Cosmic Connections to Particle Physics

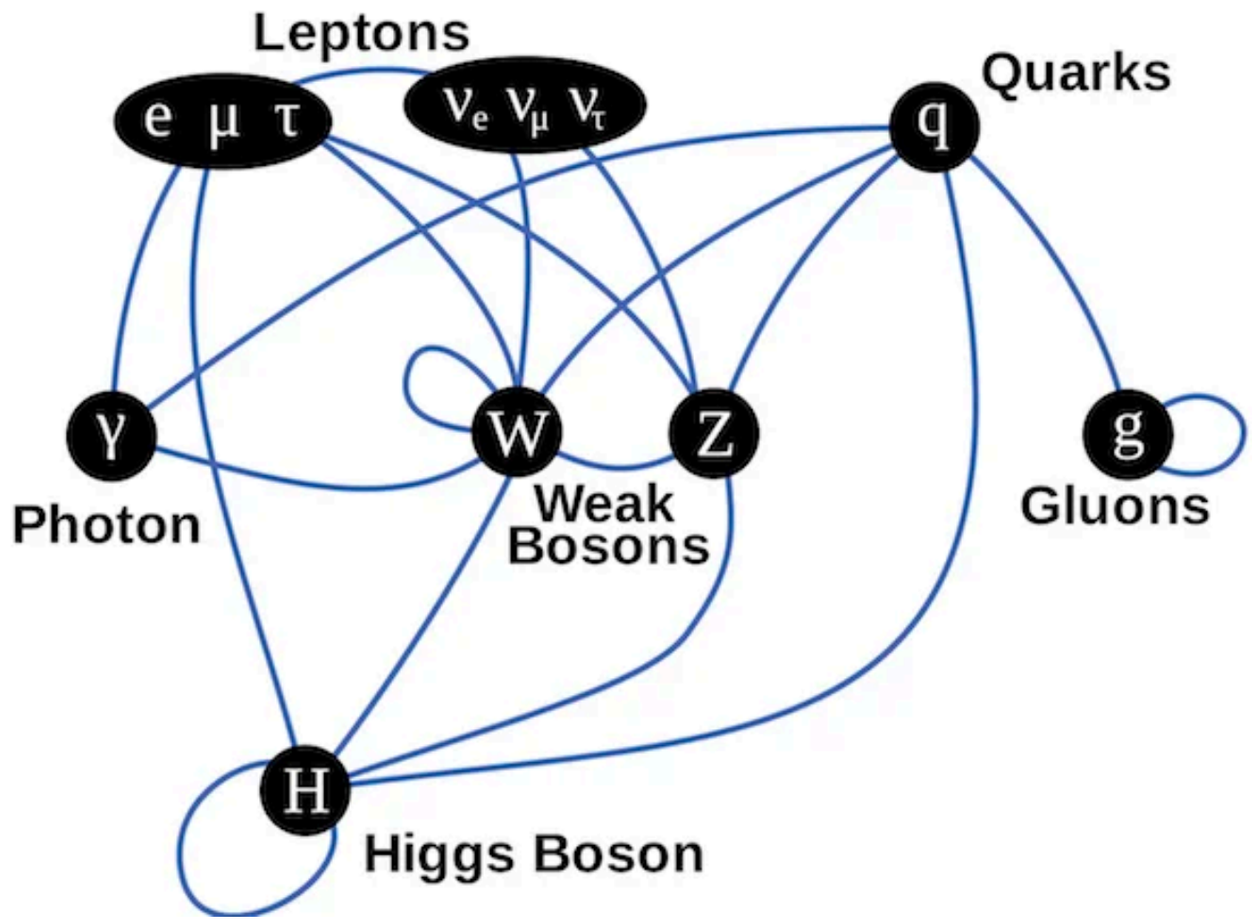
… an extremely biased survey

TeV Particle Astrophysics
TeVPA
Valencia 2025

Gordan Krnjaic

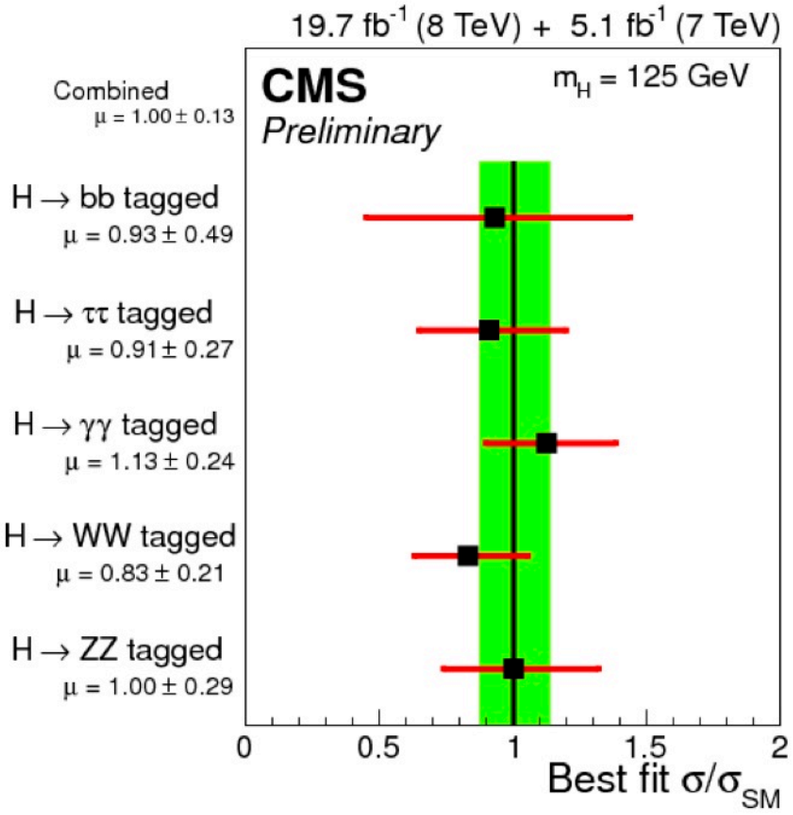
THE UNIVERSITY OF CHICAGO
KICP

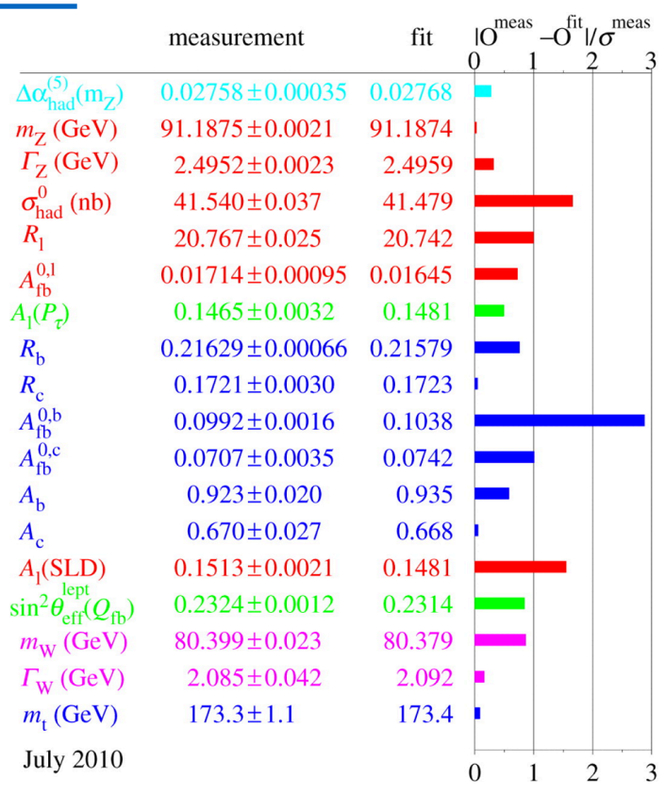
The Standard Model

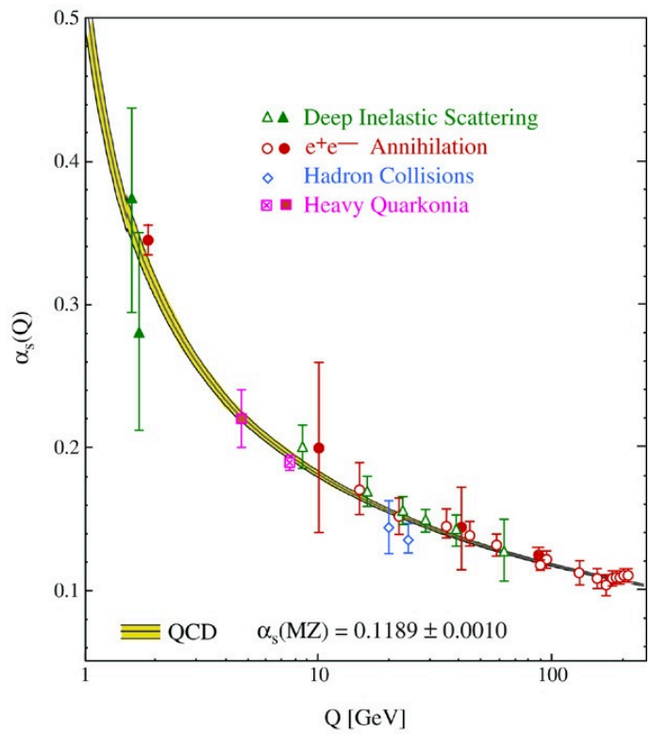


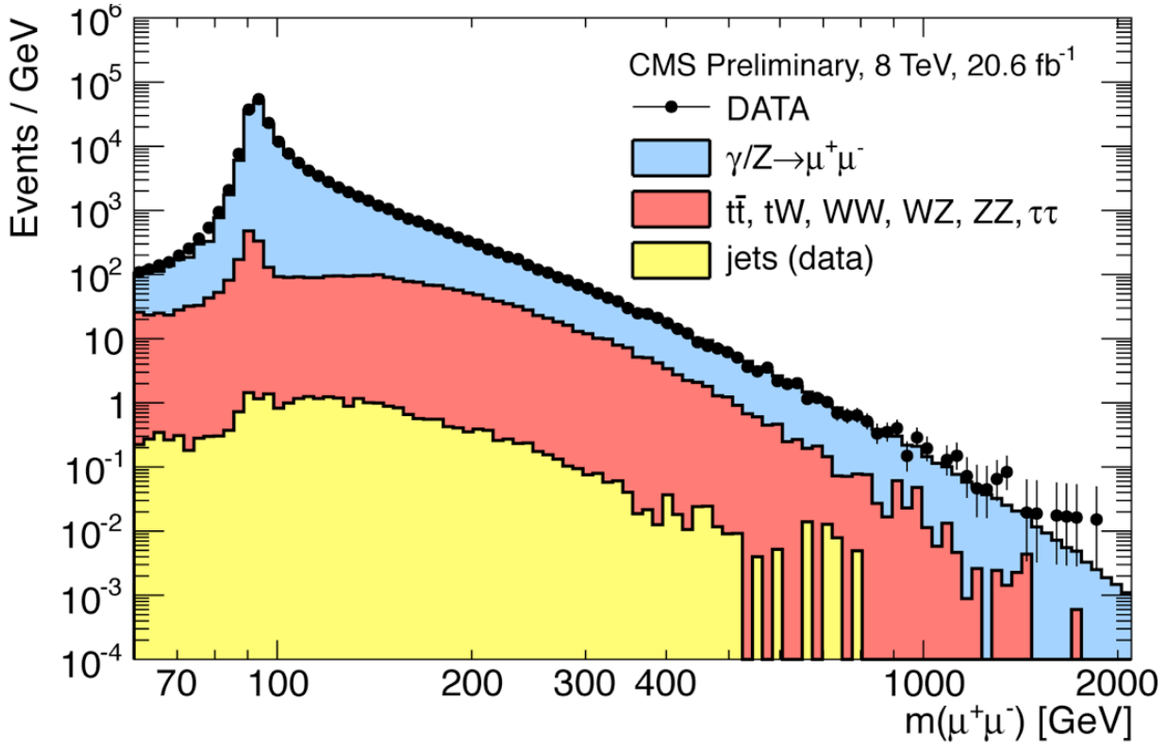
Gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$

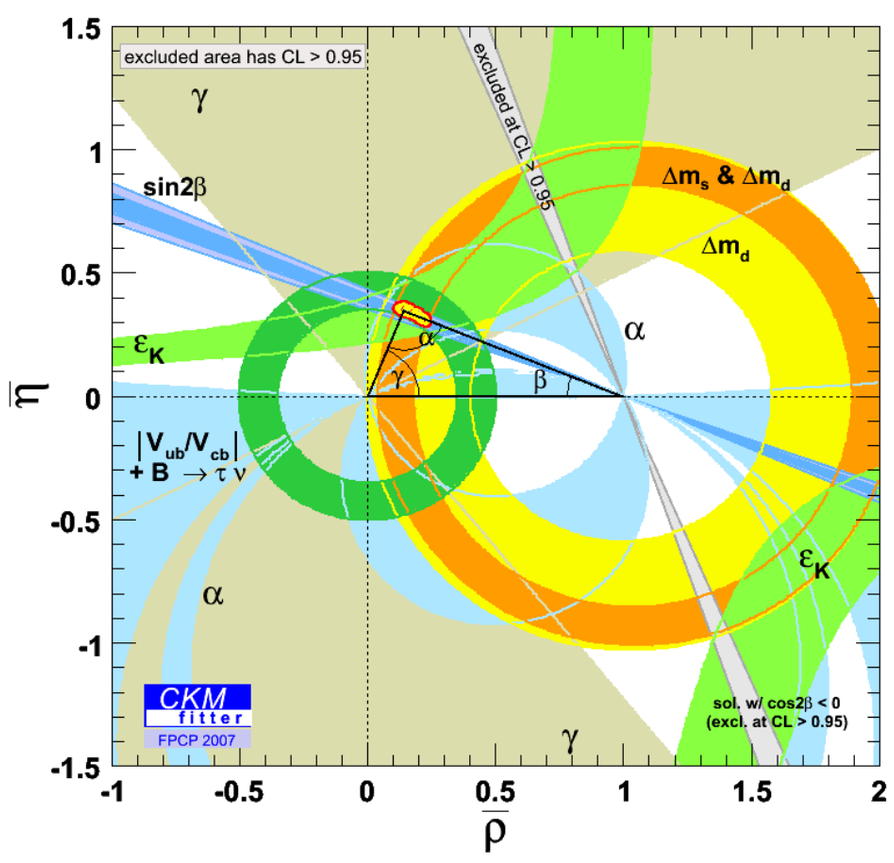
It's Wildly Successful











So we're done…

NEWS IN BRIEF

World's Physicists Complete Study Of Physics

1/14/10 9:00am • SEE MORE: SCIENCE & TECHNOLOGY

HARIMA, JAPAN—Saying that there was no more knowledge to acquire about the physical nature of the universe, the International Union of Pure and Applied Physics announced Monday that it had concluded the scientific study of matter, energy, force, and motion. "Yeah, that about does it for physics," said IUPAP member Sukekatsu Ushioda, powering down Japan's Super Photon ring particle accelerator. "All done. Math can pretty much take it from here." The world's top physicists also announced that they would celebrate the conclusion of physics by meeting at PJ's Pub later tonight for drinks.

the ONION®

The *Incomplete* Standard Model

Must-solve problems

Neutrino Masses

Dark Matter

Baryogenesis

Dark Energy

Initial Conditions

The *Incomplete* Standard Model

Must-solve problems	Troubling, but not obligatory
Neutrino Masses	Strong CP Problem
Dark Matter	Hierarchy Problem
Baryogenesis	Flavor Puzzle
Dark Energy	Cosmological Constant
Initial Conditions	Inflation

The *Incomplete* Standard Model

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Neutrino Masses	**Strong CP Problem**
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Plenaries: Aart Heijboer, Irene Tamborra, Simona Toscano, Javier Redondo

The *Incomplete* Standard Model

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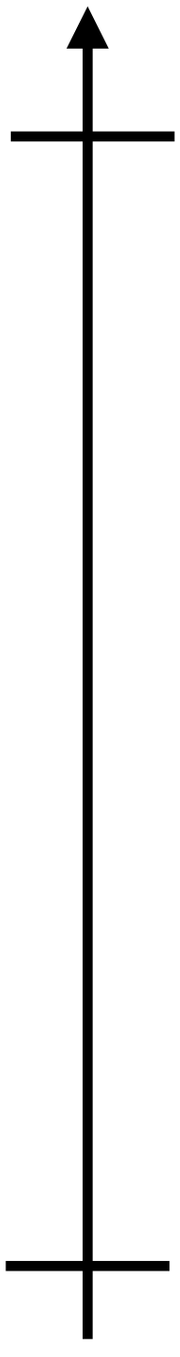
Why is the weak scale so small?



$M_{\text{Planck}} \approx 10^{19}\,\text{GeV}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_n \frac{\hat{\mathcal{O}}_n}{\Lambda^{n-4}} \qquad \Lambda \sim M_{\text{Planck}}$$

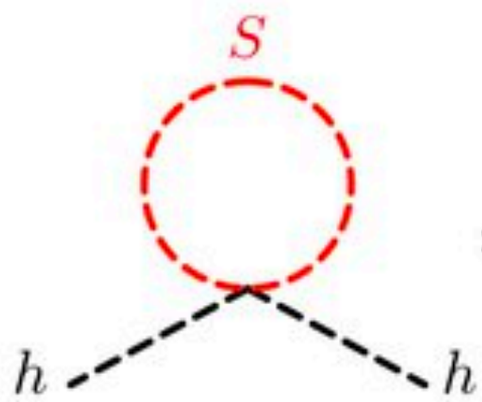
$$\Longrightarrow \quad \mathcal{L}_{\text{eff}} \supset \Lambda^2 |H|^2$$

$v = 246\,\text{GeV}$

Higgs mass not protected by any symmetry

Why is the weak scale so small?

$$\mathcal{L} \supset \lambda_S |H|^2 S^2$$



$$= \frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2 \ln\left(\frac{\Lambda_{\rm UV}}{m_S}\right) + \cdots\right]$$

this is **not** the hierarchy problem
the regulator is not physical

this is the hierarchy problem

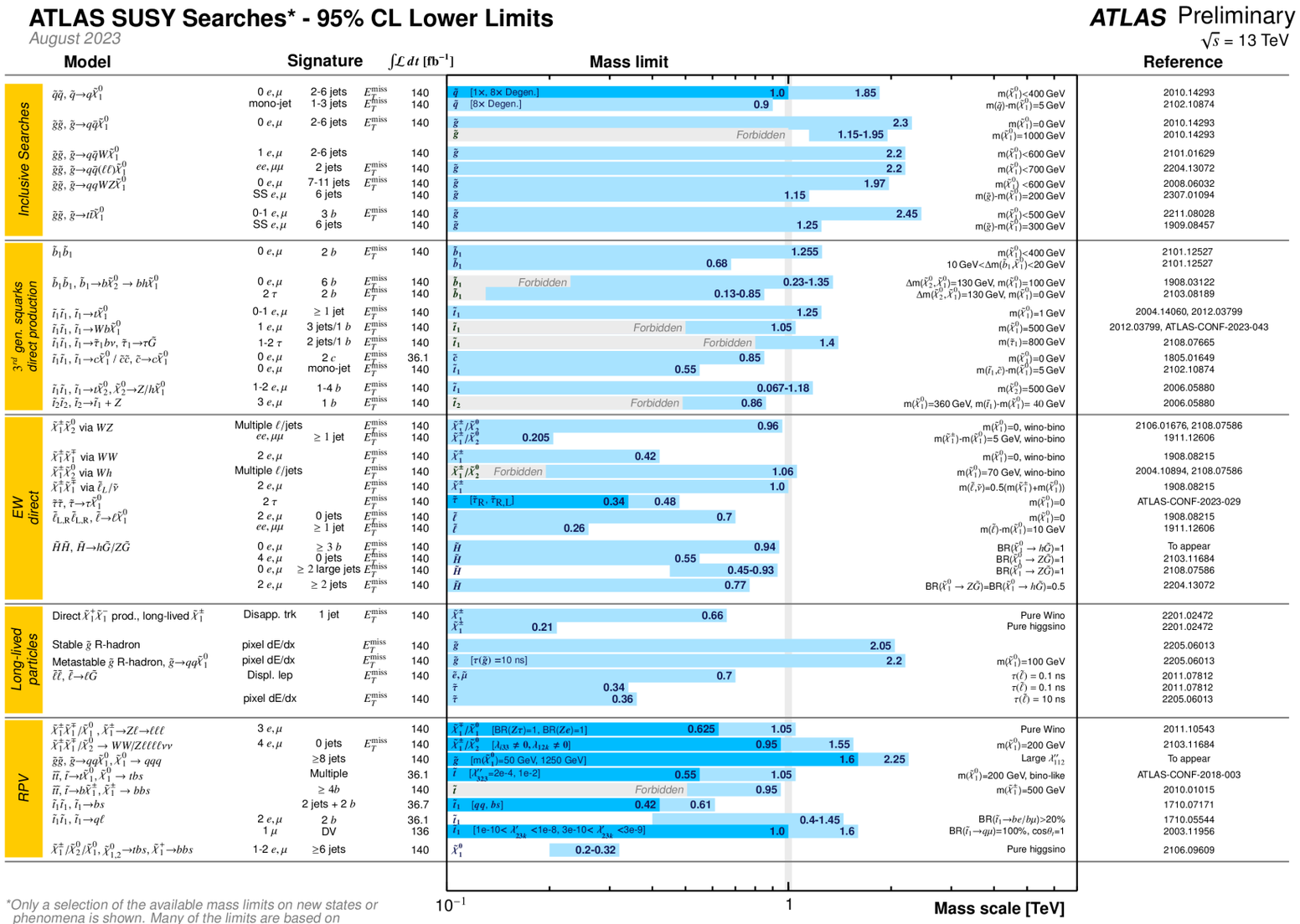
the Higgs mass is quadratically sensitive to
the mass of any new particles that couple to it

Gauge hierarchy problem: Higgs mass is sensitive to the highest scales that it couples to (Planck scale, GUT scale…)

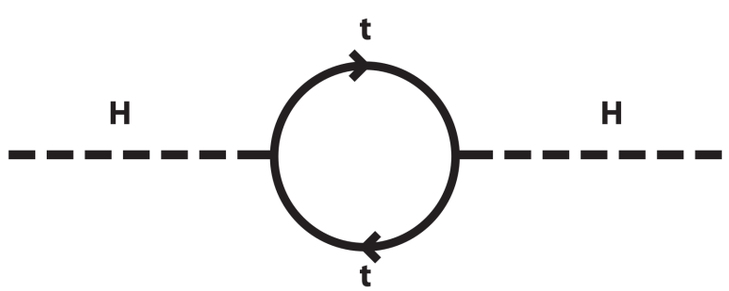
Not just loop corrections! Problem in any theory where the Higgs mass is calculable

Image: Flip Tanedo

Why is the weak scale so small?



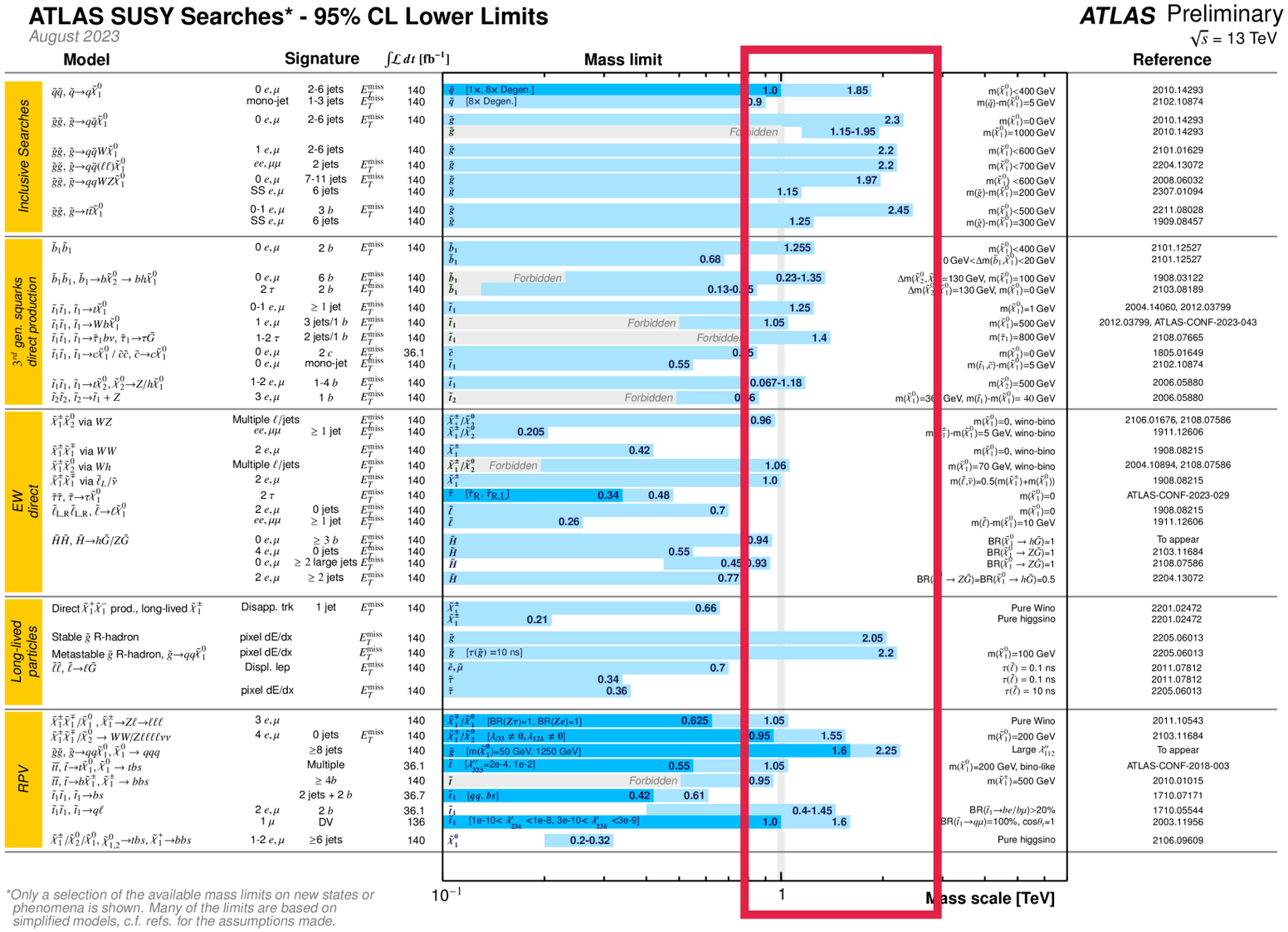
$$\Delta m_H^2 \sim$$



$+$

~ 0

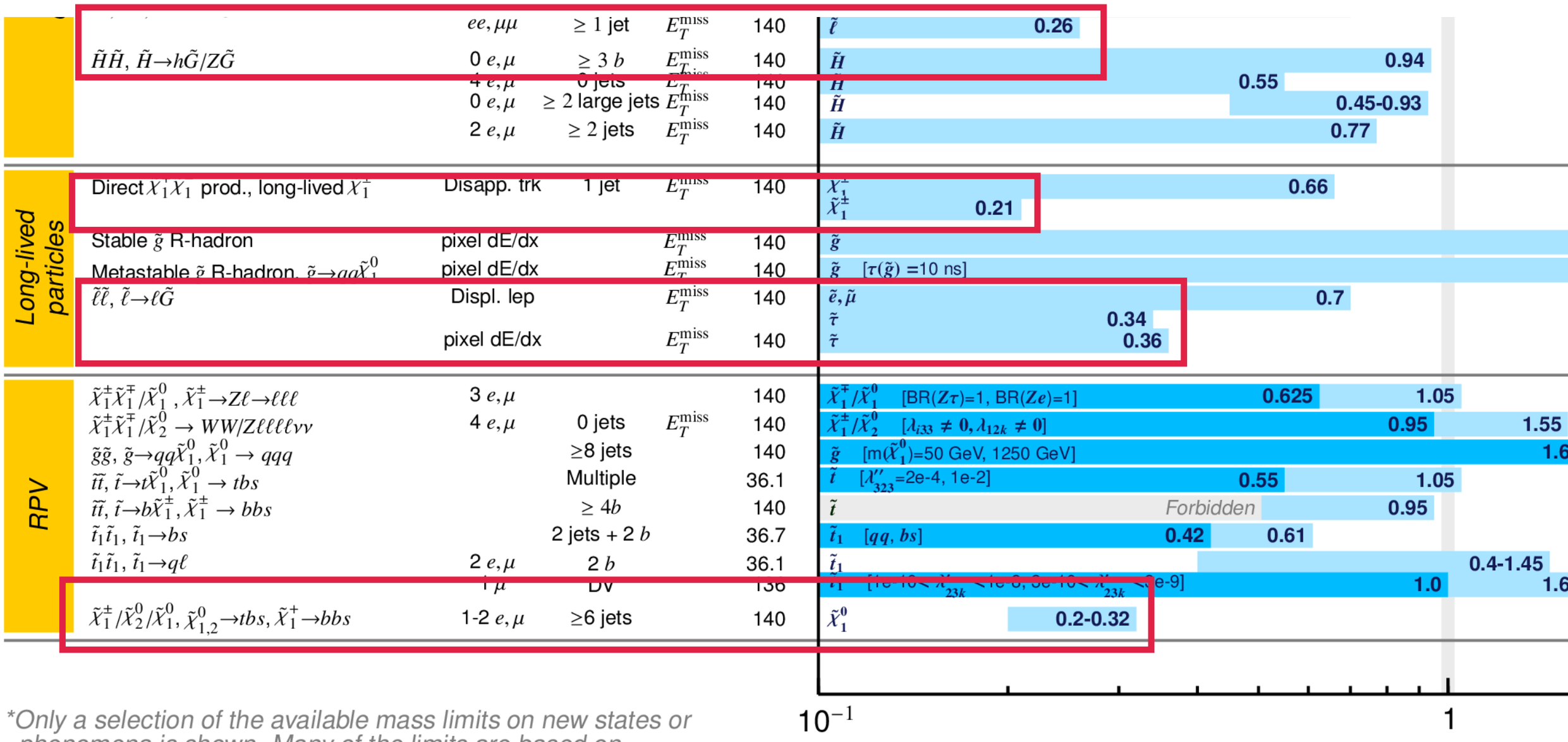
Why is the weak scale so small?



- Weak scale SUSY seems unlikely to solve hierarchy problem
- New QCD charged particles must be few TeV+

2025: we live in an era of vastly broader priors about new physics

Why is the electroweak scale so small?



*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

However, weak scale alone is *barely* probed to ~ 200 GeV

Many great reasons to go TeV — see Matt Baumgart's talk

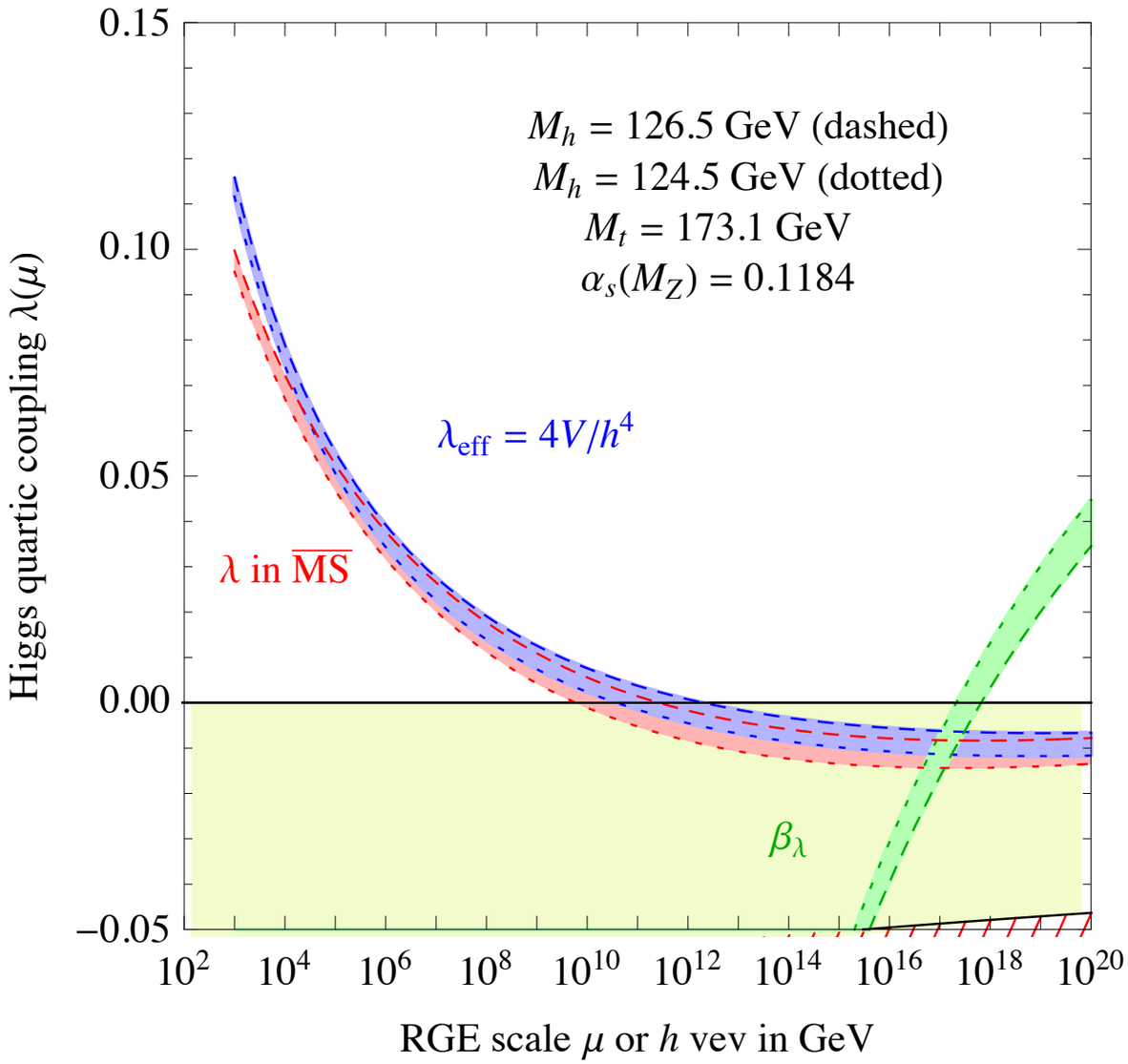
Do we live in the true vacuum?

Effective Higgs potential

$$V_{\rm eff}(h) = \frac{\lambda_{\rm eff}(h)}{4} h^4$$

SM loop corrections predict quartic runs negative in UV

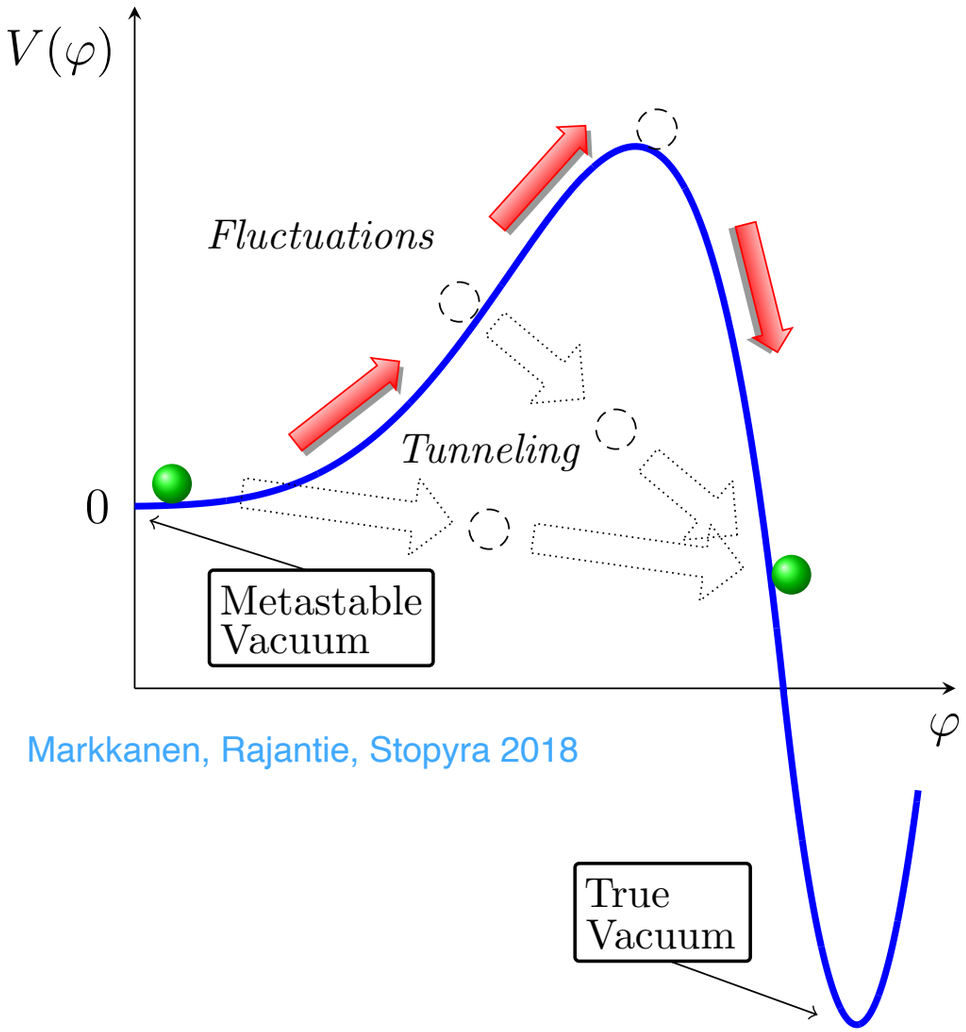
Conclusion depends sensitively on Higgs and top masses



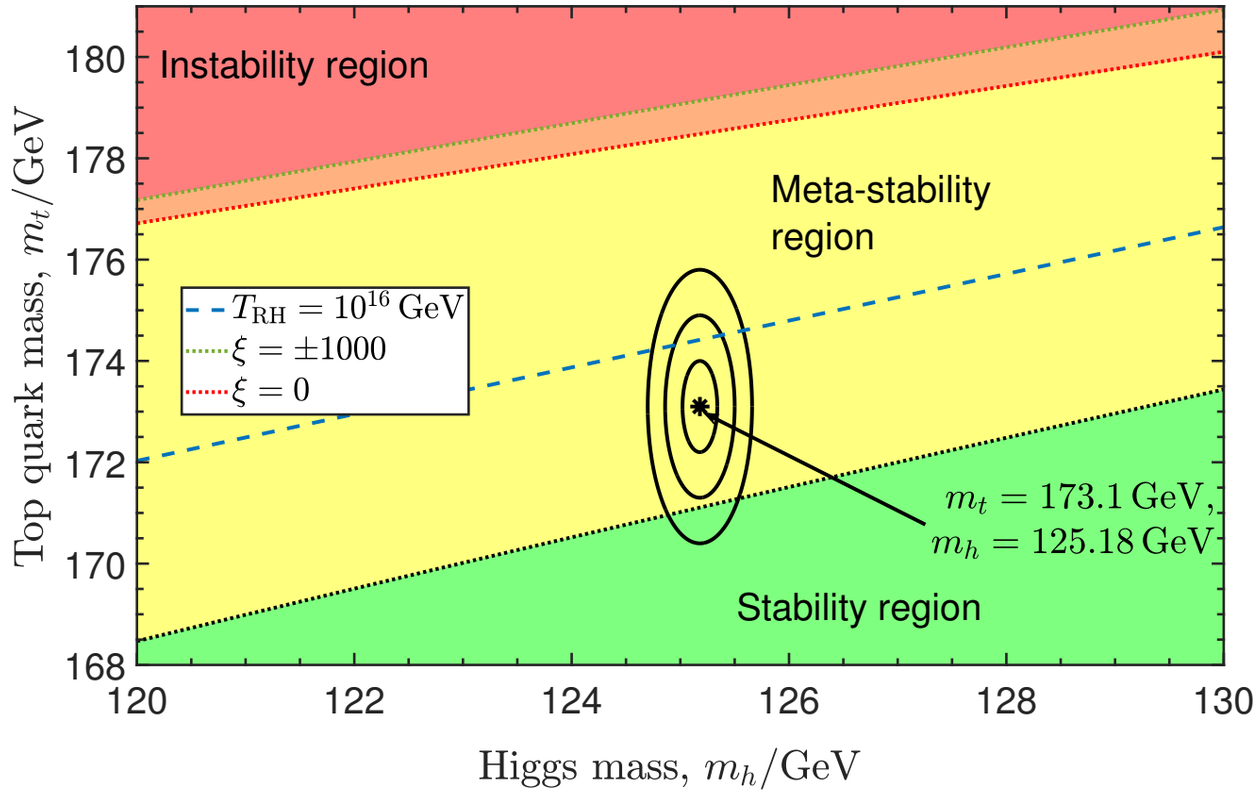
$$\begin{aligned}\lambda_{\rm eff}(h) &= e^{4\Gamma(h)} \left\{ \lambda(h) + \frac{1}{(4\pi)^2} \sum_p N_p \kappa_p^2 \left(r_p - C_p\right) \right. \\ &+ \left. \frac{1}{(4\pi)^4} y_t^4 \left[8 g_s^2 (3 r_t^2 - 8 r_t + 9) - \frac{3}{2} y_t^2 \left(3 r_t^2 - 16 r_t + 23 + \frac{\pi^2}{3} \right) \right] \right\}\end{aligned}$$

Degrassi++ 1205.6047

Do we live in the true vacuum?

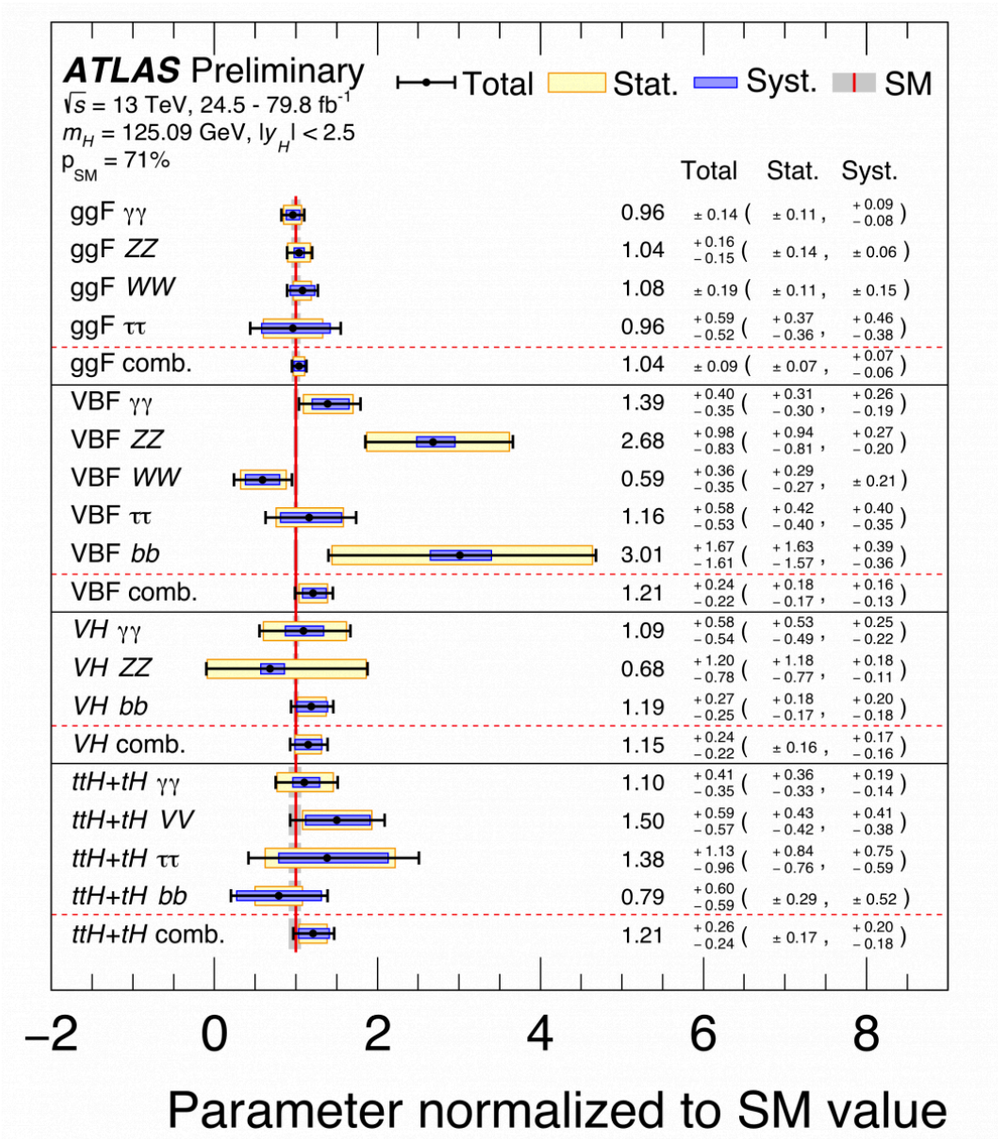


Markkanen, Rajantie, Stopyra 2018

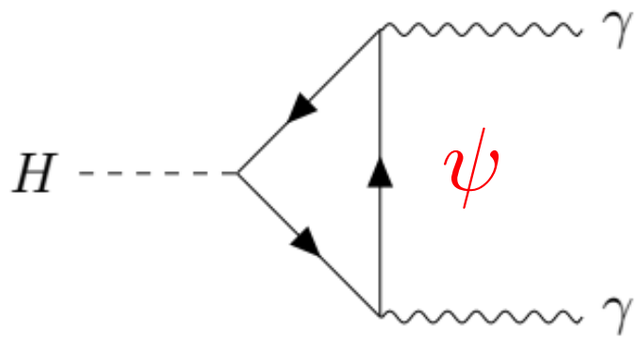


Extrapolating potential, assuming only SM interactions might imply that our vacuum is only metastable on cosmological timescales

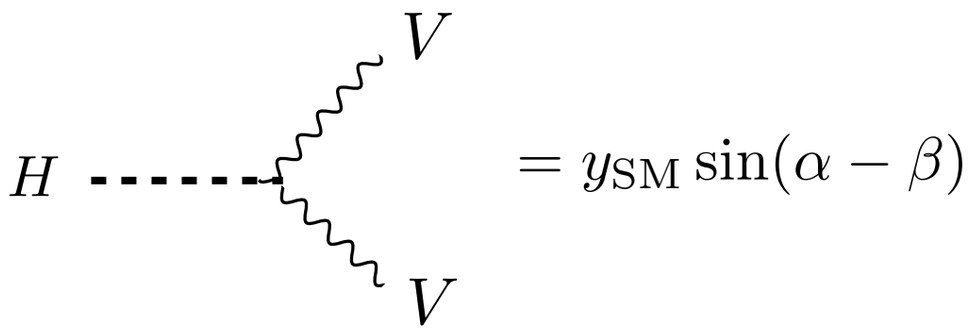
Have we actually seen the SM Higgs?



New particles can appear in loops



…or in tree level interactions (e.g. 2HDM)



Higgs mechanism only tested for gauge bosons and 3rd gen fermions!

Full LHC data set expected to reach 5 sigma for SM muon coupling!

Have we actually seen the SM Higgs?

Future colliders are our only hope for ever understanding Higgs sector

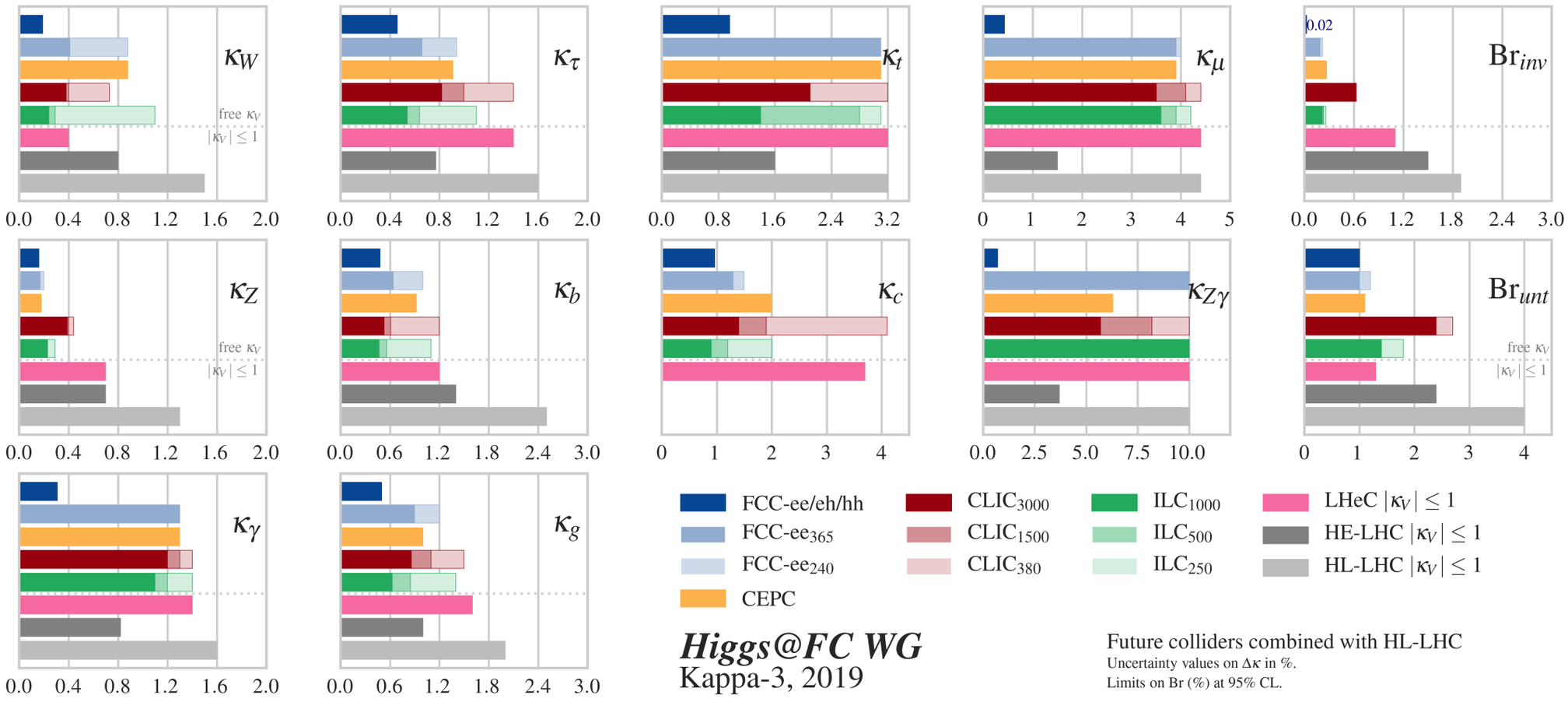


Figure 2. Expected relative precision (%) of the κ parameters in the kappa-3 scenario described in Section 2. For details, see Tables 4 and 5. For HE-LHC, the S2' scenario is displayed. For LHeC, HL-LHC and HE-LHC a constrained $\kappa_V \leq 1$ is applied.

De Blas++ 1905.03764

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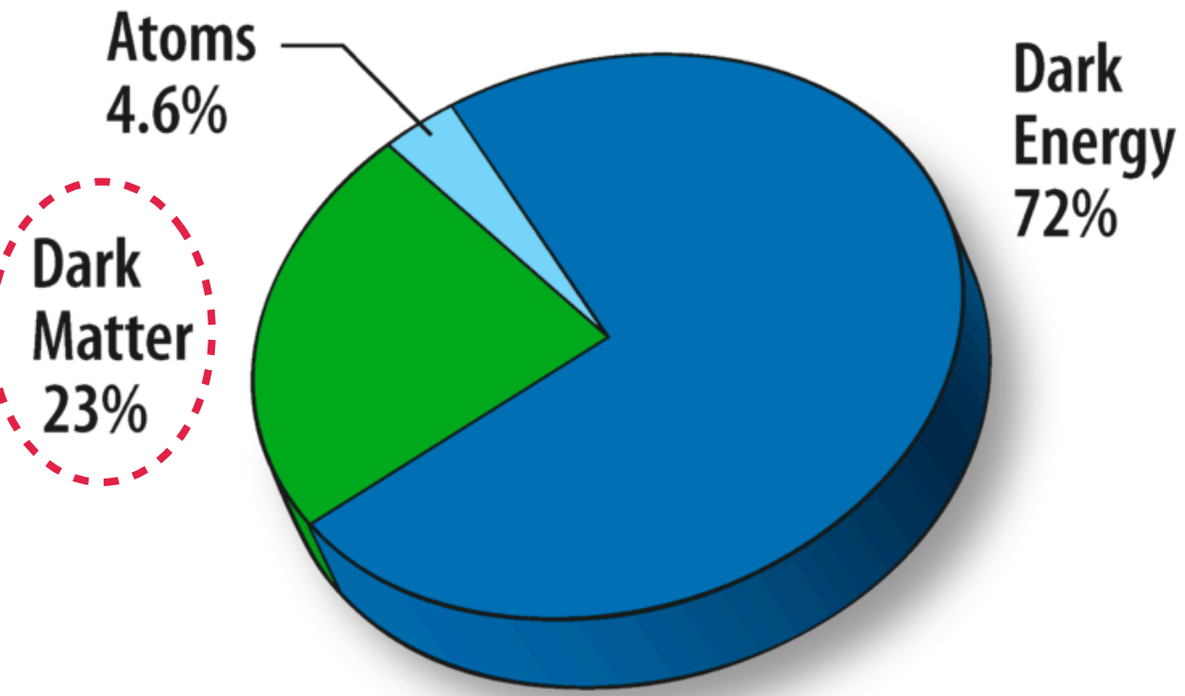
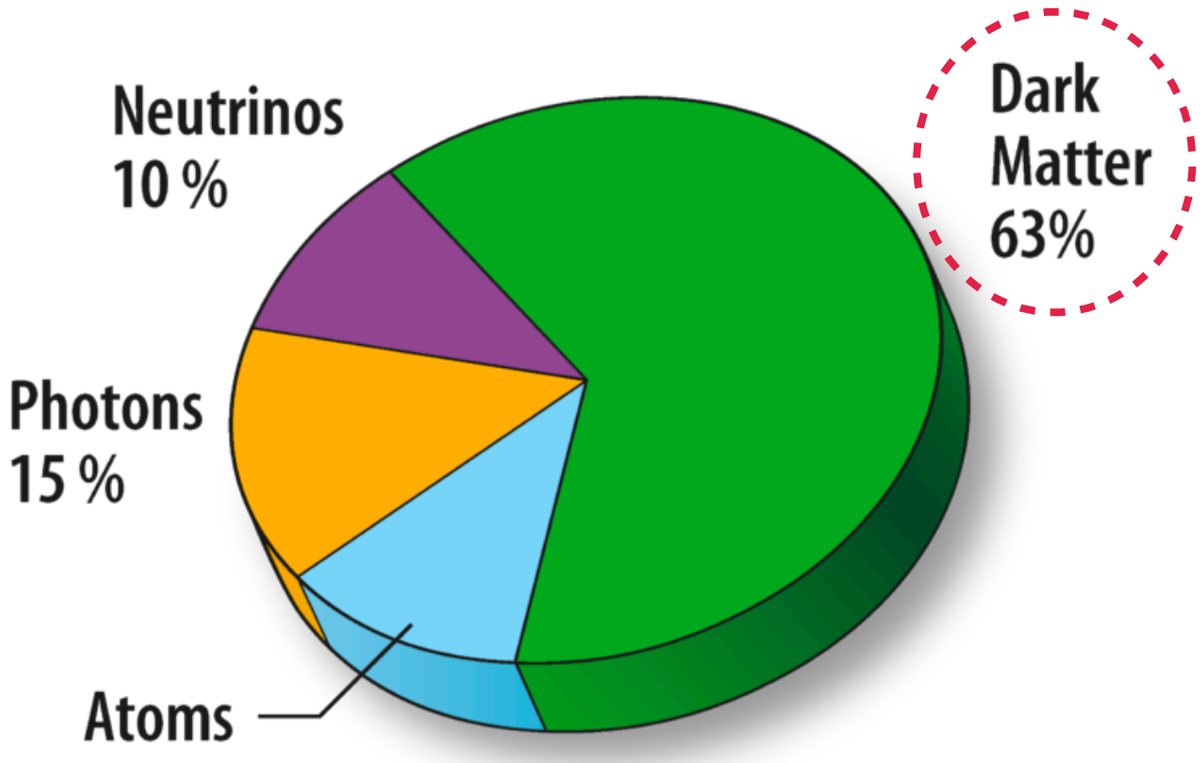
What is Dark Matter?



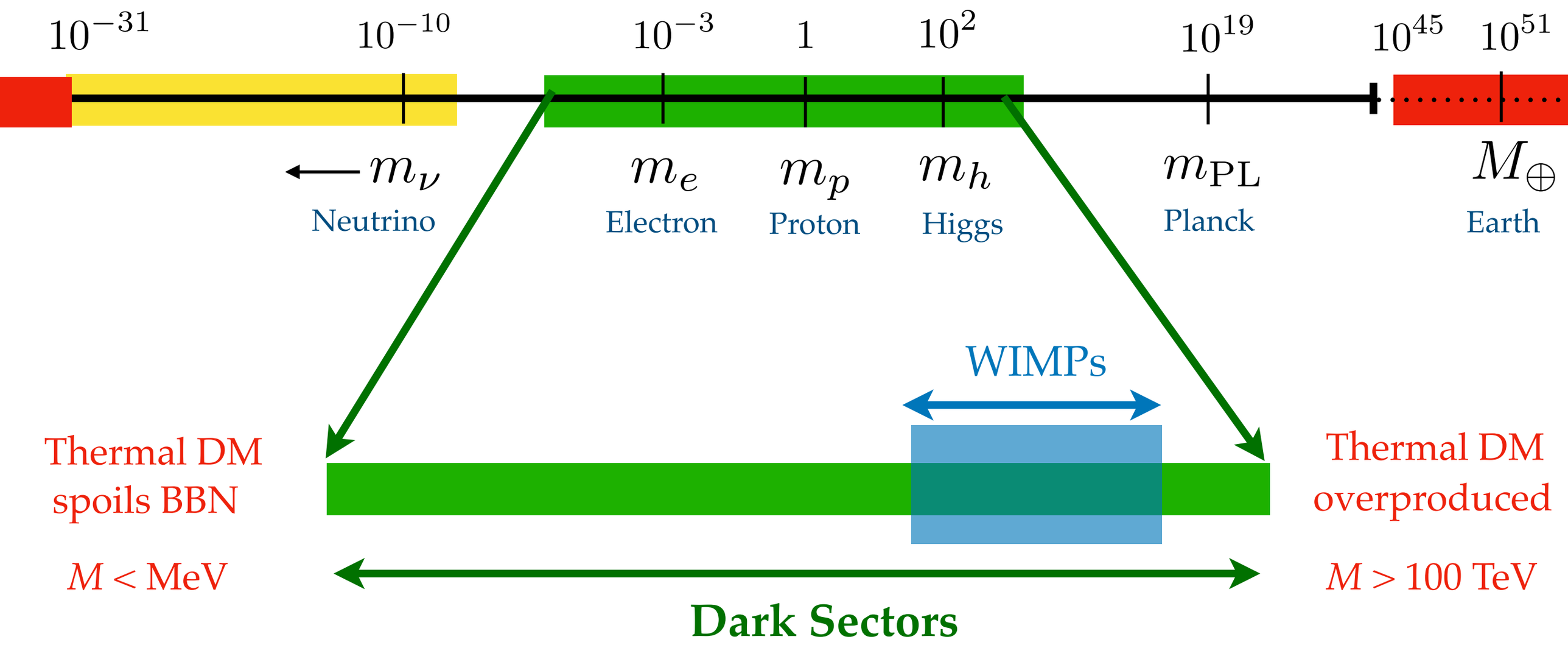
TODAY



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

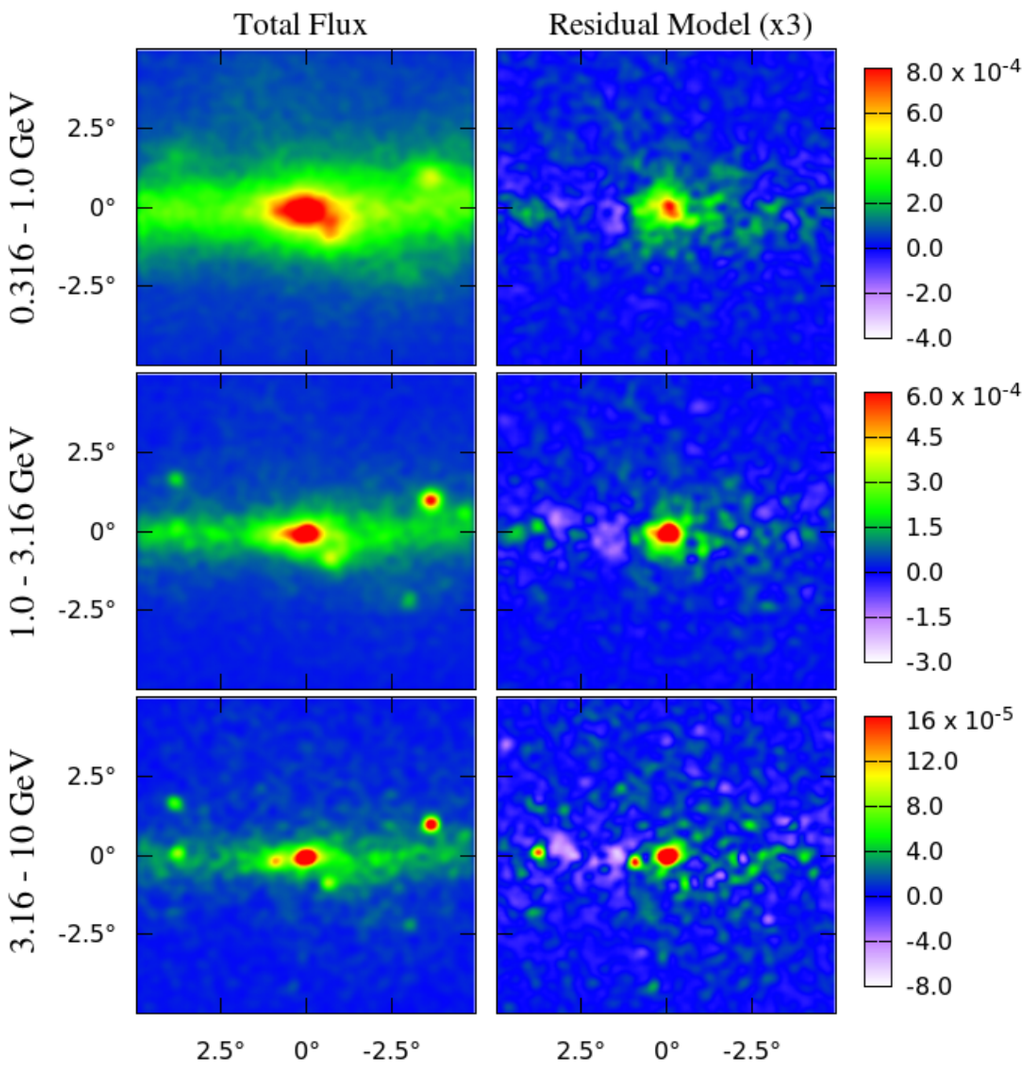
Thermal Window

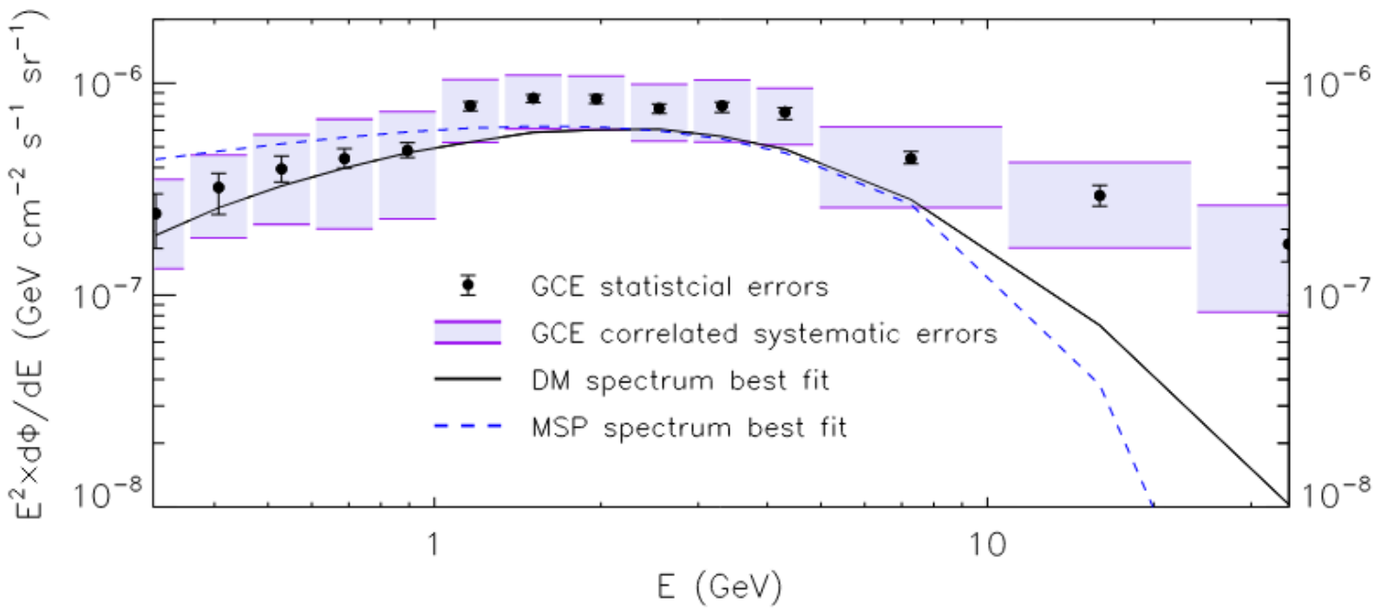


WIMPs: weak scale particles undergo freeze out

See plenaries: Marco Taoso, Christina Gao, Steven Lowette

Have we already seen WIMPs?





Highly significant gamma ray excess in GC

Consistent with weak scale WIMP

Also consistent with emission from 100,000 faint millisecond pulsars

Goodenough, Hooper 0910.2998 1010.2752

Daylan++ 1402.6703

Fist, Park, Rodd, Schoen, Wolf 2507.17804

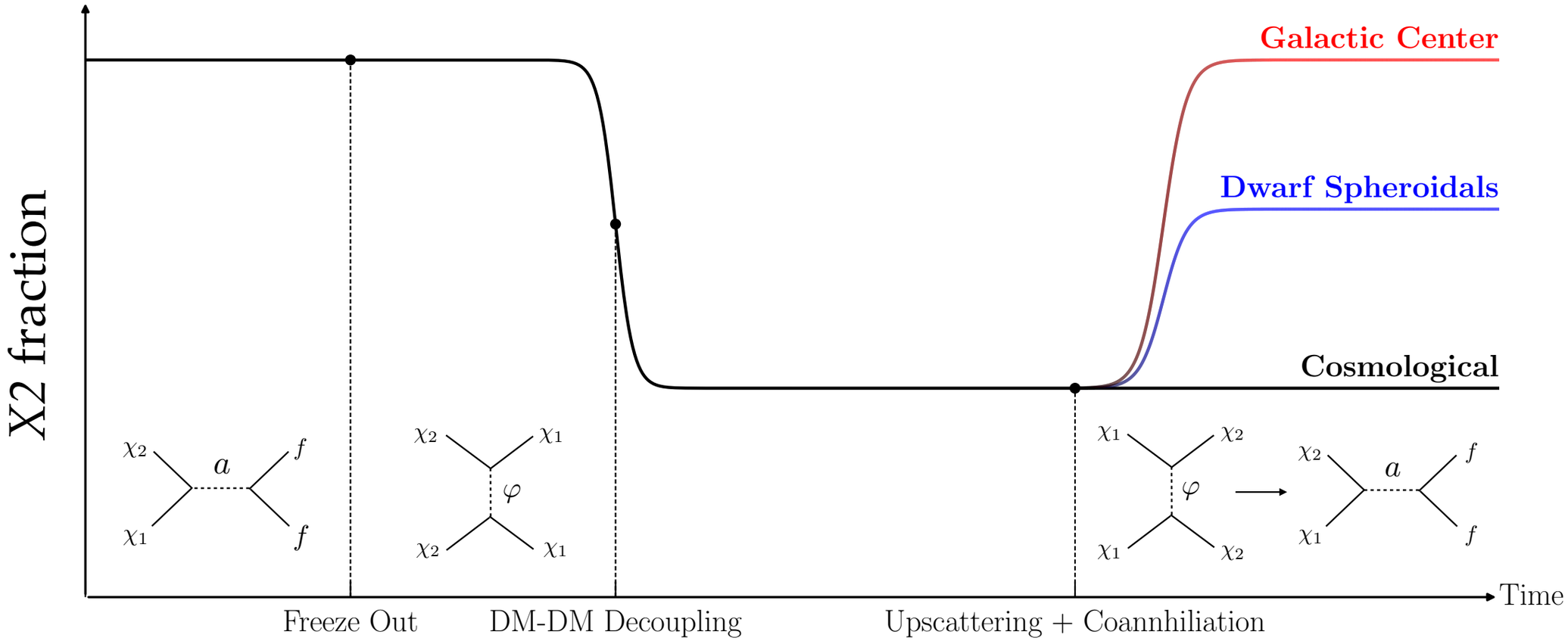
Manconi Eckner Calore Donato 2511.03350

See Christopher Eckner's talk

Dwarf limits are interesting but inconclusive Boddy++ 2401.05327

Dwarfs vs Galaxies

Important to understand environmental dependence to compare with Dwarfs



Inelastic DM with two mediators

$$\mathscr{L}_{\rm int} = y'_\chi\, \varphi\, \bar{\chi}_1 \chi_2 + y_\chi\, a\, \bar{\chi}_1 i\gamma^5 \chi_2 + y_f\, a\, \bar{f} i\gamma^5 f$$

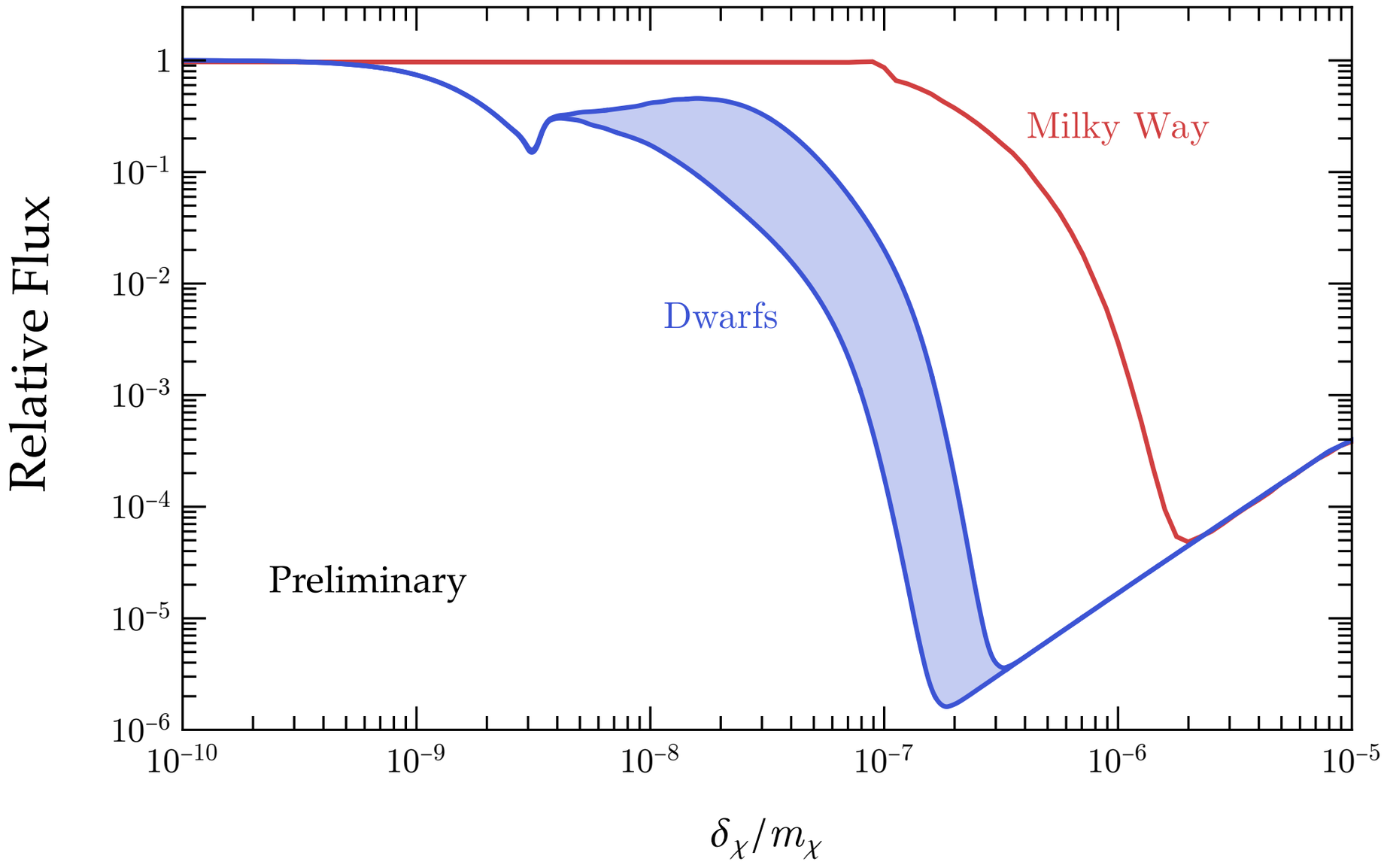
Heavy state depleted cosmologically, but revived in bound structures

Weiner Tucker-Smith 0101138

Berlin, Foster, Hooper, GK 2504.12372

Dwarfs vs Galaxies

Dwarfs have low velocity dispersion, lower X_2 density, suppressed co-annihilation

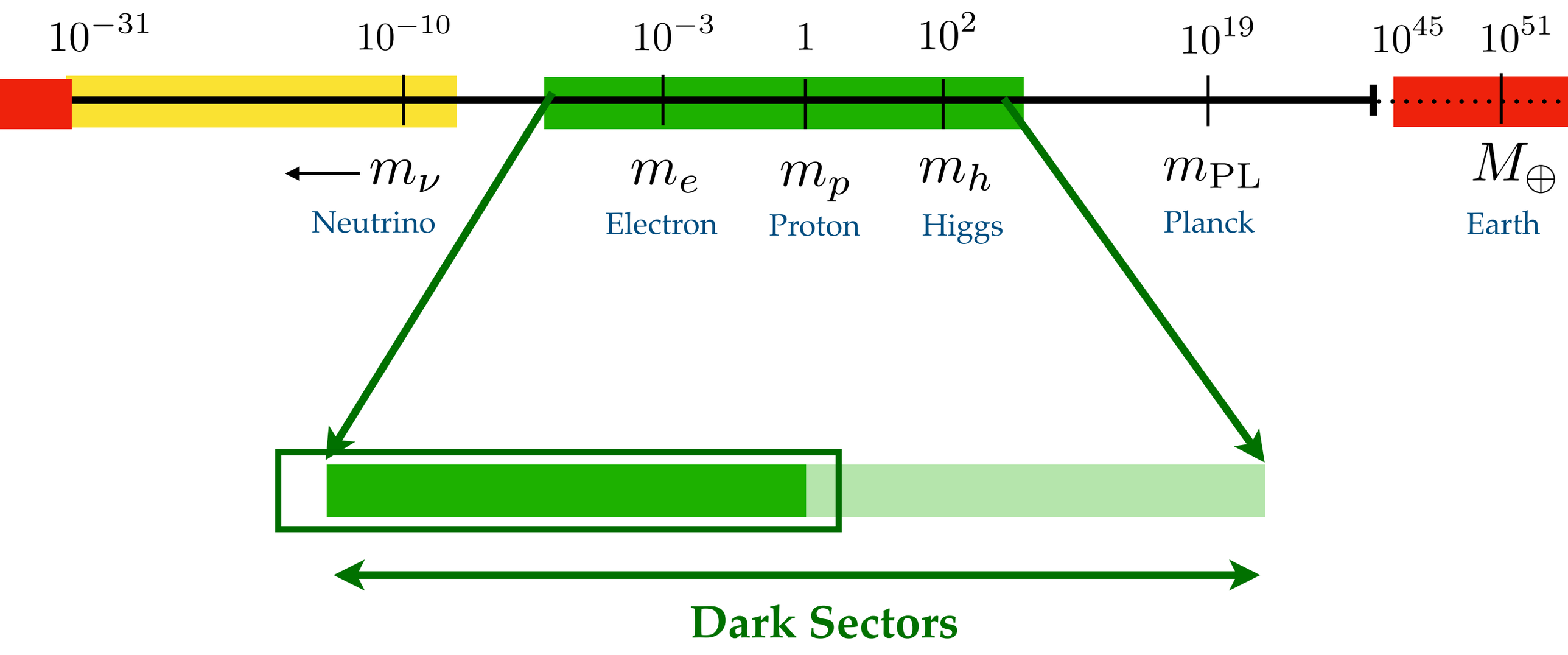


Need to understand inner galaxy with future probes — eg APT telescope

Berlin, Foster, Hooper, GK 2504.12372

Testing Predictive Dark Sectors

Also see Laura López Honorez plenary



Dark Sectors: light new hidden forces mediate DM annihilation

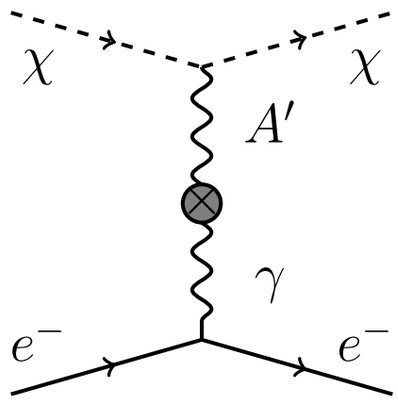
$$\sigma v \sim \frac{\alpha^2 m_\chi^2}{m_Z^4} \sim 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^2$$

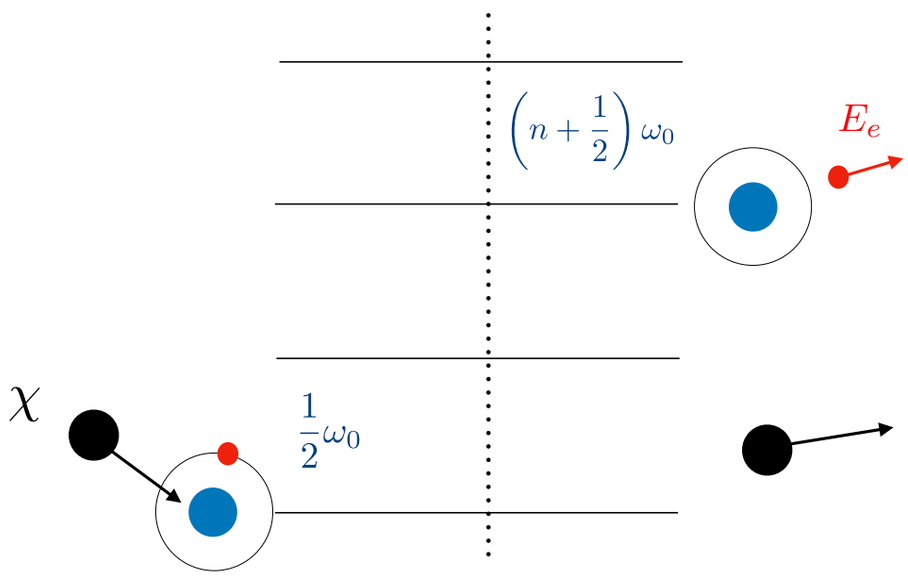
Lee / Weinberg '79

Two Revolutions in sub-GeV Sensitivity

Low-threshold direct detection

electrons, phonons, semicondcuctors …

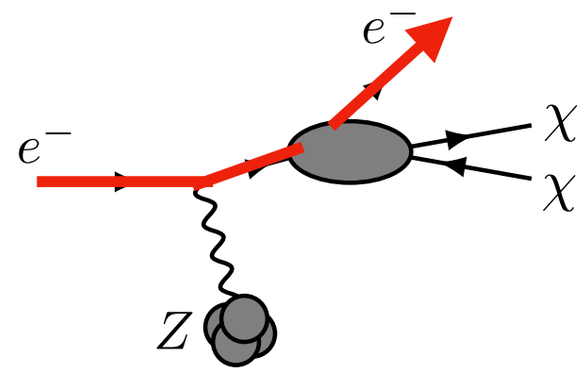


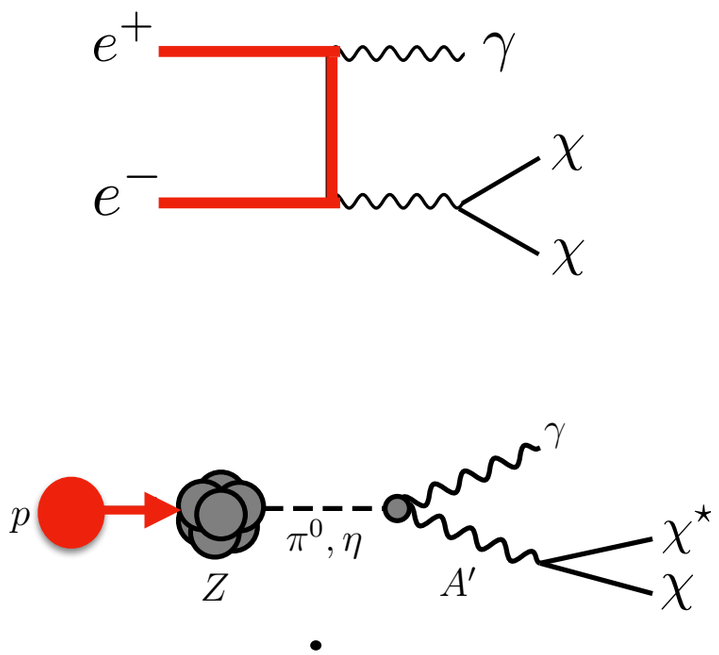


See Sravan Munagavalasa's talk

Low-energy accelerators

Fixed targets and B-factories



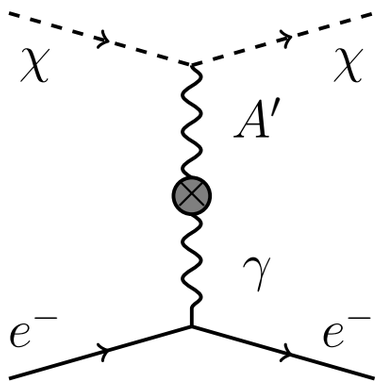


See Taylor Gray's talk

Testing Predictive Dark Sectors

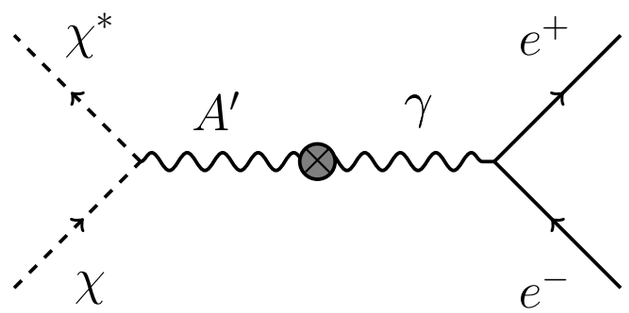
Ruled out by CMB < 20 GeV for all DM spins

Electron Scattering



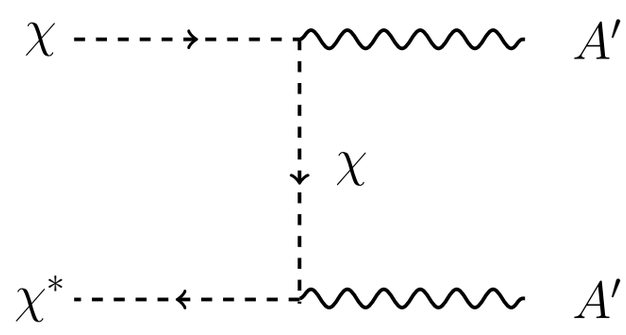
$$\sigma_e \propto \alpha_D \epsilon^2$$

Direct Annihilation



$$\sigma v \propto \alpha_D \epsilon^2$$

Secluded Annihilation



$$\sigma v \propto \alpha_D^2$$

Representative model: dark QED with massive dark photon A'

$$\mathscr{L}_{\rm int} = -A'_\mu (g_D J^\mu_D + \epsilon e J^\mu_{\rm EM})$$

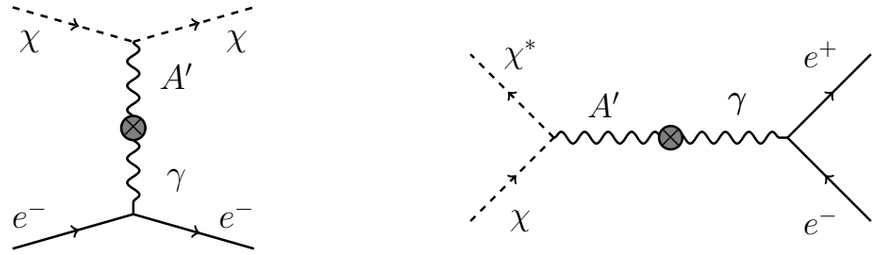
Similar models with anomaly free gauged U(1) mediators

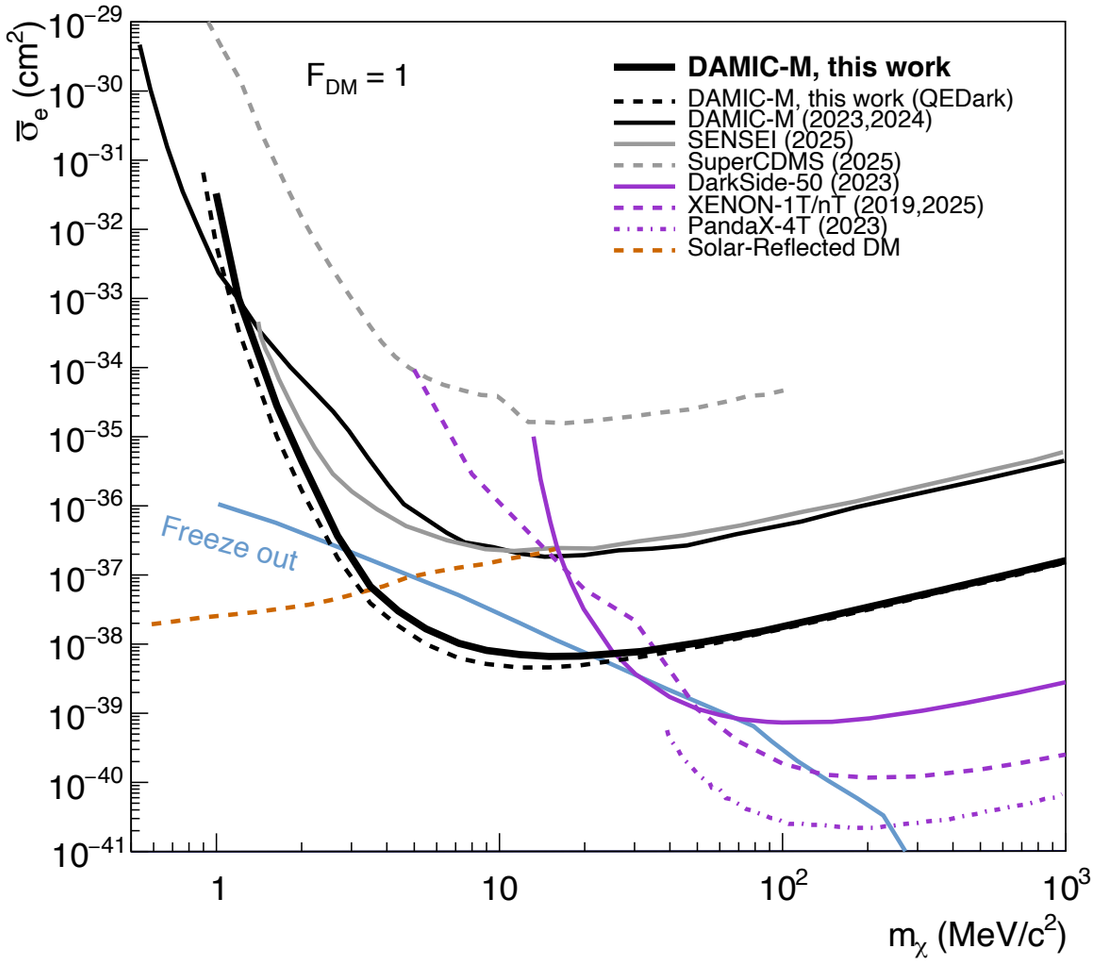
$$B - L \quad , \quad L_i - L_j \quad , \quad B - 3L_i$$

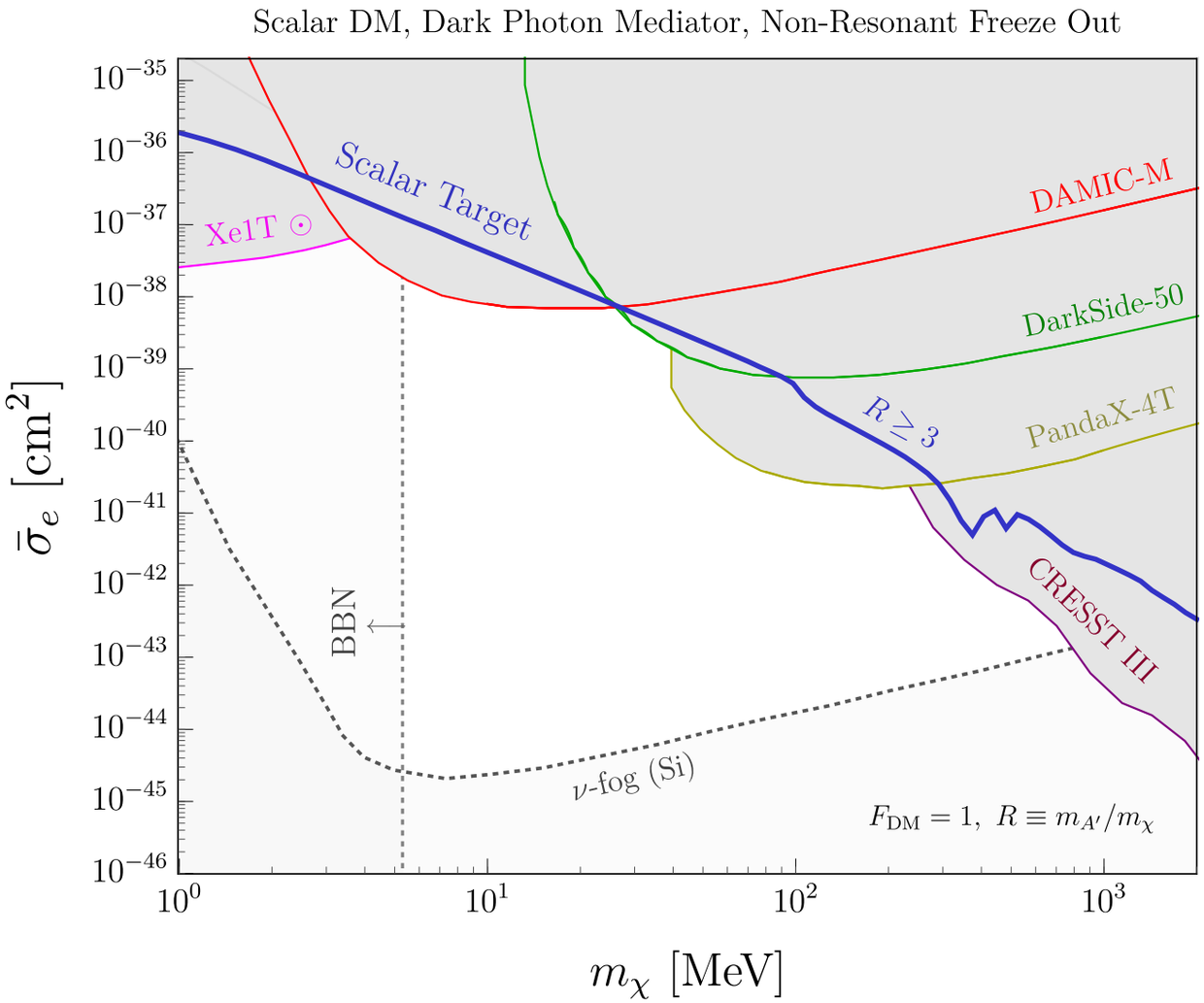
Pospelov Ritz Voloshin 0711.4866

Bauer, Foldenauer, Jaeckel 1803.05466

What's left for freeze out < GeV?







Scalar DM with vector mediator officially ruled out by Damic-M except for resonant annihilation mX ~ mA' regime

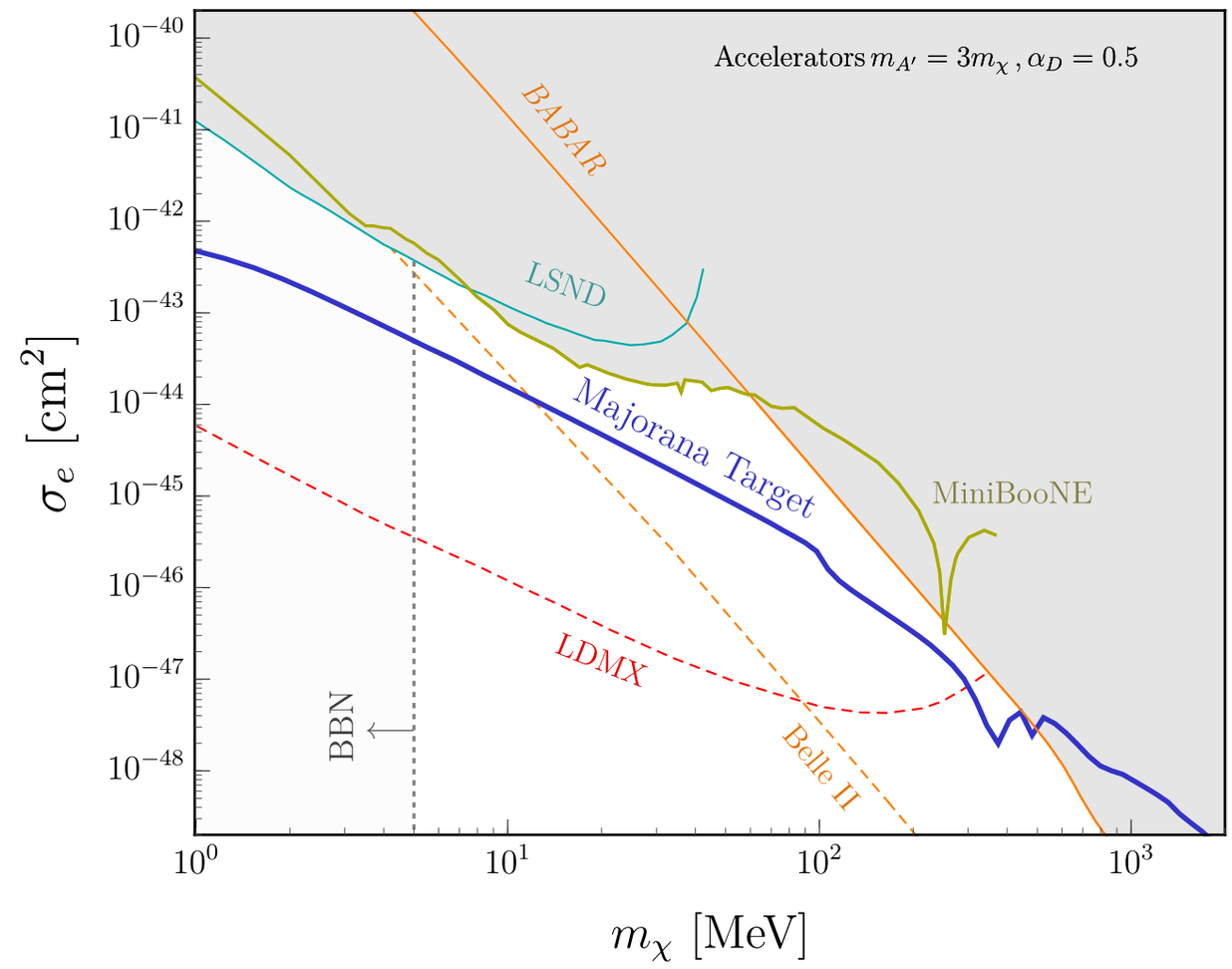
Damic-M 2503.14617

GK, 2505.04626

What's left for freeze out < GeV?

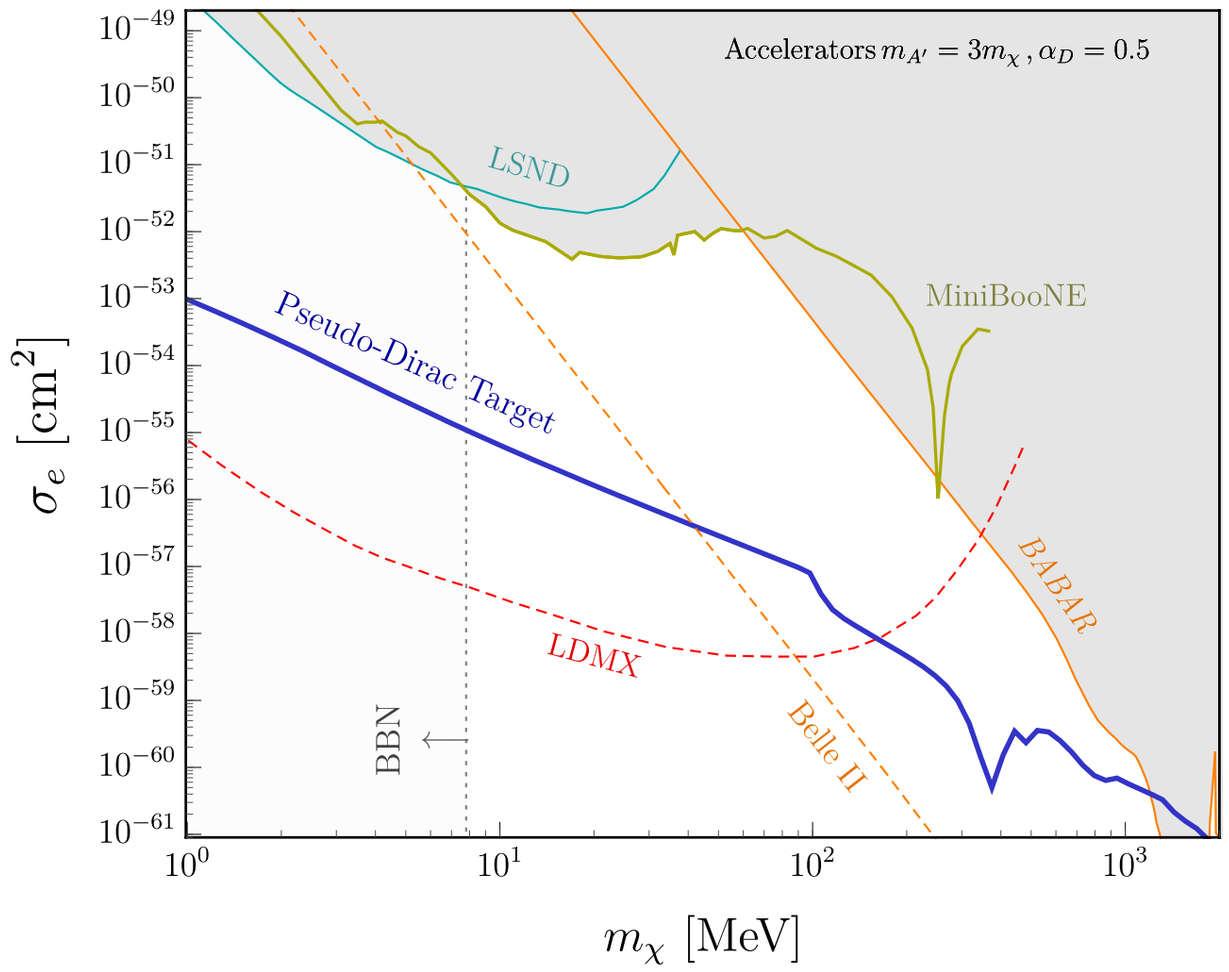
$$J_D^\mu = \frac{1}{2}\bar{\chi}\gamma^\mu\gamma^5\chi$$

Majorana DM, Dark Photon Mediator, Non-Resonant Freeze Out



$$J_D^\mu = i\bar{\chi}_1\gamma^\mu\chi_2$$

Pseudo-Dirac DM, Dark Photon Mediator, Non-Resonant Freeze Out



Fixed-target accelerator and B-factories key to testing other DM spins

Similar conclusions for any mediators with electron couplings (eg B-L)

GK, 2505.04626

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Initial Conditions	Inflation

Baryogenesis

Observed asymmetry $$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.1 \times 10^{-10}$$

Hard to explain as an initial condition (inflation dilutes)

$$n_B(t_f) = n_B(t_i)\, e^{-180}$$

Sakharov conditions (1967)

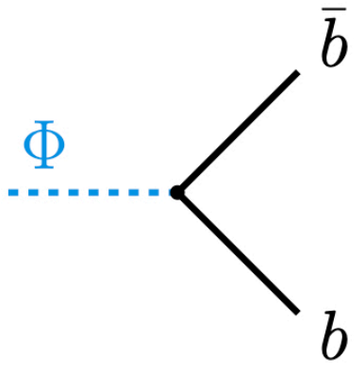
B violation, C & CP violation, universe out of equilibrium

Many candidates (GUT baryogengesis, leptogenesis…)

Typically very heavy particles, hard to test!

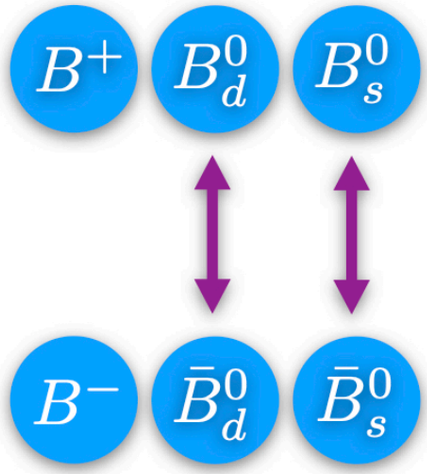
Baryogenesis and Dark Matter from B Mesons: *B-Mesogenesis*

Out of equilibrium late time decay



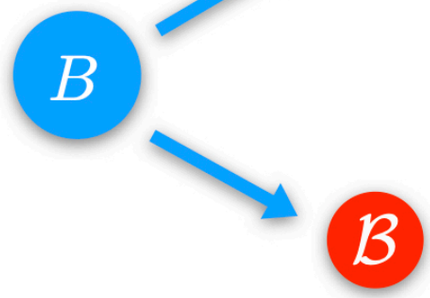
$T_R \sim 15\,\mathrm{MeV}$

CP violating oscillations



$A_{\mathrm{SL}}^d \quad A_{\mathrm{SL}}^s$

B-mesons decay into Dark Matter and hadrons



Dark Matter (anti-Baryon)

Baryon

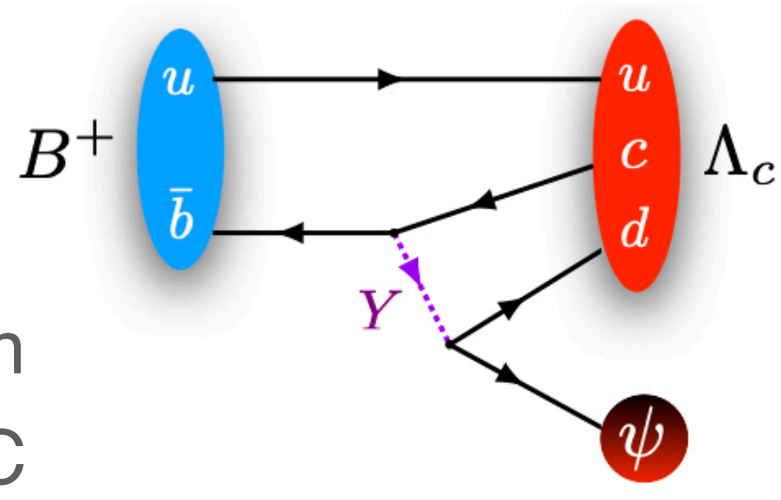
$\mathrm{Br}\,(B \to \psi + \mathcal{B} + \mathcal{M})$

Low scale baryogengesis

Universe reheats to MeV scale

B mesons oscillate/decay before thermalization

Predict DM and hadrons in rare decays @ LHC

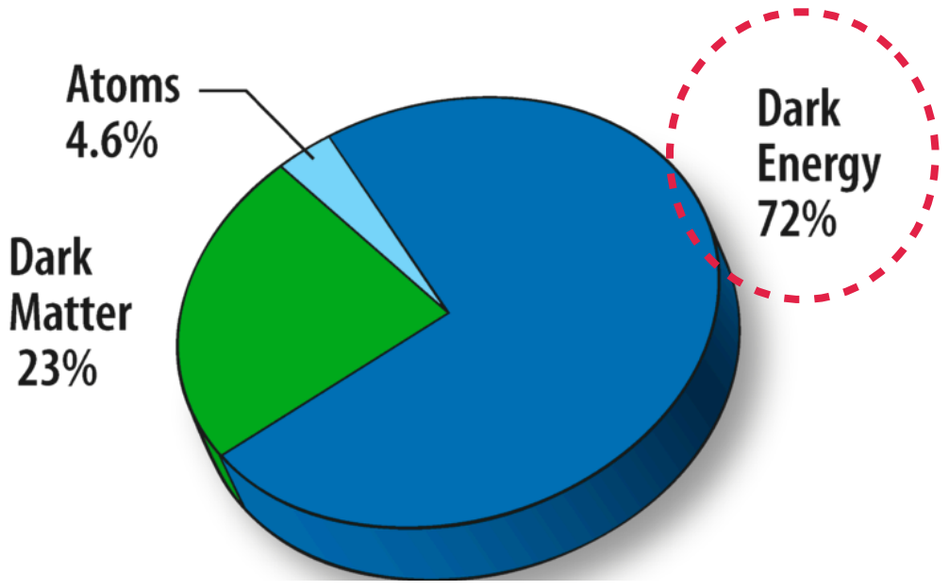


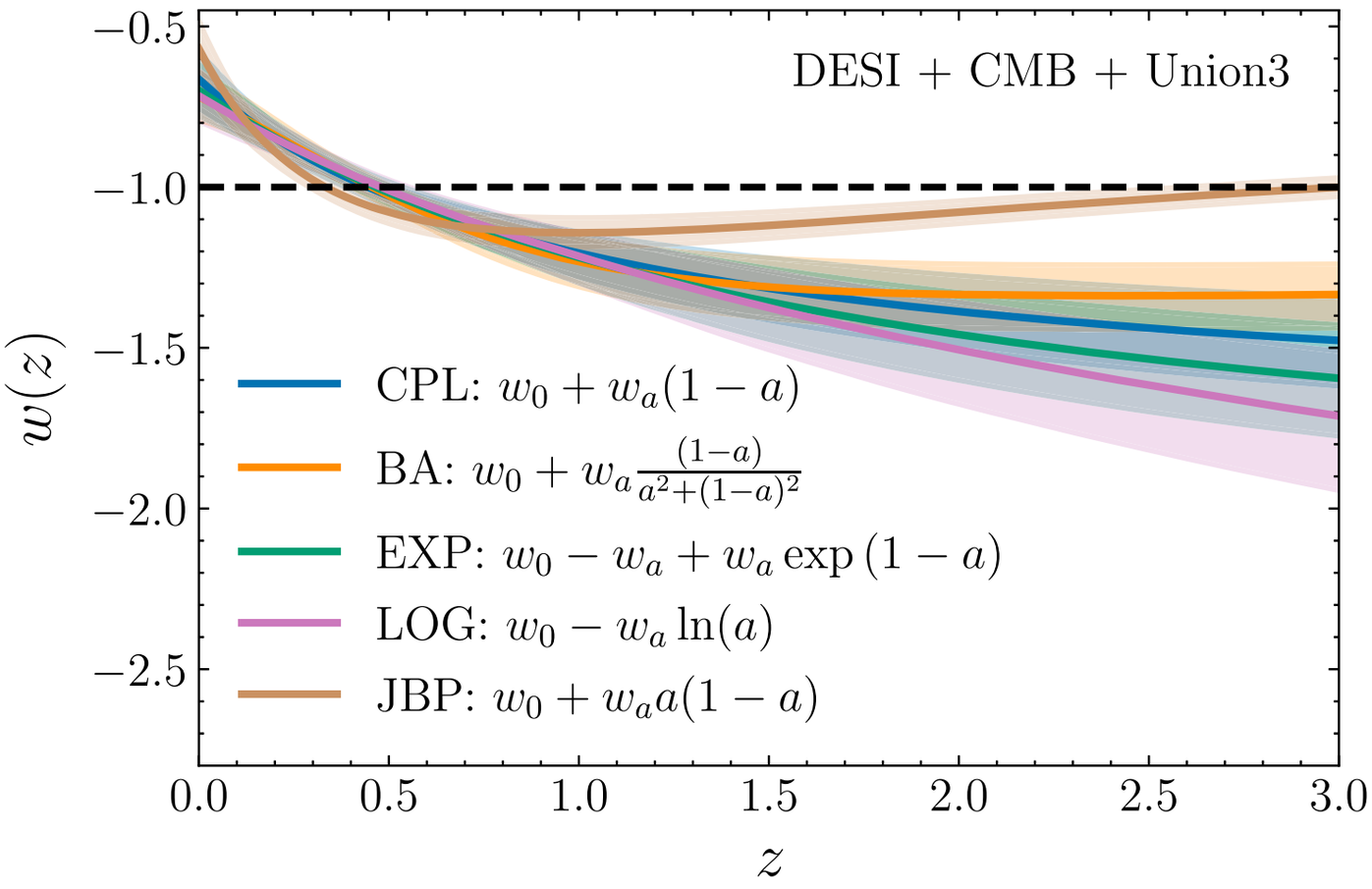
Elon Escudero Nelson 1810.00880

The *Incomplete* Standard Model

Must-solve problems	Troubling, but not obligatory
Neutrino Masses	Strong CP Problem
Dark Matter	Hierarchy Problem
Baryogenesis	Flavor Puzzle
Dark Energy	**Cosmological Constant**
Initial Conditions	Inflation

What is dark energy?





Is it an evolving fluid as suggested by interpretation of DESI data?

If so, it's very exciting! … and makes the CC problem even worse

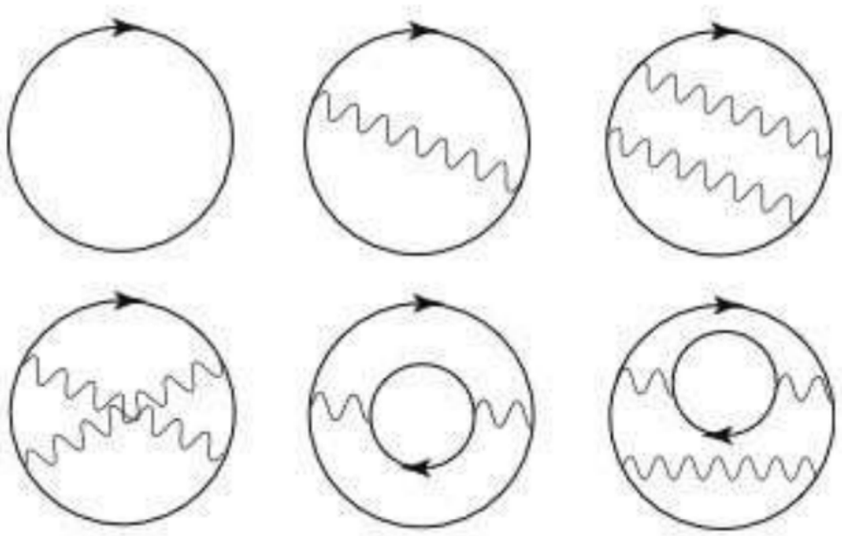
See Plenary: Ali Rida Khalife

Why is the Cosmological Constant tiny?

Observed CC is tiny

but everything gravitates

$$\Lambda_{\rm obs} \sim {\rm meV}$$



Zero point energies

$$\Longrightarrow \Lambda \sim M_{\rm Pl}$$

EW and QCD phase transitions add to CC $\Lambda \sim v, \Lambda_{\rm qcd}$

Tune unrelated classical contribution to cancel all of these

$$(M_{\rm Pl} + v + \Lambda_{\rm qcd}) - \Lambda_{\rm classical} \approx {\rm meV}$$

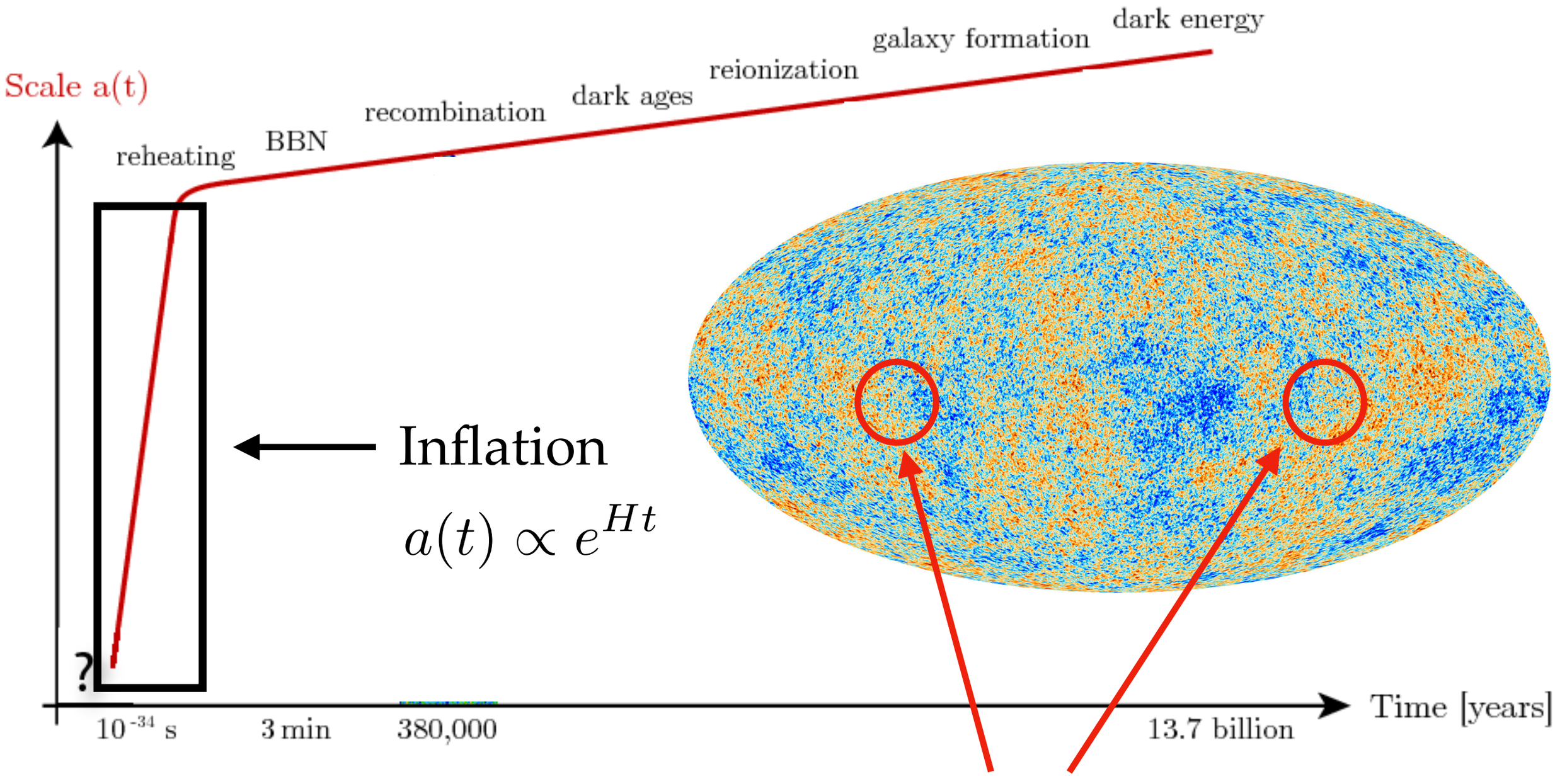
Anthropics? Weinberg (1987)

Only known "solution"

The *Incomplete* Standard Model

Must-solve problems	Troubling, but not obligatory
Neutrino Masses	Strong CP Problem
Dark Matter	Hierarchy Problem
Baryogenesis	Flavor Puzzle
Dark Energy	Cosmological Constant
Initial Conditions	**Inflation**

What is the physics of inflation?

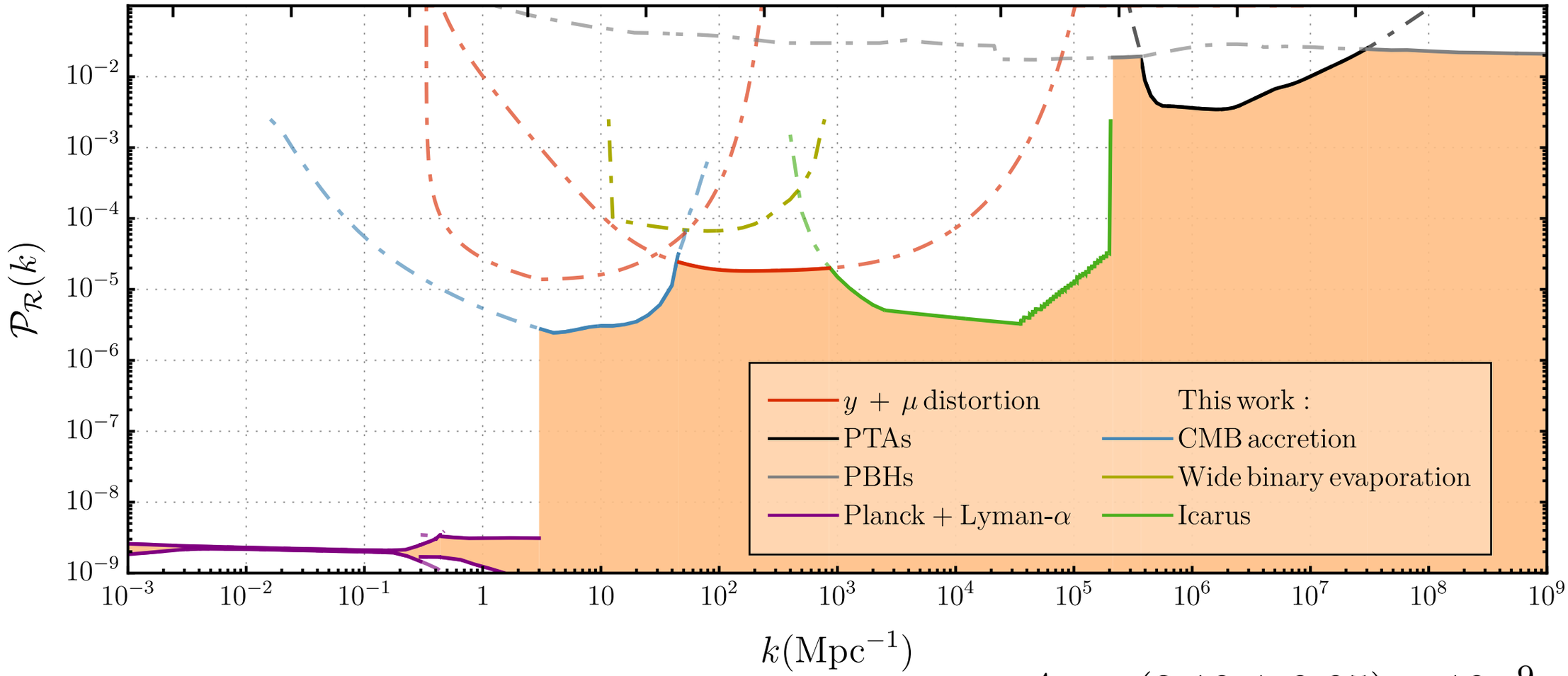


CMB naively contains causally disconnected patches on ~2 degree angular scales

Baumann arXiv:0907.5424

What sets the initial conditions?

Bringmann, Croon, Munoz 2506.20704



$$P_\mathcal{R} = A_s \left(\frac{k}{k_*}\right)^{n_s - 1}$$

$$A_s = (2.10 \pm 0.05) \times 10^{-9}$$
$$n_s = 0.9649 \pm 0.0042$$
$$k_* = 0.05\,\mathrm{Mpc}^{-1}$$

Primordial inputs to Boltzmann equations for CMB and LSS

Planck 2018

What is the physics of inflation?

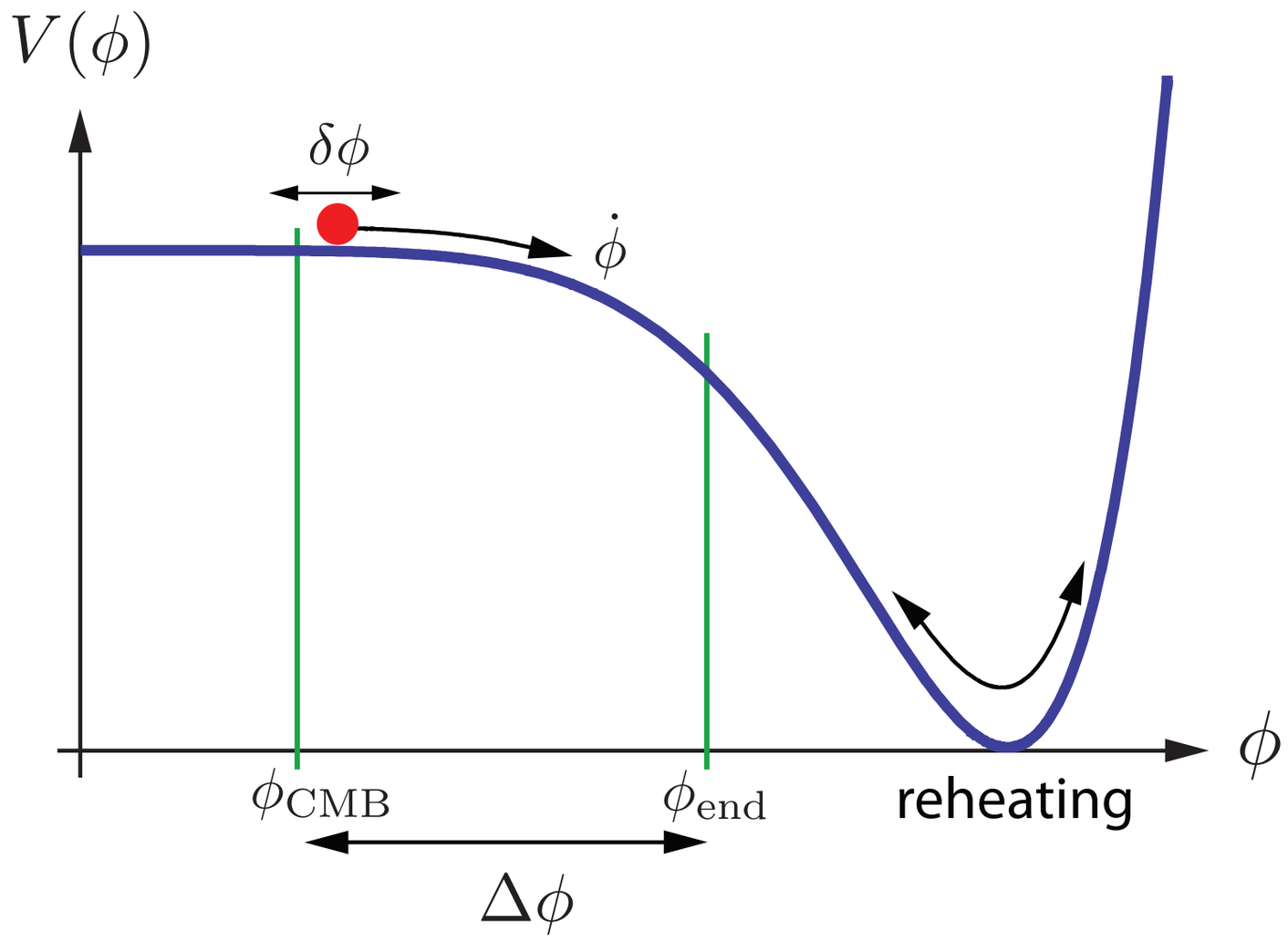
Scalar with ~flat potential drives exponential expansion

Solves many problems

Monopole problem

Horizon problem

Flatness problem

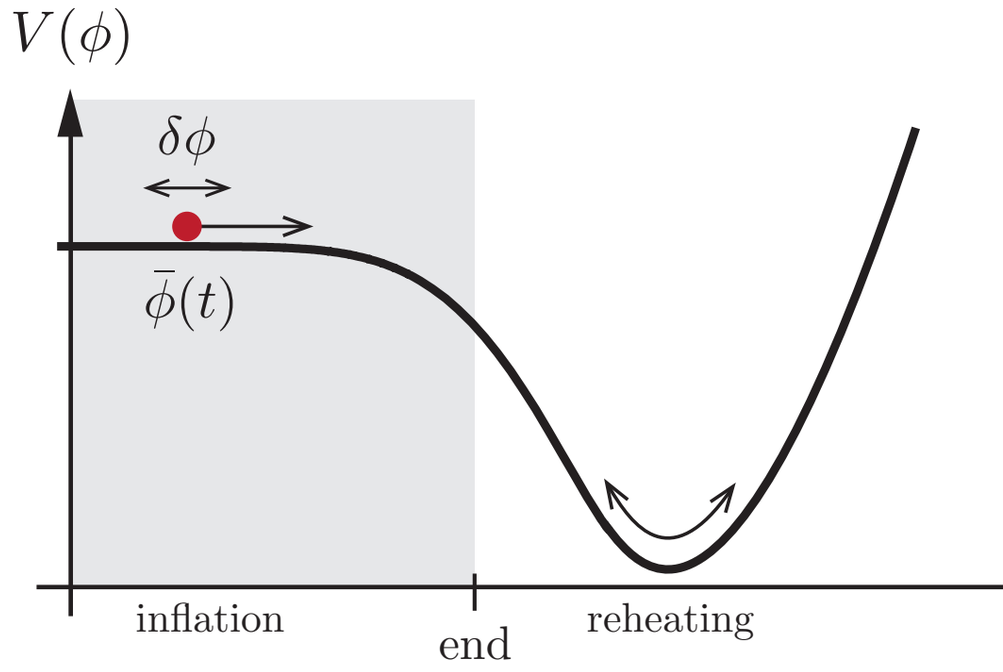


Sets initial conditions

Inflaton fluctuations

$\delta\phi \rightarrow$ CMB, LSS

What is the physics of inflation?



"Slow roll" parameters

$$\varepsilon \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V'}{V}\right)^2 \qquad \eta \equiv \frac{M_{\rm Pl}^2}{2}\left(\frac{V''}{V}\right)$$

Scalar modes measured with CMB/LSS

$$\mathcal{P}_\zeta = \frac{1}{8\pi^2\varepsilon}\frac{H_i^2}{M_{\rm Pl}^2} = A_s\left(\frac{k}{k_*}\right)^{n_s-1}$$

$$A_s = (2.10 \pm 0.05) \times 10^{-9}$$
$$n_s = 0.9649 \pm 0.0042$$
$$k_* = 0.05\,{\rm Mpc}^{-1}$$

Planck 2018

Upper limit on tensor modes

$$\mathcal{P}_h = \frac{2}{\pi^2}\frac{H_i^2}{M_{\rm Pl}^2} = A_t\left(\frac{k}{k_*}\right)^{n_t}$$

$$r \equiv \frac{A_t}{A_s} < 0.036 \pm 0.009$$

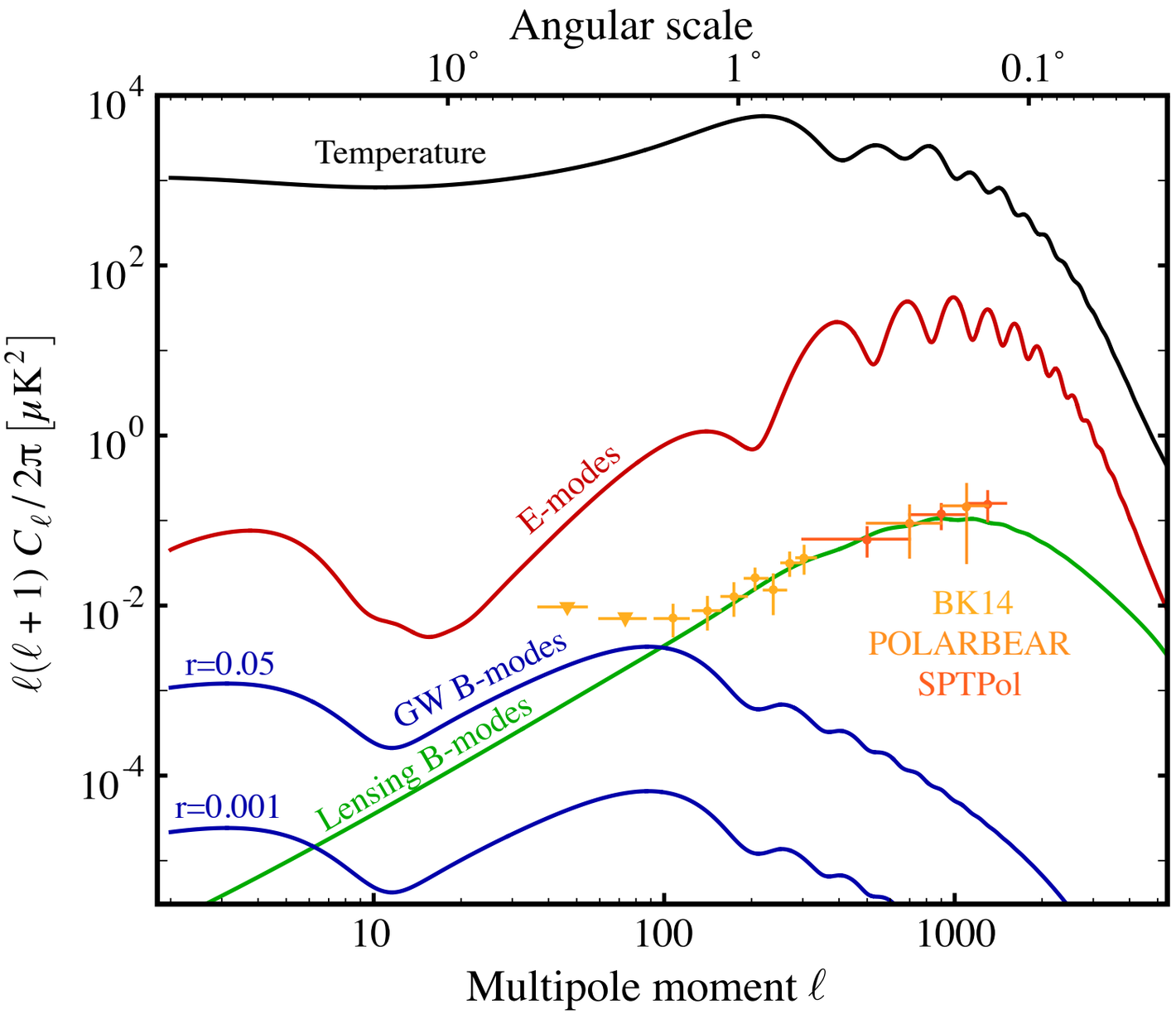
$$n_t = -r/8$$

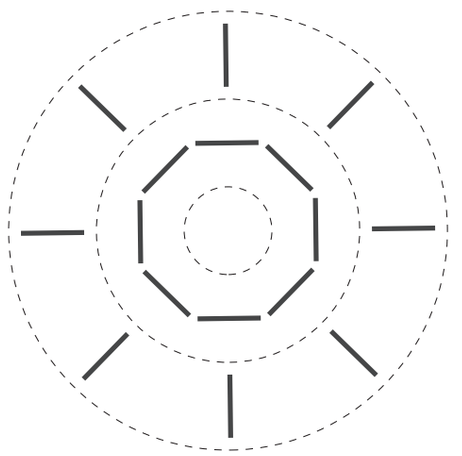
Both nearly scale invariant $n_t \sim n_s - 1 \sim 0$

BICEP/Keck 2022

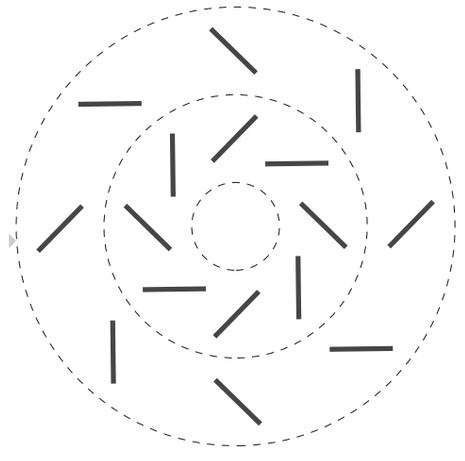
What is the physics of inflation?

Tensor perturbations source GW & CMB B-mode polarization





E-modes

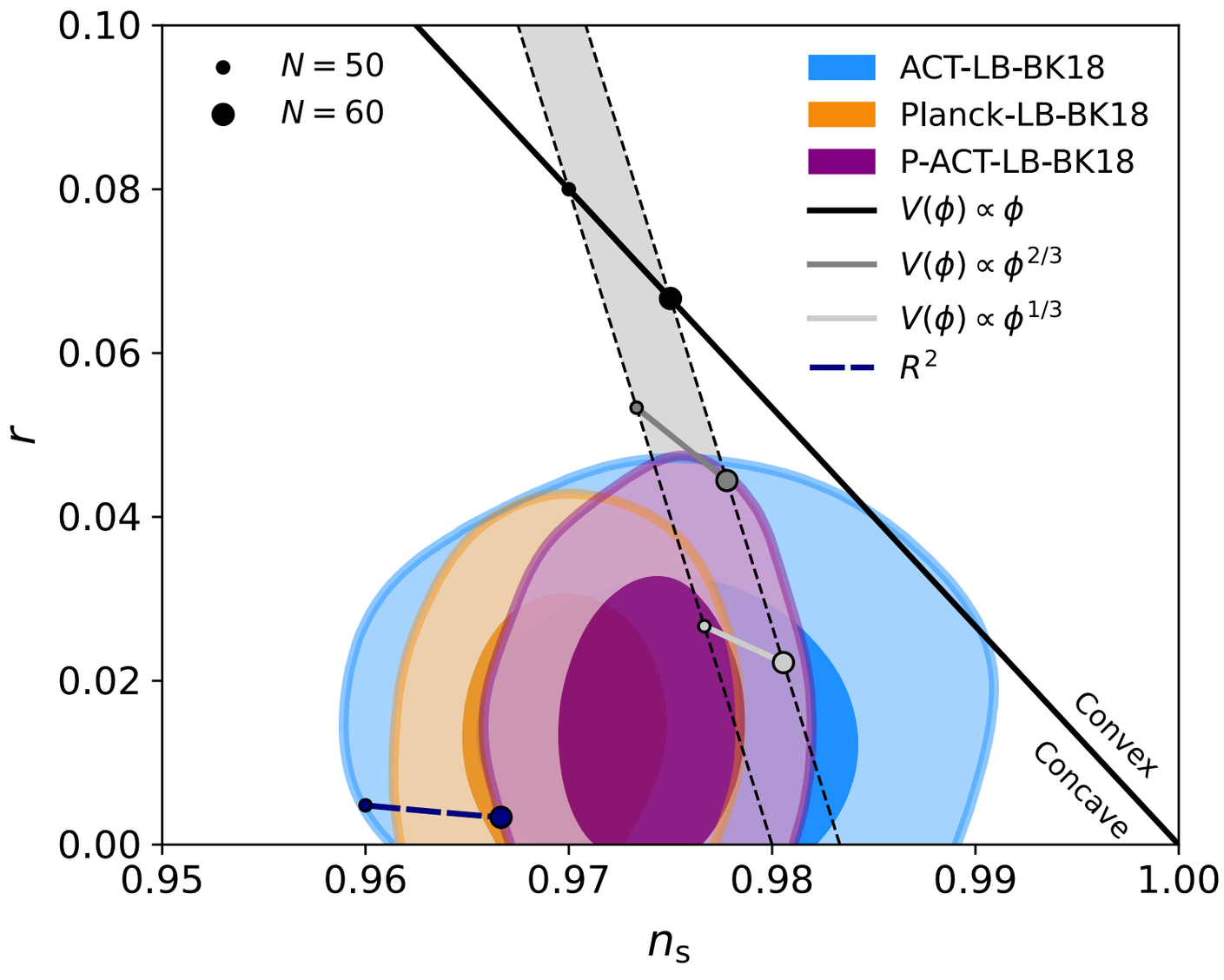


B-modes

CMB-S4 1610.02743

What is the physics of inflation?

What is the shape of the inflation potential?



tensor/scalar ratio (proxy for energy scale of inflation) $r = \frac{A_T}{A_s}$

ACT Collaboration 2503.14454

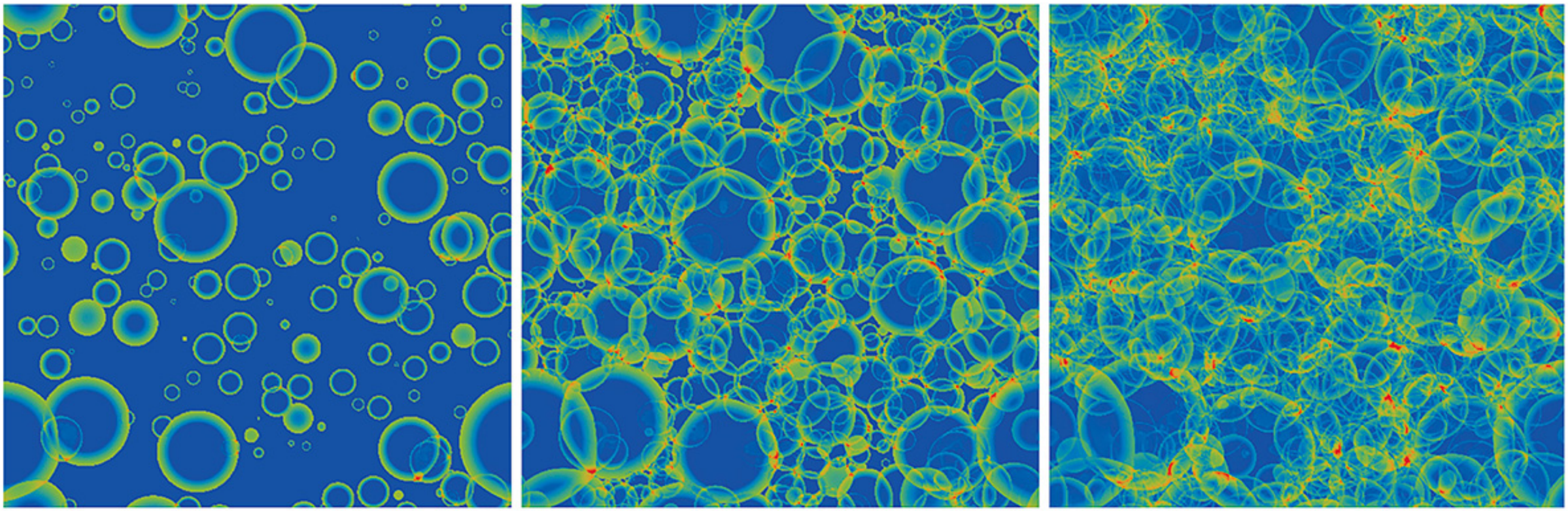
"Tensor fluctuations are a prime target for future observations of the cosmic microwave background, because if detected they can provide a conclusive verification of the theory of inflation and a unique tool for exploring the details of this theory"

— Flauger & Weinberg

Is inflation the only possible source of B-modes?

astro-ph/0703179

B-modes from late-time phase transitions



Need a new subdominant hidden sector

Electroweak PT, QCD PT not first order

See Chiara Caprini's plenary

First order phase transition

Proceeds through bubble nucleation

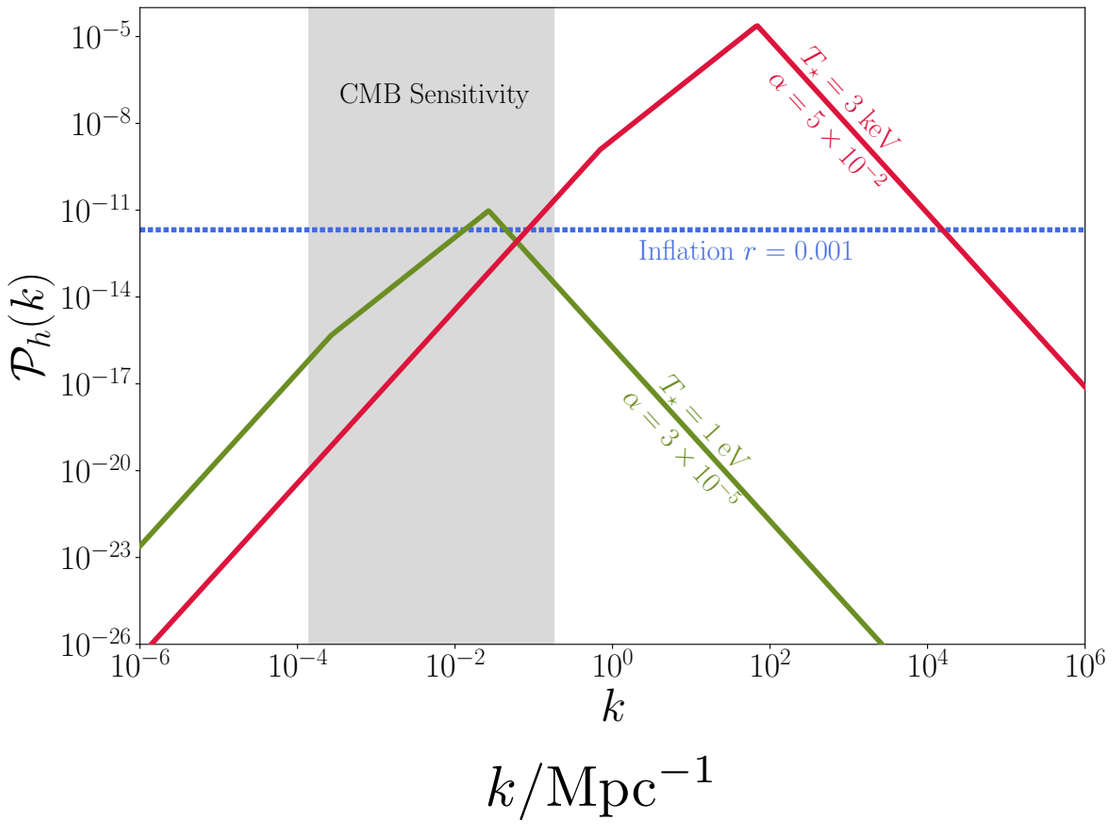
GW from bubble collisions, sound waves, turbulence…

Characteristic parameters

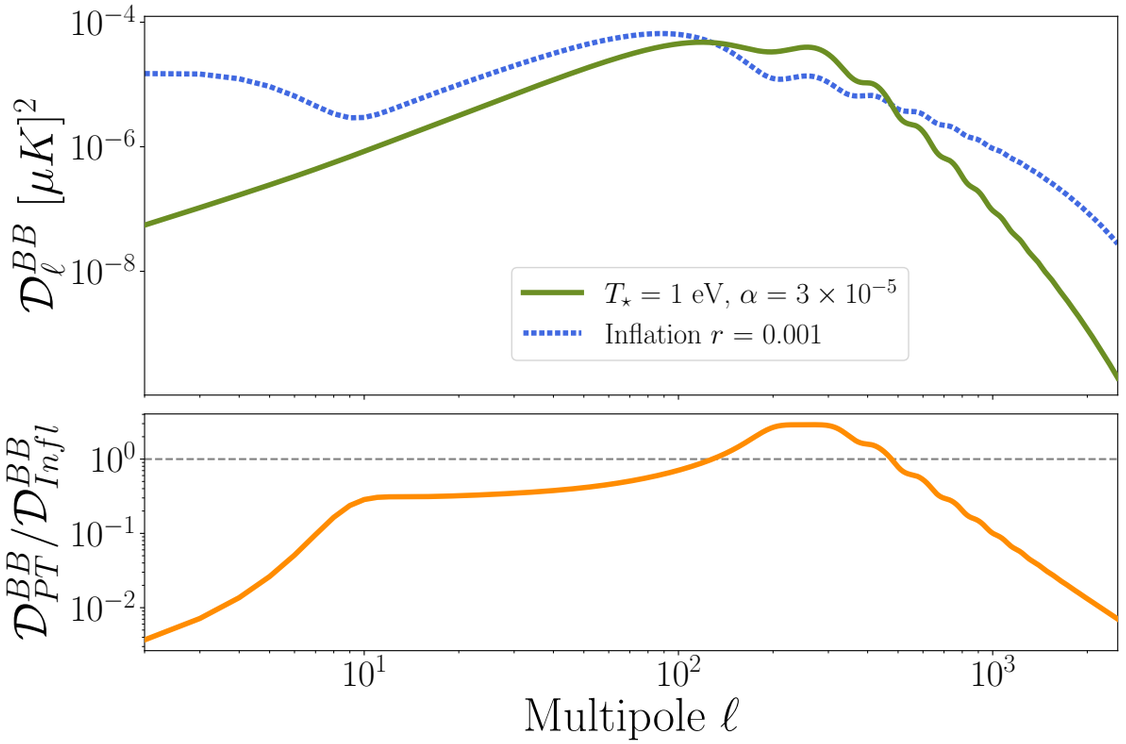
$T_* = \text{temp of PT}$ $\quad \beta^{-1} = \text{duration}$ $\quad \alpha = \dfrac{\rho_{\rm bsm}}{\rho_{\rm rad}}$ $\quad \kappa = \text{GW efficiency}$

B-modes from late-time phase transitions

Tensor power spectrum



B-mode angular spectrum



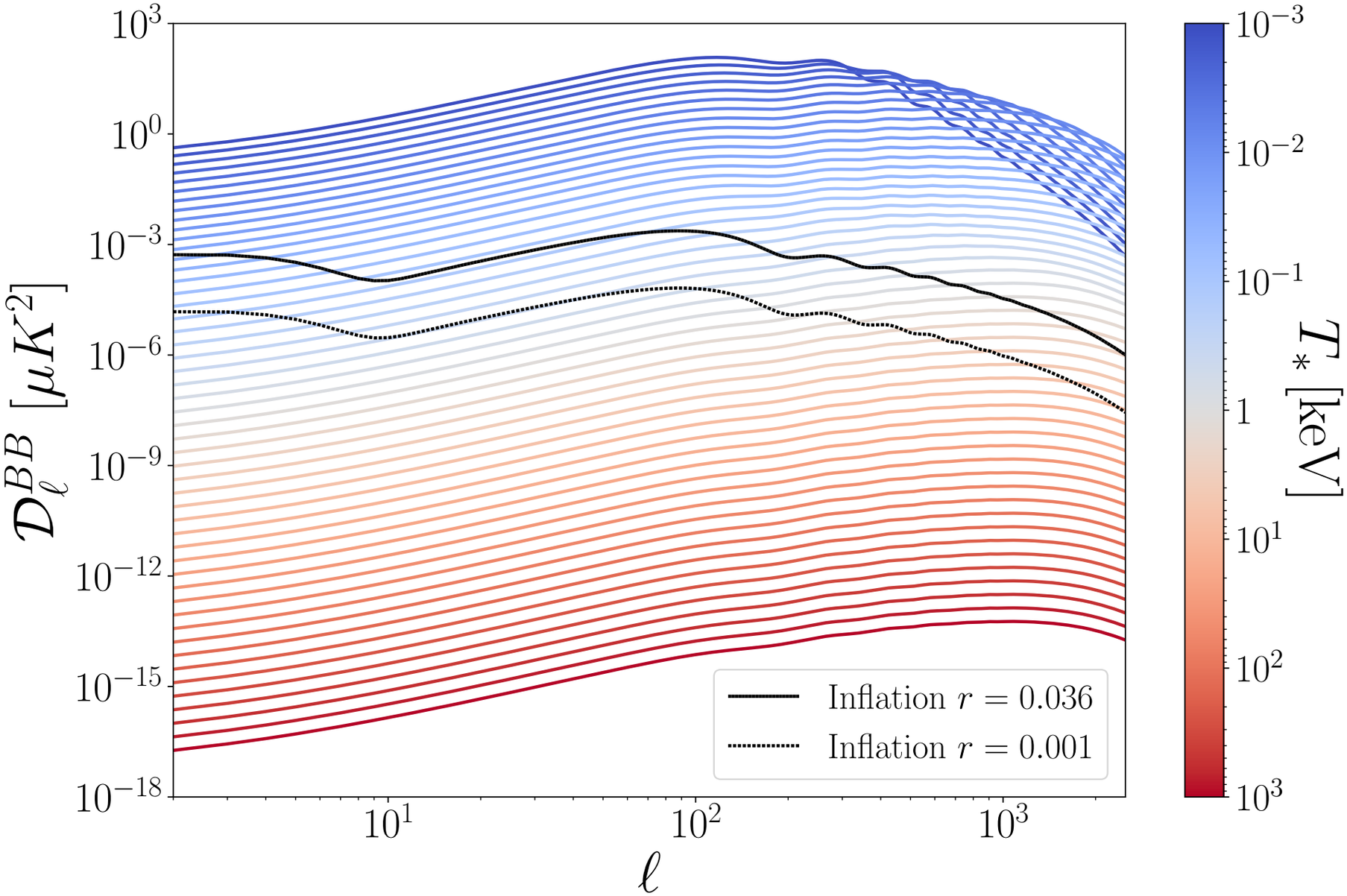
$$\mathcal{D}_\ell^{BB} = 18 T_0^2 \int_0^\infty \frac{dk}{k} \mathcal{P}_h(k) F_\ell(k)$$

PTs can compete with inflationary predictions for viable inputs

Discovery at a single multipole is not “smoking gun” for inflation

Ireland, Greene, GK, Tsai 2410.23348

B-modes from late-time phase transitions



Shape enhanced over inflation on small scales, suppression on large

No “reionization bump” for phase transitions or other “causal sources”

Ireland, Greene, GK, Tsai 2410.23348

Summary

Obligatory "in your face" problems

Dark Matter, Baryogenesis, Density Perturbations, Neutrino Masses

Nature knows the answers, but we don't

SM puzzles begging for a deeper explanation

Hierarchy Problem, Cosmological Constant, Flavor, Inflation

Tensions in data may indicate new physics

H0 tension, DESI, Galactic Center Excess, B-decay anomalies

New probes on various scales essential for future progress

Accelerators: future colliders, *B*-factories, fixed-targets
Strong complementarity with cosmic and astrophysical probes

This is an era of broader priors — must cast a wide net!

Thanks!