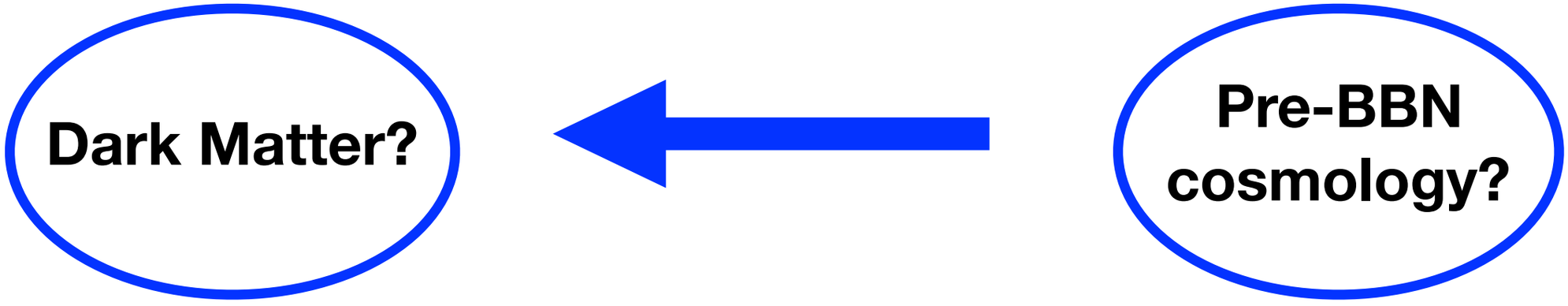
Dark Matter?

Pre-BBN cosmology?

Round table Discussion at GGI workshop, Aug 28, 2019



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Gravitational Waves

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Gravitational Waves

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Cosmic Archaeology with *Gravitational Waves* from (Axion) Cosmic Strings

Yanou Cui

University of California, Riverside

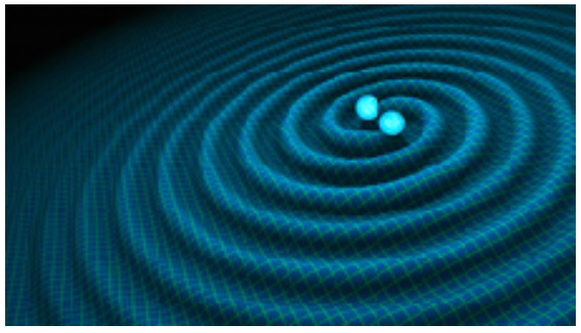
arxiv: 1711.03104 (PRD), 1808.08968 (JHEP)

YC with Marek Lewicki, David Morrissey and James Wells

work in prep, YC with Chia-Feng Chang

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?

(e.g. recent work by John, Devin, Francesc here…)

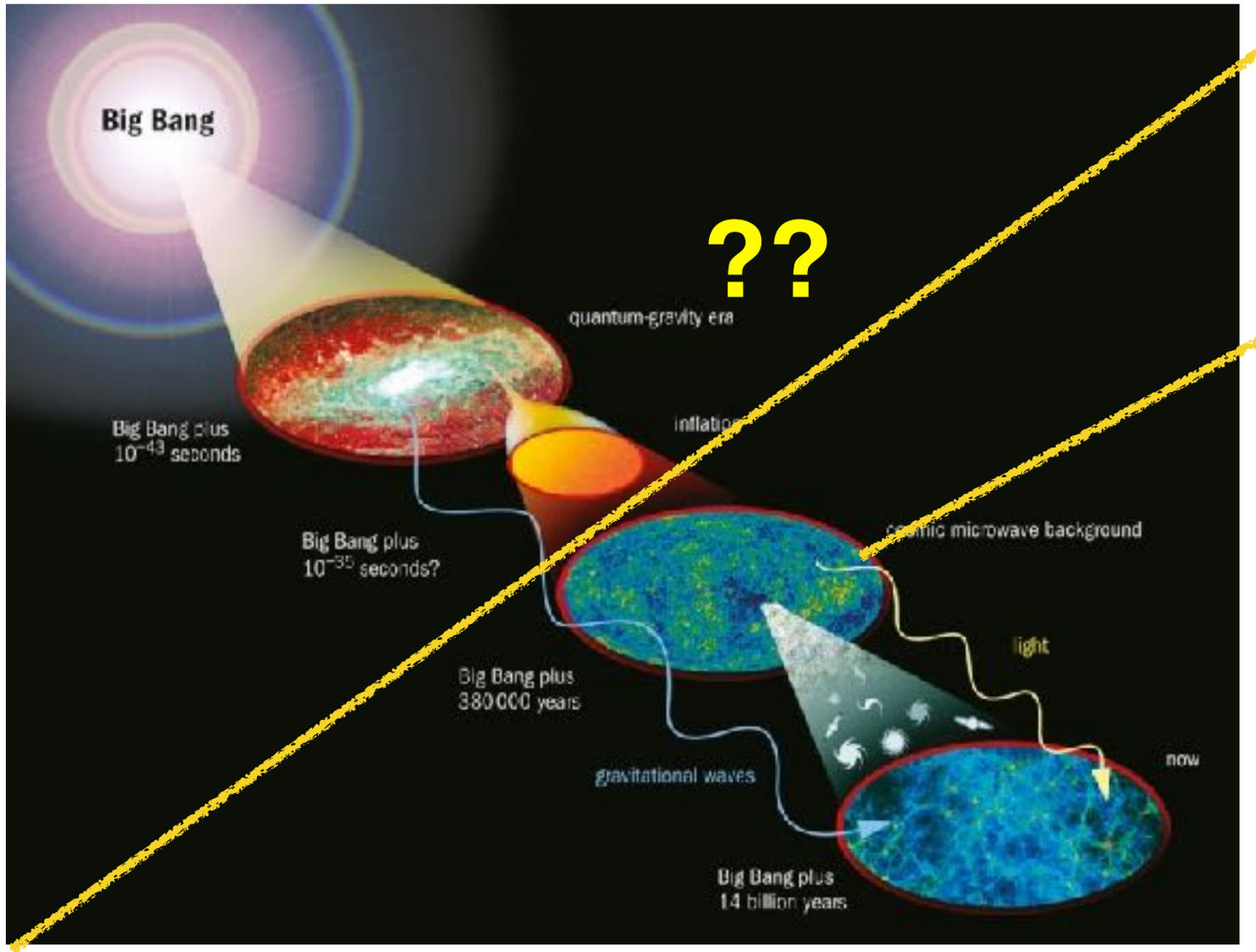
BSM Physics and GW
-what we know

- **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)

- **Potential GW probes for light bosons (potentially dark matter)**: axions, dark photons
  (e.g. Dimopoulos et al. 2016; Nelson et al. 2017; Pierce et al. 2018)

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*

Pre-BBN Cosmology

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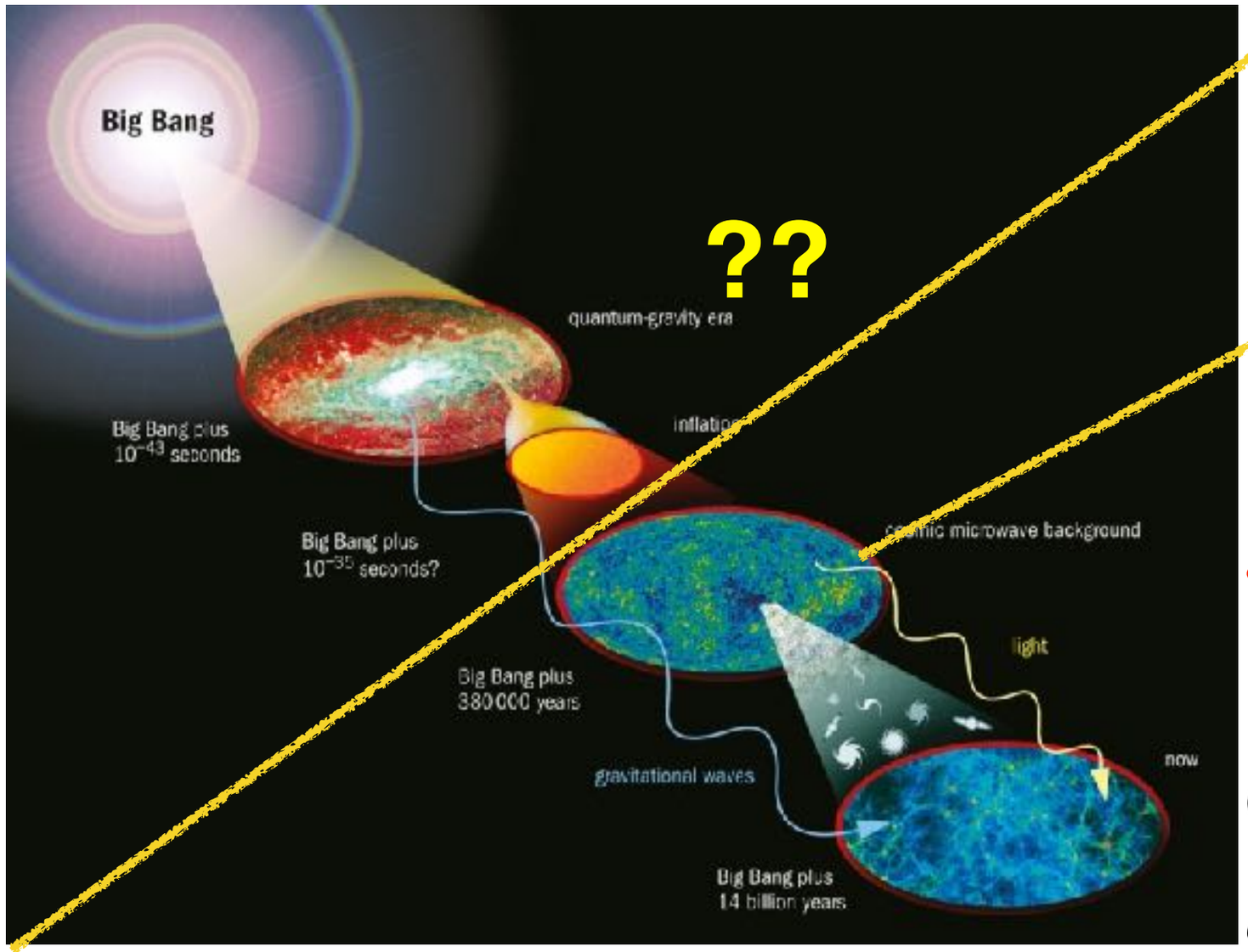


- **The horizon of confidence**: BBN
  (~1s-3 min after Big Bang)

- 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?…)

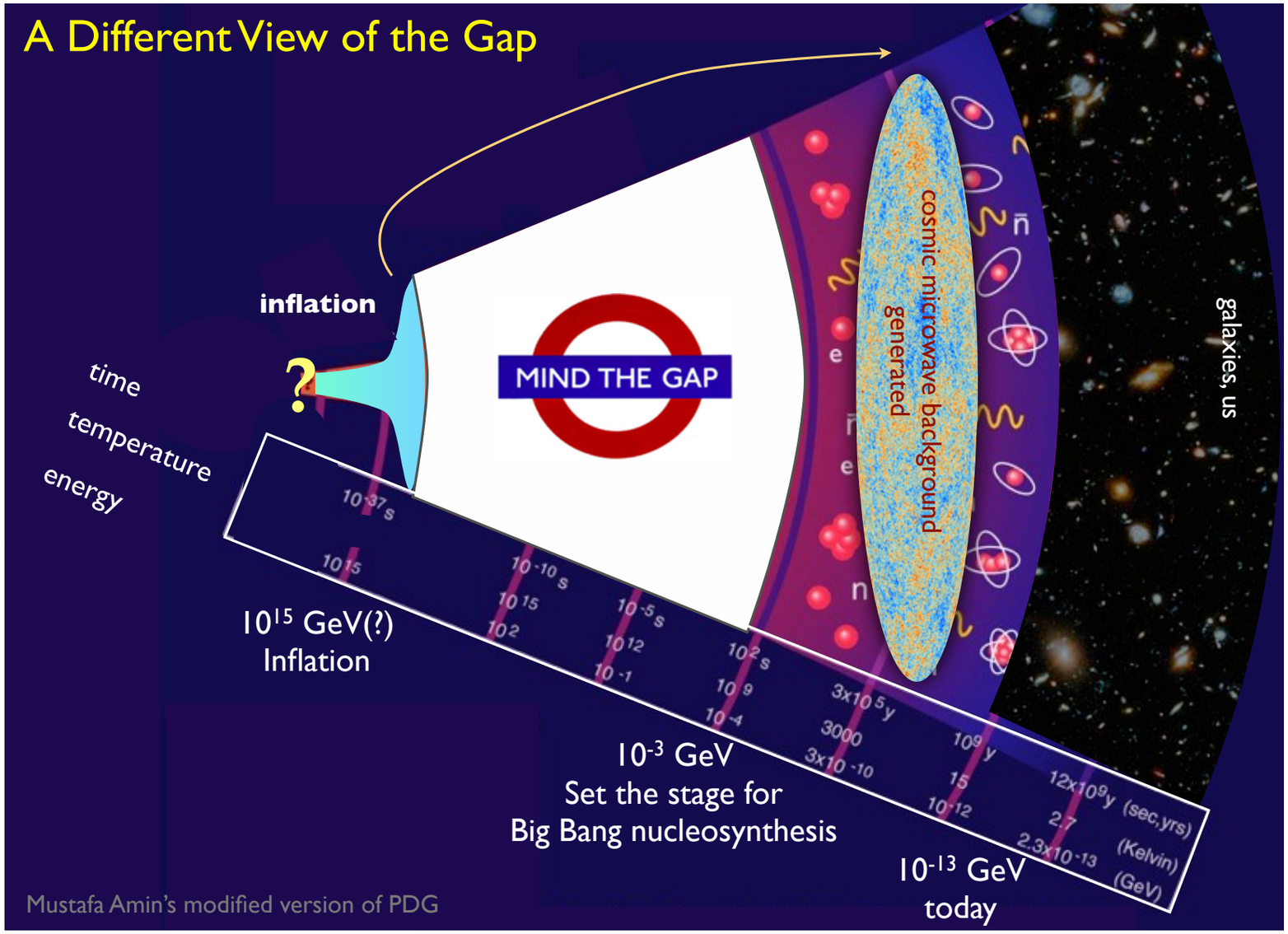
Pre-BBN Cosmology?

— *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”

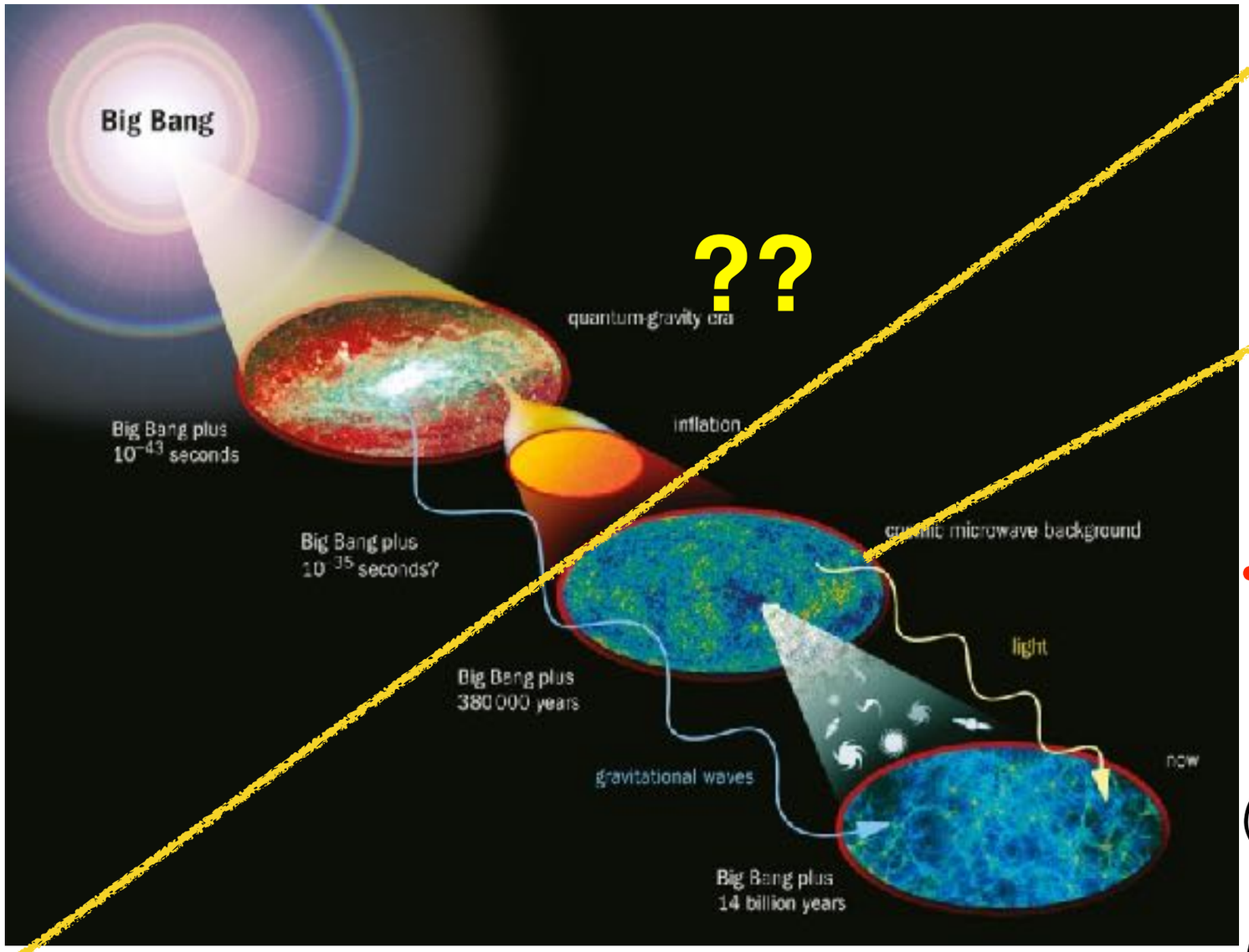
Non-standard cosmology *(early matter domination, kination, low reheating T, non-thermal history…)* **and Dark matter physics:**
potentially profound impact

- Ω_{DM}
- DM halo structure formation
- DM observational signatures

E.g. Gelmini, Gondolo 2006;
D’Eramo, Profumo et al.,
D’Eramo, Hall et al. ,
Erickcek, Watson et al.,
Kamionkowski et al. 2018,
Nelson et al. 2018,
Hardy 2019 …

Pre-BBN Cosmology

-what we do not "know"



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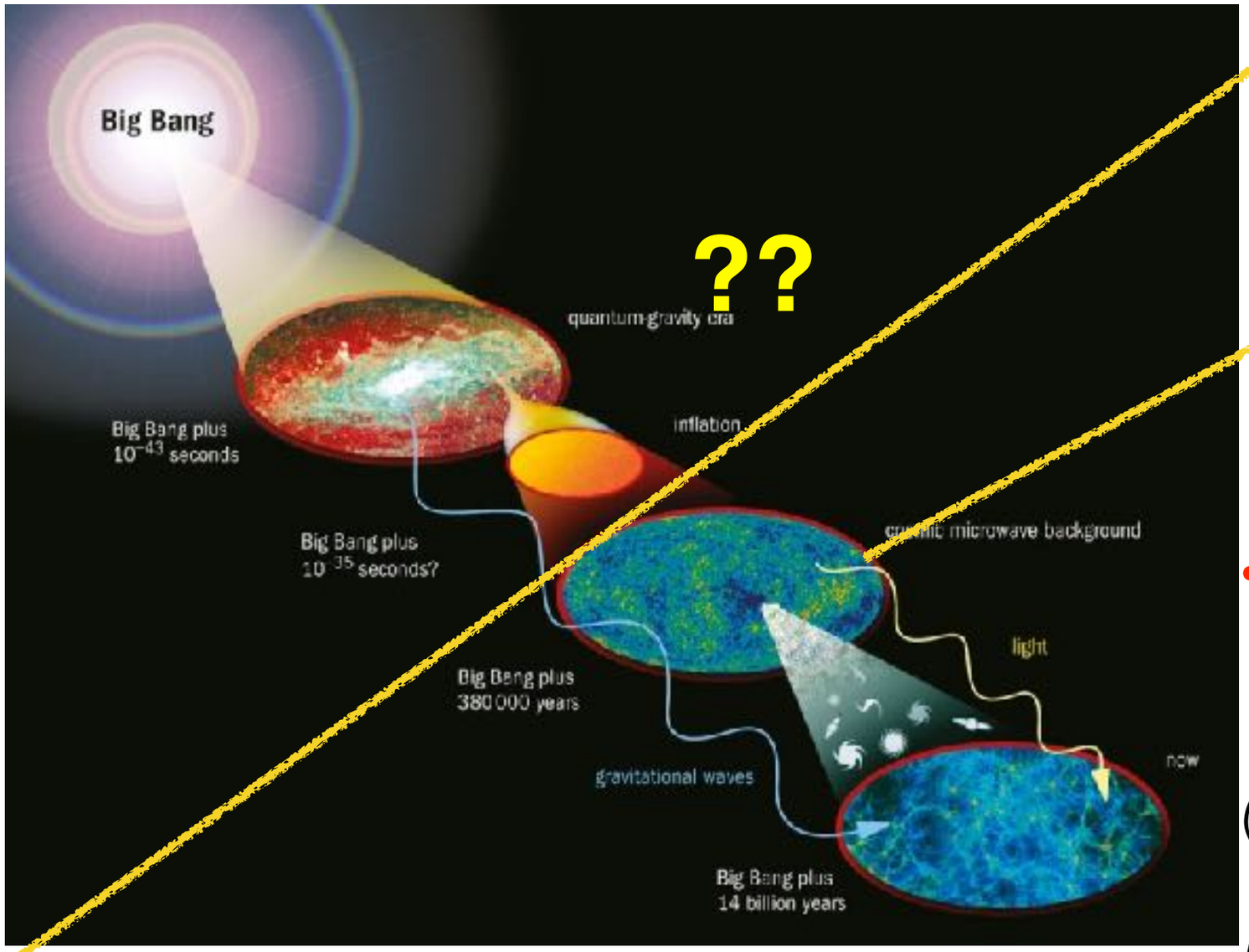
Pre-BBN Cosmology

-what we do not "know"



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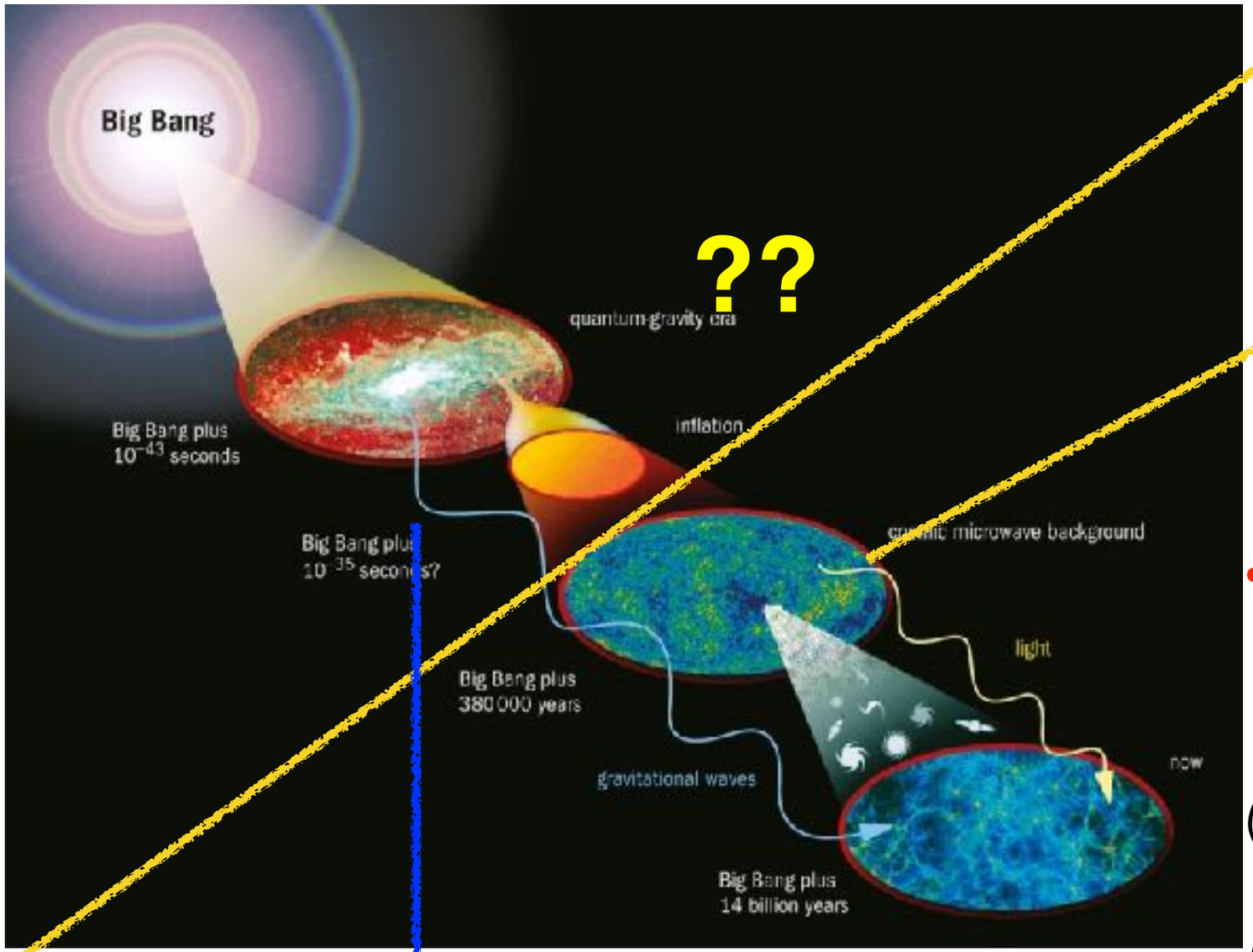
- **Direct observational probe?**

most effort so far: inflation. **Thermal history?**

Pre-BBN Cosmology

-what we do not "know"



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- **What happened before BBN?** standard cosmology, no observational proof…
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GW: the window of hope?

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

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

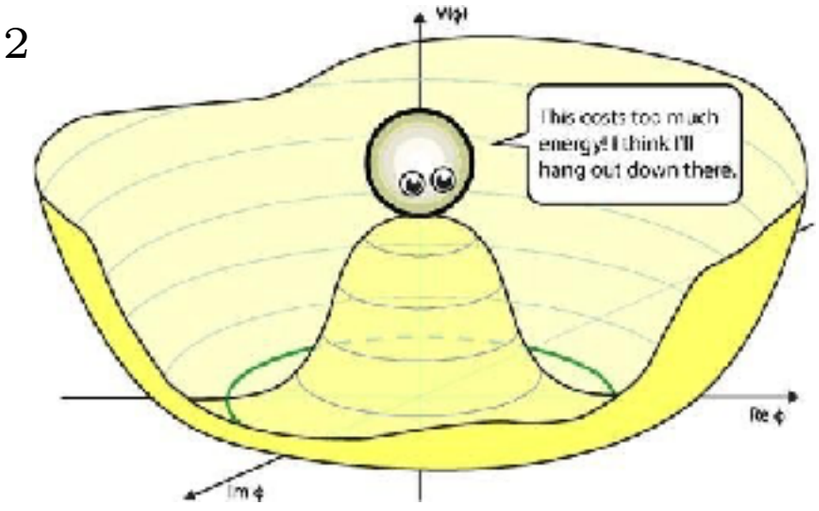
- A brief review on cosmic strings
- Test of standard cosmology: The time-frequency correspondence in the cosmic string GW spectrum
- Probe new phases of cosmic evolution *(eq. of state)*
- Probe new degrees of freedom *(beyond LHC, CMB ΔN_{eff}!)*
- Probe ALP DM models with GW from axion strings/DWs

  (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

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

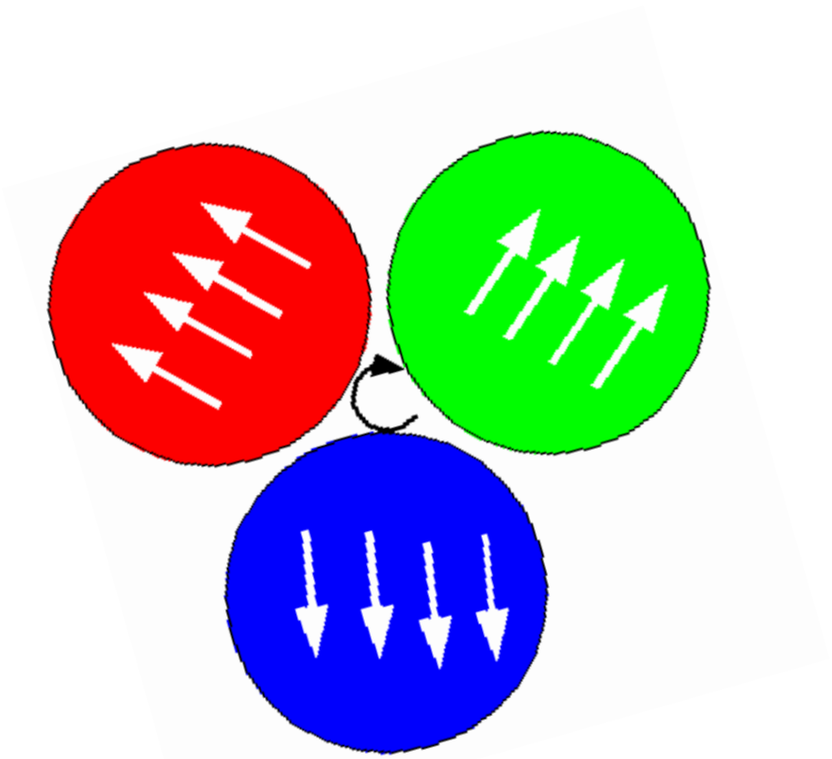
Cosmic Strings 101 (2)

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

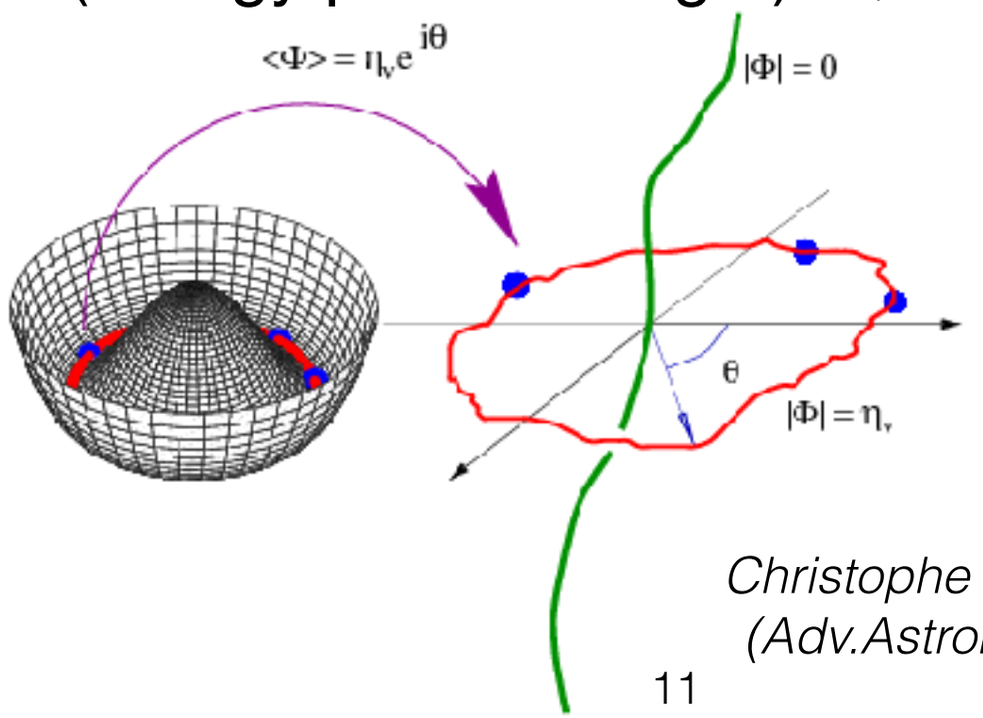
(position dependent, Nielsen and Olesen 1973;
vortex in type-II superconductor, Abrikosov 1957)

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

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



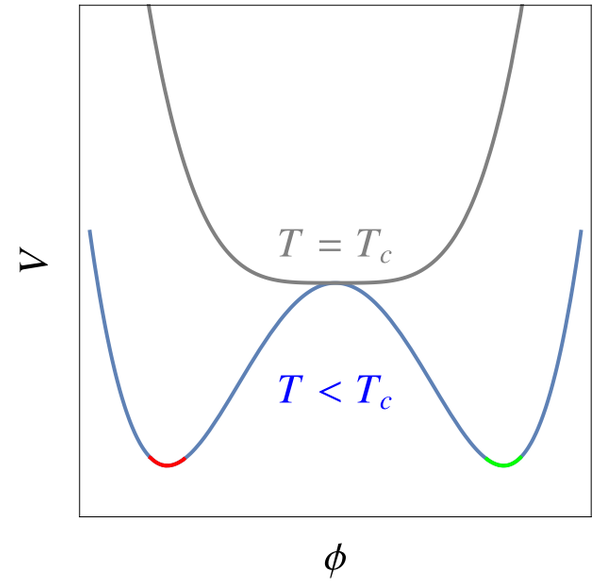
☞A tube of false vacuum (closed or infinite), string tension (energy per unit length): $\mu \sim v^2$



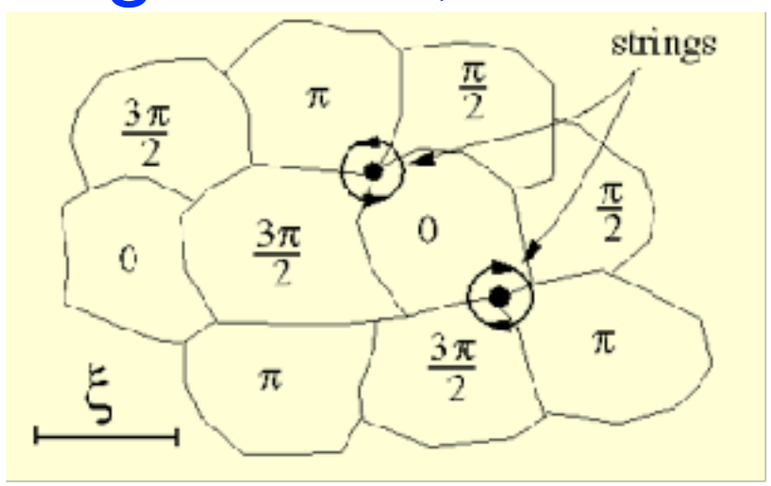
Christophe Ringeval (Adv.Astron. 2010)

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"

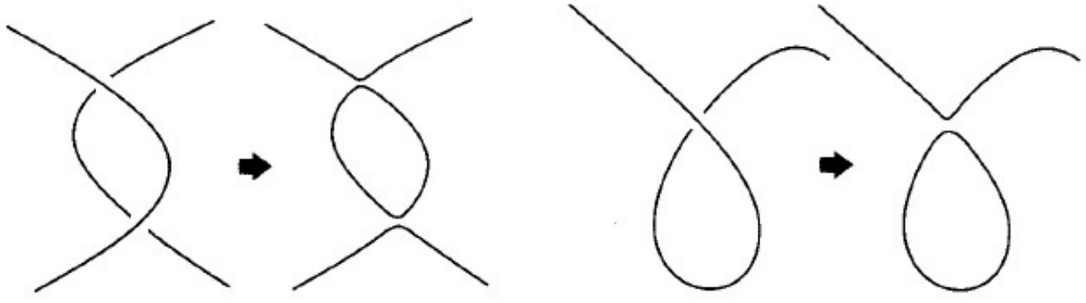


Evolution of Cosmic Strings

- 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) :

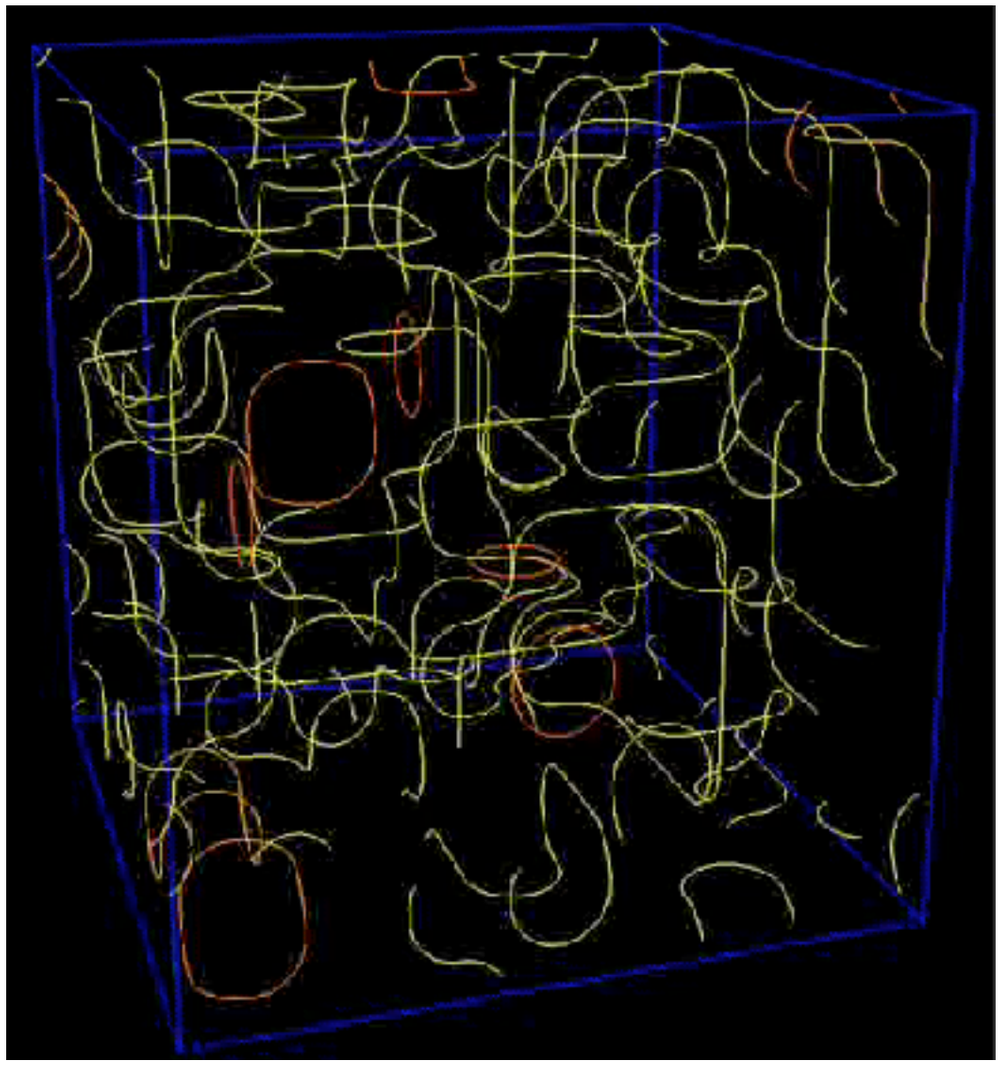
$$\frac{\rho_\infty}{\rho_{\rm bkg}} \propto G\mu$$

☞ "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



See Ed's talk on axion string simulation

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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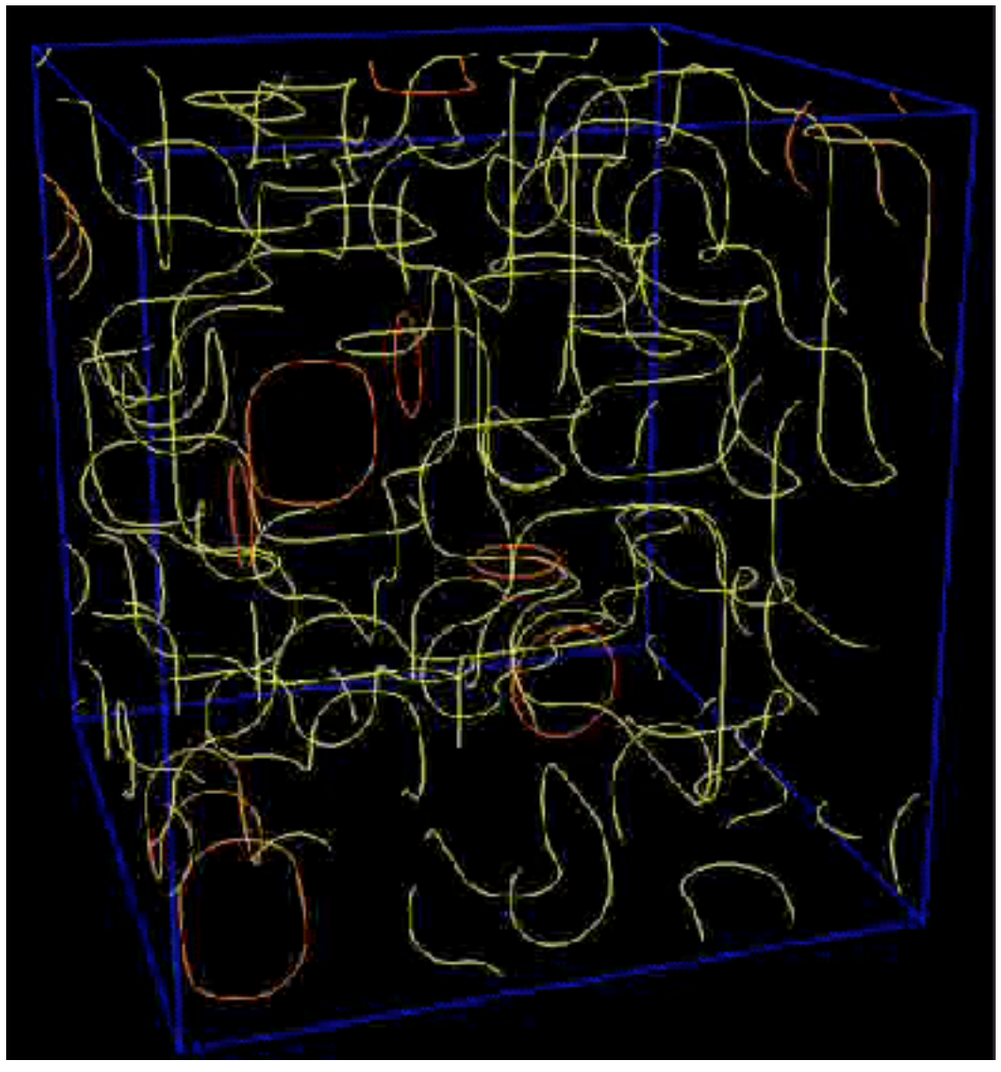

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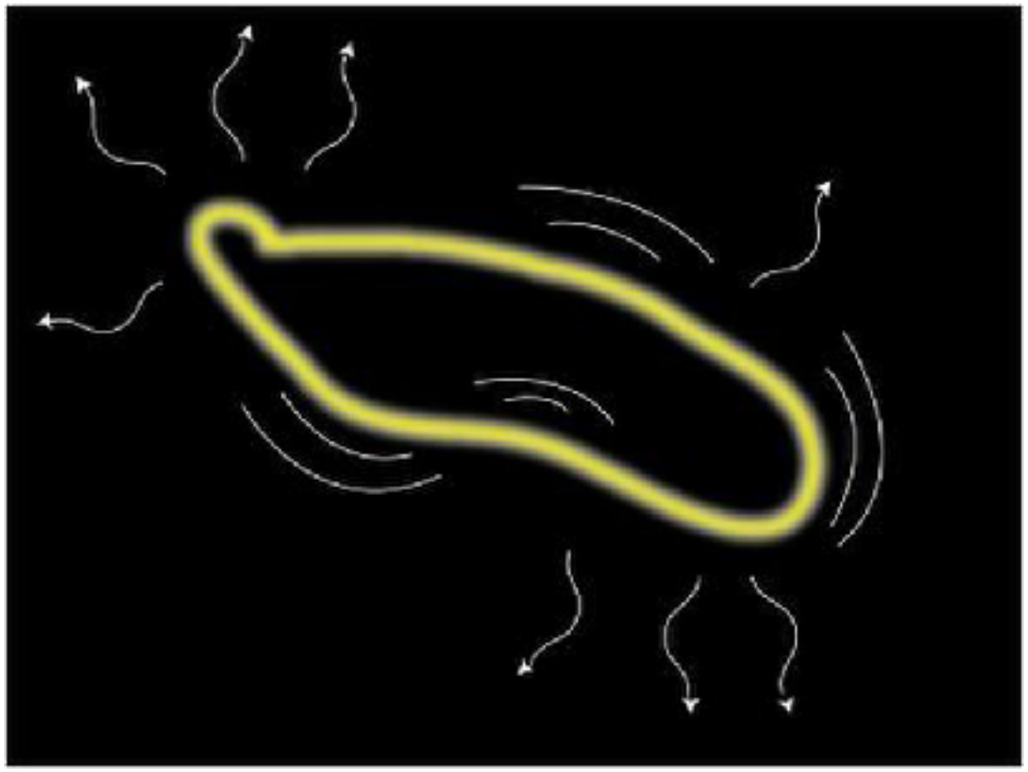
© Cambridge cosmology group

Observational Signatures

- Rich phenomenology: gravitational lensing (double imaging), CMB, structure formation, **gravitational waves,** matter emission…
- **Gravitational waves emitted from oscillating string 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):

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

- 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: oscillation mode dominates

Stochastic GW Background from Cosmic Strings

Putting things together:

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

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

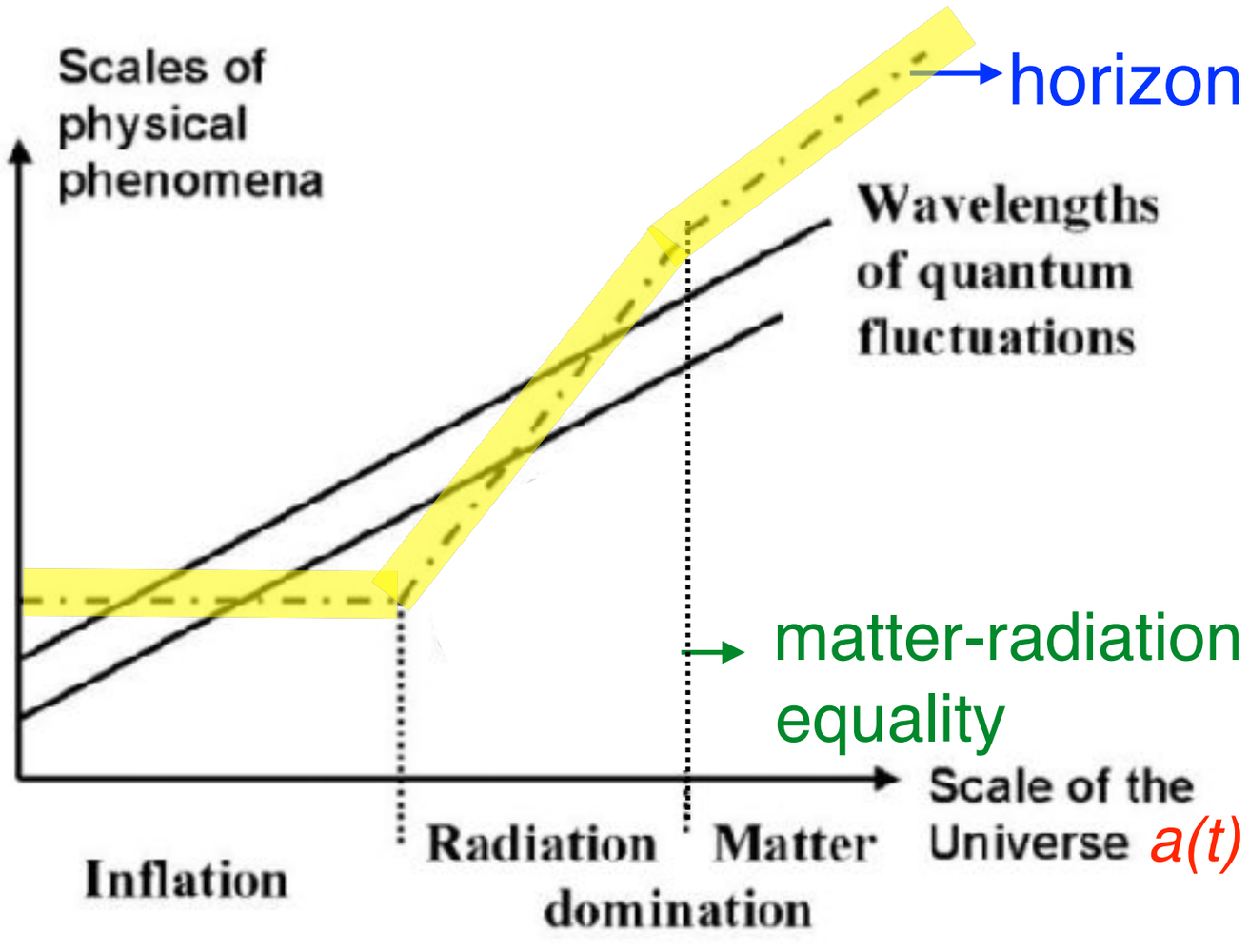
$$\Omega_{GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{(0.1)\,\Gamma_k G\mu^2}{\alpha(\alpha+\Gamma G\mu)} \times \int_{t_F}^{t_0} d\tilde{t}\ \frac{C_{eff}(t_i)}{t_i^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i)}{a(\tilde{t})}\right]^3 \Theta(t_i - t_F)$$

expansion parameter

-Evolution of cosmic bkg (*H(t)*) 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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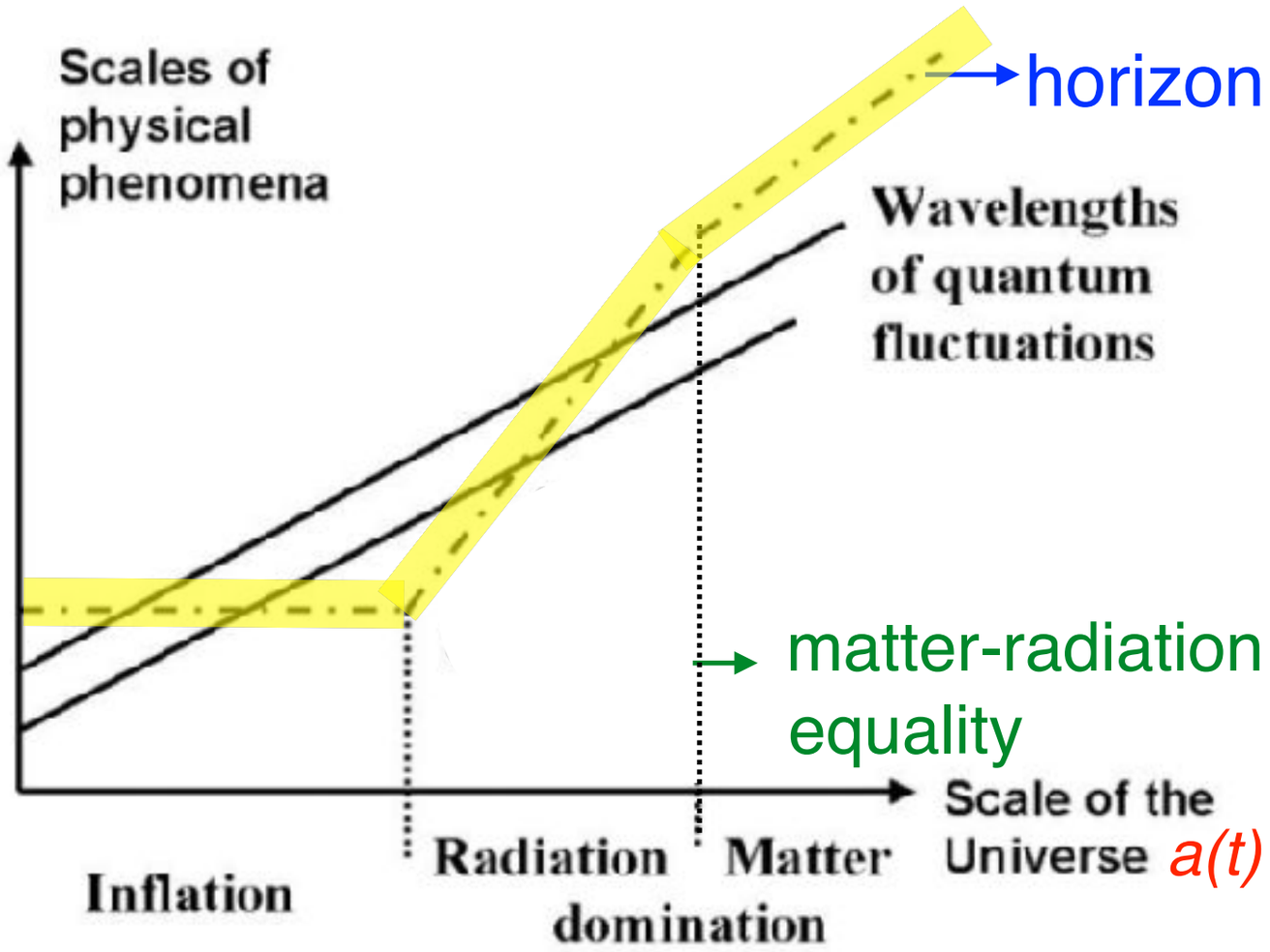

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

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

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

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

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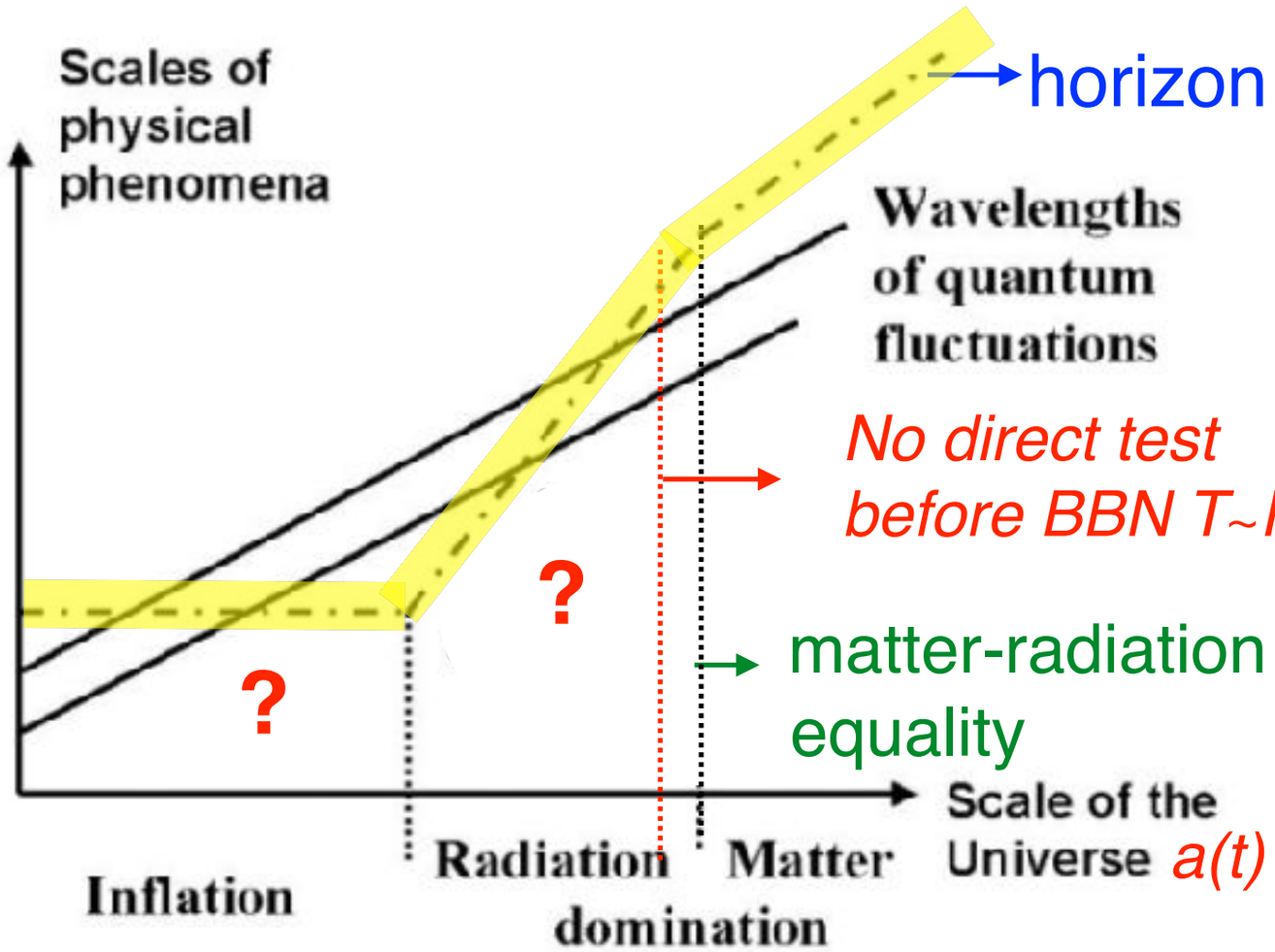

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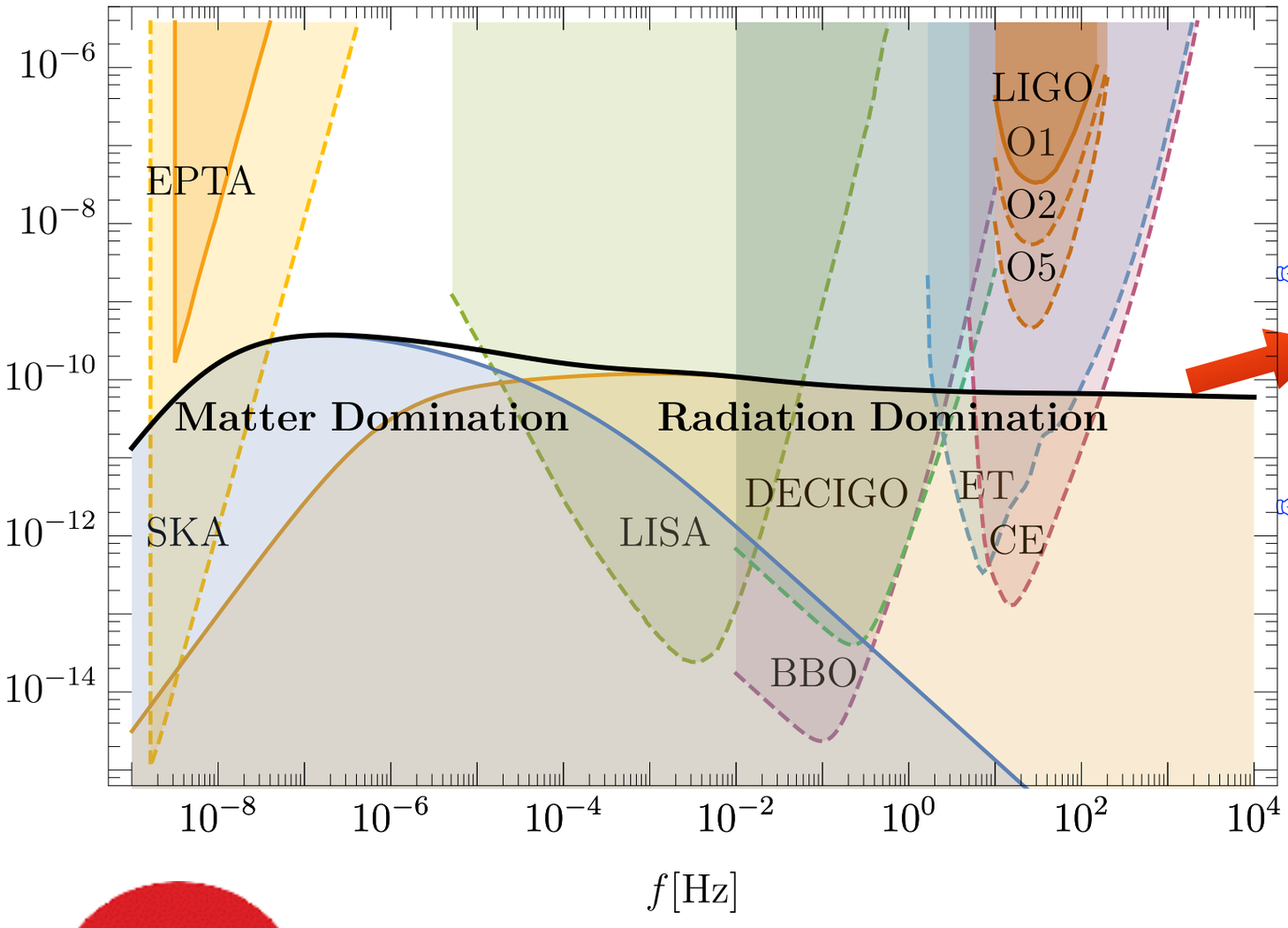
Testing Standard Cosmology w/GW Spectrum from Cosmic Strings

- 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

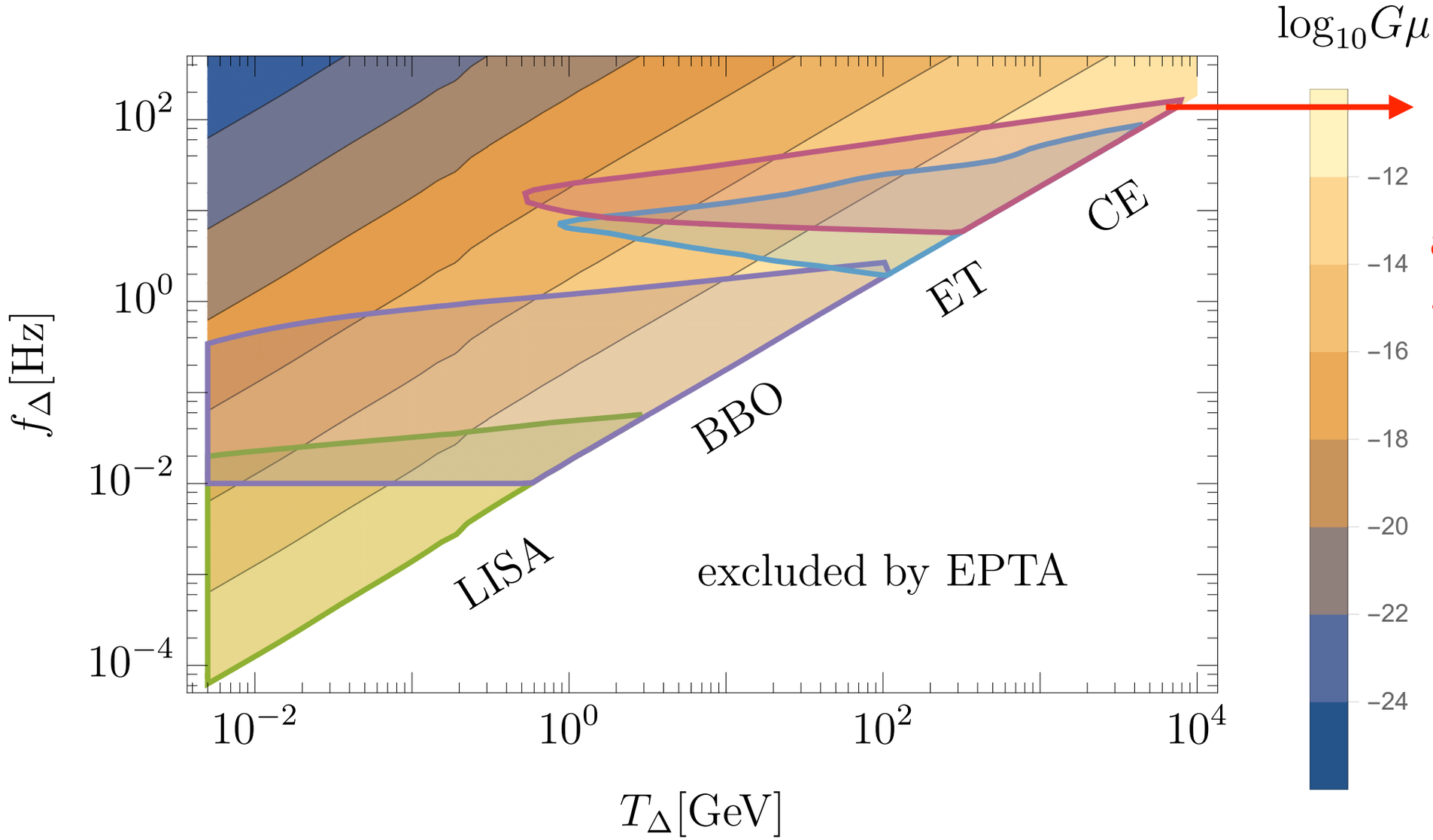
$$f_\Delta \simeq \sqrt{\frac{8}{z_{\rm eq}\alpha\,\Gamma G\mu}}\left[\frac{g_*(T_\Delta)}{g_*(T_0)}\right]^{1/4}\left(\frac{T_\Delta}{T_0}\right)t_0^{-1}$$

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)

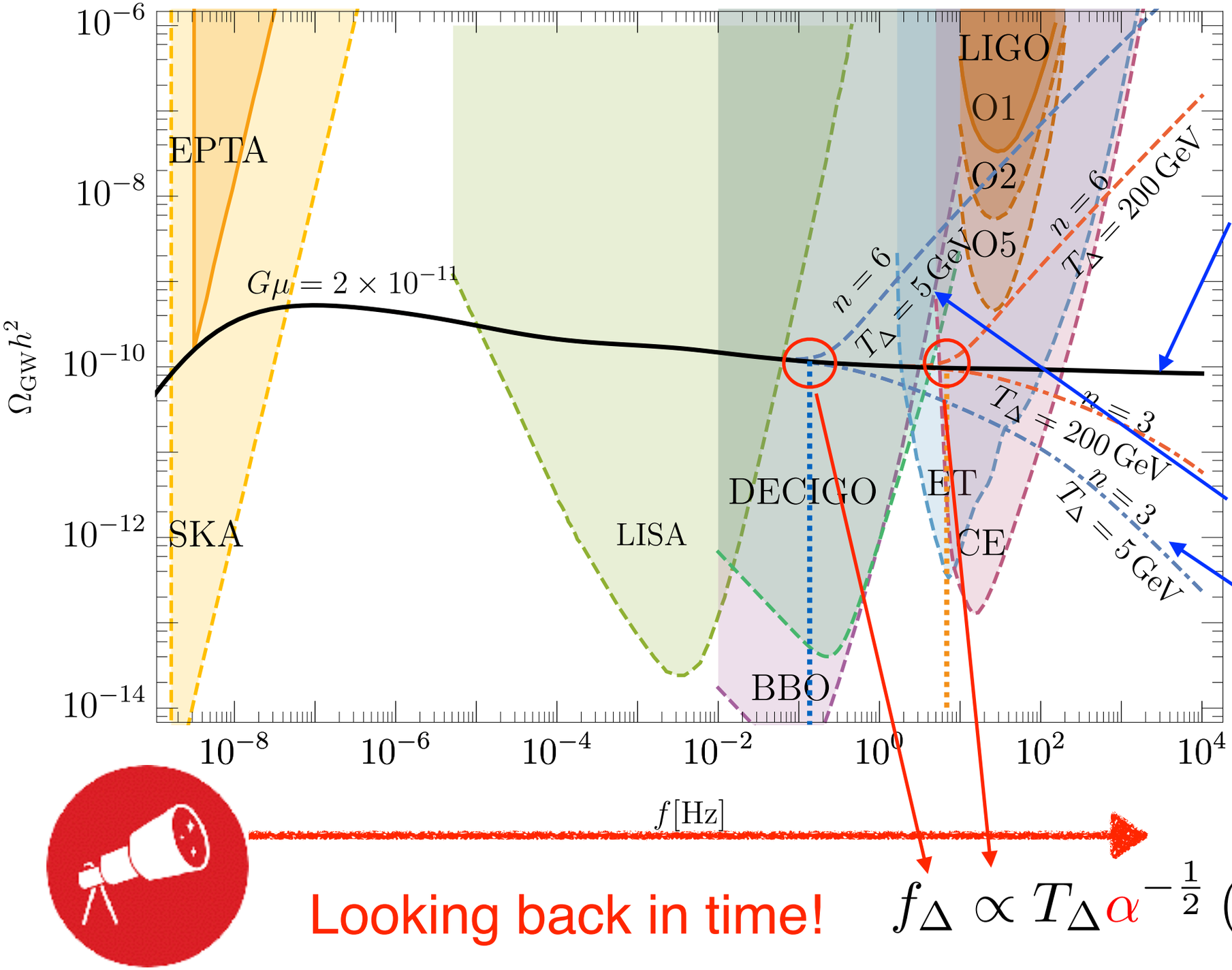


Sensitivity to T_Δ :
from BBN
all the way back to
~10^4 GeV !

- 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 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!

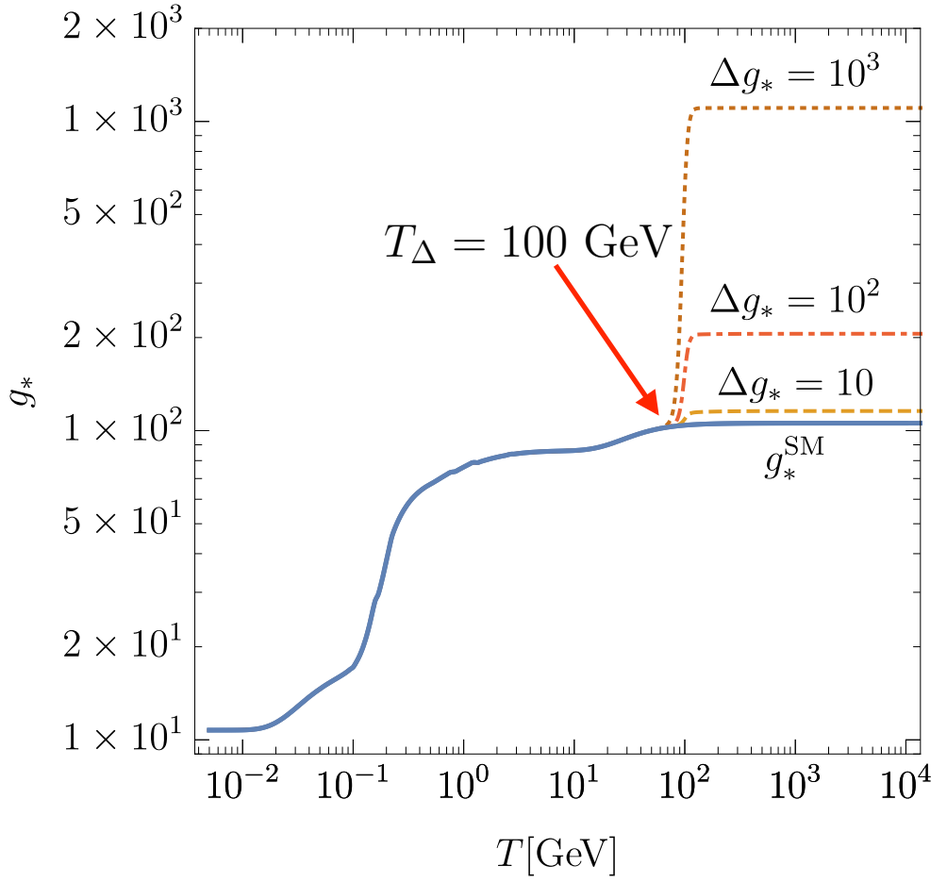
$$f_\Delta \propto T_\Delta \alpha^{-\frac{1}{2}} (G\mu)^{-\frac{1}{2}}$$

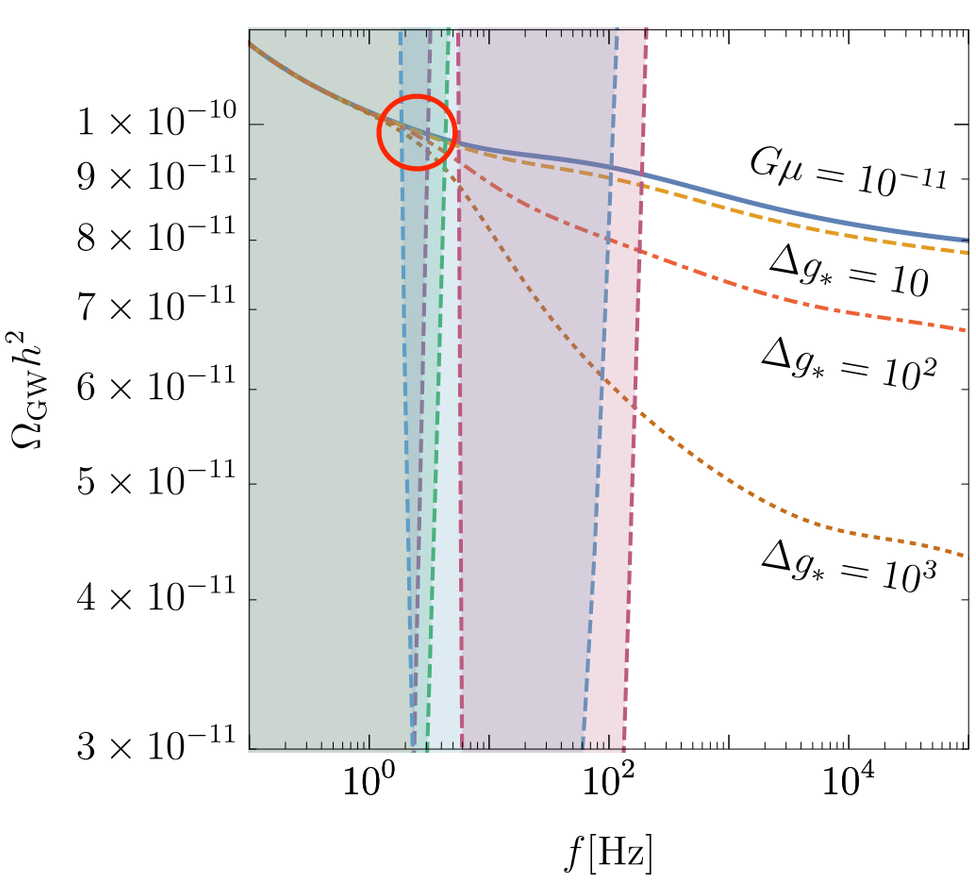
Probing New (Massive) Degrees of Freedom

Cosmological Probe for (Massive) BSM Degrees of Freedom

- Additional d.o.f's: ubiquitous in BSM theories, maybe hundreds of them!*(GUT, DM, SUSY, RS, hidden valley, twin Higgs, NNaturalness…)*
- Massive d.o.f's: radiation in the early Universe (g_*), later freezeout/decay☞can't be traced by CMB ΔN_{eff} (unlike massless d.o.f)

— GW spectrum may provide a way! $\left(H^2 \propto g_* T^4\right)$





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 ALP topological defects, potentially significant effects:

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

(Recent interest: Ed's and Francesc's talks, Martins 2018, Safdi et al. 2019, Hindmarsh et.al 2019…)

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  (Recent interest: Ed's and Francesc's talks, Martins 2018, Safdi et al. 2019, Hindmarsh et.al 2019…)

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

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

  + GW signal universal, GW detector sensitivity keep improving…

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:

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

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

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

  + GW signal universal, GW detector sensitivity keep improving…

- 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)*

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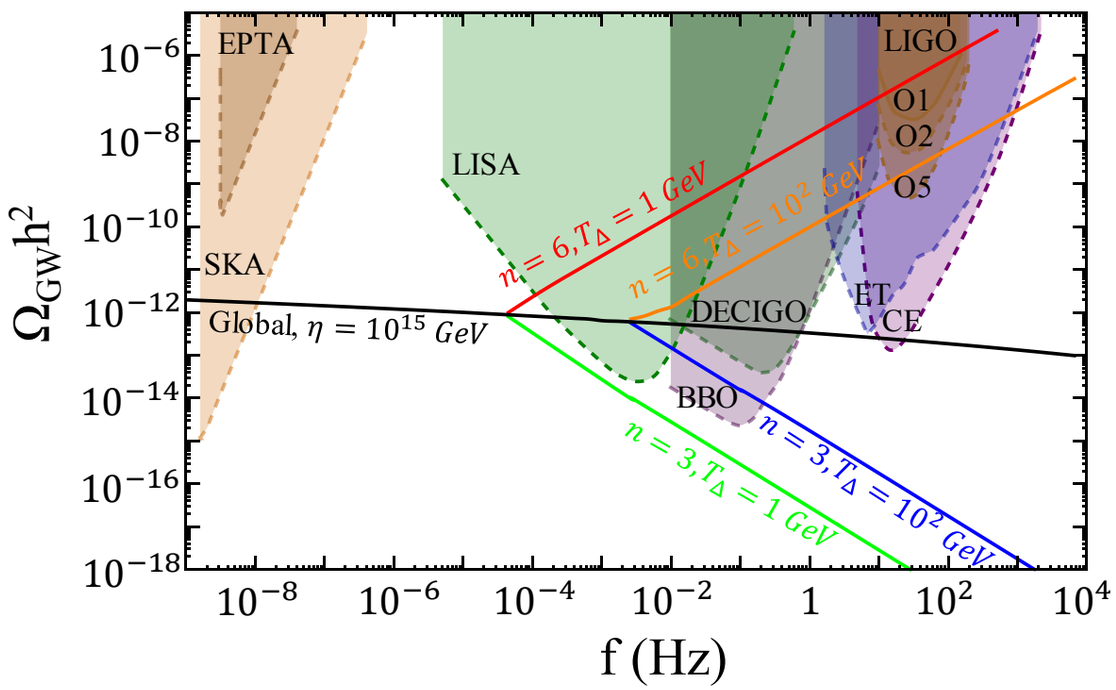
- **Our ongoing study: global→QCD axion→ALPs**

  - Preliminary result (global) ☞

    small, but observable!

  - Also advance (analytic) understanding of Ω_{DM} due to topological defects



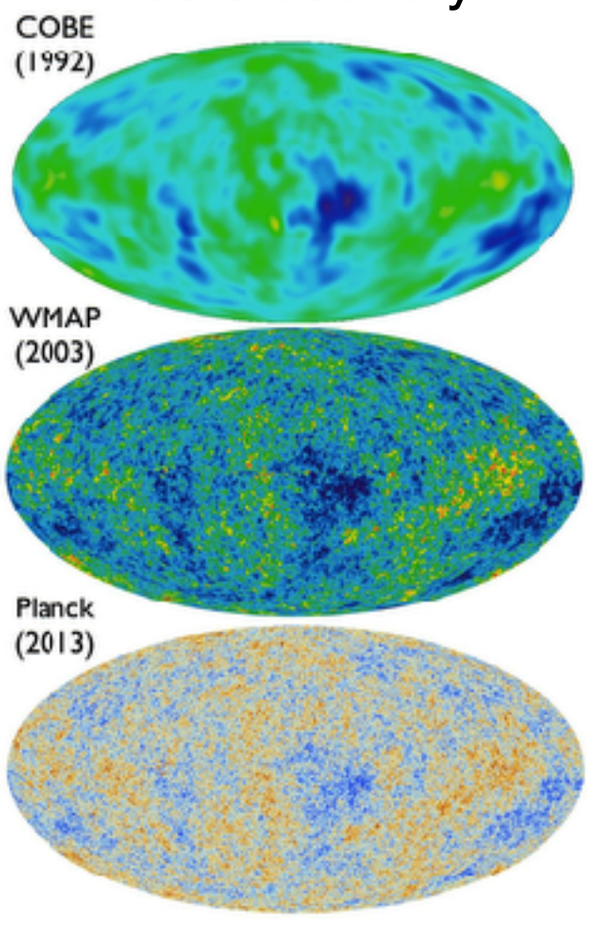
Outlook

Beyond cosmic strings:

An inspirational benchmark for exploiting the full potential of GW as a new tool for probing particle physics and cosmology *(shed light on DM? pre-BBN history?)*

The history of CMB physics

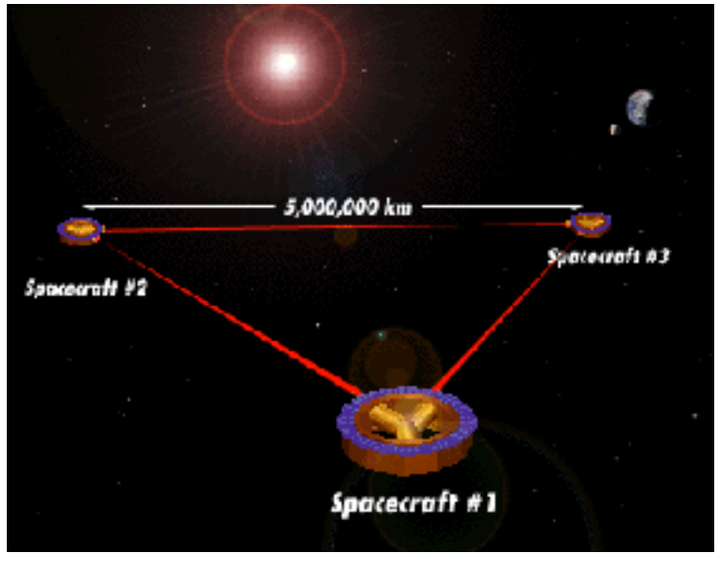
1965 discovery



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…

Thank you!

Backup Slides

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…