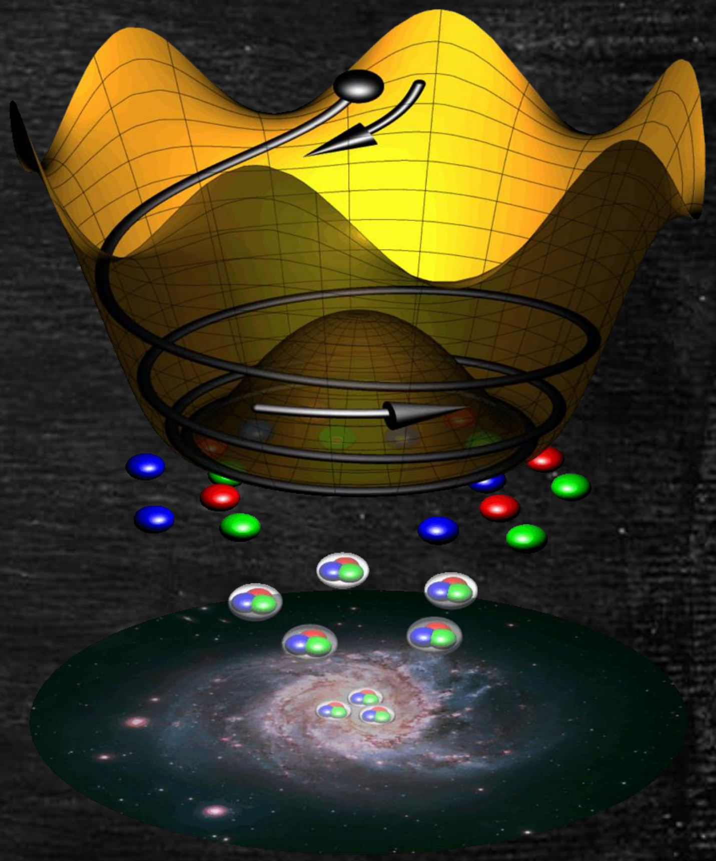
Axion Rotation

as the Icing on the Cosmic Cake



Axion in Seoul
Seoul National University

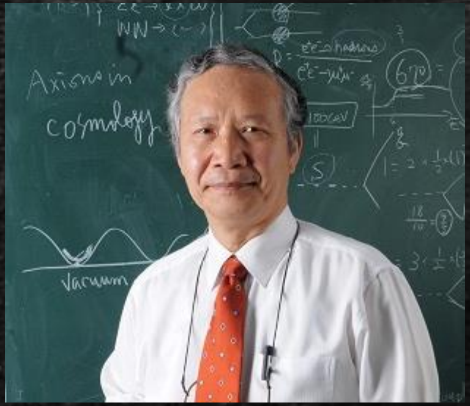
July 28th, 2026

Raymond Co

Indiana University

2510.01308 RC, Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton
2608.lHope RC, T. Lee, S.C. Lam

In Two Days



…

Top Scientist and Technologist Award of Korea 2003

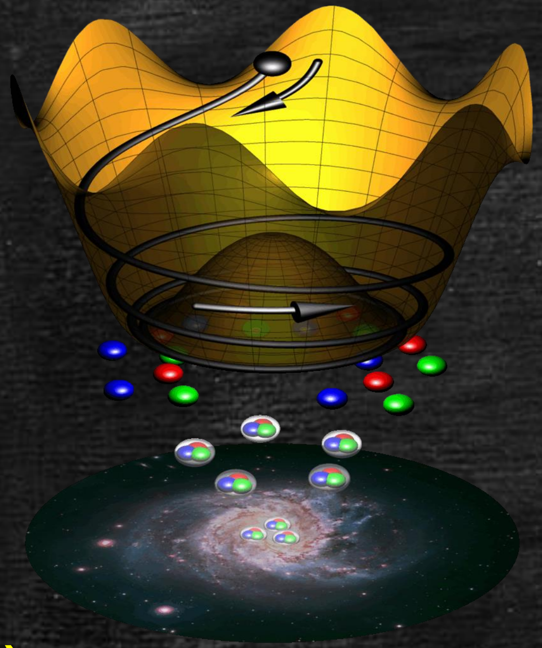
Jihn Eui Kim

born on

July 30th 1946

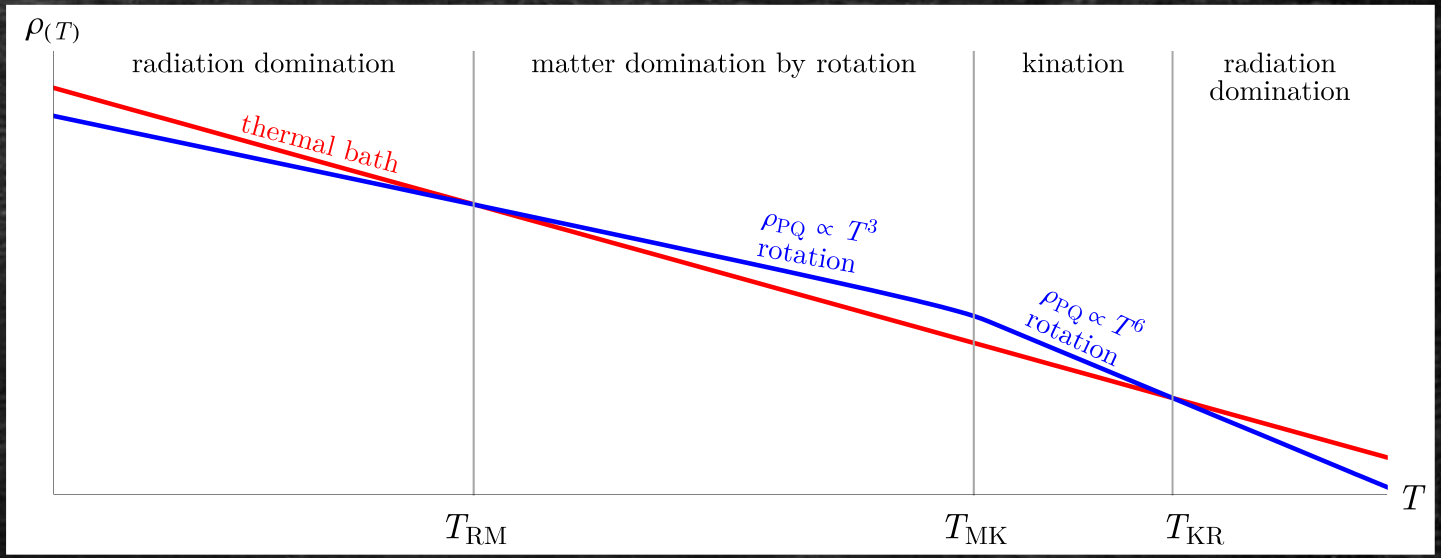
https://en.wikipedia.org/wiki/Kim_Jihn-eui

Summary of the Talk



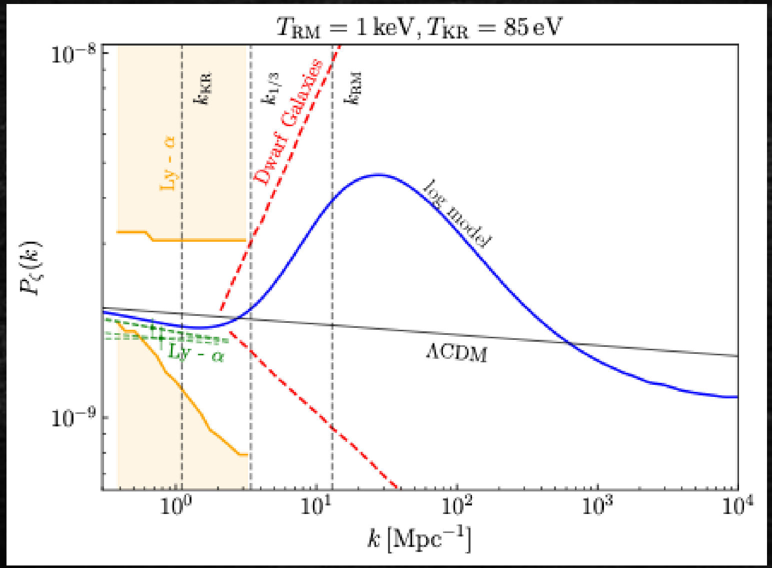
1) Axion Rotation

2) Kination cosmology

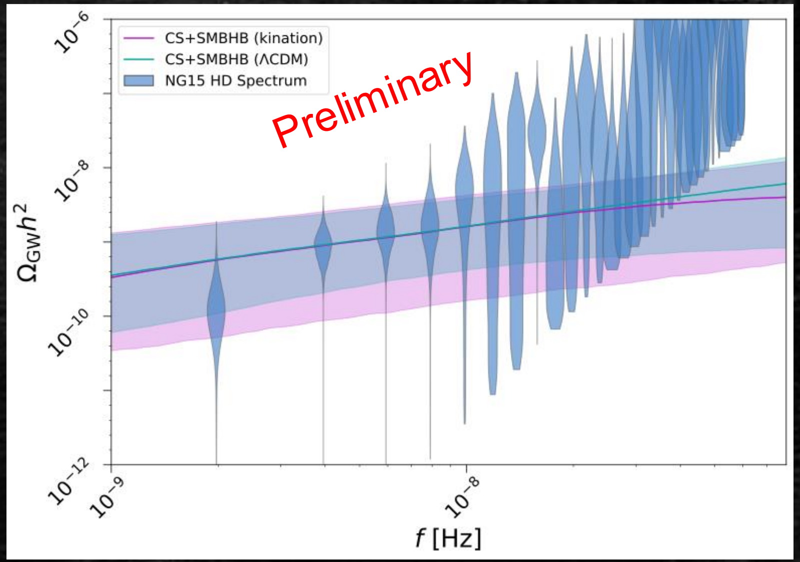


3)

Enhanced matter power spectrum



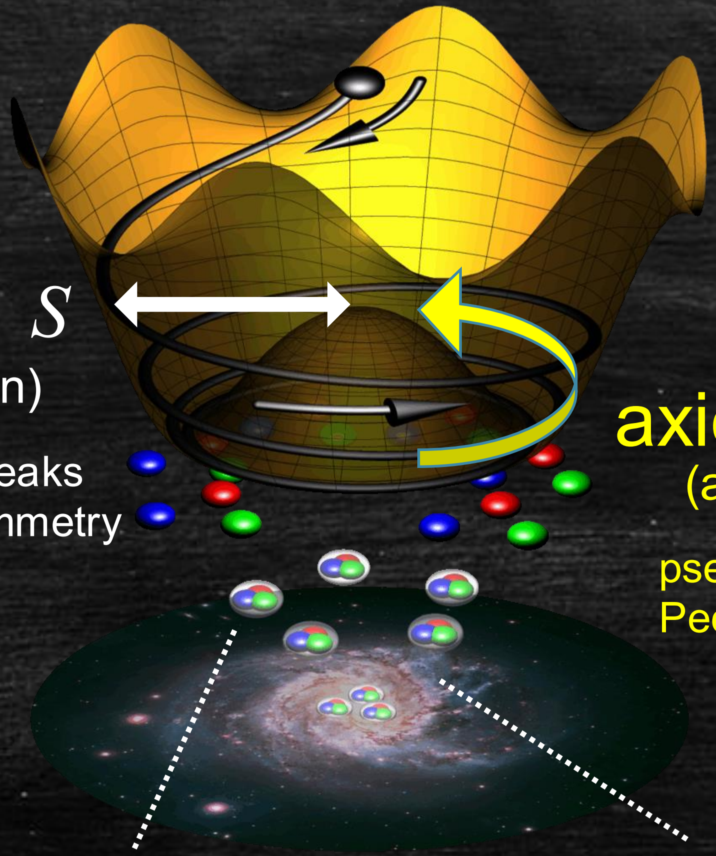
Enhanced gravitational waves

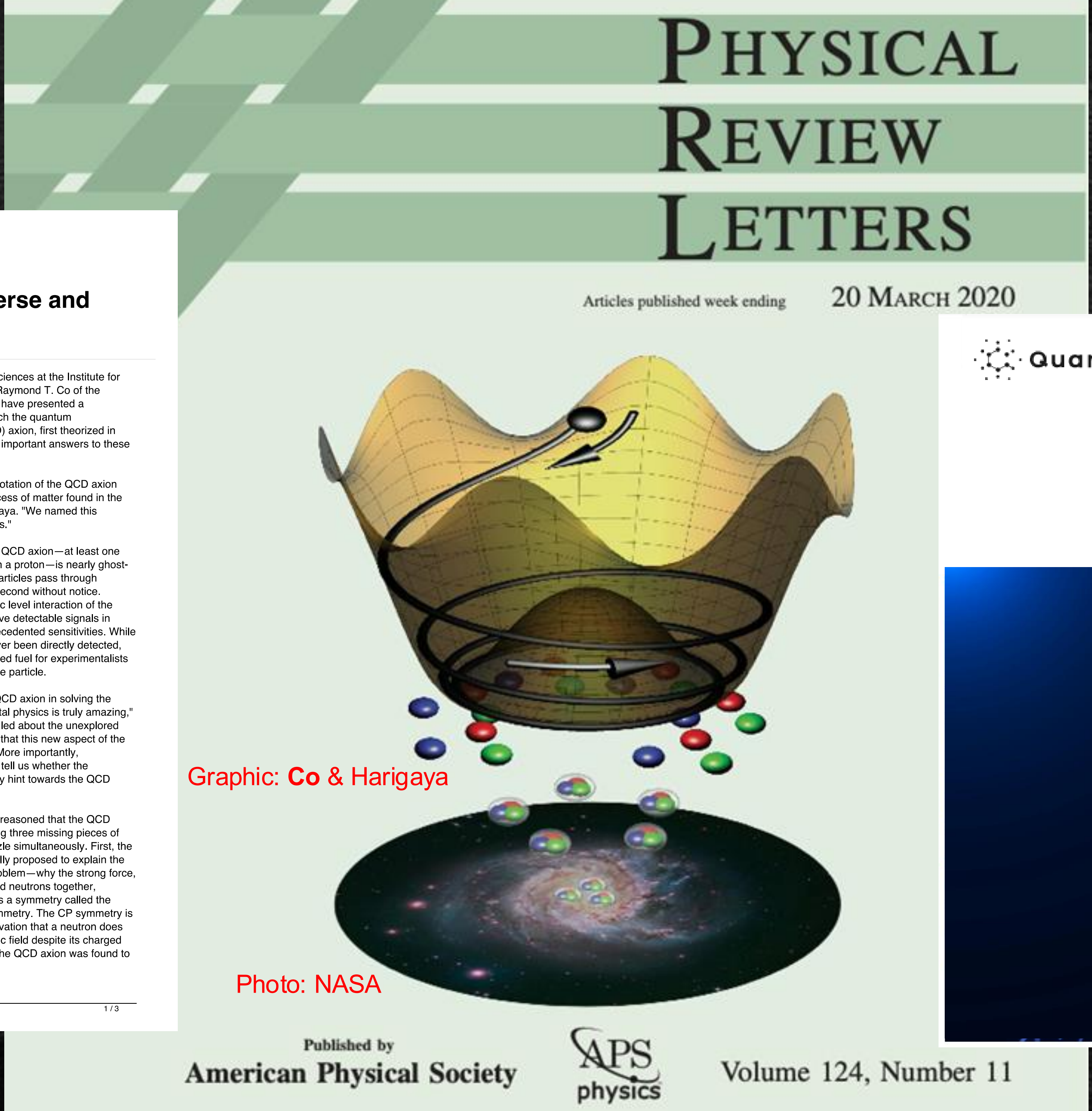


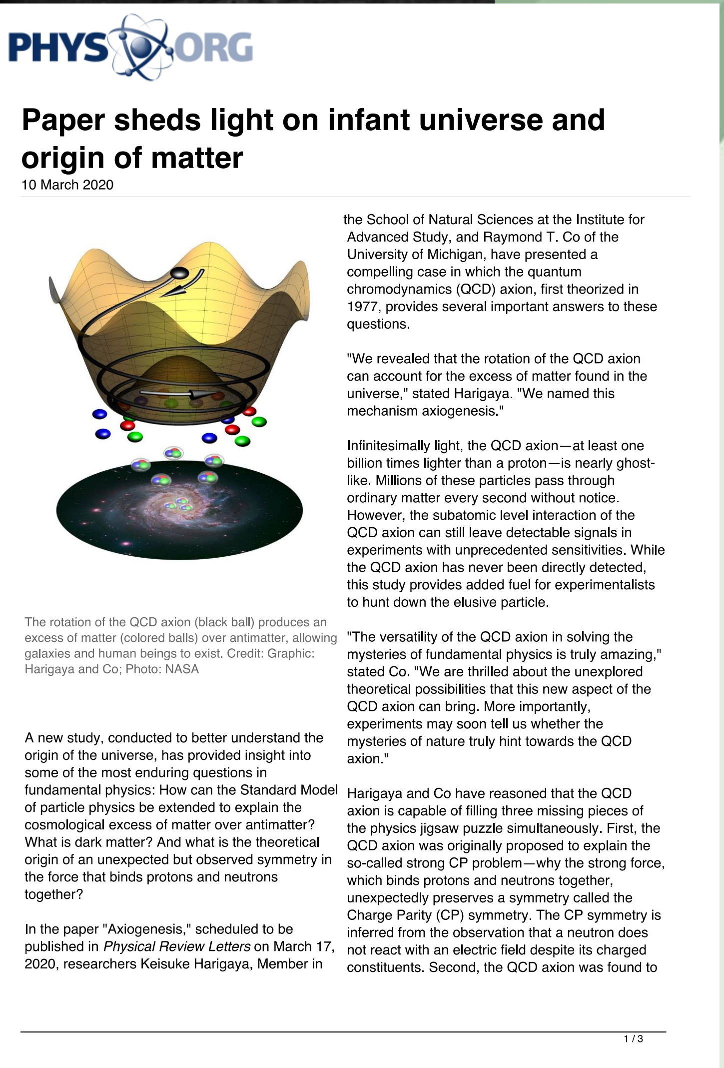
Axion Rotation

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi}\frac{a}{f_a}G_b^{\mu\nu}\widetilde{G}_{b\mu\nu}$$

$$P = \frac{S+f_a}{\sqrt{2}}e^{i\frac{a}{f_a}}$$







PHYS.ORG

Paper sheds light on infant universe and origin of matter

10 March 2020

The rotation of the QCD axion (black ball) produces an excess of matter (colored balls) over antimatter, allowing galaxies and human beings to exist. Credit: Graphic: Harigaya and Co; Photo: NASA

A new study, conducted to better understand the origin of the universe, has provided insight into some of the most enduring questions in fundamental physics: How can the Standard Model of particle physics be extended to explain the cosmological excess of matter over antimatter? What is dark matter? And what is the theoretical origin of an unexpected but observed symmetry in the force that binds protons and neutrons together?

In the paper "Axiogenesis," scheduled to be published in *Physical Review Letters* on March 17, 2020, researchers Keisuke Harigaya, Member in the School of Natural Sciences at the Institute for Advanced Study, and Raymond T. Co of the University of Michigan, have presented a compelling case in which the quantum chromodynamics (QCD) axion, first theorized in 1977, provides several important answers to these questions.

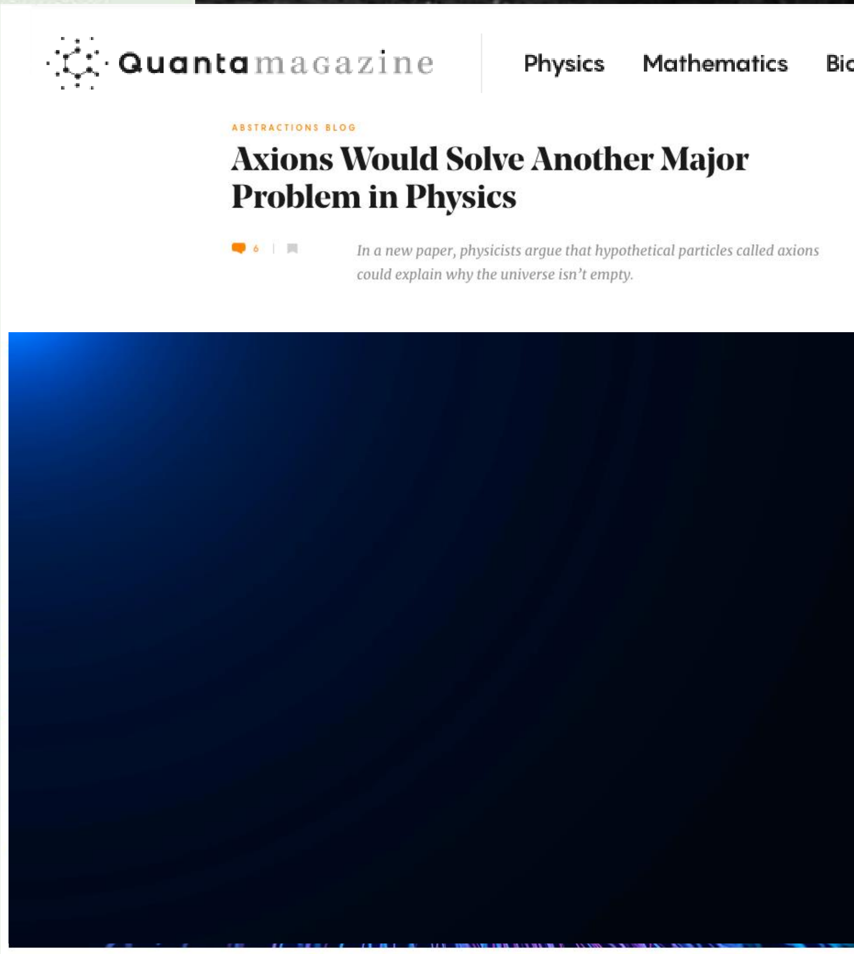
"We revealed that the rotation of the QCD axion can account for the excess of matter found in the universe," stated Harigaya. "We named this mechanism axiogenesis."

Infinitesimally light, the QCD axion—at least one billion times lighter than a proton—is nearly ghost-like. Millions of these particles pass through ordinary matter every second without notice. However, the subatomic level interaction of the QCD axion can still leave detectable signals in experiments with unprecedented sensitivities. While the QCD axion has never been directly detected, this study provides added fuel for experimentalists to hunt down the elusive particle.

"The versatility of the QCD axion in solving the mysteries of fundamental physics is truly amazing," stated Co. "We are thrilled about the unexplored theoretical possibilities that this new aspect of the QCD axion can bring. More importantly, experiments may soon tell us whether the mysteries of nature truly hint towards the QCD axion."

Harigaya and Co have reasoned that the QCD axion is capable of filling three missing pieces of the physics jigsaw puzzle simultaneously. First, the QCD axion was originally proposed to explain the so-called strong CP problem—why the strong force, which binds protons and neutrons together, unexpectedly preserves a symmetry called the Charge Parity (CP) symmetry. The CP symmetry is inferred from the observation that a neutron does not react with an electric field despite its charged constituents. Second, the QCD axion was found to

1 / 3



Quanta magazine | Physics | Mathematics | Bio

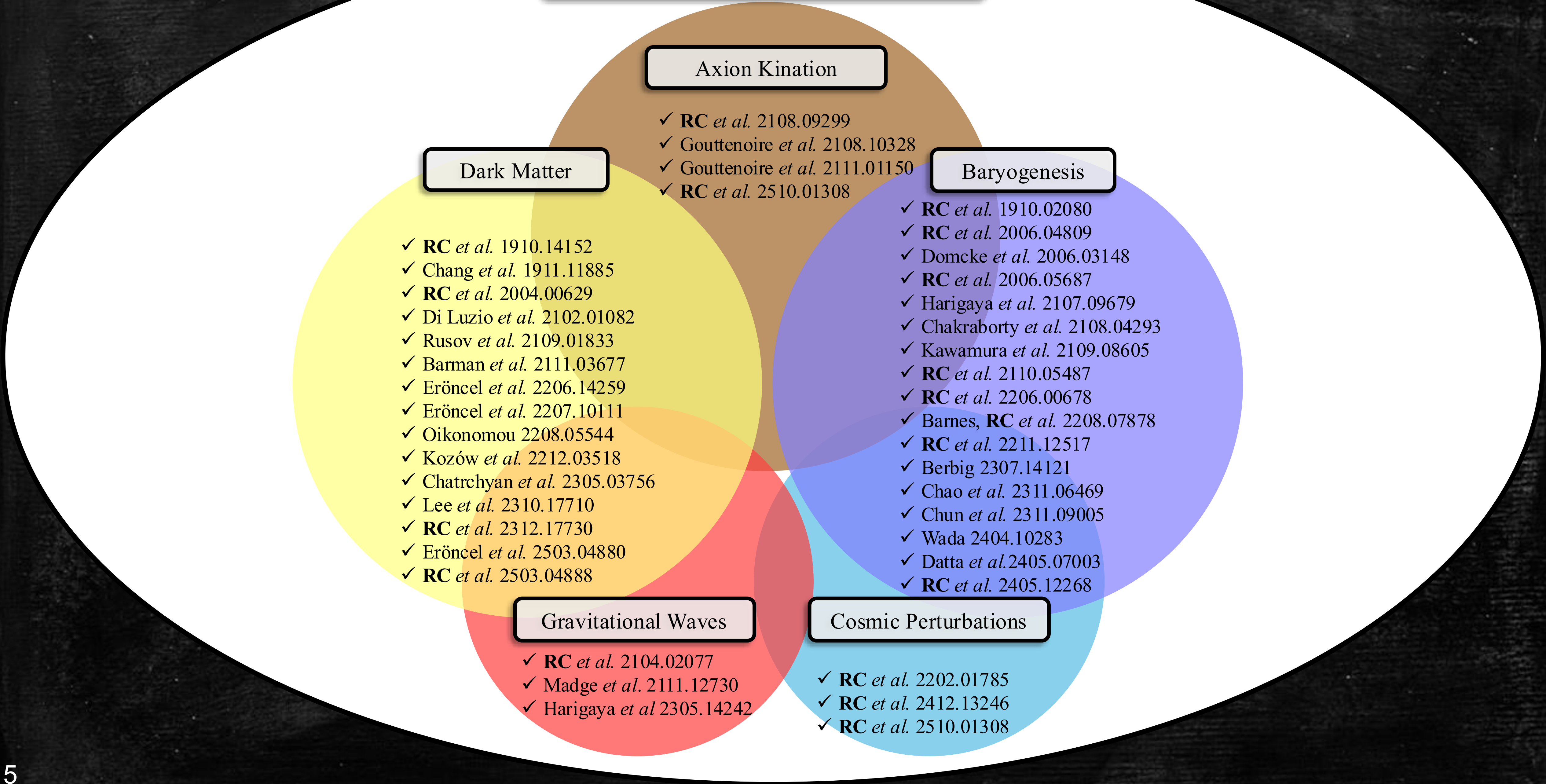
ABSTRACTIONS BLOG

Axions Would Solve Another Major Problem in Physics

6

In a new paper, physicists argue that hypothetical particles called axions could explain why the universe isn't empty.

Axion Rotations



Axion Rotations

Axion Kination

- ✓ **RC** *et al.* 2108.09299
- ✓ Gouttenoire *et al.* 2108.10328
- ✓ Gouttenoire *et al.* 2111.01150
- ✓ **RC** *et al.* 2510.01308

Dark Matter

- ✓ **RC** *et al.* 1910.14152
- ✓ Chang *et al.* 1911.11885
- ✓ **RC** *et al.* 2004.00629
- ✓ Di Luzio *et al.* 2102.01082
- ✓ Rusov *et al.* 2109.01833
- ✓ Barman *et al.* 2111.03677
- ✓ Eröncel *et al.* 2206.14259
- ✓ Eröncel *et al.* 2207.10111
- ✓ Oikonomou 2208.05544
- ✓ Kozów *et al.* 2212.03518
- ✓ Chatrchyan *et al.* 2305.03756
- ✓ Lee *et al.* 2310.17710
- ✓ **RC** *et al.* 2312.17730
- ✓ Eröncel *et al.* 2503.04880
- ✓ **RC** *et al.* 2503.04888

Baryogenesis

- ✓ **RC** *et al.* 1910.02080
- ✓ **RC** *et al.* 2006.04809
- ✓ Domcke *et al.* 2006.03148
- ✓ **RC** *et al.* 2006.05687
- ✓ Harigaya *et al.* 2107.09679
- ✓ Chakraborty *et al.* 2108.04293
- ✓ Kawamura *et al.* 2109.08605
- ✓ **RC** *et al.* 2110.05487
- ✓ **RC** *et al.* 2206.00678
- ✓ Barnes, **RC** *et al.* 2208.07878
- ✓ **RC** *et al.* 2211.12517
- ✓ Berbig 2307.14121
- ✓ Chao *et al.* 2311.06469
- ✓ Chun *et al.* 2311.09005
- ✓ Wada 2404.10283
- ✓ Datta *et al.*2405.07003
- ✓ **RC** *et al.* 2405.12268

Gravitational Waves

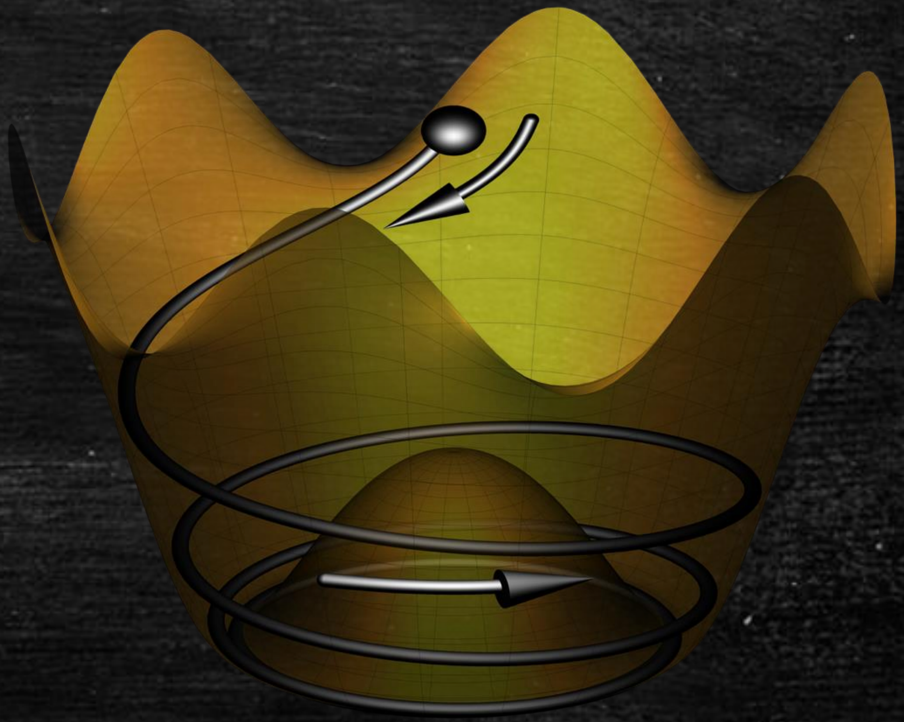
- ✓ **RC** *et al.* 2104.02077
- ✓ Madge *et al.* 2111.12730
- ✓ Harigaya *et al* 2305.14242

Cosmic Perturbations

- ✓ **RC** *et al.* 2202.01785
- ✓ **RC** *et al.* 2412.13246
- ✓ **RC** *et al.* 2510.01308

Why Rotation?

$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}}$$



Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

PRL 92, 011301 (2004) T. Chiba, F. Takahashi, M. Yamaguchi

PRL 124, 111602 (2020) RC and K. Harigaya

Why Rotation?

Wiggles :

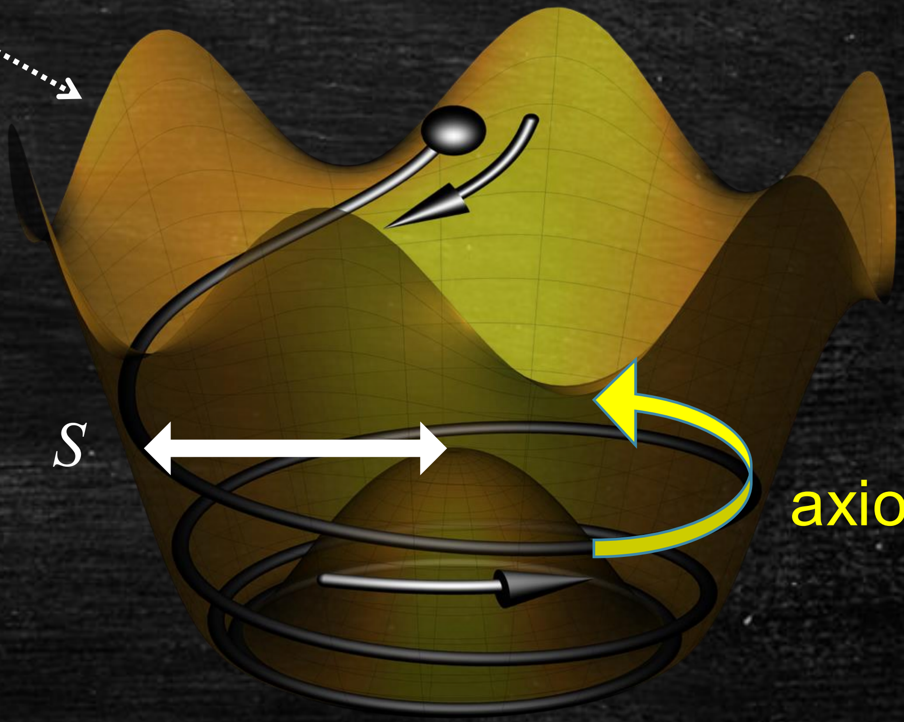
$$V(P) \sim \frac{P^n}{M^{n-4}} e^{i\varphi} + \mathrm{h.c.} \sim \frac{|P|^n}{M^{n-4}} \cos\left(n\frac{a}{f_a} + \varphi\right)$$

$$P = \frac{S + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$

Explicit PQ breaking

expected from quantum gravity
or PQ as an accidental symmetry

S. Giddings et al. 1988
S. Coleman 1988
G. Gilbert 1988



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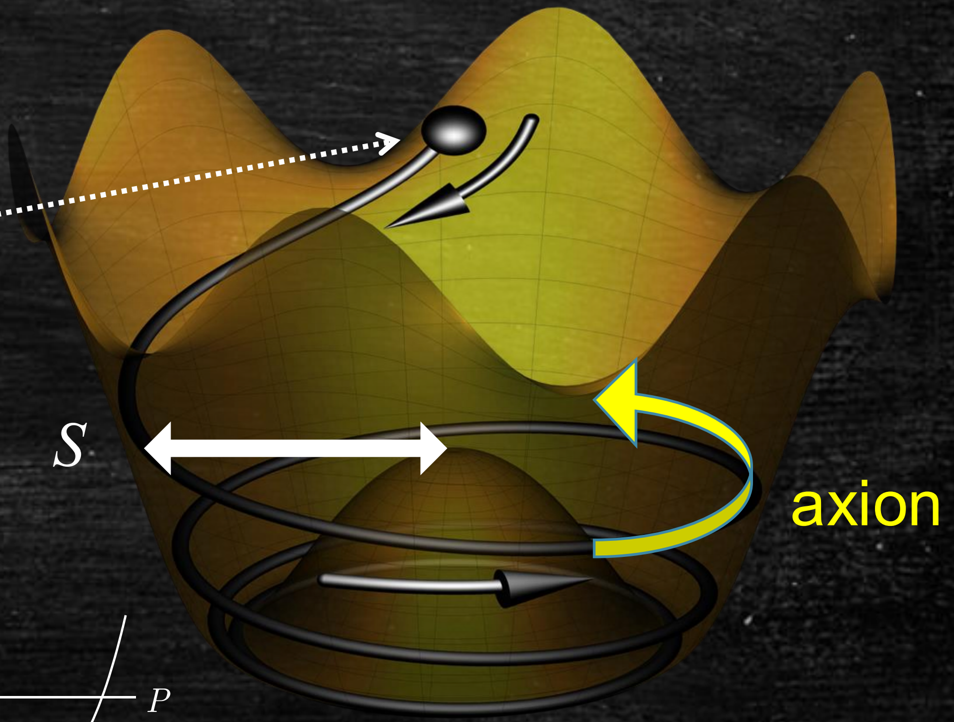
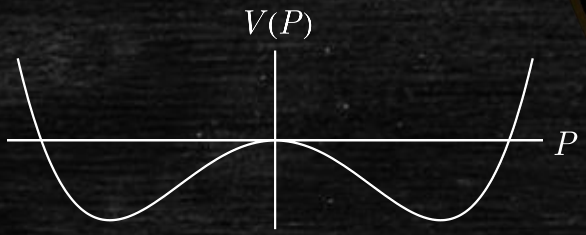


Large field value :

Flat potential

For example, as an initial condition or
set dynamically by inflationary dynamics

$$V(|P|) \sim \underbrace{-H_I^2|P|^2}_{\text{Hubble-induced mass}} + \frac{|P|^d}{M^{d-4}}$$



M. Dine, L. Randall, and S. D. Thomas 1991

Dynamics analogous to that in Affleck-Dine baryogenesis

I. Affleck and M. Dine 1991

PRL 92, 011301 (2004) T. Chiba, F. Takahashi, M. Yamaguchi
PRL 124, 111602 (2020) RC and K. Harigaya

Axion Kination

Asymmetry of PQ Charge

Noether charge associated with the shift symmetry

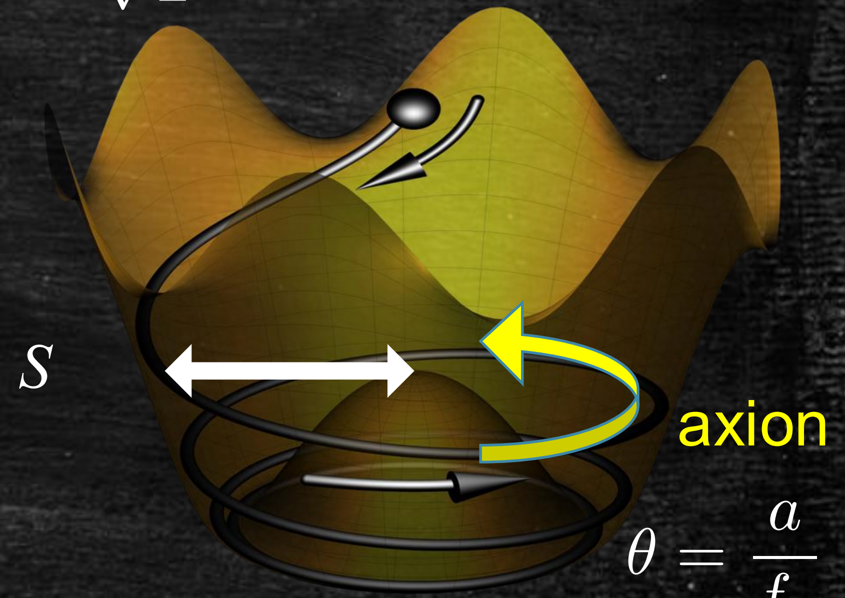
$$n_\theta = S^2 \dot{\theta}$$

this is nothing but
"angular momentum" $r^2 \omega$

PQ asymmetry
PQ charge density = Rotation of PQ field

This is conserved soon after the initial kick.

$$P = \frac{S + f_a}{\sqrt{2}} e^{i \frac{a}{f_a}}$$



$$\theta = \frac{a}{f_a}$$

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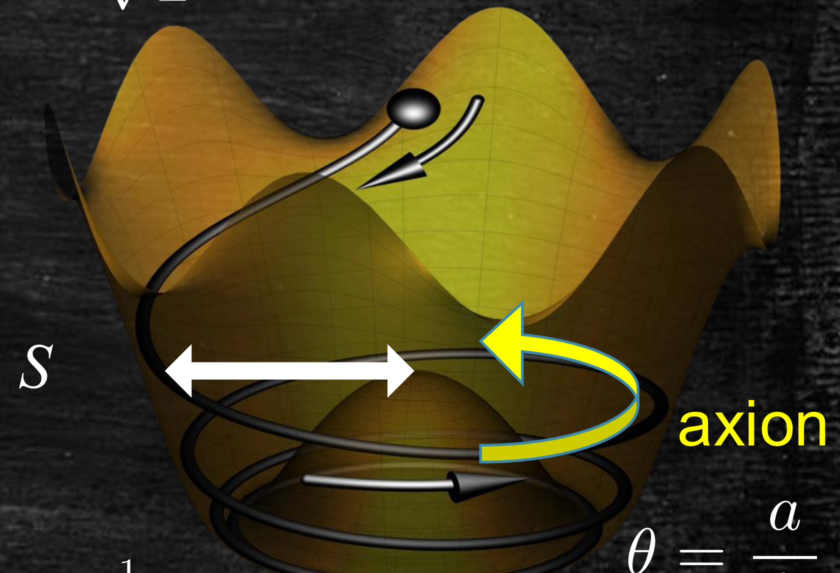


$$\theta = \frac{a}{f_a}$$

What determines $\dot{\theta}$? Centripetal force!

$$F_c = m a_c$$

$$V'(S) = S\dot{\theta}^2$$

$$m_S^2 S = S\dot{\theta}^2$$

$V(S) \simeq \frac{1}{2} m_S^2 S^2$

from supersymmetry

$$\dot{\theta} = m_S$$ which is in turn set by supersymmetry scale.

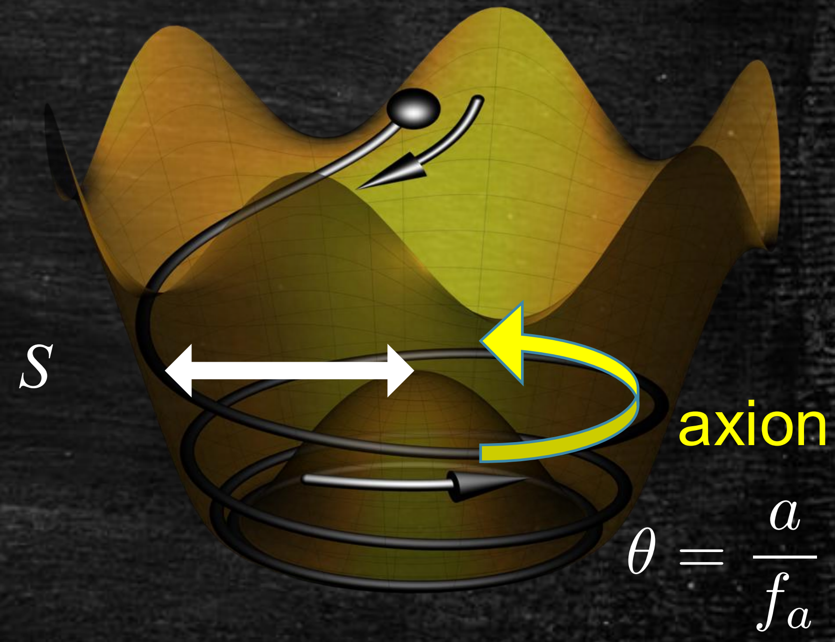
PQ Charge Evolution

Charge conservation:

scale factor of the universe

$$n_\theta = S^2 \dot{\theta} \propto \underline{R^{-3}}$$

dilution due to
cosmic expansion



PRL 124, 111602 (2020) RC and K. Harigaya

PQ Charge Evolution

Charge conservation:

scale factor of the universe

$$n_\theta = S^2 \dot{\theta} \propto \underline{R^{-3}}$$

dilution due to cosmic expansion

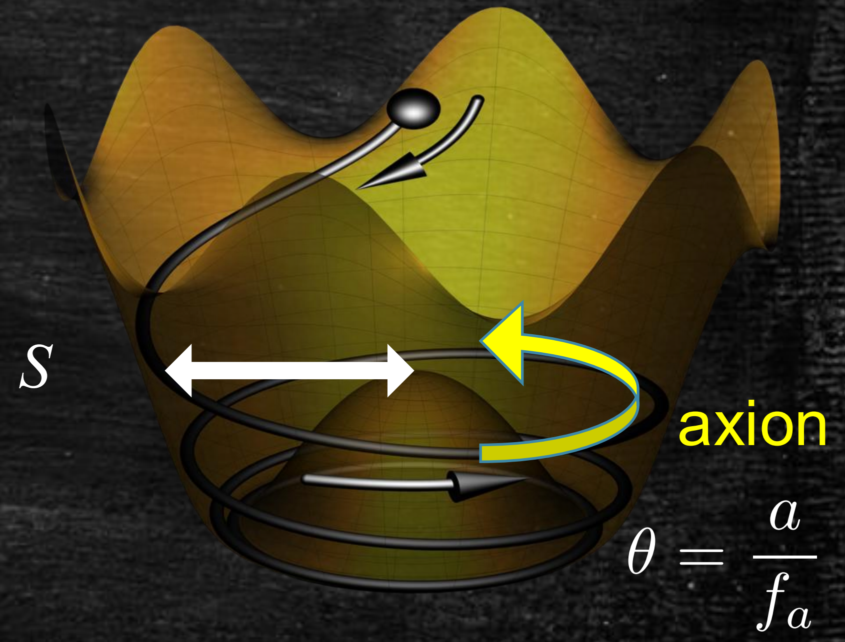
Large field ($S \gg f_a$):

$$S^2 \propto R^{-3} \qquad \dot{\theta} = \text{constant}$$

for quadratic potential
$V(S) \simeq \frac{1}{2} m_S^2 S^2$

$$\rho_\theta = \dot{\theta}^2 S^2 \propto R^{-3}$$

matter



At the minimum:

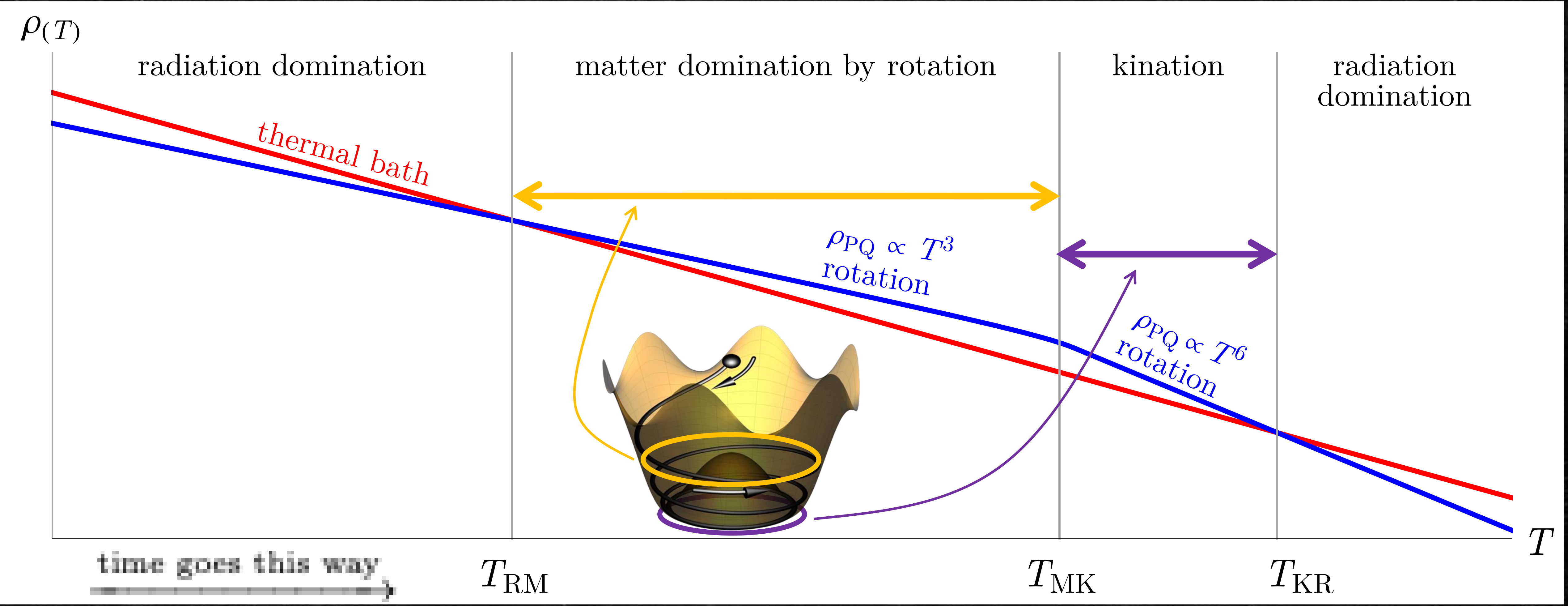
$$S^2 = f_a^2 \qquad \dot{\theta} \propto R^{-3}$$

$$\rho_\theta = \dot{\theta}^2 f_a^2 \propto R^{-6}$$

kination

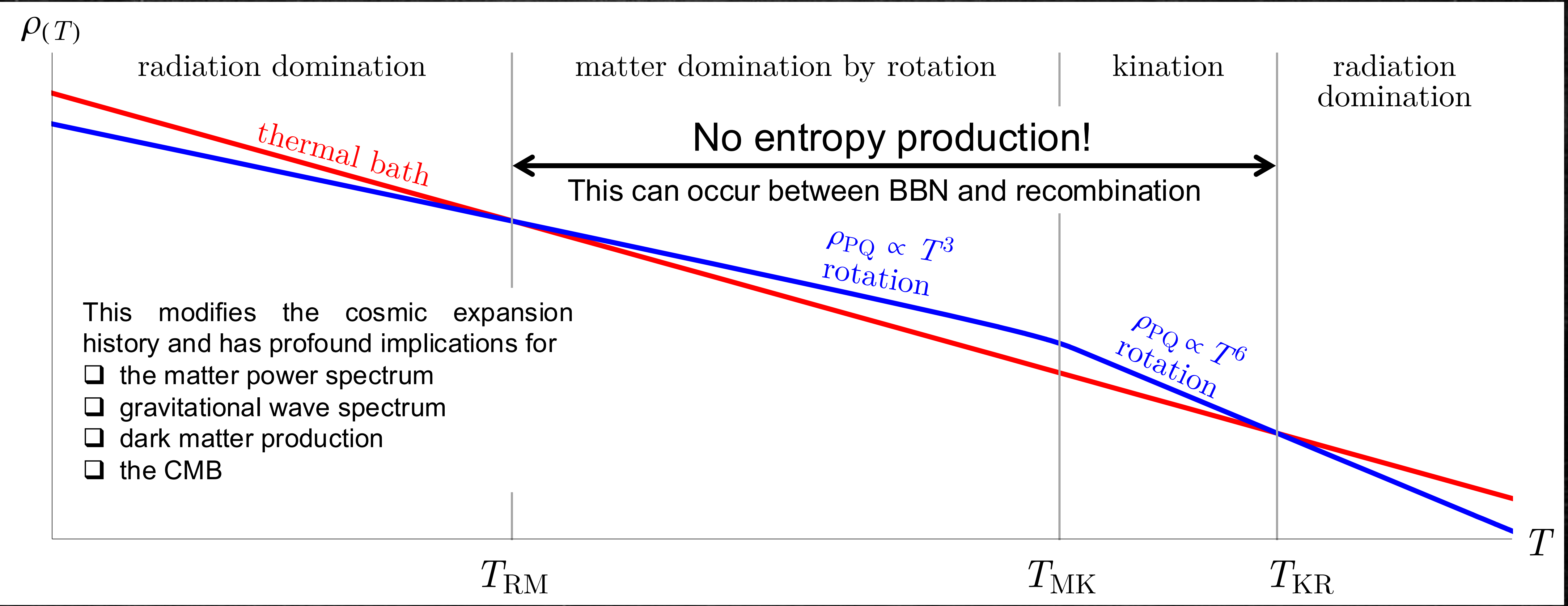
PRL 124, 111602 (2020) RC and K. Harigaya

Axion Rotations



2405.12268 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton

Evolution of Energy Densities



PQ-breaking Potential

Piecewise approximation

$$\rho_\theta \propto \begin{cases} R^{-3} & \text{for} \quad S \gg f_a \quad i.e. \quad T \gg T_{\rm MK} \\ R^{-6} & \text{for} \quad S \simeq f_a \quad i.e. \quad T \ll T_{\rm MK} \end{cases}$$

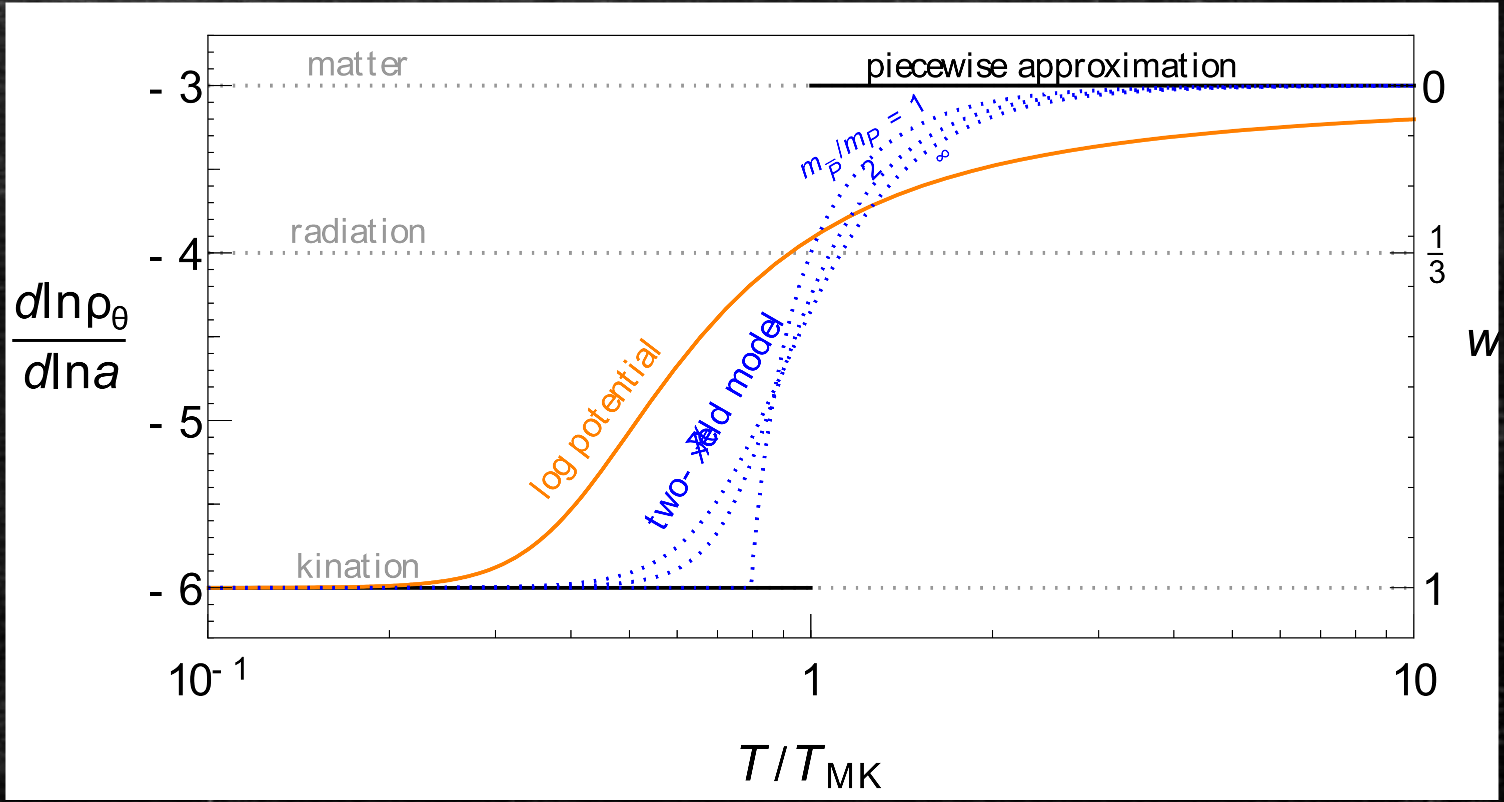
log potential

$$V(P) = m_S^2 |P|^2 \left(\ln \frac{2|P|^2}{f_a^2} - 1 \right)$$

Two-field model

$$W = X(P\bar{P} - v_P^2)$$

$$V_{\rm soft} = m_P^2 |P|^2 + m_{\bar{P}}^2 |\bar{P}|^2$$



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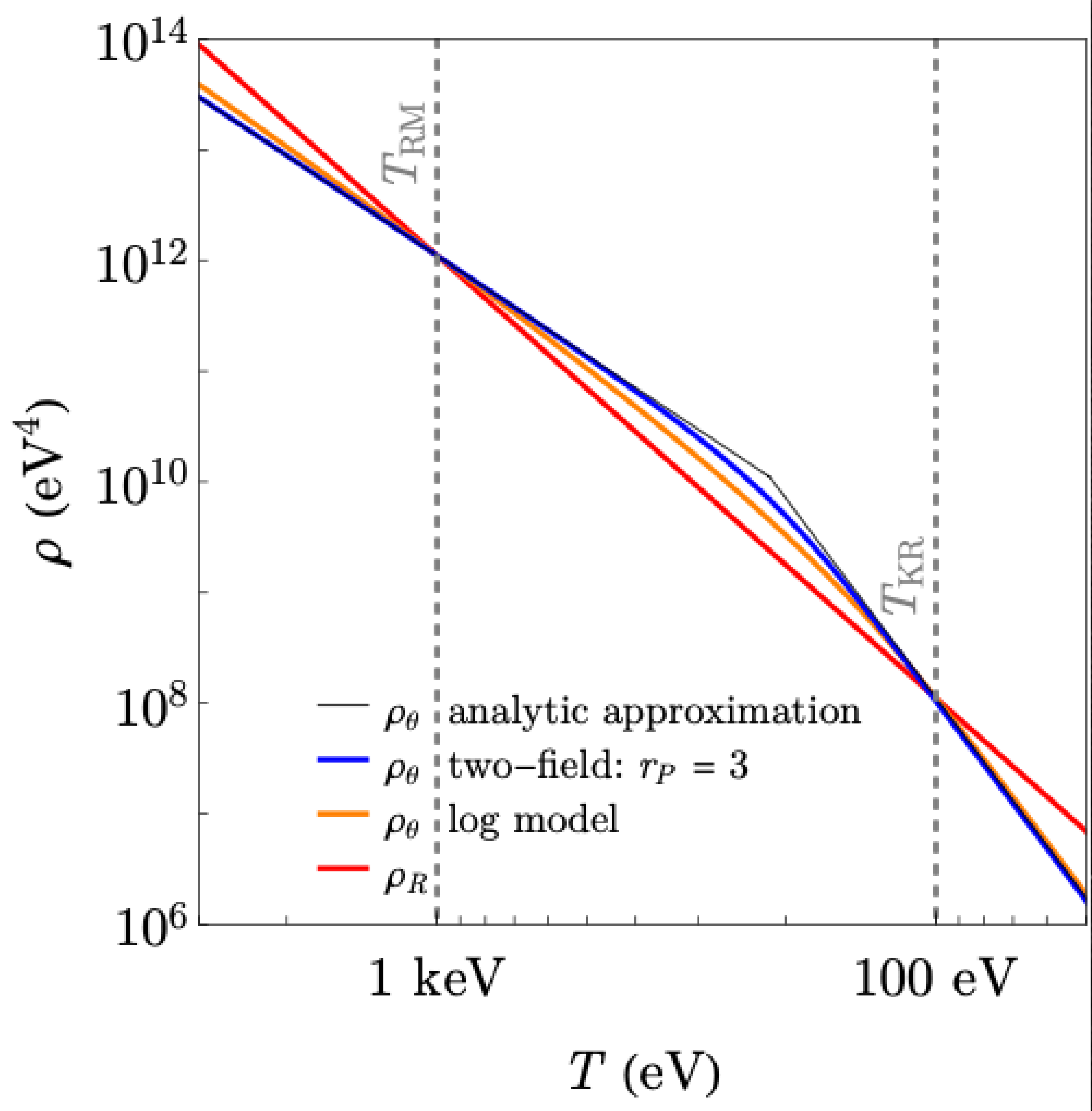
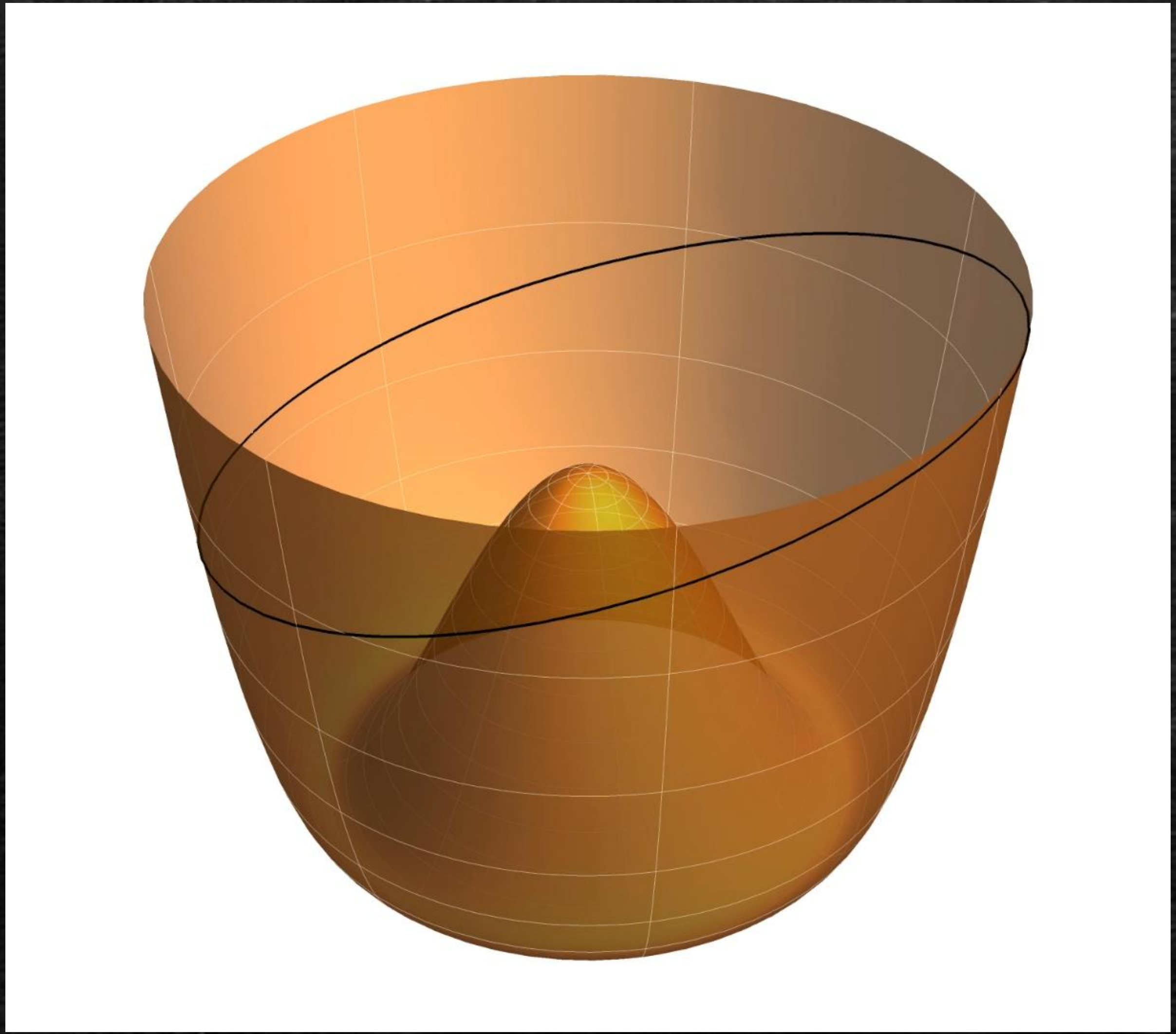


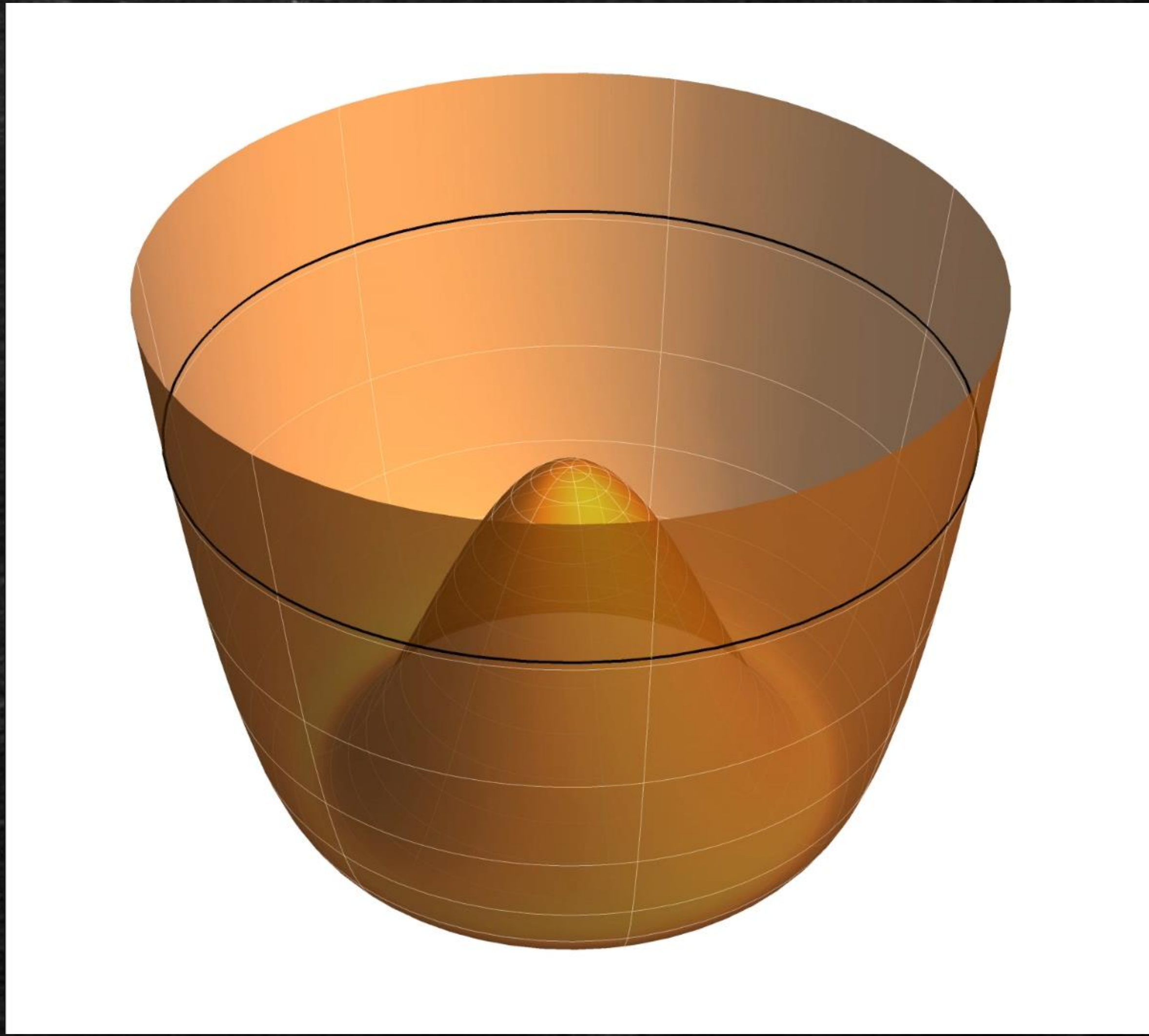
Technical Detail #2

Perfect circular motion from thermalization

Thermalization

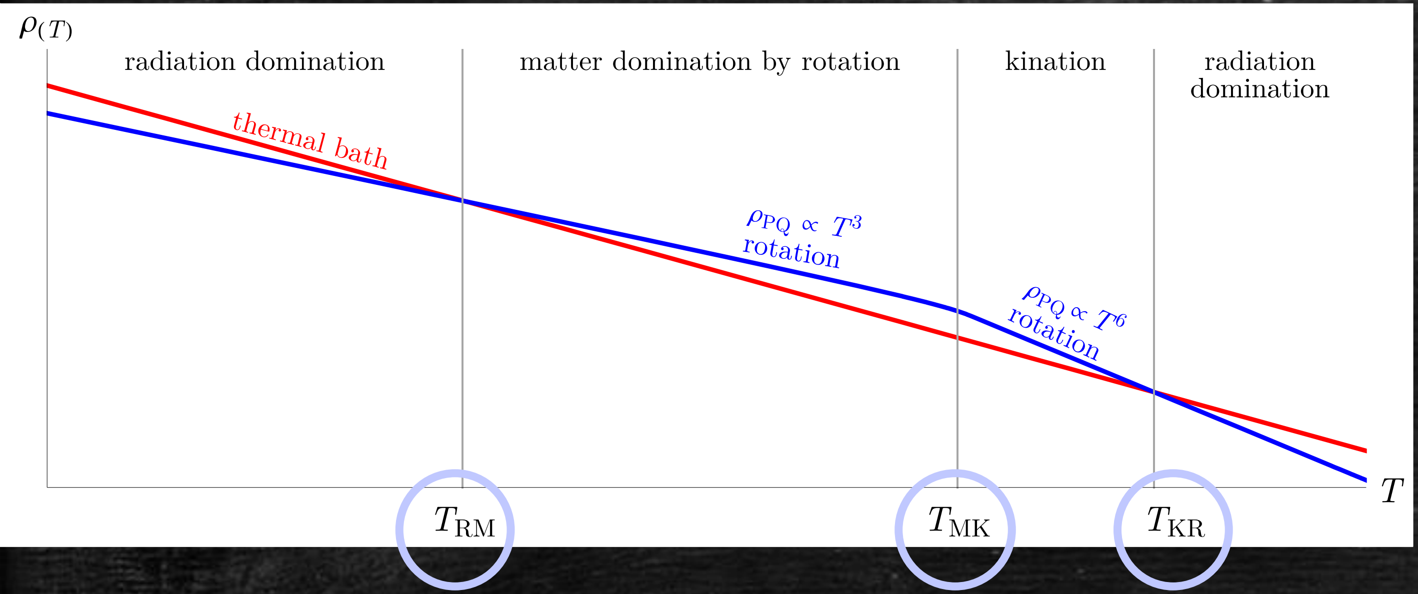


Redshift



PRL 124, 111602 (2020) RC and K. Harigaya

Relevant Temperatures



$$T_{\rm RM} = \frac{4}{3} m_S Y_\theta \simeq 10^7 \text{ GeV} \left(\frac{m_S}{100 \text{ TeV}}\right)\left(\frac{Y_\theta}{100}\right)$$

$$T_{\rm MK} = \left(\frac{45}{2\pi^2 g_*}\frac{m_S f_a^2}{Y_\theta}\right)^{\frac{1}{3}} \simeq 3 \times 10^6 \text{ GeV} \left(\frac{m_S}{100 \text{ TeV}}\right)^{\frac{1}{3}}\left(\frac{f_a}{10^9 \text{ GeV}}\right)^{\frac{2}{3}}$$

$$T_{\rm KR} = \frac{3\sqrt{15}}{2\sqrt{g_*}\pi}\frac{f_a}{Y_\theta} \simeq 2 \times 10^6 \text{ GeV} \left(\frac{f_a}{10^9 \text{ GeV}}\right)\left(\frac{100}{Y_\theta}\right)$$

$$T_{\rm MK}^3 = T_{\rm KR}^2 T_{\rm RM}$$

JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

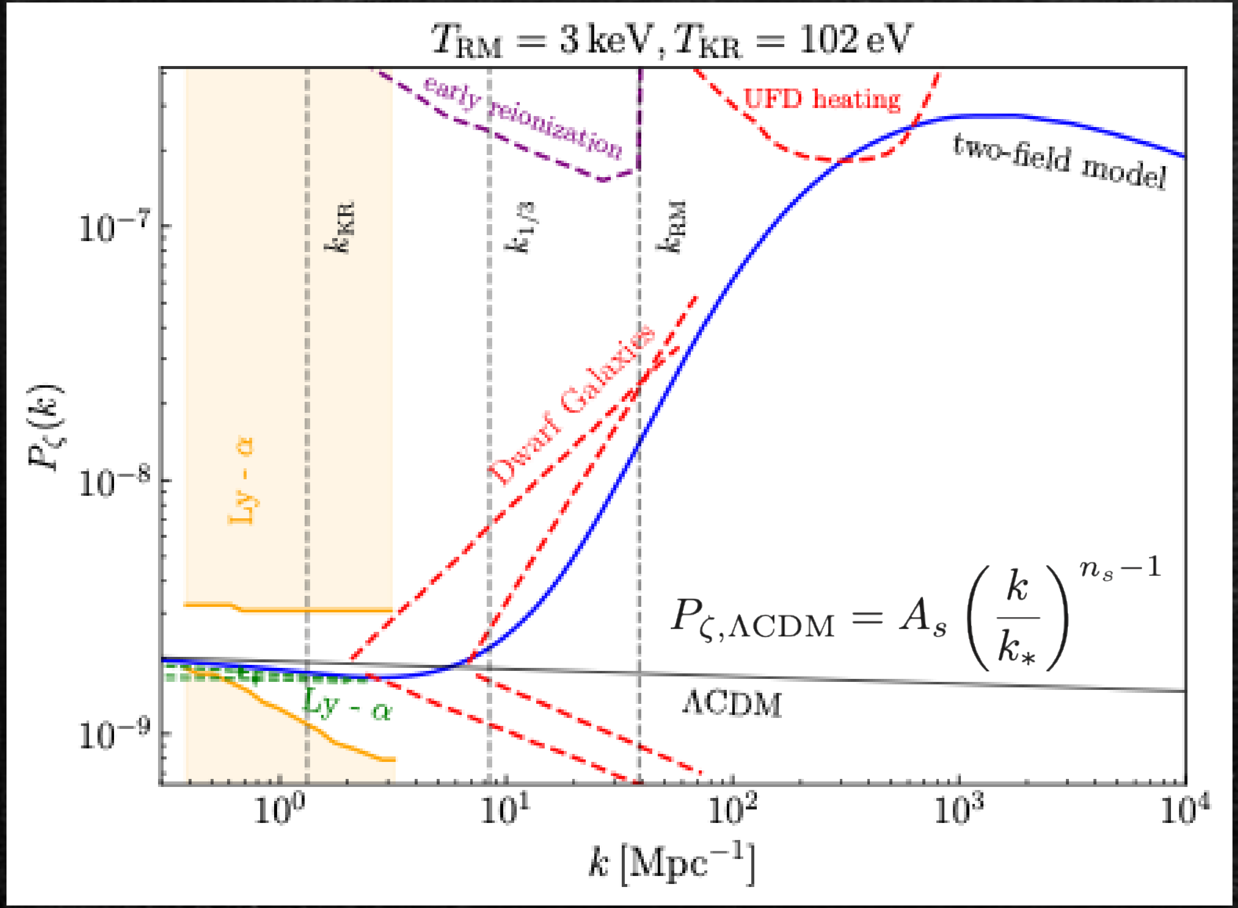
Axion Kination

Matter Power Spectrum

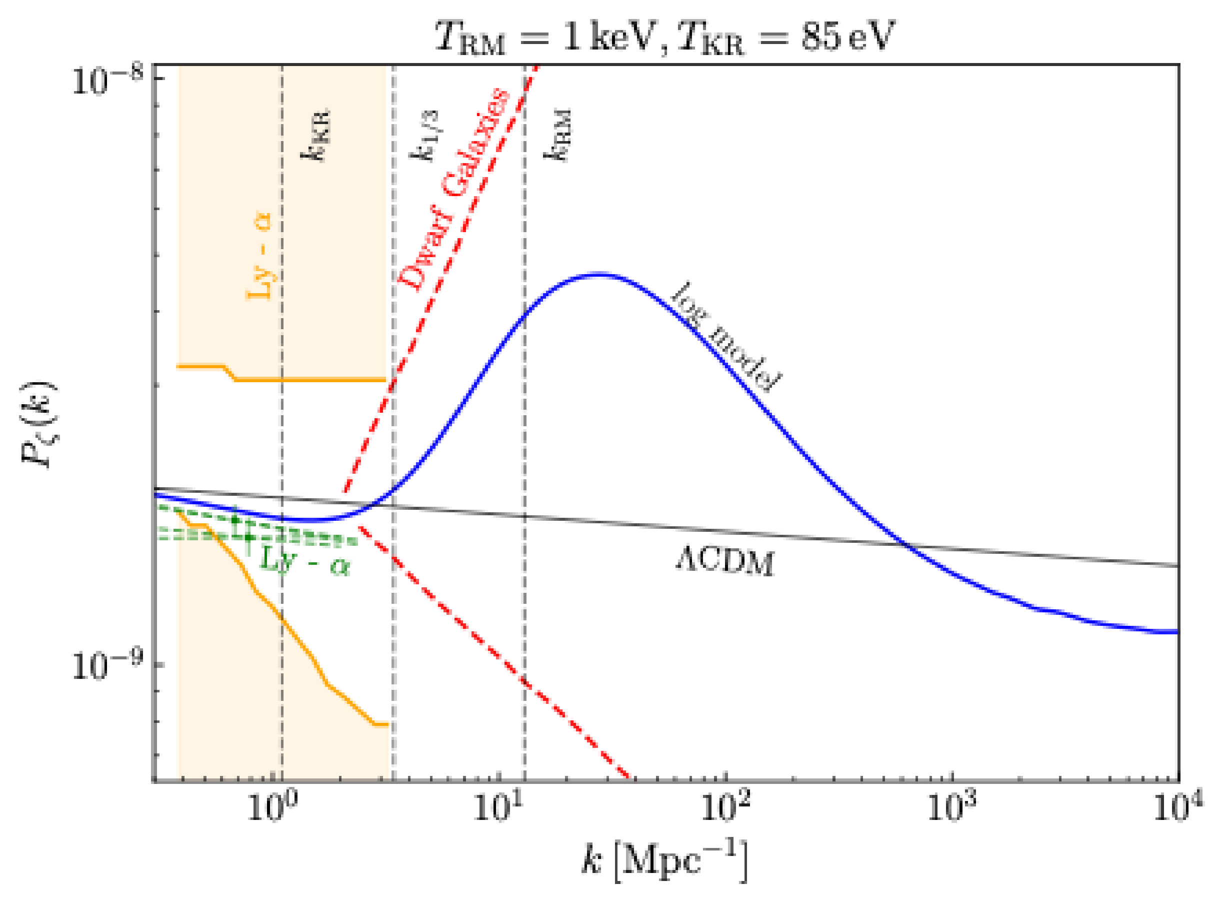
Perturbations

$$P_{\zeta,\mathrm{eff,kin}} = \frac{P_{\mathrm{kin}}(k)}{P_{\Lambda\mathrm{CDM}}(k)} P_{\zeta,\Lambda\mathrm{CDM}}$$

two-field model



log model



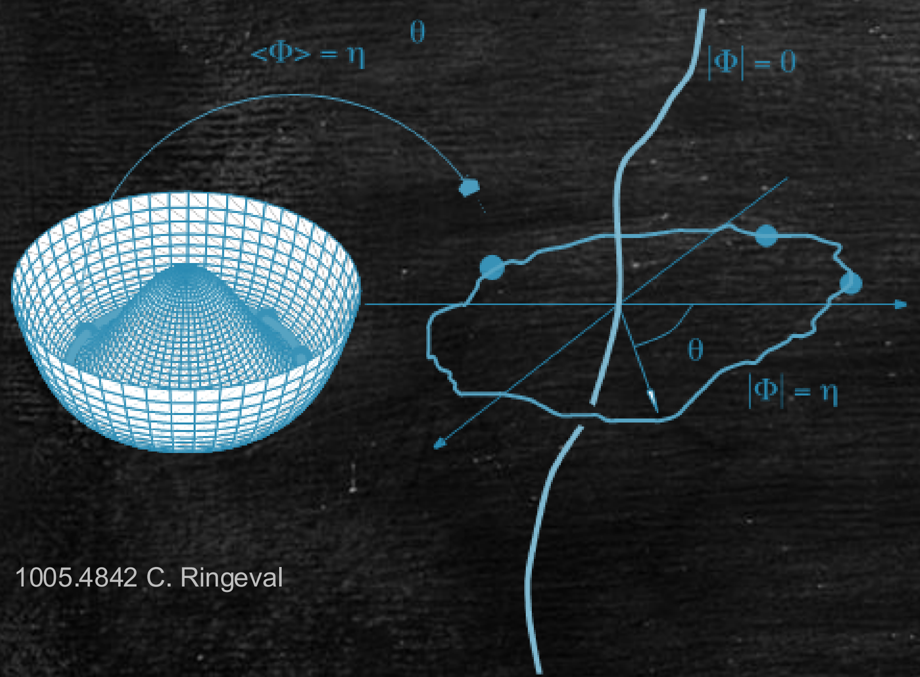
2510.01308 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton

Axion Kination

Gravitational Waves

Gravitational Waves from Cosmic Strings

Gauge symmetry breaking



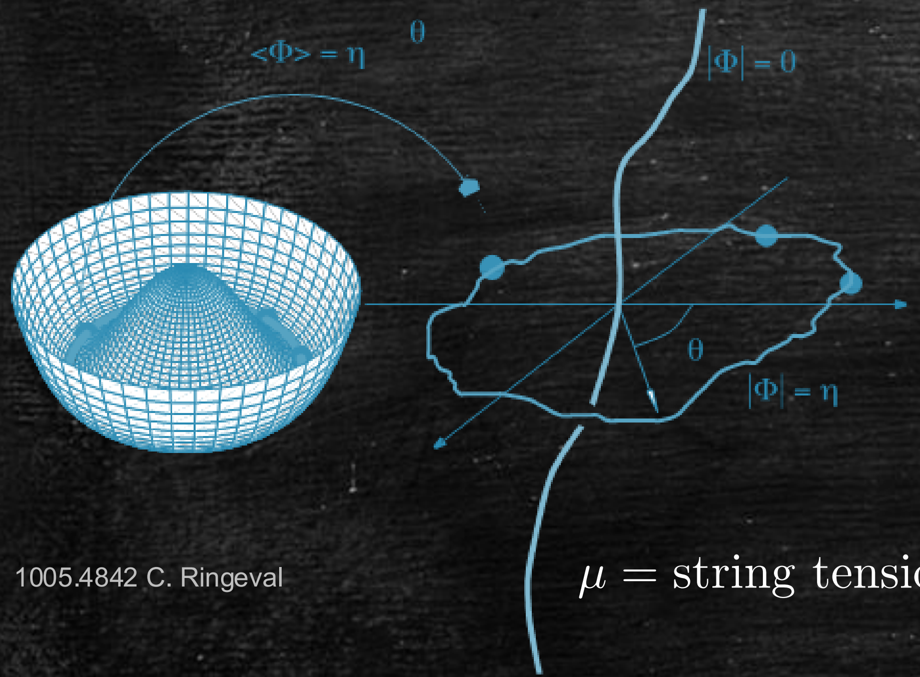
1005.4842 C. Ringeval

Daniel Dominguez/CERN

Energy emitted via GWs

Gravitational Waves from Cosmic Strings

Gauge symmetry breaking



1005.4842 C. Ringeval

$\mu = \text{string tension}$

PRD (1985) T. Vachaspati and A. Vilenkin

$$\rho_{\text{loop}} = \left(\frac{\mu \times \text{length}}{\text{volume}}\right) = \mu \frac{t_{\text{form}}}{t_{\text{form}}^3} = \mu H_{\text{form}}^2 .$$

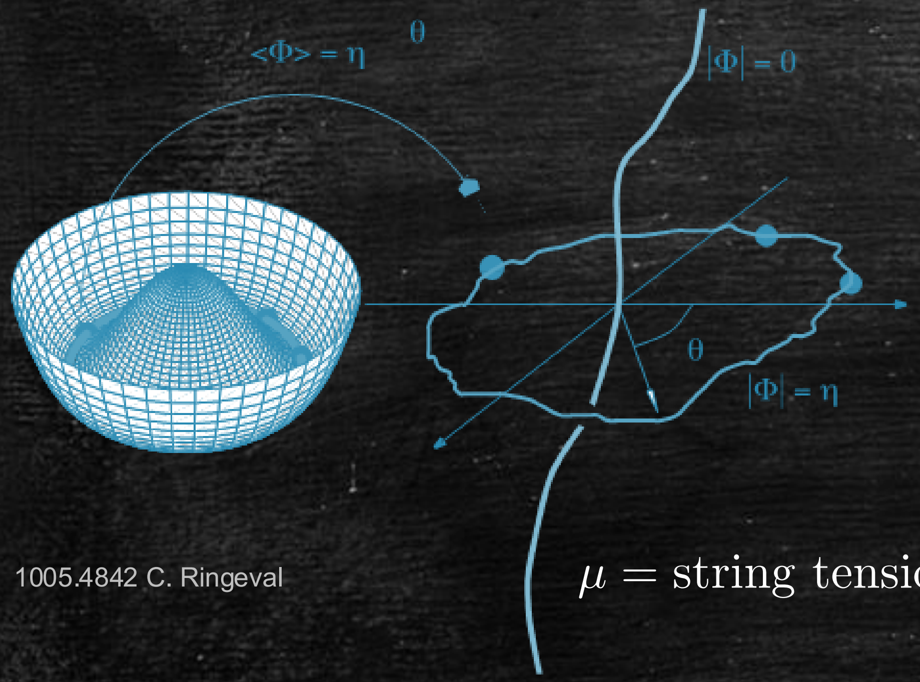
energy/loop

$$t_{\text{decay}} \sim \frac{\mu \alpha t_{\text{form}}}{\Gamma G \mu^2}$$

power emitted

Gravitational Waves from Cosmic Strings

Gauge symmetry breaking



1005.4842 C. Ringeval

$\mu =$ string tension

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$$\rho_{\text{loop}} = \left(\frac{\mu \times \text{length}}{\text{volume}}\right) = \mu \frac{t_{\text{form}}}{t^3_{\text{form}}} = \mu H^2_{\text{form}}.$$

$$\Omega_{\text{GW}} h^2 \sim \Omega_{r,0} \frac{\rho_{\text{loop}}(T_{\text{decay}})}{\rho_r(T_{\text{decay}})}$$

$$\sim \Omega_{r,0} \frac{\rho_{\text{loop}}(T_{\text{form}}) \left(\frac{T_{\text{decay}}}{T_{\text{form}}}\right)^3}{T^4_{\text{decay}}}$$

for RD

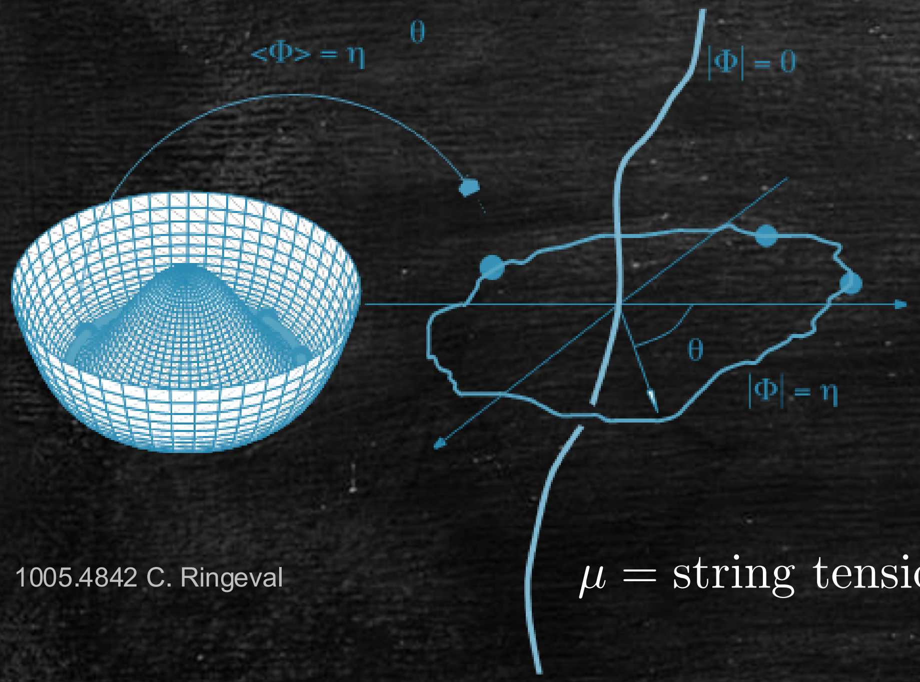
$$t_{\text{decay}} \sim \frac{\overbrace{\mu \alpha t_{\text{form}}}^{\text{energy/loop}}}{\underbrace{\Gamma G \mu^2}_{\text{power emitted}}}$$

$$\sim \Omega_{r,0} \frac{\mu H^2_{\text{form}}}{T_{\text{decay}} T^3_{\text{form}}} \sim \Omega_{r,0} \frac{\mu}{M^2_{\text{Pl}}} \frac{T_{\text{form}}}{T_{\text{decay}}}$$

1. Flat spectrum for radiation domination
2. An enhanced Hubble increases loop energy density.

Gravitational Waves from Cosmic Strings

Gauge symmetry breaking



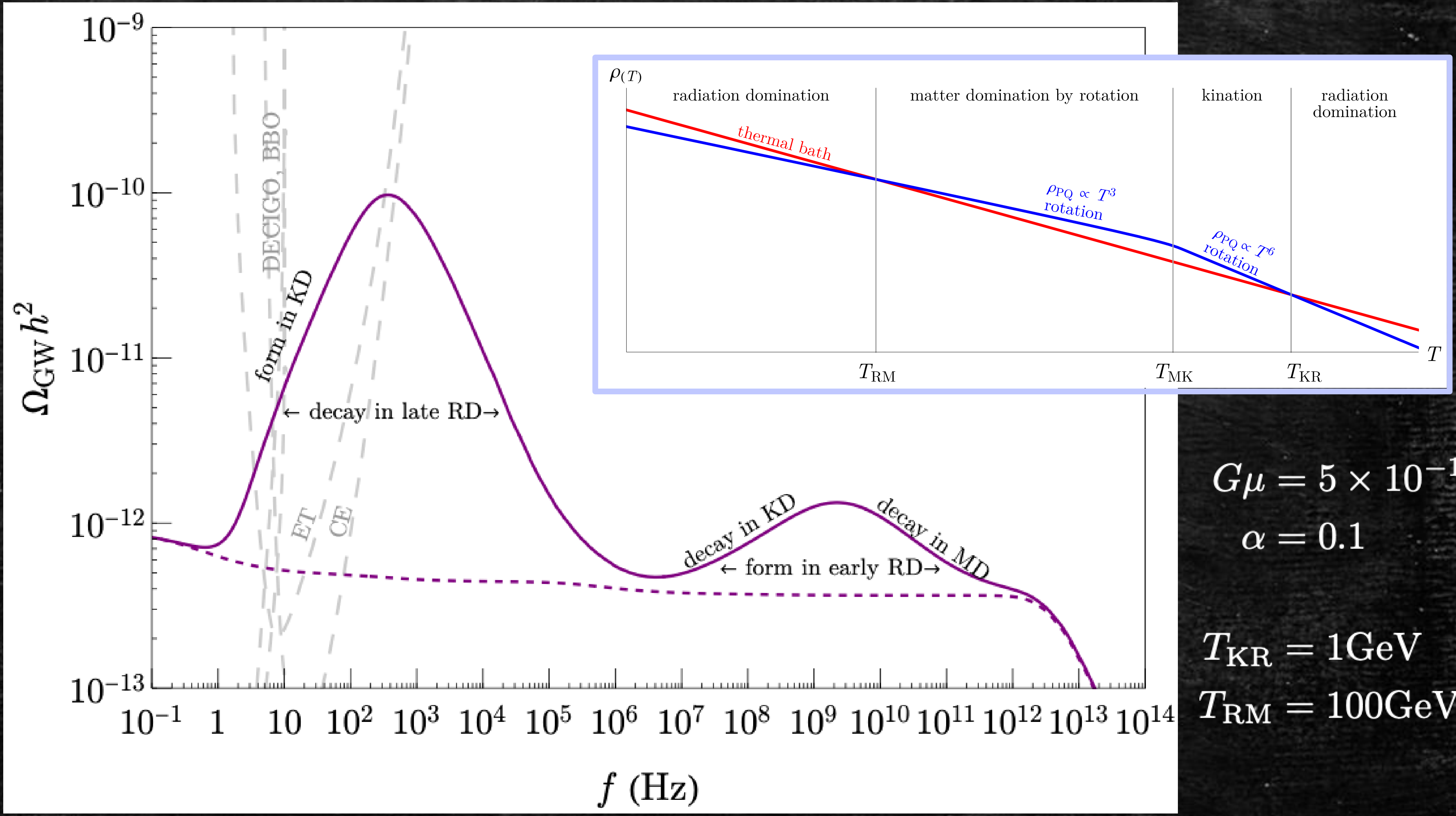
1005.4842 C. Ringeval

$\mu = \text{string tension}$

Loop formation era (columns); Loop decay era (rows)

	Radiation	Matter	Kination
Radiation	f^0	f^{-1}	f^1
Matter	$f^{-1/2}$	f^{-1}	f^1
Kination	$f^{1/4}$	$f^{-1/2}$	f^1

Gravitational Waves from Cosmic Strings



$G\mu = 5 \times 10^{-15}$

$\alpha = 0.1$

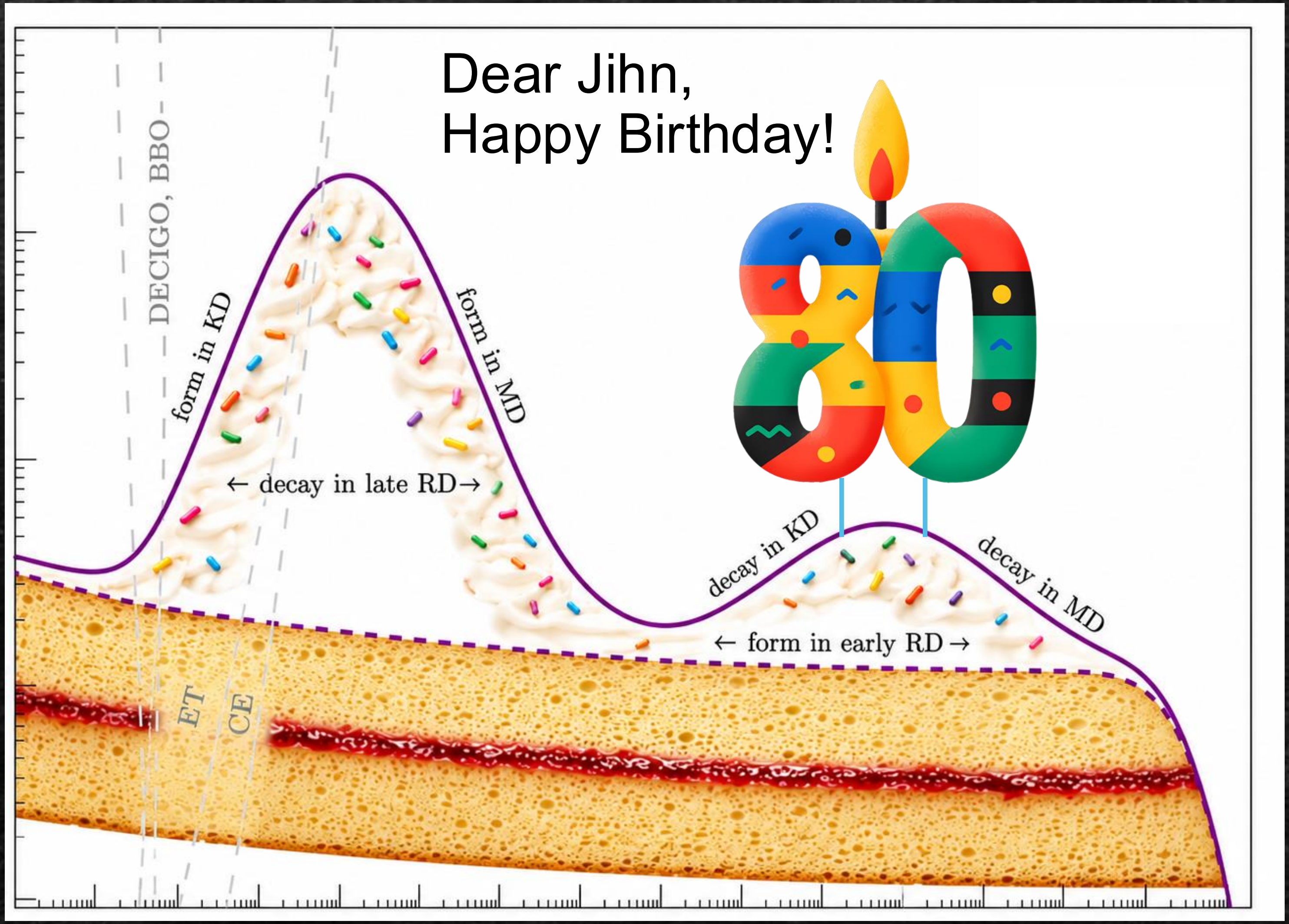
$T_{KR} = 1\text{GeV}$

$T_{RM} = 100\text{GeV}$

2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

2111.01150 Y. Gouttenoire, G. Servant, P. Simakachorn

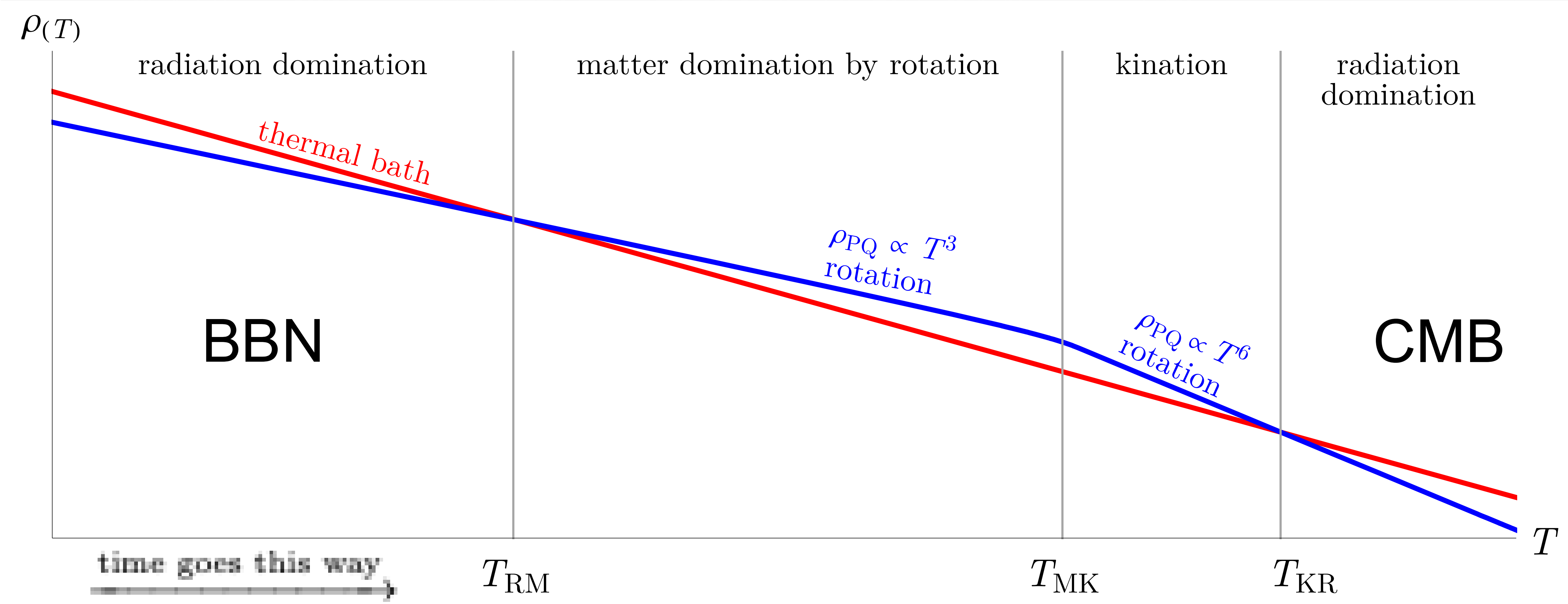
"Axion Rotation as the Icing on the Cosmic Cake"



Axion Kination

NanoHertz Gravitational Waves

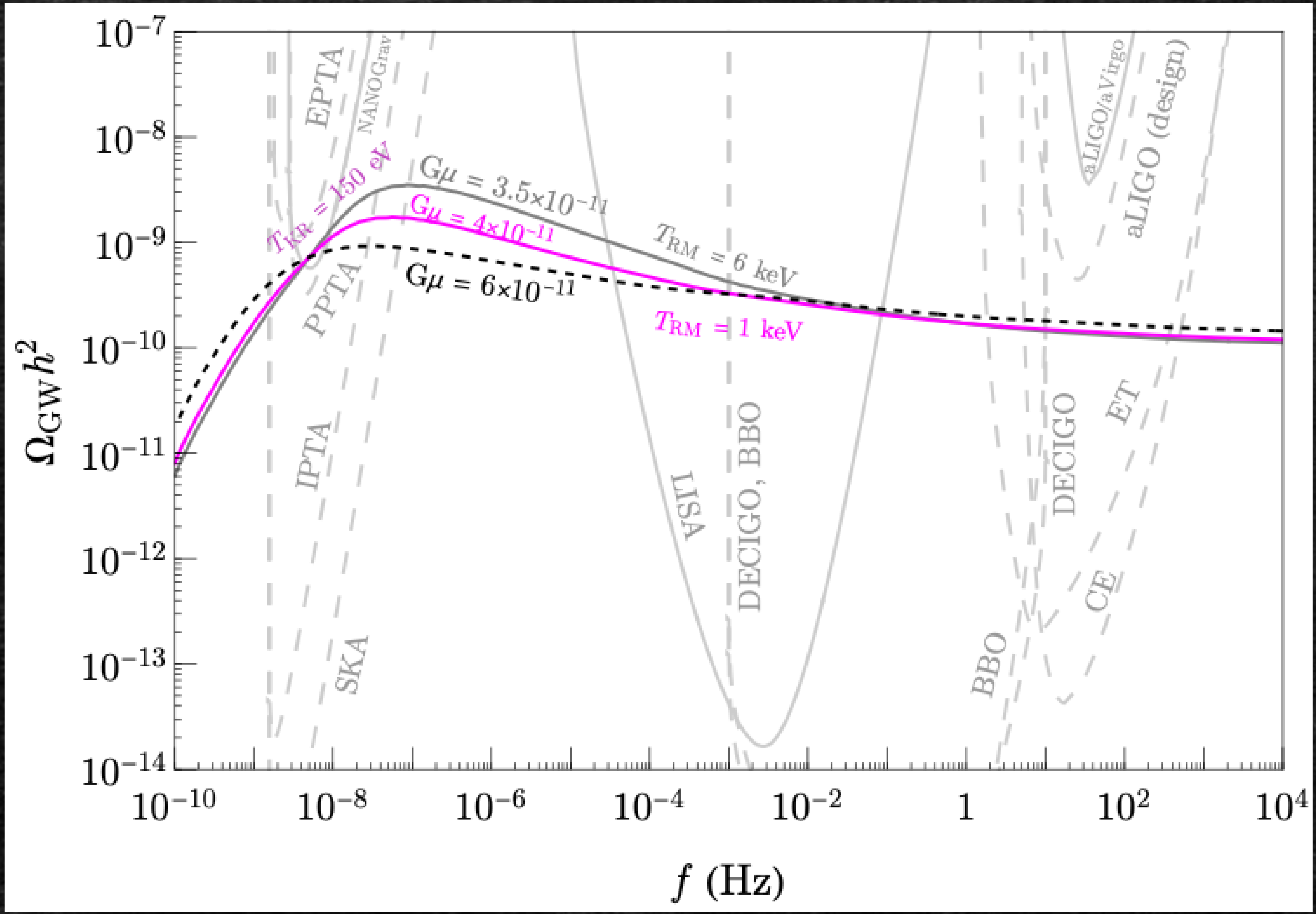
Relevant Temperatures



2405.12268 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton

Gravitational Waves from Cosmic Strings

Matter and kination domination between BBN and recombination



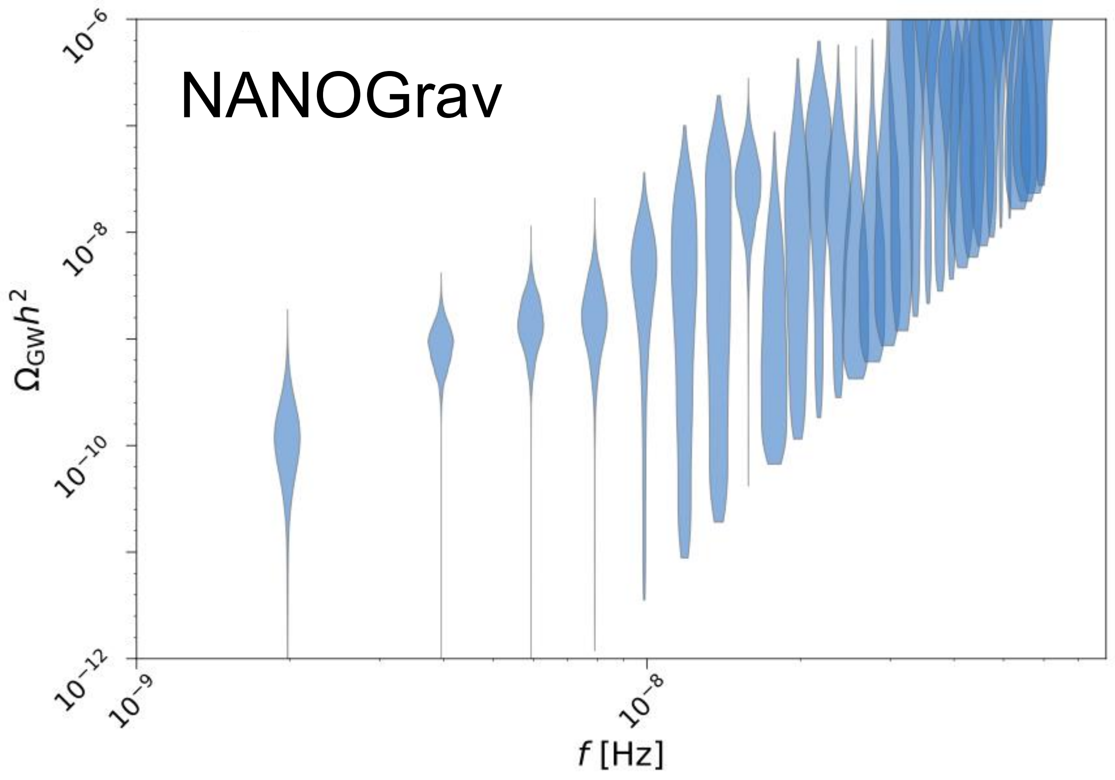
2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

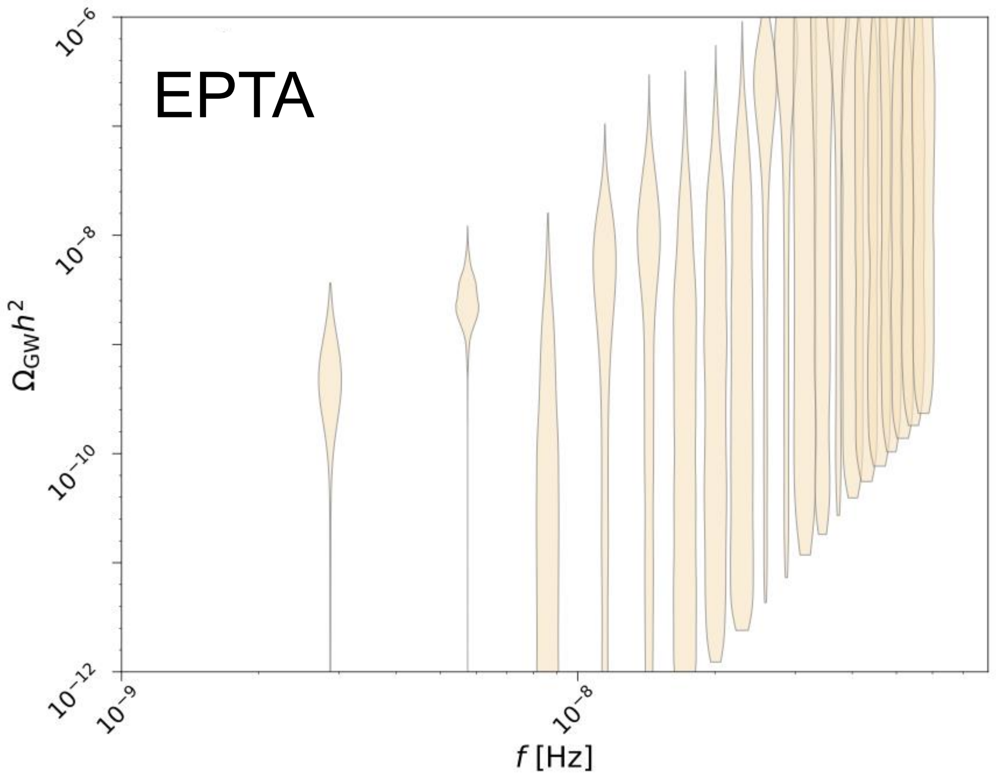
2111.01150 Y. Gouttenoire, G. Servant, P. Simakachorn

Pulsar Timing Arrays

Potential detection of nHz gravitational waves by Pulsar Timing Arrays (PTA)

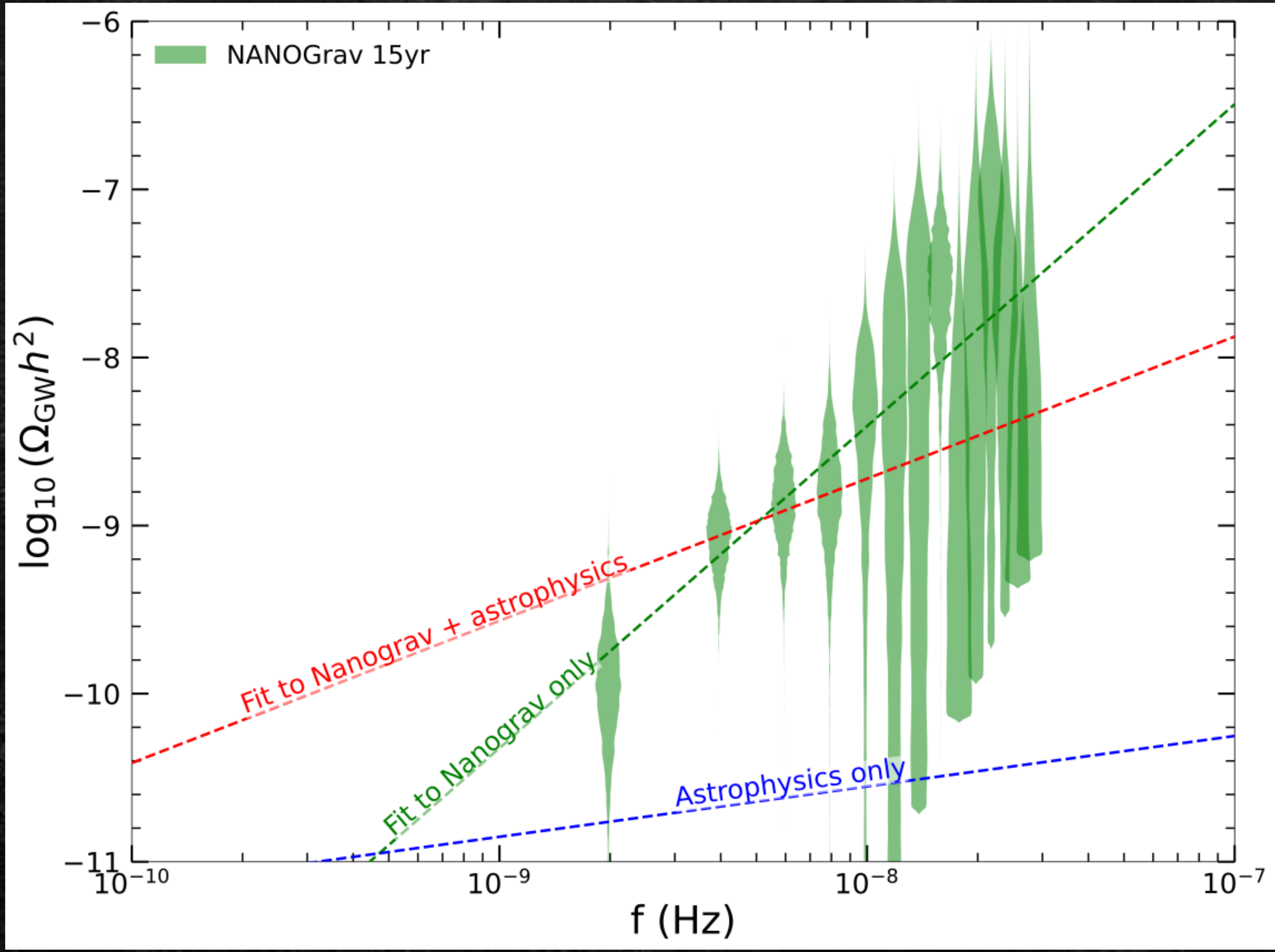
- NANOGrav 15-year data: evidence for Hellings–Downs correlations at the 3.2σ level
  2407.20510
- EPTA 10-year DR2 New+ data: ~3σ significance
  2306.16214

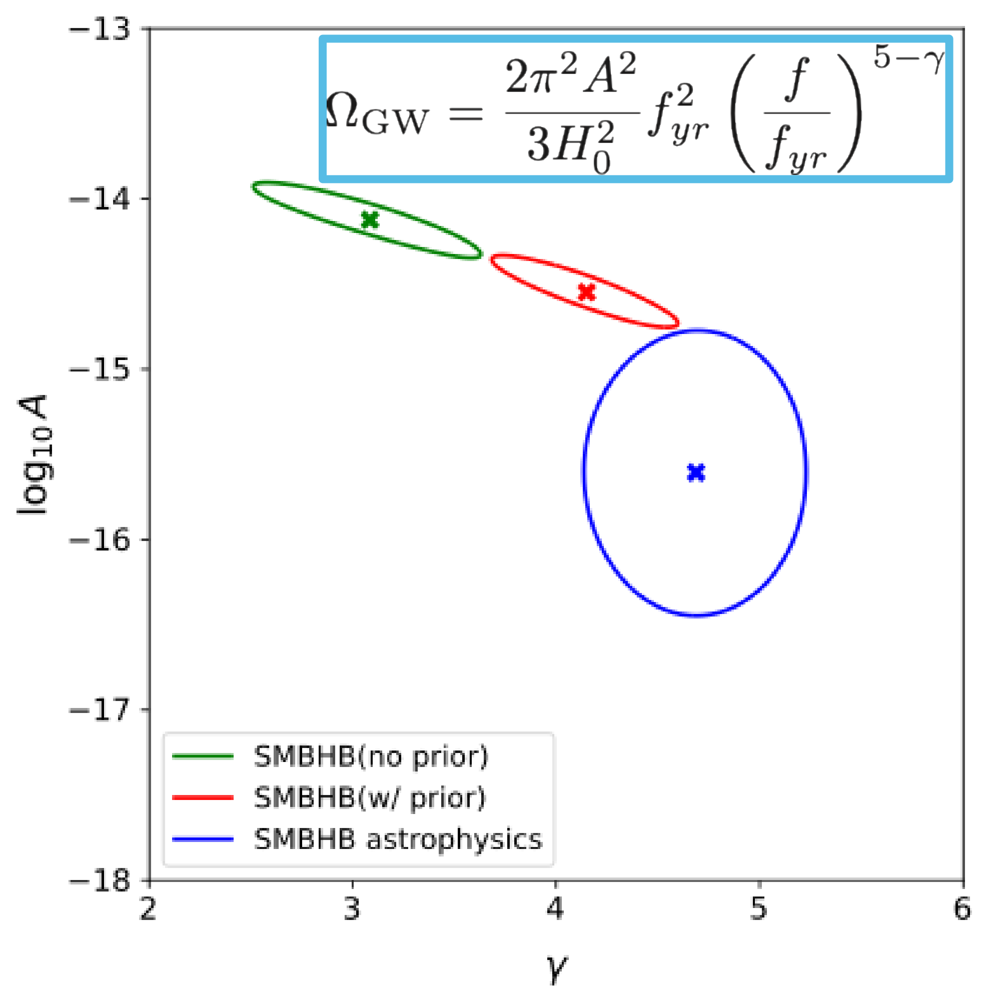




NanoHertz Gravitational Waves

Supermassive Black Hole Binaries (SMBHB)

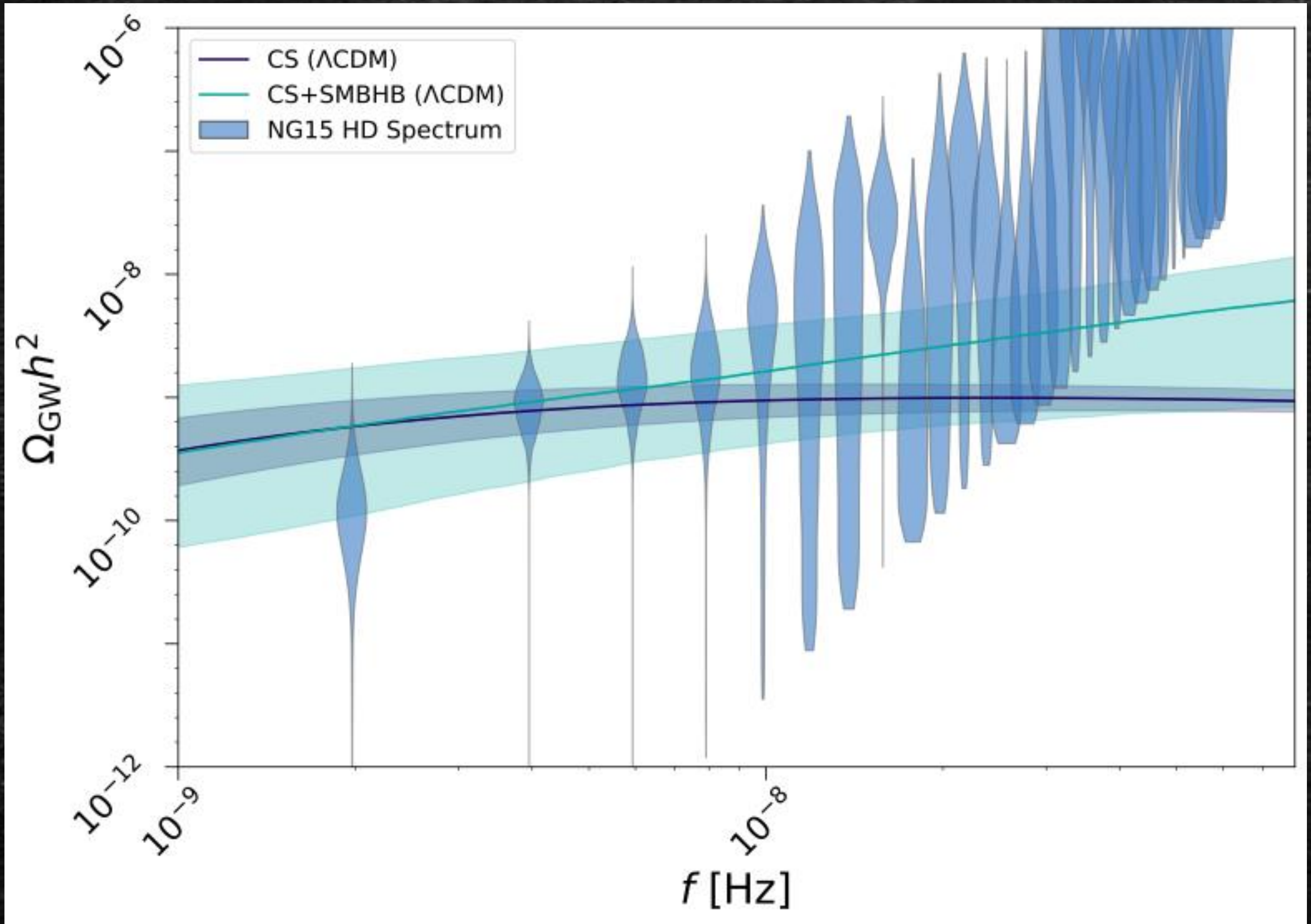




2306.16219 NANOGrav 15-yr Data Set

NanoHertz Gravitational Waves

Cosmic Strings (CS) (+ SMBGB)



Baseline Model: SMBHB

Model	Bayes Factor
CS (ΛCDM)	0.16
CS+SMBHB (ΛCDM)	0.64

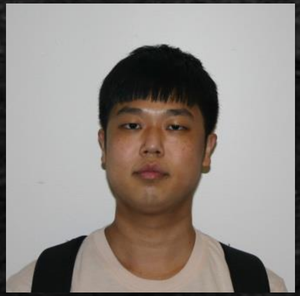
Jeffreys' scale of Bayes factor:

< 1 : Model disfavored

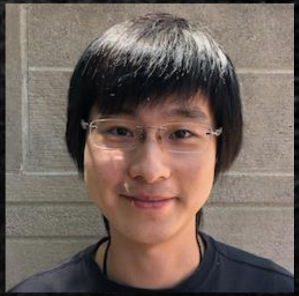
$1 - \sqrt{10}$: Negligibly small

$\sqrt{10} - 10$: Substantially strong

…



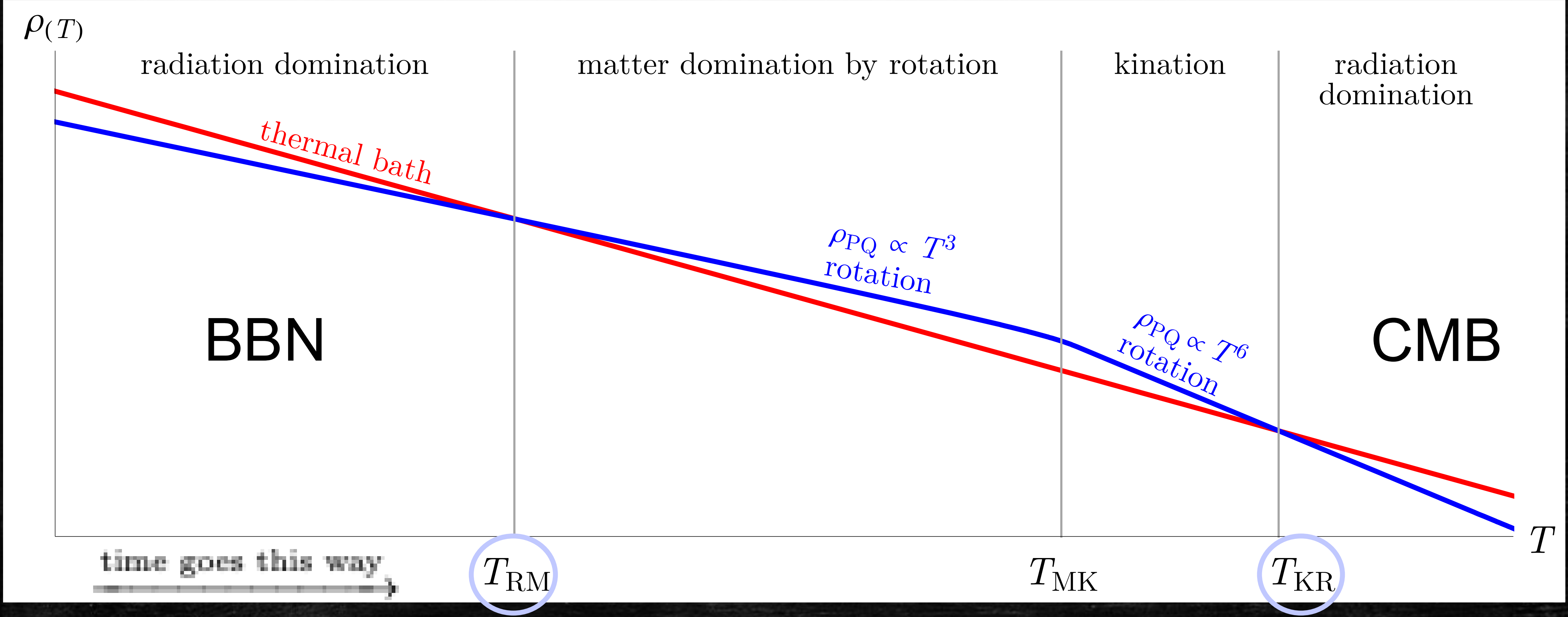
Grad student: Taegyu Lee



Grad student: Nicolas Lam

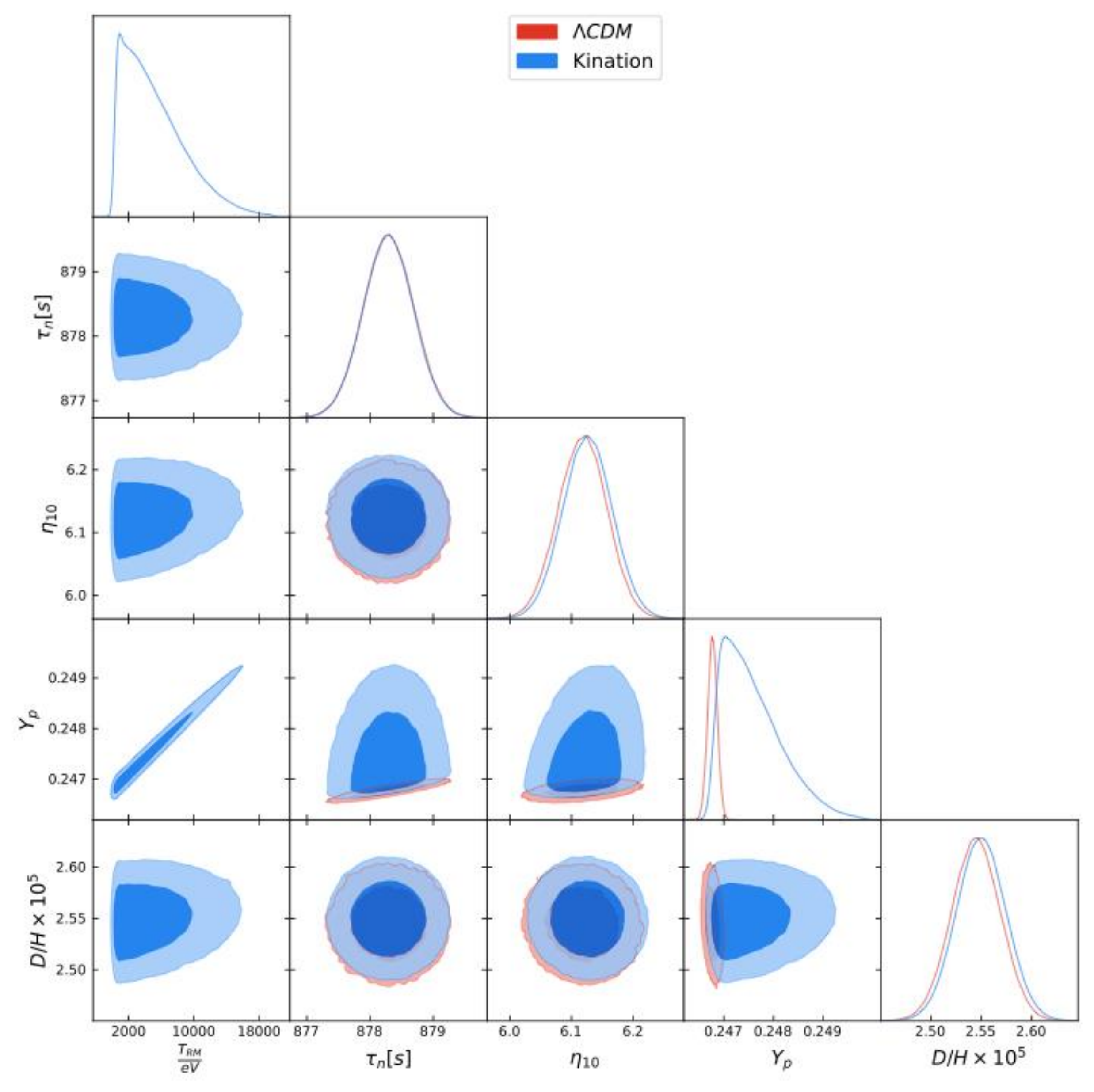
2608.IHope RC, T. Lee, S.C. Lam

Relevant Temperatures



2405.12268 RC, N. Fernandez, A. Ghalsasi, K. Harigaya, and J. Shelton

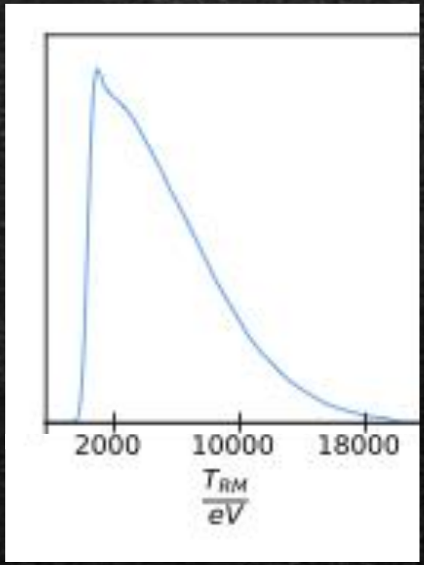
BBN

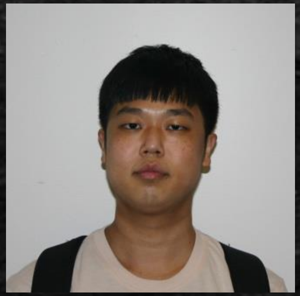


PRyMordial

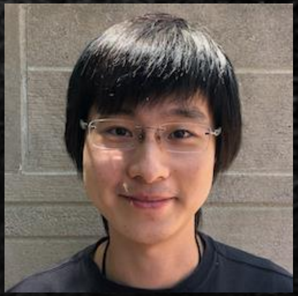
2307.07061 A. Burns, T. Tait, and M. Valli

At 2σ, $T_{\rm RM} < 12.6\ \mathrm{keV}$





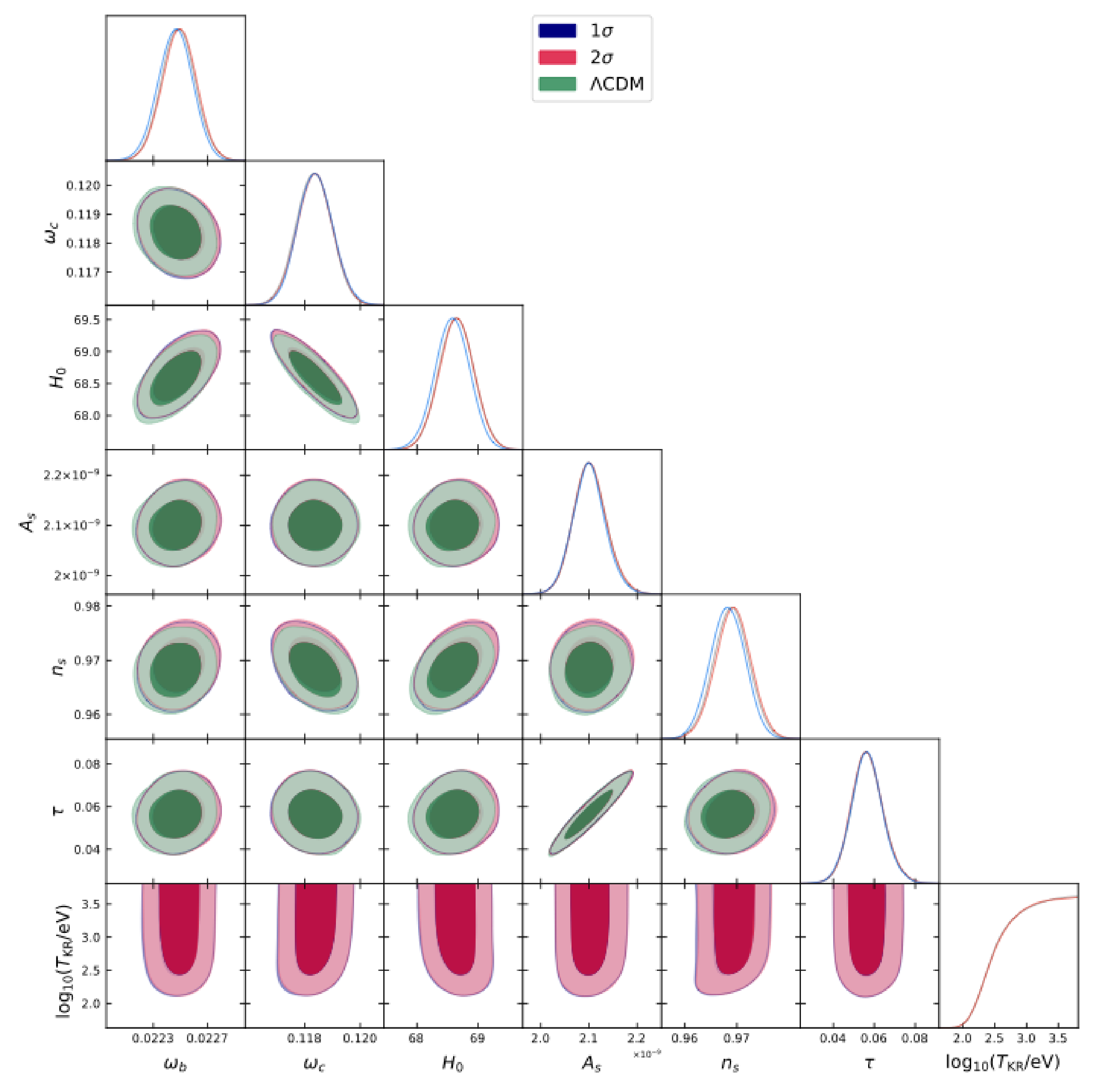
Grad student: Taegyu Lee



Grad student: Nicolas Lam

2608.IHope RC, T. Lee, S.C. Lam

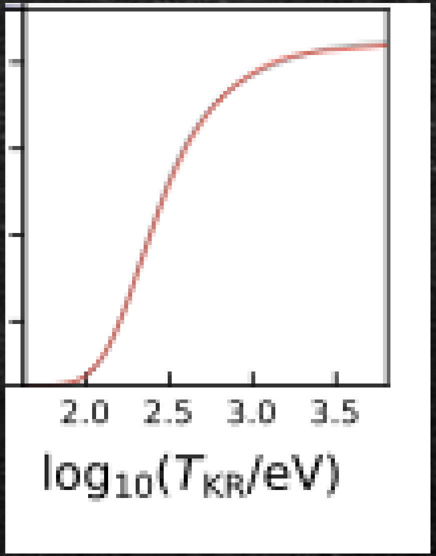
CMB



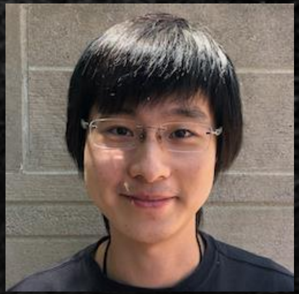
CLASS

1104.2933 B. Blas, J. Lesgourgues, and T. Tram

At 2σ, $T_{\rm KR} > 237$ eV



Grad student: Taegyu Lee

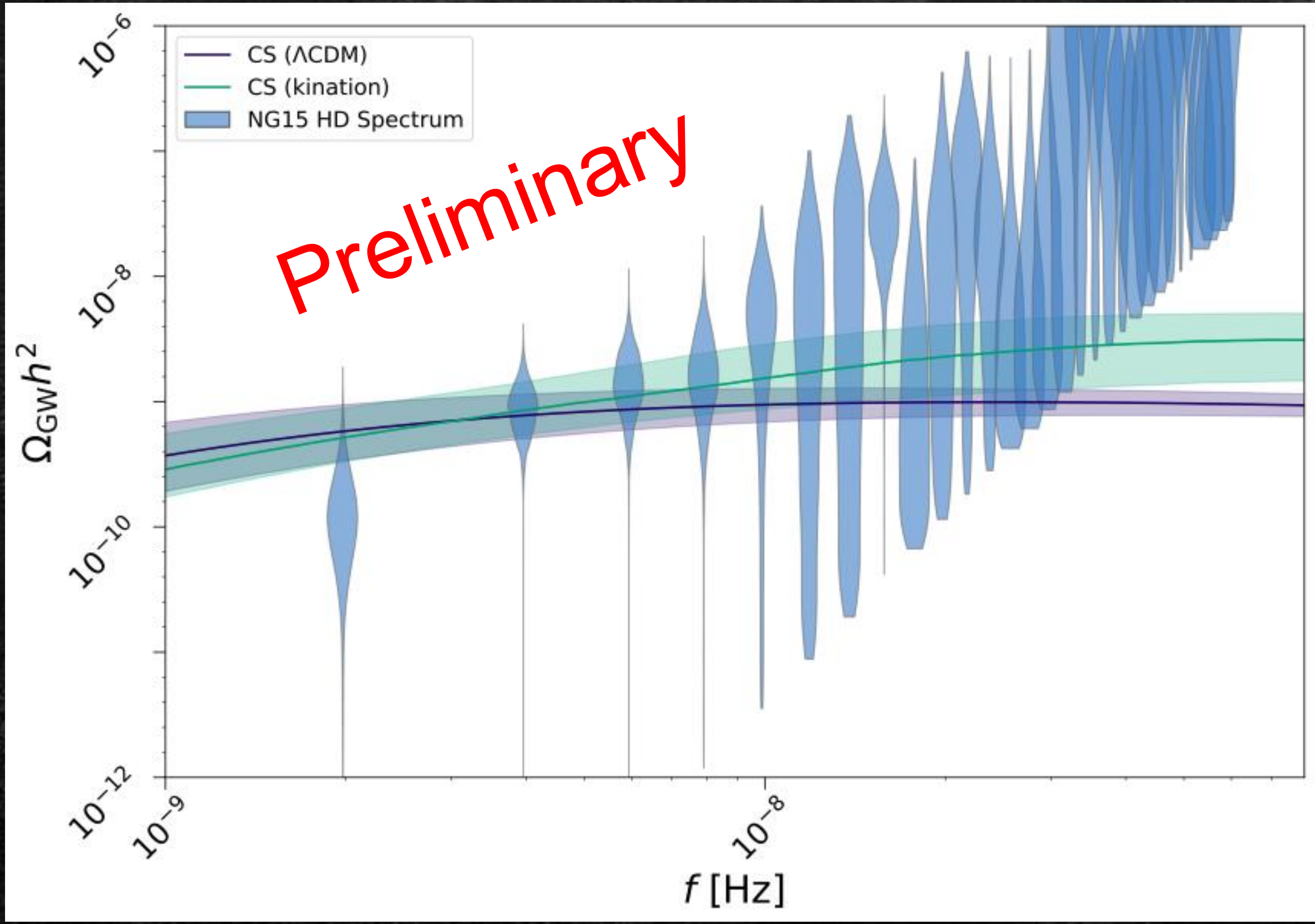


Grad student: Nicolas Lam

2608.IHope RC, T. Lee, S.C. Lam

NanoHertz Gravitational Waves

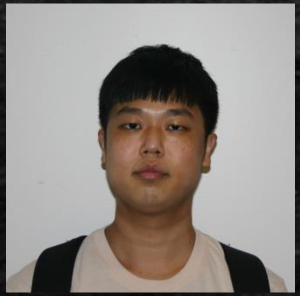
Cosmic Strings (CS)



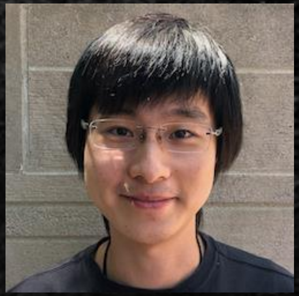
Baseline Model: SMBHB

Model	Bayes Factor
CS (ΛCDM)	0.16
CS+SMBHB (ΛCDM)	0.64
CS (kination)	0.60

Jeffreys' scale of Bayes factor:
< 1 : Model disfavored
$1 - \sqrt{10}$: Negligibly small
$\sqrt{10} - 10$: Substantially strong
…



Grad student: Taegyu Lee

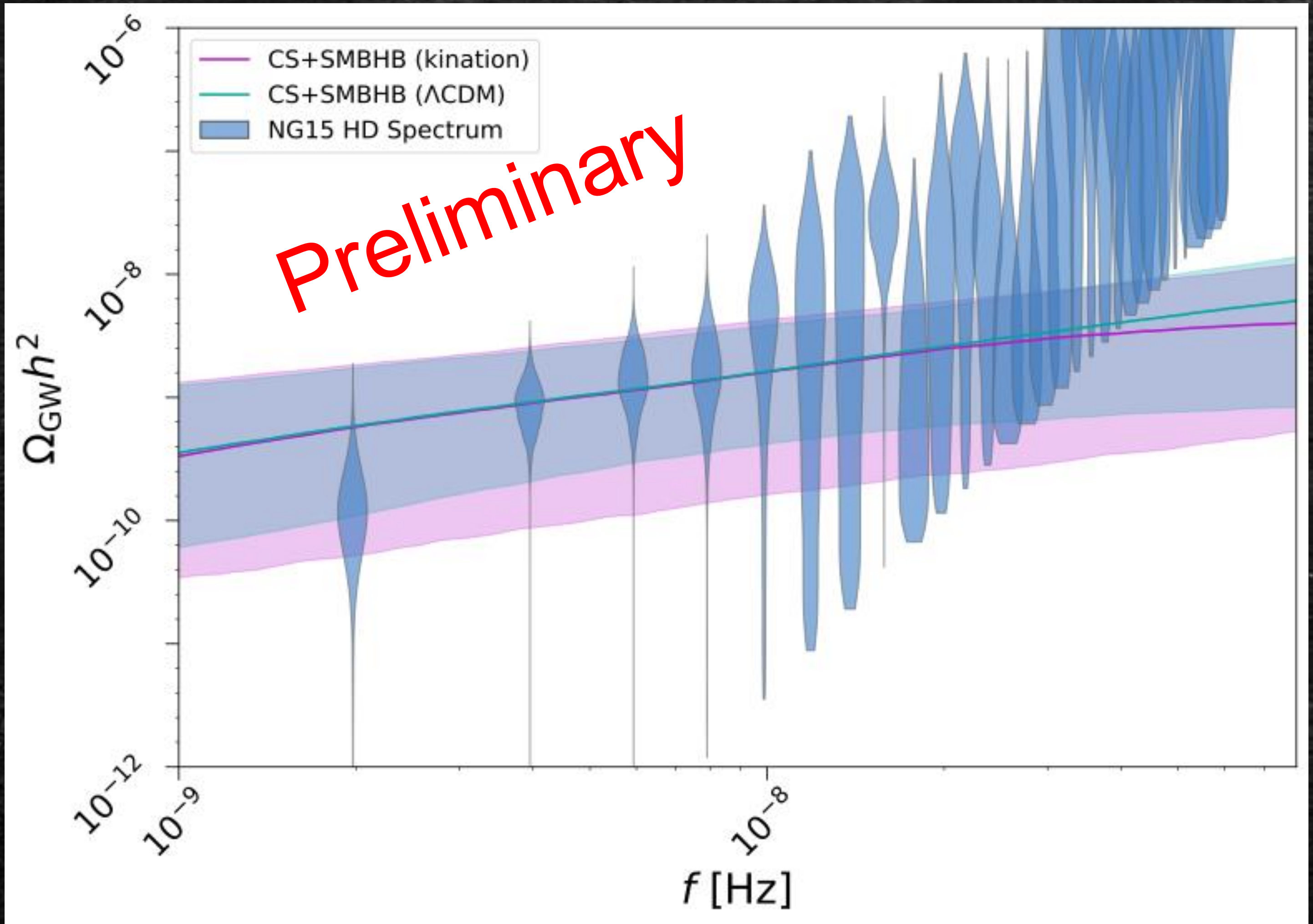


Grad student: Nicolas Lam

2608.IHope RC, T. Lee, S.C. Lam

NanoHertz Gravitational Waves

CS + SMBGB



Baseline Model: SMBHB

Model	Bayes Factor
CS (ΛCDM)	0.16
CS+SMBHB (ΛCDM)	0.64
CS (kination)	0.60
CS+SMBHB (kination)	1.28

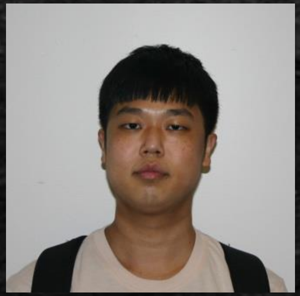
Jeffreys' scale of Bayes factor:

< 1 : Model disfavored

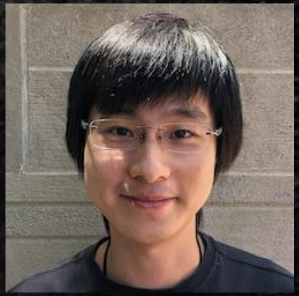
$1 - \sqrt{10}$: Negligibly small

$\sqrt{10} - 10$: Substantially strong

…



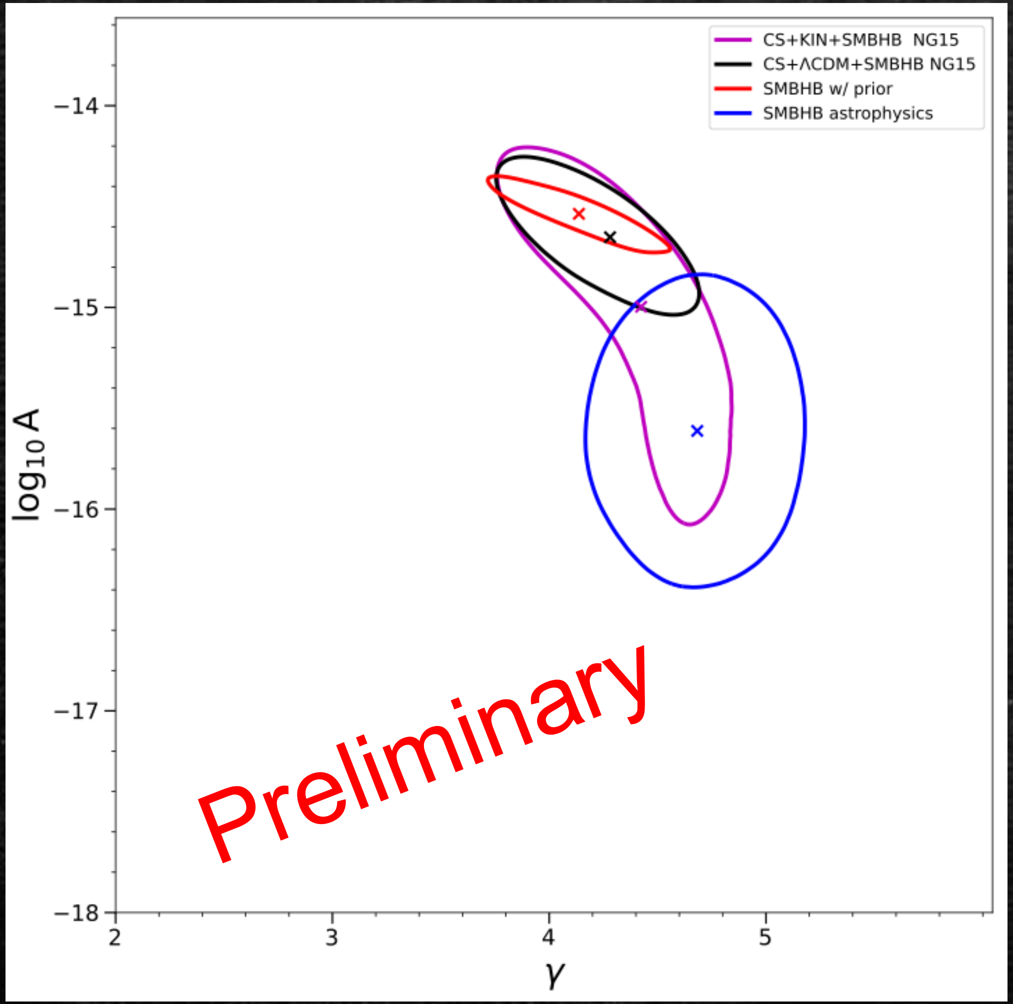
Grad student: Taegyu Lee

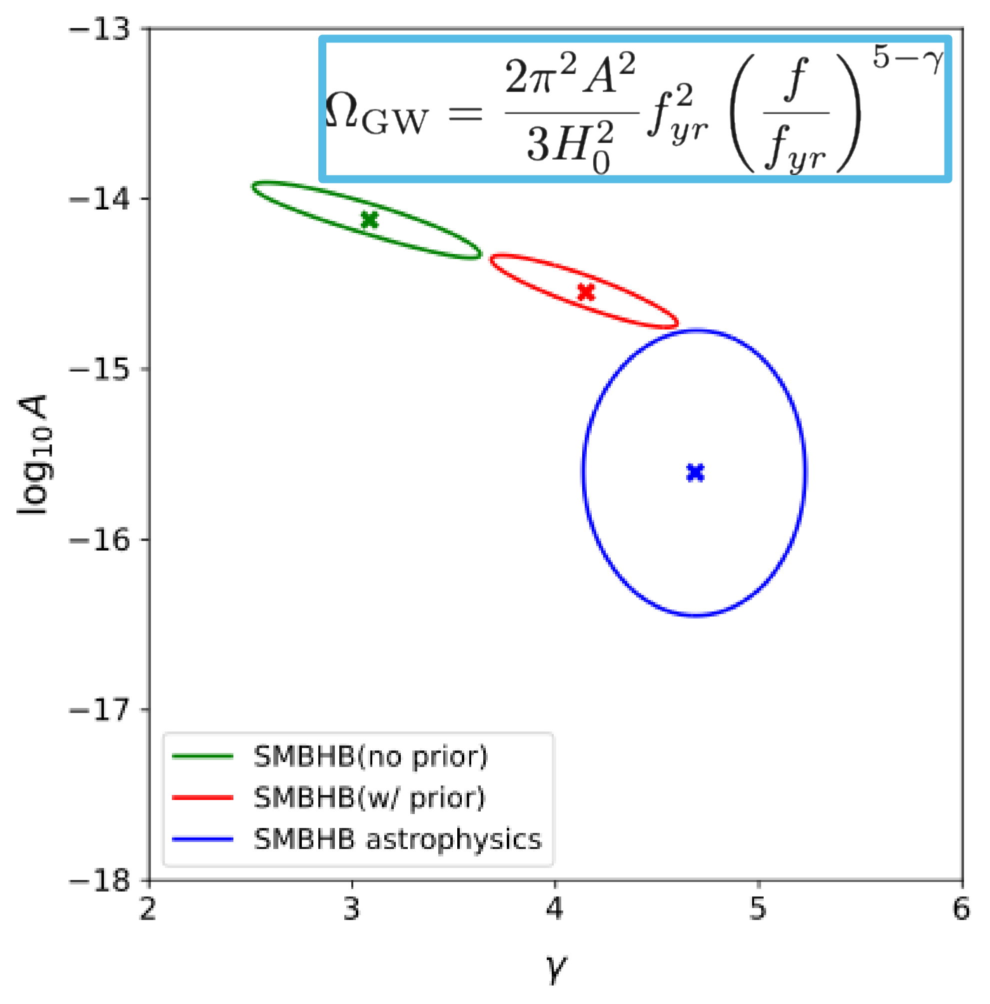


Grad student: Nicolas Lam

NanoHertz Gravitational Waves

Consistency with astrophysical simulations





2306.16219 NANOGrav 15-yr Data Set

NanoHertz Gravitational Waves

Thus far, the nHz gravitational wave signal is not yet statistically strong enough to distinguish between ΛCDM and kination cosmology.

We will need more data from

- IPTA: Continued data integration across NANOGrav, EPTA, PPTA, CPTA, and InPTA to form a unified, ultra-sensitive global.
- SKAO (Square Kilometre Array): Will dramatically increase the number of precisely timed millisecond pulsars, lowering the noise floor and allowing the detection of tens of individual supermassive black hole binaries.
- DSA-2000: A large radio radio-survey instrument in the United States that will contribute high-cadence timing and help refine gravitational wave sky-mapping and diffractive lensing measurements

Gravitational Waves from Inflation

The origin is the quantum fluctuations during inflation.

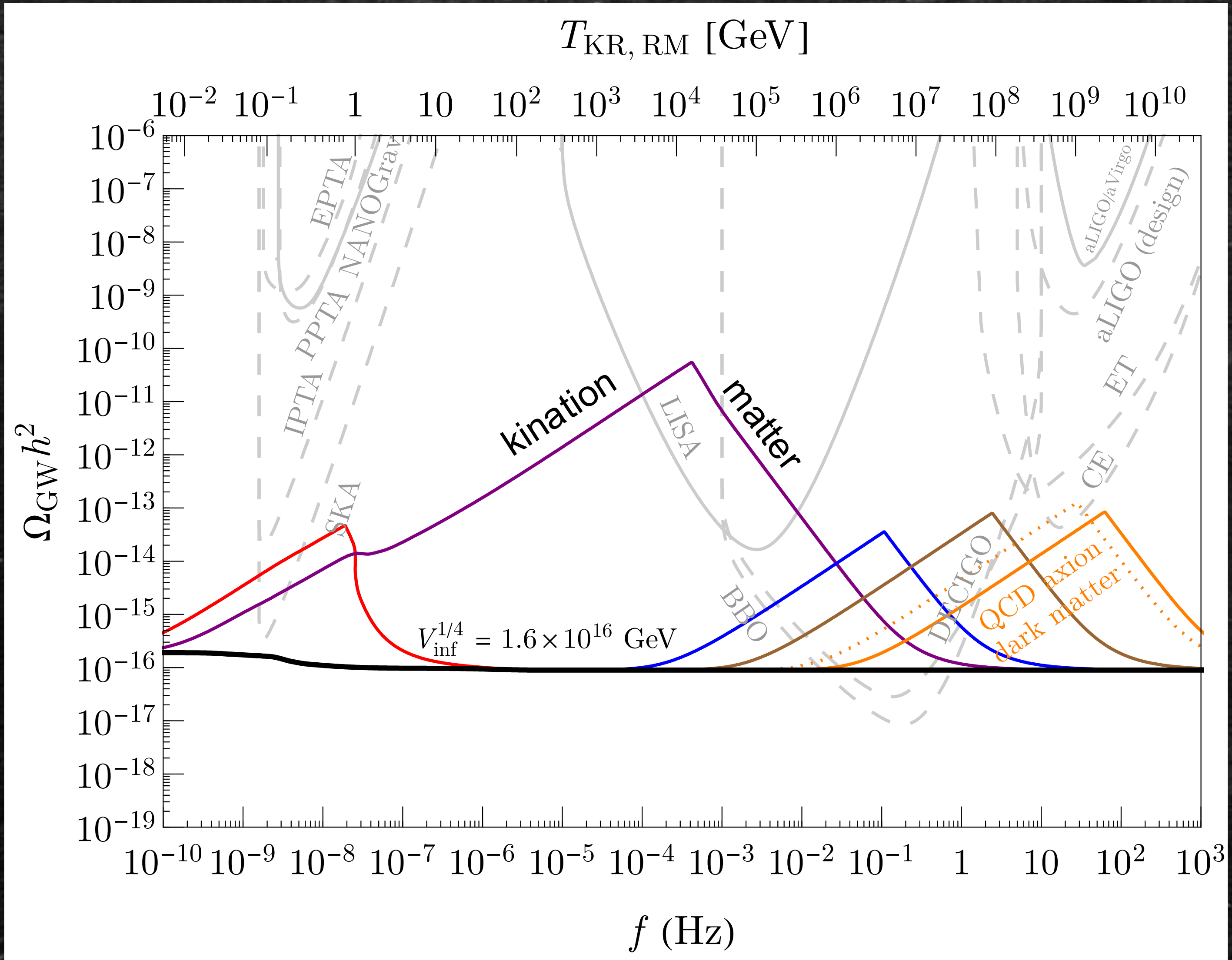
The horizon crossing, $k = H$, determines the onset of mode evolutions.

$$\Omega_{\rm GW} h^2 = \Omega_{r,0} h^2 \frac{1}{\rho_R(T_{\rm hc})} \frac{k^2}{64\pi G} \mathcal{P}_T(k) \qquad \mathcal{P}_T(k) = \frac{2H_I^2}{\pi^2 M_{\rm Pl}^2}$$

$$k = H(T_{\rm hc})$$

$$\Omega_{\rm GW} h^2 \simeq 1.4 \times 10^{-17} \left(\frac{V_{\rm inf}^{1/4}}{10^{16}\ {\rm GeV}}\right)^4 \left(\frac{g_{*,\rm SM}}{g_*(T_{\rm hc})}\right)^{\frac{1}{3}} \begin{cases} 1 & {\rm RD} : f_{\rm RM} < f \\ \left(\frac{f_{\rm RM}}{f}\right)^2 & {\rm MD} : f_{\rm MK} < f < f_{\rm RM} \\ \frac{f}{f_{\rm KR}} & {\rm KD} : f_{\rm KR} < f < f_{\rm MK} \\ 1 & {\rm RD} : f < f_{\rm KR} \end{cases}$$

Smoking Gun: Triangular Peak in Gravitational Wave Spectra



2108.09299 JHEP 09 (2022) 116 RC, D. Dunsky, N. Fernandez, A. Ghalsasi, L. Hall, K. Harigaya, J. Shelton

2108.10328, 2111.01150 Y. Gouttenoire, G. Servant, P. Simakachorn

Axion Rotations

Axion Kination

- ✓ **RC** *et al.* 2108.09299
- ✓ Gouttenoire *et al.* 2108.10328
- ✓ Gouttenoire *et al.* 2111.01150
- ✓ **RC** *et al.* 2510.01308

Dark Matter

- ✓ **RC** *et al.* 1910.14152
- ✓ Chang *et al.* 1911.11885
- ✓ **RC** *et al.* 2004.00629
- ✓ Di Luzio *et al.* 2102.01082
- ✓ Rusov *et al.* 2109.01833
- ✓ Barman *et al.* 2111.03677
- ✓ Eröncel *et al.* 2206.14259
- ✓ Eröncel *et al.* 2207.10111
- ✓ Oikonomou 2208.05544
- ✓ Kozów *et al.* 2212.03518
- ✓ Chatrchyan *et al.* 2305.03756
- ✓ Lee *et al.* 2310.17710
- ✓ **RC** *et al.* 2312.17730
- ✓ Eröncel *et al.* 2503.04880
- ✓ **RC** *et al.* 2503.04888

Baryogenesis

- ✓ **RC** *et al.* 1910.02080
- ✓ **RC** *et al.* 2006.04809
- ✓ Domcke *et al.* 2006.03148
- ✓ **RC** *et al.* 2006.05687
- ✓ Harigaya *et al.* 2107.09679
- ✓ Chakraborty *et al.* 2108.04293
- ✓ Kawamura *et al.* 2109.08605
- ✓ **RC** *et al.* 2110.05487
- ✓ **RC** *et al.* 2206.00678
- ✓ Barnes, **RC** *et al.* 2208.07878
- ✓ **RC** *et al.* 2211.12517
- ✓ Berbig 2307.14121
- ✓ Chao *et al.* 2311.06469
- ✓ Chun *et al.* 2311.09005
- ✓ Wada 2404.10283
- ✓ Datta *et al.*2405.07003
- ✓ **RC** *et al.* 2405.12268

Gravitational Waves

- ✓ **RC** *et al.* 2104.02077
- ✓ Madge *et al.* 2111.12730
- ✓ Harigaya *et al* 2305.14242

Cosmic Perturbations

- ✓ **RC** *et al.* 2202.01785
- ✓ **RC** *et al.* 2412.13246
- ✓ **RC** *et al.* 2510.01308

Conclusions

✓ New axion dynamics gives rise to interesting cosmological evolution involving matter and kination domination.

✓ This enhances Hubble expansion rate and predicts
  - ✓ enhanced matter power spectrum
  - ✓ enhanced gravitational wave spectra

✓ The same dynamics allows the QCD axion to simultaneous
  - ✓ Strong CP problem
  - ✓ dark matter abundance
  - ✓ baryon asymmetry

✓ Other possible signatures include
  - ✓ gravitational lensing of axion mini-clusters
  - ✓ warm axion dark matter

✓ New model building opportunities
  - ✓ other open questions across disciplines