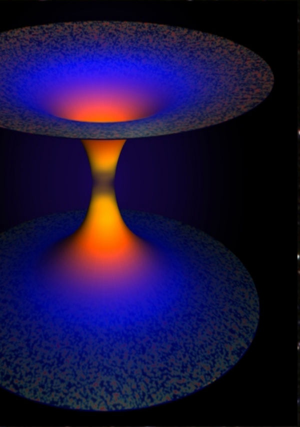

Ben-Gurion Univers
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Gravitational Waves in Bouncing Cosmology

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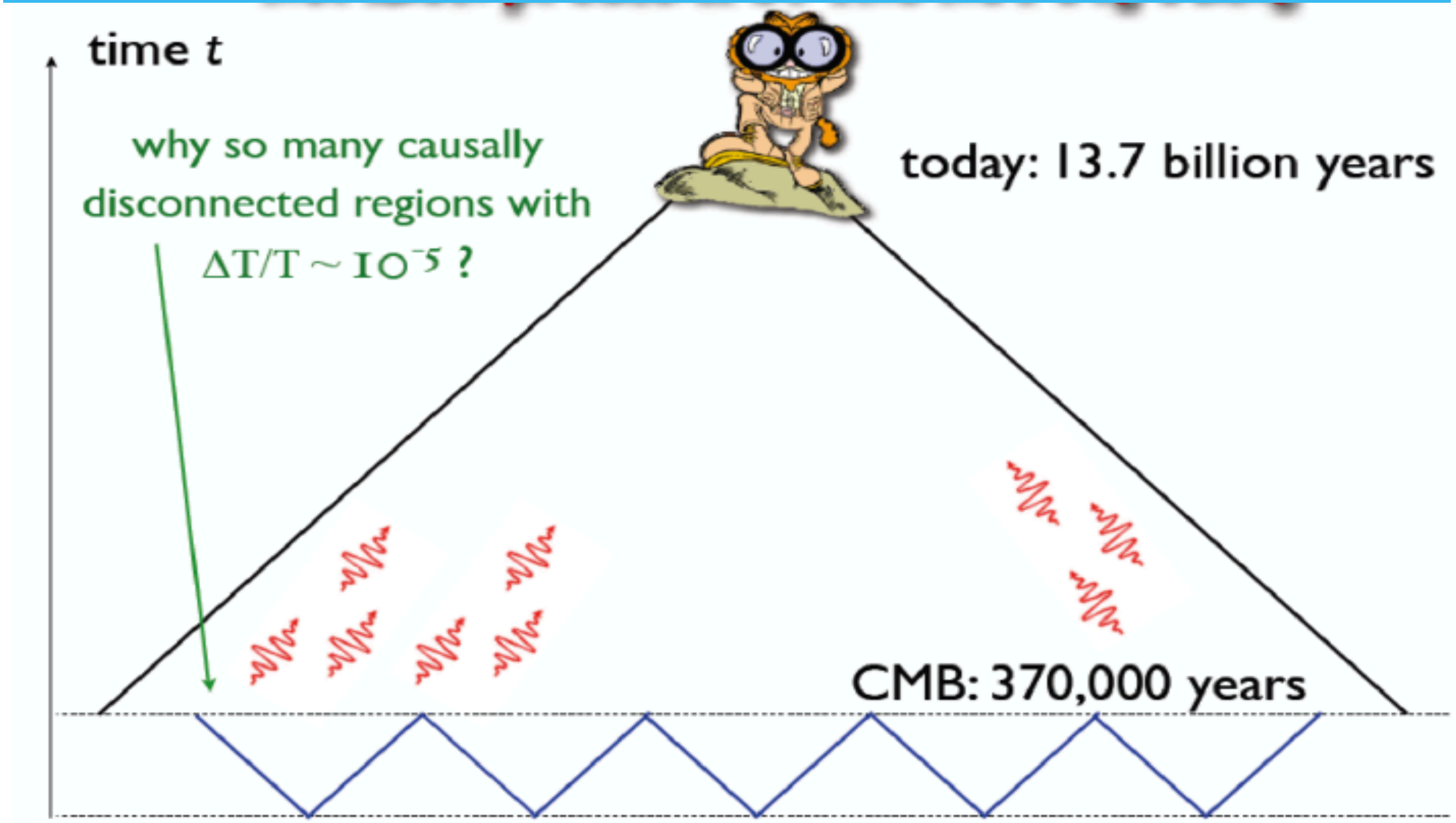
Horizon Problem of the Hot Big Bang

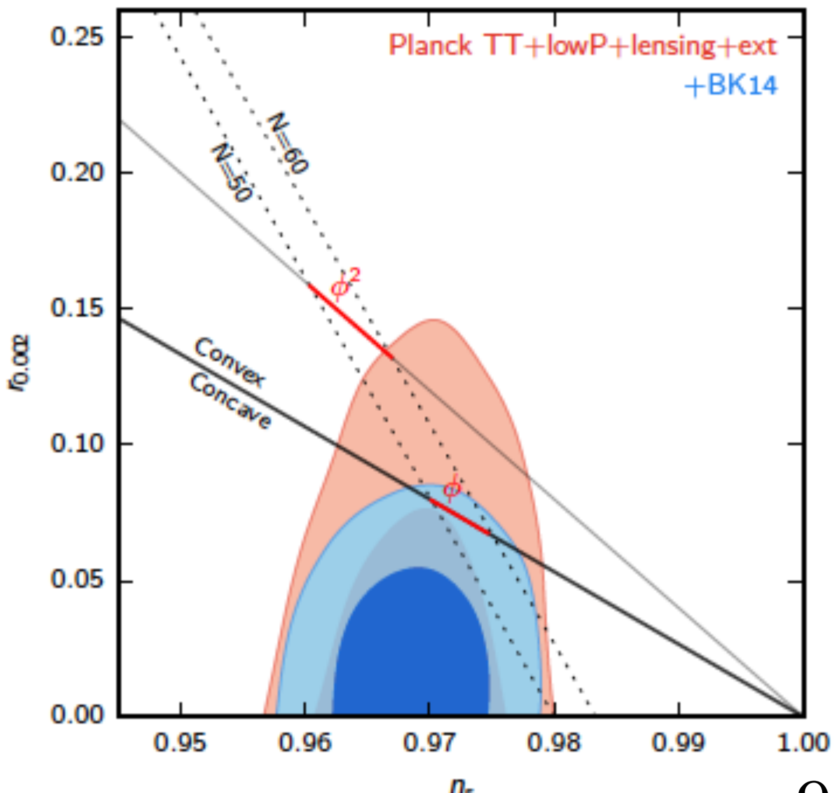


Inflation generates a nearly scale invariant primordial power spectrum of density and gravitational waves perturbations.

The Holy Grail: Primordial GW

* Proves that gravity is quantized!
* Access to energies ~10^{16} GeV
* Inflation – a period of accelerated expansion explains the flatness and isotropy of the observed Universe.
* "Slowly-rolling" scalar field
* **Vacuum fluctuations** during **inflation** predict a **nearly scale-invariant density** fluc. power spectrum and **gravitational waves (GW)** spectrum – explains structure formation in the Early Universe
* Generally, a detection of **GW** is considered a **"proof"** of inflation.

Theory meets Observations



$$P_s = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

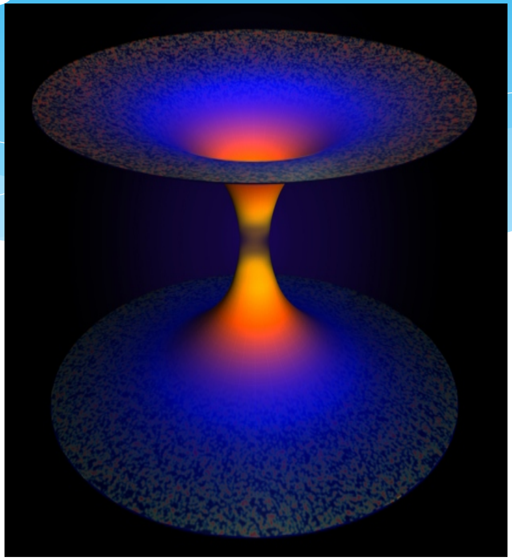
$$P_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

$$r(k_0) = \frac{P_t(k_0)}{P_s(k_0)}$$

$$A_s \simeq 2 \times 10^{-9},\ n_s \simeq 0.97,\ r < 0.07$$

$$P_t \sim H^2$$

Open Questions in Early Universe



* Big Bang Singularity?
* Primordial GW?
* Inflation vs. Alternatives?

Within Inflation:

1) UV completion (from string theory?)
2) Model selection. Simple models are ruled out
3) "Measure problem"

=> Bouncing Cosmology!

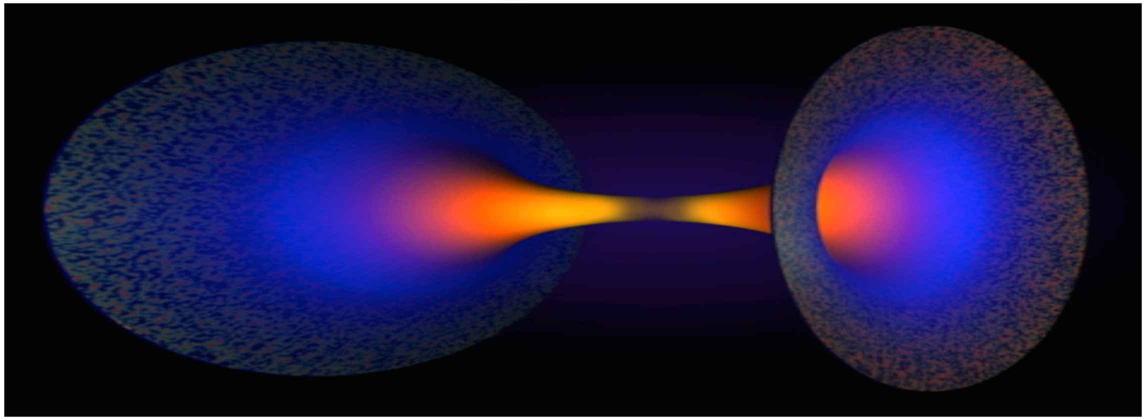
Motivation I:

Big Bang Singularity!

New Physics is necessary!

Some NP discards inflation

=>Bouncing Cosmology



Motivation II:
Sourced Fluctuations give a rich phenomenology very different from standard Slow-Roll.

Are GW on CMB scales "proof" of Inflation?

I will demonstrate:

Observable Gravitational Waves on CMB Scales (and LIGO ?) in a Bouncing Cosmology

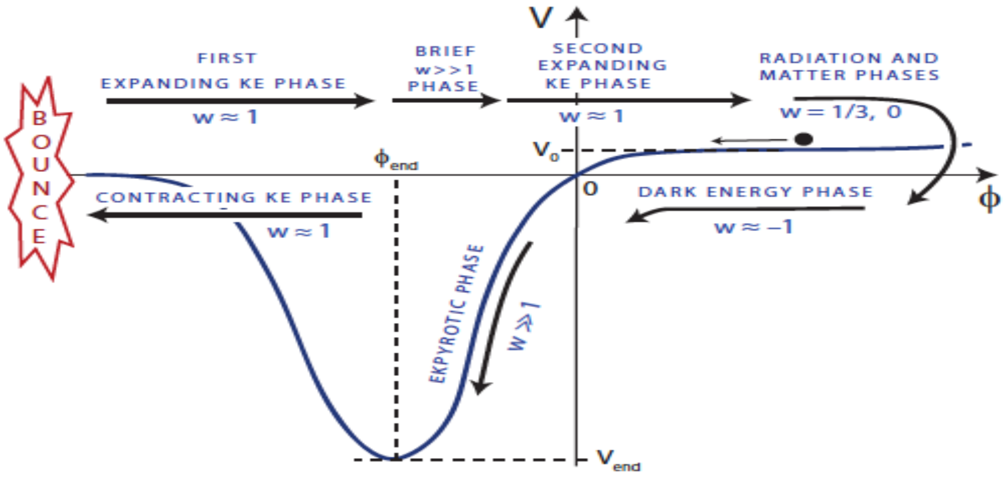
Using

Sourced Fluctuations !

Brief History of Time in a Bouncing Model

- **Universe slowly contracts. b<<1, tau<0.** Isotropizes and flattens! Vacuum fluctuations generate spectra. (Ekpyrosis/Pre Big Bang…)
- **Kinetic Energy Dominated Contraction. (b=1/2)**
- **BOUNCE!** (H flips sign), No Big Bang singularity (via Galileons, G-Bounce, Ghost condensate…). In this talk, I only discuss the slow contraction phase, not discussing the Bounce itself.
- **Kinetic Energy Dominated Expansion. (b=1/2, tau>0)**
- **Standard Hot Big Bang.**

$$a = a_0(-\tau)^b$$



Inflation-Bounce Duality

Inflation

* Power law inflation
* p->infinity
* b=-1
* $V_0>0$
* Epsilon, eta <<1

Bounce

* Ekpyrosis (slow contraction)
* 0<p<<1
* b~p<<1
* $V_0<0$
* Epsilon, eta >>1

BKL Instability!

* Matter Bounce
* p=2/3
* b=2
* $V_0<0$
* Epsilon, eta ~1

$$V(\varphi) = V_0 e^{-\sqrt{2/p}\varphi}, \qquad \epsilon = -\frac{\dot{H}}{H^2} = \frac{1}{p}$$

$$a = a_0(-t)^p = a_1(-\tau)^b, \qquad b \equiv \frac{p}{1-p}$$

Early Universe Cosmology

Inflation

* Universe expands exponentially ~dS space
* Isotropy & Homogeneity
* Vacuum fluctuations generate spectra
* Nearly scale inv. scalar spectrum
* Nearly scale inv. GW spectrum
* Geodesically Incomplete

Bounce

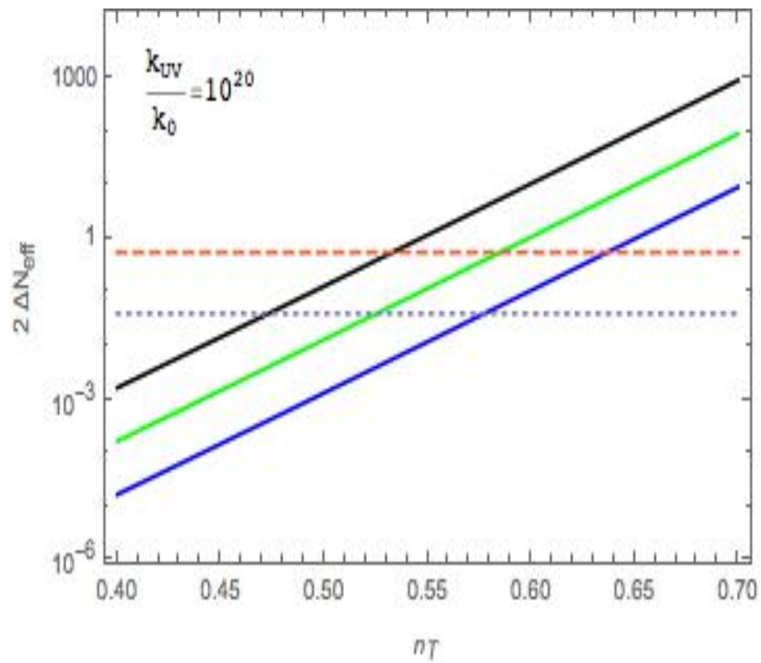
* Universe slowly contracts towards Minkowski space
* Isotropy & Homogeneity
* Vacuum fluctuations generate spectra
* Nearly scale inv. scalar spectrum* (2-fields).
* Blue GW spectrum
* Violates Null Energy Condition

Why are GW so robust?

* Depend only on the background metric.
* Valid for all FLRW cosmologies (Inflation (b=-1), bounce (b<<1) …)
* In Bouncing models $H_{CMB} << H_{CMB}^{INF}$

$$\left[\partial_\tau^2 + \left(k^2 - \frac{a''}{a}\right)\right]\frac{h_\lambda}{a} = 0$$

$$a = a_0(-\tau)^b \qquad \mathcal{P}_t \sim k^{2+2b}$$



Coupling to Gauge Fields

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}(\partial\varphi_1)^2 - V(\varphi_1) - I^2(\varphi_1)\left\{\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\gamma}{4}\tilde{F}^{\mu\nu}F_{\mu\nu}\right\}\right]$$

$$I(\varphi_1) = (-\tau)^{-n}$$

Parity Breaking Term

- Gauge Field mode equation:

$$\tilde{A}''_\lambda + \left(k^2 + 2\,\lambda\,\xi\,\frac{k}{\tau} - \frac{n\,(n+1)}{\tau^2}\right)\tilde{A}_\lambda = 0$$

$$\xi \equiv -n\gamma, \quad \tilde{A} \equiv I(\tau)A$$

- Invariance under:

$$n \to -1 - n, \quad \gamma \to -\frac{n}{1+n}\gamma$$

Gauge Fields Production

* Controlled Backreaction. (-2<n<1).

$$\frac{1}{2}\langle\vec{\tilde{E}}^2+\vec{\tilde{B}}^2\rangle \ll 3M_{pl}^2H^2 \Rightarrow H/M_{pl} \ll \sqrt{3/D_{1,2}(n)\,p^2\xi^{3/2}e^{-\pi\xi}}$$

* Exponential enhancement of gauge quanta of only one polarization
* 'Sourced Spectra' uncorrelated with vaccum fluc.

$$\tilde{A}(k,\,\tau) \simeq \sqrt{-\frac{\tau}{2\,\pi}\,e^{\pi\xi}\,\Gamma\left(|2n+1|\right)\,|2\,\xi\,k\,\tau|^{-|n+1/2|}}$$

$$-k\tau \ll 1/\xi$$

Solutions for GW with a Source

- Valid for all FLRW cosmologies (Inflation (b=-1), matter(b=2), ekpyrotic (b<<1) …)
- h- GW pert., G – Ret. Green's function, J – source, A- gauge fluc.

$$a \sim (-t)^p = (-\tau)^b$$

$$\hat{h}_\lambda(\tau, \vec{k}) = \frac{2}{M_{pl} a} \hat{Q}_\lambda(\tau, \vec{k})$$

$$\left[\partial_\tau^2 + \left(k^2 - \frac{a''}{a}\right)\right] Q_\lambda\left(\tau, \vec{k}\right) \simeq J_\lambda\left(\tau, \vec{k}\right), \quad Q_\lambda\left(\tau, \vec{k}\right) = \int^\tau d\tau' G_{ret.}(\tau, \tau')\, J_\lambda\left(\tau', \vec{k}\right),$$

$$G_{ret.}(\tau, \tau') = i\Theta(\tau - \tau')\frac{\pi}{4}\sqrt{\tau\tau'}\left[H^{(1)}_{1/2-b}(-k\tau)H^{(2)}_{1/2-b}(-k\tau') - H^{(1)}_{1/2-b}(-k\tau')H^{(2)}_{1/2-b}(-k\tau)\right]$$

$$G_{ret.}(-k\tau \ll 1, b \to 0) \simeq \Theta(\tau - \tau')\frac{\sin(-k\tau')}{k}$$

$$J_\lambda(\tau, \vec{k}) = -\frac{1}{M_{pl} a}\int \frac{d^3 p}{(2\pi)^{3/2}} \sum_{\lambda'=\pm} \epsilon_i^{(\lambda)*}(\vec{k})\epsilon_j^{(\lambda)*}(\vec{k})\epsilon_i^{\lambda'}(\vec{p})\epsilon_j^{\lambda'}(\vec{k}-\vec{p})\left\{\frac{2\xi}{-\tau}\sqrt{p|\vec{k}-\vec{p}|} + p|\vec{k}-\vec{p}|\right\}$$

$$\times \tilde{A}_{\lambda'}(\tau, \vec{p})\tilde{A}_{\lambda'}(\tau, \vec{k}-\vec{p})\left[\hat{a}_{\lambda'}(\vec{p}) + \hat{a}^\dagger_{\lambda'}(-\vec{p})\right]\left[\hat{a}_{\lambda'}(\vec{k}-\vec{p}) + \hat{a}^\dagger_{\lambda'}(-\vec{k}+\vec{p})\right]$$

$$\sim A^2 \sim e^{2\pi\xi}$$

Sourced Fluctuations

* Coupling inflaton/bouncer to gauge fields induces a source term.
* GW production shuts down at the end of slow-contraction.
* Sourced Spectra for -2<n<-5/4 (⇔1/4<n<1)

$$\left[\partial_\tau^2 + \left(k^2 - \frac{a''}{a}\right)\right]\frac{h_\lambda}{a}\left(\tau, \vec{k}\right) = J_\lambda\left(\tau, \vec{k}\right)$$

$$J_\lambda \sim \tilde{A}^2 \sim e^{2\pi\gamma|n|}$$

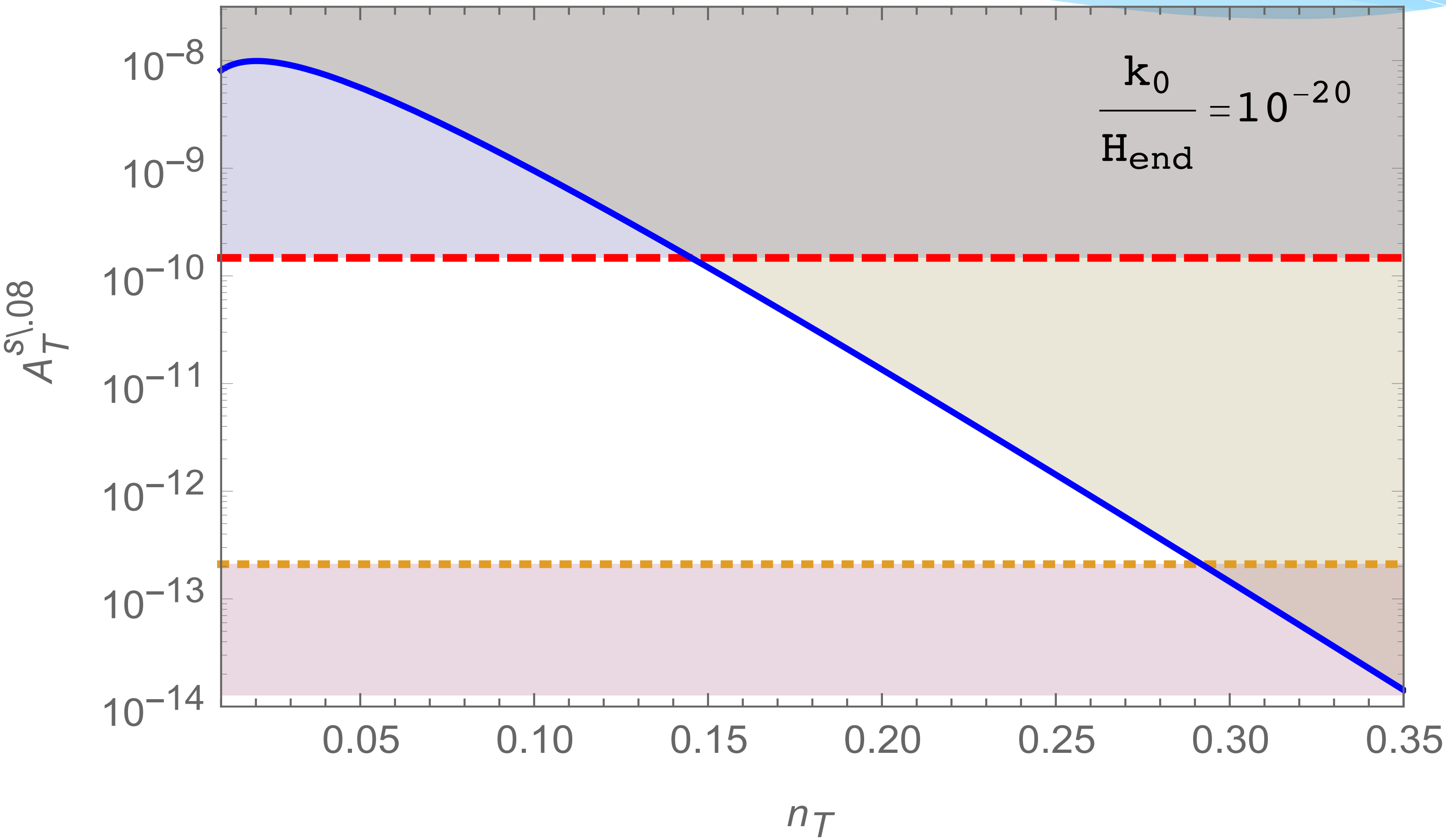
$$\mathcal{P}_t^s \sim J_\lambda^2 \sim e^{4\pi\gamma|n|}k^{4(2+n)}$$

$$\mathcal{P}_T\left(n, \xi; n \geq -1/2\right) = \mathcal{P}_T\left(-1-n, \xi; n \leq -1/2\right).$$

Exponential enhancement and arbitrarily close to scale invariance BUT BLUE and CHIRAL !

Results

* Blue chiral GW signal, $0<n_T \sim< 0.3$.
* Observable on CMB, $n_T \sim 0.3$ Observable by LIGO.

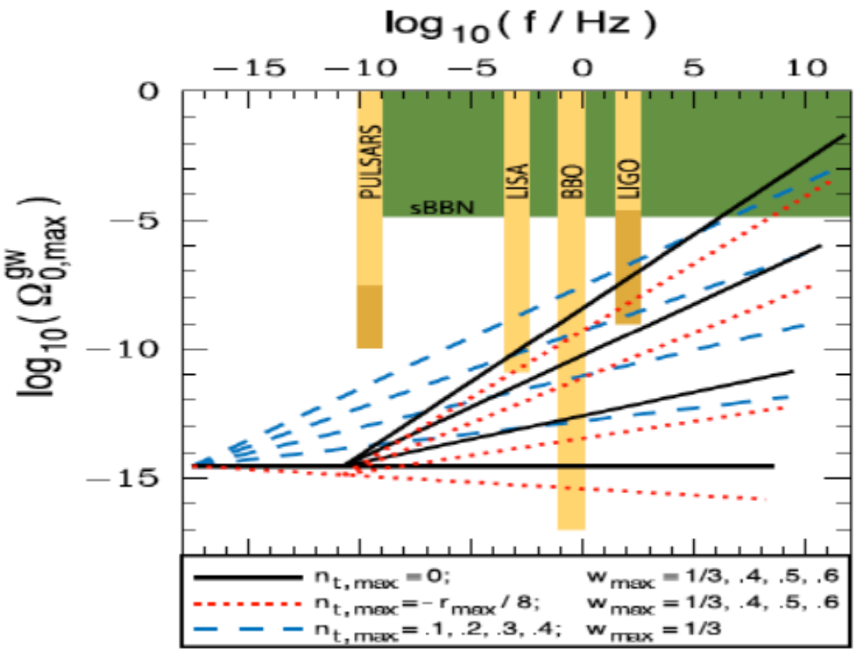


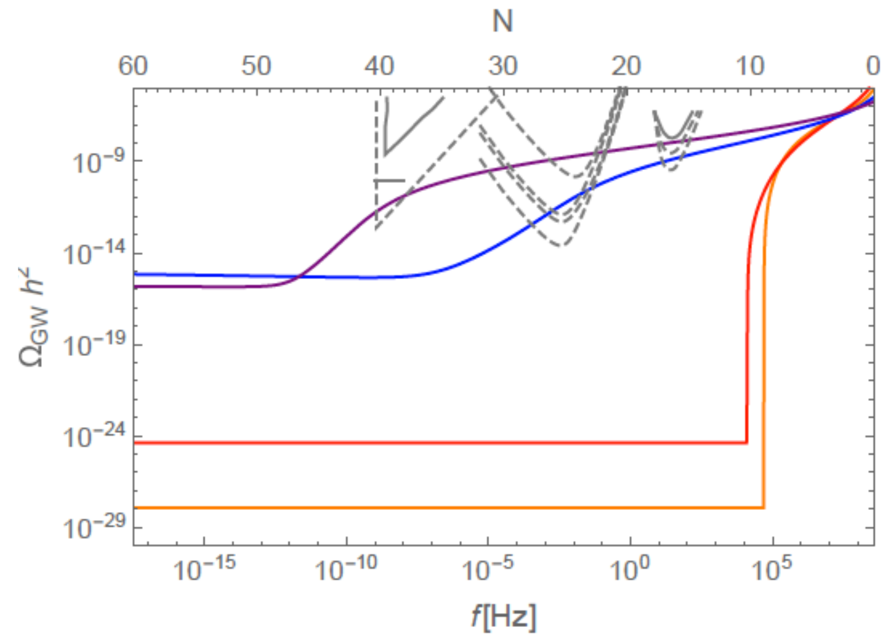
Discerning Paradigms – Work in progress

* Until now CMB slowly ruling out inflationary models
* By considering LI (and chirality) we can rule out entire paradigms!

	CMB	LI	n_T	Chirality
Slow-roll Inflation	✔	✖	~<0	✖
Sourced Inflation	✔	✔	~<0, +blue	✔
Bounce	✖	✔	~2-3	✖
Sourced Bounce	✔	✔	$0<n_T\sim<0.3$	✔

Discerning Paradigms





Sourced Inflation detectable by LI if in the strong backreaction regime. Sourced Bounce has constant n_T in the weak backreaction regime => very different spectra

Discerning Paradigms

* Null detection – ‘status quo’ maintained
* Only CMB detection – Bounce is ruled out
* Only LI detection – Slow-Roll Inflation ruled out
* Any chirality detection - Slow-Roll Inflation and Bounce ruled out, Sourced fluctuations confirmed!
* CMB and LI detection - Slow-Roll Inflation and Bounce ruled out. Constant n_T – Sourced Bounce, varying n_T – Sourced Inflation

Conclusions

* Sourced Bounce models give observable GW on CMB scales.
* Slightly blue chiral spectrum –discernable from other paradigms
* TO DO: scalar spectrum, non-gaussianity, other models, effects on bounce, novel bouncing mechanisms…

We now have a new testable paradigm for Early Universe Physics without the Big Bang singularity! By measuring GW on different scales we test whole paradigms!