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

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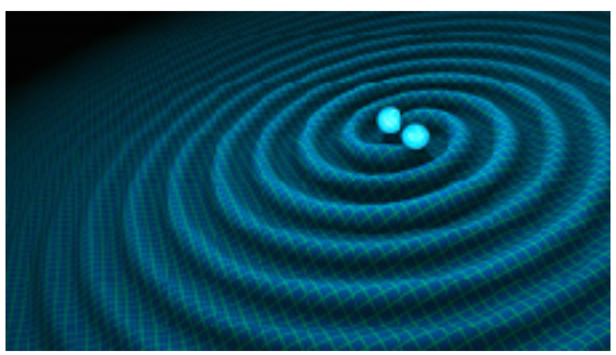
arxiv: 1711.03104 (PRD), 1808.08968

YC with Marek Lewicki, David Morrissey and James Wells

GGI BSM workshop, Sep 13, 2018

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?

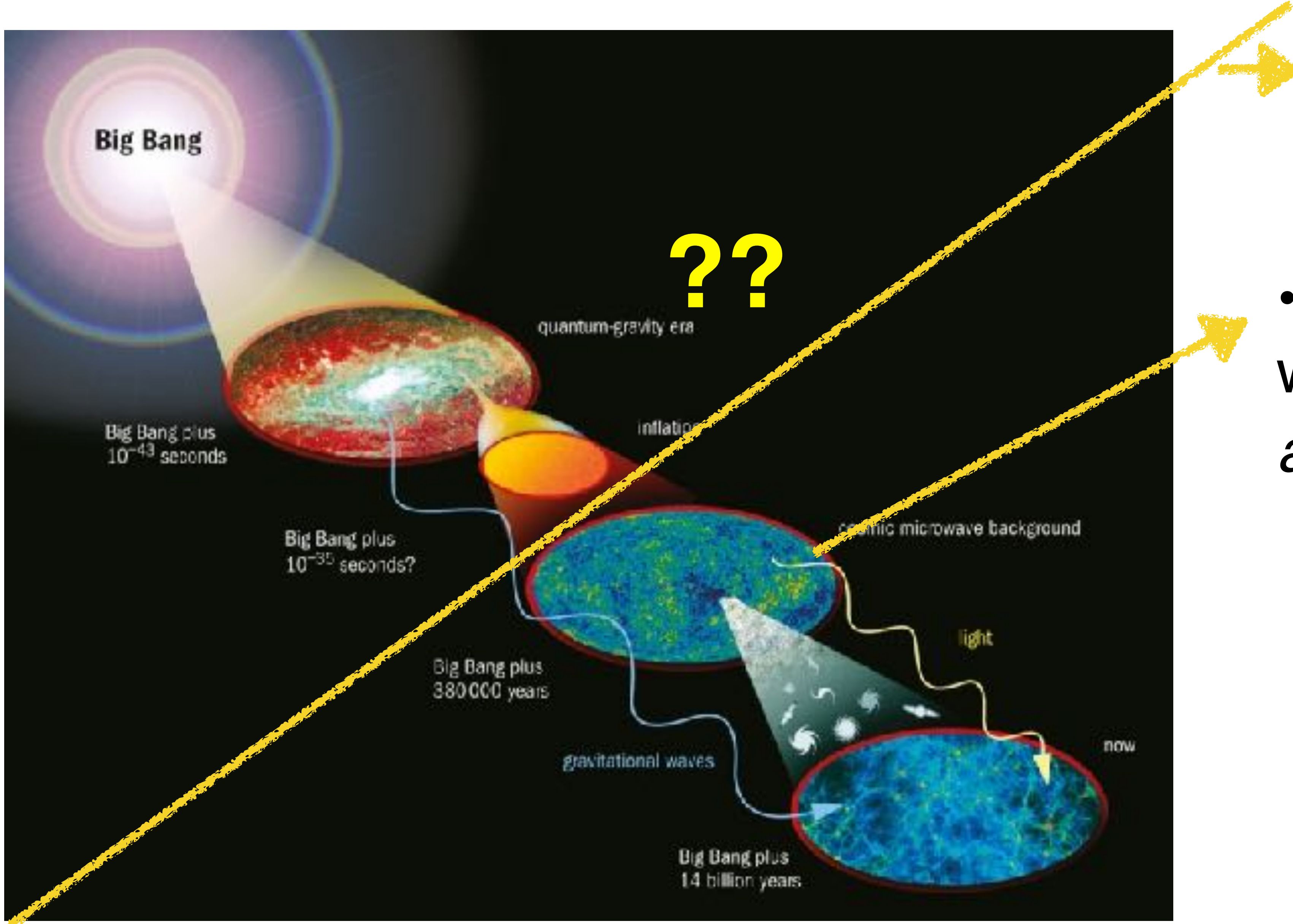
BSM Physics and GW
-what we know

- **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*', 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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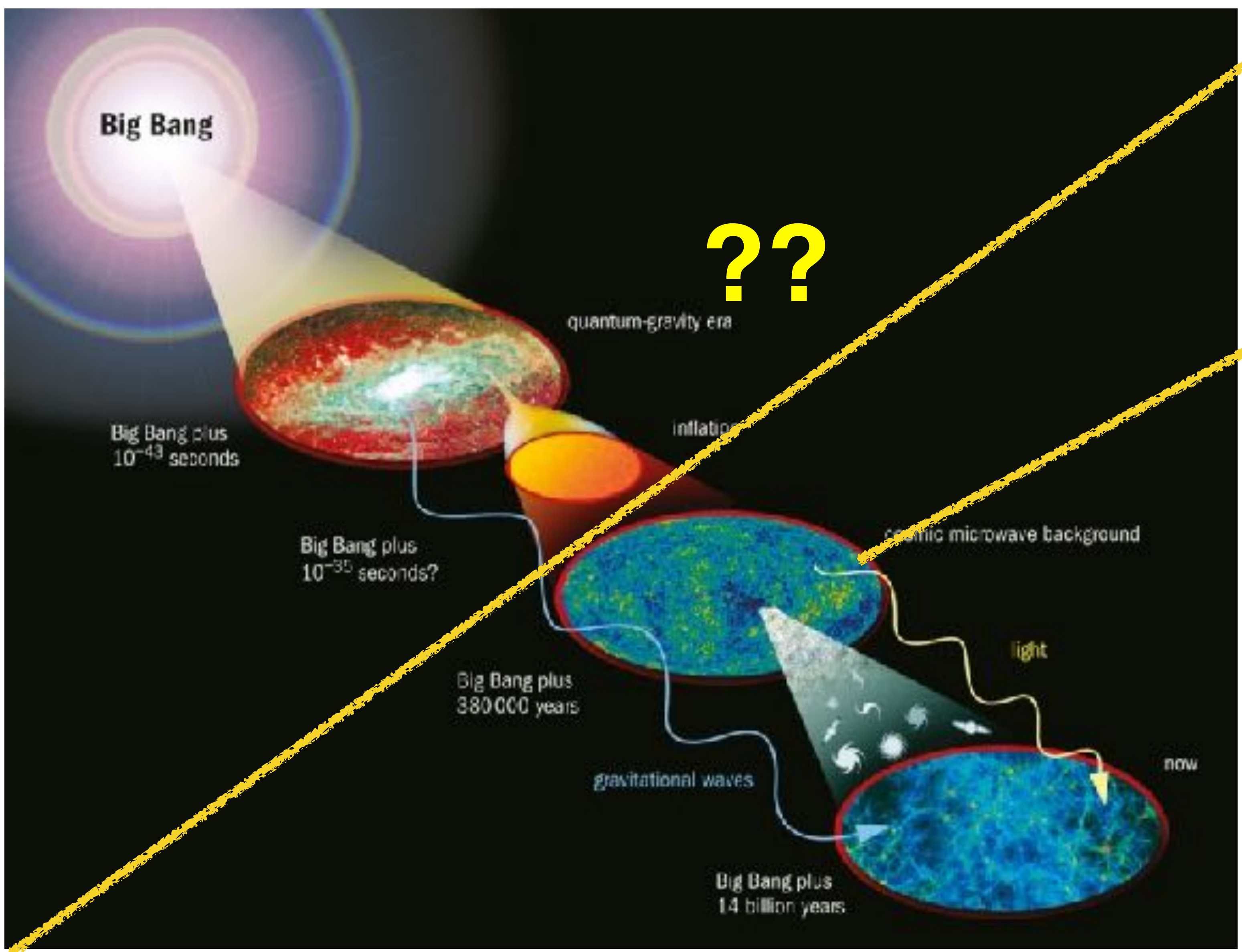


- **The horizon of confidence**: BBN
  (~1s-3 min after Big Bang)

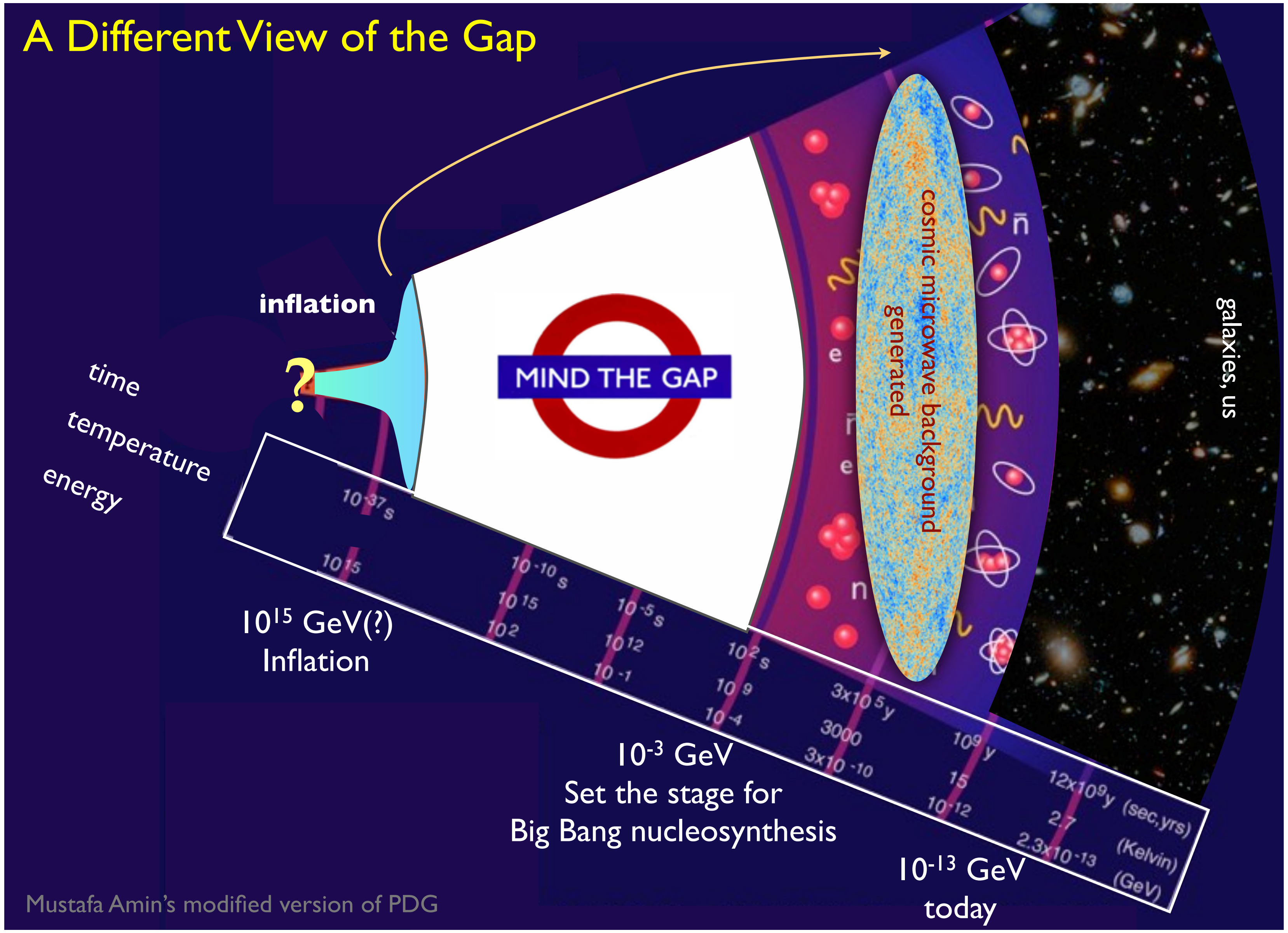
- CMB light: a direct window back to ~*400k yrs after the Big Bang*

- **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?

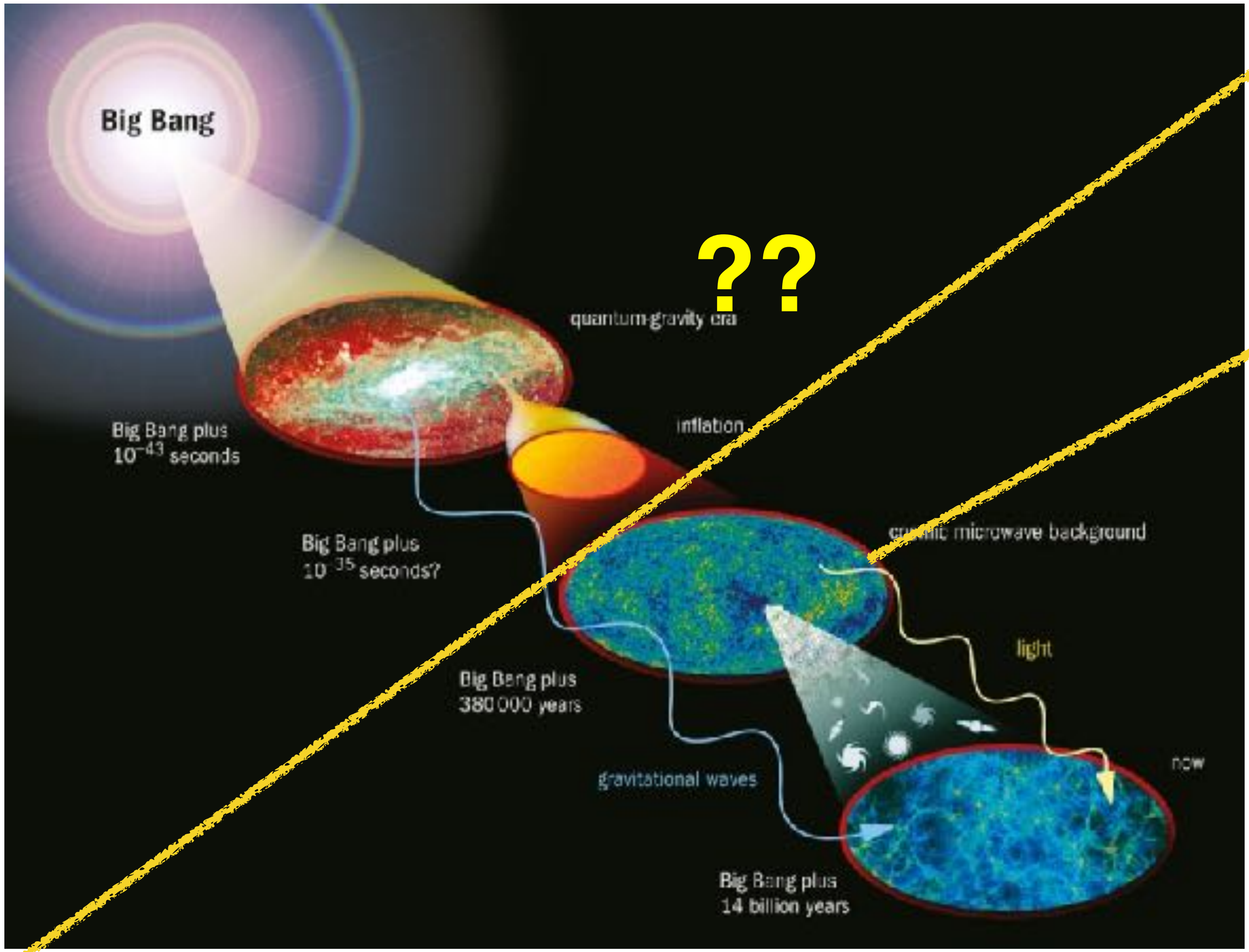
- the Primordial Dark Age

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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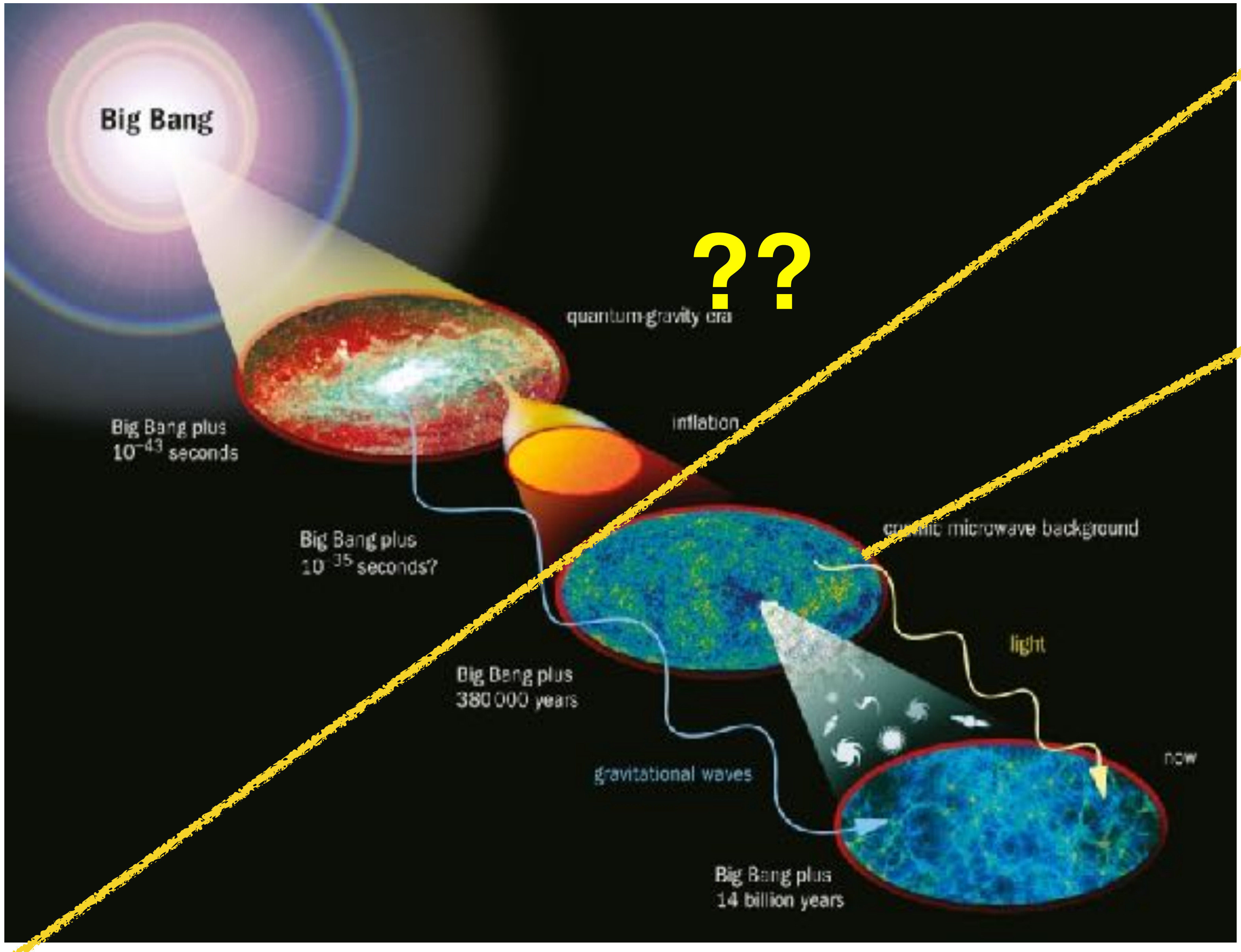

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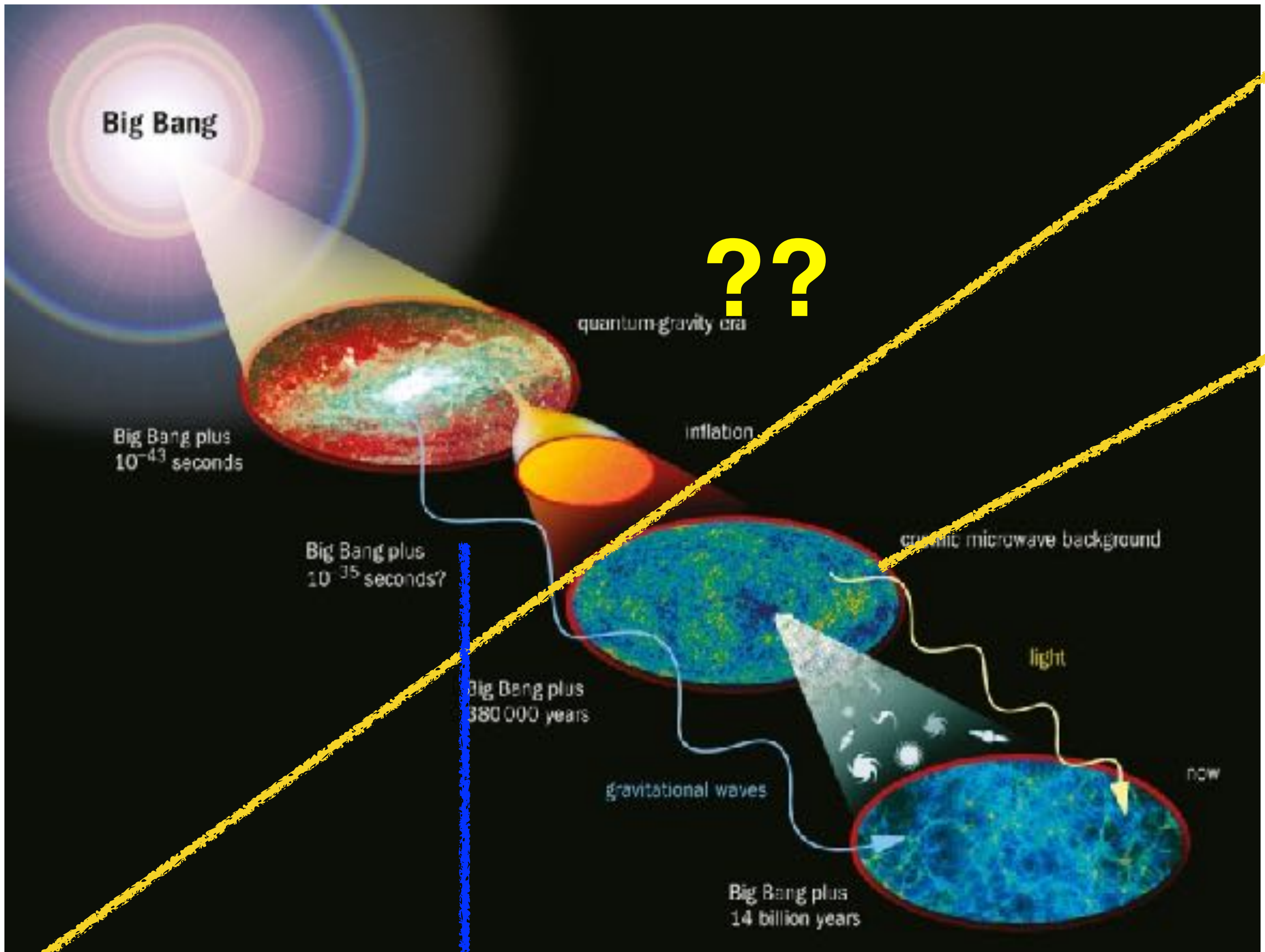
- **Direct observational probe?** most effort so far: inflation. **Thermal history?** *Mission impossible?*

Pre-BBN Cosmology

-what we do not "know"



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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
- Stochastic GW spectrum from cosmic strings (standard)
- Test of standard cosmology: The time-frequency correspondence in the CS GW spectrum
- Probe new phases of cosmic evolution *(eq. of state)*
- Probe new degrees of freedom *(beyond LHC, CMB ΔN_{eff}!)*
- Conclusion/Outlook

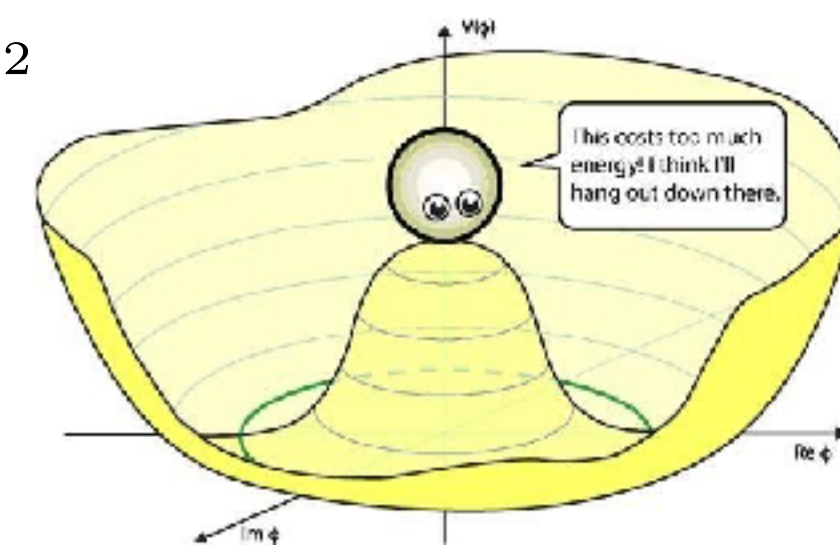
Cosmic Strings 101 (1)

- **What are Cosmic strings?**
  Stable one-dimensional topological defect, tension $\boldsymbol{\mu}$
- **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

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



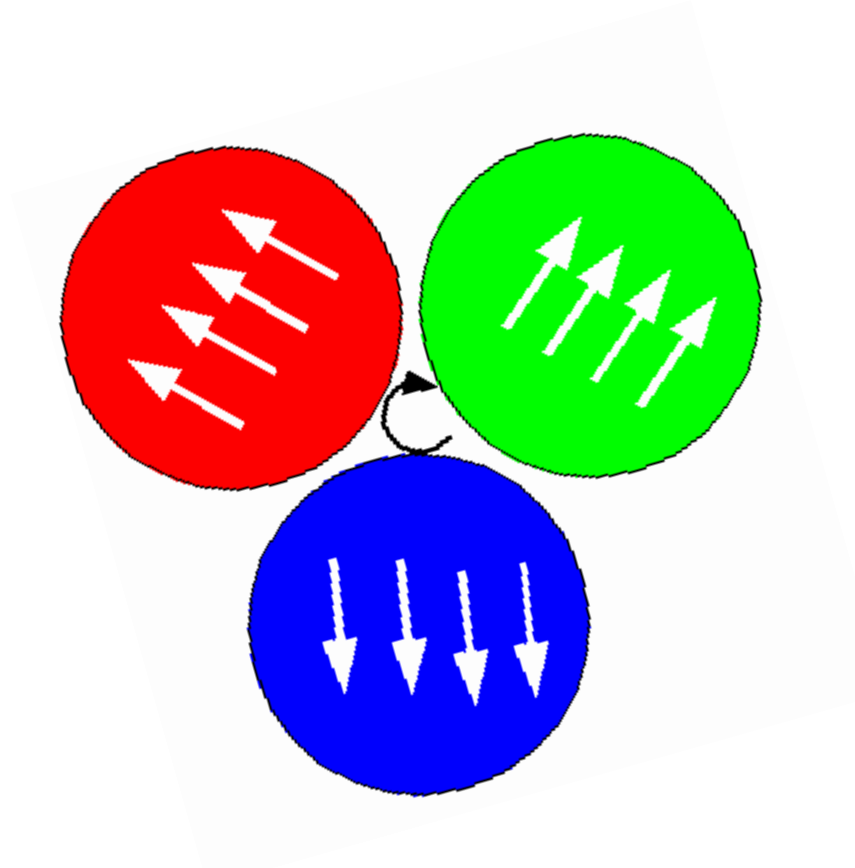
Cosmic Strings 101 (2)

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

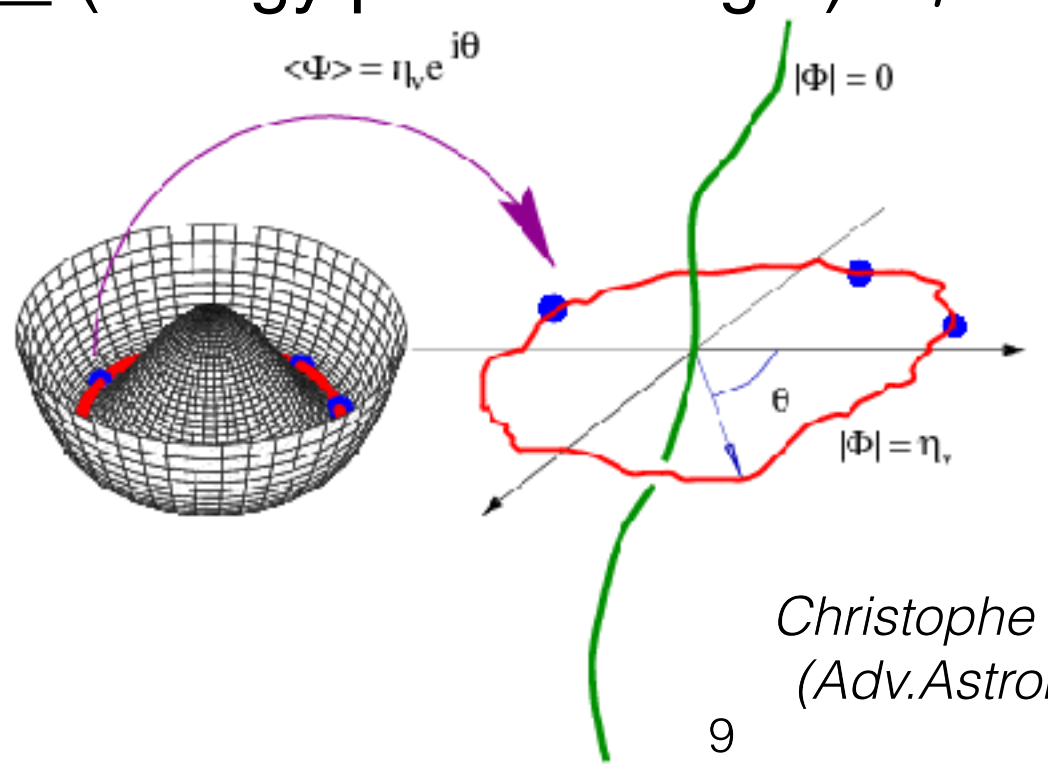
(position dependent, Nielsen and Olesen 1973;
vortex in type-II superconductor, Abrikosov 1957)

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

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



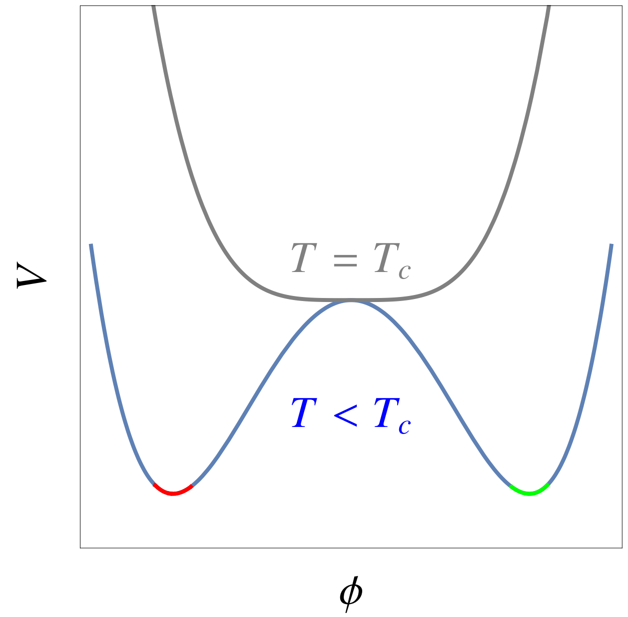
☞A tube of false vacuum (closed or infinite),
string <u>tension</u> (energy per unit length): $\mu \sim v^2$



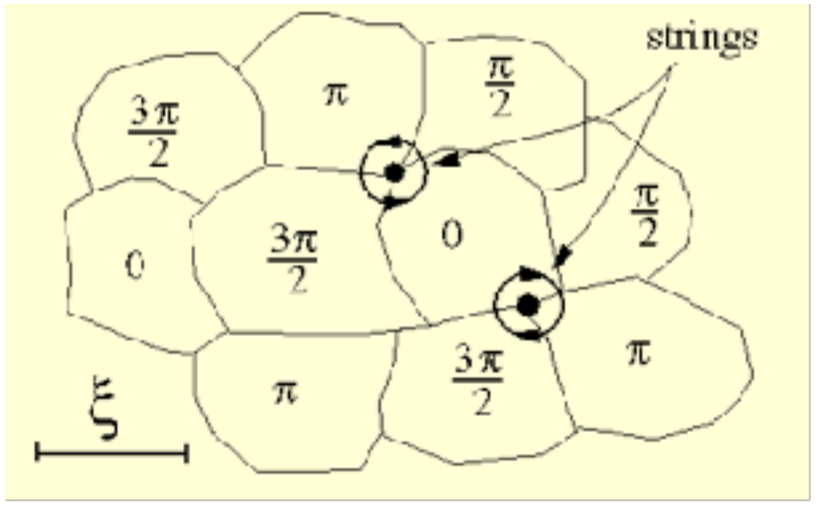
Christophe Ringeval (Adv.Astron. 2010)

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"

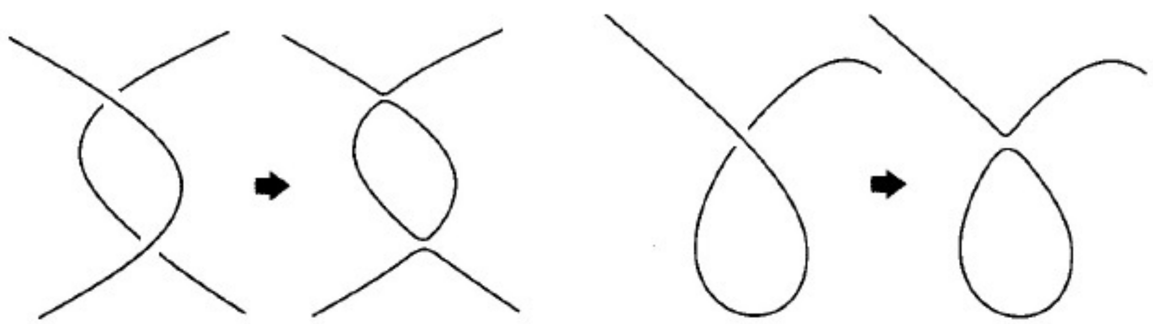


Evolution of Cosmic Strings

- 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) :

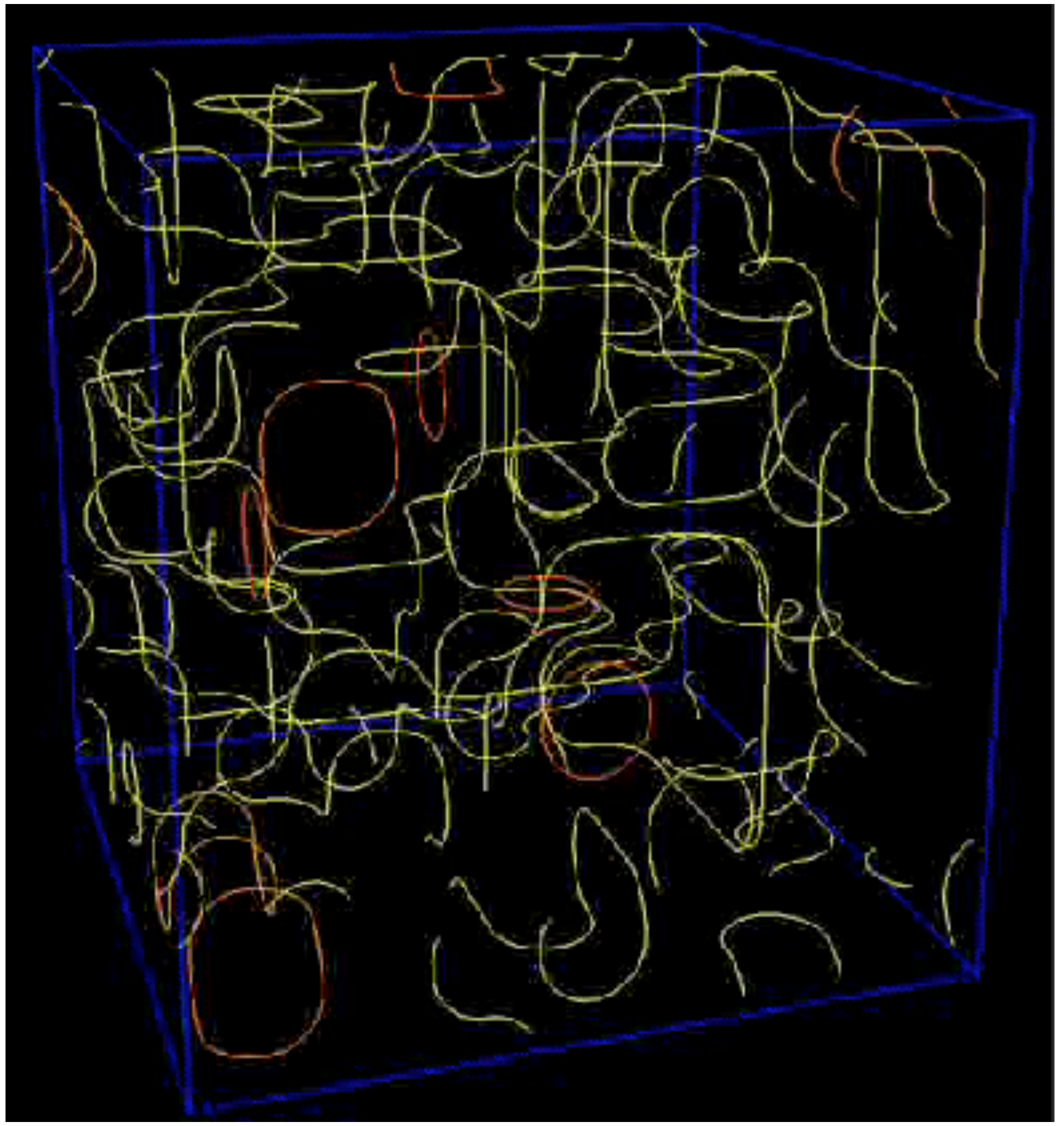
$$\frac{\rho_\infty}{\rho_{\rm bkg}} \propto G\mu$$

☞ “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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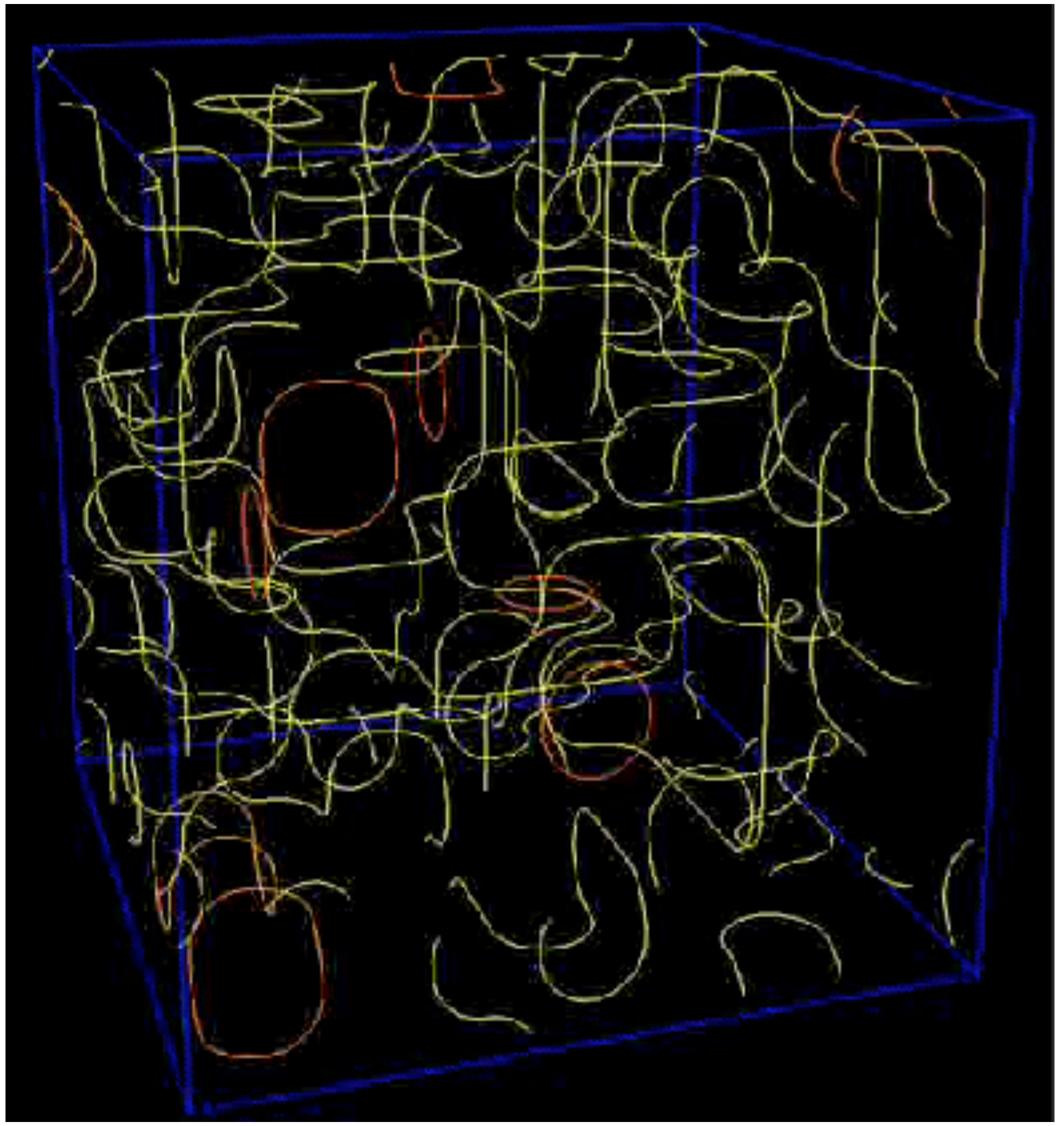

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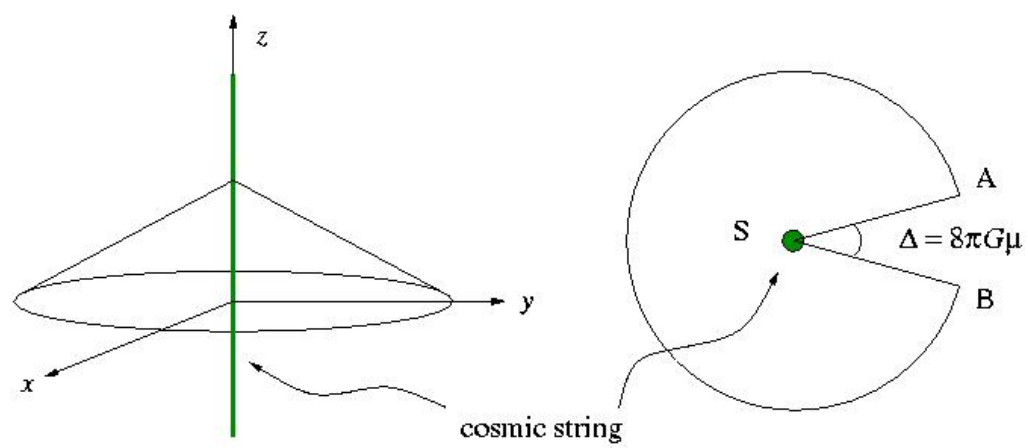
© Cambridge cosmology group

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 of galaxies

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



A, B: double images

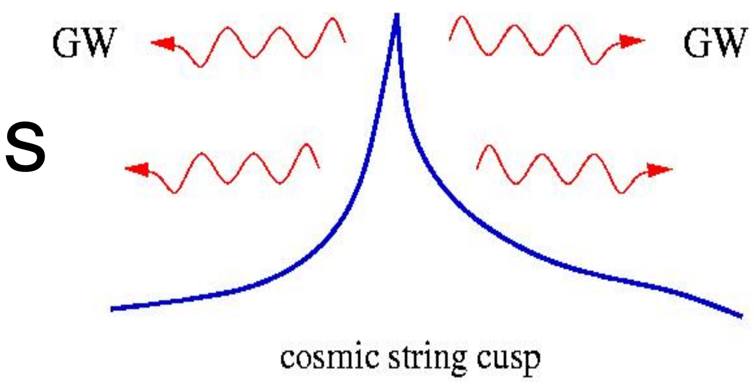
Potentially direct observational evidence: e.g. 2003 two seemingly identical galaxies very close together, 2005 found to be a pair of similar galaxies; *future observations?…*

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

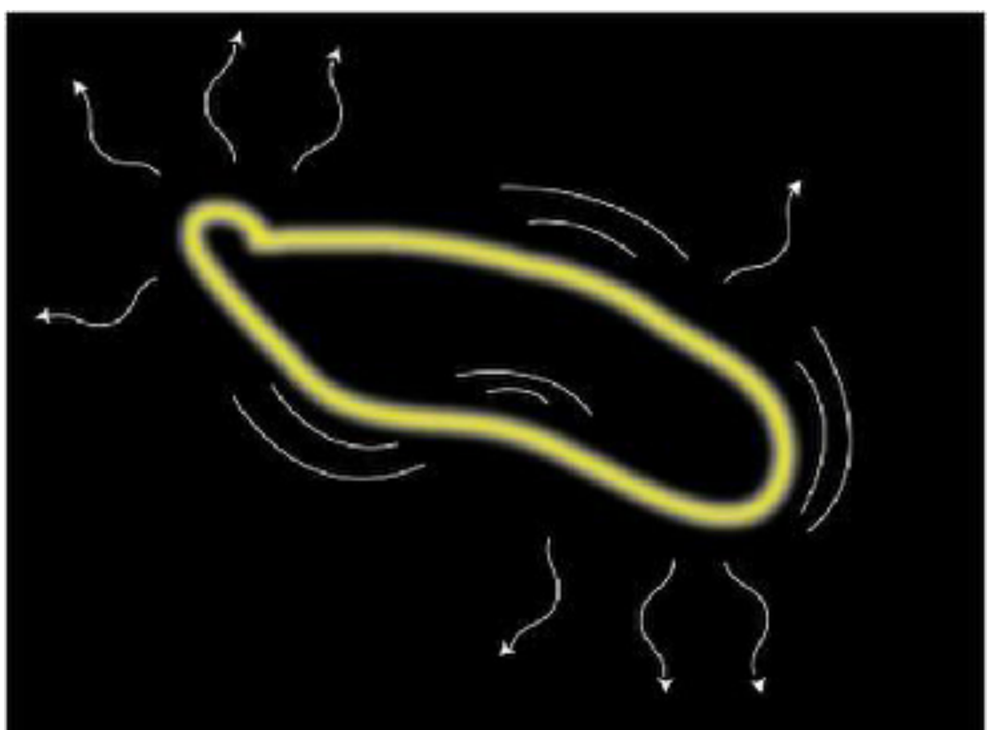
(e.g. YC w/Martin, Morrissey, Wells; YC with Morrissey 2008)

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.

⟹ 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):

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

- 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:**

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

expansion parameter

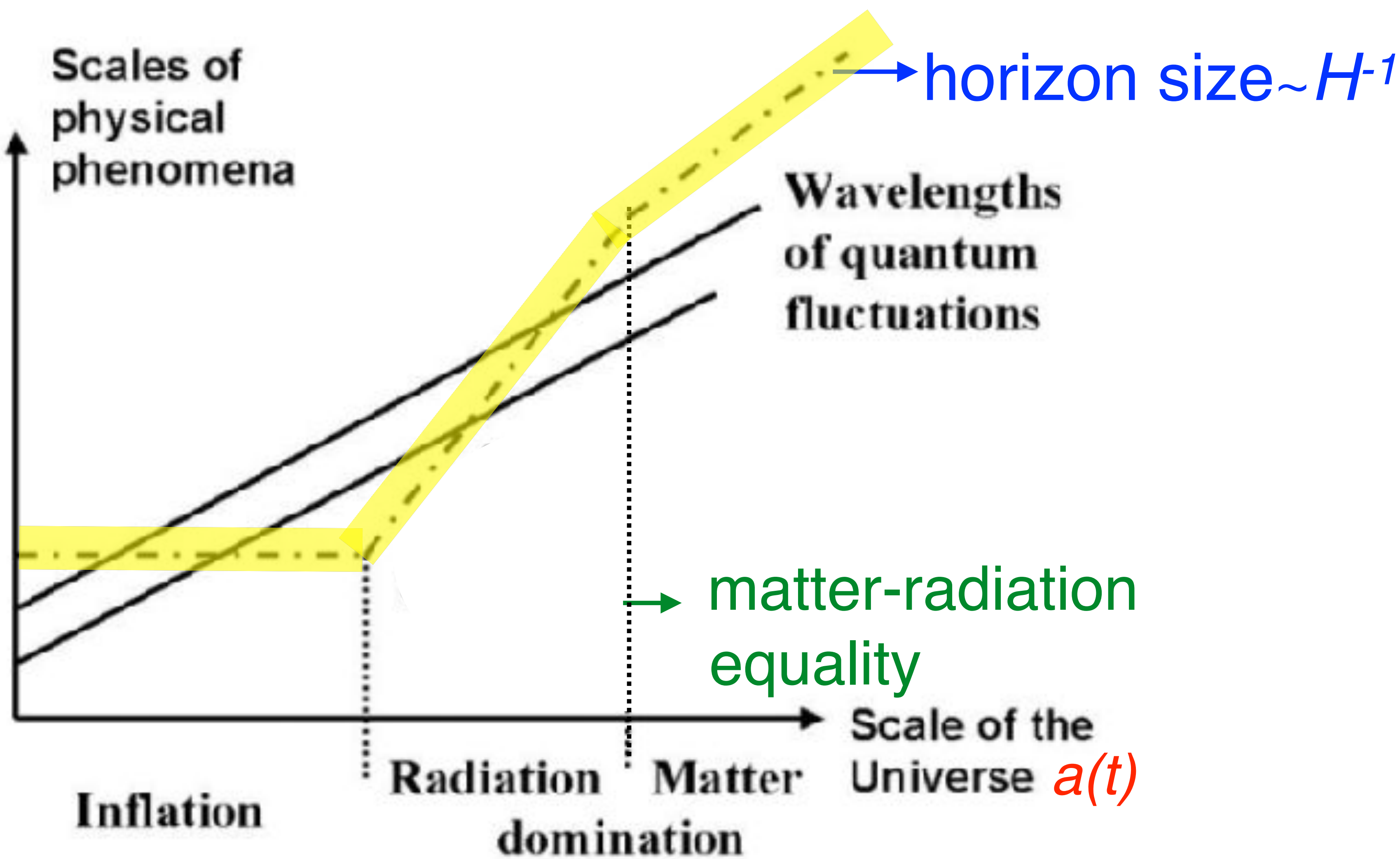
$$\Omega^{(k)}_{GW}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{(0.1)\,\Gamma_k G\mu^2}{\alpha(\alpha+\Gamma G\mu)}$$

$$\times \int_{t_F}^{t_0} d\tilde{t}\; \frac{C_{eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5 \left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \Theta(t_i - t_F)$$

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

A Brief Review of Standard Cosmology

- <u>Standard cosmology</u>:
  - Inflation (?)
  - Radiation domination (RD): primordial reheating (?) till $T_{eq}\sim eV$
  - Matter domination (MD): $T_{eq}\sim eV$ till today (Λ) *(well tested ✔)*



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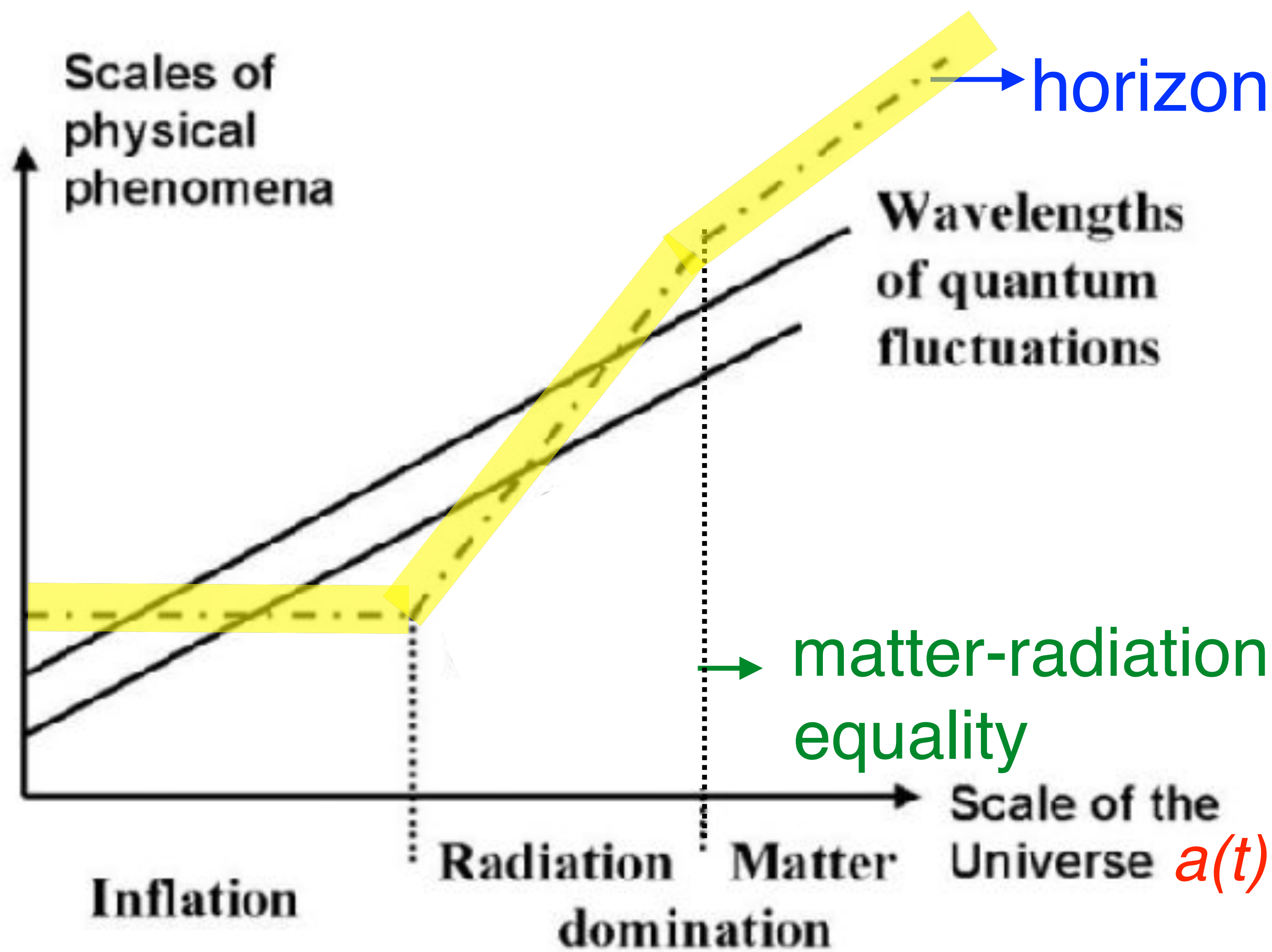

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$
$$H^2 \propto a^{-n}$$
$$(n = 3, 4 \text{ for MD, RD})$$

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

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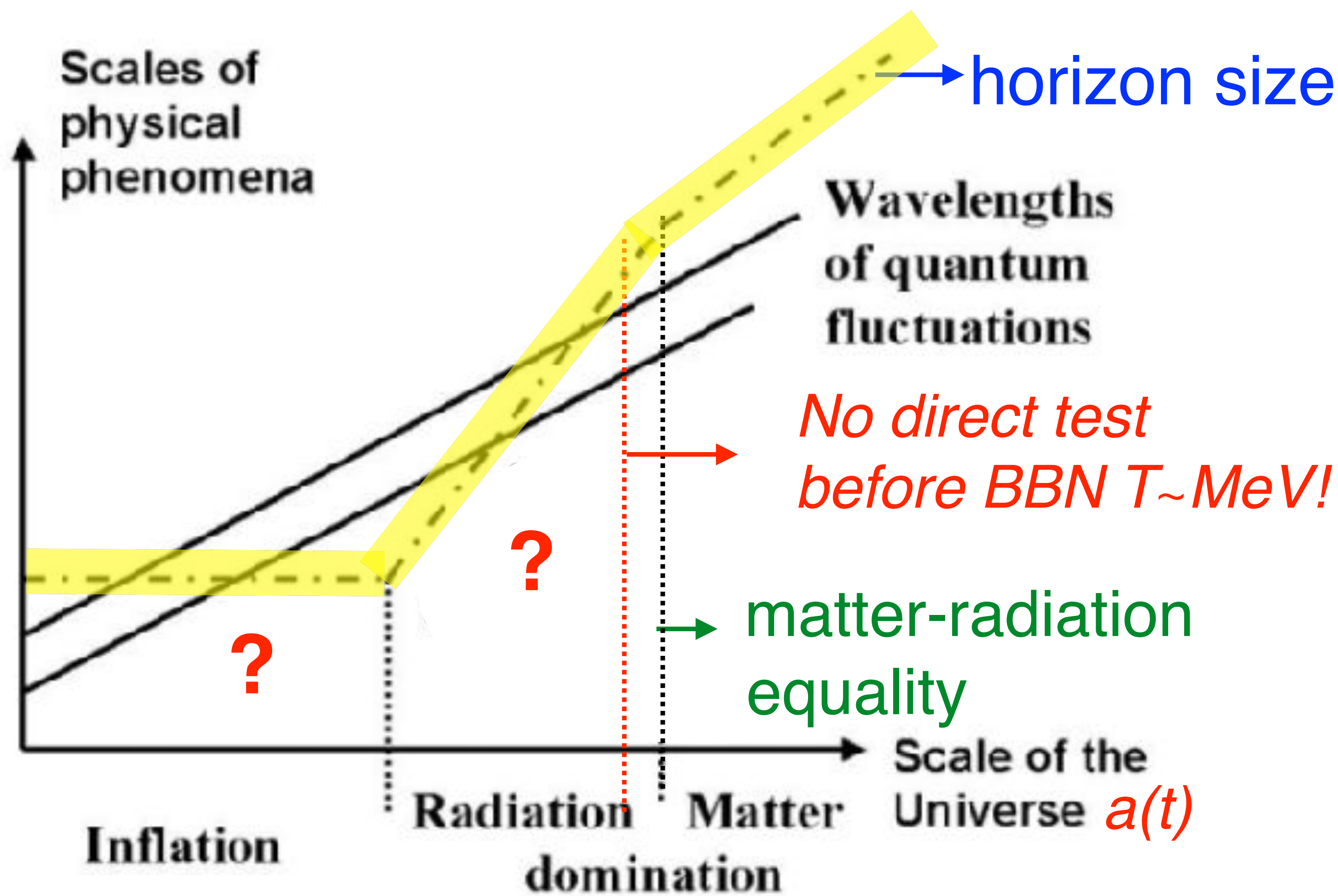

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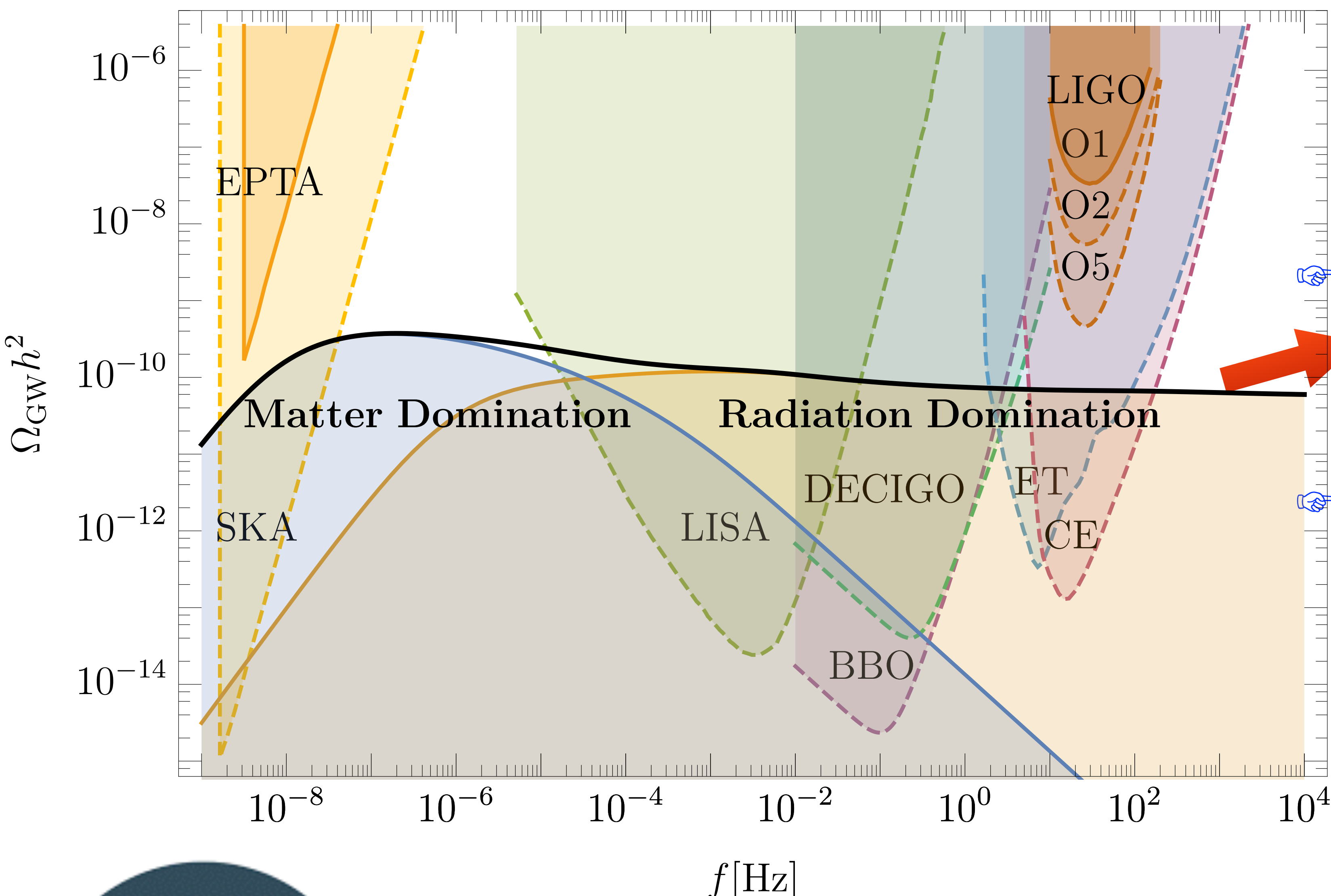
Testing Standard Cosmology w/GW Spectrum from Cosmic Strings

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



Features of the GW

☞ 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

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

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

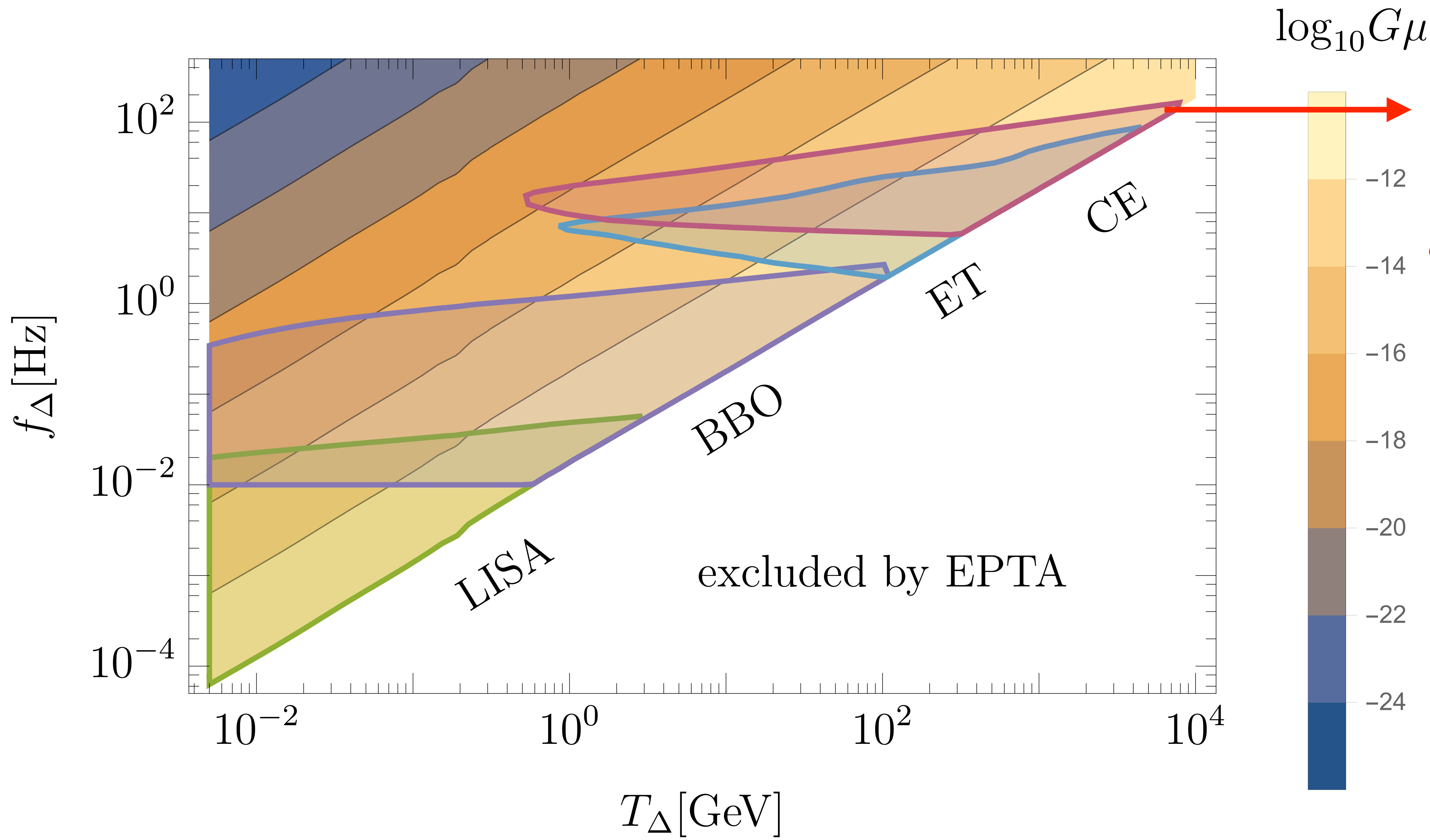
$$f_\Delta \simeq \sqrt{\frac{8}{z_{\rm eq}\alpha\,\Gamma G\mu}} \left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4} \left(\frac{T_\Delta}{T_0}\right) t_0^{-1}$$

Numerical fit:

$$f_\Delta = (8.67\times 10^{-3}\,\text{Hz}) \left(\frac{T_\Delta}{\text{GeV}}\right) \left(\frac{0.1\times 50\times 10^{-11}}{\alpha\,\Gamma G\mu}\right)^{1/2} \left(\frac{g_*(T_\Delta)}{g_*(T_0)}\right)^{\frac{8}{6}} \left(\frac{g_{*S}(T_0)}{g_{*S}(T_\Delta)}\right)^{-\frac{7}{6}}$$

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:** $n > 4 \text{ in } H^2 \propto a^{-n}$**, 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*

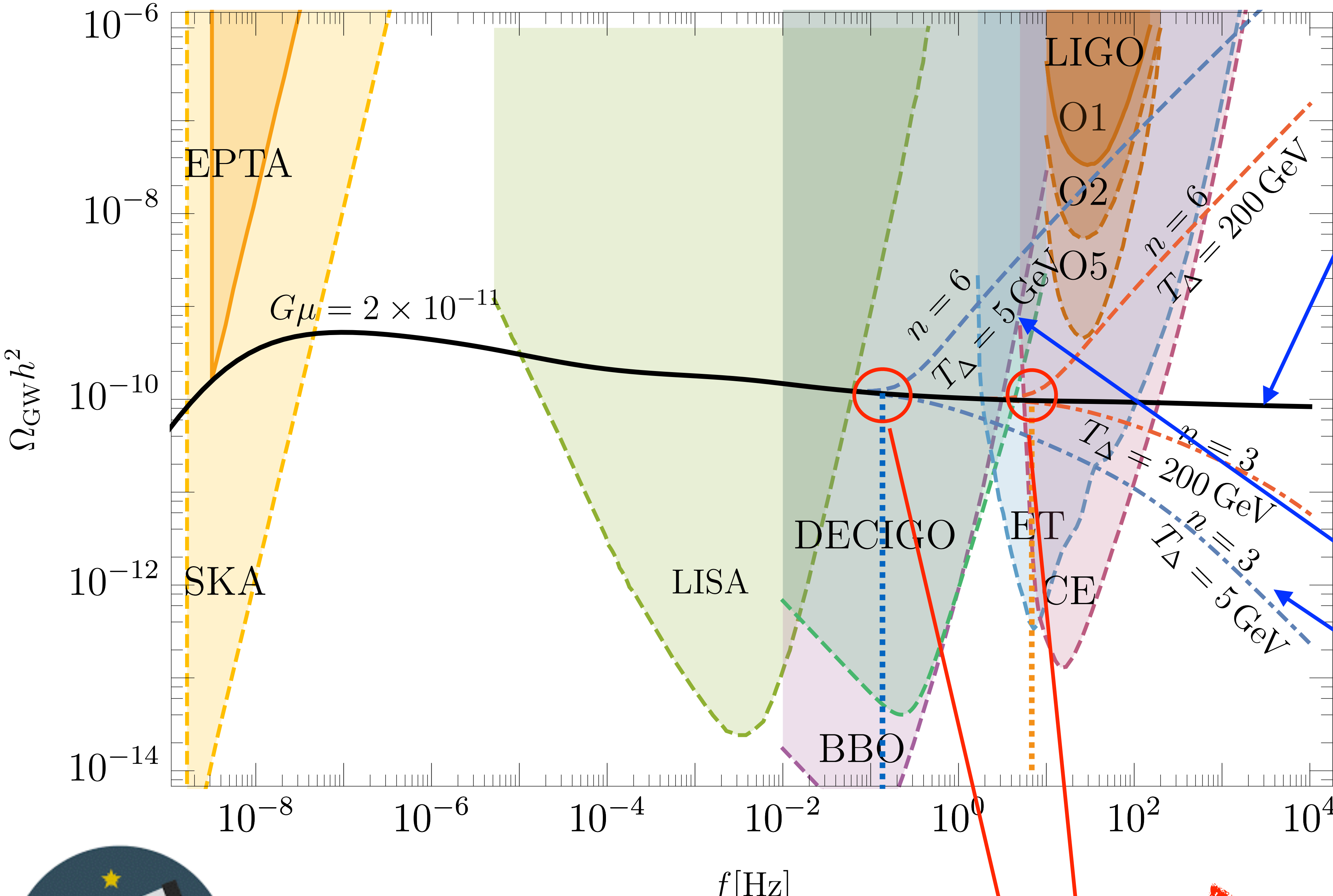
☞ $$\boxed{\Omega_{GW}(f) \propto \begin{cases} f^{\frac{8-2n}{2-n}} & n > 10/3 \\ f^{-1} & n \leq 10/3 \end{cases}}$$
(at large f)

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!

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

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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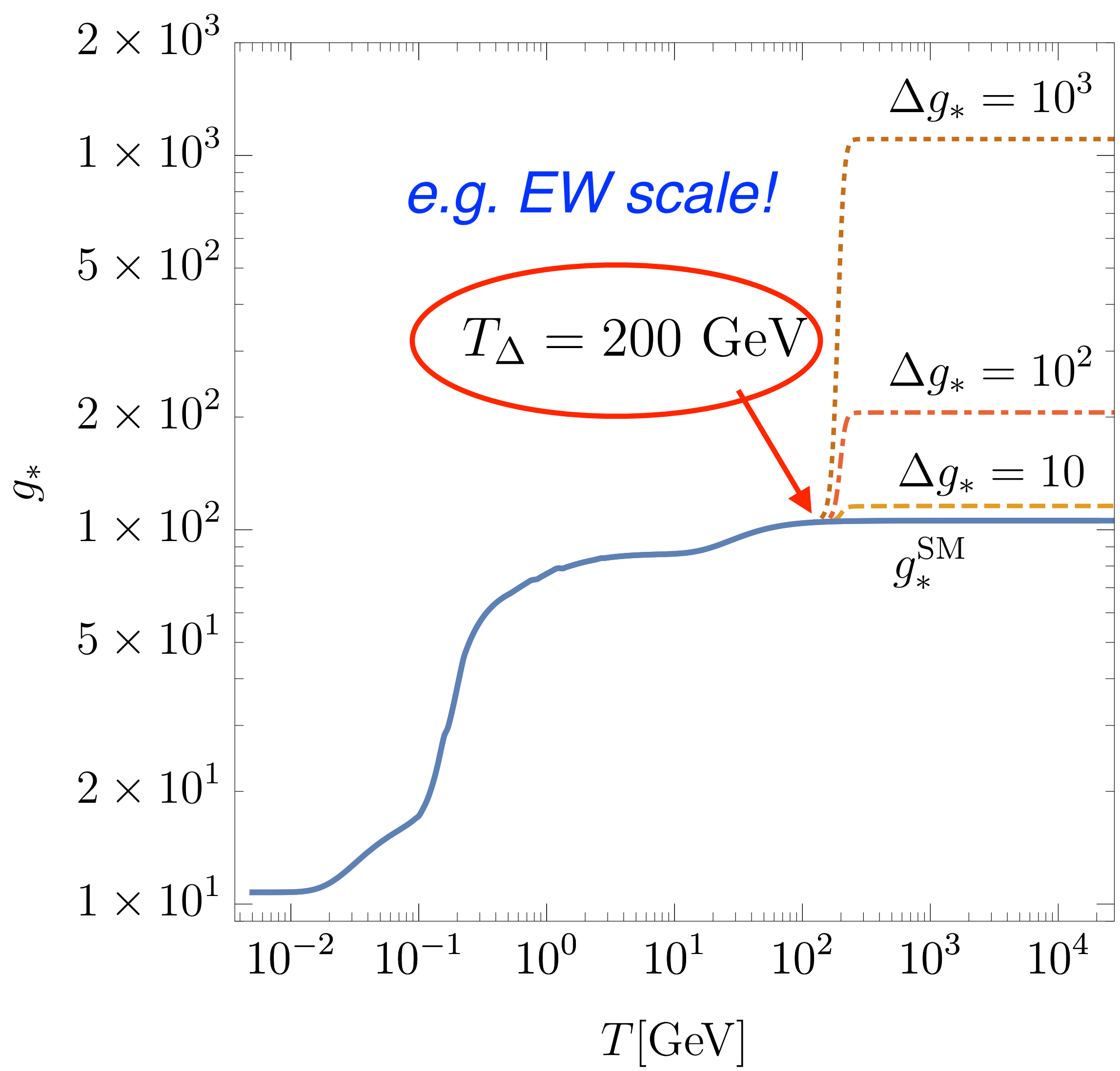

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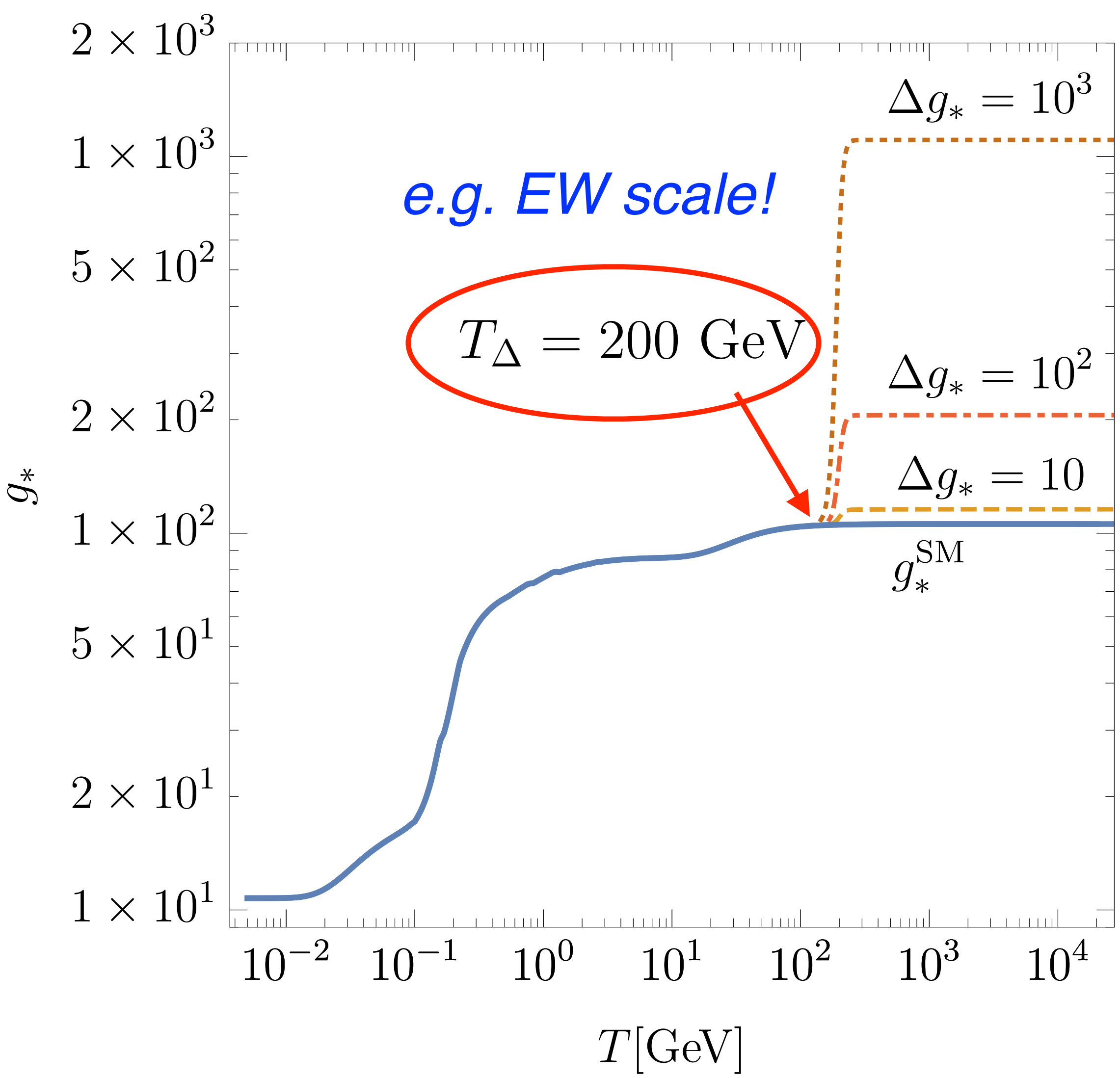


Friedman equation:

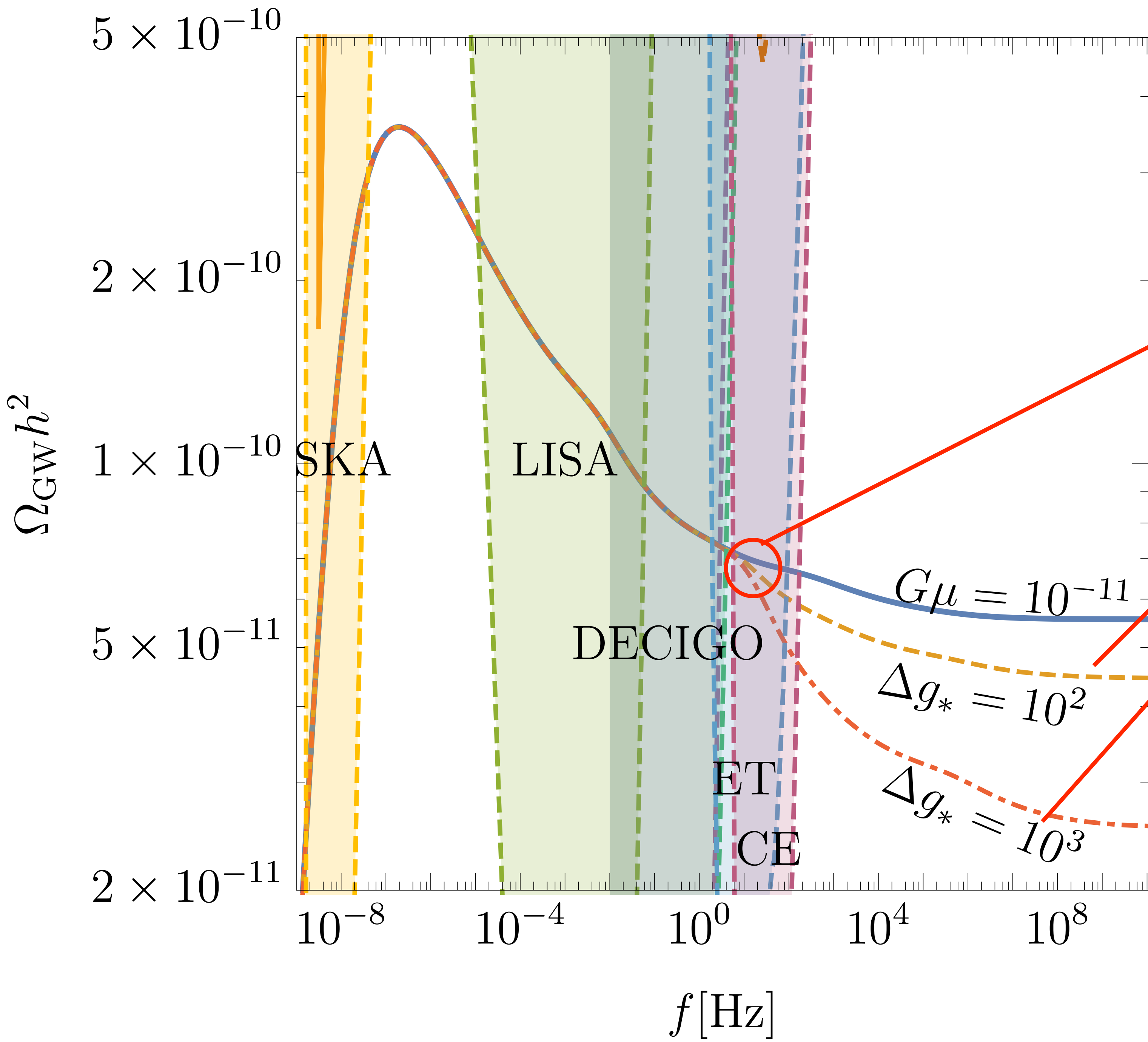
$$H^2 \equiv \left(\frac{\dot a}{a}\right)^2 = H_0^2\left[\Delta_R(a)\,\Omega_R\left(\frac{a}{a_0}\right)^{-4} + \Omega_M\left(\frac{a}{a_0}\right)^{-3} + \Omega_\Lambda\right]$$

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

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

Discussion: Confronting Detection Challenges

- **Astrophysical background**

(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 angular/direction resolution to resolve/remove astro bkg with future detectors (@ 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

- **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, 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**

- Any departure from the flat RD GW spectrum of a cosmic string network can be traced back to the corresponding cosmic temperature/time: 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)*

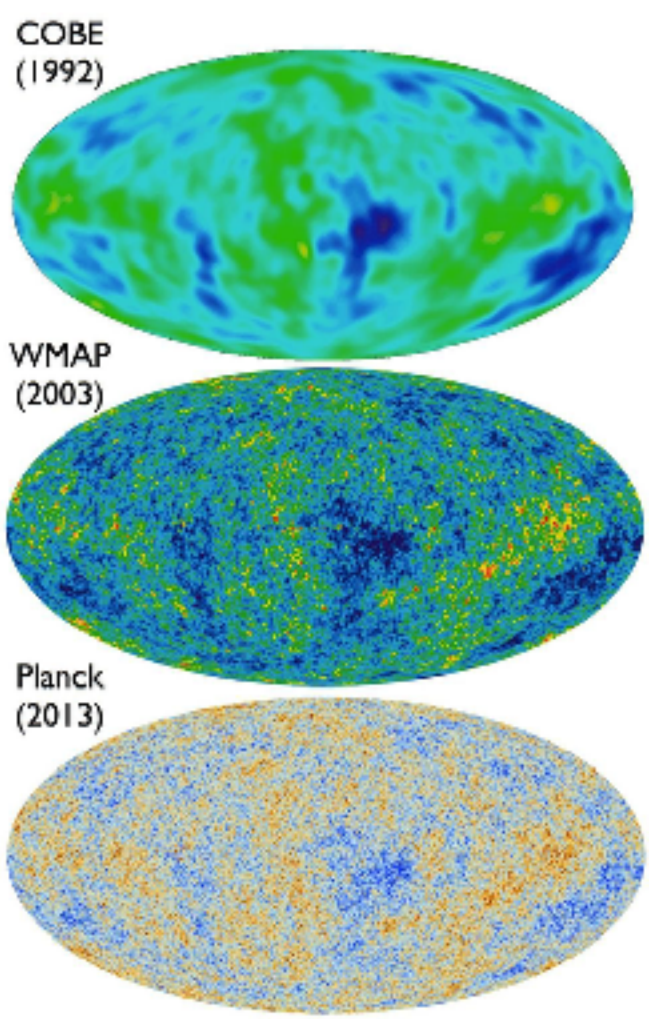
Outlook

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

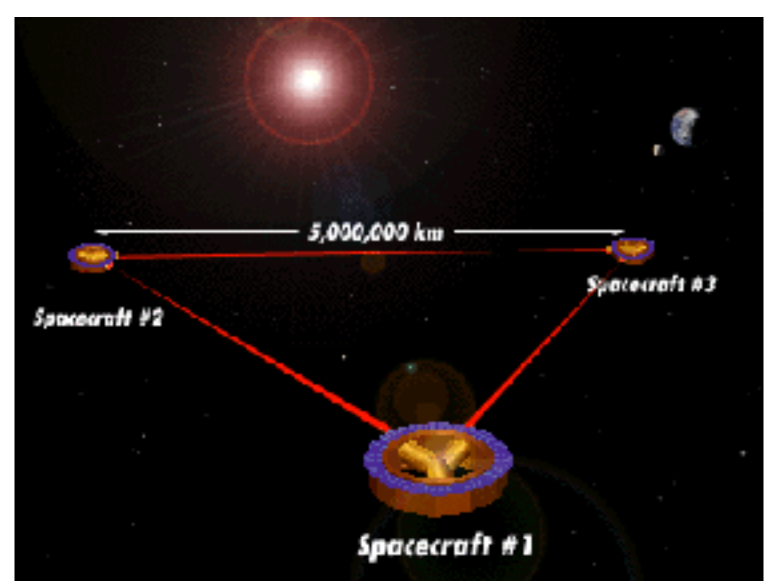
The history of CMB physics

1965 discovery



How far can GW take us?

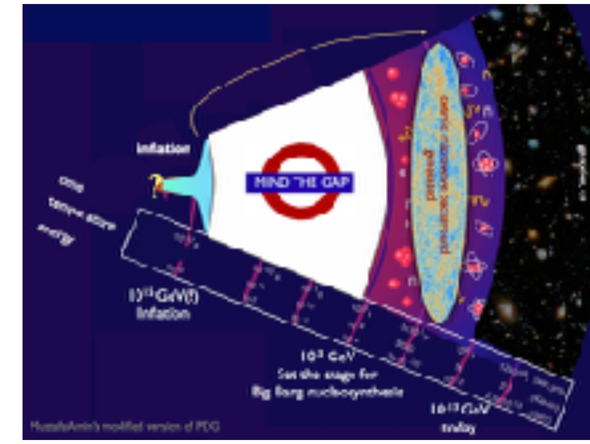
2016 LIGO discovery



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

KITP Program Jan 6-Mar 13 2020:

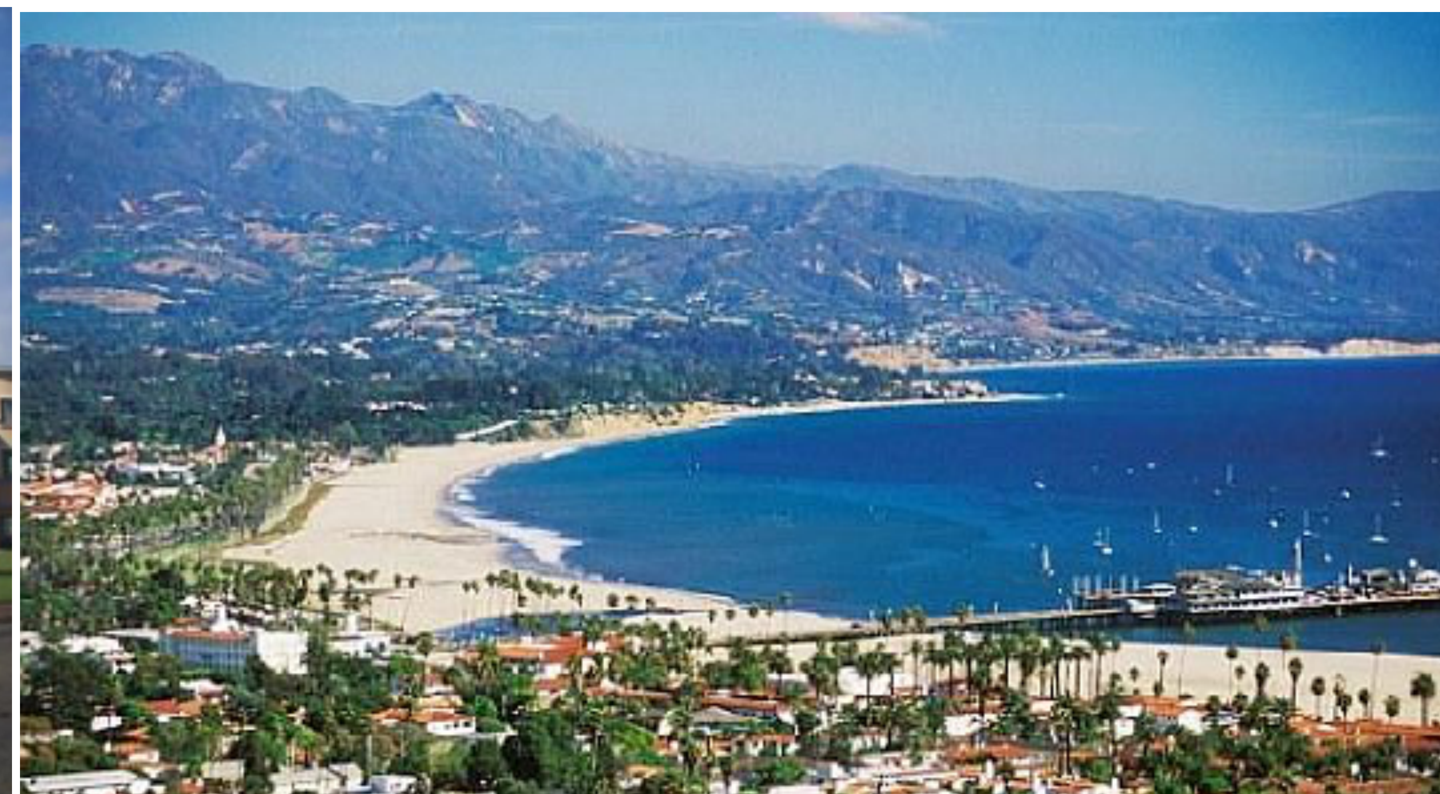
From Inflation to the Hot Big Bang



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, application deadline Oct 21 2018



Santa Barbara, California

Thank you!