CMB, Gravitational Waves and String Theory Dynamics

Brief overview plus **work** with Dodelson, Dong, Green, Flauger, Horn, Kofman, Linde, Maloney, McAllister, Mirbabayi, Senatore, Torroba, Westphal, Wrase, Zaldarriaga, ...

Data rich:

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

UV Sensitivity of Inflation

① Terms of order

$$V \cdot \frac{(\varphi - \varphi_0)^2}{M_p^2} \quad \text{(dimension 6)}$$

in the effective action can ruin inflation

② $$\frac{\Delta\varphi}{M_p} \simeq r^{\frac{1}{2}} \frac{N_e}{\sqrt{8}} \quad \text{(Lyth)}$$

GUT-scale inflation (with observable tensor modes) $\Leftrightarrow \Delta\varphi > M_p$

③ General Single-field inflation involves higher derivative terms which affect solution & perturbations

cf Non-Gaussianity

④ $g^2 \varphi^2 \chi^2$ couplings $\Rightarrow$ temporarily light fields/strings affect evolution.

(5)

(mass $> H$)

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

(5a) 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.

(5b) Time-dependent masses (from coupling to inflaton) can affect perturbations even if <u>minimal</u> mass $\underline{\mu} \gg H$:

Mirbabayi, Senatore, ES; Flauger (bi)spectrum templates

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

$$\Rightarrow \langle n_\chi \rangle \sim (g\dot\phi)^{3/2}\, e^{-\frac{\pi\mu^2}{g\dot\phi}}$$

sources $\langle \zeta\zeta \rangle$, $\langle \zeta\zeta\zeta \rangle$, ...

$\langle \gamma\gamma \rangle$, ...

MM, LS, ES, Zaldarriaga (...)

$$\delta\phi_k = \int d\eta' \, G_k(\eta,\eta')\, a(\eta')\, J_k(\eta')$$

Green's ftn

Source: $\langle J \cdots J \rangle$

determined by squeezed state of produced particles

$$\langle \zeta \zeta \rangle_{\text{production}} \sim \zeta^2_{\text{vac}}\, g^2 \frac{\bar{n}_\chi}{H^3} \sum_n \frac{\hat{h}(k_1\eta_n)^2}{(-k_1\eta_n)^2}$$

$$\frac{\zeta^3_{\text{production}} \big/ (\zeta^2_{\text{vac}})^{3/2}}{\zeta^2_{\text{prod}} \big/ \zeta^2_{\text{vac}}} \sim g \frac{\sum_n (k\eta_n)^{-3}\, \hat{h}(k\eta_n)^3}{\sum_n (k\eta_n)^{-3}\, \hat{h}(k\eta_n)^2}$$

$$\langle \zeta\zeta \rangle_{\text{production}} \sim \zeta_{\text{vac}}^2 \, g^2 \underbrace{\frac{\bar{n}_\chi}{H^3}} \sum_n \frac{\overbrace{\hat{h}(k_1 \eta_n)}^{\text{e.g. } \mathcal{O}(1)}{}^2}{(-k_1 \eta_n)^2}$$

$$\bar{n}_\chi \propto e^{-\frac{\pi \mu^2}{g \dot{\phi}}}$$

detectable/constrainable for

$$\frac{\langle \zeta\zeta \rangle}{\zeta_{\text{vac}}^2} \sim 10^{-2 \text{ or } 3}$$

$\Rightarrow$ sensitive to $\mu > \sqrt{g\dot{\phi}} \gg H$!

This dynamics is (another) source of oscillatory N-spectra in e.g. axion monodromy...

Variety of inflationary mechanisms in string theory

Many contributors (Baumann/McAllister book)

$V(\phi)$ flat
$\Delta\phi \lesssim M_p$

Accidental 1% cancellation

KKLMMT, Roulette, LARGE Fibre

$V(\phi)$
steep

Self-interactions slowing ϕ →

e.g. DBI

λ

Trapped …

[cosmic strings]

NG

$V(\phi)$ flat, $\Delta\phi > M_p$

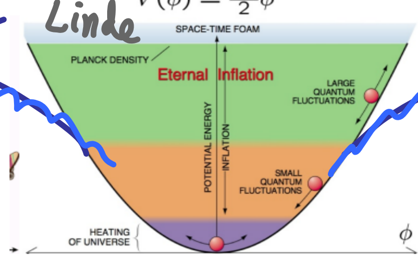
Monodromy

(impact parameter)

Linde

$p_0 = 2$

$p < 2$



N-axion Alignment
Gauge fields, …

→ $\boxed{r}$, [drifting, oscillations]

I'll focus on Axion Monodromy, but other scenarios also interesting

- KKLMMT / DBI ~ illustrates range of inflation & Non-Gaussianity; Relativity on field space

  pioneered careful assessment of Planck-suppressed contributions

- Fibre, Roulette, ...

  Exponential potential ⟷ Starobinsky

- Multiple-field effects, connections to 'weak gravity conjecture' etc.

- ...

Axions from gauge potentials

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

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

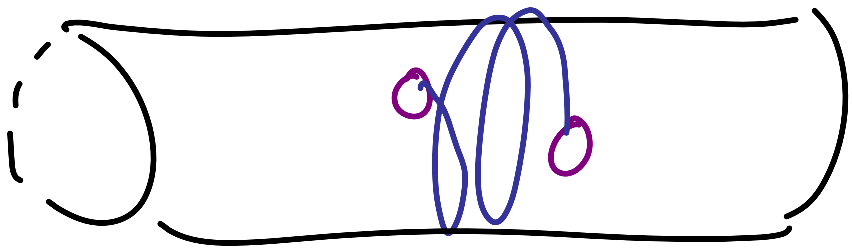
$$\int d^D x \sqrt{G} \sum_q \Big| \overbrace{F_q - C_{q-3} \wedge H + F_{q-\dots} B\wedge \dots \wedge B}^{\tilde{F}_q \text{ Gauge-invar.}} \Big|^2$$

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

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

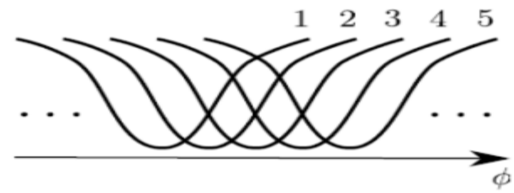
+ e.g. instantons $\rightarrow \Lambda^4 \cos b(\phi)$

+ $\boxed{\text{periodic particle/string production}}$



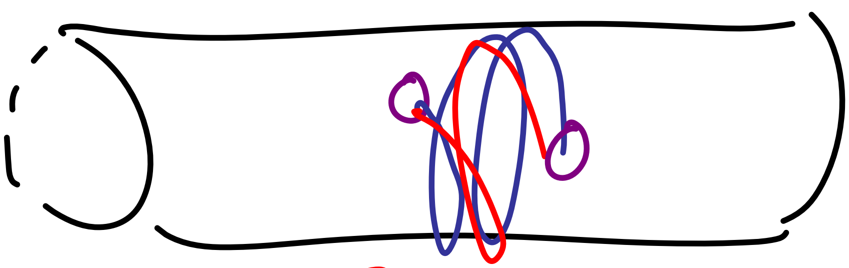
4d spacefilling flux / brane

$\Rightarrow$ large-field potential



$$+ \Lambda^4(\underline{\phi_H}) \cos \frac{\phi}{f}$$

$\Leftrightarrow$ $\boxed{m_H^2 \text{ oscillates}}$



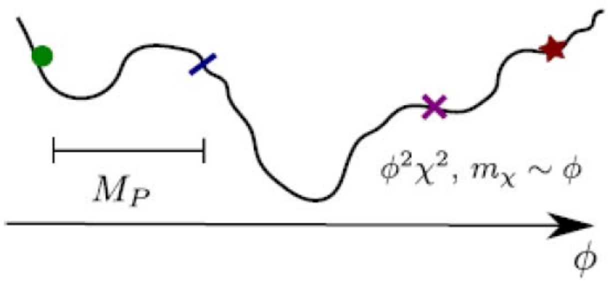
non-space filling defect,

$\boxed{\text{new sectors reach minimal mass each period}}$

$\Rightarrow$ $\boxed{\text{particle production}}$

highly model-dependent amplitude

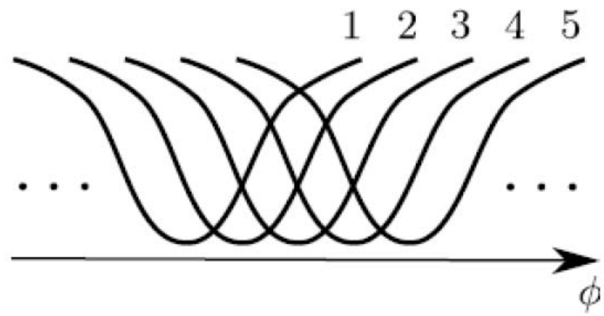
Parameterized ignorance of quantum grav.



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

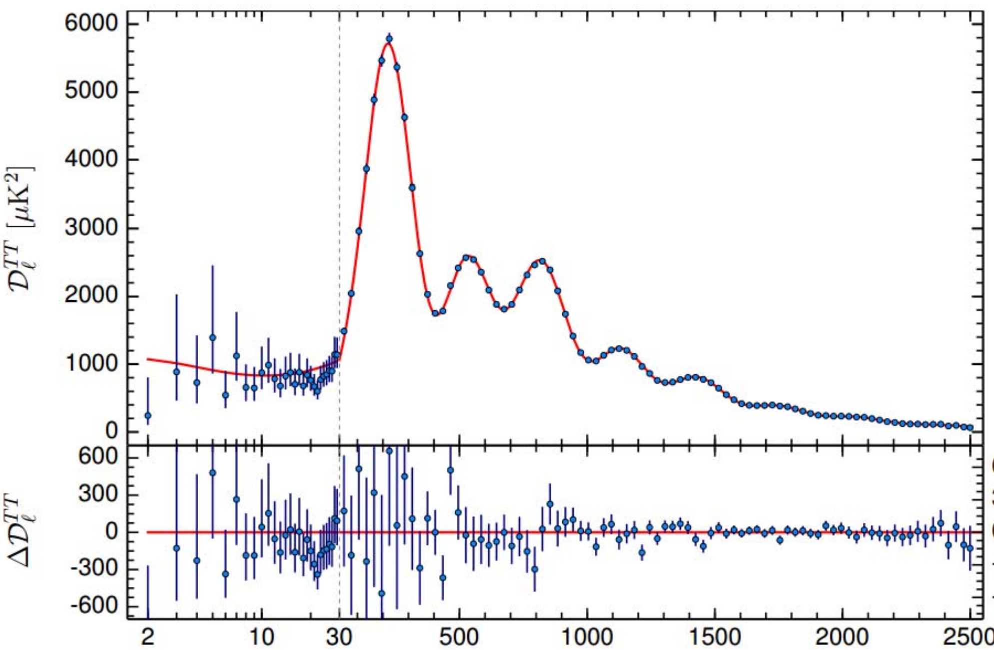
Discrete shift symm., f<<M_p

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

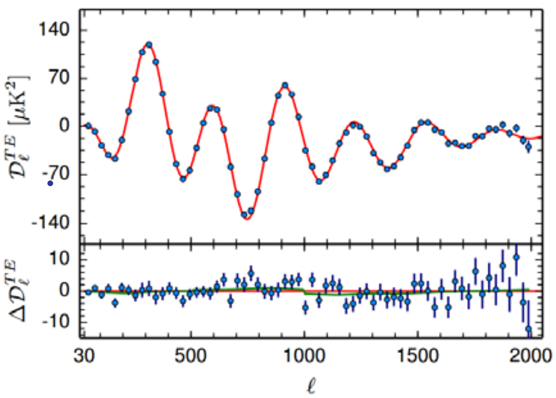
Big Picture

Power spectrum function → 2 parameters

Planck Collaboration: Cosmological parameters

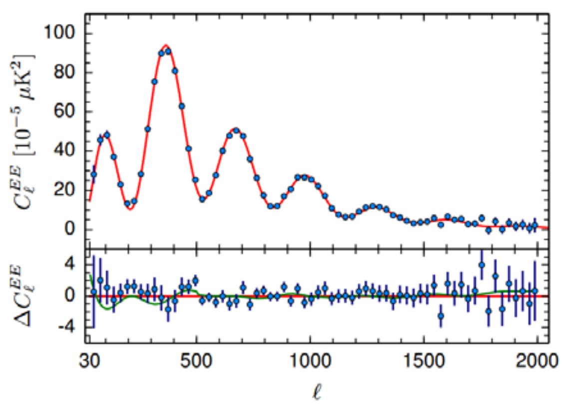


Planck15



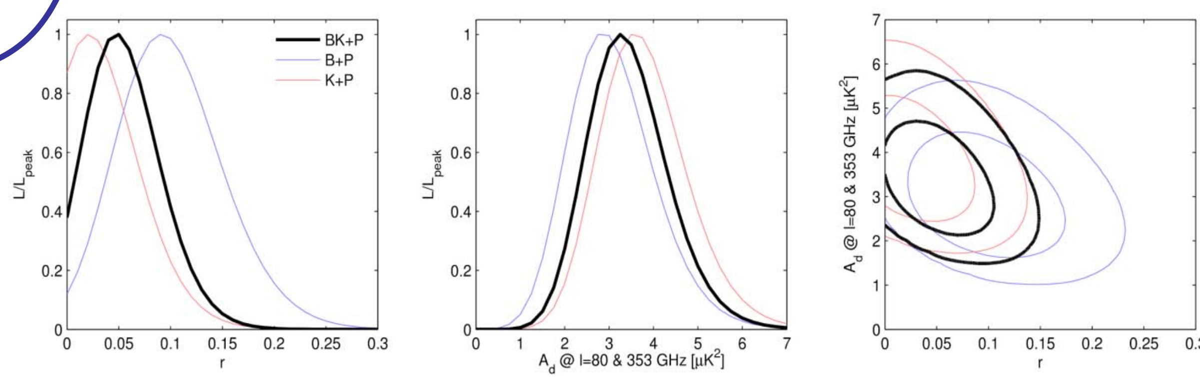
$\ell \geq 30$ we show the maximum likelihood frequency averaged kelihood with foreground and other nuisance parameters deter- the multipole range $2 \leq \ell \leq 29$, we plot the power spectrum puted over 94% of the sky. The best-fit base ΛCDM theoretical pper panel. Residuals with respect to this 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 (<u>insignificant</u>) bump centered at .05-.06, cf .04-.07 cluster axion monodromy models, tested soon...

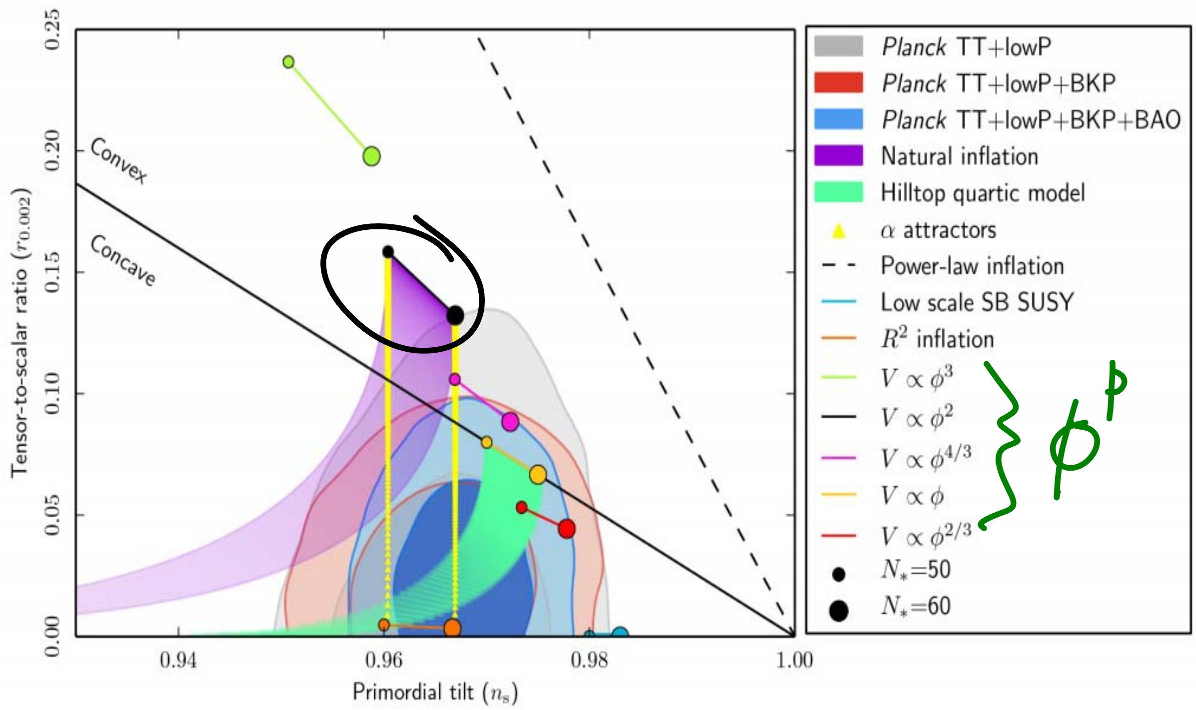


Fig. 54. Marginalized joint 68 % and 95 % CL regions for n_s and $r_{0.002}$ from *Planck* alone and in combination with its cross-correlation with BICEP2/Keck Array and/or BAO data compared with the theoretical predictions of selected inflationary models.

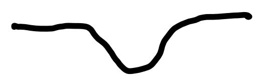
$V = \frac{1}{2} m^2 \phi^2$ 'strongly disfavo(u)red'

contains exit, 2 parameters $\leftrightarrow \langle \zeta\zeta \rangle$, N_e

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

Dong et al '10 'Flattening'

Heavy fields (mass $> H$) affect results:
they adjust in response to inflationary potential energy.

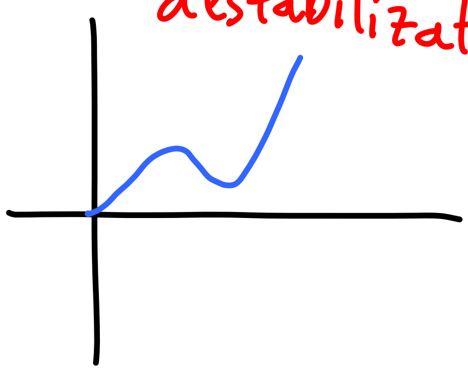


- UV completion of gravity (e.g. string theory) can introduce ϕ_{Heavy} (e.g. 'moduli' scalar fields).

- $V \propto \phi^{n} \rightarrow V \propto \phi^{p<n}$ in examples of axion monodromy

- other scenarios have lower r, additional structure

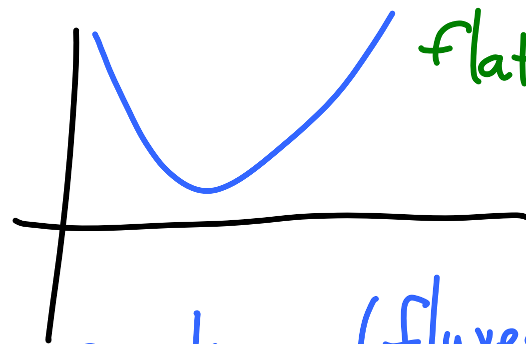
• Moduli : Two basic structures



3 - term

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

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



2 - term (fluxes)

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

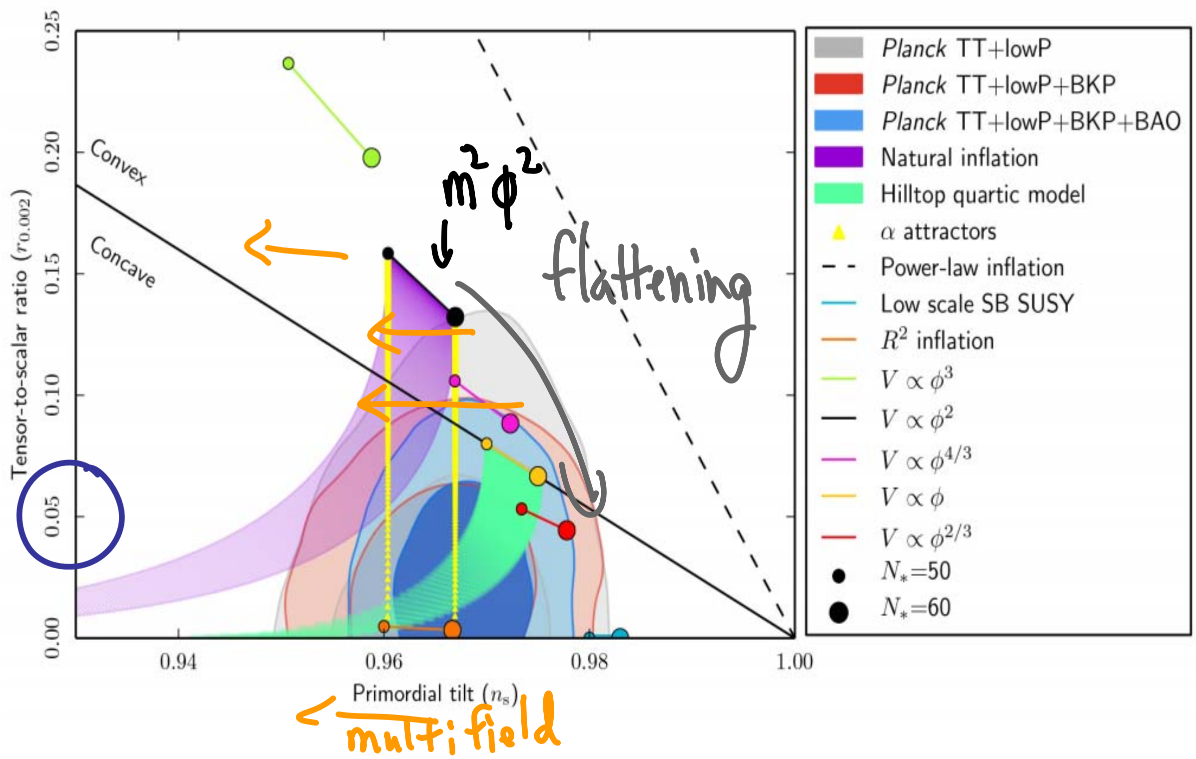
$$\Rightarrow V \propto b^{\frac{2n}{n+\tilde{n}}} < 2$$

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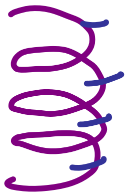
Axion monodromy remains viable only because of the flattening effect. (Tested soon by r)



Underlying periodicity

→ instanton-induced $\Lambda^4 \cos\frac{\phi}{f}$ ← well studied oscillations

particle/string production ⇐ Needs inclusion

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

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

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

In progress
Mirbabayi
Senatore
ES
Flauger

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

$\boxed{\text{Planck searches motivate covering all bases}}$

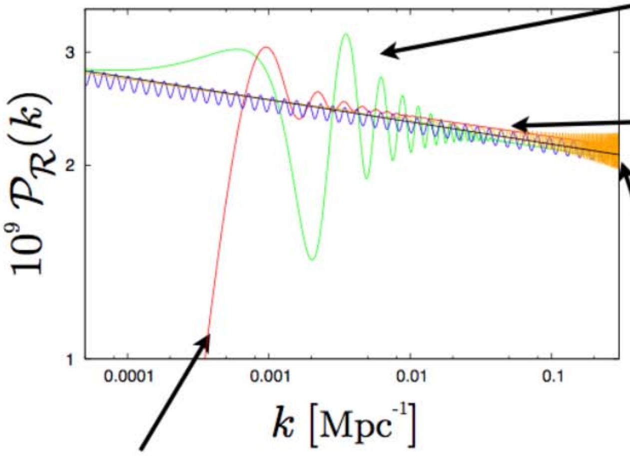
- ΛCDM Robust : $\chi_{d.o.f.} \sim 1.03$-4

- Useful searches for deviations require specific templates with limited parameters

- EFT of inflation contains arbitrary functions of time (and hence k)

$\Rightarrow$ Searches based on specific theories or additional symmetries

Searches for features: 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

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

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

- No detection from existing searches
- Some outliers

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

Power + Bispectrum

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

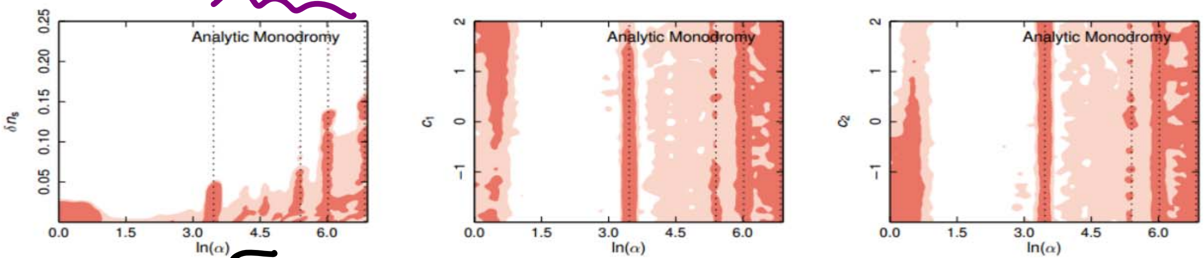


Fig. 37. Constraints on the parameters of the analytic template, showing joint 68 % and 95 % CL. The dotted lines correspond to the frequencies showing the highest likelihood improvements (see text).

$\log(35) \cong 3.5$

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

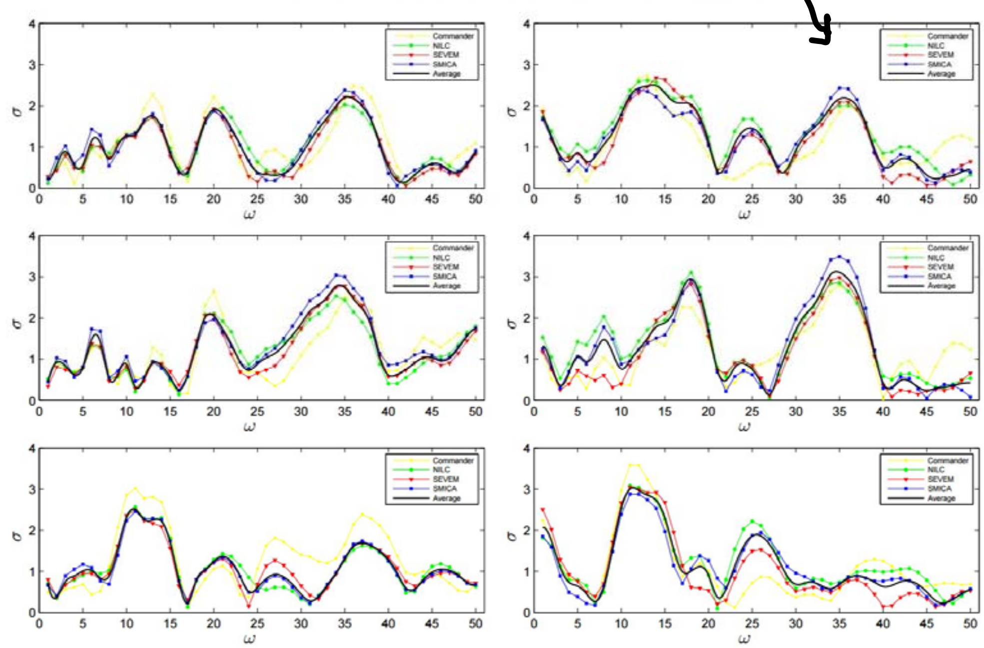


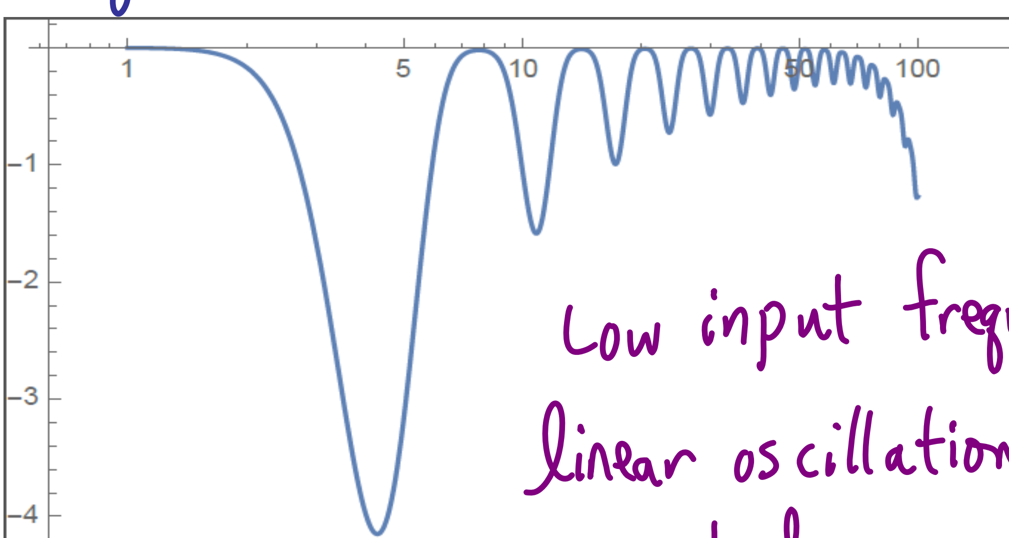
Fig. 19. Generalized resonance models analysed at $\ell_{\max} = 2000$ (E-modes $\ell_{\max} = 1500$) for the different *Planck* foreground separation methods, `SMICA` (blue), `SEVEM` (red), `NILC` (green), `Commander` (yellow), together with the SSN average (black). The upper panels apply to the constant 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).

Not significant as it stands ...

New templates from repeated particle production:

peaked for $\frac{k_i}{k_j} \sim \mathcal{O}(1)$, but oscillate in k or $\frac{k_i}{k_j}$ $\Rightarrow$ $\frac{F_{prod} \cdot F_{pure\ equilateral}}{\sqrt{F_{pr}^2}\sqrt{F_{eq}^2}} \ll 1$

- (a) sequence of events, $J \sim \theta(\eta - \eta_n)$



Low input frequency, linear oscillations generated

- (b) sinusoidal J
  - oscillates in $x_{ij} = \frac{k_i}{k_j}$
  - $$\frac{\left(S/N\right)_{\substack{\text{production}\\\text{bispectrum}}}}{\left(S/N\right)_{\substack{\text{prod.}\\\text{power}\\\text{spectrum}}}} \text{ can be } \gg \frac{\left(S/N\right)_{\substack{\text{resonant}\\\text{NG}}}}{\left(S/N\right)_{\substack{\text{oscillatory}\\\text{power}}}}$$

$\Rightarrow$ relevant for joint analysis between power spectrum & bispectrum.

- It will be interesting to see if shapes (a) or (b) affect the statistical significance, survives/improves with polarization.

- Since even $m \gg H$ fields can have effect, null results can be useful:

'Planck'-suppressed operators

Main Role so far :

- String-theory mechanisms feed into more systematic EFT & data analysis
- Planck fld range <=> r >.01 ⇒ especially relevant for r
- NG at single-field level
- discrete shift symmetries
- dissipative processes
- exotic sources

features & oscillations

⇒ Worthwhile to help make maximal use of precious data

(Yes, String Theory $\subset$ Science.)

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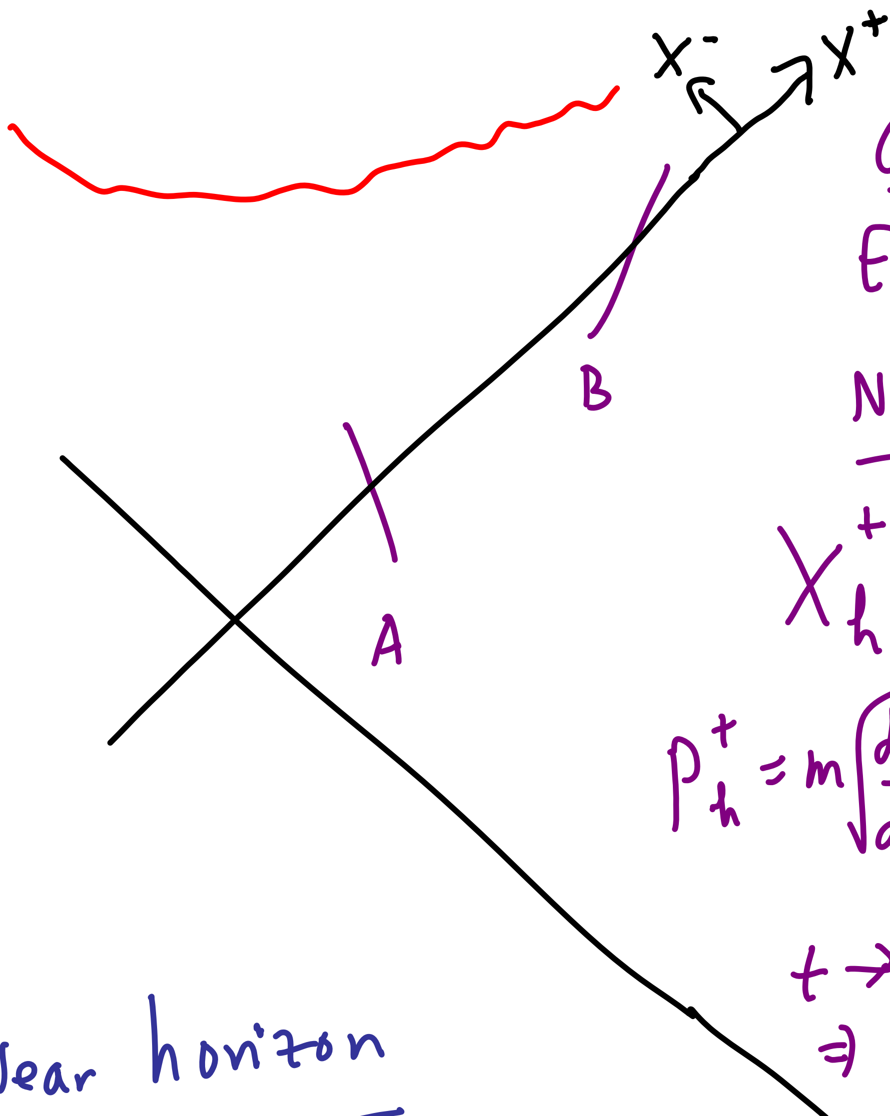
--Breakdown of EFT at horizons (ongoing work w/M. Dodelson): beyond-GR physics...

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 :

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

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

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

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

Near horizon

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

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

<u>String Spreading</u>

- Susskind '94
- Brown Polchinski Strassler Tan '06

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

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

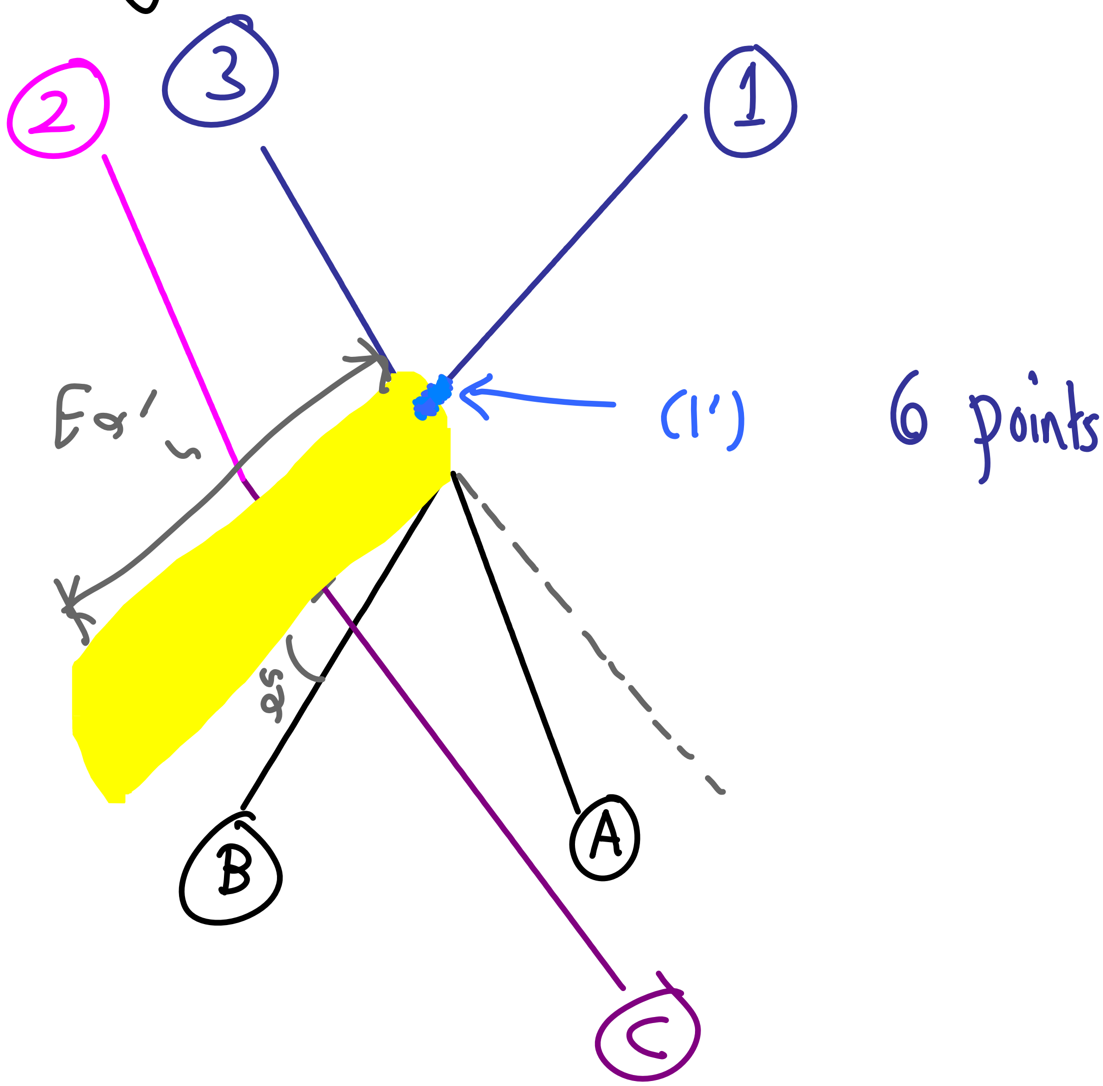
$$\langle\psi|(X_\perp - x_\perp)^2|\psi\rangle = \sum_n^{n_{max}} \frac{1}{n} = \log\frac{n_{max}}{n_0} + O\left(\frac{1}{n_{max}}\right)$$

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

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

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

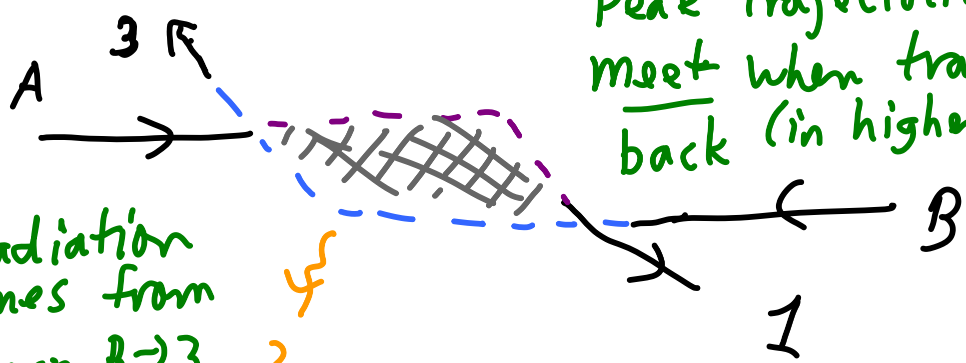
Gathering S-matrix 'data'



c → 2 peaks early by predicted longitudinal spreading scale!

Robust against parameter variations

Previous results: 4 & 5 points



Peak trajectories meet when traced back (in higher D)

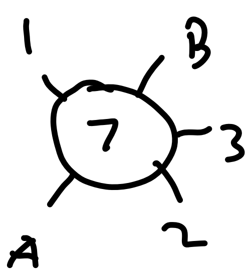
Radiation comes from turn $B \to 3$

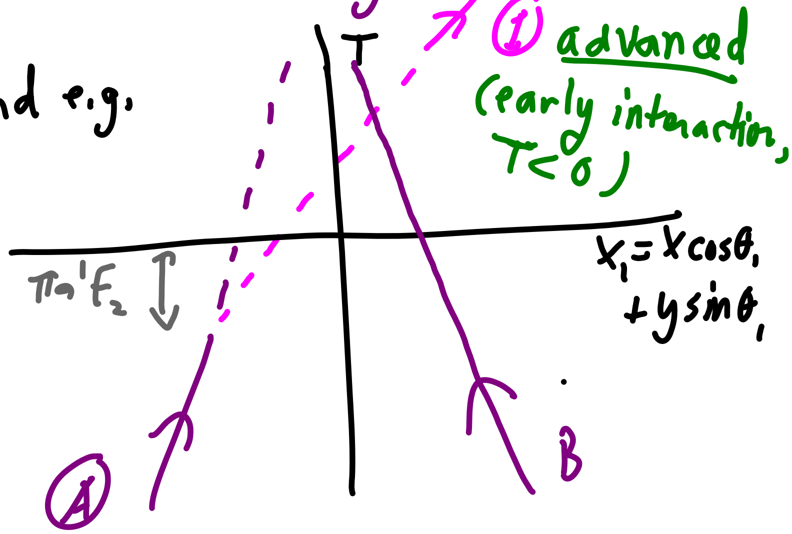
(3) Explicit & simple string solutions for intermediate S-channel states ↔ imag. parts

☆ quantitative agreement with peak b & T

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

find e.g.





*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...