Questions ouvertes en physique des particules .

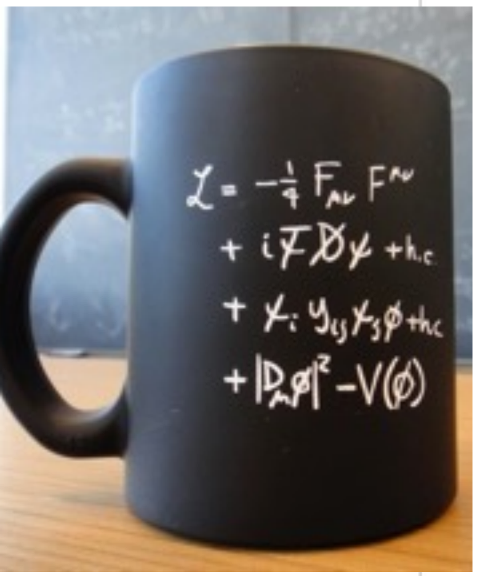
Géraldine SERVANT
DESY/U.Hamburg

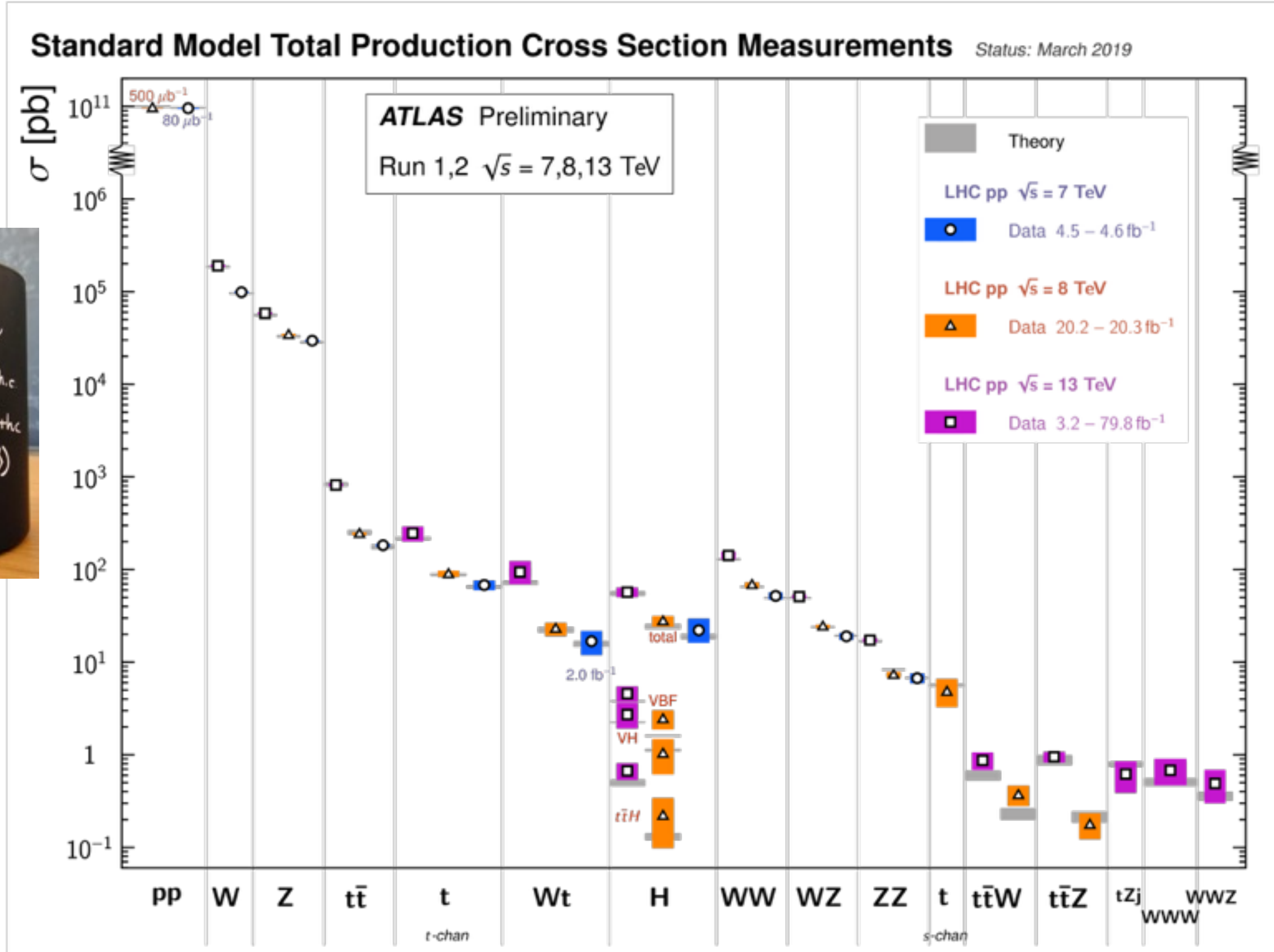
Ecole de Gif, Palaiseau
2 Septembre 2019

DESY.

Universität Hamburg

So far, all lab. measurements amazingly consistent with the Standard Model





describes phenomena over many orders of magnitude!

Open questions in particle physics .

The Standard Model of Particle Physics

- **Origin of Dark Matter**
- **Origin of Baryon Asymmetry**
- **Origin of neutrino masses**
- **Origin of the electroweak scale**
- **Origin of Flavour**
- **Origin of strong CP solution**
- **Origin of Large Scale Structures (inflation)**
- **Origin of Cosmological Constant**

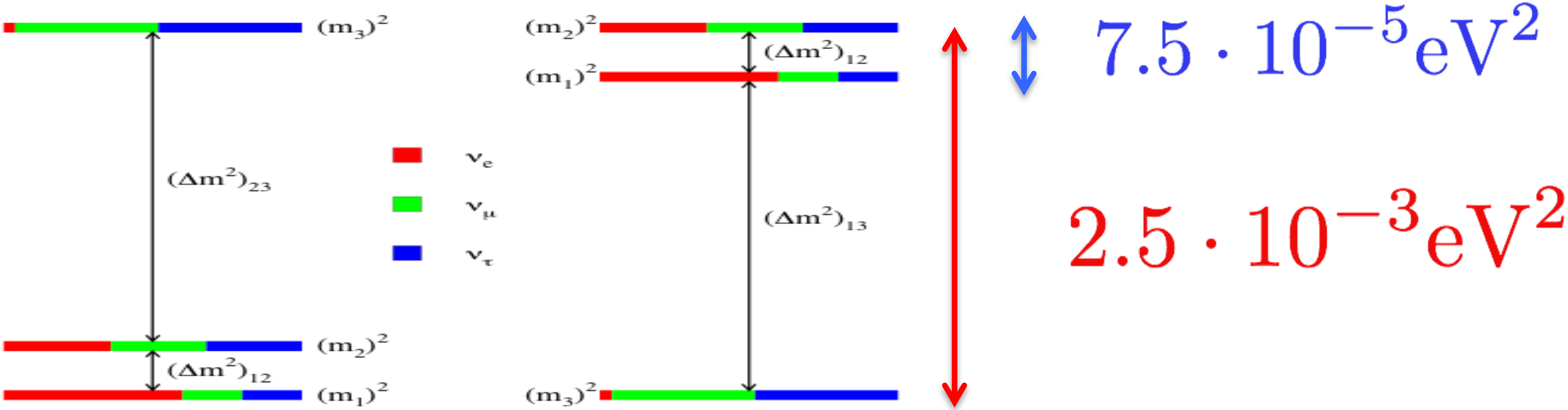
All related to physics of the early universe

Open questions in particle physics that I will not discuss today (or only briefly).

- Origin of neutrino masses
- Origin of Flavour
- Origin of strong CP solution
- Origin of Large Scale Structures (inflation)
- Origin of Cosmological Constant

All related to physics of the early universe

Origin of neutrino masses .



NO/NH

IO/IH

Normal Hierarchy

Inverted Hierarchy

Why do massive neutrinos mix so differently?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata

$\theta_{12} \sim 34^\circ$

$\theta_{23} \sim 42^\circ$ o 48°

$\theta_{13} \sim 8.5^\circ$

$\delta \sim \ ?$

CKM

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97446 \pm 0.00010 & 0.22452 \pm 0.00044 & 0.00365 \pm 0.00012 \\ 0.22438 \pm 0.00044 & 0.97359^{+0.00010}_{-0.00011} & 0.04214 \pm 0.00076 \\ 0.00896^{+0.00024}_{-0.00023} & 0.04133 \pm 0.00074 & 0.999105 \pm 0.000032 \end{pmatrix}$$

$J = (3.18 \pm 0.15) \times 10^{-5}$

PMNS

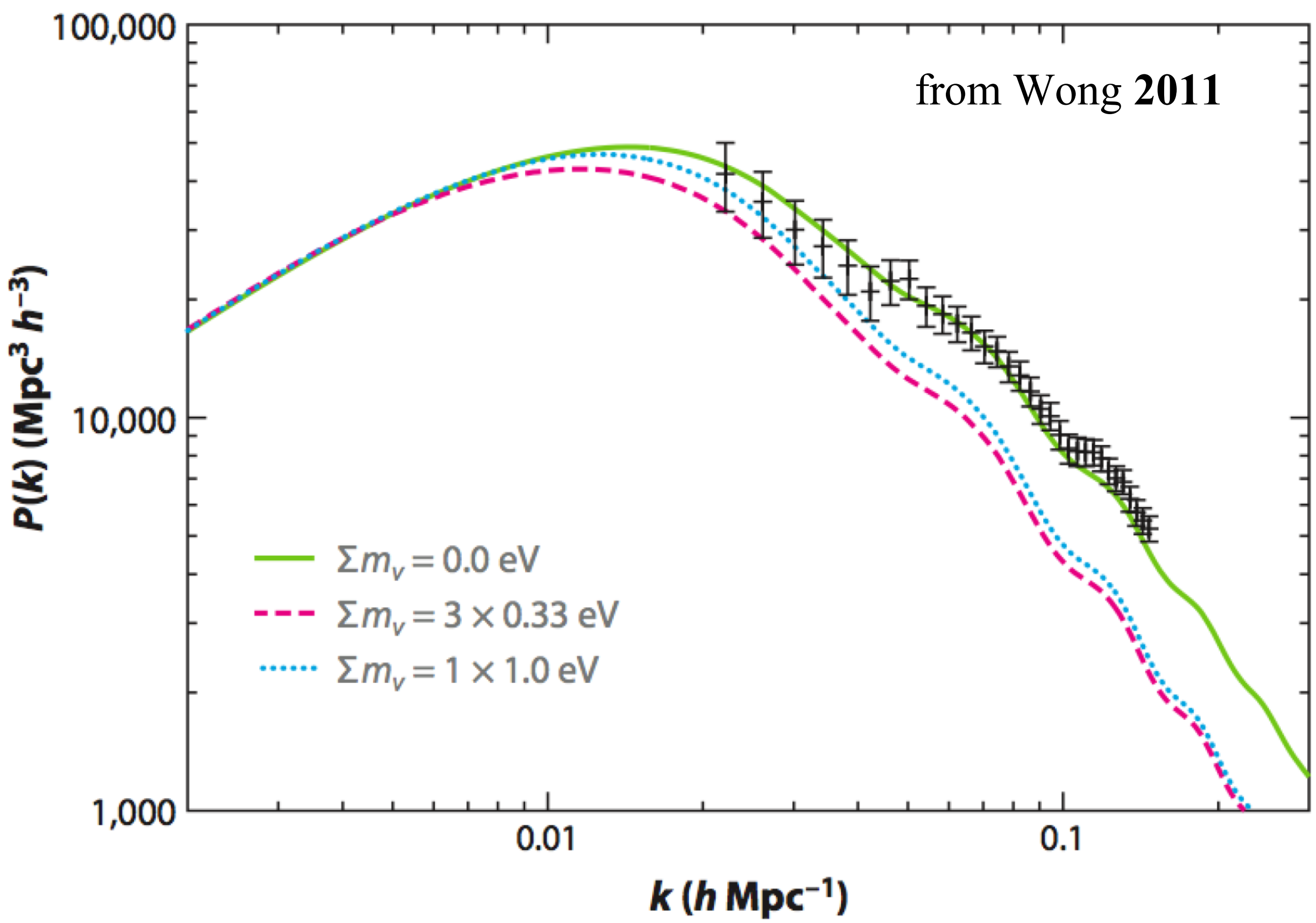
3σ

NuFIT 3.2 (2018)

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.141 \to 0.156 \\ 0.242 \to 0.494 & 0.467 \to 0.678 & 0.639 \to 0.774 \\ 0.284 \to 0.521 & 0.490 \to 0.695 & 0.615 \to 0.754 \end{pmatrix}$$

$J \simeq 0.033 \sin\delta$

Neutrino masses affect gravitational clustering

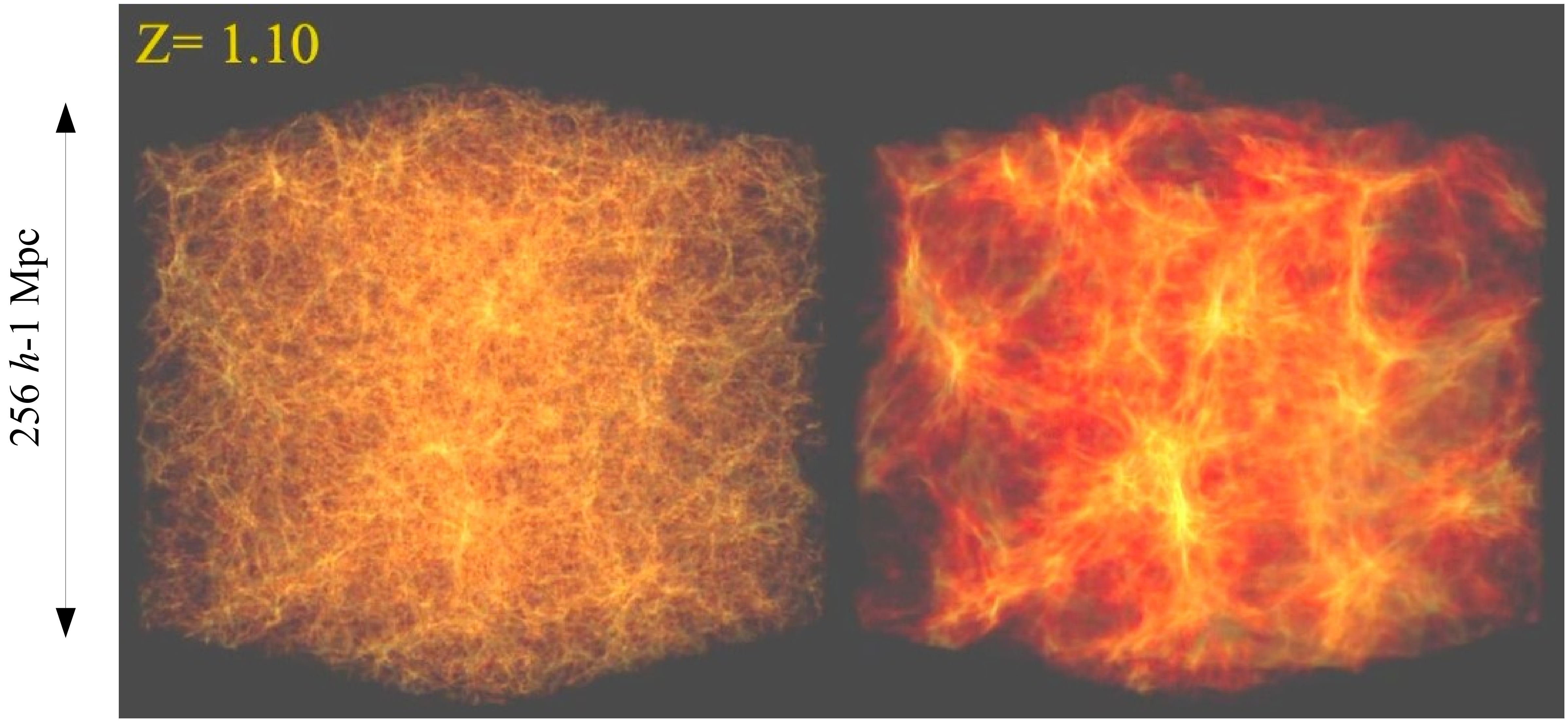


Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

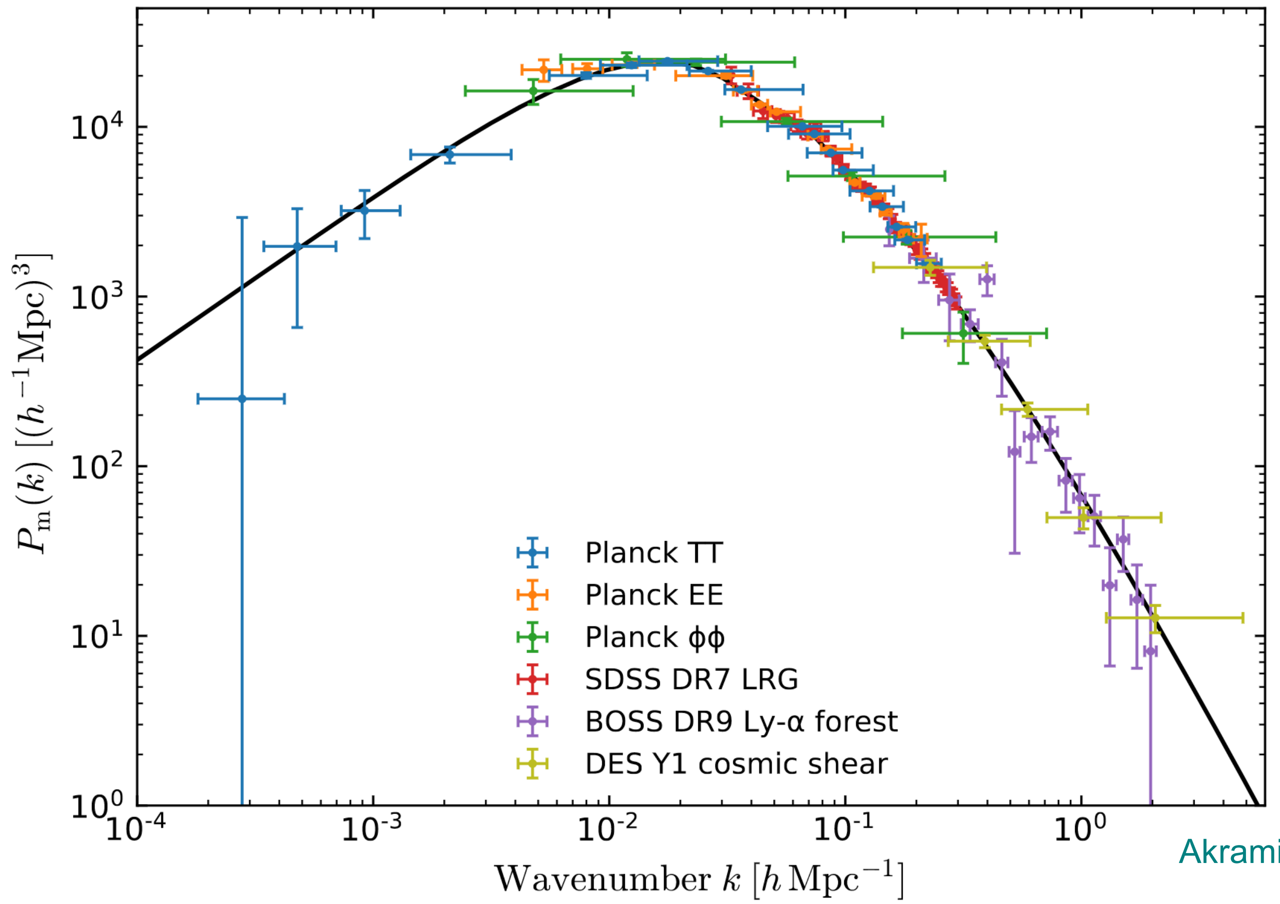
If a 10 eV-mass neutrino was the dark matter, $\lambda_{FS,max} \sim 25$ Mpc, we would not have galaxies ($\lambda \sim 10$ kpc) and galaxies clusters ($\lambda \sim 1$ Mpc)!

Cold dark matter　　　　Massive neutrinos 7 eV

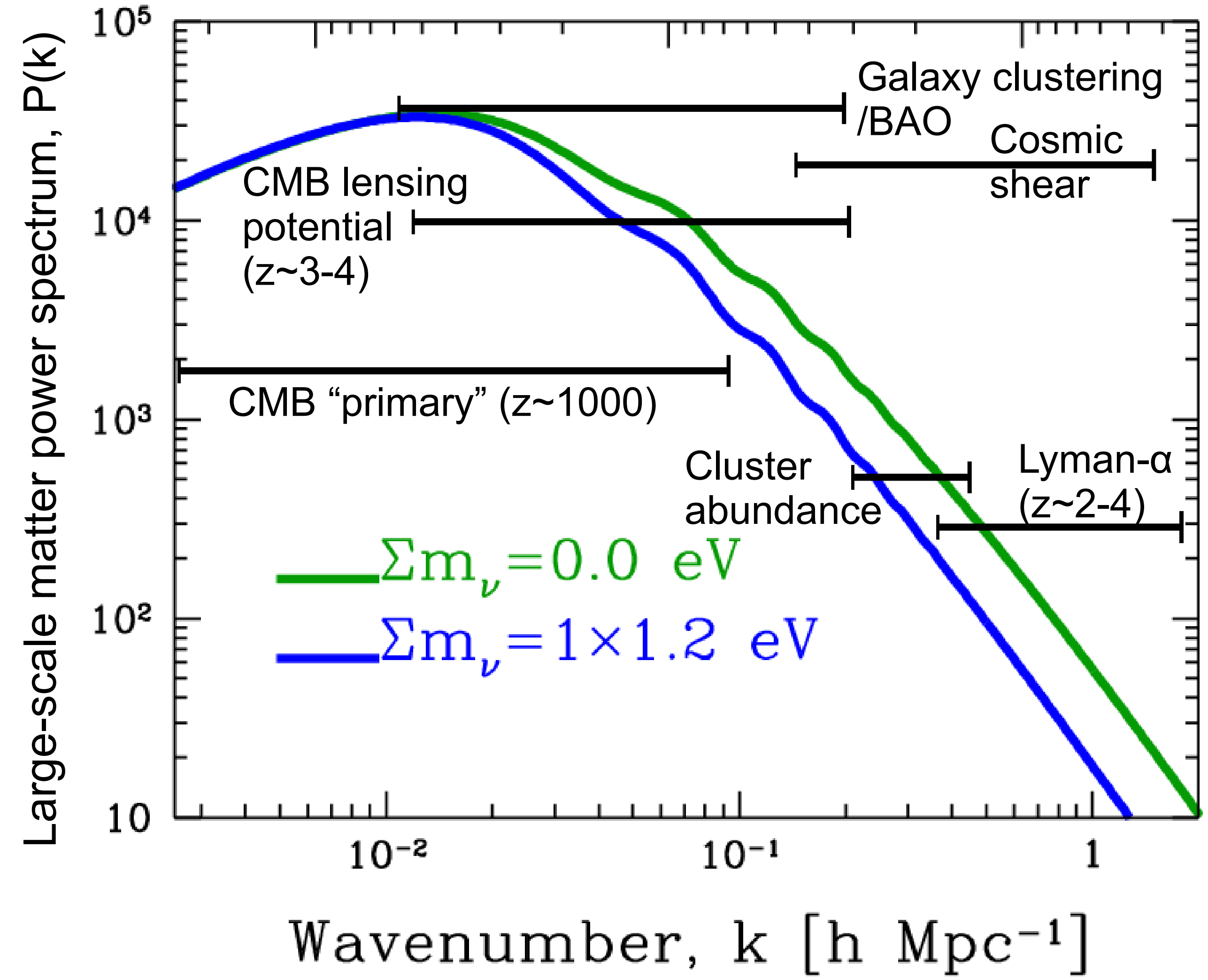


Simulations by Troels Haugbølle

Measuring the matter power spectrum

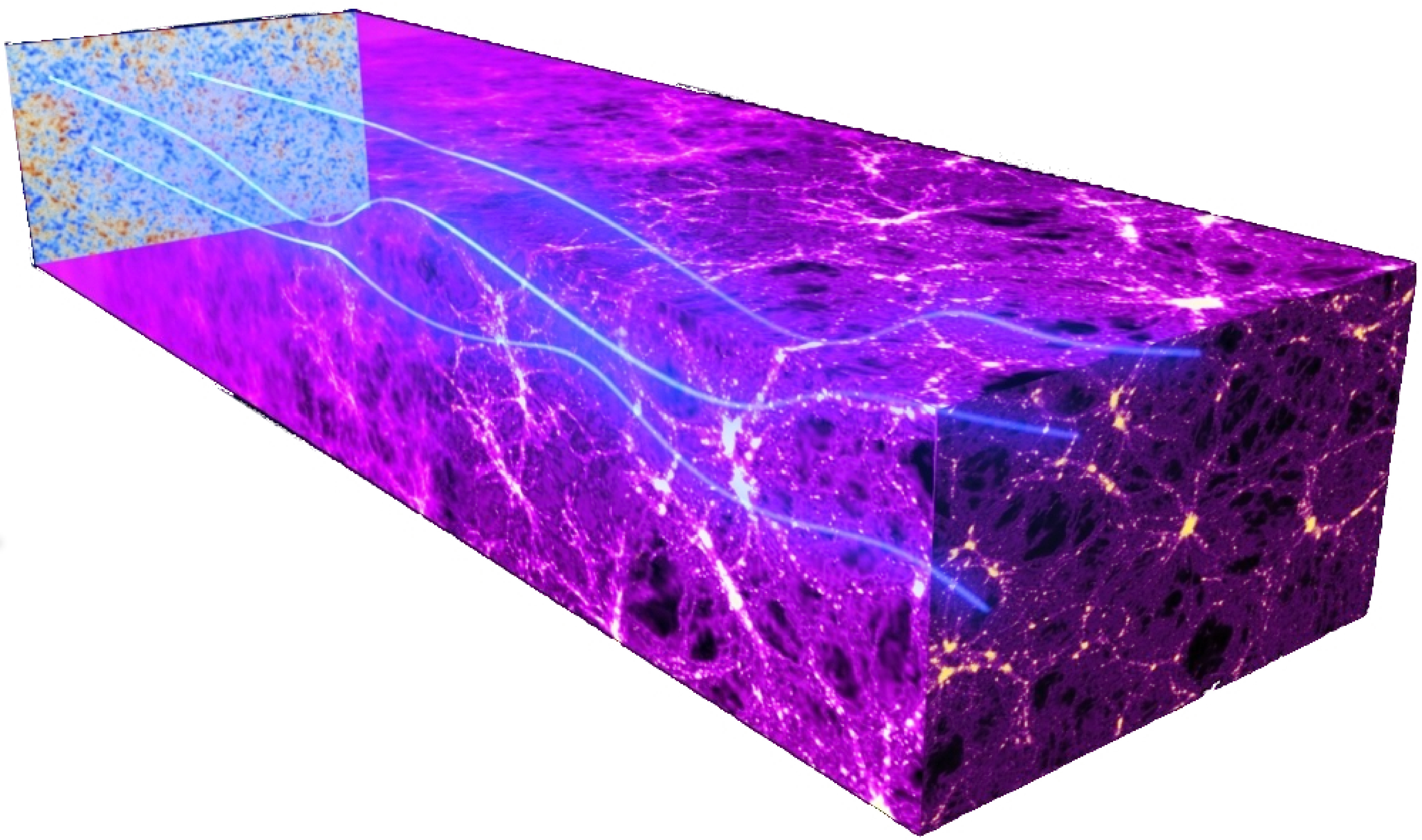


Akrami et al. 2018



Weak lensing of the CMB

CMB photons are deflected by the intervening matter distribution, leading to a slightly **distorted image** of the large scattering surface.

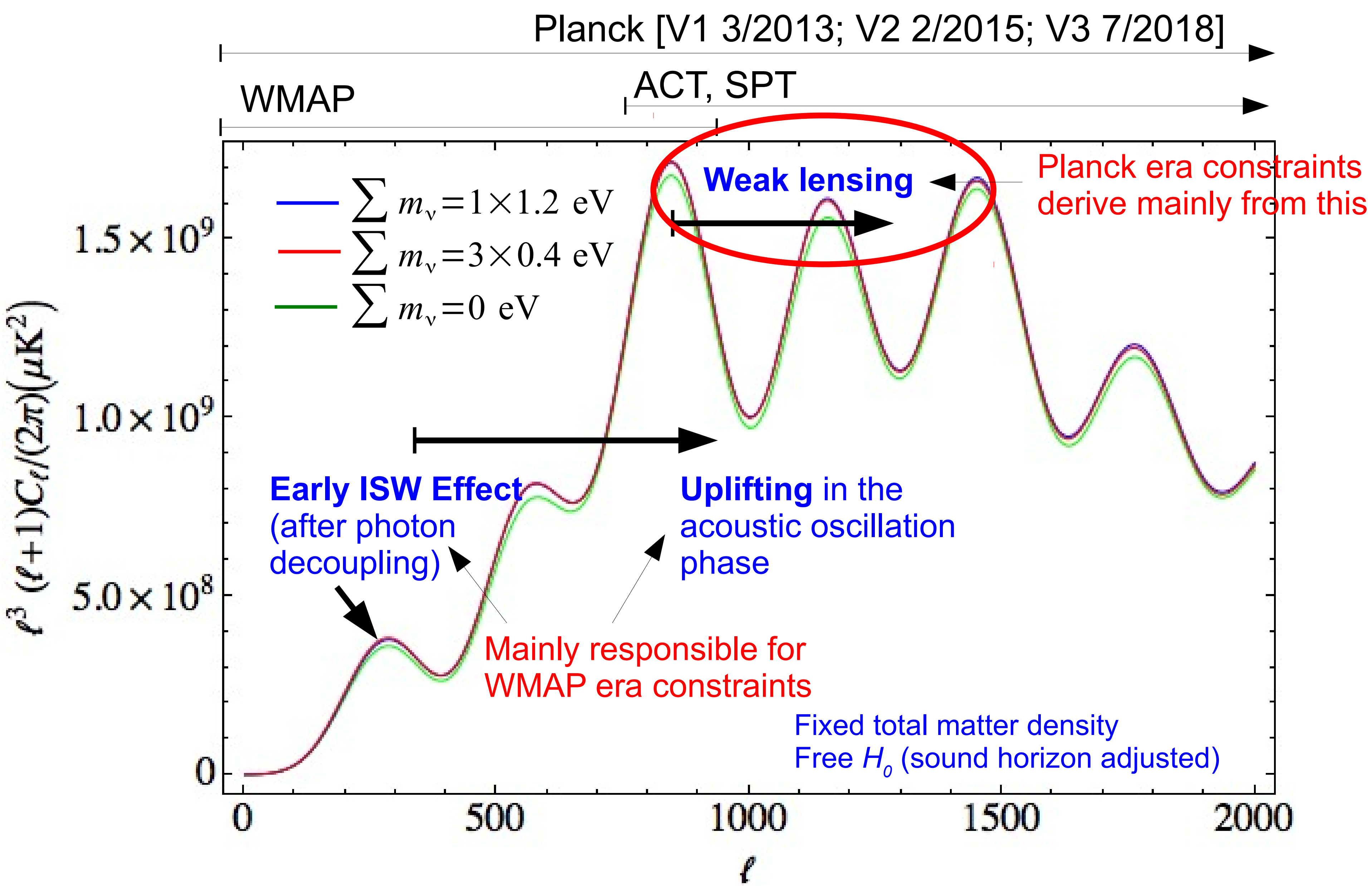


[Y. Wong]

Weak lensing

Neutrino mass and the CMB temperature...

[Y. Wong]



Planck2015 TT+lowP+Lyα $\sum m_\nu < 0.13$ eV

Palanque-Delabrouille et al. 2015

Summary on neutrinos & cosmology

The CMB anisotropies and the large-scale structure distribution can be used to probe neutrino physics.

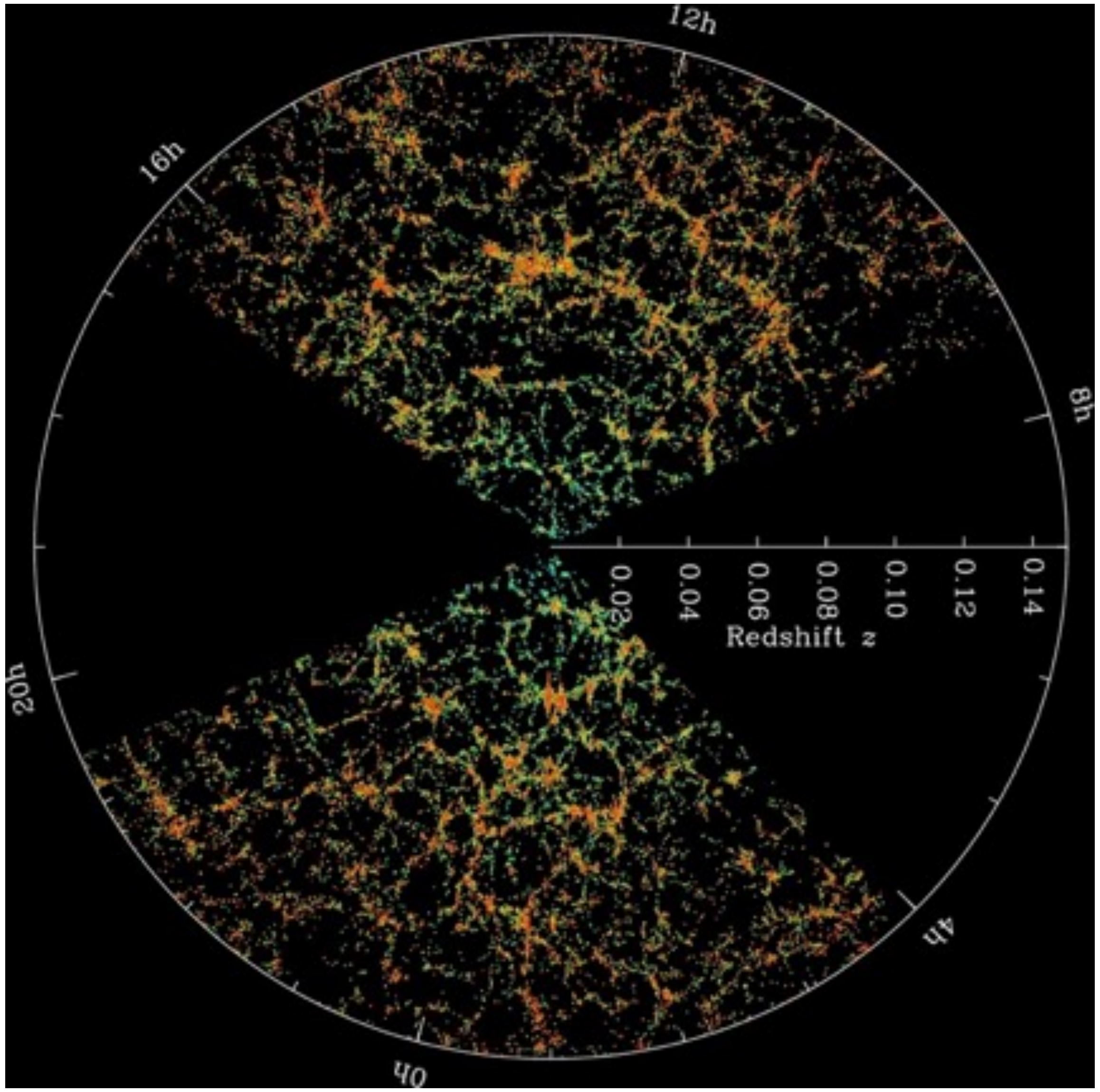
Existing data already place strong constraints on the neutrino mass.

Future probes exploiting weak gravitational lensing of CMB polarisation (e.g., CMB S4) and cosmic shear (e.g., Euclid) can potentially tighter the bound 10-fold.

[Y. Wong]

The observable universe: ~ 3000 Megaparsec (Mpc) 1 Mpc

Sloan Digital Sky Survey (SDSS) Galaxy Map

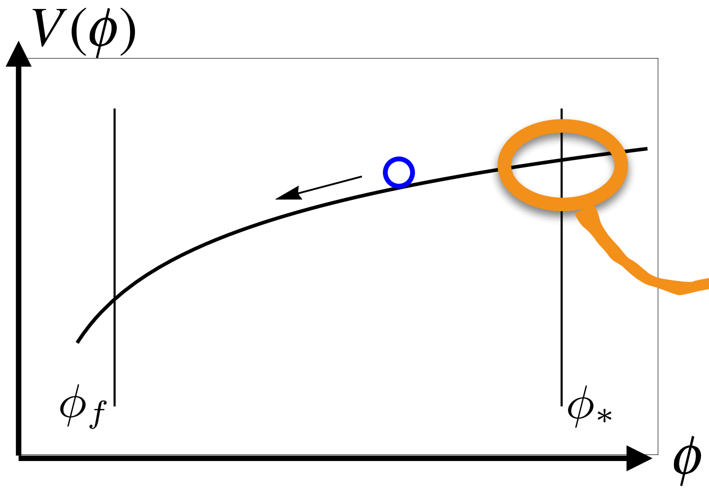


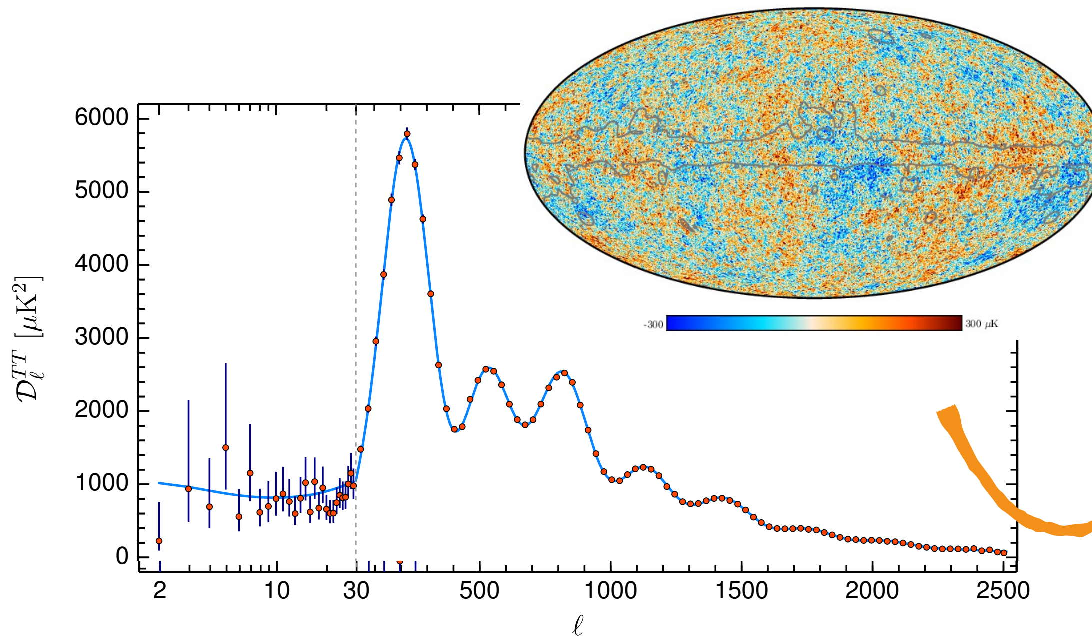
catalog of hundreds of thousands of galaxies -> measure of the matter content of the universe

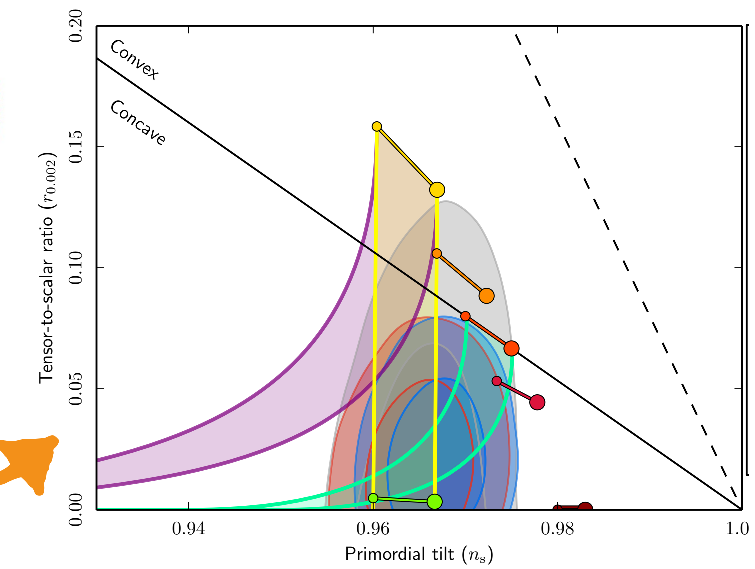
The main characteristic of our universe: homogeneous & isotropic at large scales (>100 Mpc)

At scales < 100 Mpc: very inhomogeneous structure (galaxies, clusters, super-clusters)

Inflationary paradigm







[Planck collaboration ’18]

large vacuum energy → exponential expansion → homogeneity of CMB

quantum fluctuations → become classical → tiny anisotropies in the CMB

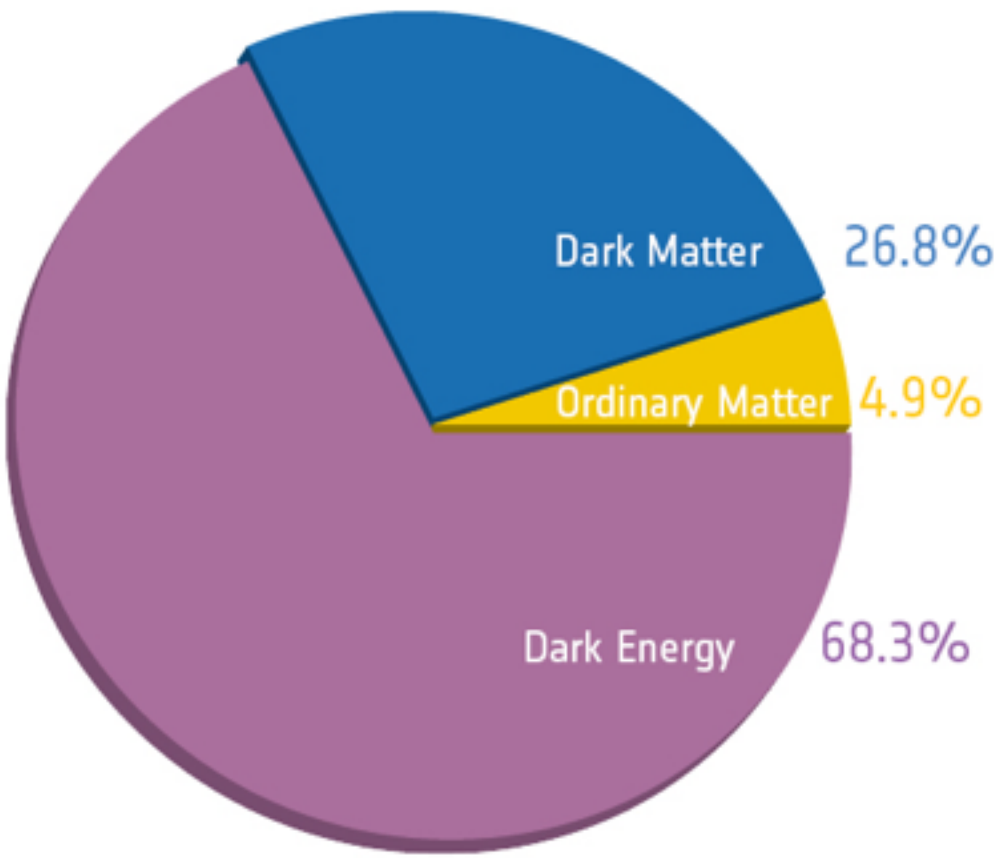
very successful paradigm, but very many possible realizations

we lack access to sub-CMB scales

[V. Domcke]

The SM does not explain any component of the energy budget of the universe

Ω



Atoms: 4.9 %

Photons: 0.0022 %

Neutrinos: 0.0016 %

Universe is accelerating…

Lessons on Dark Energy from LIGO/VIRGO .

The discovery of gravitational waves has hit very heavily the theories of dark energy...

Black-Hole Neutron-Star merger

GW170817

$$-3 \cdot 10^{-15} \leq c_g/c - 1 \leq 7 \cdot 10^{-16}$$

Dark energy simplest explanation: a CC.

Open questions in particle physics that I will discuss today.

- **Origin of the electroweak scale**

  - Hierarchy problem
  - Nature of the EW phase transition
  - Cosmological relaxation

- **Origin of Dark Matter**

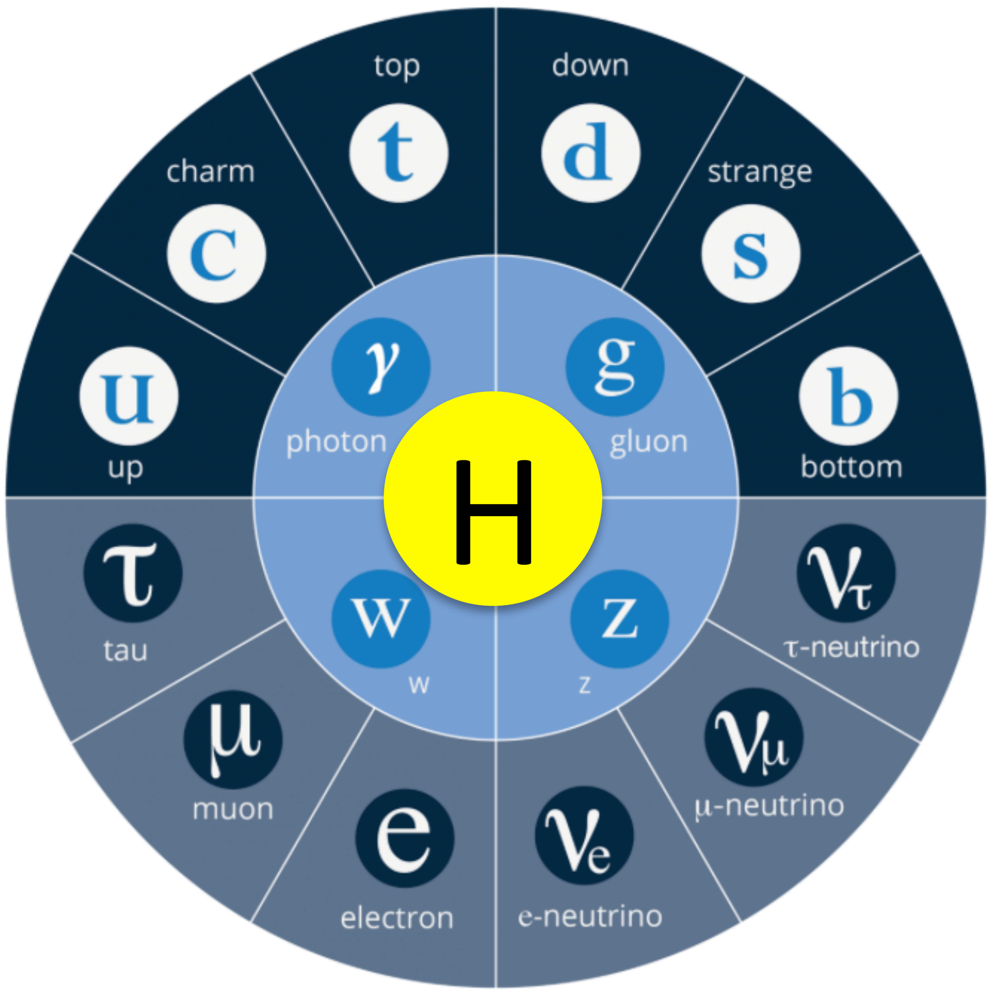
- **Origin of Baryon Asymmetry**

- **How to use Gravitational Waves to probe new physics**

-1-

Origin of the Electroweak Scale .

The Hierarchy problem



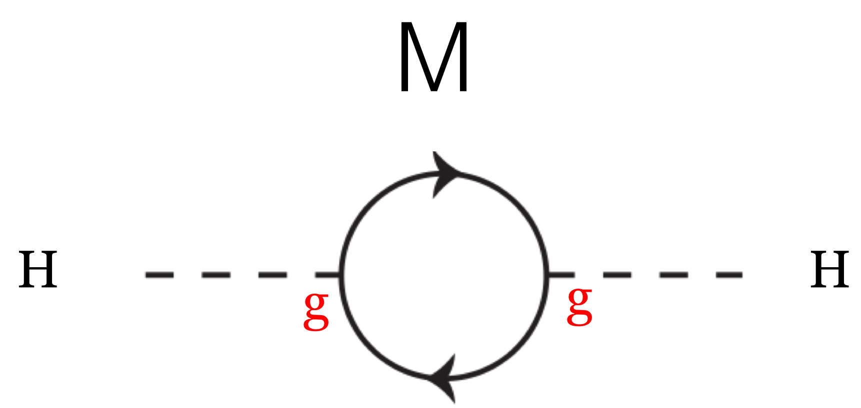
The Higgs is so special !

It gives mass to all elementary particles.

This happened when the temperature of the universe dropped below 100 billions of degrees celsius.

The Electroweak Hierarchy Problem of the Standard Model Effective Theory

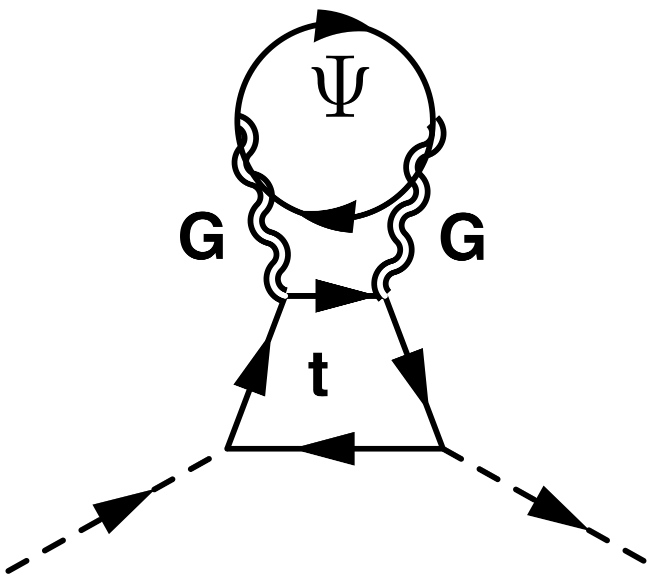
The Higgs is sensitive to heavy new particles



$$\delta m_H^2 \sim \frac{g^2}{16\pi^2} M^2$$

The Electroweak Hierarchy Problem of the Standard Model Effective Theory

Even gravitational physics is sufficient to feed through threshold corrections to the Higgs mass



$$\delta m_H^2 \sim \frac{6 y_t^2}{(16\pi^2)^3} \frac{m_\Psi^6}{M_{Pl}^4}$$

Even if the new states Ψ only couple to the Higgs gravitationally, they give a threshold correction to the Higgs mass that is proportional to the mass scale of the new states m_Ψ .

The Hierarchy Problem

If Standard Model is an effective field theory below M_{Planck}

$$V = m_h^2\, h^2 + \lambda\, h^4$$

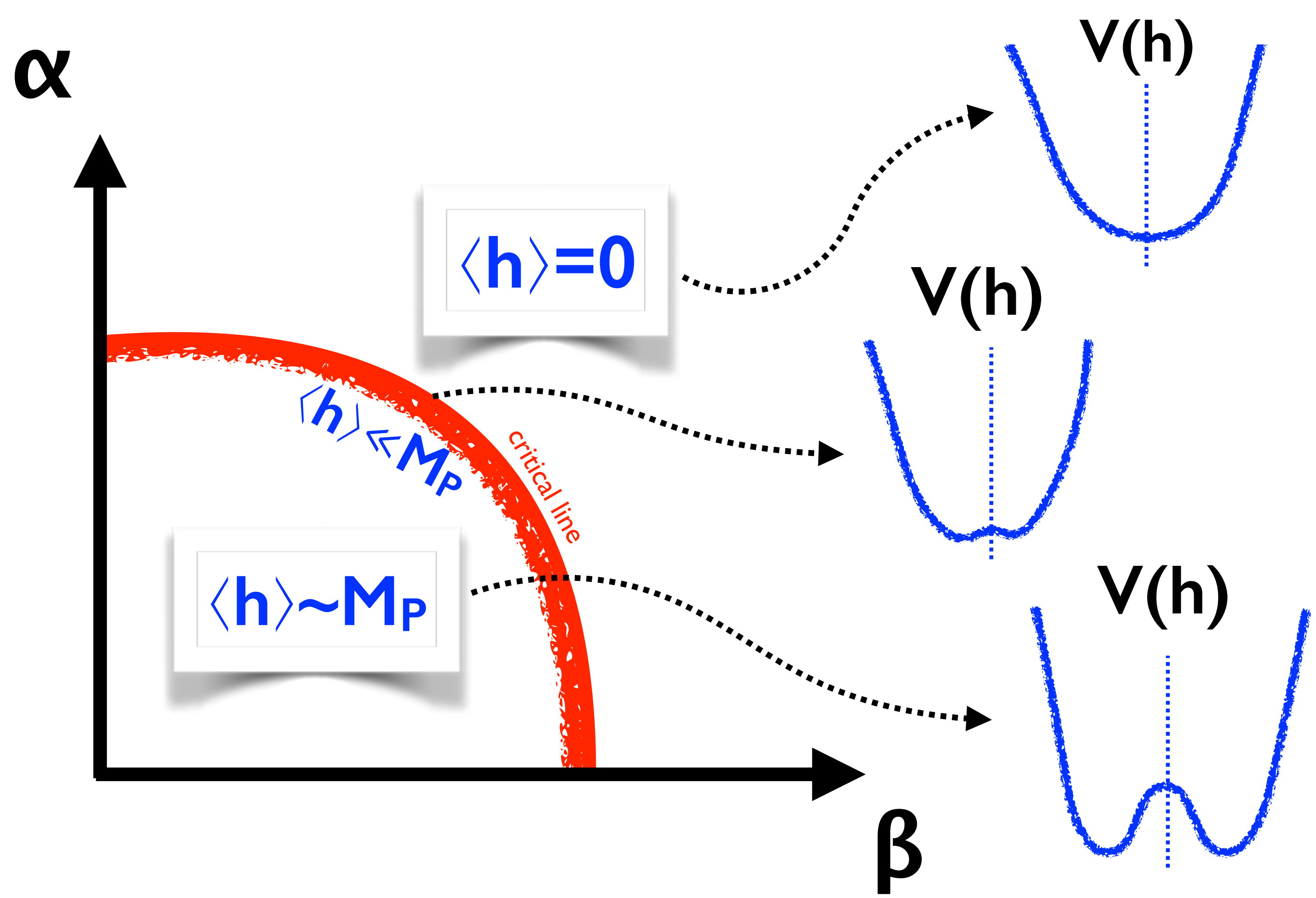
Why $m_h^2 \ll \mathrm{M}_{\mathrm{Planck}}^2$?

The Hierarchy Problem

In high energy completions of the Standard Model where the Higgs potential can be computed in terms of new parameters, α and β:

$$m_h^2 = m_h^2(\alpha, \beta)$$

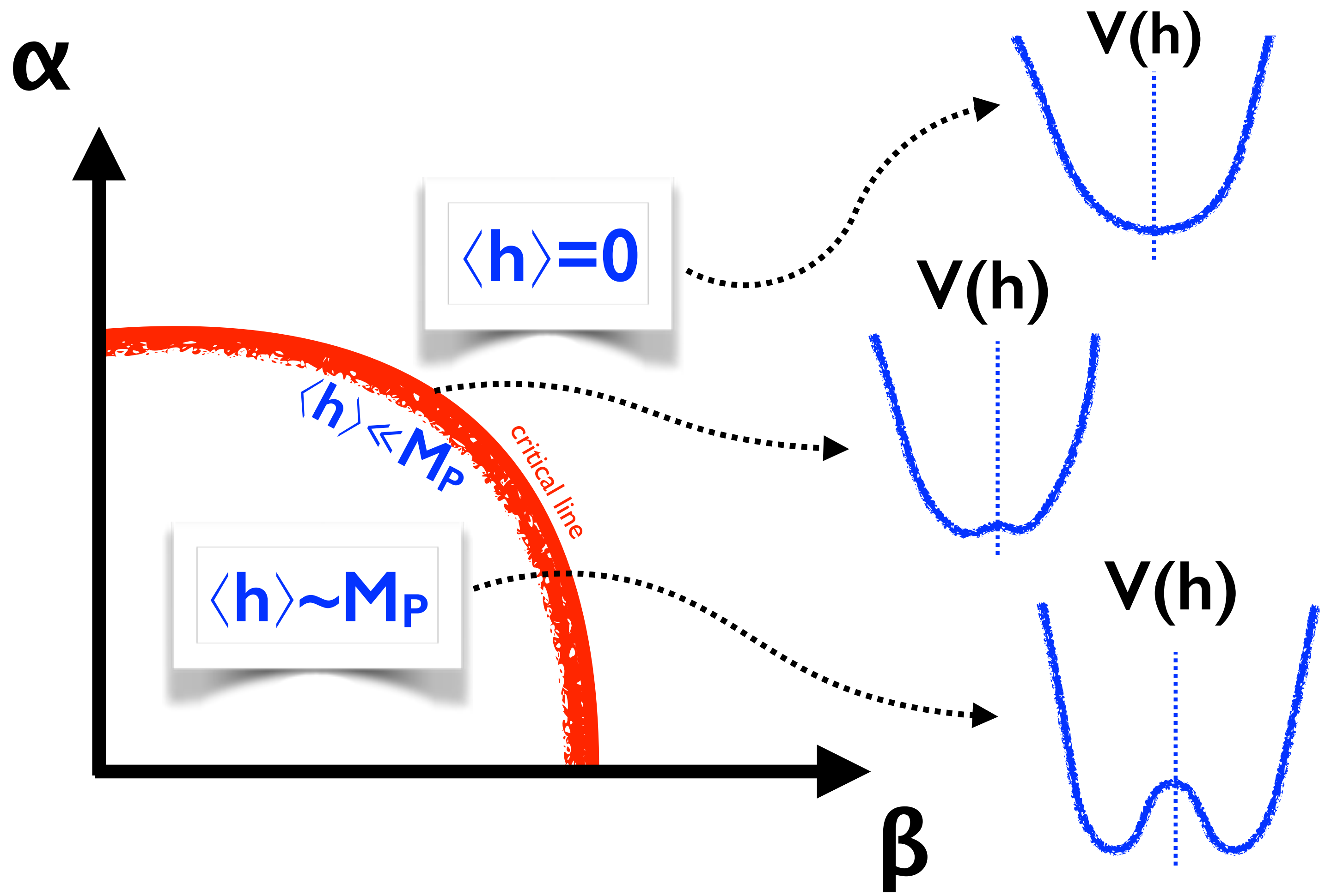
Why does the Higgs vacuum reside so close to the critical line separating the phase with unbroken ($\langle H \rangle = 0$) from the phase with broken ($\langle H \rangle \neq 0$) electroweak symmetry?



[Figure Credit:A. Pomarol]

The Hierarchy Problem

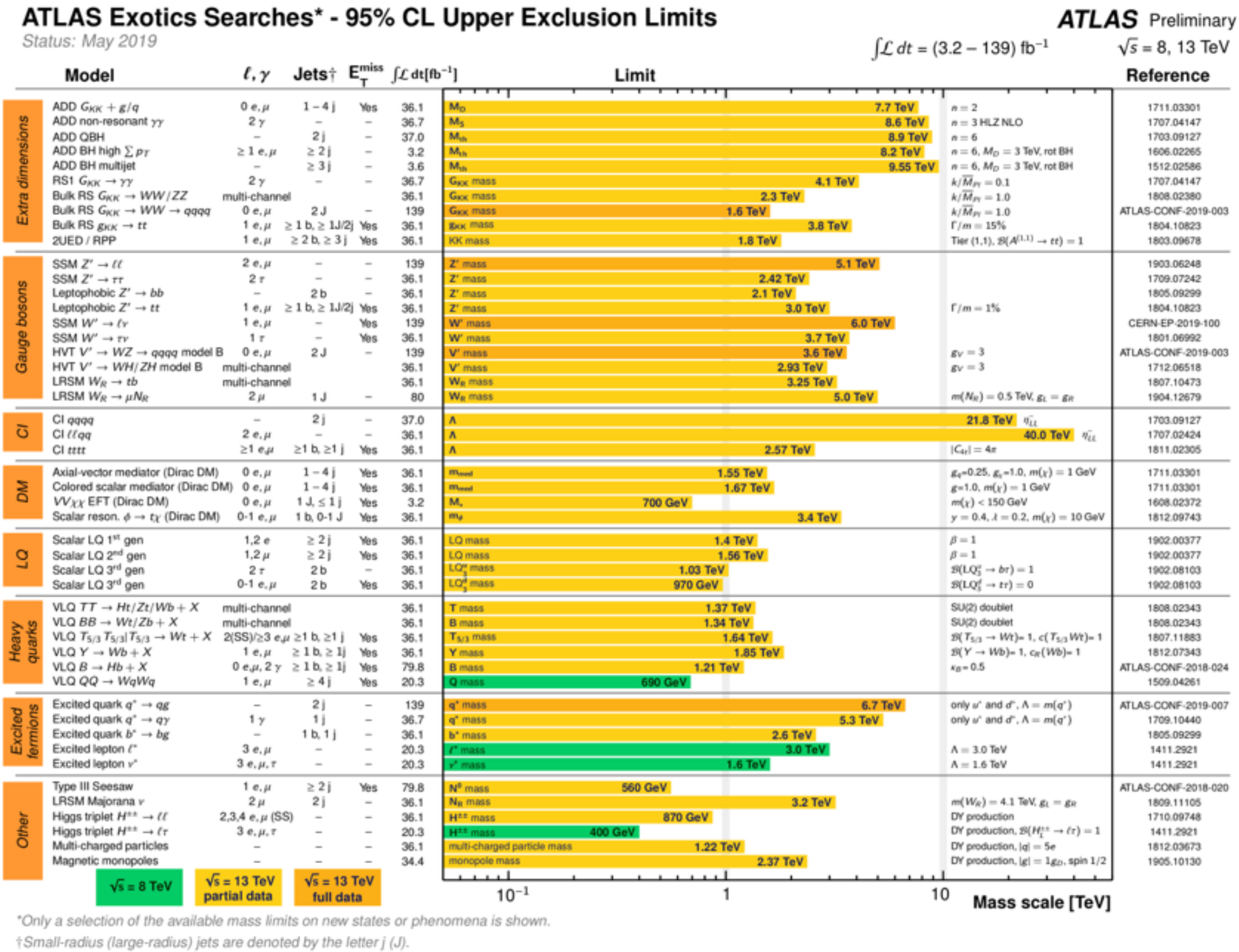
$$m_h^2 = m_h^2(\alpha, \beta)$$

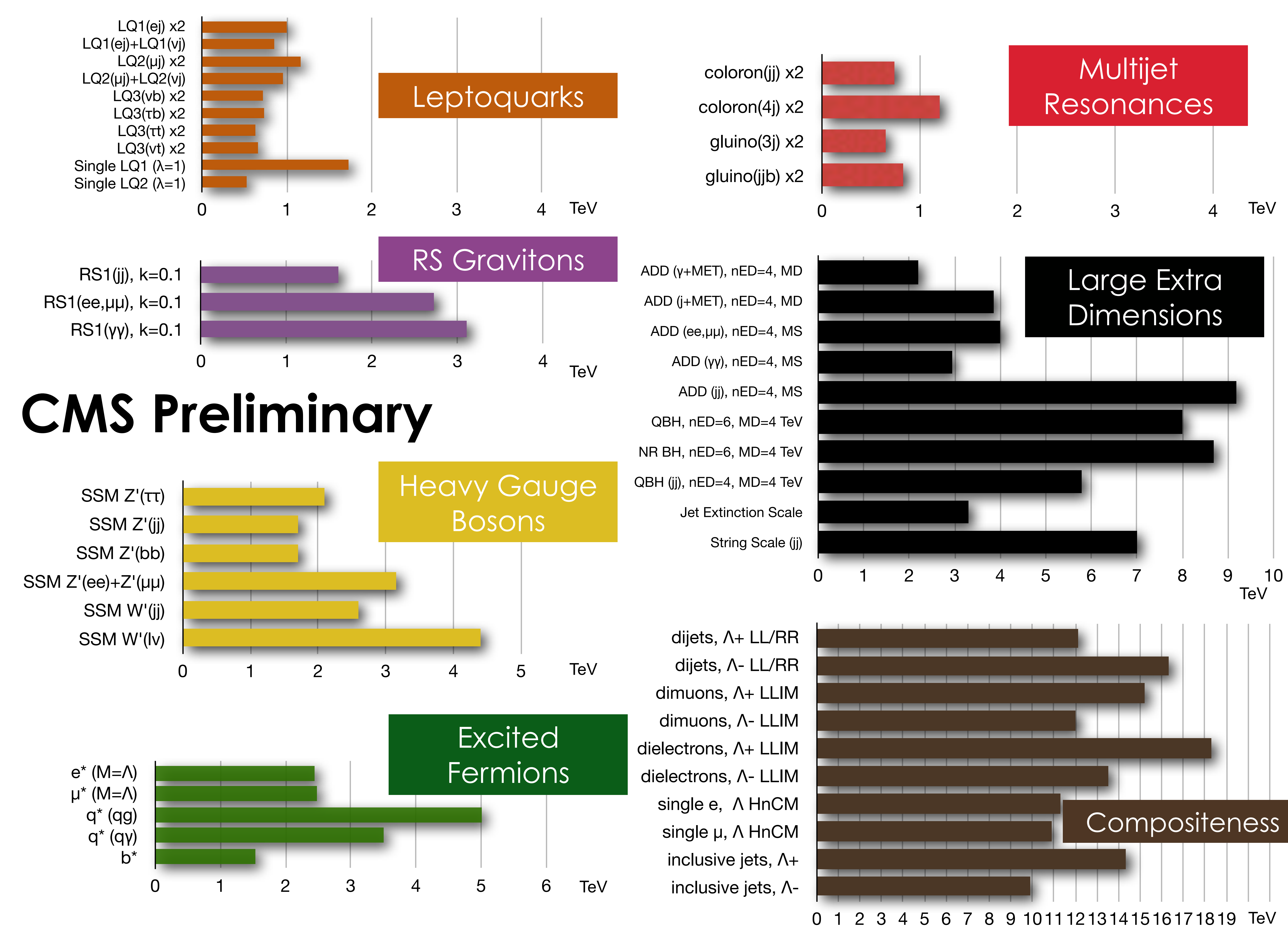


[Figure Credit: A. Pomarol]

Solution 1: Critical line is special line with enhanced symmetry-> e.g Supersymmetry, global symm.

Implications: Partner particles expected at the weak scale


ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2019
ATLAS Preliminary
$\int \mathcal{L}\,dt = (3.2 - 139)$ fb^{-1}
$\sqrt{s}$ = 8, 13 TeV
Model | ℓ, γ | Jets† | E_T^{miss} | $\int \mathcal{L}\,dt$[fb^{-1}] | Limit | Reference
Extra dimensions
ADD $G_{KK} + g/q$ | 0 e, μ | 1 – 4 j | Yes | 36.1 | M_D 7.7 TeV | $n = 2$ | 1711.03301
ADD non-resonant $\gamma\gamma$ | 2 γ | – | – | 36.7 | M_S 8.6 TeV | $n = 3$ HLZ NLO | 1707.04147
ADD QBH | – | 2 j | – | 37.0 | M_{th} 8.9 TeV | $n = 6$ | 1703.09127
ADD BH high $\sum p_T$ | ≥ 1 e, μ | ≥ 2 j | – | 3.2 | M_{th} 8.2 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1606.02265
ADD BH multijet | – | ≥ 3 j | – | 3.6 | M_{th} 9.55 TeV | $n = 6$, $M_D = 3$ TeV, rot BH | 1512.02586
RS1 $G_{KK} \to \gamma\gamma$ | 2 γ | – | – | 36.7 | G_{KK} mass 4.1 TeV | $k/\overline{M}_{Pl} = 0.1$ | 1707.04147
Bulk RS $G_{KK} \to WW/ZZ$ | multi-channel | 36.1 | G_{KK} mass 2.3 TeV | $k/\overline{M}_{Pl} = 1.0$ | 1808.02380
Bulk RS $G_{KK} \to WW \to qqqq$ | 0 e, μ | 2 J | – | 139 | G_{KK} mass 1.6 TeV | $k/\overline{M}_{Pl} = 1.0$ | ATLAS-CONF-2019-003
Bulk RS $g_{KK} \to tt$ | 1 e, μ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | g_{KK} mass 3.8 TeV | $\Gamma/m = 15\%$ | 1804.10823
2UED / RPP | 1 e, μ | ≥ 2 b, ≥ 3 j | Yes | 36.1 | KK mass 1.8 TeV | Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$ | 1803.09678
Gauge bosons
SSM $Z' \to \ell\ell$ | 2 e, μ | – | – | 139 | Z' mass 5.1 TeV | 1903.06248
SSM $Z' \to \tau\tau$ | 2 τ | – | – | 36.1 | Z' mass 2.42 TeV | 1709.07242
Leptophobic $Z' \to bb$ | – | 2 b | – | 36.1 | Z' mass 2.1 TeV | 1805.09299
Leptophobic $Z' \to tt$ | 1 e, μ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | Z' mass 3.0 TeV | $\Gamma/m = 1\%$ | 1804.10823
SSM $W' \to \ell\nu$ | 1 e, μ | – | Yes | 139 | W' mass 6.0 TeV | CERN-EP-2019-100
SSM $W' \to \tau\nu$ | 1 τ | – | Yes | 36.1 | W' mass 3.7 TeV | 1801.06992
HVT $V' \to WZ \to qqqq$ model B | 0 e, μ | 2 J | – | 139 | V' mass 3.6 TeV | $g_V = 3$ | ATLAS-CONF-2019-003
HVT $V' \to WH/ZH$ model B | multi-channel | 36.1 | V' mass 2.93 TeV | $g_V = 3$ | 1712.06518
LRSM $W_R \to tb$ | multi-channel | 36.1 | W_R mass 3.25 TeV | 1807.10473
LRSM $W_R \to \mu N_R$ | 2 μ | 1 J | – | 80 | W_R mass 5.0 TeV | $m(N_R) = 0.5$ TeV, $g_L = g_R$ | 1904.12679
CI
CI $qqqq$ | – | 2 j | – | 37.0 | Λ 21.8 TeV η_{LL}^{-} | 1703.09127
CI $\ell\ell qq$ | 2 e, μ | – | – | 36.1 | Λ 40.0 TeV η_{LL}^{-} | 1707.02424
CI $tttt$ | ≥1 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | Λ 2.57 TeV | $|C_{4t}| = 4\pi$ | 1811.02305
DM
Axial-vector mediator (Dirac DM) | 0 e, μ | 1 – 4 j | Yes | 36.1 | m_{med} 1.55 TeV | g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV | 1711.03301
Colored scalar mediator (Dirac DM) | 0 e, μ | 1 – 4 j | Yes | 36.1 | m_{med} 1.67 TeV | g=1.0, $m(\chi) = 1$ GeV | 1711.03301
$VV\chi\chi$ EFT (Dirac DM) | 0 e, μ | 1 J, ≤ 1 j | Yes | 3.2 | M_* 700 GeV | $m(\chi) < 150$ GeV | 1608.02372
Scalar reson. $\phi \to t\chi$ (Dirac DM) | 0-1 e, μ | 1 b, 0-1 J | Yes | 36.1 | m_ϕ 3.4 TeV | $y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV | 1812.09743
LQ
Scalar LQ 1st gen | 1,2 e | ≥ 2 j | Yes | 36.1 | LQ mass 1.4 TeV | $\beta = 1$ | 1902.00377
Scalar LQ 2nd gen | 1,2 μ | ≥ 2 j | Yes | 36.1 | LQ mass 1.56 TeV | $\beta = 1$ | 1902.00377
Scalar LQ 3rd gen | 2 τ | 2 b | – | 36.1 | LQ_3^u mass 1.03 TeV | $\mathcal{B}(LQ_3^u \to b\tau) = 1$ | 1902.08103
Scalar LQ 3rd gen | 0-1 e, μ | 2 b | Yes | 36.1 | LQ_3^d mass 970 GeV | $\mathcal{B}(LQ_3^d \to t\tau) = 0$ | 1902.08103
Heavy quarks
VLQ $TT \to Ht/Zt/Wb + X$ | multi-channel | 36.1 | T mass 1.37 TeV | SU(2) doublet | 1808.02343
VLQ $BB \to Wt/Zb + X$ | multi-channel | 36.1 | B mass 1.34 TeV | SU(2) doublet | 1808.02343
VLQ $T_{5/3}T_{5/3}|T_{5/3} \to Wt + X$ | 2(SS)/≥3 e,μ | ≥1 b, ≥1 j | Yes | 36.1 | $T_{5/3}$ mass 1.64 TeV | $\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1 | 1807.11883
VLQ $Y \to Wb + X$ | 1 e, μ | ≥ 1 b, ≥ 1j | Yes | 36.1 | Y mass 1.85 TeV | $\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1 | 1812.07343
VLQ $B \to Hb + X$ | 0 e,μ, 2 γ | ≥ 1 b, ≥ 1j | Yes | 79.8 | B mass 1.21 TeV | κ_B= 0.5 | ATLAS-CONF-2018-024
VLQ $QQ \to WqWq$ | 1 e, μ | ≥ 4 j | Yes | 20.3 | Q mass 690 GeV | 1509.04261
Excited fermions
Excited quark $q^* \to qg$ | – | 2 j | – | 139 | q* mass 6.7 TeV | only u^* and d^*, $\Lambda = m(q^*)$ | ATLAS-CONF-2019-007
Excited quark $q^* \to q\gamma$ | 1 γ | 1 j | – | 36.7 | q* mass 5.3 TeV | only u^* and d^*, $\Lambda = m(q^*)$ | 1709.10440
Excited quark $b^* \to bg$ | – | 1 b, 1 j | – | 36.1 | b* mass 2.6 TeV | 1805.09299
Excited lepton ℓ^* | 3 e, μ | – | – | 20.3 | ℓ^* mass 3.0 TeV | $\Lambda = 3.0$ TeV | 1411.2921
Excited lepton ν^* | 3 e, μ, τ | – | – | 20.3 | ν^* mass 1.6 TeV | $\Lambda = 1.6$ TeV | 1411.2921
Other
Type III Seesaw | 1 e, μ | ≥ 2 j | Yes | 79.8 | N^0 mass 560 GeV | ATLAS-CONF-2018-020
LRSM Majorana ν | 2 μ | 2 j | – | 36.1 | N_R mass 3.2 TeV | $m(W_R) = 4.1$ TeV, $g_L = g_R$ | 1809.11105
Higgs triplet $H^{\pm\pm} \to \ell\ell$ | 2,3,4 e, μ (SS) | – | – | 36.1 | $H^{\pm\pm}$ mass 870 GeV | DY production | 1710.09748
Higgs triplet $H^{\pm\pm} \to \ell\tau$ | 3 e, μ, τ | – | – | 20.3 | $H^{\pm\pm}$ mass 400 GeV | DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$ | 1411.2921
Multi-charged particles | – | – | – | 36.1 | multi-charged particle mass 1.22 TeV | DY production, $|q| = 5e$ | 1812.03673
Magnetic monopoles | – | – | – | 34.4 | monopole mass 2.37 TeV | DY production, $|g| = 1g_D$, spin 1/2 | 1905.10130
$\sqrt{s}$ = 8 TeV
$\sqrt{s}$ = 13 TeV partial data
$\sqrt{s}$ = 13 TeV full data
10^{-1}
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).


CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(τt) x2
LQ3(νt) x2
Single LQ1 (λ=1)
Single LQ2 (λ=1)
0 1 2 3 4 TeV
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4 TeV
RS Gravitons
RS1(jj), k=0.1
RS1(ee,μμ), k=0.1
RS1(γγ), k=0.1
0 1 2 3 4 TeV
Large Extra Dimensions
ADD (γ+MET), nED=4, MD
ADD (j+MET), nED=4, MD
ADD (ee,μμ), nED=4, MS
ADD (γγ), nED=4, MS
ADD (jj), nED=4, MS
QBH, nED=6, MD=4 TeV
NR BH, nED=6, MD=4 TeV
QBH (jj), nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 1 2 3 4 5 6 7 8 9 10 TeV
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
0 1 2 3 4 5 TeV
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dielectrons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 TeV
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4 5 6 TeV

Solutions to the Hierarchy Problem .

[N. Craig]

Adding a symmetry

-> Supersymmetry

-> Global symmetry …

Experimental signals: partners

Lowering the cutoff

-> Randall-Sundrum / Composite Higgs,

-> Large Extra Dimensions …

Experimental signals: resonances

Selecting a vacuum : Relaxation (dynamics),

Experimental signals: typically through cosmology

New Relaxion idea:
(discussed later in this lecture)

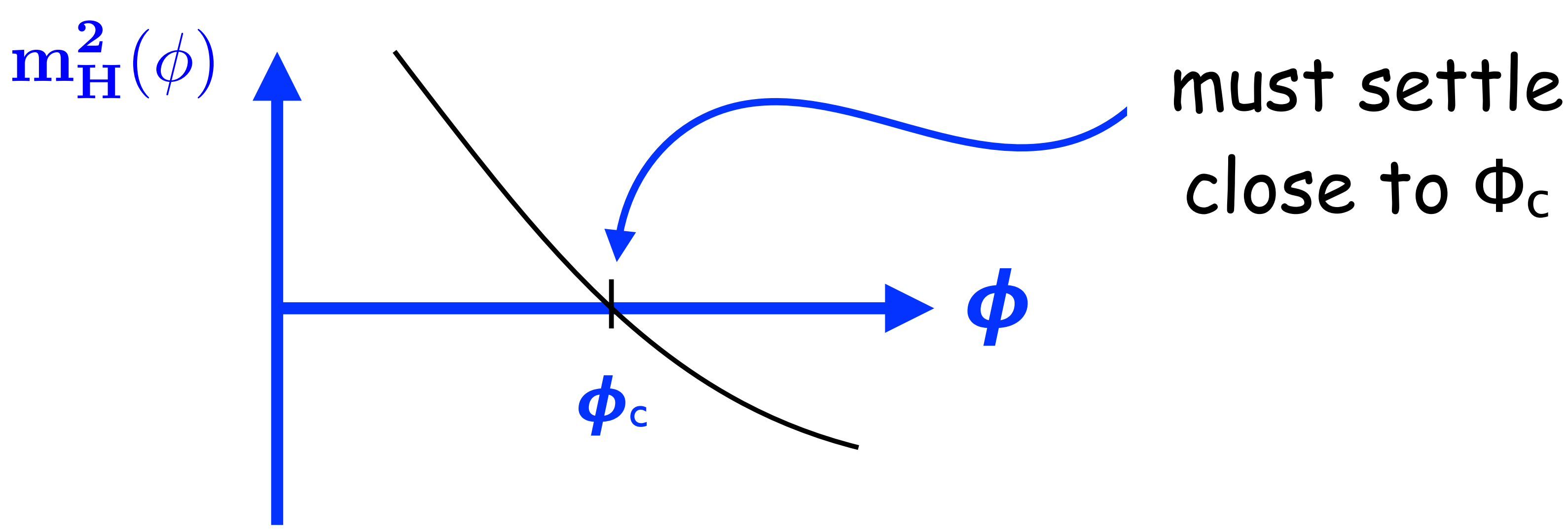
Higgs mass parameter is field-dependent

$$m^2|H|^2 \rightarrow m^2(\phi)|H|^2$$

Φ can get a value such that $m^2(\phi) \ll \Lambda^2$

UV cutoff

from a dynamical interplay between H and Φ



m_H naturally stabilized due to back-reaction of the Higgs field after EW symmetry breaking !

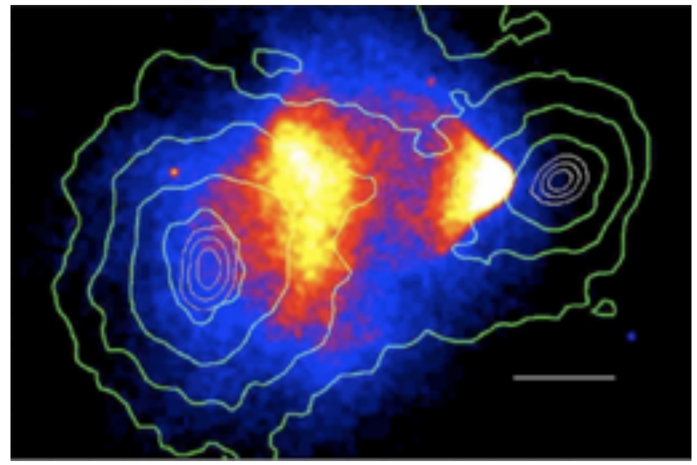
-2-

Origin of Dark Matter .

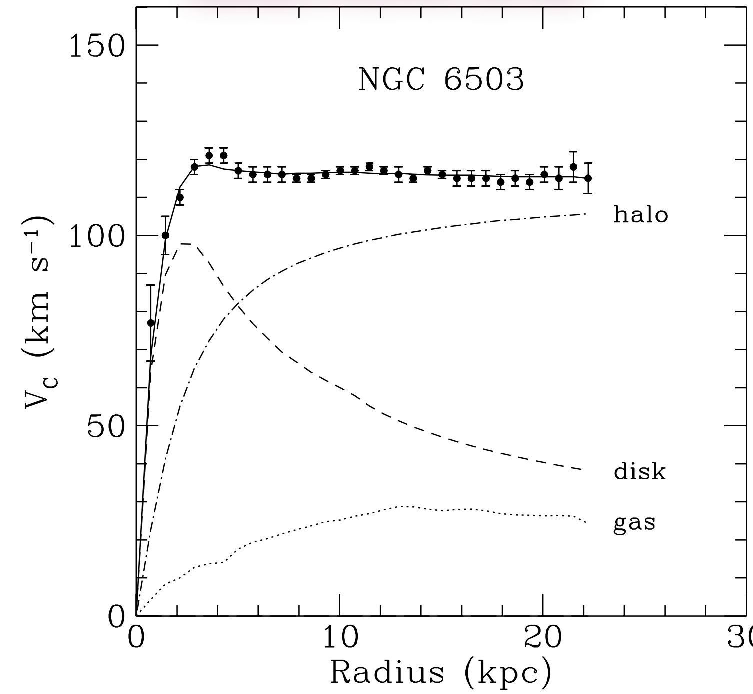
The existence of (Cold) Dark Matter has been established by a host of different methods; it is needed on all scales

Gravitational lensing

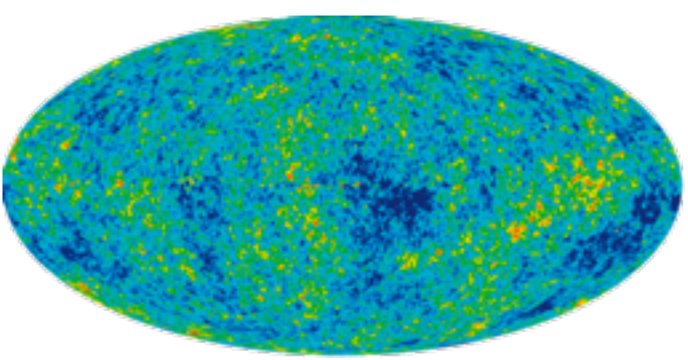
The "Bullet cluster": lensing map versus X-ray image

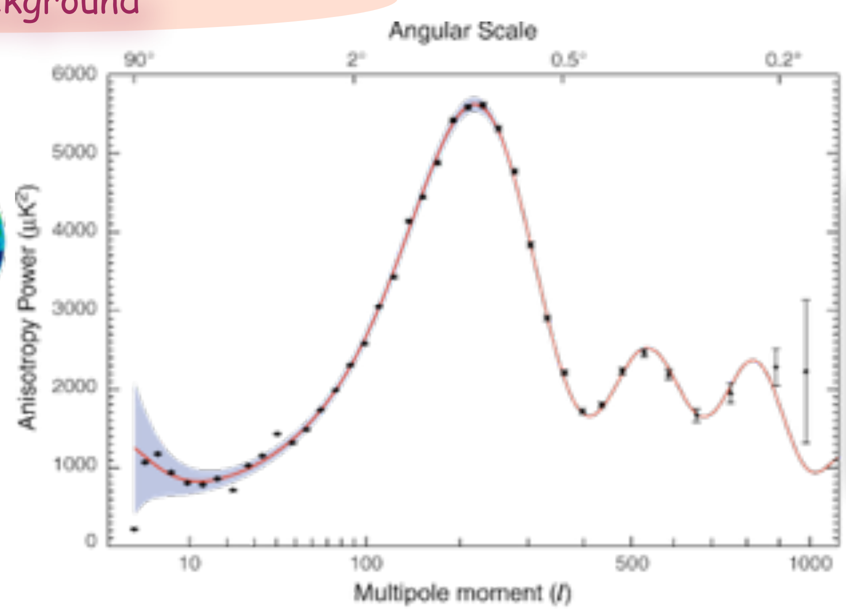


Galaxy rotation curves



Cosmic Microwave Background





... etc

-> Fraction of the universe's energy density stored in dark matter : Ω

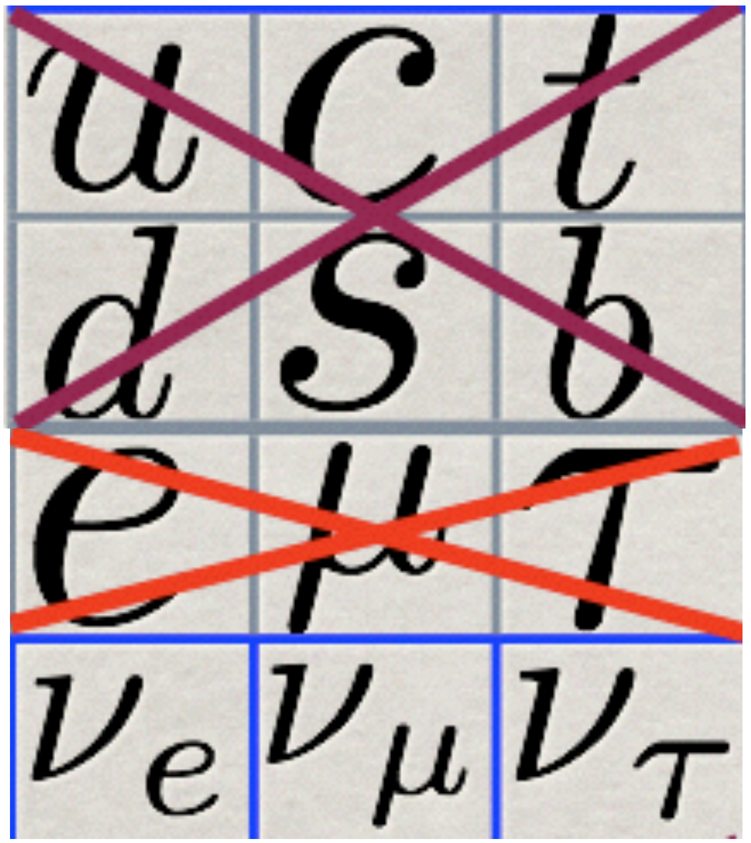
DM properties are more and more constrained (gravitationally interacting, long-lived, not hot, not baryonic ...) but its identity remains a mystery

Dark matter can't be explained by the Standard Model

Matter

quarks

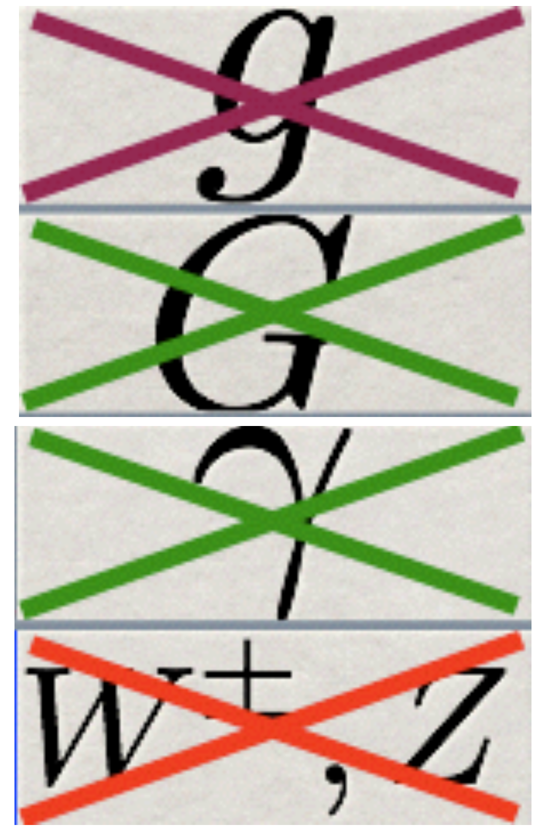
leptons



I II III

3 families of matter

Forces



force mediators

charged/unstable

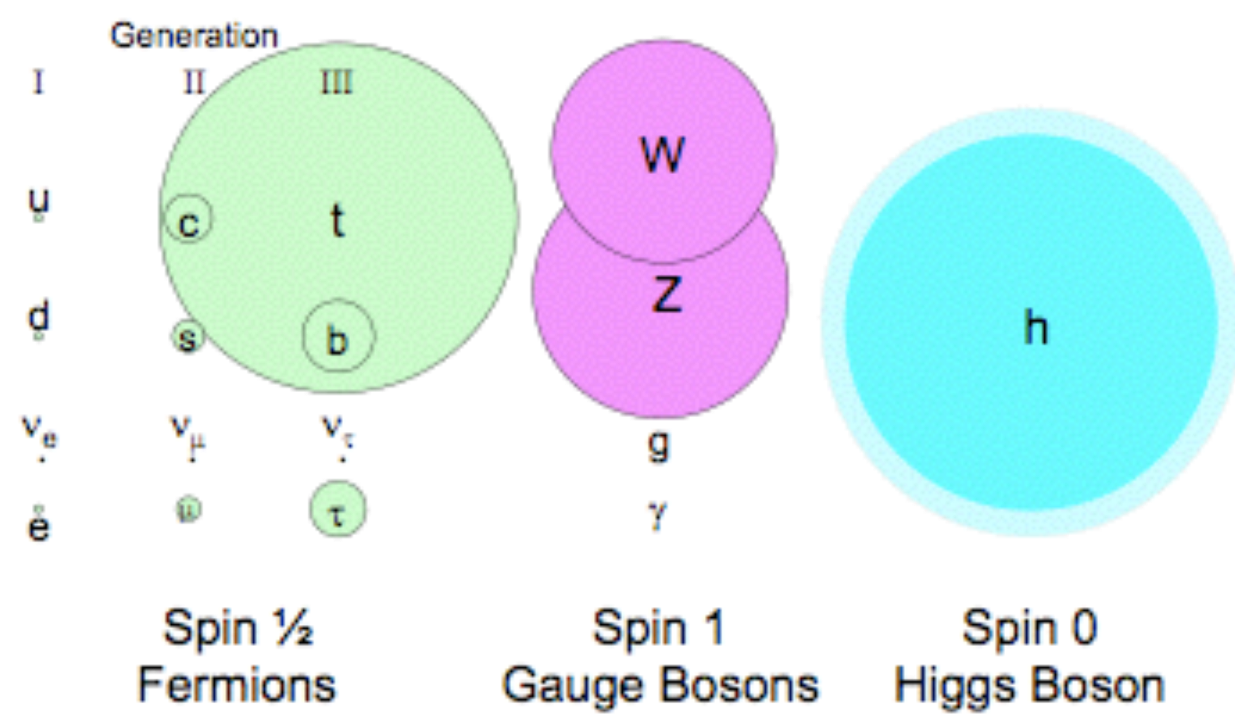
baryonic

massless

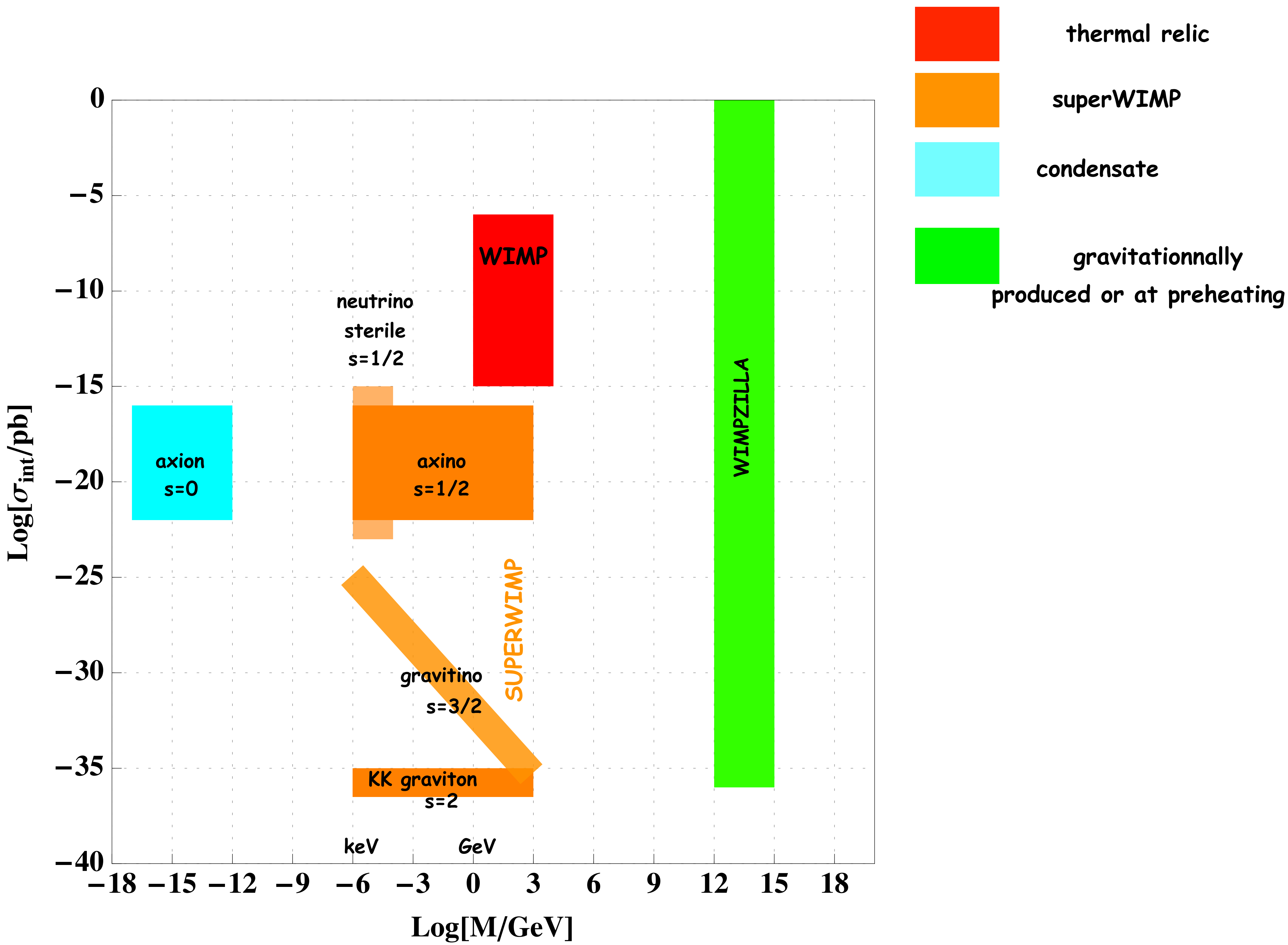
contribution to the energy budget of the universe

Particle	Ω	type
Baryons	4 - 5 %	cold
Neutrinos	< 2 %	hot
Dark matter	20 - 26 %	cold

radius of circle is proportional to the mass

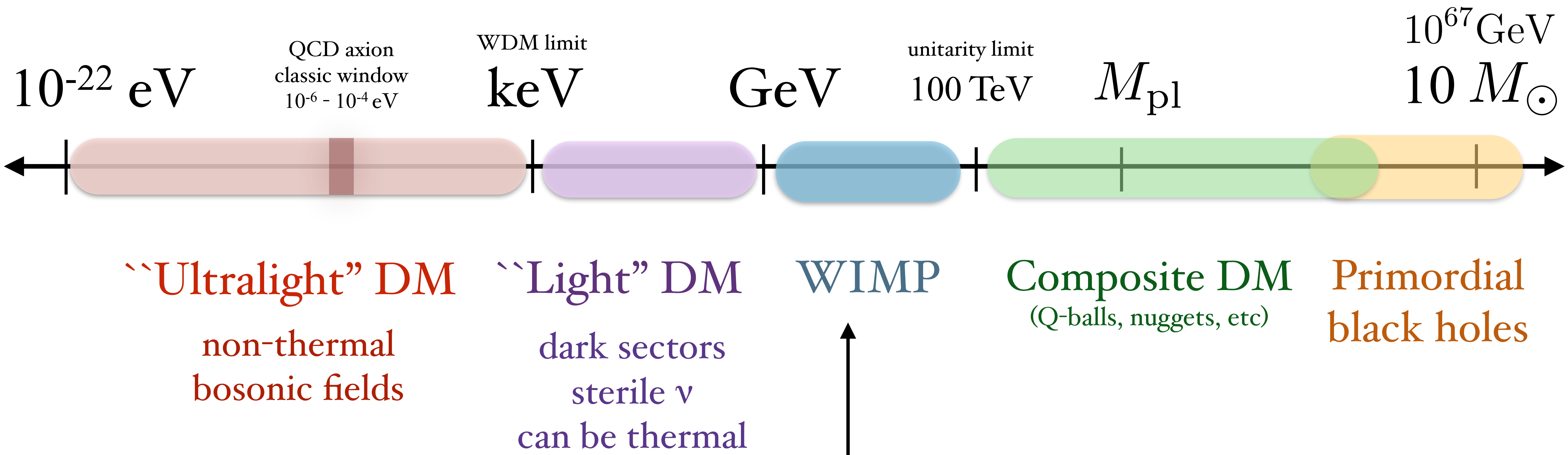


Dark Matter Candidates



Mass scale of dark matter

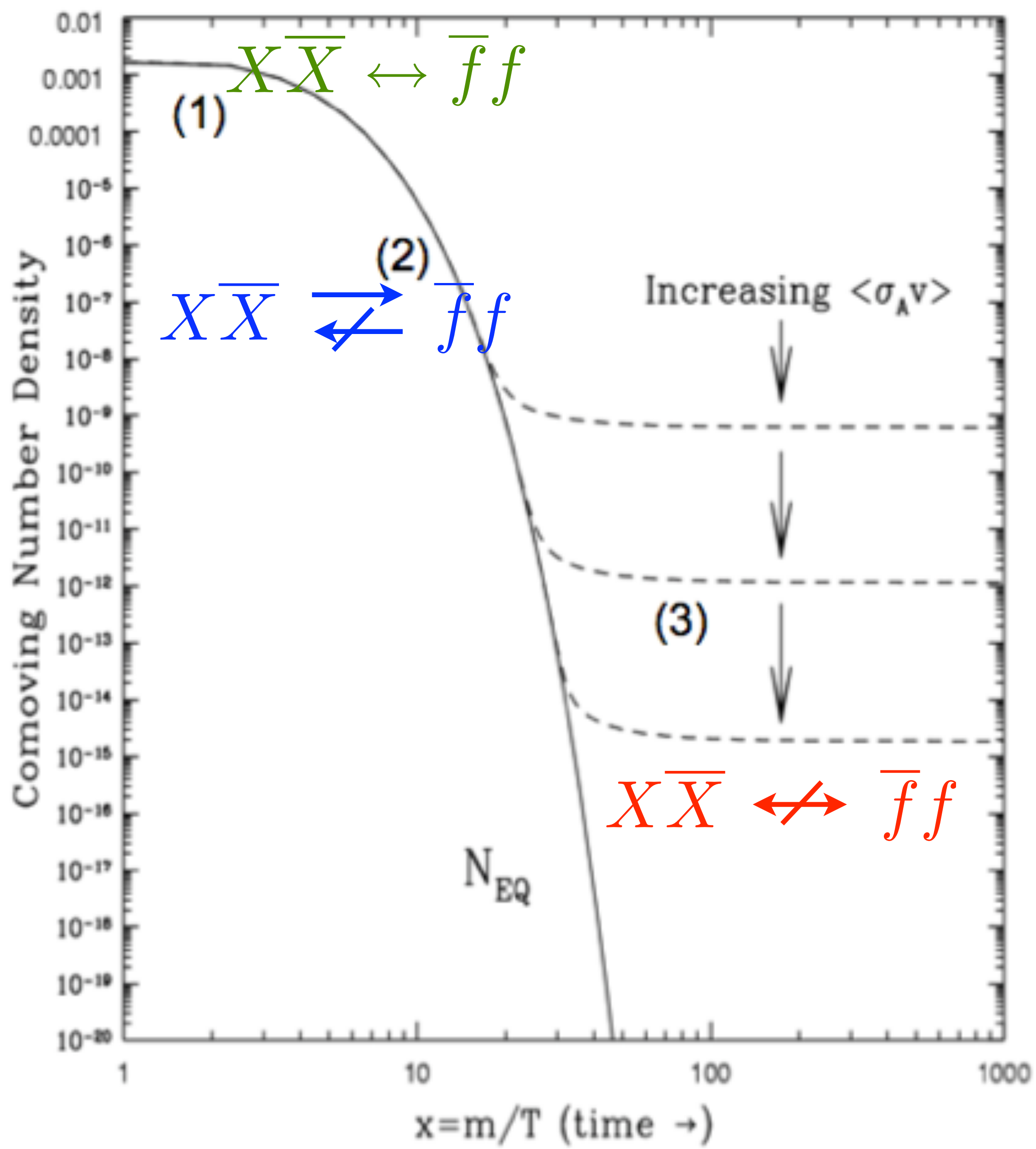
(not to scale)



has long been
favorite candidate

WIMP Relic abundance from Standard thermal freeze-out

$$\dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 - n_T^2)$$



expansion rate of universe

freese-out :

annihilation rate of particle

$$H \sim \frac{\sqrt{g}T^2}{M_P} \sim \Gamma = n\sigma v$$

Thermal relic: $\Omega_{DM} \propto 1/\sigma_{anni}$

$\Rightarrow \sigma_{anni} \approx 1$ pb

$\sigma \sim \alpha^2/m^2$

$\Rightarrow$ m ~ 100 GeV

The "WIMP miracle"

$$\boxed{\Omega \quad \frac{O(1)\text{ pb}}{\sigma}}$$

→ a particle with a typical EW-scale cross section

σ_{anni}

CLOSING IN ON THE WIMP PARADIGM

- Direct Dark Matter production at LHC
- Underground direct searches for light Dark Matter
- Indirect searches of Dark Matter annihilations in cosmic rays (gammas, e+/-, neutrinos, antiprotons.)

The Decade of the WIMP

Ce sera la décennie de la matière noire !

SCIENTIFIC AMERICAN™

Dark Matter Mystery May Soon Be Solved

Experiments to detect dark matter, which scientists believe makes up about a quarter of the universe, are underway and may yield direct evidence within a decade

THE DAILY GALAXY
GREAT DISCOVERIES CHANNEL

December 22, 2012

"We're on the Threshold of Unraveling the Biggest Mystery in Modern Physics" --World's Dark-Matter Cosmologists

SCIENCE TODAY BEYOND THE HEADLINES

TOP STORY: FEBRUARY 20, 2013

Decade of Dark Matter

Should we declare this the decade of the WIMPs? Before you

SCIENCE

'Decade of dark matter' begins

ADRIAN CHO

Last updated 12:26 31/07/2012 Like 45 Tweet 5

PHYS.ORG

Scientists sense breakthroughs in dark-matter mystery

Feb 18, 2013 by Jean-Louis Santini

La traque de la matière noire touche t-elle à sa fin ?

BFMTV > Planète > Espace

Univers : le mystère de la matière noire bientôt résolu ?

Le Point.fr - Publié le 22/02/2013 à 16:33 - Modifié le 22/02/2013 à 16:41

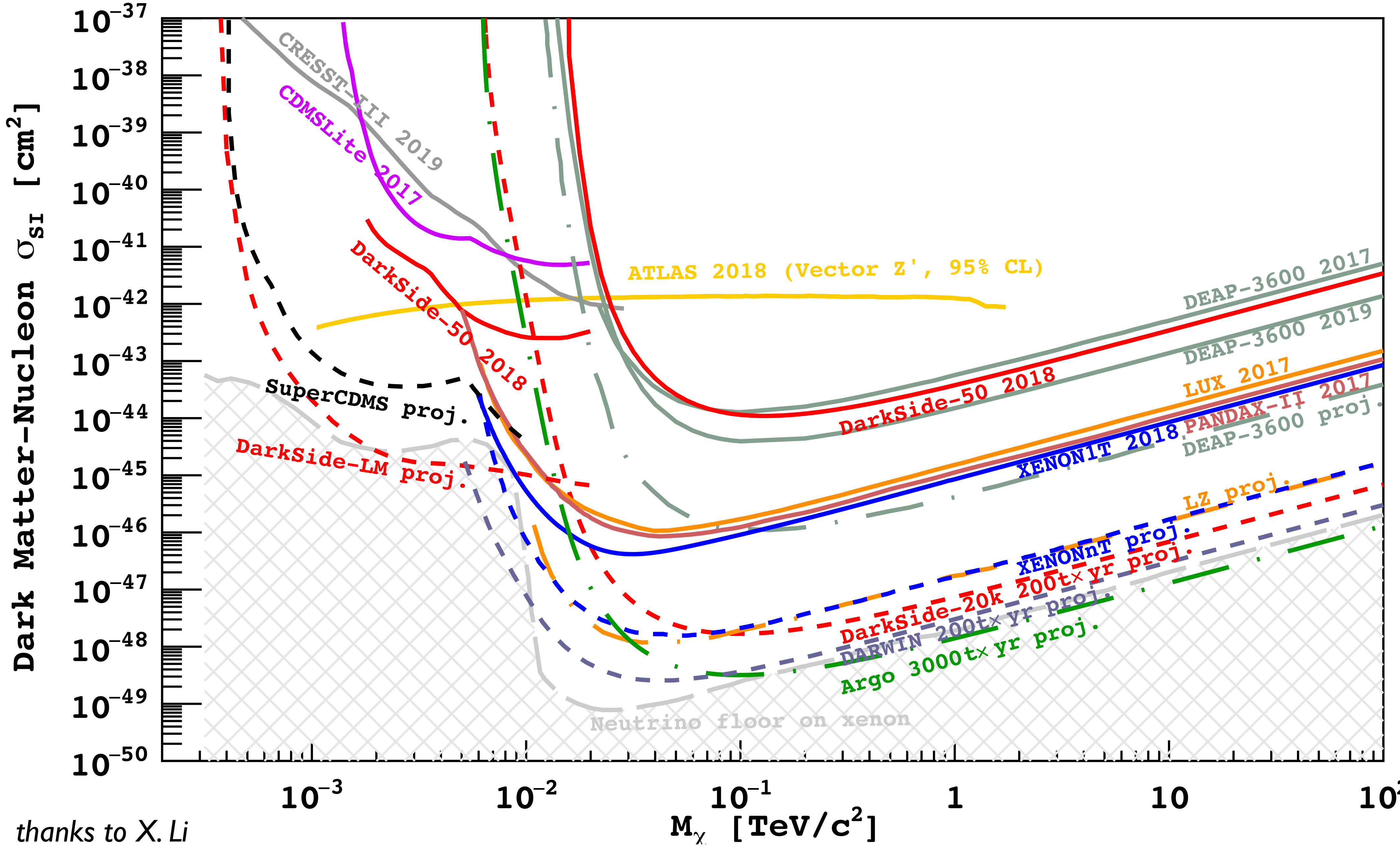
La piste de la mystérieuse matière noire se précise...

nature International weekly journal of science

18 November 2010
Gianfranco Bertone

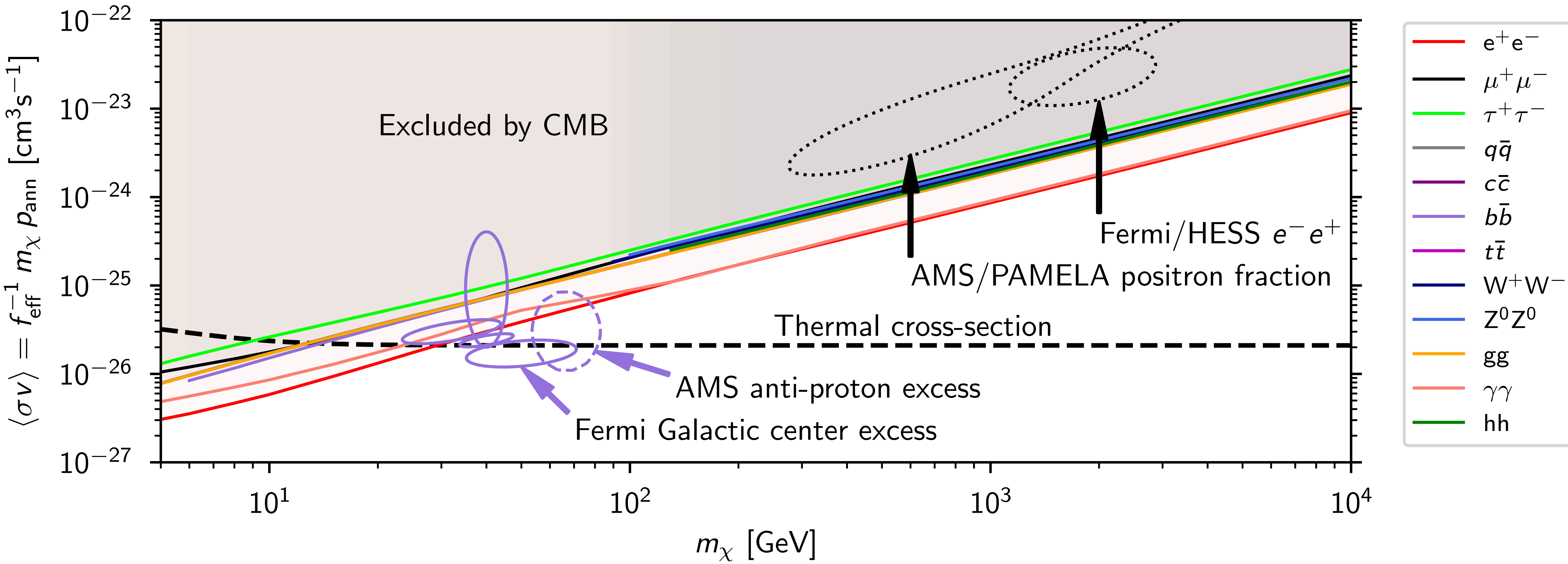
The moment of truth for WIMP dark matter

Direct detection status and prospects



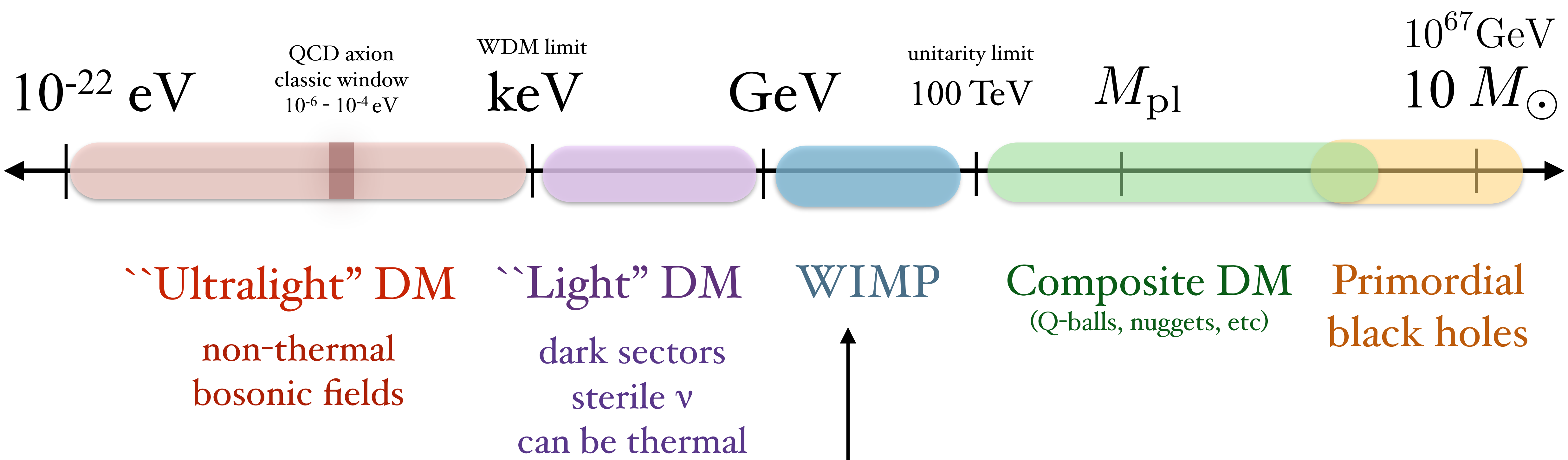
thanks to X. Li

Indirect searches.
Fermi constraints on WIMPs



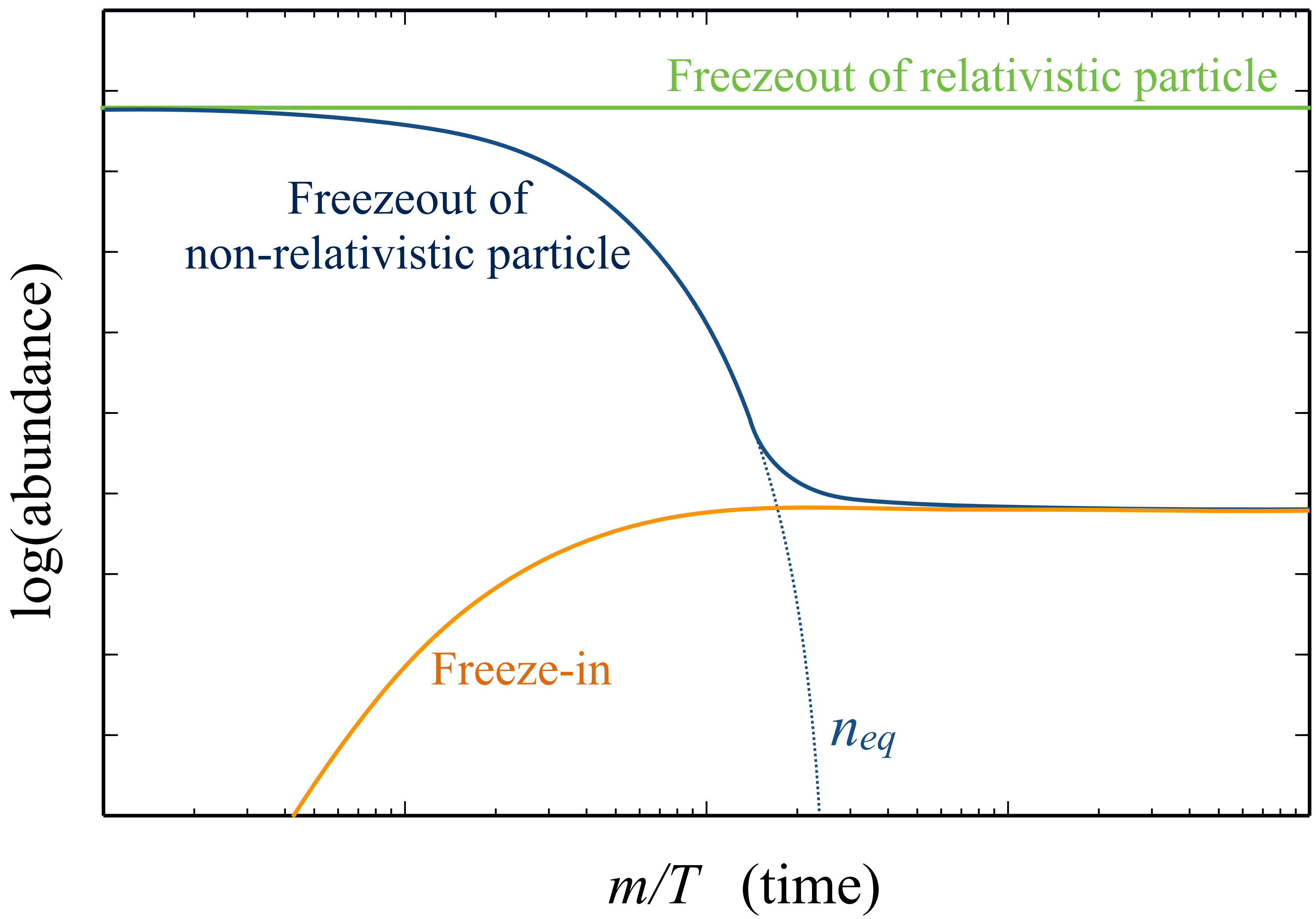
Mass scale of dark matter

(not to scale)



has long been favorite candidate

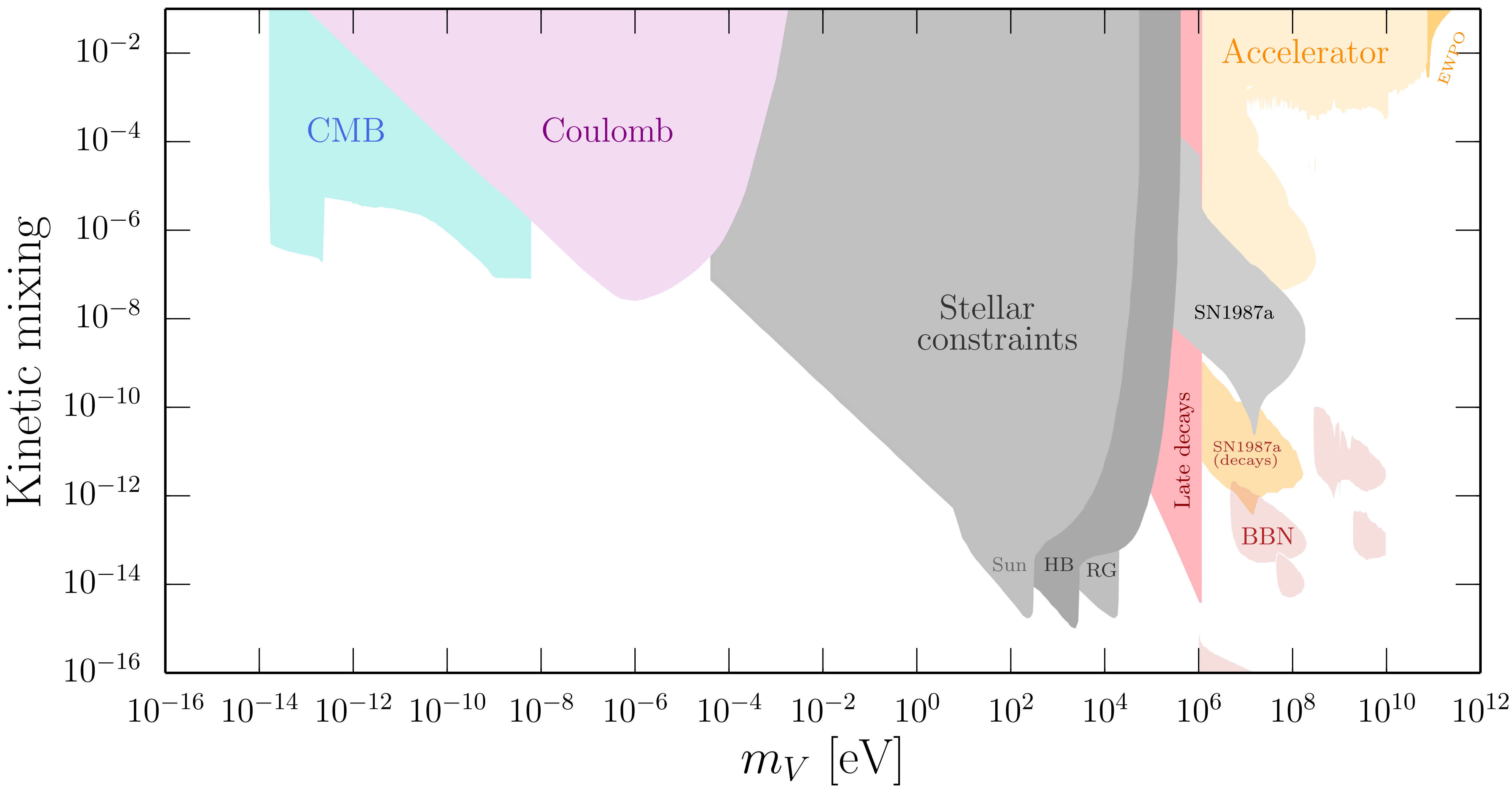
Naturalness no longer guiding principle…


Freezeout of relativistic particle
Freezeout of
non-relativistic particle
Freeze-in
n_{eq}
log(abundance)
m/T (time)

Popular Feebly-interacting long-lived particles

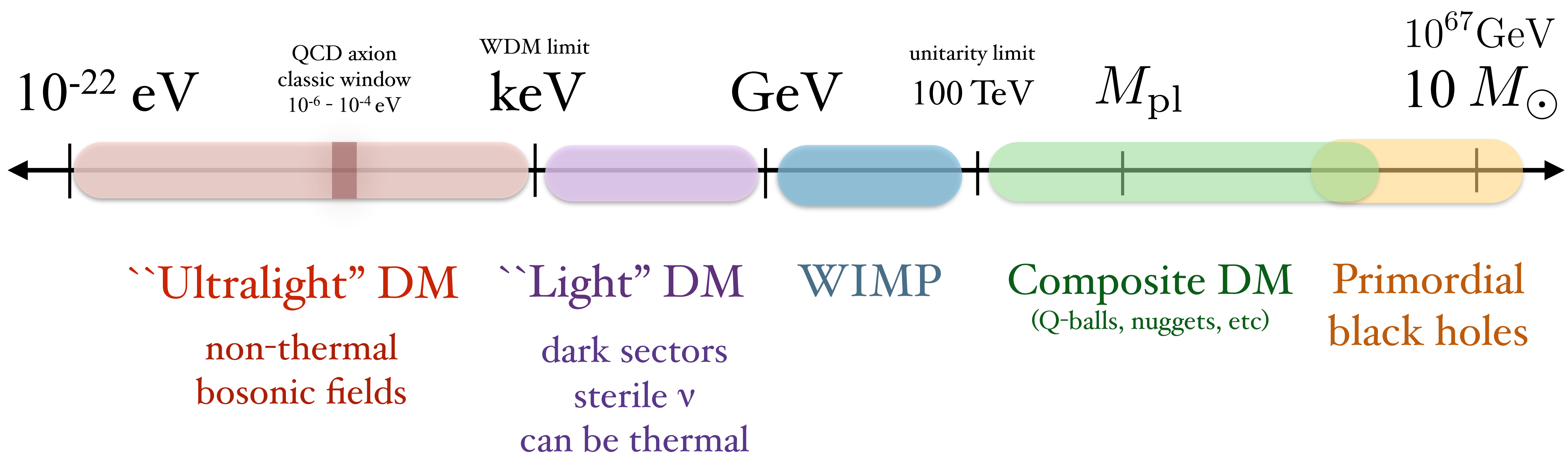
Vector Portal	$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$
Higgs portal[1]	$\epsilon_h \, \lvert h\rvert^2 \lvert\phi\rvert^2$
Higgs portal[singlet]	$A_h \lvert h\rvert^2 \phi$
Neutrino Portal	$\epsilon_\nu \, (hL)\psi$
Any currents	$\epsilon_V \bar{f}\gamma^\mu q_f f V_\mu$

Example : Constraints on vector portal



Mass scale of dark matter

(not to scale)



DARK MATTER MADE OF AXIONS?

super light and super weakly interacting particles…

Experimentally challenging.

Strong CP problem .

$$\mathcal{L} = -\bar{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$

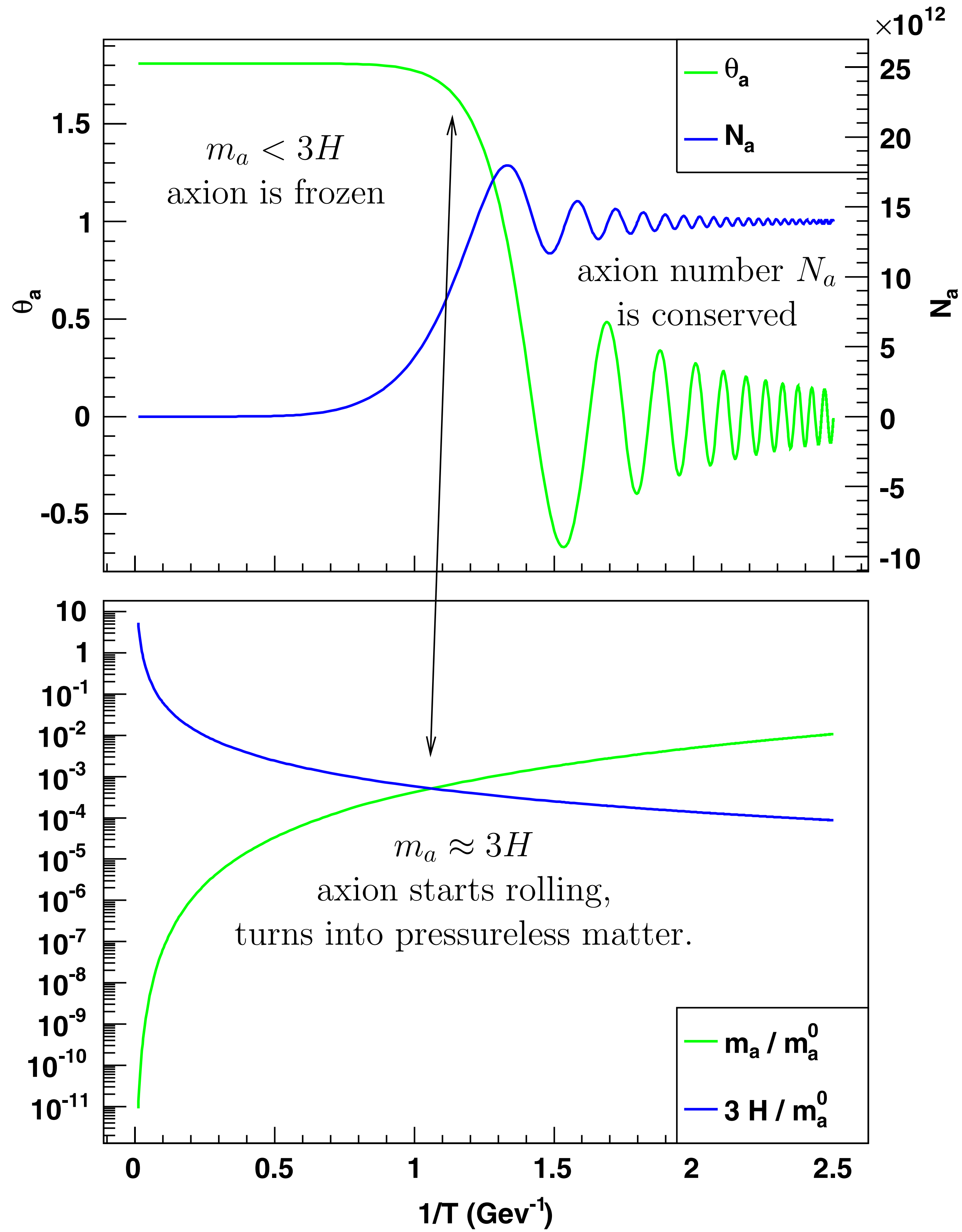
today $|\bar{\Theta}| < 10^{-11}$ as explained by Peccei-Quinn mechanism:

$$\bar{\Theta} \to \frac{a(x)}{f_a}$$

promoted to a dynamical field which relaxes to zero, to minimize the QCD vacuum energy.

in early universe, before the axion gets a mass around the QCD scale

$$|\bar{\Theta}| \sim 1$$

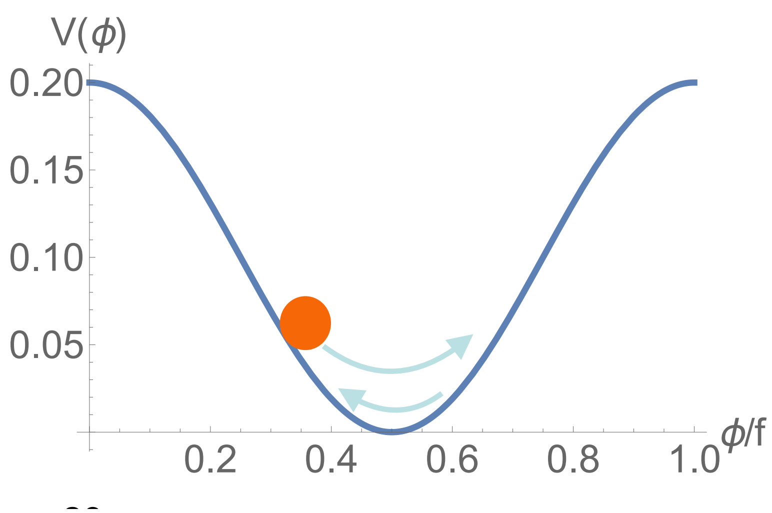


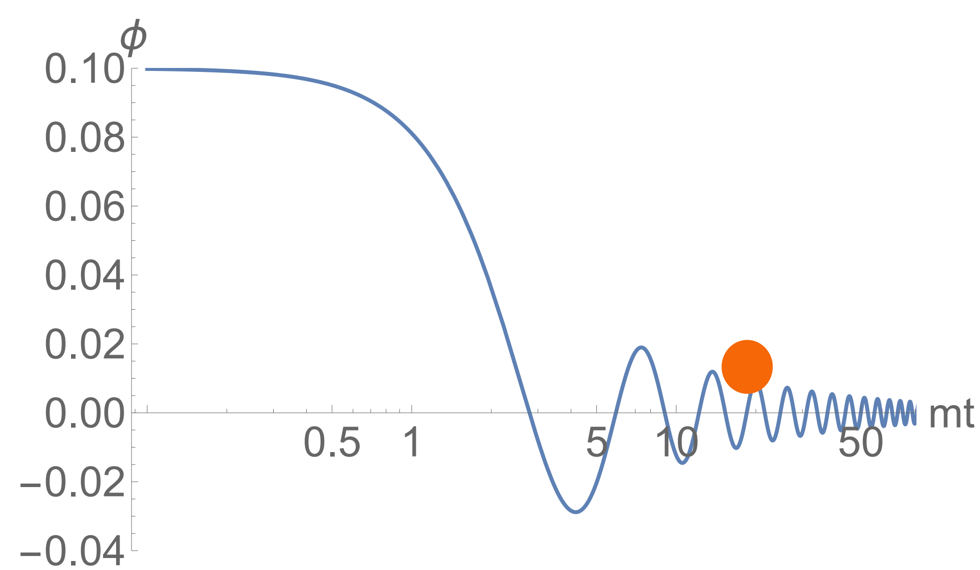
Wantz, Shellard '10

Light (pseudo-)scalar fields are featured in many UV models,
as pseudo-Nambu-Goldstone bosons (pNGBs) of spontaneously broken symmetries.

The QCD-axion is an example. (Peccei & Quinn 77, Wilczek 78, Weinberg 78)

The field would be initially displaced from a minimum of its potential during the early cosmological history

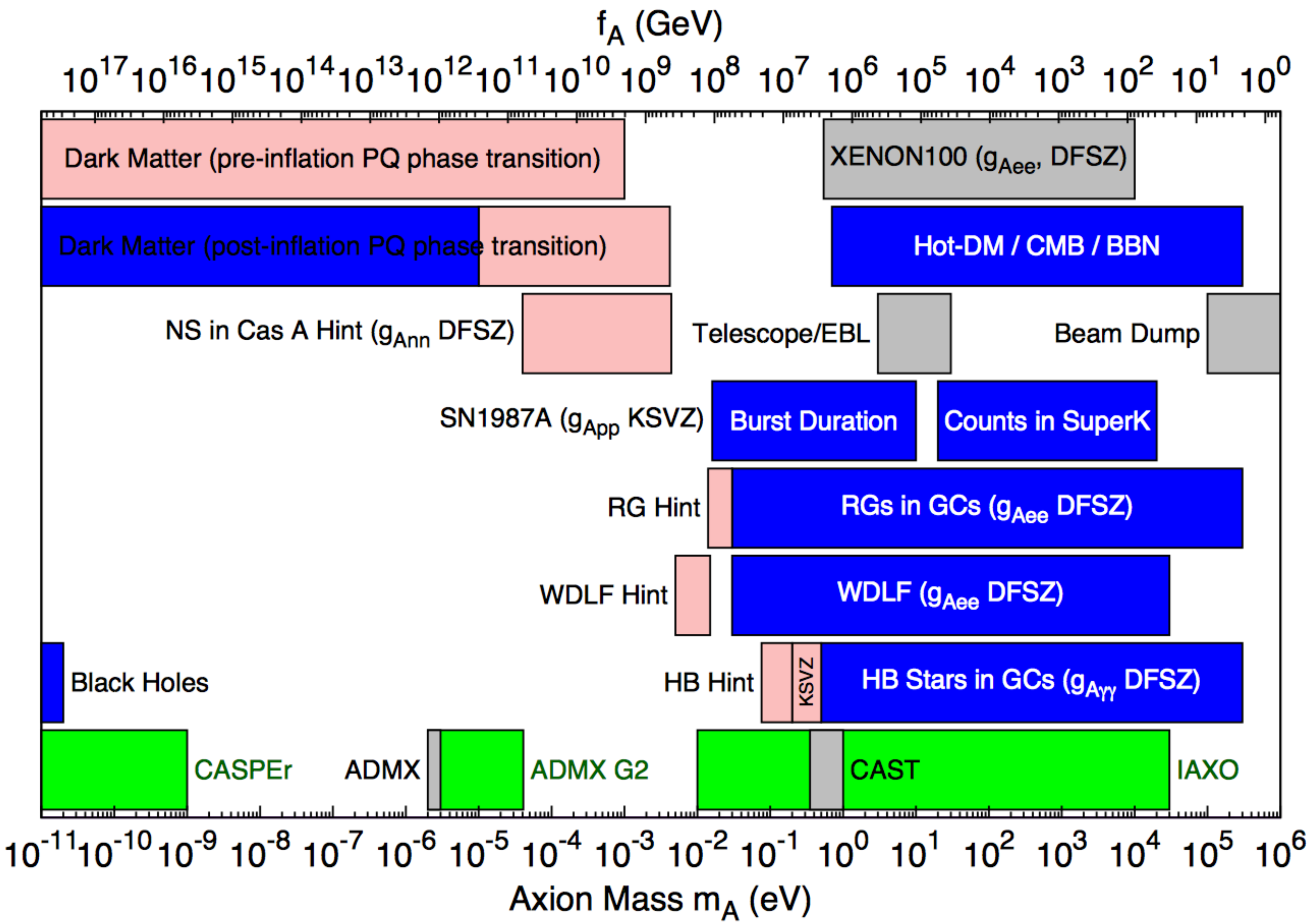




On scales much larger than de Broglie wavelength, behaves like a WIMP.

$$\lambda_{\rm dB} = \frac{2\pi}{mv} \approx 2\ {\rm kpc} \left(\frac{m}{10^{-22}\ {\rm eV}}\right) \left(\frac{v}{10\ {\rm km/s}}\right)^{-1}$$

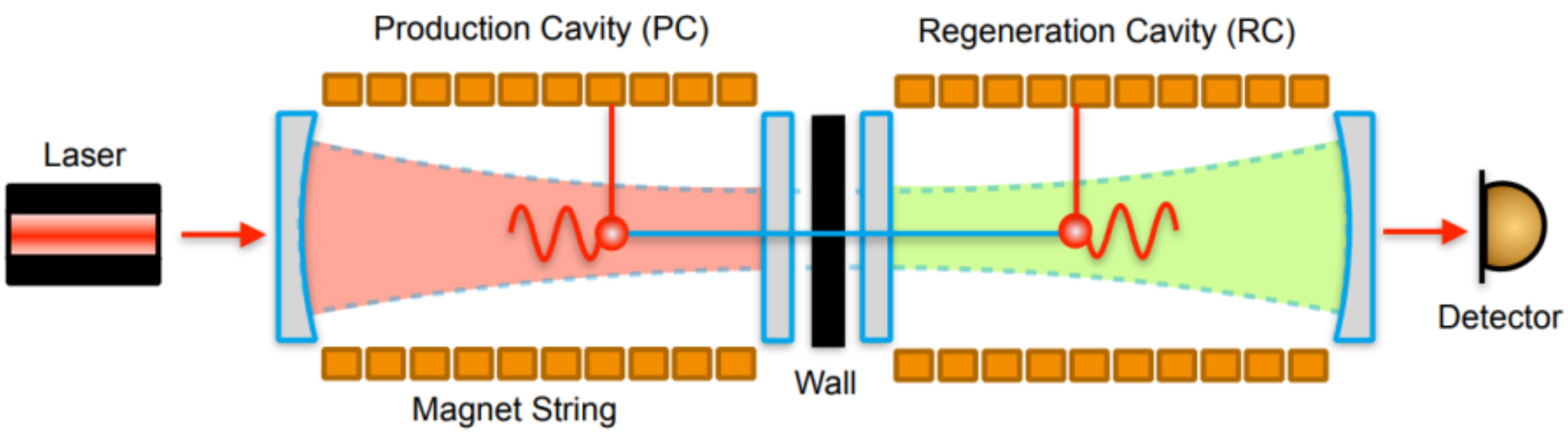
[K. Blum]



f_A (GeV)
10^{17} 10^{16} 10^{15} 10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 10^{0}
Dark Matter (pre-inflation PQ phase transition)
XENON100 (g_{Aee}, DFSZ)
Dark Matter (post-inflation PQ phase transition)
Hot-DM / CMB / BBN
NS in Cas A Hint (g_{Ann} DFSZ)
Telescope/EBL
Beam Dump
SN1987A (g_{App} KSVZ)
Burst Duration
Counts in SuperK
RG Hint
RGs in GCs (g_{Aee} DFSZ)
WDLF Hint
WDLF (g_{Aee} DFSZ)
Black Holes
HB Hint
KSVZ
HB Stars in GCs ($g_{A\gamma\gamma}$ DFSZ)
CASPEr
ADMX
ADMX G2
CAST
IAXO
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
Axion Mass m_A (eV)

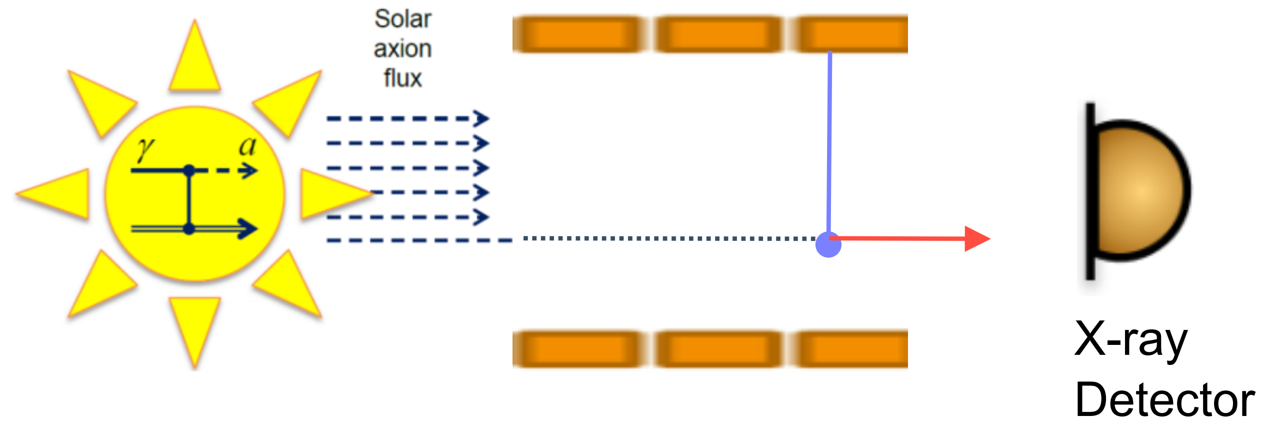
Completely different detection techniques

Light shining through a wall:

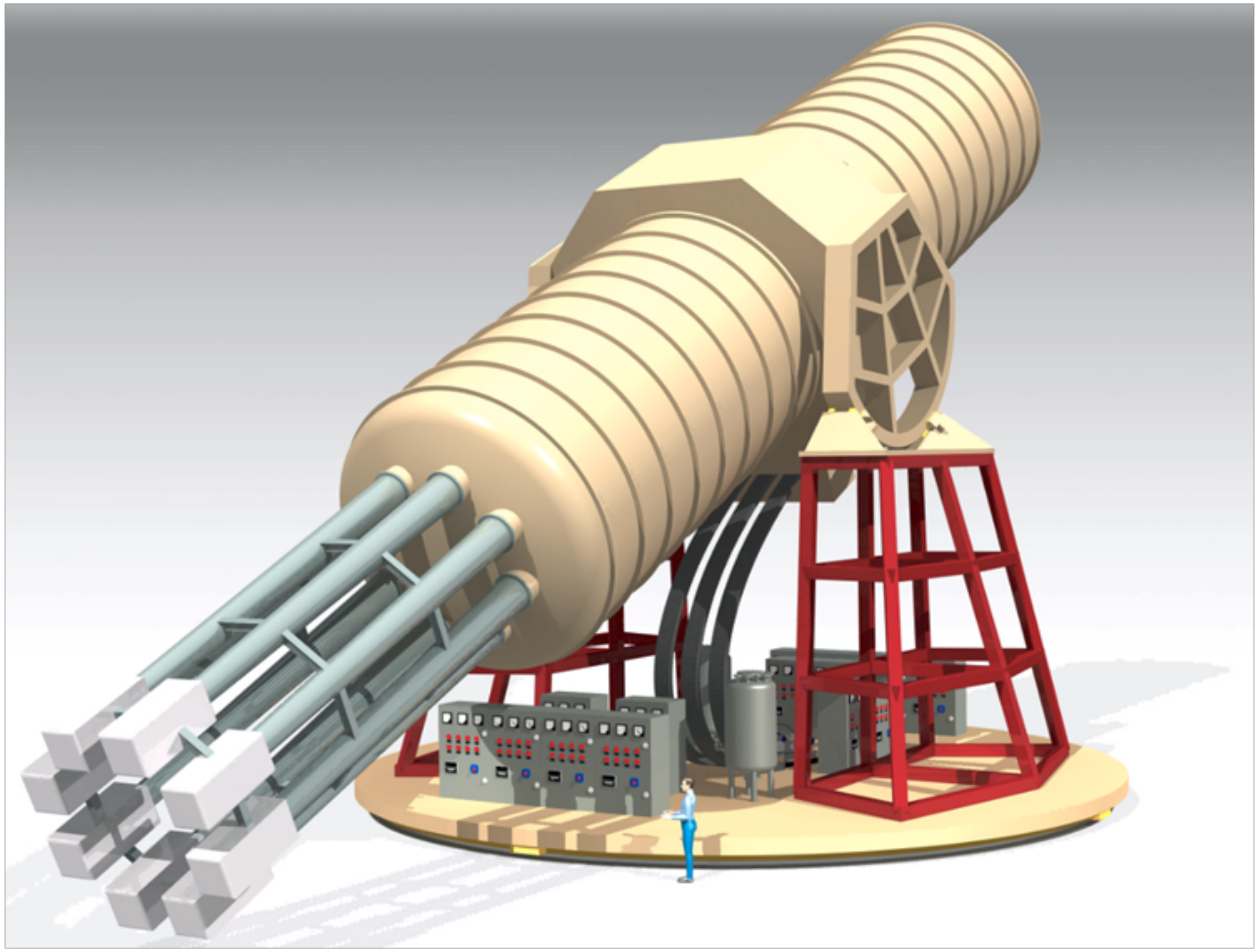


ALPS II

Helioscope:

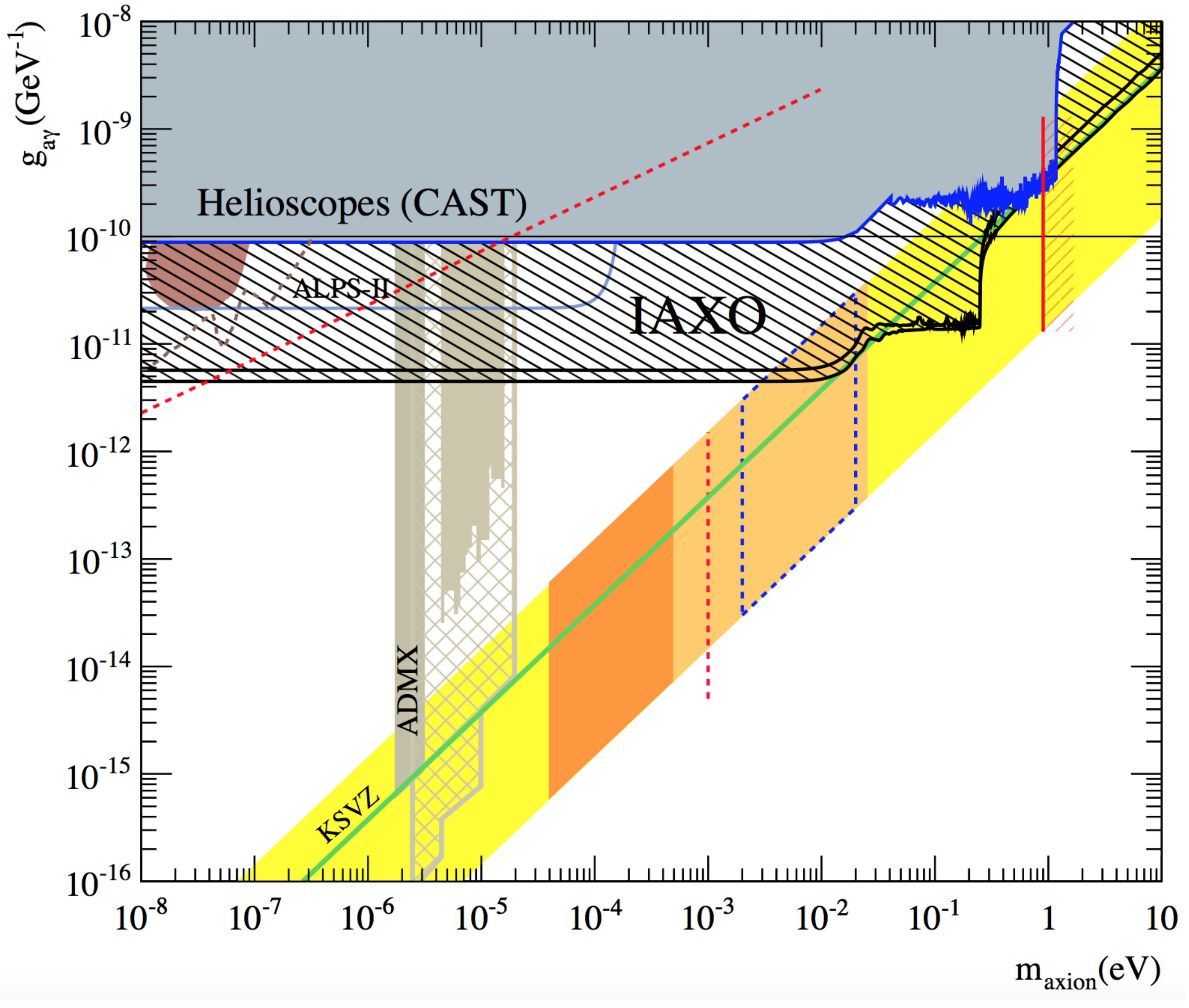


IAXO



COSMOLOGY OF AXIONS

**In the last few years,
vastly growing interest for Axion-Like Particles.**

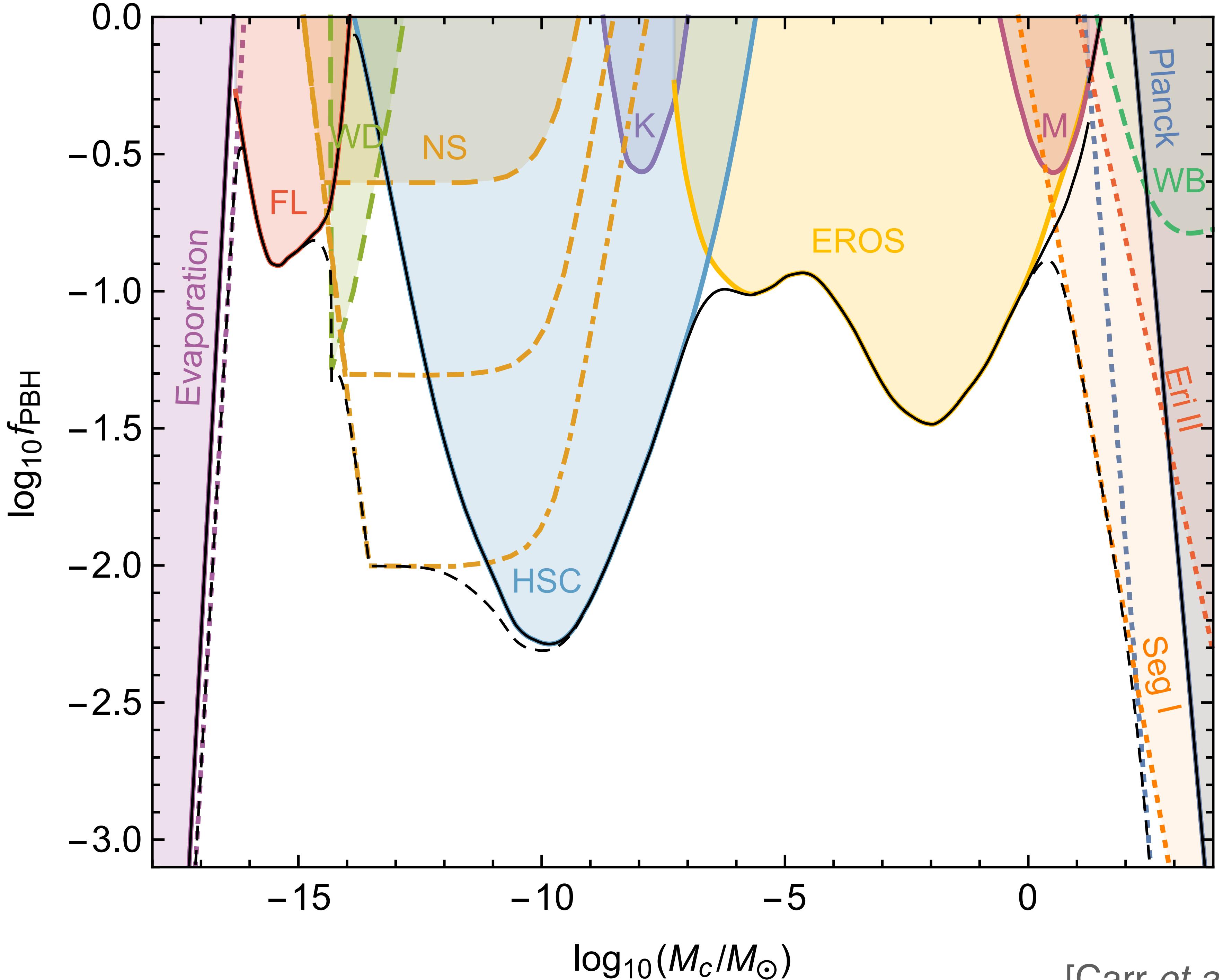


Do we really need a new particle to explain Dark Matter ?

Primordial Black Holes as Dark Matter ?

Constraints on Primordial Black Holes (PBHs) as Dark Matter

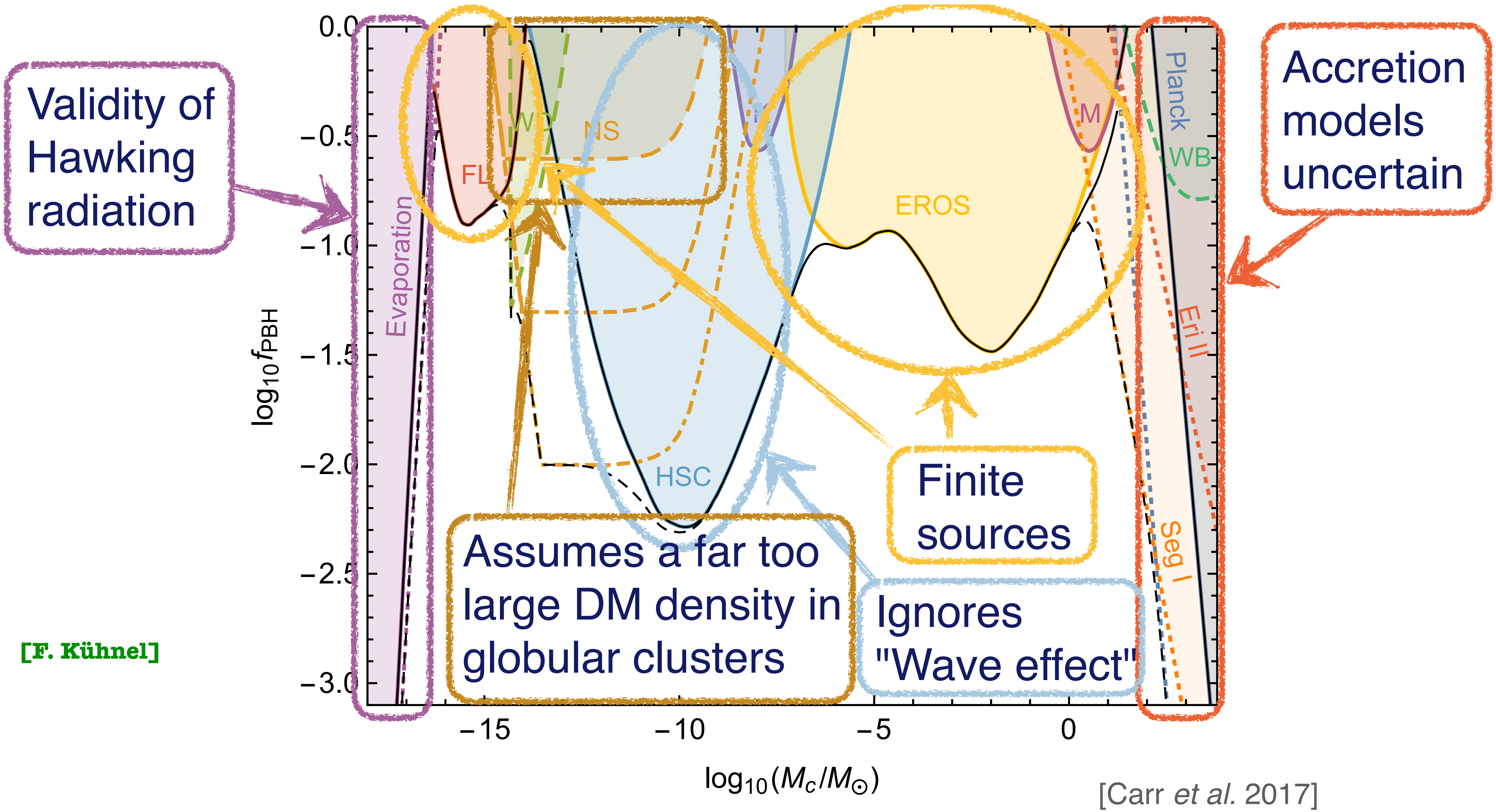
fraction of Dark Matter in PBH



[Carr *et al.* 2017]

Black Hole Mass

Constraints on Primordial Black Holes (PBHs) as Dark Matter



[F. Kühnel]

[Carr *et al.* 2017]

PBHs: a very active field !

Primordial black holes potentially influence physics on many different scales.

They could be a significant fraction of the dark matter.

A detailed understanding of their formation is crucial.

Most of the primordial black-hole constraints (GW, lensing, evaporation, CMB…) rely on uncertain assumptions. We have to understand better: Galactic dark-matter profile, Clustering
Accretion, Characteristics of the lensed sources (size, variability, …),
Composition of "probes" in general
Velocity distribution, Hawking radiation …

-3-

Origin of Baryon Asymmetry .

Matter Anti-matter asymmetry of the universe

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.7 \leq \eta_{10} \leq 6.7 \; (95\%\mathrm{CL})$$

Matter Anti-matter asymmetry of the universe

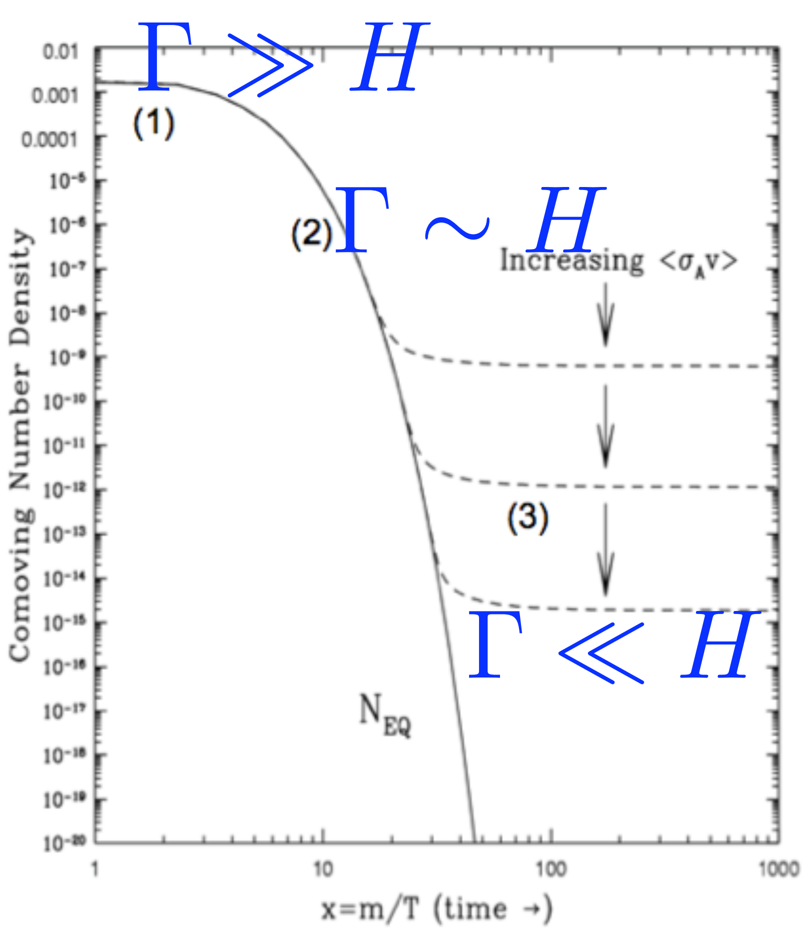
$$\boxed{\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}}$$

$$5.7 \leq \eta_{10} \leq 6.7 \ (95\%\mathrm{CL})$$

The great annihilation between nucleons & anti-nucleons

$$n + \bar{n} \to \pi + \pi \to \gamma + \gamma + \ldots$$

occurs when $\Gamma \sim (m_N T)^{3/2} e^{-m_N/T} / m_\pi^2 \sim H \sim \sqrt{g_*} T^2 / m_{Pl}$



corresponding to a freeze-out temperature $T_F \sim 20$ MeV

In absence of an asymmetry:

$$\eta \approx 5 \times 10^{-19}$$

10^9

and there are no antibaryons

-> need to invoke an initial asymmetry

(Visible)

characterized in terms of the baryon to photon ratio

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \equiv \eta_{10} \times 10^{-10}$$

$$5.1 < \eta_{10} < 6.5 \ (95\% \ \mathrm{CL})$$

The great annihilation

10 000 000 001
Matter

10 000 000 000
Anti-matter

1
(us)

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

2) C and CP violation

3) Loss of thermal equilibrium

we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Baryon number violation in the Standard Model

It follows from the Electroweak anomaly

$$\partial_\mu j^\mu_B = N_F \frac{\alpha_W}{8\pi} Tr F \tilde{F}$$

EW field strength

$$N_{CS} = \int d^3 x j^0_{CS}$$

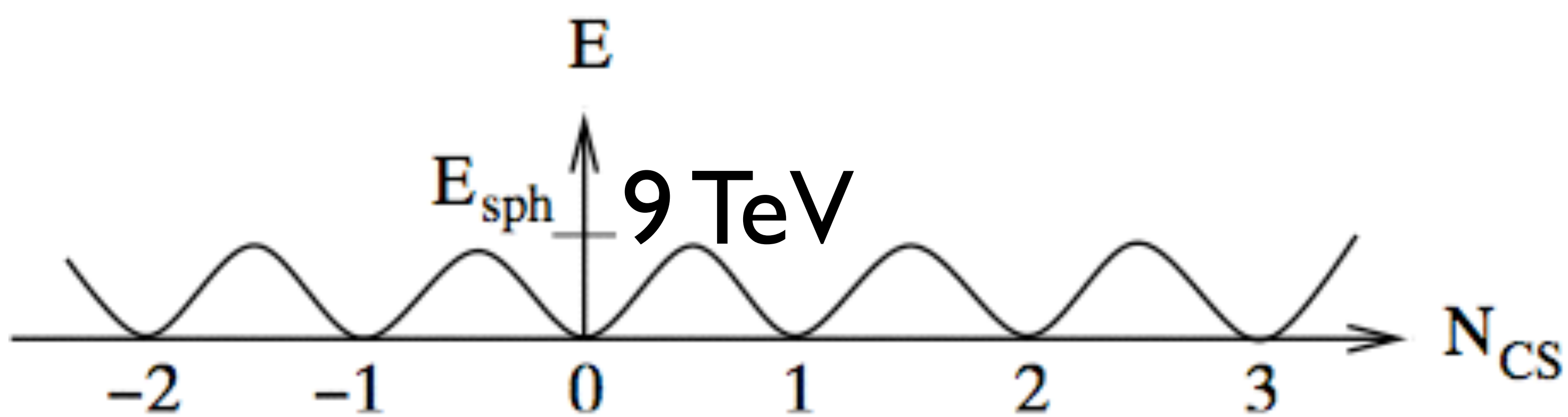
$$\Delta B = 3 \Delta N_{CS}$$

Baryon number violation in the Standard Model

due to chirality + topology

$$N_{CS}(t_1) - N_{CS}(t_0) = \int_{t_0}^{t_1} dt \int d^3x \; \partial_\mu K^\mu = \nu$$

$$\partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$



Energy of gauge field configuration as a function of Chern Simons number

$$\Delta B = N_f \Delta N_{CS}$$

baryons are created by transitions between topologically distinct vacua of the $SU(2)_L$ gauge field

$\Rightarrow$ Baryon number violation is totally suppressed in the SM at zero temperature but very efficient at high temperatures

η remains unexplained within the Standard Model

double failure:

- lack of out-of-equilibrium condition

- so far, no baryogenesis mechanism that works with only SM CP violation (CKM phase)

proven for standard EW baryogenesis

Gavela, P. Hernandez, Orloff, Pene '94
Konstandin, Prokopec, Schmidt '04

attempts in cold EW baryogenesis

Tranberg, A. Hernandez, Konstandin, Schmidt '09
Brauner, Taanila,Tranberg,Vuorinen '12

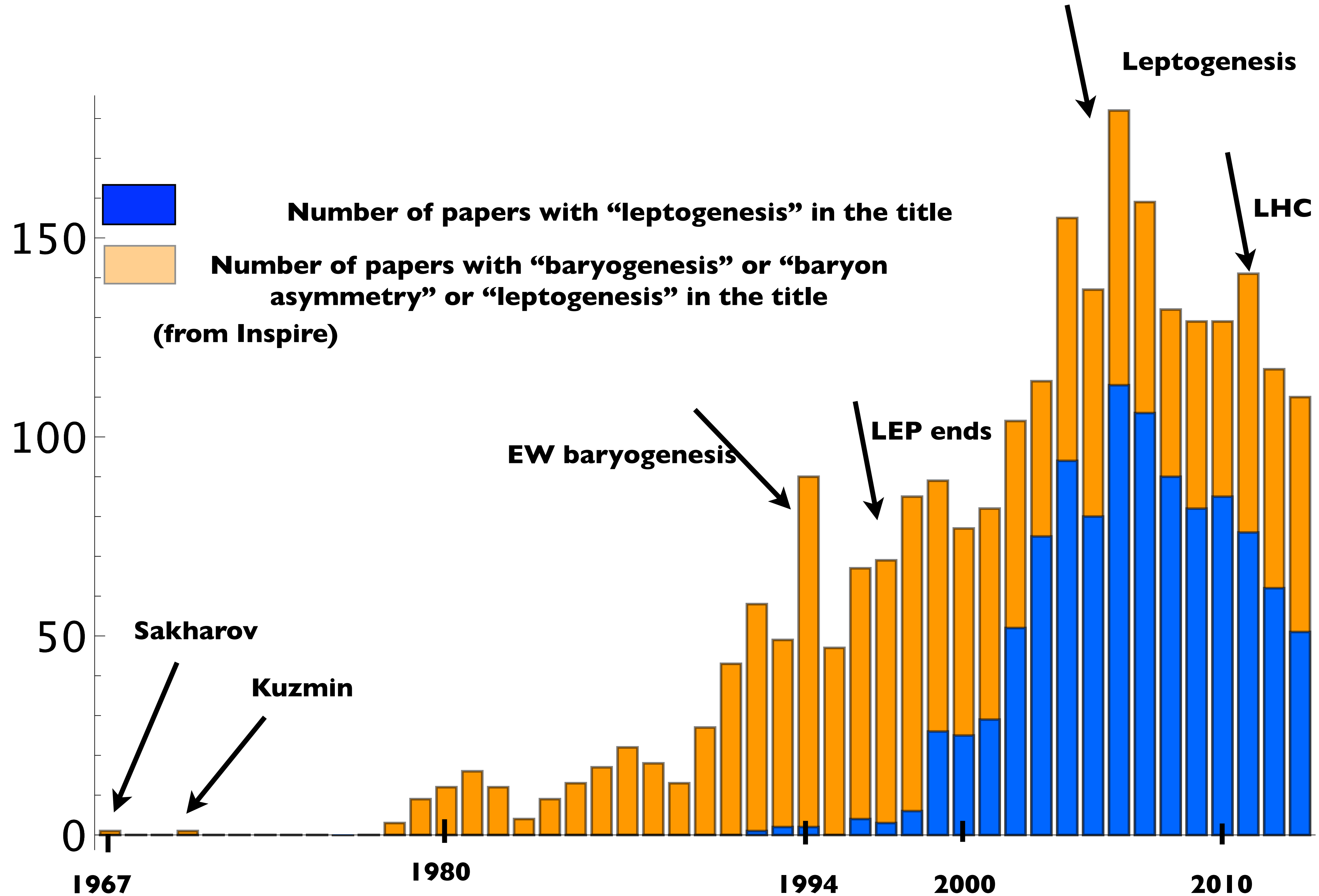
Shaposhnikov,

Journal of Physics: Conference Series **171** (2009) 012005

1. GUT baryogenesis. 2. GUT baryogenesis after preheating. 3. Baryogenesis from primordial black holes. 4. String scale baryogenesis. 5. Affleck-Dine (AD) baryogenesis. 6. Hybridized AD baryogenesis. 7. No-scale AD baryogenesis. 8. Single field baryogenesis. 9. Electroweak (EW) baryogenesis. 10. Local EW baryogenesis. 11. Non-local EW baryogenesis. 12. EW baryogenesis at preheating. 13. SUSY EW baryogenesis. 14. String mediated EW baryogenesis. 15. Baryogenesis via leptogenesis. 16. Inflationary baryogenesis. 17. Resonant leptogenesis. 18. Spontaneous baryogenesis. 19. Coherent baryogenesis. 20. Gravitational baryogenesis. 21. Defect mediated baryogenesis. 22. Baryogenesis from long cosmic strings. 23. Baryogenesis from short cosmic strings. 24. Baryogenesis from collapsing loops. 25. Baryogenesis through collapse of vortons. 26. Baryogenesis through axion domain walls. 27. Baryogenesis through QCD domain walls. 28. Baryogenesis through unstable domain walls. 29. Baryogenesis from classical force. 30. Baryogenesis from electrogenesis. 31. B-ball baryogenesis. 32. Baryogenesis from CPT breaking. 33. Baryogenesis through quantum gravity. 34. Baryogenesis via neutrino oscillations. 35. Monopole baryogenesis. 36. Axino induced baryogenesis. 37. Gravitino induced baryogenesis. 38. Radion induced baryogenesis. 39. Baryogenesis in large extra dimensions. 40. Baryogenesis by brane collision. 41. Baryogenesis via density fluctuations. 42. Baryogenesis from hadronic jets. 43. Thermal leptogenesis. 44. Nonthermal leptogenesis.

Plethora of baryogenesis models taking place at all possible scales

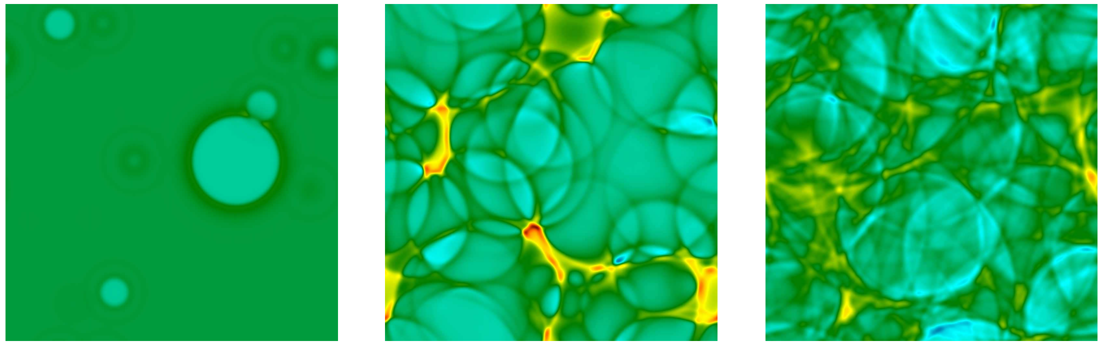
History of baryogenesis papers



Two leading candidates for baryogenesis:

--> Leptogenesis by out of equilibrium decays of RH neutrinos before the EW phase transition

--> Baryogenesis at a first-order EW phase transition



Models of Baryogenesis

T

GUT baryogenesis

B washout unless B-L ≠ 0

requires SO(10) → leptogenesis

requires too high reheat temperature to produce enough GUT particles

Thermal leptogenesis

hierarchy pb -> embed in susy-> gravitino pb (can be solved if M_gravitino>100 TeV and DM is neutralino or gravitino is stable)

Affleck-Dine (moduli decay)

Non-thermal leptogenesis (via oscillations)

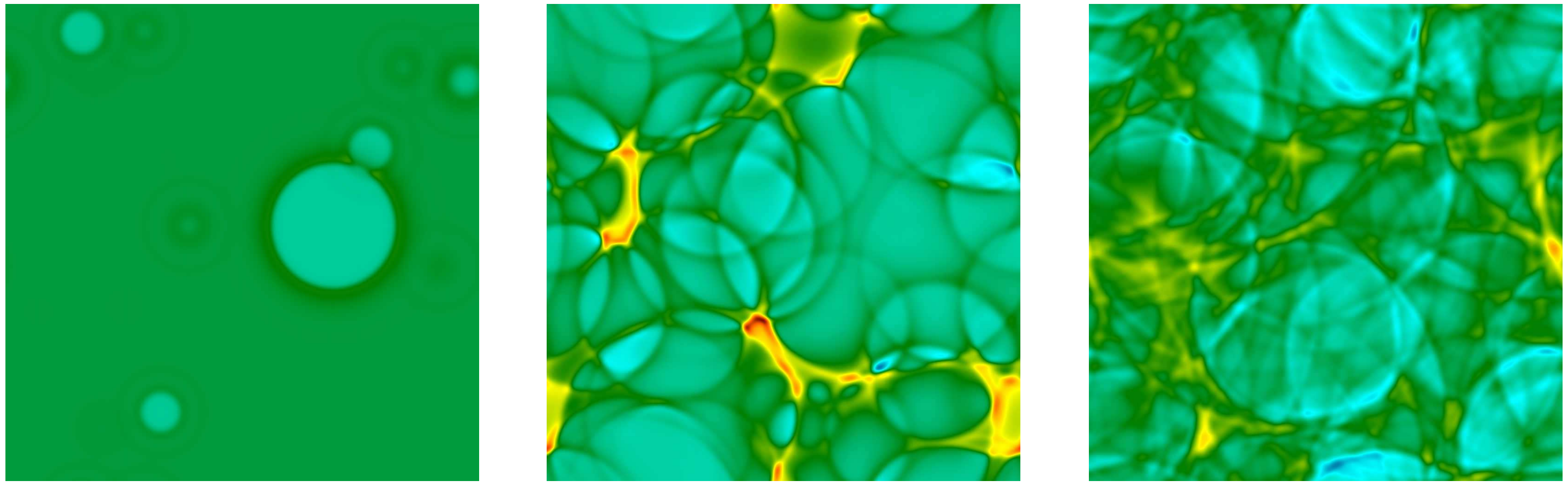
Asymmetric dark matter-cogenesis

EW breaking, sphalerons freese-out

EW (non-local) baryogenesis

EW cold (local) baryogenesis

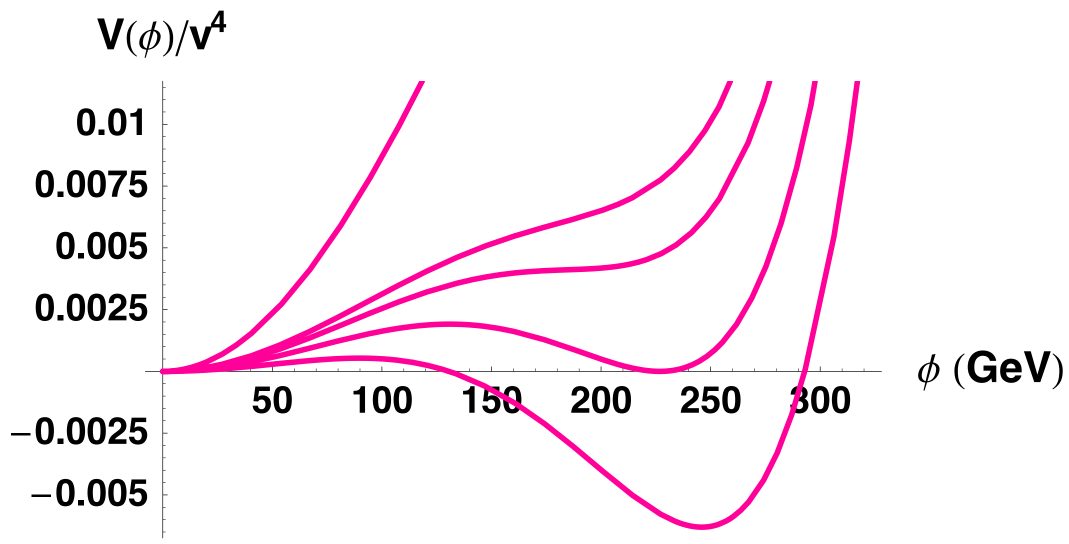
Baryogenesis
at a first-order
EW phase transition

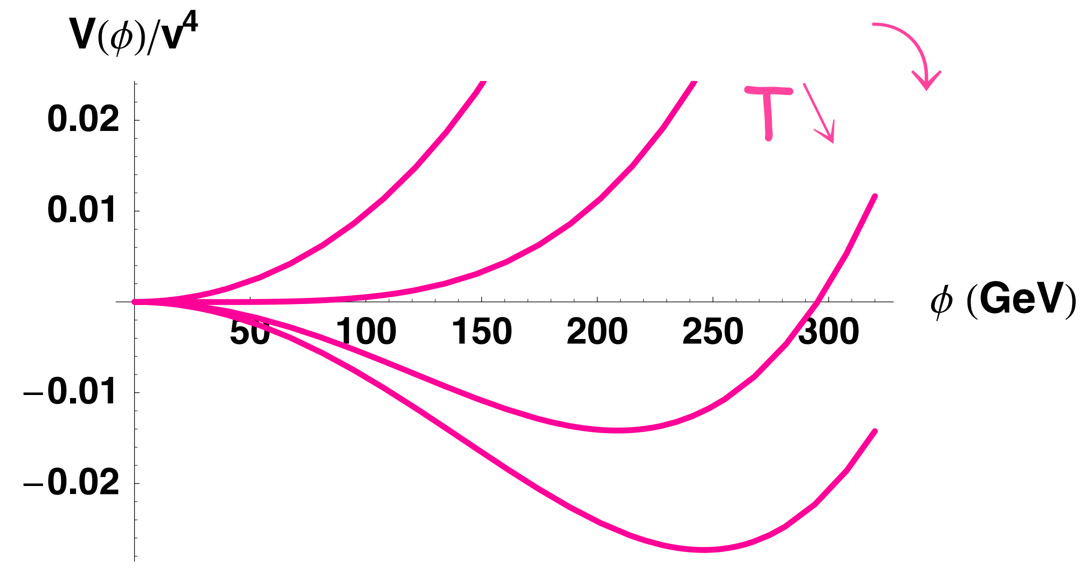


[image credit:1304.2433]

Nature of the EW phase transition

first-order or cross over?



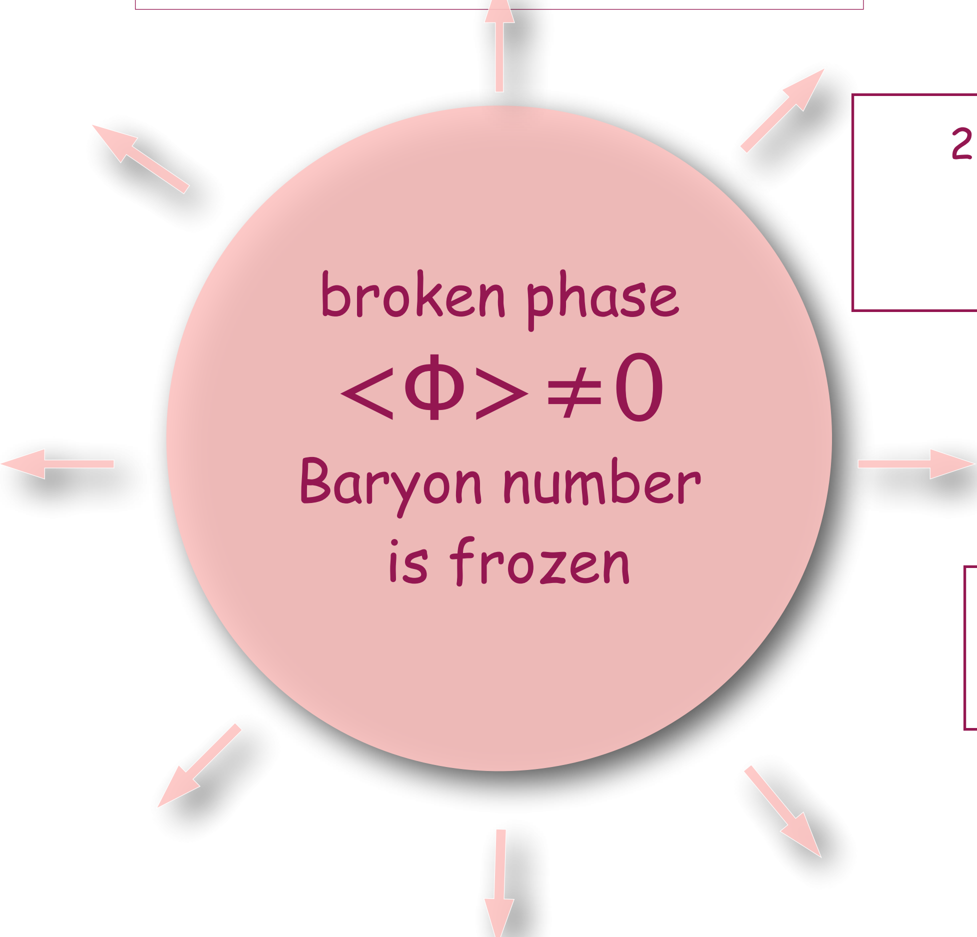


Baryon asymmetry and the EW scale

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91

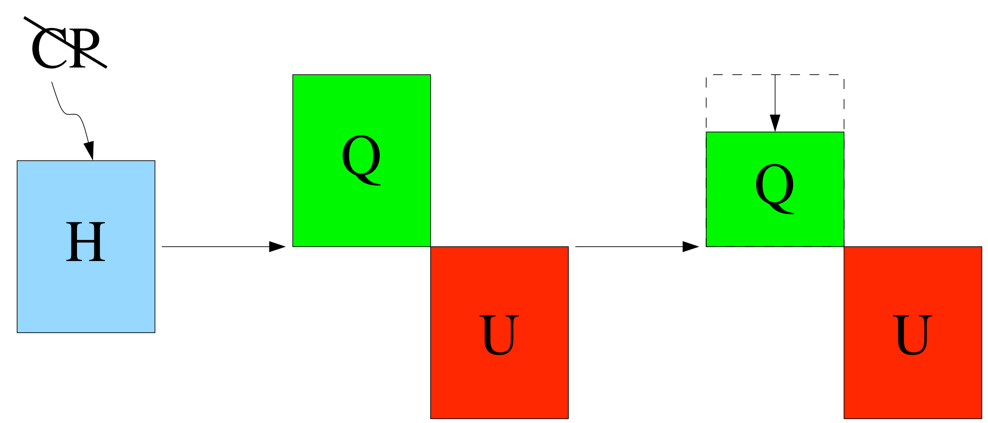
1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

Chirality Flux in front of the wall

3) In symmetric phase, $<\Phi>=0$, very active sphalerons convert chiral asymmetry into baryon asymmetry



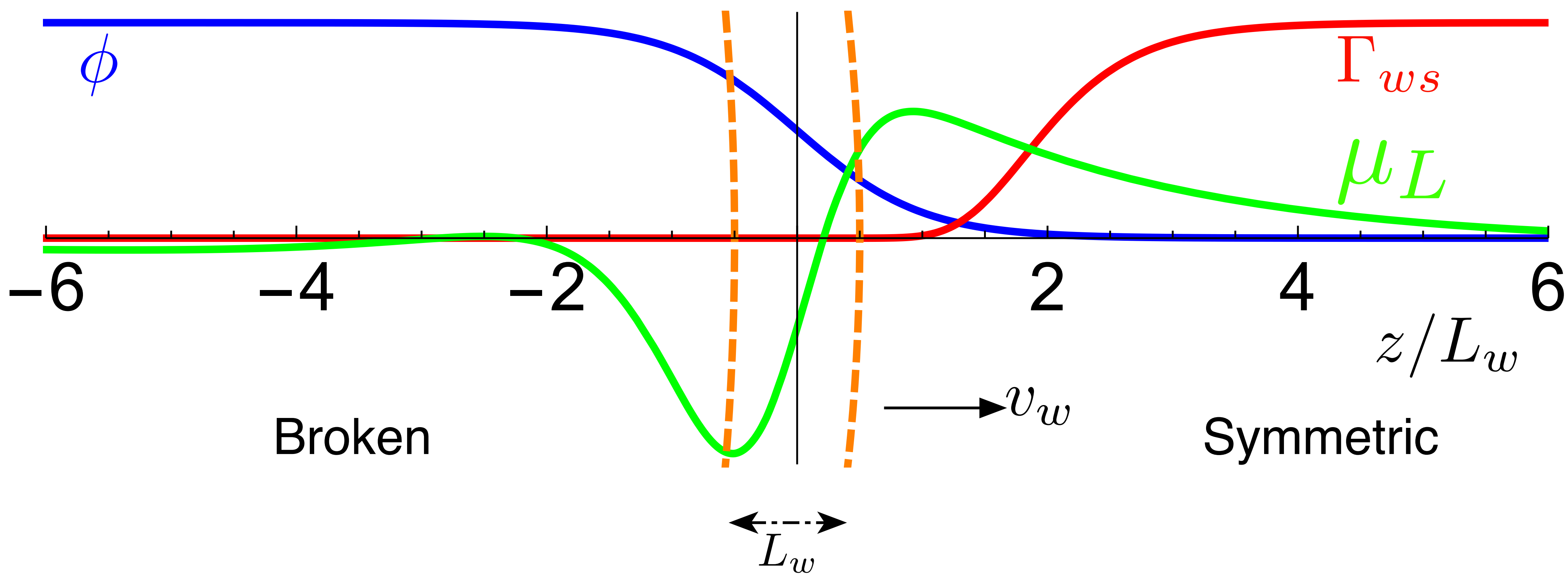
Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying $\dfrac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

The Electroweak Baryogenesis Miracle:

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

bubble wall velocity

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$: sphaleron rate



The Electroweak Baryogenesis Miracle:

$$\eta_B = \frac{n_B(-\infty)}{s} = \frac{135\ N_c}{4\pi^2 v_w g_* T} \int_{-\infty}^{+\infty} \mathrm{d}z\ \Gamma_{ws}\ \mu_L\ \mathrm{Exp}\left[-\frac{3}{2} A \frac{1}{v_w} \int_{-\infty}^{z} \mathrm{d}z_0 \Gamma_{ws}\right]$$

$$\Gamma_{ws} = 10^{-6}\ T\ e^{-\frac{E_{sph}}{T}\frac{\phi(T)}{v}}$$

$$\eta_B \sim \frac{\Gamma_{ws}\ \mu_L\ L_w}{g_*\ T}$$

$$\mu_L \sim M'' M \sim \frac{\delta_{CP}}{L_w^2\ T} \qquad\qquad L_w \sim \frac{1}{T}$$

$$\eta_B \sim \frac{\Gamma_{ws}\ \delta_{CP}}{g_*\ L_w\ T^2} \sim \frac{10^{-6}\ \delta_{CP}}{g_*} \sim 10^{-8} \delta_{CP}$$

All parameters fixed by electroweak physics. If new CP violating source of order 1 then we get just the right baryon asymmetry.

Cline, Joyce, Kainulainen '00
Konstandin, Prokopec, Schmidt '04
Huber Fromme '06
Bruggisser, Konstandin, Servant '17

Kinetic equations

$$\left(k_z\partial_z - \frac{1}{2}\left(\left[V^\dagger\left(m^\dagger m\right)' V\right]\right)_{ii}\partial_{k_z}\right) f_{L,i} \approx \mathbf{C} + \mathcal{S}$$

$$\left(k_z\partial_z - \frac{1}{2}\left(\left[V^\dagger\left(m^\dagger m\right)' V\right]\right)_{ii}\partial_{k_z}\right) f_{R,i} \approx \mathbf{C} - \mathcal{S}$$

collisions **source**

$$\eta_B = \sum_i \int_{-\infty}^{+\infty} \mathrm{d}y\ K_i(y)\ \bar{\mathcal{S}}_i(y)$$

diffusion effects & sphalerons

CP-violating source

Usual CP-violating sources in EW baryogenesis:

-Charginos/neutralinos/sfermions (MSSM) Cline et al, Carena et al, Chung et al...

-Varying phase in effective Top quark Yukawa

SM+singlet, Fromme-Huber

Composite Higgs, Espinosa, Gripaios, Konstandin, Riva, '11

2-Higgs doublet model Konstandin et al, Cline et al

- two recent alternatives: strong CP QCD axion (Servant '14)

and CP in DM sector (e.g. Cline'17)

the CKM matrix as the CP-violating source

In the SM: $\eta_B \lesssim 10^{-2}\Delta_{CP}$

Farrar, Shaposhnikov '93

$$\Delta_{CP} \sim \left(M_W^6 T_c^6\right)^{-1} \prod_{\substack{i>j\\u,c,t}} \left(m_i^2 - m_j^2\right) \prod_{\substack{i>j\\d,s,b}} \left(m_i^2 - m_j^2\right) J_{CP}$$

Gavela, *et al.* '93
Huet, Sather '94

Jarlskog constant

$$J = s_1^2 s_2 s_3 c_1 c_2 c_3 \sin(\delta) = (3.0 \pm 0.3) \times 10^{-5},$$

Based solely on reflection coefficients

If large masses during EW phase transition
->no longer suppression of CKM CP violation

Berkooz, Nir, Volansky '04

New idea: Varying SM Yukawas as CP violating source

Bruggisser, Konstandin, Servant '17

$$S \sim \text{Im}\left[V^\dagger m^{\dagger\prime\prime} m V\right]$$

V: transformation matrix for mass diagonalization

$$m = y(z) \cdot \frac{\phi(z)}{\sqrt{2}}$$

For constant y:

$$S \sim \underbrace{\text{Im}\left[V^\dagger Y^\dagger Y V\right]}_{=0} \phi''\phi$$

1-Flavour case

$$m = |m| e^{i\theta}$$

$$S \propto \mathrm{Im}\left[V^\dagger m^{\dagger\prime\prime} m V \right] = \left(|m|^2 \theta' \right)'$$

requires variation of phase

exploited in baryogenesis
through varying top quark mass.

More than 1 flavour: no need for variation of phase

Bruggisser et al '17





Flavour-EW symmetry breaking cosmological interplay

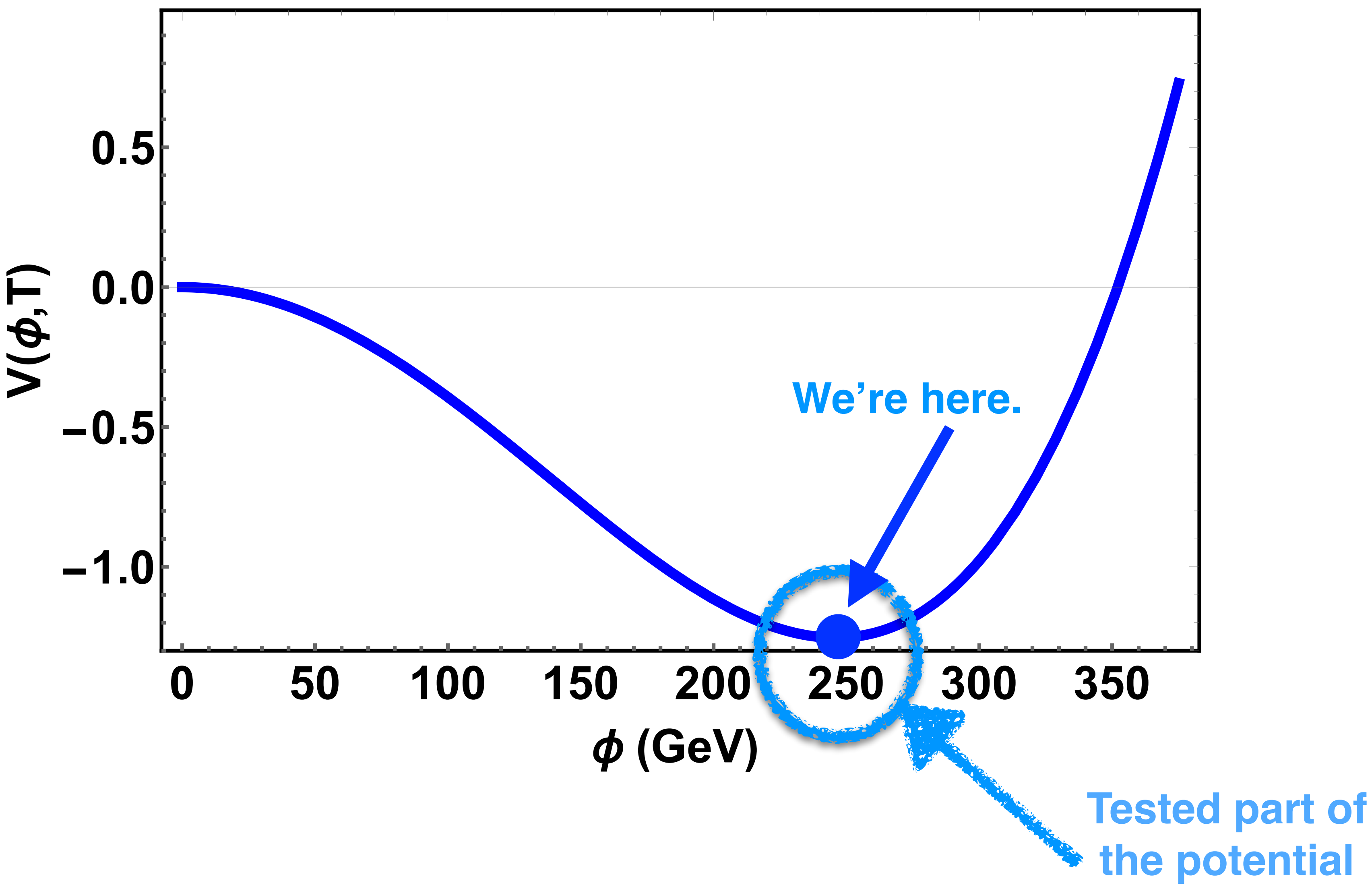
- Effect of varying Yukawas on EW phase transition
  Baldes, Konstandin, Servant, 1604.04526
- Implementation in Froggatt-Nielsen
  Baldes, Konstandin, Servant, 1608.03254
- Natural realisation of Yukawa variation in Randall-Sundrum
  Von Harling, Servant, 1612.02447
- Calculation of baryon asymmetry in models of variable Yukawas
  Bruggisser, Konstandin, Servant, 1706.08534
- Outcome in composite Higgs models **Bruggisser, VonHarling, Matsedonskyi, Servant, 1803.08546 & 1804.07314**
- High scale EW phase transition **Baldes, Servant, 1807.08770**

Nature of the EW phase transition :

Still many open exotic possibilities regarding what happened when the energy density of the universe was (EW scale)^4.

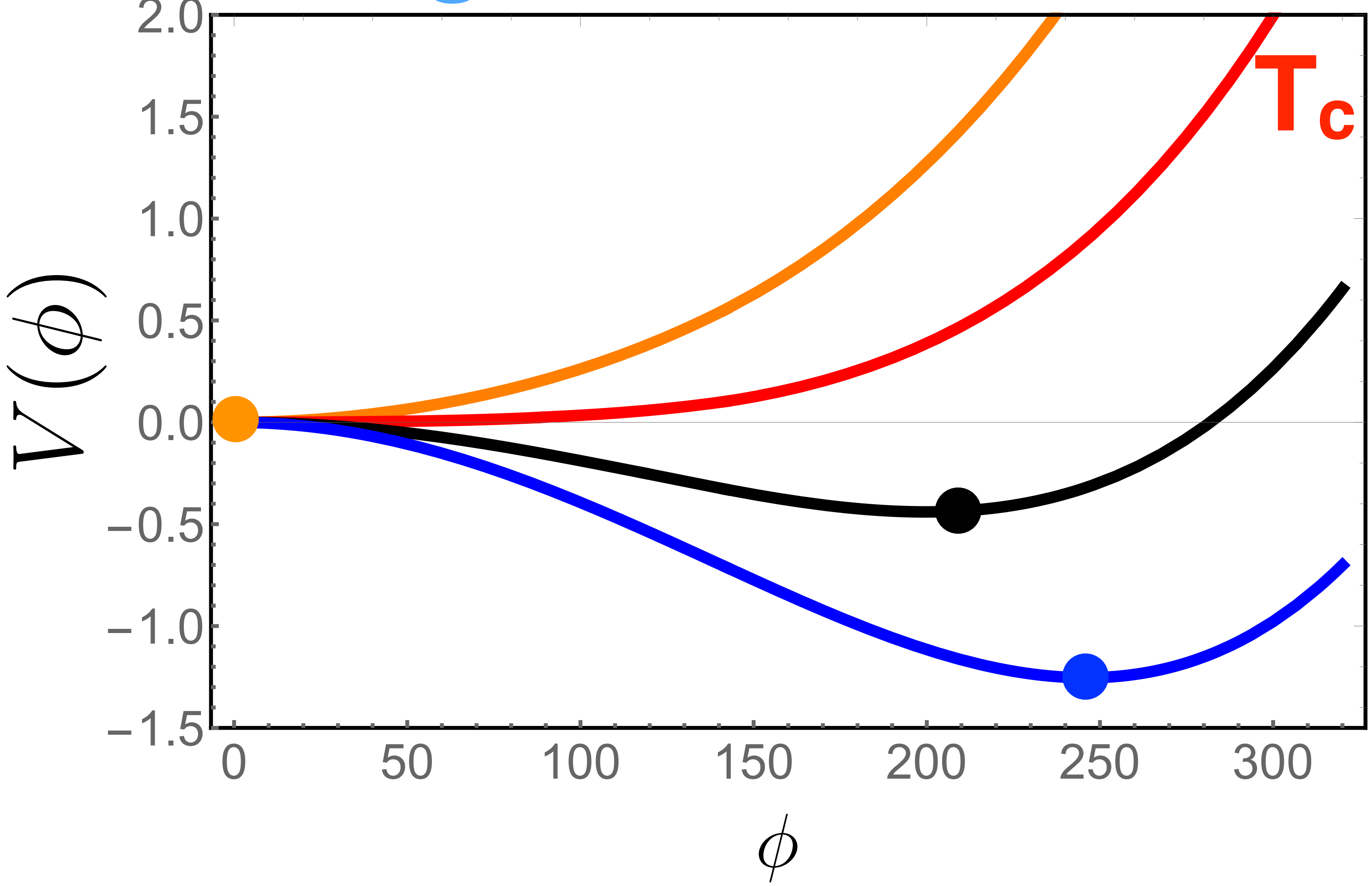
THE HIGGS POTENTIAL .

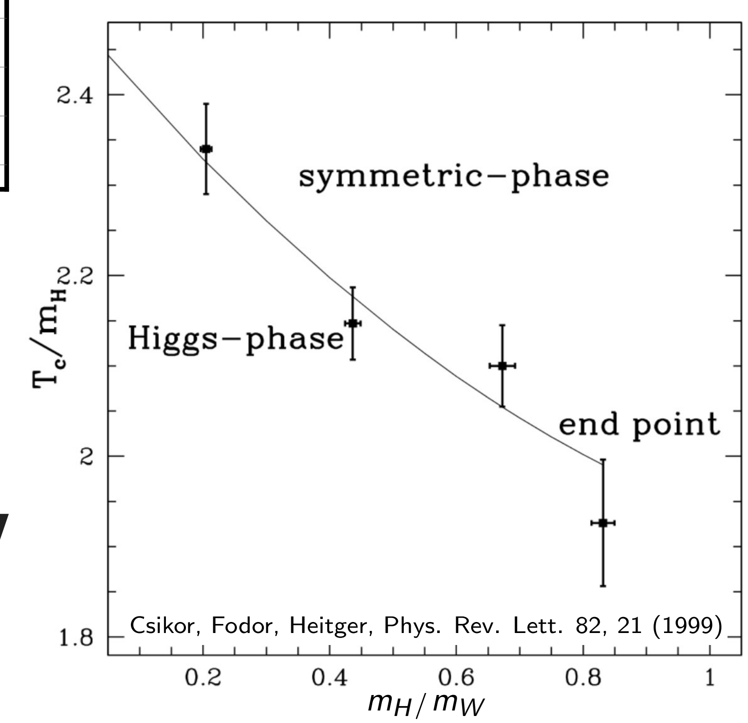
TODAY, T=0



> How did we end up here ?

EW sym. restored at T≳160 GeV*** through a smooth crossover





No departure from thermal equilibrium

It would have been different if $m_H \lesssim 70$ GeV

***1404.3565

HIGGS EFFECTIVE POTENTIAL AT HIGH TEMPERATURE

At one-loop:

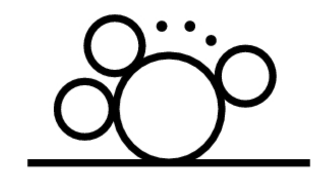
$$V_{\rm eff} = \boxed{V_{\rm tree}(\phi) + V_1^0(\phi)} + \boxed{V_1^T(\phi,T) + V_{\rm Daisy}(\phi,T)}.$$

Tree level

1-loop T=0

1-loop T≠0

Daisy resummation



$$\boxed{V_1^T(\phi,T) = \sum_i (\Delta V_{b,i}^T + \Delta V_{f,i}^T)}$$

bosons fermions

Sum over all particles coupled to the Higgs

For high-T, m/T<<1:

$$\Delta V_{b,i}^T \simeq -\frac{\pi^2 T^4}{90} + \frac{T^2 m_i^2(\phi)}{24}$$

$$\Delta V_{f,i}^T \simeq -\frac{7\pi^2 T^4}{180} + \frac{T^2 m_i^2(\phi)}{12}$$

depth of negative correction to Veff at m=0

sets the thermal mass

$$\boxed{\delta m_H^2(T) \simeq +T^2\left[\frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{3g^2}{16} + \frac{g'^2}{16}\right]}$$

Higgs Thermal Mass in the SM

HIGH TEMPERATURE EW SYM. RESTORATION.

At one-loop:

$$V_{\rm eff} = \boxed{V_{\rm tree}(\phi) + V_1^0(\phi)} + \boxed{V_1^T(\phi,T) + V_{\rm Daisy}(\phi,T)}.$$

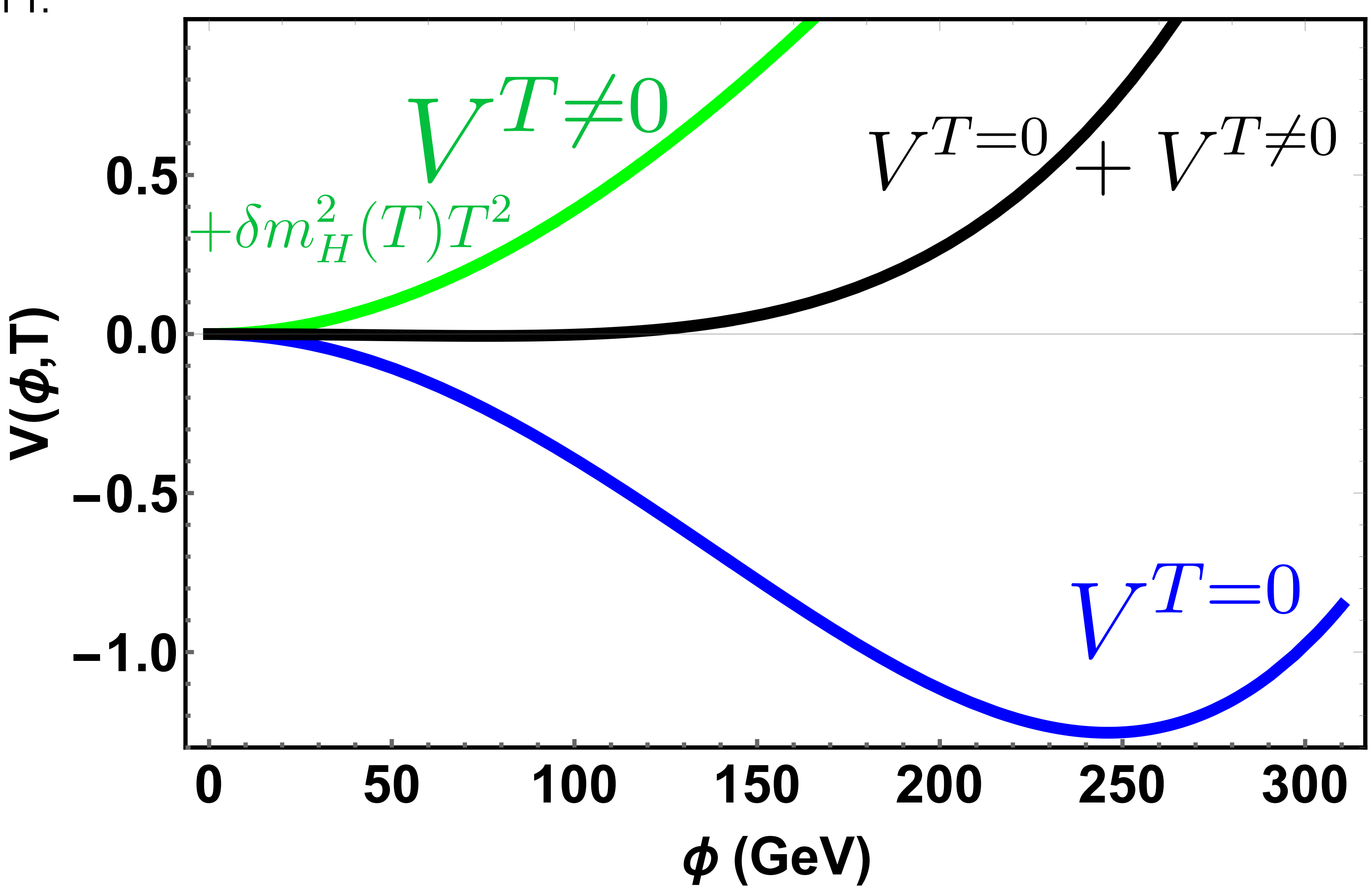
Tree level

1-loop
T=0

1-loop
T≠0

Daisy resummation

At high T:

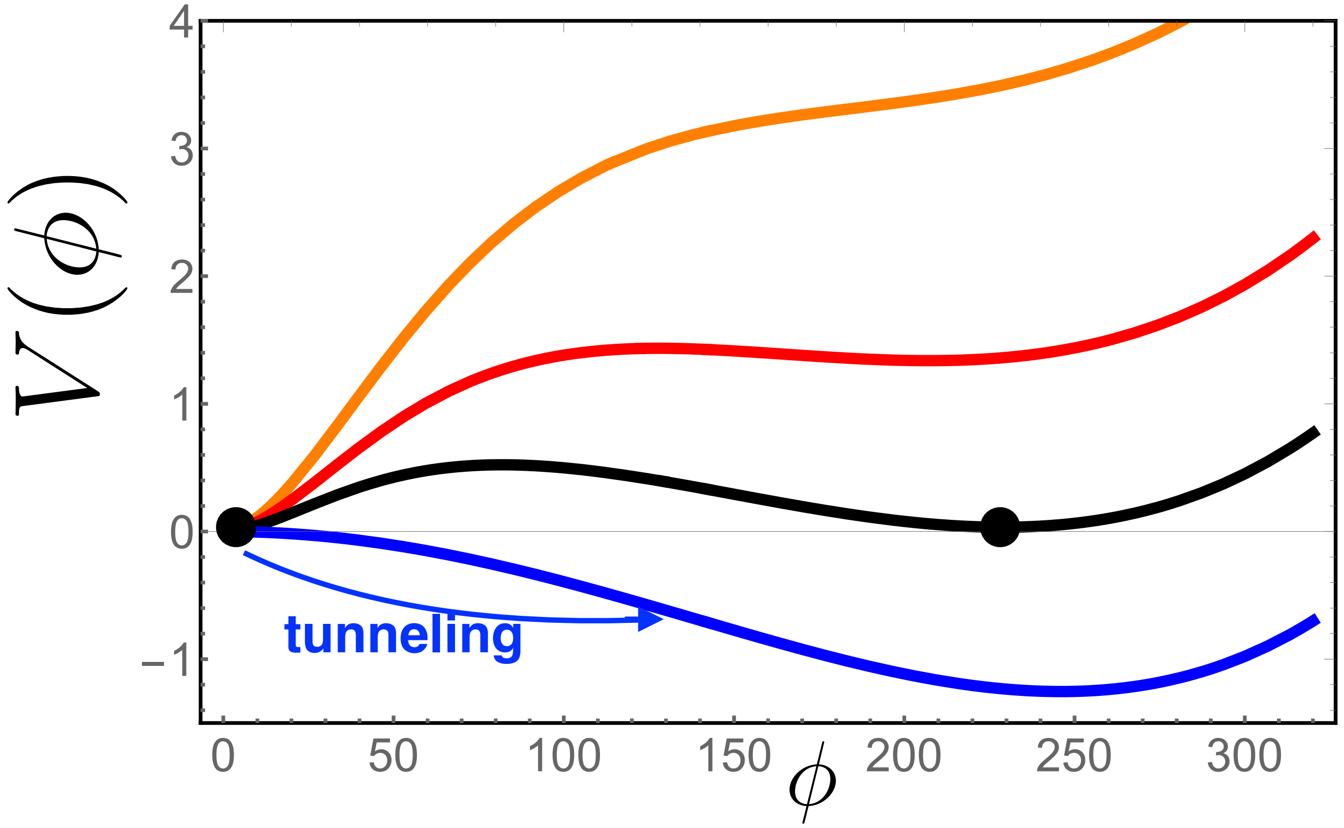


—> Symmetry restoration at Tc

WHICH ALTERNATIVE HIGGS STORIES ?

First-order EW Phase transition .

First-order EW phase transition .



Barrier separates 2 degenerate minima

2 phases can coexist

Nucleation, expansion and collision of Higgs bubbles

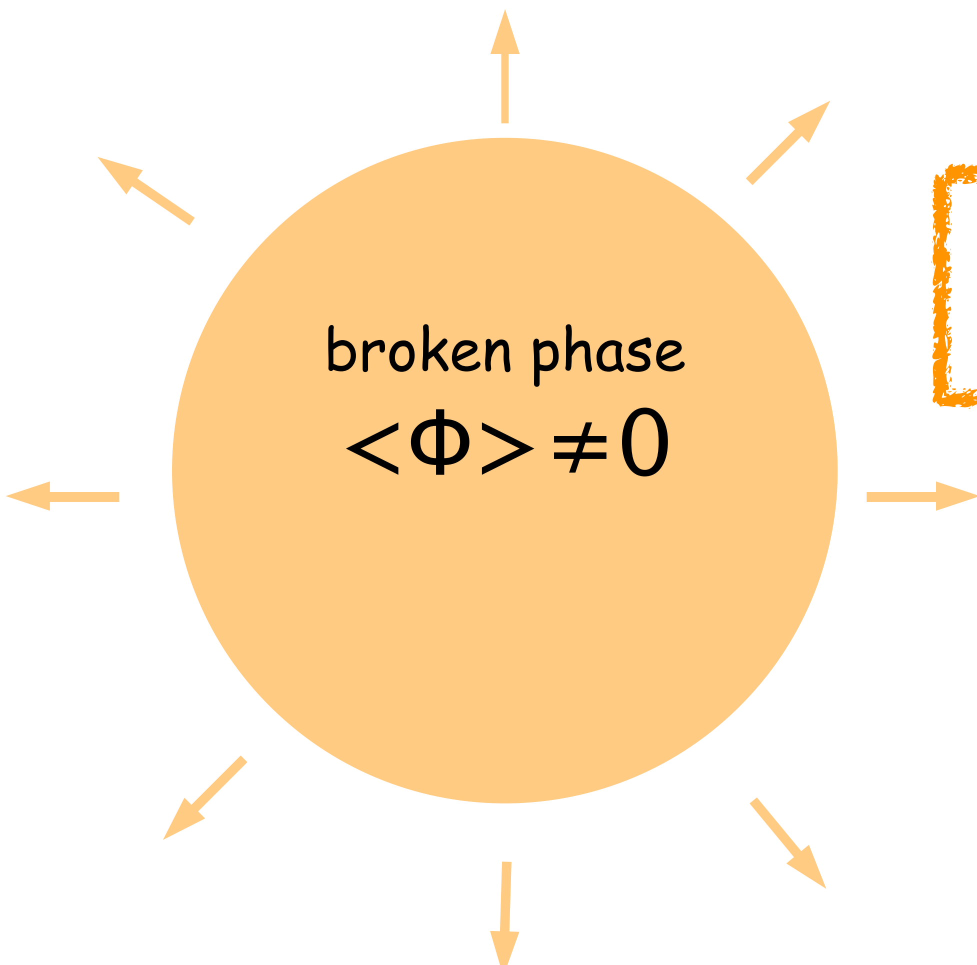
> Framework for EW baryogenesis !

> Stochastic bgd of gravitational waves detectable at LISA !

EW baryogenesis during a first-order EW phase transition

Kuzmin, Rubakov, Shaposhnikov'85

Cohen, Kaplan, Nelson'91



Baryon asymmetry created at vicinity of CP-violating bubble wall.

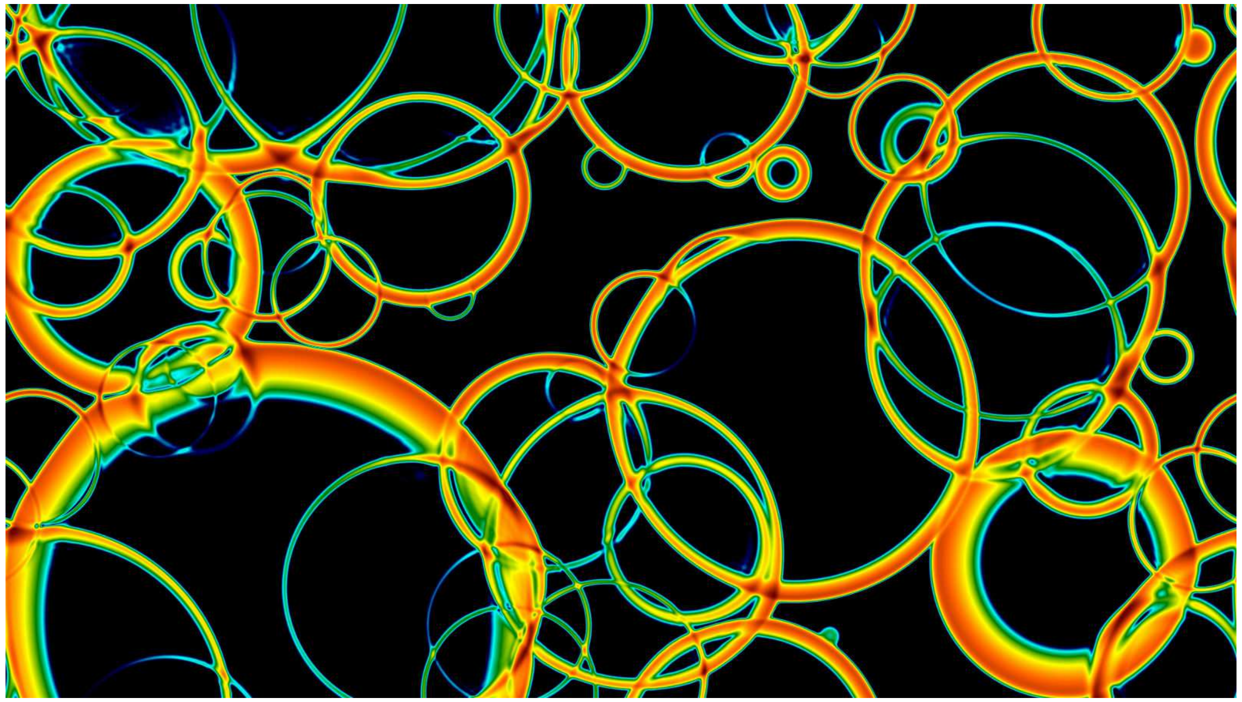
Strength of EW phase transition $\equiv \dfrac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

T_n $\equiv$ **nucleation temperature**

Gravitational Waves from a first-order phase transition .

[LISA Cosmology Working group, 1512.06239]

+ upcoming update 1906.xxxxx



[Credit:David Weir]

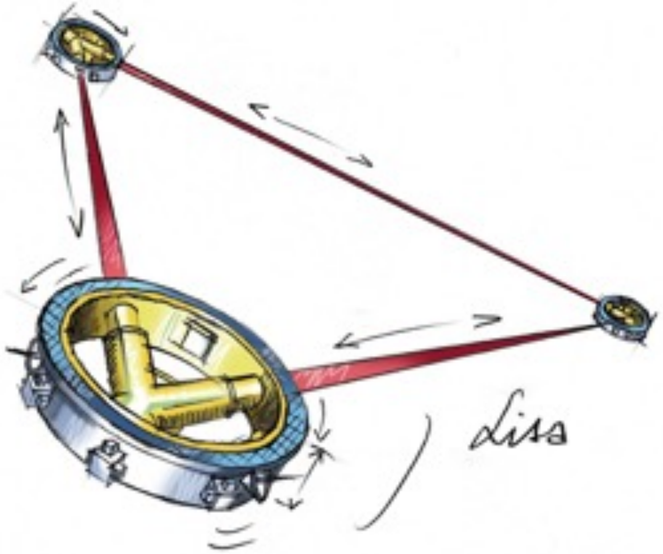
Fluid flows

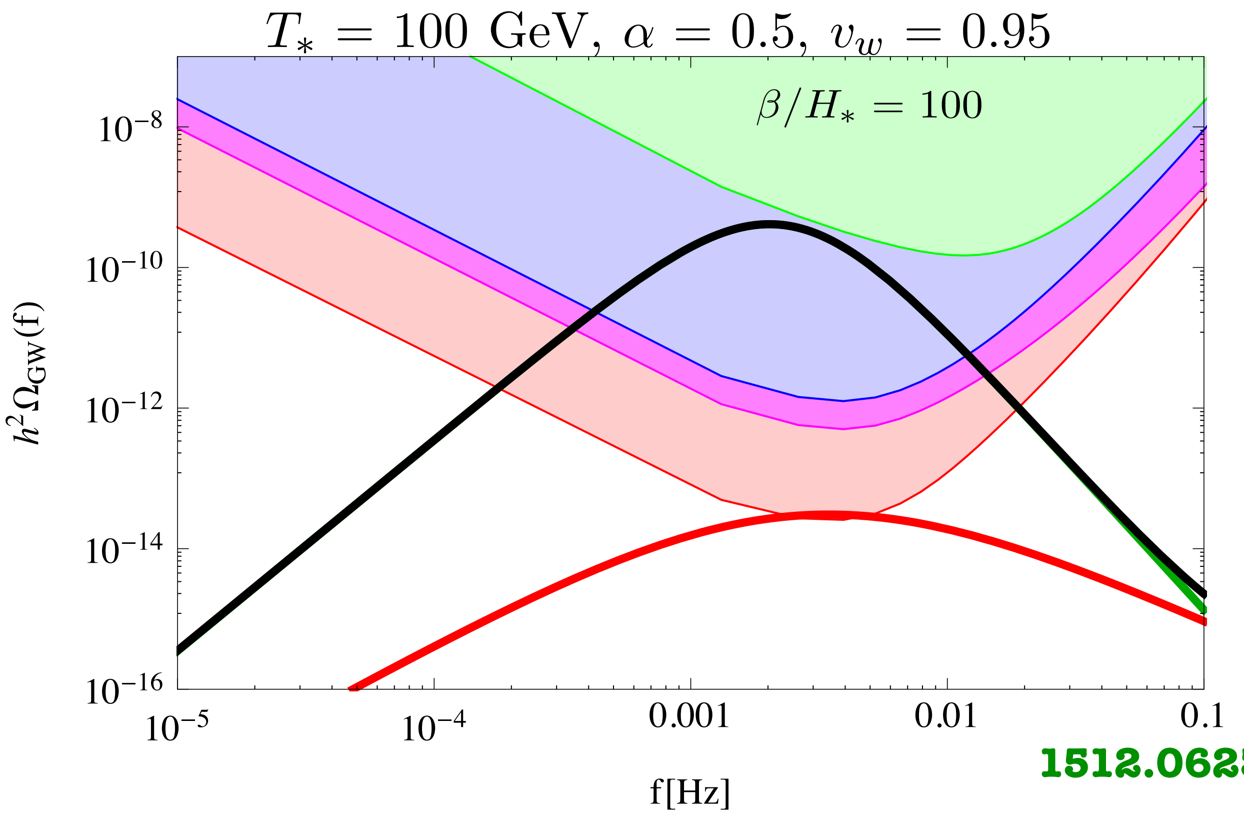
Magnetic fields

Turbulence

Stochastic bgd of gravitational radiation @ mHz

—> LISA !





1512.06239

What makes the EW phase transition 1st-order ?

> O(1) modifications to the Higgs potential

> Extra **EW-scale** scalar(s) coupled to the Higgs

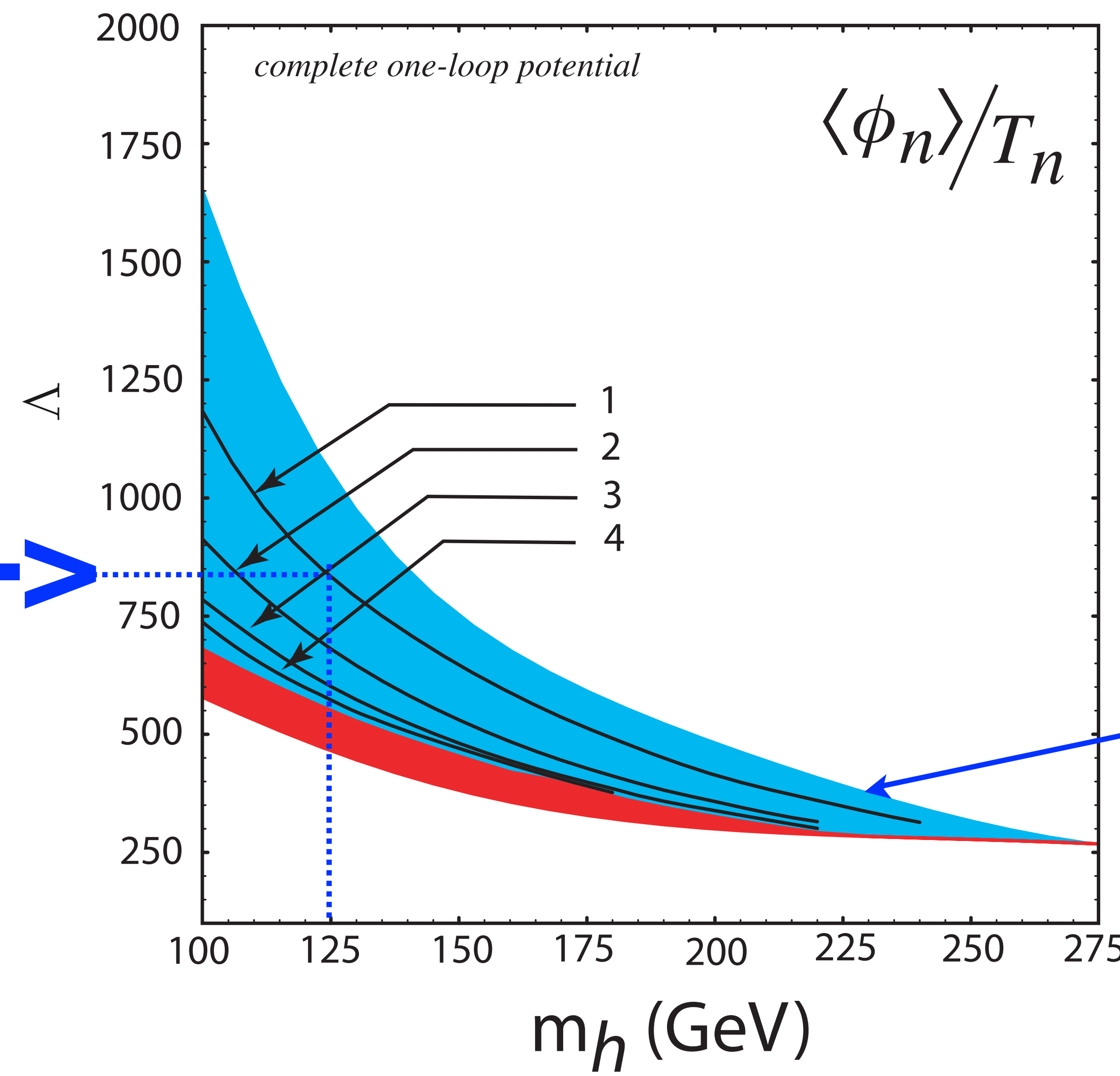
What makes the EW phase transition 1st-order ?

> Extra **EW-scale** scalar(s) coupled to the Higgs

EFT approach to EW phase transition of limited use.

$$V(\phi) = -\mu_h^2|\phi|^2 - \lambda|\phi|^4 + \frac{|\phi|^6}{\Lambda^2}$$

strong enough
for EW baryogenesis
if $\Lambda \lesssim$ 850 GeV



region where EW phase
transition is 1st order

hep-ph/0407019
0711.2511

What makes the EW phase transition 1st-order ?

> Extra **EW-scale** scalar(s) coupled to the Higgs

2 main classes of models

1- Standard polynomial potentials, e.g extra singlet S, 2HDM… under specific choices of parameters.

-Effect of cross-quartic $\lambda_{\phi S}\phi^2 S^2$

-Moderate strength of EW phase transition $\frac{\phi}{T} \lesssim \mathrm{O}(1)$

2- Higgs emerging after confinement phase transition of strongly interacting new sector.

-Higgs potential is trigonometric function

-Fate of the Higgs ruled by the dilaton

-Unbounded strength, $\frac{\phi}{T}$ can naturally be >>1

The most studied case: First-order EW phase transition from an extra scalar singlet .

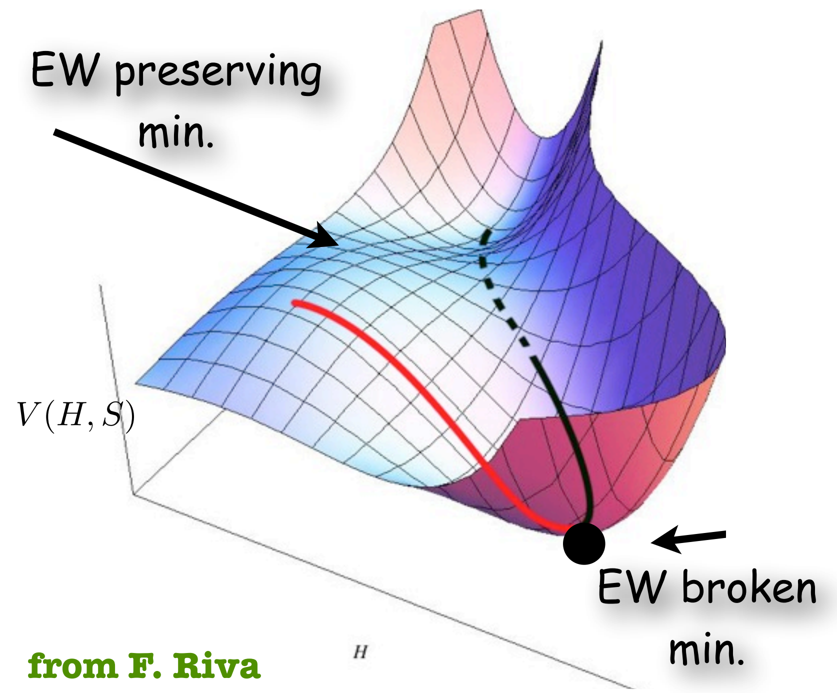
1107.5441

$\mathbf{Z}_2 \qquad s \to -s$

$$V = V^{\rm even} + V^{\rm odd}$$

$$V^{\rm even} \equiv -\mu_h^2|H|^2 + \lambda_h|H|^4 - \frac{1}{2}\mu_s^2 s^2 + \frac{1}{4}\lambda_s s^4 + \frac{1}{2}\lambda_{HS}s^2|H|^2$$

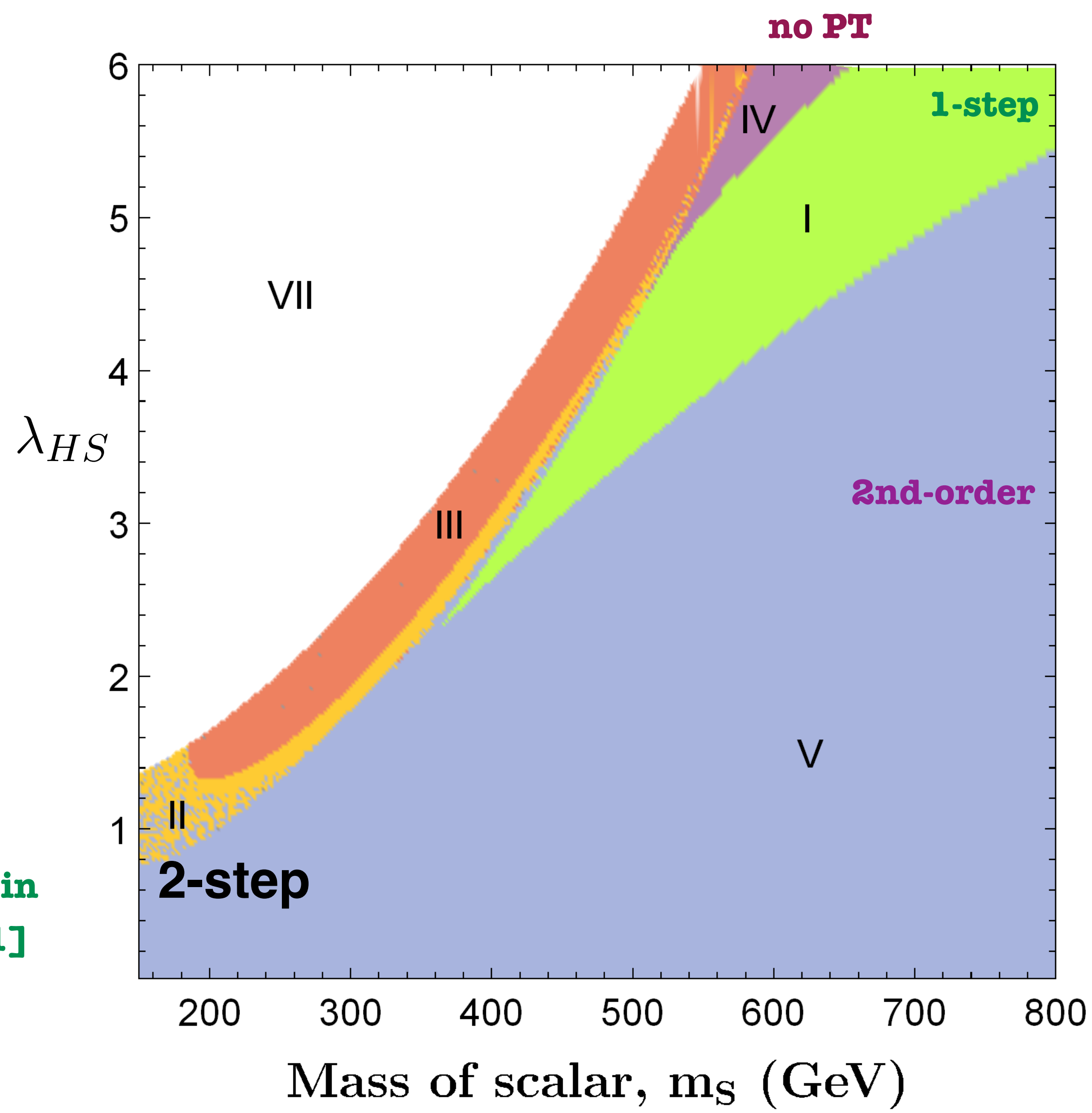
$$V^{\rm odd} \equiv \frac{1}{2}\mu_m s|H|^2 + \mu_1^3 s + \frac{1}{3}\mu_3 s^3$$



- no Z_2 : <s> ≠0 today, H-s mixing —> large modif to higgs self-coupling, LHC tests

- with Z_2 : <s> ~0 today, no mixing —>nightmare scenario

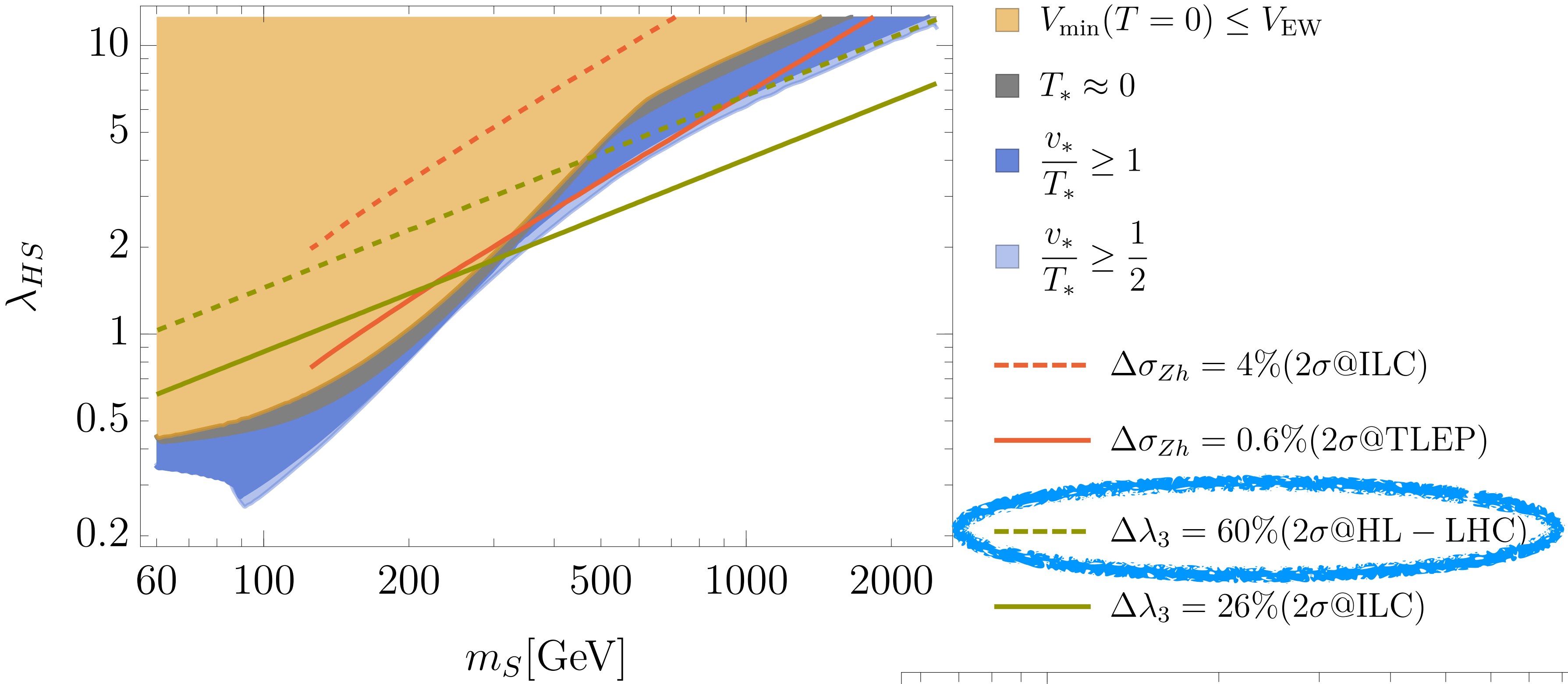
Z_2 case

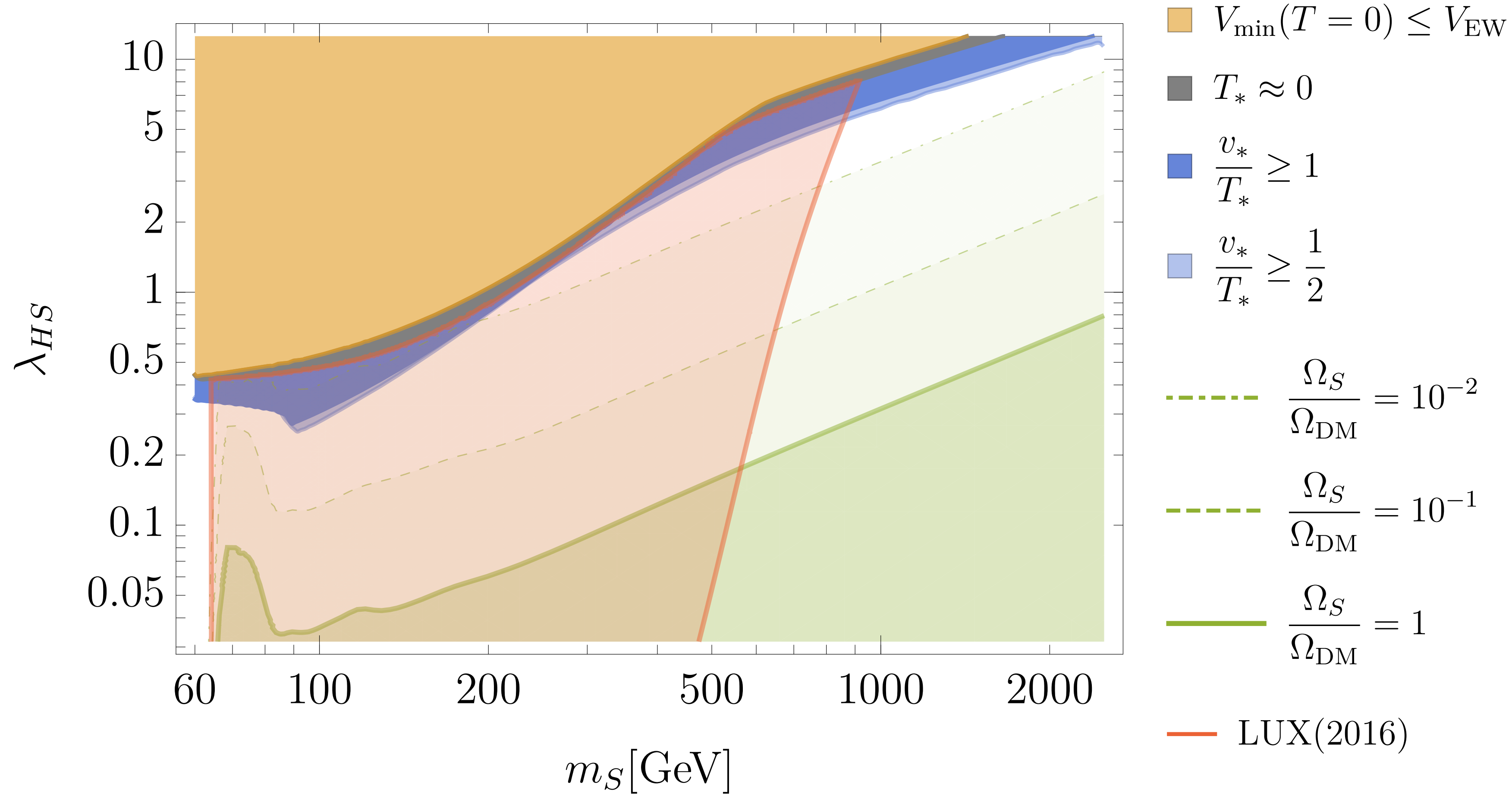


Kurup-Perelstein [1704.03381]

Z_2 case

1702.06124

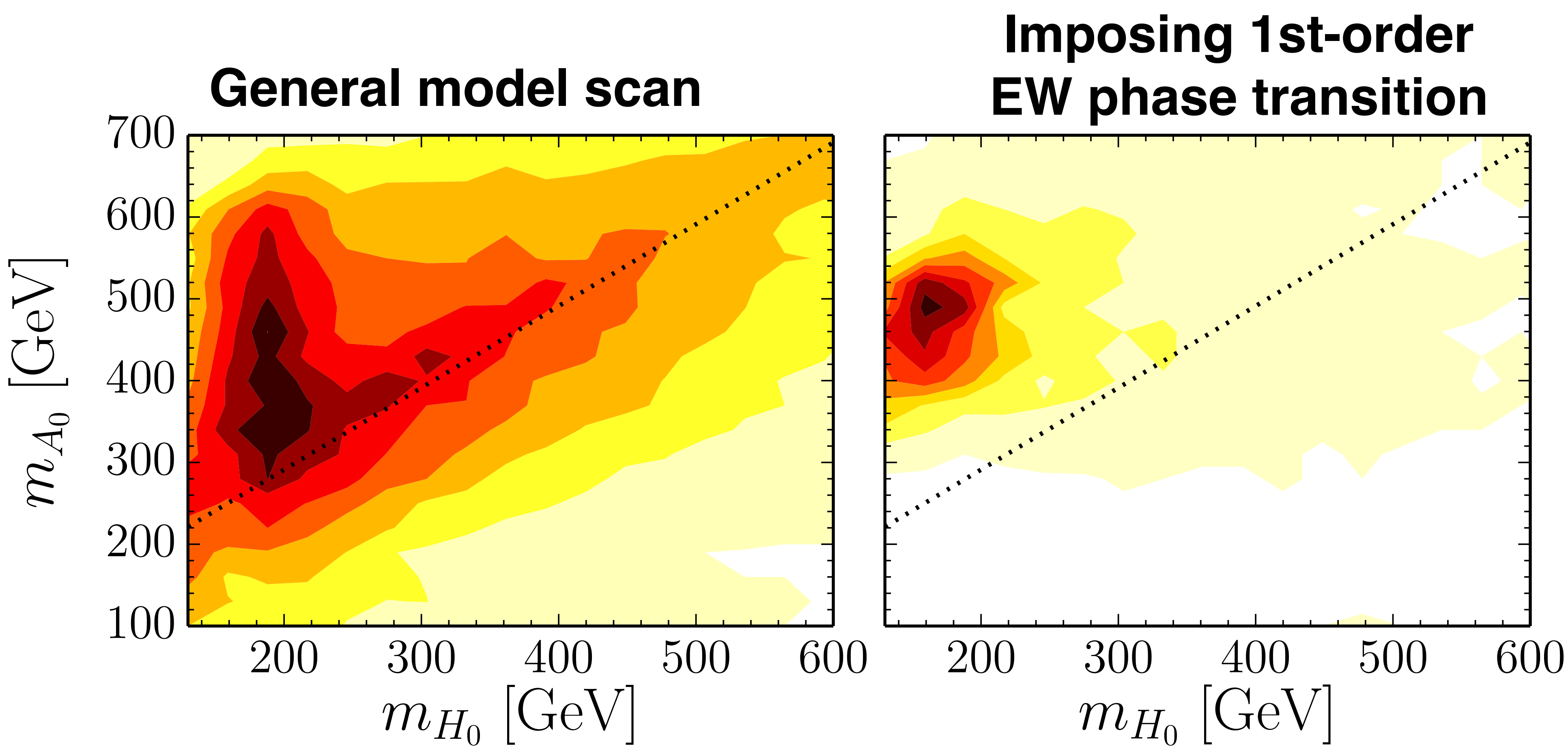




Exact Z2 case mostly excluded by direct DM searches even if S is sub-component (< 1%) of DM .

First-order EW phase transition in a 2-Higgs-doublet model .

Also requires specific parameter region



1405.5537

(type I 2HDM)

EDM threat on EW baryogenesis

$$|d_e| < 1.1 \cdot 10^{-29}\,\mathrm{e} \cdot \mathrm{cm}$$

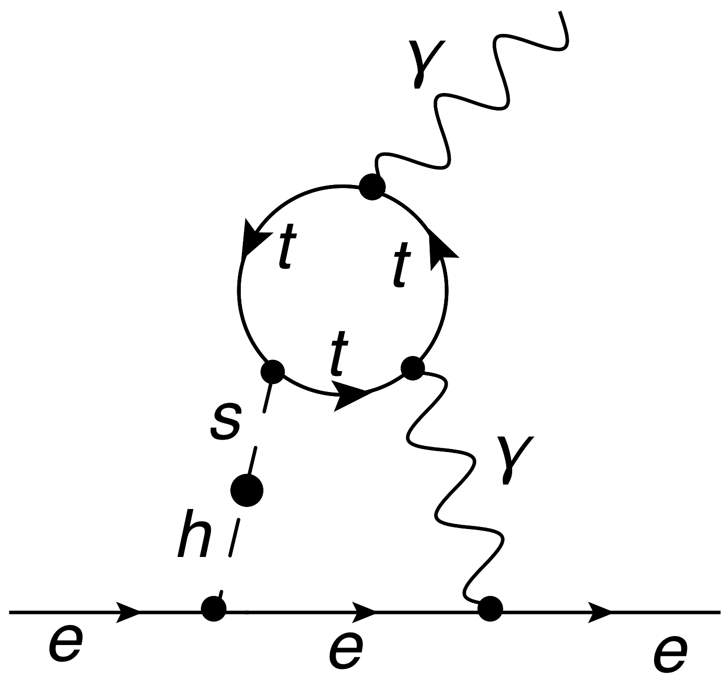
The most shaking news of the last years for EW baryogenesis practitioners!

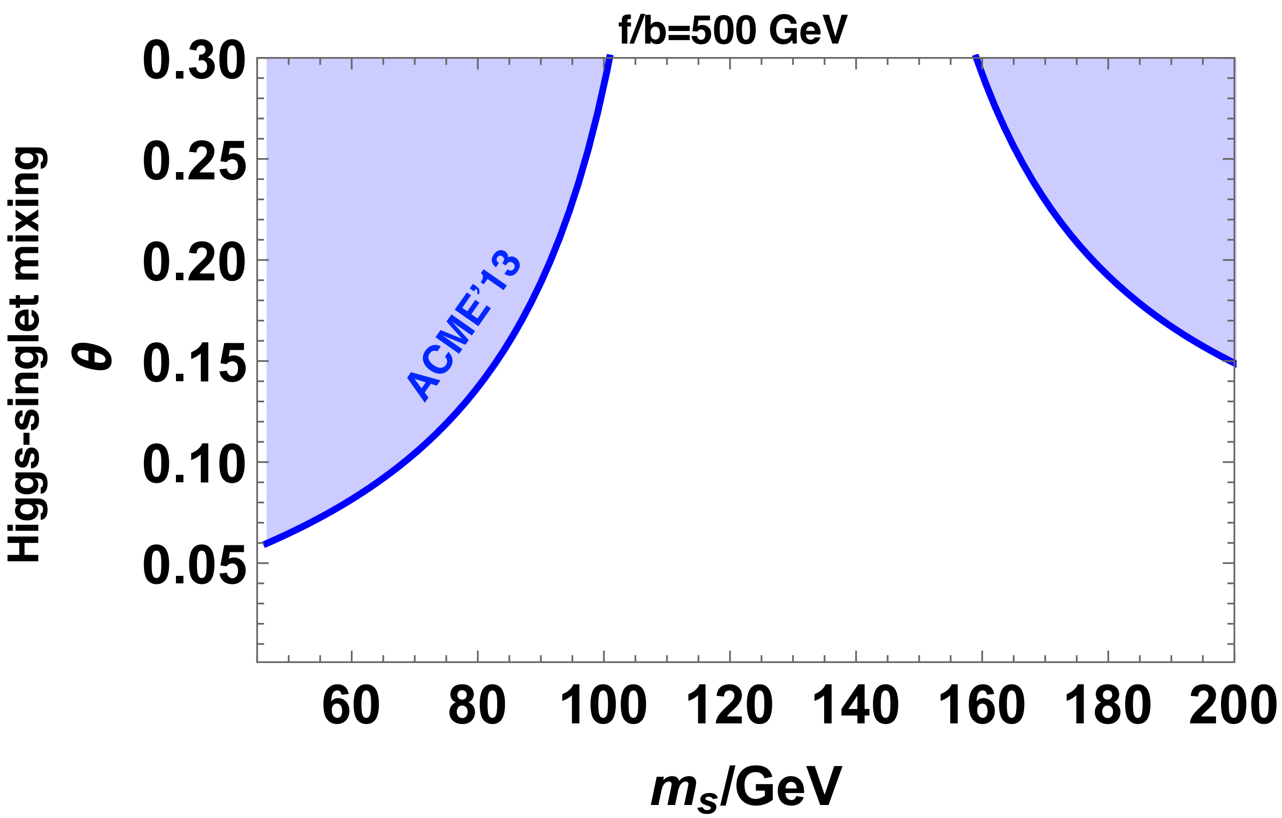
1- EW baryogenesis from extra singlet .

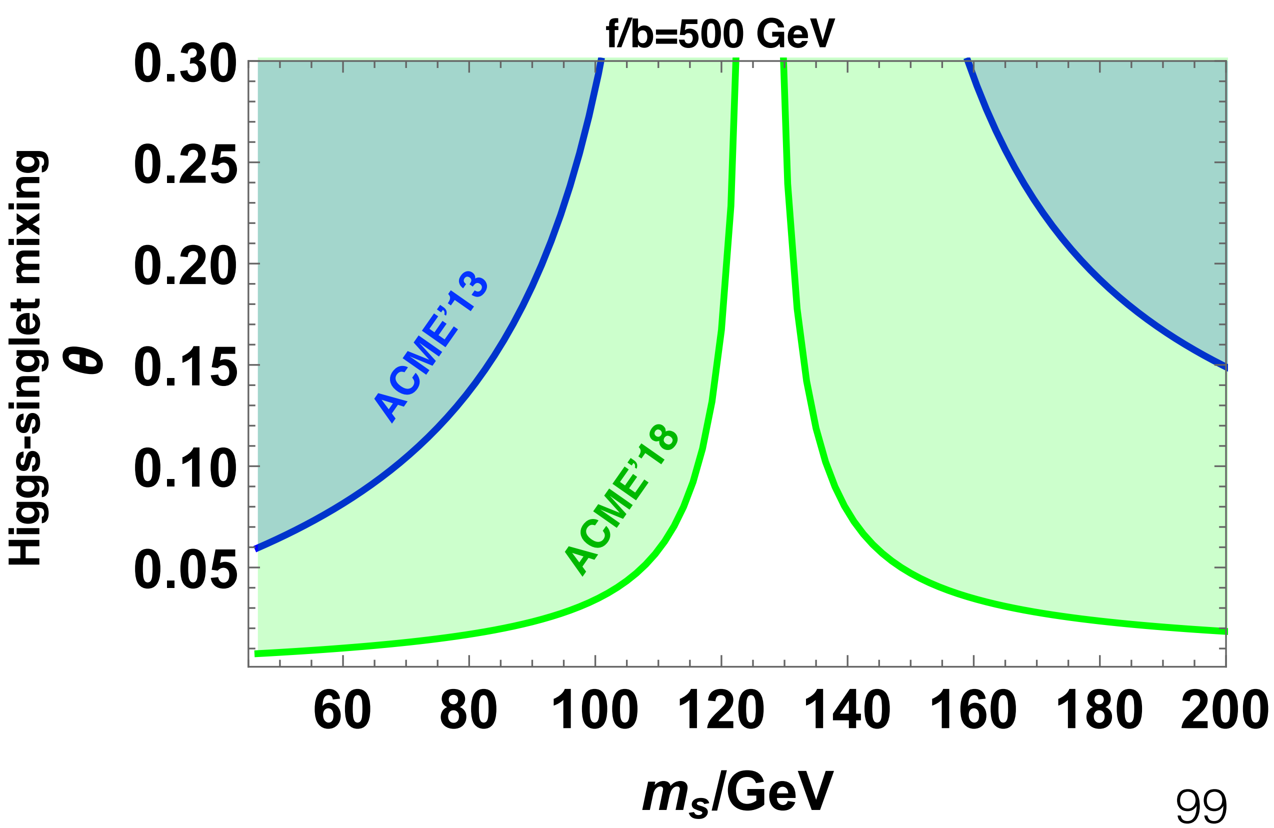
1110.2876

Well-motivated CP source for EW baryogenesis : modified Top-yukawa ("Top-transport" EW baryogenesis)

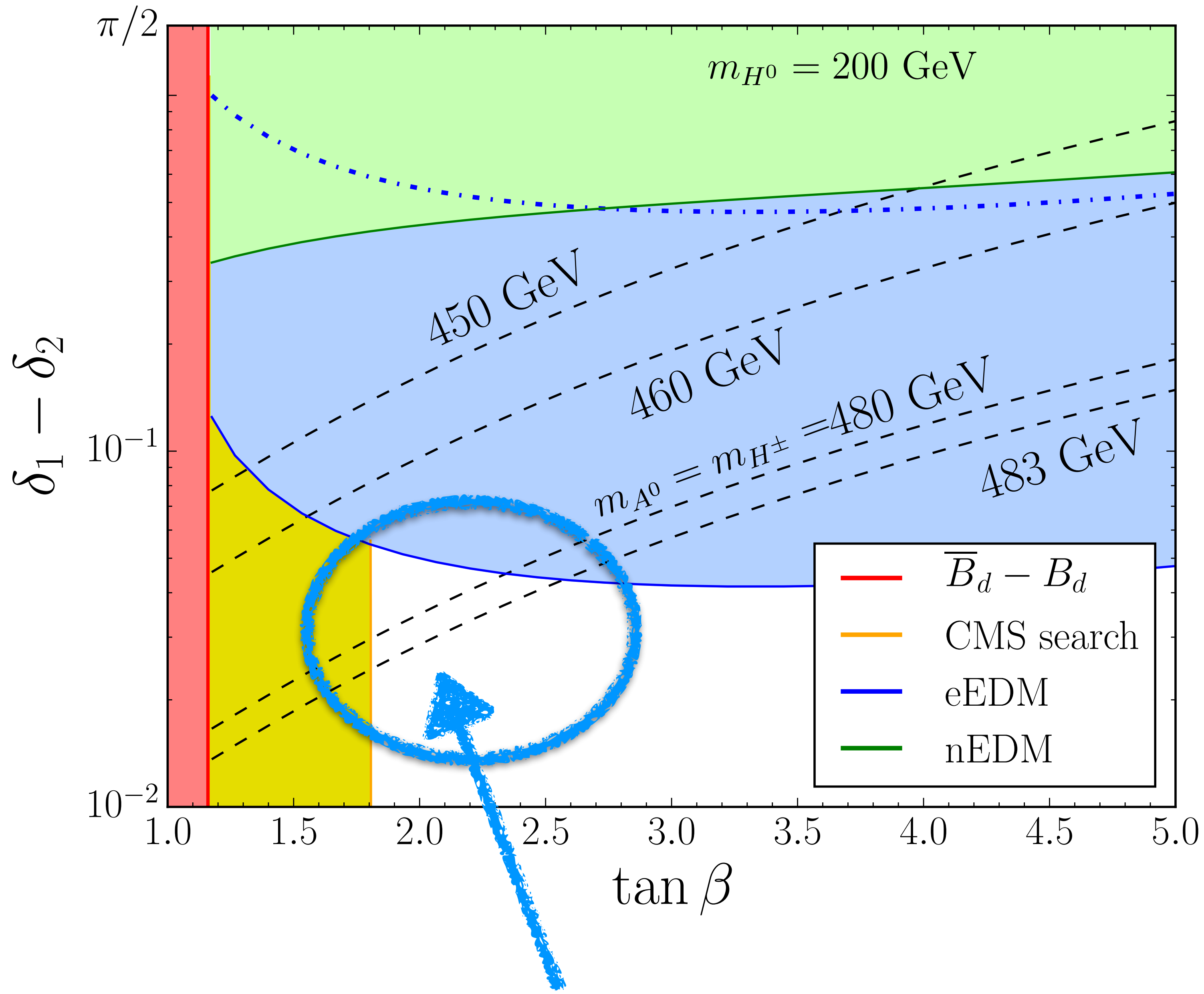
$$\frac{s}{f} H \bar{Q}_3 (a + i b \gamma_5) t + \mathrm{h.c.}$$







2- EW baryogenesis in Two-Higgs-Doublet .



Now excluded

Before ACME 18

[1611.05874]

Summary on minimally extended renormalizable scalar sectors*** .

-1- Faded motivation for EW baryogenesis with top-transport after ACME18

Ways out to evade EDM bounds: Hide $\cancel{CP}$ in leptons, or dark sector

1811.11104, 1903.11255 1811.09719

-2- Still, 1st-order EW phase transition possible

-> LHC & gravitational waves tests.

*** (Both S and 2HDM well-motivated in non-minimal Composite Higgs models)

EW Phase transition in Composite Higgs Models

EW phase transition in Composite Higgs models .

> Higgs potential emerges at E≲f .

For PNGB: $$V_h \sim f^4 \left[\alpha \sin^2\left(\frac{h}{f}\right) + \beta \sin^4\left(\frac{h}{f}\right)\right]$$

f~O(TeV): confinement scale of new strongly interacting sector, described by VEV of dilaton field <χ>, Pseudo-Nambu-Goldstone Boson of spontaneously broken conformal symmetry of the strong sector

$$V = V_\chi(\chi) + V_h(\chi, h)$$

intertwinned dynamics

χ dominates the dynamics

$$\boxed{V(\chi) = \chi^4 \times f(\chi^\epsilon)}$$

|ε|<<1

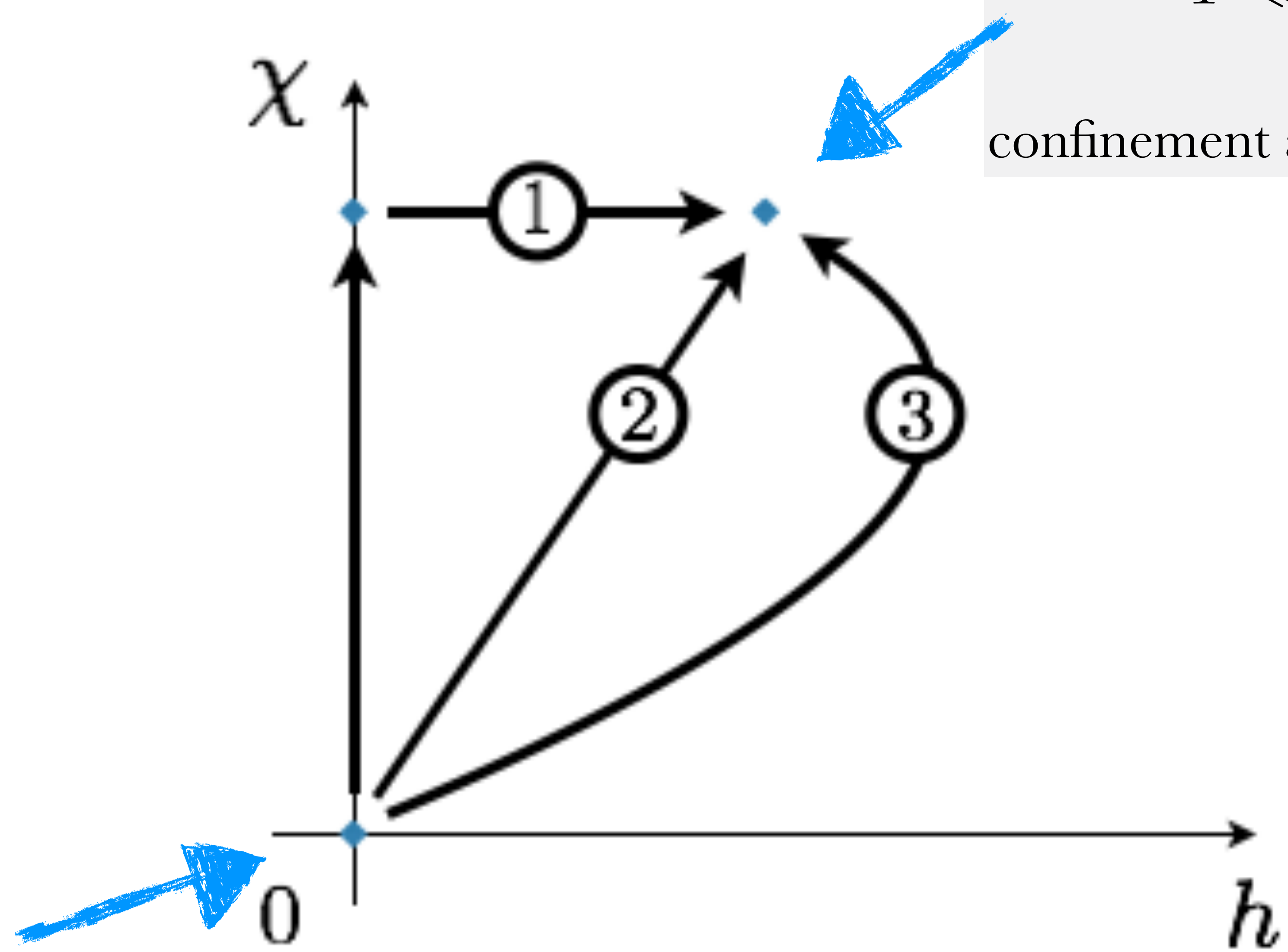
Nearly conformal potential : T_n << f , SUPERCOOLING

Higgs-dilaton intertwinned dynamics

Which path?

global minimum at
$T \ll f$

confinement and EWSB



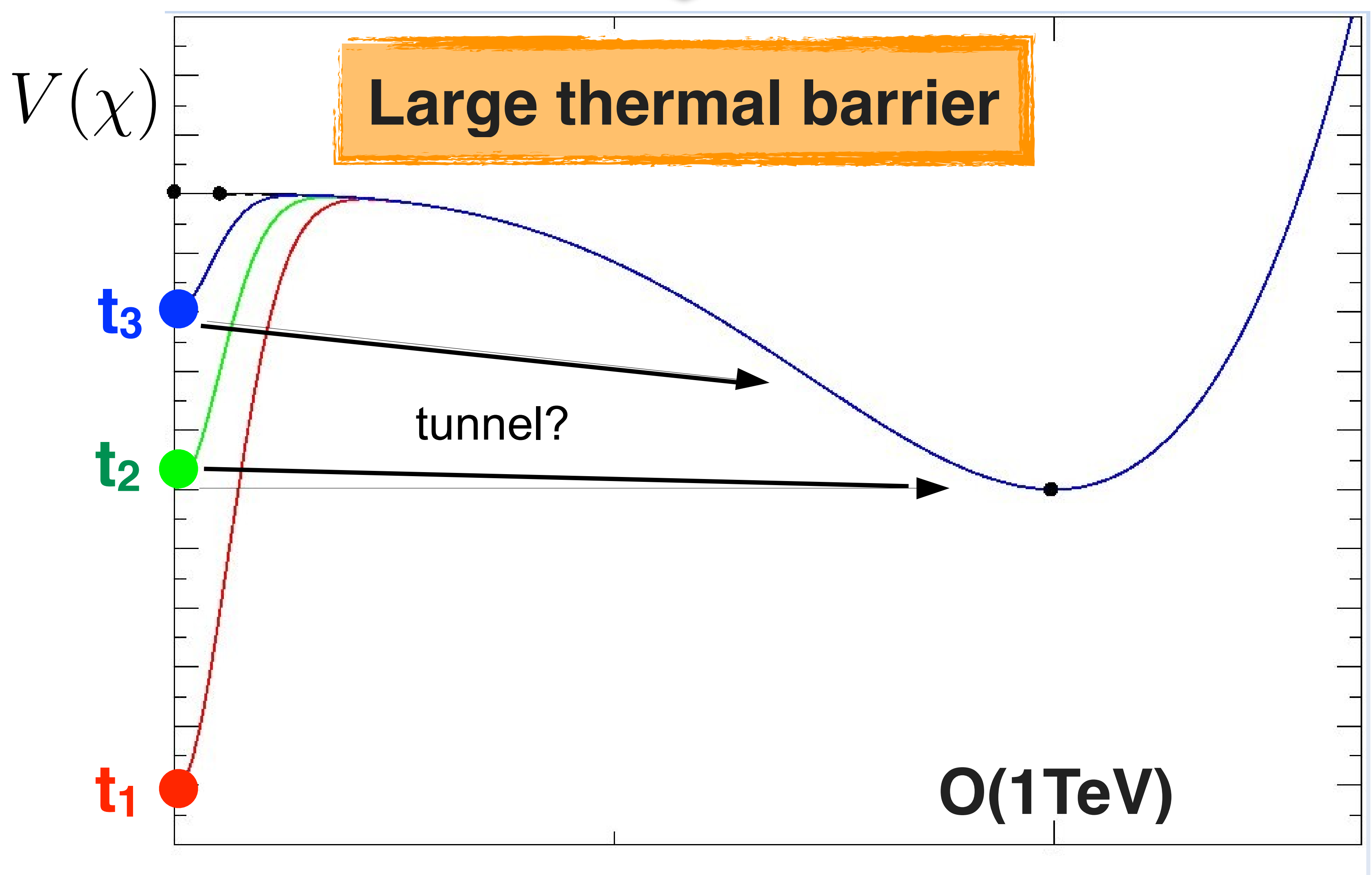
global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

1803.08546 ,1804.07314

Strongly 1st order TeV scale confinement phase transition

Large number of massless dof in deconfined phase **+** Shallow (nearly conformal) potential at T=0 with TeV minimum



Supercooled confinement phase transition

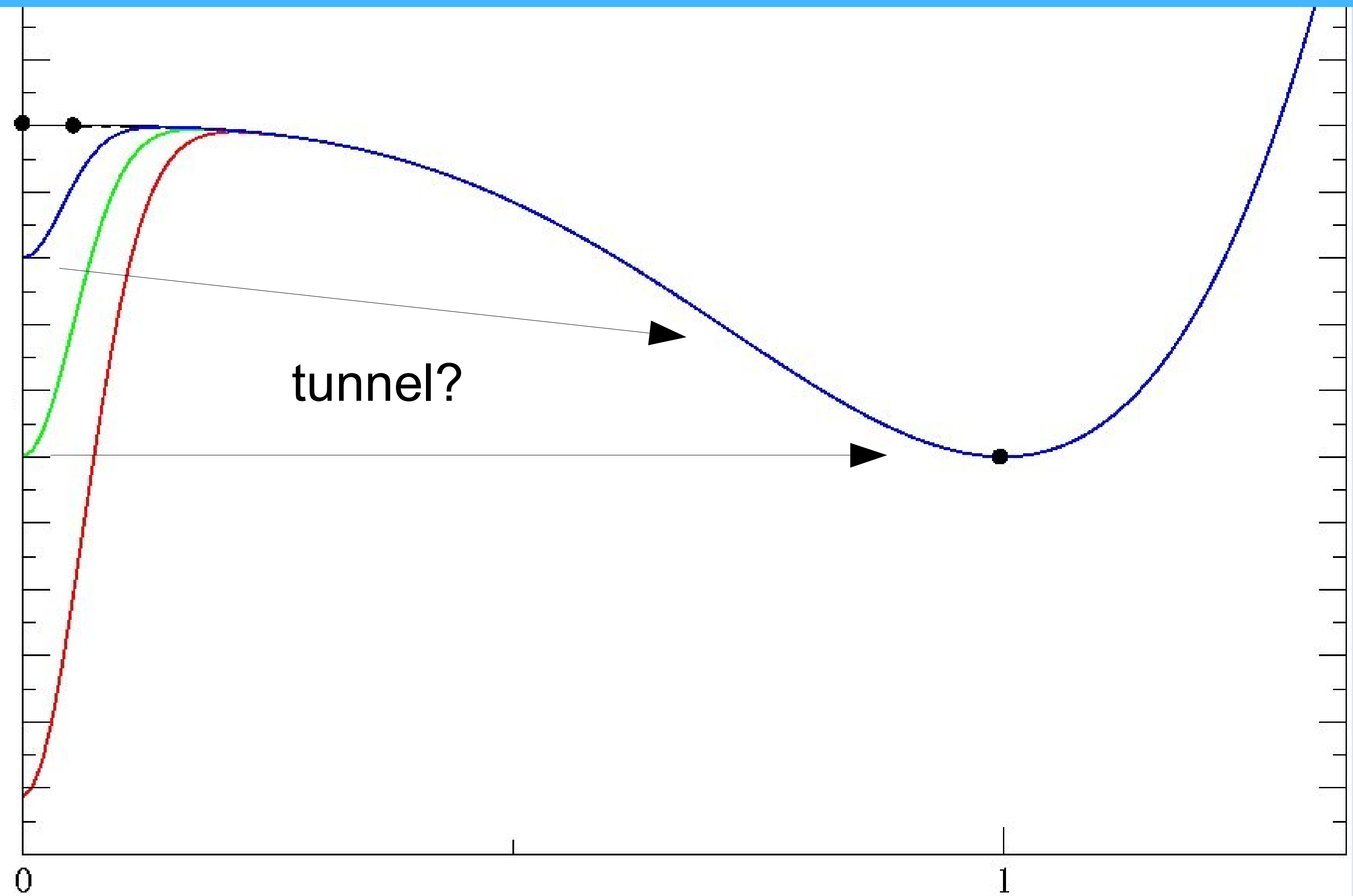
Strongly 1st order TeV scale confinement phase transition .

Nearly-conformal potential with TeV minimum

+

large number of CFT states

supercooled confinement phase transition



Creminelli, Nicolis, Rattazzi'01
Randall, Servant'06
Hassanain, March-Russell, Schwellinger'07
Nardini,Quiros,Wulzer'07
Konstandin,Servant'11
Konstandin,Nardini,Quiros'10
Bunk, Hubisz, Jain'17
Dillon, El-Menoufi,Huber,Manuel'17
VonHarling,Servant'17
Megias, Nardini, Quiros' 18
Bruggisser, VonHarling, Matsedonskyi, Servant'18
Baratella, Pomarol, Rompineve'18

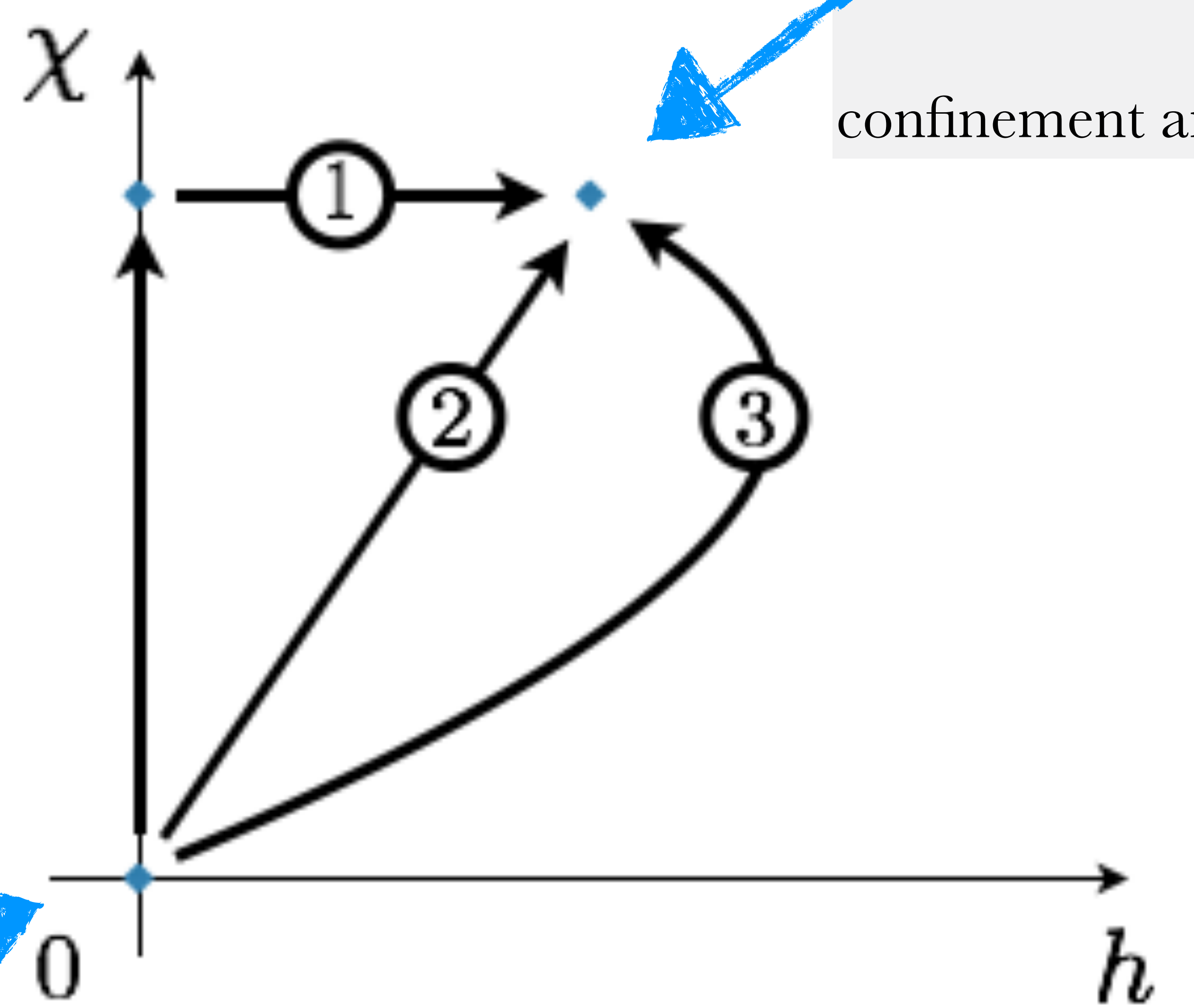
Impact on EW phase transition in Composite Higgs.

global minimum at
$T \ll f$

confinement and EWSB

(1) SM-like EW phase transition

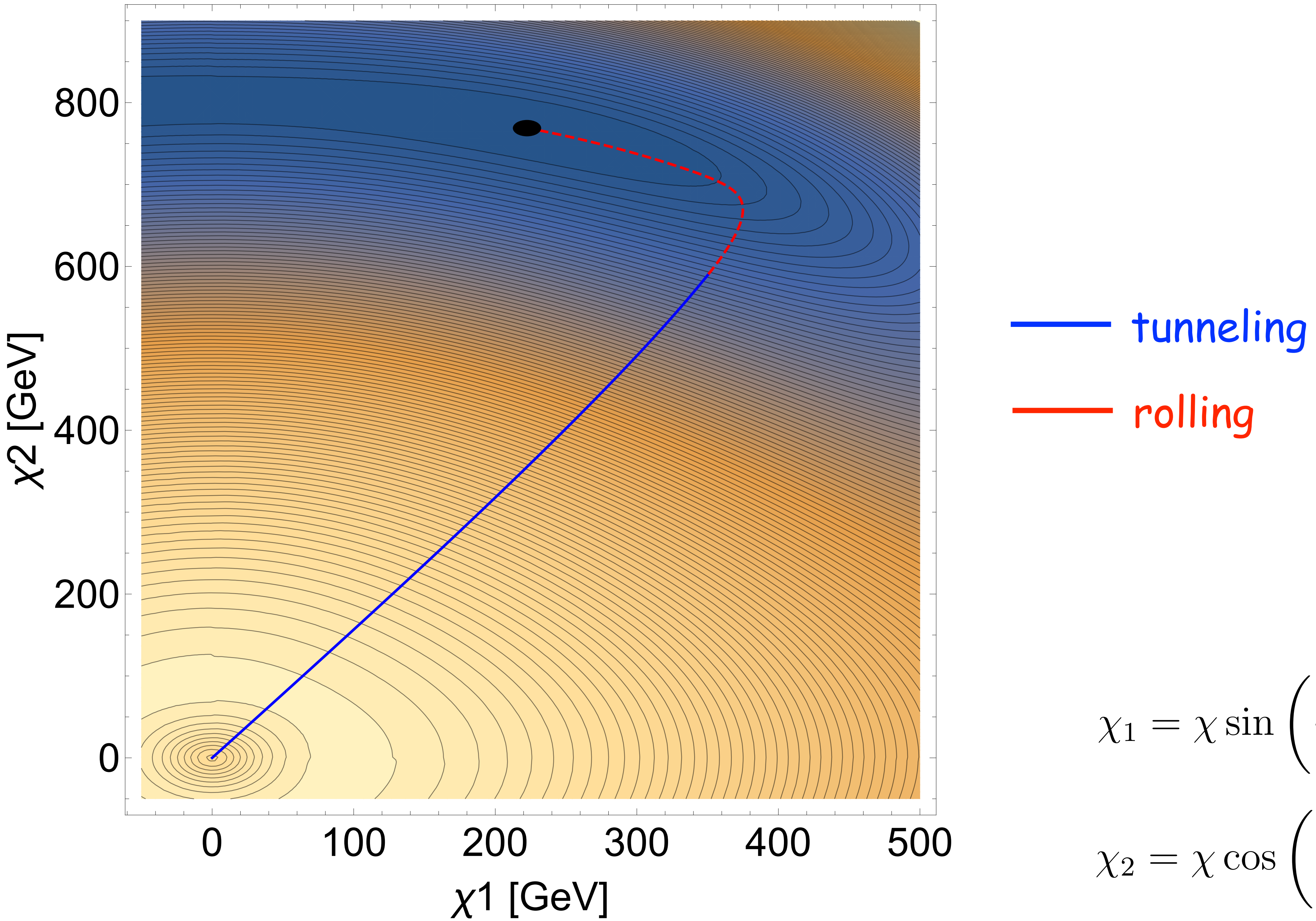
(2)-(3) Joint confinement-EW phase transitions: very rich pheno for EW baryogenesis



global minimum at
$T \gg f$

deconfined strong sector
unbroken EW symmetry

Which tunneling trajectory ?



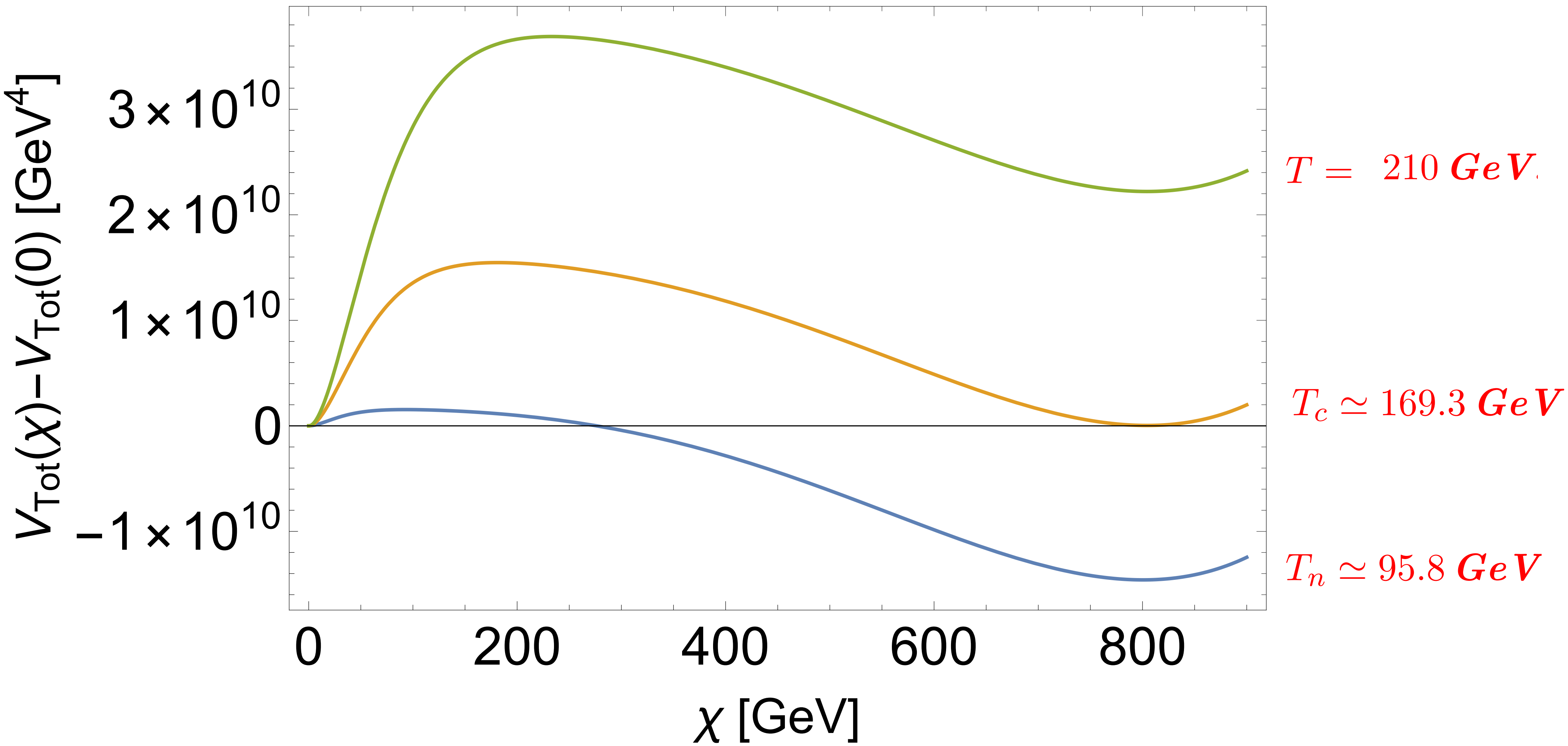
$$\chi_1 = \chi \sin\left(\frac{h}{\chi}\right)$$

$$\chi_2 = \chi \cos\left(\frac{h}{\chi}\right)$$

1804.07314

1strst-order EW phase transition

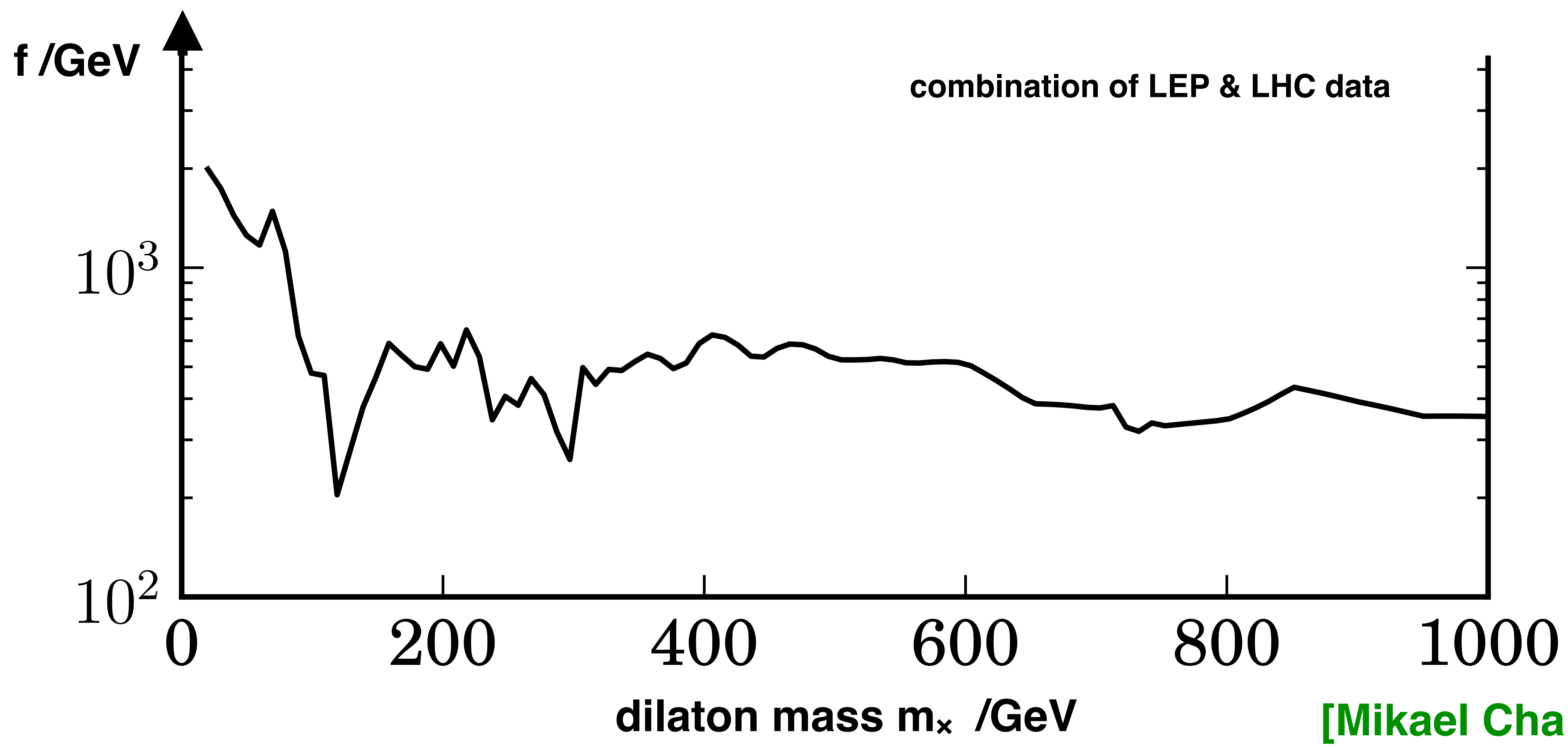
Potential along the straight line trajectory:



1804.07314

Collider bounds on dilaton

Higgs-like couplings suppressed by v/f



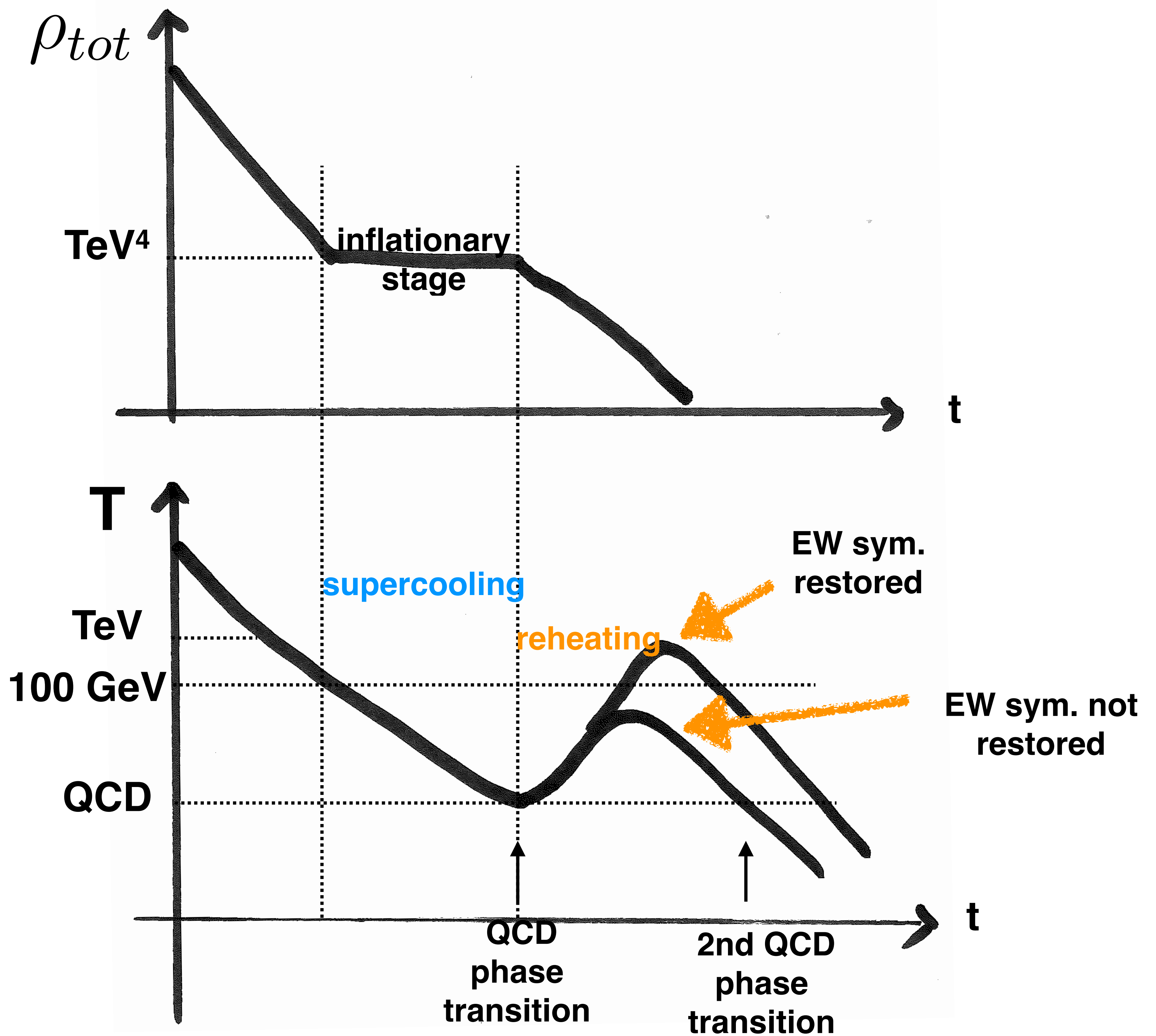
[Mikael Chala,
using HiggsBounds]

Other signatures: δg_{hhh} , δg_{Vhh} , δg_{htt} , $\delta g_{\chi tt}$

from Higgs-dilaton mixing

Supercooled EW Phase transition down to QCD temperatures.

Supercooled EW phase transition induced by TeV-scale confinement phase transition .



Implications:

-> Cold EW baryogenesis using strong CP from QCD axion

1407.0030

-> Modified QCD axion relic abundance

1711.11554
1812.06996

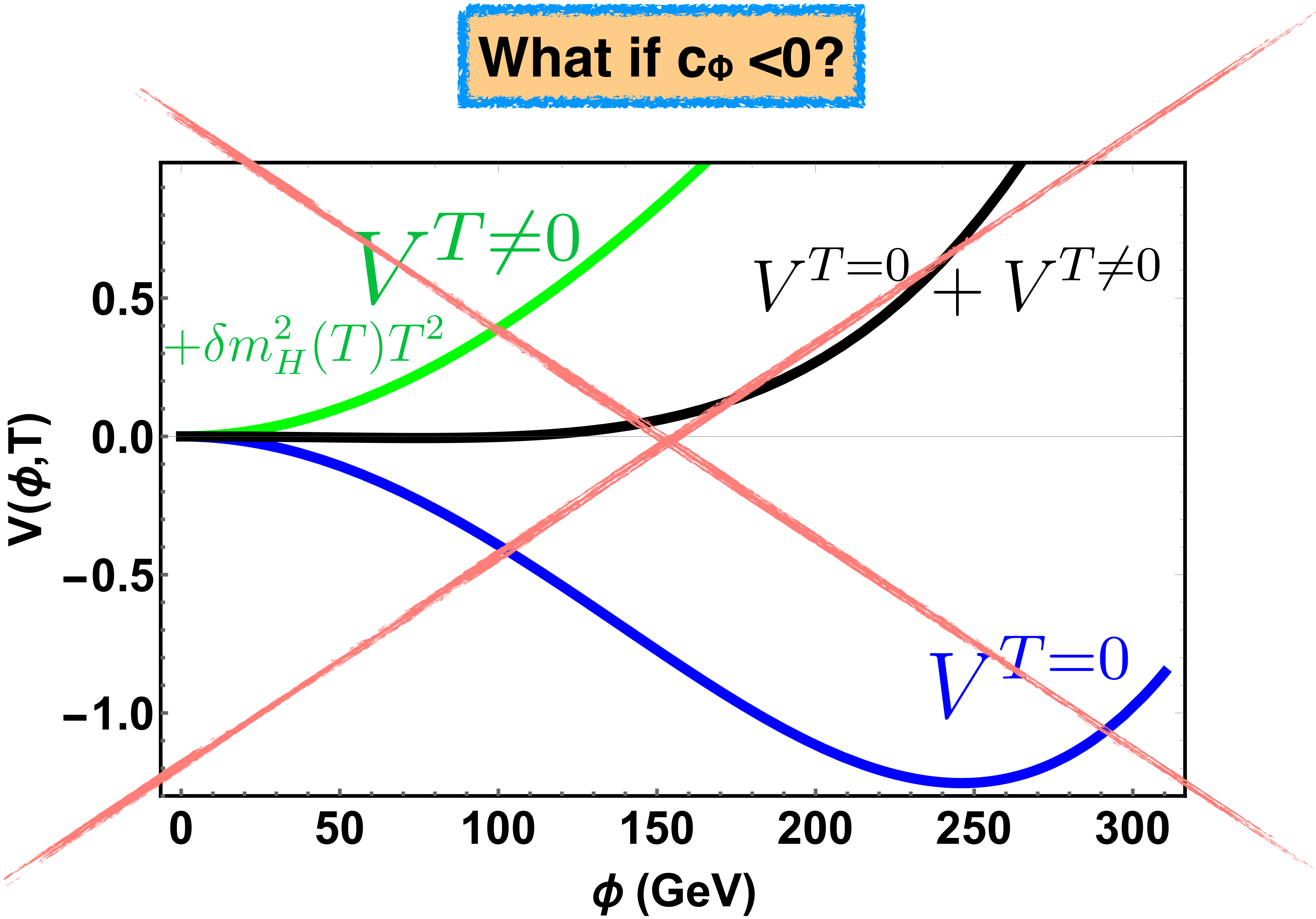
High-temperature EW symmetry non-restoration

HIGH TEMPERATURE EW SYM. RESTORATION.

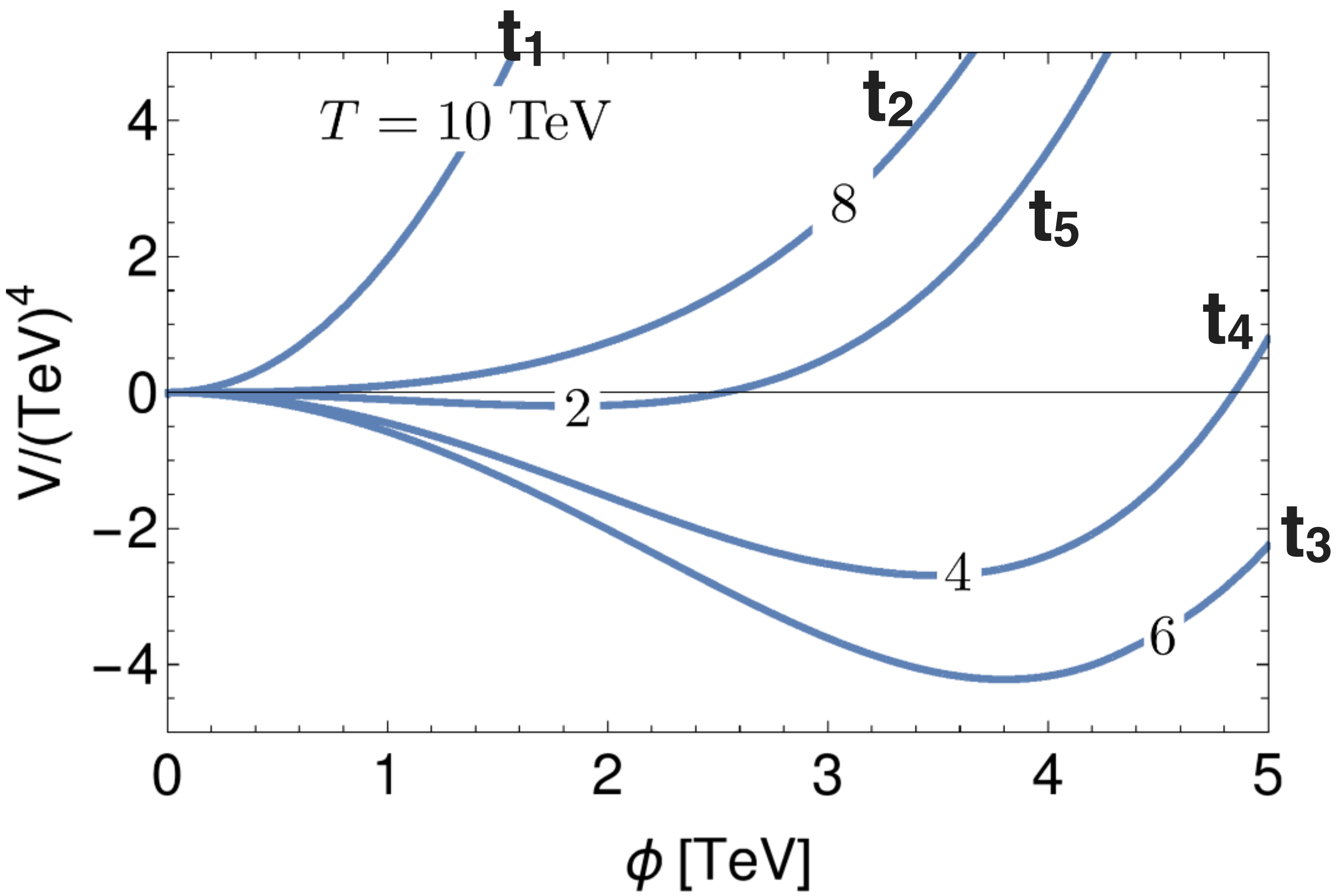
EW Symmetry restoration comes from the competition of two opposite terms in Higgs mass parameter

$$\mu_\phi{}^2(\mathrm{T}) \sim -\mu_\phi^2 + c_\phi T^2$$

What if $c_\phi < 0$?



High-scale (T>TeV) EW phase transition .

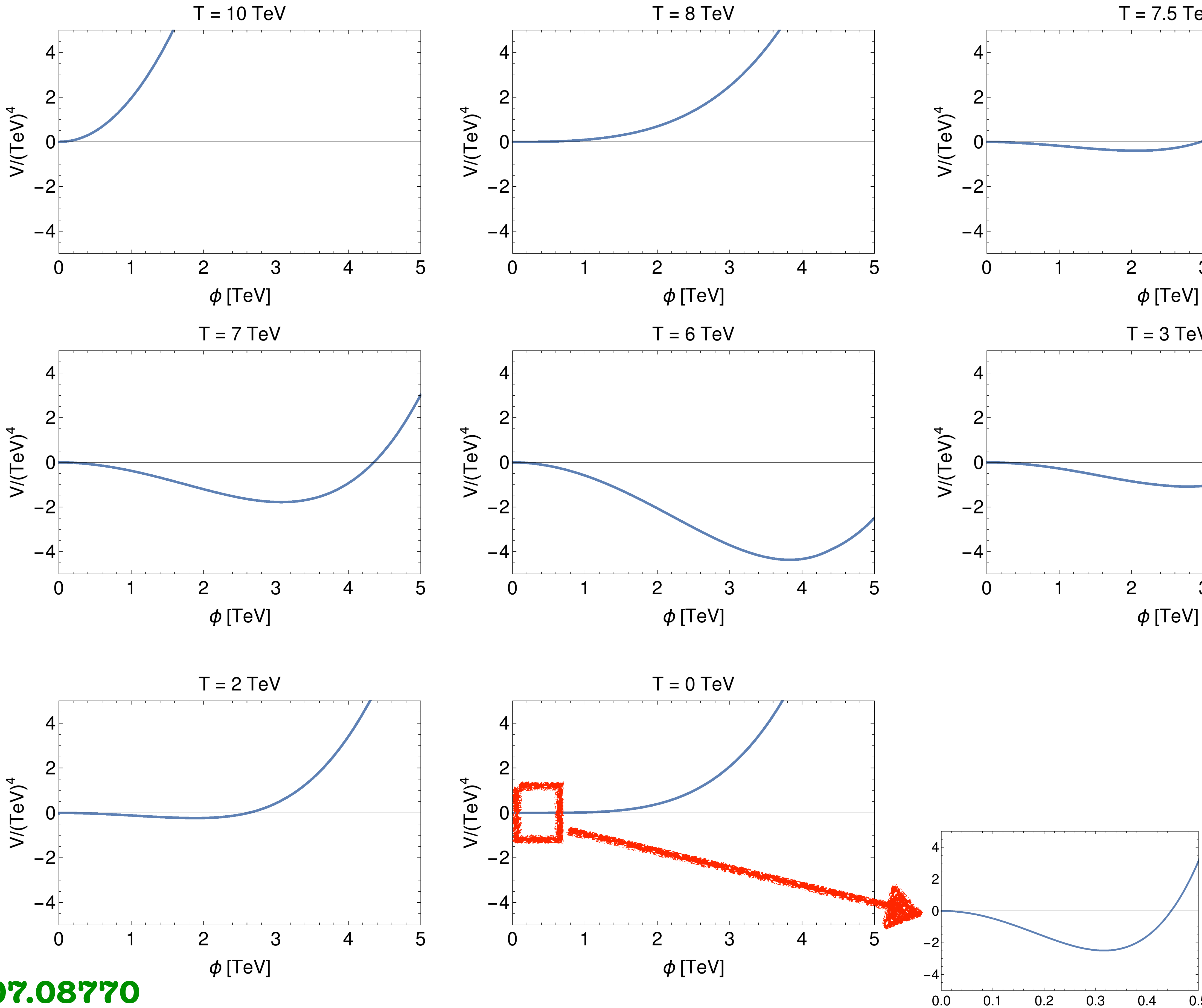


> **Motivation: EW baryogenesis using high-scale sources of CP violation, allowed by data !**

> **Prediction: Large number of new weak-scale (m<~300 GeV) scalars !**

Testable?...

High-scale (T>TeV) EW phase transition



1807.08770

EW symmetry non-restoration at T>M_H

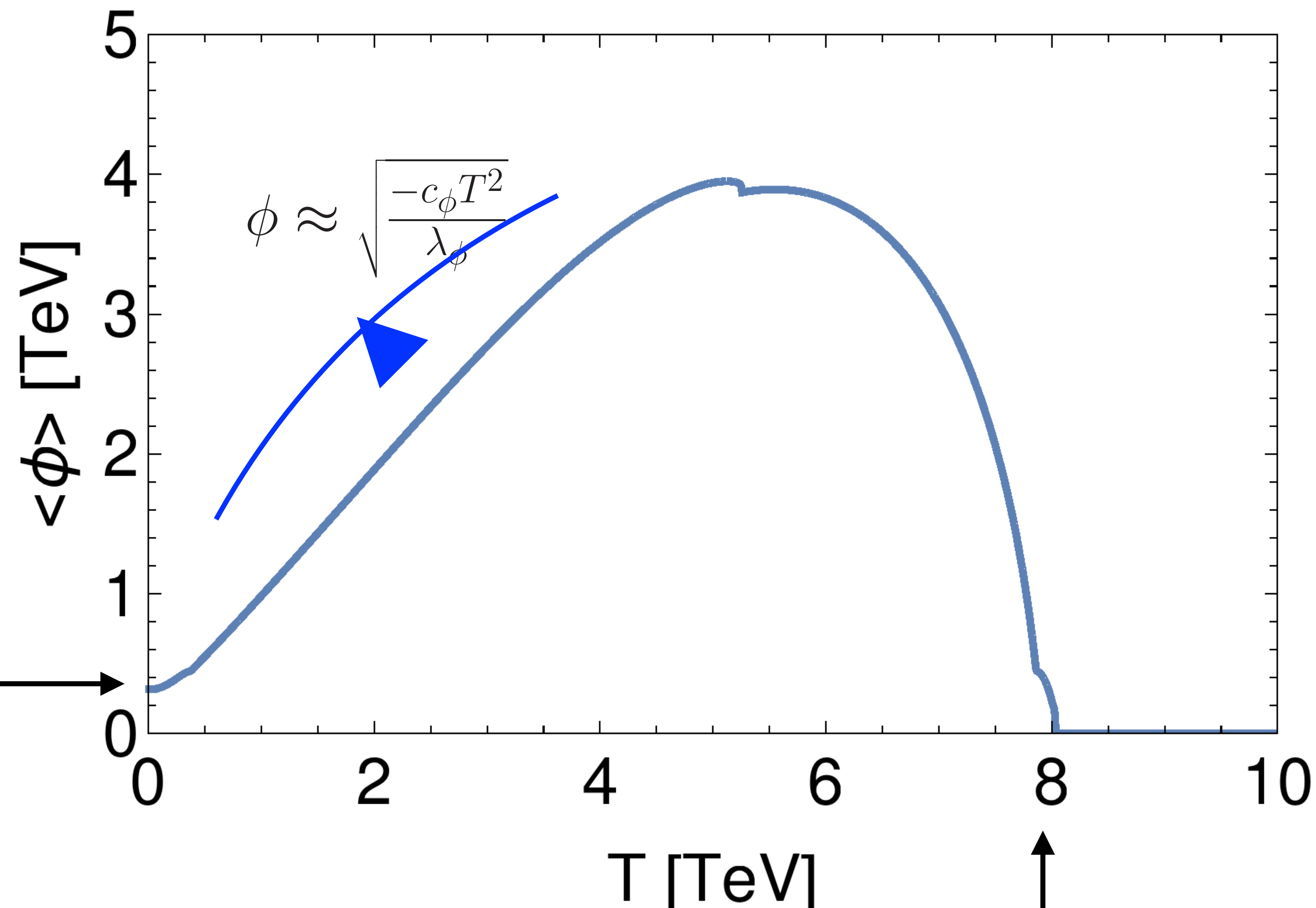
1807.07578
1807.08770
1811.11740

$$\mu_\phi^2(T) \sim -\mu_\phi^2 + \underbrace{c_\phi T^2}_{<\,0}$$

Negative thermal mass!

from negative Higgs cross-quartic coupling to large number of extra scalars χ

$\phi \approx \sqrt{\frac{-\mu_\phi^2}{\lambda_\phi}}$

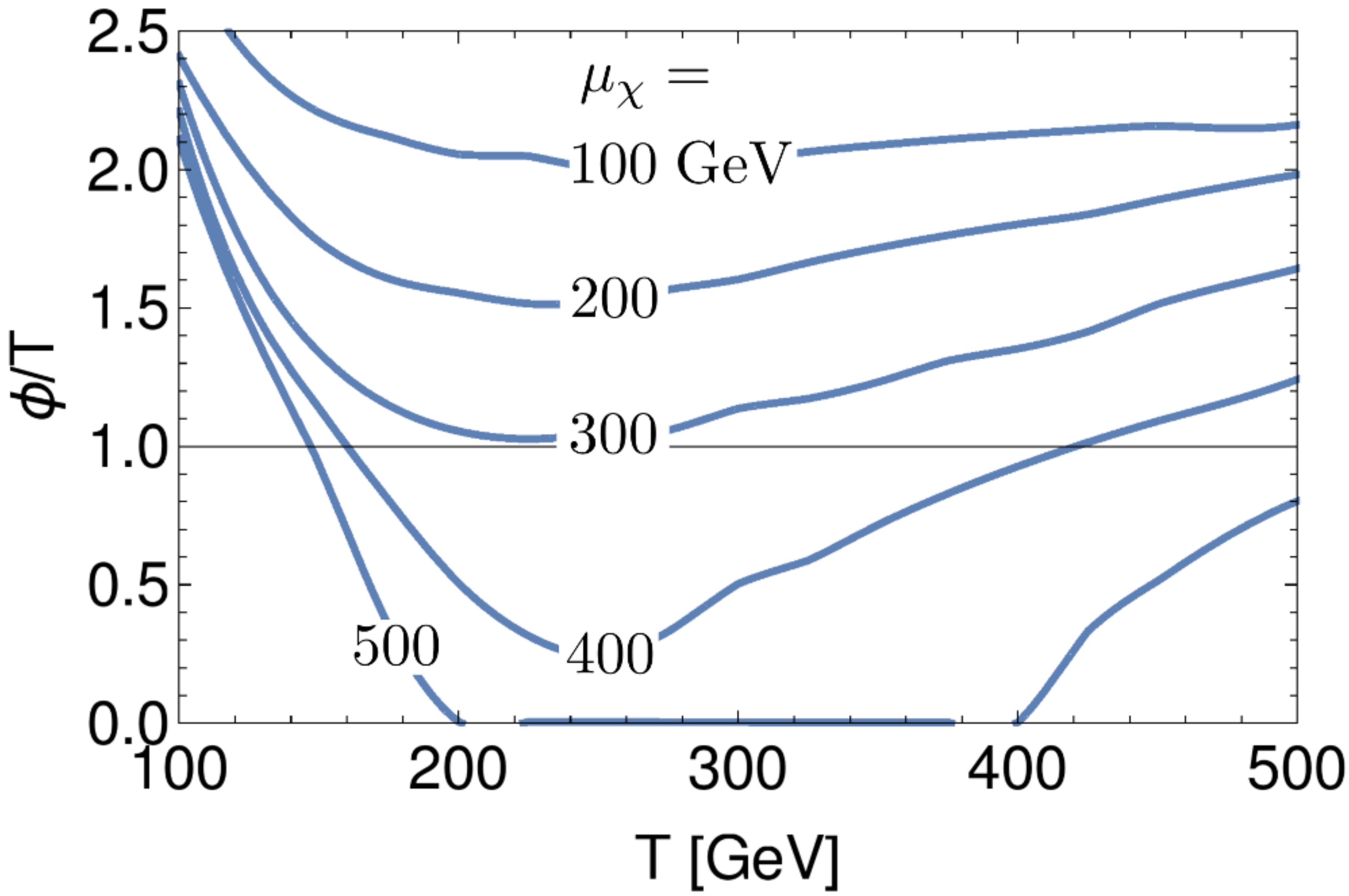


μ_S

$$c_\phi T^2 \approx \begin{cases} \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24} + N_S \frac{\lambda_{\phi S}}{24}\right) T^2 & \textbf{> 0} \quad \text{for } T \gtrsim \mu_S, \\ \left([N_\phi + 2]\,\frac{\lambda_\phi}{12} + N_\chi \frac{\lambda_{\phi\chi}}{24}\right) T^2 & \textbf{< 0} \quad \text{for } T \lesssim \mu_S. \end{cases}$$

< 0

χ's should be lighter than 300 GeV to avoid sphaleron washout of baryon asymmetry!



1807.08770

High-scale EW phase transition from new EW-scale singlet fermions .

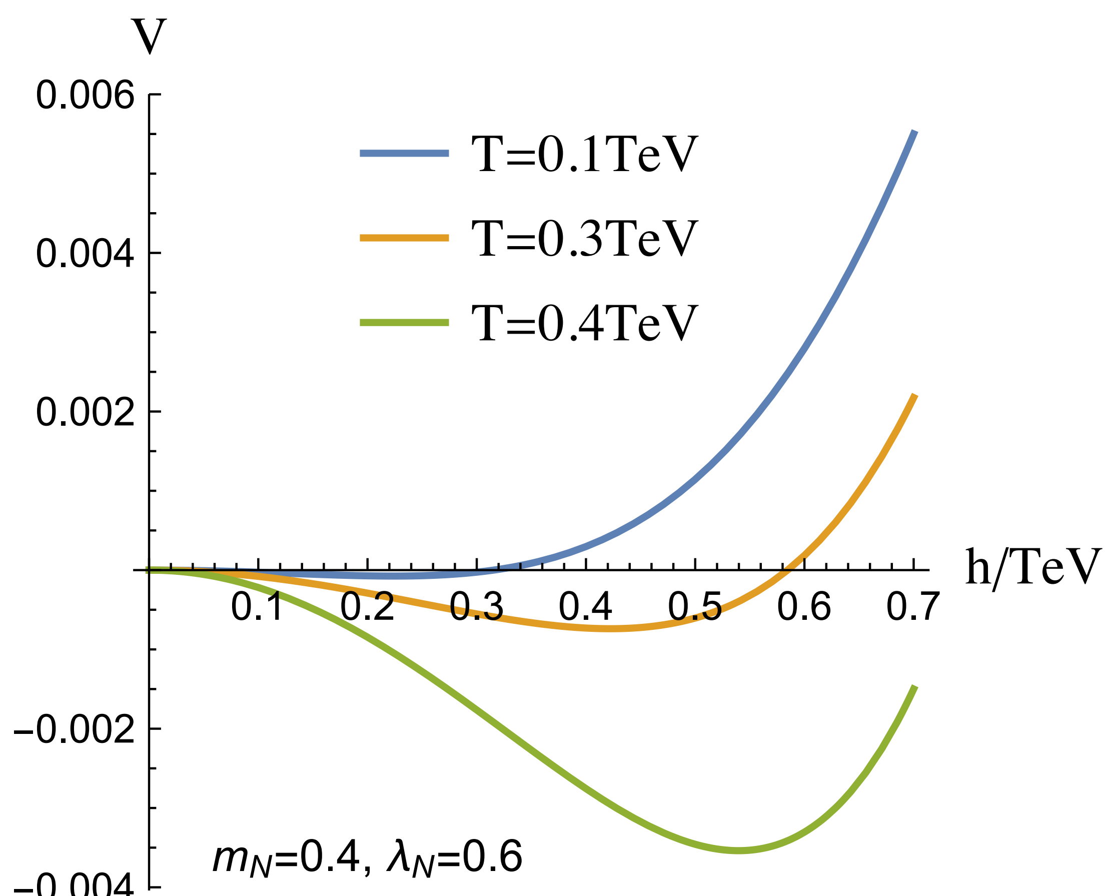
Add n new fermions N with Higgs-dependent mass contribution. Mass vanishes at <h>≠0

Matsedonskyi et al, 19xx.xxxxx

$$m_N(h) = m_N^{(0)} - \lambda_N h^2/\Lambda = 0 \quad \longrightarrow \quad h^2 = m_N^{(0)}\Lambda/\lambda_N,$$

$$\delta m_h^2[T] \simeq n\frac{T^2}{12}(m_N^2(h))'' = -n\lambda_N \frac{m_N^{(0)}}{3\Lambda}T^2.$$

Negative thermal mass



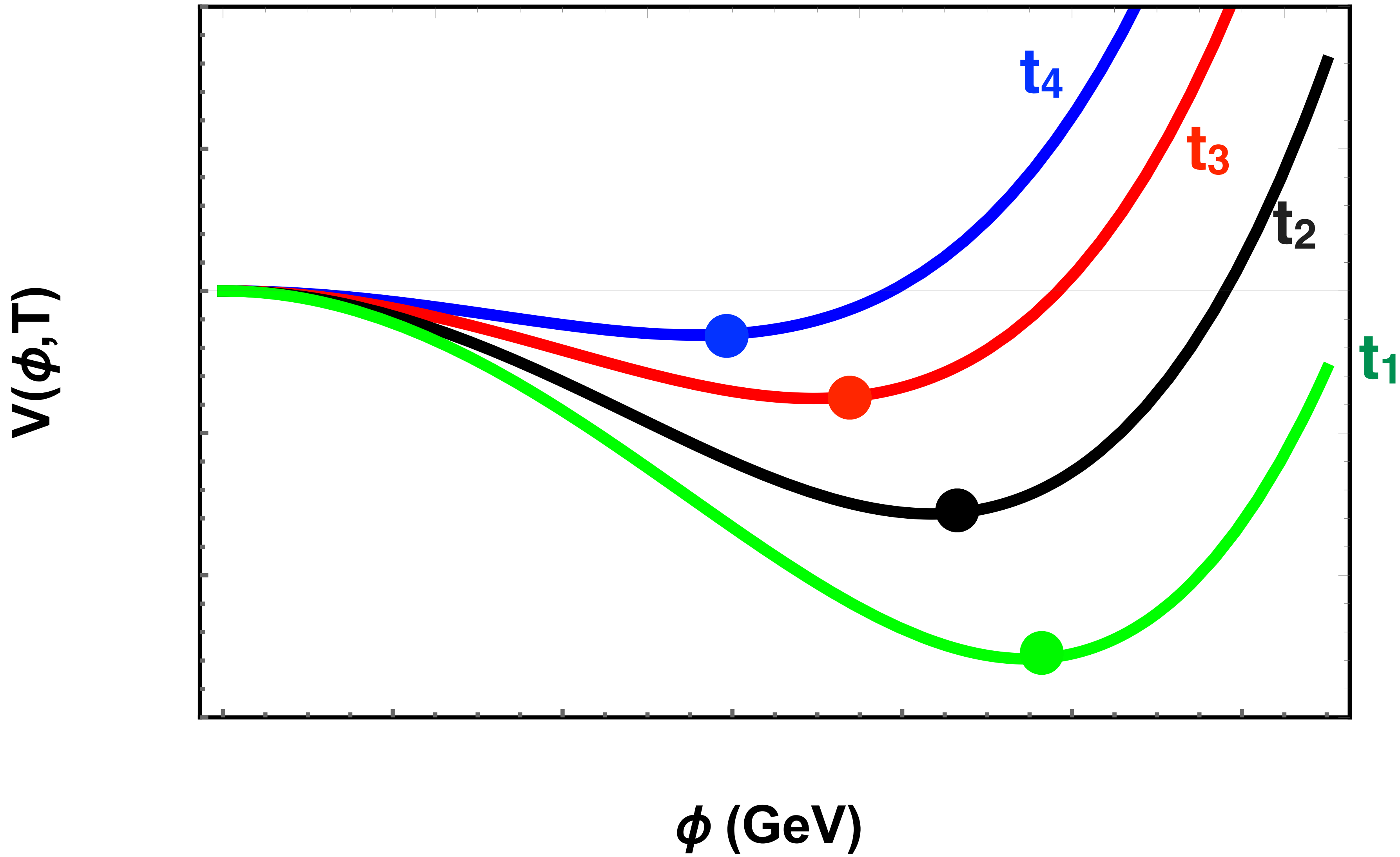
Enables to push Tc to ~ 500 GeV while keeping <h>/T>1 for T<Tc.

EW symmetry: never-restored .

1807.07578

$$-\mu^2 + c\,T^2$$

< 0, Negative thermal mass !



> No EW phase transition ! Baryogenesis without sphalerons ?

Summary on EW phase transition .

It remains very open how EW symmetry got broken in early universe

- **First-order EW phase transition: well alive and still likely**

supercooled EW phase transition: generic in Composite Higgs with light dilaton, rich pheno and cosmo.
Testable through light dilaton signatures

- **EW baryogenesis: under threat by EDM bounds**

Remaining options:

- Top transport may remain open only in composite Higgs.
- ~~C~~P in hidden sector, e.g. new leptons
- EW phase transition occurring at high temperatures >> 100 GeV, via large number of new O(few100 GeV) singlet scalars or singlet fermions.

- **Broken EW sym. at early times may happen in models of EW scale cosmological relaxation (not a temperature effect) but followed by SM-like EW phase transition (see next part)**

Associated predictions: light weakly coupled relaxion.
Testable signatures: not yet clear, work in progress.

Summary on EW phase transition (continued) .

Scalar fields are ubiquitous in physics beyond the Standard Model
Many well-motivated models predict a strong first-order EW phase transition.

Probing the EW phase transition will keep us busy for the next 2 decades through complementarity of studies in theory, lattice, experiments in Colliders, EDMs, gravitational waves, cosmology, axions.

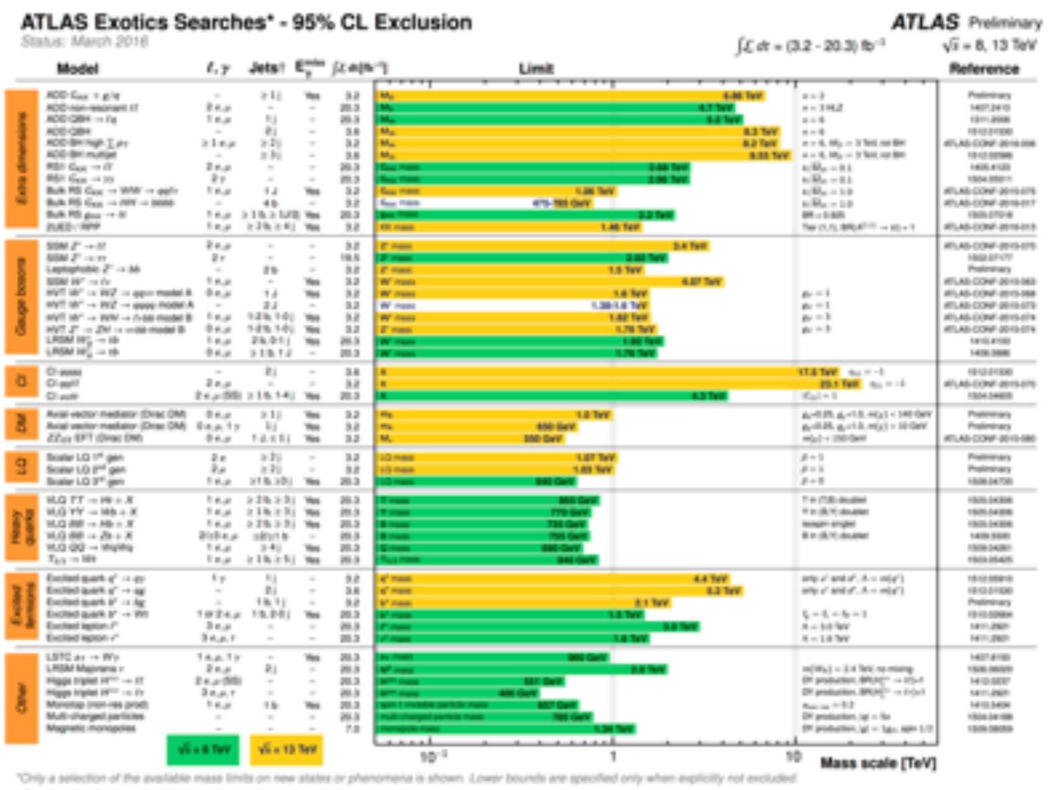
LISA: Beautiful and complementary window on the TeV scale

Sensitive to a large region of parameter space, thanks to recent analysis of sensitivity curves to stochastic backgrounds + improved estimates of the signal (large contribution from sound waves)

Cosmological Relaxation of the EW scale

Graham, Kaplan, Rajendran [1504.07551]

A newborn paradigm following absence of new physics after LHC Run I



“It is in moments of **crisis** that new ideas develop,” **Gian Giudice**

The Hierarchy Problem

If Standard Model is an effective field theory below M_{Planck}

$$V = m_h^2\, h^2 + \lambda\, h^4$$

Why $m_h^2 \ll \mathrm{M}_{\mathrm{Planck}}^2$ **?**

New paradigm:

Hierarchies are induced/created by the time evolution/the age of the Universe

Dramatic implications for strategy to search for new physics explaining the Weak scale

The idea that hierarchies in force scales could have something to do with cosmological evolution goes back to Dirac (hypothetizes a relation between ratio of universe sizes to ratio of force strengths)

FEBRUARY 20, 1937 NATURE 323

Letters to the Editor

the ratio of the mass of the proton to that of the electron), the larger numbers, namely the ratio of the electric to the gravitational force between electron and proton, which is about 10^{39}, and the ratio of the mass of the universe to the mass of the proton, which is about 10^{78}, are so enormous as to make one think that some entirely different type of explanation is needed for them.

According to current cosmological theories, the universe had a beginning about 2×10^{9} years ago, when all the spiral nebulæ were shot out from a small region of space, or perhaps from a point. If we express this time, 2×10^{9} years, in units provided by the atomic constants, say the unit e^2/mc^3, we obtain a number about 10^{39}. This suggests that the above-mentioned large numbers are to be regarded, not as constants, but as simple functions of our present epoch, expressed in atomic units. We may take it as a general principle that all large numbers of the order 10^{39}, 10^{78} . . . turning up in general physical theory are, apart from simple numerical coefficients, just equal to t, t^2 . . . , where t is the present epoch expressed in atomic units. The simple numerical coefficients occurring here should be determinable theoretically when we have a comprehensive theory of cosmology and atomicity. In this way we avoid the need of a theory to determine numbers of the order 10^{39}.

P. A. M. DIRAC.

St. John's College,
Cambridge.
Feb. 5.

A MECHANISM FOR REDUCING THE VALUE OF THE COSMOLOGICAL CONSTANT

L.F. ABBOTT [1]
Physics Department, Brandeis University, Waltham, MA 02254, USA

Received 30 October 1984

A mechanism is presented for relaxing an initially large, positive cosmological constant to a value near zero. This is done by introducing a scalar field whose vacuum energy compensates for the initial cosmological constant. The compensating sector involves small mass scales but no unnatural fine-tuning of parameters. It is not clear how to incorporate this mechanism into a realistic cosmology.

$$V = \epsilon B/f_B - \Lambda_{\mathrm{ph}}^4 \cos(B/f_B) + V_0,$$

PHYSICAL REVIEW D, VOLUME 70, 063501

Cosmic attractors and gauge hierarchy

Gia Dvali[1] and Alexander Vilenkin[2]

[1]*Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, New York 10003, USA*

[2]*Institute of Cosmology, Department of Physics and Astronomy, Tufts University, Medford, Massachusetts 02155, USA*

(Received 31 July 2003; published 1 September 2004)

We suggest a new cosmological scenario which naturally guarantees the smallness of scalar masses and vacuum expectation values , without invoking supersymmetry or any other (nongravitationally coupled) new physics at low energies. In our framework, the scalar masses undergo discrete jumps due to nucleation of closed branes during (eternal) inflation. The crucial point is that the step size of variation decreases in the direction of decreasing scalar mass. This scenario yields exponentially large domains with a distribution of scalar masses, which is sharply peaked around a hierarchically small value of the mass. This value is the "attractor point" of the cosmological evolution.

Relaxion idea

[Graham, Kaplan, Rajendran '15

inspired by Abbott's attempt to solve the CC problem, '85

What if the weak scale is selected by cosmological dynamics, not symmetries?

Special point in parameter space:

$m^2{}_H = 0$ not related to a symmetry

Instead, related to early-universe dynamics!

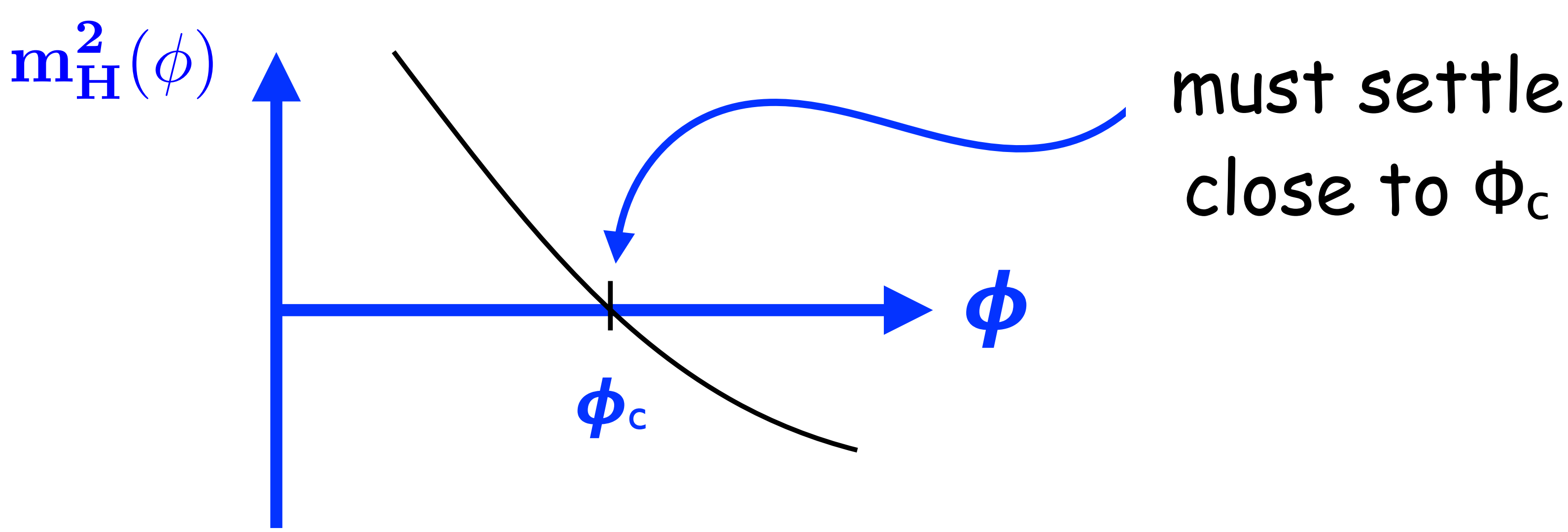
Key idea: Higgs mass parameter is field-dependent

$$m^2|H|^2 \to m^2(\phi)|H|^2$$

Φ can get a value such that $m^2(\phi) \ll \Lambda^2$

UV cutoff

from a dynamical interplay between H and Φ



Key question: How to make m_H a special point of the Φ potential?

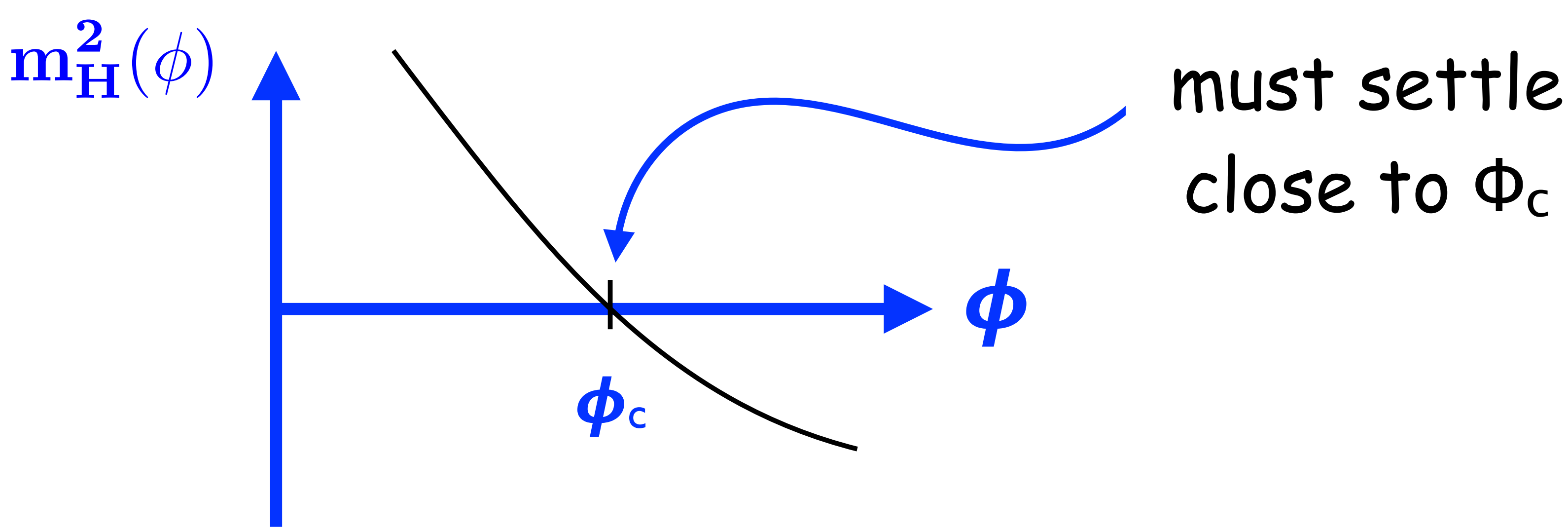
Key idea: Higgs mass parameter is field-dependent

$$m^2|H|^2 \to m^2(\phi)|H|^2$$

Φ can get a value such that $m^2(\phi) \ll \Lambda^2$

from a dynamical interplay between H and Φ

UV cutoff



when $m_H^2 < 0$, Higgs vev gives quark masses which give axion potential (->"Relaxion")

m_H naturally stabilized due to back-reaction of the Higgs field after EW symmetry breaking !

Higgs (h) and Axion-like (ϕ) Interplay

3 terms:

$$V(\phi, h) = \boxed{\Lambda^3 g\phi} - \boxed{\frac{1}{2}\Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)h^2} + \boxed{\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)}$$

relaxion rolling potential

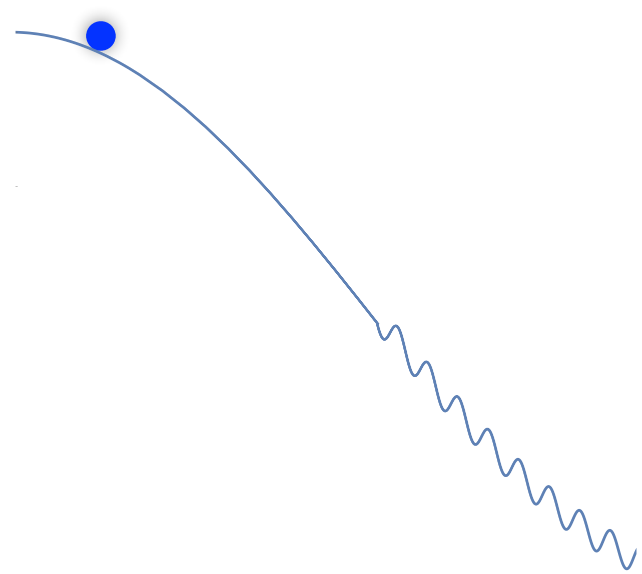
slope for Φ to move forward

relaxion-dependent Higgs mass

Φ scans the Higgs mass

Backreaction sector

barrier stopping Φ when <h> turns on



Higgs (h) and Axion-like (ϕ) interplay

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

g<<1, breaks the shift symmetry $\phi \rightarrow \phi + c$

ϵ <<1, breaks the shift symmetry

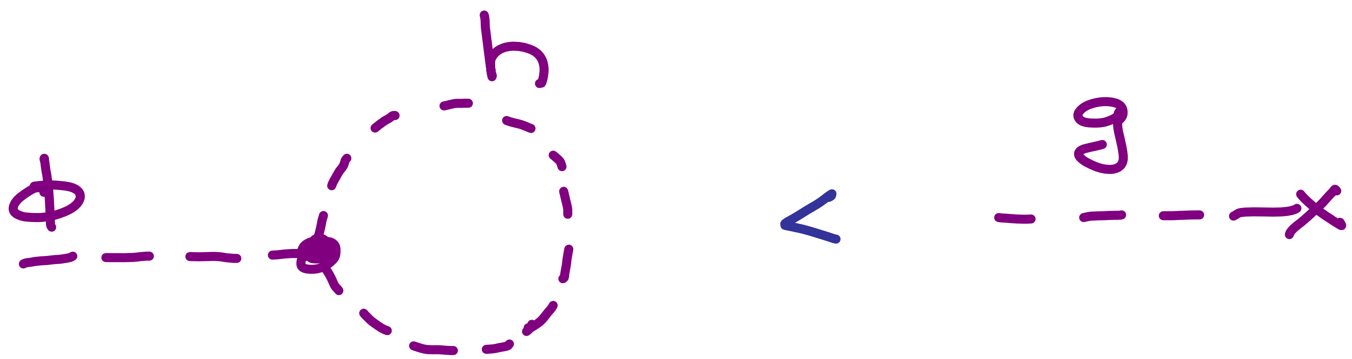
respects $\phi \rightarrow \phi + 2\pi f$

$\phi \rightarrow -\phi$

Potential stable under radiative corrections!

Technical naturalness

V(H,Φ) is radiatively stable



$$g\Lambda \times \frac{\Lambda^2}{16\pi^2} < g\Lambda^3$$ ✓

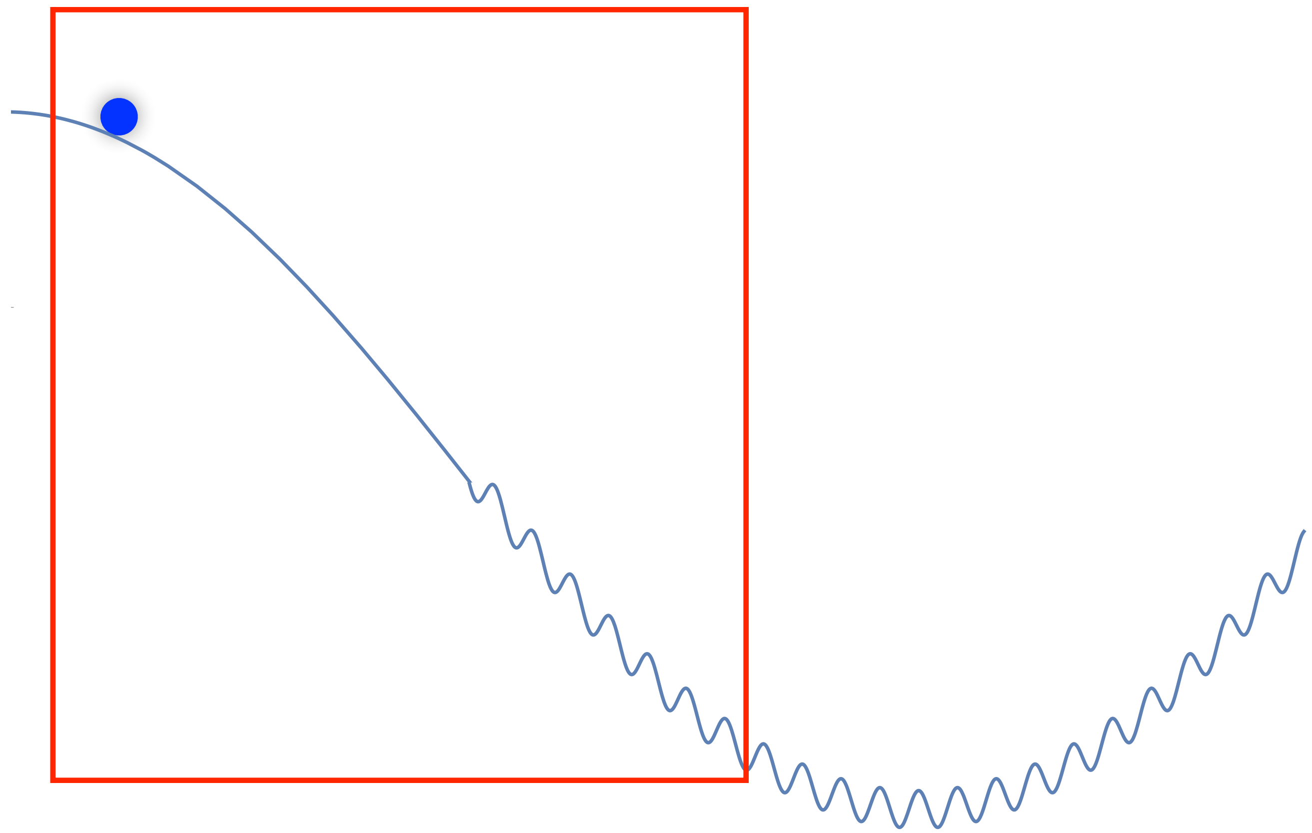
Concerns about V(h,Φ) ?

Relaxion potential may be obtained without breaking of shift symmetry but with hierarchy of decay constants, e.g. "clockwork axion"

Is this natural -> multiple axion models

Choi, Im'15
Kaplan, Rattazzi'15

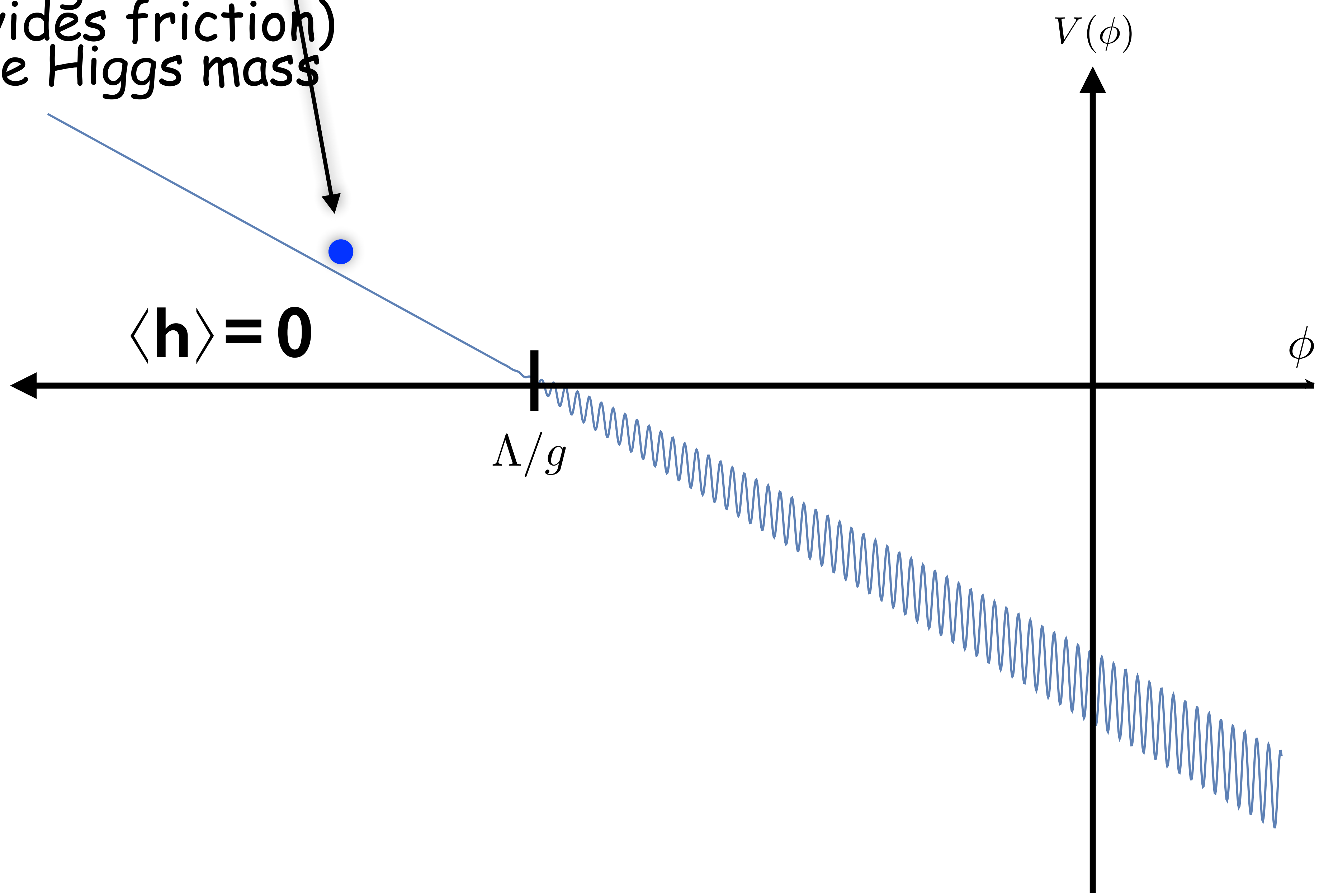
$$V \sim A\cos(\frac{\phi}{f_{eff}}) + B\cos(\frac{\phi}{f_{eff}})h^2 + C(h)\cos(\frac{\phi}{f}), \qquad f_{eff} \sim e^{\zeta N} f \gg f$$



Cosmological evolution

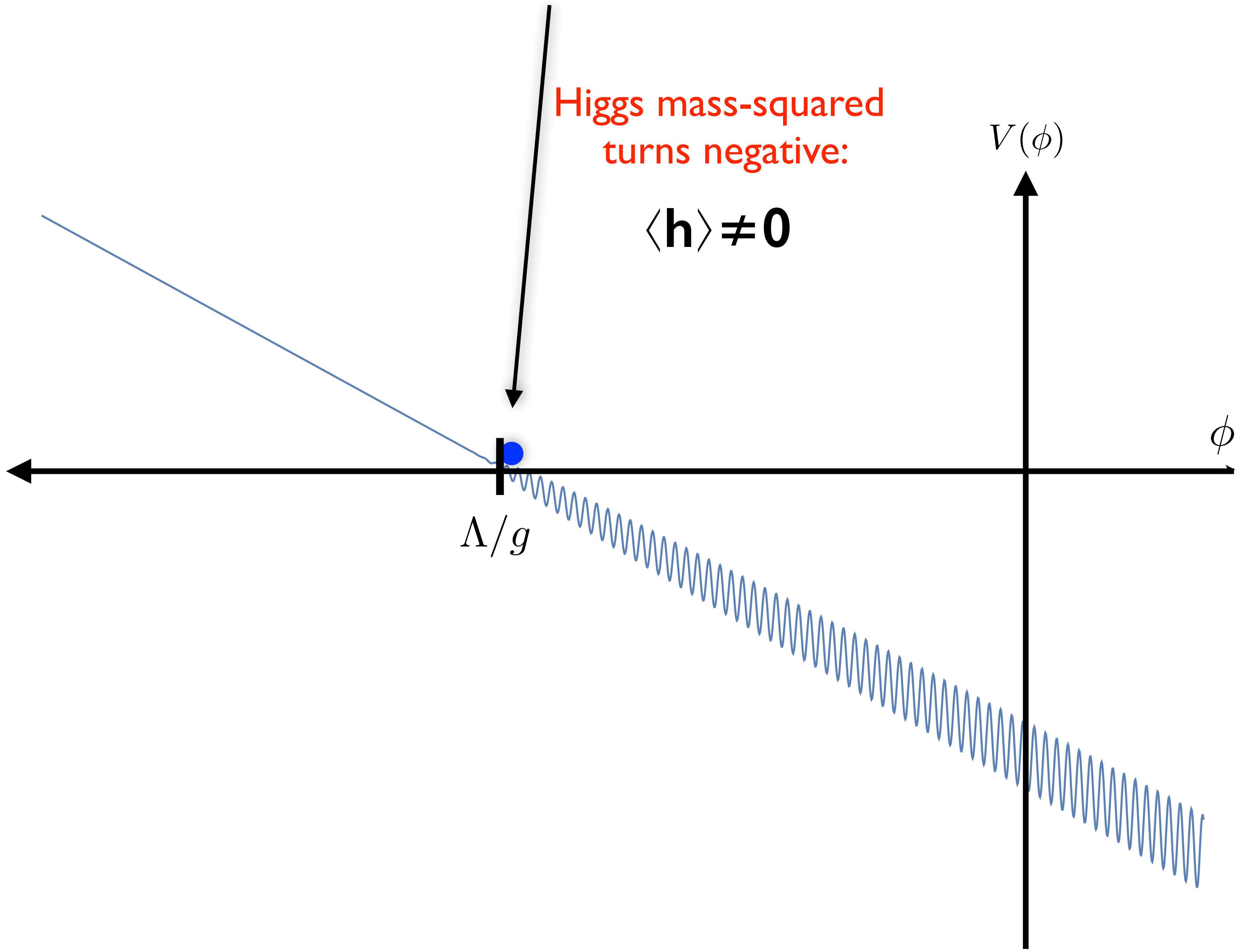
$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

slowly rolling field
(inflation provides friction)
that scans the Higgs mass



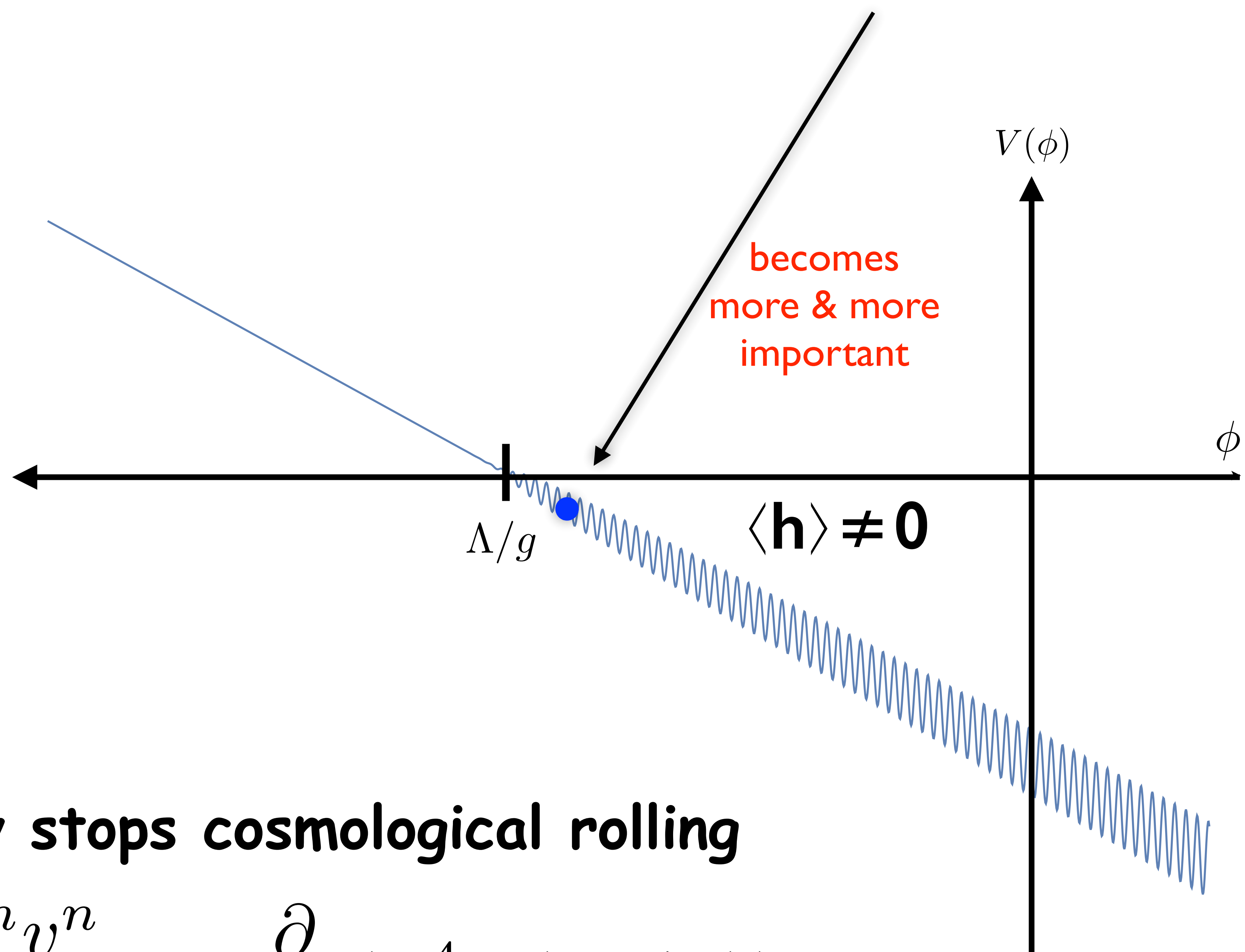
Cosmological evolution

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$



Cosmological evolution

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

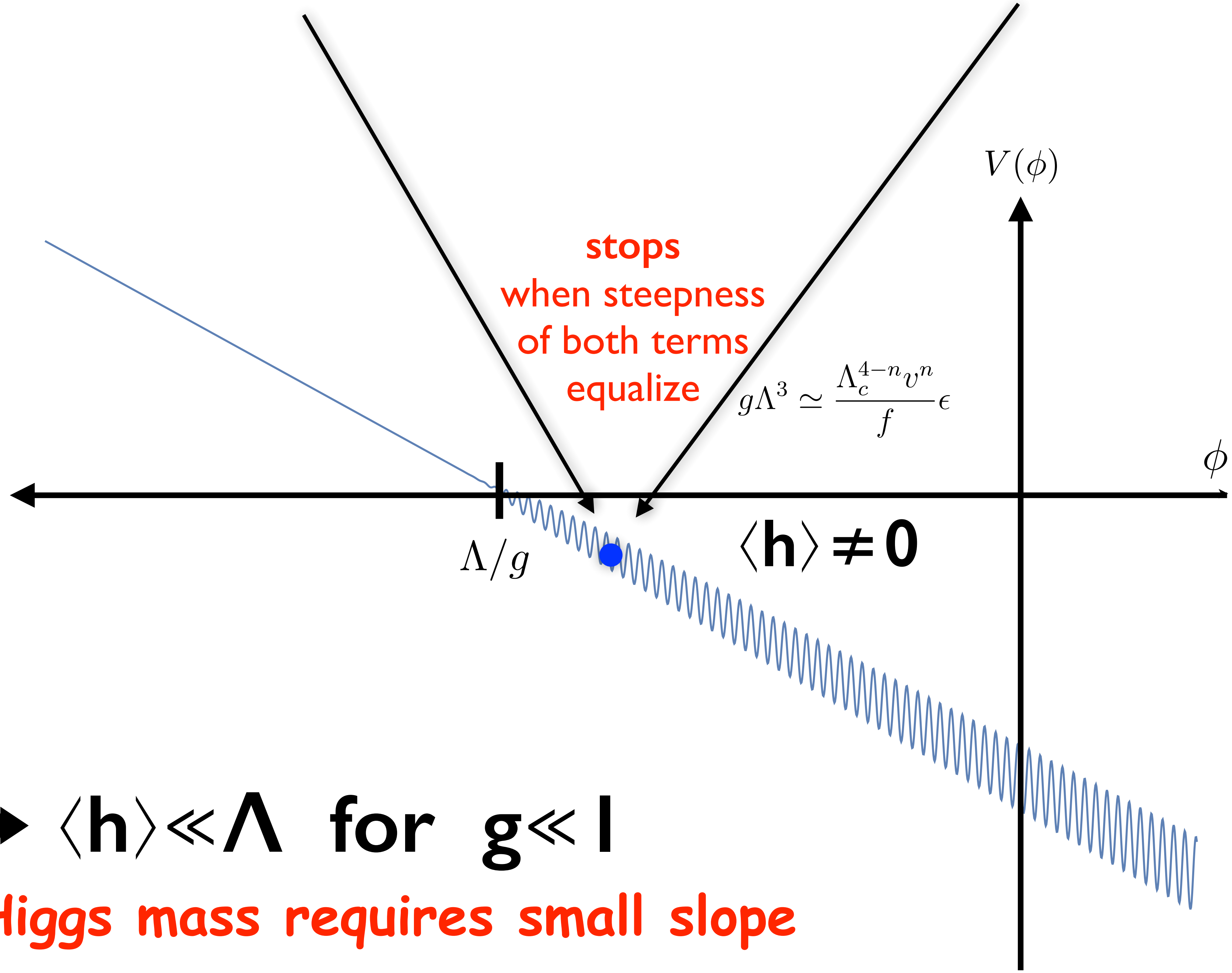


Higgs vev stops cosmological rolling

$$\frac{\Lambda_c^{4-n} v^n}{f}\epsilon \sim \frac{\partial}{\partial\phi}(\Lambda^4 V(g\phi/\Lambda))$$

Cosmological evolution

$$V(\phi,h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2\left(1-\frac{g\phi}{\Lambda}\right)h^2 + \epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$



➥ $\langle h \rangle \ll \Lambda$ for $g \ll 1$

small Higgs mass requires small slope

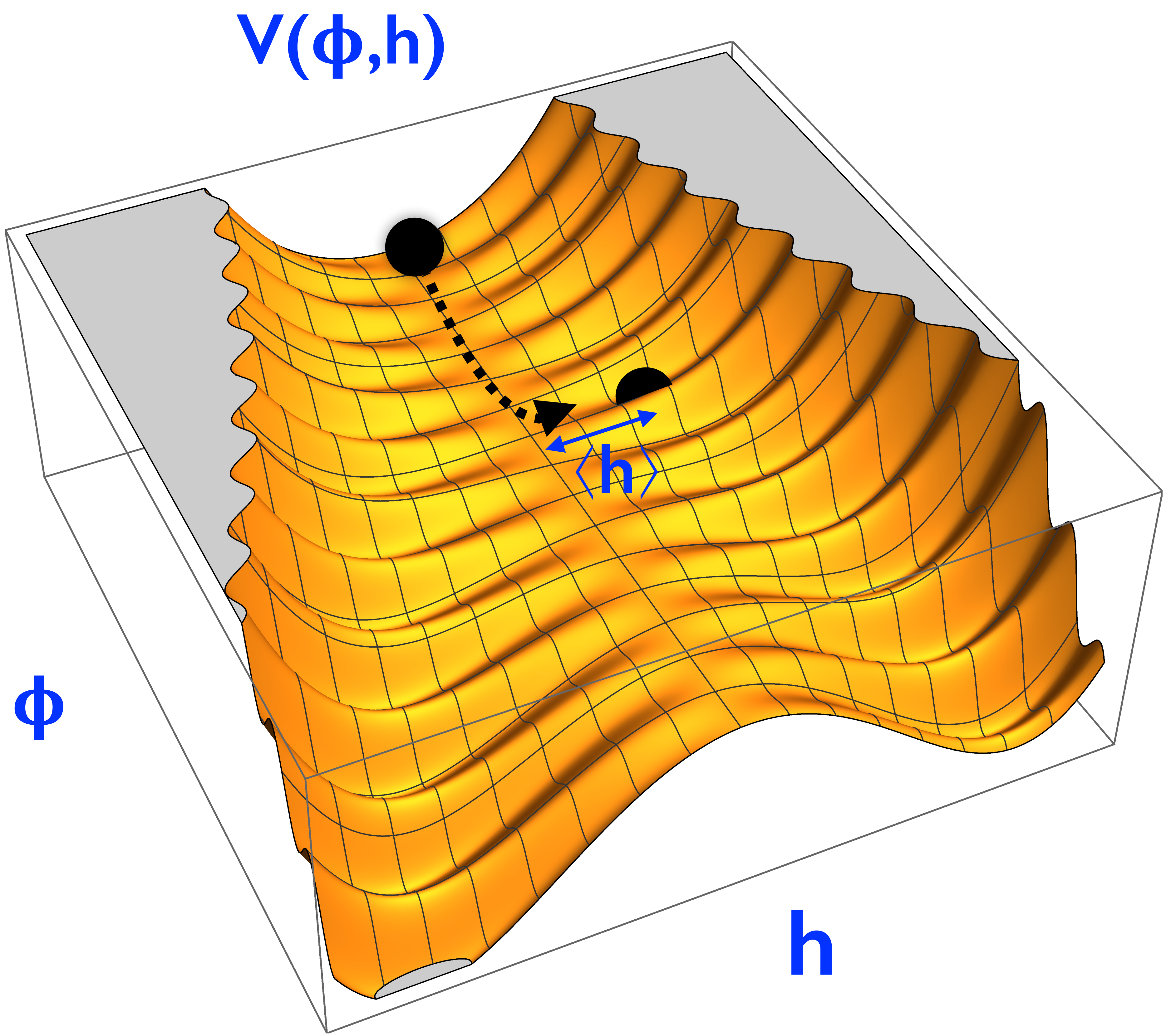
Cosmological evolution

$$V(\phi, h) = \Lambda^3 g\phi - \frac{1}{2}\Lambda^2 \left(1 - \frac{g\phi}{\Lambda}\right) h^2 + \epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$$

Large field excursions for ϕ needed

$$\phi \sim \Lambda/g \gg \Lambda$$

No dependence on initial conditions, provided that this takes place during inflation


V(ϕ,h)
⟨h⟩
ϕ
h

Conditions:

Slow rolling: $$H_I > \frac{\Lambda^2}{M_P}$$ ensures that the energy density stores in not affect inflation

from friction due to inflation

Needed to avoid overshooting the EW range vacua

$$N_{efolds} \gtrsim \frac{H_I^2}{g^2\Lambda^2}$$

for complete scanning of the Higgs mass

Classical rolling

classical displacement over one Hubble time > quantum fluctuation

$$\frac{1}{H_I}\frac{d\phi}{dt} = \frac{1}{H_I^2}\frac{dV}{d\phi} = \frac{g\Lambda^3}{H_I^2} > H_I$$

-> $$H_I \lesssim g^{1/3}\Lambda$$

putting all these constraints together tells you what is the maximal cutoff Λ

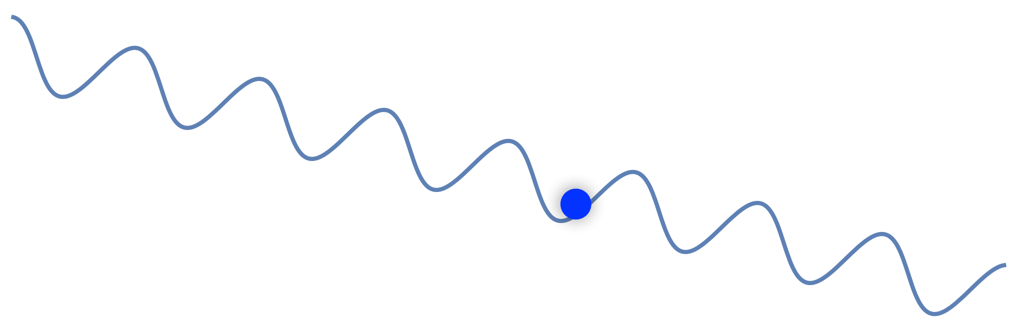
n=2: $$\Lambda \lesssim (v^4 M_P^3)^{1/7} \simeq 2 \times 10^9\,\mathrm{GeV}$$

Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$

For n=1: From QCD condensate $\Lambda_c = \Lambda_{QCD}$

$$\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu} \longrightarrow m_u(h)\langle q\bar{q}\rangle\cos(\phi/f)$$

but leads to $\theta_{QCD} \sim 1$ **due to the tilt!**



Problem solved if the tilt disappears at the end of inflation but one gets

$\Lambda \lesssim 30$ TeV

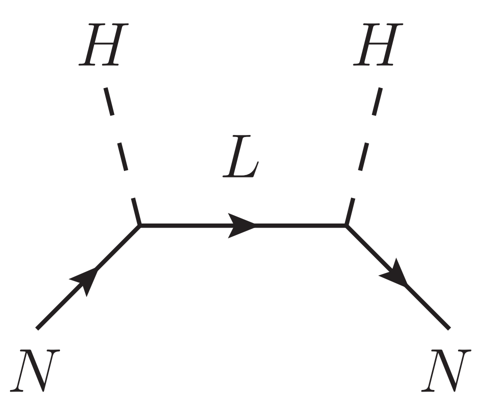
Origin of $\epsilon\Lambda_c^4\left(\frac{h}{\Lambda_c}\right)^n\cos(\phi/f)$

For n=2: $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$ **gauge invariant, no need to rely on QCD**

Similarly to QCD, the anomalous interaction term $\frac{\phi}{f}G'_{\mu\nu}\tilde{G}'^{\mu\nu}$

can be rotated away by a chiral rotation for N , and replaced by the term

$m_N e^{i\phi/f}\bar{N}N + h.c \to \Lambda^3 m_N\cos(\phi/f)$ where $\langle\bar{N}N\rangle\sim\Lambda^3$



$m_N\sim y^2|H|^2/m_L$

but $\epsilon\Lambda_c^4\cos(\phi/f)$ is generated by closing H in loop

Origin of $\epsilon\Lambda_c^4 \left(\frac{h}{\Lambda_c}\right)^n \cos(\phi/f)$

For n=2: $\epsilon\Lambda_c^2|H|^2\cos(\phi/f)$ **gauge invariant, no need to rely on QCD**

but $\epsilon\Lambda_c^4\cos(\phi/f)$ is generated by closing H in loop

and will stop ϕ before the Higgs vev develops

for the Higgs VEV to be responsible for stopping the rolling of phi, we need

$$\Lambda_c \lesssim v$$

By making the envelop of the oscillatory potential field-dependent, there is no new physics at the weak scale

J.R. Espinosa, C. Grojean, G. Panico, A. Pomarol, O. Pujolàs, G. Servant, [1506.09217]

Axions: ubiquitous in String Theory

Massless fields with axion-like properties generically arise in string theory compactifications

Their number is determined by the topology of the compact manifold
(non-equivalent embeddings of a closed two-surface into a reasonably complicated six-dimensional manifold.)

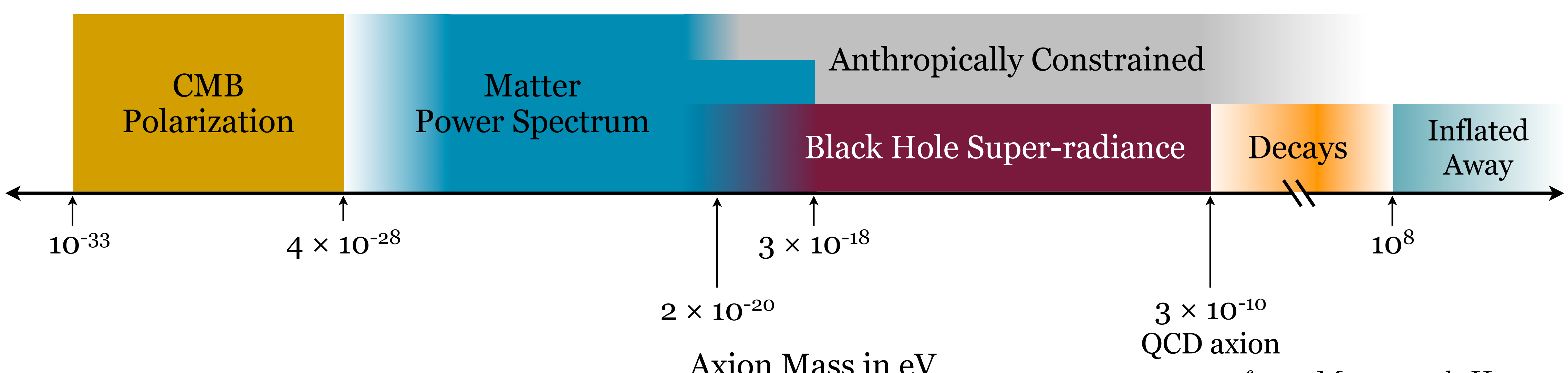
In most compactifications this number is of the order of several hundreds!

higher-dimensional gauge invariance -> shift symmetry in 4D!

broken non-perturbatively by couplings to gauge fields -> generates a mass

-> provides many particles with the qualitative properties of the QCD axion.

["String Axiverse" 0905.4720]



$f_a \approx M_{GUT}$ and $H_{inf} \sim 10^8$ eV.

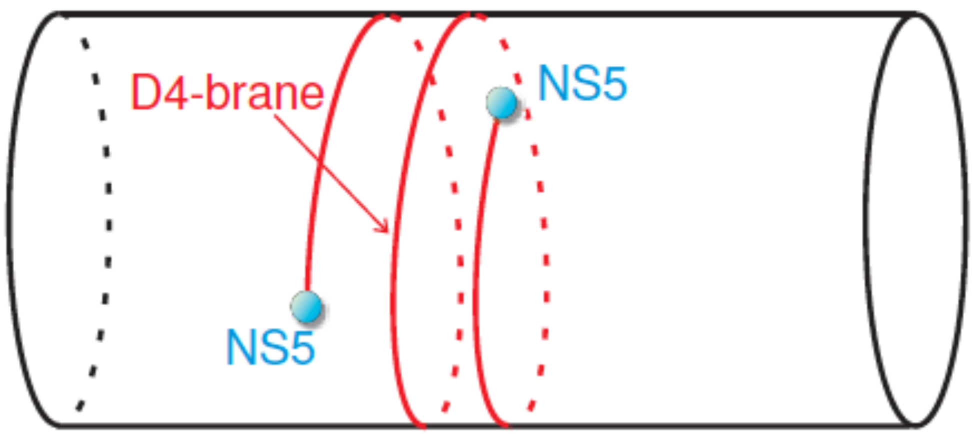
String Theory origin of the relaxion potential?

String Axion Monodromy

McAllister, Silverstein, Westphal, '08

Discrete shift symmetry broken by wrapping a brane along the 2-cycle associated to the axion

$$V = \mu_a^3 \phi_a + \Lambda^4 \cos\left(\frac{\phi_a}{2\pi f_a}\right)$$



Energy changes at each cycle due to coupling to fluxes

--> Devastating consequences for the relaxion

McAllister, Schwaller, Servant, Stout, Westphal, to appear

Not a complete theory !

A new playground at the crossroads between particle phenomenology, cosmology, strings...

Supersymmetrize the SM + the QCD relaxion:

$$S = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\,\theta\,\tilde{a} + \theta^2 F$$

srelaxion

relaxion

relaxino (goldstino)

susy breaking

Batell, Giudice, McCullough '15

relaxion superfield is the SUSY breaking sector

scanning of Higgs mass through scanning of SUSY breaking scale

Mass spectrum Phenomenology

"natural mini-split"

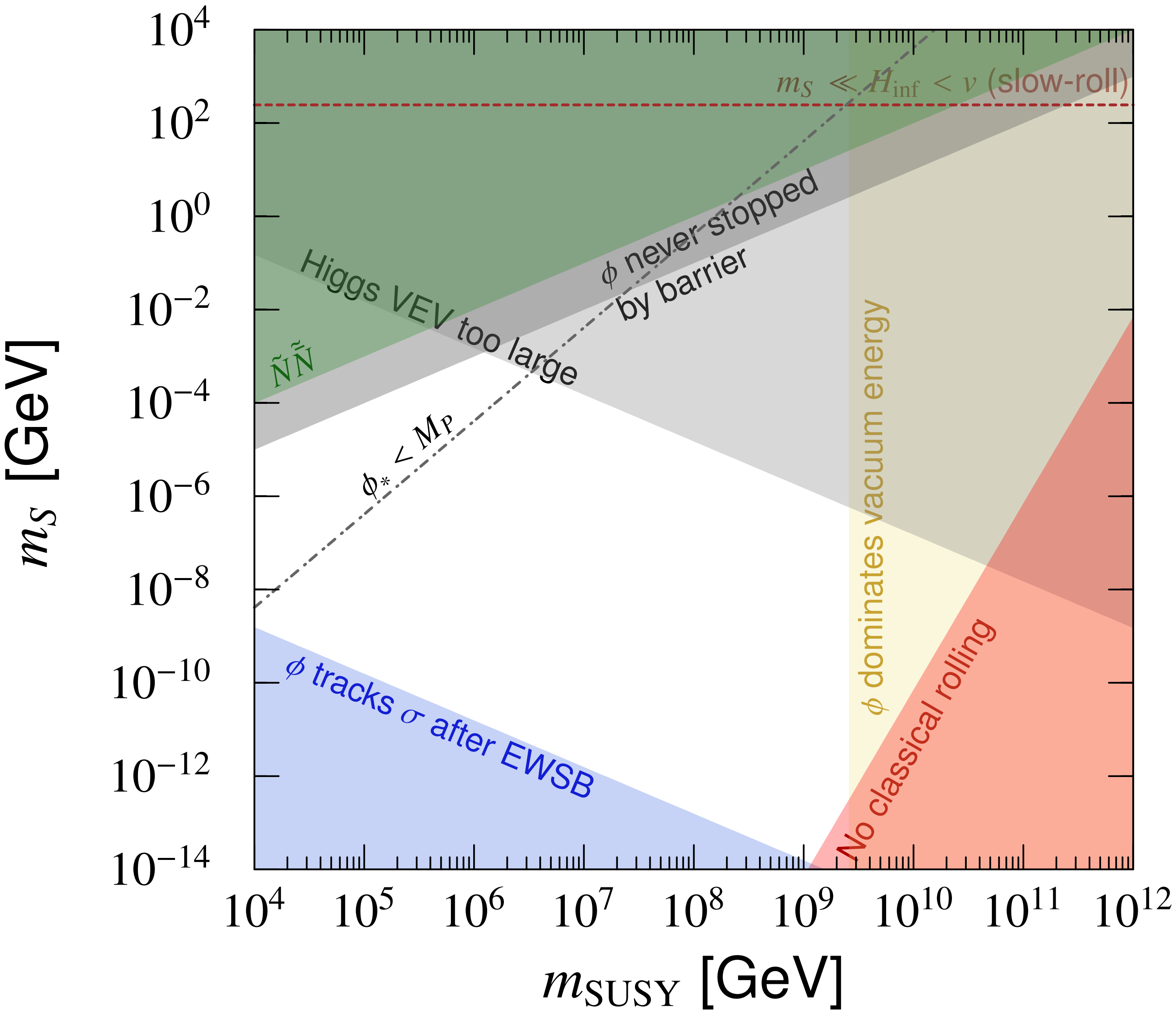
$\tilde{q}, \tilde{\ell}, \tilde{H}, s$	$\sim$ 100 TeV	OK for m_H, flavor, dim-5 p-decay
$\tilde{g}, \tilde{W}, \tilde{B}$	$\sim$ 1 TeV	could be within LHC reach
SM	$\sim$ 100 GeV $\Leftrightarrow$ MeV	
$\tilde{a}\,(\tilde{G})$	$\sim$ keV $\Leftrightarrow$ GeV	LSP, DM for $T_{RH} \sim \tilde{m}$
a	$\sim 10^{-2} \Leftrightarrow 10^{-5}$ eV	DM for $f \sim 10^{11\text{-}12}$ GeV (rel)axion couplings related to soft terms

Supersymmetrize the 2-scanner CHAIN model:

Evans, Gherghetta, Nagata, Thomas '16

preserves the QCD axion solution to the strong CP pb

scanning of Higgs mass through scanning of SUSY breaking scale



restores naturalness in split SUSY models

relaxino is dark matter

Summary

- A new approach to the hierarchy problem based on intertwined cosmological history of Higgs and axion-like states.
  Connects Higgs physics with inflation & (DM) axions.

- An existence proof that technical naturalness does not require new physics at the weak scale

$$\Lambda < \left(v^4 M_P^3\right)^{1/7} = 3 \times 10^9 \,\mathrm{GeV}$$

- Change of paradigm:

  no signature at the LHC , new physics are weakly coupled light states which couple to the Standard Model through their tiny mixing with the Higgs.

- Experimental tests from cosmological overabundances, late decays, Big Bang Nucleosynthesis, Gamma-rays, Cosmic Microwave Background...

Open Questions

- Main challenge: Large (superplanckian) field excursions $\frac{\Delta\phi}{f} \sim 10^8 - 10^{28}$
  -> monodromy? McAllister, Servant, Schwaller, Stout, Westphal, '16
- Weak gravity conjecture
  Heidenreich, Reece, Rudelius '15
  Hebecker, Rompineve, Westphal '15
- UV completion? Choi, Im '15 Kaplan, Rattazzi '15
  Fonseca, Lima, Machado, Matheus'16
  Giudice, MacCullough'16
  Fonseca, Von Harling, Lima, Machado'17
- Inflation model building (at low scale) $N_e \sim 10^{15} - 10^{50}$
- Friction from particle production
  Hook, Marques-Tavares'16
  Fonseca, Morgante, Servant'18
- Signatures in low-energy experiments? Flacke, Frugiuele, Fuchs, Gupta, Perez; '16
- Can other scales be relaxed too? SUSY breaking scale?

  Batell, Giudice, McCullough '15
  Evans, Gherghetta, Nagata, Thomas '16

-> Use the relaxion mechanism to solve the Little Hierarchy and then SUSY takes over.

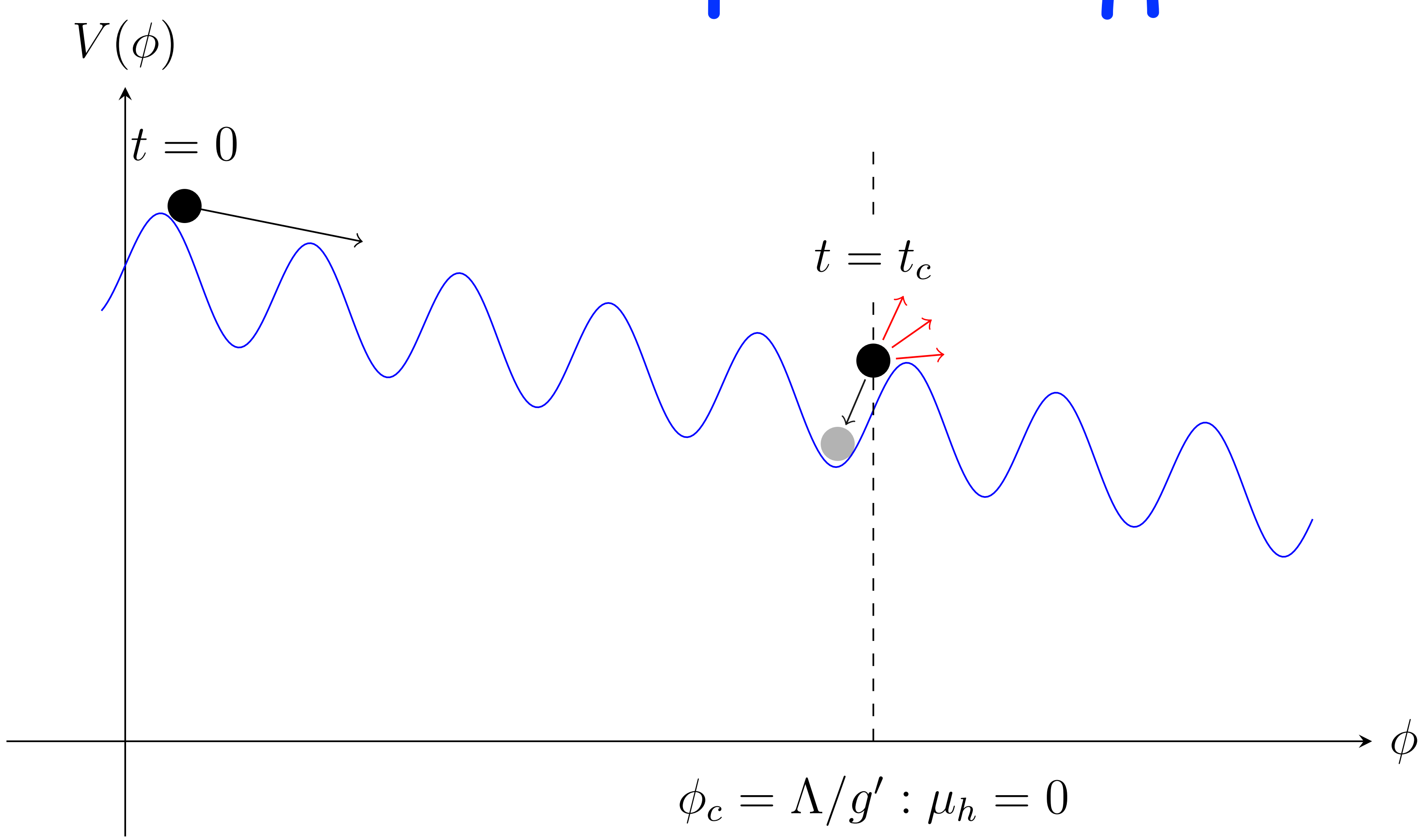
An alternative Relaxion mechanism

Hook, Marques-Tavares '16;
Fonseca, Morgante, Servant '18

— Barriers across entire potential

$$V(\phi,h) = \Lambda^4 - g\Lambda^3\phi + \frac{1}{2}\left(-\Lambda^2 + g'\Lambda\phi\right)h^2 + \frac{\lambda}{4}h^4 + \Lambda_b^4\cos\left(\frac{\phi}{f'}\right)$$

— Novel source of dissipation from gauge boson production turns on at special $m^2_H = 0$ point



Relaxion coupling to massive gauge fields

inspired by [Anber—Sorbo 0908.4089]

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}\partial_\mu h\partial^\mu h - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} - \frac{\phi}{4f}V_{\mu\nu}\widetilde{V}^{\mu\nu} + \frac{g_V^2}{2}V_\mu V^\mu h^2 - \mathcal{V}(\phi, h)$$

Equation of motion for transverse polarisation

$$\ddot{V}_\pm + (k^2 + m_V^2 \mp k\frac{\dot{\phi}}{f})V_\pm = 0 \qquad m_V^2 = g_V^2 h^2$$

Exponentially growing solution for $|\dot{\phi}| \gtrsim 2 f m_{\rm V}$

Growing mode drains energy from Φ: (take g=g')

$$\ddot{\phi} - g\Lambda^3 + g\Lambda h^2 + \frac{\Lambda_c^4}{f'}\sin\frac{\phi}{f'} + \frac{1}{4f}\langle V\widetilde{V}\rangle = 0$$

$$\langle V\widetilde{V}\rangle = \frac{1}{4\pi^2}\int_0^\Lambda dk\, k^3 \frac{d}{dt}(|V_+|^2 - |V_-|^2)$$

Original relaxion model:

$$\frac{\phi}{f} G\tilde{G}$$

+

Inflation

Alternative proposal:

$$-\frac{\phi}{4f}\left(g_2^2 W\widetilde{W} - g_1^2 B\widetilde{B}\right)$$

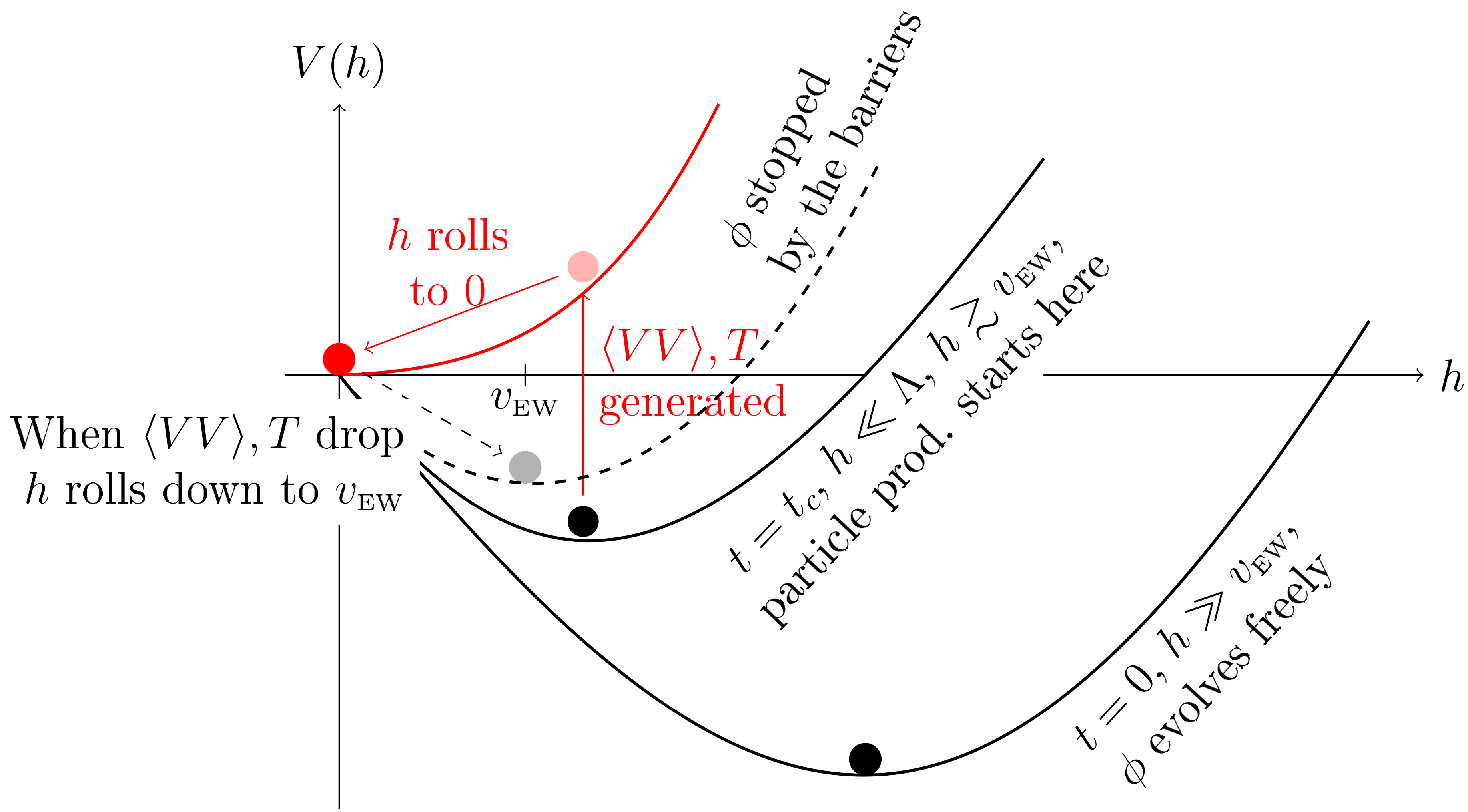
$f \sim \Lambda^2/(2\, m_Z)$

$$+ \quad \Lambda_b^4 \cos\frac{\phi}{f'}$$

Exponential growth of EW gauge bosons around h~v slows down relaxion.

Cannot couple to photons!
(natural with symmetries,
e.g., SU(2)L x SU(2)R)

Higgs field evolution during cosmological relaxation intertwined with gauge boson production

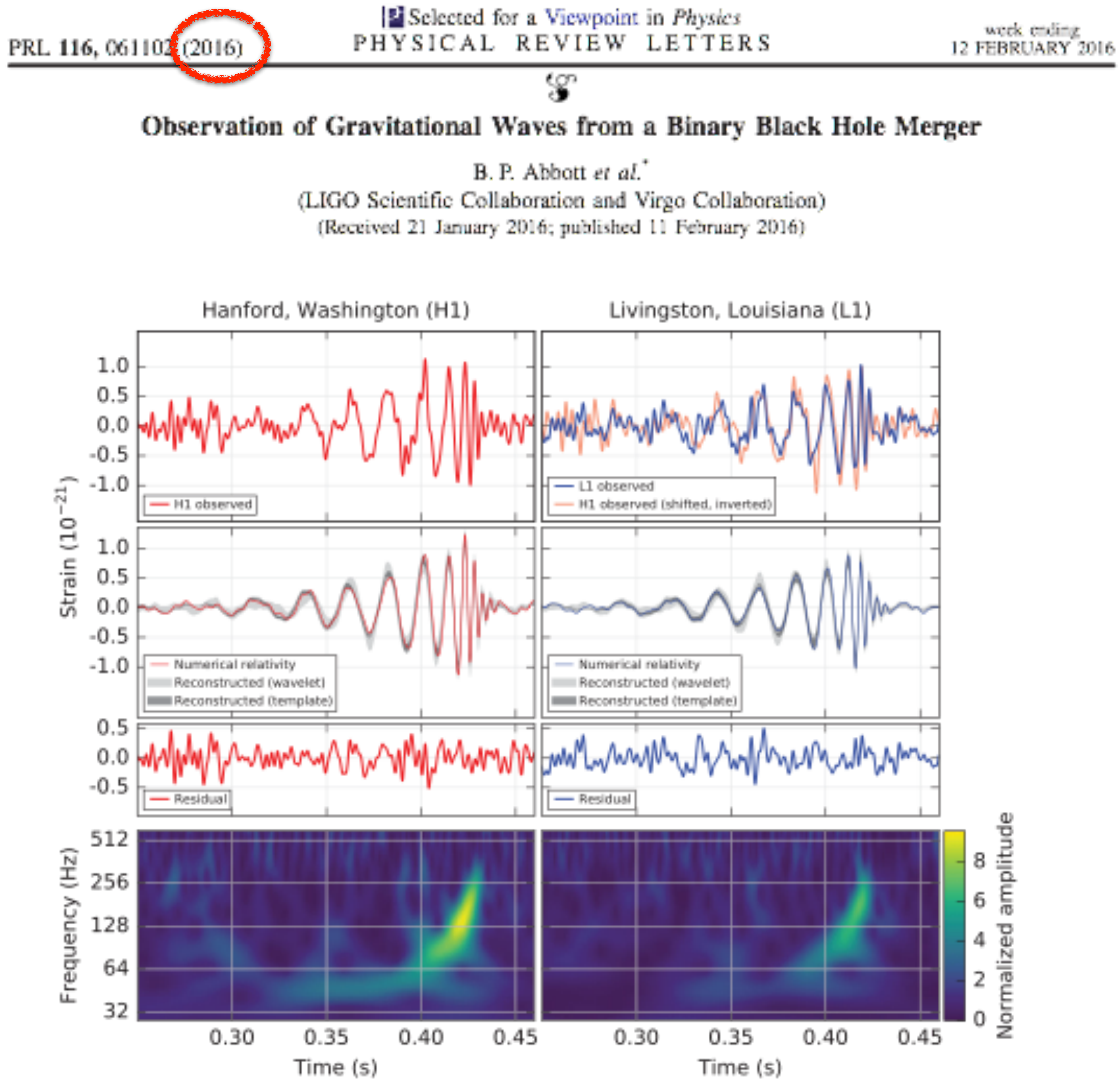


$$\ddot{\phi} - g\Lambda^3 + g'\Lambda h^2 + \frac{\Lambda_b^4}{f'}\sin\frac{\phi}{f'} + \frac{1}{4f}\langle V\widetilde{V}\rangle = 0$$

$$\ddot{h} + (g'\Lambda\phi - \Lambda^2)h + \lambda h^3 - \frac{1}{2}g_V^2\langle V_\mu V^\mu\rangle h = 0$$

$$\ddot{V}_\pm + (k^2 + m_V^2 \mp k\frac{\dot{\phi}}{f})V_\pm = 0$$

Using Gravitational Waves to probe new physics


PRL 116, 061102 (2016) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

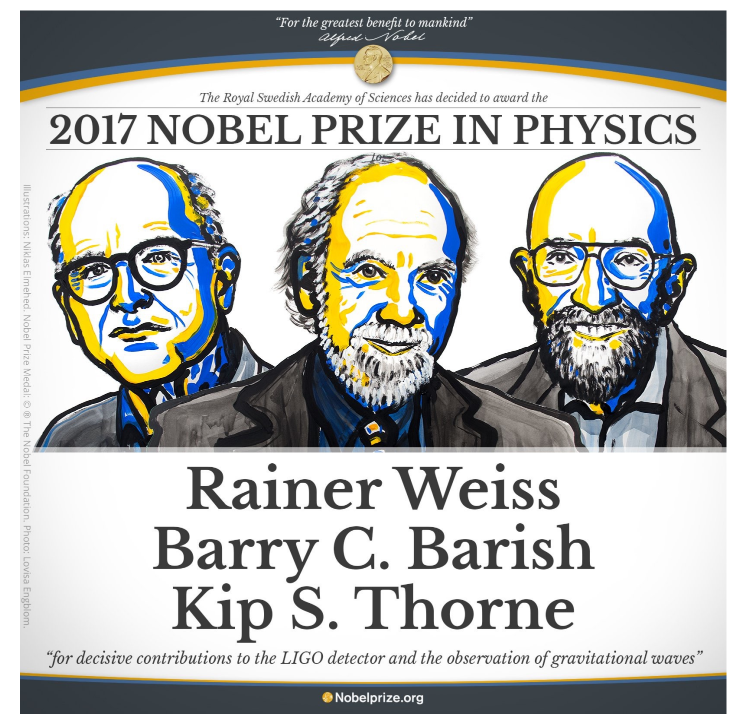
(Received 21 January 2016; published 11 February 2016)


688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Sber Preuss. Akad. Wiss. 1916, I

Näherungsweise Integration der Feldgleichungen der Gravitation.

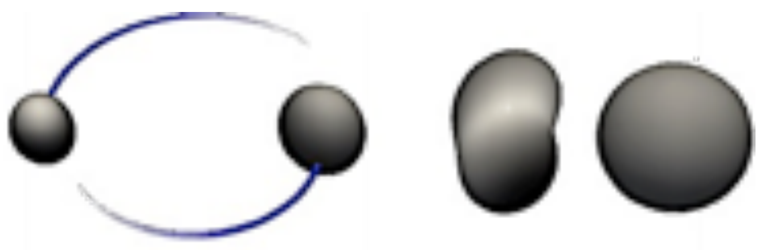
Von A. Einstein.



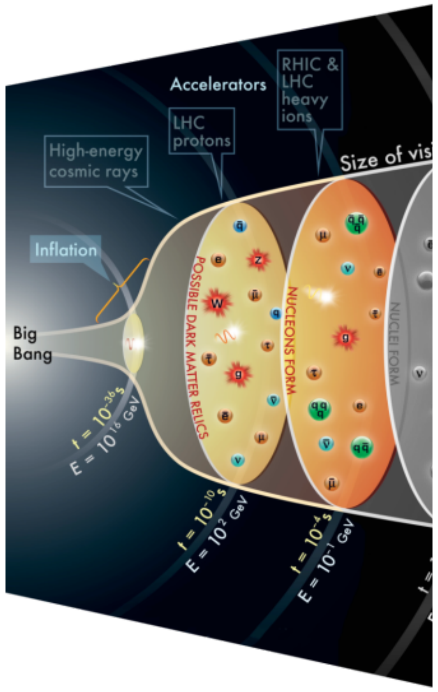
Gravitational waves

2 types of signals:

- from astrophysical sources (in the late universe)



- cosmological background filling the whole universe (relic from the primordial universe)



Well-known sources

-> Cosmological Phase Transitions

-> Inflation

-> Cosmic strings

Frequencies

T_* **temperature of the universe at time of emission**

$$f \sim f_* \frac{T_0}{T_*} \sim \mathcal{O}(H_*) \frac{T_0}{T_*} \sim \frac{T_*}{M_{Pl}} T_0 \sim T_* \times 10^{-18} 10^{-12}$$

If T_* **~ 100 GeV:**

$$f \sim 10^{-28}\ \mathrm{GeV} \sim 10^{-28} \times 10^{25}\ \mathrm{Hz} \sim \mathrm{mHz}$$

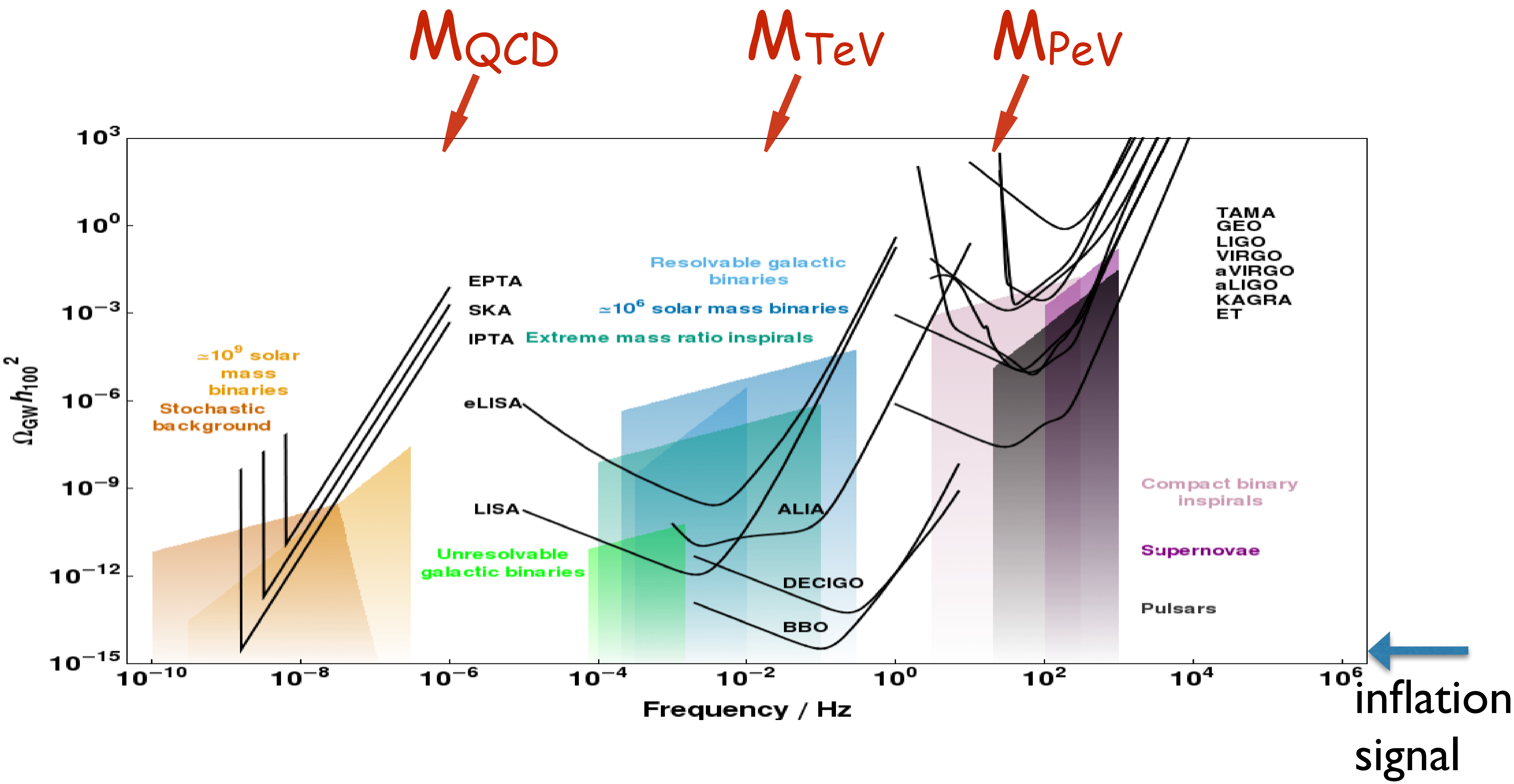
LISA !

GW Stochastic background: isotropic, unpolarized, stationary

GW energy density:

$$\Omega_G = \frac{\langle \dot{h}_{ij}\dot{h}^{ij}\rangle}{G\rho_c} = \int \frac{dk}{k}\frac{d\Omega_G(k)}{d\log(k)}$$

A huge range of frequencies



Particularly motivated sources

-> Cosmological phase transitions

-> Inflation

-> Reheating of the universe

-> Primordial Black Holes from Inflation

-> Dark Matter interactions

-> Mechanism behind mass generation of Dark Matter

-> Axion-like particles

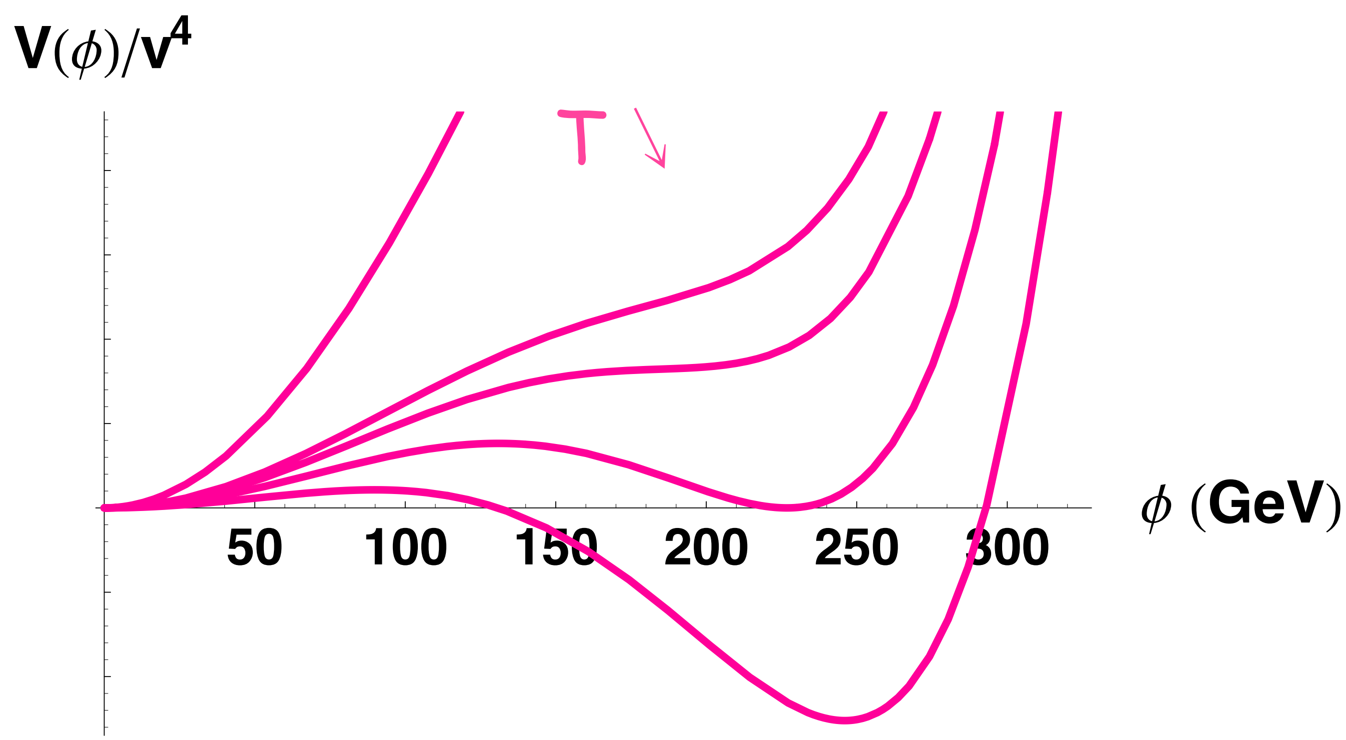
-> Cosmological relaxation of the electroweak scale

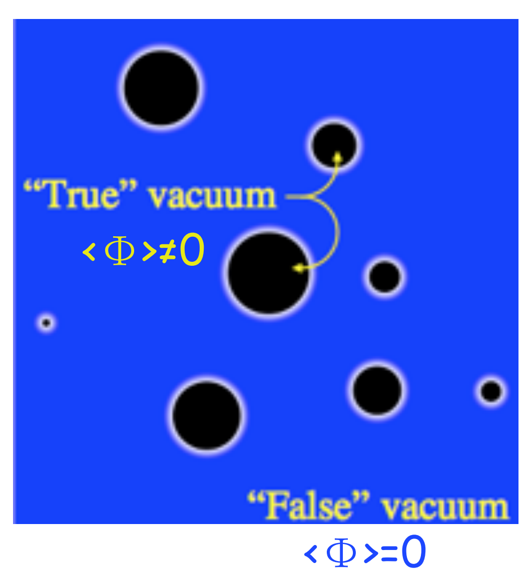
-> Baryogenesis

-> Relativistic degrees of freedom in the early universe

Gravitational Waves from cosmological phase transitions.

Phase transition described by temperature evolution of scalar potential





GW from a 1st-order cosmological phase transition

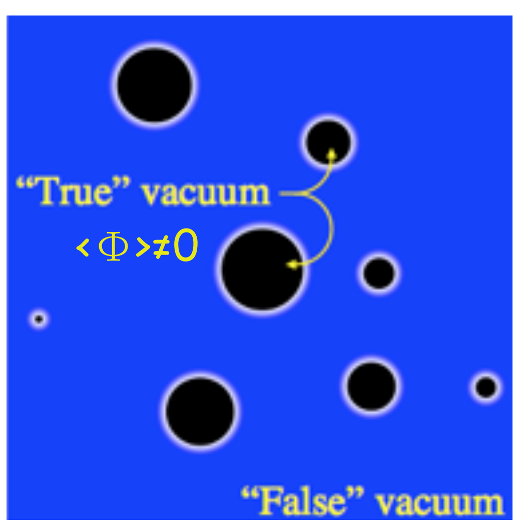
$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 8\pi G a^2 T_{ij}^{(TT)}(k,t)$$

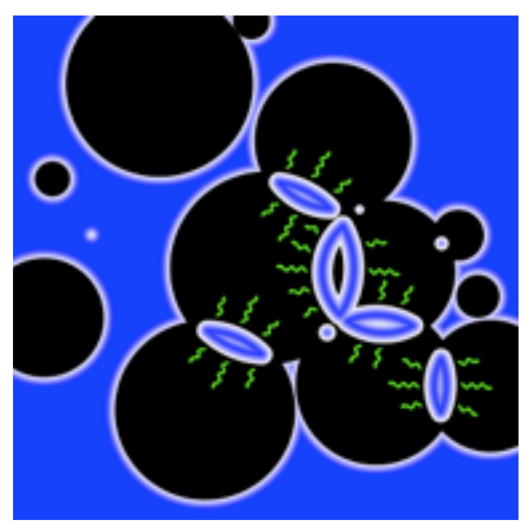
$$T_{ab}(\mathbf{x}) = (\rho + p)\frac{v_a(\mathbf{x})v_b(\mathbf{x})}{1 - v^2(\mathbf{x})}$$

Source of GW:
anisotropic stress

Bubble nucleation

Bubble percolation





$\langle\Phi\rangle = 0$

Fluid flows

turbulence

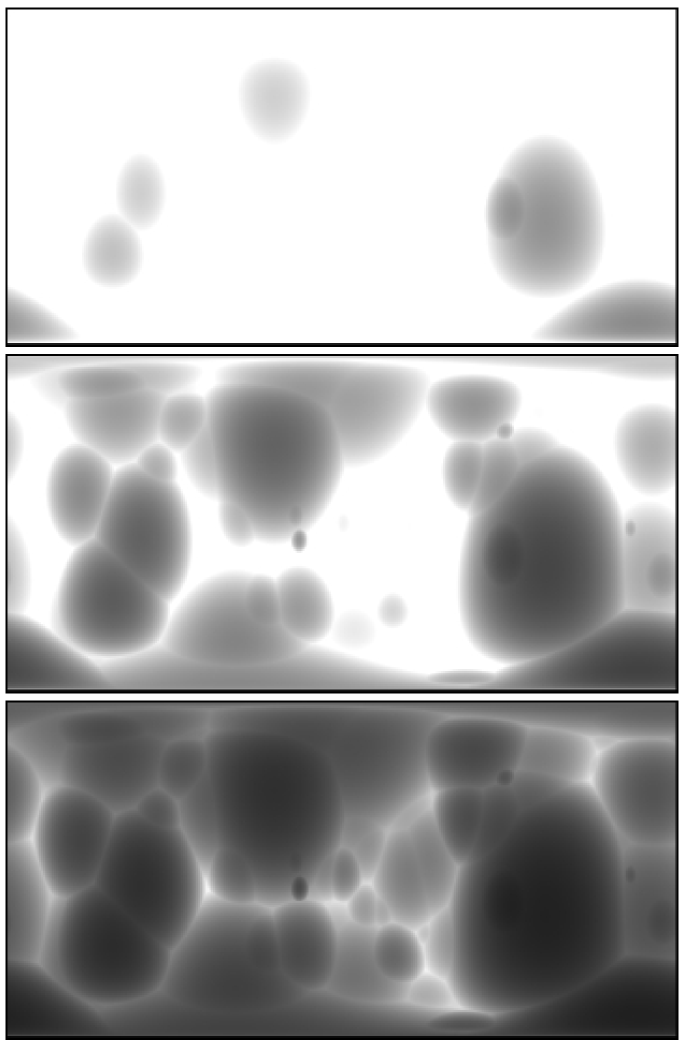
Magnetic fields

GW

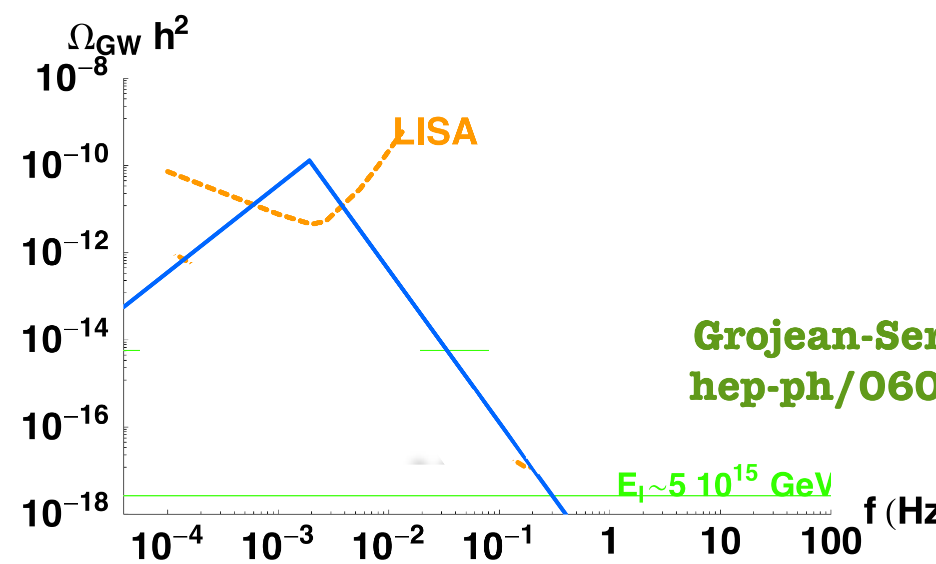
violent process if v

GW from a 1st-order cosmological phase transition

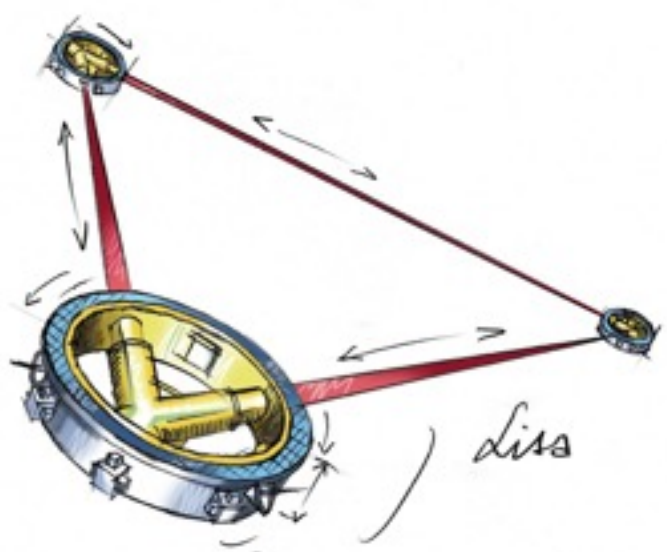
Electroweak Phase Transition
-> milli-Hertz -> LISA!



Konstandin'18



Grojean-Servant
hep-ph/0607107



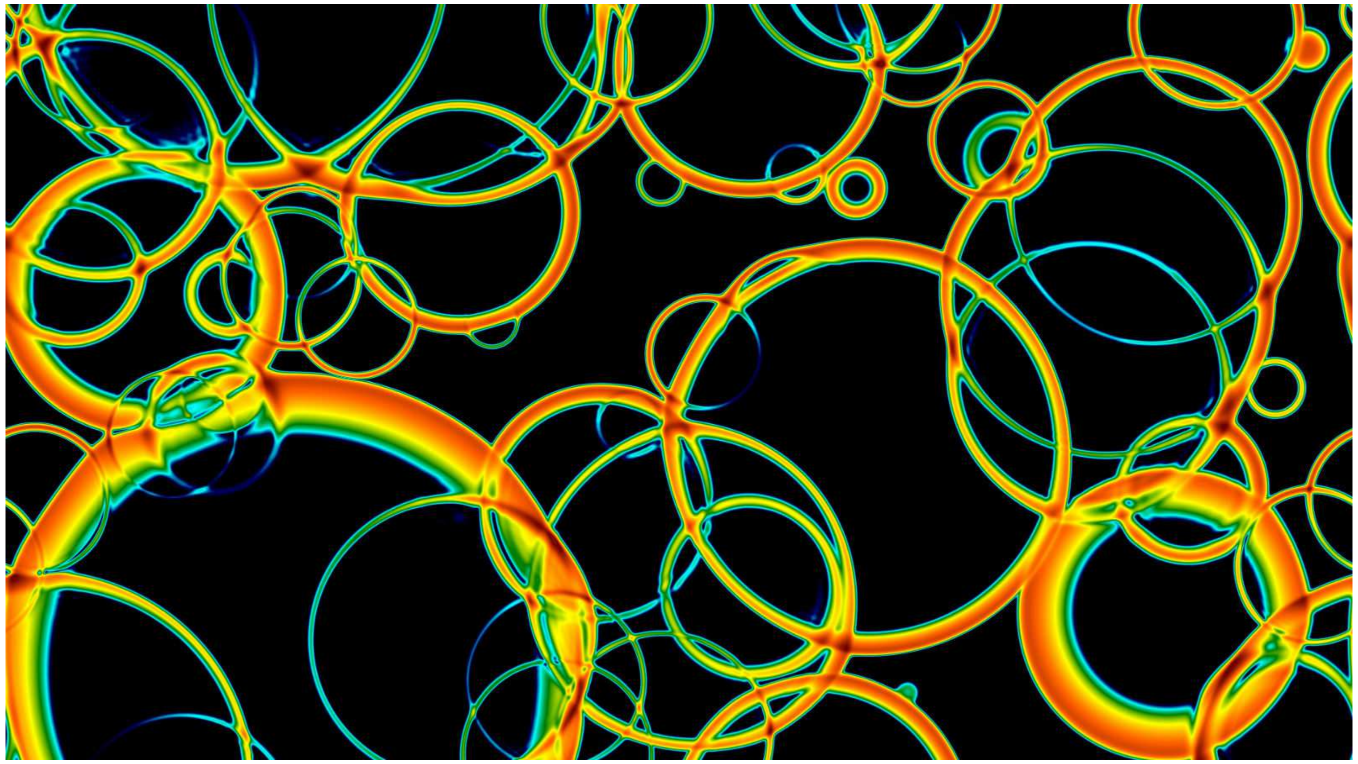
LISA: a new window
on the Weak Scale

complementary to collider informations

First-order Phase Transition in the early universe

Formation of “bubbles”

[simulation: David Weir]



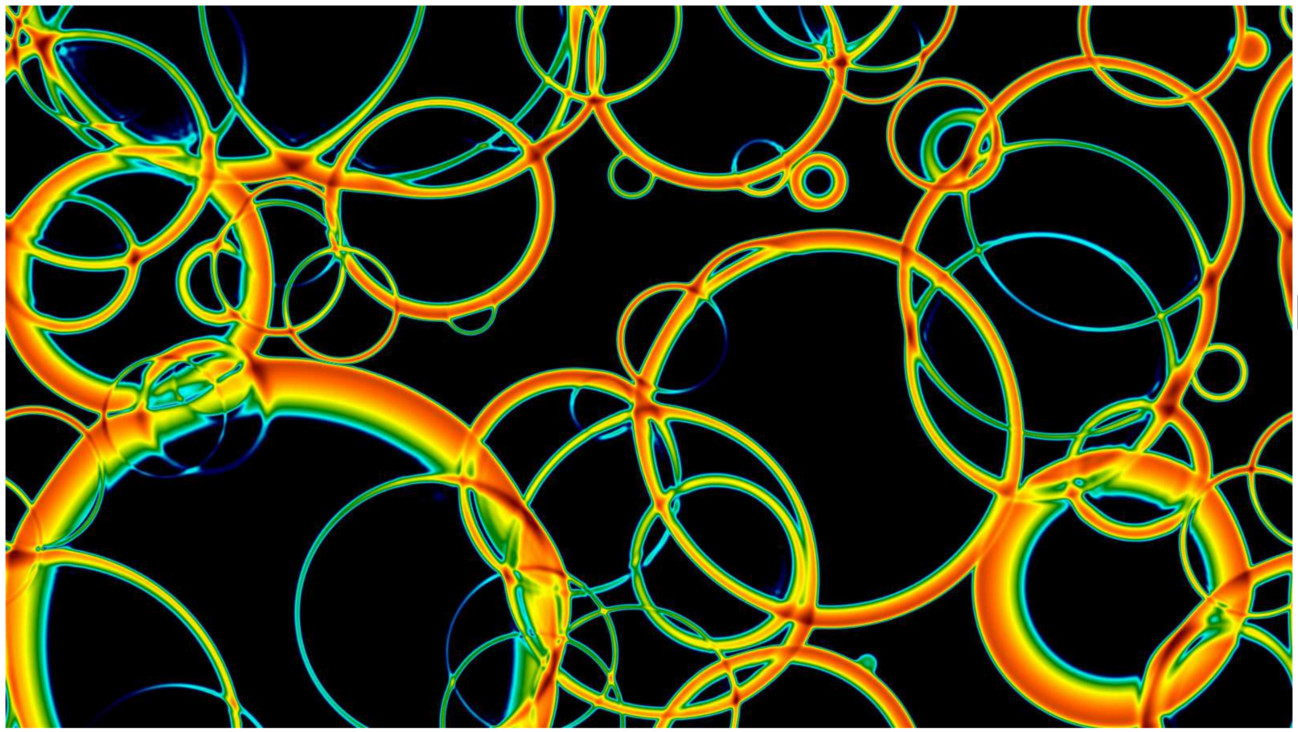
[Credit:David Weir]

- Bubbles nucleate, most energy goes into plasma, then:
  1. $h^2\Omega_\phi$: Bubble walls and shocks collide – ‘envelope phase’
  2. $h^2\Omega_{\text{sw}}$: Sound waves set up after bubbles have collided, before expansion dilutes KE – ‘acoustic phase’
  3. $h^2\Omega_{\text{turb}}$: MHD turbulence – ‘turbulent phase’
- These sources then add together to give the observed GW power:

$$h^2\Omega_{\text{GW}} \approx h^2\Omega_\phi + h^2\Omega_{\text{sw}} + h^2\Omega_{\text{turb}}$$

- Each phase’s contribution depends on the nature of the phase transition.

Gravity wave signals from 1st order cosmological phase transitions



[Credit:David Weir]

[LISA Cosmology Working group, 1512.06239]

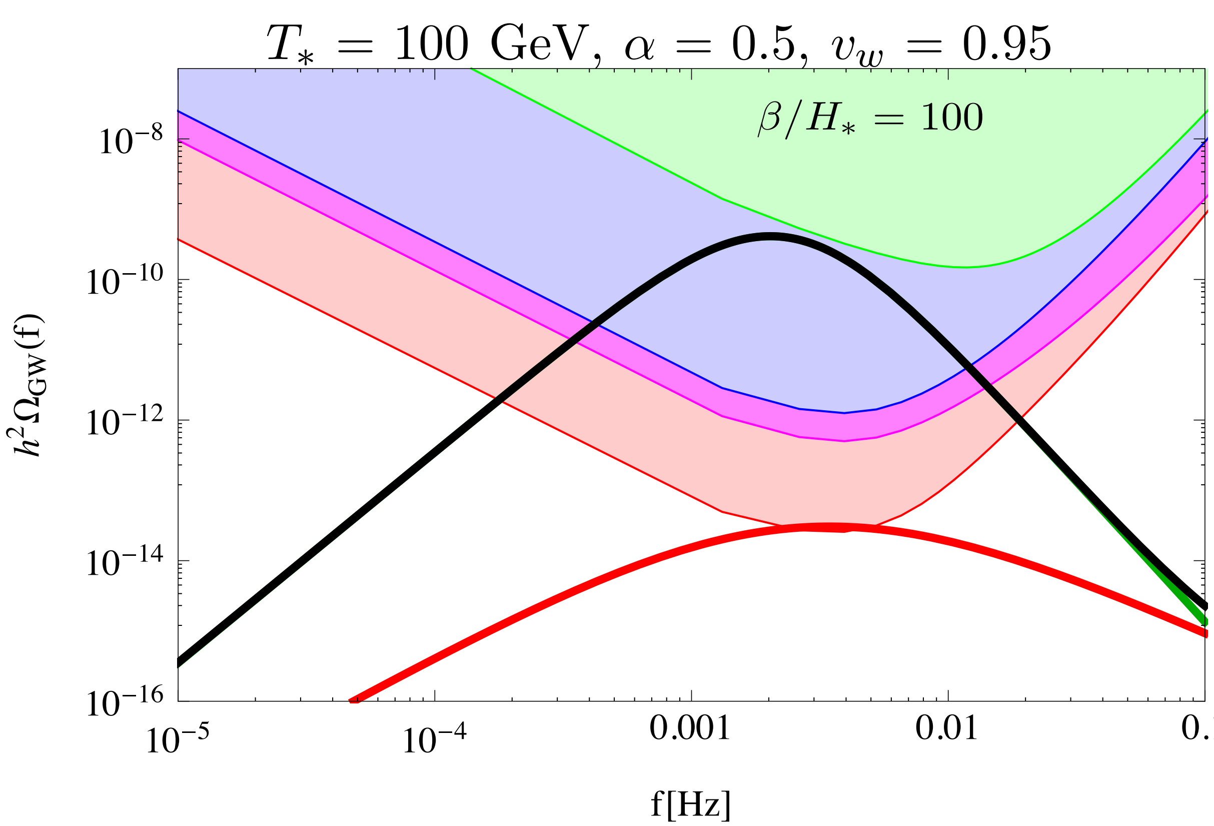
Fluid flows

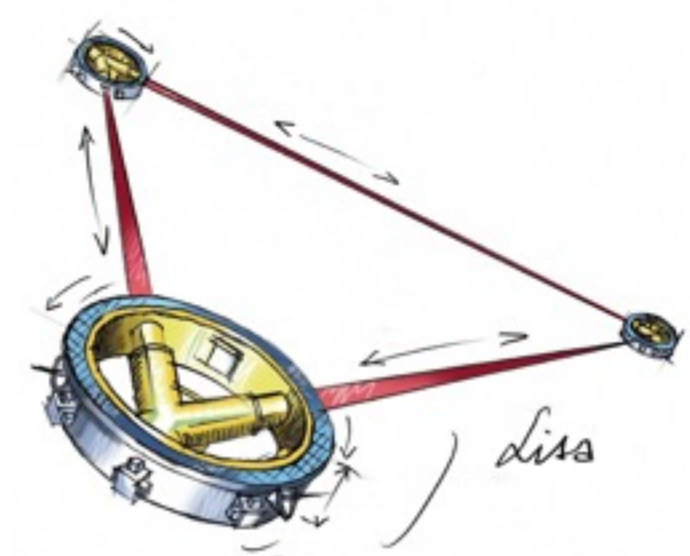
turbulence

Magnetic fields

→ Stochastic background of gravitational radiation

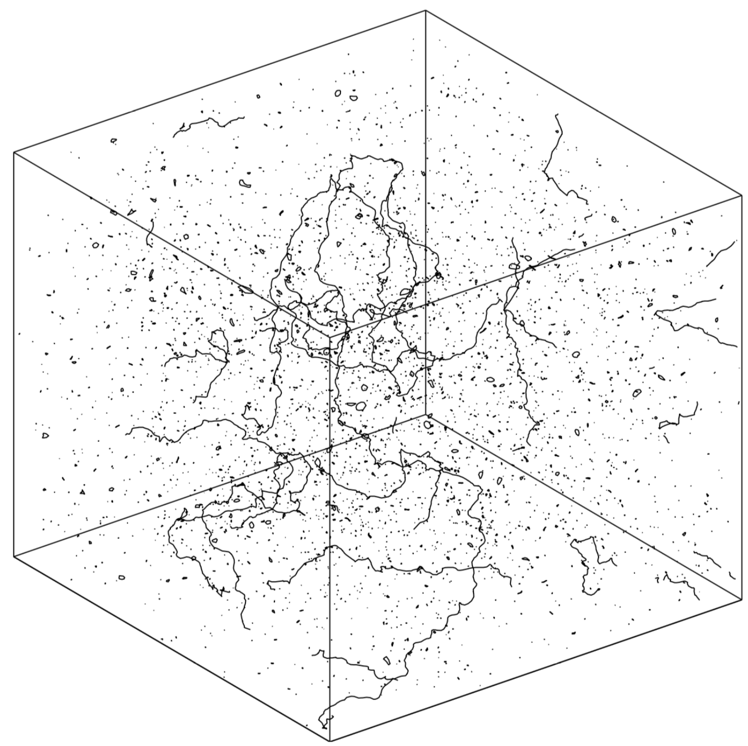
EW phase transition -> mHz -> LISA!





Gravitational Waves from Cosmic Strings.

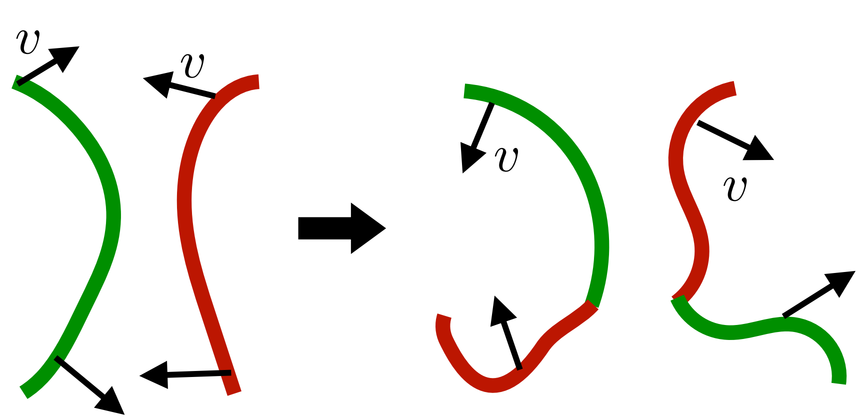
Generated from **symmetry-breaking phase transition** [Kibble1976]

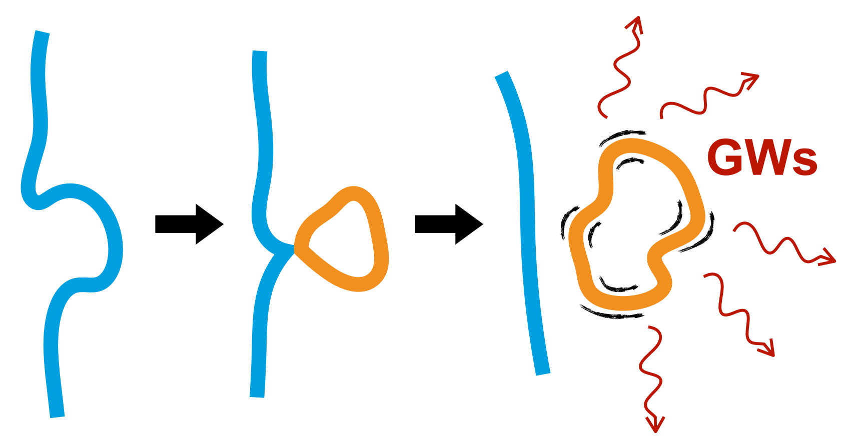


[Allen & Shellard, 1990]

String **inter-commuting**:

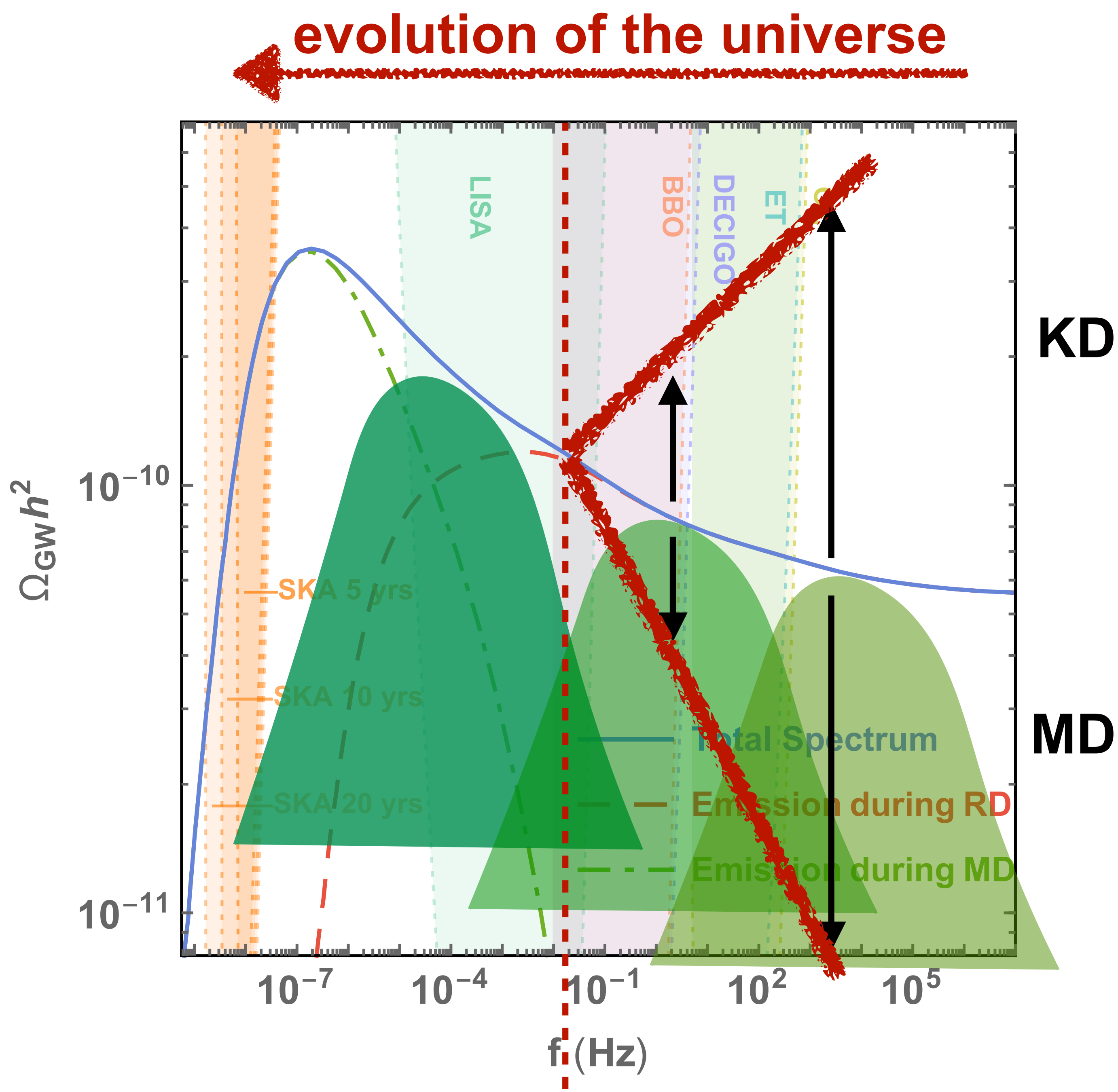
crossing, **loop formation**



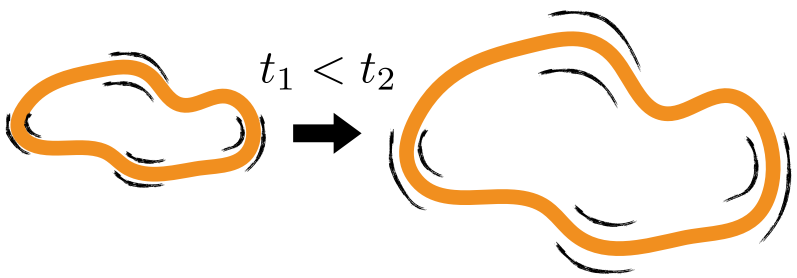


Loops from the string network continuously produced and they decay via emission of gravitational waves

[P. Simakachorn]



Higher f ⇔ Earlier emission



smaller loop ⇔ higher oscillation f

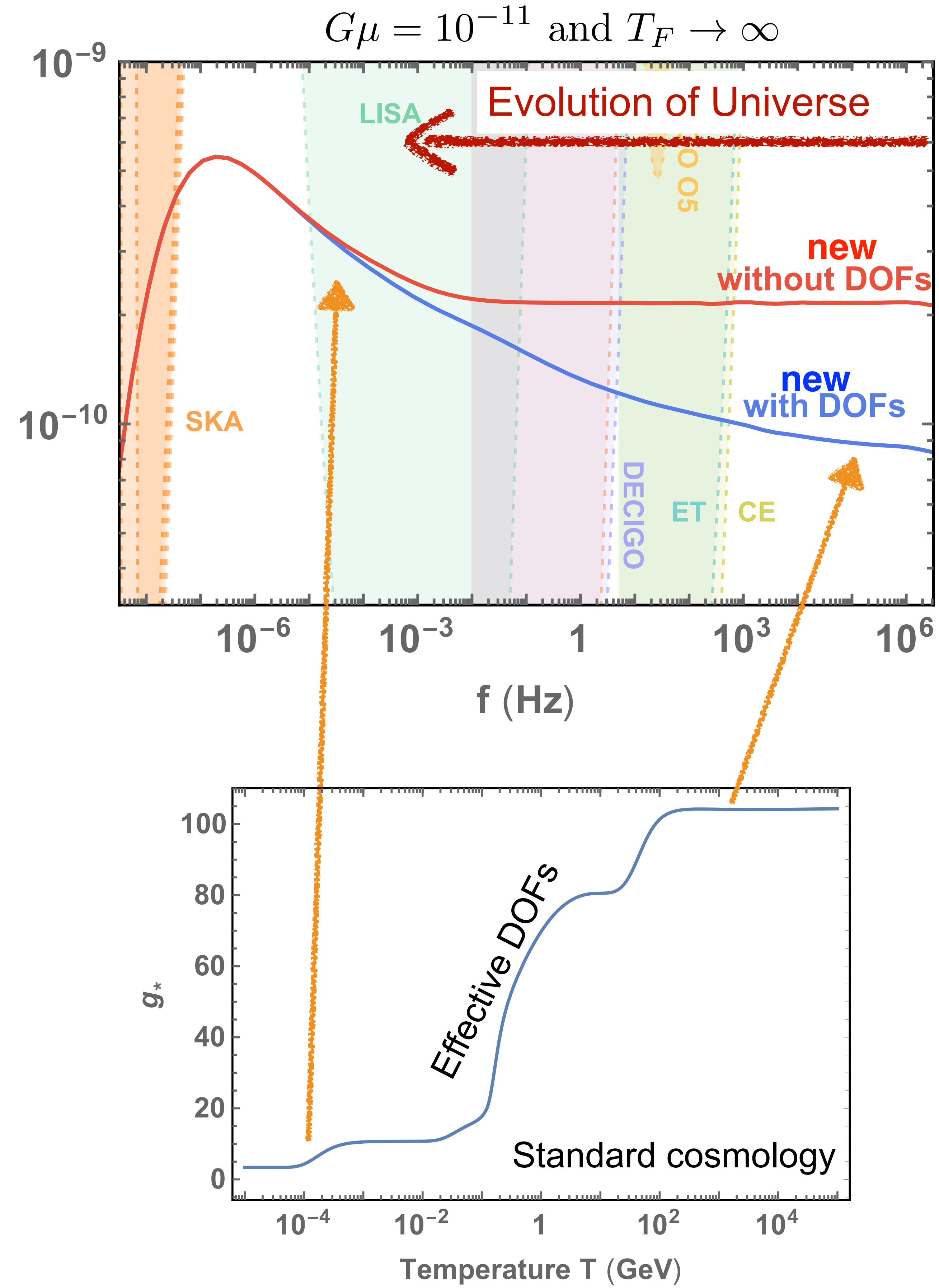
GW from cosmic strings can probe

the **cosmic history** due to a

continuous GW production

$\Rightarrow$ non-standard DOF & eras

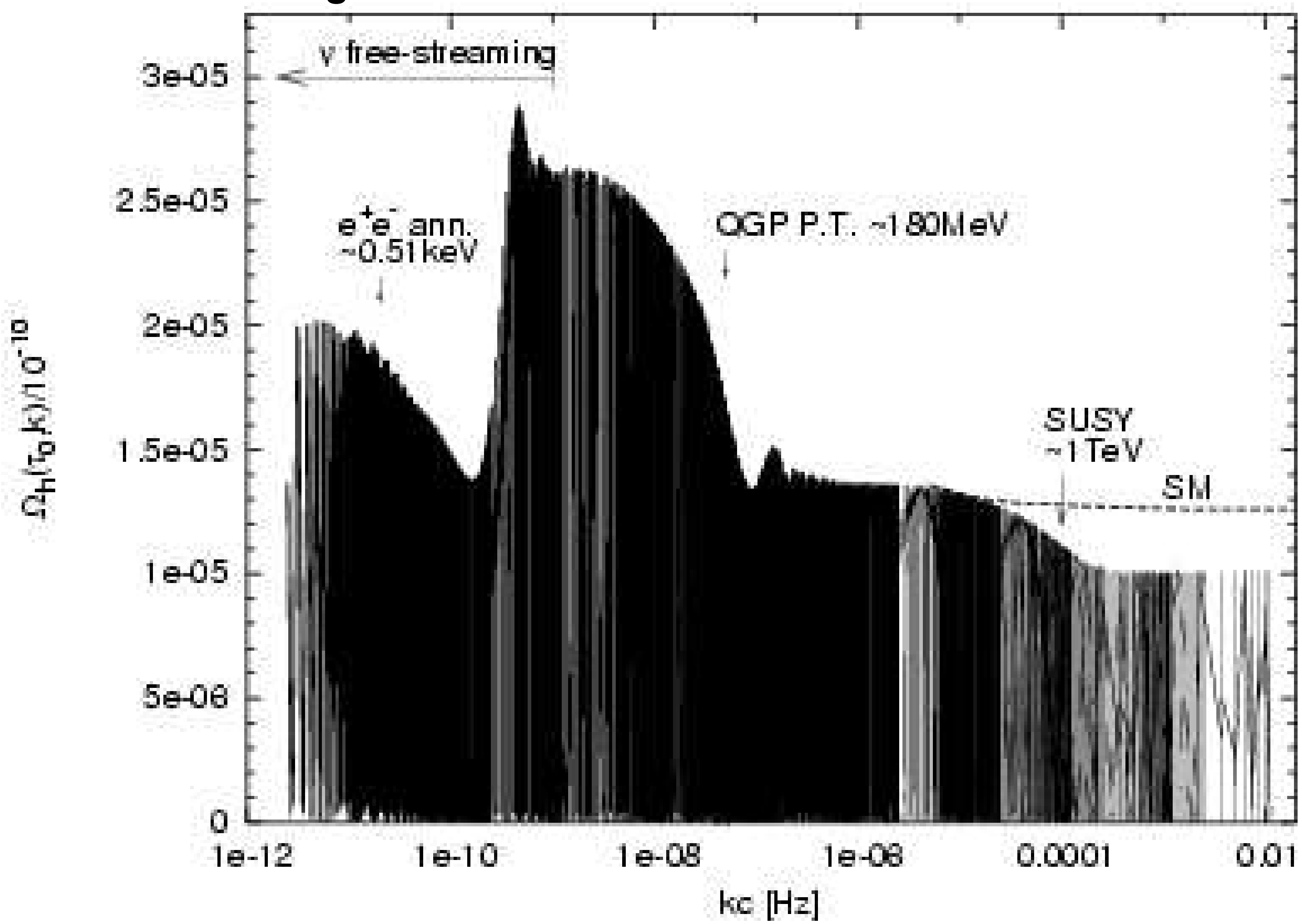
[1808.08968]



Injected entropy in thermal bath

$\Rightarrow$ **Dilution** of the GWs existing before DOF decay

Reading the number of dof in the early universe in features of the GW background from inflation or cosmic strings



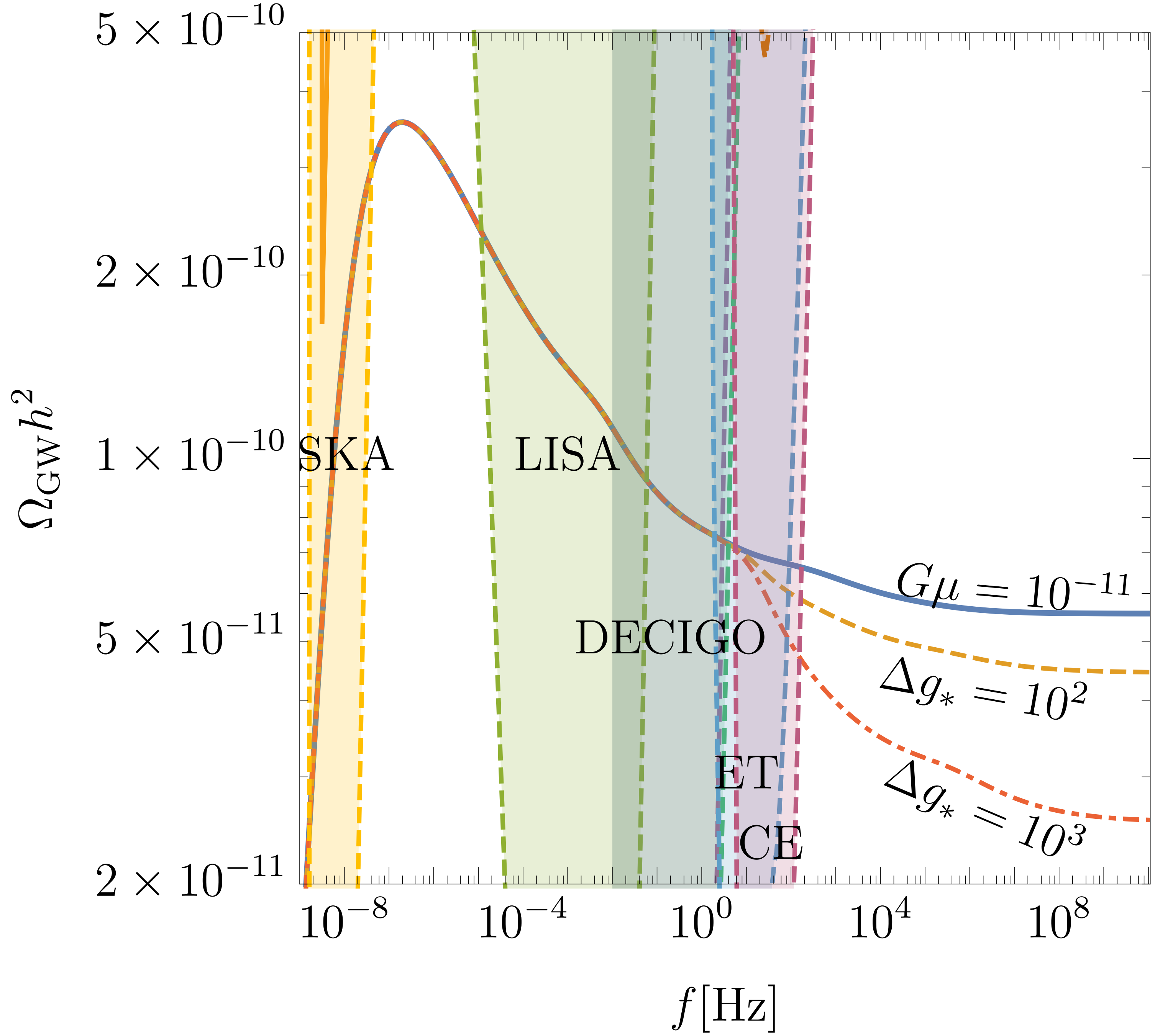
deviate from $\rho \propto a^{-4}$.

Watanabe Komatsu '06

Suppression of GWs from increased number of relativistic degrees of freedom

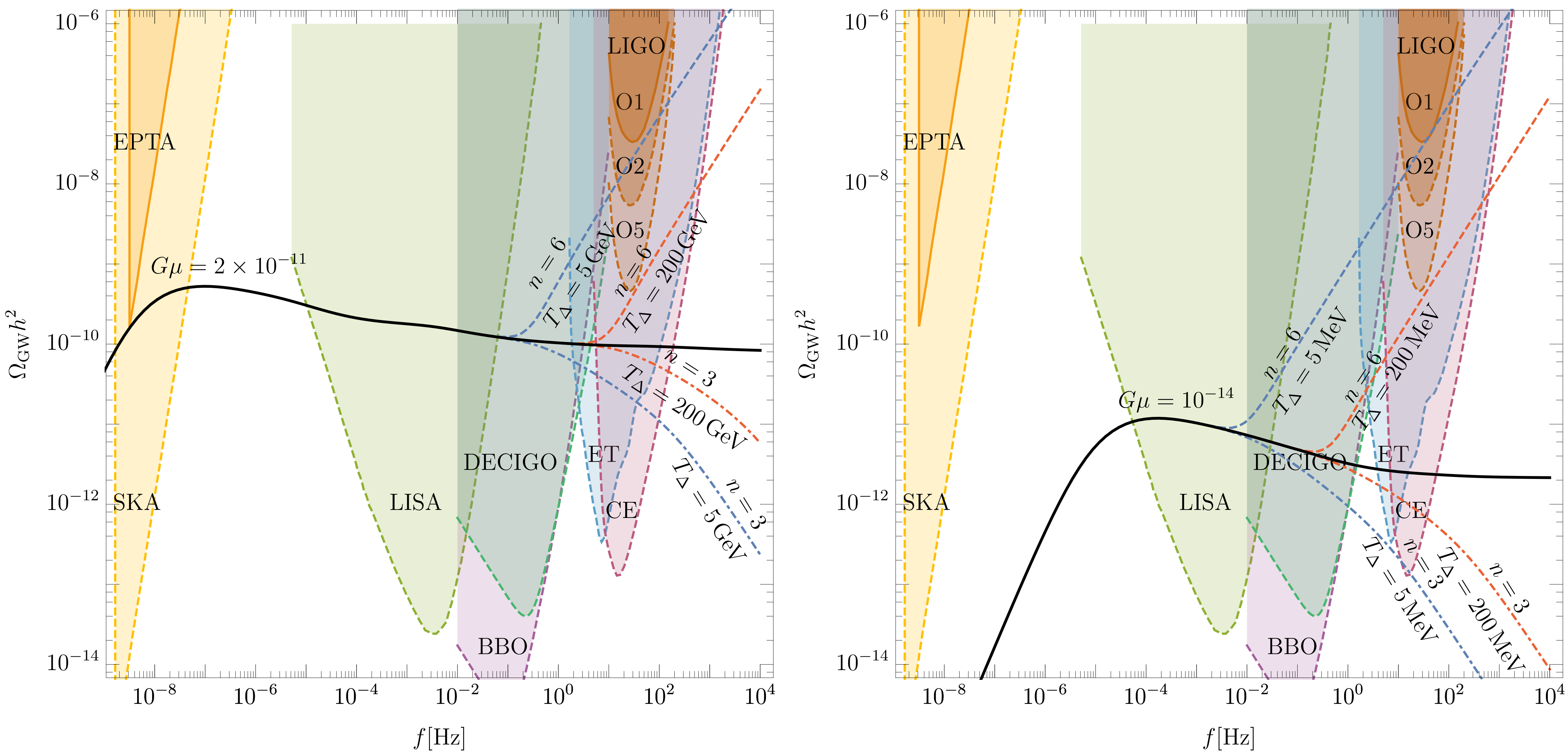
Changes make the evolution of radiation energy density deviate from the conventional adiabatic evolution, $\varrho_r \propto a^{-4}$, and thus cause the expansion rate of the universe to change suddenly at each transition which, in turn, modifies the spectrum of primordial gravitational waves.

Probing equation of state of the early universe



[1808.08968]

Probing non-standard pre-Big Bang Nucleosynthesis evolution of the universe



[1808.08968]

and much more to explore through gravitational waves

-> Cosmological phase transitions

-> Inflation

-> Reheating of the universe

-> Primordial Black Holes from Inflation

-> Dark Matter interactions

-> Mechanism behind mass generation of Dark Matter

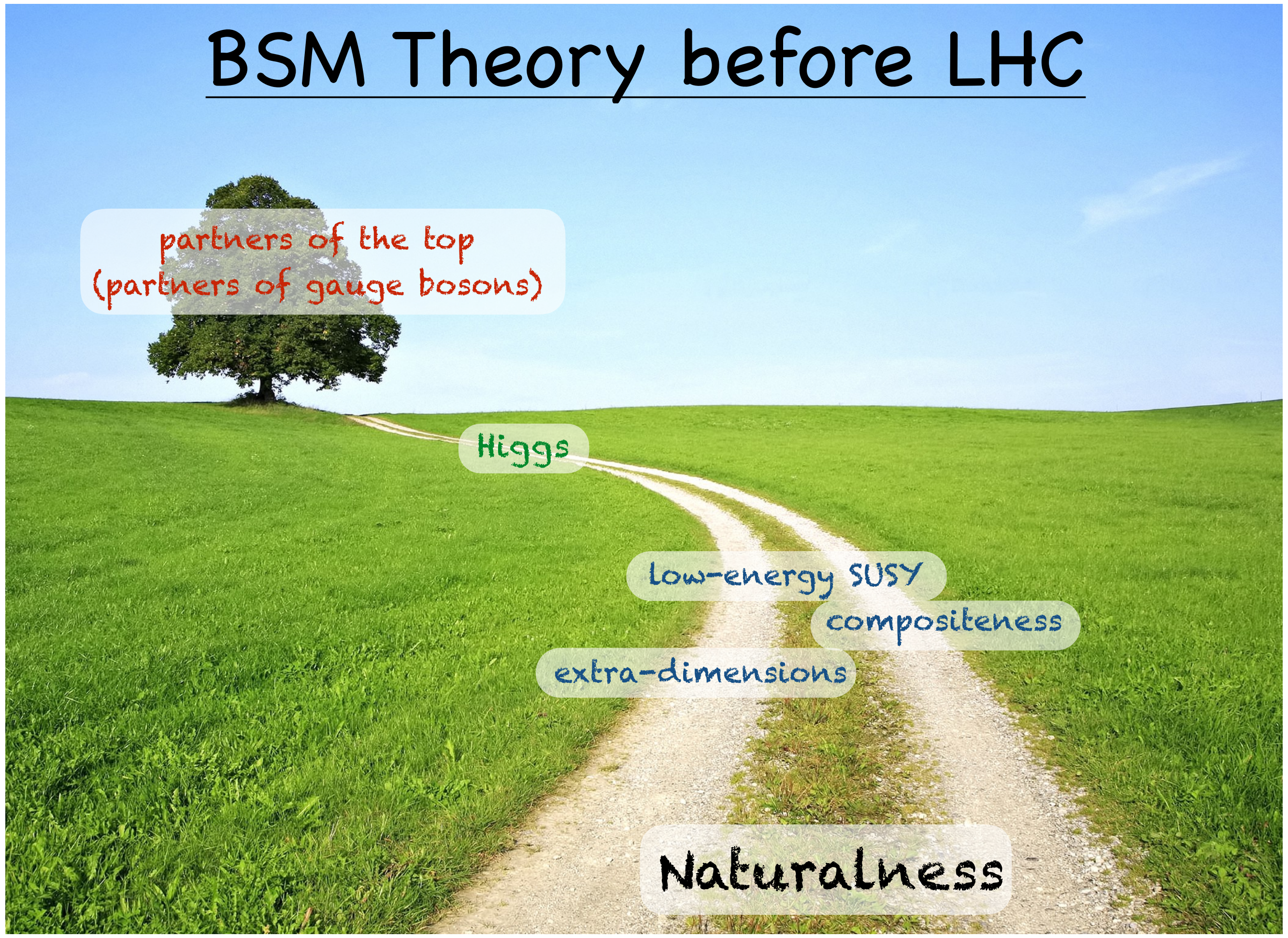
-> Axion-like particles

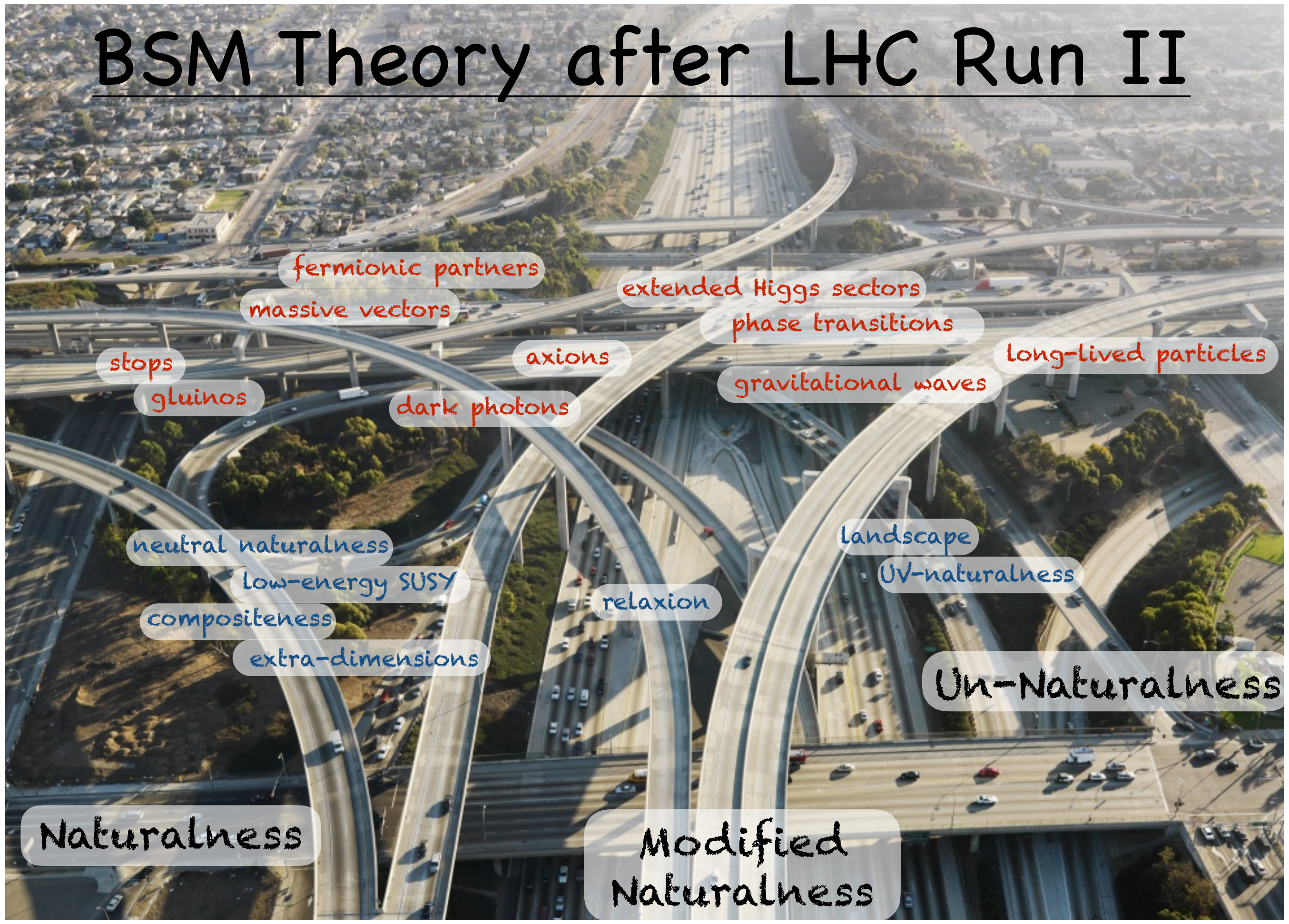
-> Cosmological relaxation of the electroweak scale

-> Baryogenesis

-> Relativistic degrees of freedom in the early universe

Conclusion.





[G. Panico, EPS'19]

Explore alternative theory paradigms

Look for BSM physics in non-colliders experiments

(eg. table-top, cosmological tests, ...)