Probing the Early Universe with *Gravitational Waves* from Cosmic Strings

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arxiv: 1711.03104 (PRD), 1808.08968 (JHEP)

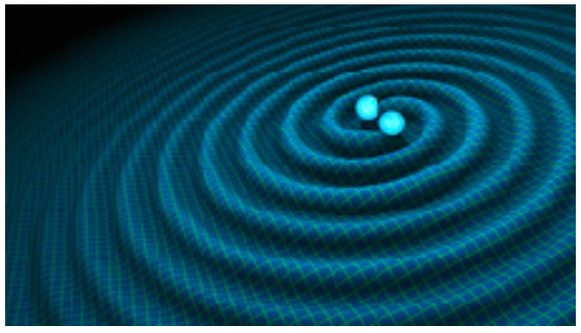
YC with Marek Lewicki, David Morrissey and James Wells

work in prep, YC with Chia-Feng Chang

KITP workshop, Jul 5, 2019

Gravitational Waves: An Unprecedented Window to New Physics?

- LIGO discovery 2016:
  A new era of observational astronomy
  (blackholes, neutron stars…)



- New opportunities for probing
  new particle physics/
  early universe cosmology?

BSM Physics and GW
-what we know

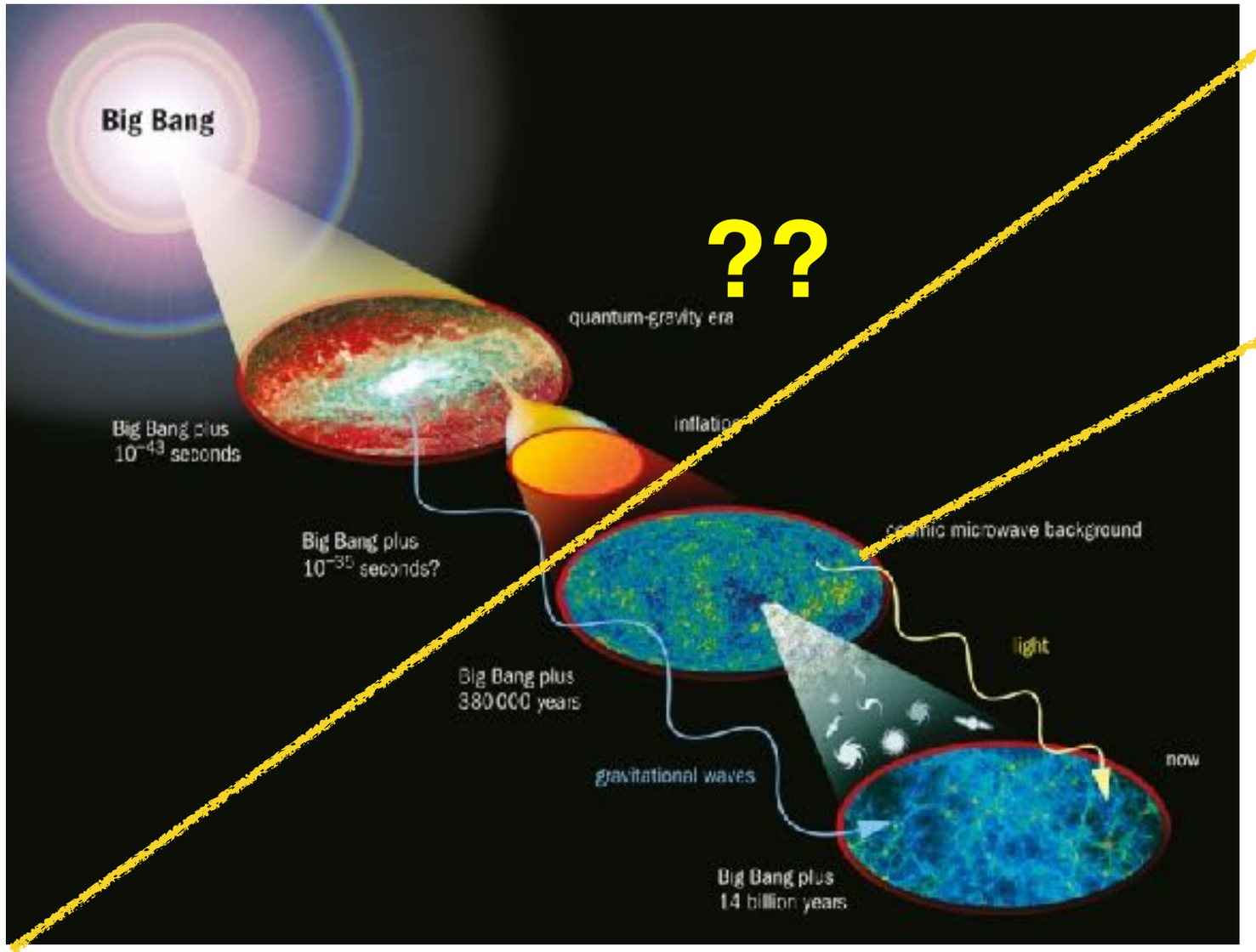
- **Cosmological sources of GW:**
  - Inflation
  - Preheating
  - 1st order phase transition: EWPT/EWBG
  - **Cosmic strings ★:** *e.g.* following a spontaneous U(1) symmetry-breaking (at any scale: γ', Z', $U(1)_{B-L}$, axion…) or superstring theory
    (arxiv: 1712.01168 by LIGO and Virgo collaboration)

☞ *Dramatic events in the (pre-BBN) early universe*

- **Effects on GW from BH/NS**: axions, light bosons
  (e.g. Dimopoulos et al. 2016; Nelson et al. 2017)

Pre-BBN Cosmology

-what we do not "know"



- **The horizon of confidence**: BBN *(~1s-3 min after Big Bang)*

- CMB light: a direct window back to *~400k yrs after the Big Bang*

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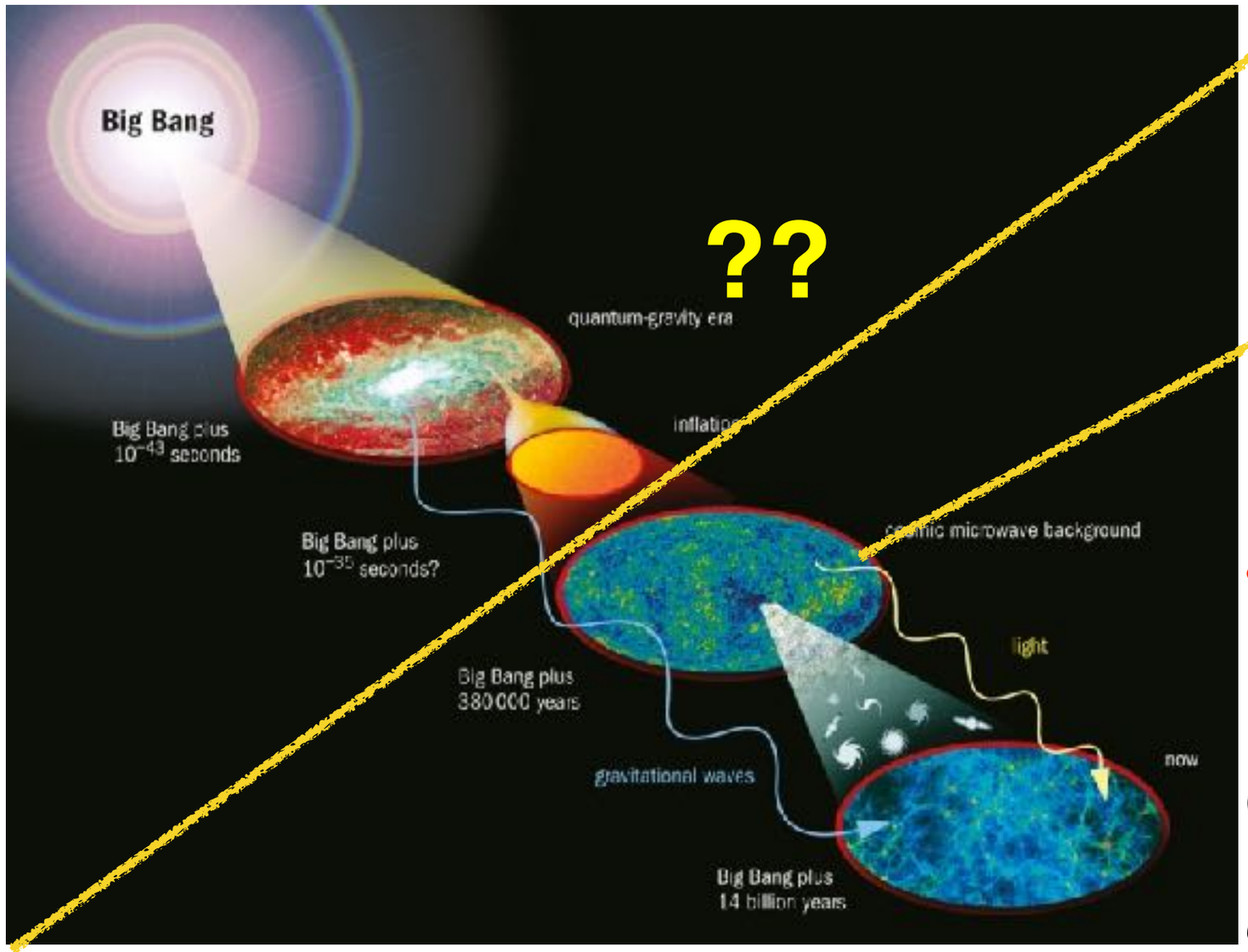


- **The horizon of confidence**: BBN
  (~1s-3 min after Big Bang)

- CMB light: a direct window back to *~400k yrs after the Big Bang*

- **What happened before BBN?**
  Theory: standard cosmology; **many unknowns!**

(scale of inflation/reheating? early matter domination (moduli)? early phase transitions? new d.o.f?…)

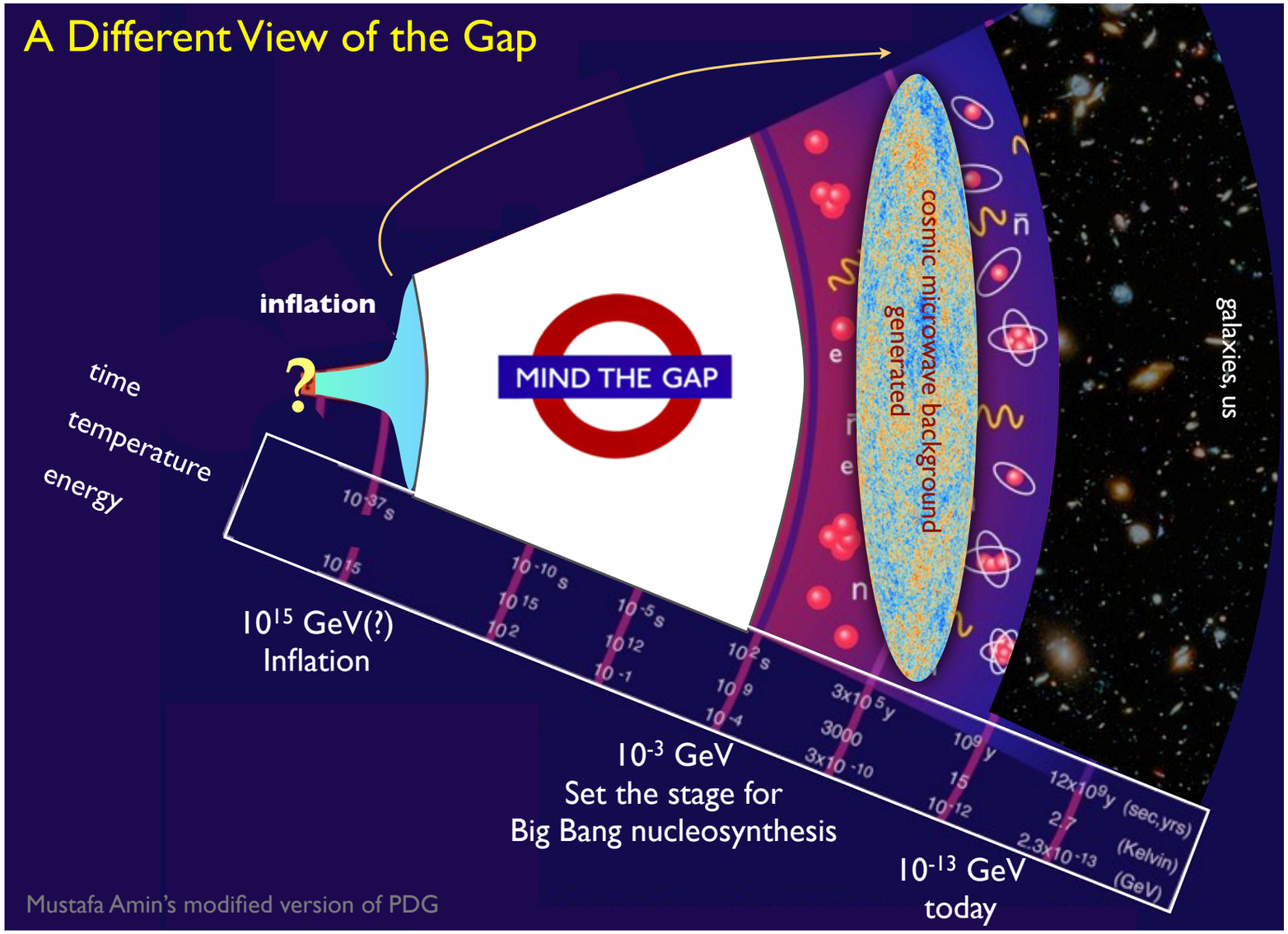
Pre-BBN Cosmology?

— *the Primordial Dark Age*

(Boyle and Steinhardt 2005, Boyle and Buonanno 2007)

What happened within the first ~1 sec?

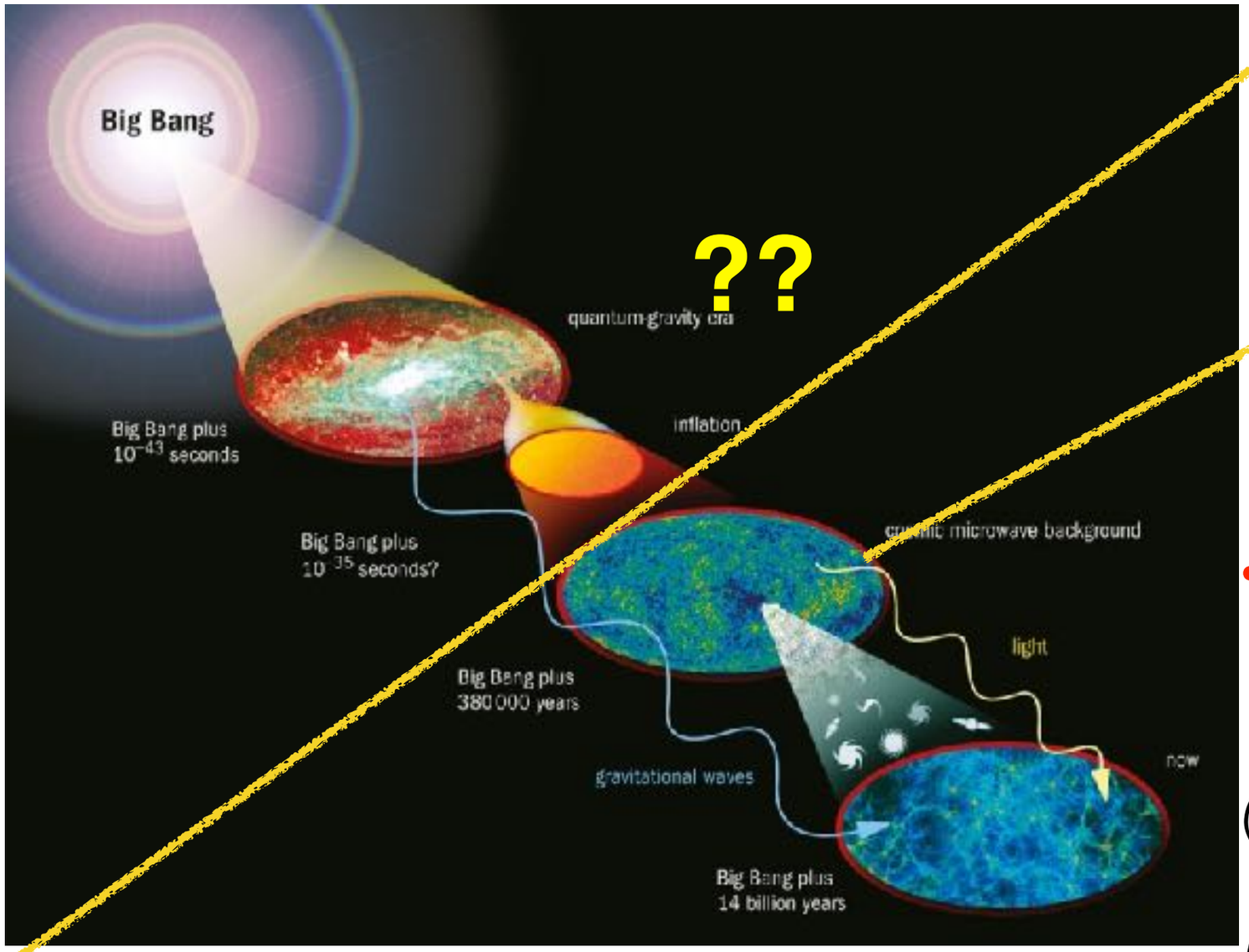
The gap amplified on Log scale of temperature T ($\propto a^{-1}$)! ☞



The Universe is RD with SM content from T_{eq} all the way back to the end of inflation: *up to 24 orders of magnitudes on T scale!* — **IS IT??**

Pre-BBN Cosmology

-what we do not "know"



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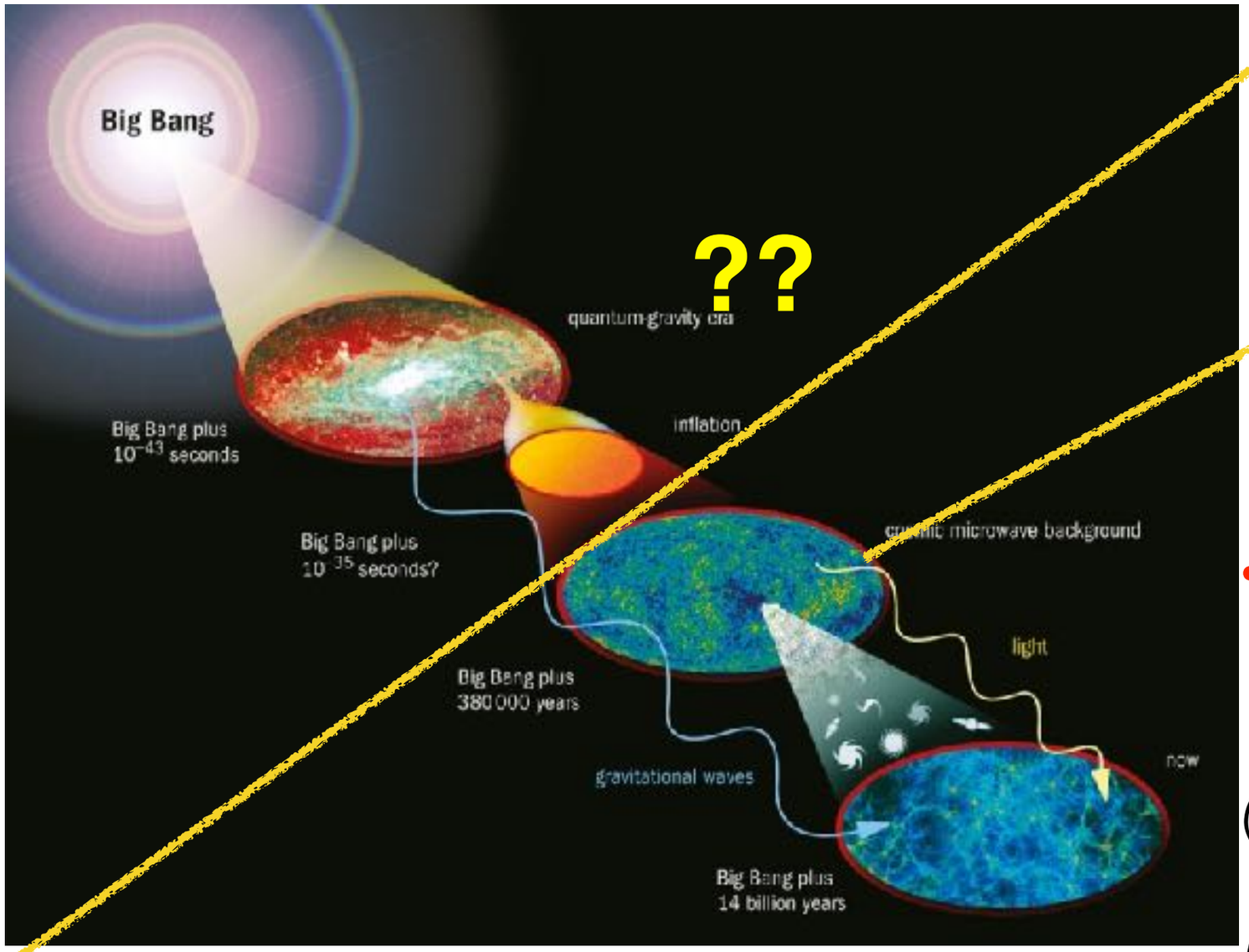

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- **Direct observational probe?** most effort so far: inflation. **Thermal history?** *Mission impossible?*

Pre-BBN Cosmology

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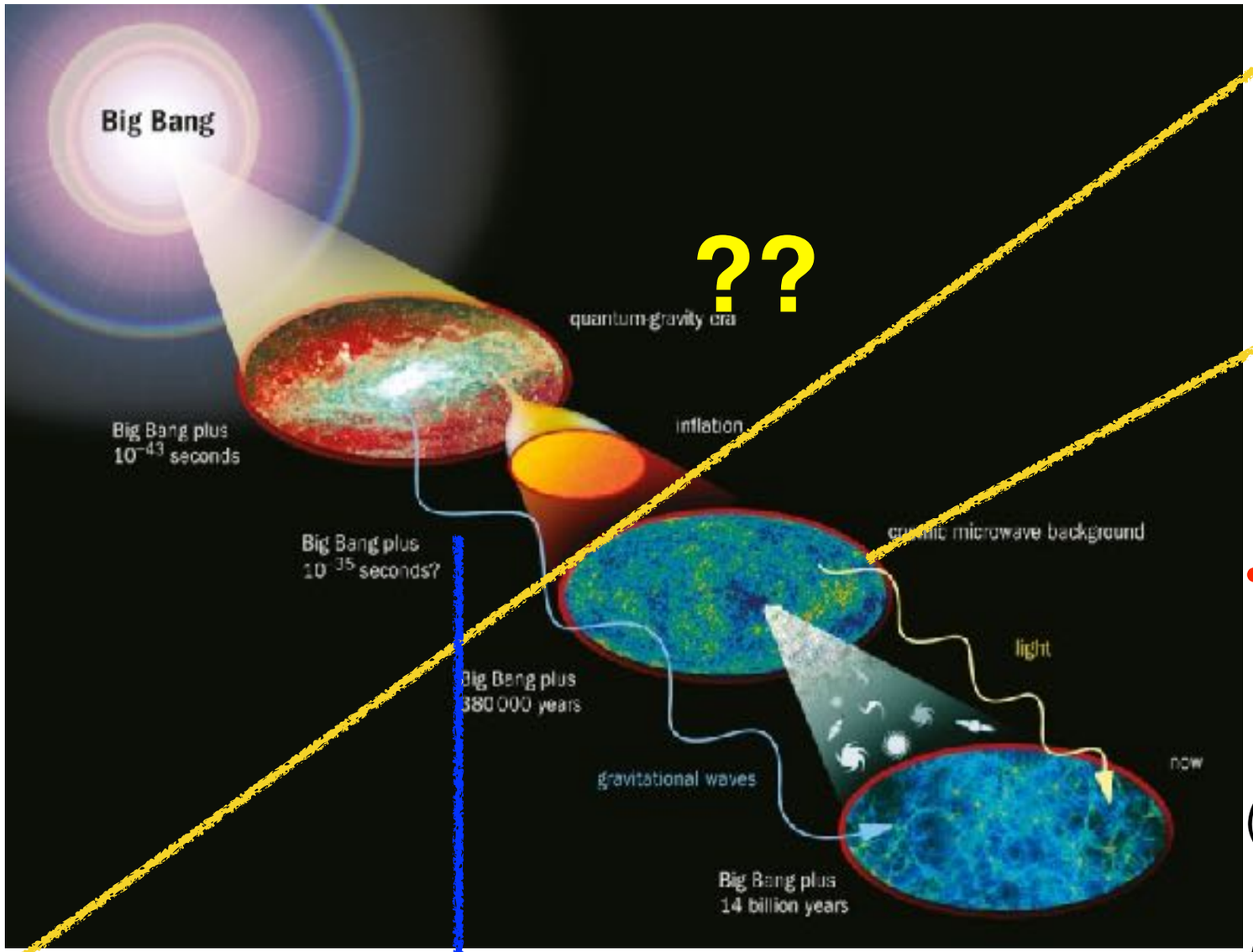

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GW: the window of hope?

- **Direct observational probe?** most effort so far: inflation. **Thermal history?** *Mission impossible?*

Cosmic Archaeology with GWs from Cosmic Strings

(arxiv: 1711.03104, 1808.08968, YC with Lewicki, Morrissey and Wells)

— ***A direct probe of pre-BBN Universe with GWs***

Outline

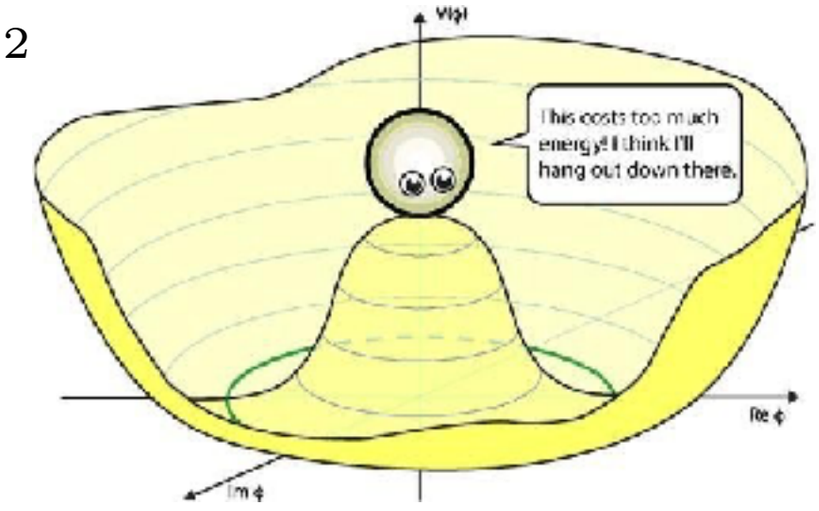
- A brief review on cosmic strings
- Test of standard cosmology: The time-frequency correspondence in the cosmic string GW spectrum
- Probe new phases of cosmic evolution *(eq. of state)*
- Probe new degrees of freedom *(beyond LHC, CMB ΔN_{eff}!)*
- Probe ALP DM models with GW from axion strings/DWs

  (work in prep with Chang)
- Discussion/Conclusion/Outlook

Cosmic Strings 101 (1)

- **What are Cosmic strings?**
  Stable one-dimensional topological defect, tension μ
- **The origins of cosmic strings:**
  - Predictions from superstring theory: fundamental (F-) string, D-string *(Polchinski 2003-2008)*
  - Vortex-like (soliton) solutions of field theory: e.g. spontaneous broken U(1) symmetry (gauge or global)

Charged complex scalar: $V = \lambda\left(\Phi^\dagger\Phi - \frac{v^2}{2}\right)^2$



Adding gauge field: Abelian Higgs model

$$\mathcal{L} = D_\mu\Phi D^\mu\Phi^\dagger - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \lambda(\Phi^\dagger\Phi - v^2/2)^2$$

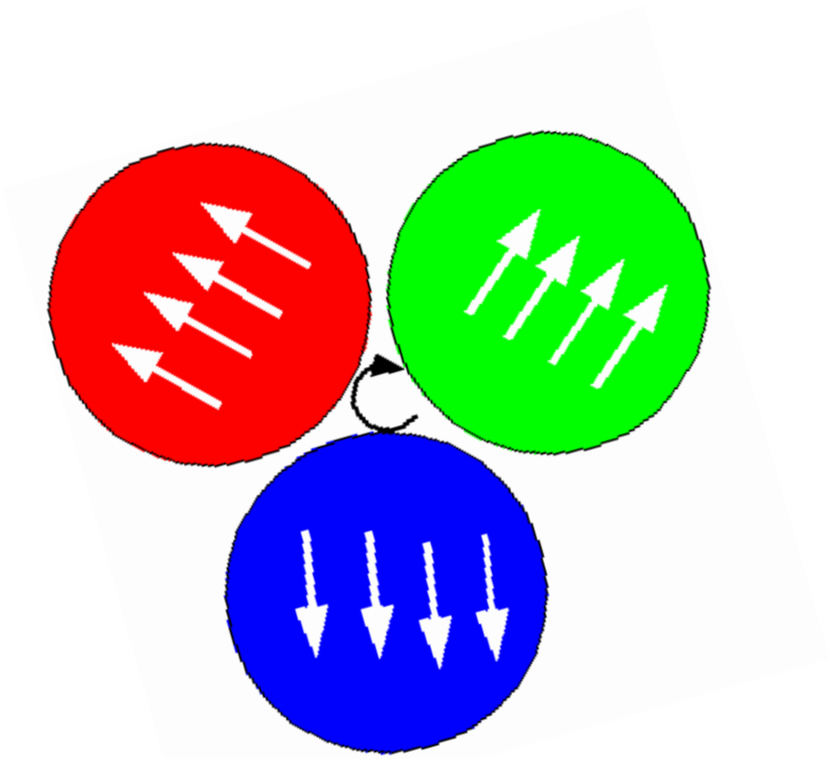
Cosmic Strings 101 (2)

- The familiar solution: $\langle\Phi\rangle = v/\sqrt{2}$ everywhere
- **The string solution to abelian Higgs model**

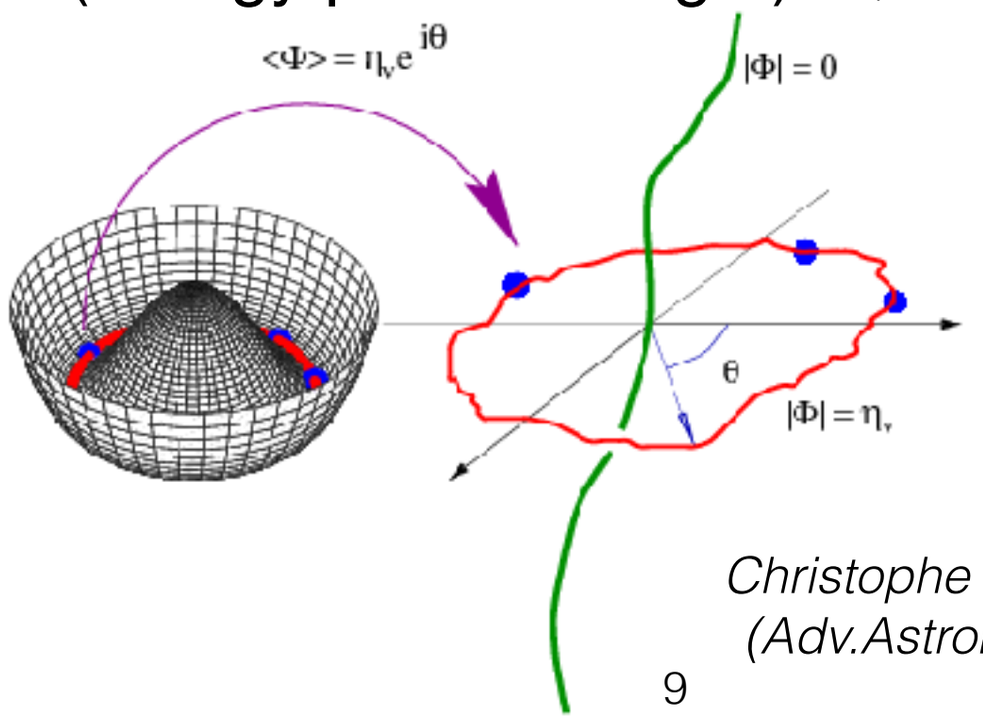
(position dependent, Nielsen and Olesen 1973;
vortex in type-II superconductor, Abrikosov 1957)

$$\text{at } r \to \infty \qquad \Phi \;\to\; \frac{v}{\sqrt{2}} \exp(iN\theta)$$

$$\langle\Phi\rangle = 0 \text{ at the origin}$$



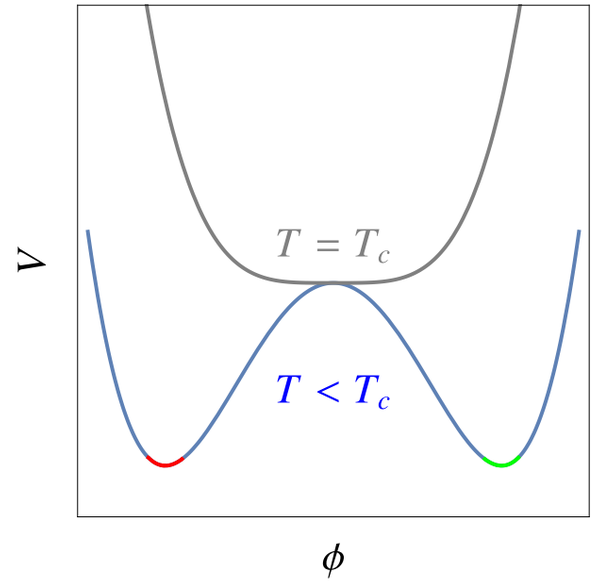
☞A tube of false vacuum (closed or infinite), string tension (energy per unit length): $\mu \sim v^2$



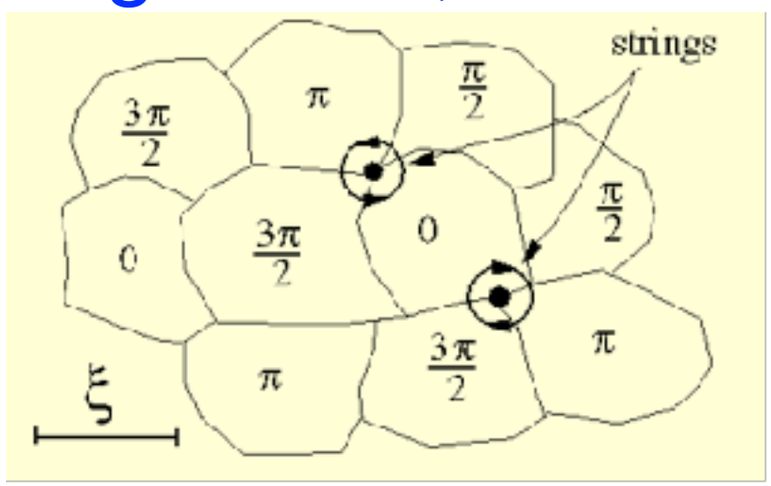
Christophe Ringeval (Adv.Astron. 2010)

Formation of Cosmic Strings

- **Formation**: Kibble mechanism
  - Symmetry restoration at $T > T_c$
  - Spontaneous symmetry breaking at $T \sim T_c$, but $\langle \Phi \rangle$ *(phase!)* cannot be correlated on scales larger than the finite horizon size $d_H \propto M_p/T^2$!



☞ Cosmic strings: non-trivial vacuum configuration, necessarily formed at boundaries of causally disconnected domains.
— "frozen in"

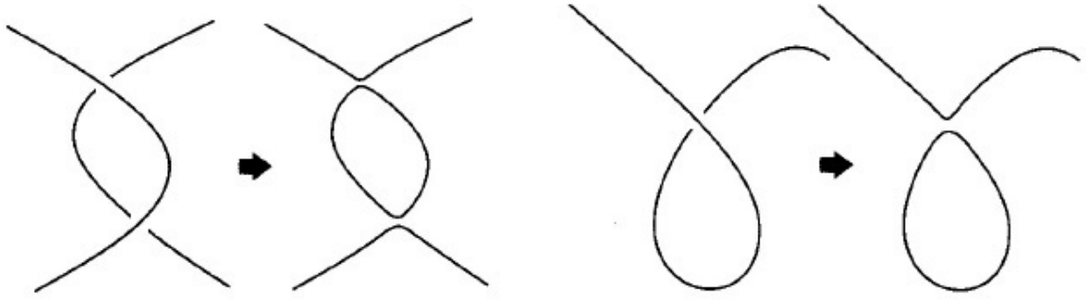


Evolution of Cosmic Strings

- Static string network would redshift as:

$$\rho_\infty \propto a^{-2}$$ *- dangerous! dominate universe today!*

- Dynamics: strings inter-commute on collision, shed string loops that radiate away



☞ regulate energy density of the string network

- Total energy of the network eventually scales with background energy density (MD or RD) :

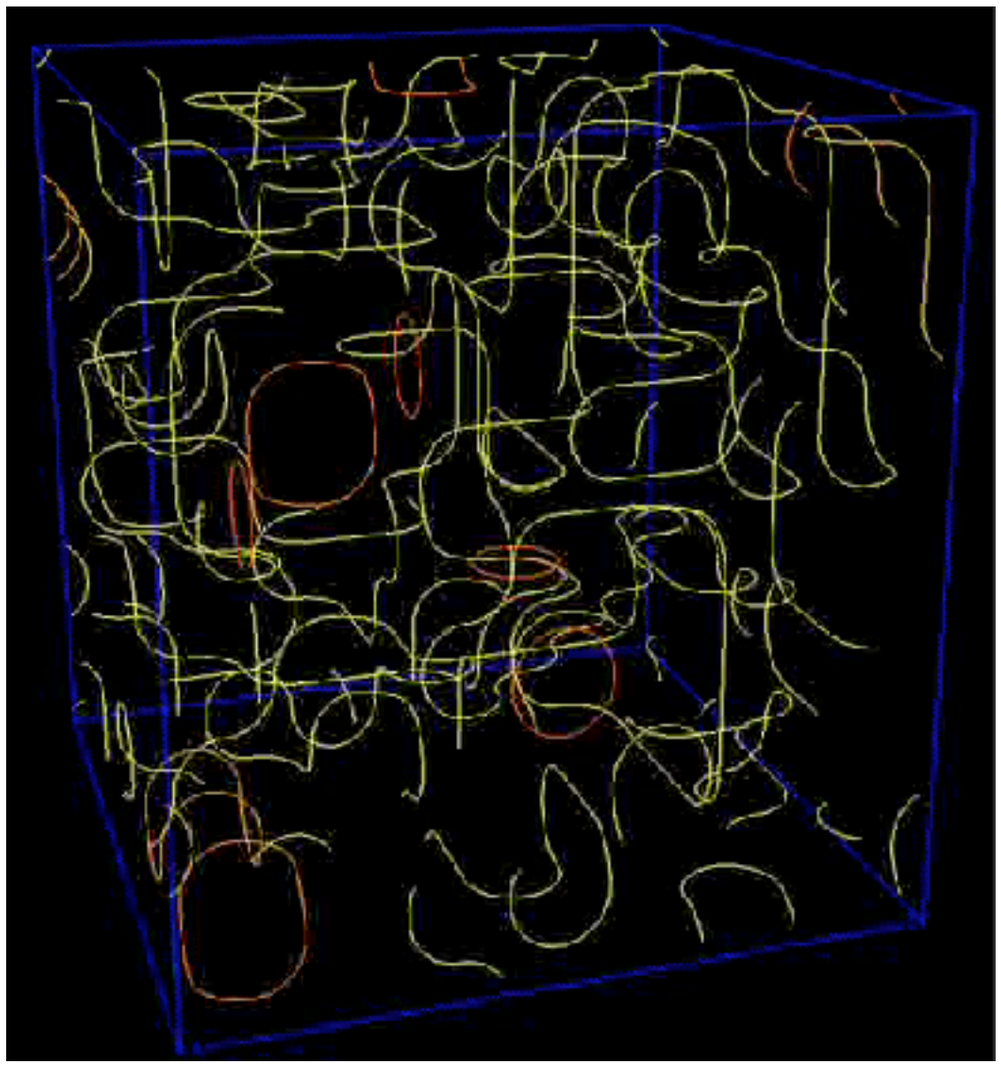
$$\frac{\rho_\infty}{\rho_{\rm bkg}} \propto G\mu$$

☞ "safe" to have stable cosmic strings!
(unlike domain walls, monopoles…)

How does a string network look like

- Per horizon volume:
  O(1) horizon size long strings + copious string loops

—requires dedicated numerical simulations



Simulation of a cosmic string network. Long strings are represented in yellow and cosmic string loops are shown in red.
© Cambridge cosmology group

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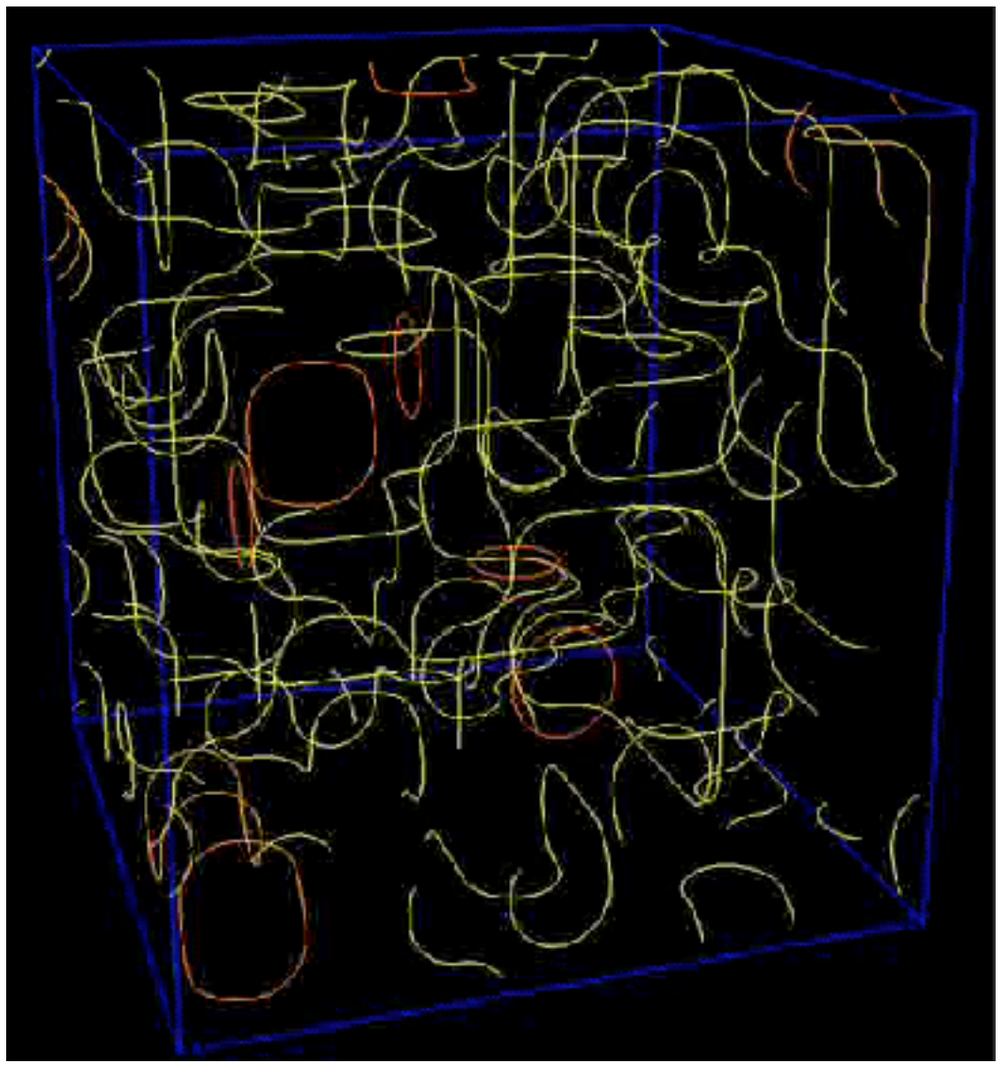

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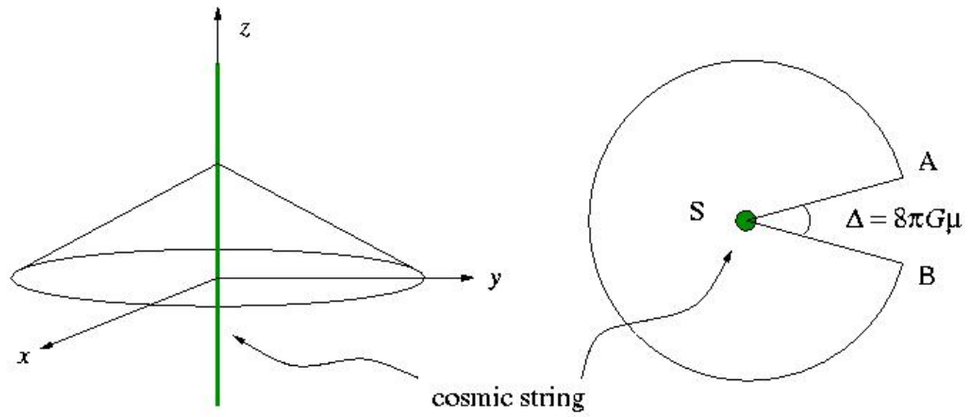
© Cambridge cosmology group

Rich Phenomenology/Complementarity-1

- History: potentially provide primordial density perturbation for structure formation, CMB observation→inflation dominates; CMB constraint: $G\mu \lesssim 10^{-7}$

- Gravitational lensing: double image

conic space-time around a string: deficit angle $\Delta = 8\pi G\mu$



A, B: double images

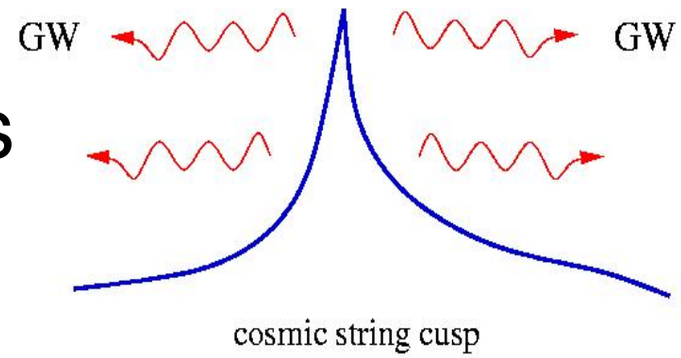
Potentially direct observational evidence: e.g. 2003 two seemingly identical galaxies very close together, 2005 found to be a pair of similar galaxies; double quasar Q0957+561A,B (1979); *future observations?…*

- Non-thermal production of matter from string decay: axions, gauge/Higgs fields, dark matter, cosmic ray…

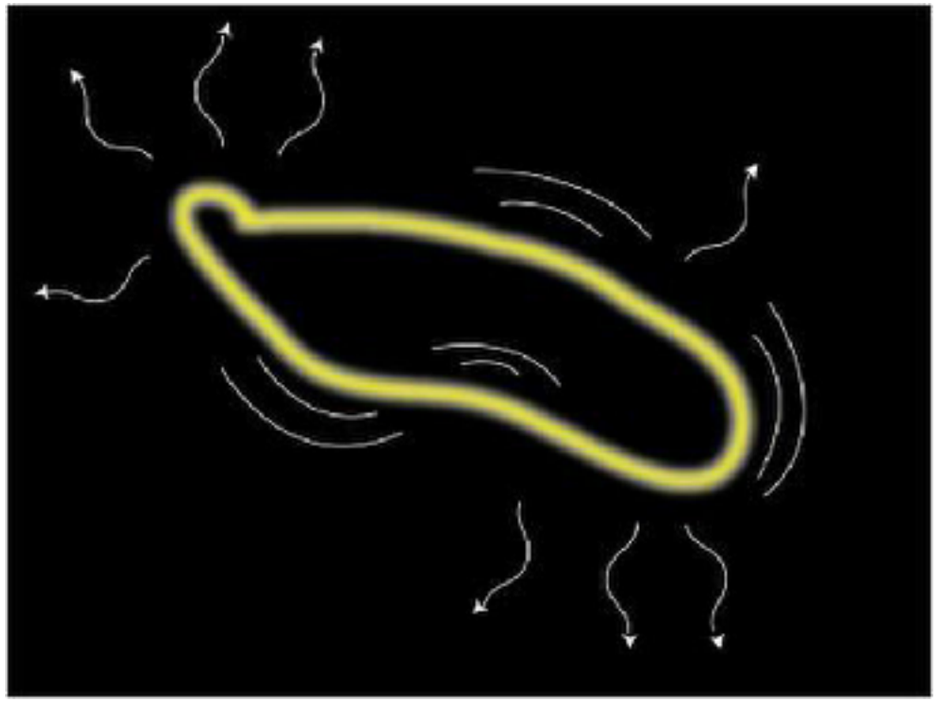
(e.g. YC w/Martin, Morrissey, Wells; YC w/Morrissey 2008; Vachaspati 2009; Long, Hyde, Vachaspati 2014, Long, Wang 2019…)

Rich Phenomenology/Complementarity-2

- **Gravitational waves emitted from oscillating string loops**
  - GW bursts from cusps on the loops



- Relic stochastic GW background: <u>continuous</u> emission throughout the string network history ★*(c.f. 1st order PT)*



Credit: Matt DePies/UW.

$\Longrightarrow$ spectrum spanning a <u>wide</u> frequency range

$$f \propto L^{-1}$$

$$dE/dt = \Gamma G \mu^2$$

$$(\Gamma \approx 50)$$

Stochastic GW Background from Cosmic Strings

- We use a simplified loop size distribution (at formation) justified by recent simulation results:

$$l_i = \alpha t_i, \quad \alpha \approx 0.1$$

- The loop formation rate per unit V per unit time (t):

$$n(l,t) = \frac{C_{\rm eff}(t_i)}{\alpha^2 t_i^4} \frac{a^3(t_i)}{a^3(t)}$$

- After its creation, each loop radiates GW energy at a constant rate:

$$\frac{dE}{dt} = -\Gamma G\mu^2, \quad \Gamma \approx 50$$

Stochastic GW Background from Cosmic Strings

- Consequently, the loop size decreases as

$$l = \alpha t_i - \Gamma G\mu \left(t - t_i\right)$$

- The observed GW frequency today from a loop of size l

$$f = \frac{a(\tilde{t})}{a(t_0)} \frac{2k}{l}$$

k=1 oscillation mode dominates

Stochastic GW Background from Cosmic Strings

Putting things together:

- **GW density per unit frequency seen today:**

$$\Omega_{GW}(f) = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} = \sum_k \Omega_{GW}^{(k)}(f)$$

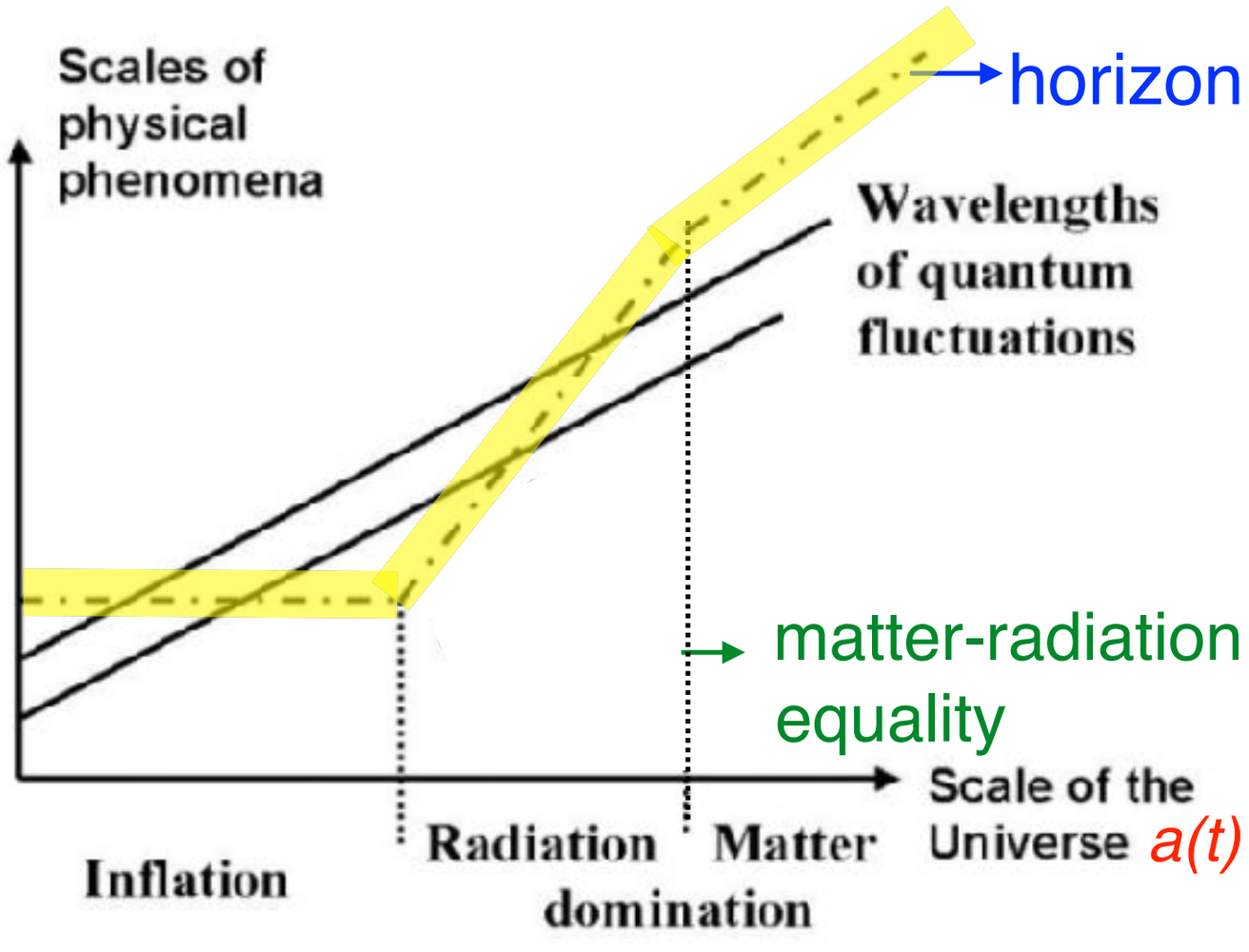
$$\Omega_{GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{(0.1)\,\Gamma_k G\mu^2}{\alpha(\alpha+\Gamma G\mu)} \times \int_{t_F}^{t_0} d\tilde{t}\ \frac{C_{eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \Theta(t_i - t_F)$$

expansion parameter

-Evolution of cosmic bkg (state equation) encoded in $a(\tilde{t})$!

A Brief Review of Standard Cosmology

- Standard cosmology:
  - Inflation (?)
  - Radiation domination (RD): primordial reheating (?) till T_{eq}~eV
  - Matter domination (MD): T_{eq}~eV till today (Λ)*(well tested ✔)*



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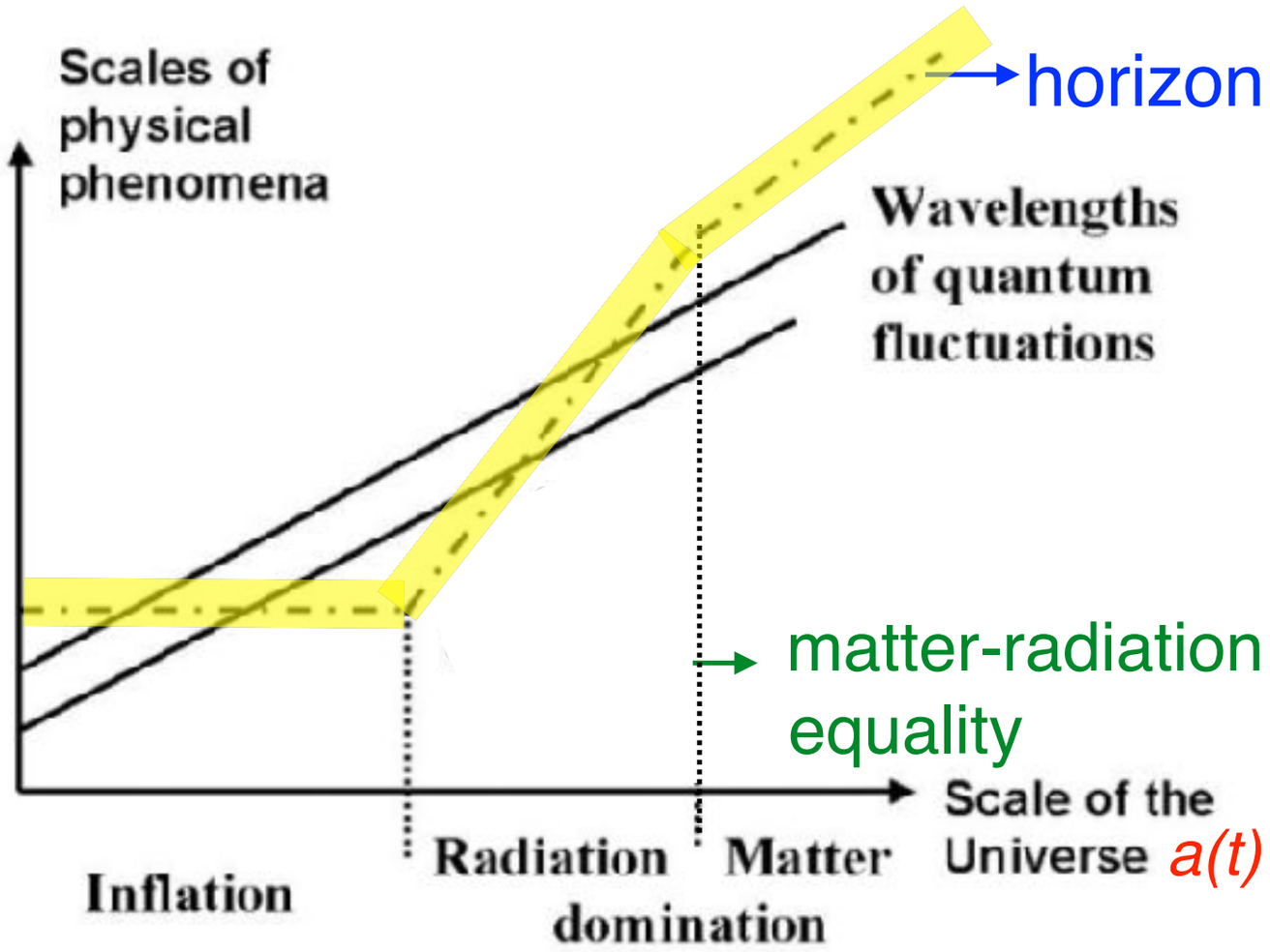

horizon size~H^{-1}

matter-radiation equality

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$H^2 \propto a^{-n}$$

$$(n = 3, 4 \text{ for MD, RD})$$

-Determined by the eq. of state of the dominating energy component

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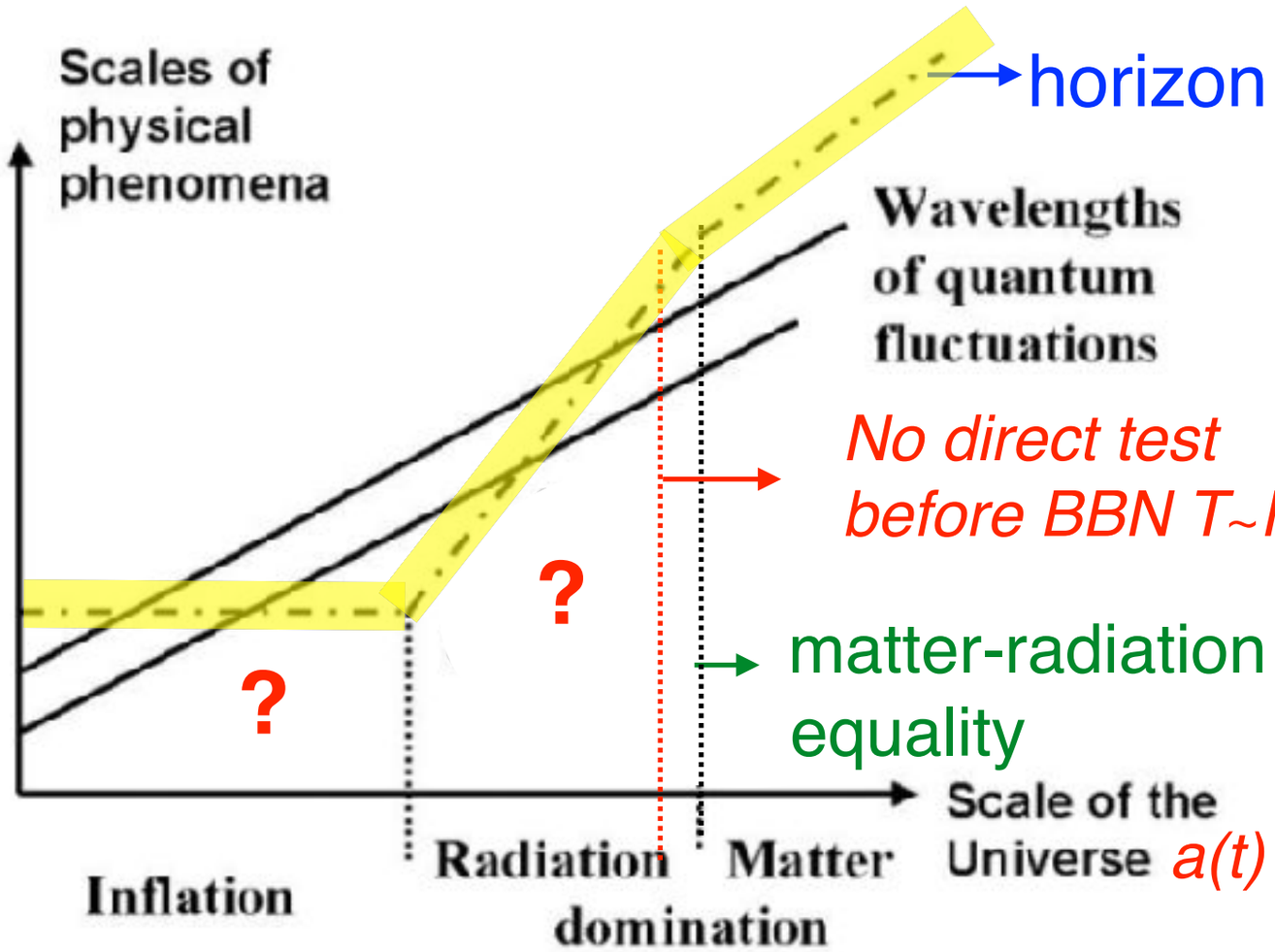

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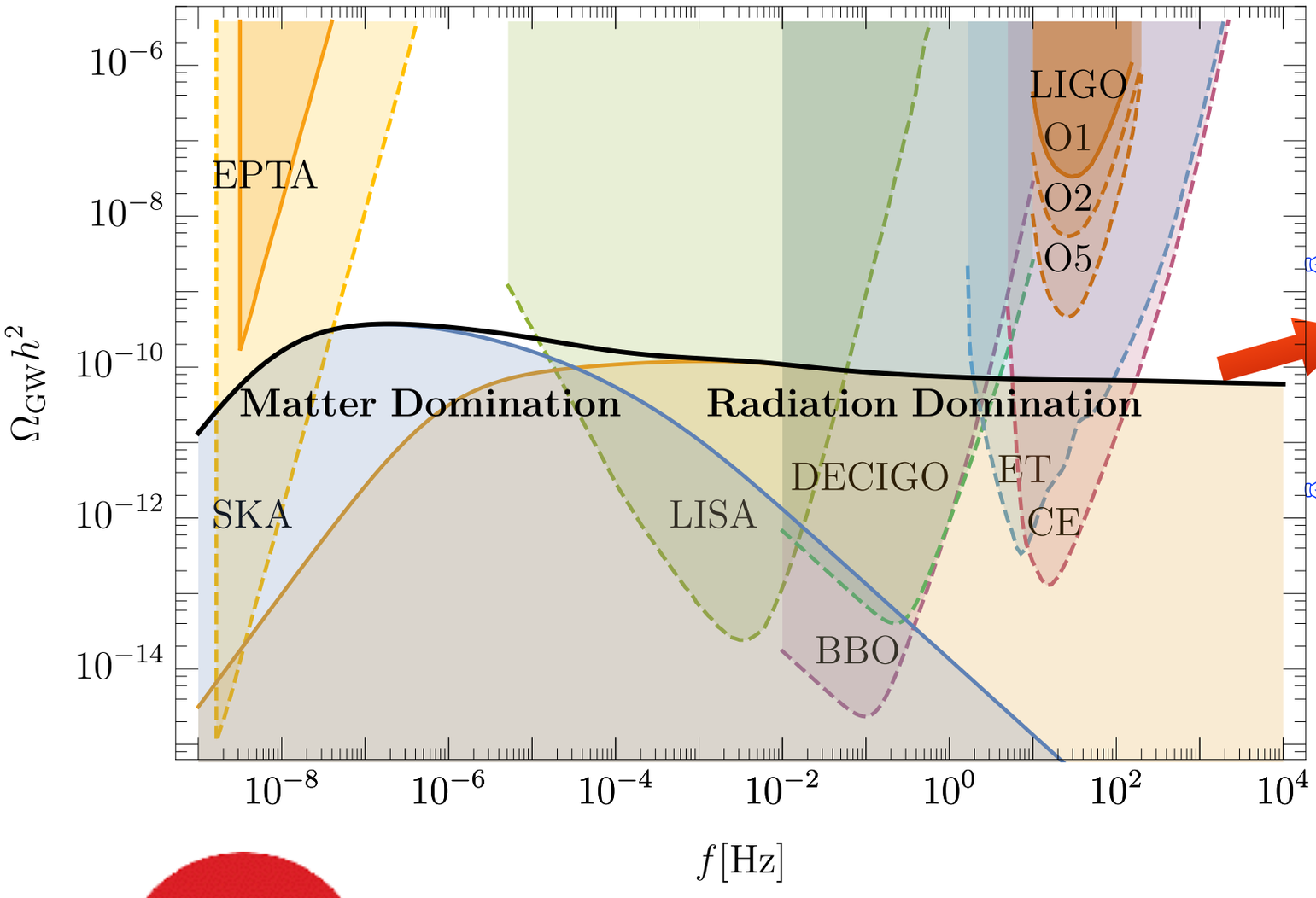
Testing Standard Cosmology w/GW Spectrum from Cosmic Strings

- An example: $G\mu = 2\times10^{-11}$, α=0.1 (in standard cosmology)



Features of the GW spectrum:

☞ A long (nearly) flat plateau: emission during RD epoch, *deviation could be easy to see!*

☞ GW with a given *f* was dominantly contributed by loops formed at a certain *t/T* (higher *f* ↔ earlier time)

(next slide…)

Looking back in time!

The GW Frequency-Time (Temperature) Correspondence

arxiv: 1711.03104, 1808.08968, YC with Lewicki, Morrissey and Wells

- Quantify/utilize the *f*-*T* correspondence

$$\text{GW frequency} \leftrightarrow \text{temperature}$$

GW with a given *f* was dominantly contributed by loops formed at a certain t/T

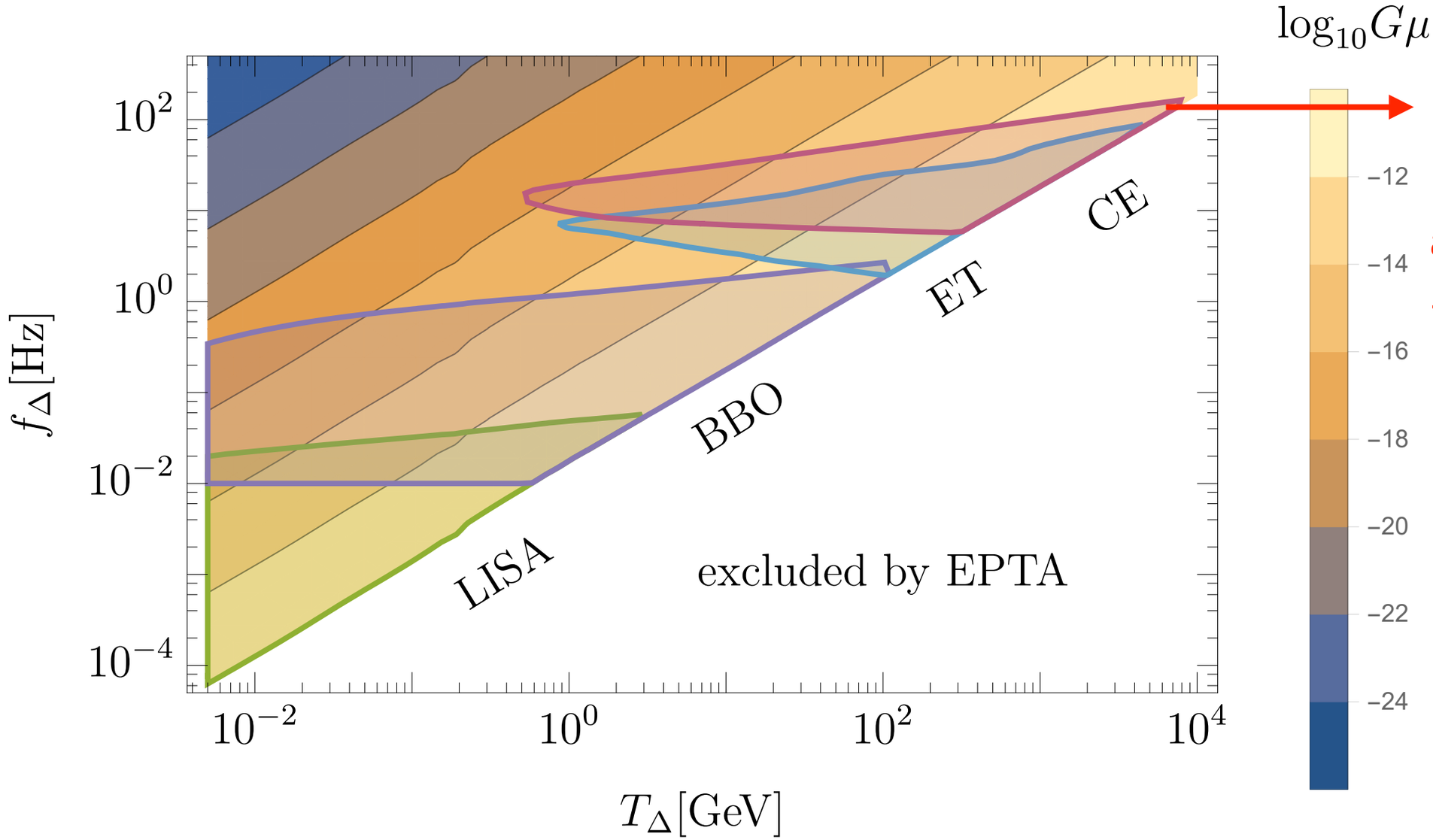
$$f_\Delta \simeq \sqrt{\frac{8}{z_{\rm eq}\alpha\,\Gamma G\mu}}\left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4}\left(\frac{T_\Delta}{T_0}\right)t_0^{-1}$$

Numerical fit:

$$f_\Delta = (8.67\times10^{-3}\,\text{Hz})\left(\frac{T_\Delta}{\text{GeV}}\right)\left(\frac{0.1\times50\times10^{-11}}{\alpha\,\Gamma G\mu}\right)^{1/2}\left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}}\left(\frac{g_{*S}(T_0)}{g_{*S}(T_\Delta)}\right)^{-\frac{7}{6}}$$

Experimental Detection Prospects

(f-T correspondence)



Sensitivity to T_Δ :
from BBN
all the way back to
~10^4 GeV !

- Fig.: f_Δ required to test the standard cosmology up to radiation T_Δ for a range of Gμ, α=0.1. Shaded regions: signal within detection sensitivity by the corresponding GW detector.

Probing New Phases in Cosmological Evolution

Probing New Phases in Cosmological Evolution

- Standard cosmology: the Universe is RD from T_{eq} all the way back to the end of inflation—**IS IT??**

  — often taken for granted, but no direct observational support for pre-BBN era! Important to test: re-assure or surprise…

- New cosmology are well motivated: *e.g.*
  - **Early matter-domination** (ends with a reheating phase): a long-lived massive particle, oscillation of a scalar field in ϕ^2 potential (moduli); e.g. SUSY, baryogenesis, the end of inflation…
  - **A "kination" period:** $n > 4$ in $H^2 \propto a^{-n}$, **a stiff component, redshifts faster than radiation!** e.g. oscillation of a scalar field in a non-renormalizable potential-quintessence models for DE/ inflation, axion model… $V(\phi) \propto \phi^N$, $n = 6N/(N+2)$

Rising interest recently: effects of EMD/kination on DM physics…

Probing New Phases in Cosmic History with Cosmic String GWs

- Consider a general cosmology: we assume the Universe dominated by a single component

$$H^2 \propto a^{-n} \qquad a(\tilde{t}) \propto \tilde{t}^{\frac{2}{n}}$$ ☞ parametrized by *n*

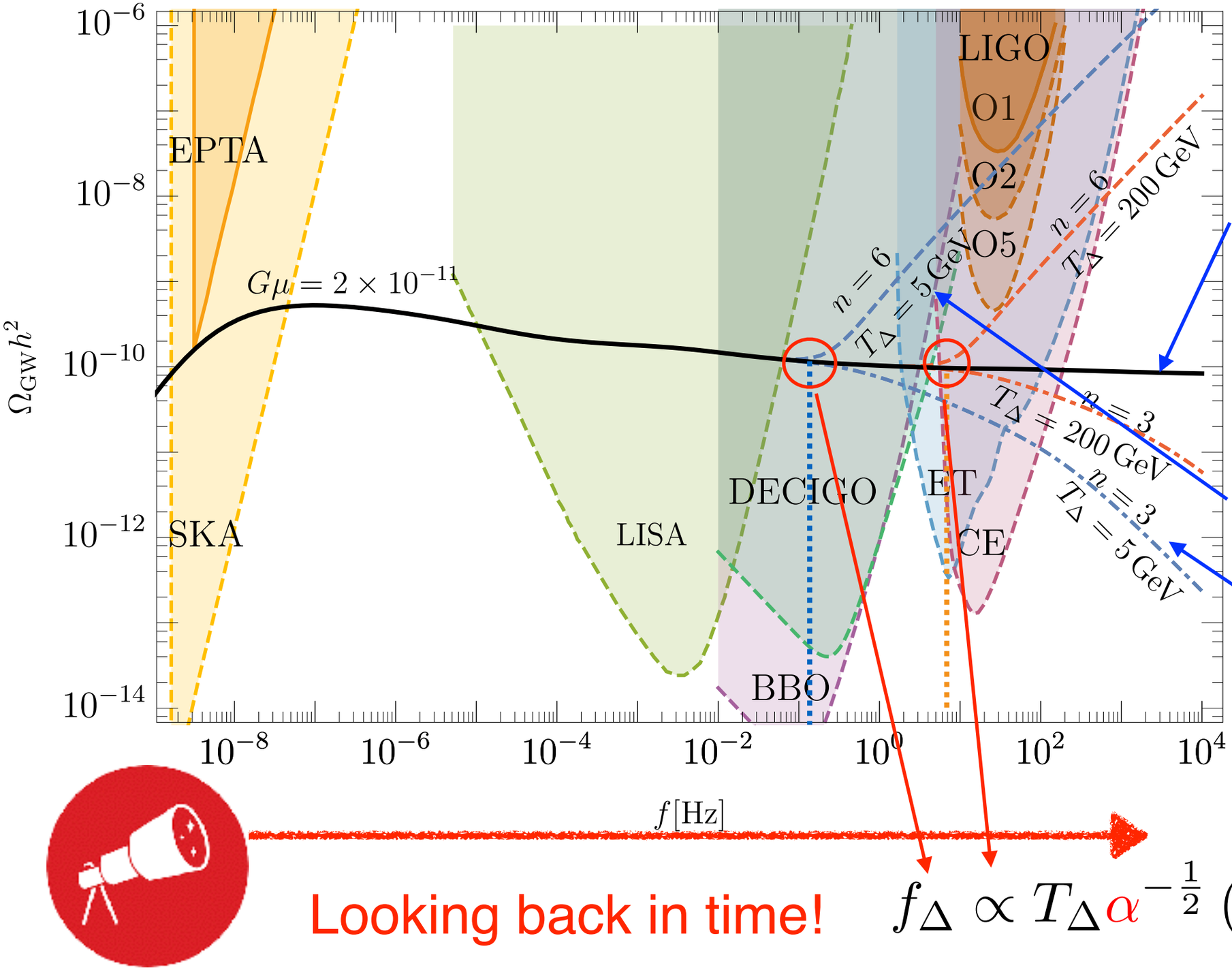
☞ $\Omega_{GW}(f) \propto \begin{cases} f^{\frac{8-2n}{2-n}} & n > 10/3 \\ f^{-1} & n \leq 10/3 \end{cases}$ *(at large f)*

n=4: RD flatness explained!

- GW spectrum with a departure from RD at t_Δ ? Model the transition:

$$\rho(t) = \begin{cases} \rho_{st}(t) & ; t \geq t_\Delta \\ \rho_{st}(t_\Delta) \left[\frac{a(t_\Delta)}{a(t)}\right]^n & ; t < t_\Delta \end{cases}$$

Probing New Phases in Cosmic History with Cosmic String GWs



$\alpha = 10^{-1}$

- n=4: RD (standard, flat)

Assume a transition at T_Δ = 5, 200 GeV:

- n=6: kination (rise)
- n=3: early MD (fall)

☞*Dramatic departure from RD flatness!*

Looking back in time!

$$f_\Delta \propto T_\Delta \alpha^{-\frac{1}{2}} (G\mu)^{-\frac{1}{2}}$$

Probing New (Massive) Degrees of Freedom

Probing New (Massive) Degrees of Freedom with Cosmic String GWs

- Additional d.o.f's: ubiquitous in BSM theories, maybe hundreds of them!*(DM, SUSY, RS, hidden valley, twin Higgs, clockwork, NNaturalness…)*
- Massive d.o.f's: in form of radiation in the early Universe (g_*), beyond the reach of CMB (ΔN_{eff}) or LHC

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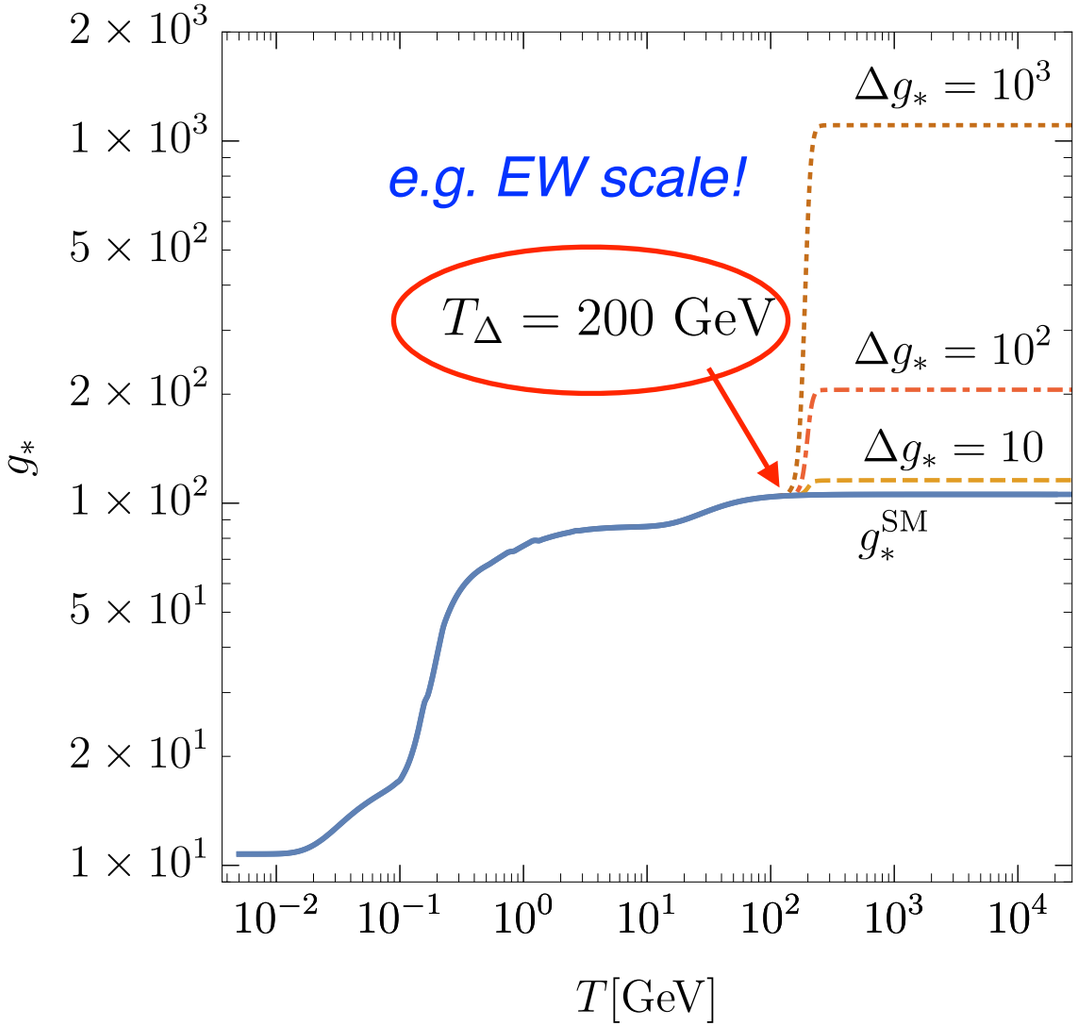

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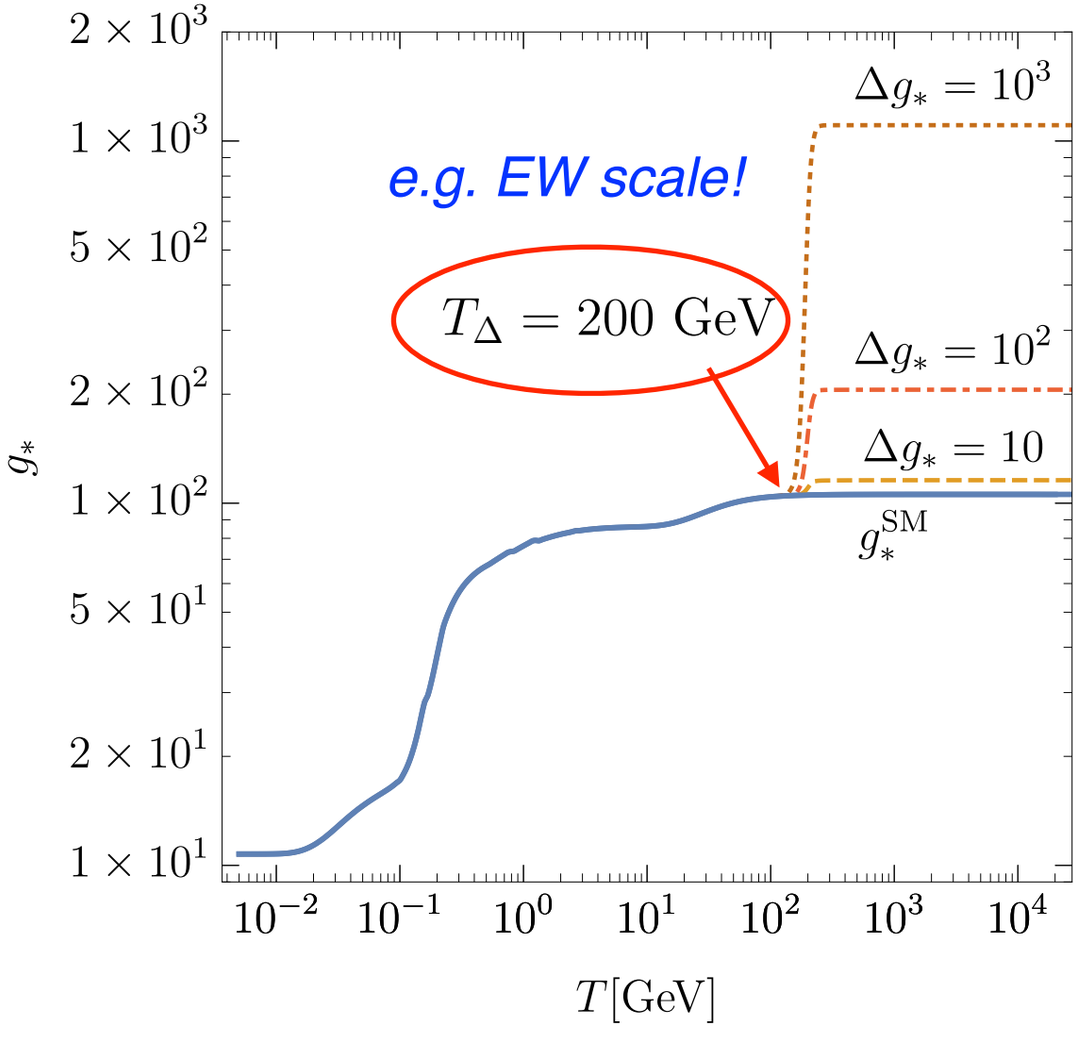


Friedman equation:

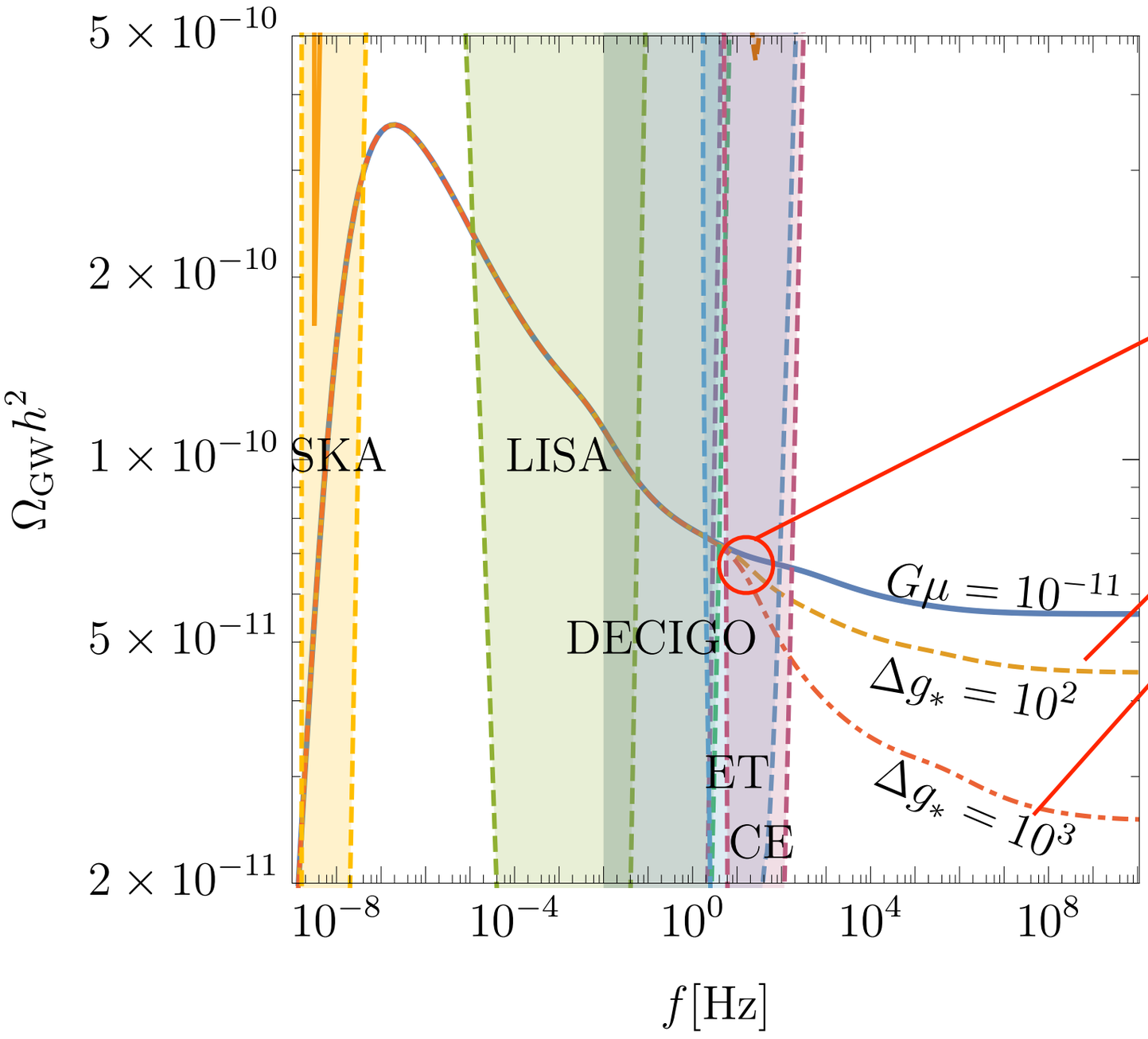
$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2 \left[\Delta_R(a)\,\Omega_R \left(\frac{a}{a_0}\right)^{-4} + \Omega_M \left(\frac{a}{a_0}\right)^{-3} + \Omega_\Lambda\right]$$

dominates in RD era

$$\Delta_R(a) = \frac{g_*(a)}{g_*(a_0)} \left(\frac{g_{*S}(a_0)}{g_{*S}(a)}\right)^{4/3}$$

—the source of g_* dependence

Probing New (Massive) Degrees of Freedom with Cosmic String GWs



- Falling spectrum starting $f_\Delta(T_\Delta)$

$\Longrightarrow$ a lowered new RD plateau

$$\Omega_{\rm GW}^{\Delta g_*}(f) \approx \Omega_{\rm GW}^{\rm SM}(f) \left(\frac{g_*^{\rm SM}}{g_*^{\rm SM} + \Delta g_*} \right)^{\frac{1}{3}} \quad (f > f_\Delta)$$

Novel Probes of ALP DM Models with GWs from Axion Topological Defects

(work in prep with Chia-Feng Chang)

— An interesting twist when switch gear to a global U(1)…

Novel Probes of ALP DM Models with GWs from Axion Topological Defects

- Axion-like particle (ALP) DM: ultra-light (pseudo-)goldstone boson from a global $U(1)_{PQ}$ breaking, leading alternative to WIMP paradigm, a lot of interest/effort recently; QCD axion, generic (hidden) ALPs also motivated *(e.g. string axiverse)*

- **A relatively under-developed aspect of ALP studies:** implication of <u>ALP topological defects</u>

ALP cosmic strings/domain walls: indispensable companion of ALP particles for $U(1)_{PQ}$ breaking after inflation, independent of ALP-SM interaction

☞ Can significantly affect Ω_{DM} prediction + potential new probes

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- *A natural inspiration from the gauge string story:*

GW signature from axion cosmic strings?

(complementary, could be the smoking gun for "hidden" ALPs…)

Novel Probes of ALP DM Models with GWs from Axion Topological Defects

- GW signature from global/axion cosmic strings: an overlooked, yet potentially important discovery channel

— *Why Overlooked? "too small" by naive estimate*

Sub-dominant relative to goldstone emission:

$$P_{\rm GW} \sim \Gamma G\mu^2 \ll P_g \sim \Gamma_g \eta^2,$$

$\mu \sim \eta^2 \log(L/\delta)$ correlation length: $L \sim H^{-1}$, string core width: $\delta \sim \eta^{-1}$

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- BUT: rare decay mode can be discovery mode! (e.g. Higgs discovery, axion/goldstone search strategy model dependent…)

  + GW detector sensitivity will keep improving…

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- The effect of pre-BBN cosmology? OR: probe pre-BBN universe with GW spectrum from axion strings? *(non-standard cosmology and axion DM: Poulin, Smith, Grin, Kawal, Kamionkowski arxiv:1806.10608, A. Nelson and Xiao arxiv: 1807.07176)*

Novel Probes of ALP DM Models with GWs from Axion Topological Defects

(work in prep with Chia-Feng Chang)

- **Challenges:**
  - Very limited literature: even for pure global U(1)
    (GW spectrum from global strings: Battye and Shellard 1996, needs update!)
  - More complex for axion strings: cosmic strings + domain walls
  - Ongoing development of global string simulation

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- **Our ongoing study: global→QCD axion→ALPs**

  - Preliminary result (global)
    small, but observable!
  - Also advance understanding of
    Ω_{DM} due to topological defects

Discussion:
Confronting Detection Challenges

- **Astrophysical foreground**

  (With assumptions) LIGO expect to detect stochastic GW bkg from unresolved binary mergers (peak: $\Omega \sim 10^{-9}$ *at* $f \sim 10^{3}$ *Hz*), possibly overwhelm primordial signals…

  Solutions:

  - Optimized statistical strategy to identify/subtract astro bkg @ LIGO *(arXiv:1712.00688)*
  - Improved resolution to resolve/remove astro bkg with future detectors (@ LISA, ET/CE, BBO) → down to $\Omega \sim 10^{-13}$ or even better

    — Important newly developing research area!

    (Analogy: CMB foreground removal, DM indirect detection)

Discussion:
Confronting Detection Challenges

Work in progress with Barry Barish and Simeon Bird: distinguish cosmogenic/primordial sources stochastic GW background from astro-foreground…

- **Distinguish from other primordial GW sources**
  - Characteristic flat plateau at high *f*, difficult to mimic by most other sources (e.g. GW from 1st order PT has peaky structure—split power law)
  - Exception: GW from minimal inflation has a RD flat plateau, BUT much smaller amplitude, rising at low *f*

Conclusion

- **Cosmic strings:** generically motivated (U(1) breaking, axion, superstring…); a strong, well-understood source of GWs that can serve as a "standard candle" for probing very early Universe

  — a unique and powerful tool for **reconstructing a timeline for pre-BBN cosmic history** *(the f-T correspondence)*

- In principle we could probe the expansion rate of the Universe even above $T \sim 10^4$ *GeV* using GW from cosmic strings!
  - Probe new phases (eq. of state) of early Universe
  - Probe (massive) BSM d.o.f's using GW *(beyond CMB, LHC)*

- GWs from axion strings/domain walls may be the **smoking gun** for dark matter…

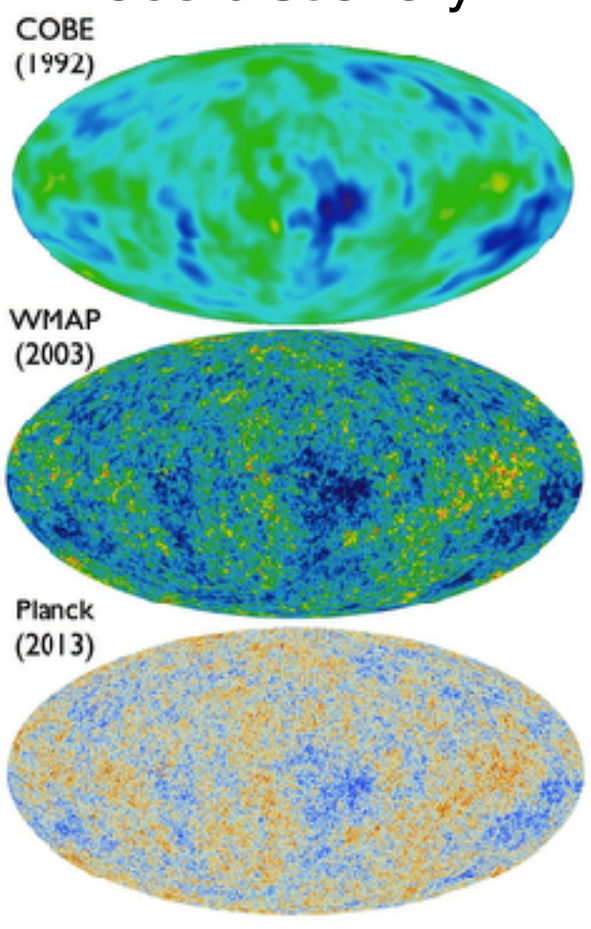
Outlook

Beyond cosmic strings:

An inspirational benchmark for exploiting the full potential of GW as a new tool for probing particle physics and cosmology beyond the horizon of our current knowing

The history of CMB physics

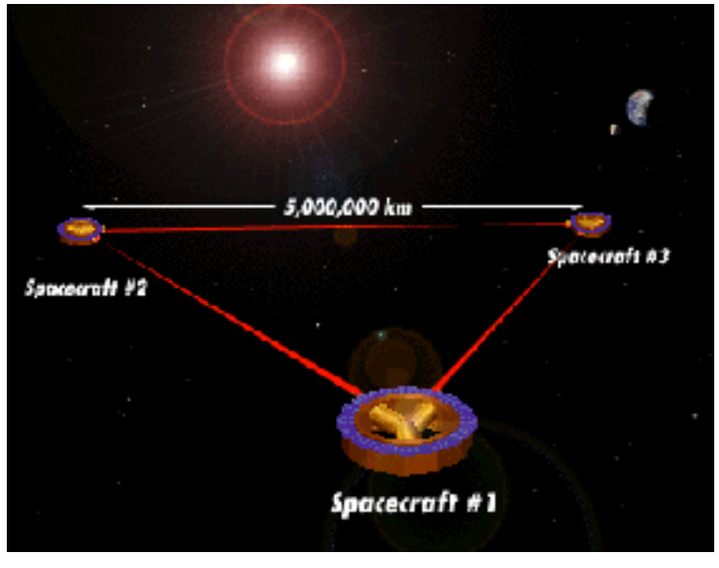
1965 discovery



CMB-S4 (2020's)

How far can GW take us?

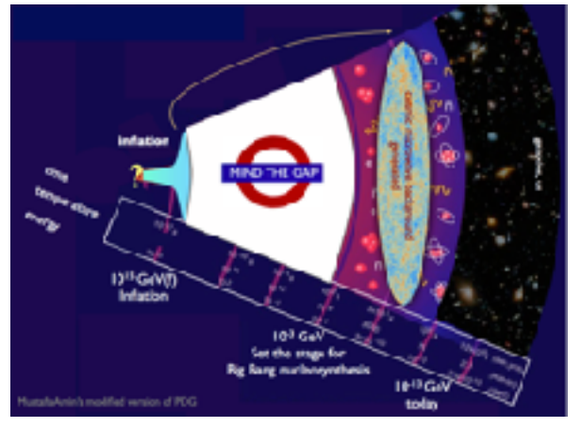
2016 LIGO discovery



Future GW experiments in sight: LISA, BBO, DECIGO, ET, CE, TianQin, Taiji…

KITP Program Jan 6-Mar 13 2020:

From Inflation to the Hot Big Bang



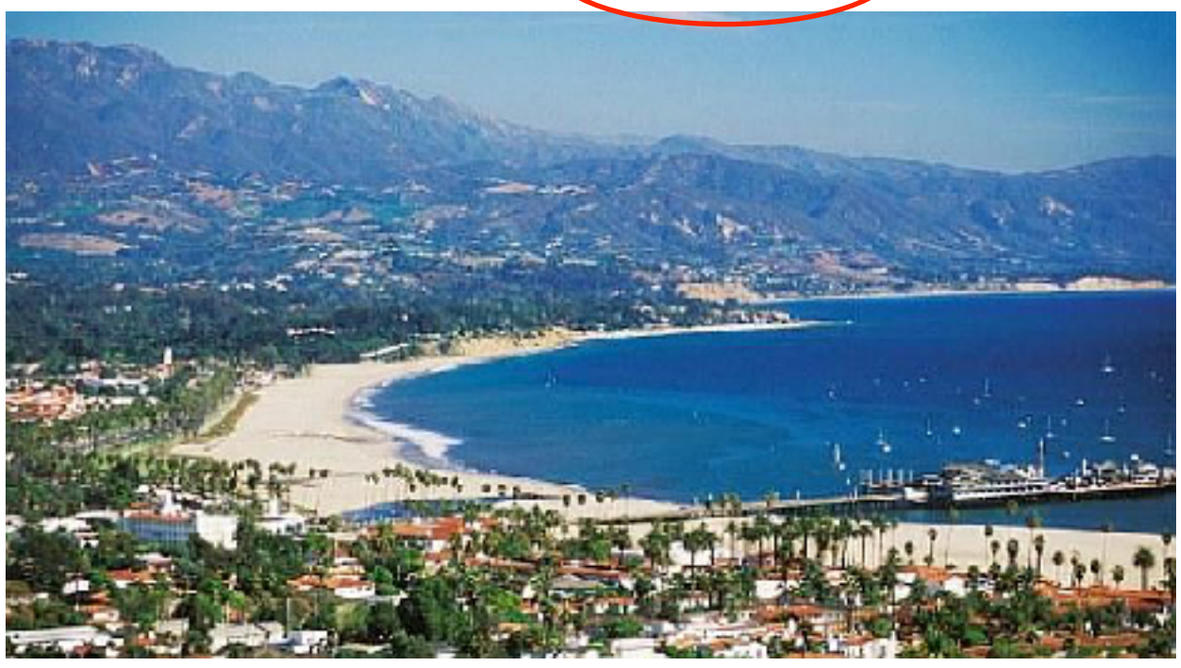
Coordinators: Peter Adshead, Yanou Cui, Raphael Flauger, and Scott Watson

Scientific Advisors: Robert Brandenberger, Andrei Linde, and Raman Sundrum

https://www.kitp.ucsb.edu/activities/inflation20, (waitlist…)

Associated conference: *https://www.kitp.ucsb.edu/activities/inflation-c20*

Feb 3-6 2020, registration deadline Jan 5 2020



HERE again, in winter…

Thank you!