# Theory: Particle Cosmology

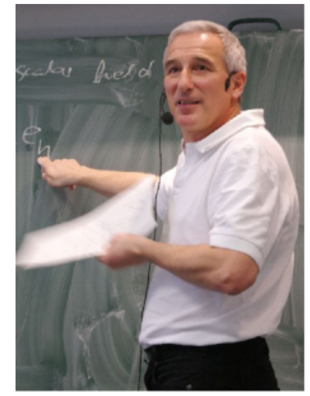
87th PRC meeting, 21 May 2019

Filippo Sala

# People - Staff








- ★ Wilfried Buchmüller (honorary member)
- ★ Valerie Domcke (5yrs)
- ★ Thomas Konstandin
- ★ Rafael Porto* (Zeuthen, but located in Hamburg)
- ★ Andreas Ringwald
- ★ Filippo Sala (5yrs)
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- ★ Alexander Westphal*

*External fundings: 2 ERC consolidator grants

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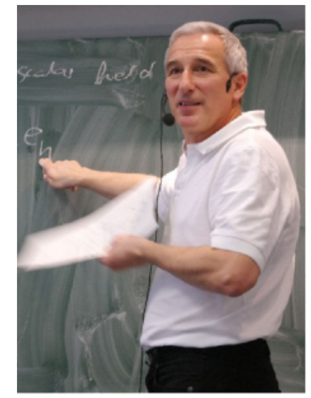


- ★ Wilfried Buchmüller (honorary member)
- ★ Valerie Domcke (5yrs) → Offered 6 year CERN-EPFL staff position (starting date negotiated to May 2020)
- ★ Thomas Konstandin
- ★ Rafael Porto* (Zeuthen, but located in Hamburg)
- ★ Andreas Ringwald
- ★ Filippo Sala (5yrs) → Ranked 1st in CNRS section02 competition (starting date etc to be negotiated)
- ★ Geraldine Servant
- ★ Alexander Westphal*

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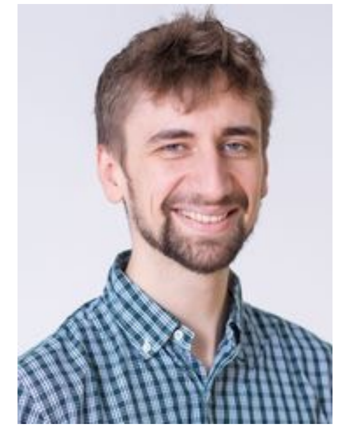
# People - Postdocs/Students/Other








+ more later

- ★ Federico Carta*
- ★ Luca Di Luzio* (arrives Fall 2019)
- ★ Yohei Ema*
- ★ Nayara Fonseca
- ★ Ryusuke Jinno*
- ★ Enrico Morgante
- ★ Kyohei Mukaida*
- ★ Ryosuke Sato
- ★ Yvette Welling*

- ★ Felix Giese
- ★ Yann Gouttenoire
- ★ Jakob Moritz*
- ★ Henrique Rubira
- ★ Peera Simachakorn
- ★ Stefan Sanders

- ★ Prof. Jorge Gamboa (Humboldt visitor Apr-July 2019)

*External fundings (partial or all) - japanese JSPS fellowships, ERC, Marie Curie

# External Fundings and Networks

- ★ Excellence Cluster (participation to "Quantum Universe" proposal)
- ★ ERC consolidator grant "Stringflation" (Alexander)
- ★ ERC consolidator grant "LHCtoLISA" (Rafael, Zeuthen but located in Hamburg)
- ★ Cost European Network "Fundamental Connections"
- ★ Invisibles-Plus RISE and Elusives European ITN Network

  (Horizon2020 projects, University of Goettingen-DESY node)
- ★ PIER Seed project funding (Filippo&Geraldine)

  "Dark Matter at 10 TeV and beyond, a new goal for cosmic-ray experiments"


- ★ Nordic Network of Dark Matter (Thomas, funds Danish Research Council)
- ★ Member of ANTARES collaboration (Filippo, observer status)

# Event Organisation (since 2018)

## Local

- ★ 6 Apr 2018 - Gravitational Waves: windows of opportunities
- ★ 18-22 Jun 2018 - 14th Patras Axion-WIMP workshop
- ★ 21-23 Aug 2018 - Probing strong-field QED in $e-\gamma$ interactions
- ★ 25-28 Sep 2018 - DESY theory workshop
- ★ 19-20 Mar 2019 - Quantum Universe Kickoff meeting


## External

- ★ 14-18 May 2018, CERN
  Primordial vs Astrophysical origin of Black Holes
- ★ 9-21 July 2018, Corsica, Cargese Summer School
- ★ 7-13 April 2019, Benasque, Light Scalars Workshop
- ★ 10-21 June 2019, ICTP Trieste, Particle Physics summer school
- ★ 7-12 July 2019, Valencia, GR22

# Lectures and Teaching (since 2018)

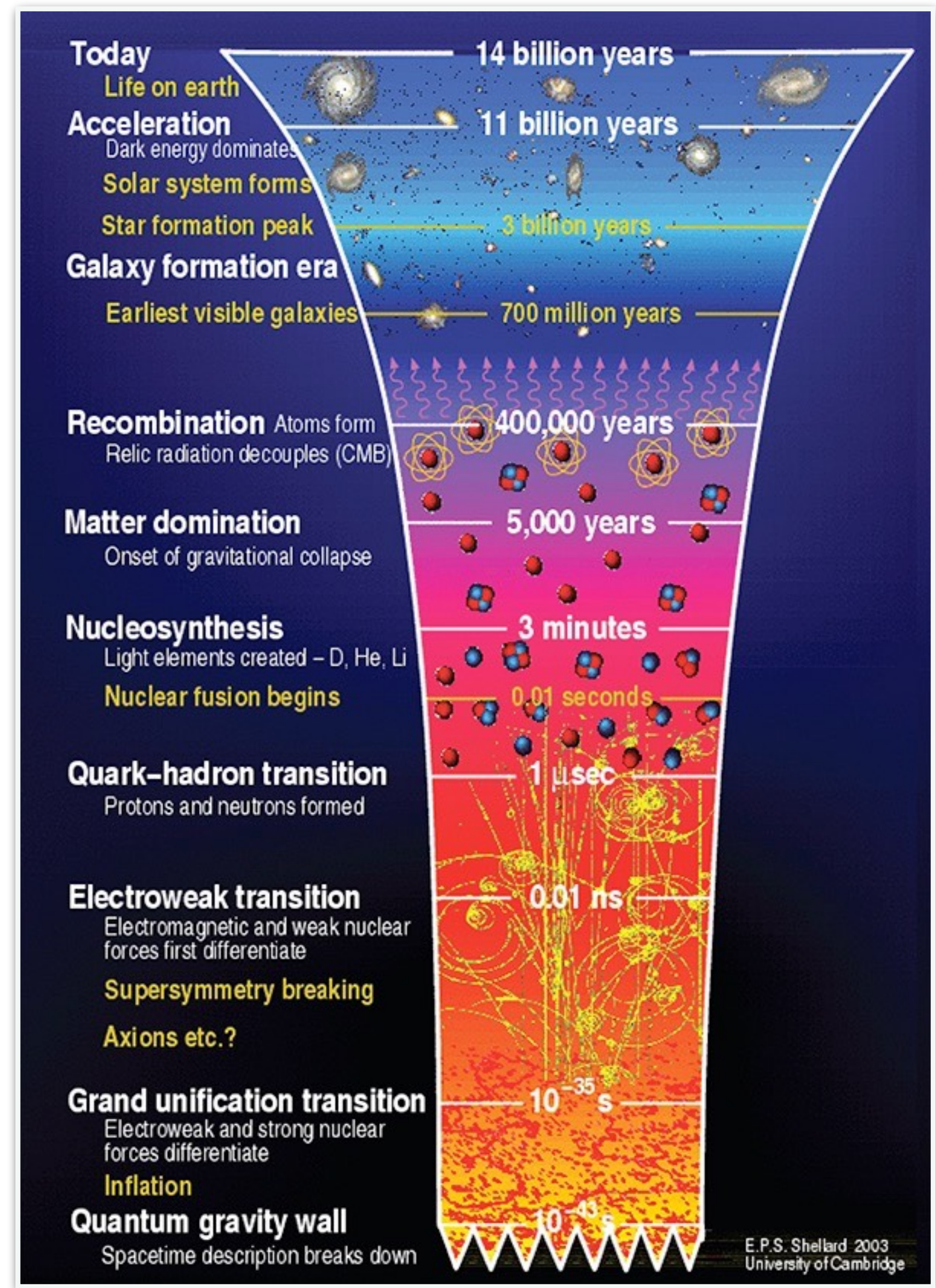
- ★ Summer semester 2018, Uni. Hamburg, Theoretical Cosmology course [Servant+Westphal]
- ★ Summer semester 2018, DESY, “Workshop Seminar” on Flavour Physics, 11 lectures
- ★ June 2018, Erice, “Erice international school of science journalism”, 1 lecture [Servant]
- ★ July 2018, Mainz, “MITP Summer School 2018”, 4 lectures [Domcke]
- ★ July 2018, Trieste, “Jennifer summer school on particle physics and detectors”, 2 lectures [Sala]
- ★ Winter semester 2018, DESY, “Workshop Seminar” on Hot Topics in QFT&String theory, 12 lectures
- ★ Summer semester 2019, DESY, “Workshop Seminar” on Semiclassical objects in QFT, 11 lectures
- ★ Summer semester 2019, Uni. Hamburg, Theoretical Cosmology course [Domcke+Servant]
- ★ August 2019, Ljubljana, Summer School, 2 lectures + 2 tutorings [Sala+Gouttenoire]

# Research: The Big Picture

We work to understand:

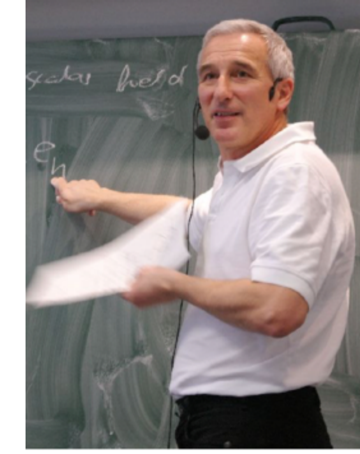
- Dark Matter
- Baryon Asymmetry
- Neutrino Oscillations
- Quantum Gravity
- Inflation
- Dark Energy
- EW symmetry breaking
- Strong CP problem
- Origin of SM flavour
- ….

Our lab:



# SMASH

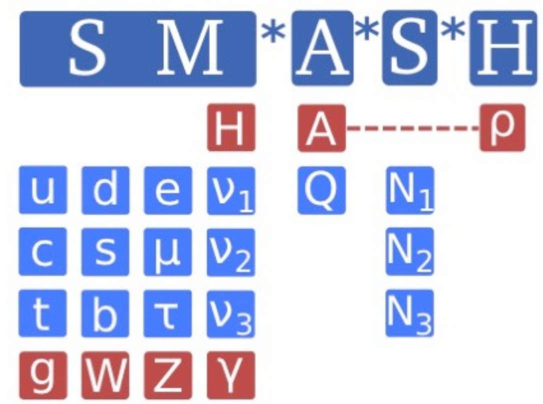
## Self-contained and consistent description of particle physics and cosmology

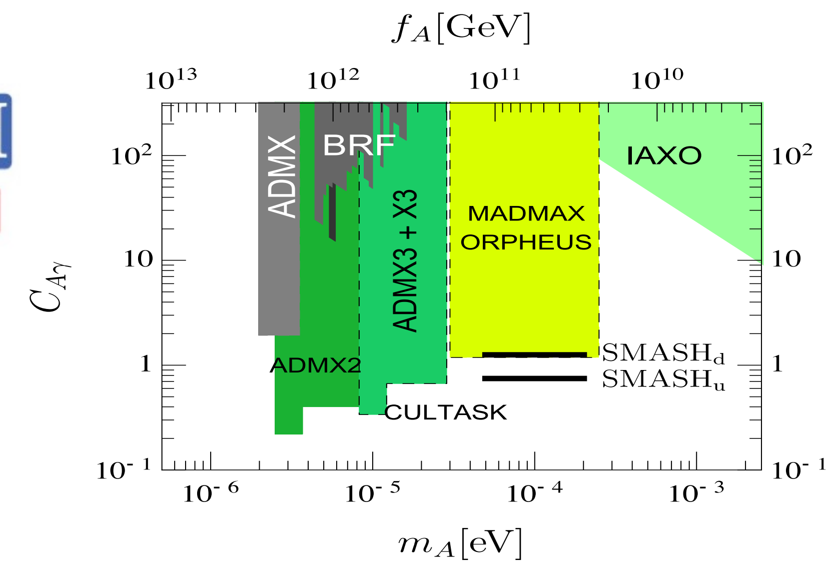


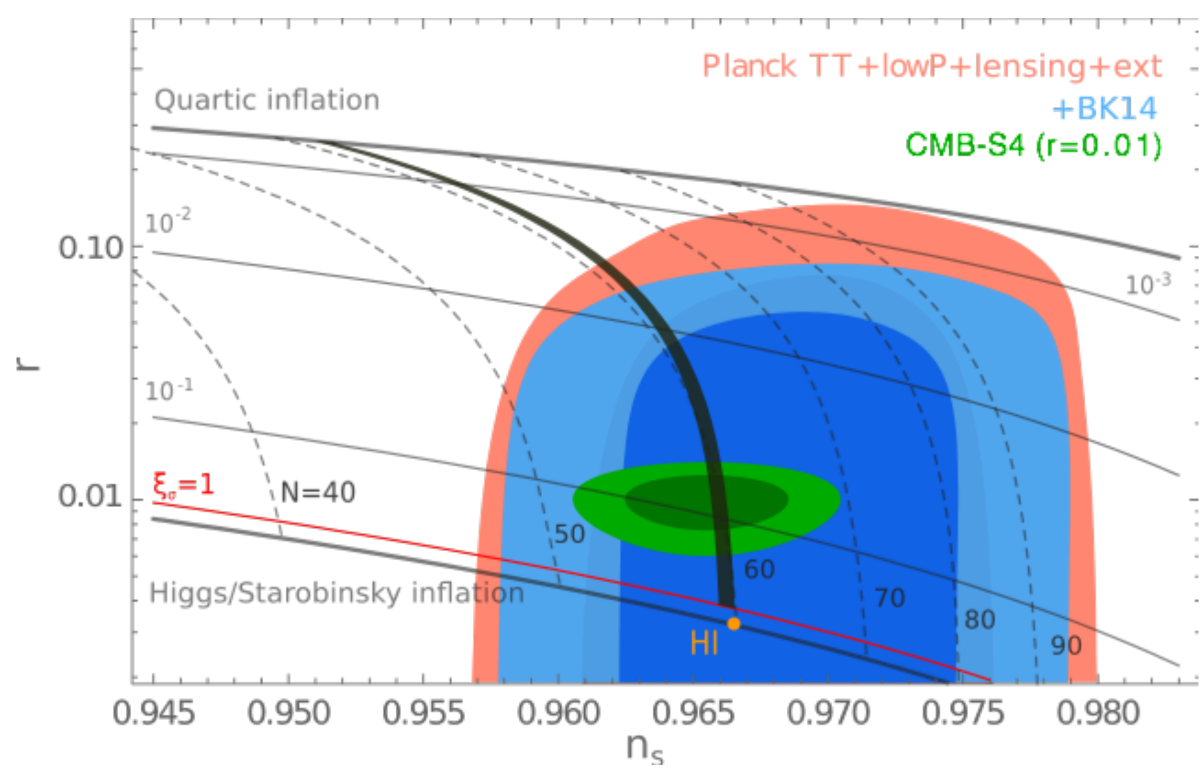
### SMASH

- Added to Standard Model (SM) singlet complex scalar field featuring spontaneously broken Peccei-Quinn symmetry, a vector-like quark, and three right-handed singlet (sterile) neutrinos
- Model solves several problems of particle physics and cosmology in one stroke:
  - Inflation (non-minimal chaotic PQ/H field inflation)
  - Baryogenesis (leptogenesis)
  - Dark matter (axion)
  - Strong CP problem (axion)
  - Neutrino masses and mixing (seesaw)

[Ballesteros,Redondo,Ringwald,Tamarit 1608.05414; 1610.01639]



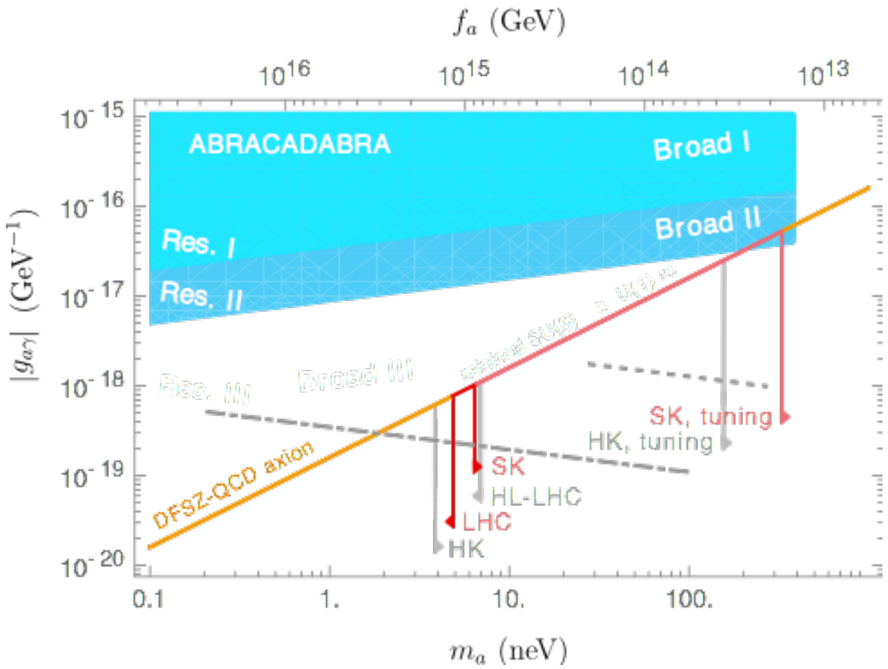



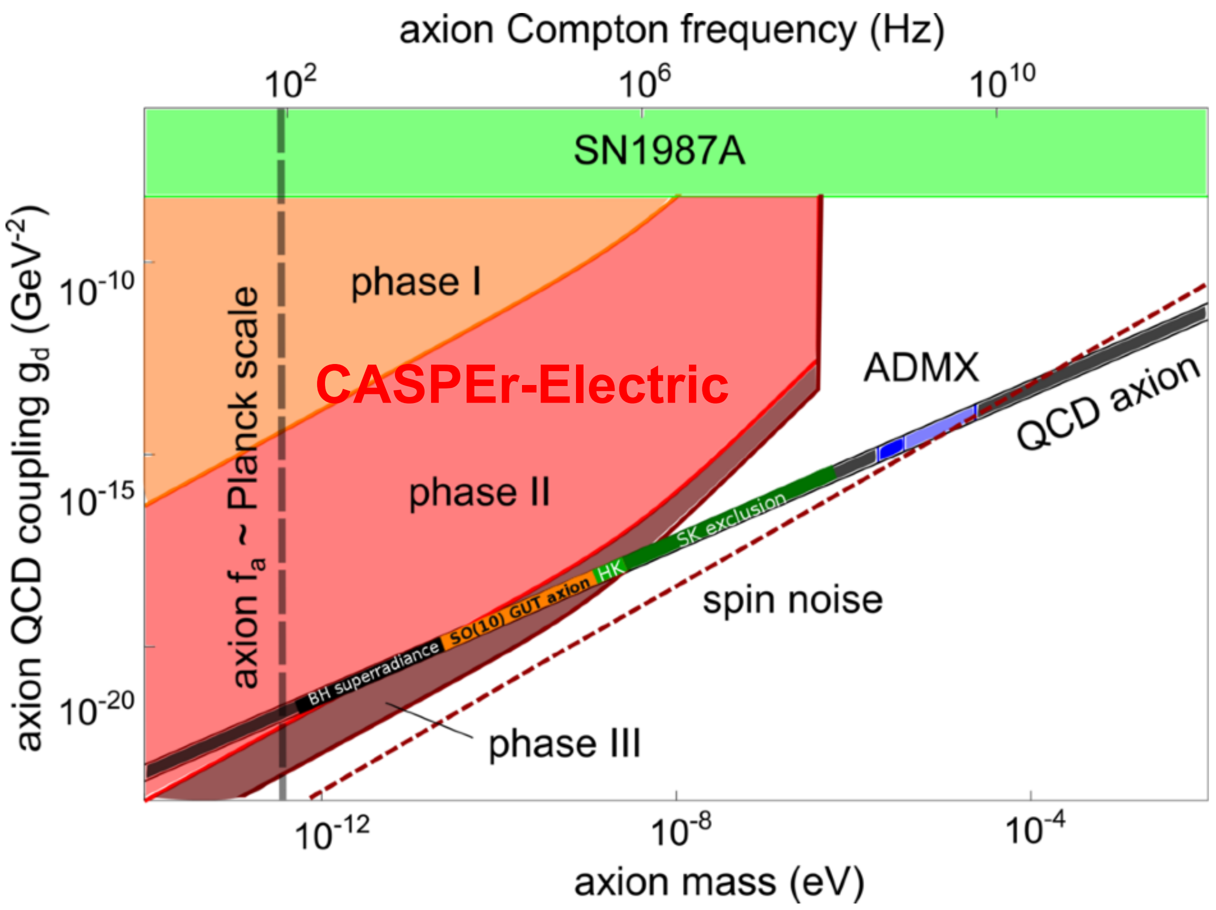
# GUT SMASH

## Self-contained and consistent description of particle physics and cosmology

### Non-SUSY GUT SMASH

- Non-SUSY $SO(10) \times U(1)_{PQ}$ and $SU(5) \times U(1)_{PQ}$ models addressing both neutrino masses and gauge coupling unification predict axion mass in window accessible in axion DM direct detection
- Intriguing possibility that Higgs field required for GUT breaking may be responsible for inflation




[Ernst 18; CASPEr prospects from Kimball et al. 17]

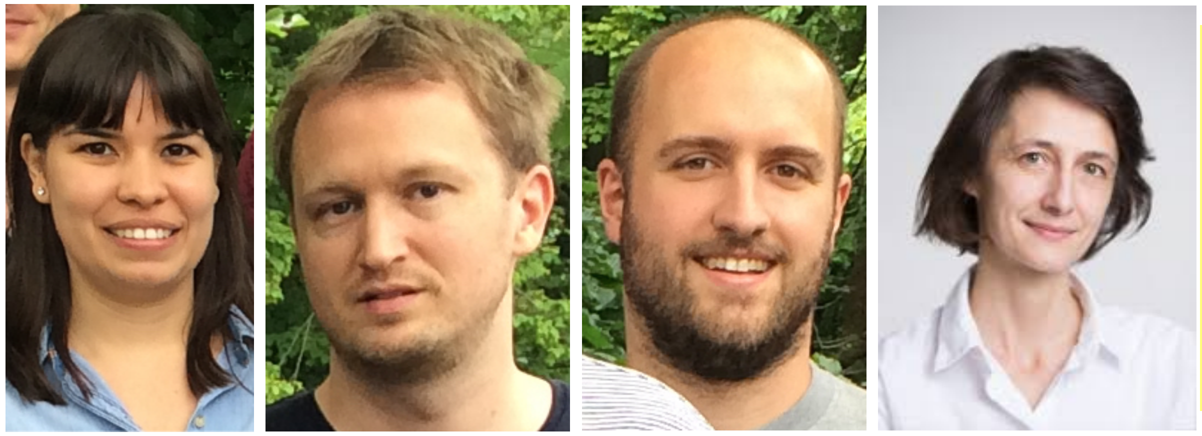
[Ernst,Ringwald,Tamarit 1801.04906; Di Luzio,Ringwald,Tamarit 1807.09769]






# Flavour-Electroweak symmetry breaking cosmological interplay

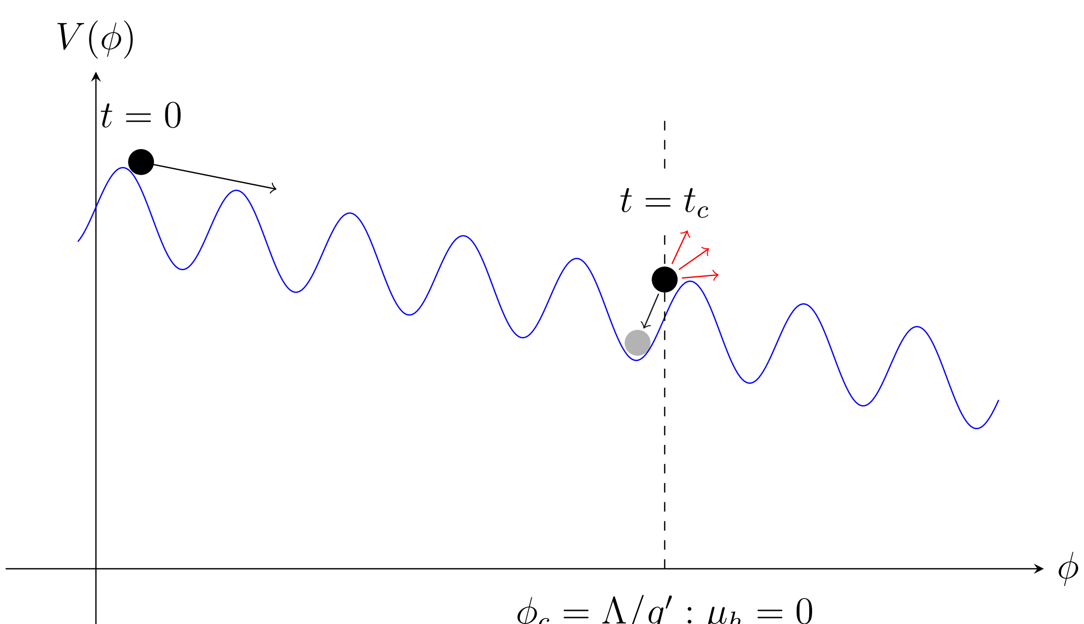
- Effect of varying Yukawas on EW phase transition
  **Baldes, Konstandin, Servant, 1604.04526**
- Implementation in Froggatt-Nielsen
  **Baldes, Konstandin, Servant, 1608.03254**
- Natural realisation of Yukawa variation in Randall-Sundrum
  **Von Harling, Servant, 1612.02447**
- Calculation of baryon 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**

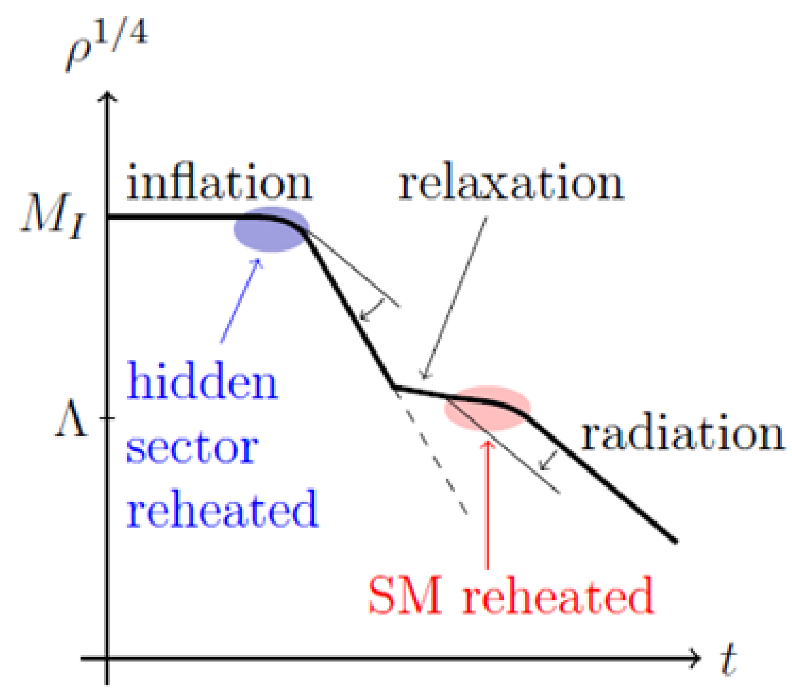


# Cosmological relaxation of the electroweak scale

- UV completion in Randall-Sundrum type of models

  **Fonseca, Von Harling, De Lima, Machado, 1712.07635**
- Higgs relaxation after inflation **Fonseca, Morgante, Servant, 1805.04543**
- Relaxation dark matter **Fonseca, Morgante, 1809.04534**



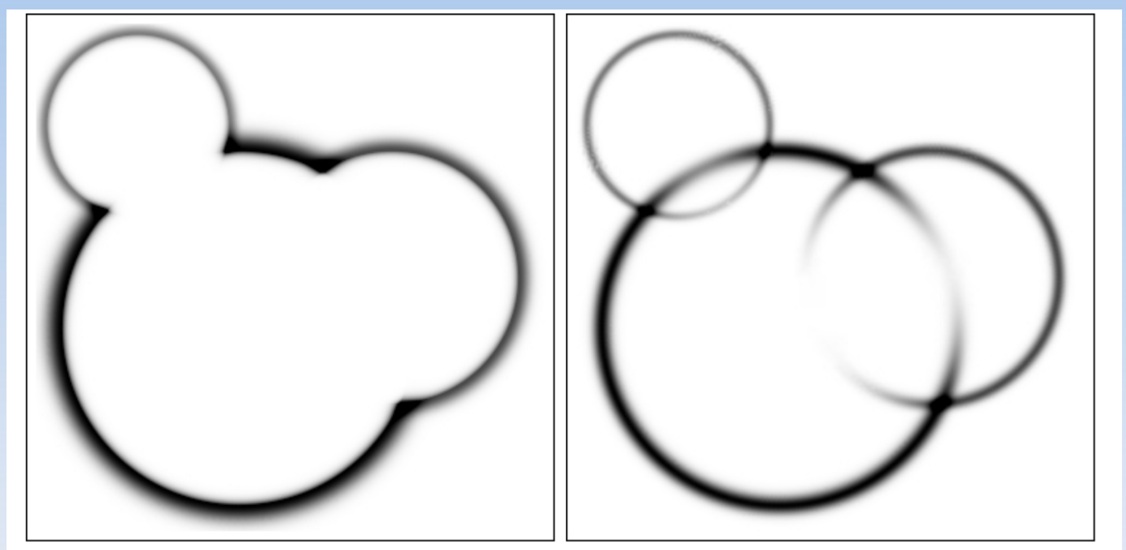



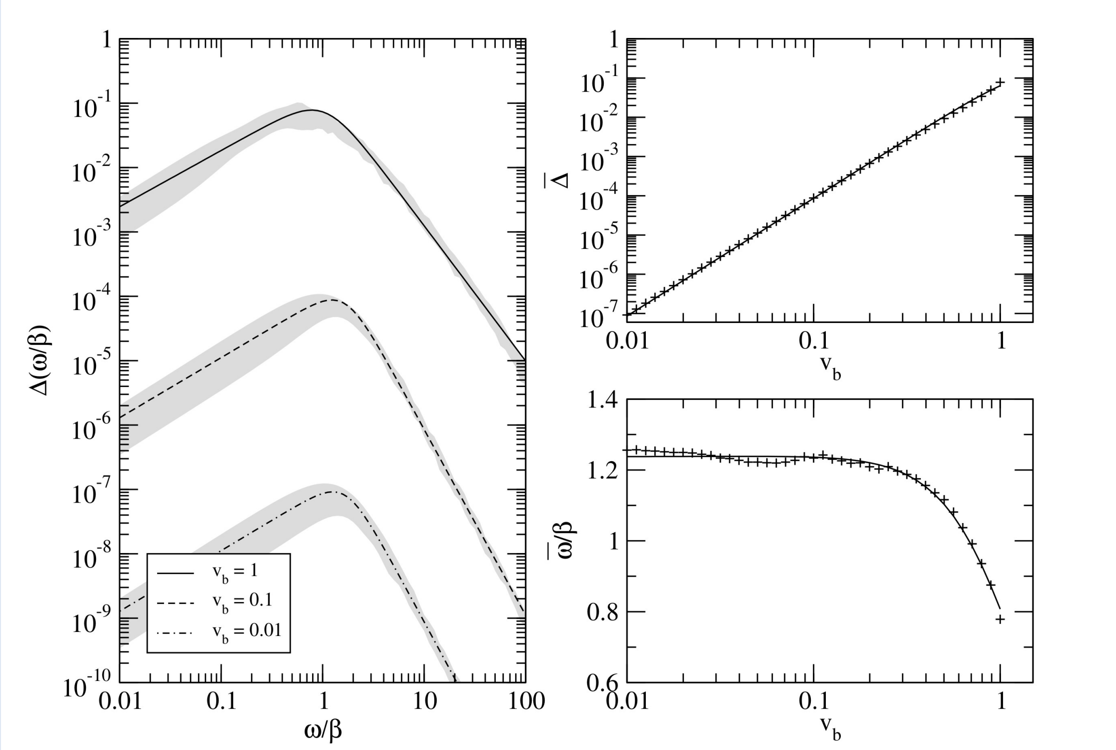
# GW spectra from fluid models

Predictions of gravitational waves from cosmological phase transitions often rely on hydrodynamic lattice simulations.

These simulations are limited by grid resolutions and time scales.

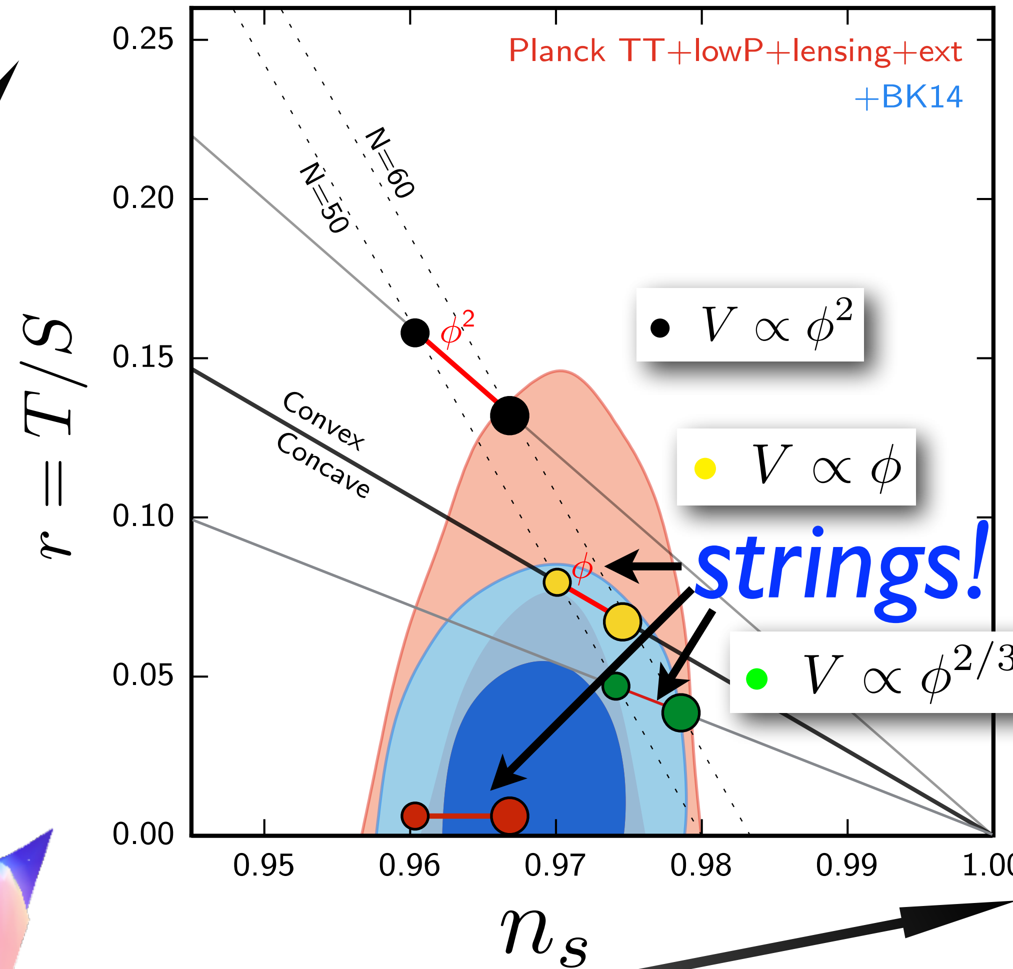
Semi-analytic models can assess these regimes. They are based on energy considerations and fluid modelling from the simulations.



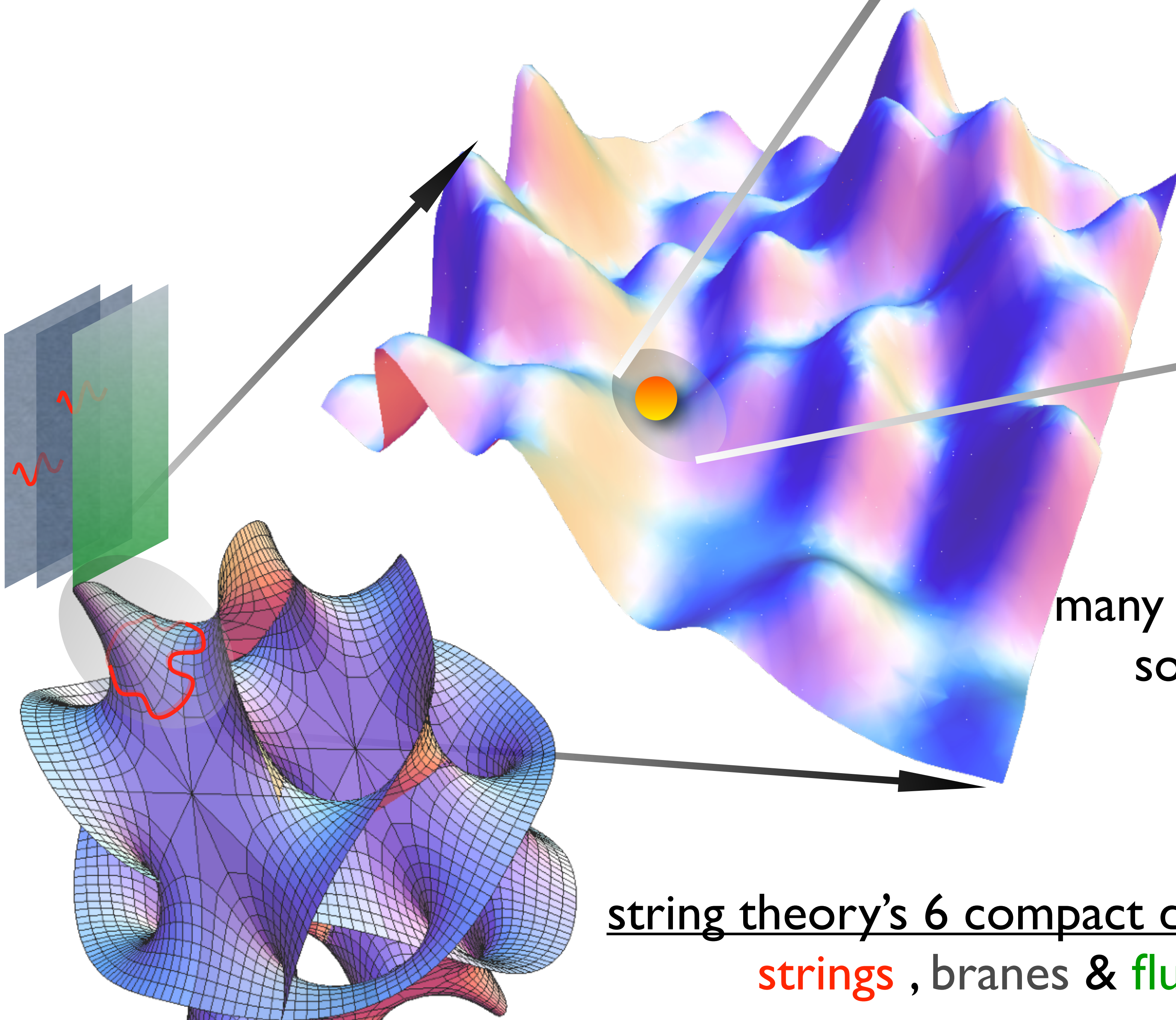



[TK ’17]

# test string theory with inflation & CMB




cosmological CMB data



the string theory *landscape*:

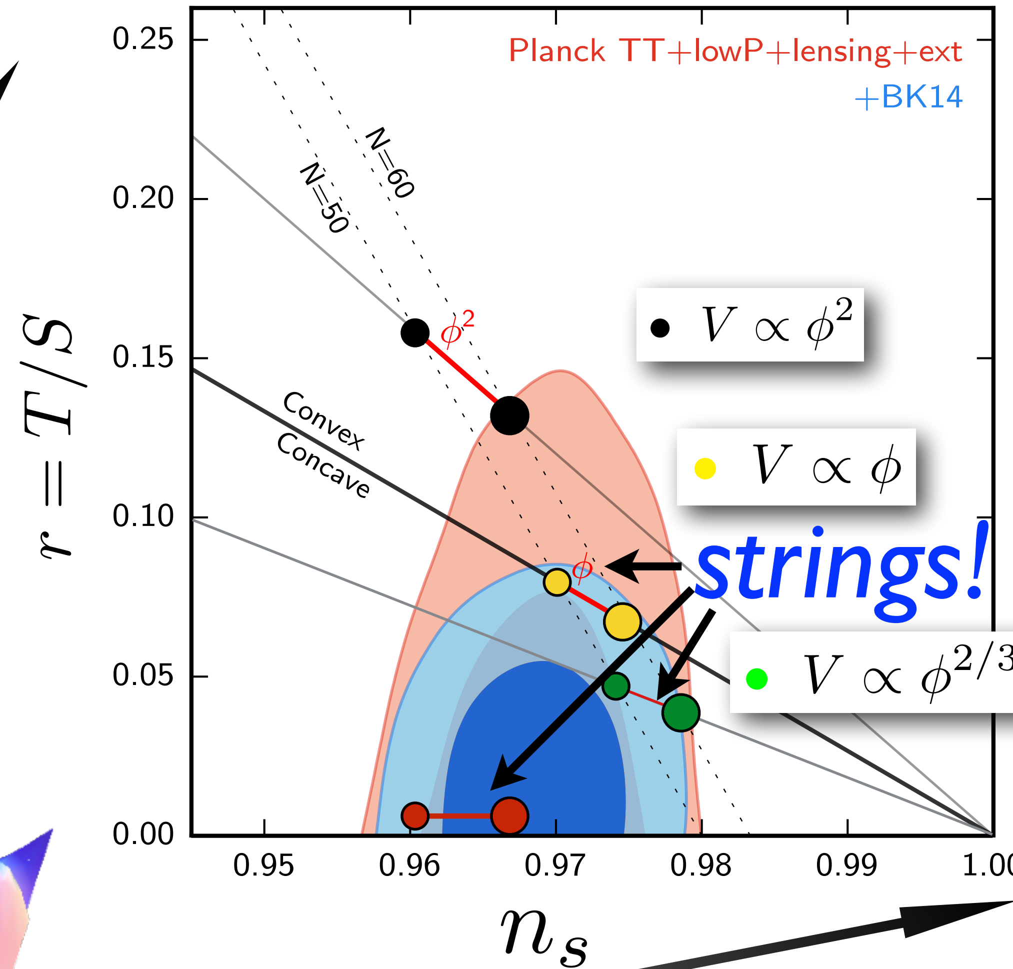
many isolated *vacua*, connected by tunneling

some mountain slopes drive *inflation*

string theory's 6 compact dimensions:

strings , branes & fluxes

# test string theory with inflation & CMB

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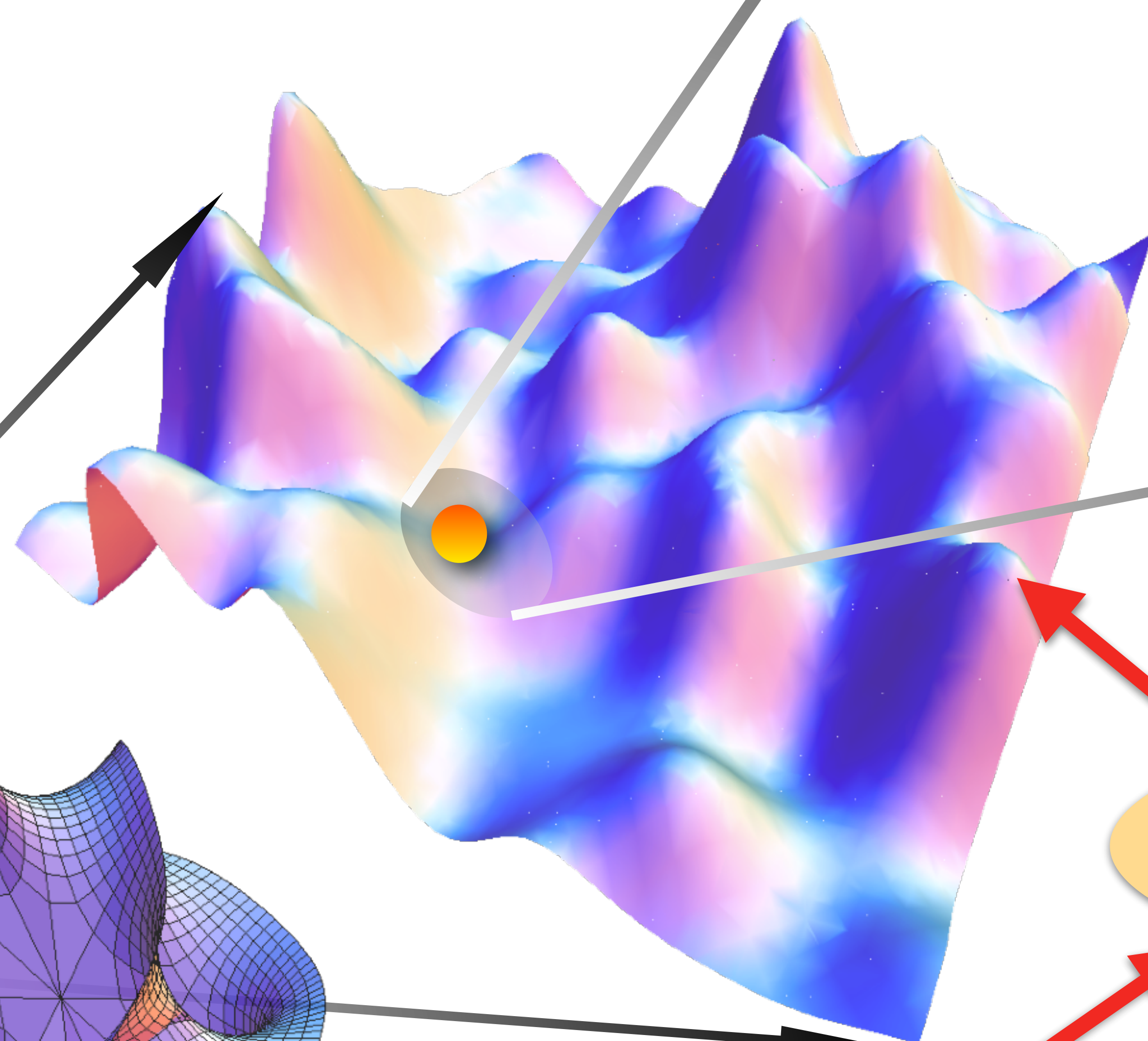
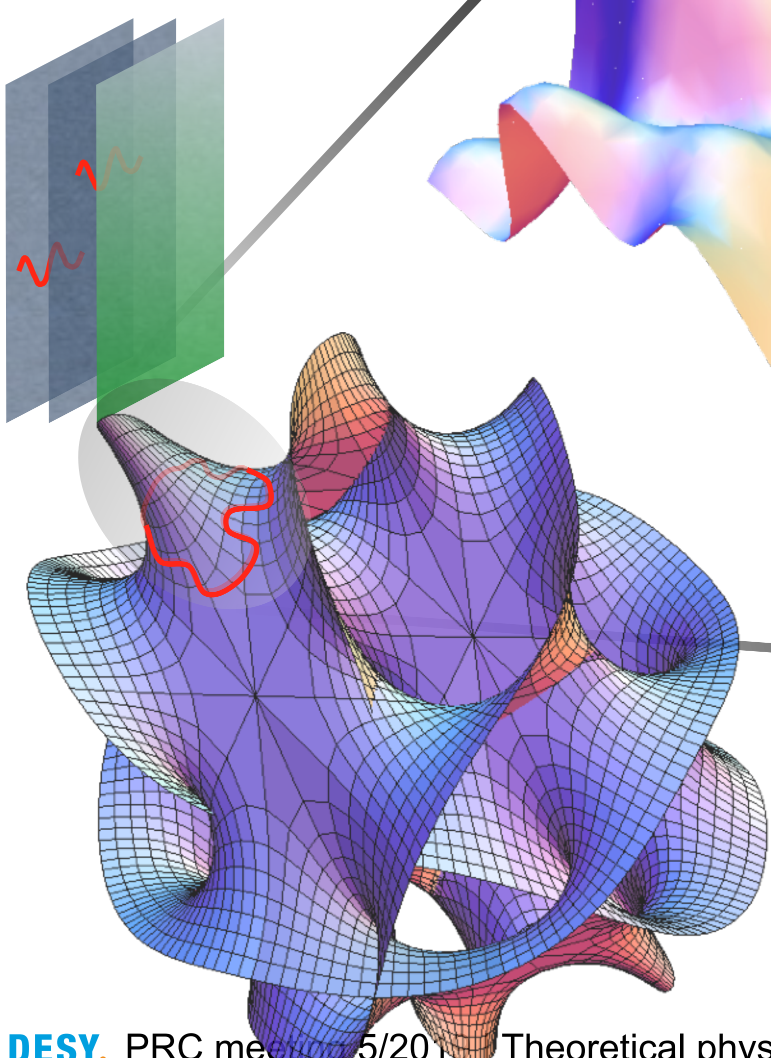


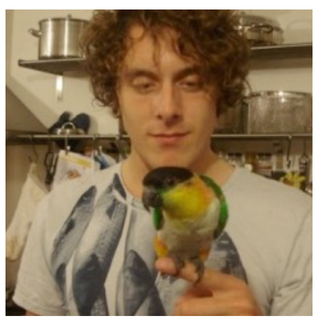


**moduli & axions: light scalars ...**

string theory's 6 compact dimensions:

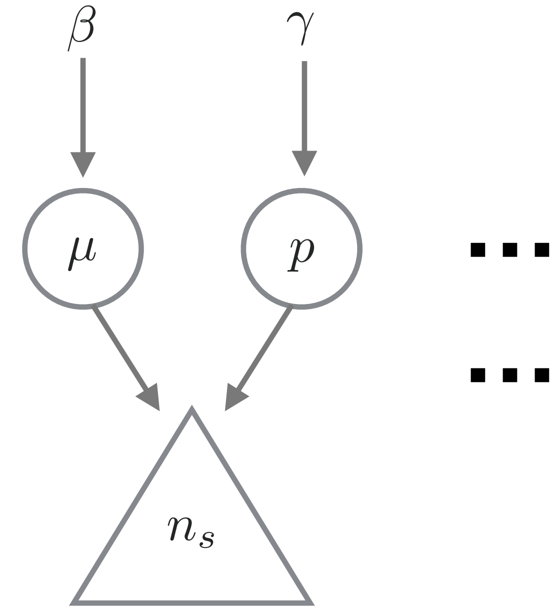
strings , branes & fluxes

# machine learning for axion monodromy inflation



Steps:

1. Identify relevant scales (class of models)
2. Learn the mapping from parameters to observables
3. Study how predictions change according to prior choice




Use numerical methods developed in previous work to generate a large sample assuming

$$\mu \sim \mathcal{U}(0.1, 1) \quad p \sim \mathcal{U}(0.1, 2)$$

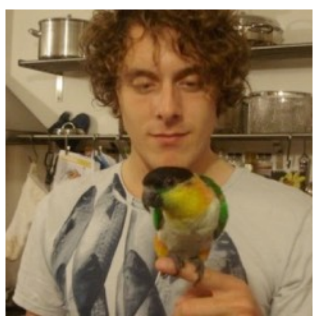
$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0 \left[ \left( 1 + \left( \frac{\phi}{\mu} \right)^2 \right)^{p/2} - 1 \right] + \Delta V_{p,np}$$

- Take a random draw of $\mu$ and $p$
- Solve background equations of motion
- Solve equations of motion for the perturbations and compute $n_s$
- Repeat many times
- Use machine learning to get $n_s(\mu, p)$

Dias, Frazer, Mulryne, Seery: Implementations in C++, Python and Mathematica public at https://transportmethod.com

# machine learning for axion monodromy inflation





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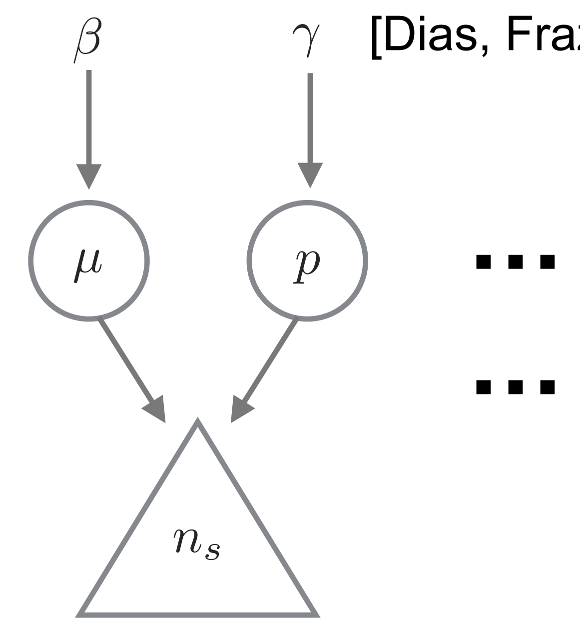
[Dias, Frazer & AW '18]

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$$\mu \sim \mathcal{U}(0.1, 1) \quad p \sim \mathcal{U}(0.1, 2)$$

**$\Delta V_{n,np}$: full model — 12 parameters !**

- Take a random draw of $\mu$ and $p$
- Solve background equations of motion
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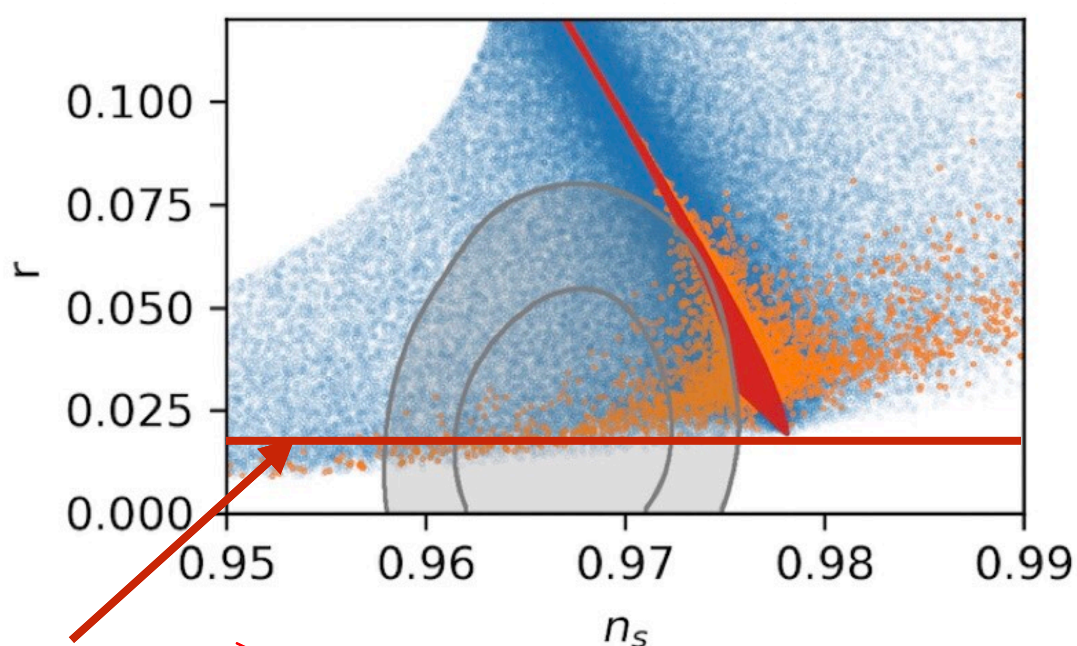



**lower bound $r \gtrsim 0.015$ independent of $\mu$**

Dias, Frazer, Mulryne, Seery: Implementations in C++, Python and Mathematica public at https://transportmethod.com

# Particle production during inflation

**Slow-roll inflation** → **very flat scalar potential**

**Reheating after inflation** → **coupling to the SM**

↓

**Inflaton as Pseudo Goldstone Boson with shift-symmetric couplings**

$$\phi F_{\mu\nu}\tilde{F}_{\mu\nu}$$

$$(\partial_\mu \phi)\bar{\psi}\gamma^\mu\gamma^5\psi$$

**explosive helical gauge boson production**

**additional friction modifies dynamics of inflation, see also relaxion models**

**Strongly enhanced non-gaussian polarized GW spectrum at scales. of LIGO and LISA**

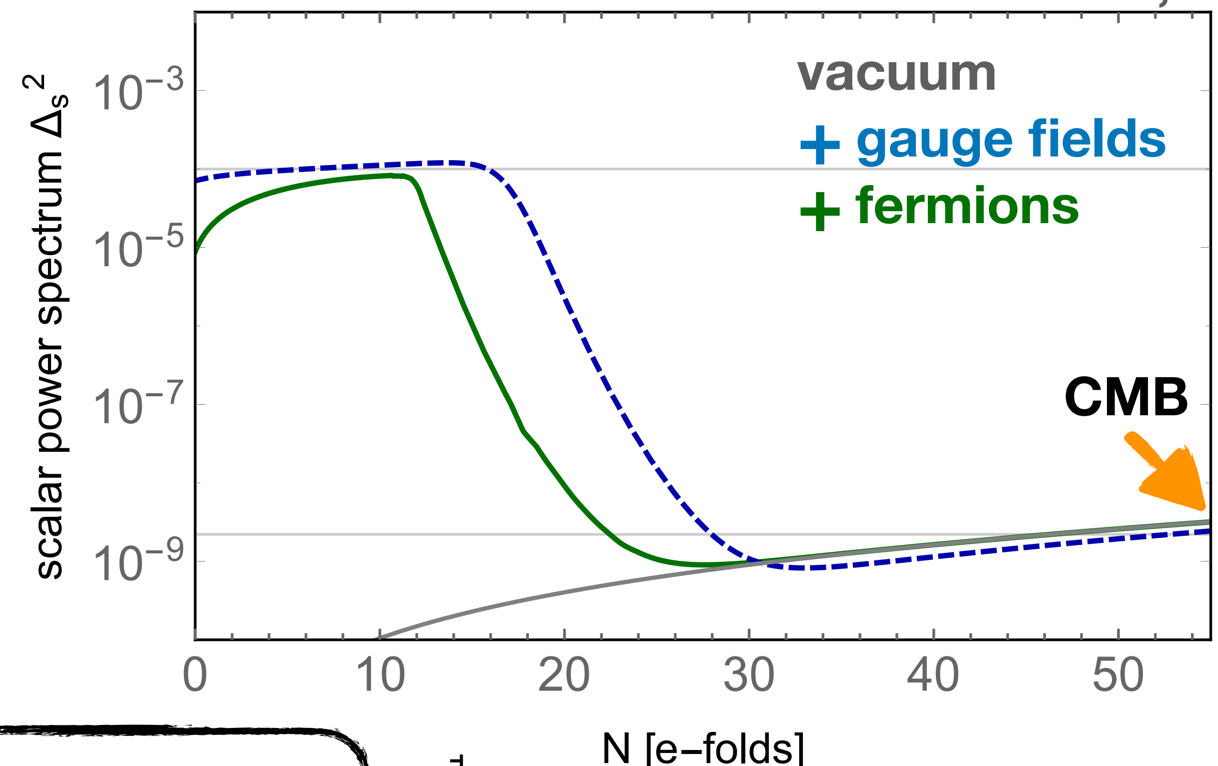
**chiral fermion production**

**baryogenesis through spontaneous CPT violation**

**backreaction through induced current modifies gauge boson production**

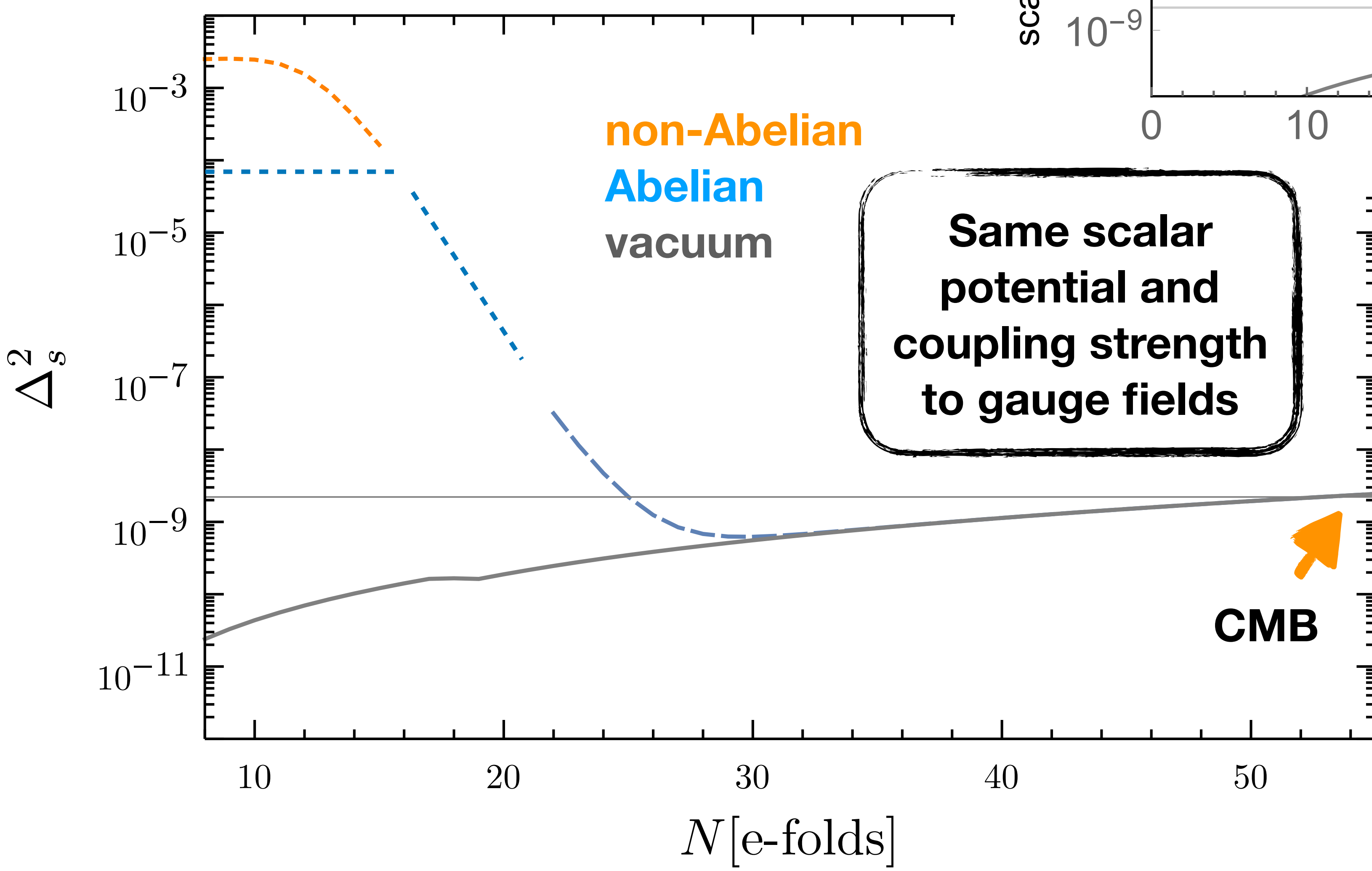
# Particle production during inflation

Domcke, Mukaida ‘18




**One example:**
**Scalar power spectrum at small scales**

Domcke, Mares, Muia, Pieroni ‘18



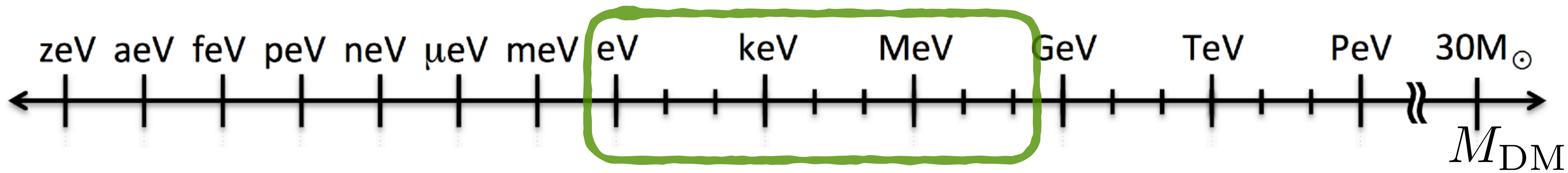

**Same scalar potential and coupling strength to gauge fields**

**Different inflaton couplings can be probed by observations!**

**(PBHs, UCMHs, mu-distortions)**

**Similar effects (expected) in GW spectrum**

# Light Dark Matter at Neutrino Experiments




**Experiment** $E_{\rm recoil} \lesssim {\rm keV}$ ⟶ Standard Detectors not sensitive (Xenon1T,…)

**Theory** New connections in recent years (w/flav. anomalies, hierarchy problem, …)

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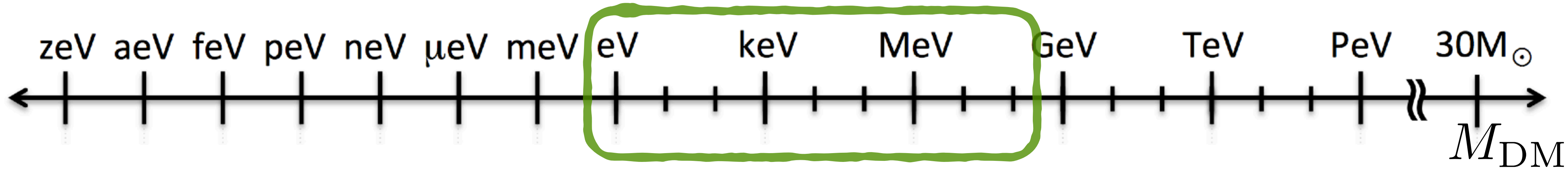


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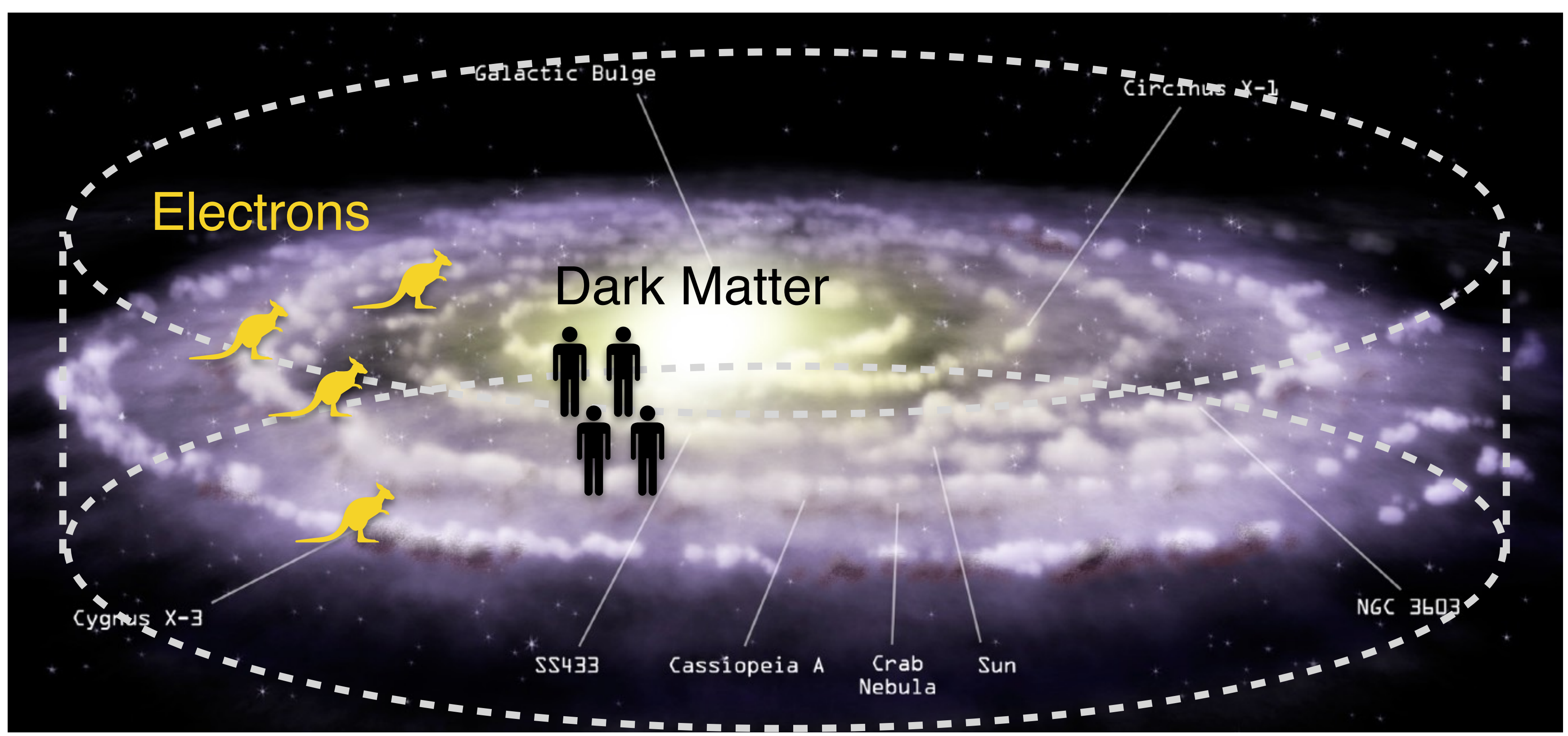
Ema Sala Sato PRL 122 (2019) no.18:

**High-speed DM component** unavoidably generated by **Cosmic-ray scatterings**!



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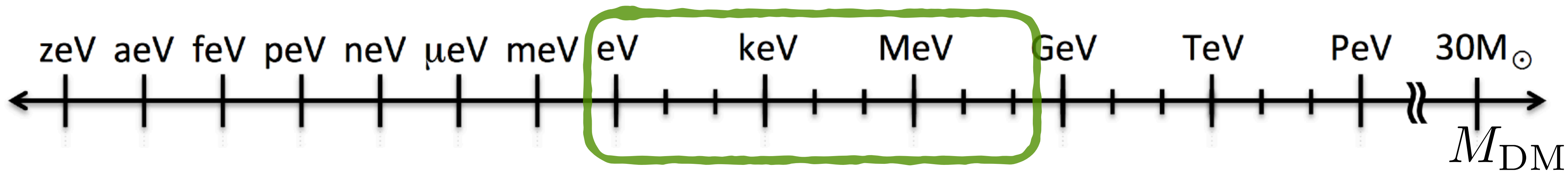


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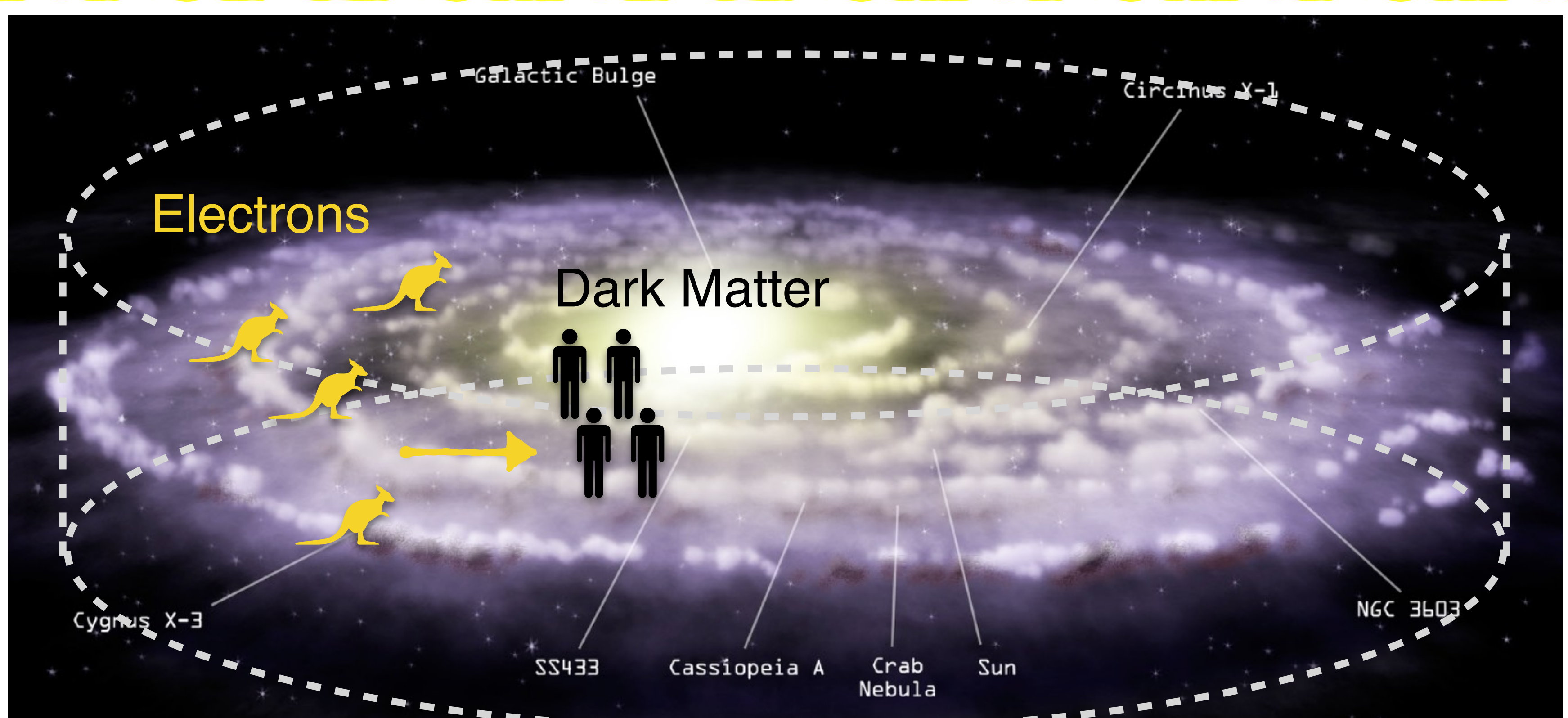

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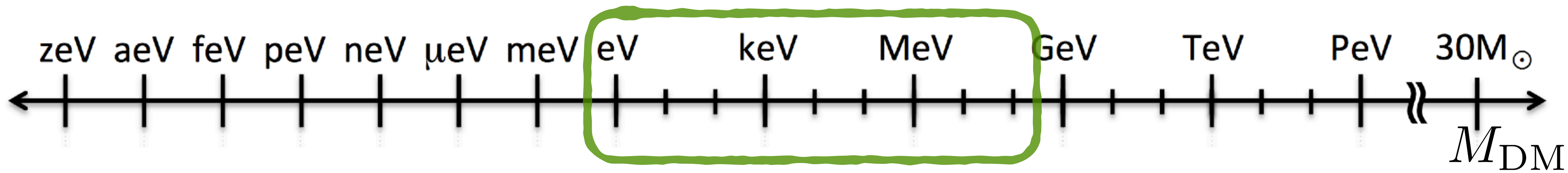


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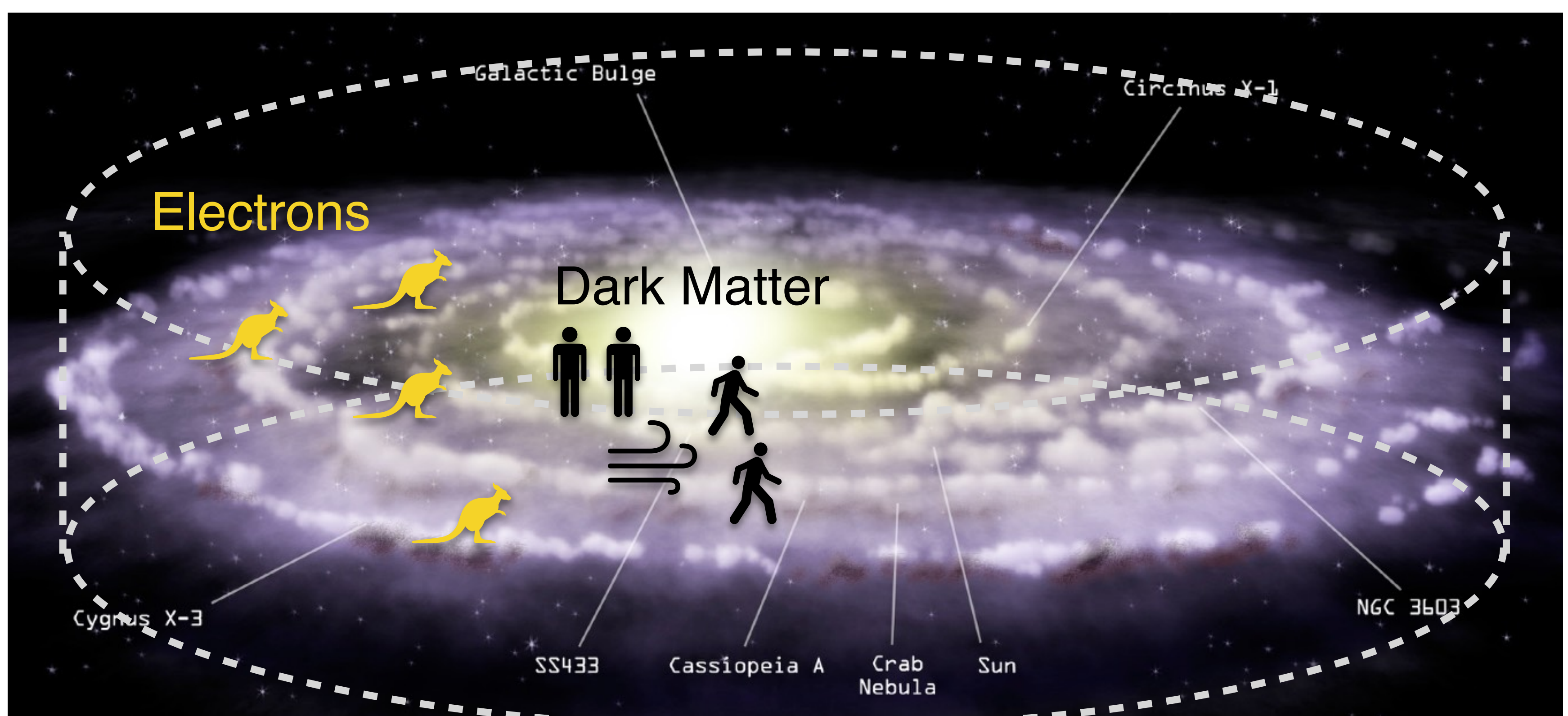
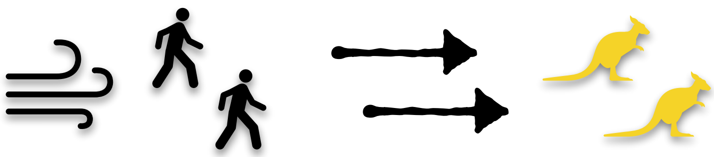


Ema Sala Sato PRL 122 (2019) no.18

# Light Dark Matter at Neutrino Experiments



Energies > 10 MeV → go to biggest existing detectors!

Ema Sala Sato PRL 122 (2019) no.18

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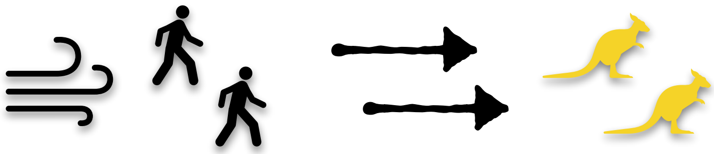

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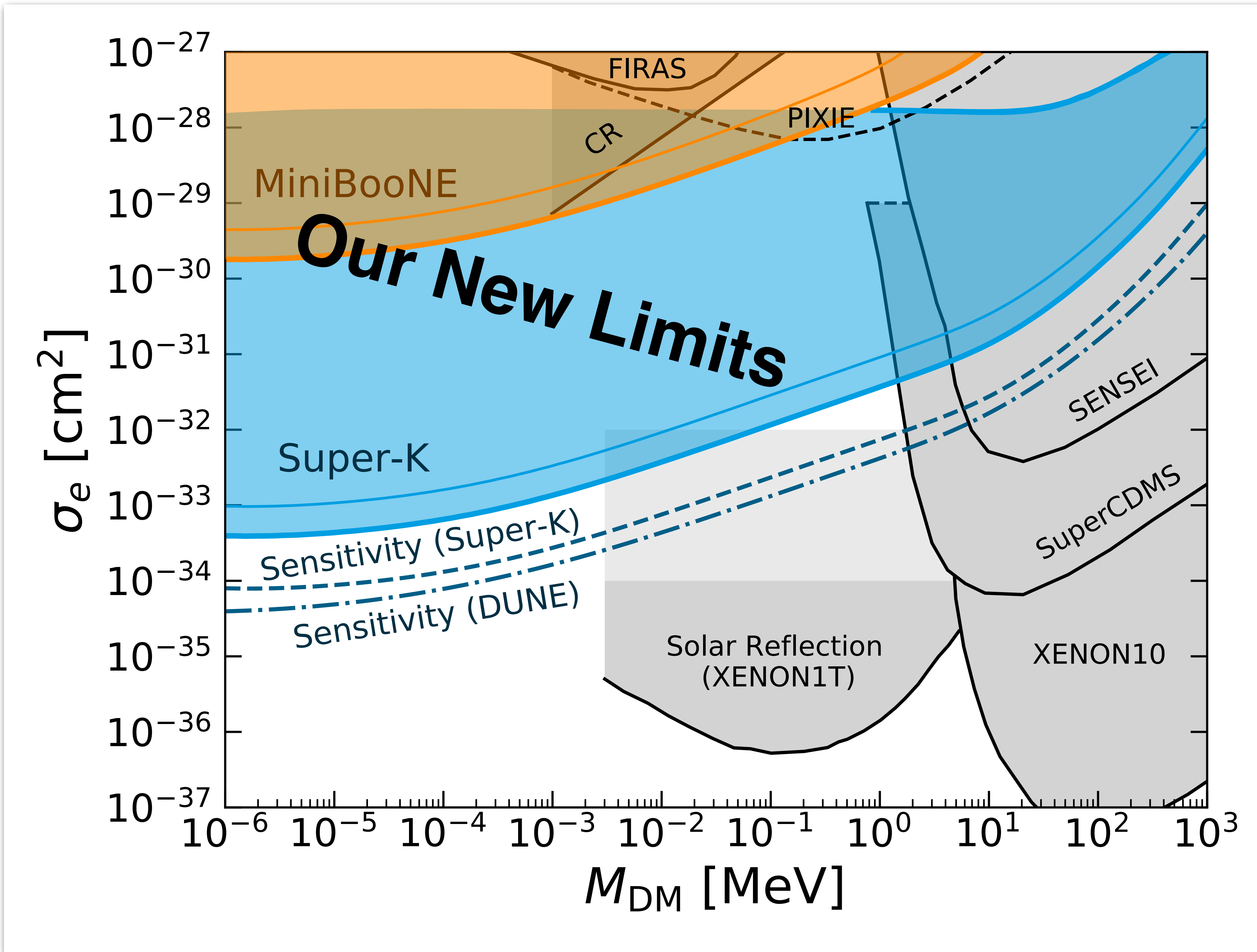
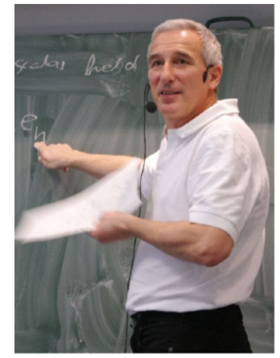


# Cosmo approaches to the Big Picture




## We work to understand:

- ★ Dark Matter
- ★ Baryon Asymmetry
- ★ Neutrino Oscillations
- ★ Quantum Gravity
- ★ Inflation
- ★ Dark Energy
- ★ EW symmetry breaking
- ★ Strong CP problem
- ★ Origin of SM flavour
- ★ ….