MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
HEIDELBERG

Gravitational waves from Peccei-Quinn symmetry breaking

Christian Döring

4.5.2018 @Uni Bielefeld
13. Kosmologietage

Collaborators:
- Jörg Jäckel (Uni Heidelberg)
- Kai Schmitz (MPIK, Heidelberg)

Content

- Motivation: What is the Strong CP-Problem?
- Solution: The QCD-Axion
- A Cosmological CV of the Axion
- Cosmological Phase Transitions (CPT)
- Gravitational Waves (GW) from CPT's
- GW's from Peccei-Quinn Symmetry breaking?
- Conclusion

Motivation

There is a problem in the theory of strong interactions ...

QCD Lagrangian: $\mathcal{L}_{\mathrm{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

Motivation

There is a problem in the theory of strong interactions ...

QCD Lagrangian: $\mathcal{L}_{\text{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

CP-Violating term:

Motivation

There is a problem in the theory of strong interactions ...

QCD Lagrangian: $\mathcal{L}_{\text{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

CP-Violating term:

$$\mathcal{L}_{\bar{\theta}} = (\theta_{\text{QCD}} + \arg\det M_u M_d) \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu} = \bar{\theta} \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}$$

QCD vacuum angle

Mass term

Motivation

There is a problem in the theory of strong interactions ...

QCD Lagrangian: $\mathcal{L}_{\text{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

SU(3)

CP-Violating term:

$$\mathcal{L}_{\bar{\theta}} = (\theta_{\text{QCD}} + \arg\det M_u M_d) \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu} = \bar{\theta} \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}$$

QCD vacuum angle

Mass term

Motivation

There is a problem in the theory of strong interactions …

QCD Lagrangian: $\mathcal{L}_{\text{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

SU(3)

CP-Violating term:

$$\mathcal{L}_{\bar{\theta}} = (\theta_{\text{QCD}} + \arg\det M_u M_d) \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu} = \bar{\theta} \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}$$

QCD vacuum angle

Mass term

Electric dipole moment of Neutron:

$|d_n| < 10^{-26}$ ecm

$|\bar{\theta}| < 10^{-9}$

Motivation

There is a problem in the theory of strong interactions …

QCD Lagrangian: $\mathcal{L}_{\text{QCD}} = \underbrace{\frac{1}{4} G_{a,\mu\nu} G_a^{\mu\nu}}_{\text{Gluons}} + \underbrace{\sum_f^{N_f} \bar{\psi}_f (\gamma_\mu \cdot \mathcal{D}_\mu + m_f) \psi_f}_{\text{Quarks}}$

SU(3)

CP-Violating term:

$$\mathcal{L}_{\bar{\theta}} = (\theta_{\text{QCD}} + \arg\det M_u M_d) \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu} = \bar{\theta} \frac{g_s^2}{32\pi^2} G_{a,\mu\nu} \tilde{G}_a^{\mu\nu}$$

QCD vacuum angle

Mass term

Electric dipole moment of Neutron:

$|d_n| < 10^{-26}$ ecm

$|\bar{\theta}| < 10^{-9}$

The strong CP Problem states:
Why is the phase so small?

Solution: QCD-Axion

Idea: Interpret the phase as a dynamical (pseudo)scalar field rather then a fixed constant

$$\mathcal{L}_a := \frac{1}{2}\partial_\mu a(x)\partial^\mu a(x) - \frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

Related scale

$$\mathcal{L}_\theta \to \mathcal{L}_\theta + \mathcal{L}_a - V(a)$$

Such that $\langle \theta - a(x)/f_a \rangle = 0$ after QCD-phase transition

Solution: QCD-Axion

Idea: Interpret the phase as a dynamical (pseudo)scalar field rather then a fixed constant

$$\mathcal{L}_a := \frac{1}{2}\partial_\mu a(x)\partial^\mu a(x) - \frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

Related scale

$$\mathcal{L}_\theta \to \mathcal{L}_\theta + \mathcal{L}_a - V(a)$$

Such that $\langle \theta - a(x)/f_a \rangle = 0$ after QCD-phase transition

Solution: QCD-Axion

Idea: Interpret the phase as a dynamical (pseudo)scalar field rather then a fixed constant

$$\mathcal{L}_a := \frac{1}{2}\partial_\mu a(x)\partial^\mu a(x) - \frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

Related scale

$$\mathcal{L}_\theta \to \mathcal{L}_\theta + \mathcal{L}_a - V(a)$$

Such that $\langle \theta - a(x)/f_a \rangle = 0$ after QCD-phase transition

Hence CP symmetry gets restored, thanks to the axion!

Solution: QCD-Axion

Idea: Interpret the phase as a dynamical (pseudo)scalar field rather then a fixed constant

$$\mathcal{L}_a := \frac{1}{2}\partial_\mu a(x)\partial^\mu a(x) - \frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

Related scale

$$\mathcal{L}_\theta \to \mathcal{L}_\theta + \mathcal{L}_a - V(a)$$

Such that $\langle \theta - a(x)/f_a \rangle = 0$ after QCD-phase transition

Hence CP symmetry gets restored, thanks to the axion!

New Ingredients	Math. form.
Global chrial symmetry	$U_{PQ}(1)$
Complex scalar field	$\phi := \rho e^{ia(x)/f_a}$
Exotic vector like quarks	$\tilde{Q}, Q$

Solution: QCD-Axion

Idea: Interpret the phase as a dynamical (pseudo)scalar field rather then a fixed constant

$$\mathcal{L}_a := \frac{1}{2}\partial_\mu a(x)\partial^\mu a(x) - \frac{g_s^2}{32\pi^2}\frac{a(x)}{f_a}G_{a,\mu\nu}\tilde{G}_a^{\mu\nu}$$

Related scale

$$\mathcal{L}_\theta \to \mathcal{L}_\theta + \mathcal{L}_a - V(a)$$

Such that $\langle \theta - a(x)/f_a \rangle = 0$ after QCD-phase transition

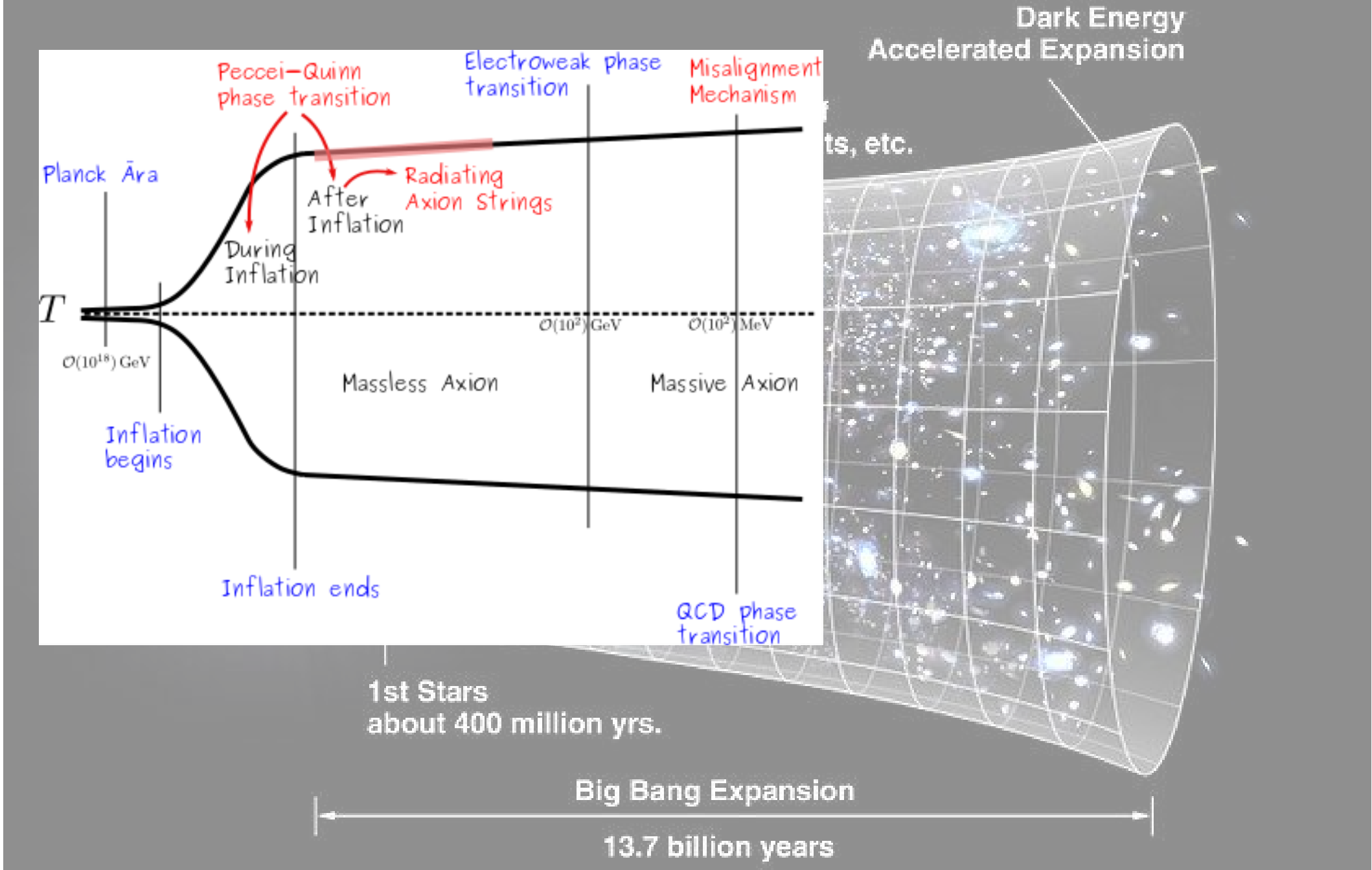
Hence CP symmetry gets restored, thanks to the axion!

KSVZ Model

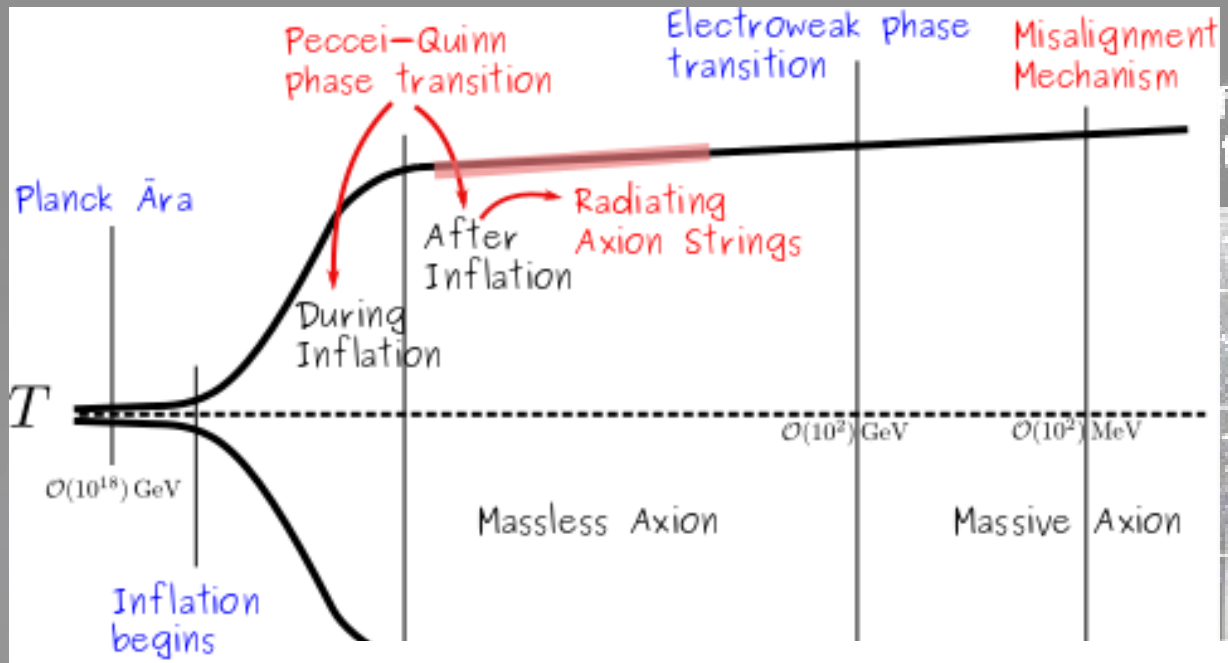
New Ingredients	Math. form.
Global chrial symmetry	$U_{PQ}(1)$
Complex scalar field	$\phi := \rho e^{ia(x)/f_a}$
Exotic vector like quarks	$\tilde{Q}, Q$

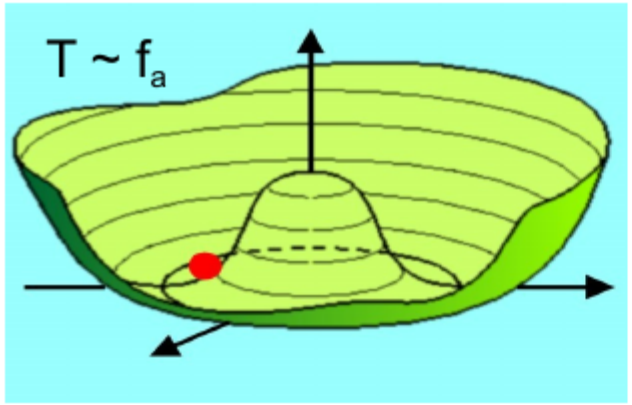
Axion=Nambu-Goldstone boson

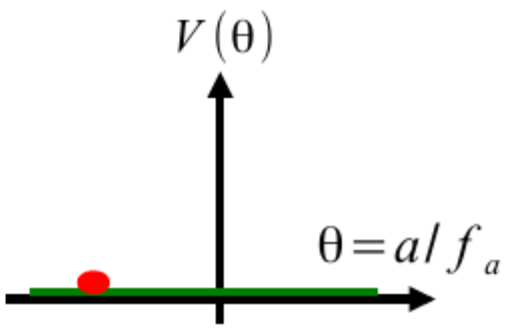
A Cosmological CV of the Axion



A Cosmological CV of the Axion



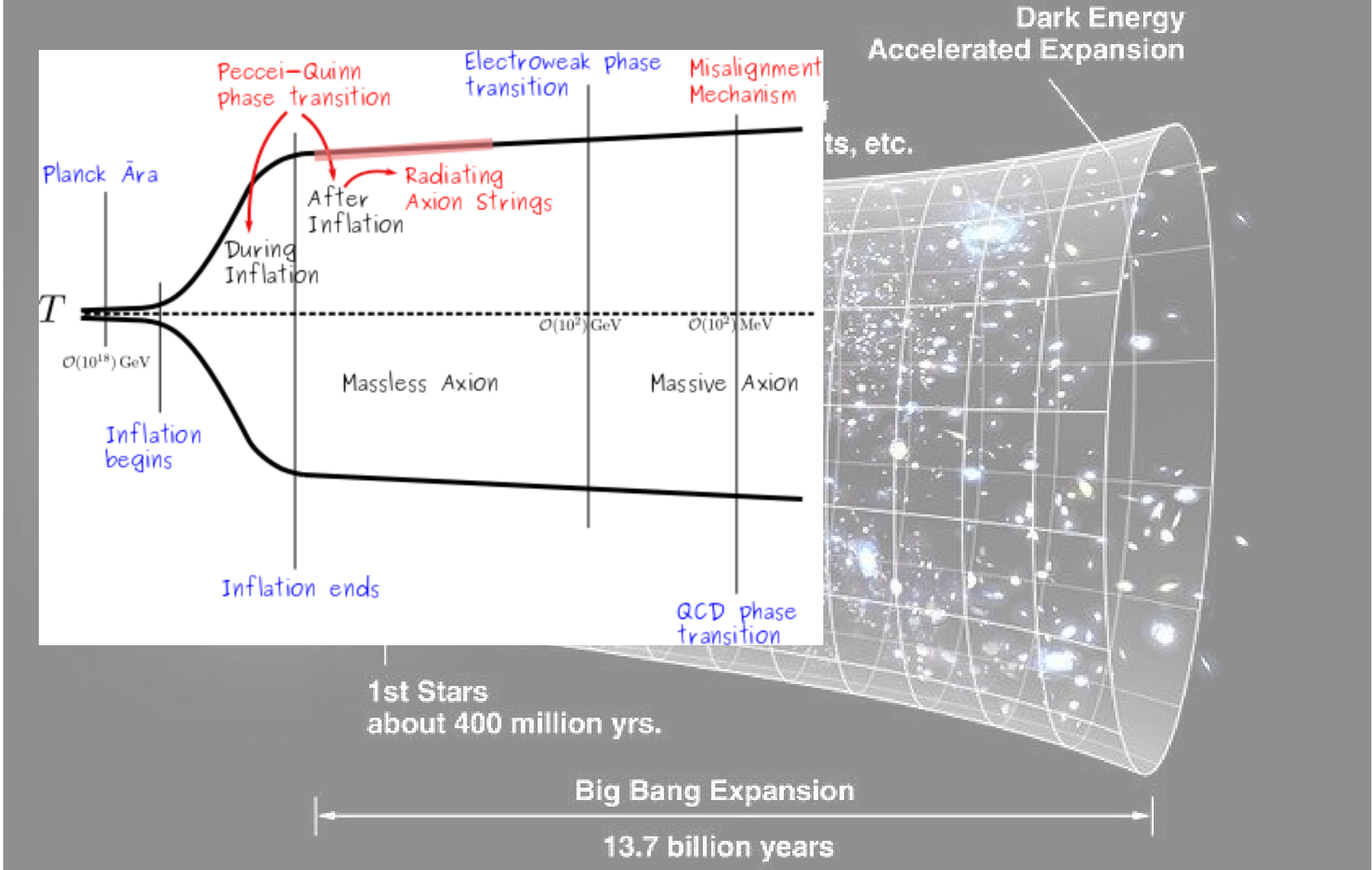




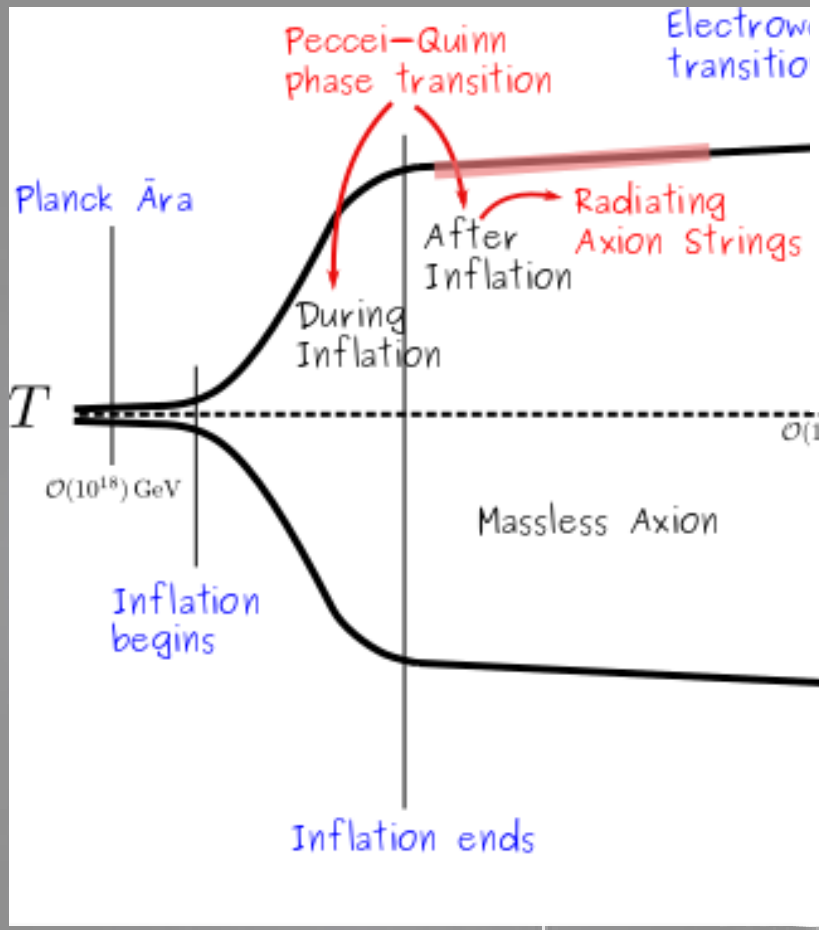
Big Bang Expansion

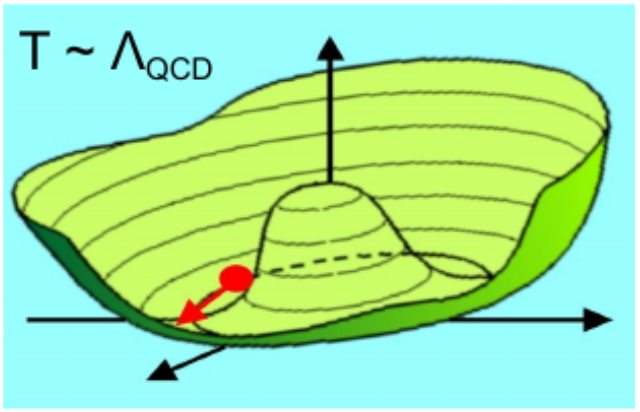
13.7 billion years

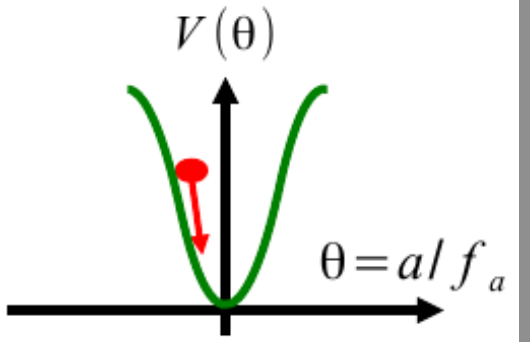
A Cosmological CV of the Axion



A Cosmological CV of the Axion







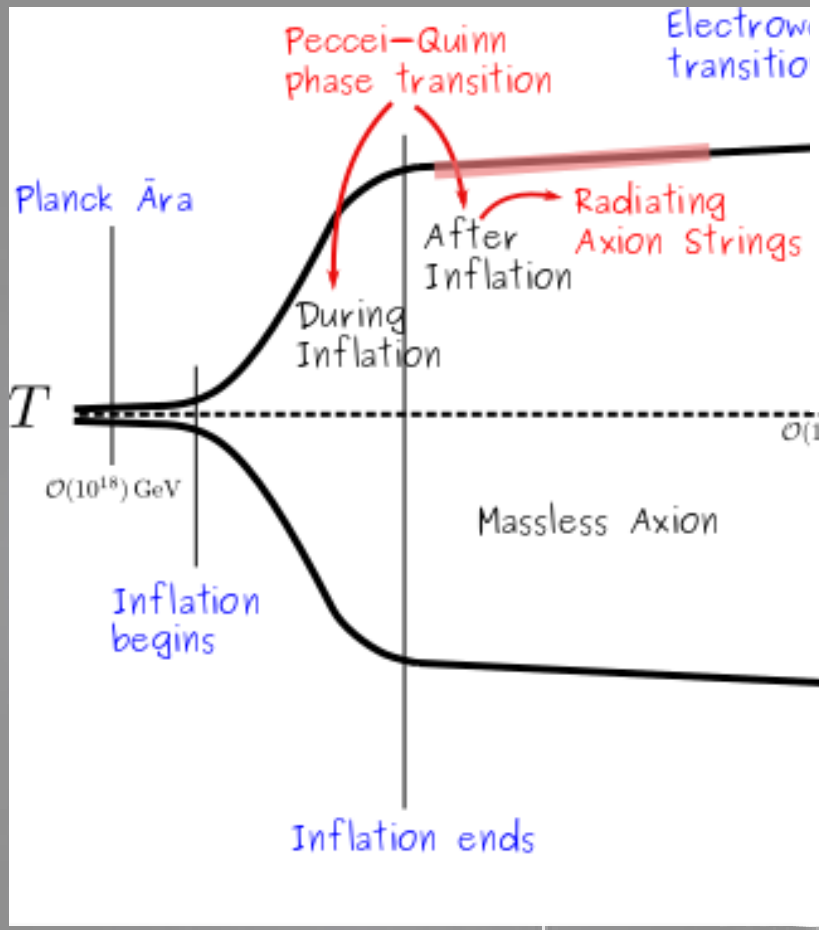
Dark Energy

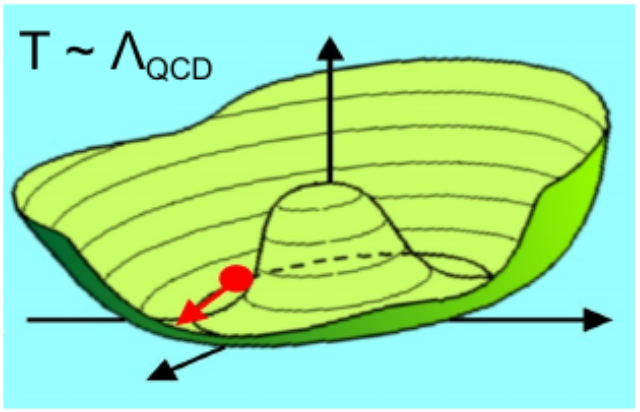
1st Stars
about 400 million yrs.

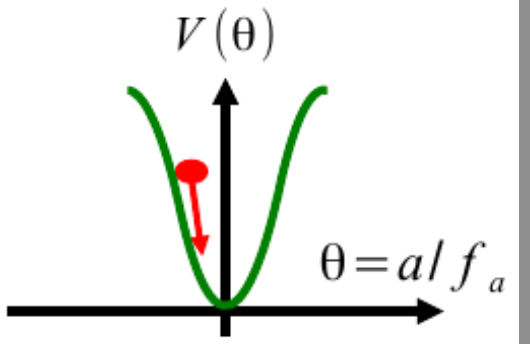
Big Bang Expansion

13.7 billion years

A Cosmological CV of the Axion







One pair of quarks here.
More quarks→ Domain Wall Problem

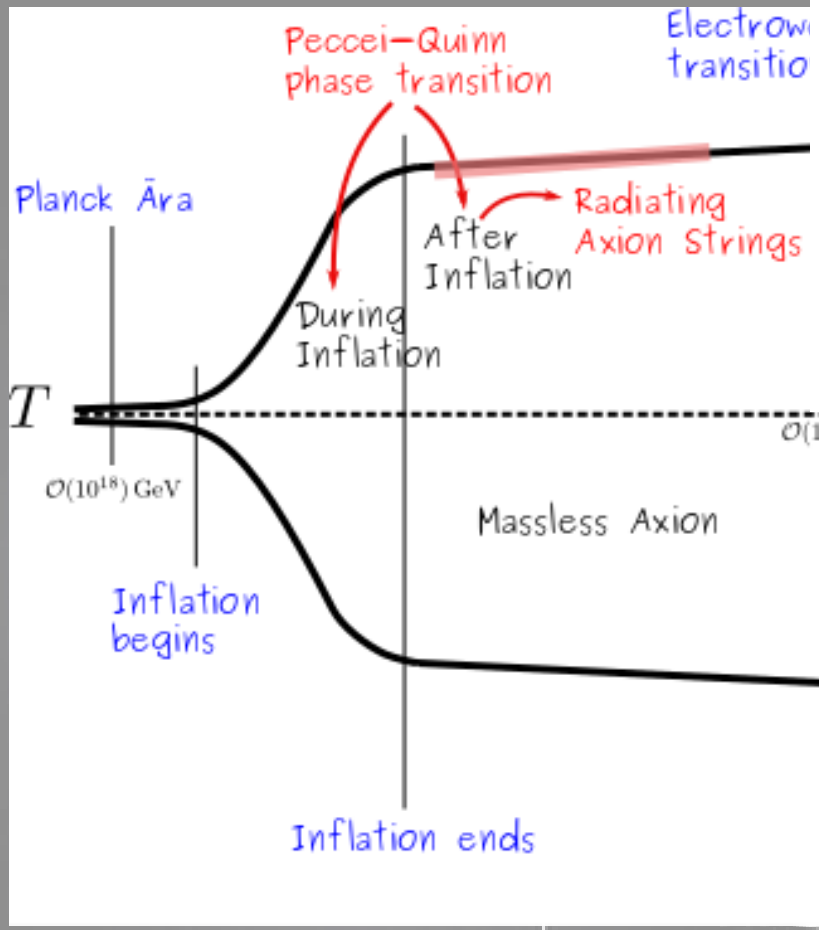
Dark Energy

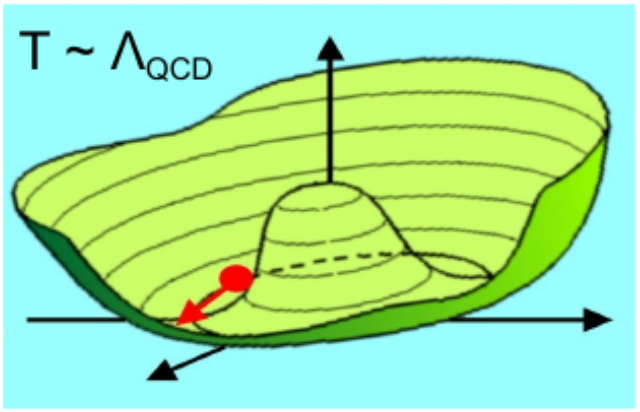
1st Stars
about 400 million yrs.

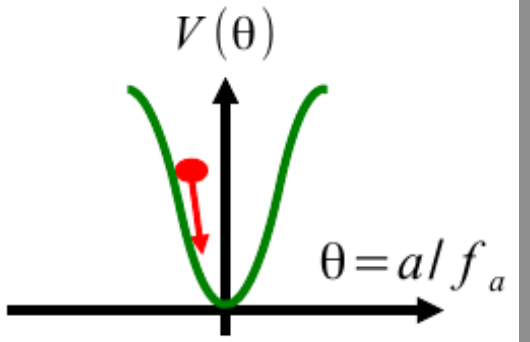
Big Bang Expansion

13.7 billion years

A Cosmological CV of the Axion







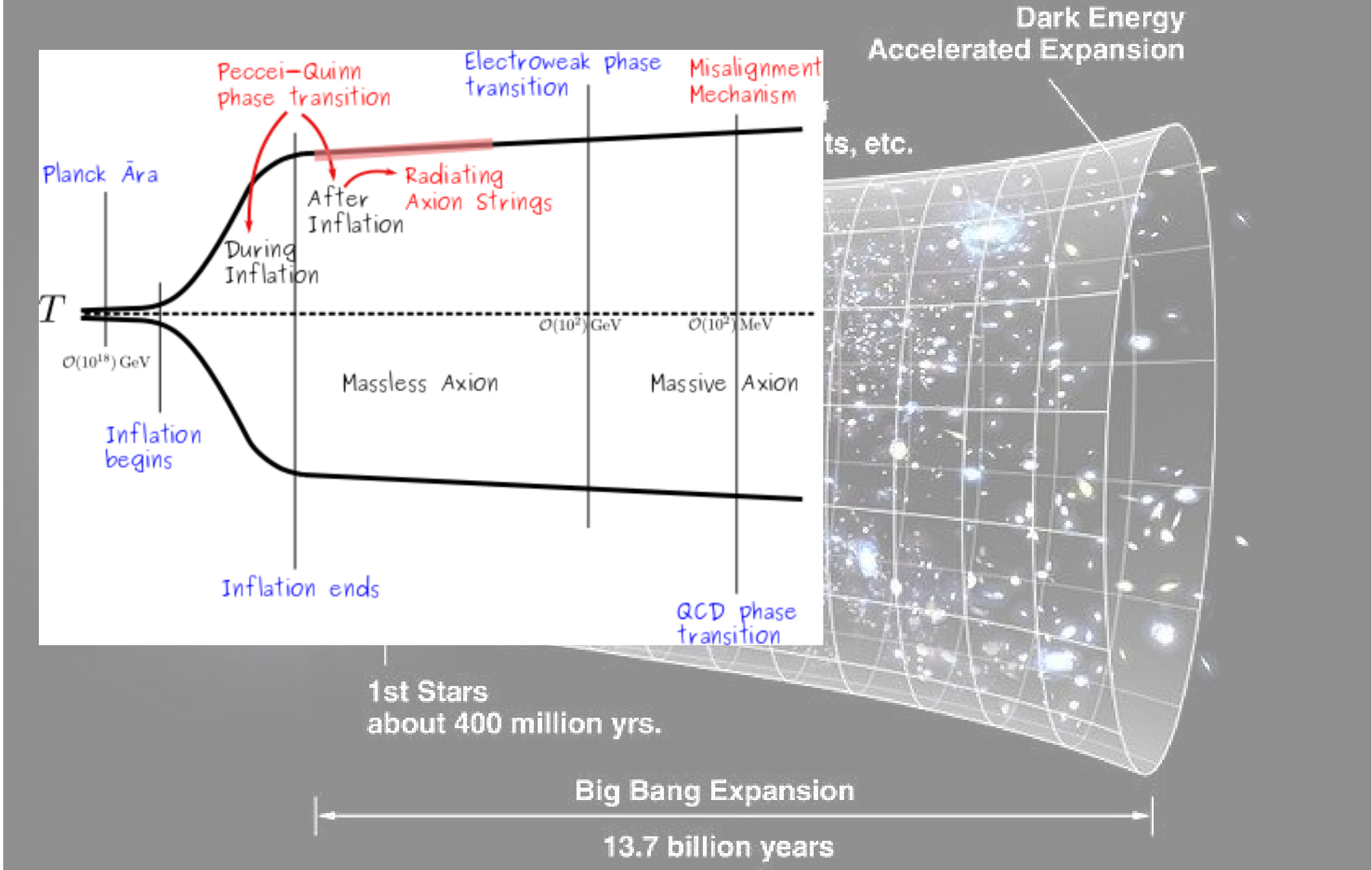
Dark Energy

1st Stars
about 400 million yrs.

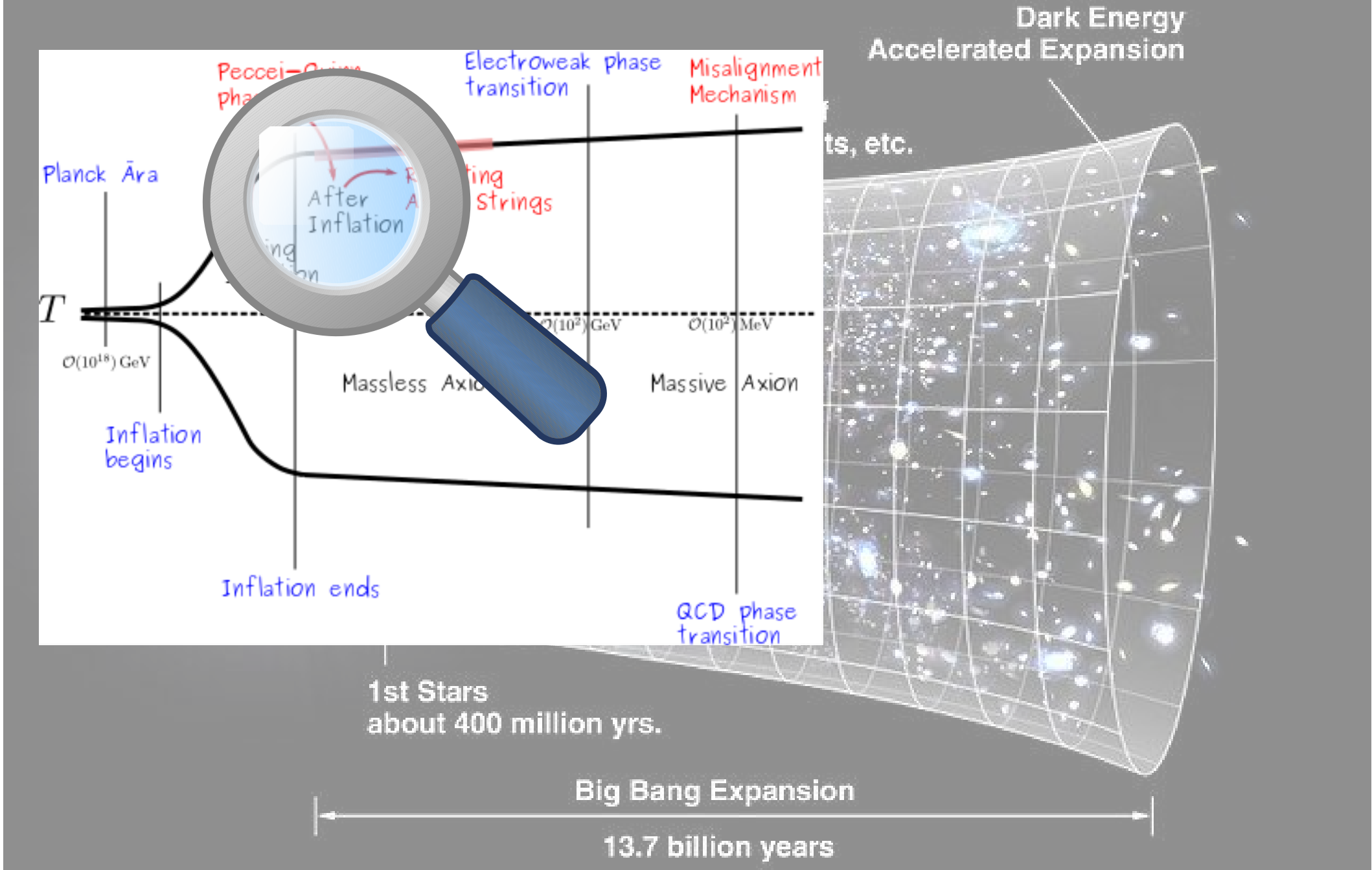
Big Bang Expansion

13.7 billion years

A Cosmological CV of the Axion

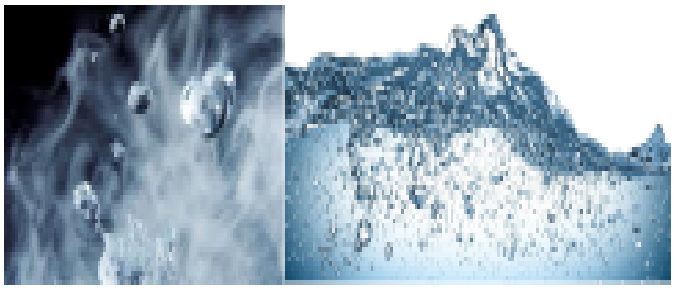


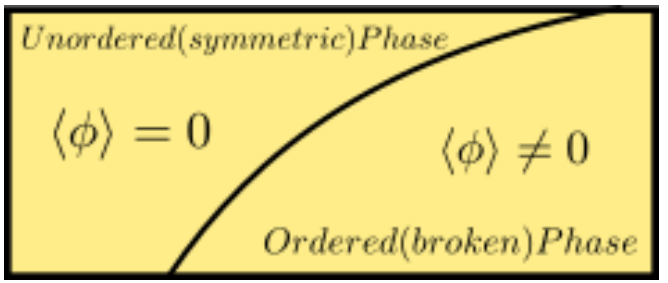
A Cosmological CV of the Axion



Cosmological Phase Transitions

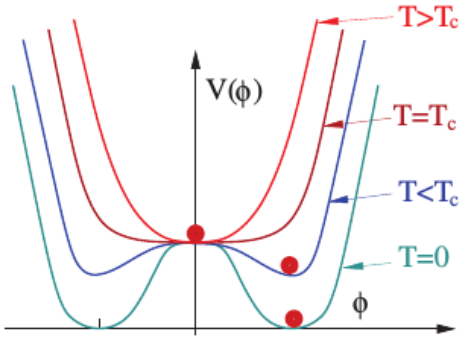
- CPT= change in vacuum expectation value (vev)



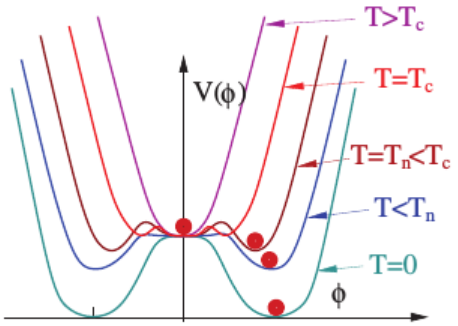


- vev=Minimum of the (eff. free energy) potential

2. order

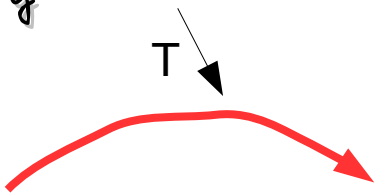


1. order



- Breaking of Symmetry

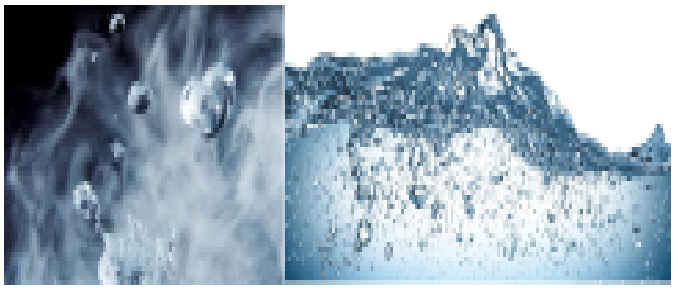
Symmetry of Groundstate = Symmetry of Lagrangian

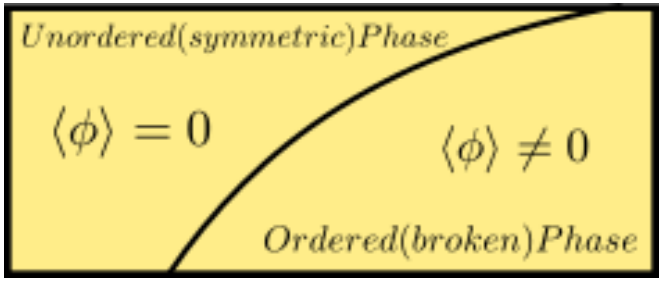


Symmetry of Groundstate ≠ Symmetry of Lagrangian

Cosmological Phase Transitions

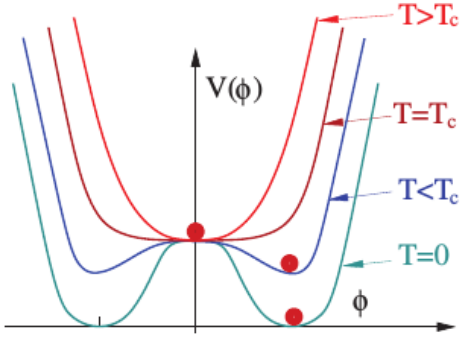
- CPT= change in vacuum expectation value (vev)



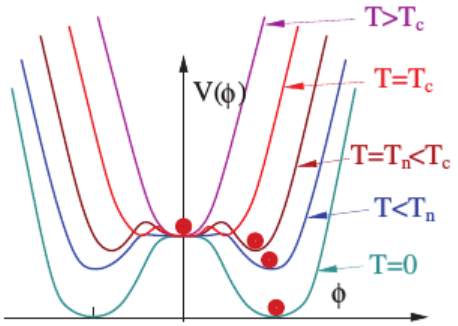


- vev=Minimum of the (eff. free energy) potential

2. order



1. order

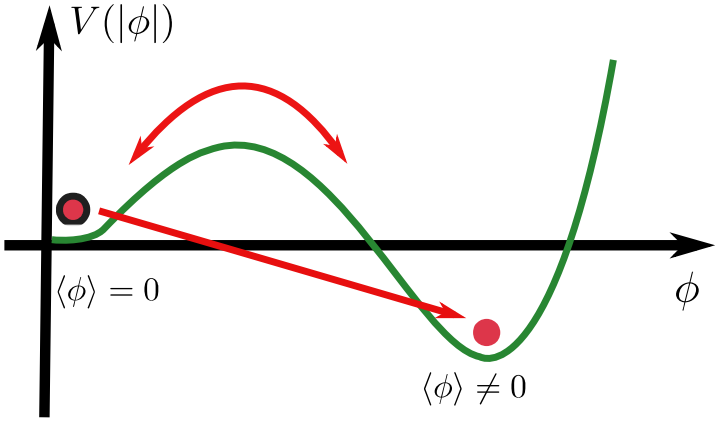


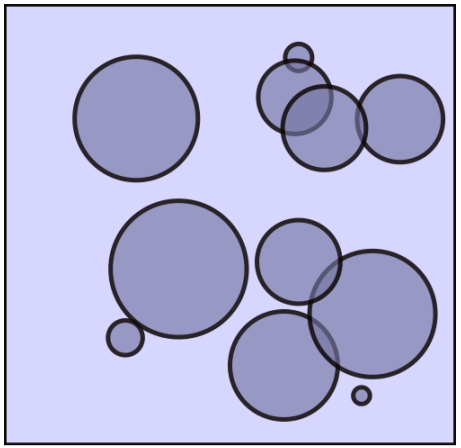
- Breaking of Symmetry

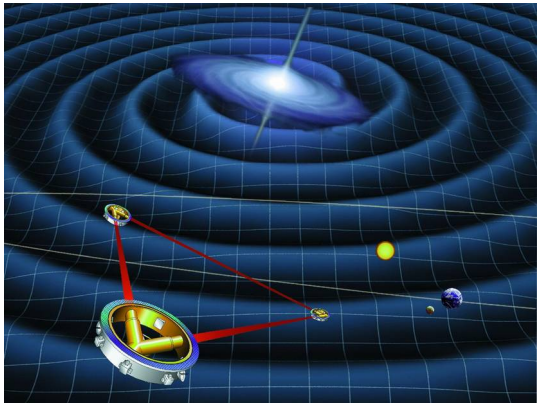
Important consequence: Particles coupled to the field get mass

Symmetry of Groundstate ≠ Symmetry of Lagrangian

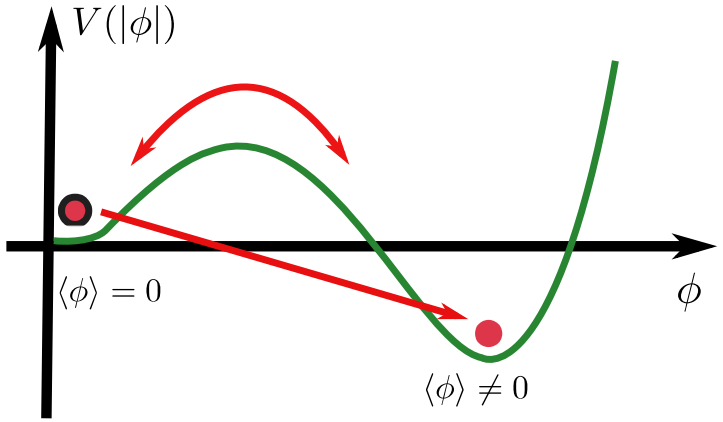
Gravitational Waves from 1st order CPT's

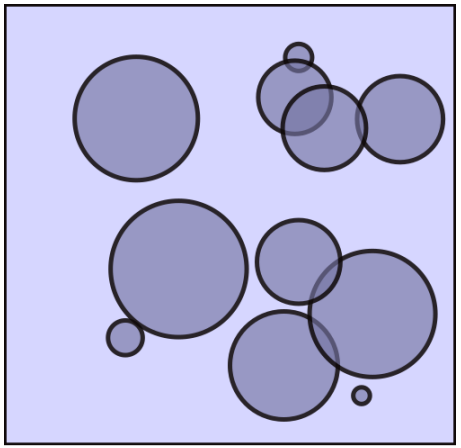


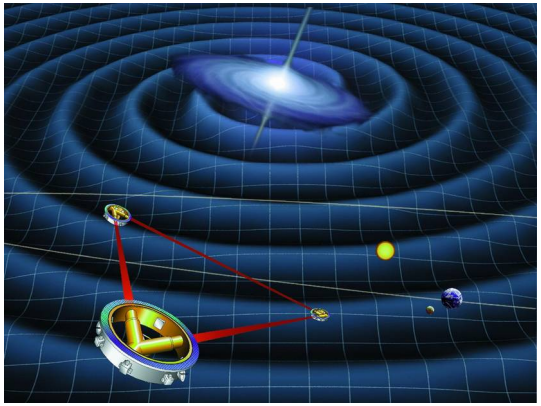




Gravitational Waves from 1st order CPT's







Phase Trans.
Latent heat α
Bubble nucleation rate β
Strength $\frac{\langle\phi\rangle}{T_c} \geq 1$

Bubble Growth
Wall velocity v_W
Latent heat fraction κ
PT-Energy$\rightarrow$ T_{kin}(Bubble)

Abundance $\Omega_{GW}(f) = \Omega_{BC}(f) + \Omega_{SW}(f) + \Omega_{MHD}(f)$

GW Frequence

Bubble Collison Sound Wave Magnetic Fields

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

$$V_{\text{loop}} \sim \frac{1}{64\pi^2} \sum_{\{\text{particles}\}} m_p(\phi)^4 (-1)^{B/F} n_p \left[\ln \frac{m_p(\phi)^2}{\mu^2} - c_i \right]$$

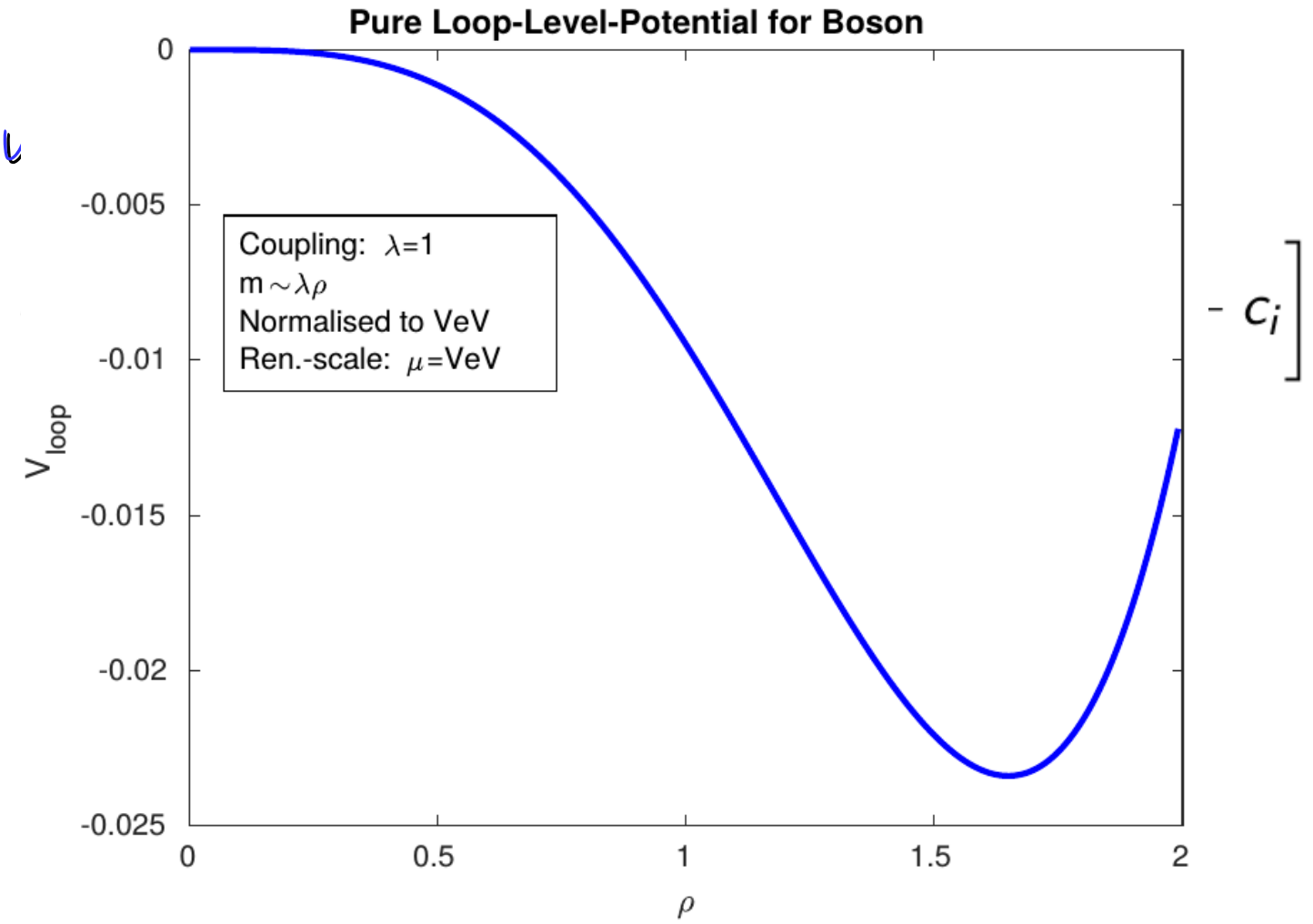
GW's from PQ breaking?

Question:

1) What do

How to bu

V_{loop}



$- c_i \Big]$

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

$$V_{\text{loop}} \sim \frac{1}{64\pi^2} \sum_{\{\text{particles}\}} m_p(\phi)^4 (-1)^{B/F} n_p \left[\ln \frac{m_p(\phi)^2}{\mu^2} - c_i \right]$$

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

$$V_T^{(1)}(\phi) = \frac{T^4}{2\pi^2}\left[\sum_p (-1)^{B/F} n_p J^{B}/F_T(m)\right]$$

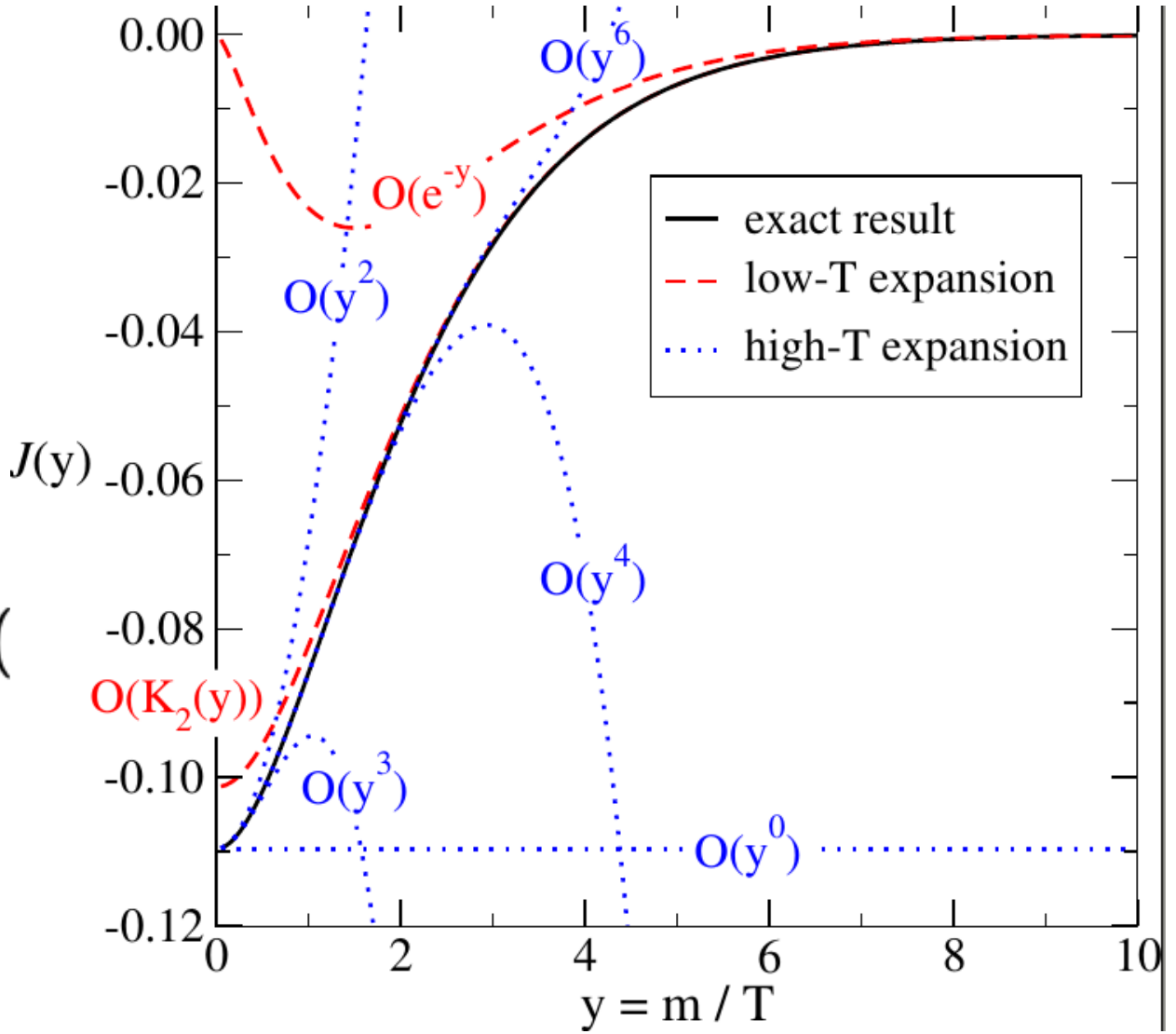
GW's from PQ breaking?

Question:

1) What do we

How to built

$V_T^{(1)}($



GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

How to built a potential?

$$V_T^{(1)}(\phi) = \frac{T^4}{2\pi^2}\left[\sum_p (-1)^{B/F} n_p J^{B}/F_T(m)\right]$$

GW's from PQ breaking?

Question:

1) What do we need for 1st order PQ symmetry breaking?

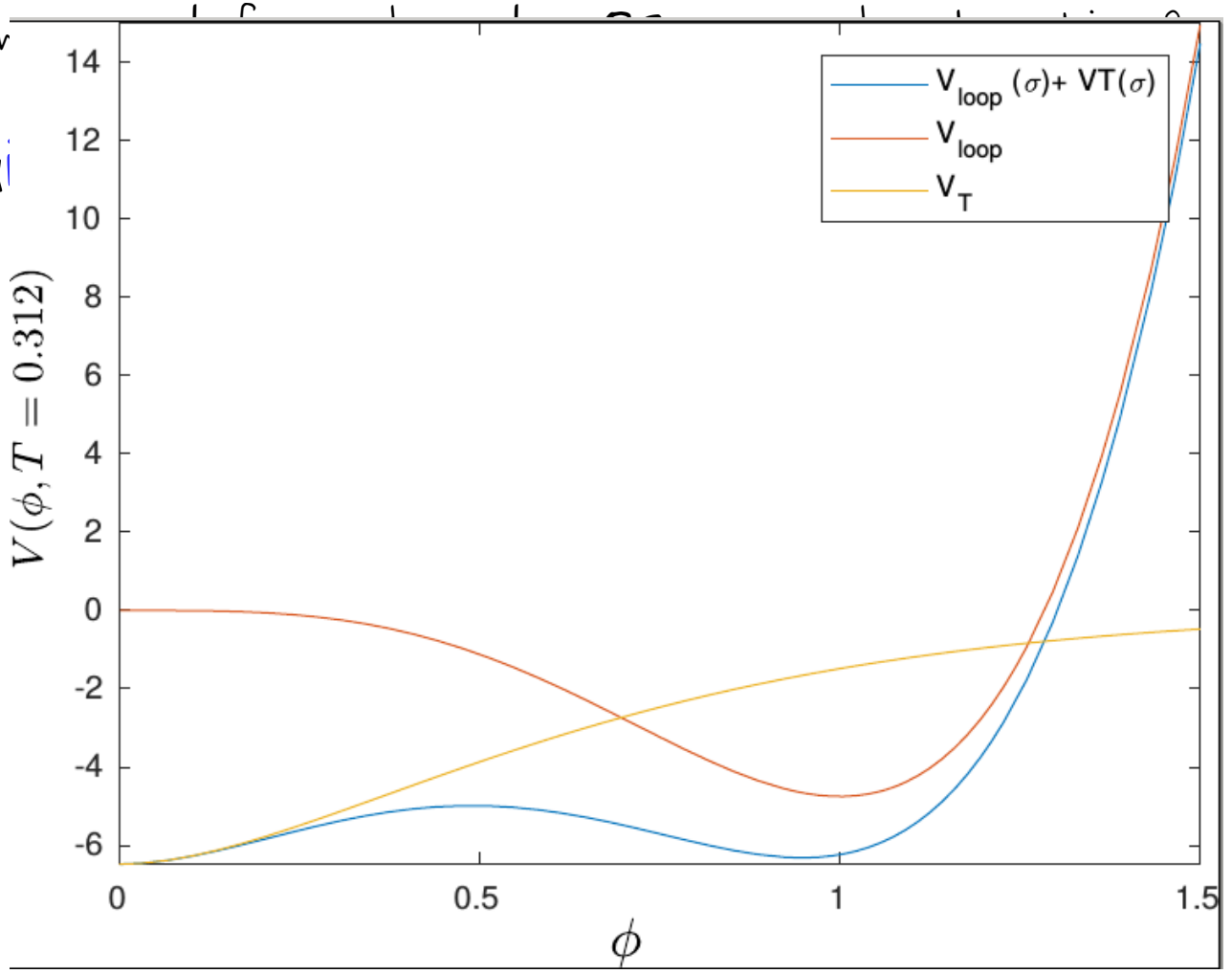
How to built a potential?

GW's from PQ breaking?

Question:

1) What do w

How to bui



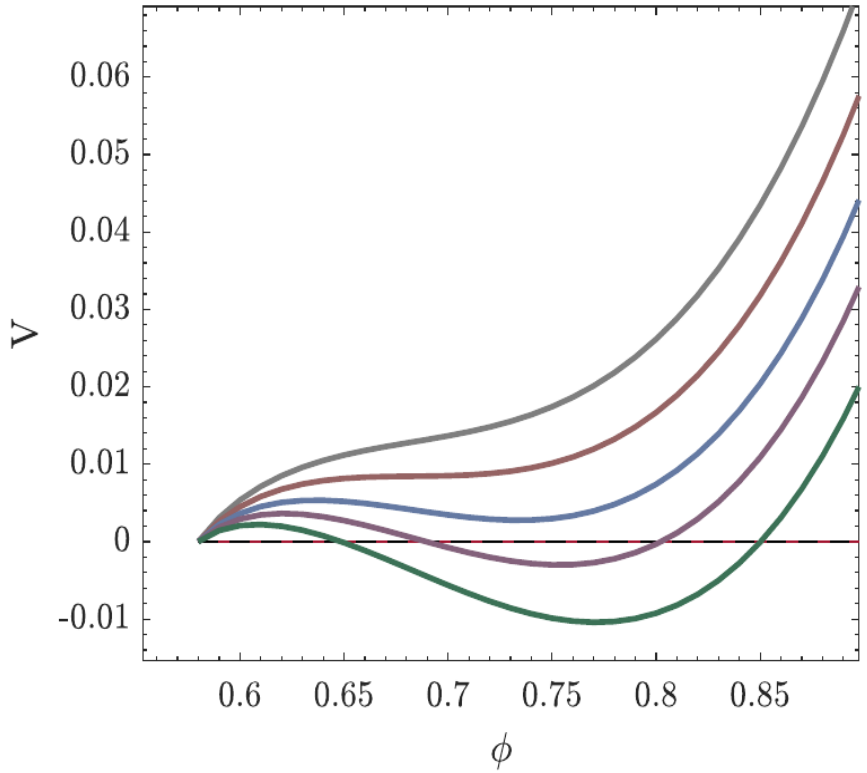
GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion

GW's from PQ breaking?

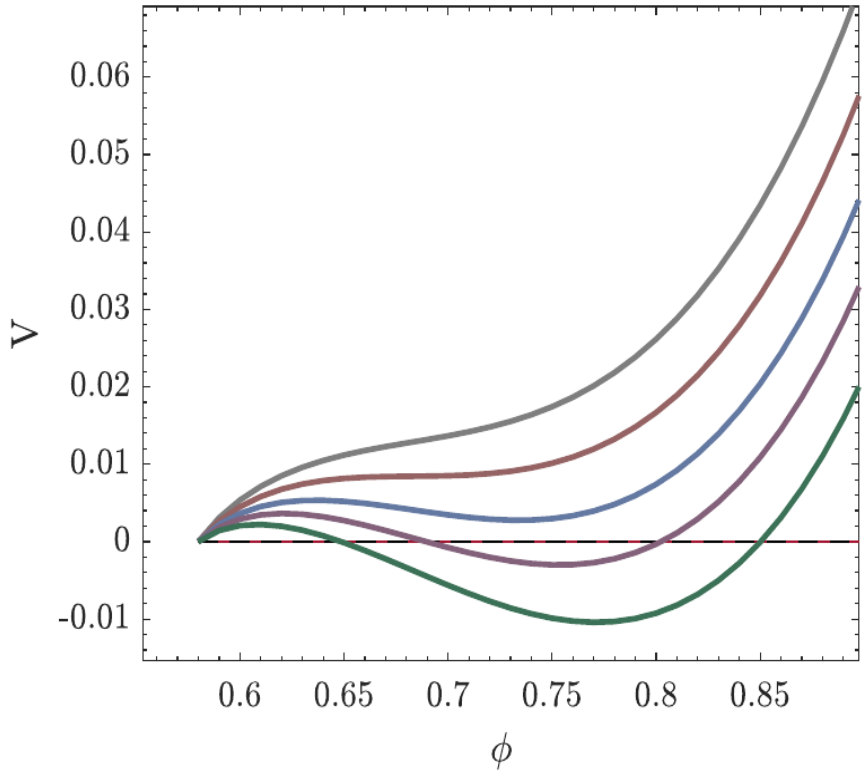
Inaredients:

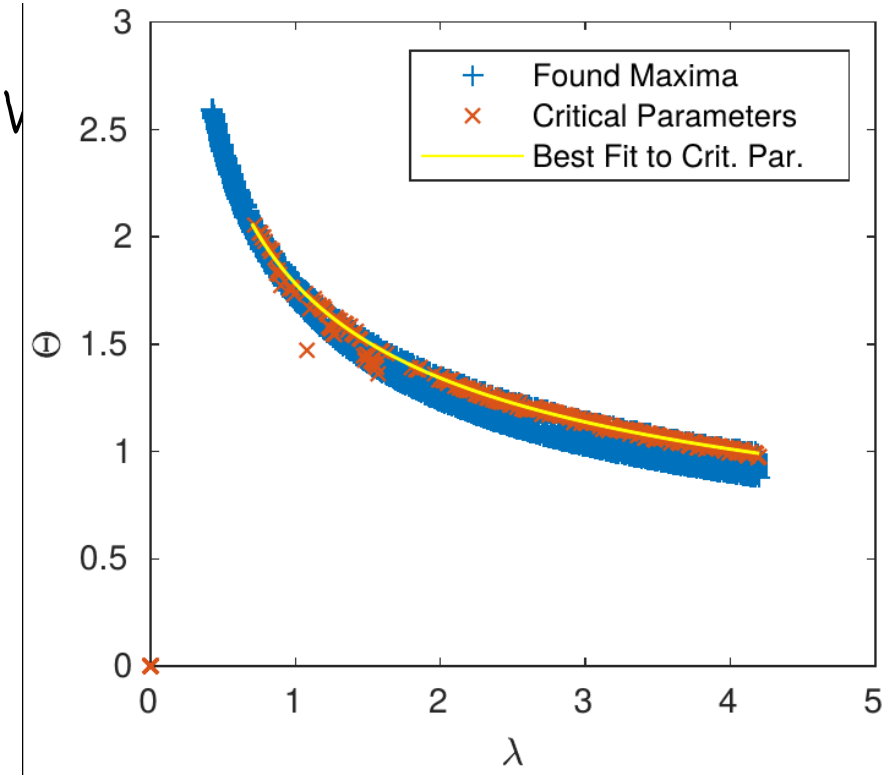
- 

with the axion

GW's from PQ breaking?

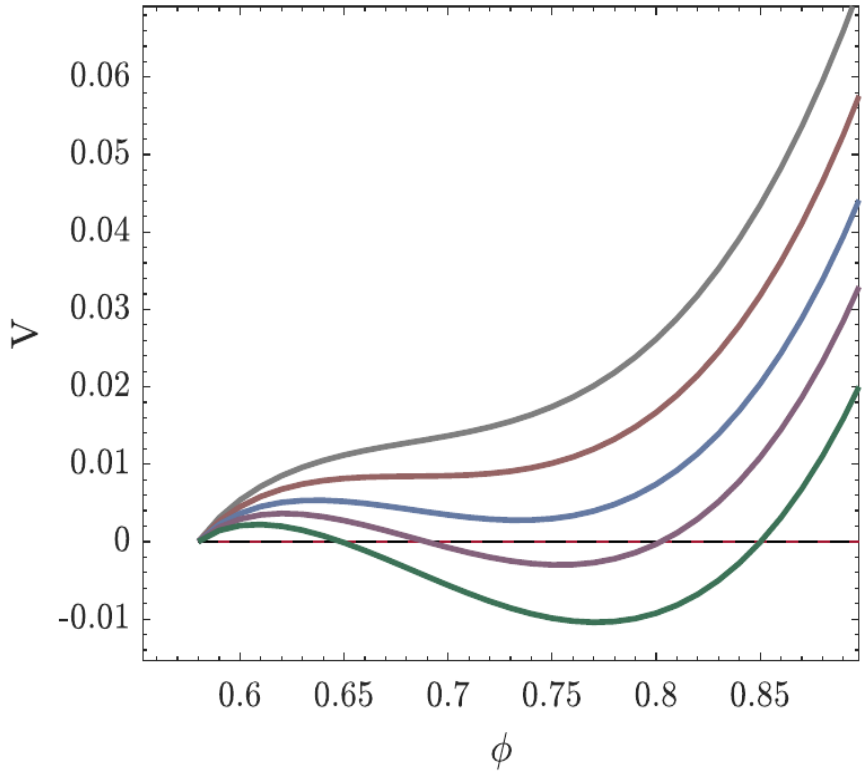
Inaredients:

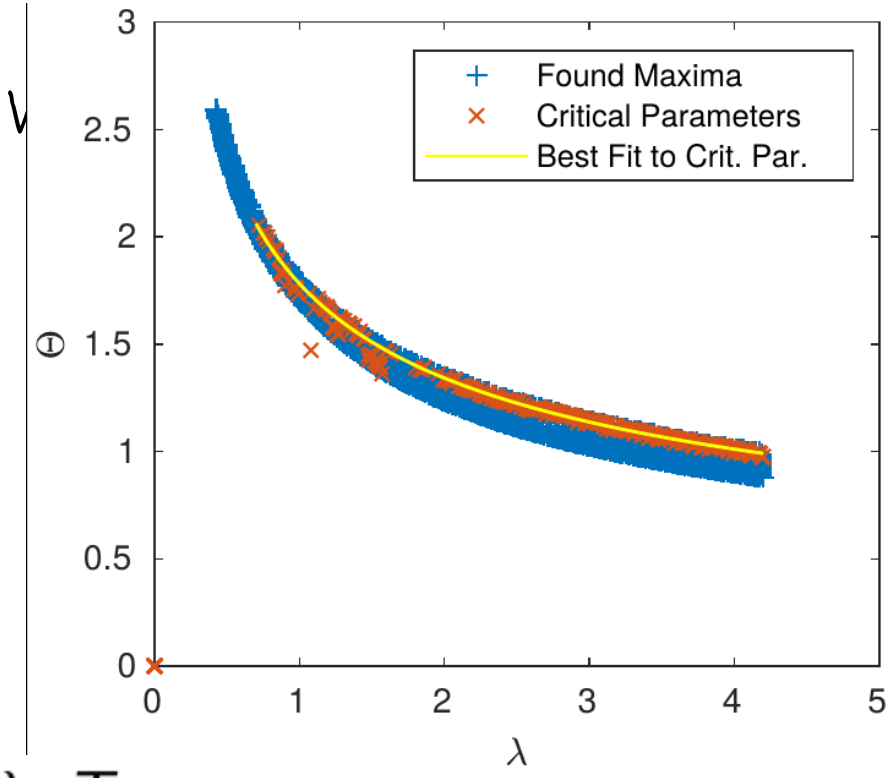
- 



GW's from PQ breaking?

Inaredients:

- 



But: $\frac{\lambda_\phi T_c}{m} \sim \mathcal{O}(1)$

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)
- At least one further scalar field (Higgs)

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)
- At least one further scalar field (Higgs)

2) Which terms in the „SMASH-Model" must be removed for 1st order PQ?

→ SMAS~~H~~

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)
- At least one further scalar field (Higgs)

2) Which terms in the „SMASH-Model" must be removed for 1st order PQ?

$\mathcal{L} \subset -y\tilde{Q}\phi Q + \{\text{optional}\}$

→ SMAS~~H~~

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)
- At least one further scalar field (Higgs)

2) Which terms in the „SMASH-Model" must be removed for 1st order PQ?

→ SMAS~~H~~

$$\mathcal{L} \subset -y\tilde{Q}\phi Q + \{\text{optional}\}$$

$$V(\phi, H) := \frac{\lambda_\phi}{4}\left(|\phi|^2 - v_\phi^2\right)^2 + \frac{\lambda_H}{4}\left(H^\dagger H - v_H^2\right)^2 + \frac{\lambda_{H\phi}}{4}\left(|\phi|^2 - v_\phi^2\right)\left(H^\dagger H - v_H^2\right)$$

GW's from PQ breaking?

Ingredients:

- Complex scalar field with the axion
- Additional Quark(s) (Color anomaly)
- At least one further scalar field (Higgs)

2) Which terms in the „SMASH-Model" must be removed for 1st order PQ?

$\mathcal{L} \subset -y\tilde{Q}\phi Q + \{\text{optional}\}$

⟶ SMASH

$$V(\phi, H) := \frac{\lambda_\phi}{4}\left(|\phi|^2 - v_\phi^2\right)^2 + \frac{\lambda_H}{4}\left(H^\dagger H - v_H^2\right)^2 + \frac{\lambda_{H\phi}}{4}\left(|\phi|^2 - v_\phi^2\right)\left(H^\dagger H - v_H^2\right)$$

Task:
Scan parameter space for allowed regions. Detectability?

Possible Extension:
Correlate GW signals from different events in cos. History of the axion

Conclusion/Outlook

- QCD-Axion interesting solution to the strong CP Problem
- Gravitational Waves provide a test for CPT models in the future
- Investigating the first order Peccei-Quinn symmetry breaking after inflation is an interesting field to study
- Correlating different sources of GW's from cosmological history of the Axion

References

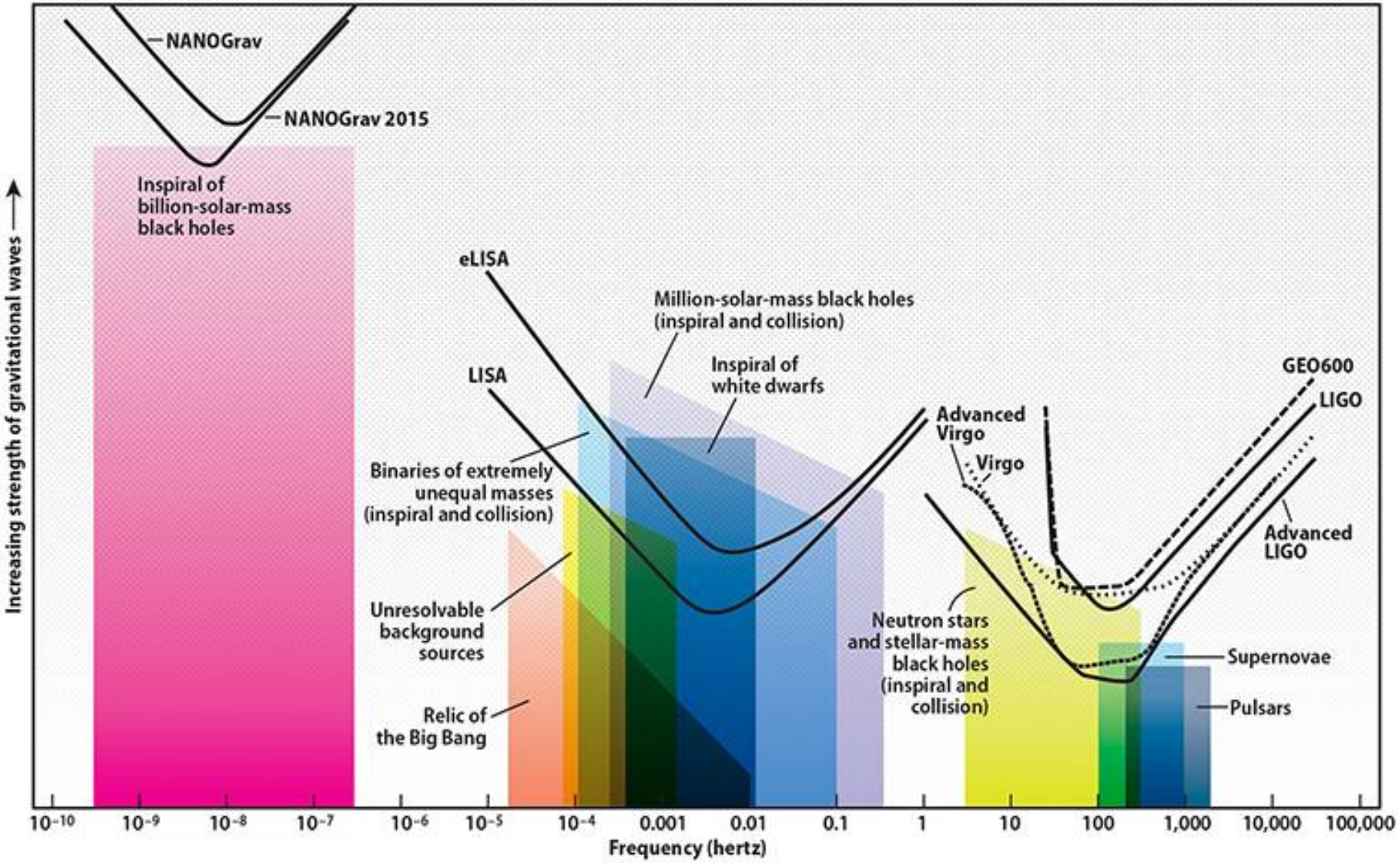
- Peccei Quinn ´77 PRL. 38 (25) doi:10.1103/PhysRevLett.38.1440
- Yvonne Y.Y. Wong, RWTH Aachen
- ArXiv: 0803.1593v5 E.Vicari, H. Panagopoulus
- D.Sticlet Phase Transition in the early universe
- ArXiv: 1701.01554 Mikko Lainen
- Public Domain, https://commons.wikimedia.org/w/index.php?curid=10372273
- KVSZ Modell J.Kim, Phys. Lett. 43 (1979) 103; M.A.Shifman, A.I.Vainshtein, V.I.Zakharov, Nucl. Phys. B166 (1980) 493
- arXiv:1602.03901 Jörg Jäckel et al. PRD94 (2016) no.10, 103519
- SMASH arXiv:1610.01639 JCAP 1708 (2017) no.08, 001 G. Ballesteros et al.

Backup 1

- GW‘s from symmetry breaking
- GW‘s from axion radiating strings
- GW‘s from Domain Walls

Correlate GW signals

Backup 2



Astronomy: Roen Kelly, after C. Moore, R. Cole, and C. Berry (Institute of Astronomy, Univ. of Cambridge