Beyond the Standard Model

Review of Higgs physics
Motivations for physics beyond the SM:
Higgs mysteries
Status of $g_\mu - 2$

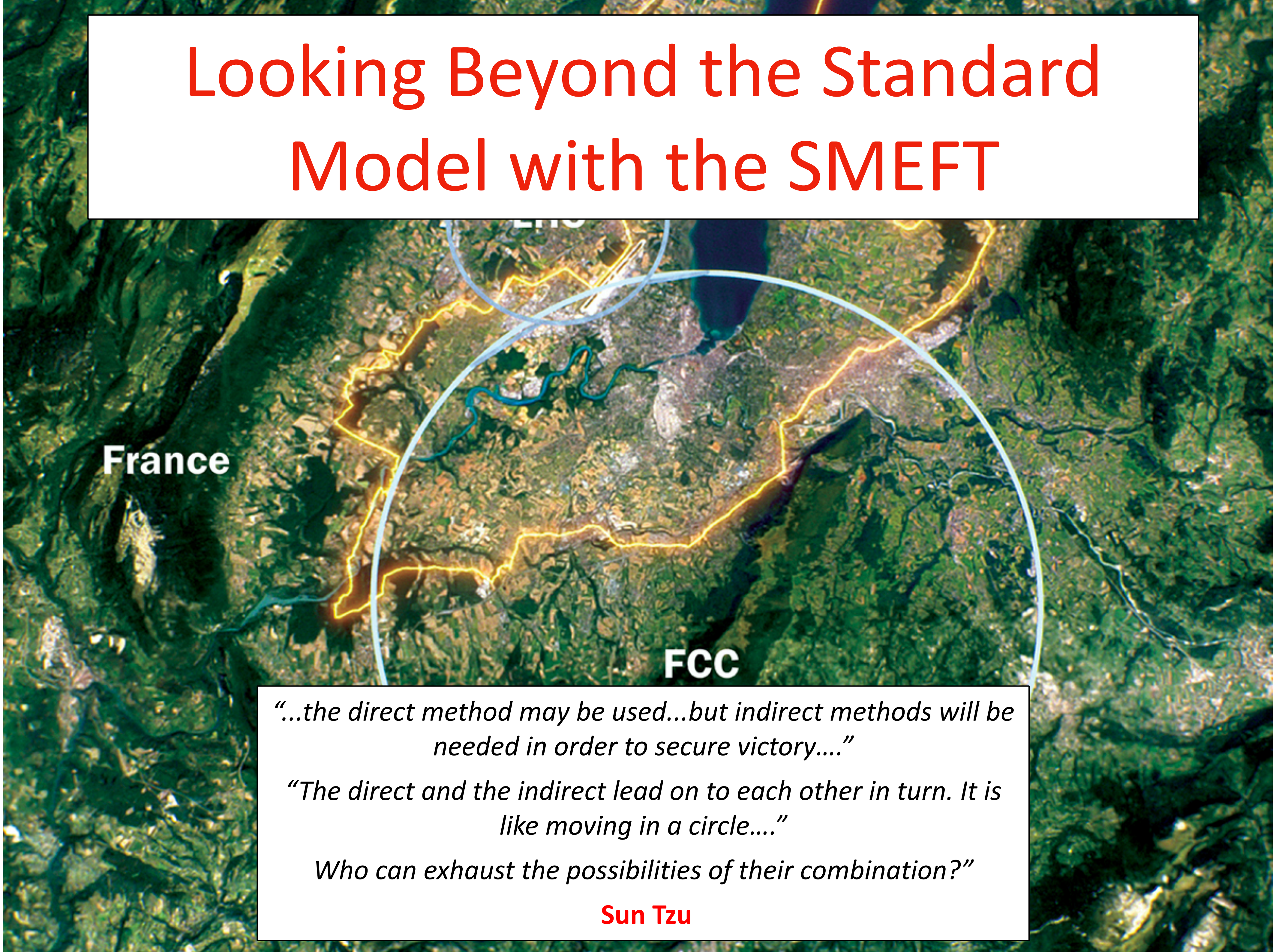
SM Effective Field Theory to scan for new physics
Dark matter: heavy fermions or light bosons?
New physics in gravitational waves?

YEARS /ANS CERN
1954-2024

John Ellis

KING'S College LONDON

Looking Beyond the Standard Model with the SMEFT



"...the direct method may be used...but indirect methods will be needed in order to secure victory...."

"The direct and the indirect lead on to each other in turn. It is like moving in a circle...."

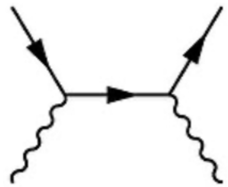
Who can exhaust the possibilities of their combination?"

Sun Tzu

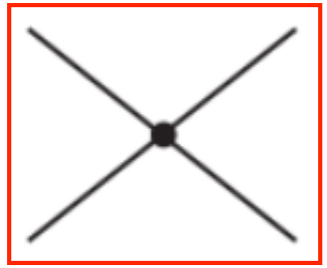
Effective Field Theories (EFTs)

a long and glorious History

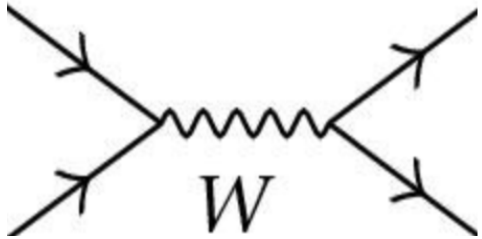
- 1930's: "Standard Model" of QED had d=4



- **Fermi's four-fermion theory of the weak force**

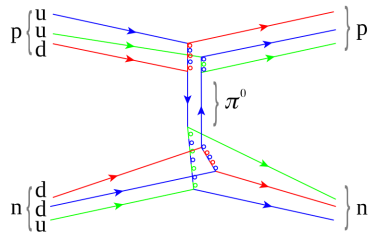


- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?



- V-A ➔ massive vector bosons ➔ gauge theory

- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? ➔ pions



- Chiral dynamics of pions: (∂π∂π)ππ clue ➔ QCD

A Note on Units and Dimensional Analysis

- Use "natural" units: Planck's constant, velocity of light = 1
- Count mass dimensions: [M] = 1 = [E] = [p] = [∂]
- Consistent with Lorentz invariance: $E^2 = p^2 + m^2$
- Quantum mechanics: [x] = [t] = -1
- Action $A = \int \mathcal{L} d^4x$ has [A] = 0, so [$\mathcal{L}$] = 4

$$\mathcal{L} \ni \partial\phi\partial\phi, \psi\partial\psi, F_{\mu\nu}F^{\mu\nu}$$

- So [ϕ] = 1, [ψ] = 3/2, [A_μ] = 1

Standard Model Effective Field Theory

a more powerful way to analyze the data

- Assume the Standard Model Lagrangian is correct (quantum numbers of particles) but incomplete
- Look for additional interactions between SM particles due to exchanges of heavier particles
- Analyze Higgs data together with electroweak precision data and top data
- Most efficient way to extract largest amount of information from LHC and other experiments
- **Model-independent way to look for physics beyond the Standard Model (BSM)**

Summary of Analysis Framework

- Include all leading dimension-6 operators?

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i=1}^{2499} \frac{C_i}{\Lambda^2} \mathcal{O}_i$$

- Simplify by assuming flavour $SU(3)^5$ or $SU(2)^2 \times SU(3)^3$ symmetry for fermions
- Work to linear order in operator coefficients, i.e. $\mathcal{O}(1/\Lambda^2)$
- Use G_F, M_Z, α as input parameters

Dimension-6 SMEFT Operators

- Including 2- and 4-fermion operators
- Different colours for different data sectors
- Grey cells violate $SU(3)^5$ symmetry
- Important when including top observables

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar{l}_p e_r H)$
$\mathcal{O}_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^\star(H^\dagger D_\mu H)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar{q}_p d_r H)$
$\mathcal{O}_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$		$\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$		$\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$		$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$		$\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

Anomalous magnetic moments

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

Flavour anomalies

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}^j_p \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}^k_s \sigma^{\mu\nu} u_t)$		

Baryon decay

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

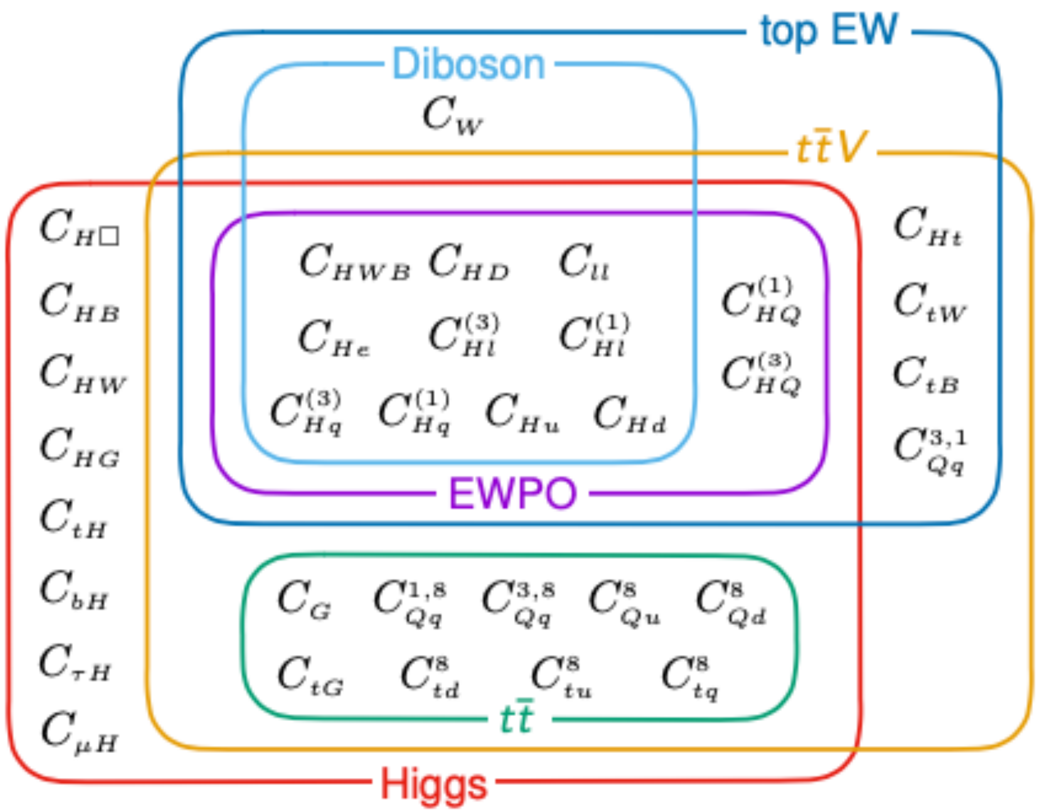
Global SMEFT Fit

to Top, Higgs, Diboson, Electroweak Data

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

- Global fit to dimension-6 operators using precision electroweak data, W^+W^- at LEP, top, Higgs and diboson data from LHC Runs 1, 2
- Search for BSM
- Constraints on BSM
  - At tree level
  - At loop level

341 measurements included in global analysis

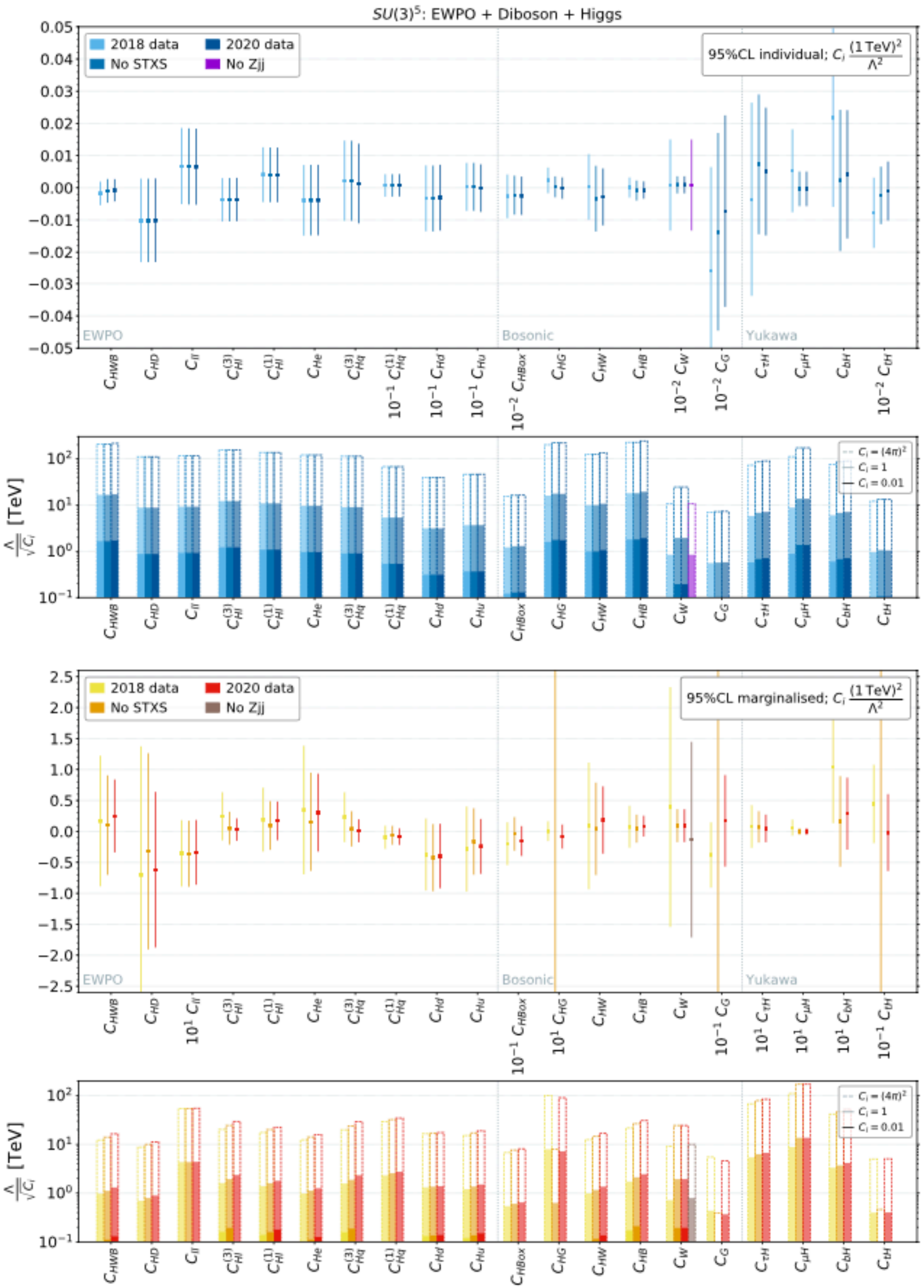


Dimension-6 Constraints with Flavour-Universal SU(3)^5 Symmetry

- **Individual operator coefficients**
- **Marginalised over all other operator coefficients**

No significant deviations from SM

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779



Single-Field Extensions of the Standard Model

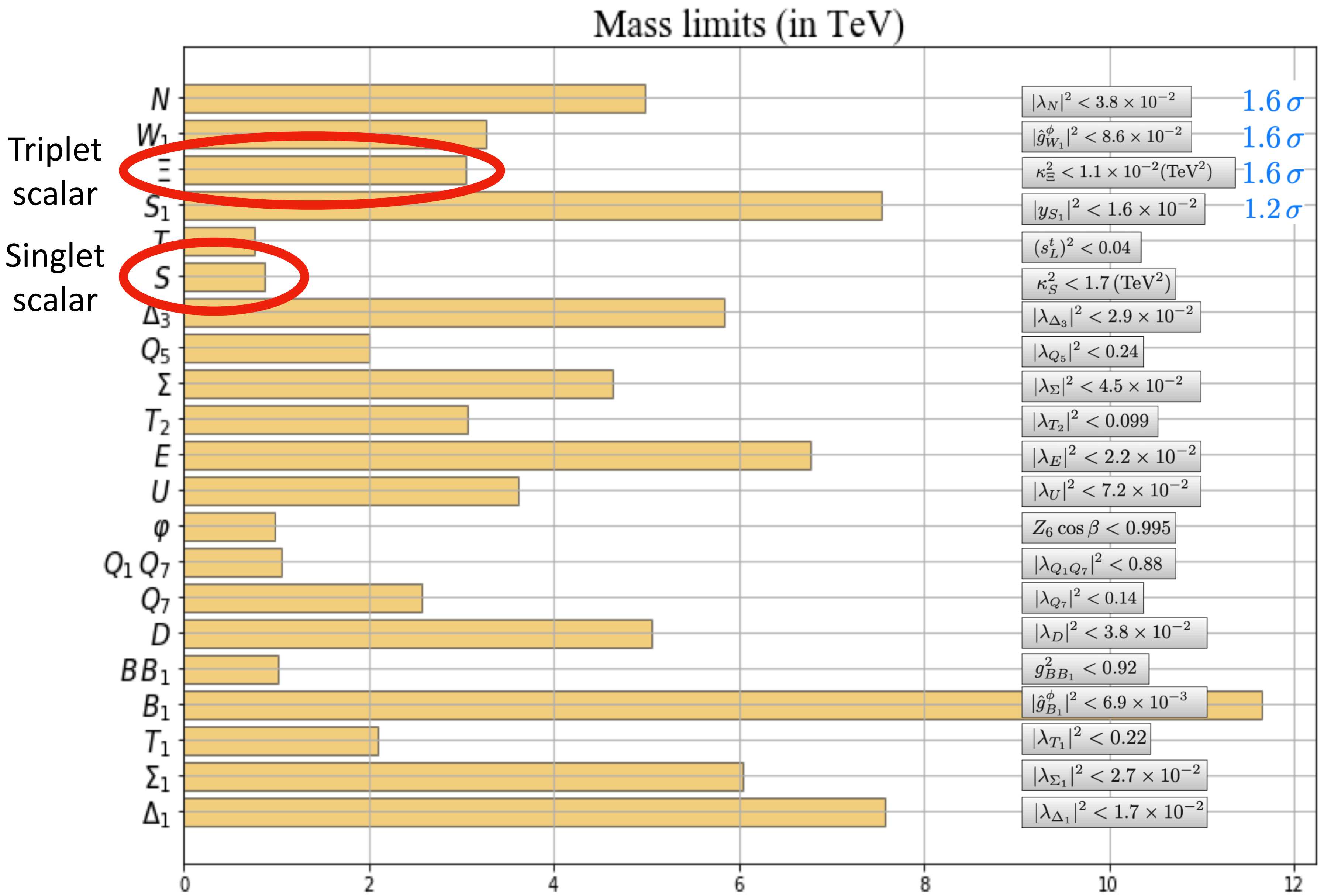
Name	Spin	SU(3)	SU(2)	U(1)	Name	Spin	SU(3)	SU(2)	U(1)
S	0	1	1	0	Δ_1	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
S_1	0	1	1	1	Δ_3	$\frac{1}{2}$	1	2	$-\frac{1}{2}$
φ	0	[illegible]	2	$\frac{1}{2}$	Σ	$\frac{1}{2}$	1	3	0
Ξ	0	1	3	0	Σ_1	$\frac{1}{2}$	1	3	-1
Ξ_1	0	1	3	1	U	$\frac{1}{2}$	3	1	$\frac{2}{3}$
B	1	1	1	0	D	$\frac{1}{2}$	3	1	$-\frac{1}{3}$
B_1	1	1	1	1	Q_1	$\frac{1}{2}$	3	2	$\frac{1}{6}$
W	1	1	3	0	Q_5	$\frac{1}{2}$	3	2	$-\frac{5}{6}$
W_1	1	1	3	1	Q_7	$\frac{1}{2}$	3	2	$\frac{7}{6}$
N	$\frac{1}{2}$	1	1	0	T_1	$\frac{1}{2}$	3	3	$-\frac{1}{3}$
E	$\frac{1}{2}$	1	1	-1	T_2	$\frac{1}{2}$	3	3	$\frac{2}{3}$
T	$\frac{1}{2}$	3	1	$\frac{2}{3}$	TB	$\frac{1}{2}$	3	2	$\frac{1}{6}$

Spin zero

Vector

JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

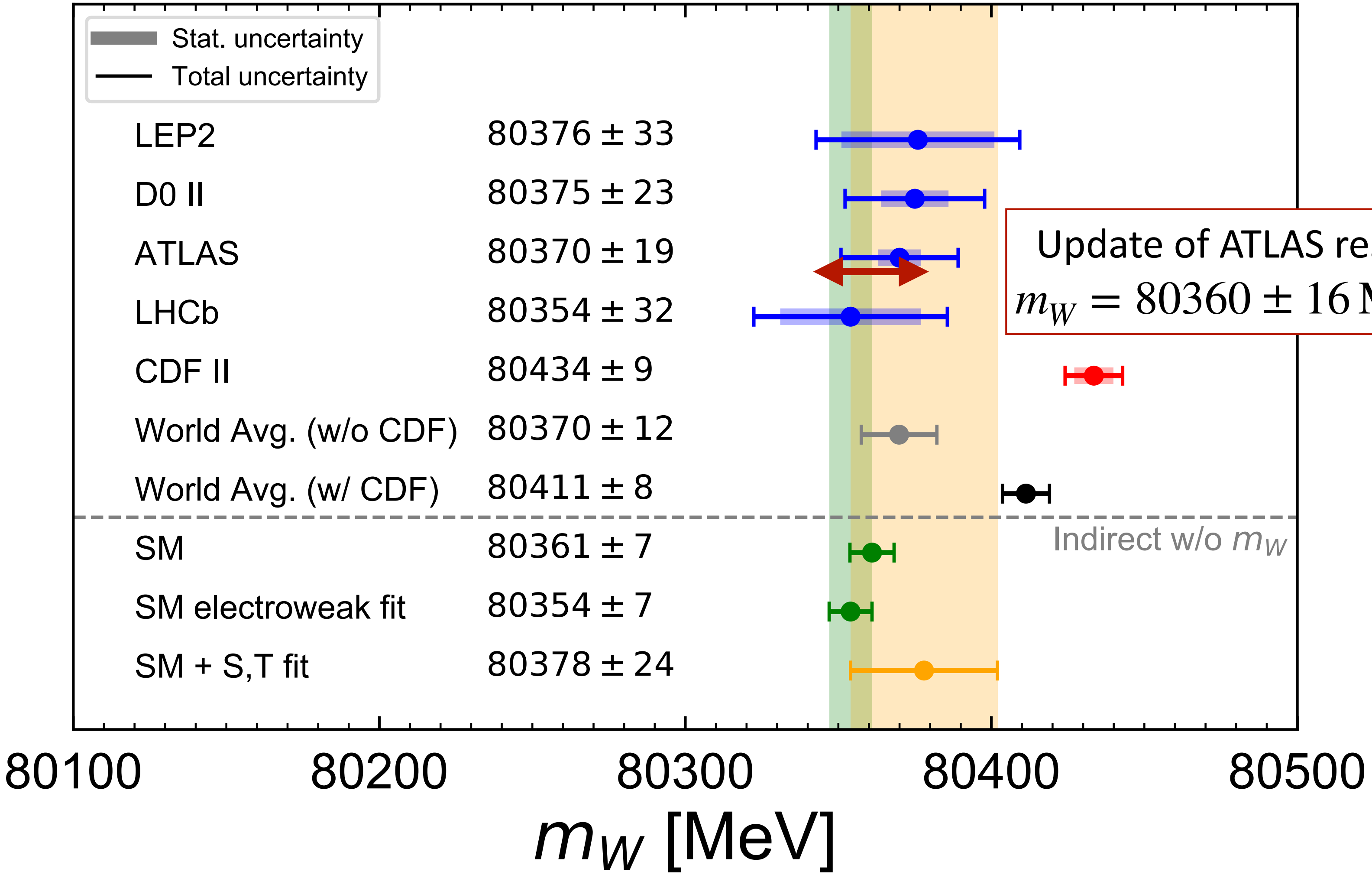
Single-Field Extensions of the Standard Model



JE, Madigan, Mimasu, Sanz & You, arXiv:2012.02779

CDF Measurement of m_W

compared with other measurements



Update of ATLAS result
$m_W = 80360 \pm 16\,\mathrm{MeV}$

Tension: 7-σ discrepancy with Standard Model?

SMEFT Operators that can Contribute to W Mass

- Relevant SMEFT operators

$$\mathcal{O}_{HWB} \equiv H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}, \quad \mathcal{O}_{HD} \equiv \left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$$

$$\mathcal{O}_{\ell\ell} \equiv \left(\bar{\ell}_p \gamma_\mu \ell_r\right)\left(\bar{\ell}_s \gamma^\mu \ell_t\right), \quad \mathcal{O}^{(3)}_{H\ell} \equiv \left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{\ell}_p \tau^I \gamma^\mu \ell_r\right)$$

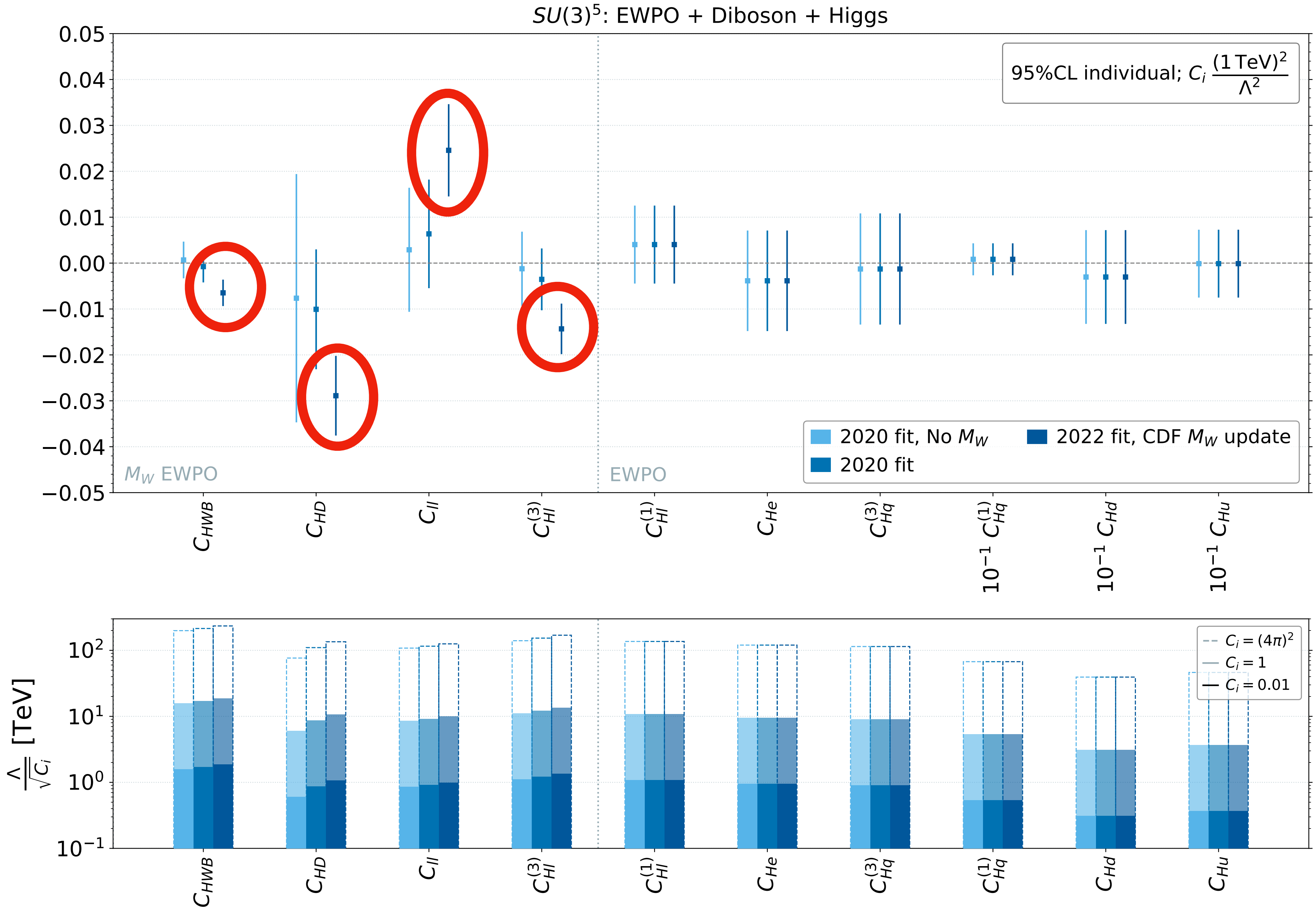
- Contributions to W mass

$$\frac{\delta m_W^2}{m_W^2} = -\frac{\sin 2\theta_w}{\cos 2\theta_w}\frac{v^2}{4\Lambda^2}\left(\frac{\cos\theta_w}{\sin\theta_w} C_{HD} + \frac{\sin\theta_w}{\cos\theta_w}\left(4C^{(3)}_{Hl} - 2C_{ll}\right) + 4C_{HWB}\right)$$

- Contributions to *S* and *T* oblique parameters

$$\frac{v^2}{\Lambda^2} C_{HWB} = \frac{g_1 g_2}{16\pi} S \quad , \quad \frac{v^2}{\Lambda^2} C_{HD} = -\frac{g_1 g_2}{2\pi(g_1^2 + g_2^2)} T$$

SMEFT Fit with the Mass of the W Boson



Non-zero coefficients for any of four operators can fit W mass

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Single-Field Models that can Contribute to W Mass

Model	C_{HD}	C_{ll}	$C_{Hl}^{(3)}$	$C_{Hl}^{(1)}$	C_{He}	$C_{H\square}$	$C_{\tau H}$	C_{tH}	C_{bH}
S_1		X							
Σ			X	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			X	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	X					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	X					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$

Wrong sign

Right sign

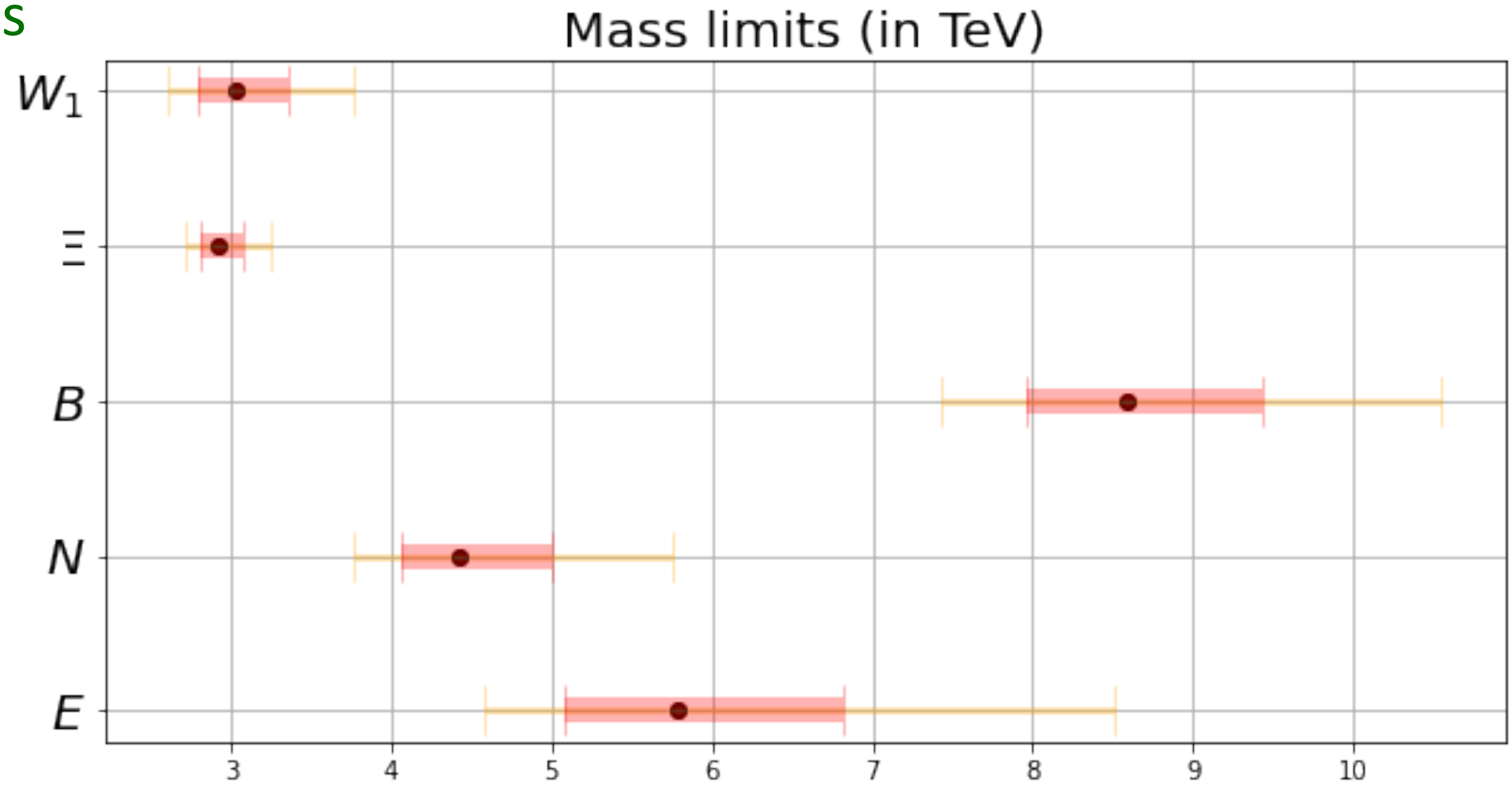
Operators contributing to m_W

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Models Fitting the Mass of the W Boson

Spins

V
S
V
F
F



68 and 95% CL ranges of masses assuming unit couplings, mass range proportional to coupling

Bagnaschi, JE, Madigan, Mimasu, Sanz & You, arXiv:2204.05260

Beyond Dimension-6:

Dimension-8 Operators

- Dimension-8 contributions scaled by quartic power of new physics scale:

$$\Delta\mathcal{L}(\text{dim-8}) = \sum_j \frac{\tilde{c}_j}{\tilde{\Lambda}^4}\mathcal{O}_j = \sum_j \frac{\text{sign}(\tilde{c}_j)}{\Lambda_j^4}\mathcal{O}_j$$

- Include dimension-8 as well as -6 in data analysis, check convergence

JE, Mimasu & Zampedri, arXiv:2304.06663

- Study processes without dimension-6 contributions,

e.g., light-by-light scattering, $gg \to \gamma\gamma, Z\gamma, \ldots$

JE, Mavromatos & You, arXiv:1703.08450

JE, Mavromatos, Roloff & You, arXiv:2203.17311

JE & Ge, arXiv:1802.02146

JE, Ge & Ma, arXiv:2112.06729

- Neutral triple-gauge couplings (nTGCs): $\gamma\gamma^*Z, \gamma ZZ^*$

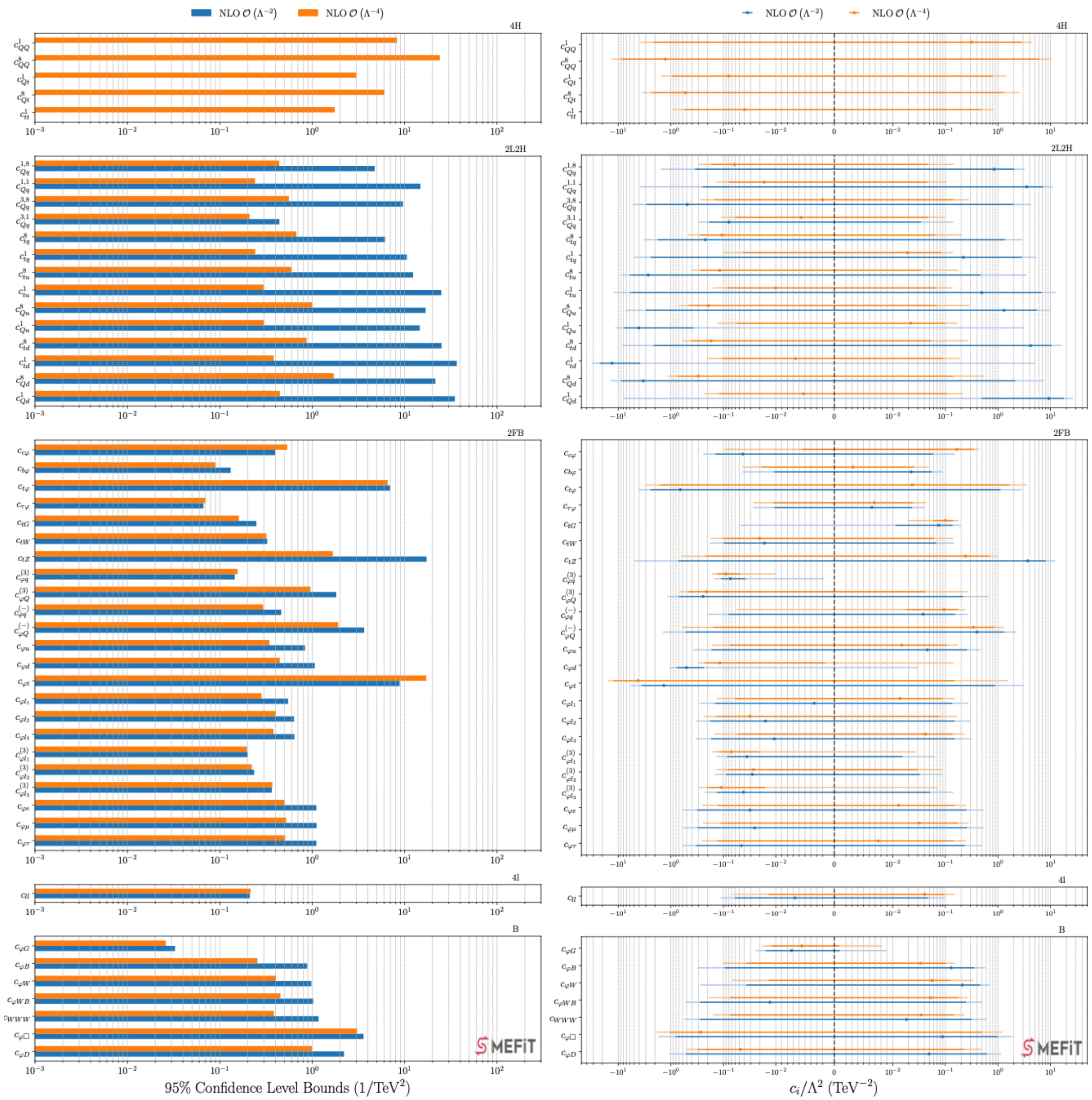
JE, Ge, He & Xiao, arXiv:1902.06631

JE, He & Xiao, arXiv:2008.04298

JE, He & Xiao, arXiv:2206.11676

Liu, Xiao, Li, JE, He, Yuan, arXiv:2404:15937

SMEFiT Analysis



- Includes linear dimension-8 as well as quadratic dimension-6
- No significant evidence for non-zero operator coefficients
- Experiments, please enter the game!

Celada et al, arXiv:2004.12809

Quo Vadis SMEFT?

- Powerful framework for global analyses of LHC and other data
- Systematic way to search for BSM physics
- Can be used in principle to identify "interesting" BSM scenarios
- Dimension-6 operators are a first approximation
- Important to check lesser importance of dimension-8, convergence towards ultraviolet-complete model
- Interesting direct windows on dimension-8 operators

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?**

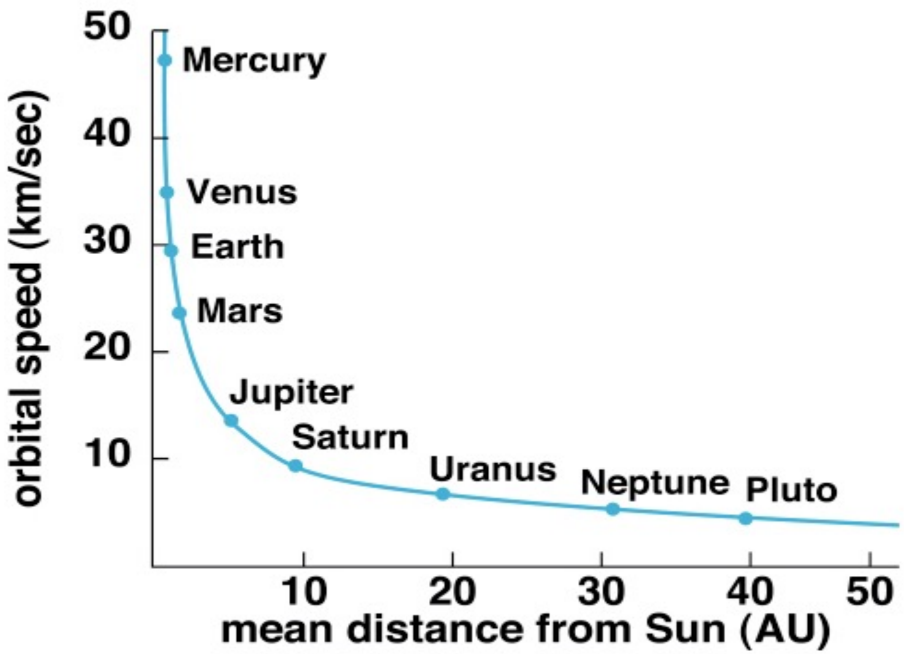
The Rotation Curves of Galaxies

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

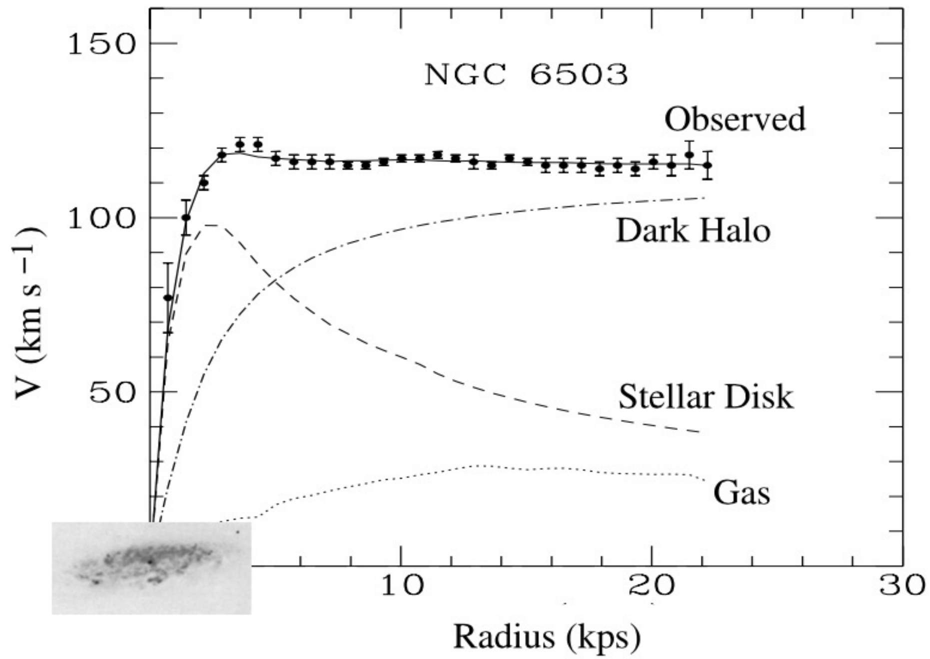
- **Further strong evidence for dark matter**
- Also:
  – Structure formation, cosmic background radiation, …

Galactic Rotation Curves

- In the Solar System



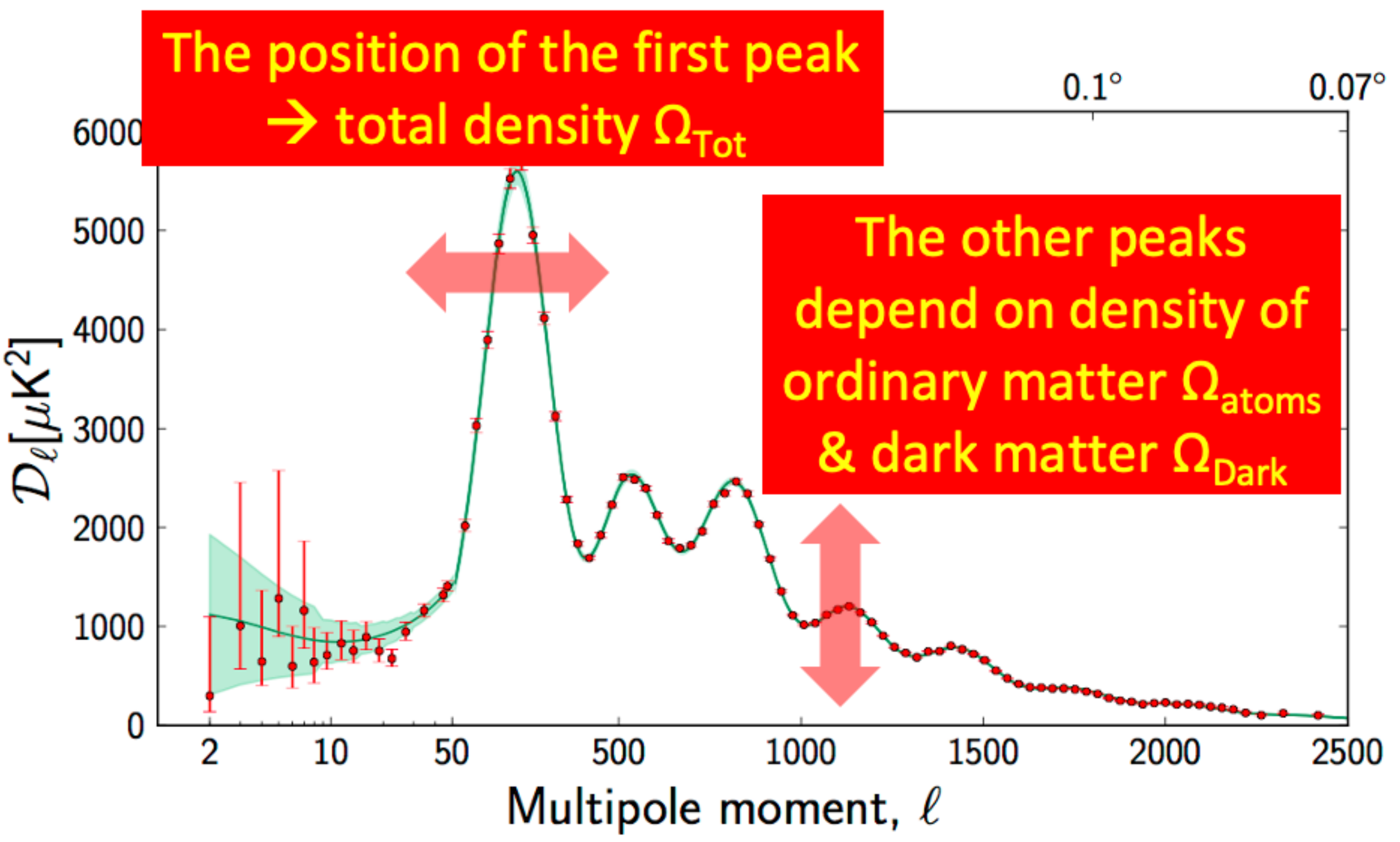
- In galaxies



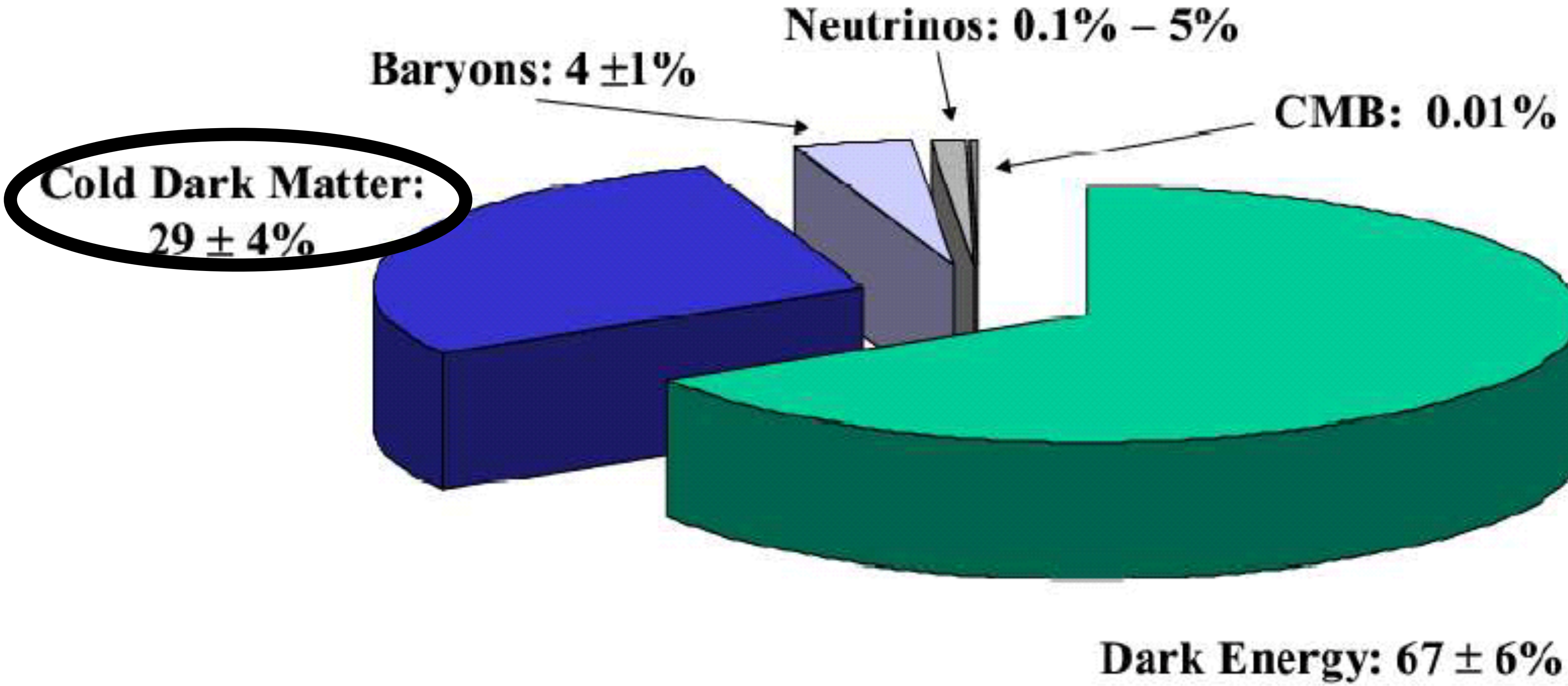
- The velocities decrease with distance from Sun
- The velocities do not decrease with distance

- Mass lumped at centre
- Dark matter spread out

The Spectrum of Fluctuations in the Cosmic Microwave Background



Strange Recipe for a Universe



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

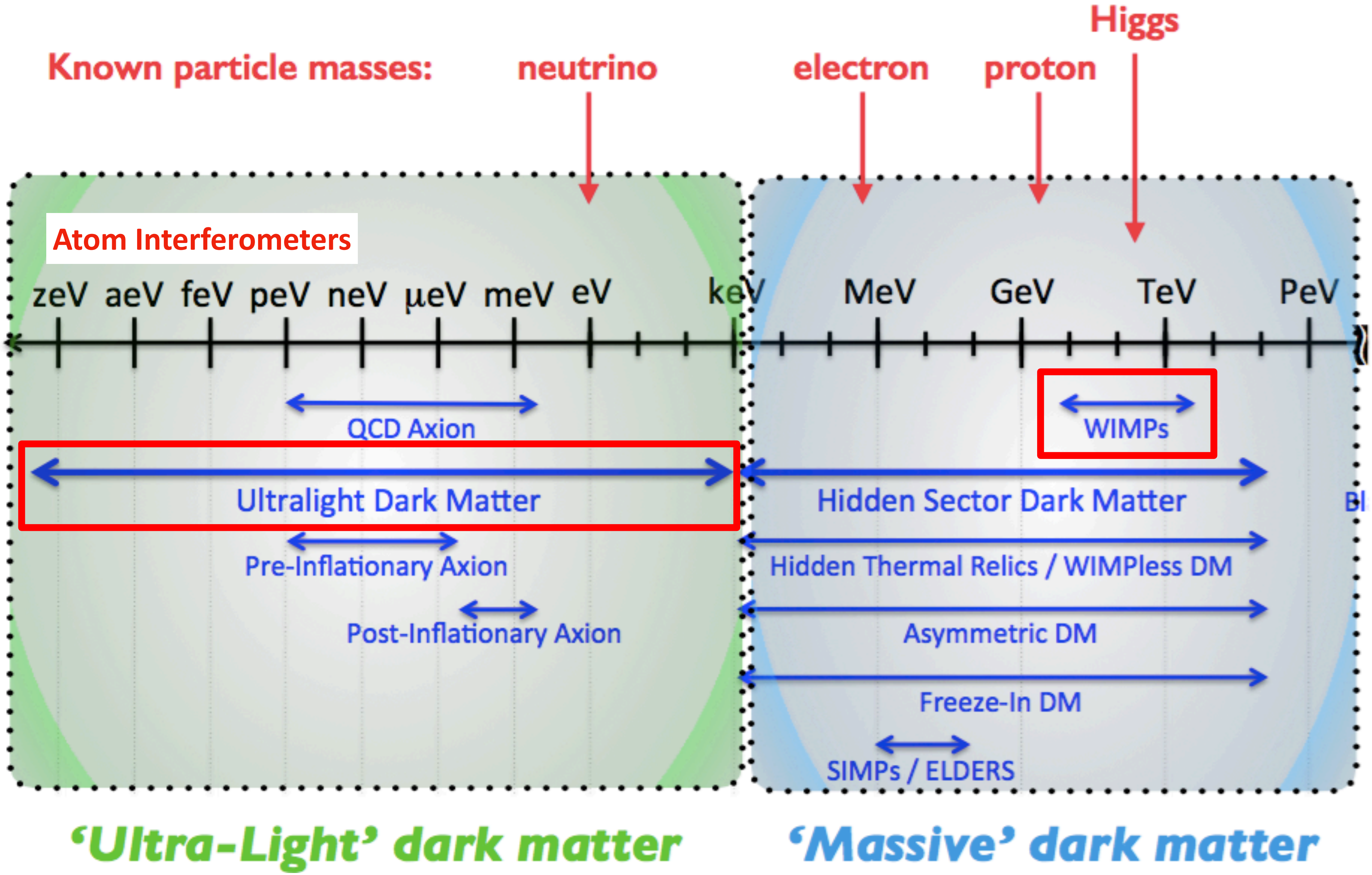
Properties of Dark Matter

- 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 be non-relativistic
  - Needed for forming and holding together structures in the Universe: galaxies, clusters, …

Neutrinos

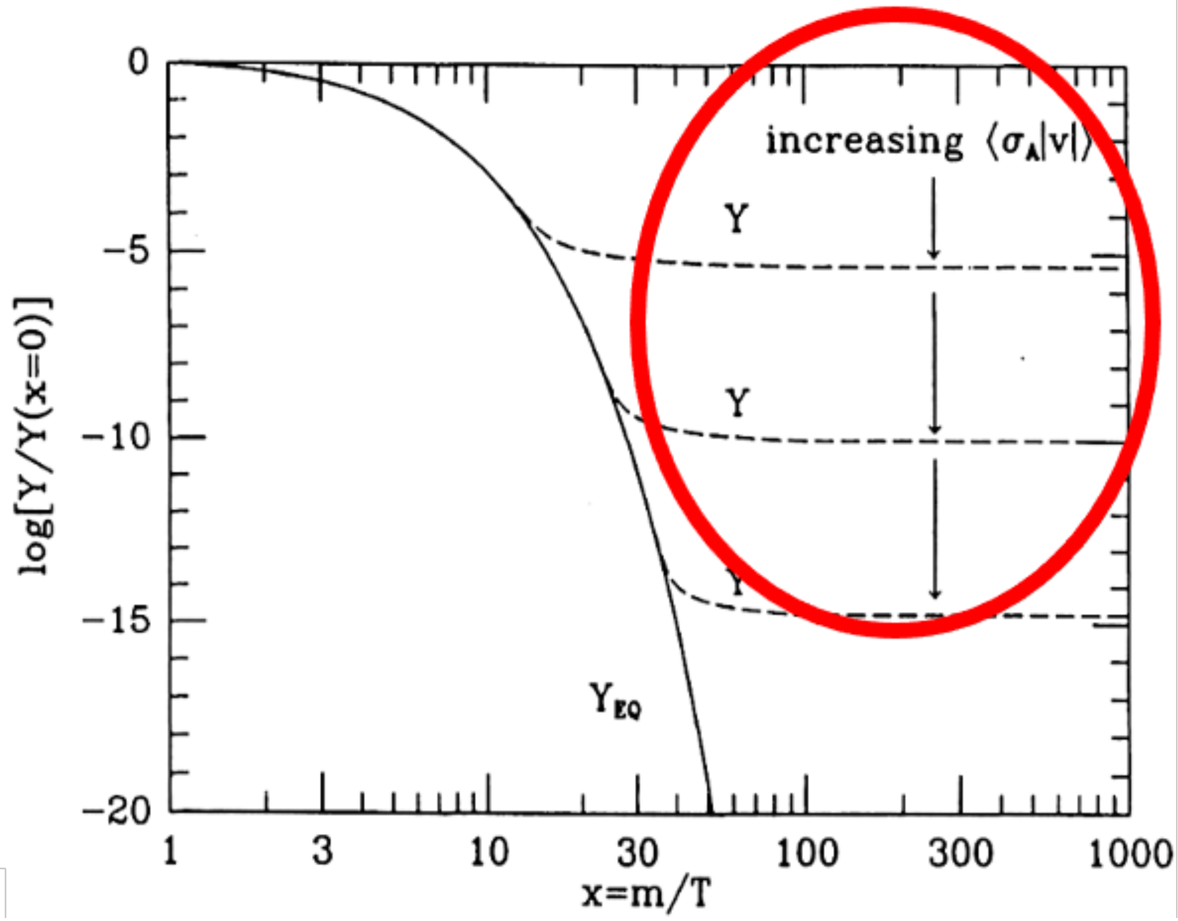
- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe some other neutrinos beyond the Standard Model? **Sterile neutrinos?**

BSM Candidates for 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



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**

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

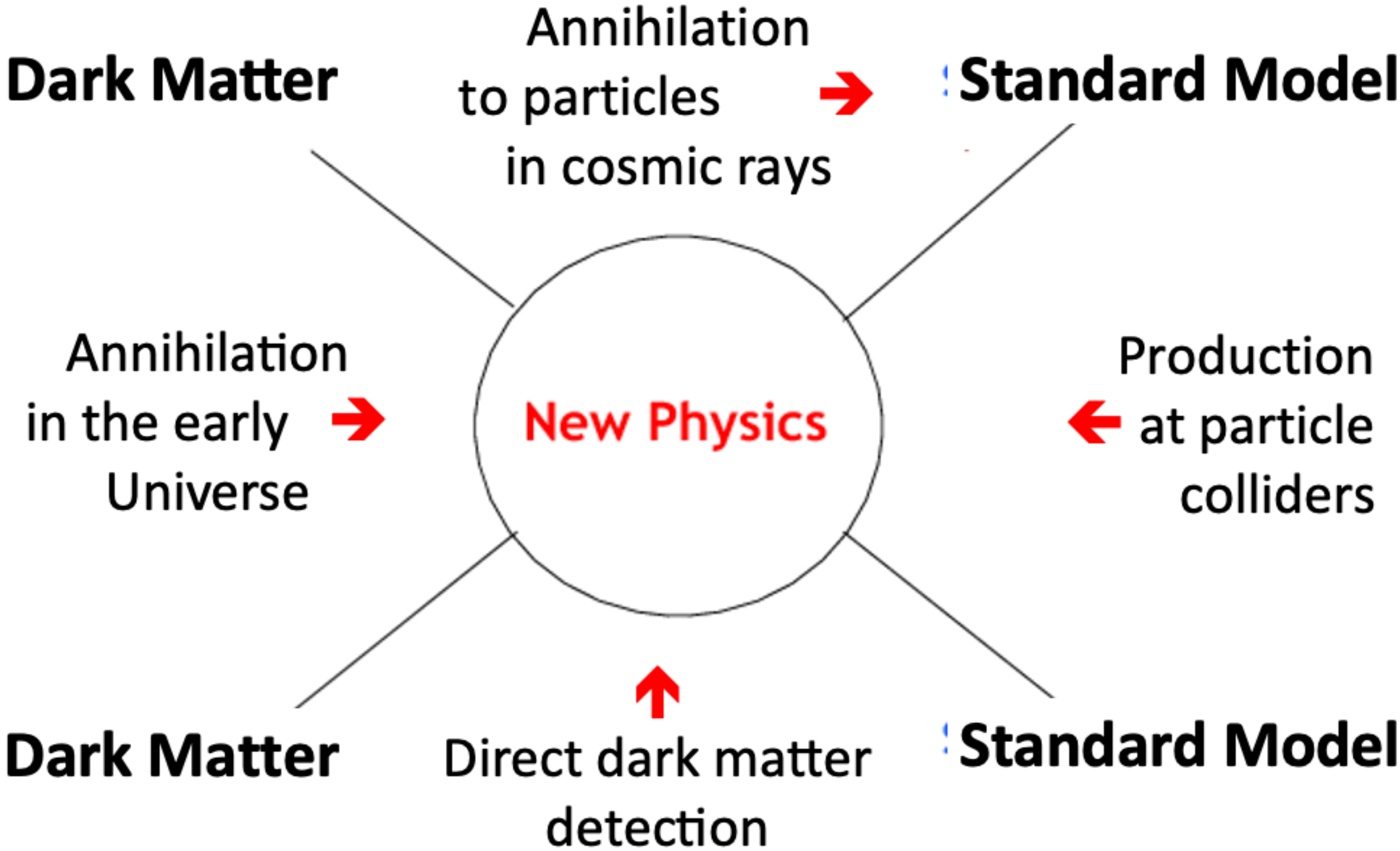
  (Excluded by LEP, direct searches)

  Lightest neutralino χ (partner of Z, H, γ)

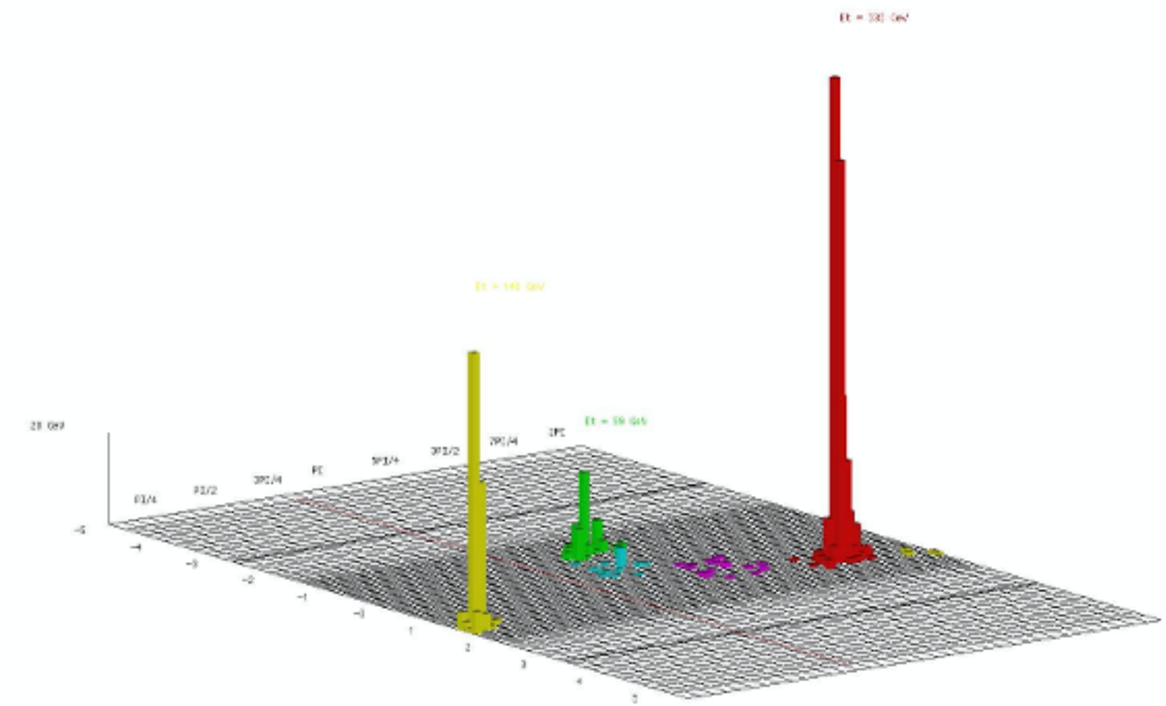
  Gravitino

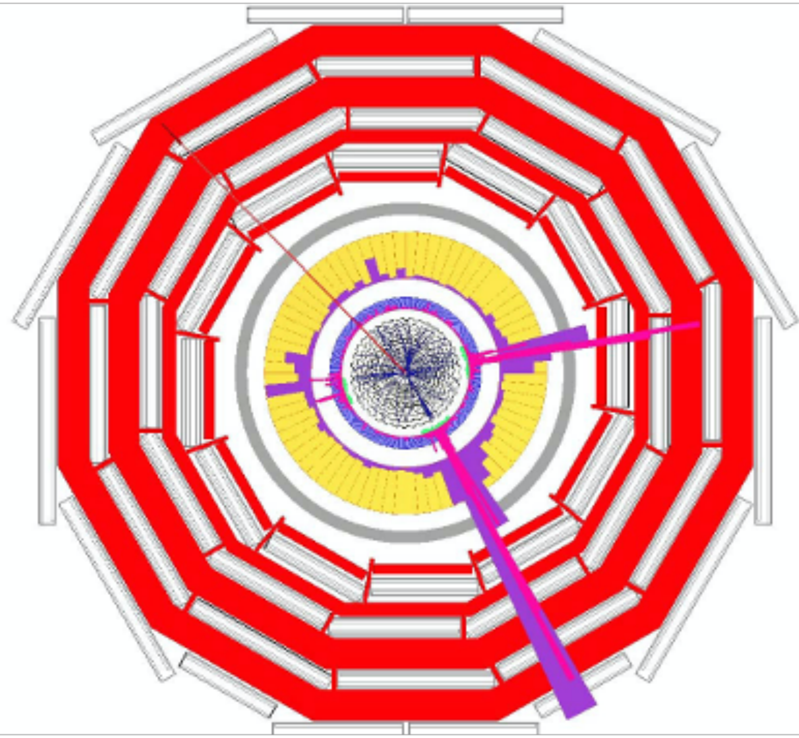
  (nightmare for detection)

Searches for WIMP Dark Matter



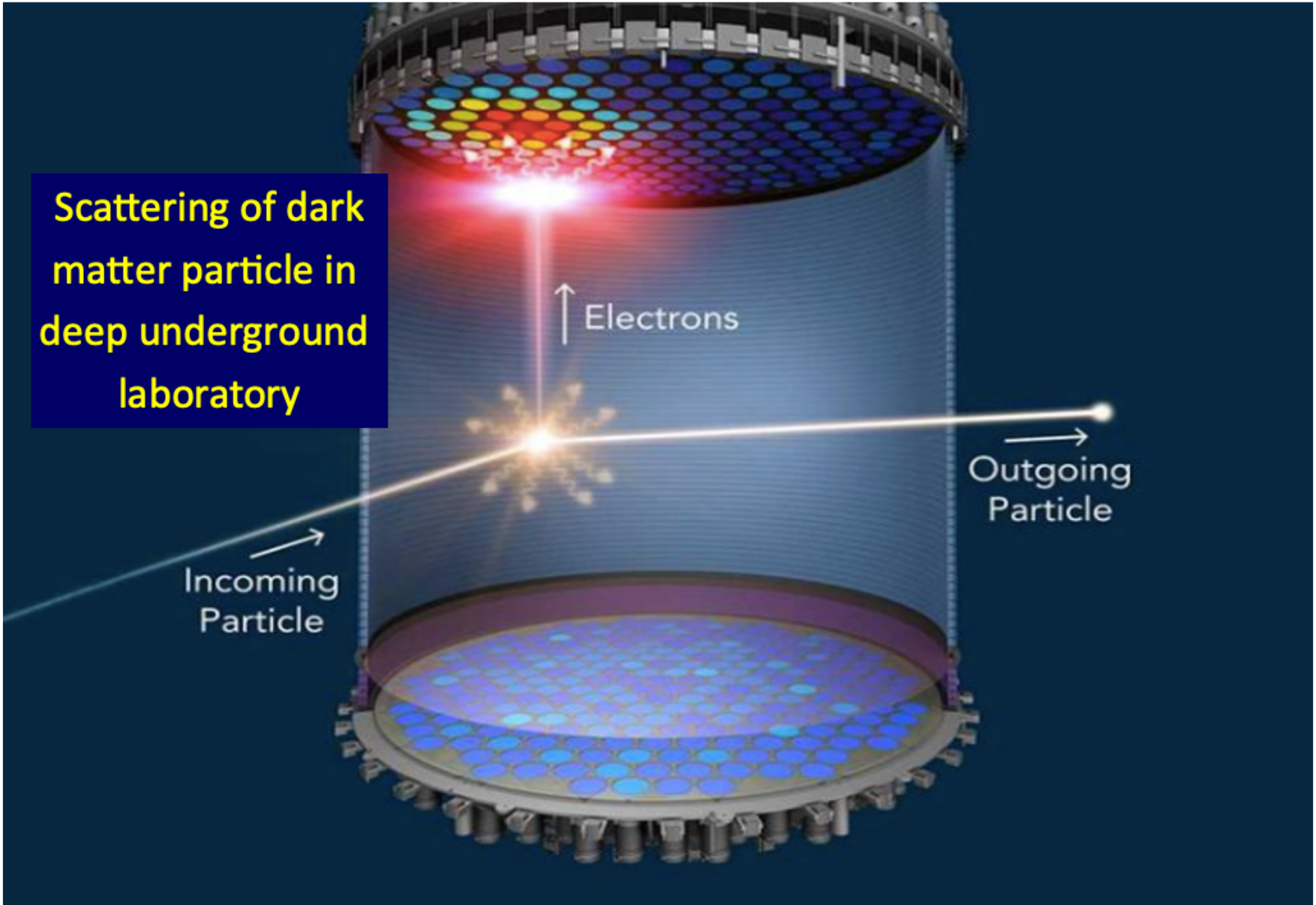
Classic Dark Matter Signature





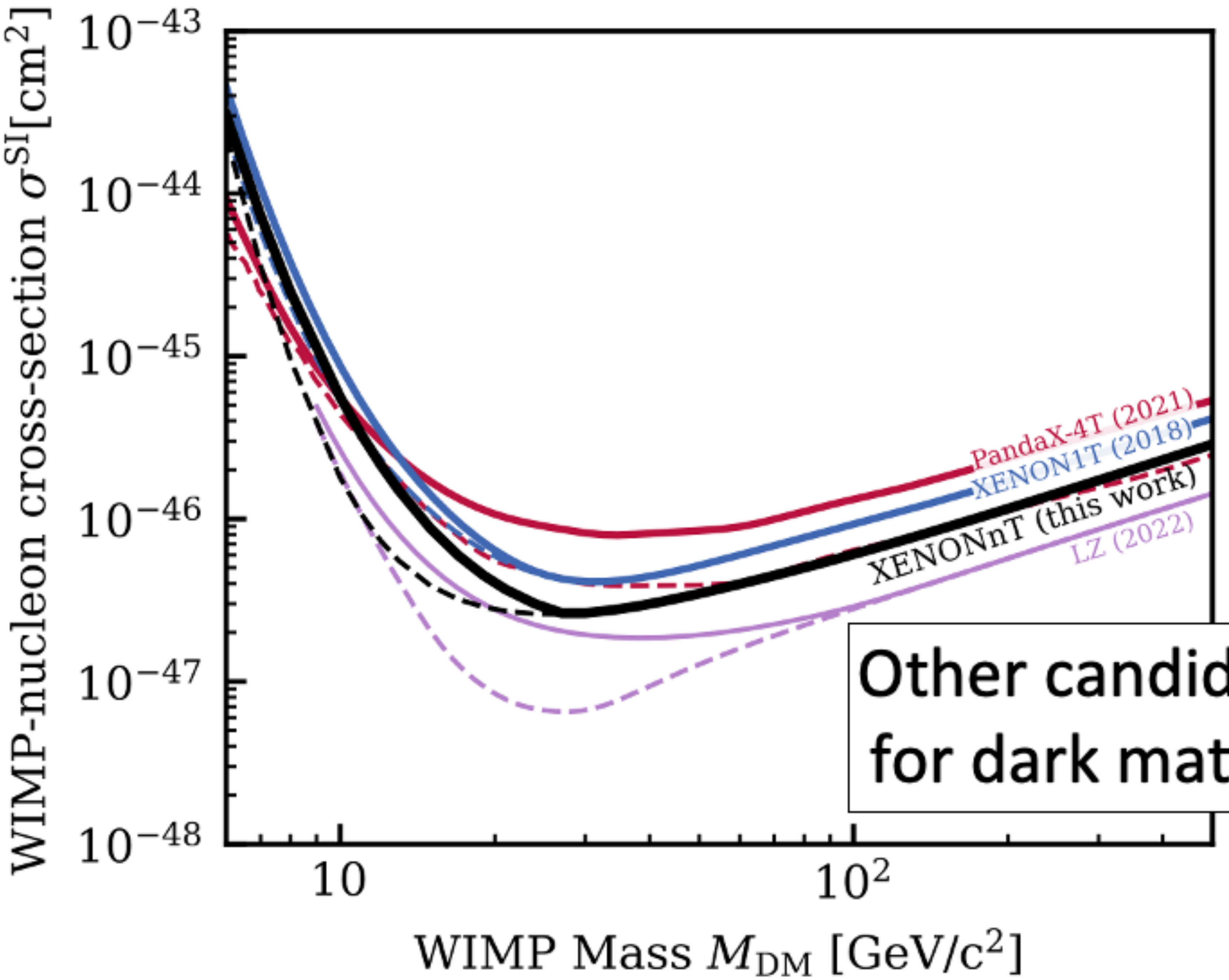
Missing transverse energy carried away by dark matter particles

Direct Dark Matter Detection



Direct Dark Matter Searches

Latest experimental results

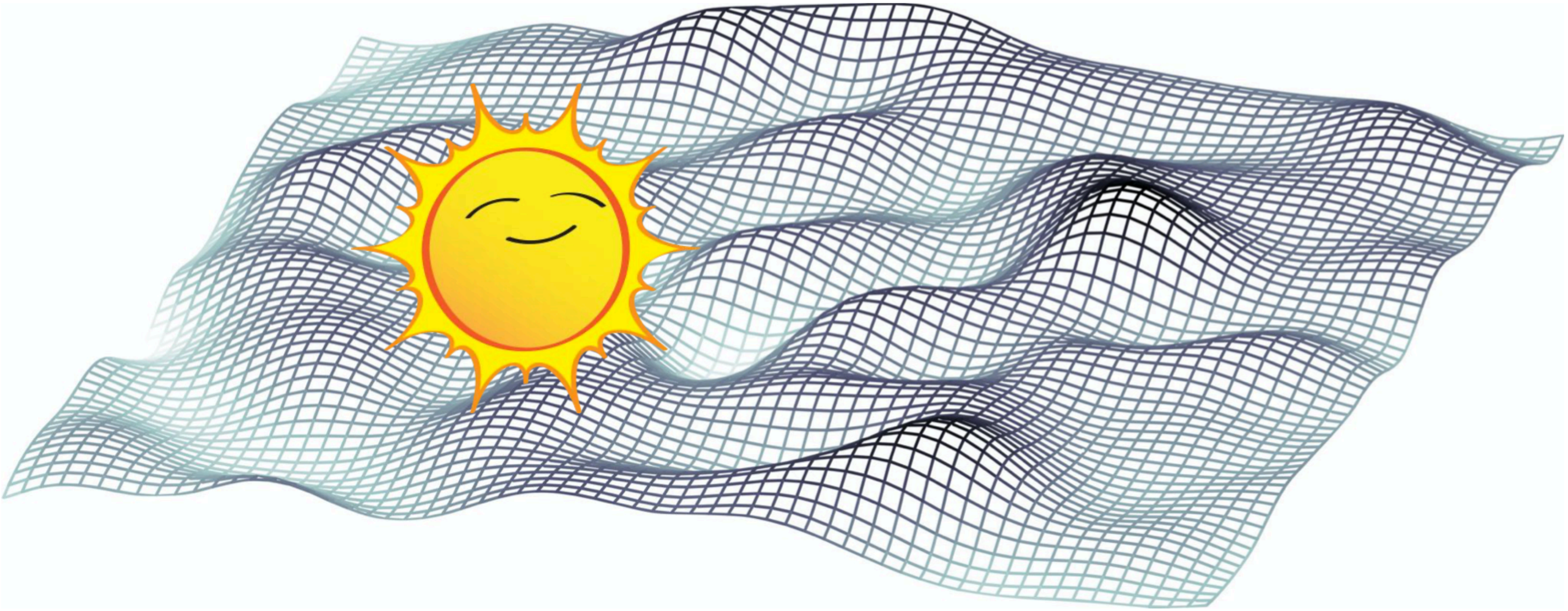


Other candidates for dark matter?

AION

Ultralight Dark Matter

A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System

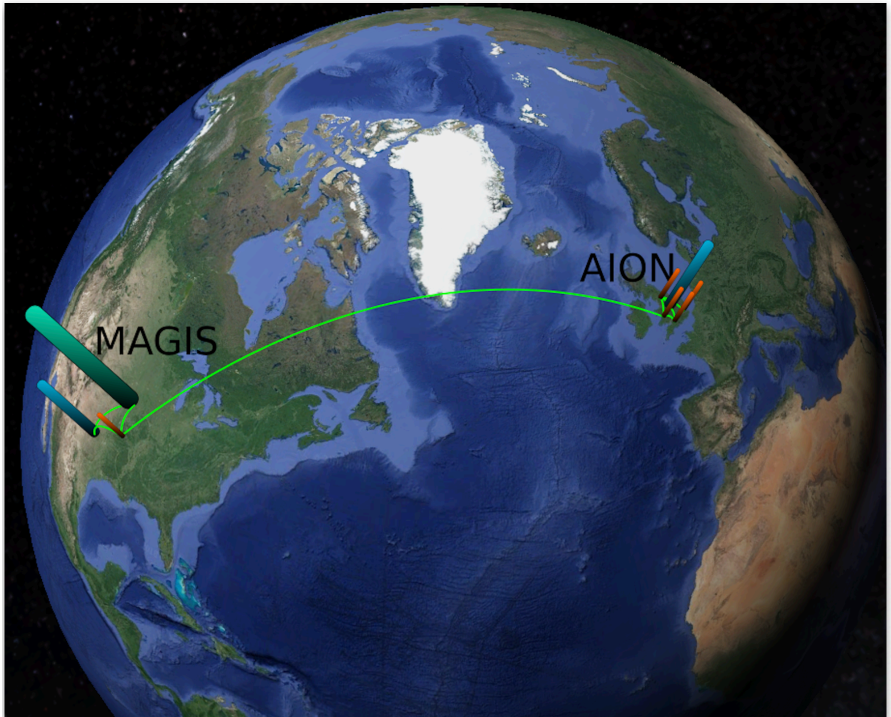


The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentin[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1]
D. Bortol[illegible], [illegible]owcock[5], W. Bowden[6,*], C. Brew[illegible], O. Buchmueller[6], J. Colema[illegible], J. Carlton
G. Elertas[illegible], J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
M. Holynski[illegible], A. Khazov[2], M. Langlois[4], S. [illegible][4], Y.H. Lien[4], R. Maiolino[7],
P. Majewski[2], S. Malik[6], J. March-Russell[illegible], C. McCabe[illegible], D. Newbold[2], R. Preece[3],
B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. [illegible], M. Tarbutt[6], M. A. Uchida[7],
T. V-Salazar[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7],
J. Zielinska[6]

[1]Kings College London, [2]STFC Rutherford Appleton Laboratory, [3]University of Oxford, [4]University of Birmingham, [5]University of Liverpool, [6]Imperial College London, [7]University of Cambridge

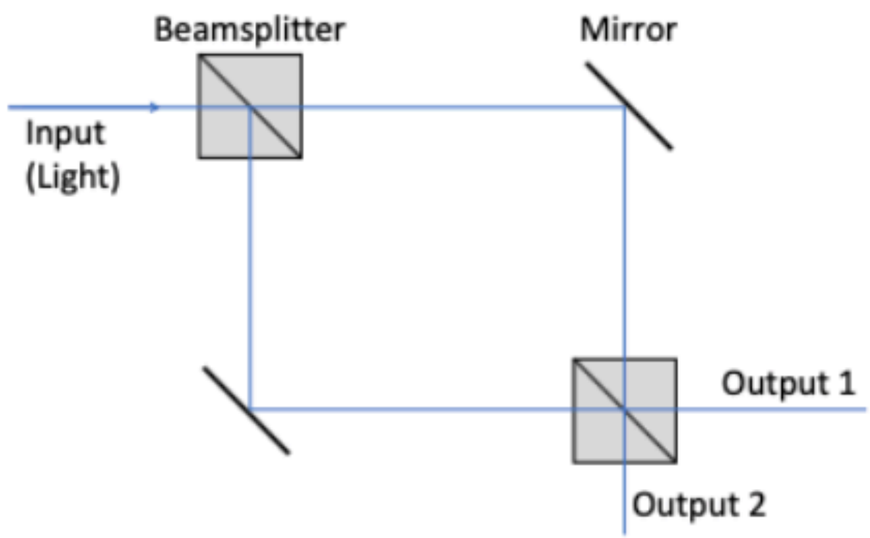


Network with MAGIS project in US

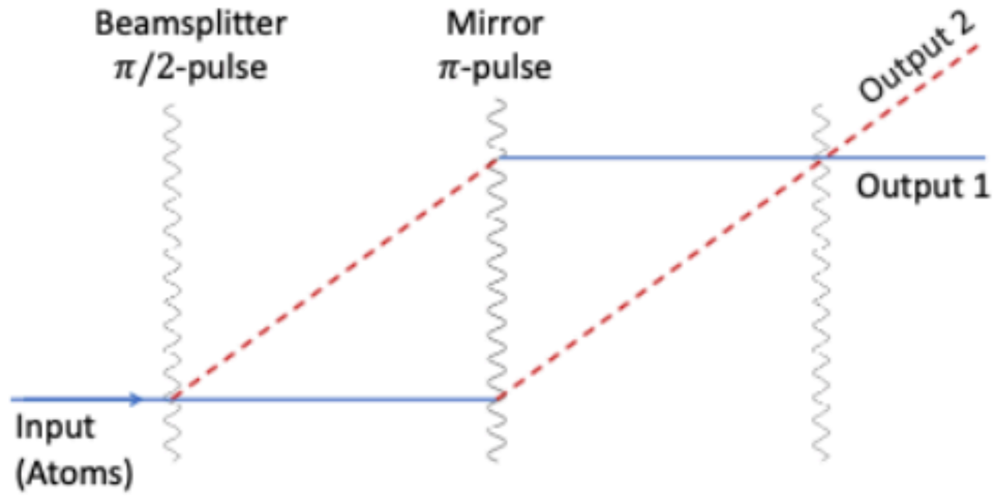
MAGIS Collaboration (Abe et al): arXiv:2104.02835

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

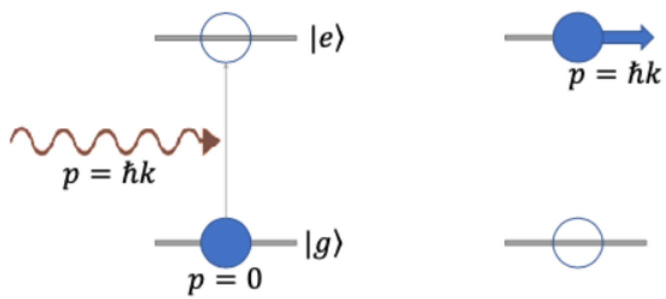


Atom Interferometer

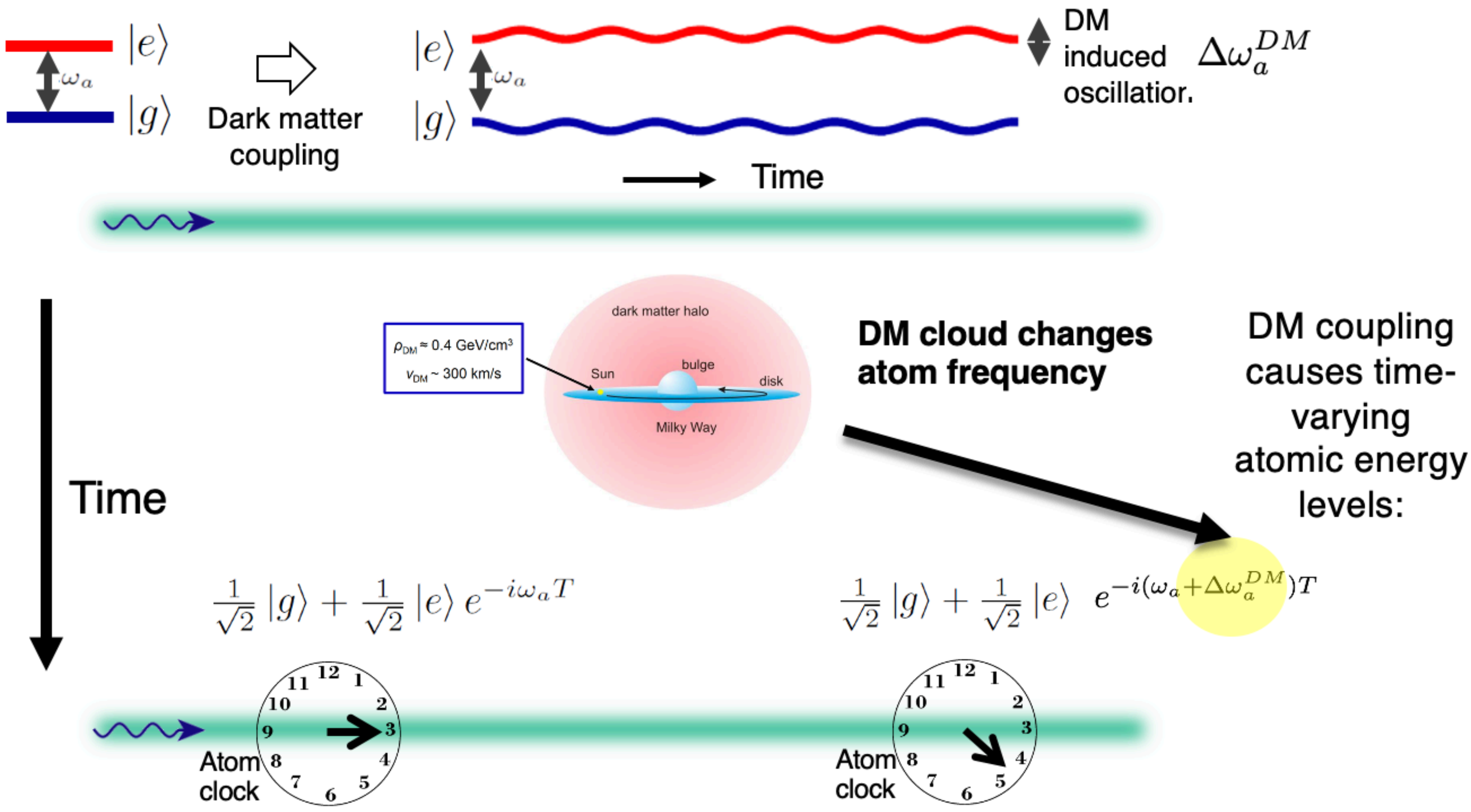


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

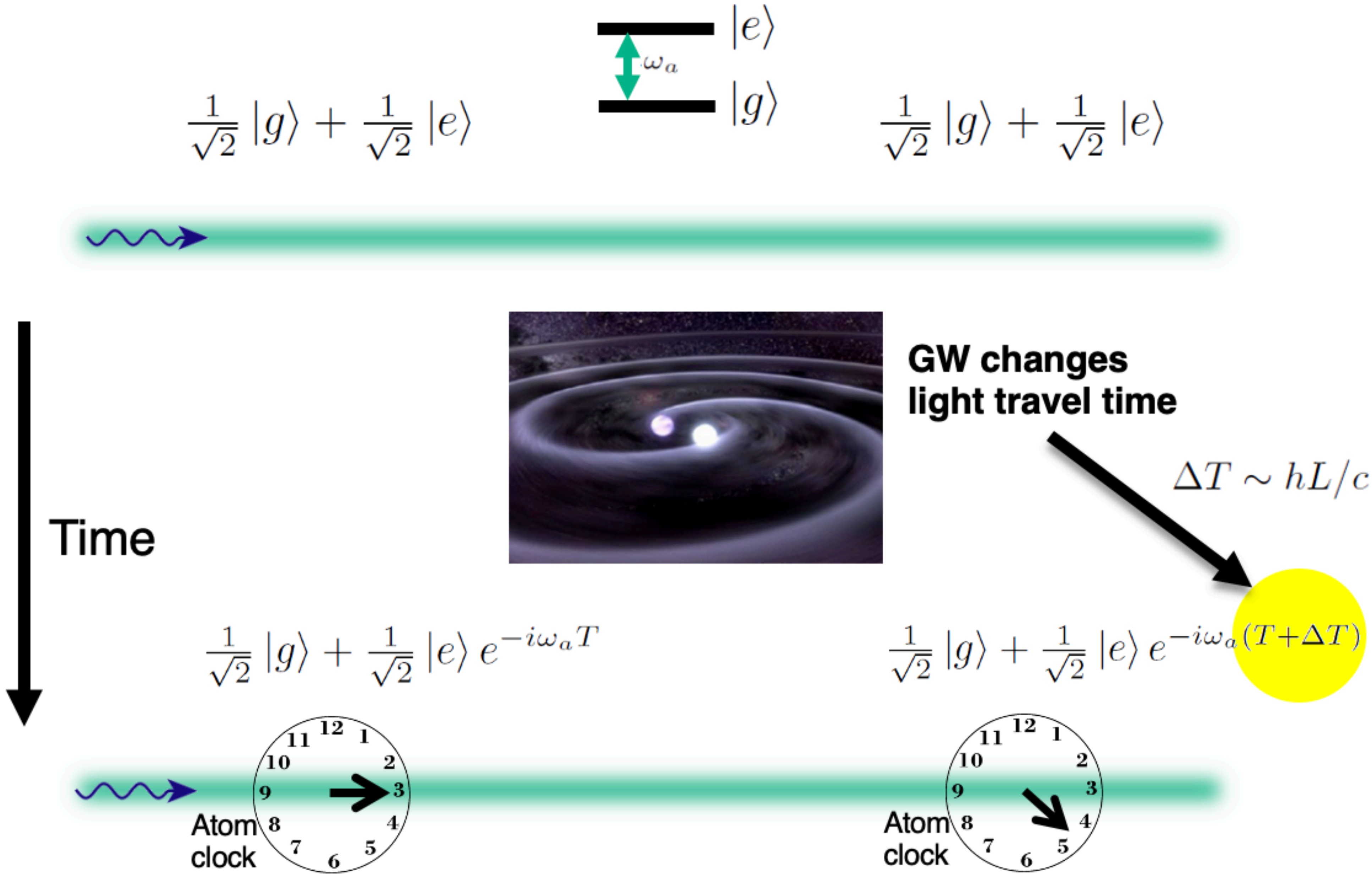
Interference between atoms following different paths



Effect of Dark Matter on Atom Interferometer



Effect of Gravitational Wave on Atom Interferometer



AION

AION – Proposed Programme

- AION-10: Stage 1 [year 1 to 3]
  - 1 & 10 m Interferometers & site investigation for 100m baseline

Oxford

Initial funding from UK STFC

- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning

Boulby? CERN?

- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4
  - Space-based version

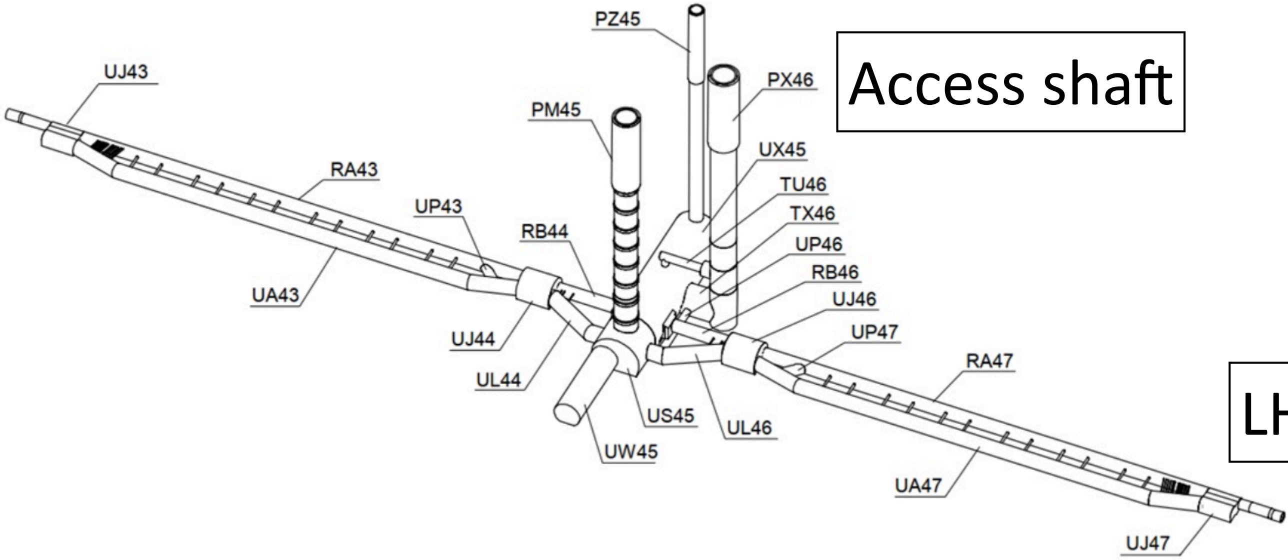
AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

AION

Possible CERN Location

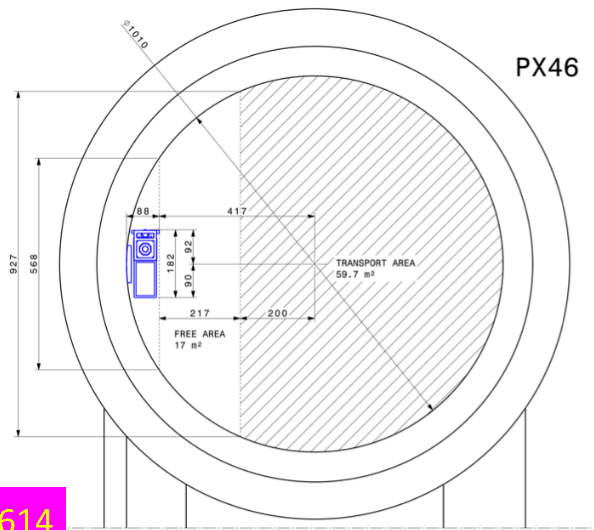
LHC

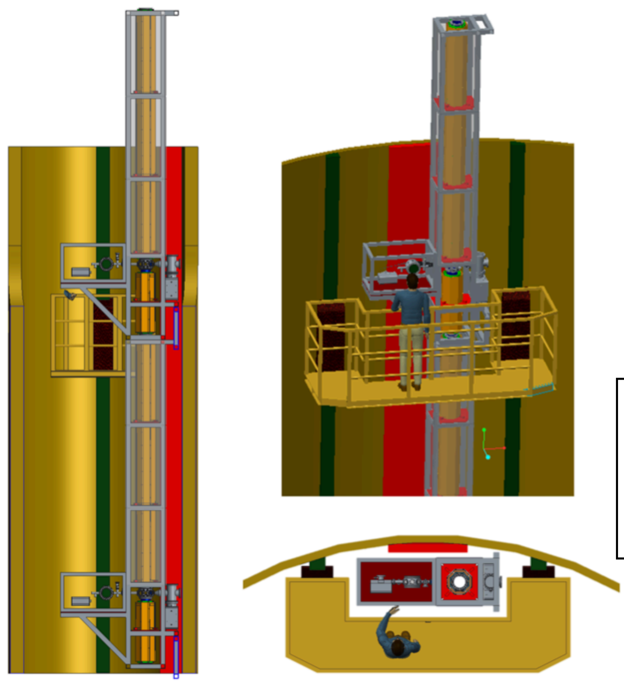
Access shaft



LHC

Cross-section of access shaft





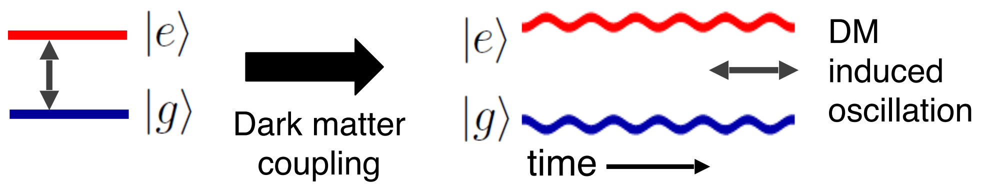
Layout of experiment

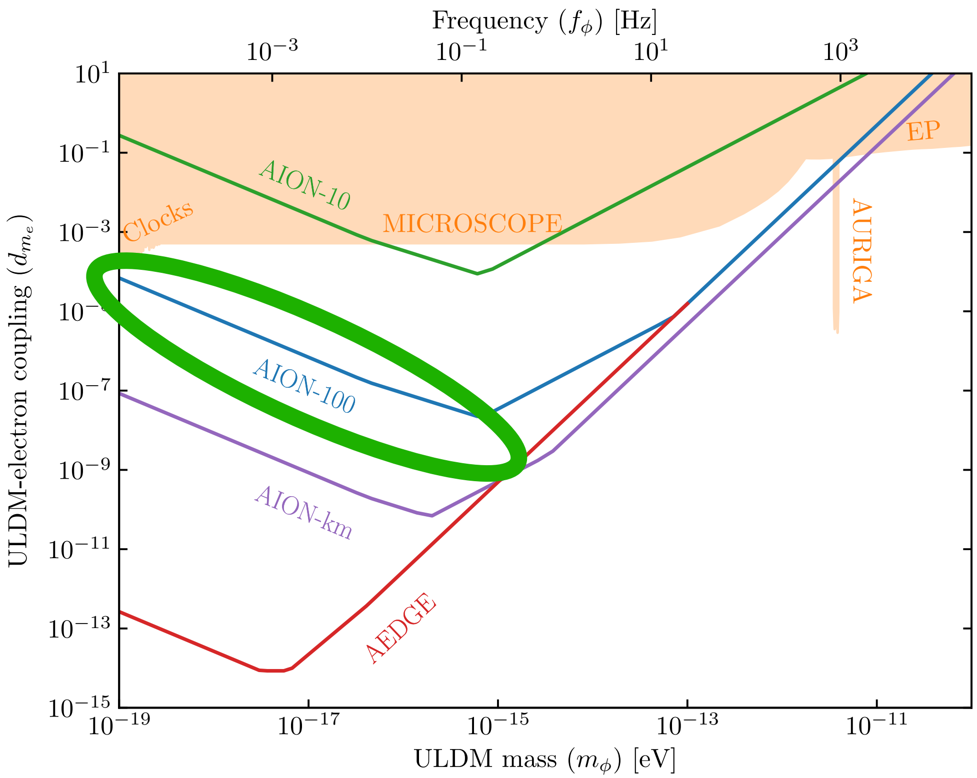
Arduini et al: arXiv:2304.00614

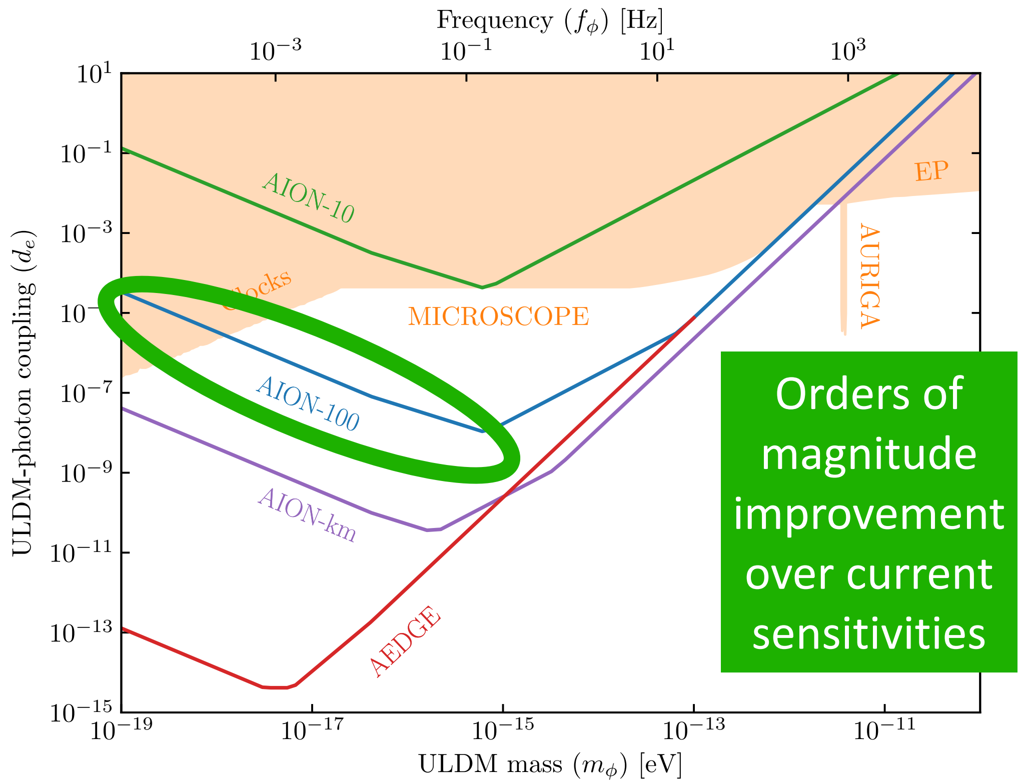
Searches for Light Dark Matter AION

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi\left[+\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right]$$







AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Gravitational Waves

- General relativity proposed by Einstein 1915
- He predicted gravitational waves in 1916

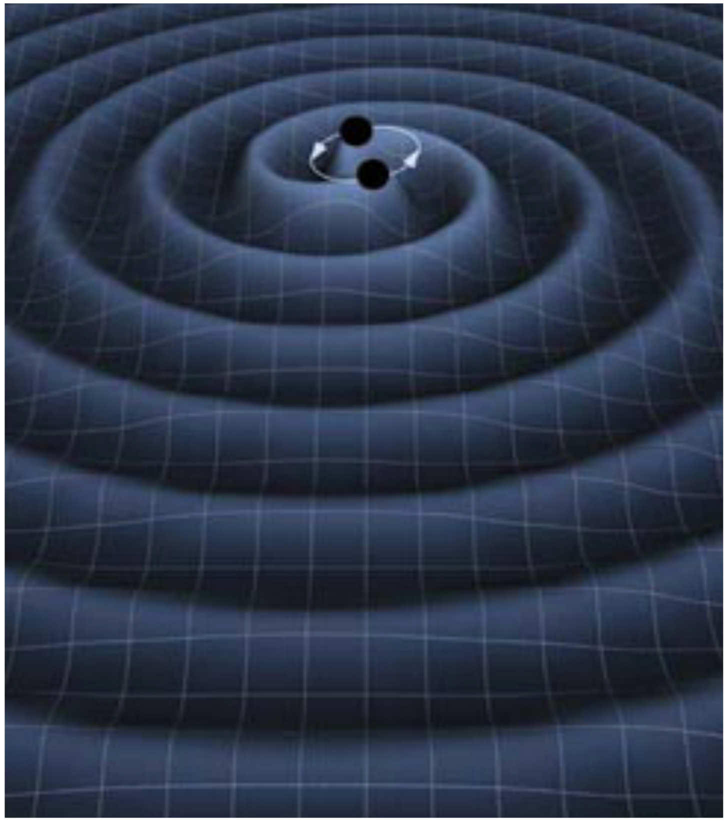
Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probl
auf dem Gebiete der Gravitationstheorie kann man sich damit begnü
die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich
Vorteil der imaginären Zeitvariable x_4 = it aus denselben Gründen
in der speziellen Relativitätstheorie. Unter »erster Näherung« ist d
verstanden, daß die durch die Gleichung

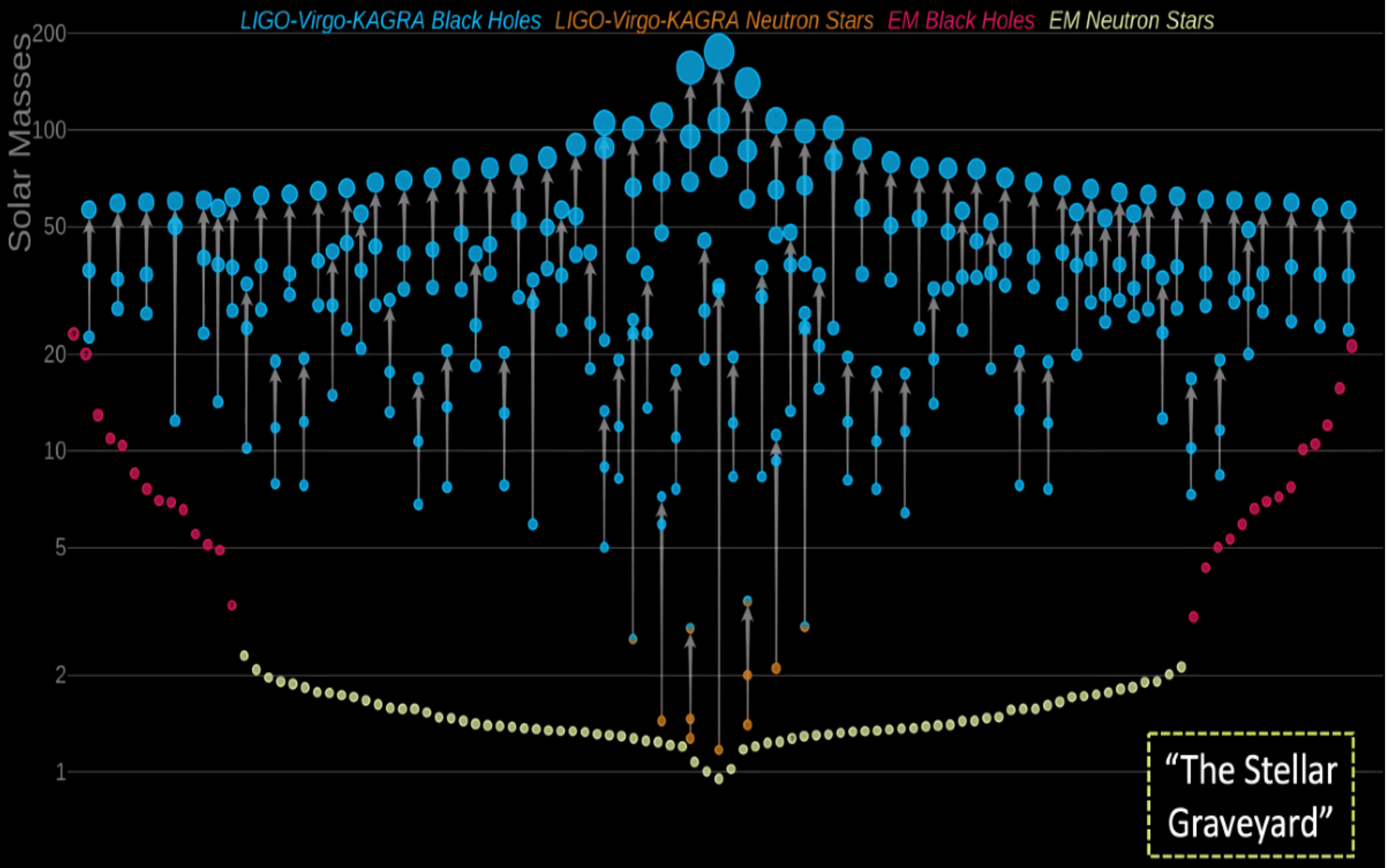
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916

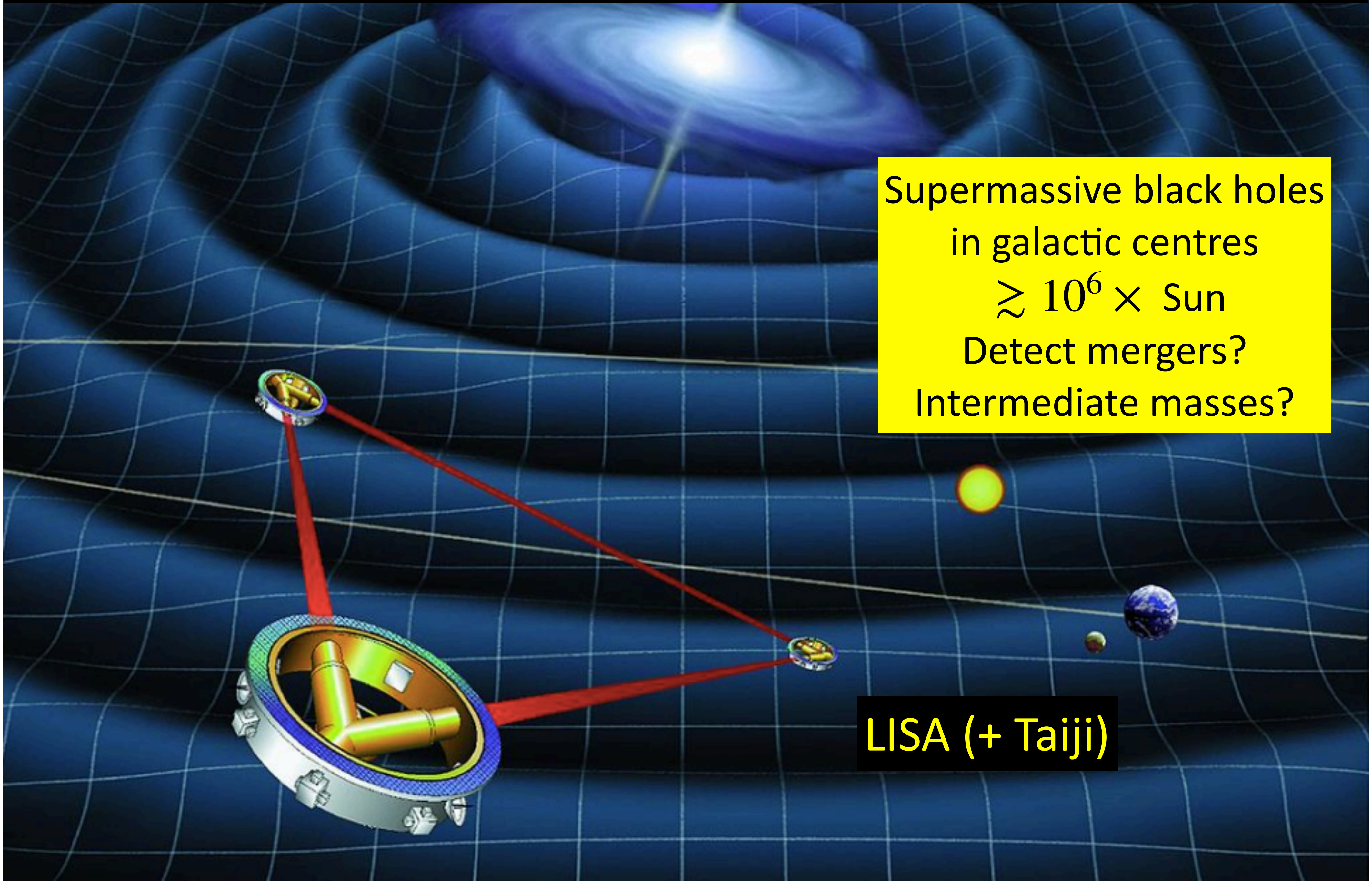


- Tried to retract prediction in 1936!

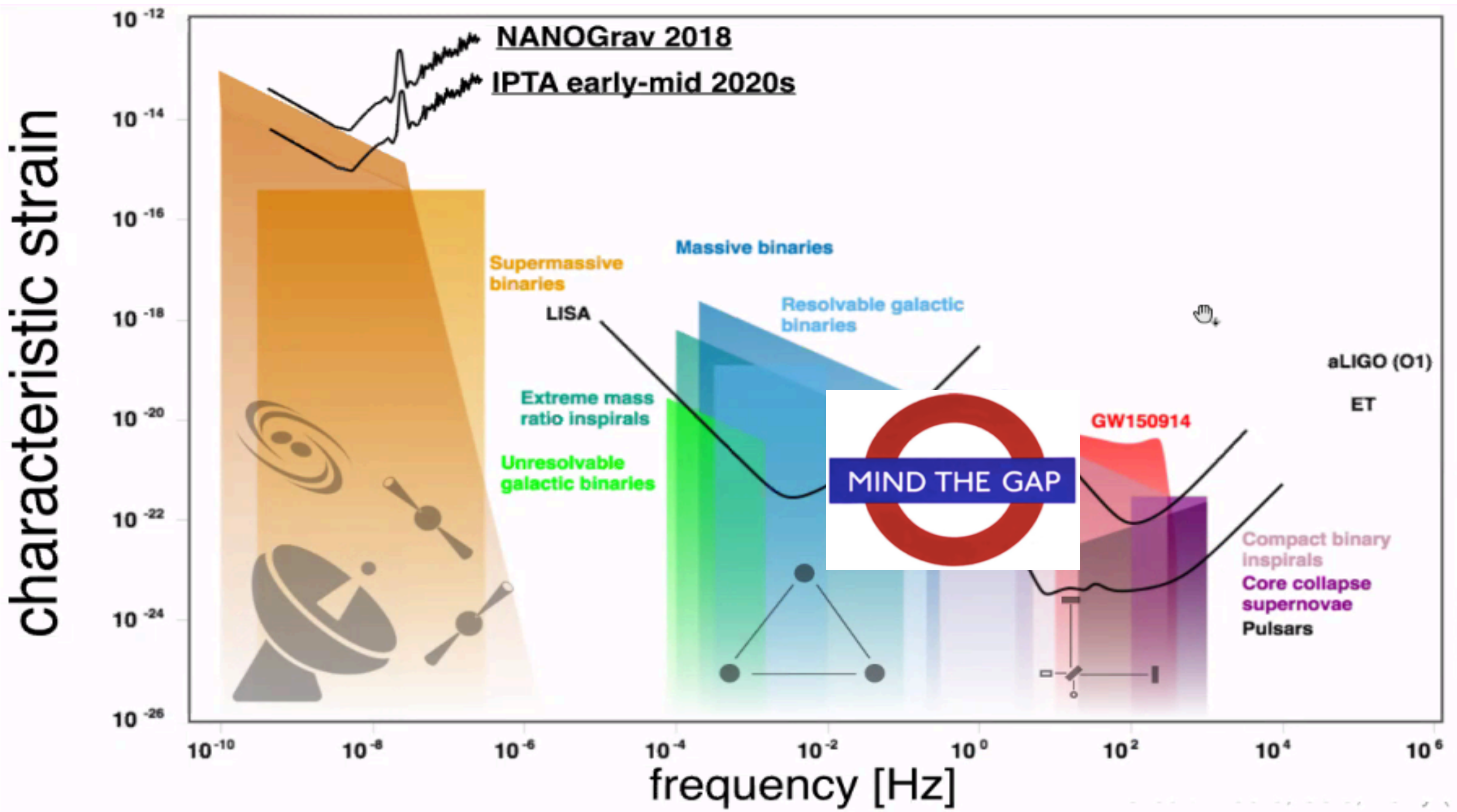
LIGO-Virgo-KAGRA Black Holes & Neutron Stars



Future Step: Interferometer in Space



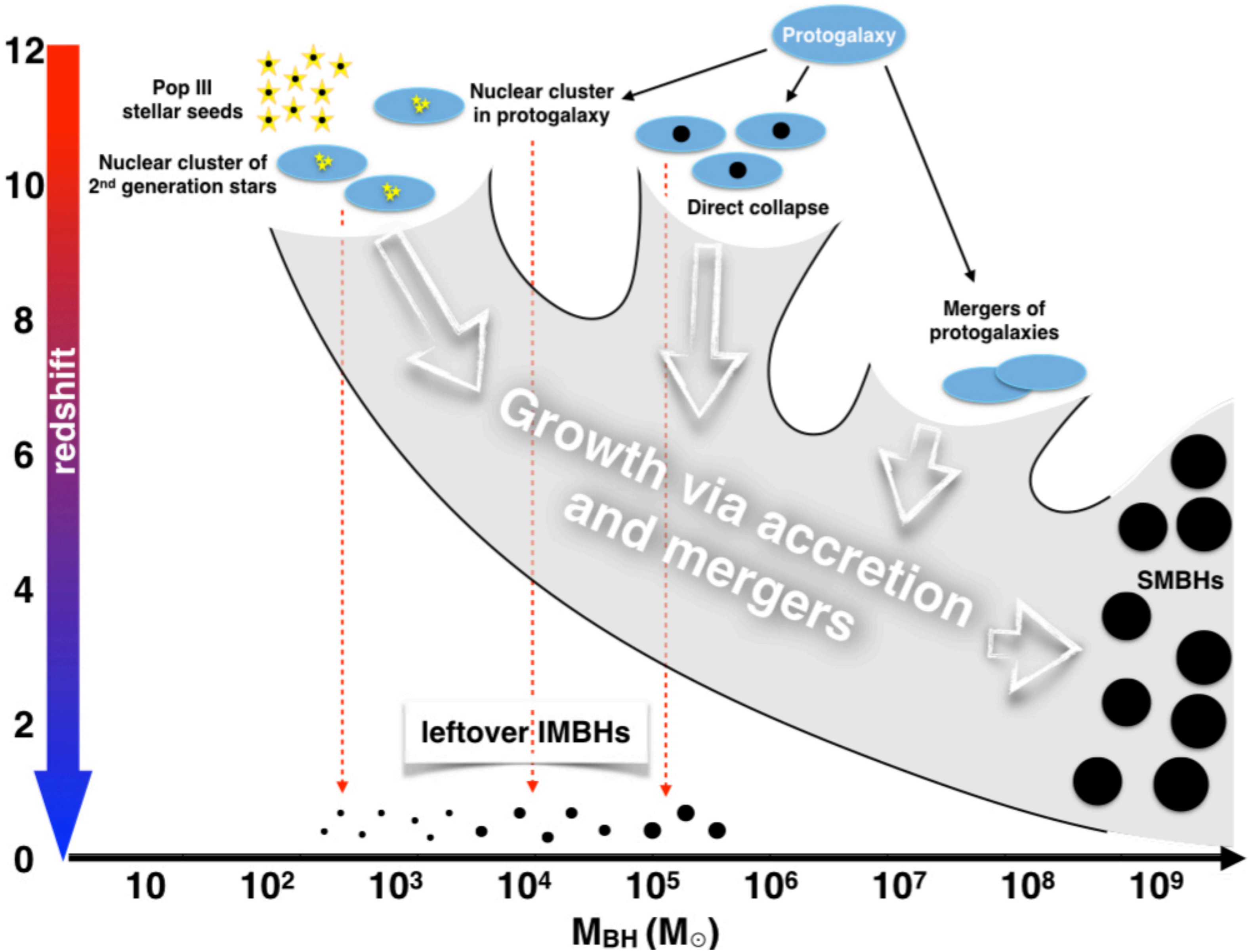
Gravitational Wave Spectrum



- Gap between ground-based optical interferometers & LISA
  - Formation of supermassive black holes (SMBHs)?
  - Supernovae? Phase transitions? …

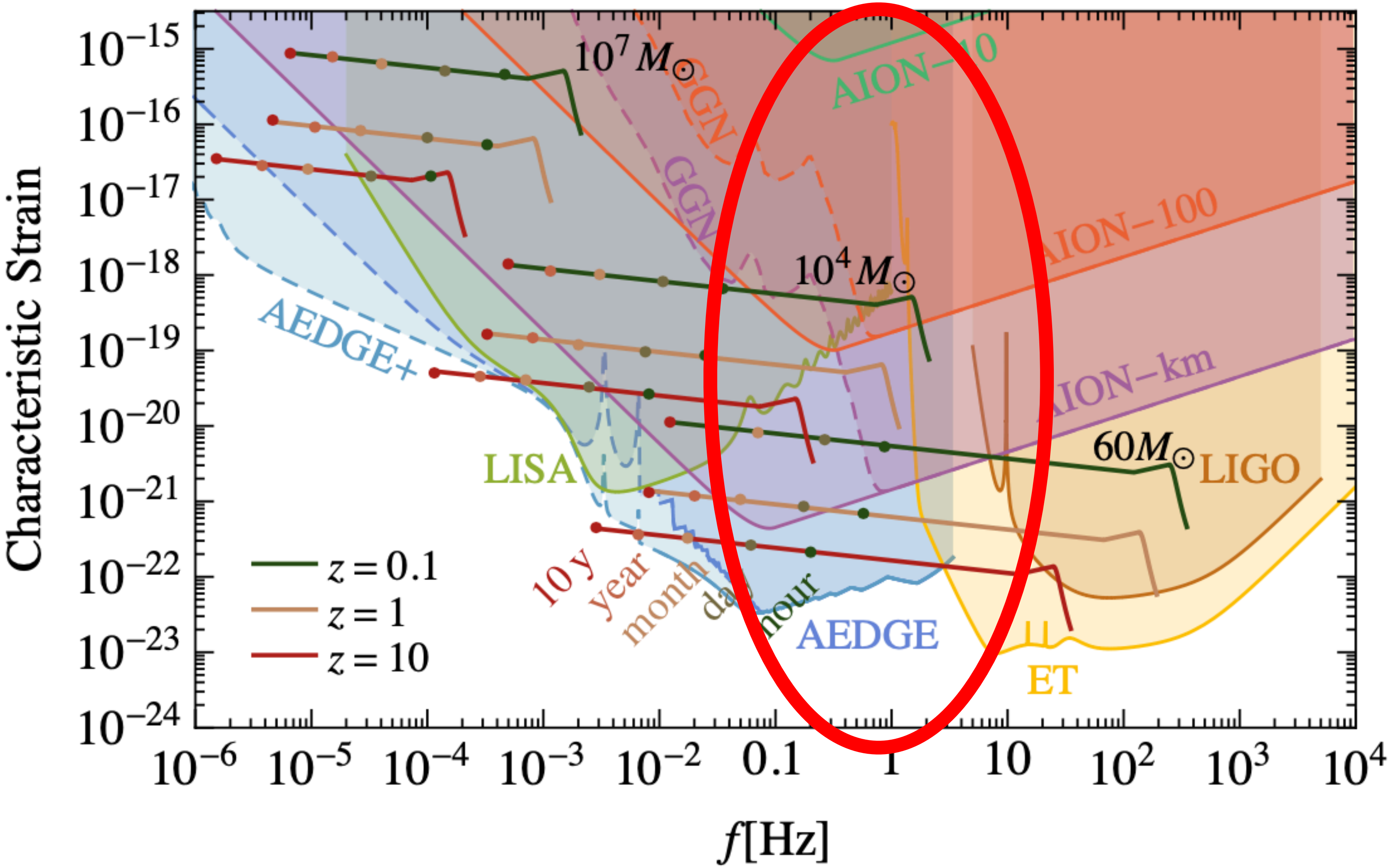
How to Make a Supermassive BH?

SMBHs from mergers of intermediate-mass BHs (IMBHs)?



Gravitational Waves from IMBH Mergers

AION

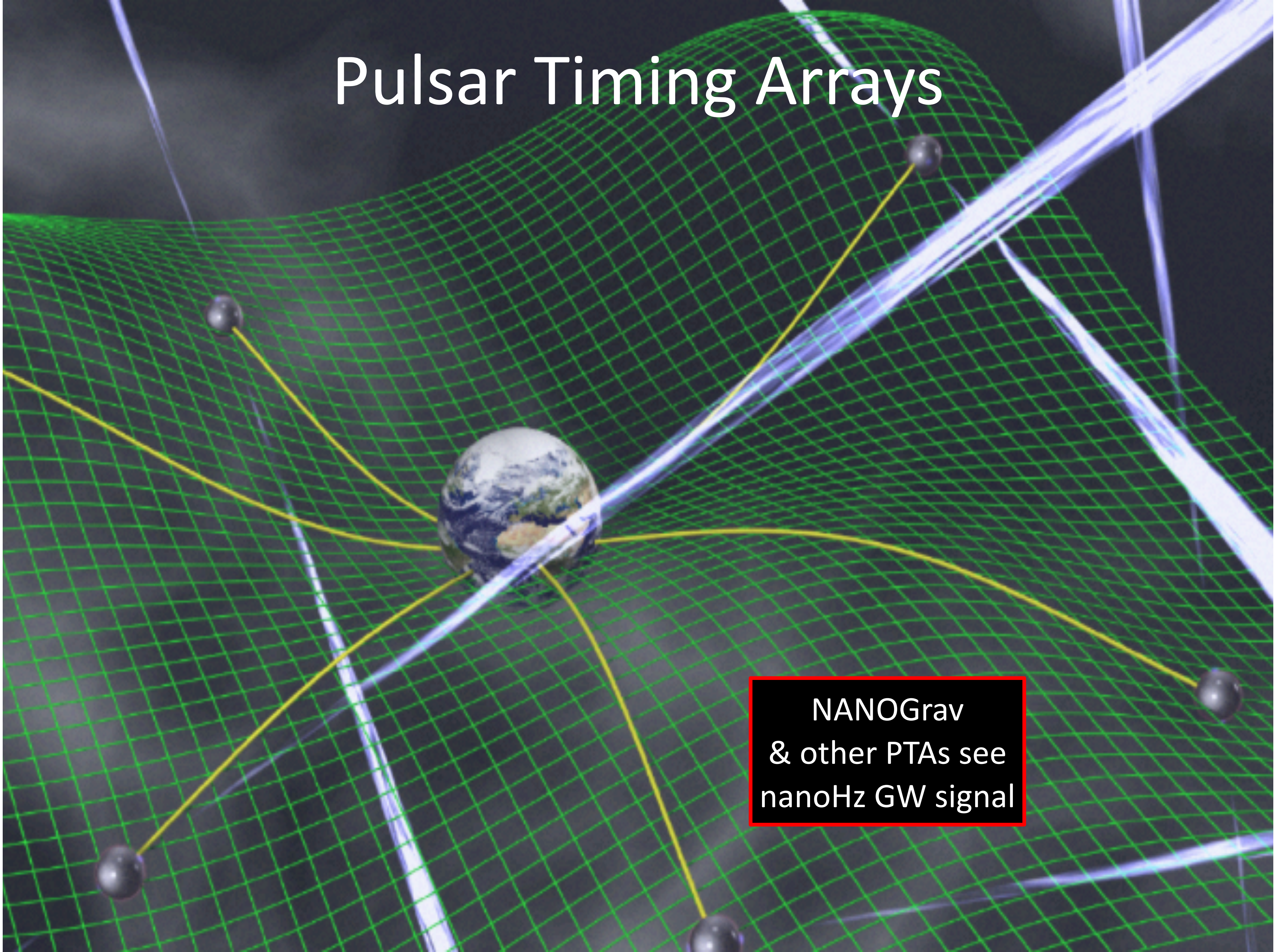


Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

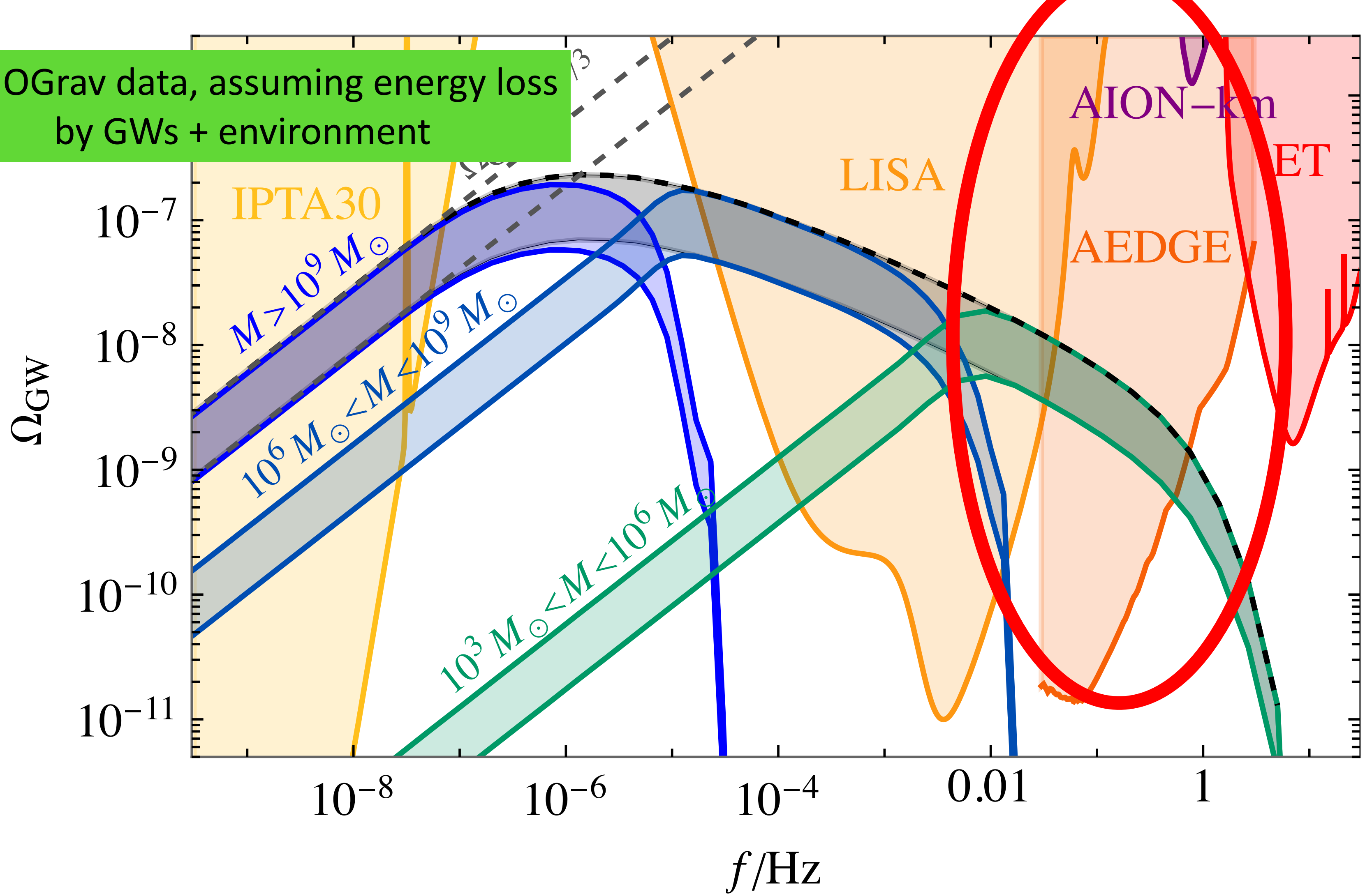
Pulsar Timing Arrays



The Biggest Bangs since the Big Bang

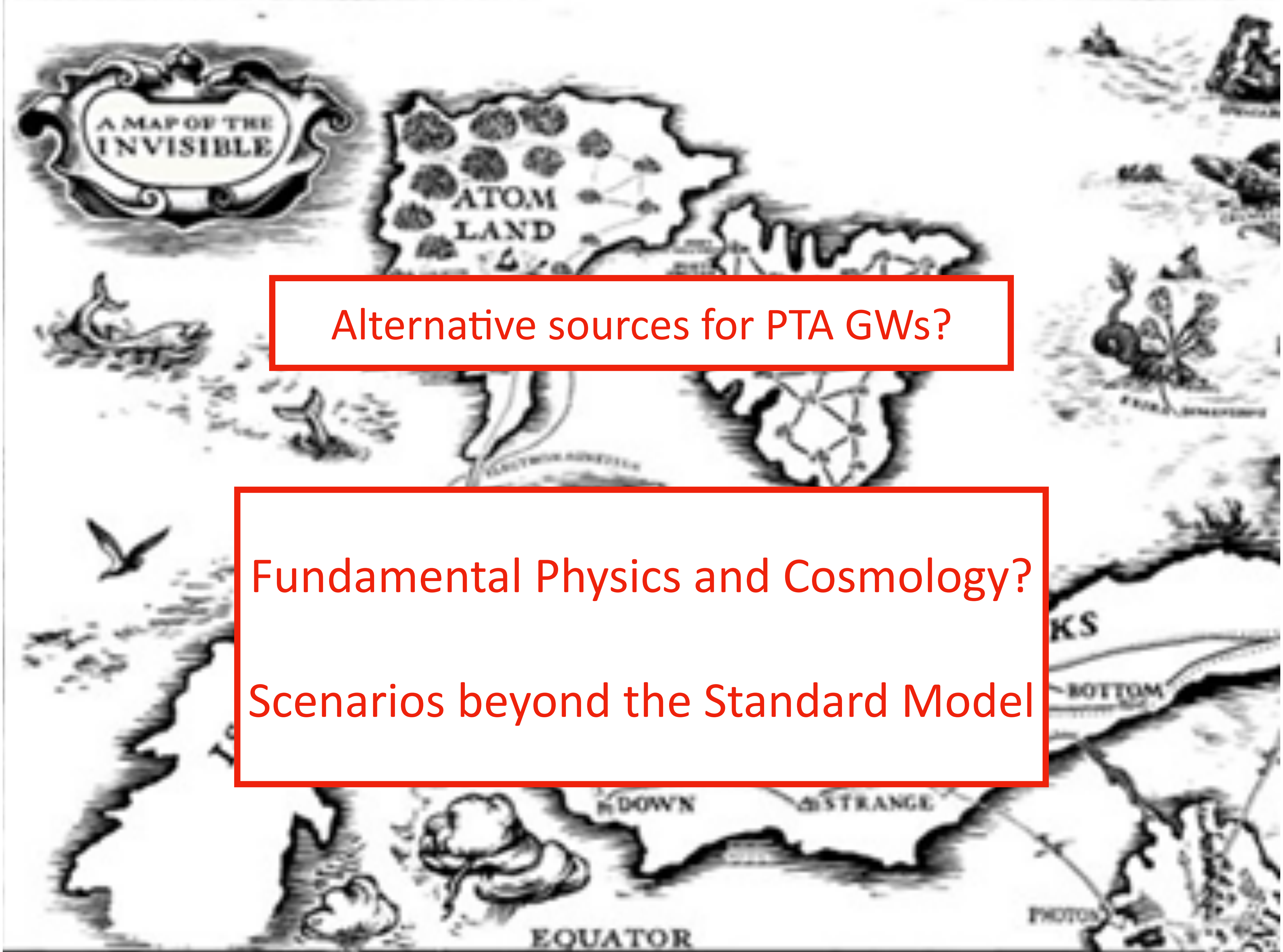
Stochastic GW Background from BH Mergers

NANOGrav data, assuming energy loss by GWs + environment



Black dashed line is maximum possible Ω_{GW}, i.e., $p_{BH} = 1$

JE, Fairbairn, Hütsi, Raidal', Urrutia, Vaskonen & Veermäe: arXiv:2306.17021

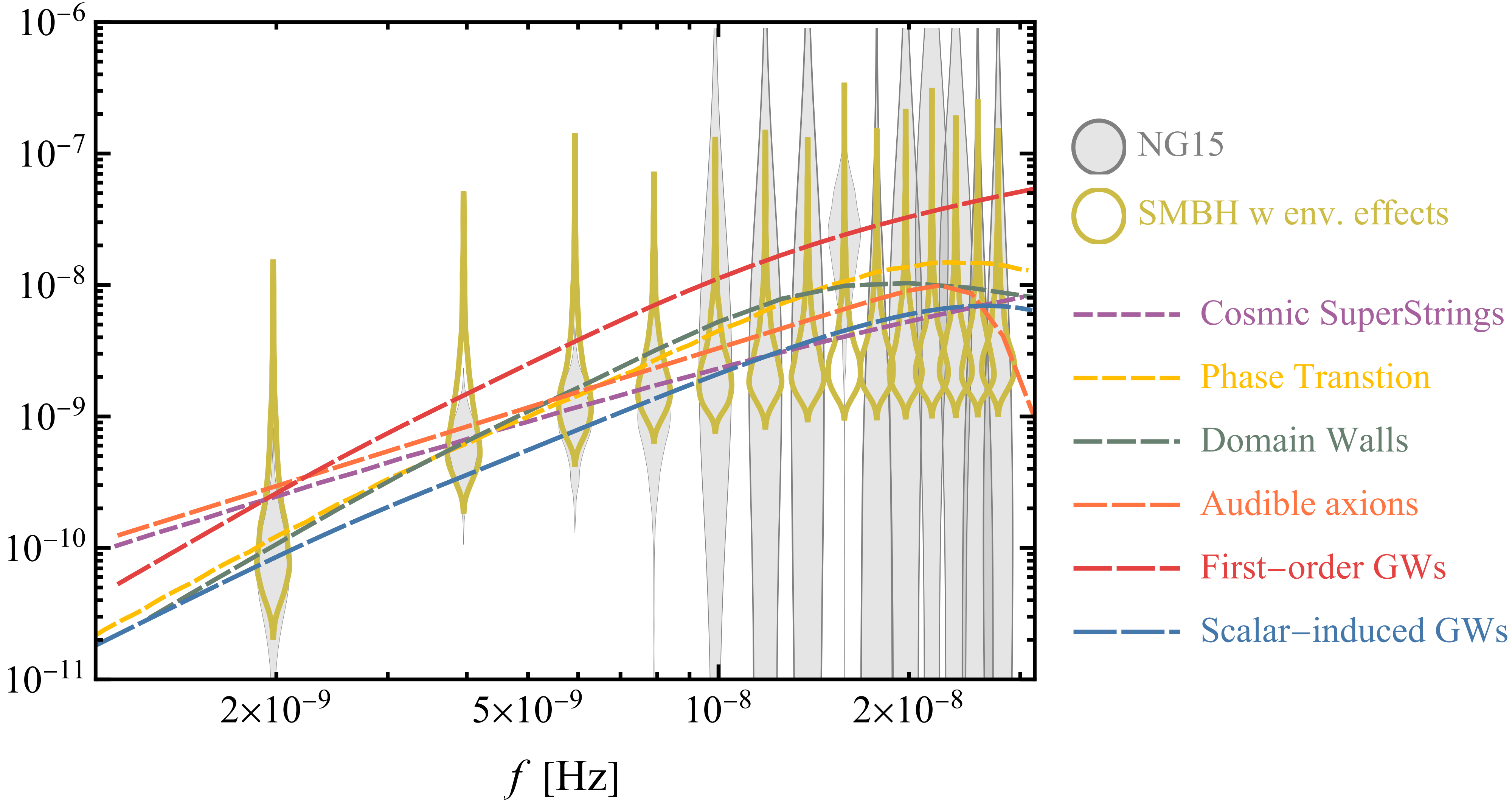


Alternative sources for PTA GWs?

Fundamental Physics and Cosmology?

Scenarios beyond the Standard Model

Fits to NANOGrav

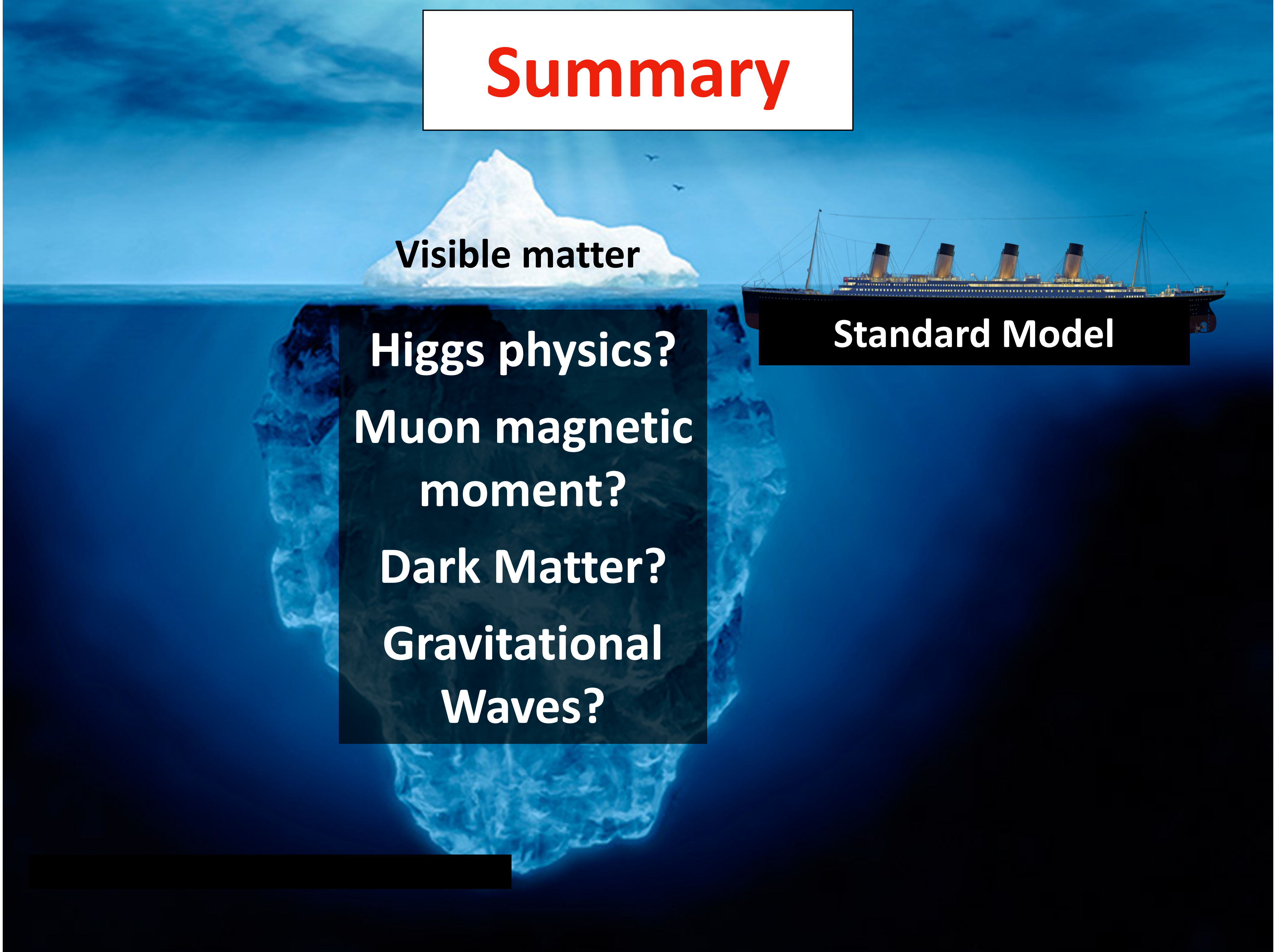


JE, Fairbairn, Franciolini, Hütsi,, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Quo Vadis NANOGrav?

- **Astrophysics or fundamental physics?**
- Biggest bangs since the Big Bang, or physics beyond the SM?
- SMBH binaries driven by GWs alone disfavoured
- SMBH binaries driven by GWs and environmental effects fit better
- Better fits with cosmological BSM models
- **Discrimination possible with future measurements: fluctuations, anisotropies, polarization, experiments at higher frequencies - including atom interferometers** AION
- **Time and more data will tell!**

JE, Fairbairn, Franciolini, Hütsi,, Iovino, Lewicki, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546


Summary
Visible matter
Standard Model
Higgs physics?
Muon magnetic moment?
Dark Matter?
Gravitational Waves?
[redacted]