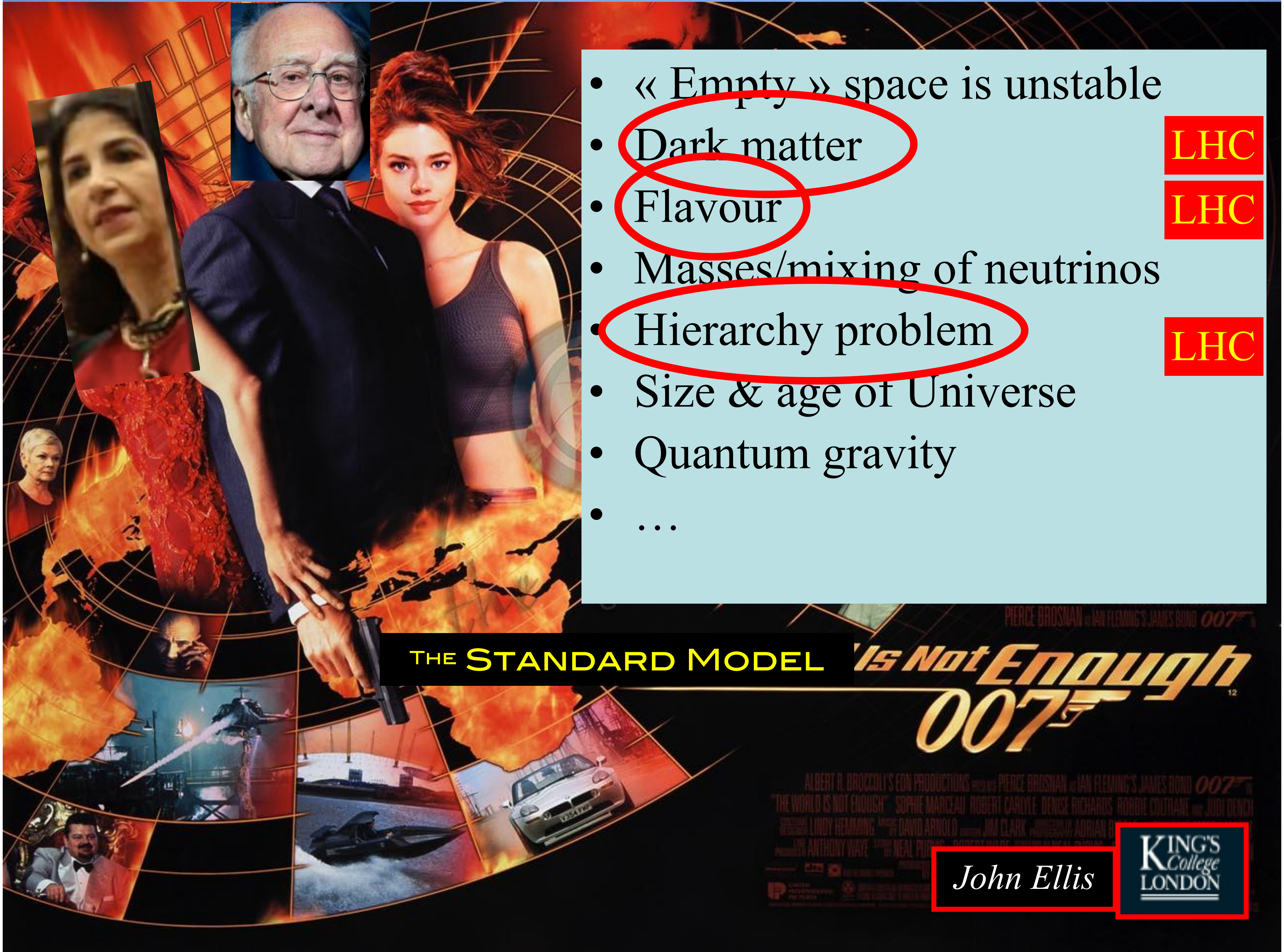


- « Empty » space is unstable
- Dark matter LHC
- Flavour LHC
- Masses/mixing of neutrinos
- Hierarchy problem LHC
- Size & age of Universe
- Quantum gravity
- …

THE STANDARD MODEL

John Ellis

KING'S College LONDON

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

The Rotation Curves of Galaxies

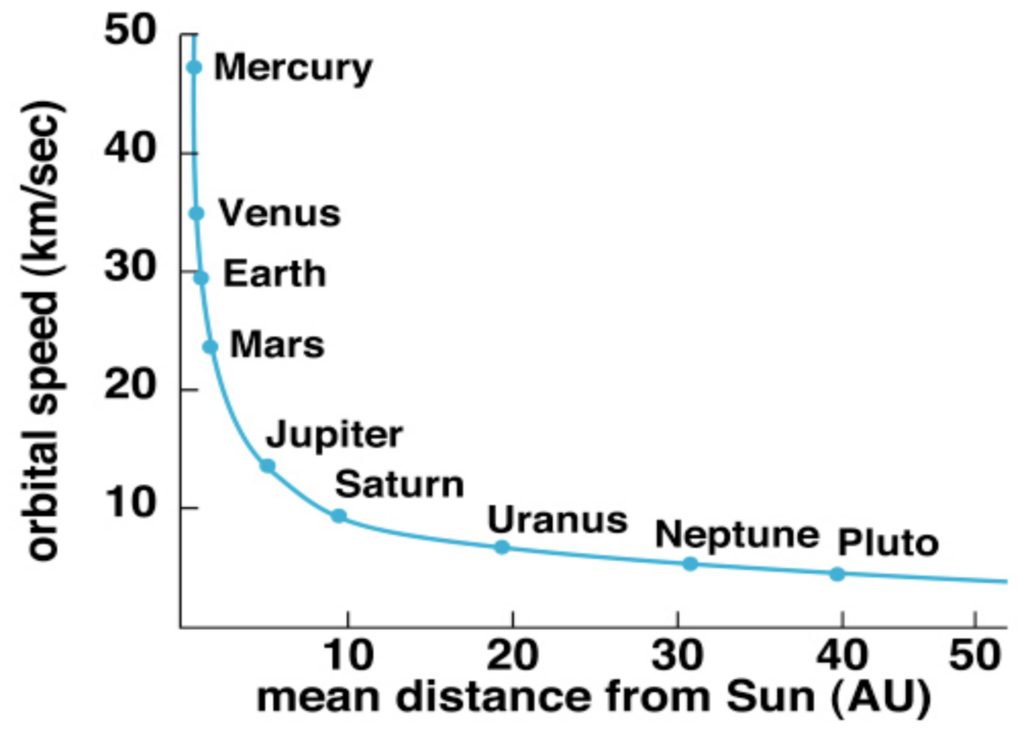
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American
Institute of Physics

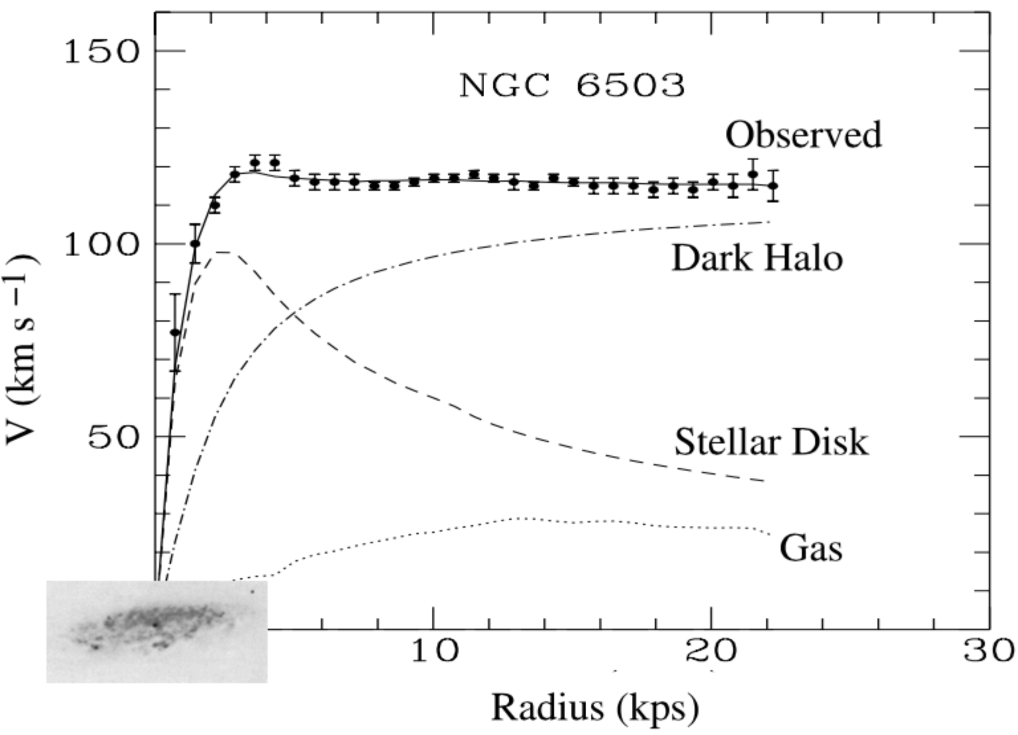
- **Further strong evidence for dark matter**
- Also:
  - Structure formation, cosmic background radiation, …

Rotation Curves

- In the Solar System



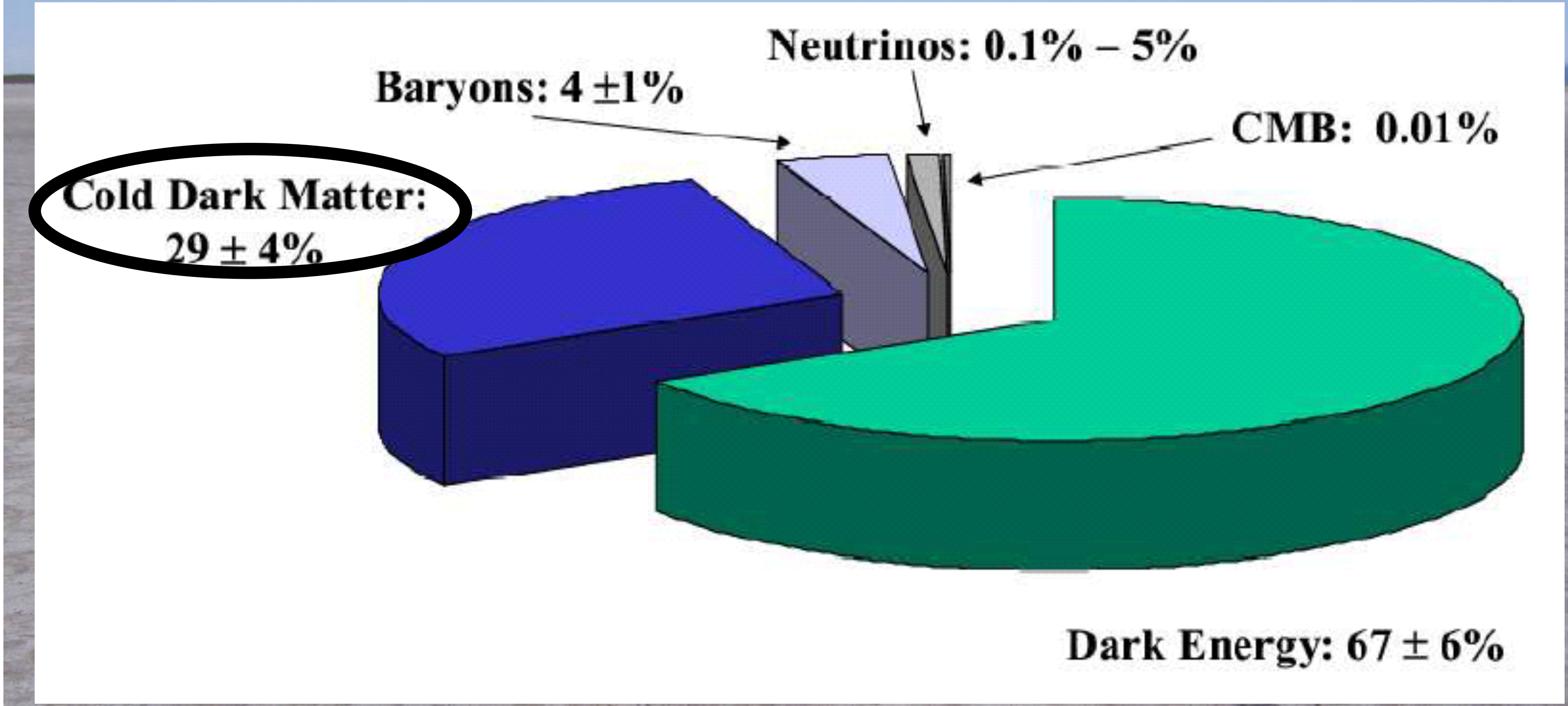
- In galaxies



- The velocities decrease with distance from Sun
- Mass lumped at centre

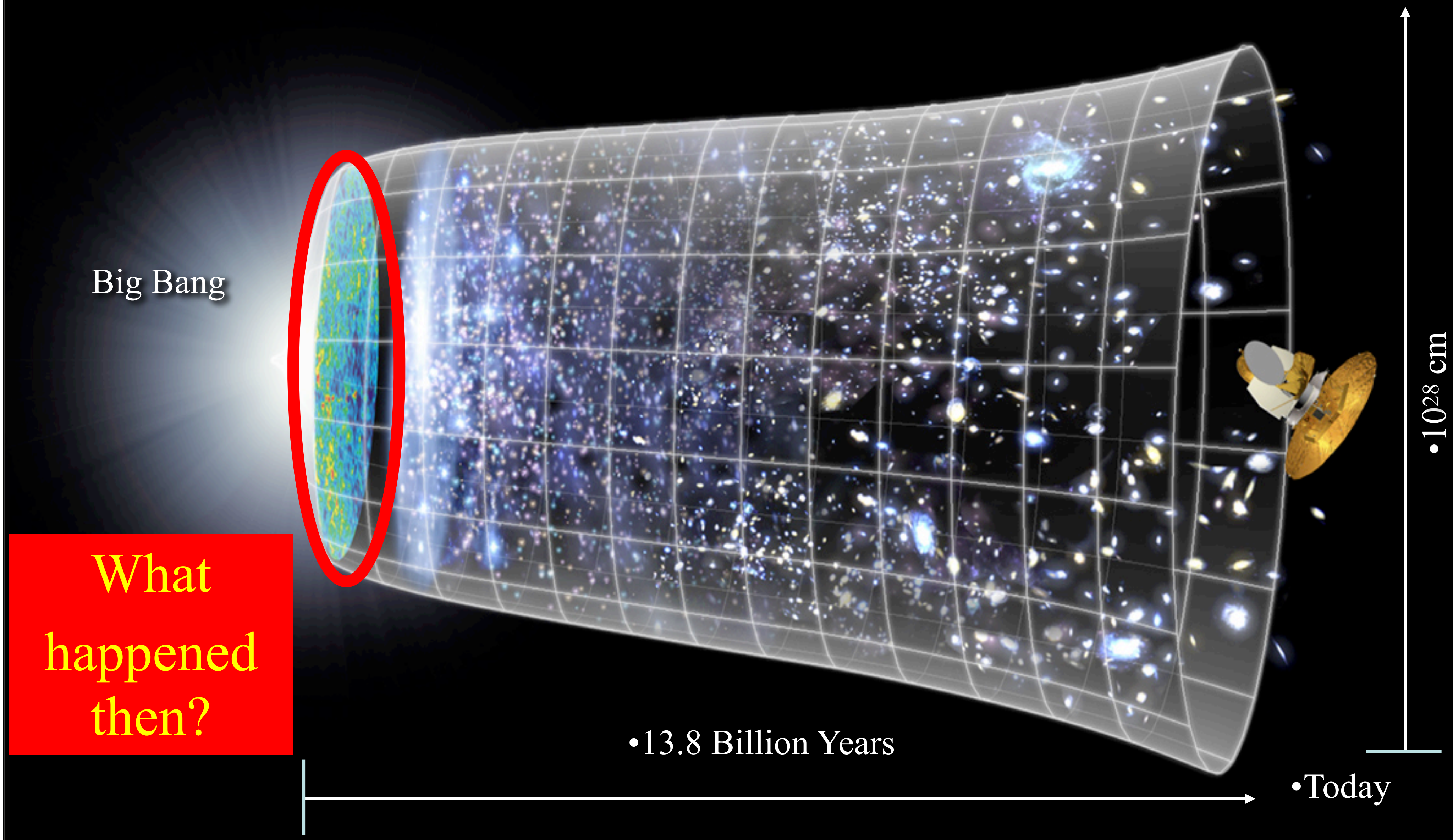
- The velocities do not decrease with distance
- Dark matter spread out

Strange Recipe for a Universe



The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Evolution of the Universe



Big Bang

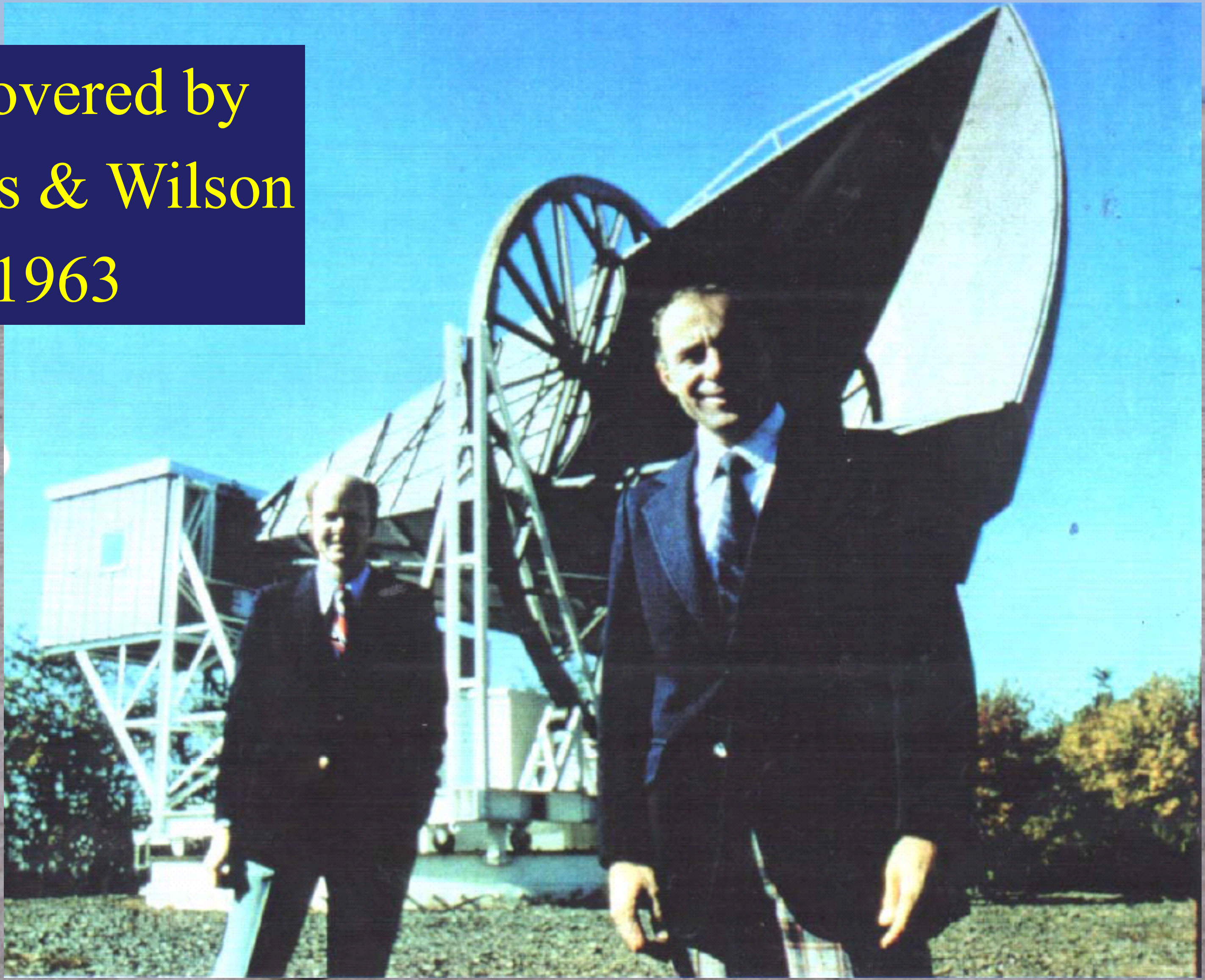
What happened then?

•13.8 Billion Years

•Today

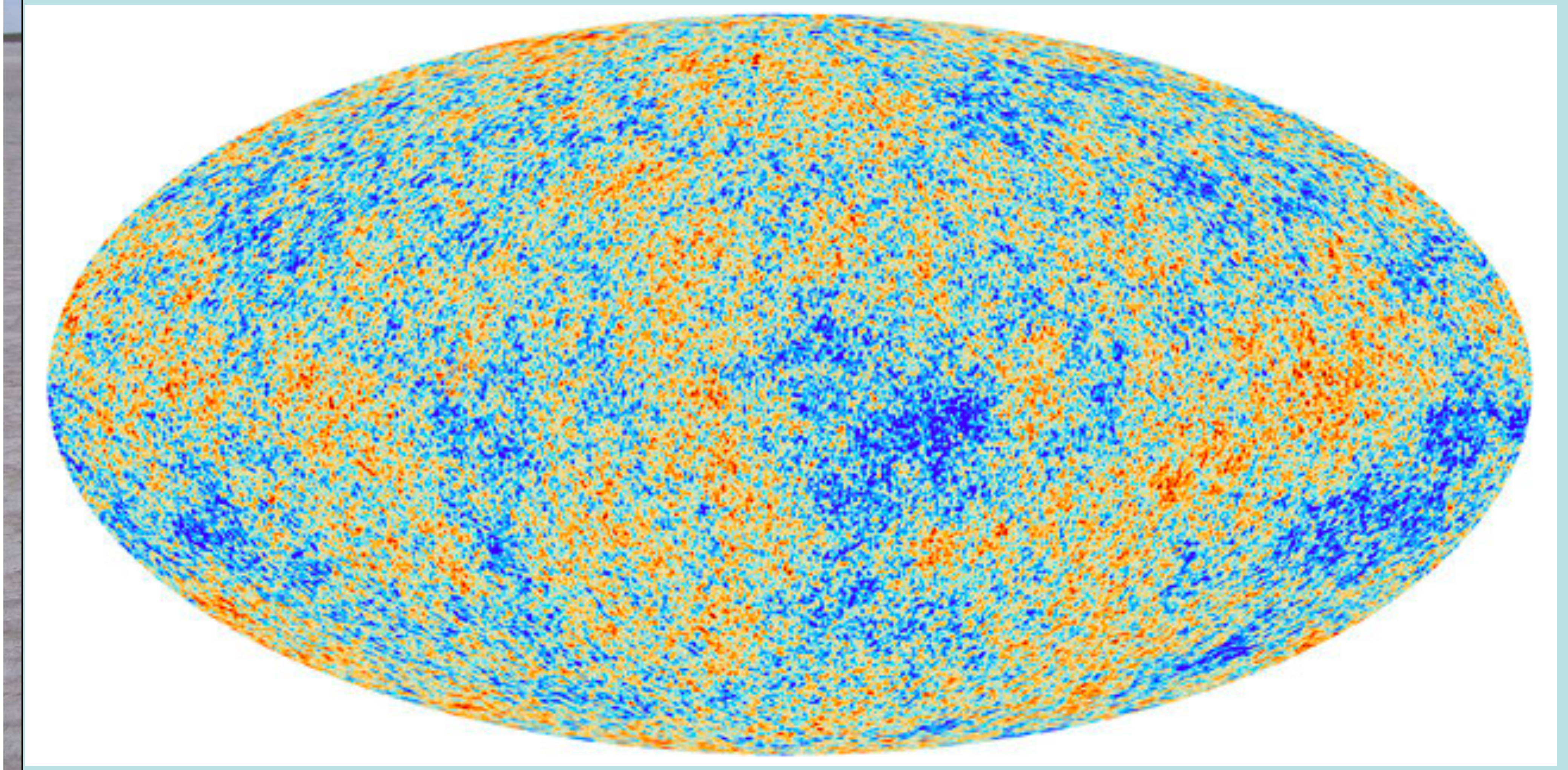
•10^{28} cm

The Cosmic Microwave Background

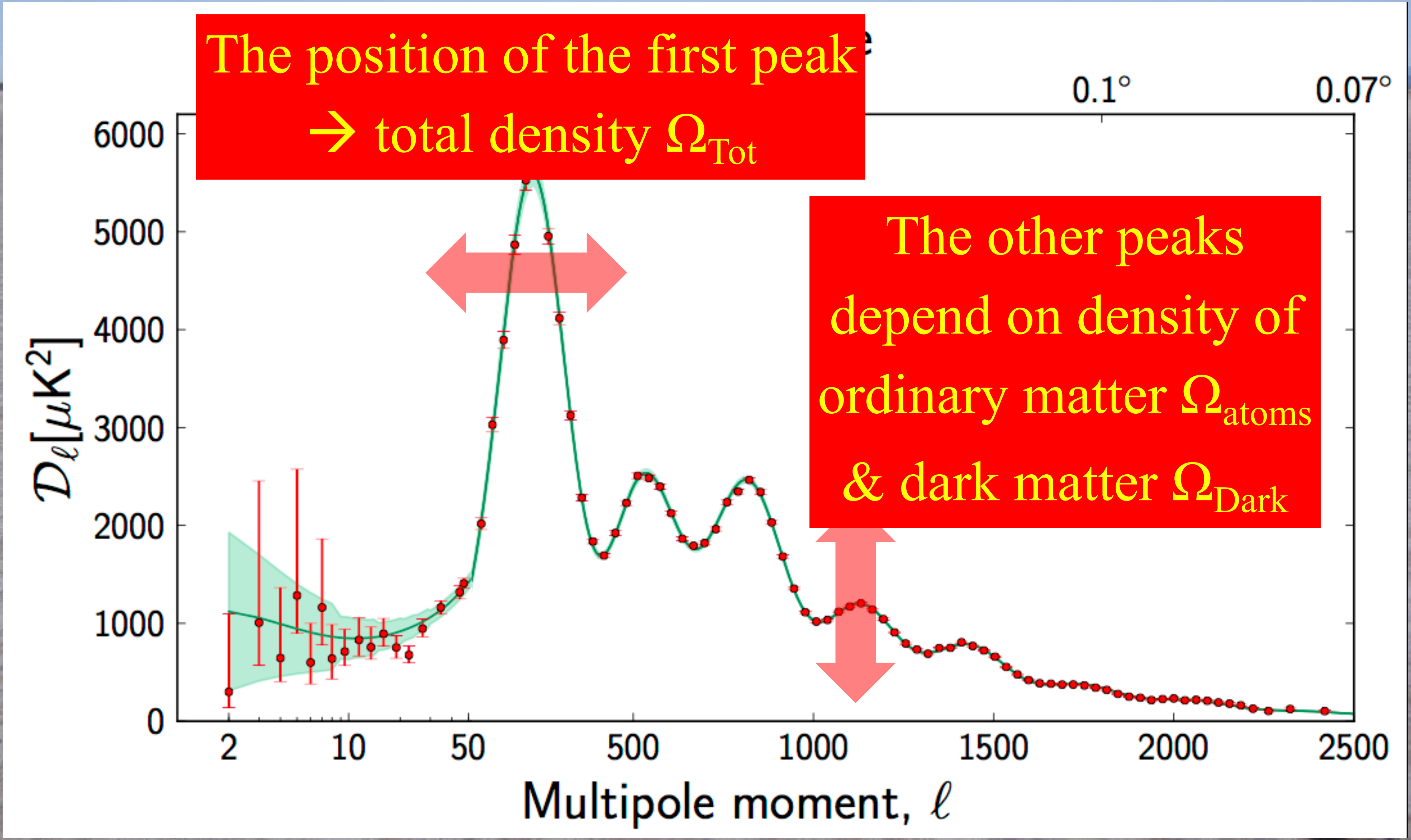


Discovered by
Penzias & Wilson
1963

Cosmological Microwave Background as seen by Planck Satellite



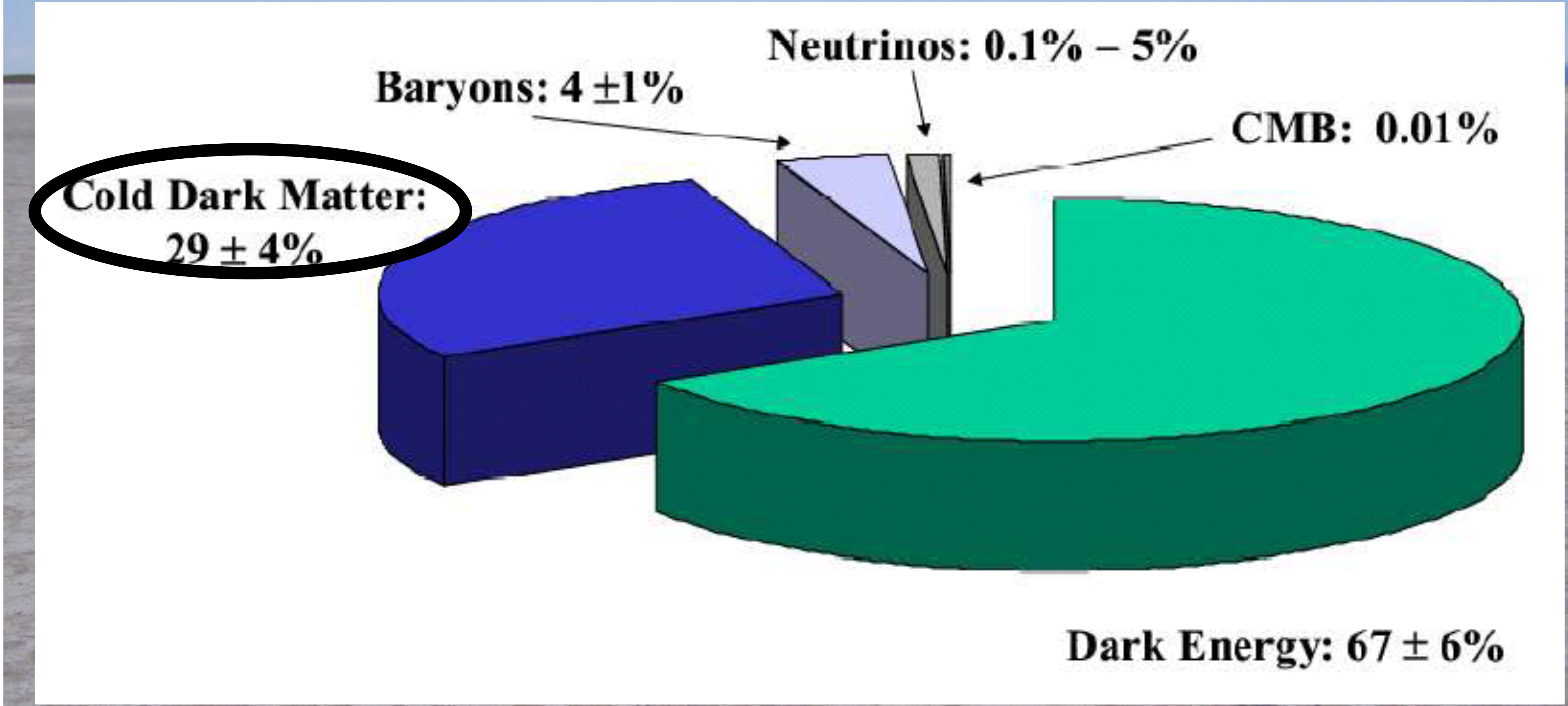
The Spectrum of Fluctuations in the Cosmic Microwave Background



The position of the first peak
→ total density Ω_{Tot}

The other peaks
depend on density of
ordinary matter Ω_{atoms}
& dark matter Ω_{Dark}

Strange Recipe for a Universe



The ‘Standard Model’ of the Universe indicated by astrophysics and cosmology

Properties of Dark Matter

- Should not have (much) electric charge
  - Otherwise we would have seen it
- Should interact weakly with ordinary matter
  - Otherwise we would have detected it, either directly or astrophysically
- Should not be too light
  - Needed for forming and holding together structures in the Universe: galaxies, clusters, …

A Successful Theory of the Formation of Structures in the Universe

Dark matter:

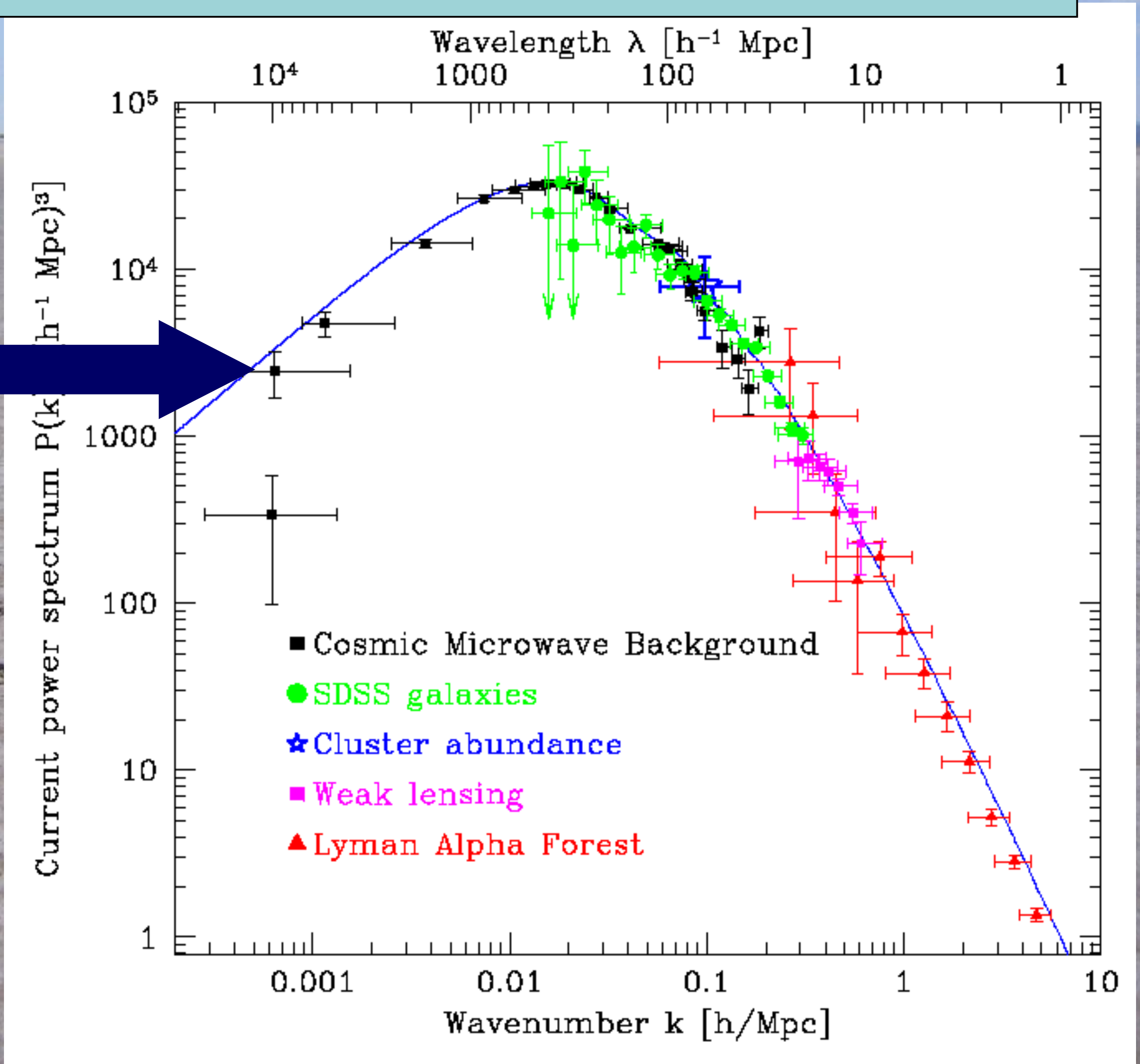
$\Omega_{CDM} \sim 0.25,$

Visible matter:

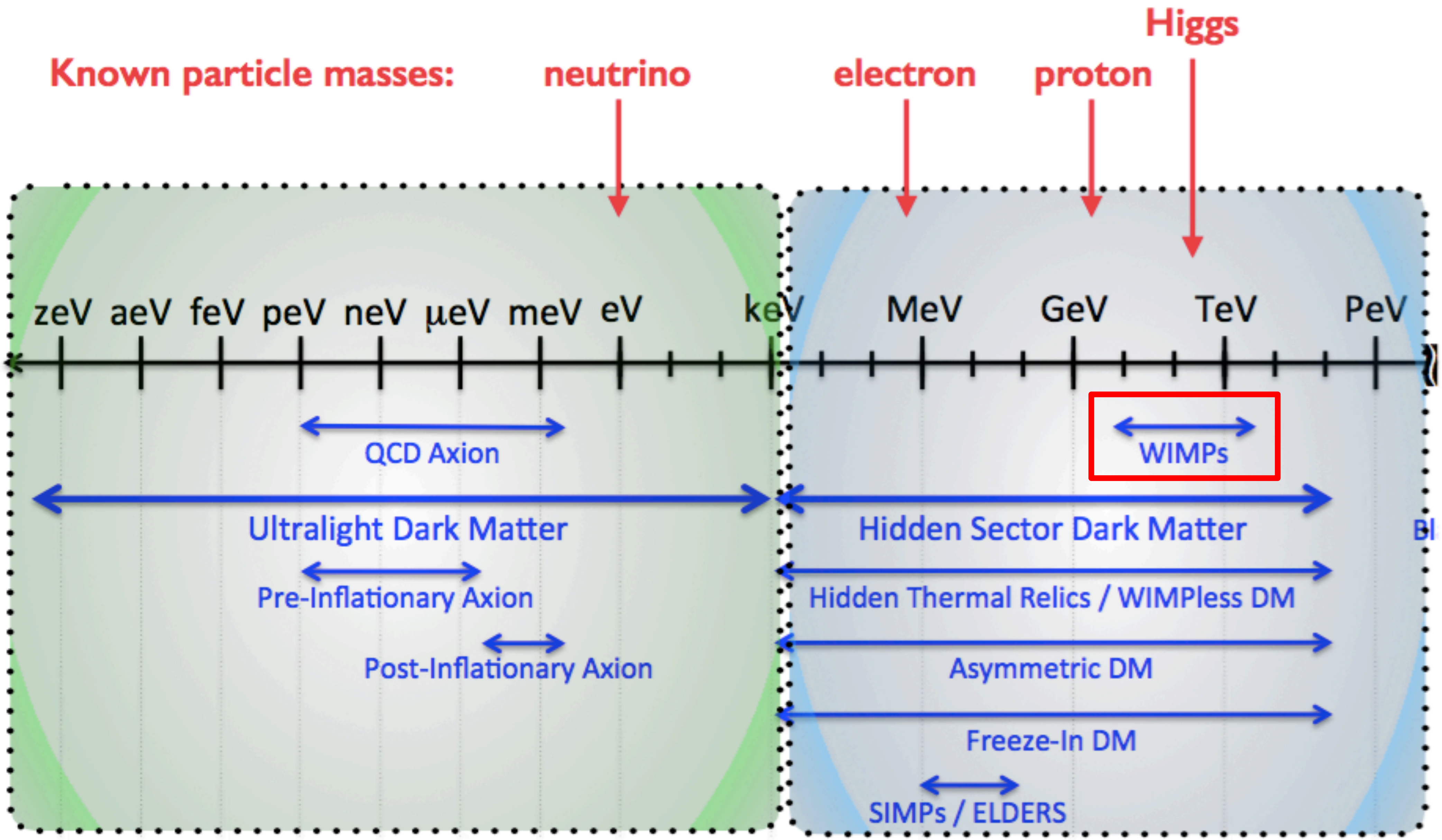
$\Omega_b \sim 0.05,$

Dark energy:

$\Omega_\Lambda \sim 0.7$



Searches for Dark Matter



Known particle masses: neutrino electron proton Higgs

zeV aeV feV peV neV μeV meV eV keV MeV GeV TeV PeV

QCD Axion

WIMPs

Ultralight Dark Matter

Hidden Sector Dark Matter

Bl

Pre-Inflationary Axion

Hidden Thermal Relics / WIMPless DM

Post-Inflationary Axion

Asymmetric DM

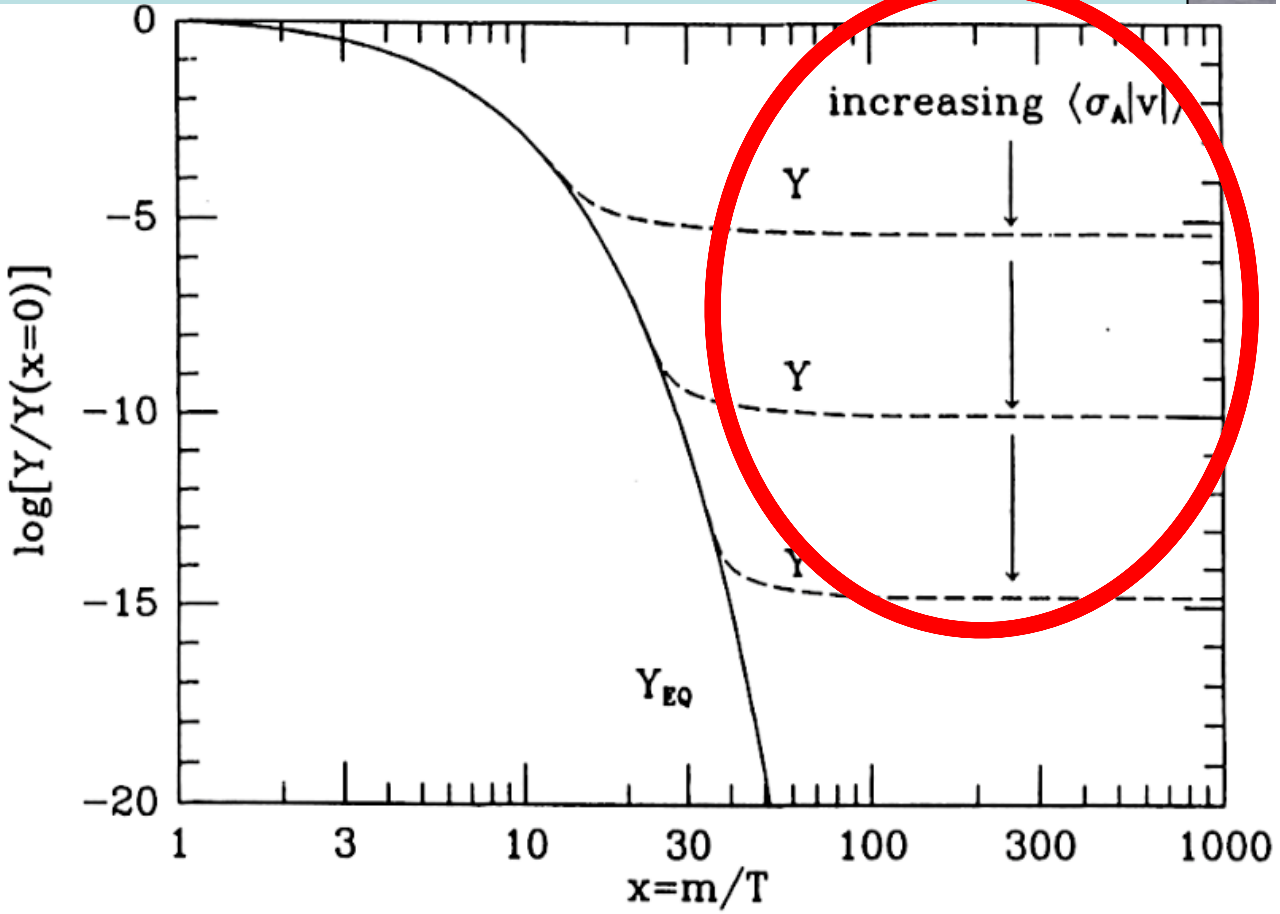
Freeze-In DM

SIMPs / ELDERS

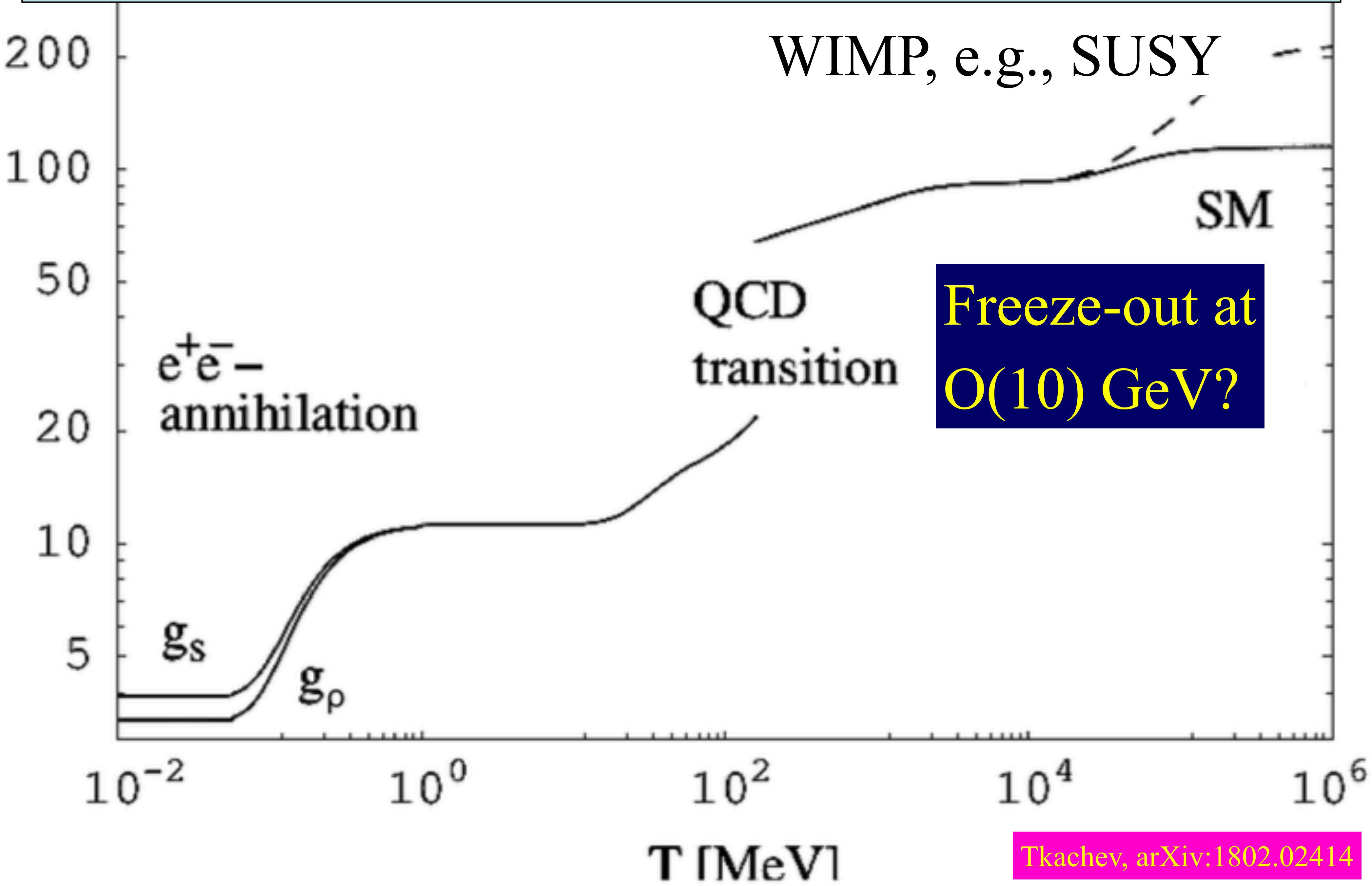
‘Ultra-Light’ dark matter **‘Massive’ dark matter**

Weakly-Interacting Massive Particles (WIMPs)

- Expected to have been numerous in the primordial Universe when it was a fraction of a second old, full of a primordial hot soup
- Would have cooled down as Universe expanded
- Interactions would have weakened
- WIMPs decoupled from visible matter
- "Freeze-out"
- Larger σ → lower Y



‘Standard’ Thermal History of Early Universe



Freeze-out at O(10) GeV?

Tkachev, arXiv:1802.02414

The WIMP 'Miracle'

- The TeV scale from cosmology: $\mathrm{TeV} \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}$
- Generic density from freeze-out:

$$\Omega_X h_0^2 \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}} \simeq \frac{1}{10^3 \langle \sigma v \rangle} \frac{1}{\mathrm{TeV}^2}$$

- Generic annihilation cross-section: $\sigma v \simeq \frac{c\alpha^2}{m^2}$
- Generic relic mass:

$$m \simeq \sqrt{M_{\mathrm{Pl}} \times 2.7\,\mathrm{K}}\; 16\alpha\sqrt{C}\,\sqrt{\frac{\Omega_X h_0^2}{0.25}}$$

$$\simeq \mathrm{TeV}\; 16\alpha\sqrt{C}\,\sqrt{\frac{\Omega_X h_0^2}{0.25}}\,.$$

- Putting the numbers in: $m \lesssim \tfrac{1}{2}\sqrt{10C}\,\mathrm{TeV} \lesssim 5\,\mathrm{TeV}$

Dimopoulos, PLB246, 347 (1990)

WIMP Candidates

- Could have right density if weigh 100 to 1000 GeV (accessible to LHC experiments?)
- Present in many extensions of Standard Model
- Particularly in attempts to understand strength of weak interactions, mass of Higgs boson
- Examples:
  - Extra dimensions of space
  - **Supersymmetry**

♥

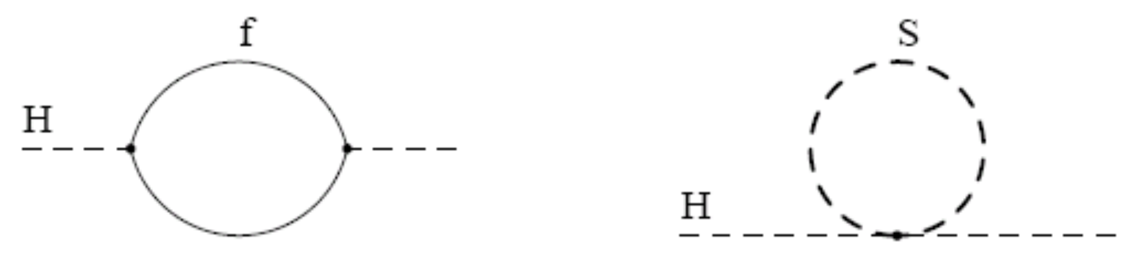
We still believe in supersymmetry

You must be joking!

Naturalness of hierarchy of mass scales

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f{}^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$\lambda_S = y_f^2$ x 2 **Supersymmetry!**

Minimal Supersymmetric Extension of Standard Model (MSSM)

- Double up the known particles:

$$\begin{pmatrix}\frac{1}{2}\\ 0\end{pmatrix}\ e.g.,\ \begin{pmatrix}\ell\ (lepton)\\ \tilde{\ell}\ (slepton)\end{pmatrix}\ or\ \begin{pmatrix}q\ (quark)\\ \tilde{q}\ (squark)\end{pmatrix}$$

$$\begin{pmatrix}1\\ \frac{1}{2}\end{pmatrix}\ e.g.,\ \begin{pmatrix}\gamma\ (photon)\\ \tilde{\gamma}\ (photino)\end{pmatrix}\ or\ \begin{pmatrix}g\ (gluon)\\ \tilde{g}\ (gluino)\end{pmatrix}$$

- Two Higgs doublets
  - 5 physical Higgs bosons:
  - 3 neutral, 2 charged
- Lightest neutral supersymmetric Higgs looks like the single Higgs in the Standard Model

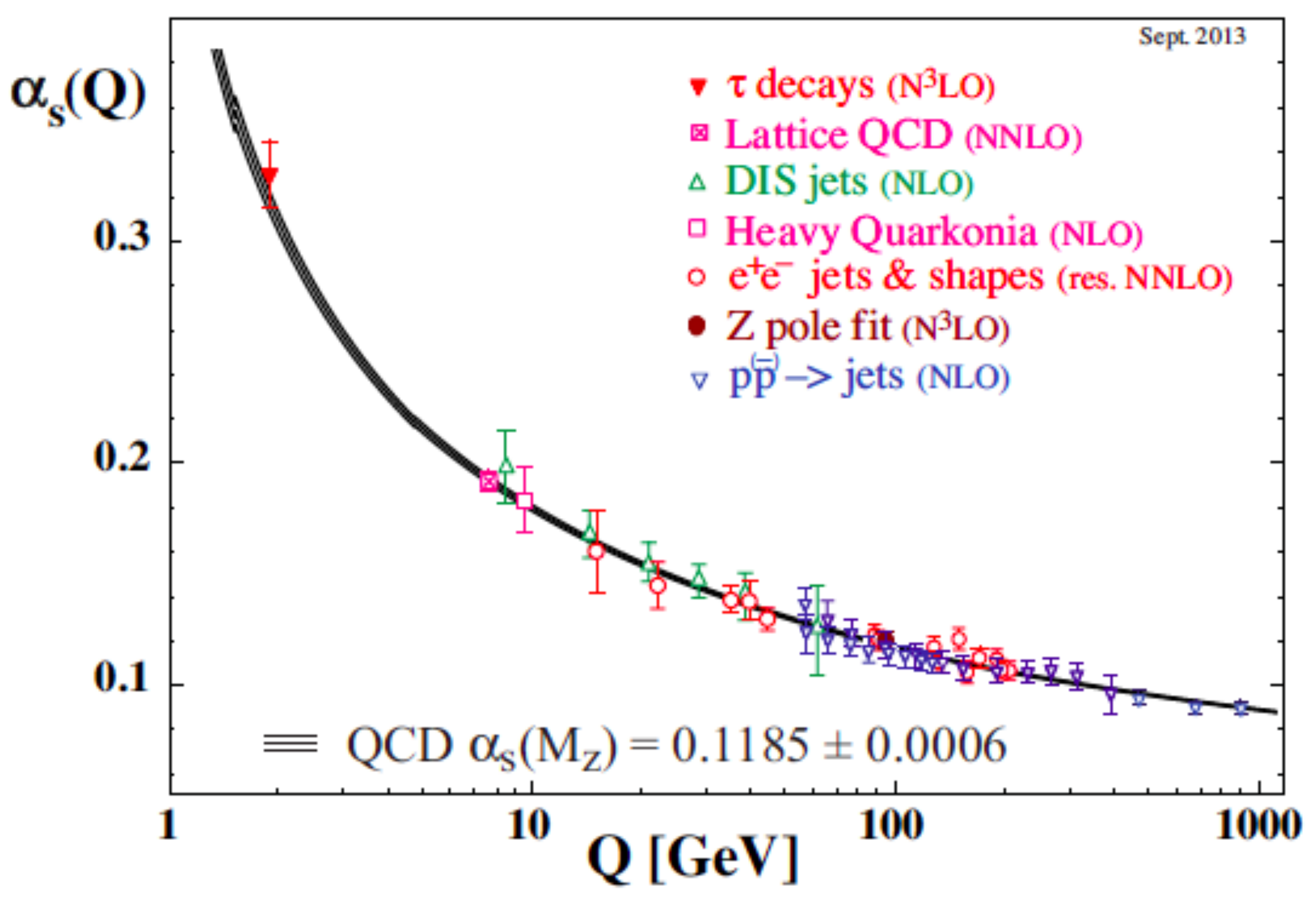
Towards Grand Unification

Pati & Salam
Georgi & Glashow
Georgi, Quinn & Weinberg

- The three Standard Model gauge couplings are different: $g_3 >> g_2, g'$
- Ratio $\sin^2\theta_W \equiv \frac{g'^2}{g'^2 + g_2^2}$ is free parameter in Standard Model
- All couplings vary energy scale, calculable using renormalisation group
- Best known is decrease of $\alpha_s \equiv \frac{g_3^2}{4\pi}$, "asymptotic freedom"
- Offers prospect of unifying couplings at high energy, as in simple group structure, and predicting $\sin^2\theta_W$

Strong Coupling “Constant” …

- … is not constant: weaker at higher energies



- **Asymptotic freedom**

Towards Grand Unification

- At one-loop order without/**with** supersymmetry:

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}$$

$$\boxed{b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}}$$

- At two-loop order without/**with** supersymmetry:

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\boxed{b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}}$$

1974

Georgi, Quinn & Weinberg

Grand Unification of Couplings

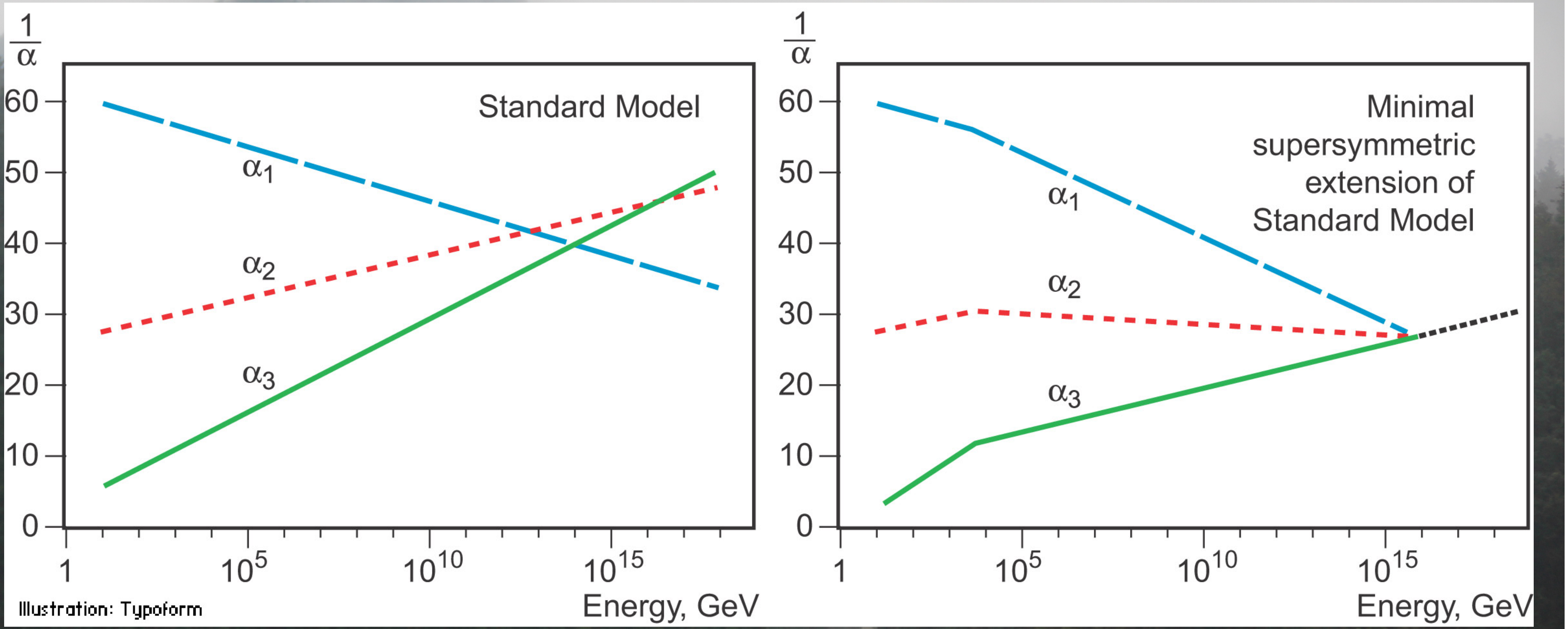


Illustration: Typoform

Almost works with just Standard Model particles
Better with supersymmetric particles

1974

Georgi & Glashow

Simplest Grand Unified Theory

- Electromagnetic charge embedded in simple group: charge quantized

$$\sum_{q,\ell} Q_i = 3Q_u + 3Q_d + Q_e = 0$$

- Minimal model: SU(5)
- Fermions of a single generation accommodated

$$\bar{5} : (\psi_i)_L = \begin{pmatrix} \bar{d}_1 \\ \bar{d}_2 \\ \bar{d}_3 \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad 10 : (\chi^{ij})_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & \bar{u}_3 & -\bar{u}_2 & u_1 & d_1 \\ -\bar{u}_3 & 0 & \bar{u}_1 & u_2 & d_2 \\ u_2 & -\bar{u}_1 & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^+ \\ -d_1 & -d_2 & -d_3 & -e^+ & 0 \end{pmatrix}_L$$

- “Explain” “random” quantum numbers
- **Renormalization prediction** $\sin^2\theta_W \simeq 0.23$

Supersymmetry Breaking

- Supersymmetry must be broken, many models, no clear guidance from theory
- Assume universality at GUT scale? (CMSSM)
  - Renormalisation effects increase $\tilde{q}$ masses relative to $\tilde{\ell}$, $\tilde{g}$ mass relative to $\tilde{W}^{\pm}$
  - Lighter stop squark may have $m_{\tilde{t}_1} < m_{\tilde{q}}$
  - Renormalization can drive $m_H^2 < 0$, enabling spontaneous gauge symmetry breaking
- Alternatively: treat particle masses as free parameters (pMSSM)

Lightest Supersymmetric Particle

- Stable in many models because of conservation of R parity:

  $R = (-1)^{2S - L + 3B}$

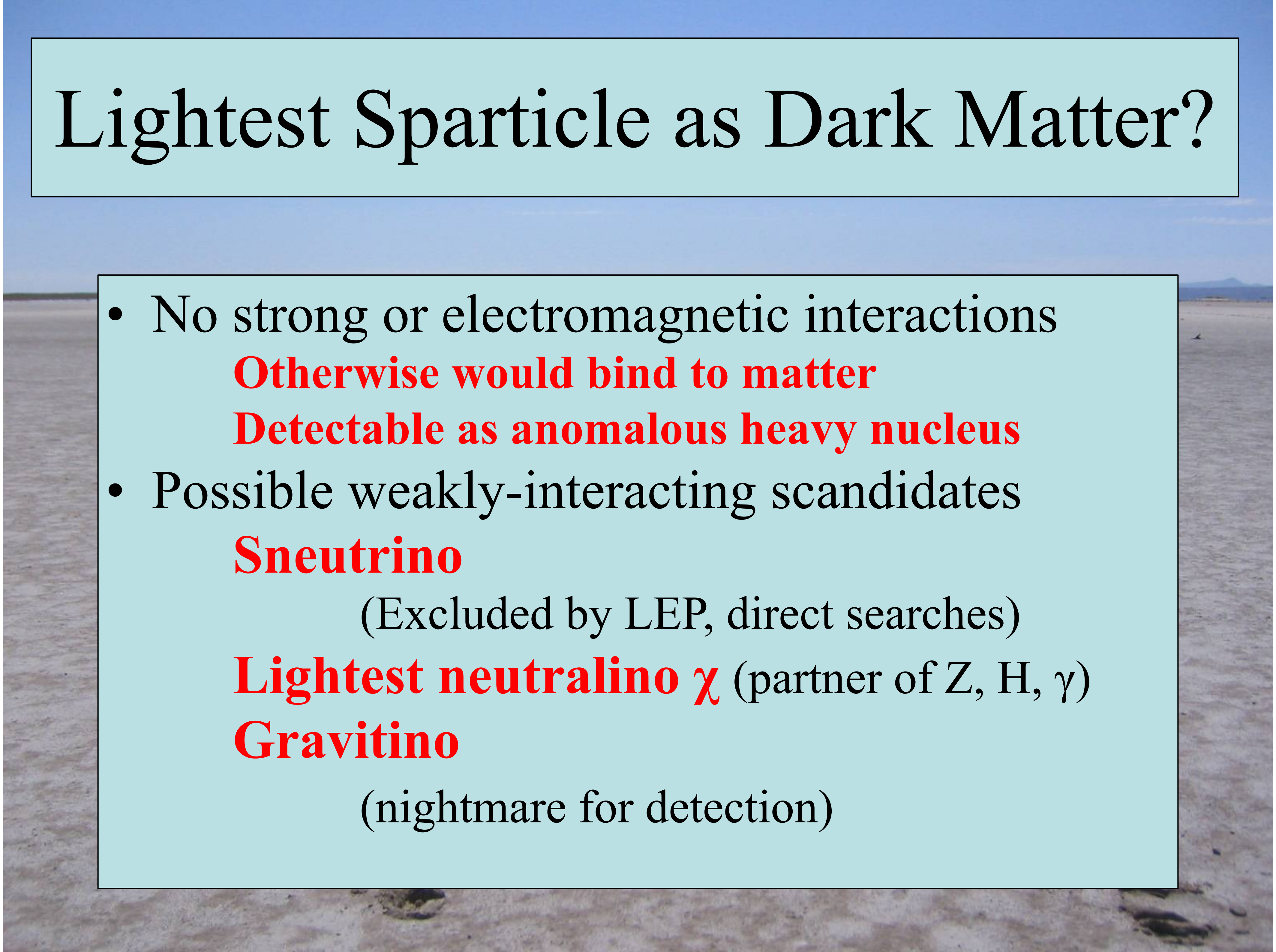
  where S = spin, L = lepton #, B = baryon #

- Particles have R = +1, sparticles R = -1:

  Sparticles produced in pairs

  Heavier sparticles → lighter sparticles

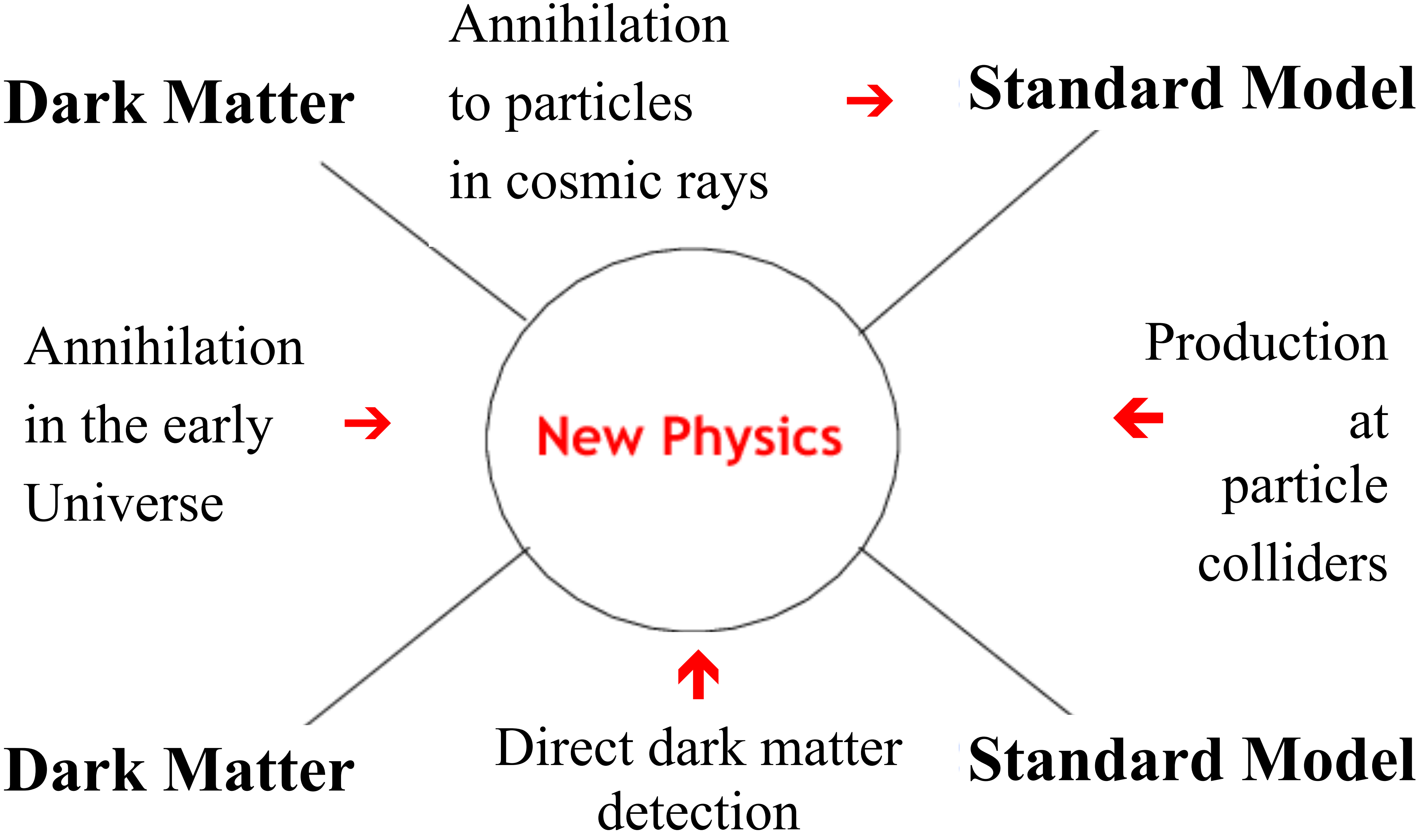
- **Lightest supersymmetric particle (LSP) stable**



Lightest Sparticle as Dark Matter?

- No strong or electromagnetic interactions
  - **Otherwise would bind to matter**
  - **Detectable as anomalous heavy nucleus**
- Possible weakly-interacting scandidates
  - **Sneutrino**
    - (Excluded by LEP, direct searches)
  - **Lightest neutralino χ** (partner of Z, H, γ)
  - **Gravitino**
    - (nightmare for detection)

Searches for WIMP Dark Matter



Dark Matter

Annihilation
to particles
in cosmic rays →

Standard Model

Annihilation
in the early
Universe →

New Physics

← Production
at
particle
colliders

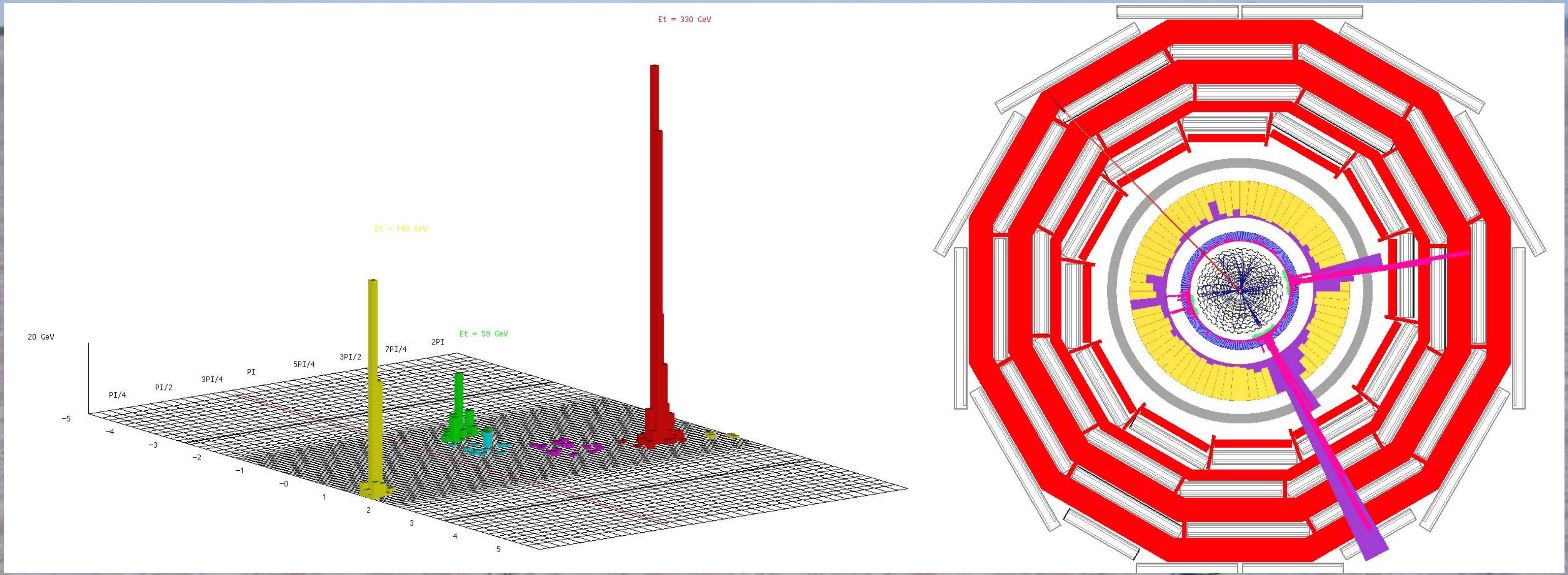
↑

Direct dark matter
detection

Dark Matter

Standard Model

Classic LHC Dark Matter Signature

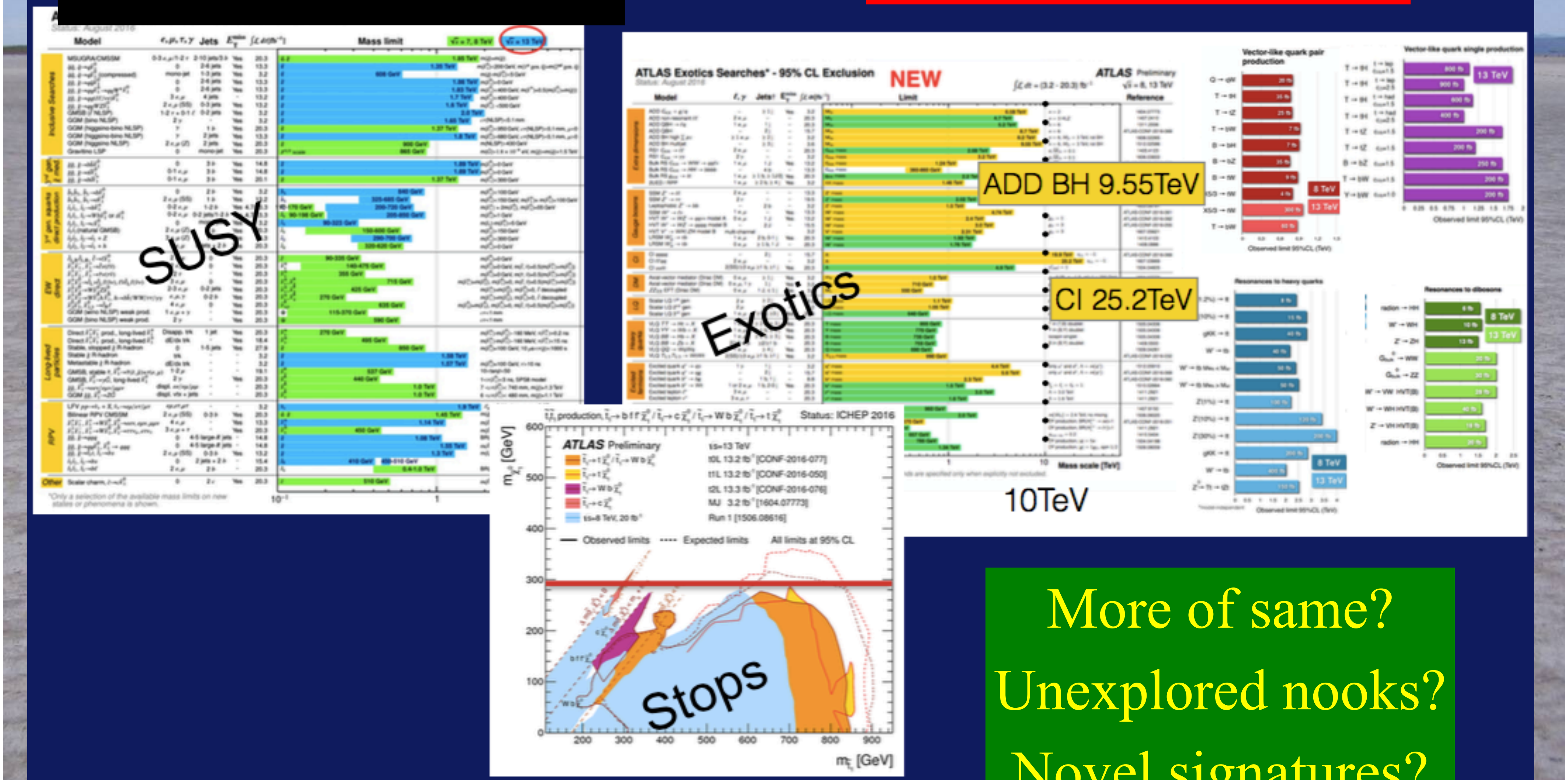


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



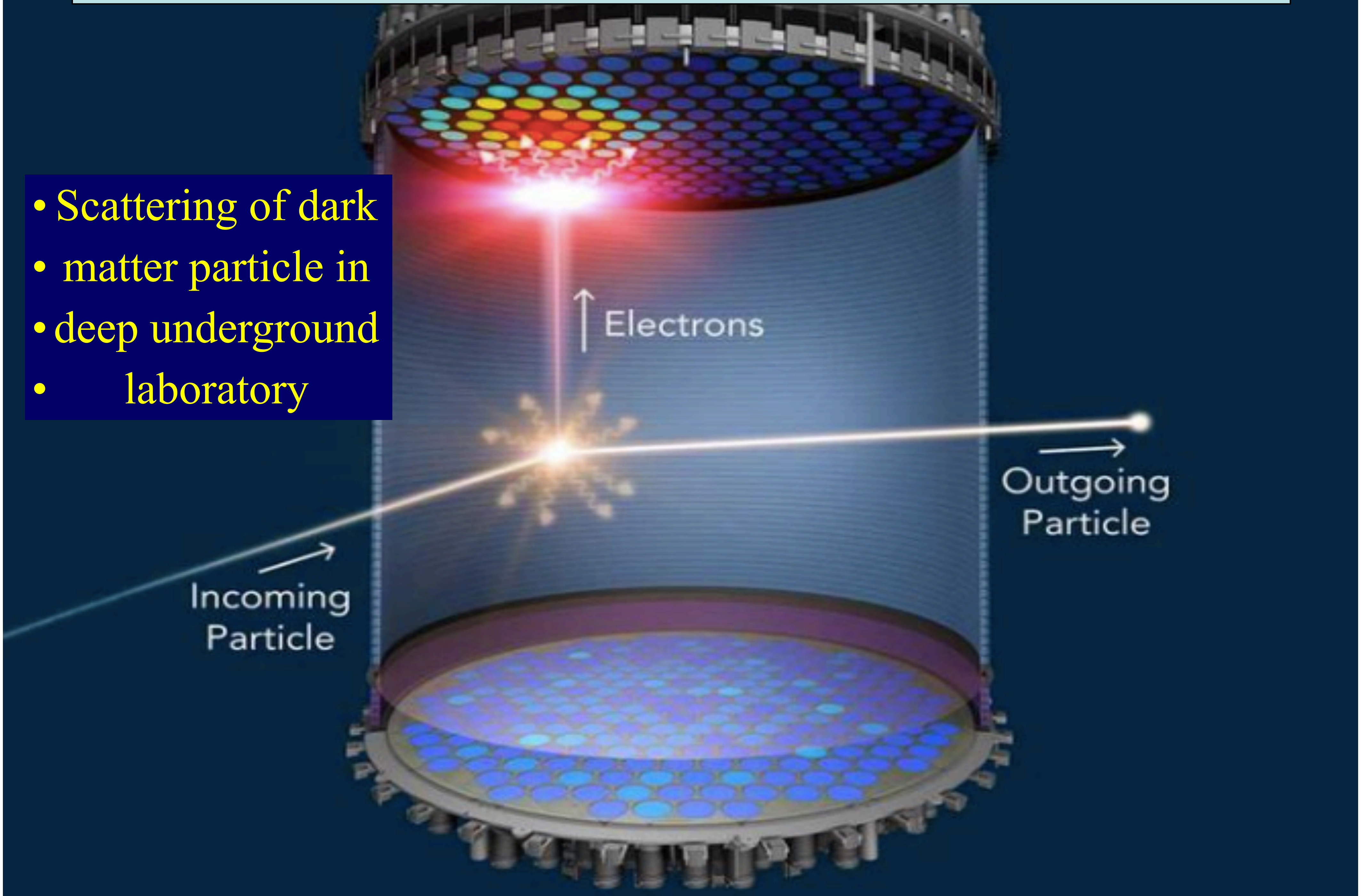
More of same?

Unexplored nooks?

Novel signatures?

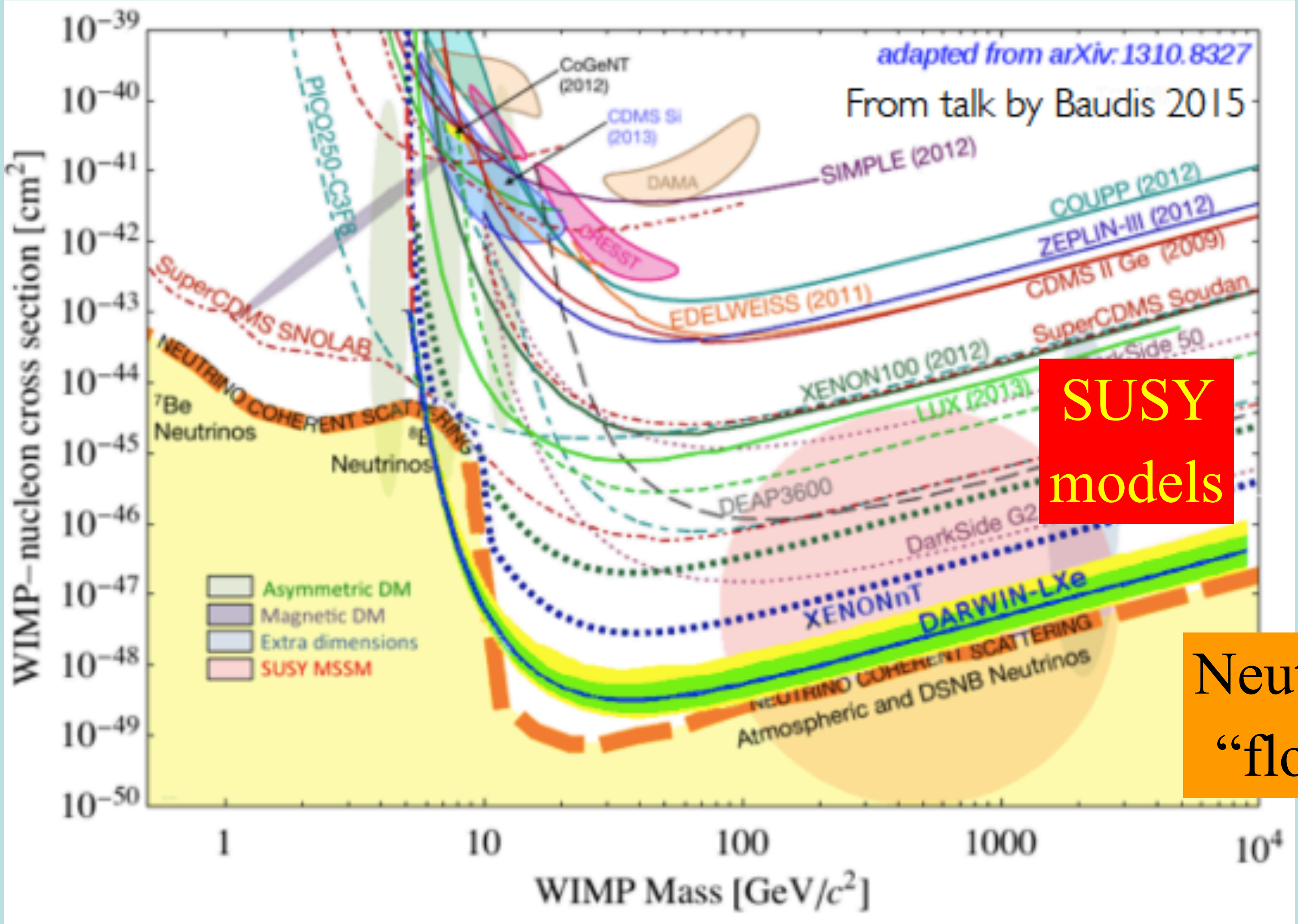
Direct Dark Matter Detection

- Scattering of dark
- matter particle in
- deep underground
- laboratory



Direct Dark Matter Searches

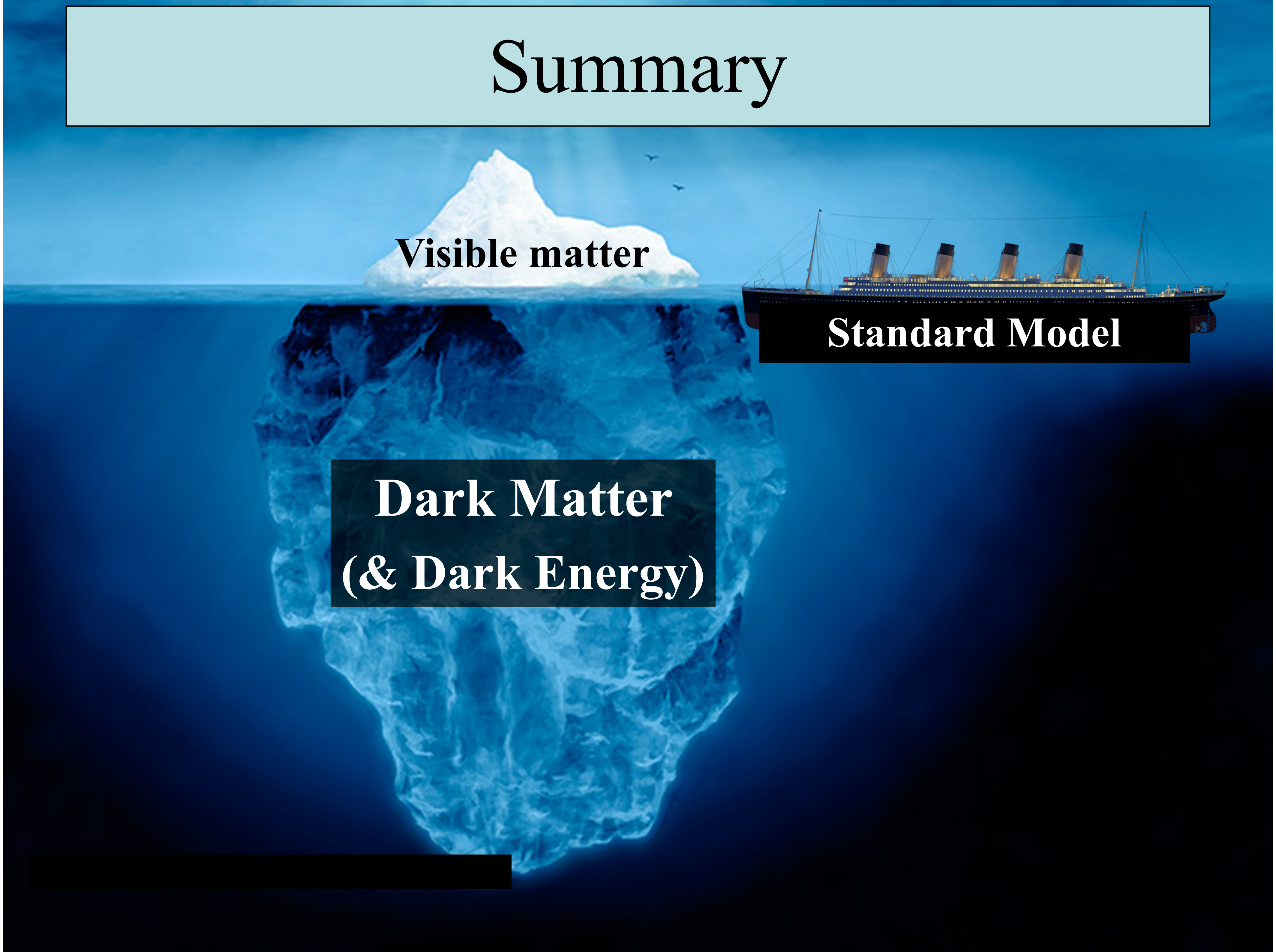
- Compilation of present and future sensitivities



SUSY models

Neutrino “floor”

Summary



Visible matter

Standard Model

Dark Matter

(& Dark Energy)

[redacted]

Known knowns (= SM)

Known unknowns (= DM)

Unknown unknowns

Lepton flavour violation in B decays?

$g_\mu - 2$?

Lepton Flavour Universality Violation in $B \to K\ell^+\ell^-$ Decays?

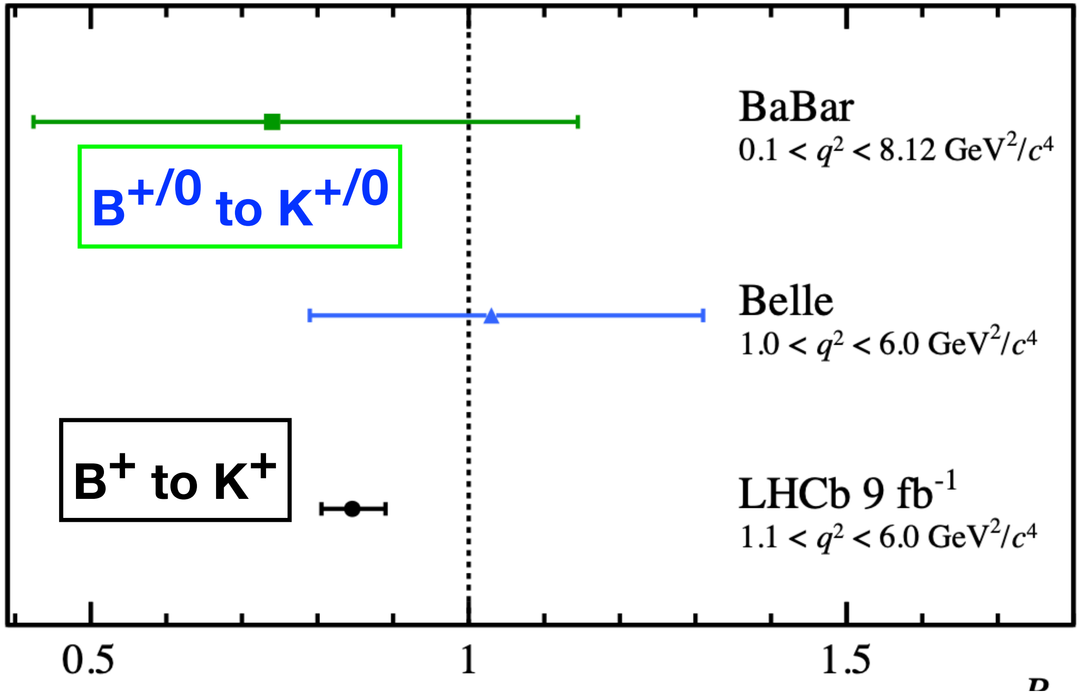
B decays to $e^+e^- > \mu^+\mu^-$

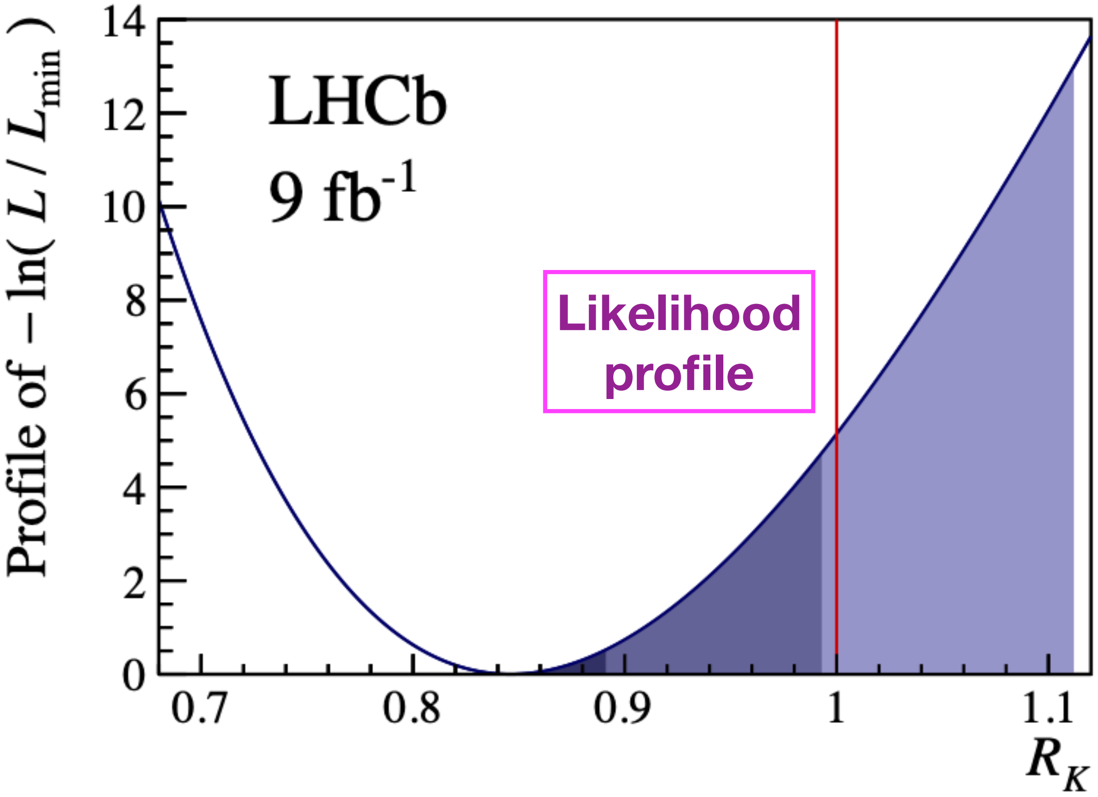
Prima facie violation of lepton universality

SM interactions flavour-universal

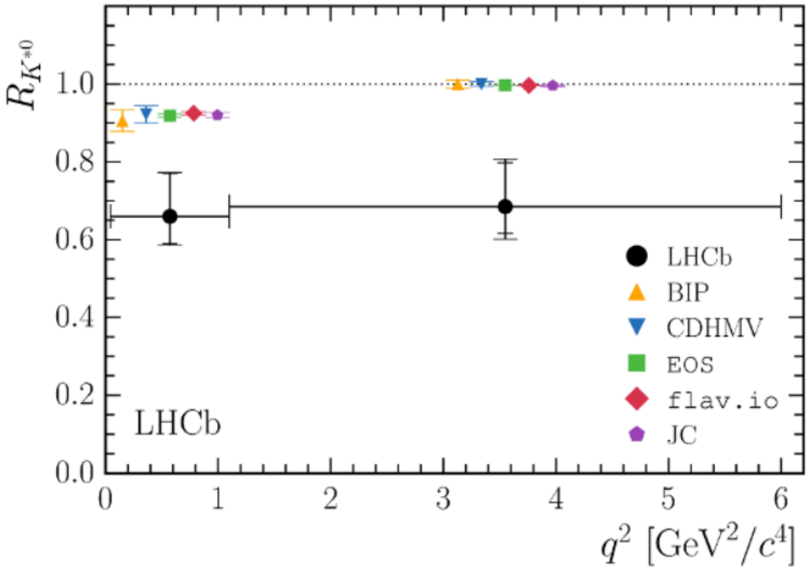
Except for Higgs couplings ∝ masses

LHCb Collaboration, arXiv:2103.11769

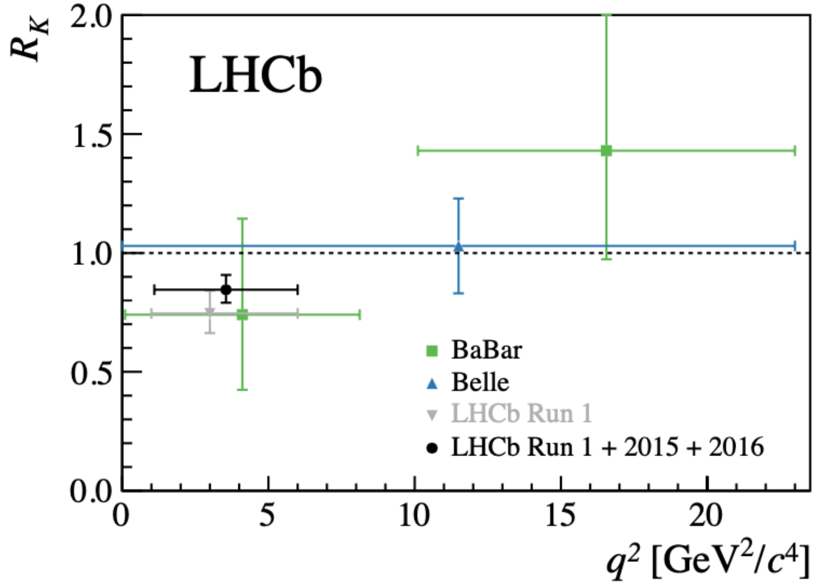


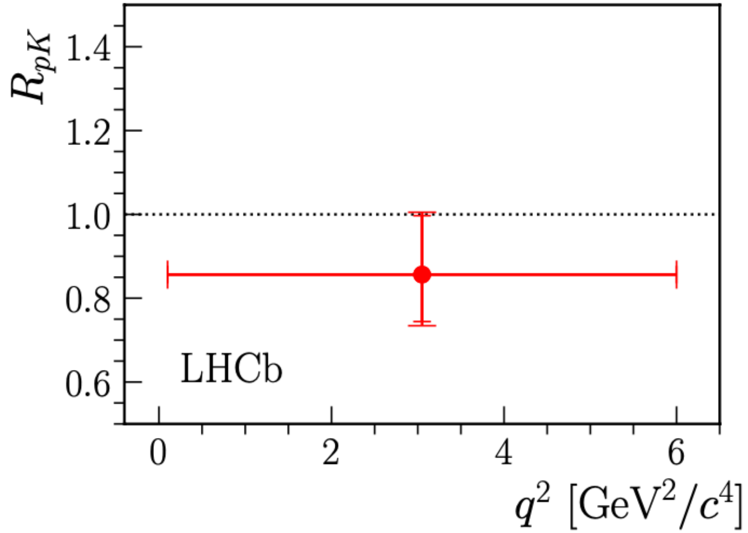


Previous LHCb & Other Measurements



BaBar:[PRD86(2012)032012],Belle:[PRL103(2009)171801]





Left: $B^0 \to K^{*0}\ell^+\ell^-$ R_{K^*} 3fb^{-1}
[JHEP08(2017)055]

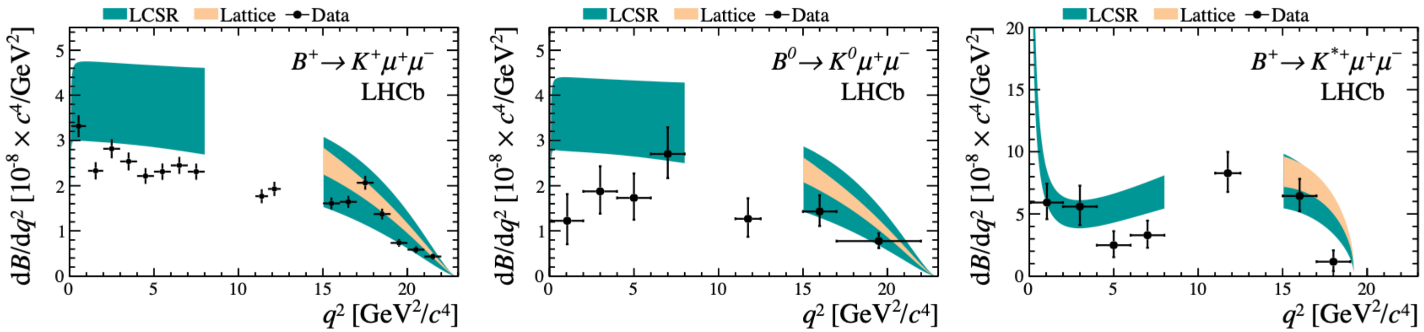
Right: $B^+ \to K^+\ell^+\ell^-$ R_K 5fb^{-1}
[PRL122(2019)191801]

Bottom: $\Lambda_b \to pK\ell^+\ell^-$ R_{pK} 4.7fb^{-1}
[JHEP05(2020)040]

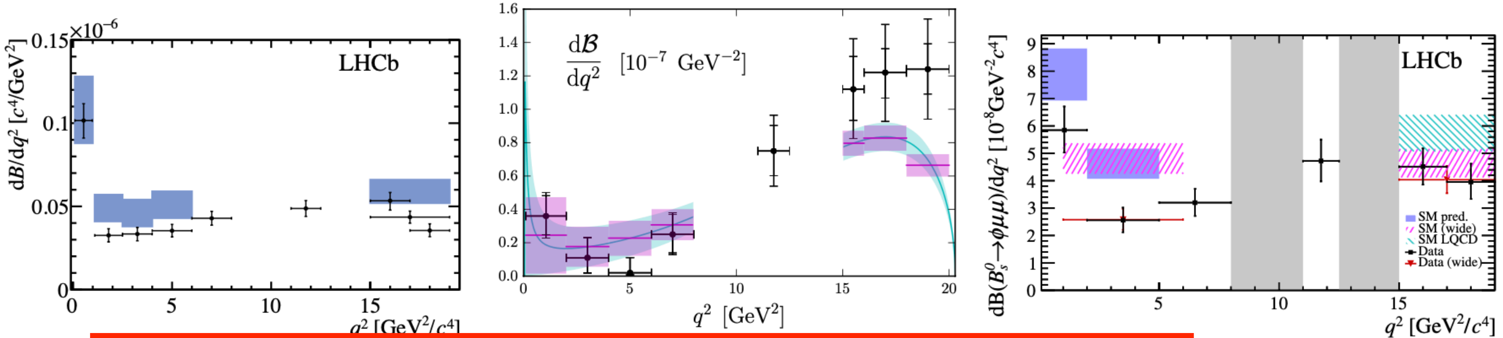
Other Previous Measurements

Rates

[JHEP06(2014)133]

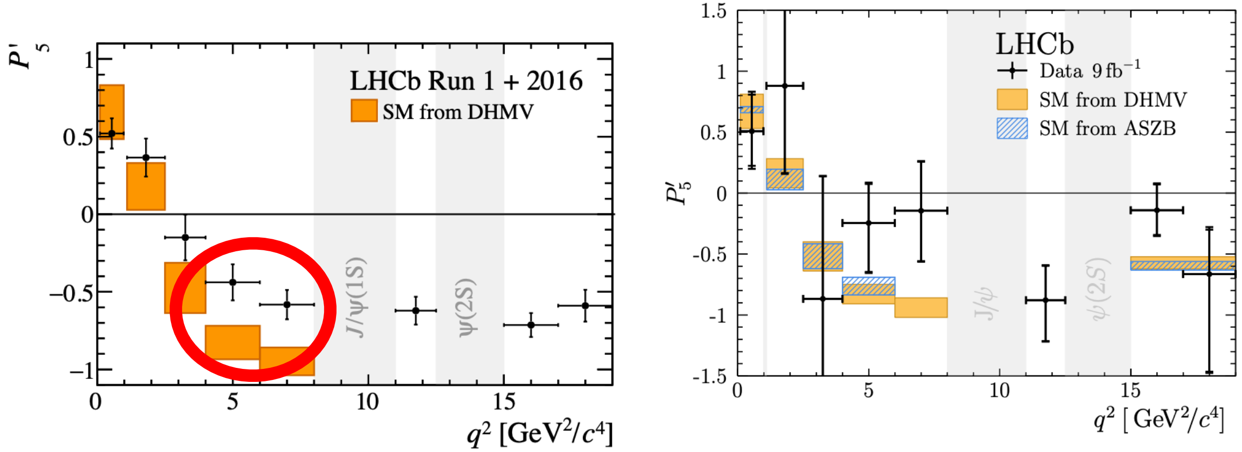


$B^0 \to K^{*0}\mu^+\mu^-$ [JHEP11(2016)047], $\Lambda_b \to \Lambda\mu^+\mu^-$ [JHEP06(2015)115] $B_s \to \phi\mu^+\mu^-$ [JHEP09(2015)179]



- SM predictions suffer from large hadronic uncertainties

Left: $B^0 \to K^{*0}\mu^+\mu^-$ [PRL125011802(2020)], Right: $B^+ \to K^{*+}\mu^+\mu^-$ [arXiv:2012.13241]



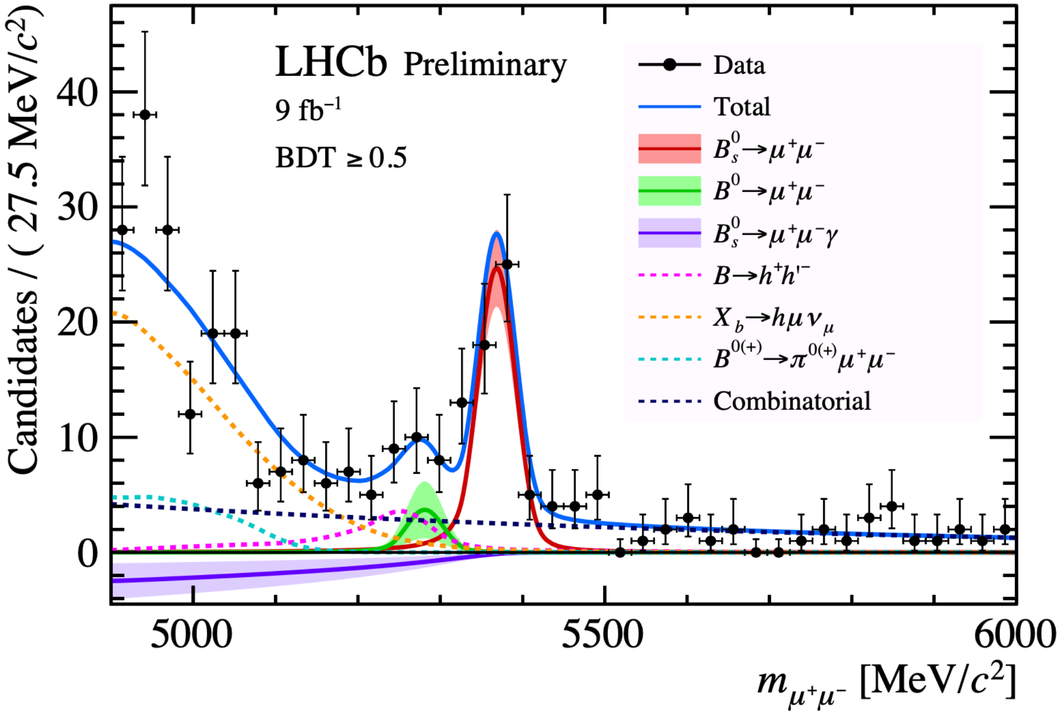
Angular distributions

New LHCb BR($B_s \to \mu^+\mu^-$) Measurement

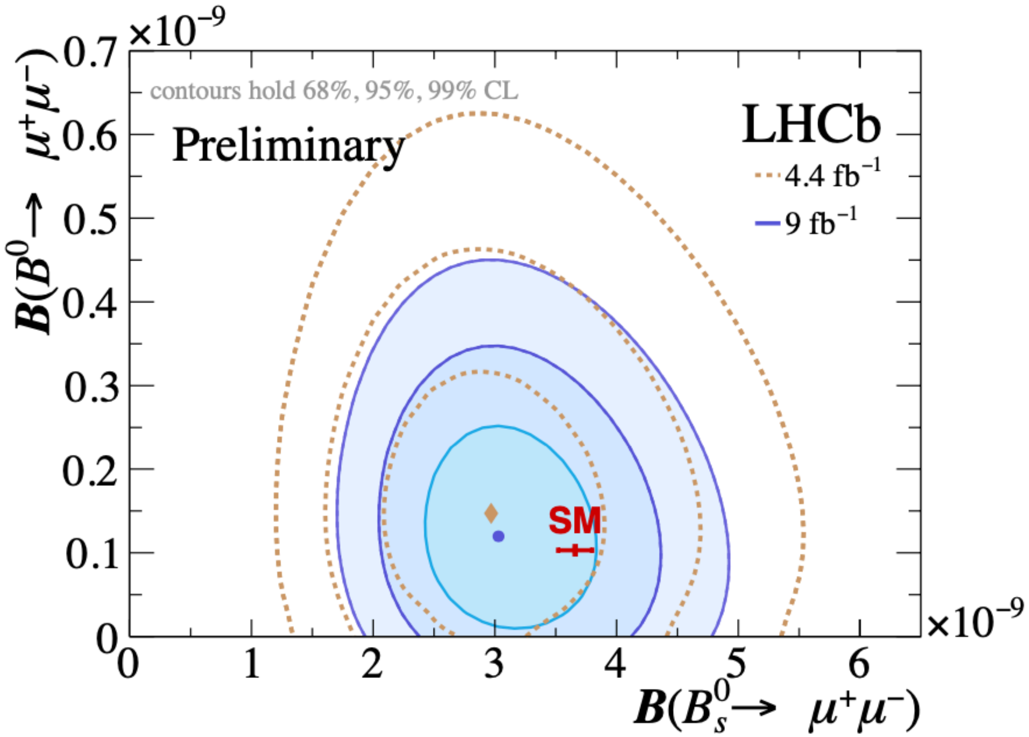
Rare decay induced by loop diagrams in SM

Measured value < SM prediction (insignificantly)

Include in search for new physics associated with the muon



● $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)



Flavour Anomalies in b→s Decays

- Parametrize using effective dimension-6 operators:

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm SM} - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_{\ell=e,\mu} \sum_{i=9,10,S,P} \left(C_i^{bs\ell\ell} O_i^{bs\ell\ell} + C_i'^{bs\ell\ell} O_i'^{bs\ell\ell} \right) + \text{h.c.}$$

- Operators appearing in analysis:

$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)\,,$$

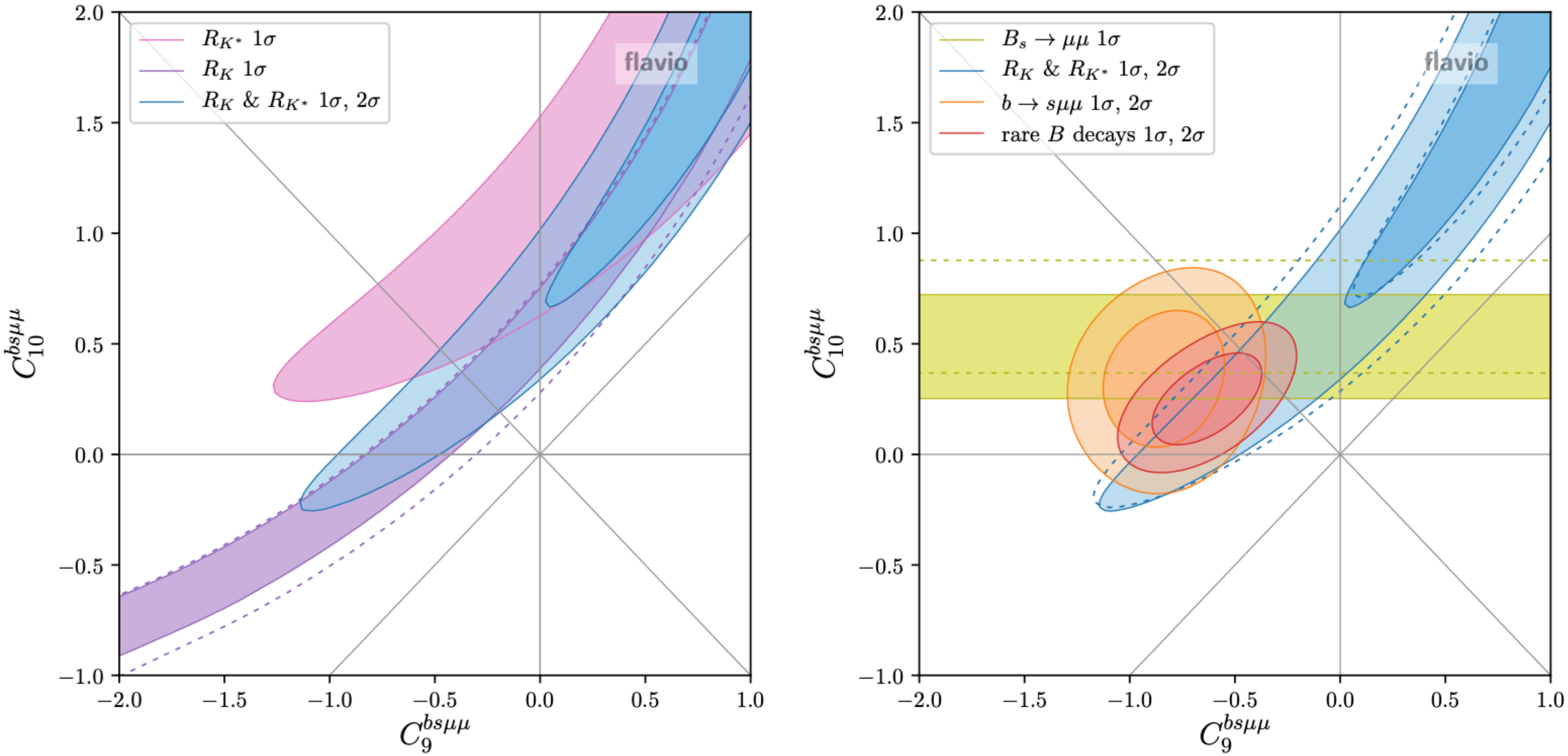
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,, \qquad O_{10}'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

$$O_S^{bs\ell\ell} = m_b(\bar{s} P_R b)(\bar{\ell}\ell)\,, \qquad O_S'^{bs\ell\ell} = m_b(\bar{s} P_L b)(\bar{\ell}\ell)\,,$$

- $O_P^{bs\ell\ell} = m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5 \ell)\,, \qquad O_P'^{bs\ell\ell} = m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5 \ell)\,.$
- Evidence for non-zero coefficient of $O_9^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$
- Maybe also non-zero coefficient of $O_{10}^\mu \equiv (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$.
- No evidence of operators with electrons

Flavour Anomalies in b→s Decays

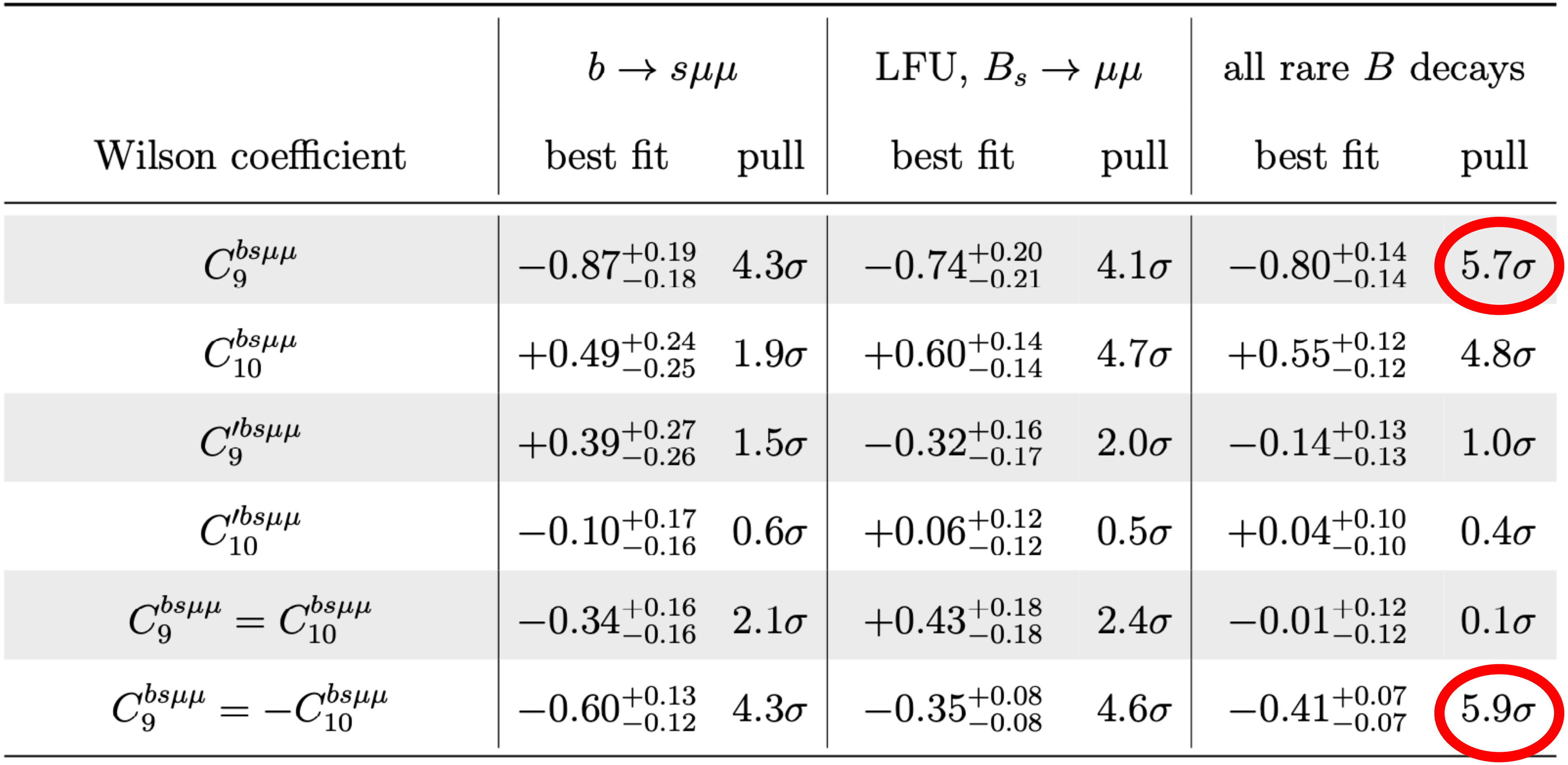
- Results from global fit to $C_{9,10}^{bs\mu\mu}$



Altmannhofer & Stangl, arXiv:2103.133702

Flavour Anomalies in b→s Decays

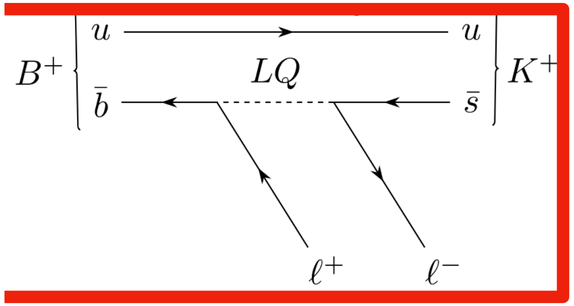
- Results for operator coefficients



Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
$C_9^{bs\mu\mu}$	$-0.87^{+0.19}_{-0.18}$	4.3σ	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.49^{+0.24}_{-0.25}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	4.7σ	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$+0.39^{+0.27}_{-0.26}$	1.5σ	$-0.32^{+0.16}_{-0.17}$	2.0σ	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$-0.10^{+0.17}_{-0.16}$	0.6σ	$+0.06^{+0.12}_{-0.12}$	0.5σ	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.34^{+0.16}_{-0.16}$	2.1σ	$+0.43^{+0.18}_{-0.18}$	2.4σ	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.13}_{-0.12}$	4.3σ	$-0.35^{+0.08}_{-0.08}$	4.6σ	$-0.41^{+0.07}_{-0.07}$	5.9σ

Altmannhofer & Stangl, arXiv:2103.133702

Leptoquarks?

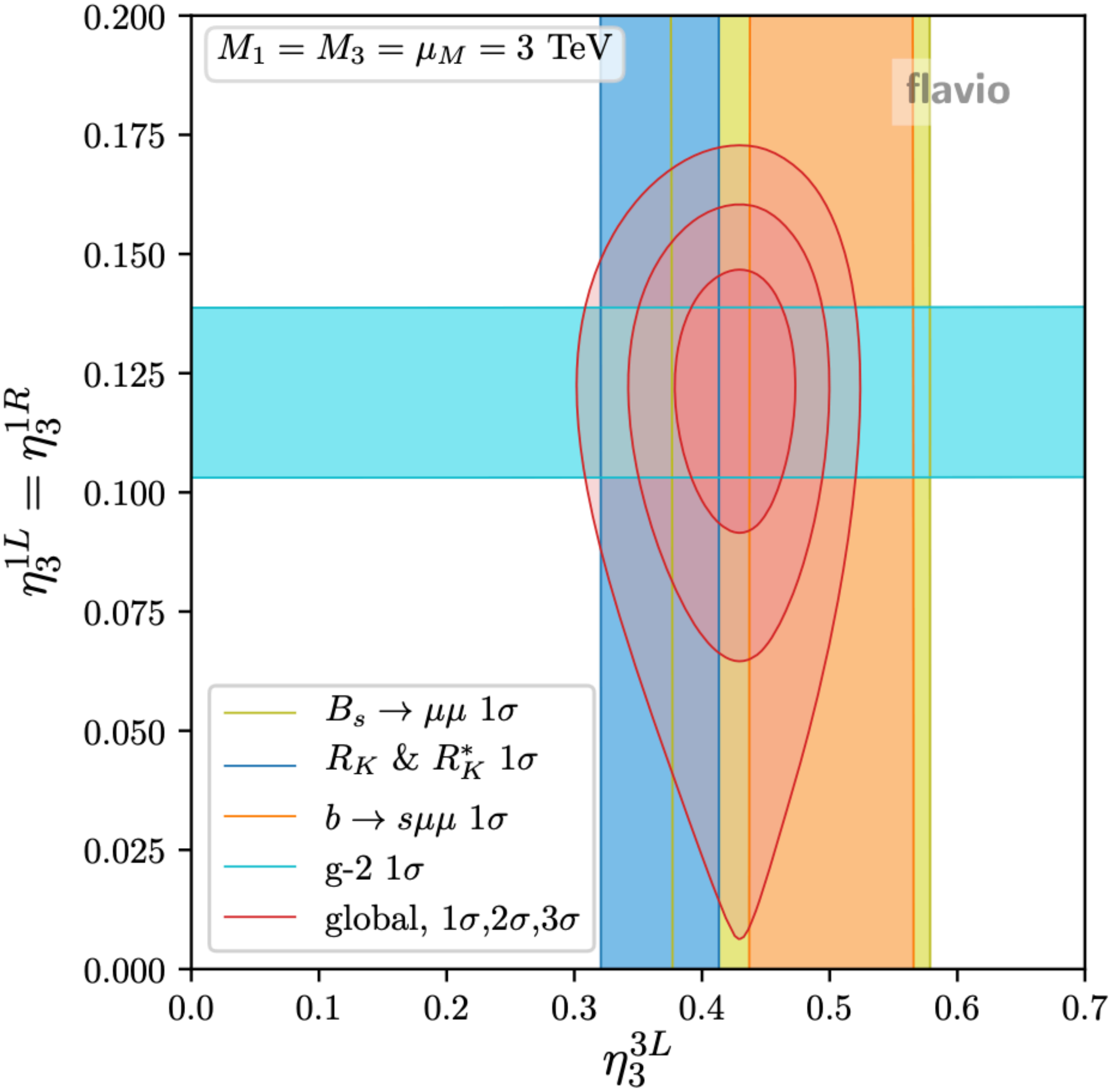


Bosons that couple leptons to quarks

$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\mathrm{SM}-V_H} &+ |D_\mu \Phi|^2 + |D_\mu S_1|^2 + |D_\mu S_3|^2 - \tfrac{1}{4} X_{\mu\nu}^2 \\
&- \Big(\boxed{\eta_i^{3\mathrm{L}}\, \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2\, S_3 - \eta_i^{1\mathrm{L}} \overline{q}_{\mathrm{L}}^{c\,i} \ell_{\mathrm{L}}^2 S_1 - \eta_i^{1\mathrm{R}} \overline{u}_{\mathrm{R}}^{c\,i} \mu_{\mathrm{R}} S_1} \\
&- \tilde{\eta}_i^{1\mathrm{R}} \overline{d}_{\mathrm{R}}^{c\,i} \nu_{\mu,\mathrm{R}} S_1 + \mathrm{h.c.} \Big) + \tfrac{1}{2} \varepsilon_{BX} B_{\mu\nu} X^{\mu\nu} \qquad (2) \\
&- V_{H\Phi}(H, \Phi) - V_{13}(H, \Phi, S_1, S_3) + \bar{\nu}_{\mathrm{R}}^i i \not{D} \nu_{\mathrm{R}}^i \\
&- \left(y_\nu^{ij}\, \bar{\ell}_{\mathrm{L}}^i \tilde{H} \nu_{\mathrm{R}}^j + M_{\mathrm{R}}^{ij} \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + y_\Phi^{ij} \Phi\, \bar{\nu}_{\mathrm{R}}^{ci} \nu_{\mathrm{R}}^j + \mathrm{h.c.} \right) ,
\end{aligned}
$$

Greljo, Stangl & Thomsen, arXiv:2103.13991

Leptoquark Model of $B \to K$ Anomalies and $g_\mu - 2$



B decays indicate $\eta_3^{3L} \neq 0$

$g_\mu - 2$ indicates $\eta_3^{1L,1R} \neq 0$

Greljo, Stangl & Thomsen, arXiv:2103.13991

Possible Z' Interpretations

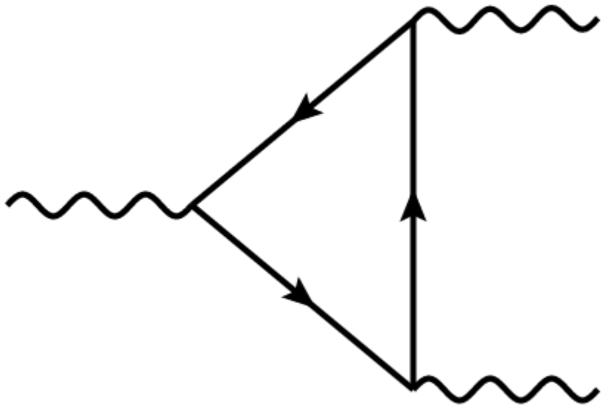
- Coupling to muons, not electrons (LEP), tau?
- Prefer vector-like coupling to muons
- Coupling to LH charge – 1/3 quarks
- Prefer universal couplings to 1st/2nd generation quarks (FCNC)
- Different coupling to 3rd generation quarks to get bs flavour change
- Non-zero couplings of RH charge 2/3 quarks?
- **Additional 'dark' sector or heavy vector-like lepton?**

JE, Fairbairn & Tunney, arXiv:1705.03447

Formulation of U(1)' Models

(also for dark matter?)

- Gauge bosons of U(1)' may have vector and/or axial-vector couplings
- Consistency of theory requires cancellation of anomalous triangle diagrams



- Standard Model has

  quark-lepton cancellation
- Should be re-examined in models with extra fermions and/or gauge bosons

JE, Fairbairn & Tunney, arXiv:1705.03447

Anomaly Cancellation Conditions

- Colour/U(1)’: (a) $[\mathrm{SU}(3)_C^2]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{T^i,T^j\}Y']=0$,
- $\mathrm{SU}(2)_W$/U(1)’: (b) $[\mathrm{SU}(2)_W^2]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\{T^i,T^j\}Y']=0$,
- $\mathrm{U}(1)_Y^2$/U(1)’: (c) $[\mathrm{U}(1)_\mathrm{Y}^2]\times[\mathrm{U}(1)']$, which implies $\mathrm{Tr}[\mathrm{Y}^2Y']=0$,
- $\mathrm{U}(1)_Y/\mathrm{U}(1)'^2$: (d) $[\mathrm{U}(1)_Y]\times[\mathrm{U}(1)'^2]$, which implies $\mathrm{Tr}[YY'^2]=0$,
- $\mathrm{U}(1)'^3$: (e) $[\mathrm{U}(1)'^3]$, which implies $\mathrm{Tr}[Y'^3]=0$,
- Gravity/U(1)’:: (f) Gauge-gravity, which implies $\mathrm{Tr}[Y']=0$.
- **Non-trivial set of constraints**

JE, Fairbairn & Tunney, arXiv:1705.03447

U(1)’ models of Flavour Anomalies & Dark Matter

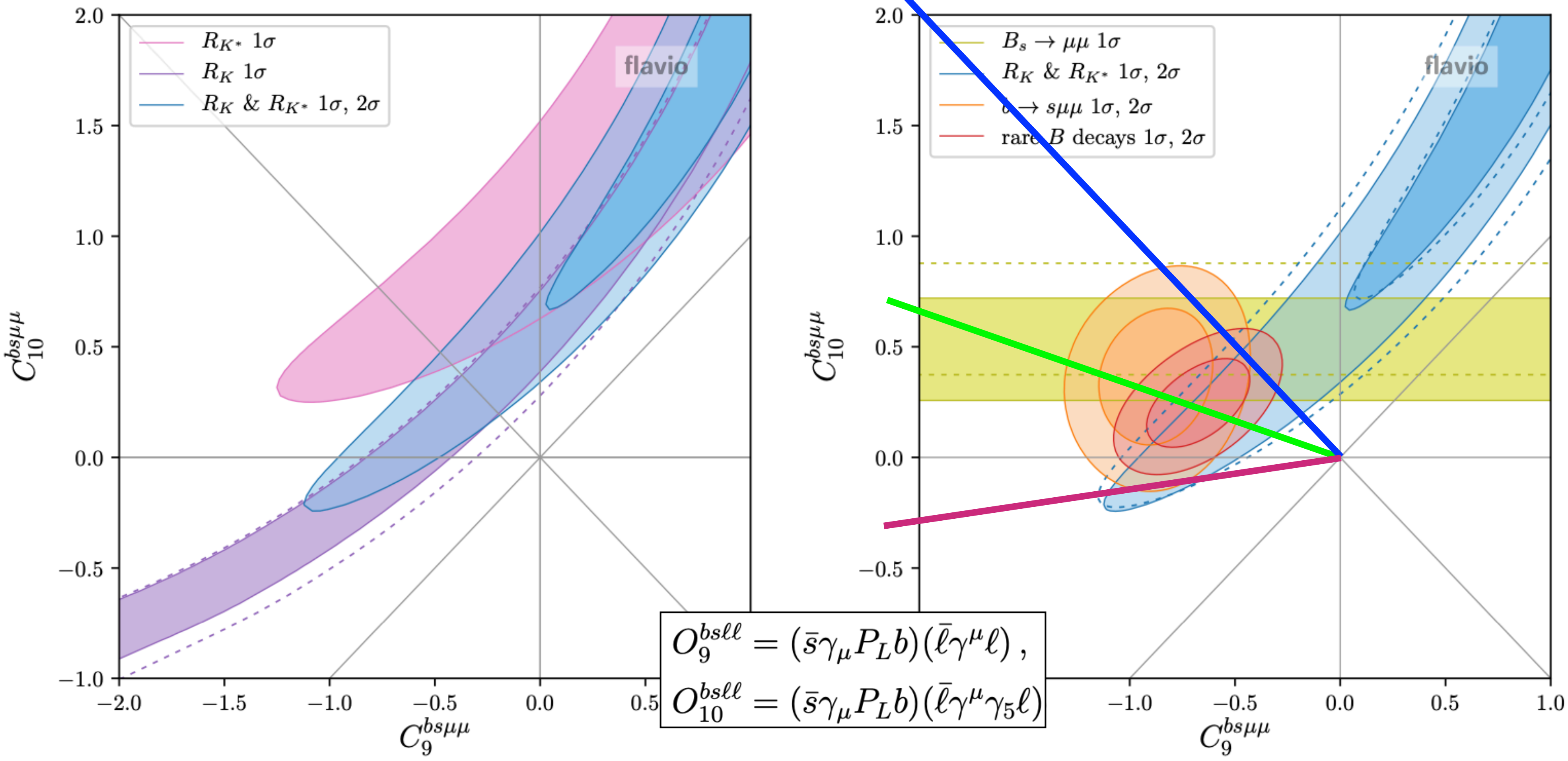
JE, Fairbairn & Tunney, arXiv:1705.03447

Models with only left-handed quark couplings and two dark fermions

Y'_{q_L}	Y'_{t_L}	Y'_{μ_L}	Y'_{μ_R}	Y'_{τ_L}	Y'_{τ_R}	Y'_{A_L}	Y'_{A_R}	Y'_{B_L}	Y'_{B_R}
1/3	-2/3	2/3	1/3	-2/3	-1/3	0	1	-1/3	-4/3

Models with right-handed charge 2/3 quark couplings and one DM fermion

	Y'_{q_L}	Y'_{q_R}	Y'_{t_L}	Y'_{t_R}	Y'_{μ_L}	Y'_{μ_R}	Y'_{τ_L}	Y'_{τ_R}	Y'_{χ_L}	Y'_{χ_R}
Vector-like μ coupling and axial DM coupling										
(A)	0	1	1	0	-2	-2	-1	-2	1	-1
Vector-like μ couplings										
(B)	1/3	1/3	-1/3	0	-1	-1	0	-1/3	1	1/3
(C)	1/2	0	-1/2	1	-1/2	-1/2	-1	-3/2	1	0
No first- and second-generation couplings										
(D)	0	0	1/2	1	-3/2	-2	0	0	1	0
(E)	0	0	1/2	1	-3/2	0	0	-2	1	0



$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10}^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

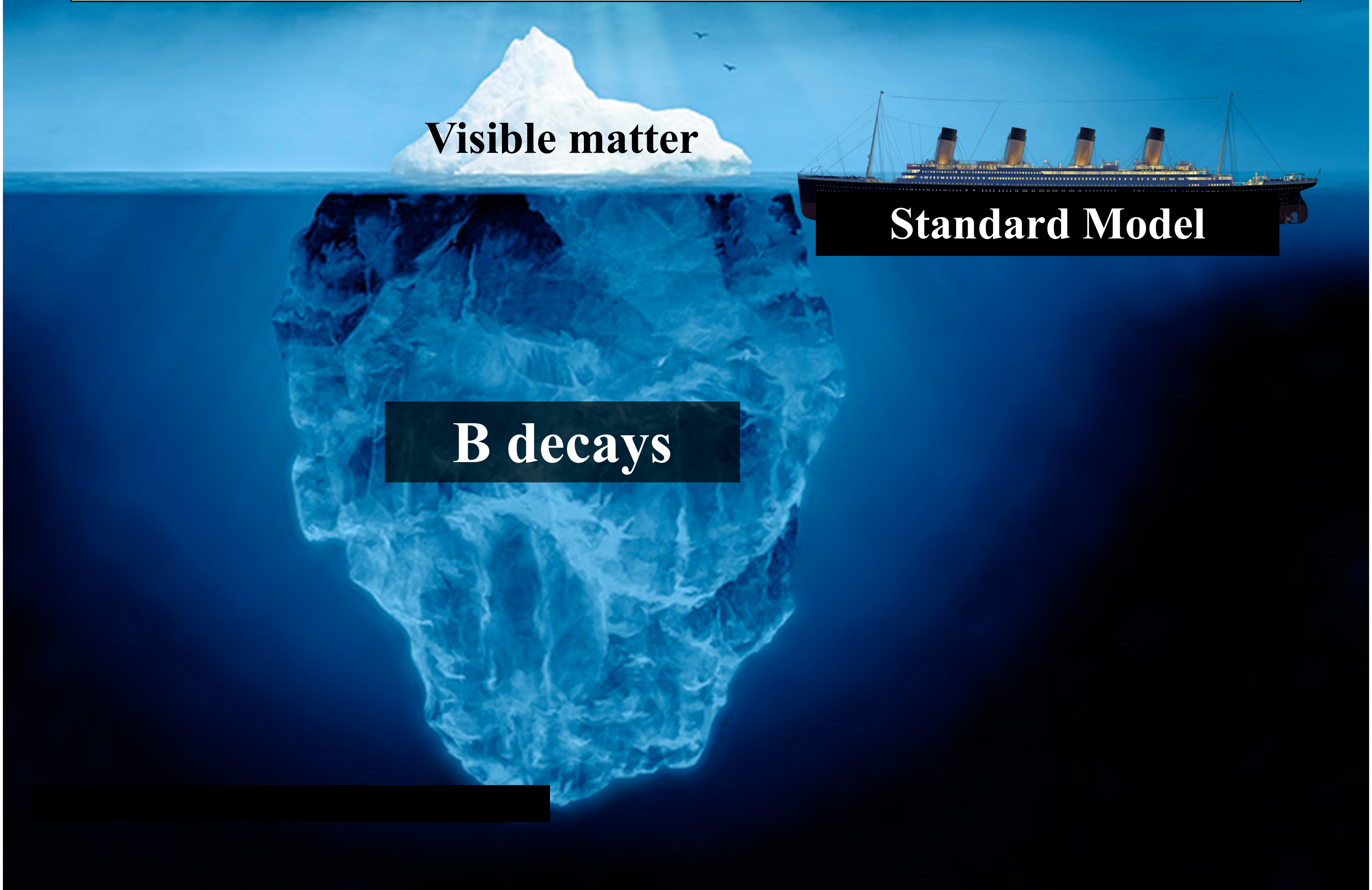
Possible Experimental Signatures

- 2 ‘dark’ SM-singlet fermions?
  - Decays of heavier mass eigenstate
  - Z’ coupling to muons not vector-like $\boxed{Y'_{\mu_V}/Y'_{\mu_A} = -3}$
  - Strong LHC dilepton constraint
  - No DM candidate with axial coupling
- If RH quark charges and one DM fermion?
  - Models with vector-like muon, axial Z’ DM couplings
  - Models without 1st/2nd generation couplings have weaker LHC constraints:

$\boxed{Y'_{\mu_V}/Y'_{\mu_A} = 7}$ $\boxed{Y'_{\mu_V}/Y'_{\mu_A} = -1}$

JE, Fairbairn & Tunney, arXiv:1705.03447

Summary



Visible matter

Standard Model

B decays

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