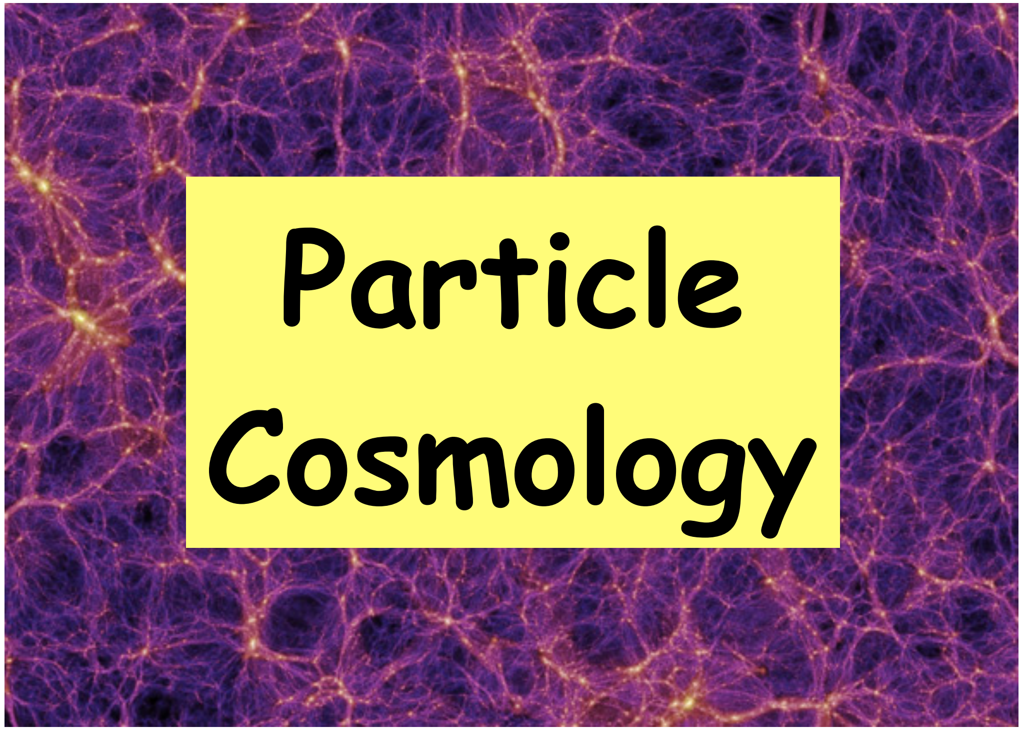

Particle Cosmology

Géraldine SERVANT
DESY/U.Hamburg

80th PRC, Hamburg
October 22 2015

HELMHOLTZ GEMEINSCHAFT

DESY

Particle Cosmology @ DESY

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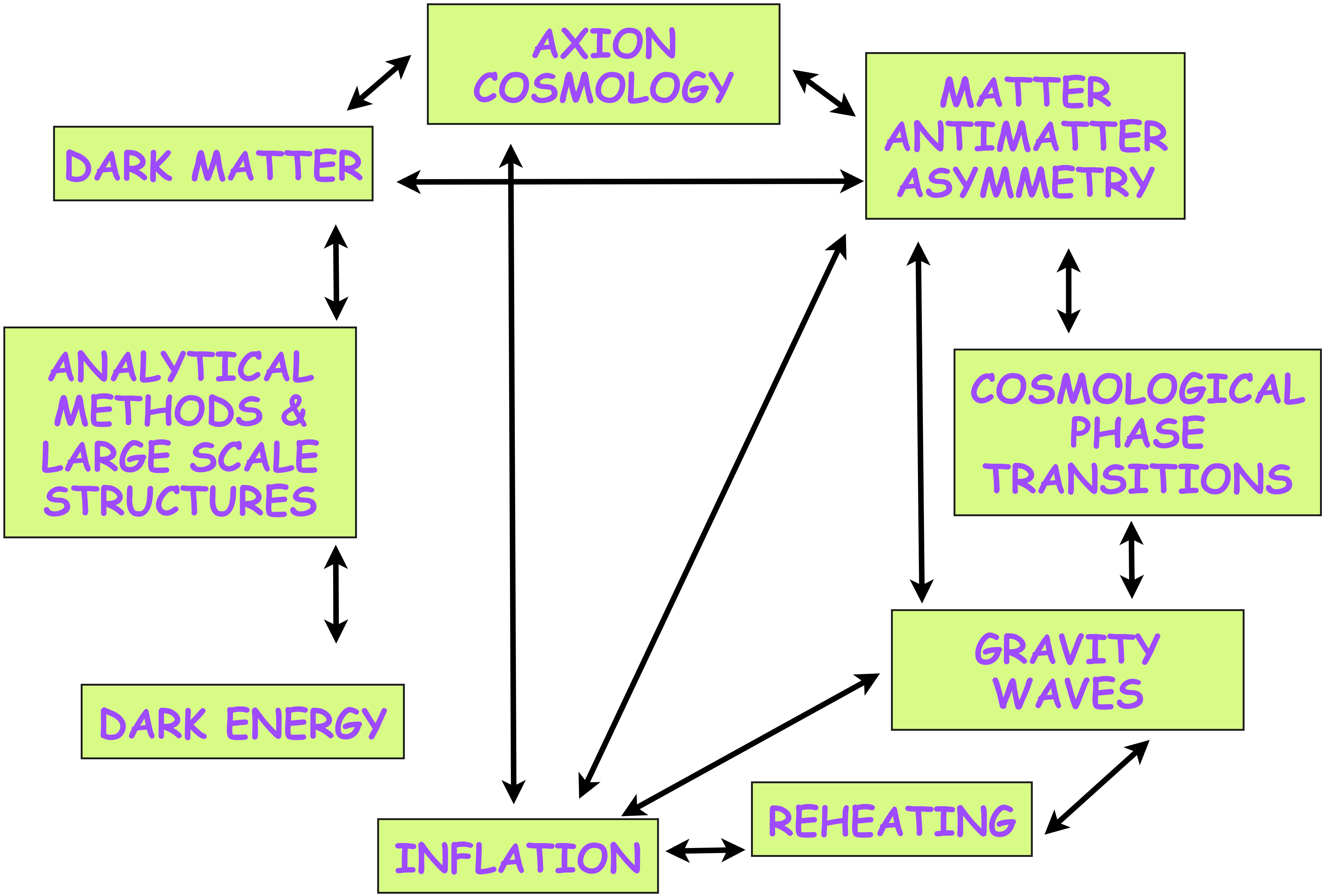
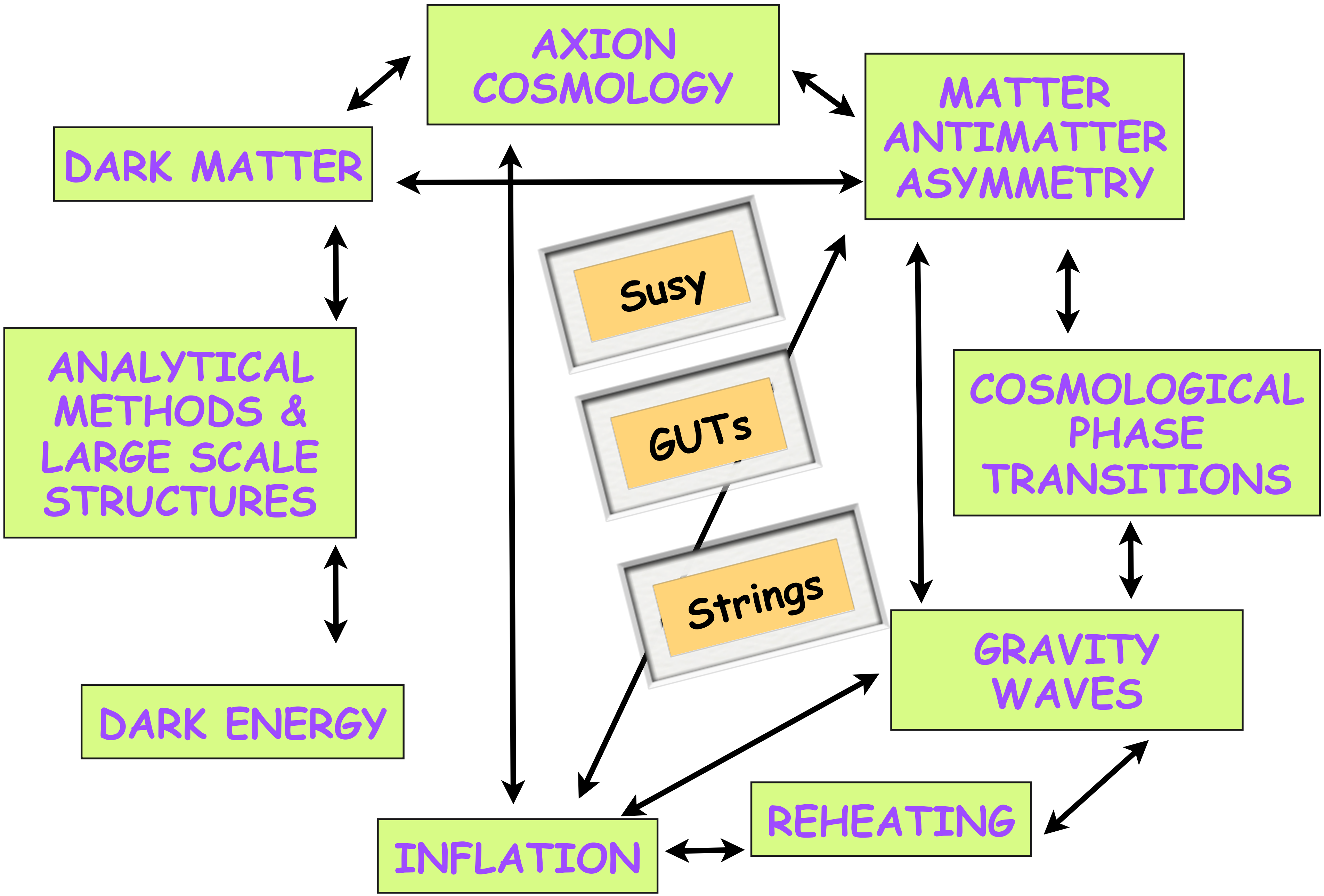
The cosmic frontier plays a crucial role in the global particle physics programme

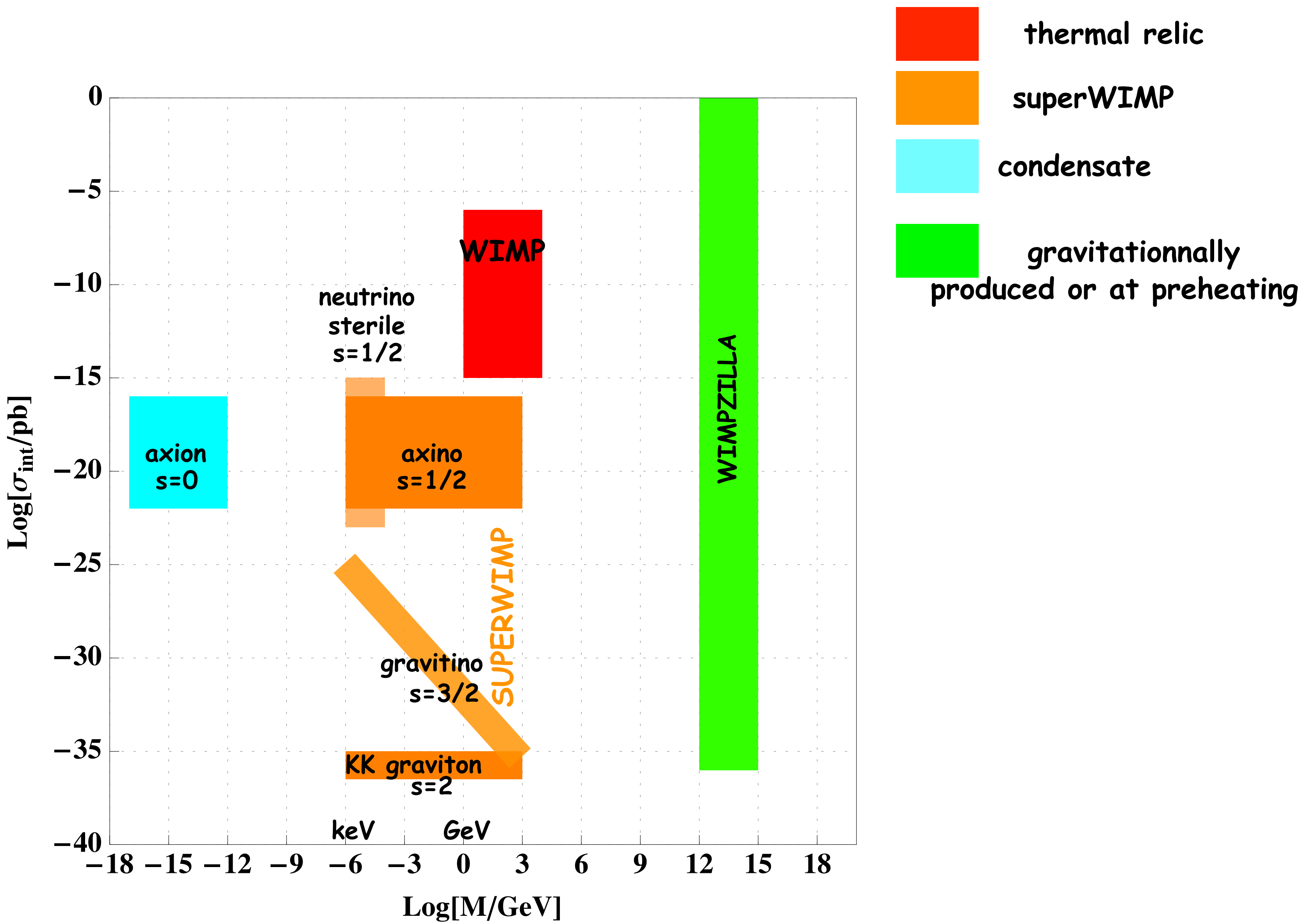
The understanding of the universe goes hand in hand
with our understanding of fundamental forces





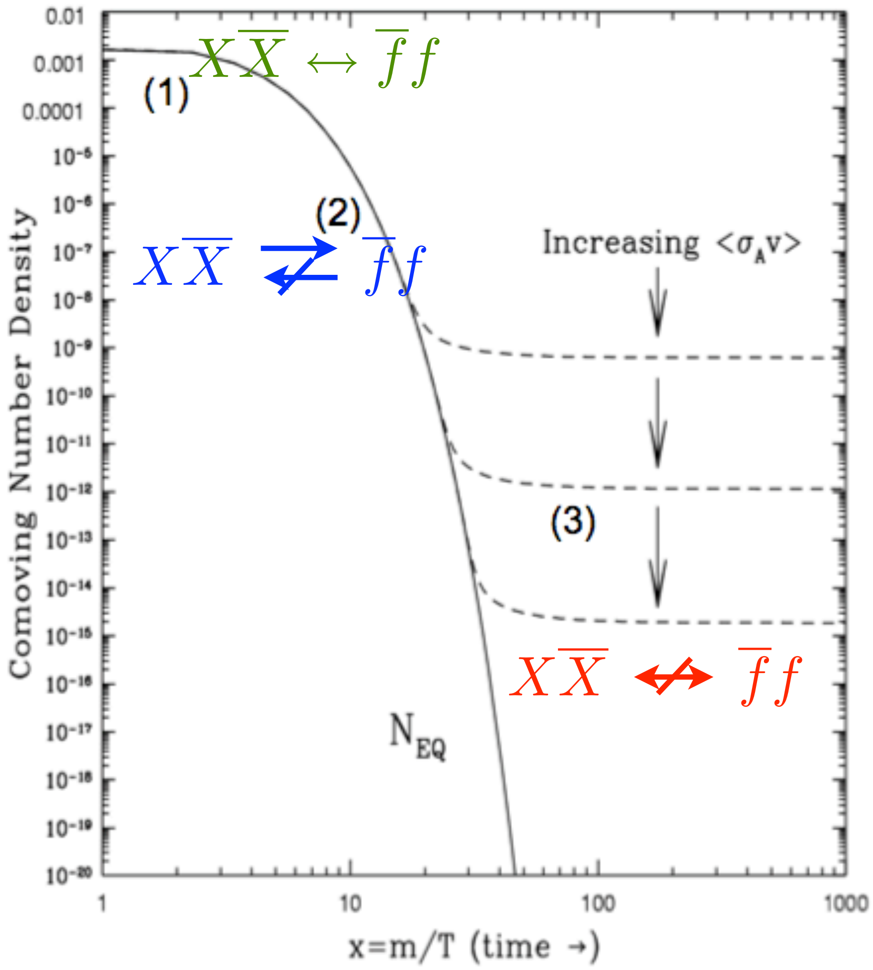
Works in all these interface areas are carried out in DESY

Dark Matter Candidates



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

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

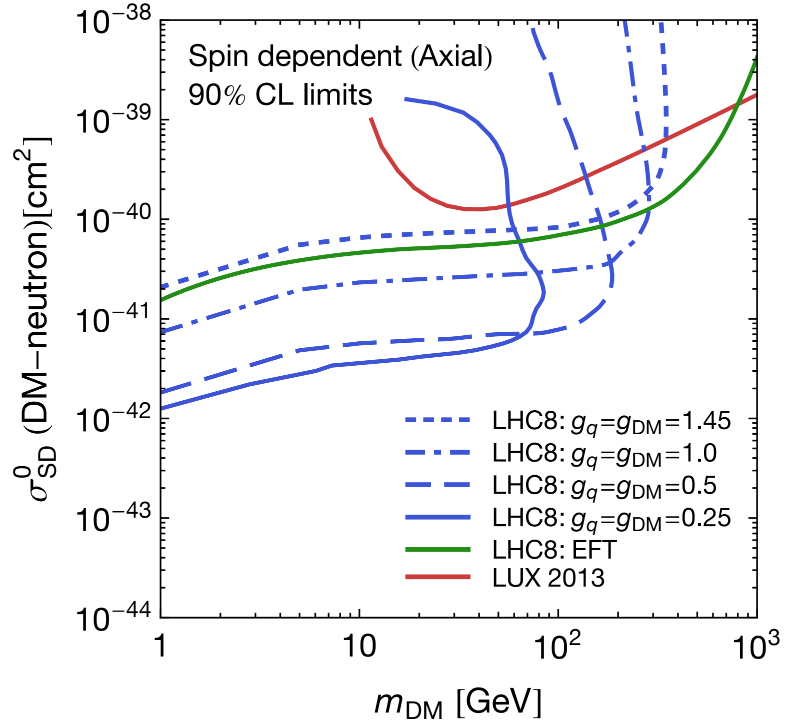
$\Rightarrow$ m ~ 100 GeV

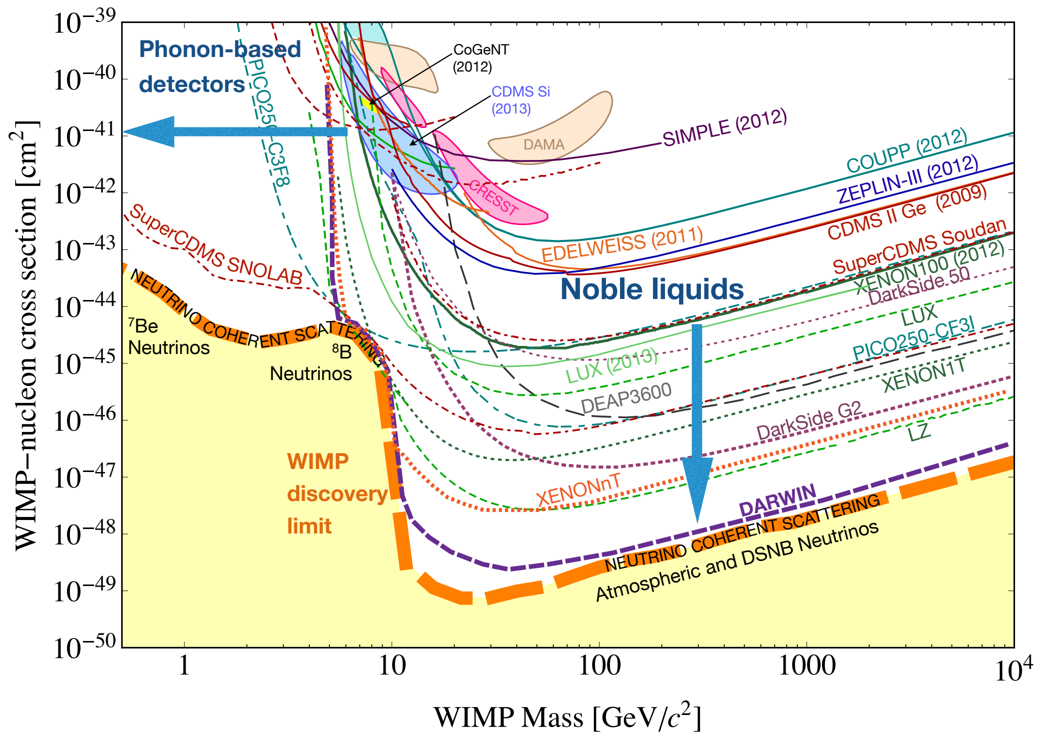
The "WIMP miracle"

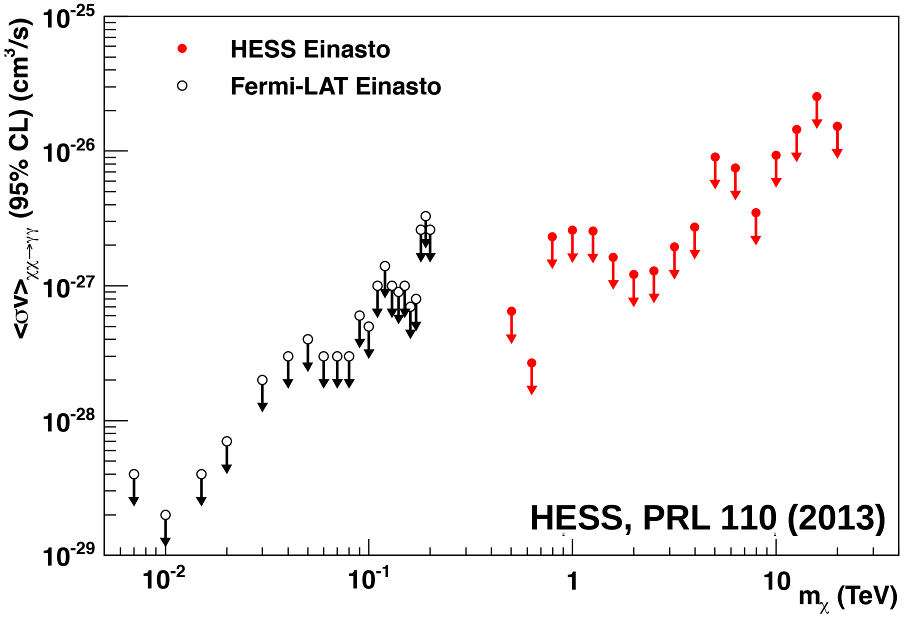
$$\boxed{\Omega_{DM} \approx \frac{O(1)\ \text{pb}}{\sigma_{anni}}}$$

→ a particle with a typical EW-scale cross section $\sigma_{anni} \approx 1$ pb leads to the correct dark matter abundance.

Wimps under pressure from the LHC, Fermi, Xenon, LUX ...

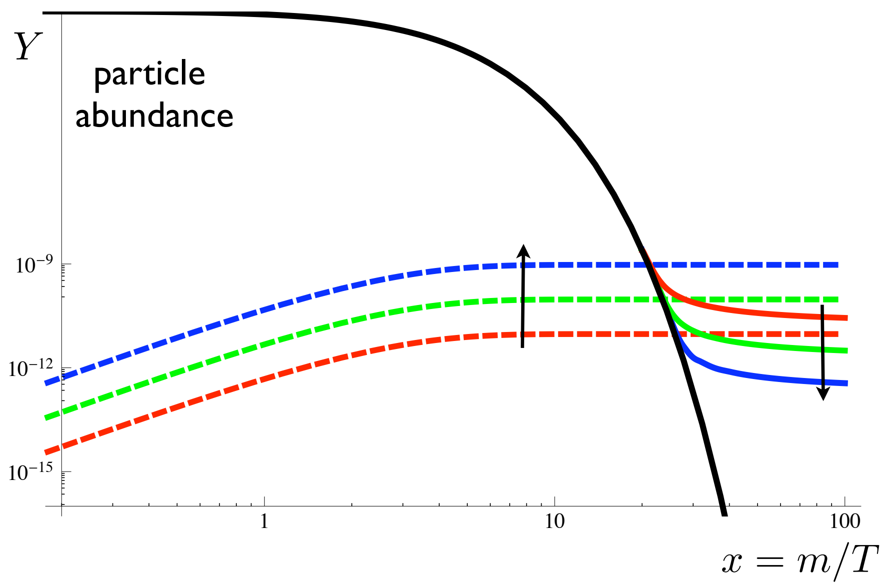






Beyond WIMPS. Dark Matter production mechanisms

- Freese-in versus Freese-out



- Freese-out and decay

- Non-thermal, e.g. from preheating

- Asymmetric production

- Misalignment

...

CLOSING IN ON THE WIMP PARADIGM

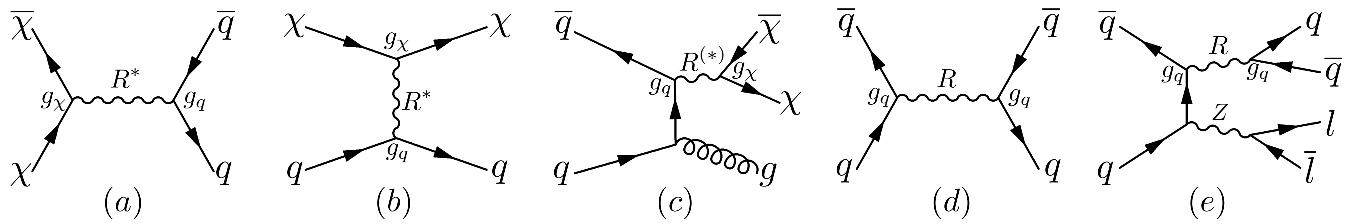
- Underground direct searches for light DM
- Indirect searches of DM annihilations in cosmic rays
- Direct DM production at LHC
- Non-minimal DM models
- Displaced objects at colliders
- DM at future colliders

DARK MATTER – LHC Connection

Constraining Dark Sectors with Monojets & Dijets

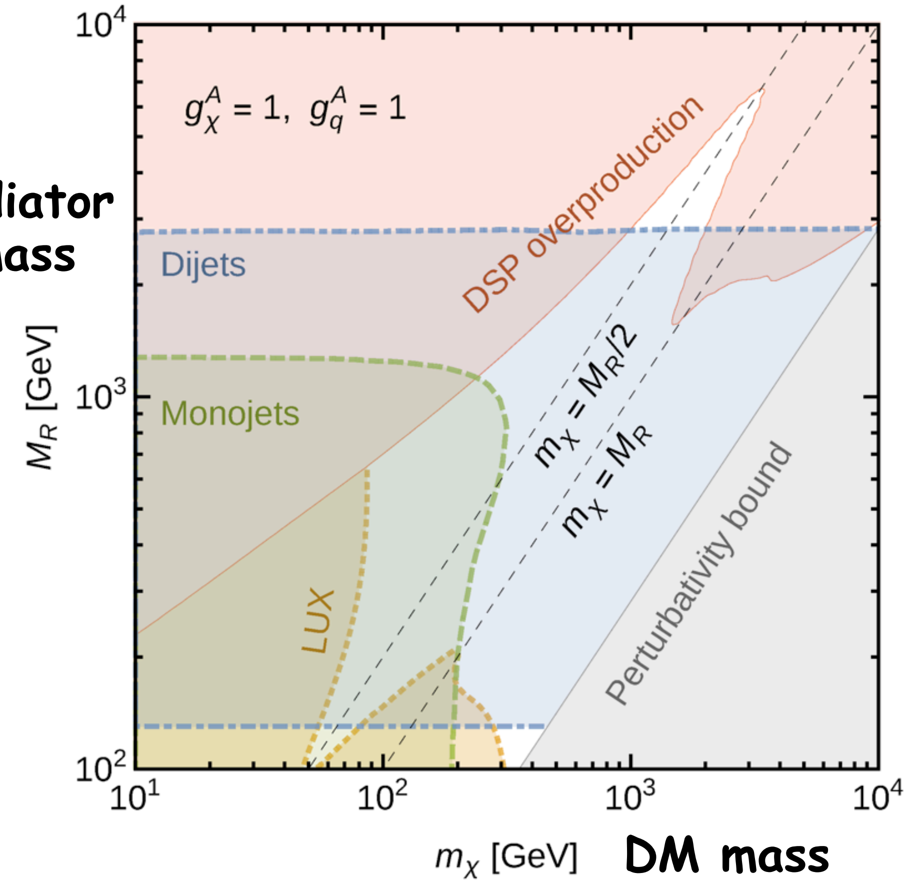
[Chala, Kahlhoefer, McCullough, Nardini, Schmidt-Hoberg, 1503.05916]

Complementarity between monojets, dijets, direct detection & relic abundance



DM annihilation | **DM scattering** | **monojet** | **dijet** | **dijet associated production**

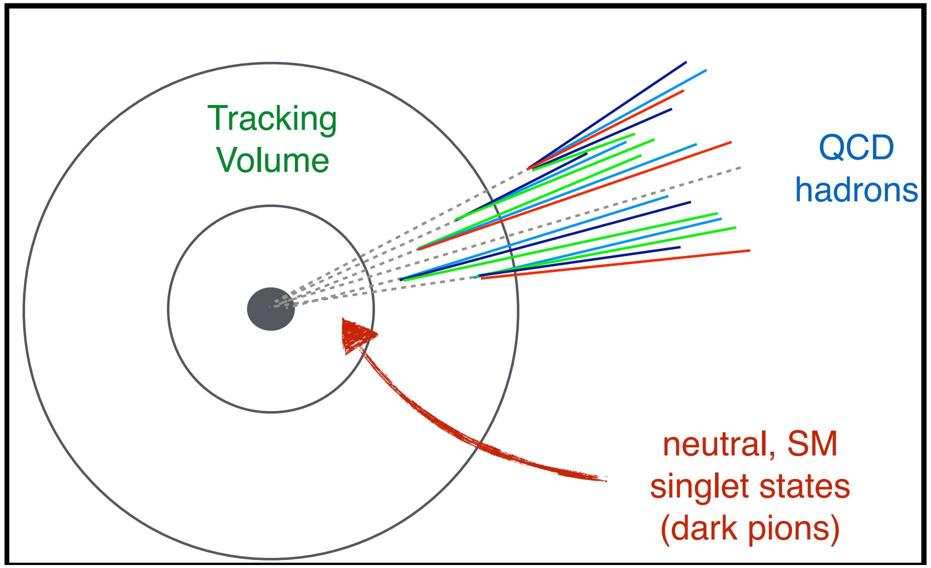
Mediator mass



DM mass

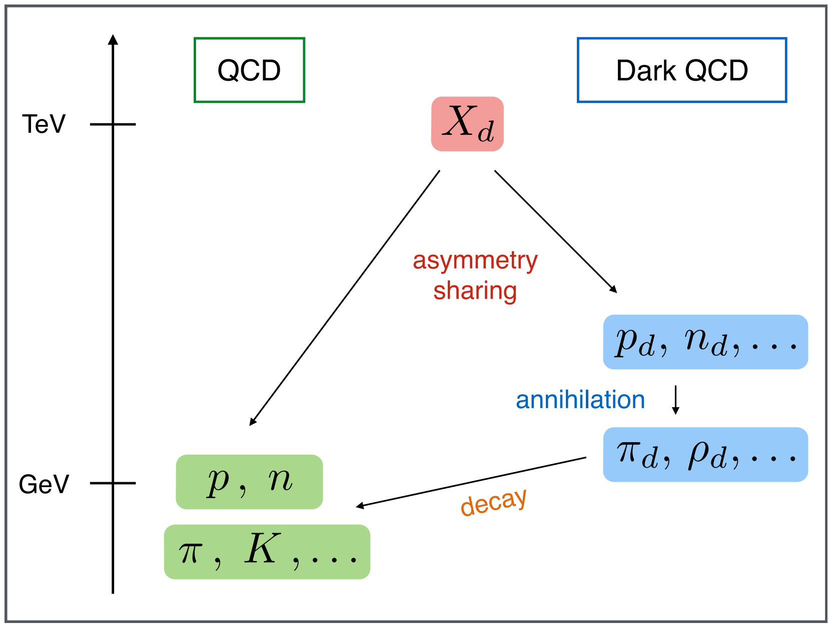
Displaced Collider Signals: "Emerging Jets" from composite dark sectors

[Schwaller, 1502.0540]



Dark QCD

Connecting Dark Matter and Baryogenesis



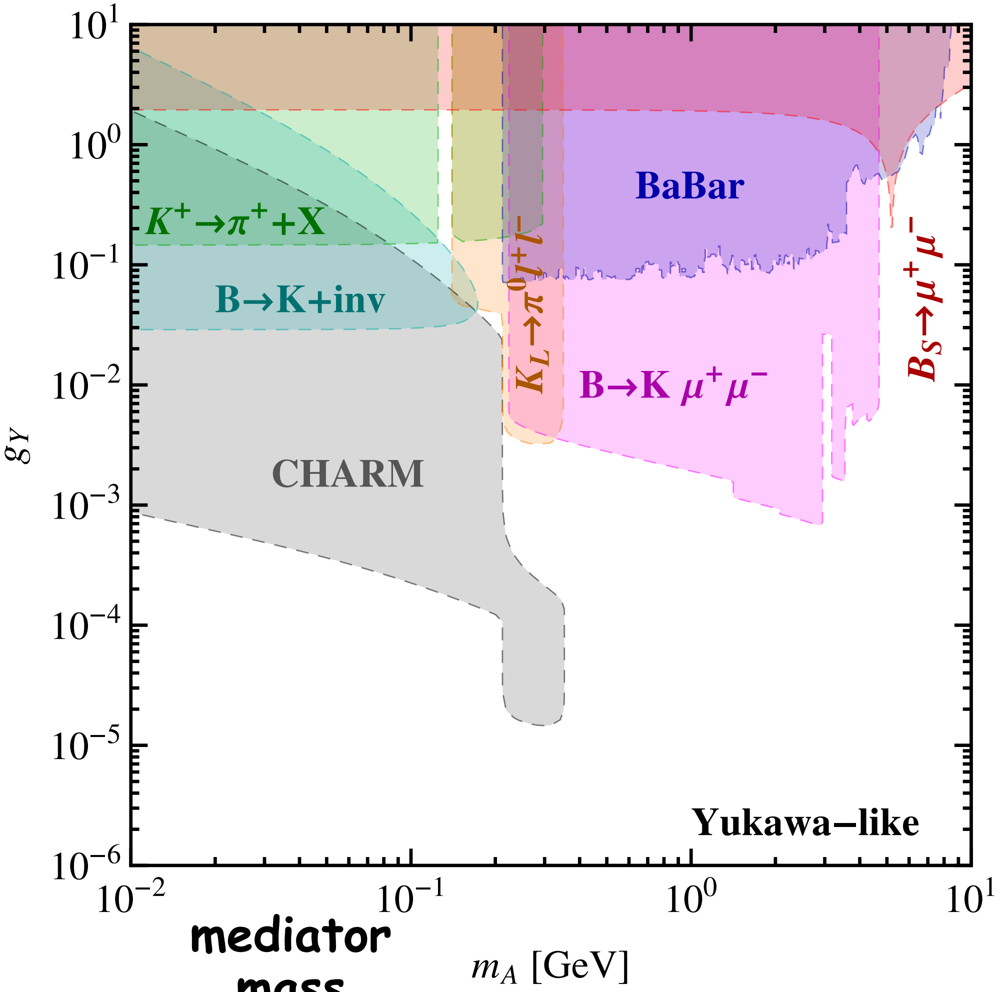
DARK MATTER - Flavour Connection

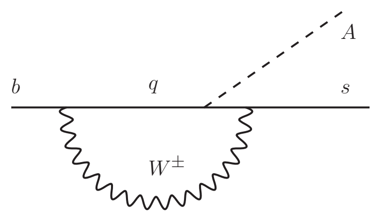
Dark Matter-Flavour Connection

Dolan, Kahlhoefer, McCabe, Schmidt-Hoberg, 1412.5174

Constraints on light (sub-GeV) pseudo-scalar mediators from rare meson decays (otherwise allowed by direct searches & LHC)

mediator mass





mediator mass

DARK MATTER & Astrophysics

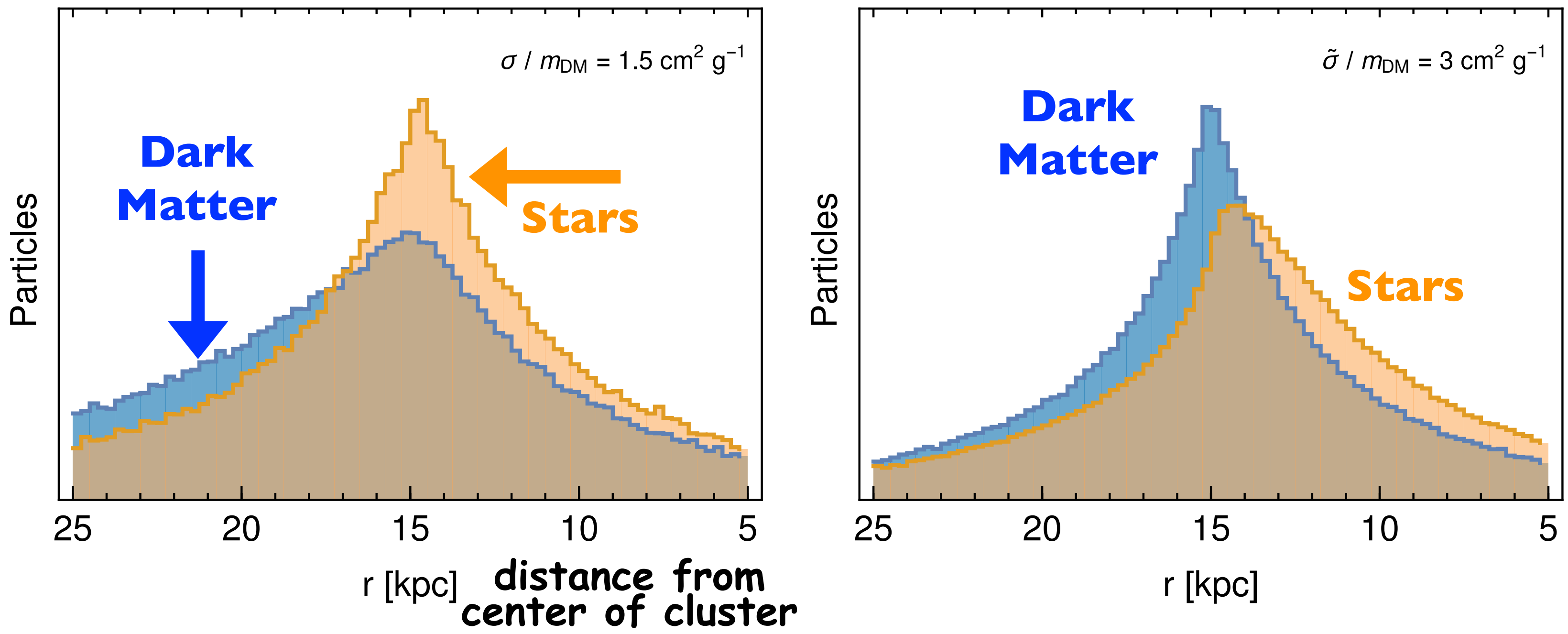
Astrophysical probes of self-interacting Dark Matter

DM Self interactions can lead to observable separation between the DM halo and the stars of a galaxy

Drag force slows down any DM subhalo falling into a larger DM halo compared to objects experiencing only gravitational forces, such as the stars bound in the subhalo.

Interpretation of separation between DM and stars in galaxy cluster Abell 3827 due to DM self-interactions

[Kahlhoefer, Schmidt-Hoberg, Kummer, Sarkar 1504.06576]



very large cross section needed. In tension with other astro observations.

DARK MATTER and Large Scale Structures

Analytical models & Large scale structures

Cosmological perturbation Theory at 3-loop order

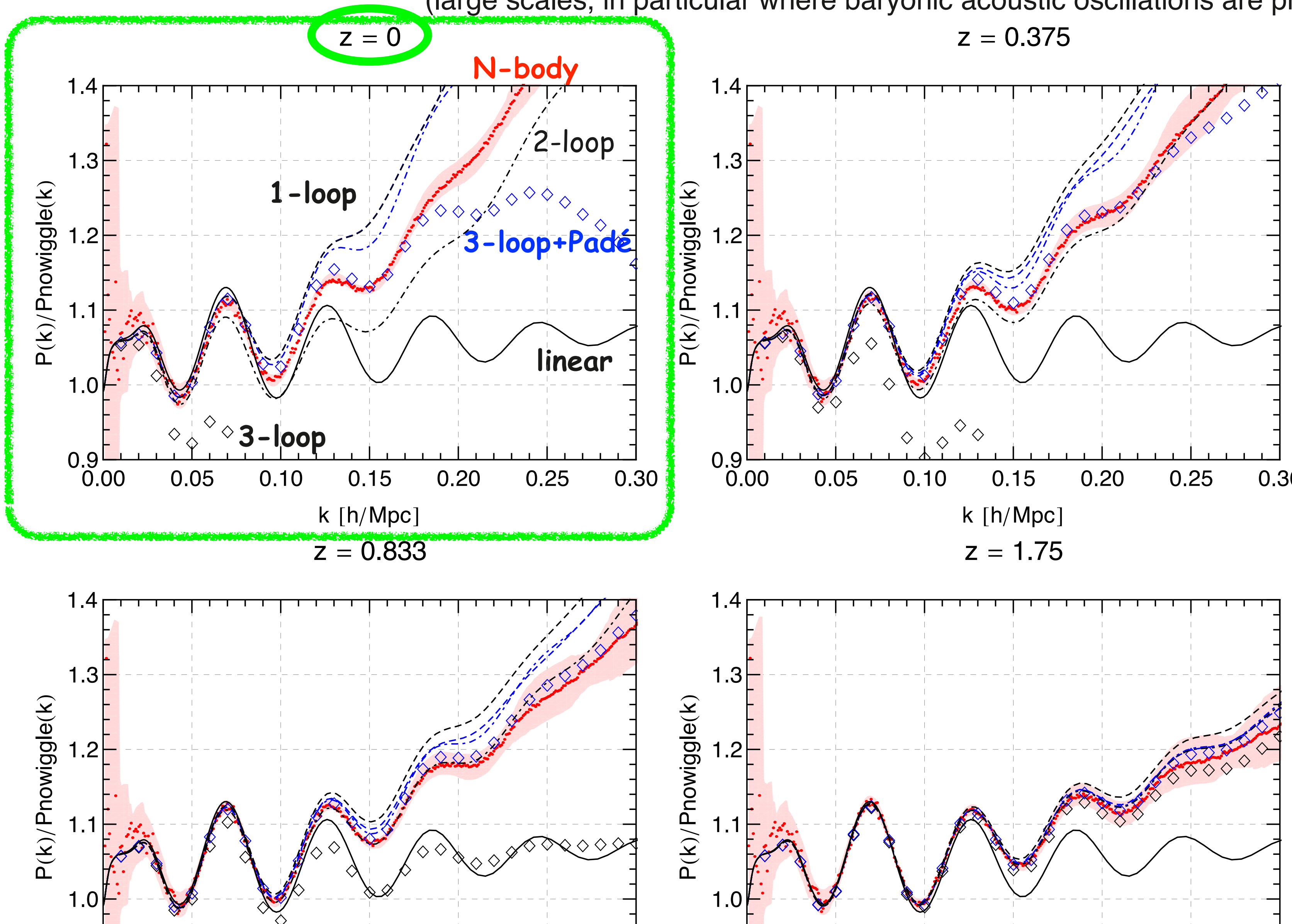
[Blas, Garny, Konstandin 1309.3308]

Large-scale structure surveys are the next leading probe for precision cosmology

Analysis of Dark Matter power spectrum at three-loop order in standard perturbation theory of large scale structure.

Restoration of the convergence in the limit of small momentum (large scales, in particular where baryonic acoustic oscillations are present).

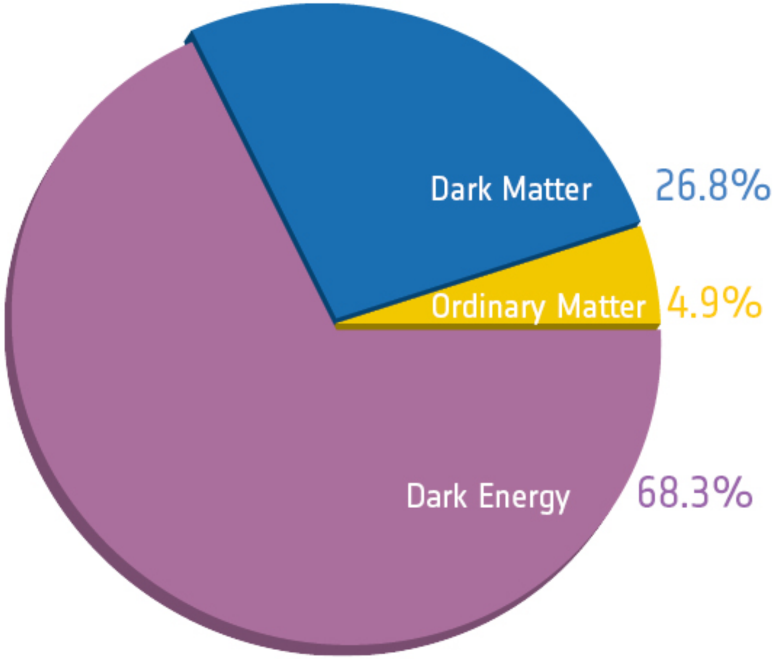
Comparison with data from N-body simulations at different redshifts



DARK MATTER – BARYOGENESIS CONNECTION

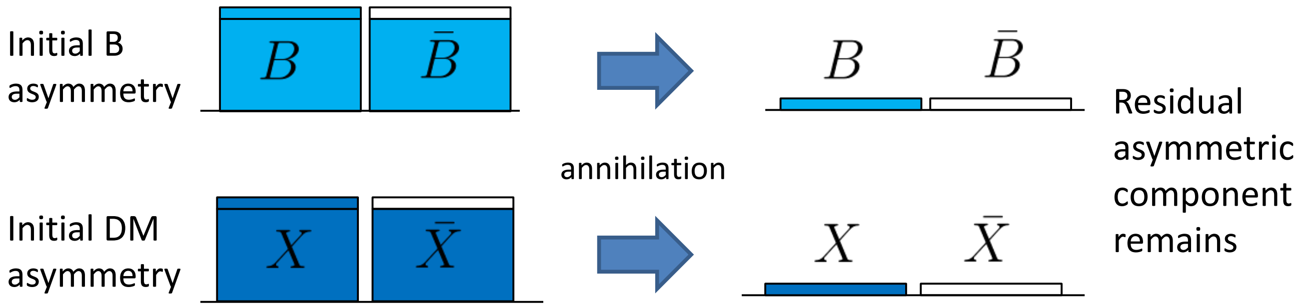
Are the Dark Matter and baryon abundances related ?

$\Omega_{DM} \approx 5\ \Omega_{baryons}$



Atoms: 4.9 %
Photons: 0.0022 %
Neutrinos: 0.0016 %

natural WIMP-baryogenesis Connection: Asymmetric dark matter

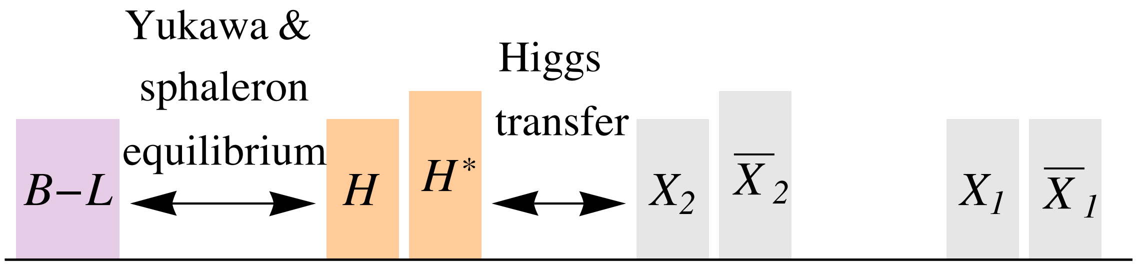


and the Higgs may be responsible for the transfer of asymmetries

Servant & Tulin, 1304.3464

MATTER ANTIMATTER ASYMMETRY

- Electroweak Baryogenesis @ LHC
- Cold Baryogenesis
- Leptogenesis: connecting the baryon asymmetry with neutrino masses
- Higgs-catalysed transfer of matter asymmetries between Dark & Visible sectors (Higgsogenesis)



1304.3464

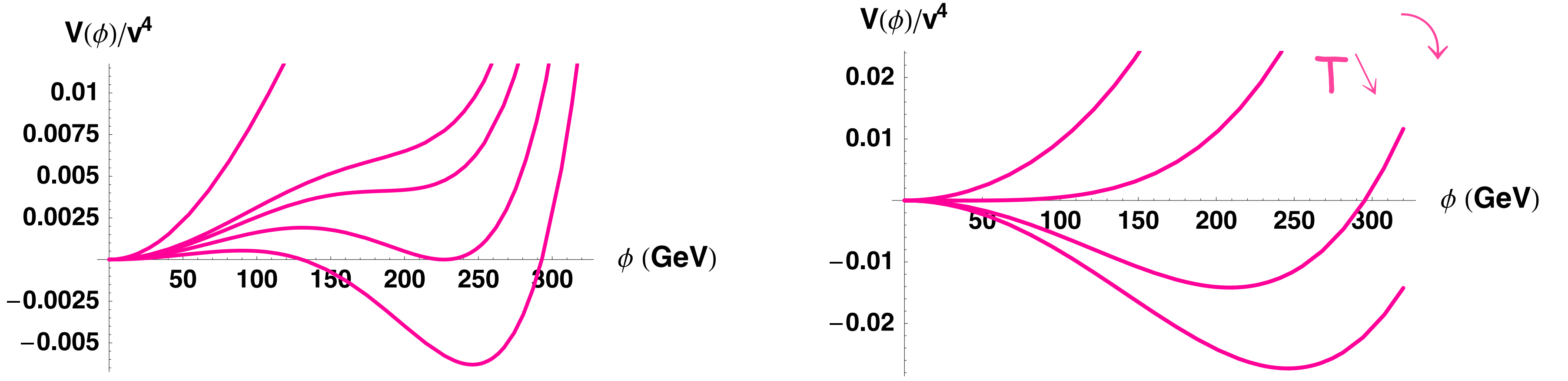
- Higgs Effective Potential

stability of EW vacuum

EW phase transition

COSMOLOGICAL PHASE TRANSITIONS

first-order or second-order?

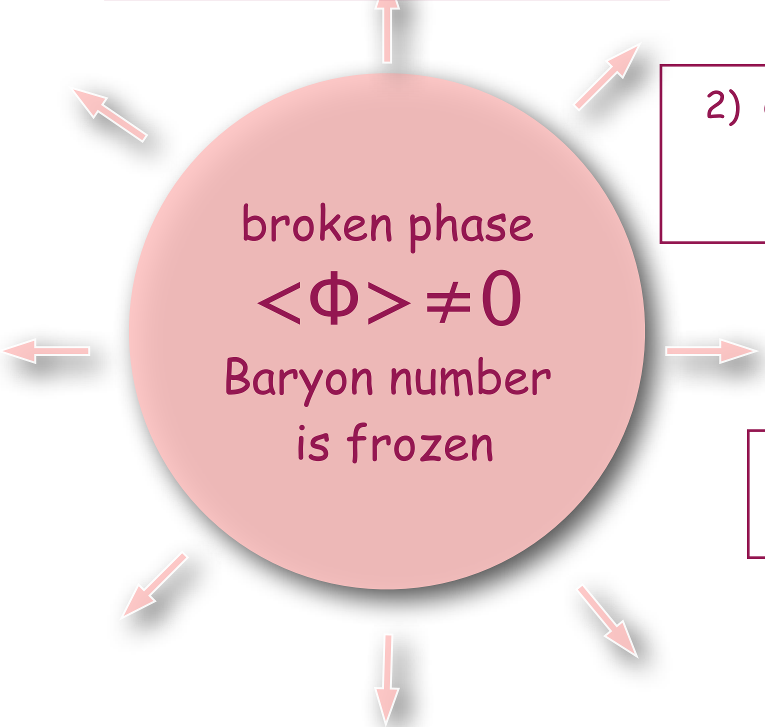


MATTER
ANTIMATTER
ASYMMETRY

Electroweak Baryogenesis

review on Quantum transport mechanism by Konstandin 1302.6713

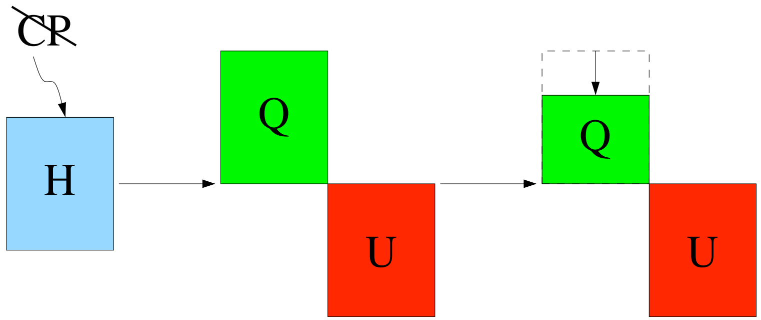
1) nucleation and expansion of bubbles of broken phase



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

Chirality Flux in front of the wall

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



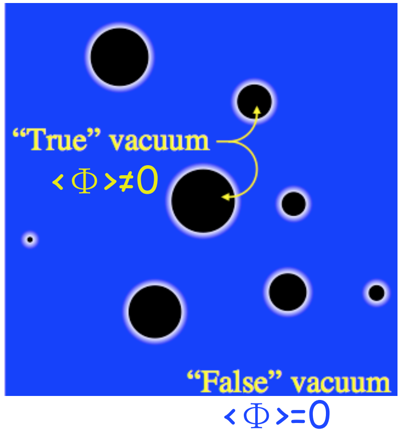
Electroweak baryogenesis mechanism relies on a first-order phase transition satisfying $\frac{\langle \Phi(T_n) \rangle}{T_n} \gtrsim 1$

Gravitational Waves

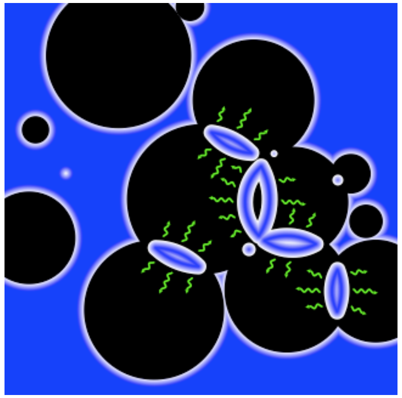
Gravity wave signals from 1st order cosmological phase transitions

[Konstandin, Nardini, Schwaller, Servant involved in activities of eLISA Cosmology Working group]

Bubble nucleation

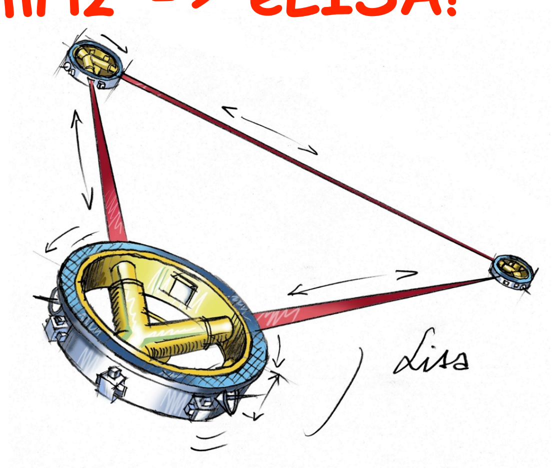


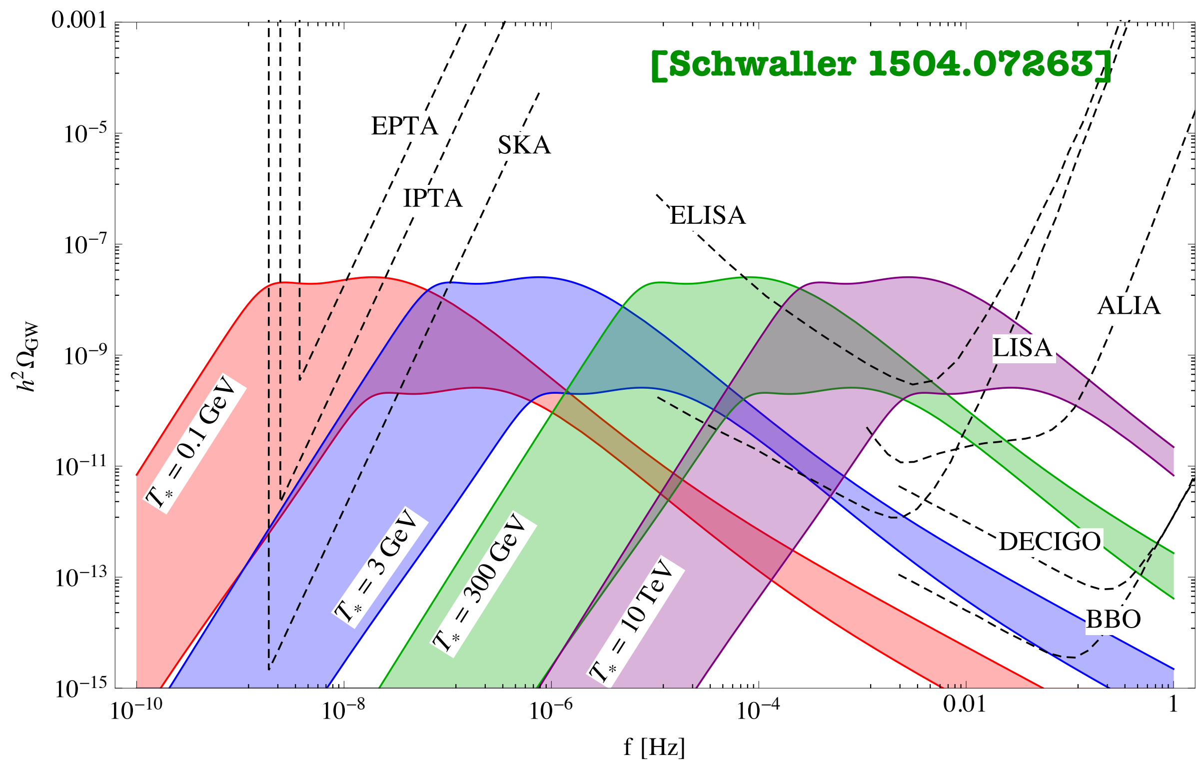
Bubble percolation



Stochastic background of gravitational radiation

EW phase transition -> mHz -> eLISA!

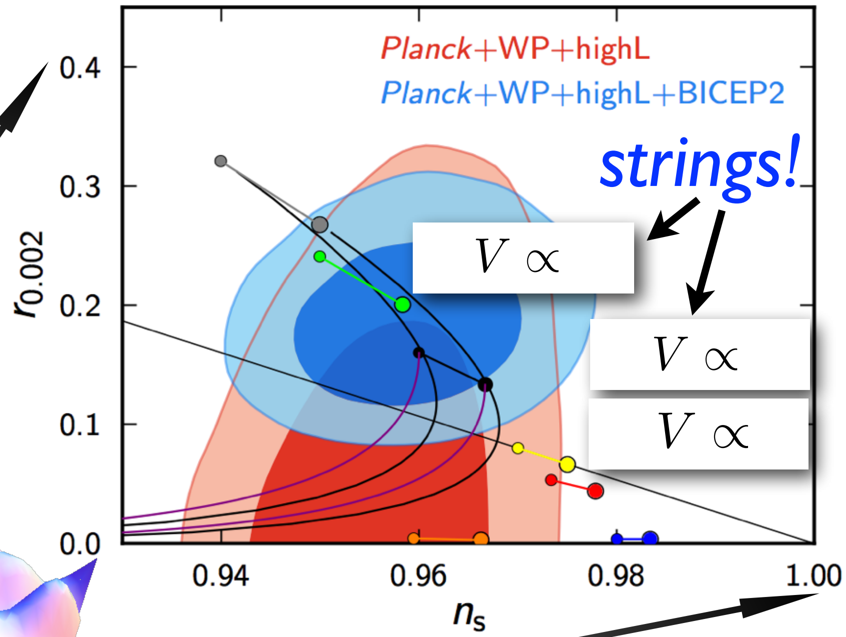


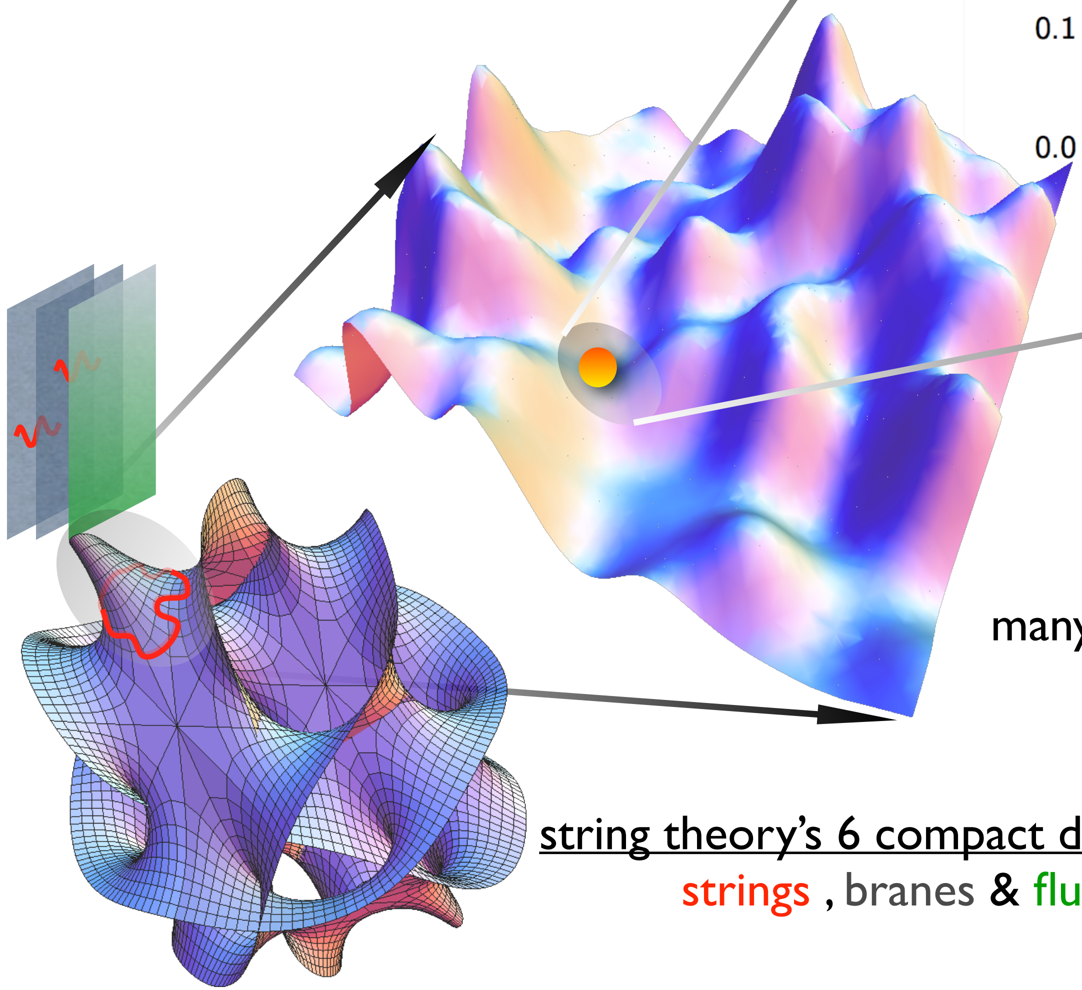


INFLATION

Westphal

test string theory with inflation & CMB





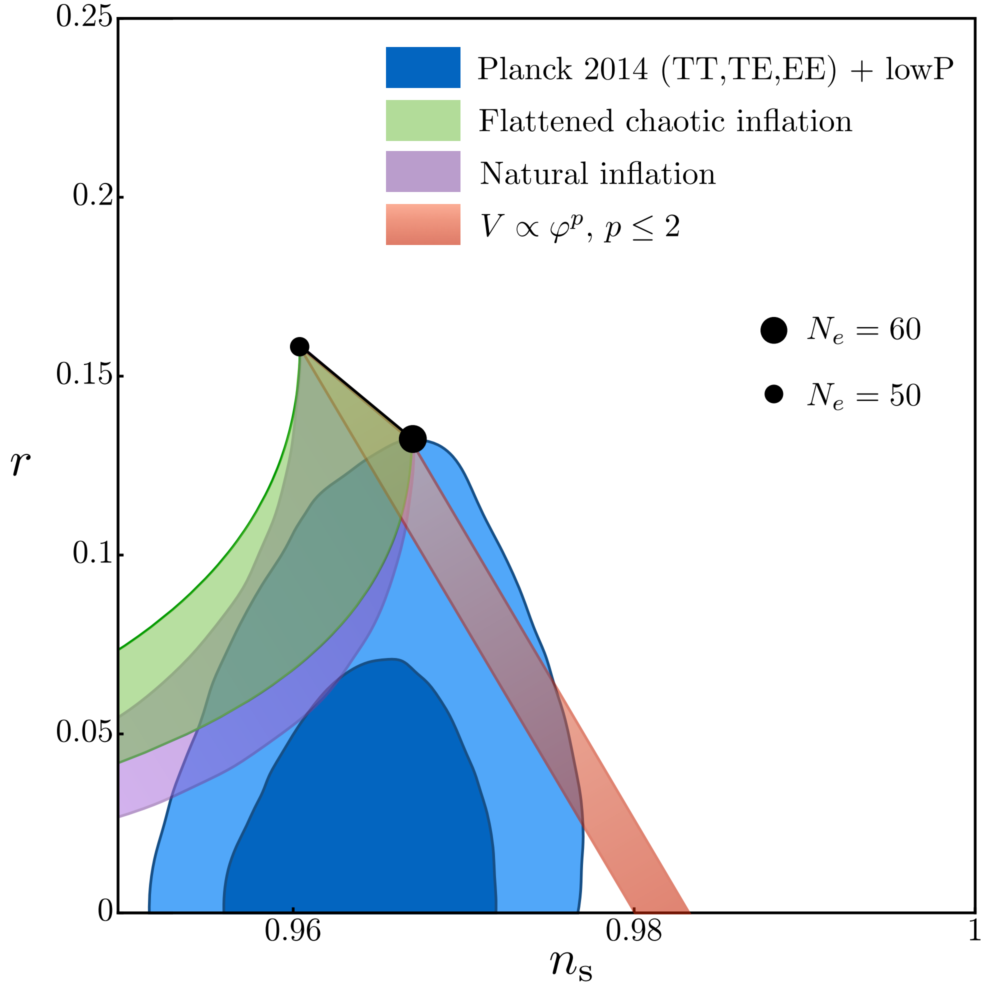
cosmological CMB data

inflation in string theory:
many solutions, some drive *inflation*

string theory's 6 compact dimensions:
strings , branes & fluxes

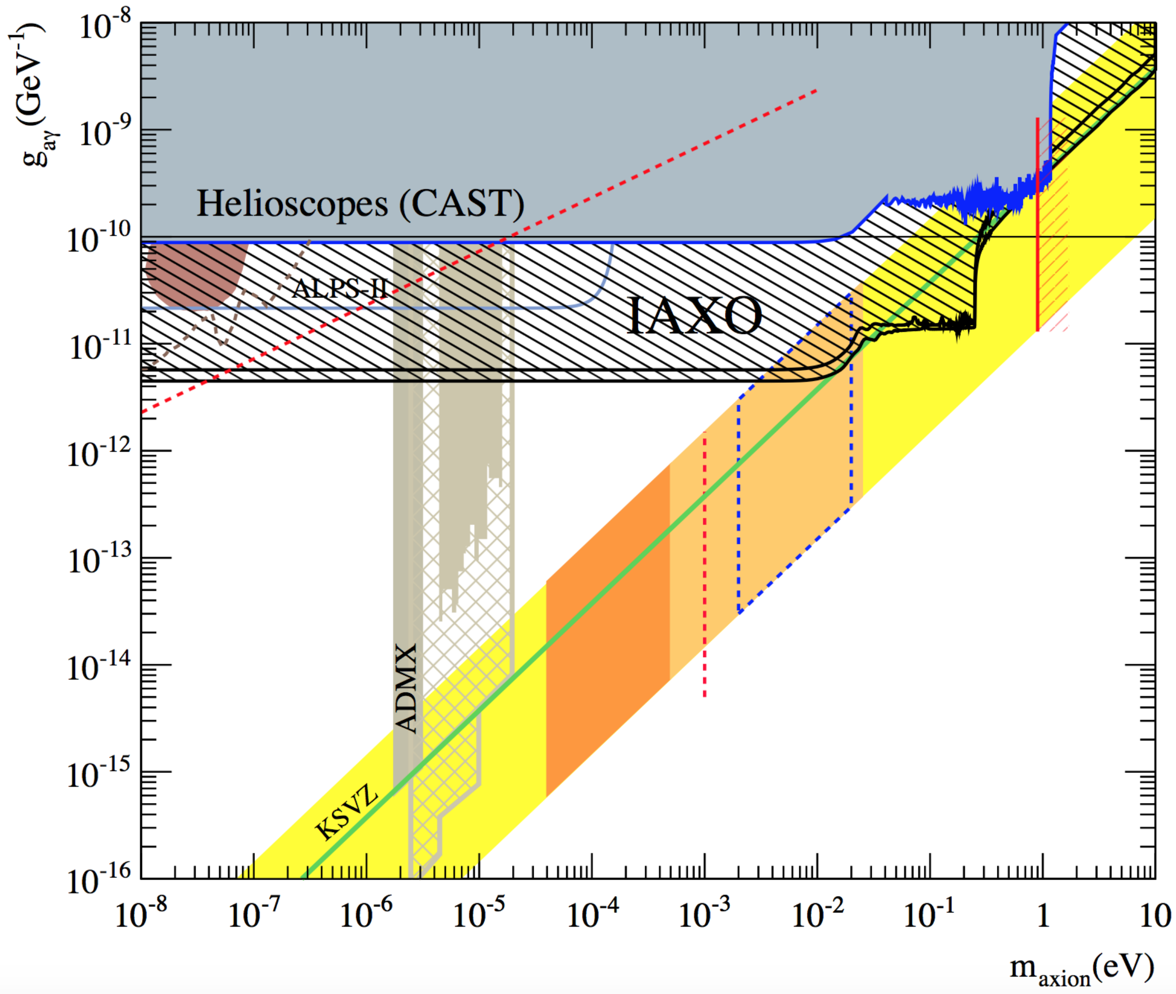
Universal CMB predictions from Supergravity Inflaton

Buchmuller, Dudas, Heurtier, Westphal, Wieck, Winkler 1501.05812



COSMOLOGY OF AXIONS

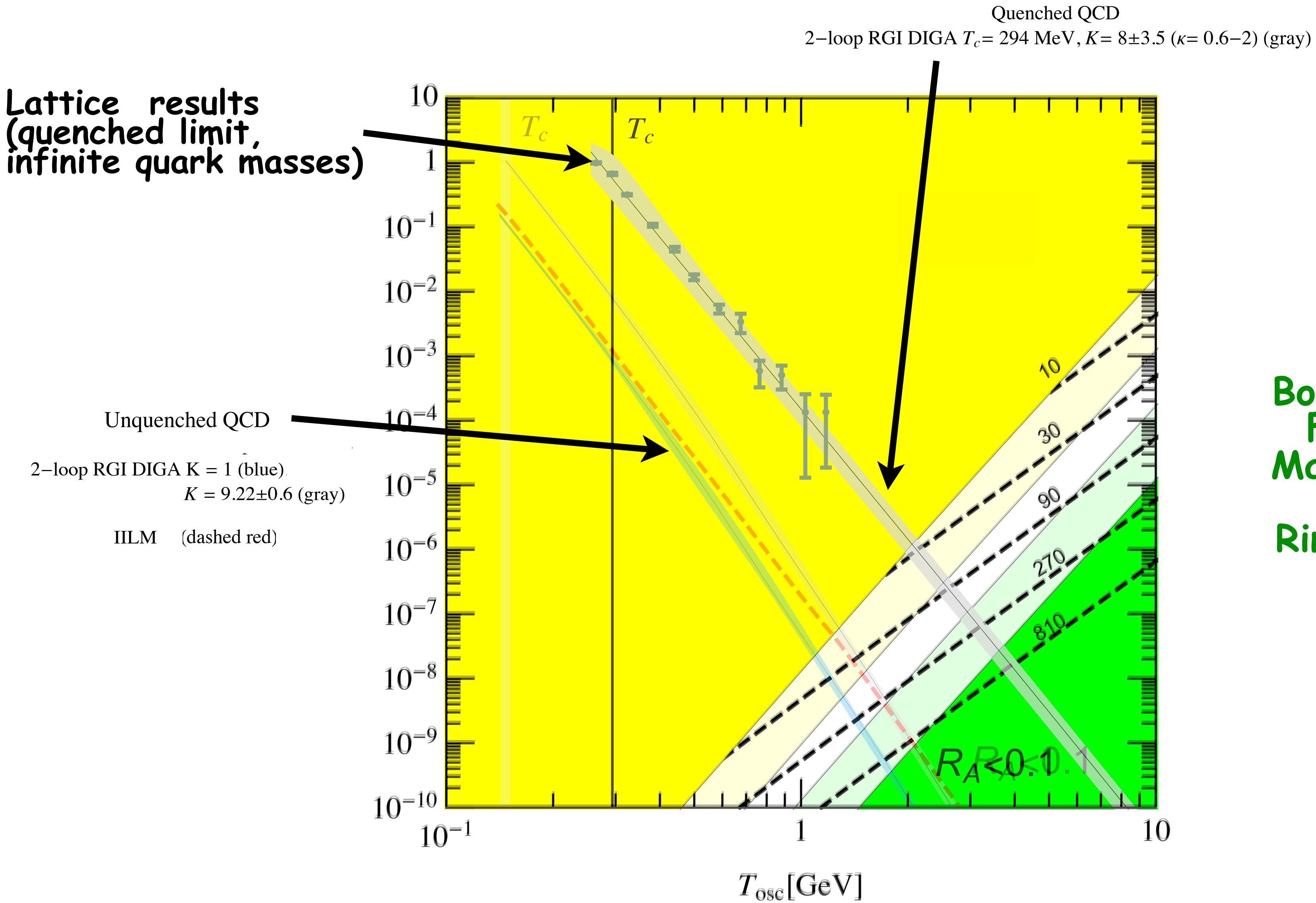
In the last few years, the interest for Axion-Like Particles has greatly accelerated. The Hamburg group, which has long been active in this area, should remain a key player in this new race and benefit from close interactions between theorists and experimentalists.



AXION
DARK MATTER

AXION COSMOLOGY & LATTICE QCD

The amount of QCD axion Dark Matter today depends on the temperature dependence of the axion mass controlled by the free energy in QCD. This sets the time when axion oscillations start. -> Non-perturbative calculations.



Borsanyi, Dierigl, Fodor, Katz, Mages, Nogradi, Redondo, Ringwald, Szabo 1508.06917

-> Derive Bound on axion mass from correct relic abundance

Baryogenesis from the QCD axion

A coupling of the type ~ $\frac{a(t)}{f_a} F\tilde{F}$ ← EW field strength

will induce from the motion of the axion field a chemical potential for baryon number given by

$$\frac{\partial_t a(t)}{f_a}$$

This is non-zero only once the axion starts to oscillate after it gets a potential around the QCD phase transition.

Time variation of axion field can be CP violating source for baryogenesis if EW phase transition is supercooled

Servant, 1407.0030

$\longrightarrow$ **Cold Baryogenesis**

requires a coupling between the Higgs and an additional light scalar: testable @ LHC & compatible with usual QCD axion Dark matter predictions

Axion DARK MATTER & The hierarchy Problem

New paradigm ?

Recently, a new approach to the Higgs Mass Hierarchy has been proposed

Graham, Kaplan, Rajendran [1504.07551]

- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe.
- The mass-squared relaxes to a small negative value.
- The electroweak symmetry breaking stops the time-dependence.
- The small electroweak scale is fixed until today.

Key Question:

Does this require new degrees of freedom at the weak scale?

Key idea: **Higgs mass parameter is field-dependent**

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

$$m^2(\phi) = \Lambda^2\left(1 - \frac{g\phi}{\Lambda}\right)$$

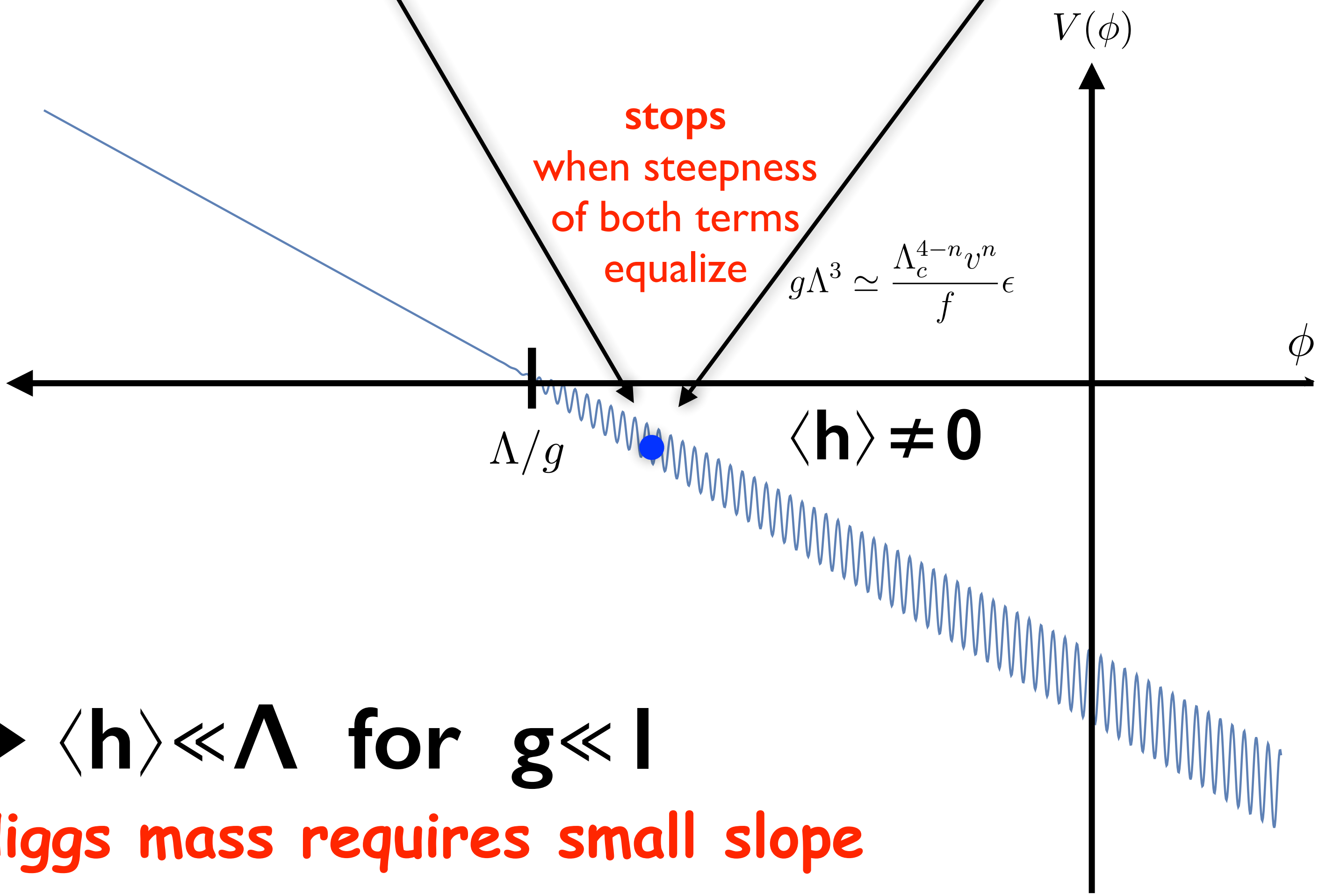
$\downarrow$

stabilized such that $m^2(\phi) \ll \Lambda^2$

Λ **: cutoff of the theory**

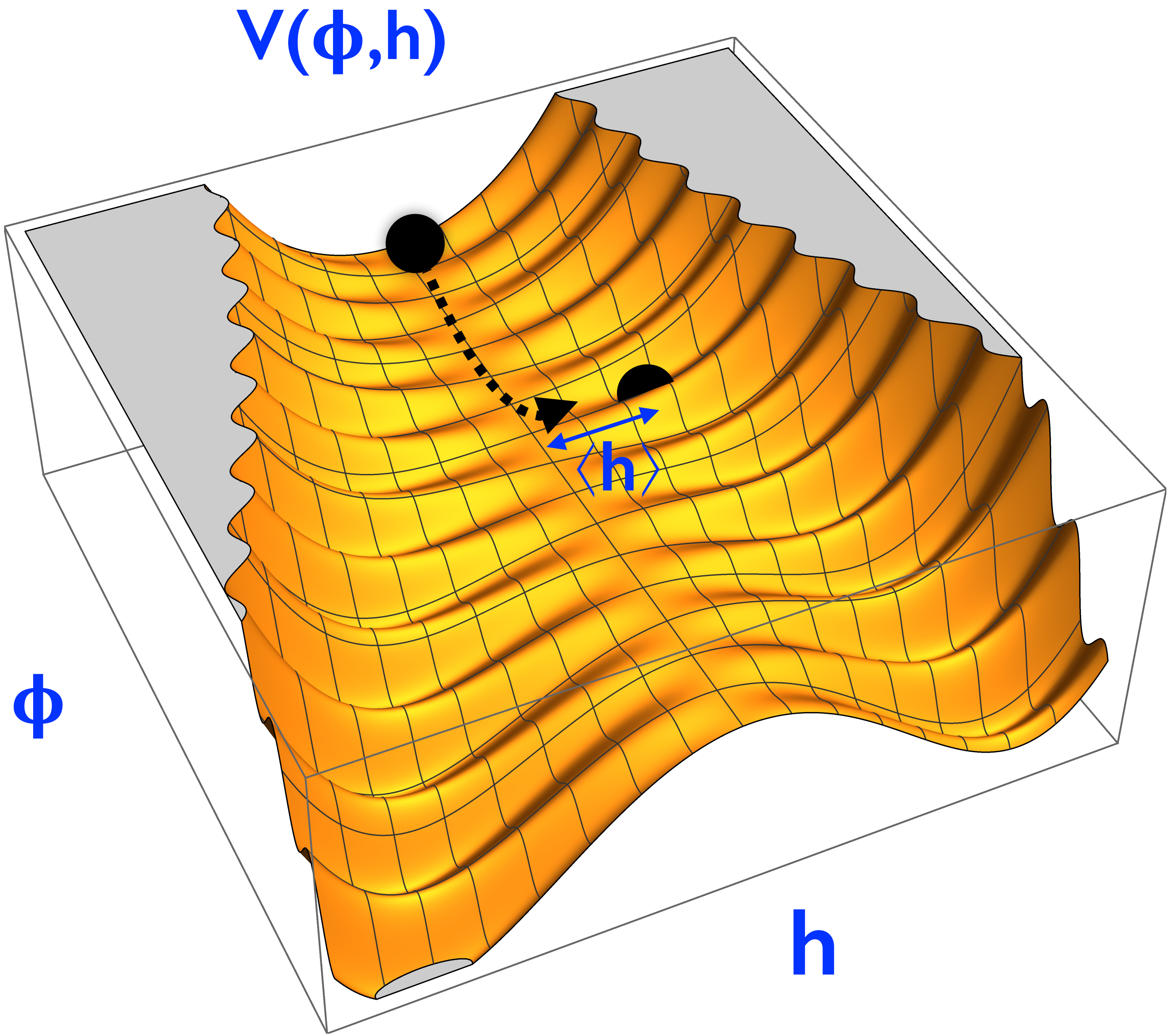
Cosmological evolution (during inflation)

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



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

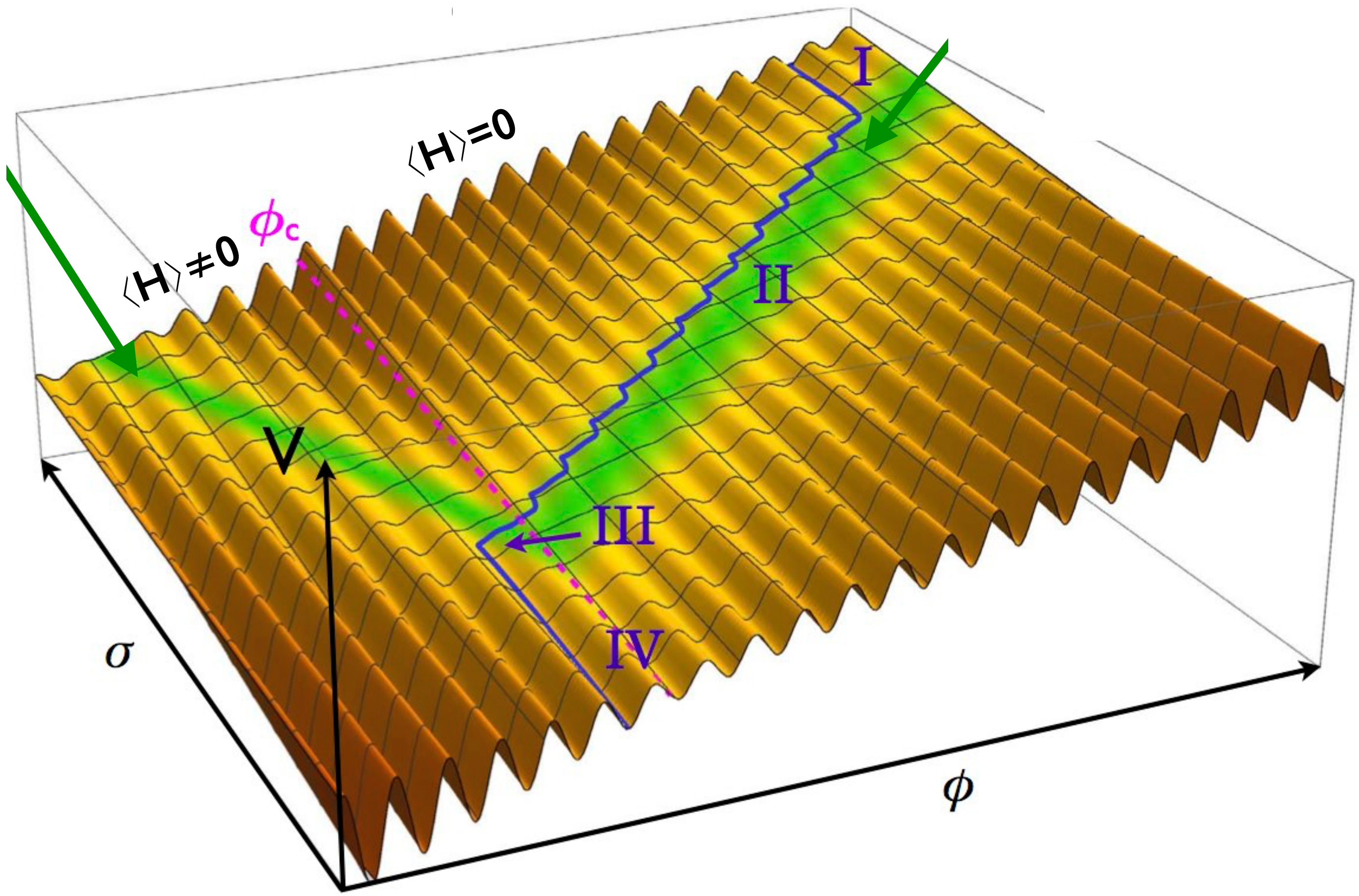
small Higgs mass requires small slope



V(ϕ,h)
⟨h⟩
ϕ
h

Cosmological Higgs-Axion Interplay for a Naturally Small Electroweak Scale

existence proof of a model that generates a large mass gap between the Higgs mass and the new physics threshold, with no new physics @ the weak scale. Only ultra-light scalars.



Espinosa, Grojean, Panico, Pomarol, Pujolàs, Servant, 1506.09217

SUMMARY

- Cosmology is a growing and fast-evolving field.
- Visionary investigations fueled by intense experimental activity in the near and long term future
- Interdisciplinary problems such as Dark Matter, Dark Energy, Baryogenesis and Inflation require a complementarity of approaches
- Coherence within the Theory group in the area of early Universe cosmology and in the connections with high energy theory and particle phenomenology
- Emergent activities related to the late Universe and large scale structures, where gravitational physics plays a key role

Connections of early universe particle cosmology: A multi-form and integrated approach