Comments/questions on String Phenomenology opportunities in CMB and GW

Based on works with Dodelson, Dong, Green, Flauger, Horn, Kofman, Linde, Maloney, McAllister, Mirbabayi, (Peiris/Planck), Senatore, Torroba, Westphal, Wrase, Zaldarriaga, ...

Data rich:

- Λ discovered '98 ⇒ Theory behind exp't
- CMB prime time → r, n_s, $\langle \delta\delta \rangle$ (Mukhanov et al), $\langle \delta\delta\delta \rangle$
  - ↓ LSS
  - PBK discovered
  - a new parameter!
  - other phenomenological opportunities*
- LIGO, EHT ↔ horizon physics*
- DM / LHC

Outline

CMB phenomenology

(0) Brief intro: r, n_s, & axion inflation

(1) Oscillatory spectra & bispectra* from particle/string production

* equilateral w/ linear + log-spaced oscillations, enhanced bispectrum

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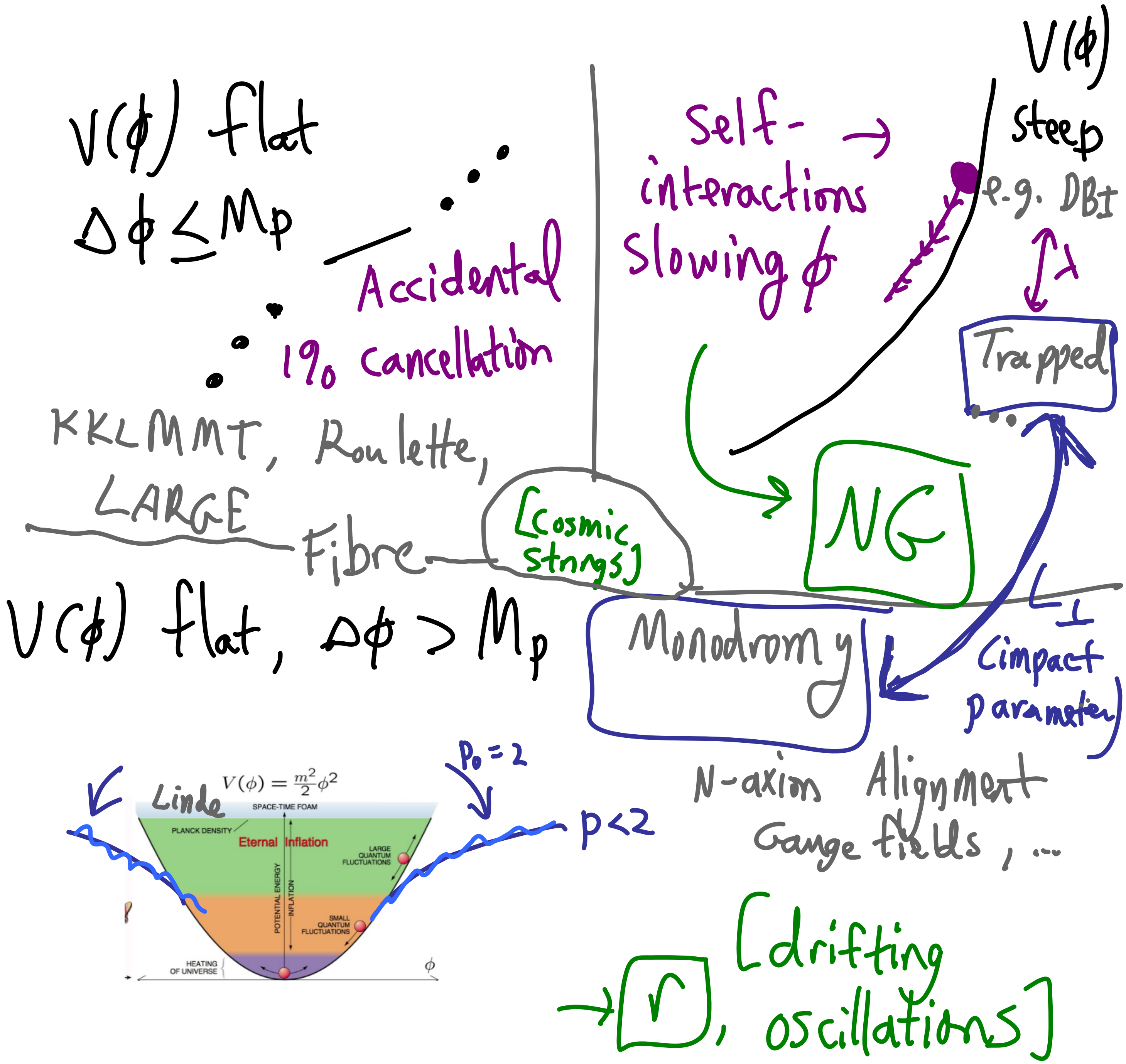
(2) Breakdown of EFT in string theory at horizons

GW/EHT phenomenology ??

Variety of inflationary mechanisms in string theory

Many contributors (* Madrid Group!)



UV/IR

String-theory mechanisms feed into more systematic EFT & data analysis

- ranges of r   Planck fld range <=> r >.01
- NG at single-field level
- discrete shift symmetries
- dissipative processes

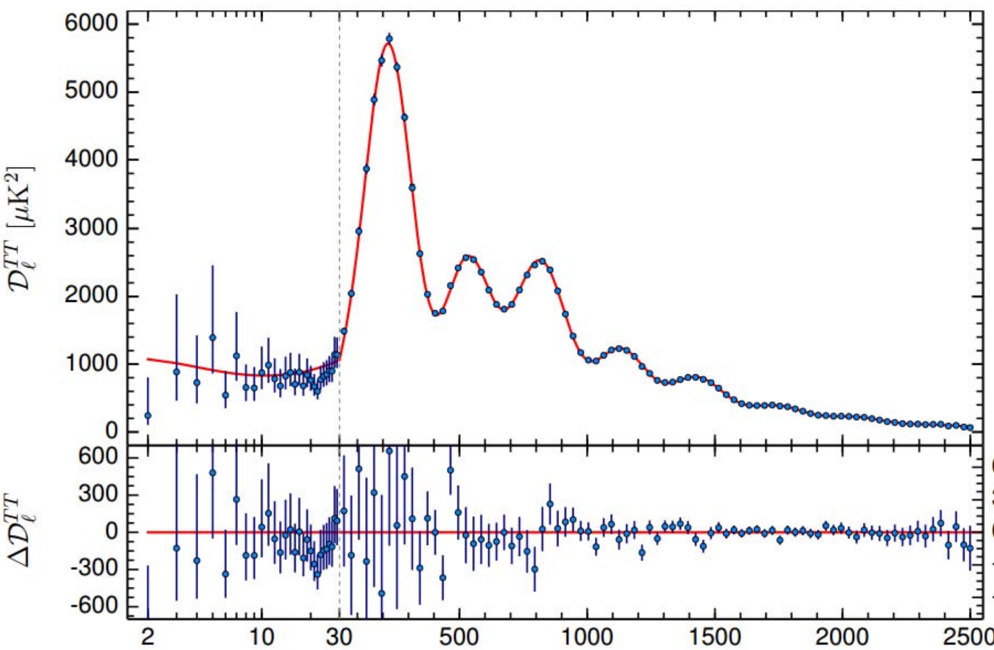
} features & oscillations

- exotic sources

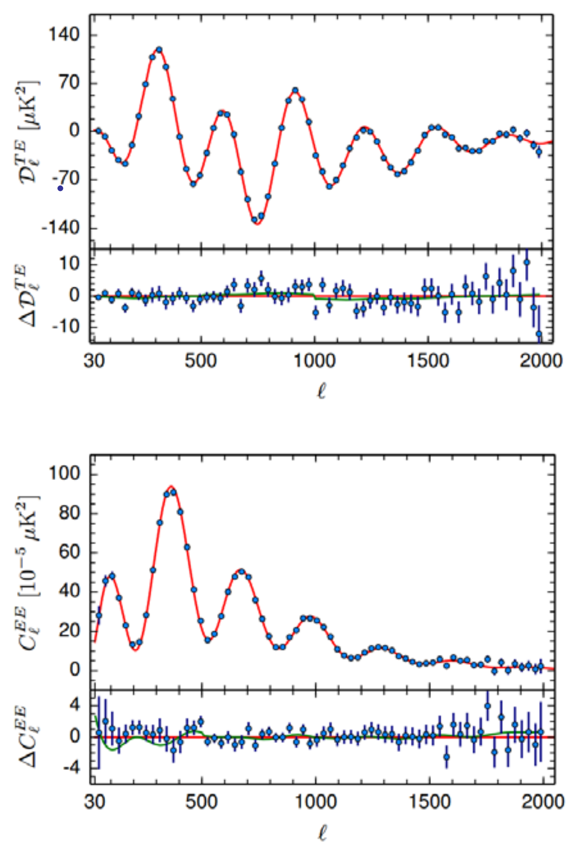
⇒ Worthwhile also just to help make maximal use of precious data

Big Picture

Power spectrum function → 2 parameters



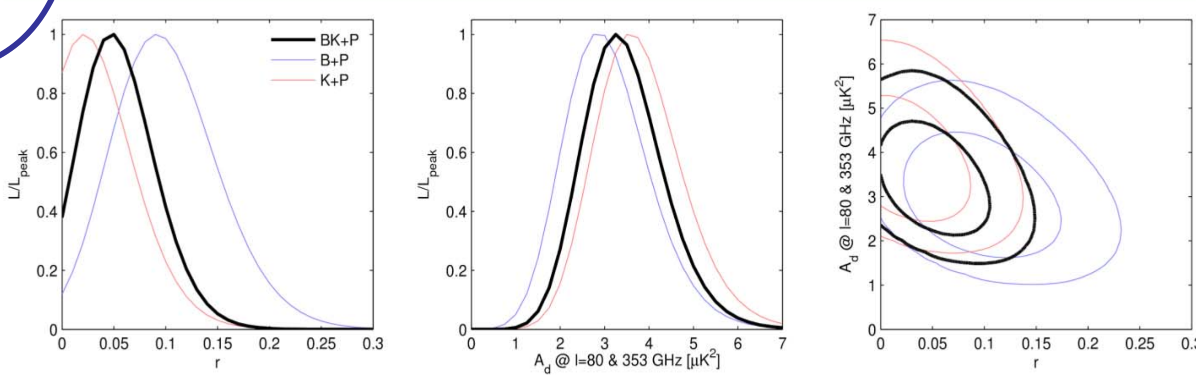
Planck 15



$\ell \geq 30$ we show the maximum likelihood frequency averaged
kelihood with foreground and other nuisance parameters deter-
the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum
puted over 94% of the sky. The best-fit base ΛCDM theoretical
pper panel. Residuals with respect to this model are shown in

Small perturbations from ΛCDM allowed (tensors, features/oscillations, non-Gaussianity), but wildly dramatic effects highly constrained r

Multi-component Likelihood Analysis



r constraint consistent with zero (For BK+P L_0/L_{peak} is 0.4, which happens 8% of the time in a dust only model.)

Dust is detected with 5.1 σ significance

As expected, dust and r are anticorrelated

BICEP/Keck - Planck

- Use single and cross-frequency spectra between BK 150 GHz and Planck 217 & 353 GHz channels
- Try including:
  - Gravitational wave signal with amplitude r
  - Dust signal with amplitude A_d (specified at ℓ =80 and 353 GHz)

Major advance experimentally: direct bound competitive with indirect (TT) bound. Planck-BICEP/Keck reduced viable n_s-r region by 29 percent. Primed for key range of r down to Planck field range. Current (insignificant) bump centered at .05-.06, cf .04-.07 cluster of one canonical class of string models, tested soon...

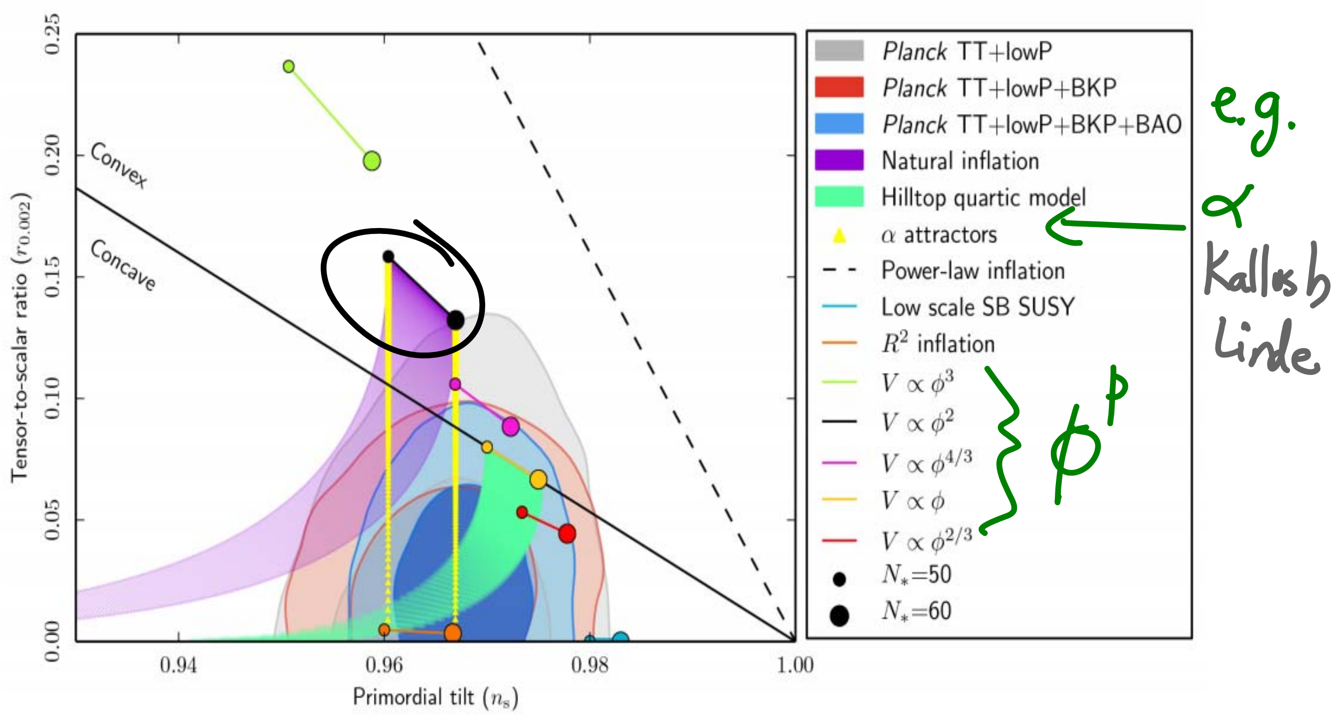


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

$V = \frac{1}{2} m^2 \phi^2$ 'strongly disfavo(u)red'

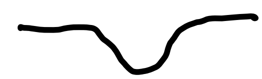
← contains exit, 2 parameters ↔ $\langle \zeta\zeta \rangle$, N_e

Given that this minimal possibility is excluded, require additional parameter. ★ Expected from UV:

(mass > H)   'Flattening' Dong et al '10

<u>Heavy</u> fields affect results:

they adjust in response to inflationary potential energy. QFT toy model

$$V(\varphi_L, \varphi_H) = g^2\varphi_L^2\varphi_H^2 + m^2(\varphi_H - \varphi_0)^2$$ 

$$\frac{\partial V}{\partial \varphi_H} \equiv 0 \Rightarrow V = \frac{g^2\varphi_L^2}{g^2\varphi_L^2 + m^2} m^2 \varphi_0^2$$

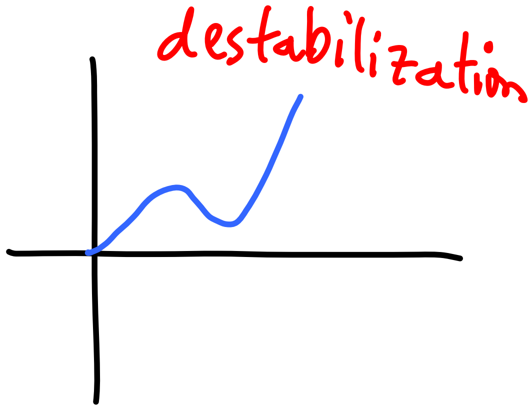
($\dot{\varphi}_H^2$ term subdominant)

flatter: energetically favorable.

• UV completion of gravity (e.g. string theory) can introduce ϕ_H (e.g. 'moduli' scalar fields).

↪ $V \propto \phi^n \to V \propto \phi^{p<n}$ in examples.

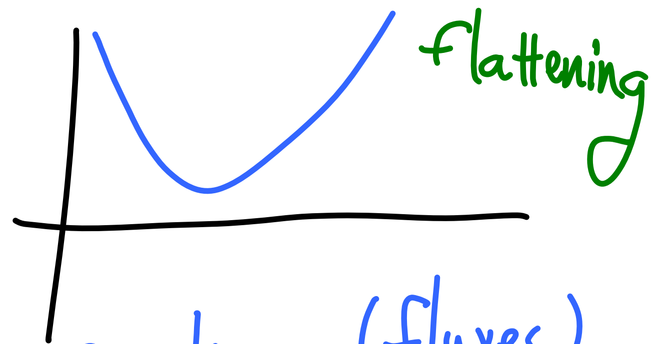
• Moduli: Two basic structures



3-term

$$\hat{a}x - \hat{b}x^2 + \hat{c}x^4$$

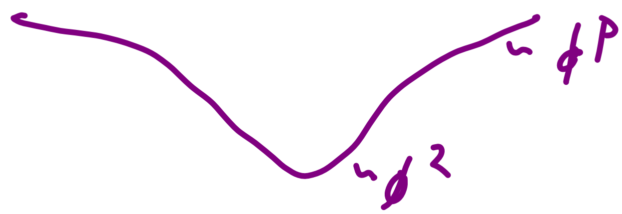
Need $\frac{\hat{a}\hat{c}}{\hat{b}^2}$ to stay w/in $\mathcal{O}(1)$ window for minimum



2-term (fluxes)

$$\left(\frac{L_1}{L_2}\right)^n Q_1^2 + \left(\frac{L_1}{L_2}\right)^{\tilde{n}} (bQ_2)^2$$

$$\Rightarrow V \propto b^{\frac{2n}{n+\tilde{n}}} \quad \frac{2n}{n+\tilde{n}} < 2$$

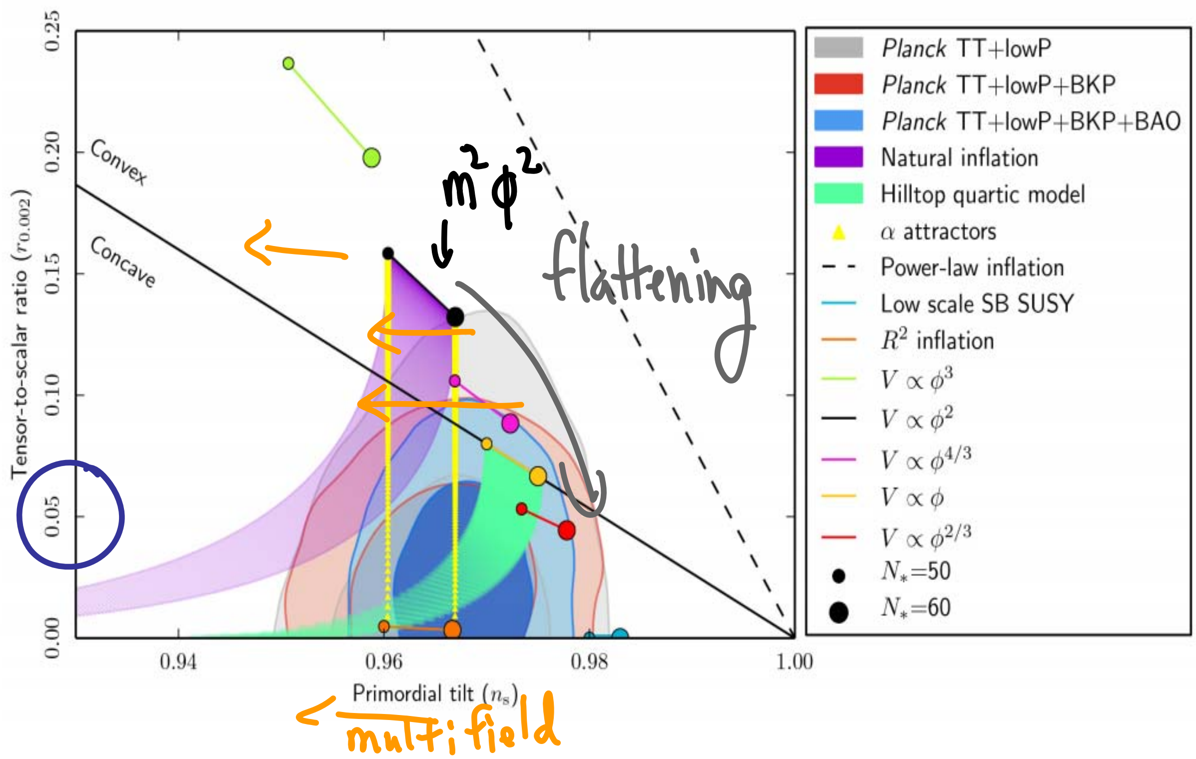


In specific models, find

$$V \sim \hat{V}_1(x)\,\phi^{p_0} + V_0(x)\Big|_{x_{min}}$$

$$\simeq \mu^{4-p}\phi^p + \Lambda^4(\phi)\cos\big(b(\phi)\big)$$

with $p < p_0$; $p = 3, 2, 4/3, 1, 2/3$



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Axion monodromy remains viable because of the flattening effect. (Tested soon by r)

$$S = \frac{1}{2\alpha'^{\frac{D-2}{2}}} \int d^D x \sqrt{-G}\, e^{-2\phi_s} \left(R - \frac{D-10}{\alpha'} + 4(\partial\phi_s)^2 \right) + S_{matter}\,. \qquad (3.1)$$

$$S_{matter} = \int d^D x \sqrt{-G} \{ \; - \; \sum_{n_B} \tau_{n_B} \frac{\delta^{(D-1-n_B)}(x_\perp)}{\sqrt{G_\perp}} + \sum_{n_O} \tau_{n_O} \frac{\delta^{(D-1-n_O)}(x_\perp)}{\sqrt{G_\perp}} + \; e^{-2\phi_s}|H_3|^2 + \sum_p |\tilde{F}_p|^2 + C.S. + h.d. \} \qquad (3.2)$$

$$\int d^D x \sqrt{G} \sum_q \Big| \overbrace{F_q - C_{q-3} \wedge H + F_{q'} B \wedge \cdots \wedge B}^{\tilde{F}_q \text{ Gauge-invar.}} \Big|^2$$

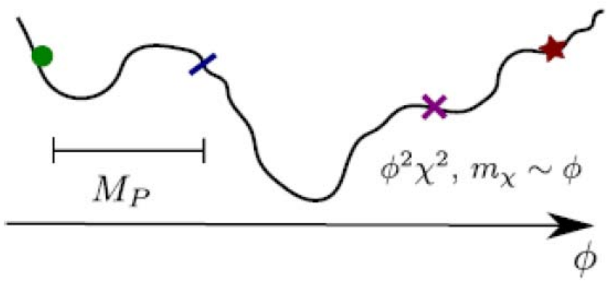
fluxes $\int_{\Sigma_q} F_q = Q_q$

axions $b = \int_{\Sigma_2} B$ (Direct Dependence)

+ e.g. instantons $\rightarrow \Lambda^4 \cos b(\phi)$

+ periodic particle/string production

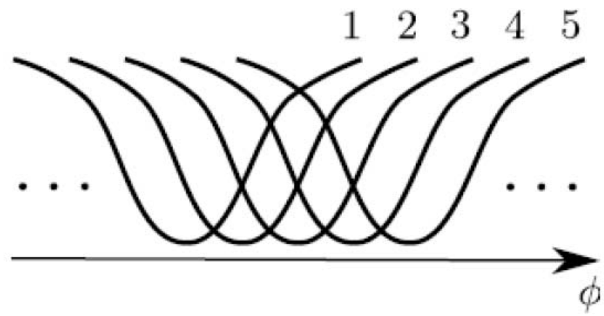
Parameterized ignorance of quantum grav.



New degrees of freedom each $\Delta\Phi \sim M_P$

No continuous global symm. in QG

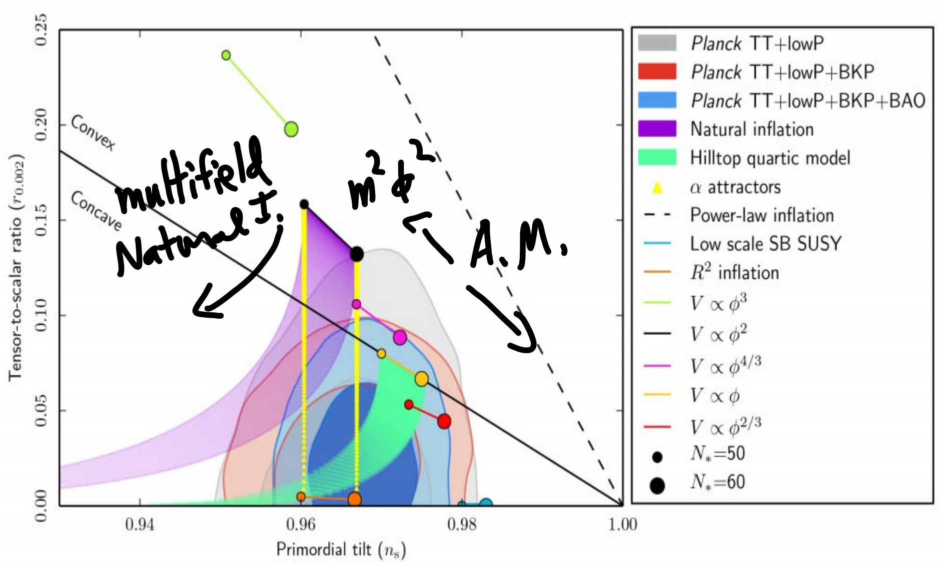
String Theory axions (and duals)



From ubiquitous Axion-Flux couplings

Discrete shift symm., f<<M_p

[cf Chaotic Infl.(Linde), Natural Infl. (Freese et al)]



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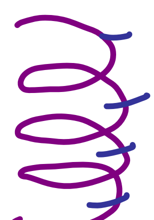
Are there theoretical constraints to compare to data constraints?

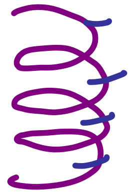
- Multifield Natural Inflation & WGC?
  - Kim Nilles Peloso (axion alignment) – N-flation

- Axion Monodromy parameter ranges?

- Periodic Particle/string production & oscillatory NG



w/ Senatore Flanagan...



Underlying periodicity

→ { instanton-induced $\Lambda^4 \cos\frac{\phi}{f}$

particle/string production

$$g^2 \sum_n \chi_n^2 \left[(\phi-\phi_n)^2+\mu^2\right]$$

Each event ⇒ $\bar{n}_\chi \sim \dot{\phi}^{3/2} e^{\frac{-\pi\mu^2}{\dot{\phi}}}$

($g \sim 1$, loops $\sim \frac{1}{16\pi^2}$)

In progress
Senatore
ES
Flauger
...

☆ Work in slow roll regime, keeping track of discreteness of events → oscillatory (log + linear!) equilateral non-Gaussianity, consistent w/ power spectrum

Shape of resulting $\langle \pi\pi \rangle$, $\langle \pi\pi\pi \rangle$

Mirbabayi et al '14 ; Senatore ES Flauger ...

- Events at conformal times η_n

produce $X_{i,n} = 1$ with probability

cell ↗ i, time (discrete) ↖ n

$p_i = \bar{n}\, a_n^3\, \delta V_i$ (volume element: δV_i)

$$\pi_k(\eta) = \frac{M}{2\epsilon M_p^2 H^2} \sum_n G_k(\eta, \eta_n) \sum_i X_{i,n}\, e^{i\vec{k}\cdot\vec{x}_i}$$

$$\langle \pi_{k_1} \pi_{k_2} \rangle' = \frac{M^2}{(2\epsilon M_p^2)^2 k^3} \left[\frac{\bar{n}_x}{H^3} \sum_n \frac{\overbrace{(\sin k\eta_n - k\eta_n \cos k\eta_n)}^{g(k\eta_n)}{}^2}{-k^3 \eta_n^3} \right]$$

$$\langle \pi_{k_1} \pi_{k_2} \pi_{k_3} \rangle' = \frac{M^3}{(2\epsilon M_p^2)^3 k_1^2 k_2^2 k_3^2} \left[\frac{\bar{n}_x}{H^3} \sum_n \prod_{i=1}^{3} \frac{g(k_i \eta_i)}{-k_i \eta_i} \right]$$

Bispectrum $\begin{cases} \text{enhanced by } \sum_n \text{ at large } |k\eta| \\ \text{log \& linear oscillatory equilateral} \end{cases}$

Planck searches motivate revisiting this:

ΛCDM favored: $\chi_{d.o.f.} \sim 1.03\text{-}4$

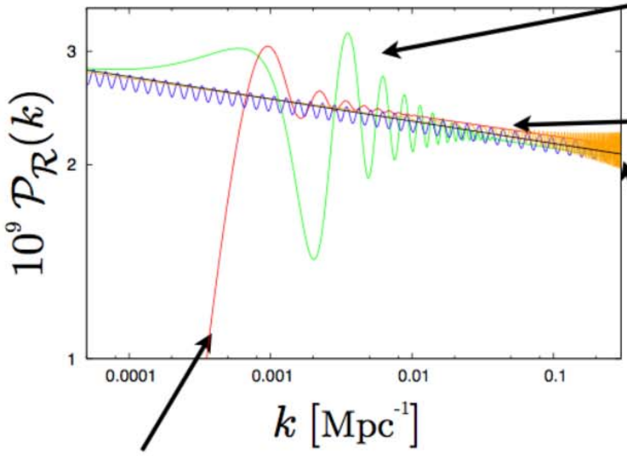
1.04 × 2000 ℓ-modes in power spectrum ~ Room for $\Delta\chi^2 \sim 80$ improvement, if ∃ additional structure

- Ongoing work in & out of Planck
  w/ Peiris et al   w/ Flanger et al
- Evidently polarization systematics still in progress, wait for final application to such searches

Planck ; Flauger Easther Gratton
Peiris Meerburg Spergel
Fergusson Shellard Wandelt ...

Searches for features:

(G. Efstathiou/Planck)



Feature in the potential:

$$V(\phi) = \frac{m^2}{2}\phi^2\left[1 + c\tanh\left(\frac{\phi-\phi_c}{d}\right)\right]$$

Non vacuum initial conditions/instanton effects in axion monodromy

$$V(\phi) = \mu^3\phi + \Lambda^4\cos\left(\frac{\phi}{f}\right)$$

$$\mathcal{P}_\mathcal{R}^{\log}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\log}\cos\left(\omega_{\log}\ln\left(\frac{k}{k_*}\right) + \varphi_{\log}\right)\right].$$

Linear oscillations as from Boundary EFT

$$\mathcal{P}_\mathcal{R}^{\rm lin}(k) = \mathcal{P}_\mathcal{R}^0(k)\left[1 + \mathcal{A}_{\rm lin}\left(\frac{k}{k_*}\right)^{n_{\rm lin}}\cos\left(\omega_{\rm lin}\frac{k}{k_*} + \varphi_{\rm lin}\right)\right]$$

Just enough e-folds, i.e. inflation preceded by a kinetic stage

- No detection
  (Instantons naturally suppressed in slow-roll AM, but interesting model-dep't signature.)

- A few interesting low-σ anomalies / 'hints'
  e.g. multi-frequency log-spaced & linear oscillations & equilateral NG
  $\gtrsim 3\sigma$ (enhanced w/polarization)
  still working

Some phenomenology to do?

multipeak equilateral signal rose from 1.9σ (T-only) to 3.1σ (T+E) after adjusting for the 'look elsewhere' effect, while the flattened signal went from 2.4σ (T-only) to 3.2σ (T+E). These interesting results, reflecting those obtained for feature models, suggests the fit to any underlying NG signal might await alternative, but related, oscillatory models for a more compelling explanation. We note that the frequency range for this nascent resonant bispectrum analysis is still very limited (relative to the power spectrum analysis). It will remain a high priority to investigate resonance models for the final *Planck* data release, expanding the frequency domain and improving the differentiation between a variety non-scaling models.

Planck15 NG paper

I can't help noticing:

← can be subdominant to vac. ππ

$$\langle \pi_{\mathbf{k}_1} \pi_{\mathbf{k}_2} \rangle' = \frac{M^2}{(2\epsilon M_{\rm Pl}^2)^2 k^3} \left[\frac{\bar{n}_X}{H^3} \sum_n \frac{g^2(k\eta_n)}{-k^3\eta_n^3} \right]. \quad \text{(B4)}$$

Where prime means that $(2\pi)^3\delta^3(\mathbf{k}_1 + \mathbf{k}_2)$ has been omitted. The sum gets contribution only from those η_n for which $k\eta_n = \mathcal{O}(1)$. Thus the expression in brackets is $\mathcal{O}(N_X)$. The calculation of 3-point function of π is very similar and gives

$$\langle \pi_{\mathbf{k}_1} \pi_{\mathbf{k}_2} \pi_{\mathbf{k}_3} \rangle' = \frac{M^3}{(2\epsilon M_{\rm Pl}^2)^3 k_1^2 k_2^2 k_3^2} \left[\frac{\bar{n}_X}{H^3} \sum_n \prod_i \frac{g(k_i\eta_n)}{-k_i\eta_n} \right]. \quad \text{(B5)}$$

enhanced by $\int_{\eta_{ur}}^{\eta_0} d\eta(\dots)$

Regime with particle/string production: oscillatory equilateral linear + log

$g(\eta k) \sim \sin k\eta - \eta k \cos \eta k$

Mirbabayi et al '14

It will be interesting to see if this shape affects the statistical significance, survives/improves with polarization.

More broadly

- No compelling evidence currently
  but maybe some hint(s)?
- Data leaves room for additional structures
- Possible opportunity for (string) phenomenology — Planck / DIY
  worth checking fully.

Final Numerology:

$\Delta \frac{\omega}{H}$ consistent w/ 1 & 2 instanton effects

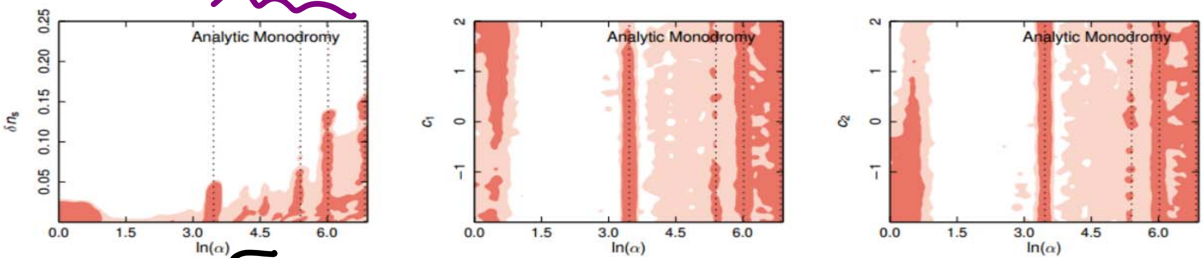


Fig. 37. Constraints on the parameters of the analytic template, showing joint 68 % and 95 % CL. The dotted lines correspond to the frequencies showing the highest likelihood improvements (see text).

$\log(35) \simeq 3.5$

Planck Collaboration: *Planck* 2015 Results. Constraints on primordial NG

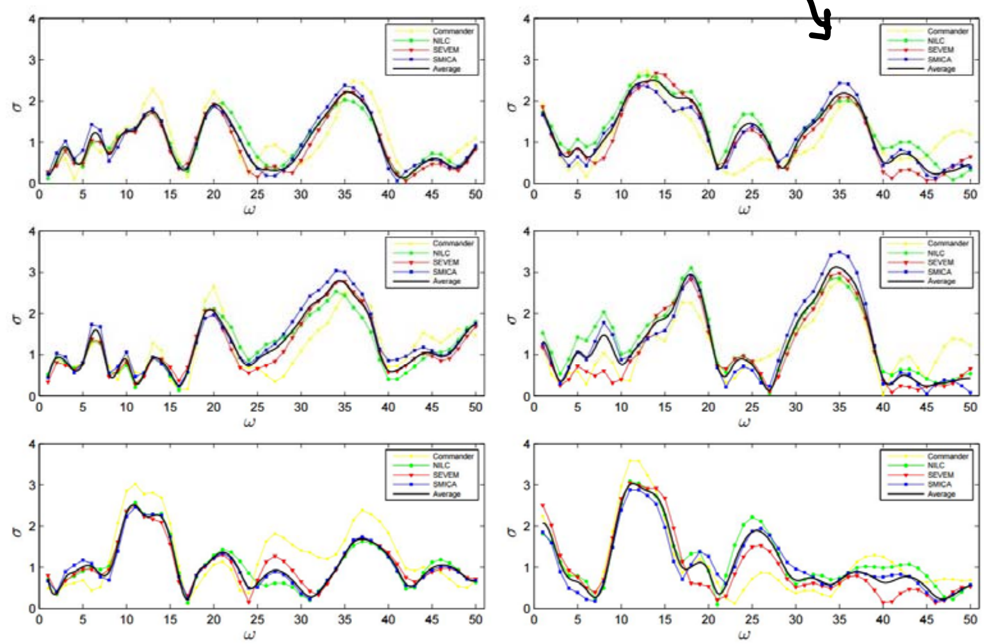


Fig. 19. Generalized resonance models analysed at $\ell_{max} = 2000$ (E-modes $\ell_{max} = 1500$) for the different *Planck* foreground separation methods, SMICA (blue), SEVEM (red), NILC (green), Commander (yellow), together with the SSN average (black). The upper panels apply to the constant resonance model (Eq. 10), with T-only (left) and T+E (right), the middle panels give results for the equilateral resonance model (Eq. 13), and the lower panels for the flattened resonance model (Eq. 14). Both the equilateral and flattened resonance models produce broad peaks which are reinforced with polarization (middle and bottom right panels).

Ongoing extension to higher $\frac{\omega}{H}$

More Direct String Theory Signatures?
--cosmic strings, bubbles, etc. (H. Tye et al...)

Alternatives to inflation that are more sensitive to strong curvature (singular) regimes?
--but black hole thermodynamics precludes some exotic sources for bounces

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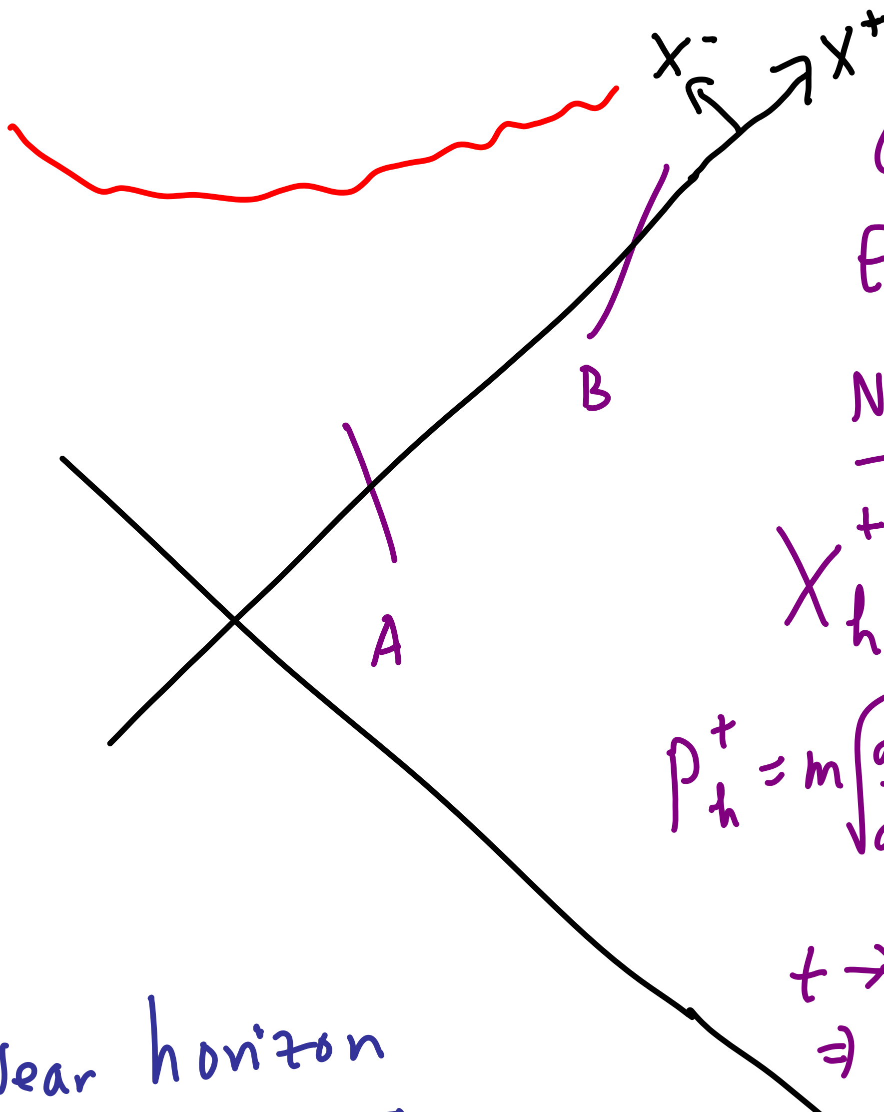
--Breakdown of EFT at horizons (ongoing work w/M. Dodelson): beyond-GR physics...

In the presence of horizons, the breakdown of effective field theory is not well estimated by

alpha' R << 1:

This may lead to new effects relevant for thought experiments and conceivably real ones.

$$ds^2 = -\frac{2r_s}{r} e^{1-\frac{r}{r_s}} dX^+ dX^- + r^2 d\Omega^2$$



Outside:

E, m fixed

Near Horizon:

$$X_h^+ = 2r_s\sqrt{e}\,\frac{E}{m}\,e^{\eta}$$

$$p_h^+ = m\sqrt{\frac{dX^+}{dX^-}}\bigg|_h = m e^{\eta}$$

$$t \to t + \Delta t$$

$$\Rightarrow \eta \to \eta + \frac{\Delta t}{2r_s}$$

Near horizon

- $s \sim 2 p^+_{B,h}\, p^-_{A,h} \sim e^{\frac{\Delta t}{2r_s}} m^2$
- $X_B^+ - X_A^+ \propto p_B^+ \propto e^{\frac{\Delta t}{2r_s}}$

Near horizon: huge Energy, but separated along X^+.

String Spreading

- Susskind '94
- Brown Polchinski Strassler Tan '06

Light Cone gauge $X^- \sim p^- \tau$,

Constraint determines X^+ in terms of $X^\perp$

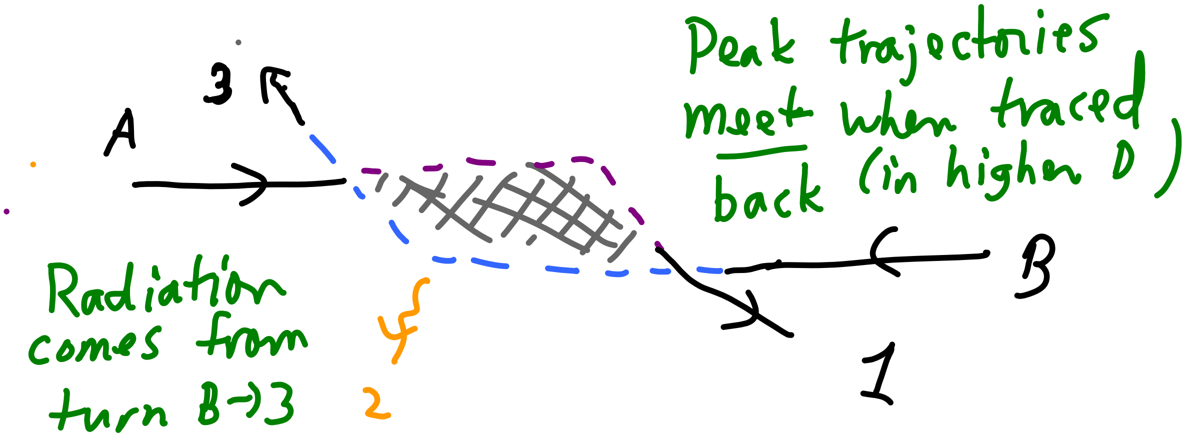
$$\langle \psi | (X_\perp - x_\perp)^2 | \psi \rangle = \sum_n^{n_{max}} \frac{1}{n} = \log \frac{n_{max}}{n_0} + O\left(\frac{1}{n_{max}}\right)$$

$$\langle \psi | (X^+ - x^+)^2 | \psi \rangle \simeq \frac{1}{(p^-)^2} \sum^{n_{max}} n \simeq \frac{n_{max}^2}{(p^-)^2}$$

$n_{max} \leftrightarrow$ light cone time resolution + detector trajectory

$$\boxed{n_{max} \sim \frac{s}{-t} \text{ explicitly}}$$

Gathering S-matrix 'data'

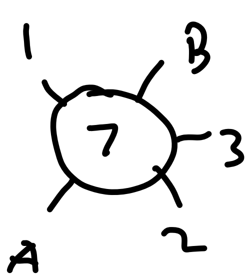


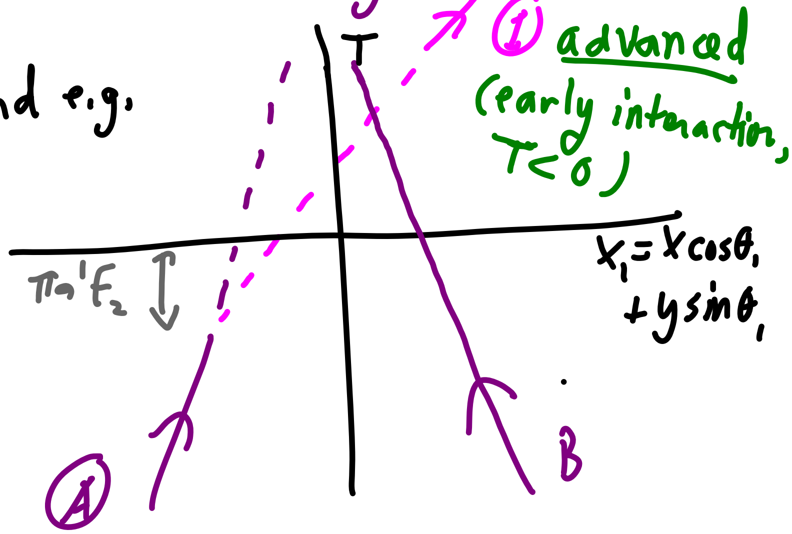
(3) Explicit & simple string solutions for intermediate S-channel states ↔ imag. parts

★ quantitative agreement with peak b & T

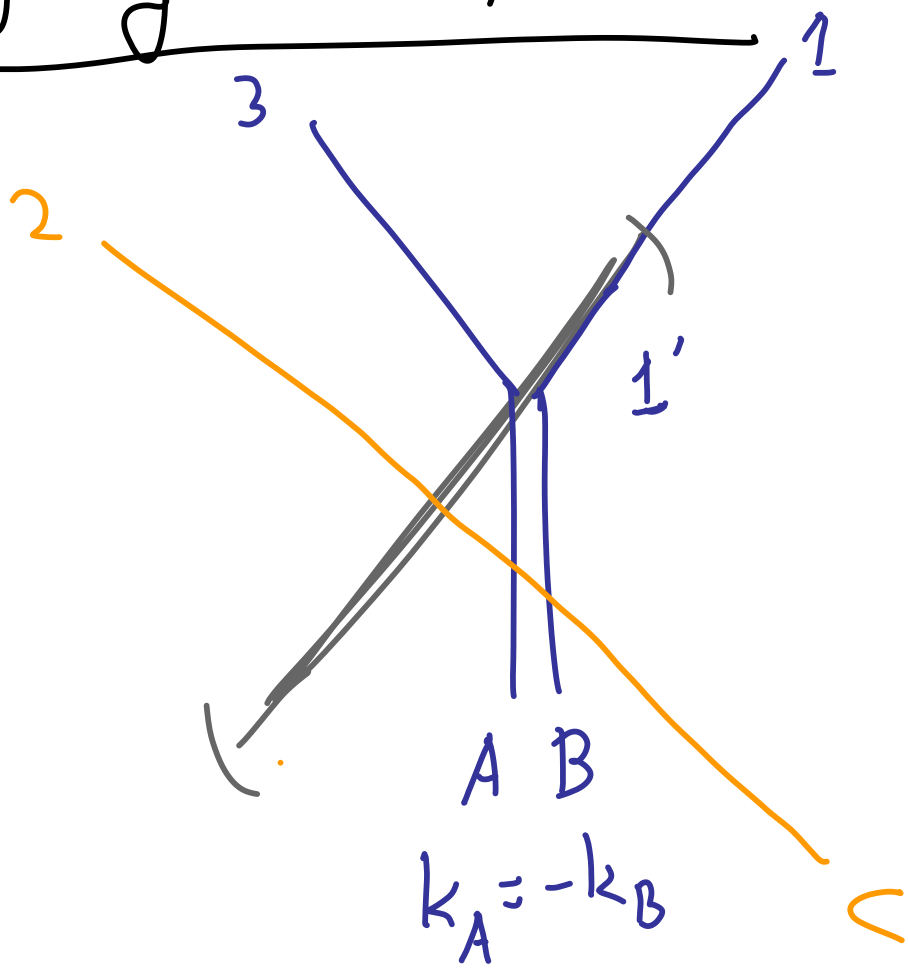
(4) use causality and limited ⊥ spreading to isolate longitudinal effects

find e.g.





Ongoing : 6 points



C → 2 interacts w/ 1' via spreading. Amplitude has shifted, deformed step function at scale $\Delta x^+ \sim E\alpha'$

*Cosmo horizons: safe in early U given Bunch-Davies, safe in late U given that age of U of order 1/H. Any residual effect, e.g. constraings on more exotic scenarios?

*Black hole horizons:

The longitudinal-spreading induced interactions as derived above are similar in amplitude to quasinormal modes. These are expected to be seen in GW detectors (e.g. LIGO) in the ringdown signal from black hole or neutron star mergers. Could there be string theoretic physics beyond GR to be derived? (Interestingly, not a model building exercise -- just uses extent of fundamental strings, although so far restricted to weak coupling regime.)

Early days but fun questions...