. driven by scalar field potential energy **V**(ϕ)

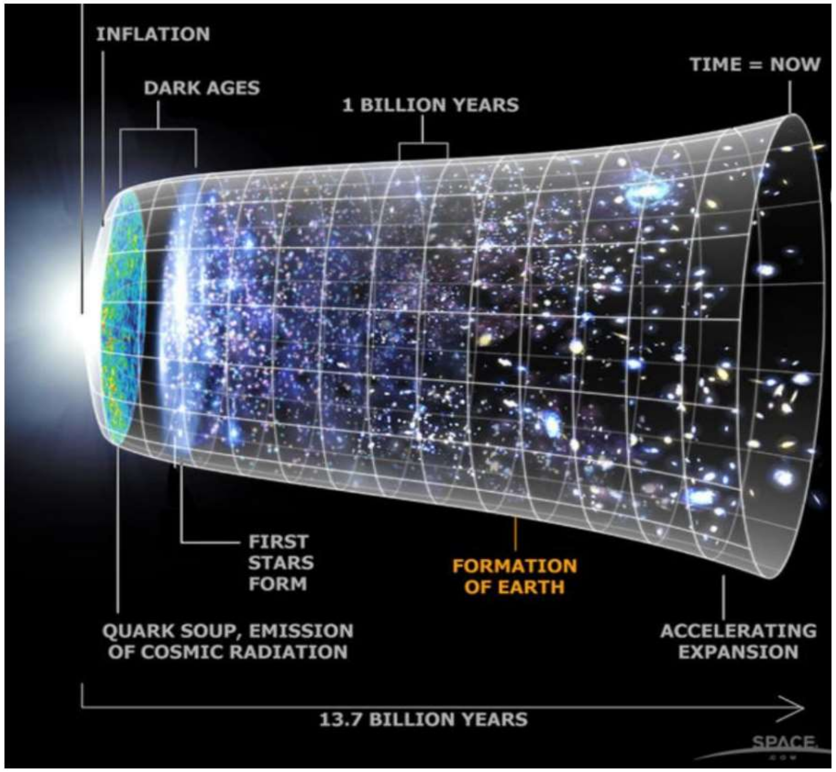


quantum fluctuations



Amplitude fixed by uncertainty principle:

δϕ ~ H



CMB streams to us from when atoms formed. It carries imprint of density fluctuations that originate earlier.

Large-scale structure (LSS) also carries imprint of primordial fluctuations, requiring new insights to disentangle from nonlinear evolution

Quantum seeds for structure:

- Quantum fields obey the Heisenberg uncertainty principle, fluctuate in spacetime.
- For black holes, this leads to their decay (Hawking radiation). Information problem: leading calculation => featureless radiation.
- In cosmology, these quantum fluctuations are seeds for all the observed structure in the universe

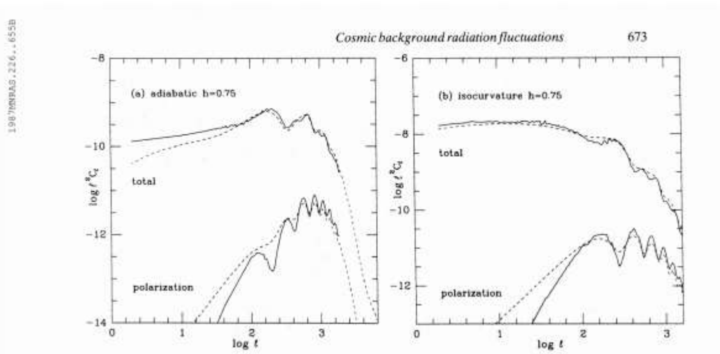


Figure 7. Power spectra for the two $h = 0.75$ scale-invariant CDM models. The solid lines show results from equation (4.17) and the dotted lines show approximate results derived from equation (4.19).

(a) Bond Efstathiou 1987

Chibisov/Mukhanov, Starobinsky, et al

Quantum fluctuations from inflaton field as seeds for stucture fits data well: small spectral tilt as expected as H(t) decreases slowly; super-horizon at CMB formation

$<\delta T\ \delta T>$ CMB temperature fluctuations (and polarization, lensing)

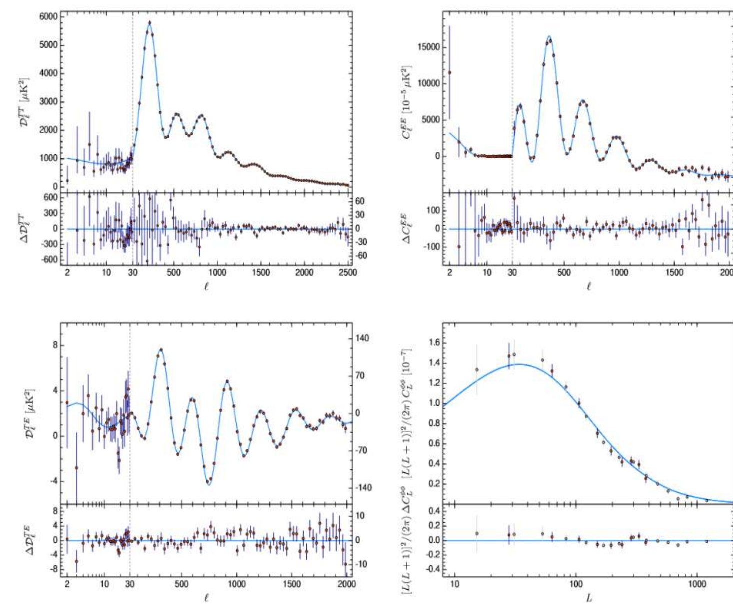
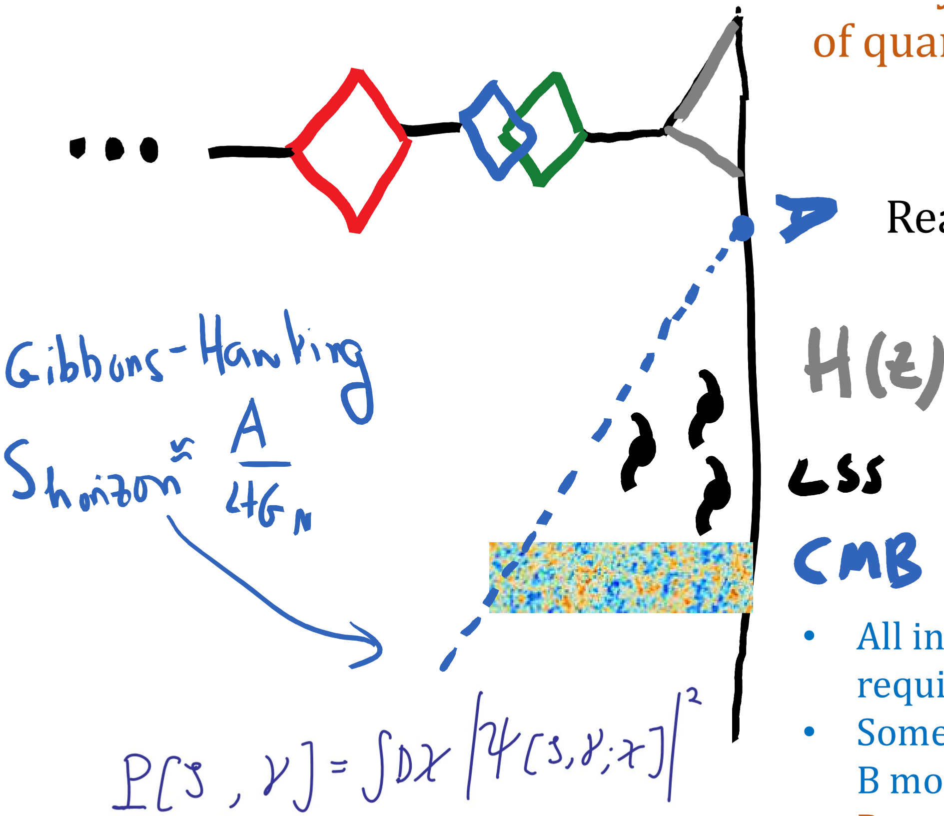


Fig. 1. *Planck* 2018 CMB angular power spectra, compared with the base-ΛCDM best fit to the *Planck* TT,TE,EE+lowE+lensing data (blue curves). For each panel we also show the residuals with respect to this baseline best fit. Plotted are $\mathcal{D}_\ell = \ell(\ell+1)C_\ell/(2\pi)$ for TT and TE, C_ℓ for EE, and $L^2(L+1)^2 C_L^{\phi\phi}/(2\pi)$ for lensing. For TT, TE, and EE, the multipole range $2 \le \ell \le 29$ shows the power spectra from Commander (TT) and SimAll (TE, EE), while at $\ell \ge 30$ we display the co-added frequency spectra computed from the Plik cross-half-mission likelihood, with foreground and other nuisance parameters fixed to their best-fit values in the base-ΛCDM cosmology. For the *Planck* lensing potential angular power spectrum, we show the conservative (orange dots; used in the likelihood) and aggressive (grey dots) cases. Note some of the different horizontal and vertical scales on either side of $\ell = 30$ for the temperature and polarization spectra and residuals.

Deep and successful theory, but requires UV and IR completion



Gravity not decoupled globally, rich IR dynamics of quantum fields.

Real observations, statistical inferences

- All inflation models UV sensitive, satisfactory theory requires control of QG effects.
- Some testable signatures from string theory mechanisms: B modes, power spectrum features and non-Gaussianity
- Describe/classify perturbations and what we actually measure via bottom up EFT

Or perhaps more globally: $\Sigma_I c_I \, (above \times disconnected\ components)_I$
Singularities & topology change.

Remarkable recent advances and new opportunities on these fronts:

Contents

• Examples of control parameters
- numeric
- parametric

• genericity, rigidity, & simplifications

- universality • inflation/DM/strong-CP

- CMB: r, P(s) ; LSS information

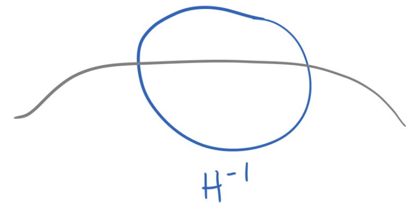
+ (non)-perturbative EFT & topology

- ~~BPS~~ → integrable deformations

- numeric & analytic metrics/PDEs, robustness of inflation (Thms)

- physics (cosmo)-inspired algorithms

Primordial perturbations:



$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt)$$

scalar

$$h_{ij} = a(t)^2 \left[e^{2\zeta} \delta_{ij} + \gamma_{ij} \right]$$

tensor (GW)

$$\Psi(\zeta(\mathbf{x}), \gamma(\mathbf{x}), \{\chi(\mathbf{x})\}; \{\lambda\})$$ Wave functional

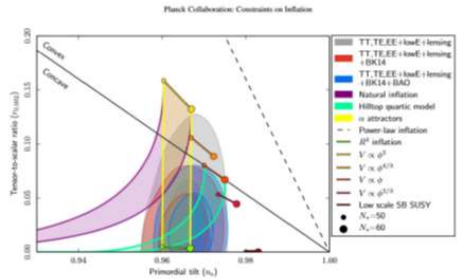
additional fields

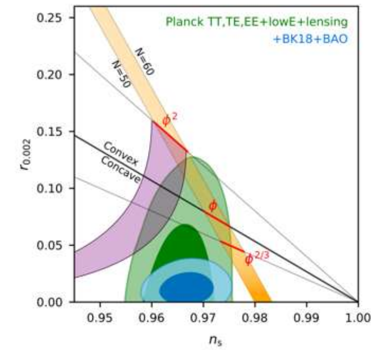
$$\mathcal{L}(\zeta(\mathbf{x})|\{\lambda\}) = \int D\chi |\Psi(\zeta(\mathbf{x}), \chi(\mathbf{x}); \{\lambda\})|^2$$ Likelihood

$$\langle \zeta_{k_1} \zeta_{k_2} \rangle \equiv P_\zeta \delta(\mathbf{k} + \mathbf{k}') \qquad \langle \gamma_{s_1,k_1} \gamma_{s_2,k_2} \rangle \equiv P_\gamma \delta_{s_1 s_2} \delta(\mathbf{k} + \mathbf{k}')$$

Will present current observational status (CMB, LSS, …) below after theory overview (TF – including TF01-- needed to fully interpret and motivate observational data!)

Observational Reach

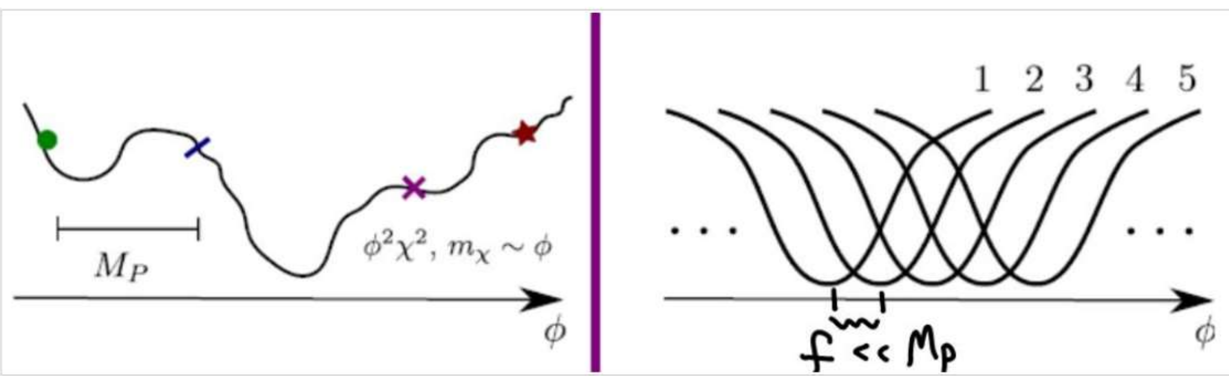


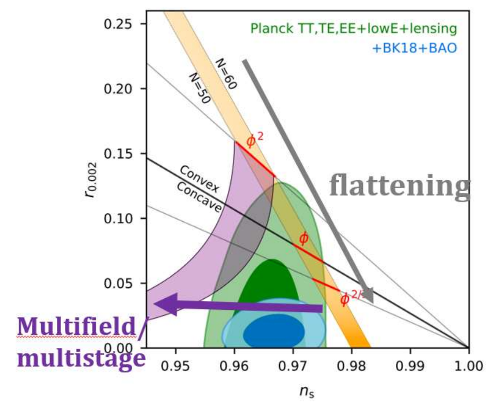


- Sensitivity to parameters of quantum field theory and even string theory.

$$\epsilon \equiv \frac{M_P V'}{V} \ll 1, \quad \eta \equiv M_P^2 \frac{V''}{V} \ll 1 \ \text{ but } \ \Delta V = V_0(\phi)\frac{(\phi-\phi_0)^2}{M_P^2} \Rightarrow \eta \simeq 1$$

Kachru Kallosh Maldacena McAllister Trivedi,… (top down); discrete symmetries can help even for small field (bottom up Baumann/Green,…)





Freese Friemann Olinto; Linde, Kaloper Lawrence D'Amico… (bottom up) McAllister, ES, Westphal, Wenren, Wrase, Kleban (top down) …

Model-dependent* tests; novel signatures

Statistics of the primordial perturbations:

$$\Psi[\zeta(\vec{x}), \gamma(\vec{x}); \chi(\vec{x}), t]$$

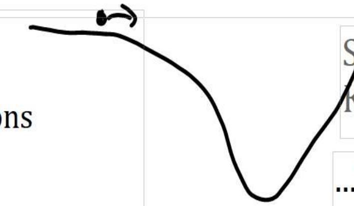
Generically a mixed state

$$P[\zeta, \gamma] = \int D\chi \, |\Psi[\zeta, \gamma; \chi]|^2$$

Sensitive to number of fields and their interactions. For free scalar fields, the ground state is Gaussian. Otherwise, non-Gaussian.

Previous Non-Gaussianity Theory

slow roll
V flat =>
small interactions



Srednicki et al,...
Komatsu/Spergel,...

...3pf calc: Maldacena

- Additional fields not so constrained

Curvaton (Mukhanov/Linde...)
Modulated reheating (Dvali/Zaldarriaga, Kofman,...)
(p)reheating dynamics (Bond/Braden/ Frolov et al, Amin...)

- Even for single field, self-interactions on steep potential => larger NG

ES Tong,Alishahiha,Horn,Green,Senatore,...

- More systematic EFT

Chen/Huang/Kachru/Shiu; Senatore et al

- Oscillations (axions), imprints of heavier fields,...

Easther/Lim, Flauger, Peiris et al, McAllister, ES, Westphal, Mirbabayi, Senatore, Chen/Wang, Baumann Green, Arkani-Hamed Maldacena,..

EFT Advances

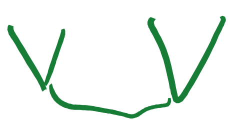
- Perturbative structure (amplitudes, bootstrap)

Arkani-Hamed, Maldacena, Baumann et al, Gorbenko et al, Pajer et al, Joyce et al,…

e.g.

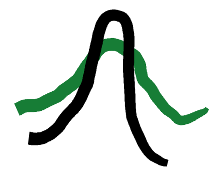
Proofs of bulk unitarity at level of late-time correlators

Elegant formulas for correlators assuming derivative couplings



Conservative observationally (minimality of couplings)

- Non-perturbative NG tails, non-adiabaticity



Bond et al, '…
Flauger et al '16
Baumgart/Sundrum '19
Panagopoulos ES '19,
Gorbenko-Senatore '19,
Mirbabayi '19
Creminelli et al '21
Cohen Green … '21

e.g.

Stochastic Inflation from QFT

Calculations of shapeof tails in various models.

Massive particle production: highest S/N beyond 3pf, sensitivity to mass >> Hubble.

hyperbolic field space ⇒ Exp[-Log(ζ)^2] NG tail

cf Kallosh/Linde, Brown, …

Novel observational probes & PBH mechanism

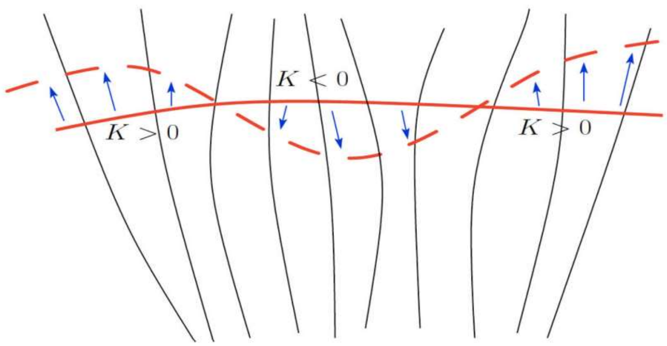
Conservative theoretically (generic couplings consistent with inflation)

Recent results extend the range of initial conditions consistent with inflation

Clough Creminelli East Flauger Kleban Lim Linde Mirbabayi Senatore Vasy...

Mean-Curvature Flow

– Take a surface, and deform it forward or backward according to sign of K



– The change of volume: $\frac{\partial V}{\partial \lambda} = \int d^3x K^2 \sqrt{h} \equiv \langle K^2 \rangle \geq 0$

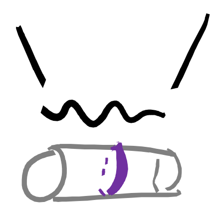
– So this procedure either converges to an extremal surface, if it can exist, with $K = 0$ everywhere

– or it gives a surface of larger volume indefinitely

Mathematical proofs so far in special cases, numerical GR results in realistic cases.

Note Bunch-Davies initial condition not required (though it is enough to start from nothing and generate all structure). Many choices of wavefunction are consistent with inflation.

Spacetime singularities involve stringy and/or quantum gravity effects



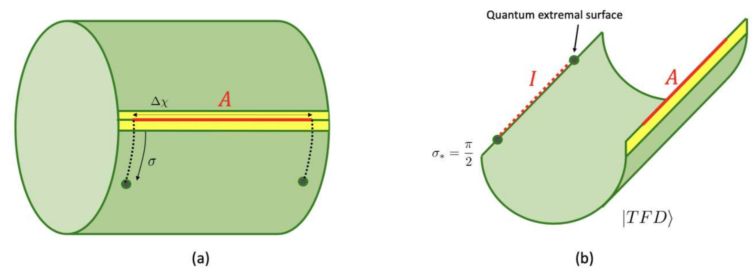
What about the wavefunction of the universe(s) or measure??

cf Landscape structure (below)

One possibility: Hartle-Hawking no-boundary proposal.

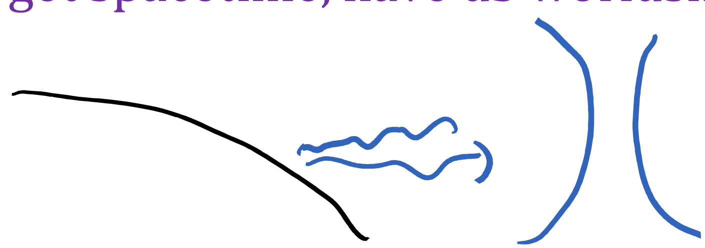
Turns out nontrivial topology (`bra-ket wormhole') contribution is crucial for the Euclidean no boundary gravitational path integral to create a consistent state of matter for the resulting quantum fields (at least in the AdS/CFT context). Chen Gorbenko Maldacena, also Z. Yang et al

In cosmology: original not clearly viable (Hubble->0) cf Linde et al



Cosmo case? QG + matter has multiple states. Low-d toys:

- String worldsheet: in nontrivial target spacetime, have dS worldsheet and string production ...Martinec

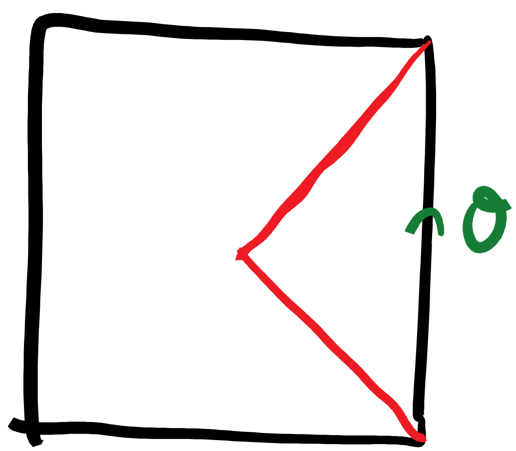


- Duals of TT-bar deformations with solvable spectrum (below)

Difficult to jump to such ultimate conclusions.
Help from `thought-experimental data'

Gravitational calculations suggest a thermodynamic interpretation of the de Sitter observer horizon, somewhat analogous to black hole thermodynamics

Gibbons-Hawking … Anninos et al (logarithmic corrections)



$$S = S_{GH} - 3\log(S_{GH}) + \ldots$$

$\frac{A}{4G_N}$ (A) dS_3 case

Suggests theory with a finite Hilbert space might capture the observer patch.
Many interesting approaches (dS/CFT, dS/dS FRW/FRW, FRW/CFT, various matrix models many authors – see white papers/reviews for refs)

At the `pure gravity' level, the *real dressed spectrum* of the universal and solvable

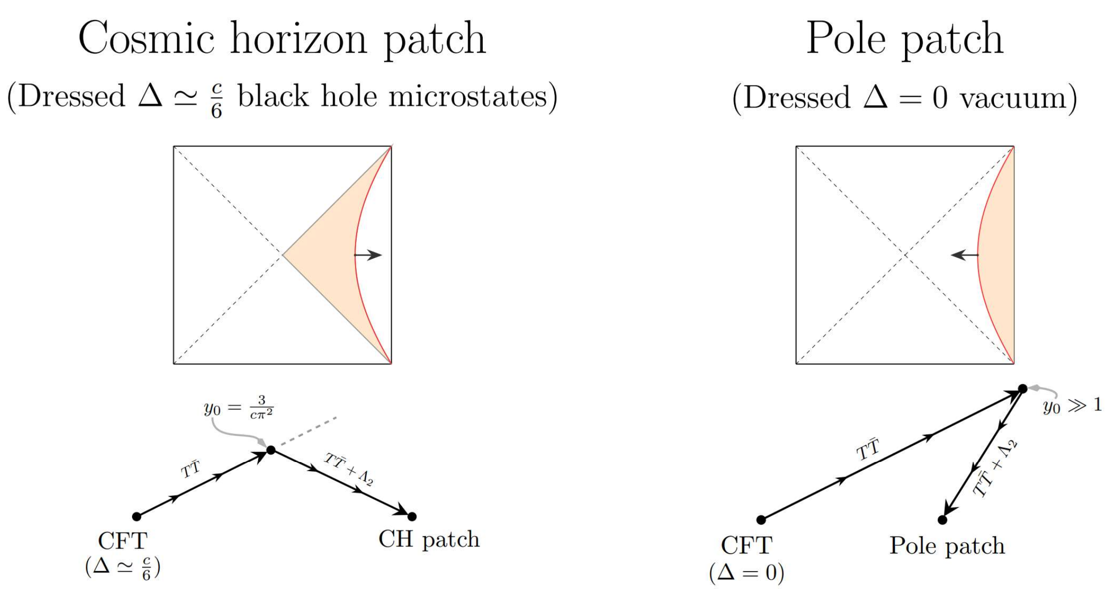
$T\bar{T} + \Lambda_2$ deformation

$$\frac{\partial}{\partial \lambda} \log Z = -2\pi \int d^2x \sqrt{g}\, \langle T\bar{T} \rangle + \frac{1-\eta}{2\pi\lambda^2} \int d^2x \sqrt{g}$$

Zamalodchikov et al, Dubovsky et al, Cavaglia et al … Gorbenko ES Torroba '18

of a CFT on a cylinder captures the <u>microstates and the geometry</u> of the dS_3 observer patch Shyam, Coleman et al '21

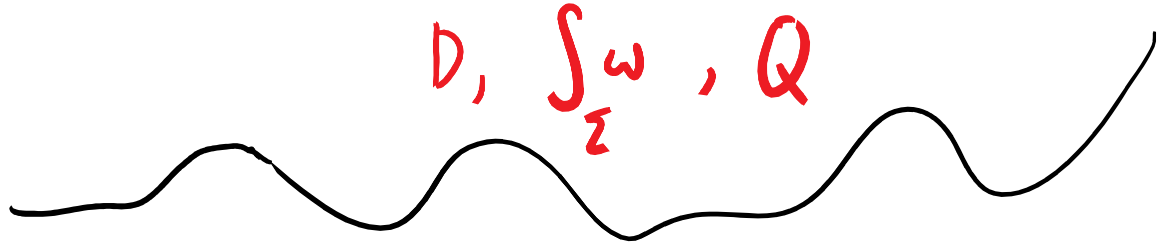
$$\mathcal{E} = \frac{1}{\pi y}\left(1 \mp \sqrt{\eta + \frac{y}{y_0}(1-\eta) - 4\pi^2 y \left(\Delta - \frac{c}{12}\right) + 4\pi^4 y^2 J^2}\right)$$



$\mathcal{E} = \frac{1}{\pi y}\left(1 + \sqrt{\eta + \ldots}\right)$ ⟵ related by $\pm\sqrt{}$ ⟶ $\mathcal{E} = \frac{1}{\pi y}\left(1 - \sqrt{\eta + \ldots}\right)$

BPS black hole state counting (Strominger/Vafa), used extended SUSY to control weak → strong coupling deformations preserving state count. Here we have a **new type of controlled deformation** applicable to dS, again preserving state count: 'integrable deformation' of non-integrable seed theory.

String theory[=QG] and Cosmology[≃ST]

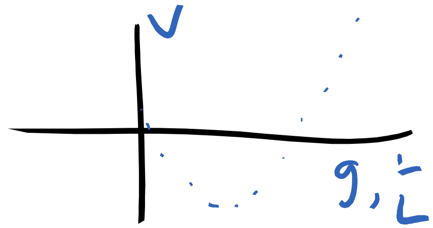


Structure of dS and inflation in string theory

--model-dependent UV sensitive observational tests

--microphysics of dS quantum gravity

--targets and methods for modern numerical methods and machine learning



Douglas '09

4d effective potential

Mostly positive
$D\cdot D_c$, $-R$, $(Q_1 + \text{axion}\, Q_2)^2$, ...
+ intermediate negative
O-planes, Quantum

$$V_{eff}[g^{(D-4)},\ldots] = \frac{\ell_D^{D-2}}{2G_N^2}\frac{\int d^{D-4}y\,\sqrt{g^{(D-4)}}e^{-2\Phi}u^2|_c\left(-R^{(D-4)} - \frac{1}{4}\ell_D^{D-2}T^\mu_\mu - 3\left(\frac{\nabla u}{u}\right)^2\Big|_c\right)}{(\int d^{D-4}y\sqrt{g^{(D-4)}}e^{-2\Phi}u|_c)^2}$$

net curvature

$$ds^2 = e^{2A(y)}ds^2_{dS_4} + e^{2B(y)}(g_{\mathbb{H}ij} + h_{ij})dy^i dy^j \qquad u(y) = e^{2A(y)}$$

$R<0$ rigid, $R=0$ (CY) SUSY

u(y) satisfies GR constraint (its equation of motion):

$$\left(-\nabla^2 - \frac{1}{3}\left(-R^{(D-4)} - \frac{1}{4}\ell_D^{D-2}T^\mu_\mu\right)\right)u = -\frac{C}{6}$$

Like a Schrodinger problem for

$$C\ell^2 \sim H^2\ell^2 \ll 1$$

$$\Rightarrow \quad V_{eff} = \frac{C}{4G_N} = \frac{R^{(4)}_{\text{symm}}}{4G_N}.$$

warp factor stabilizes runaway negativity
e.g. $-B'^2$

dS examples stabilizing extra dimensions:

Reviews of various aspects: Polchinski, Baumann/McAllister, Douglas/Kachru, Denef, Frey, Hebecker; ES TASI '16, ...

- Non-perturbative stabilization

  [--GKP '01/KKLT '03 and many) followups, e.g.
  --large volume scenario

  Sub-KK scale SUSY breaking

- Power-law stabilization

  --(D-Dc), O-planes, flux, asymmetric orbifold (large-D expansion) '01-'02
  (...other examples...)
  [--hyperbolic space, Casimir, flux '21]

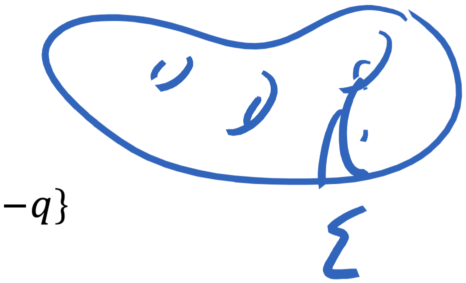
  -- RG logs & powers Burgess/Quevedo '22

  --including explicit uplifts of AdS/CFT
  [D1-D5 theory -> dS3 '10,
  M2 brane theory -> dS4 '21]

  ≥KK scale SUSY breaking

Weak-coupling EFT/large-N/Large-D/small W_0 control.
Ongoing studies of internal equations of motion in various cases & models, including ones with significant gradients e.g. Cordova et al, ...

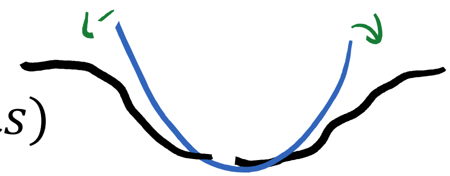
Fluxes and axions in string theory



$$a = \int_{\Sigma} A \qquad \tilde{F}_p = F_p + A_q \wedge F_{\{p-q\}}$$

Apparently universal (unlike other properties like SUSY).
Rich topology → multiple axions (light in some corners – see below)
Stuckelberg flux couplings → axion monodromy.

Flux $\propto \frac{\mathrm{Q}}{\mathrm{Vol(cycle)}} \Rightarrow$ *axion potential* $\tilde{F}^2$ *back reacts* (*flattens*)



=> time-dependent spectrum, but unimportant over inflationary field range in existing models. e.g.

$$\mathcal{U}|_{\sigma=\sigma_{min}} \sim M_P^4 \left\{ C_h^2 n_3^2 \frac{1}{\mathcal{V}^{2/3}} + C_h^4 (q_3^2 + q_1^2 b^2) \mathcal{V}^{2/3} + C_h^4 q_5^2 \right\} \qquad b \propto 1/\mathcal{V}^{2/3} \qquad \frac{\dot{b}^2}{\mathcal{V}^{2/3}} \propto \dot{b}^2 b \Rightarrow \phi_b \propto b^{3/2} \quad V \approx \mu^{10/3} \phi^{2/3}$$

In this example, the underlying axion b is tied by the dynamics (back reaction) to the size L of the space, $b \propto 1/L^4$ and is related to the canonically normalized inflaton field by $\phi \propto b^{3/2}$. During inflation, ϕ evolves from $10M_p$ to M_p, rescaling by a factor of $1/10$. Hence b rescales by a factor of $1/10^{2/3}$ and L rescales by a factor of $10^{1/6}$. The change in L changes the Kaluza-Klein masses, $M_{KK} \propto 1/L$. But the rescaling of those by a factor of $10^{-1/6}$ is unimportant in the dynamics.

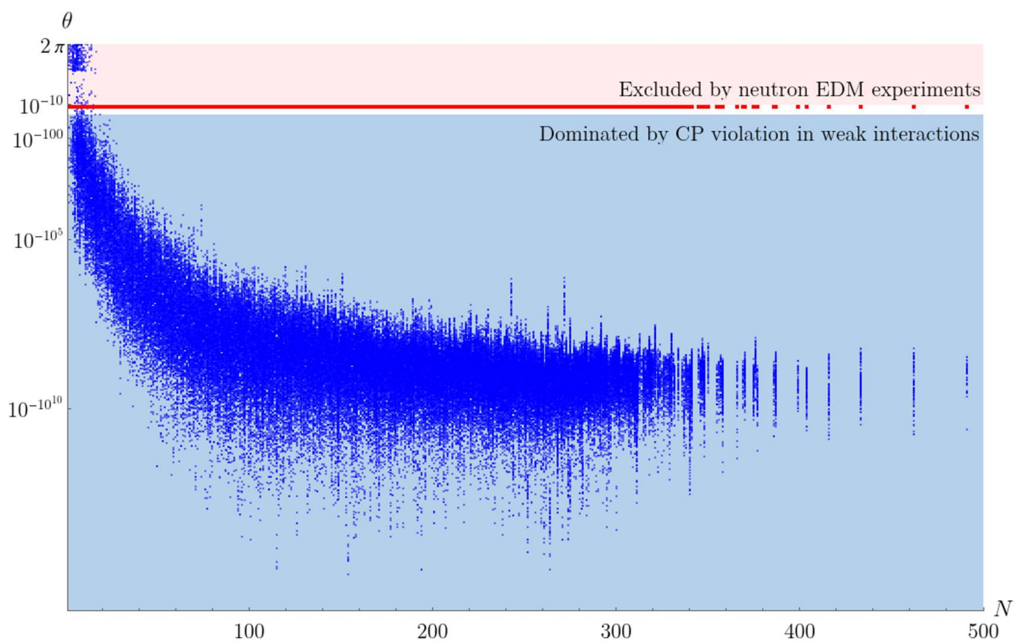
Calabi-Yau case: Explicit realization of KKLT control parameter, AdS examples, and axion spectra.

McAllister + collabs (Kachru, Kim, Zimet; Long, McQuirk, Stout, Demirtan, Marsh,Moritz, Rios-Tascon, Gendler,…)

$$W = W_0 + \sum_{D_I} \mathcal{A}_{D_I} \exp\left(-\frac{2\pi}{c_{D_I}} T_{D_I}\right) + \ldots$$

worldsheet instantons

instantons



Planck-suppressed operators or too-large f_{axion} could have spoiled strong CP solution, but for

$$N_{axions} > 20$$

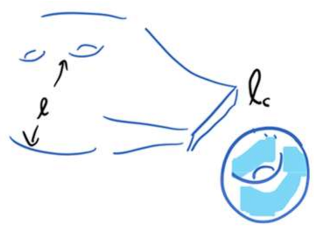
no such problems (calculable in CY corner of string theory, with some numerical advances).

Realizes `axiverse' idea

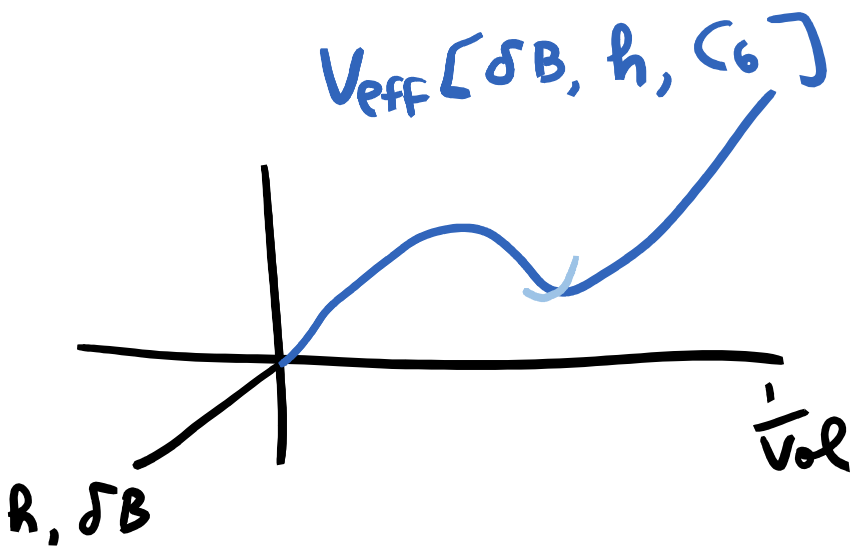
Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell 09

Curved internal dim's: New mechanism for Λ from string/M theory

(w/G.B. De Luca, G. Torroba '21: recorded talks at Strings '21, Str Pheno '21, TIFR, SITP seminars and others):



M theory (EFT: 11d SUGRA) on explicit infinite discrete family of finite-volume hyperbolic spaces with $\int -R - 3u'^2 \ll -\int R$ **parametrically**, automatically-generated Casimir energy, 7-form flux yields immediate volume stabilization and approximate piecewise solution dressed with warp & conformal variations.

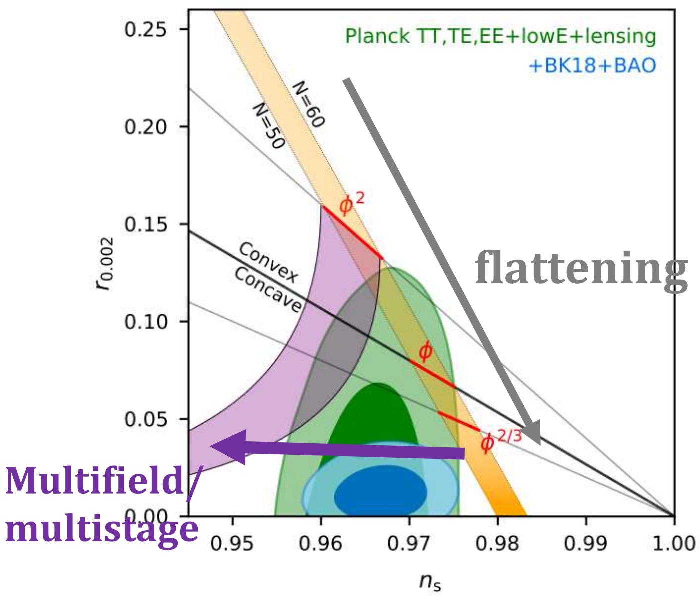


Strong positive Hessian contributions from hyperbolic rigidity and from warping (redshifting) effects on conformal factor and on Casimir energy.

Gaussian observables:

$r = \frac{P_\gamma}{P_\zeta}$, $\quad n_s = 1 + \frac{d\log P_\zeta}{d\log k}$:

flattening and multifield effects



Integrating out heavy fields flattens V (energetics), Multiple fields and/or stages favored.

Dong et al, Dimopoulos et al, D'Amico Lawrence Kaloper Westphal, Wenren, …

Natural Inflation (QFT axion) excluded.

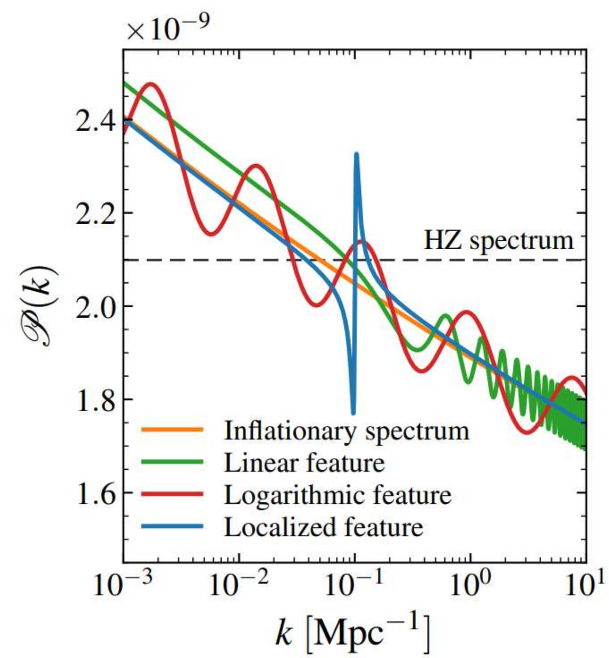
Higgs/Starobinsky/α −attractors from string theory?

Kallosh/Linde

UV physics can imprint on the power spectrum beyond these two numbers

$$\langle \zeta_{k_1} \zeta_{k_2} \rangle \equiv P_\zeta \delta(\mathbf{k} + \mathbf{k}')$$

e.g. constraints on oscillatory features (e.g. from underlying axion periodicity) Decadal 2020 white paper `Scratches from the Past'



Empirically testable **axion** scenarios: axion dark matter, light axions and BH super-radiance, axion (monodromy) inflation (multi-field) e.g. Marsh review

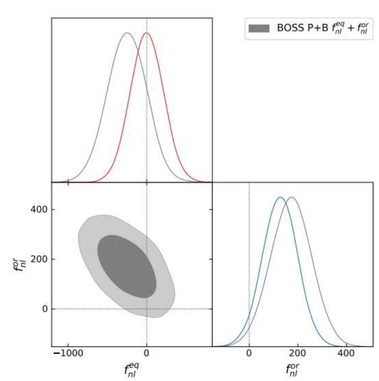
CMB and **LSS**:

- **CMB** Polarization & foreground
  Stage 3-4 sensitive to primordial GW $\delta r < 0.01$, N_{eff}, clusters, etc
- **LSS challenge**: extract Gaussian features and non-Gaussian information from surveys, controlling Standard Model nonlinearities

-Independent determination of cosmological parameters using existing LSS data (independent of CMB data) Senatore et al, Zaldarriaga et al,…

-Surveys promise to collect large volume's worth of modes Boss, SphereX,…Megamapper,21 cm?

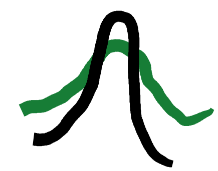
-Ongoing effort to control calculations to extract constraints on non-Gaussianity, in a wide variety of forms EFT (D'Amico et al; Ivanov et al '22), locality vs primordial (Baumann & Green '21), ML & forward mapping (Seljak, Wandelt, …),..



	BOSS	WMAP	Planck
$f_{\rm NL}^{\rm equil.}$	2 ± 212	51 ± 136	-26 ± 47
$f_{\rm NL}^{\rm orth.}$	126 ± 72	-245 ± 100	-38 ± 24
$f_{\rm NL}^{\rm loc.}$	-30 ± 29	37.2 ± 19.9	-0.9 ± 5.1

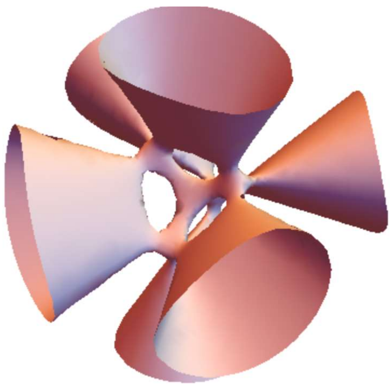
Figure 2: *Left:* $f_{\rm NL}^{\rm equil.} - f_{\rm NL}^{\rm orth.}$ contour for the joint analysis (grey) and for the single $f_{\rm NL}$ analyses (red) and (blue) respectively. *Right:* 68%-confidence intervals for the BOSS analysis, as well as the WMAP [94] and Planck [95] final results. We find no evidence of primordial non-Gaussianity.

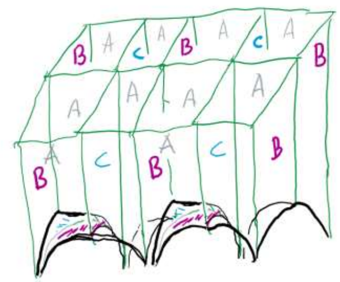
Non-perturbative NG challenge: Find appropriate estimators for heavy tail events. Non-perturbative in QFT, UV sensitive in early U EFT and in LSS EFT. Heavy particle production case (Flauger et al '17) solved by Munchmeyer/Smith '19



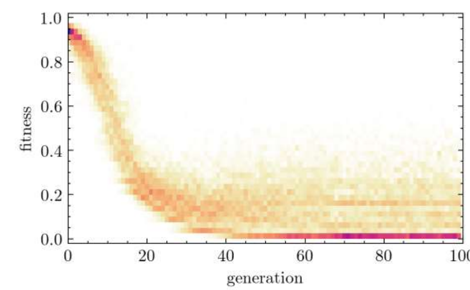
Connections

- Mathematics: compactification geometry and topology





Kachru Tripathy Zimet, De Luca ES Torroba,…



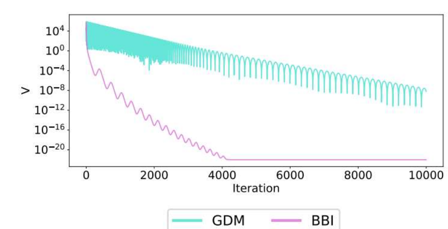
- Numerics & Machine Learning (industry)

  -- Learn metrics, brane models and PDE solutions Anderson et al, Douglas et al, Jejjala et al, Shiu et al, Halverson et al,… De Luca et al

  --Cosmological evolution → ML optimization

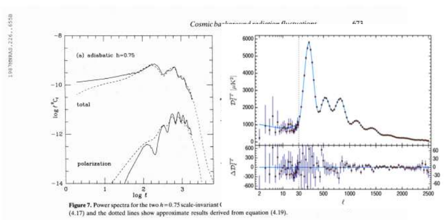
De Luca ES '22

$$E = \frac{V}{\sqrt{1 - \frac{\dot{\Theta}^2}{V}}} = \sqrt{V(V + \mathbf{\Pi}^2)} = \text{constant}.$$

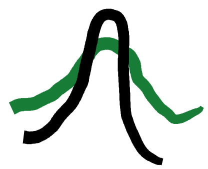


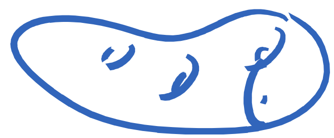
Conclusions:

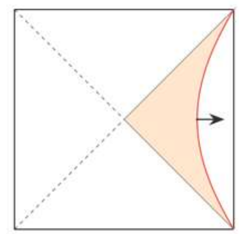
- Cosmological horizons lead to well-tested observational consequences (including the quantum origin of all structure!), phenomenological opportunities to test physical parameters in conjunction with more systematically analyzing the dynamics, and major challenges but new tools in quantum gravity.

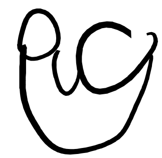


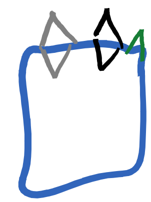
(a) Bond Efstathiou 1987











- On the former, real experimental side, there are well defined signatures with detectable signal/noise that require theoretical, computational and observational insight to extract and interpret.
- On the latter, `thought experimental' side, we have renewed traction on emergent space-time thanks to various research directions involving string theory, semiclassical QG, and strongly coupled quantum field theory and its tractable parameter deformations. Also progress on generic regimes of string/M theory.
- New connections to mathematics and machine learning