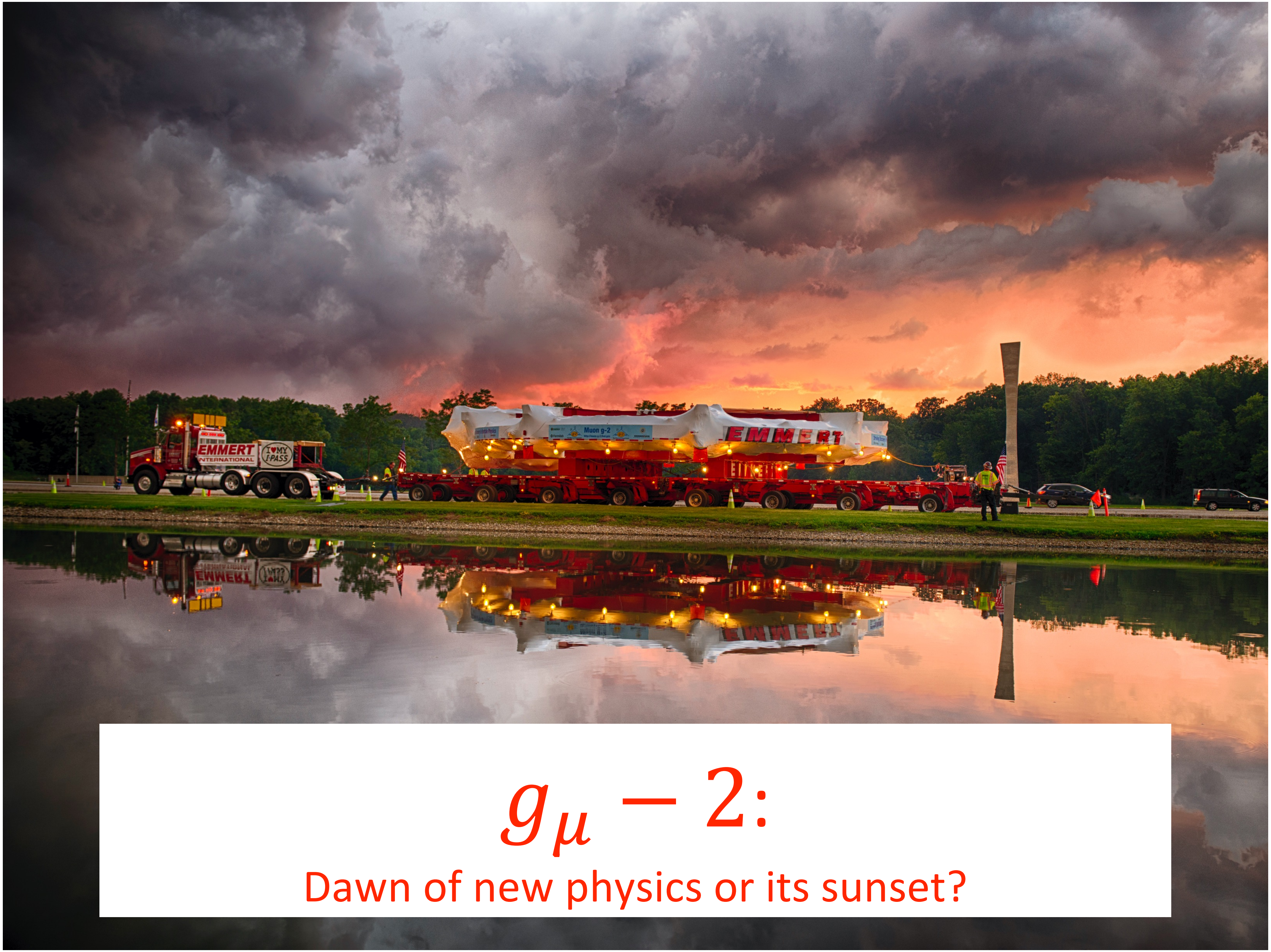
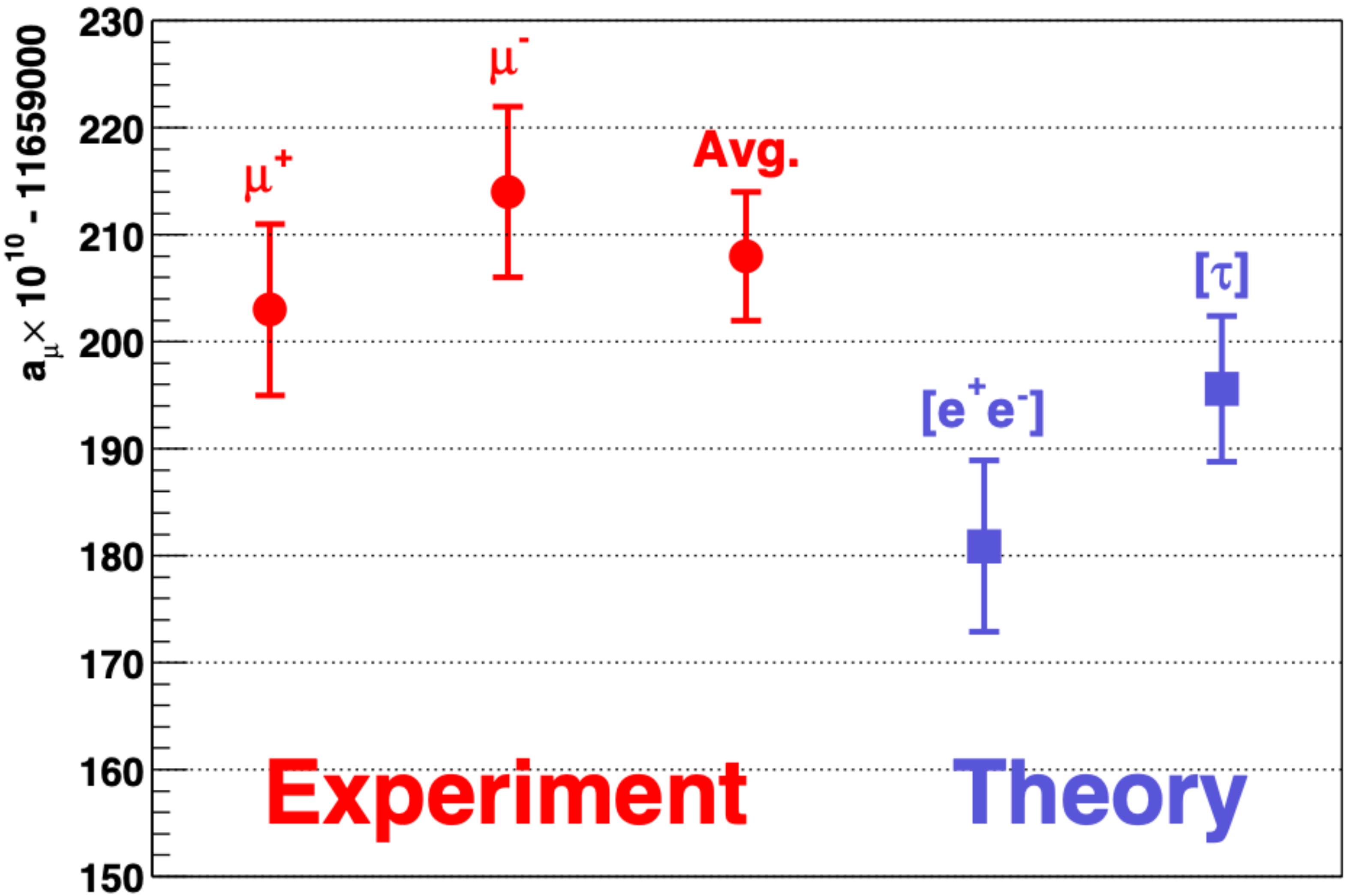


$g_\mu - 2$:

Dawn of new physics or its sunset?

Possible Discrepancy with Theory?

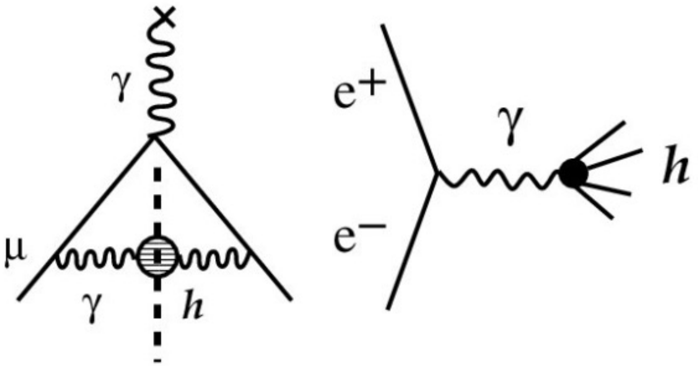


$$\delta a = \pm 0.47 \text{ppm}$$

BNL E821 experiment, 2001 - 2006

Theory Initiative

- Comprehensive review of calculations of the Standard Model contributions to $g_\mu - 2$
- Including discussion of the uncertainties
- Particularly in calculation of leading-order vacuum polarisation



Aoyama et al, arXiv:2006.04822

Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

[1] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[2] *Nishina Center, RIKEN, Wako 351-0198, Japan*
[3] *Kobayashi–Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan*
[4] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[5] *LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France*

* Corresponding authors.
E-mail address: MUON-GM2-THEORY-SC@fnal.gov (G. Colangelo, M. Davier, S.I. Eidelman, A.X. El-Khadra, M. Hoferichter, C. Lehner, T. Mibe, A. Nyffeler, B.L. Roberts, T. Teubner).

https://doi.org/10.1016/j.physrep.2020.07.006

Hadronic Vacuum Polarization

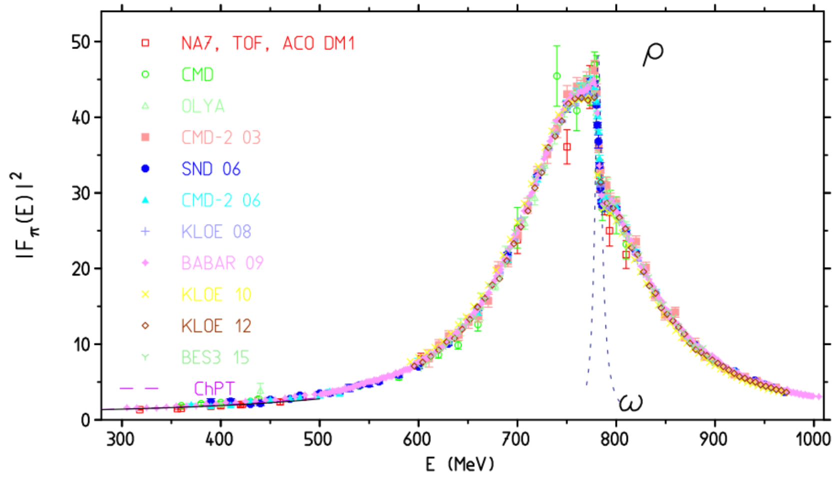
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

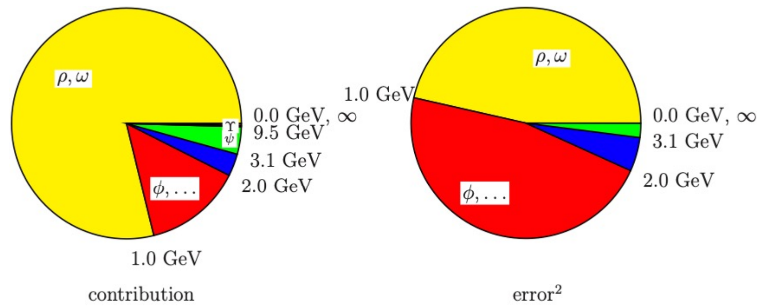
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

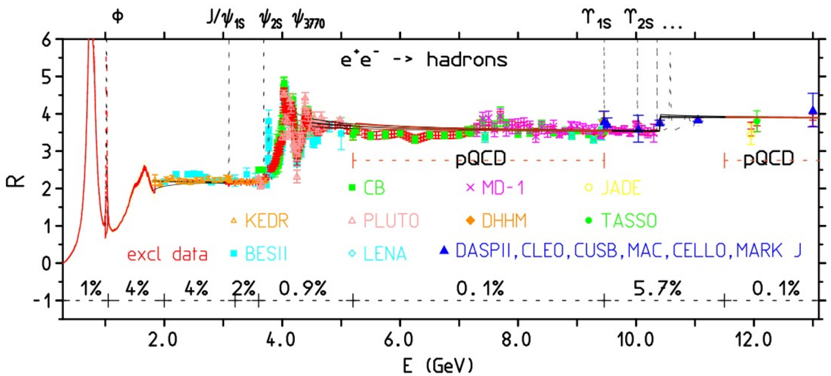
- High energies under good control from

$$a_\mu^{\text{HVP, LO}} = 693.1(2.8)_{\text{exp}}(2.8)_{\text{sys}}(0.7)_{\text{DV+QCD}} \times 10^{-10}$$
$$= 693.1(4.0) \times 10^{-10}\,.$$

Aoyama et al, arXiv:2006.04822





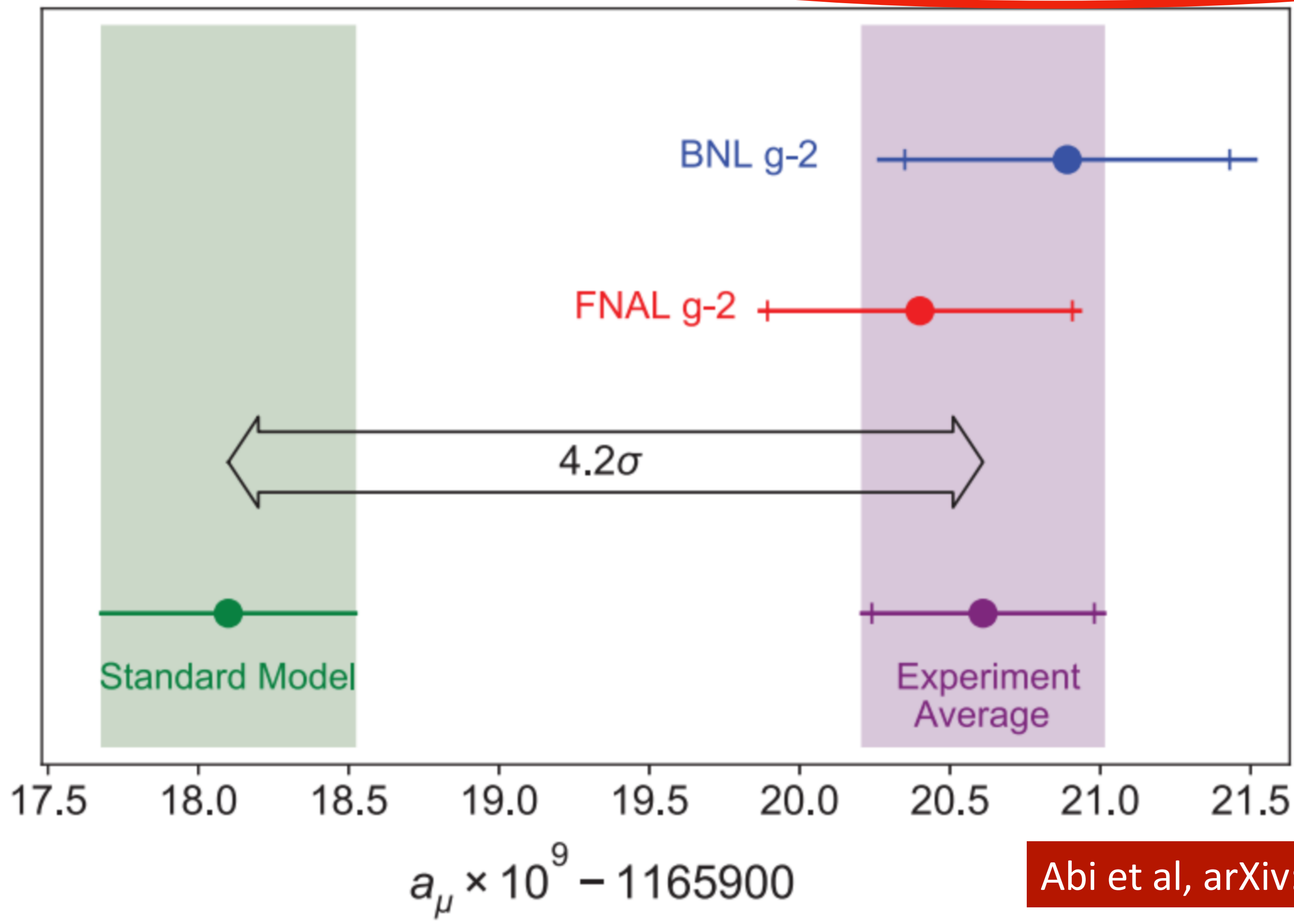


Fermilab Measurement

FNAL result: $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$

Combined result: $a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$

Difference from Standard Model: $a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM}) = (251 \pm 59) \times 10^{-11}$



Abi et al, arXiv:2104.03281

Interpretation Papers

2104.05685	Vector LQ	B	Du	
5656	L_\mu - L_\tau	DM	Borah	
5006	B_q - L_\mu	B	Cen	Leptoquarks
4494	LFV	LFV	Li	
4503	Pseudoscalar	DM, H decays	Lu	Extra U(1)
4456	2HDM	DM	Arcadi	
3542	B-LSSM	H decays	Yang	Extra Higgs
3701	Leptophilic spin 0	H factory	Chun	
3839	SUSY	HL-LHC	Aboubrahim	Supersymmetry
3691	Survey	DM, LHC	Athron	
3705	Seesaw	g_e	Escribano	Axion
3699	Gauged 2HDM	B	Chen	
3239	SUSY	Gravitino DM	Gu	
3284	NMSSM	DM	Cao	
3262	GUT-constrained SUSY	DM, LHC	Wang	
3292	MSSM	CPV	Han	
3296	lepton mass matrix	Flavour	Calibbi	
3280	Z_d	Cs weak charge	Cadeddu	
3334	E_6 3-3-1	H stability	Li	
3242	\mu-\tau-philic H	\tau decays, LHC	Wang	
3259	Anomaly mediation	DM	Yin	
3245	pMSSM	DM, fine-tuning	Van Beekveld	
3274	NMSSM	DM, AMS-02 pbar	Abdughani	
3290	MSSM	DM	Cox	
3367	2HDM	V-like leptons	Ferreira	
3267	Axion	Low-scale	Buen-Abad	
3340	L_\mu - L_tau	AMS-02 positrons	Zu	
3282	ALP	V-like fermions	Brdar	
3301	Lepton portal	DM	Bai	
3276	Dark axion portal	Dark photon	Ge	
3491	GmSUGRA	LHC	Ahmed	
3227	2HDM	LHC	Han	
3302	SUSY	small \mu	Baum	
3238	Scalar	DM, p radius	Zhu	
3489	\mu \nu SSM	B, H decays	Zhang	
3287	pMSSM	ILC	Chakraborti	
3228	DM	B, H decays	Arcadi	

890	Radiative seesaw		Chiang
2103.13991	Scalar LQ	B, H decays	Greljo
2012.11766	DM		D'Agnolo
2012.07894	Axions		Darmé
1812.06851	Charmphilic LQ		Kowalska
2104.04458	GUT-constrained SUSY	DM	Chakraborti
5730	LQ + charged singlet	B, Cabibbo	Marzocca
6320	L-R symmetry		Boyarkin
6858	L_\mu - L_\tau	\nu masses	Zhou
6854	D-brane	U(1), Regge	Anchordoqui
6656	vector LQ	B	Ban
7597	SUSY	LHC, landscape	Baer
7047	3HDM	Fermion masses	Carcamo
7680	Leptophilic Z'	Global analysis	Buras
8289	Custodial symmetry	Light scalar + pseudoscalar	Balkin
9205	U(1)D	Neutrino mass	Dasgupta
8819	Lepton non-universality	Naturalness	Cacciapaglia
8640	2x2x1	Higgses, heavy nus	Boyarkina
8293	Multi-TeV sleptons in FSSM	Extended H, tau decays	Altmannshofer
10114	SO(10)	Yukawa unification	Aboubrahim
7681	U(1)B-L	DUNE	Dev
10324	Gauged lepton number	Dark matter	Ma
10175	2HDM	Lighter Higgs?	Jueid
11229	LQ	Matter unification	Fileviez
15136	U(1)	HE neutrinos, H tension	Alonso
2105.00903	Anomalous 3-boson vertex	W mass	Arbuzov
7655	U(1)T3R	RK(*)	Dutta
8670	Leptoquark	nu mass, LFV	Zhang

$g_\mu - 2$ in Supersymmetry

- One-loop contribution from smuon/neutralino loop

$$\Delta(g-2)_\mu = -ab(\cos\alpha \sin\alpha/4\pi^2)(m_\mu/m_{\tilde{G}})$$
$$\times \{1/(1-\eta_1) + 2\eta_1/(1-\eta_1)^2$$
$$+ [2\eta_1/(1-\eta_1)^3] \log \eta_1 - (\eta_1 \leftrightarrow \eta_2)\},$$

- where $\eta_i \equiv (m^2_{s\mu_i}/m^2_{\tilde{G}})$
- and $\mathcal{L} = a\sqrt{2}\, s_\mu \bar{\mu}_L \tilde{G} + b\sqrt{2}\, t_\mu \bar{\mu}_R \tilde{G}$

Volume 116B, number 4 PHYSICS LETTERS

(1982)

SPIN-ZERO LEPTONS AND THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

John ELLIS, John HAGELIN and D.V. NANOPOULOS
CERN, Geneva, Switzerland

Received 14 June 1982

The anomalous magnetic moment of the muon $(g-2)_\mu$ imposes constraints on the masses and mixing of spin-zero leptons (sleptons). We develop the predictions of models of spontaneous supersymmetry breaking for the slepton mass matrix, and show that they are comfortably consistent with the $(g-2)_\mu$ constraints.

During the present resurgence of interest in supersymmetry broken at low energies [1] new significance is attached to the classical phenomenological playgrounds of gauge theories such as the anomalous magnetic moments of the electron and muon [2], flavour-changing neutral interactions [3–5] parity [6] and *CP* violation [7,8] in the strong interactions. The three latter phenomena make life rather difficult [3,7] for the most general form of soft supersymmetry breaking, whereas simple models [9–11] of spontaneously broken supersymmetry naturally [3,4 7] respect the $\Delta F \neq 0$, *P* and *CP* violation constraints. As for the anomalous magnetic moments of the leptons, it has long been known that they vanish in an exactly supersymmetric theory [12], and Fayet [2] showed that in his model of supersymmetry breaking $(g-2)_\mu$ would be compatible with experiment if the spin-zero muon (smuon) masses were heavier than 15 GeV. Direct experimental searches [13] now exclude the existence of lighter smuons. Fayet's analysis [2] was in the context of a model with a very light photino $\tilde{\gamma}$ (see fig. 1a), and Grifols and Méndez [14] have recently made the interesting observation that his analysis is significantly altered for massive gauginos (see figs. 1b, 1c). They show that there are potentially nontrivial constraints on the smuon masses in models of broken supersymmetry.

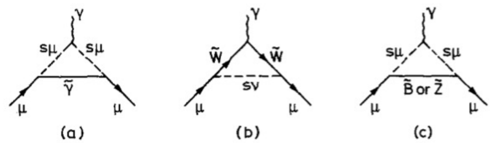


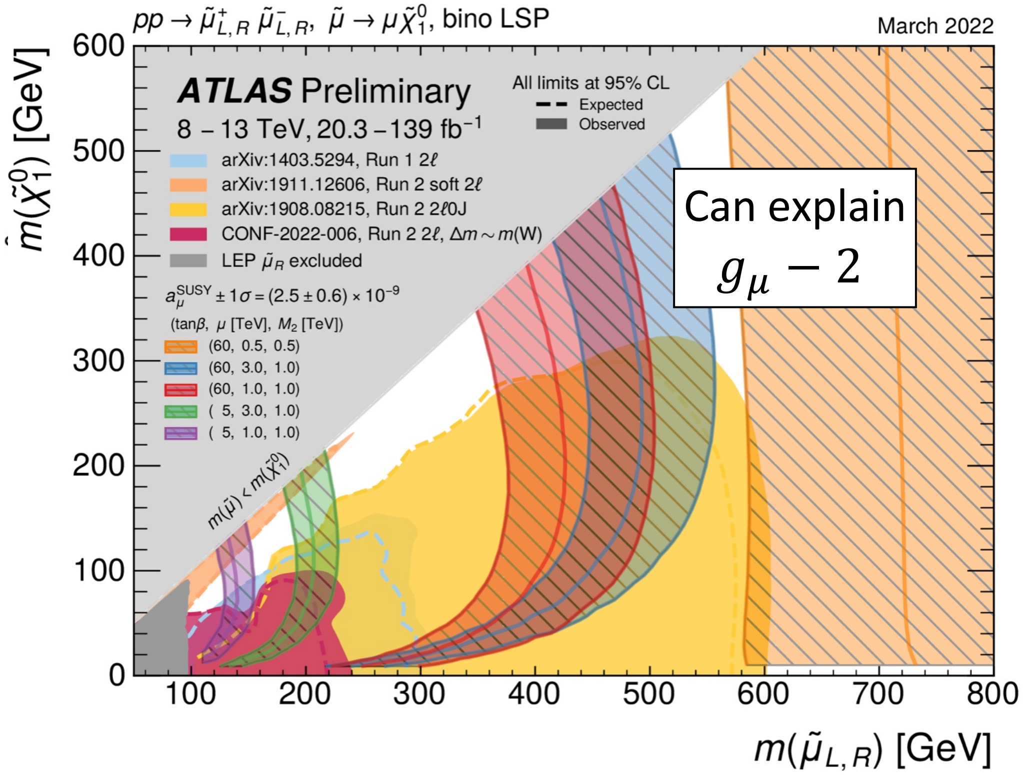
Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino $(\tilde{\gamma})$ exchange, (b) $\tilde{W}$ and sneutrino $(s\nu)$ exchange, and (c) $\tilde{B}$ or $\tilde{Z}$ exchange.

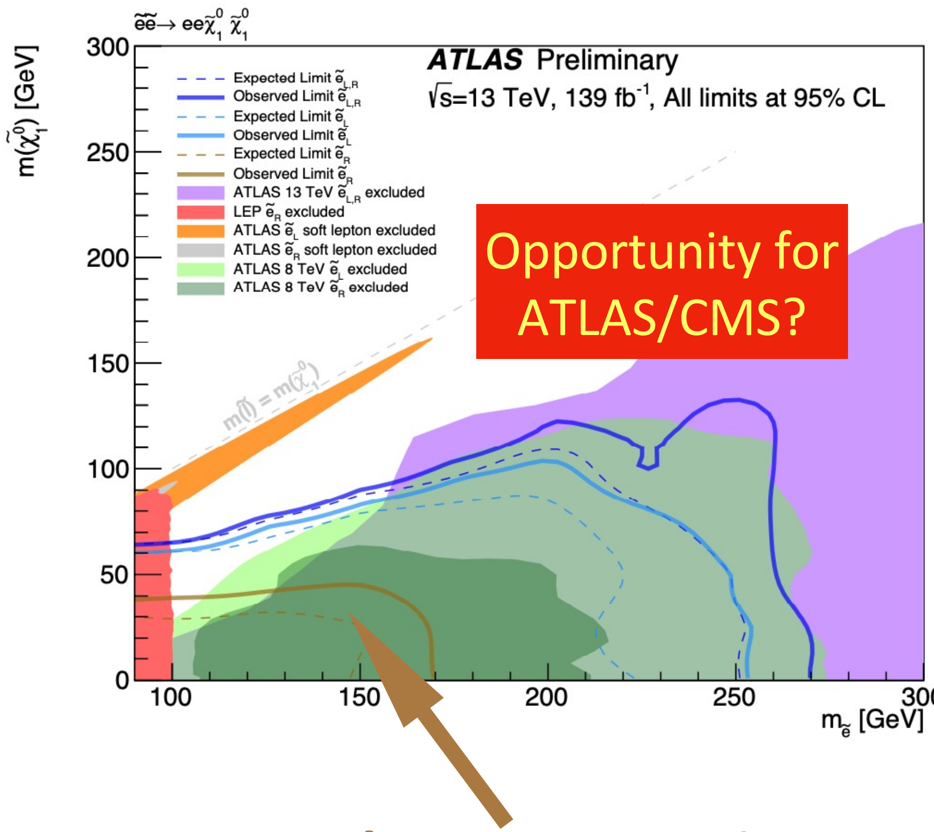
right transition operator there is a GIM [15]-like cancellation between the smuon mass eigenstates in fig. 1c which provides a potential suppression mechanism. We analyze recent models [10,11] of spontaneous supersymmetry breaking originating in the *D* and *F* sectors, respectively. We show that in the former case $(g-2)_\mu$ is suppressed by near degeneracy between the smuon mass eigenstates, while in the latter case $(g-2)_\mu$ is suppressed by small mixing angles between the left- and right-handed smuons. We close with some remarks about $(g-2)_e$ and about parity violation in the strong interactions.

When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\tilde{\gamma}$ diagram of fig. 1a and the $\tilde{W}$ diagram of fig. 1b as compared to the massive $\tilde{B}$ or $\tilde{Z}$ diagram of fig. 1c. The

LHC vs Supersymmetry

- LHC favours squarks & gluinos > 2 TeV (but loopholes)
- Does not exclude lighter electroweakly-interacting particles, e.g., sleptons

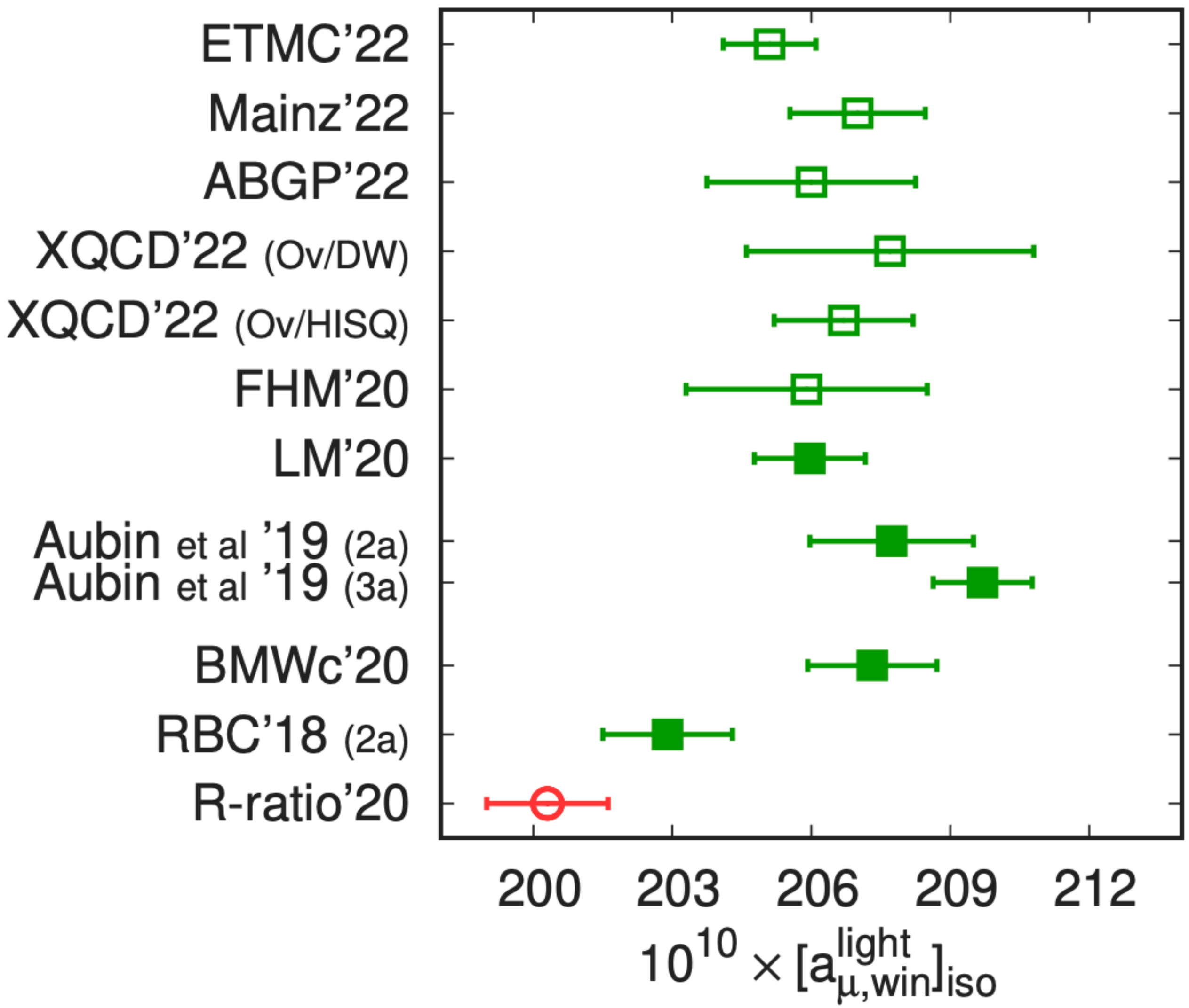




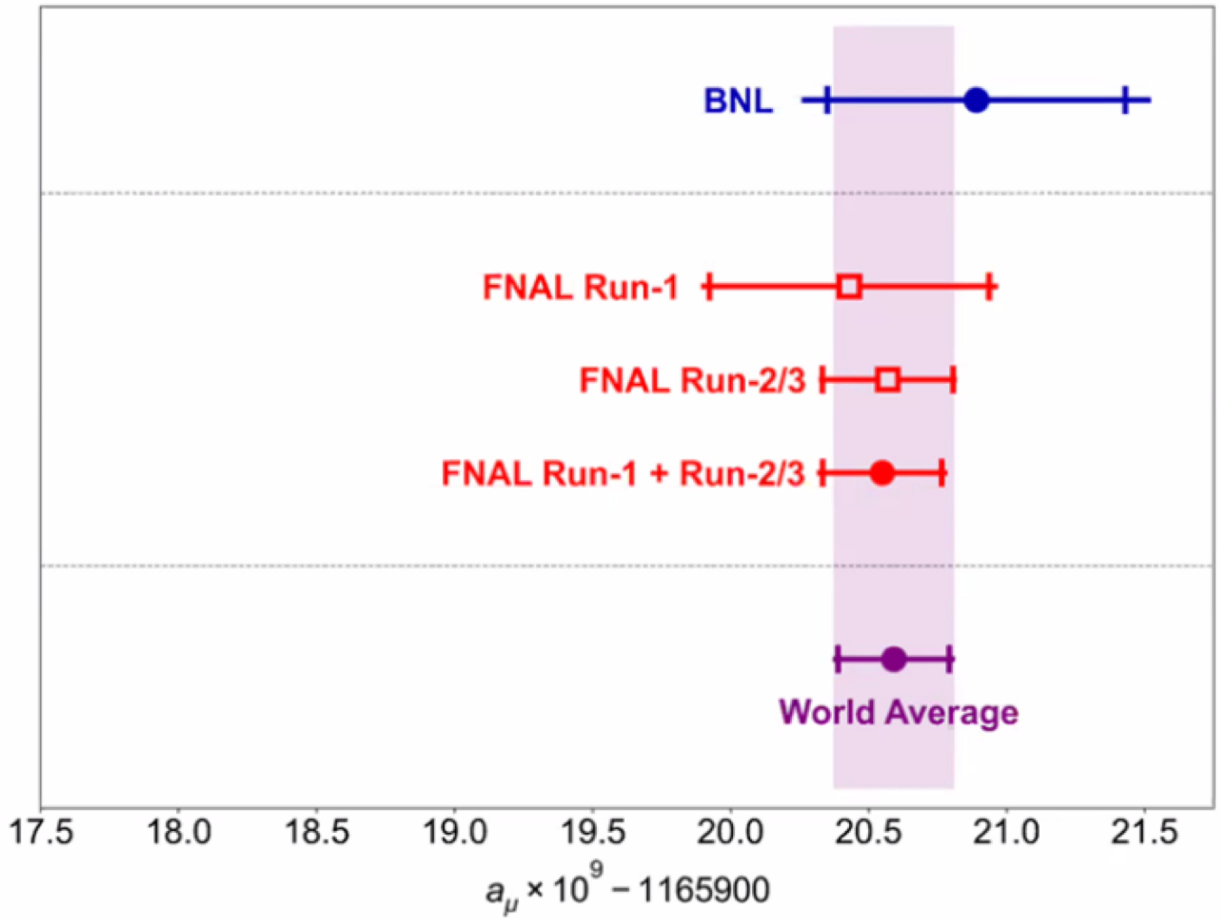
- Most models have $m_{\tilde\mu_L} > m_{\tilde\mu_R}$ but $m_{\tilde\mu_R} \simeq m_{\tilde e_R}$: **relevant constraint**

ATLAS Collaboration

Recent Lattice Calculations



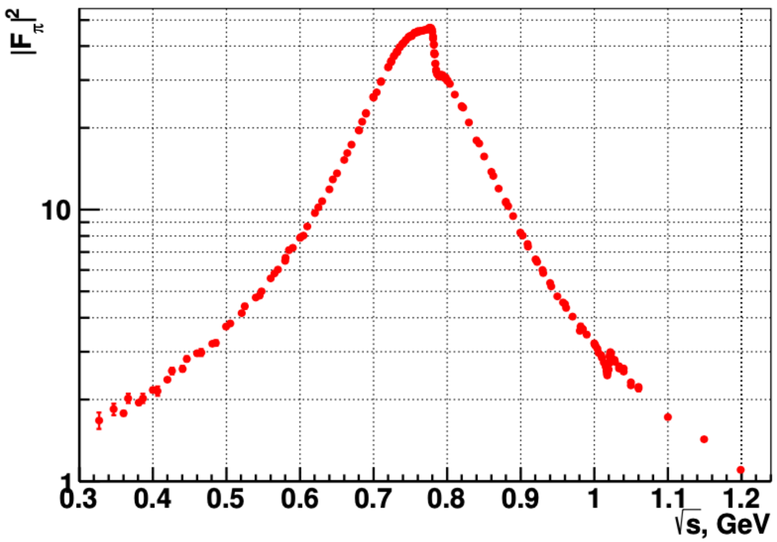
Quo Vadis $g_\mu - 2$?



- New Fermilab result confirms previous measurements, uncertainty reduced by factor ~ 2

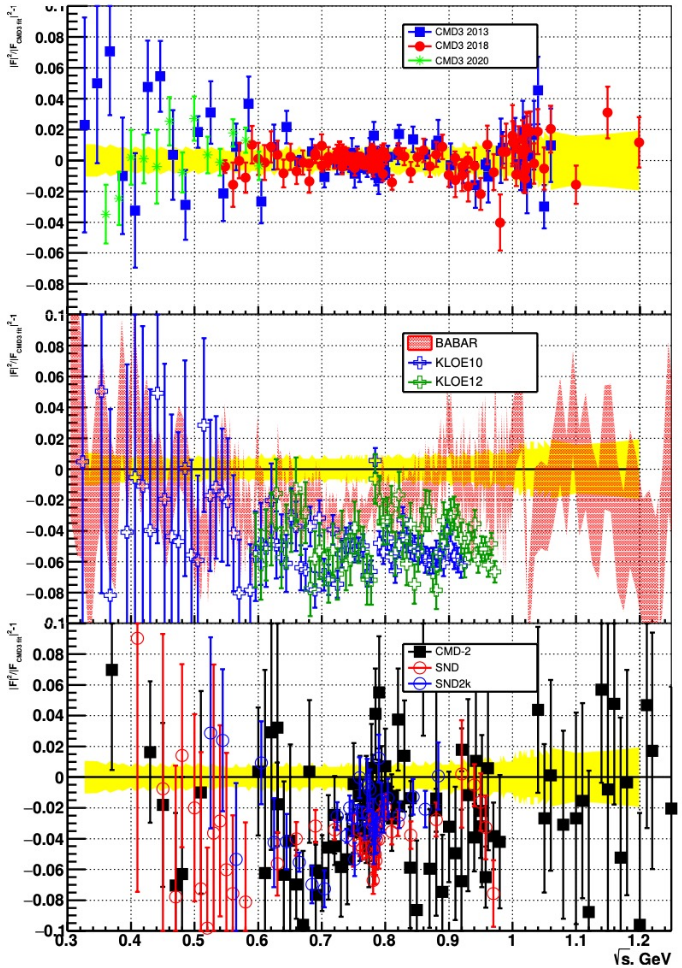
Updated CMD-3 Measurement of HVP

$e^+e^- \to \pi^+\pi^-$ form factor



CMD-3 Collaboration, arXiv:2309.12910

Comparison with previous results

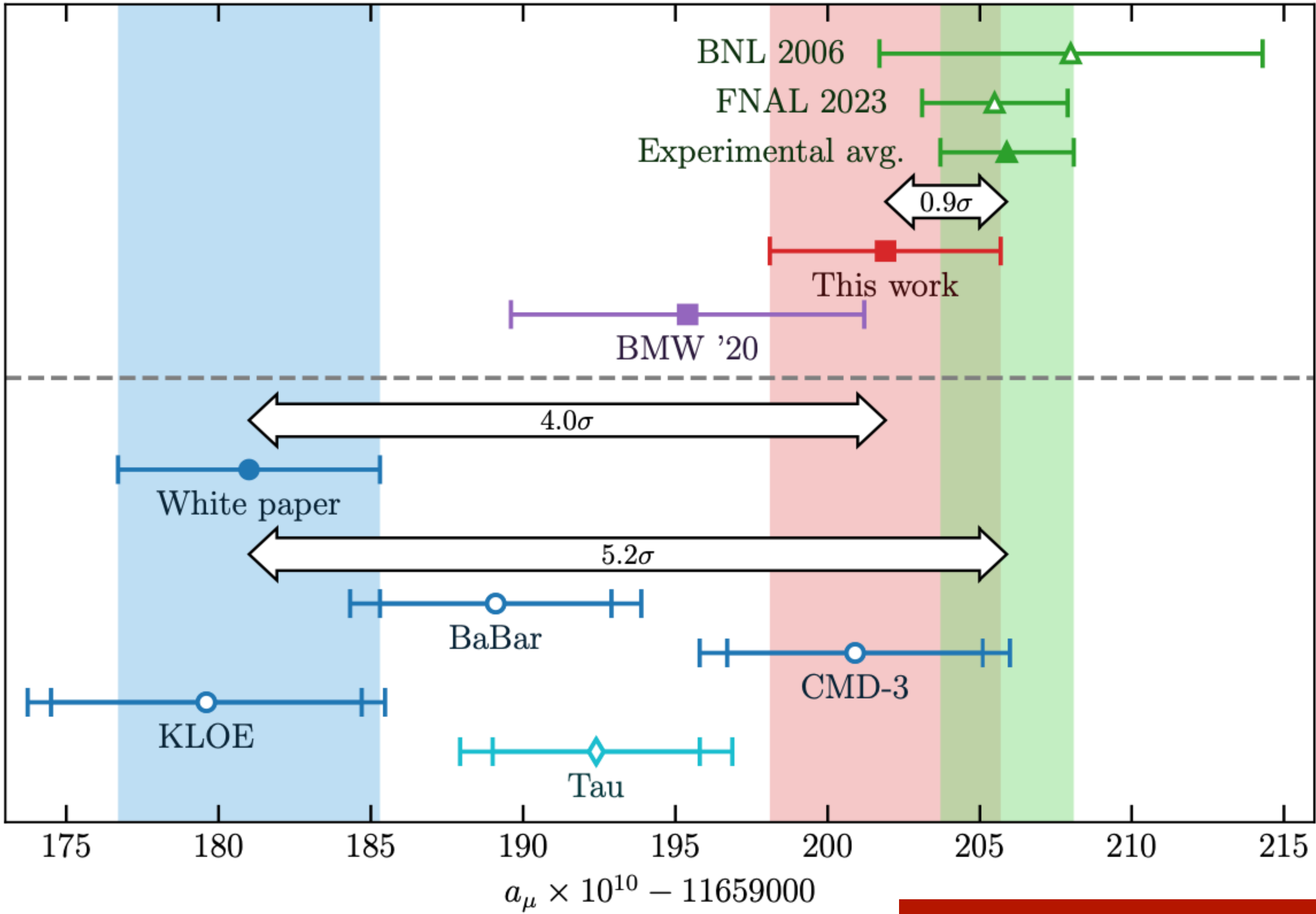


$(g_\mu - 2)$ —HVP discrepancy

$$\Delta a_\mu = (49 \pm 55)\times 10^{-11}$$

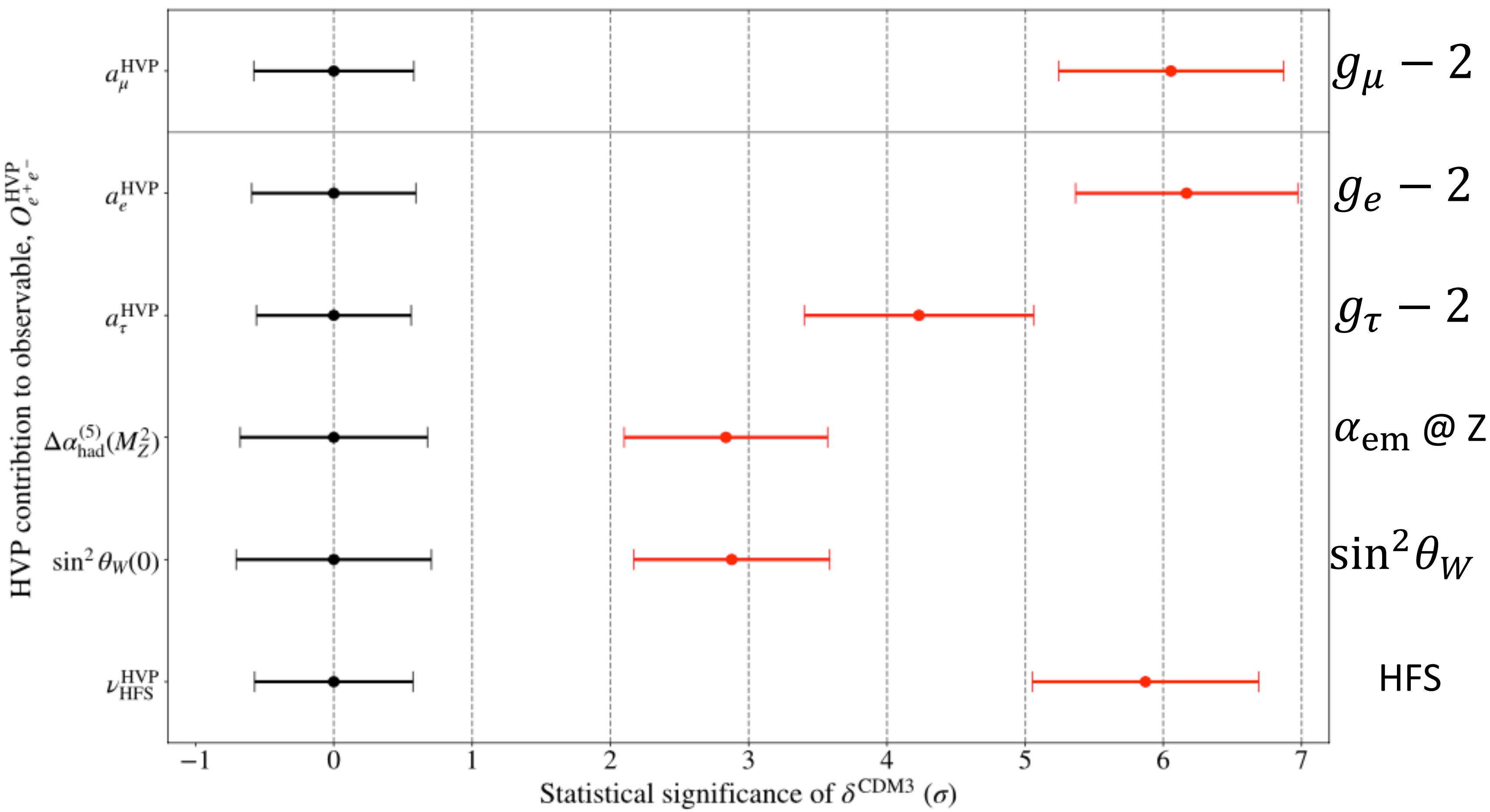
Consistent with no BSM signal

New Lattice Calculation of $g_\mu - 2$



Boccaletti et al, arXiv:2407.10913

Impacts on Other Observables



- Important effects on $g_e - 2$, HFS, lesser effects on $\alpha_{\rm em}$, $\sin^2\theta_W$

Luzio, Keshavarzi, Masiero & Paradisi, arXiv:2407.01123

$g_\mu - 2$ in SUSY Models

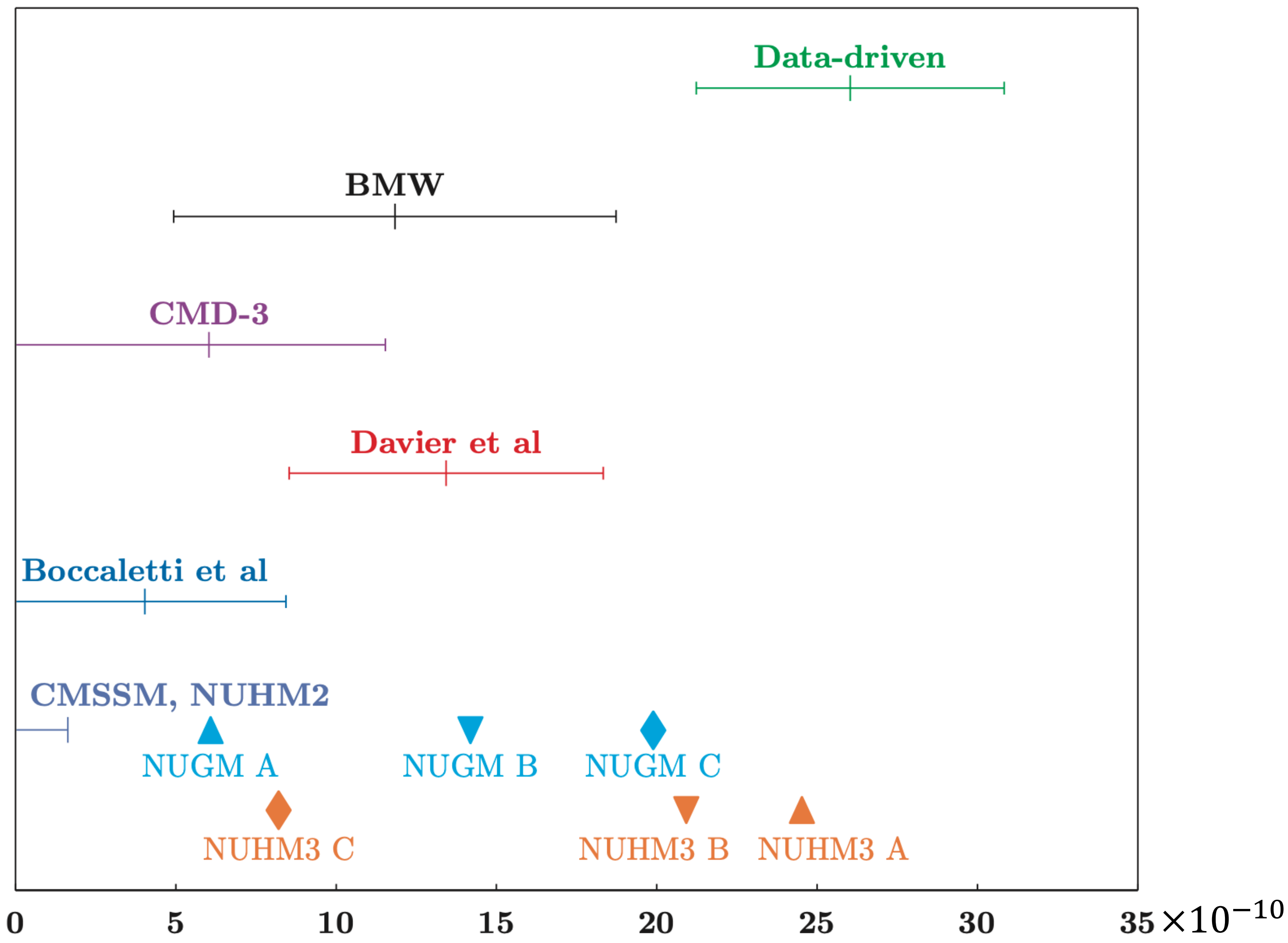
- LHC constraints on strongly-interacting sparticles exclude significant contribution to $g_\mu - 2$ in constrained minimal supersymmetric model (CMSSM)

- Violate universality in gaugino masses: $M_1 \neq M_2 \neq M_3$? NUGM

- Violate universality in sfermion and Higgs supersymmetry-breaking masses: $m_{\tilde{t}}, m_{\tilde{b}}, m_{\tilde{\tau}} \neq$other squarks, sleptons and Higgs masses? NUHM3

- Can accommodate "any" value of $g_\mu - 2$

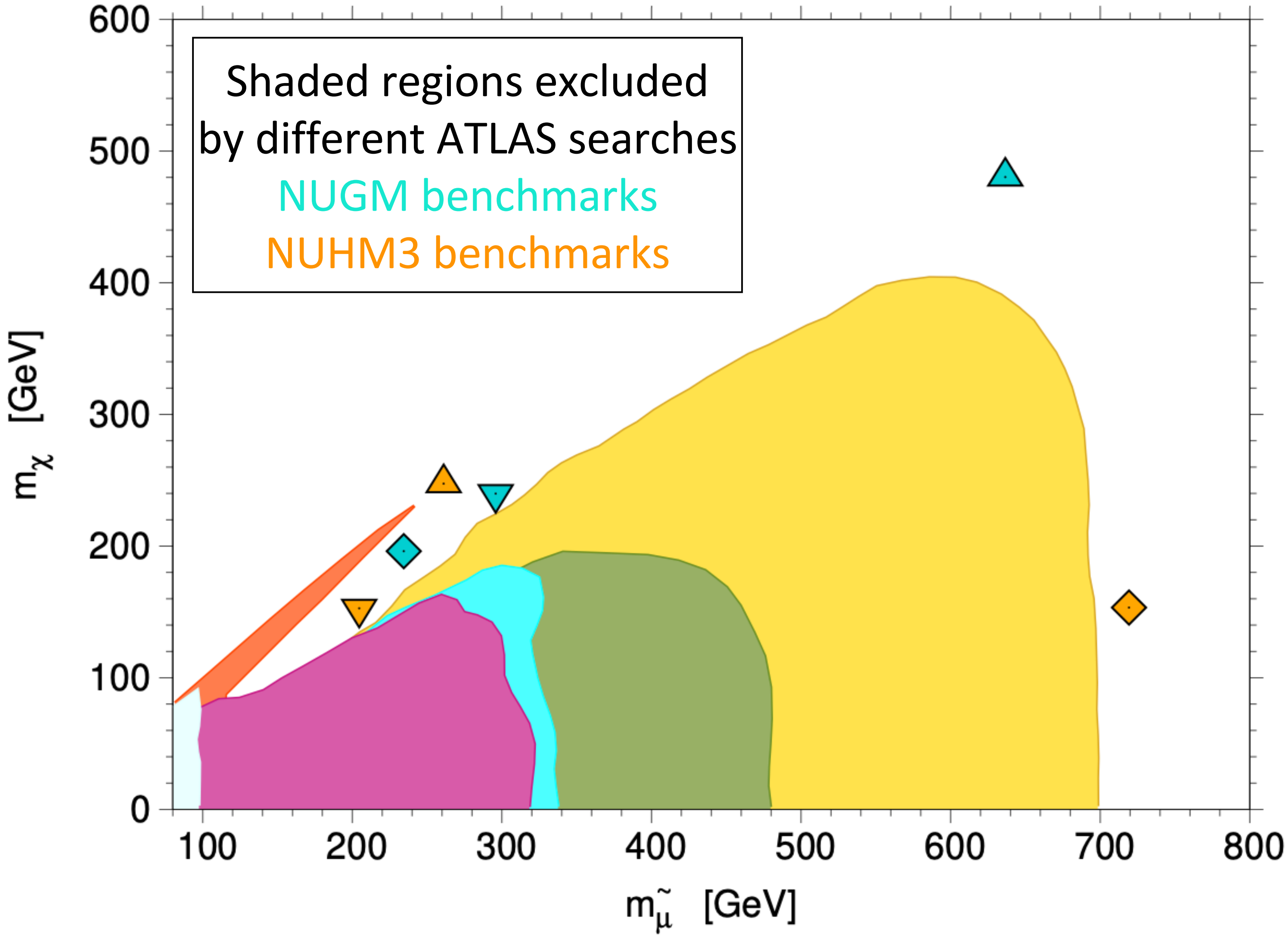
$g_\mu - 2$ in Benchmark SUSY Scenarios



Comparison of experimental and theoretical estimates of Δa_μ
with calculations in supersymmetric models including benchmarks

JE, Olive, Spanos, arXiv:2407.08679

Comparison of Benchmarks with ATLAS Limits



Prospects for future discovery

JE, Olive, Spanos, arXiv:2407.08679

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?**

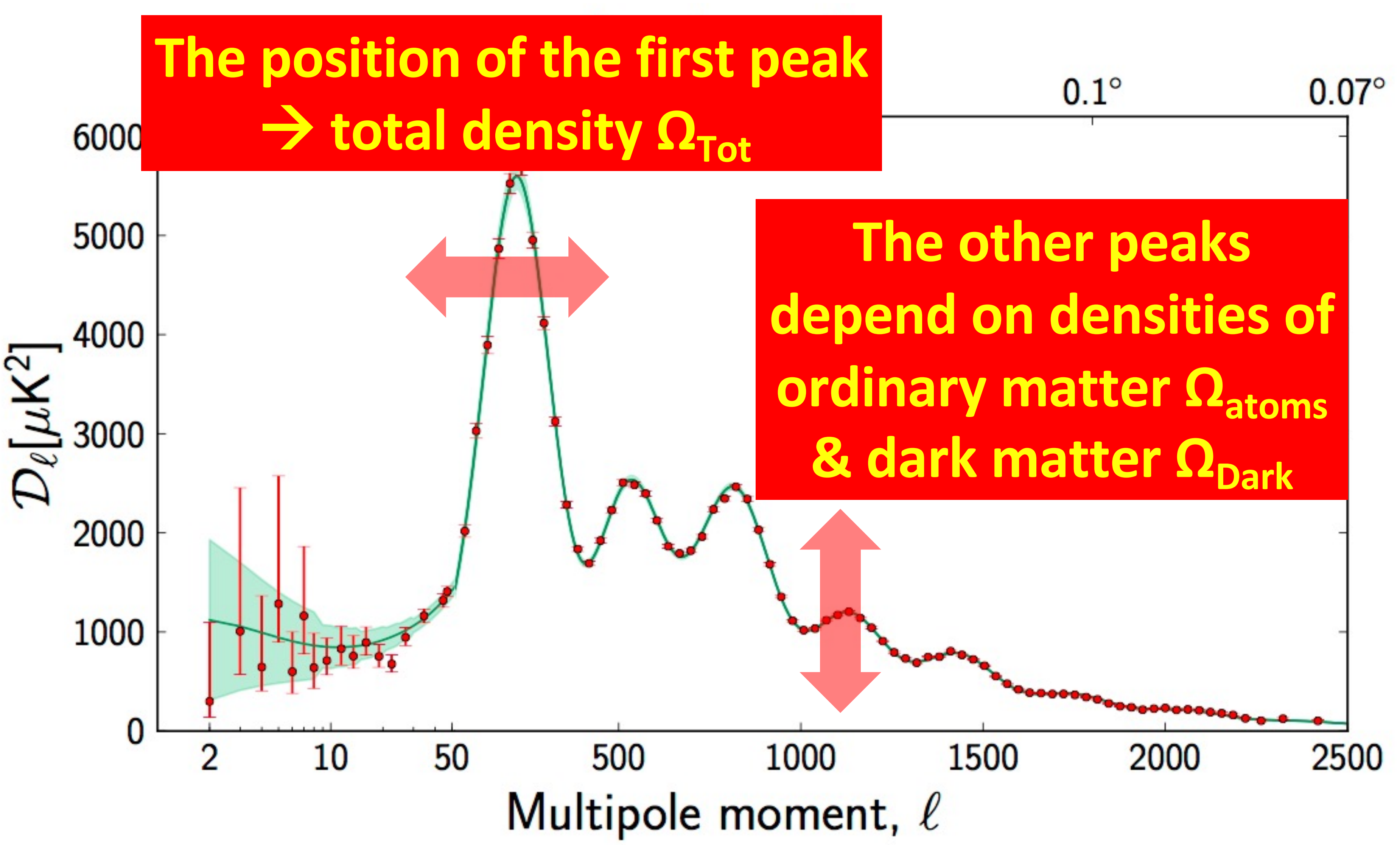
The Rotation Curves of Galaxies

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

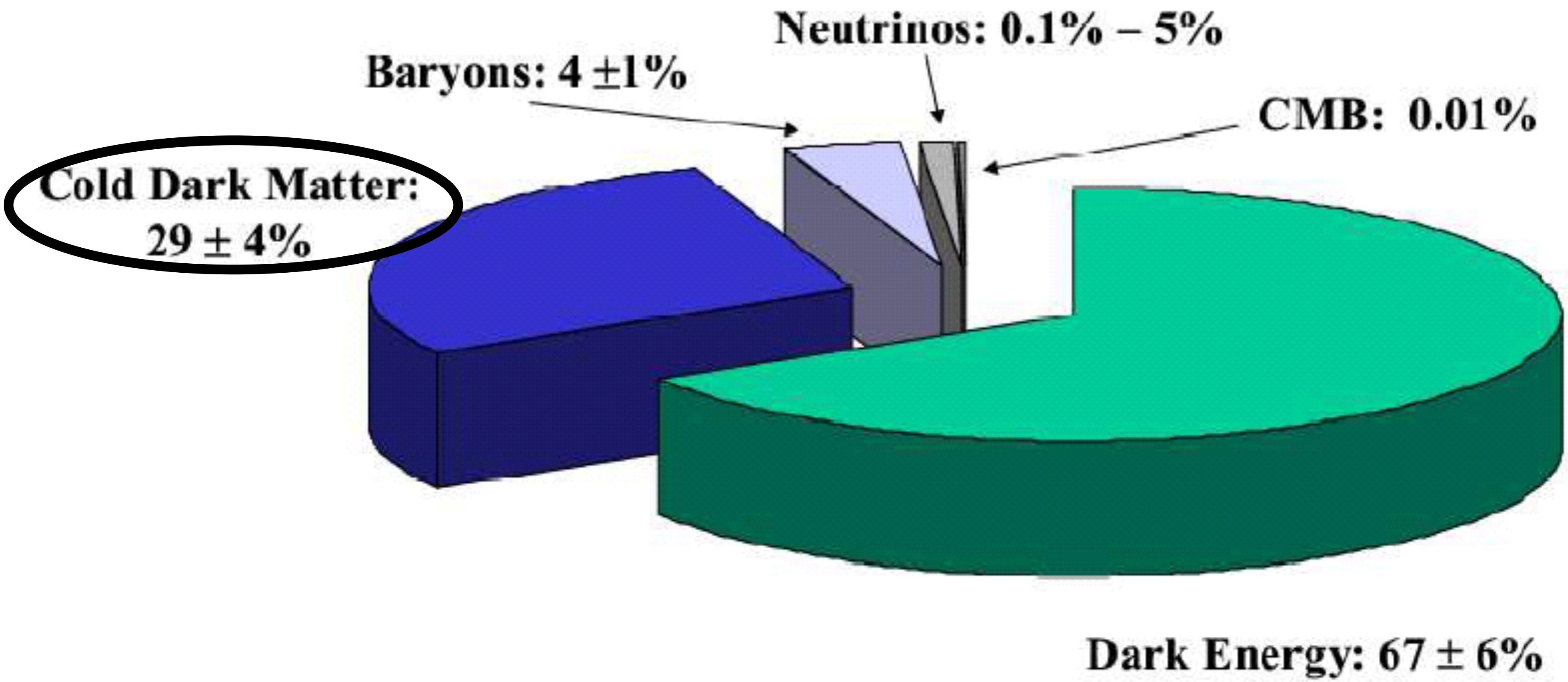
Scanned at the American Institute of Physics

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

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

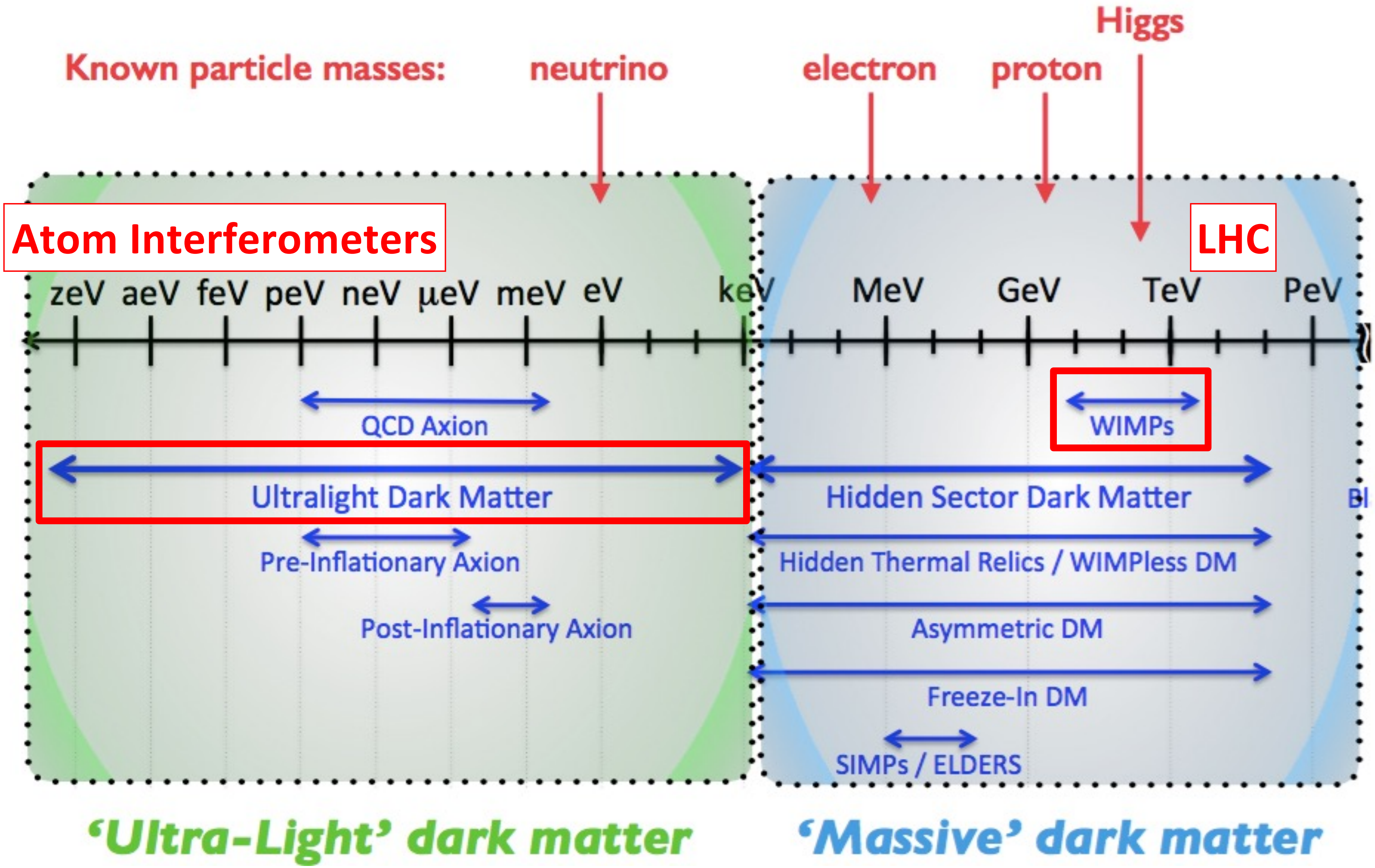
Properties of Dark Matter

- 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

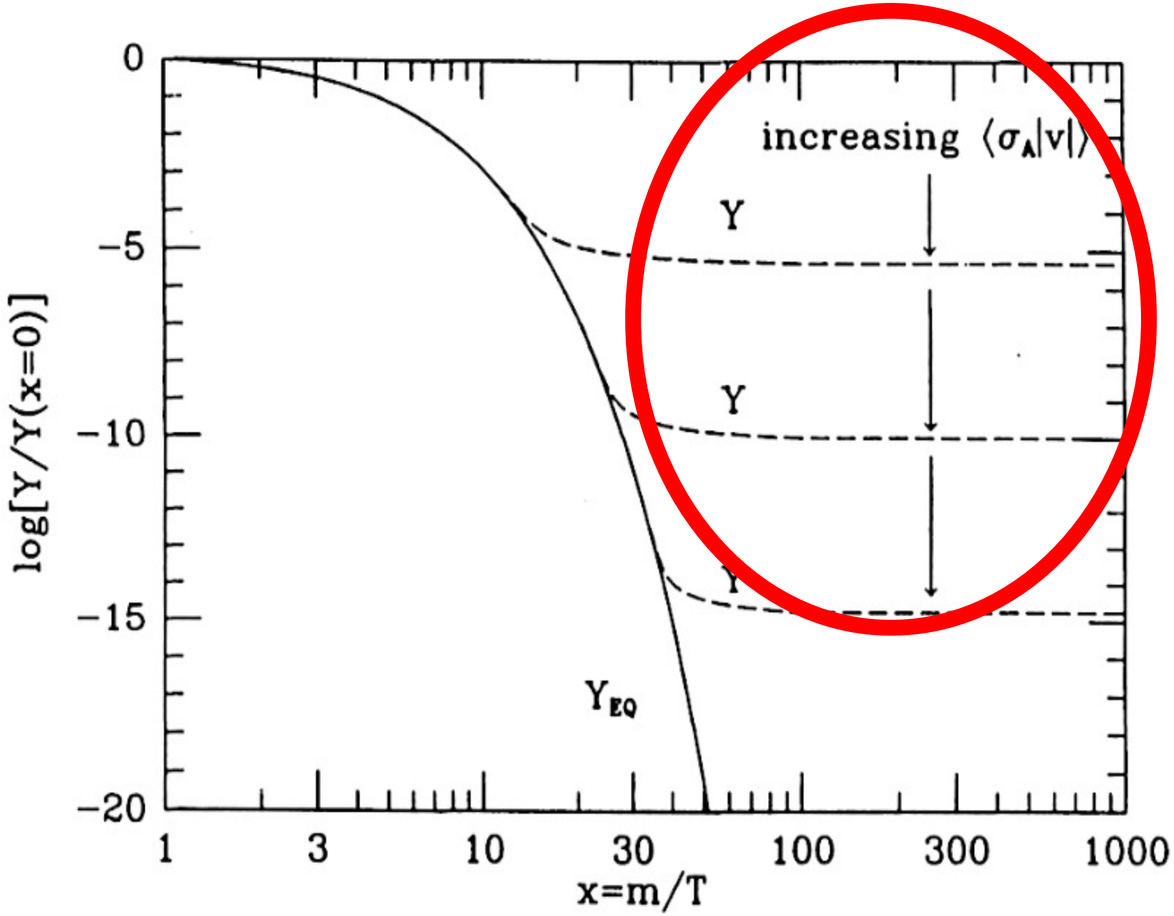
- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe other neutrinos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

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

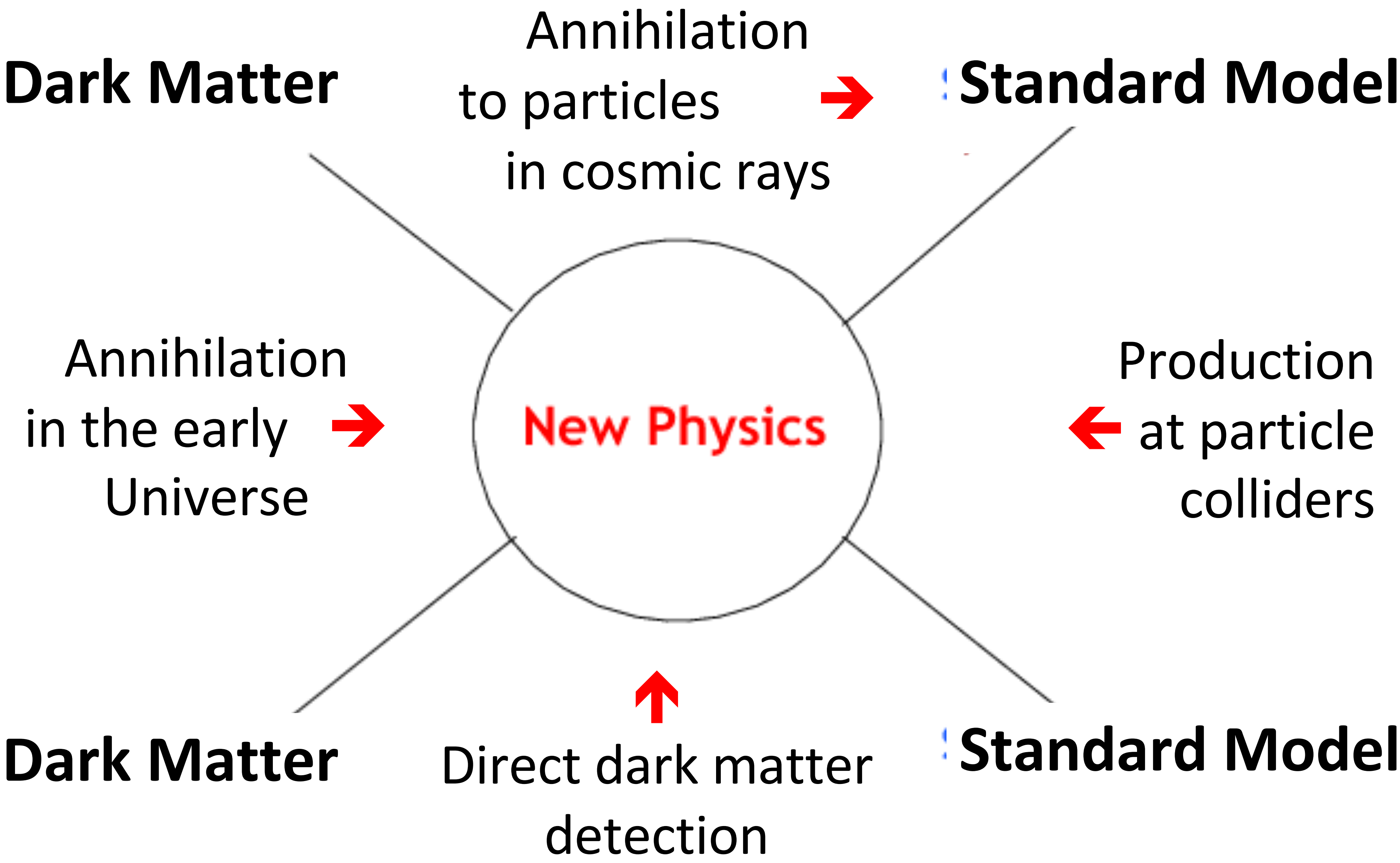
  (Excluded by LEP, direct searches)

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

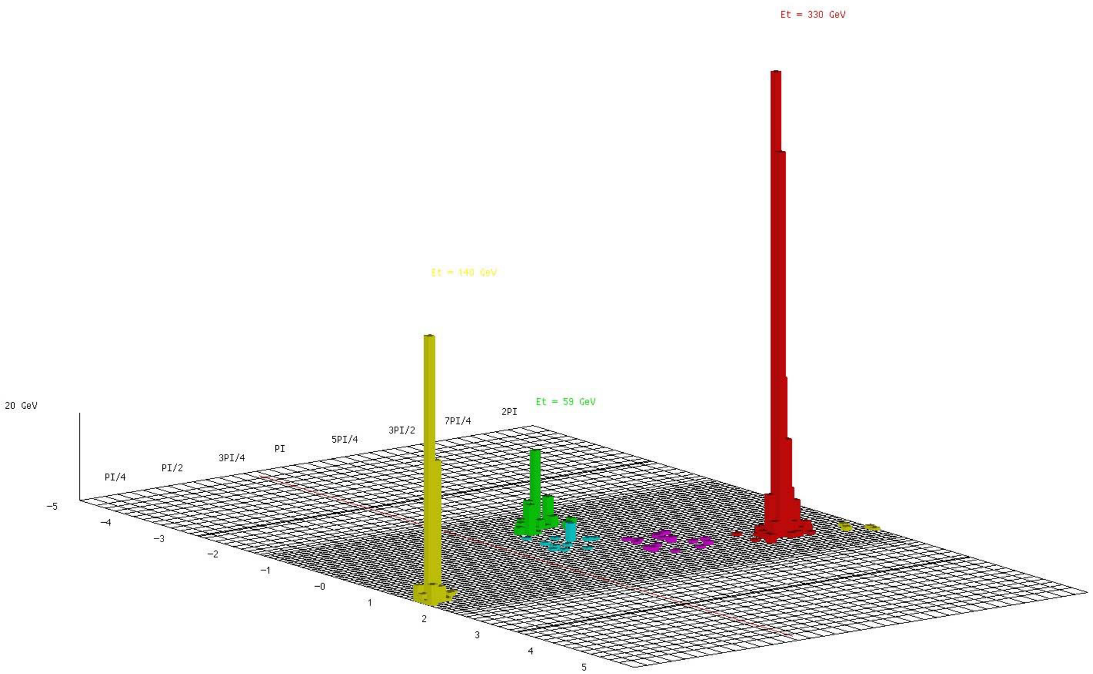
  Gravitino

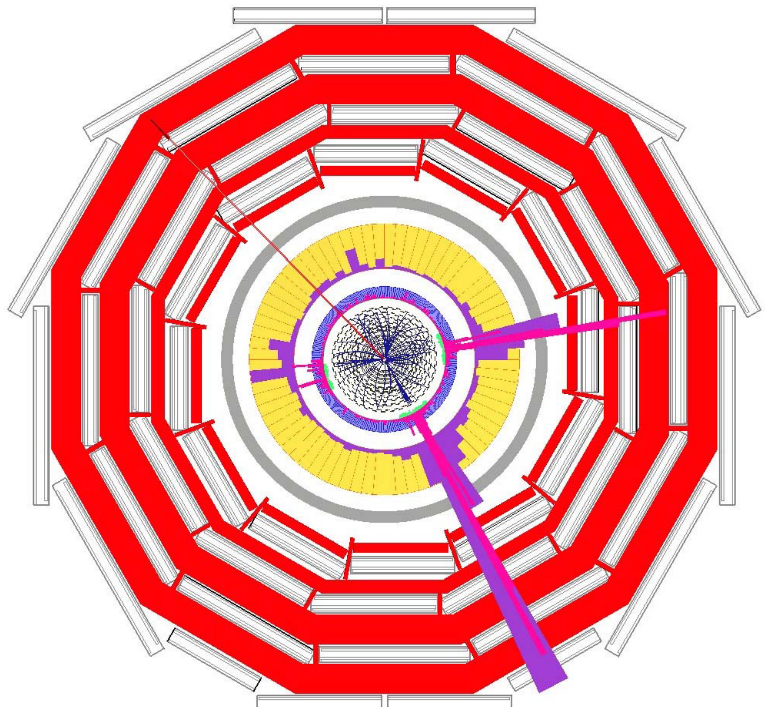
  (nightmare for detection)

Searches for Dark Matter



Classic Dark Matter Signature



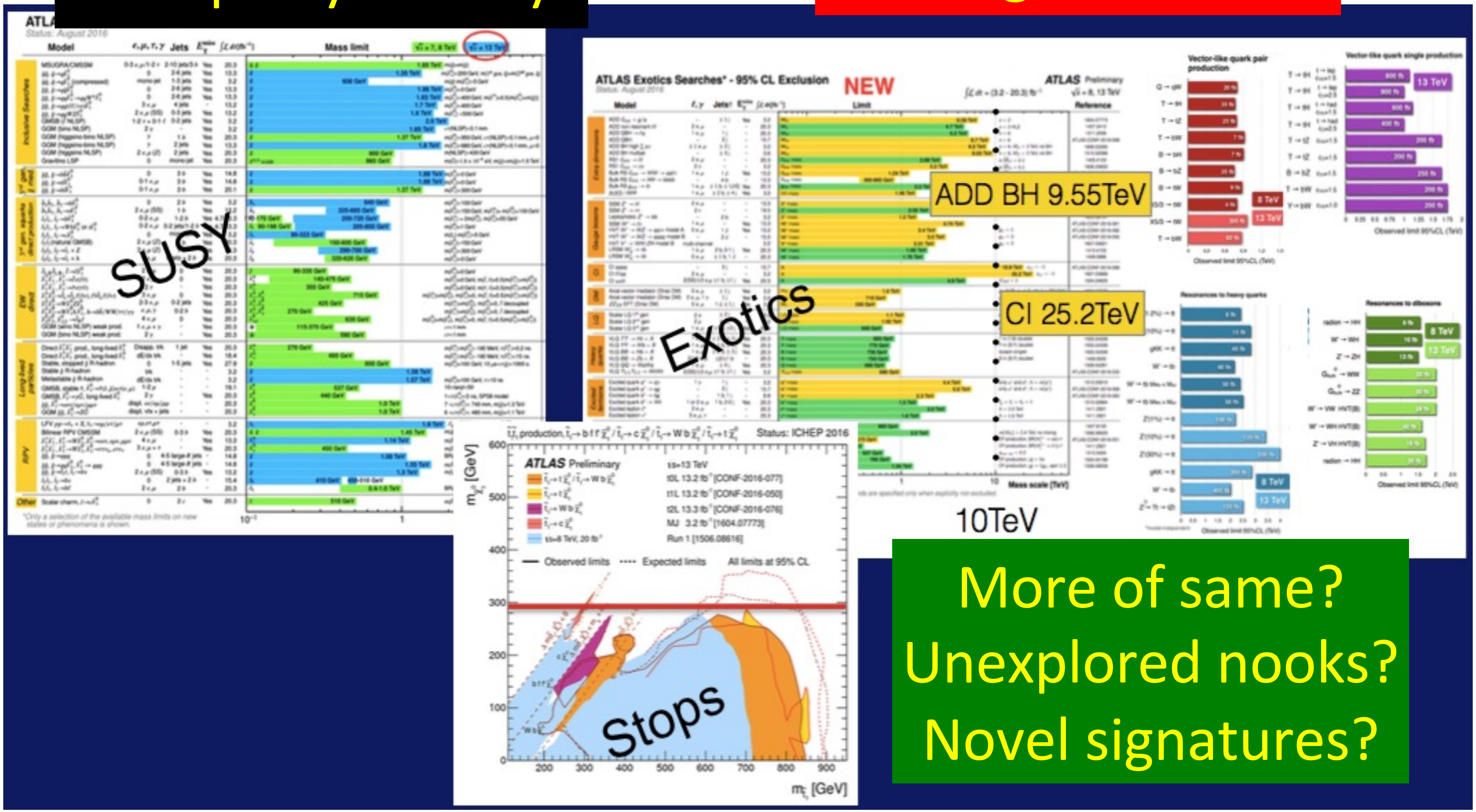


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?

Unexplored nooks?

Novel signatures?

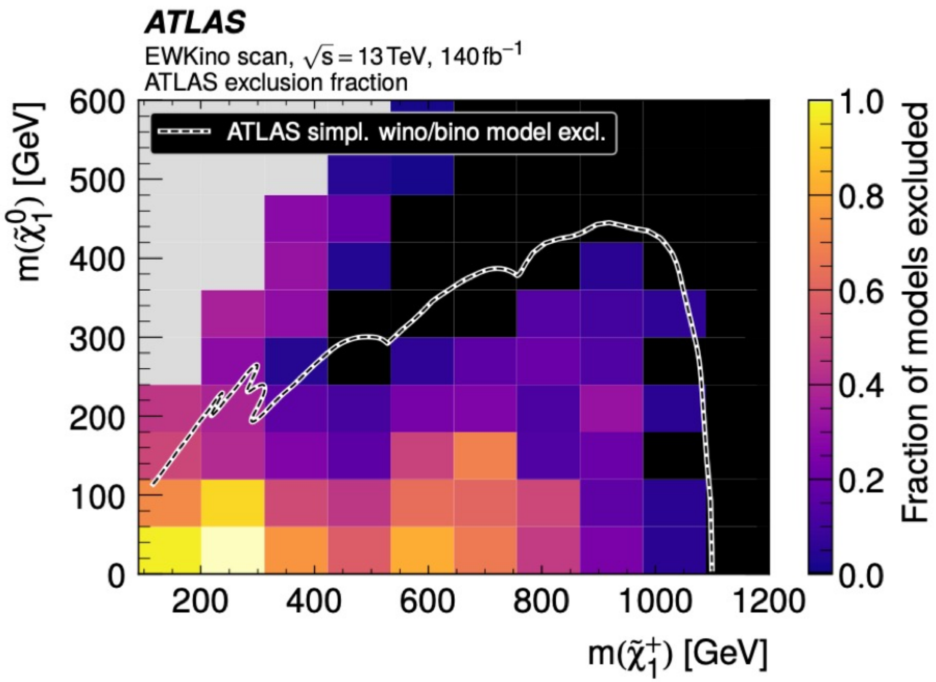
Fraction of Models Excluded

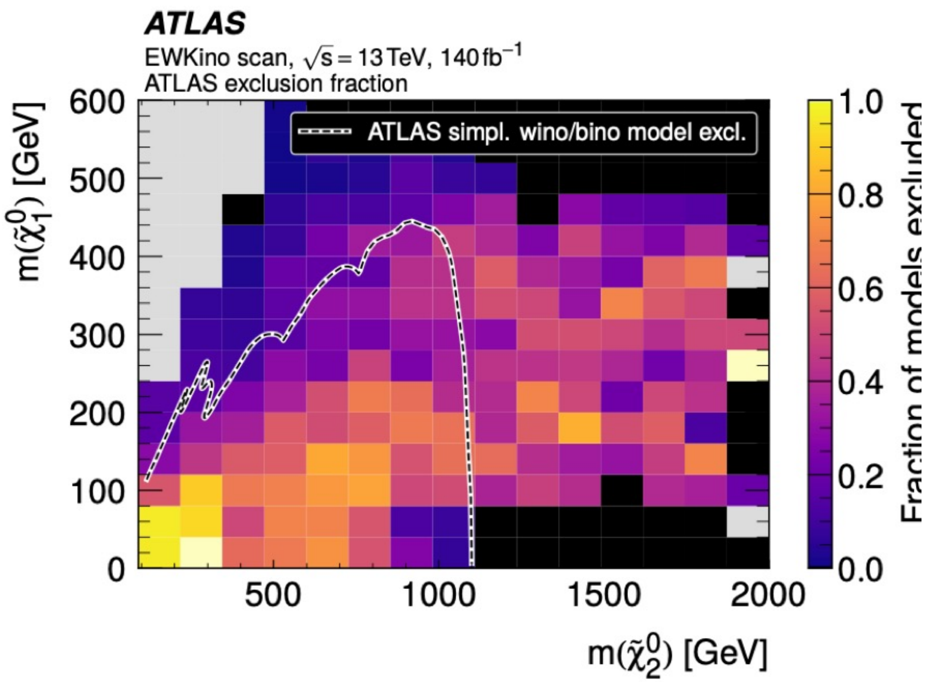
Exclusions not 100%, not as strong as often stated

Lines = Exclusions in searches with simplifying assumptions on spectrum and decay modes

Black = < 10% of pMSSM models excluded

Cream = > 90% of pMSSM models excluded

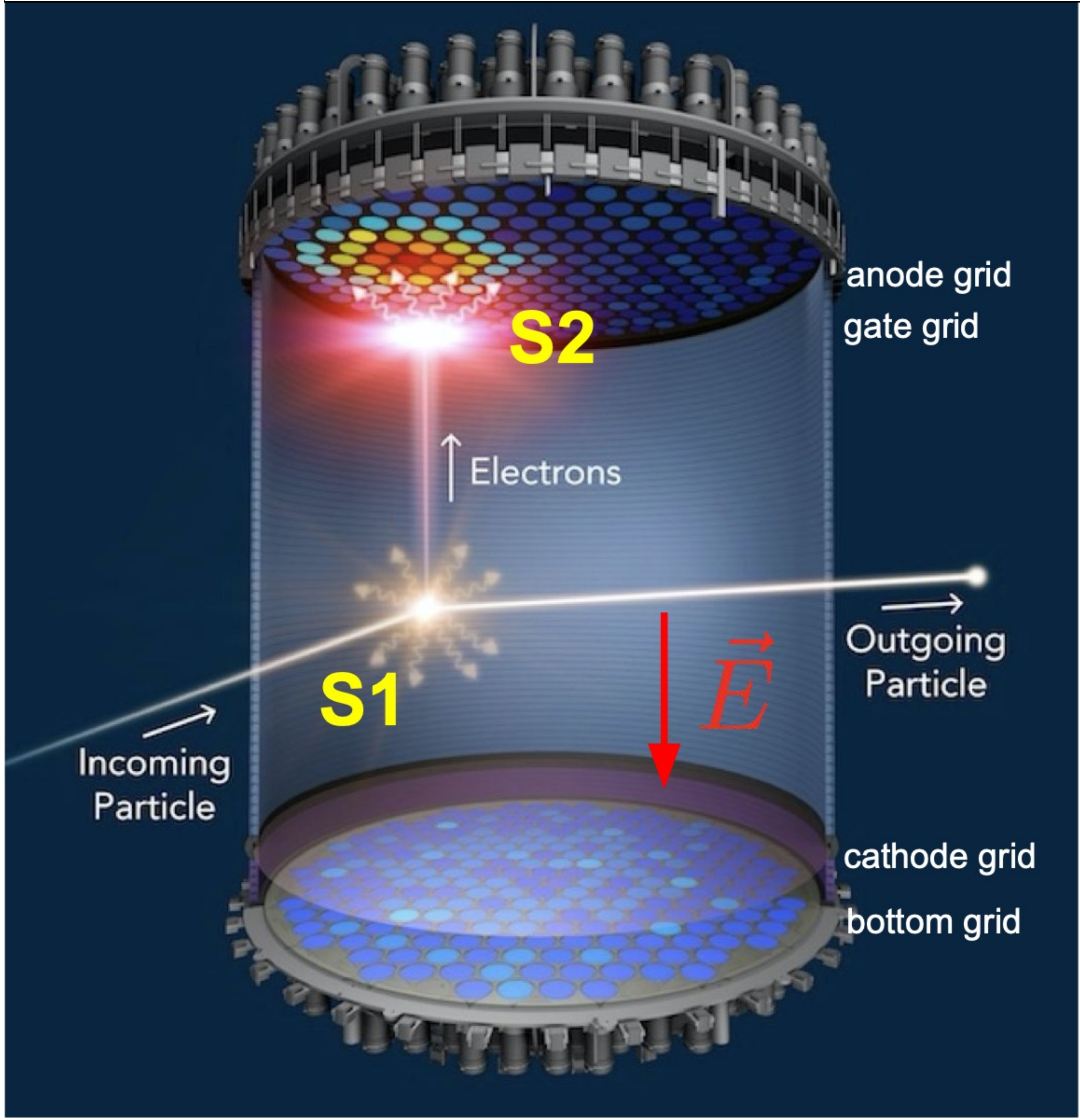


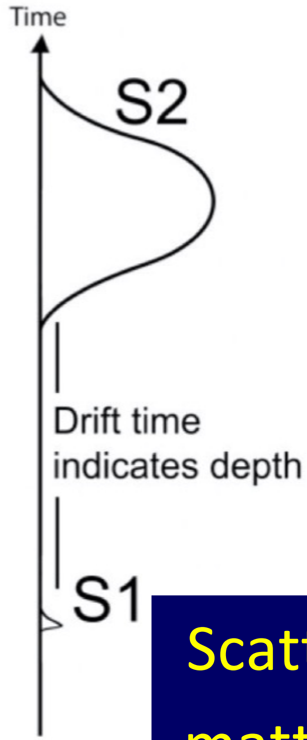


Many low-mass pMSSM models consistent with constraints

Hope springs eternal!

Direct Dark Matter Detection

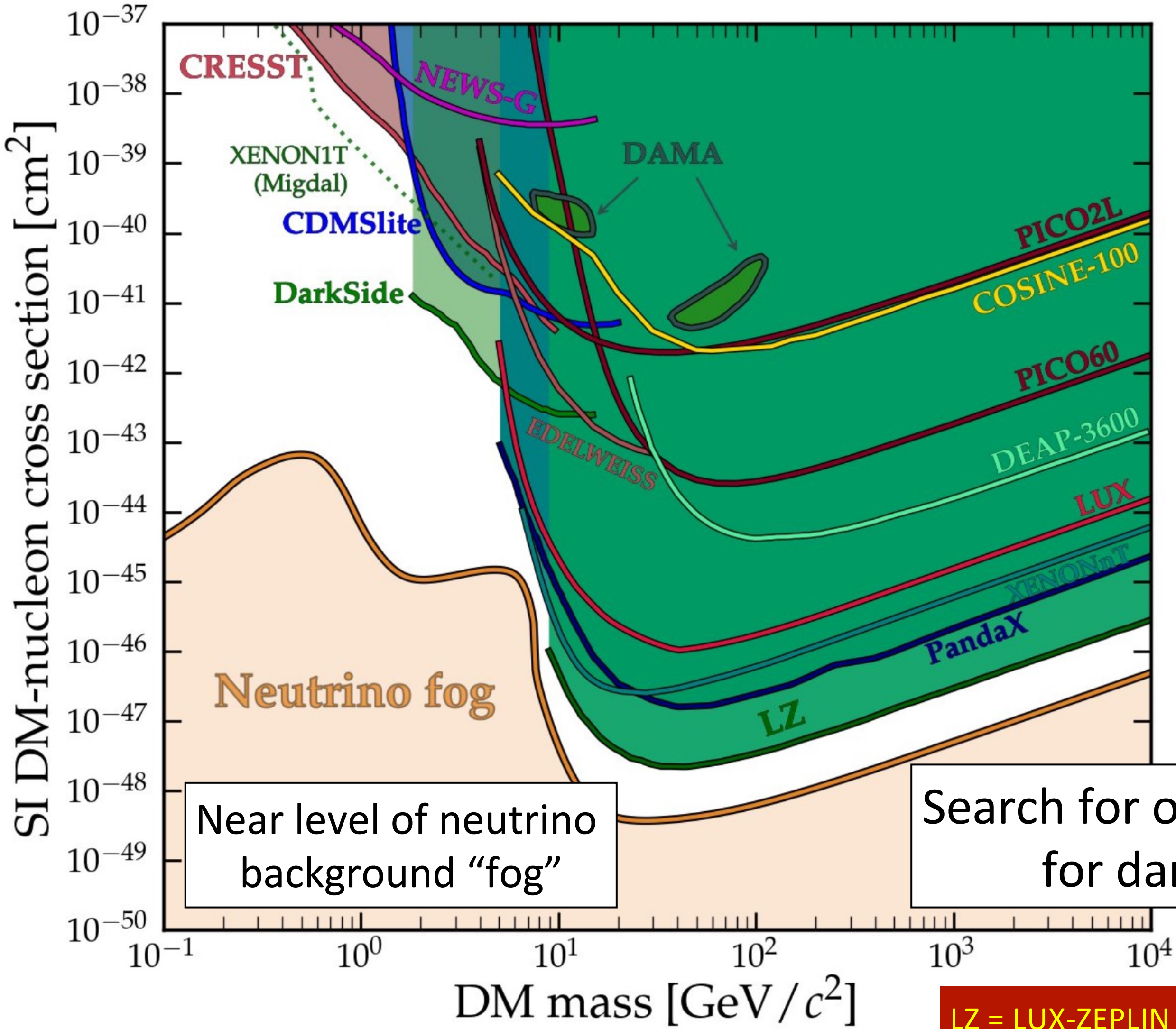




Scattering of dark matter particle in deep underground laboratory: example of liquid xenon detector

Direct Dark Matter Searches

Latest experimental results



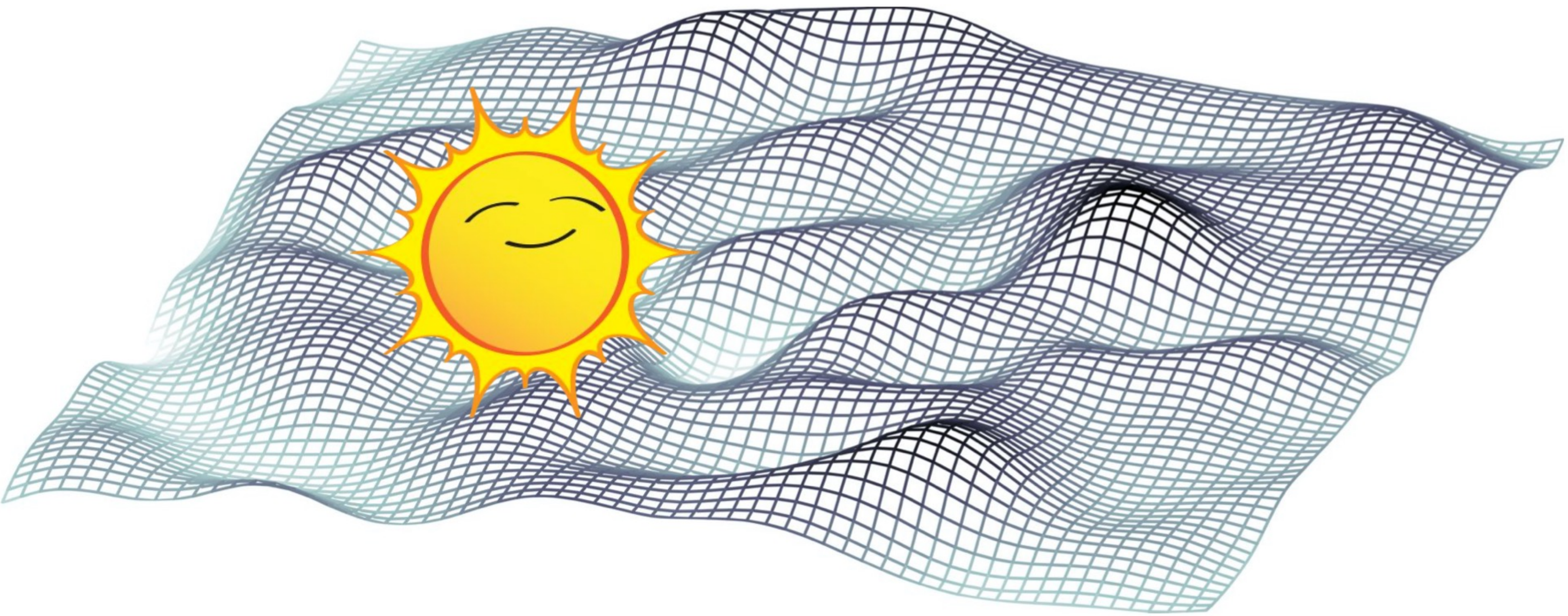
Near level of neutrino background "fog"

Search for other candidates for dark matter?

LZ = LUX-ZEPLIN collaboration, *preliminary*

Ultralight Dark Matter

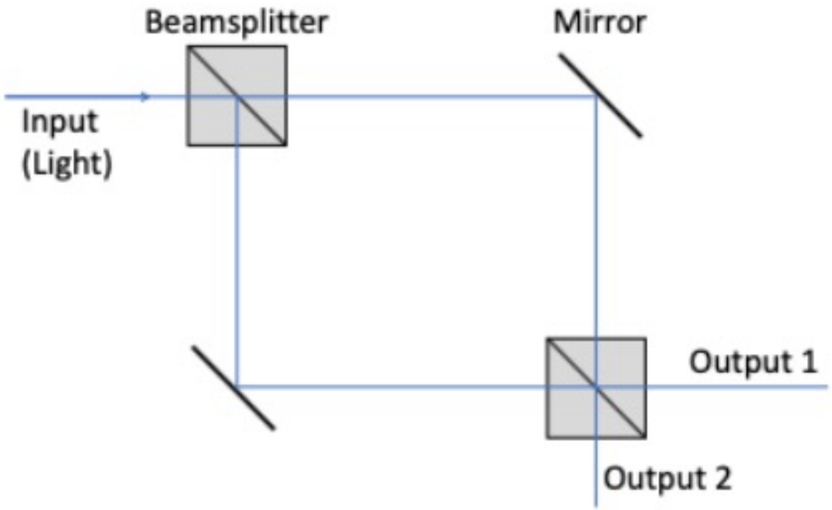
A scalar ULDM $\phi(\mathbf{x}, t)$ field would be present throughout the Solar System



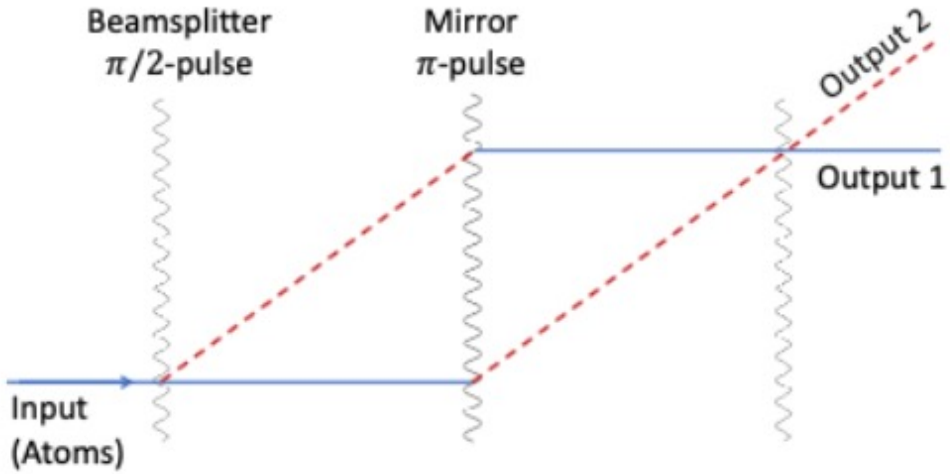
The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

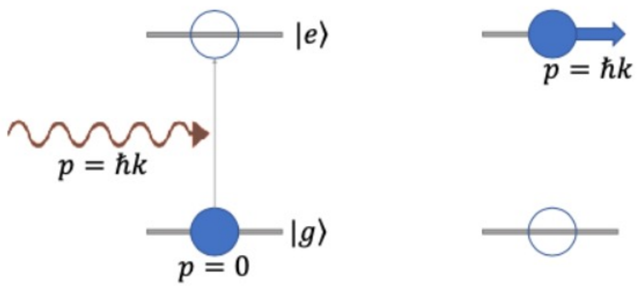


Atom Interferometer

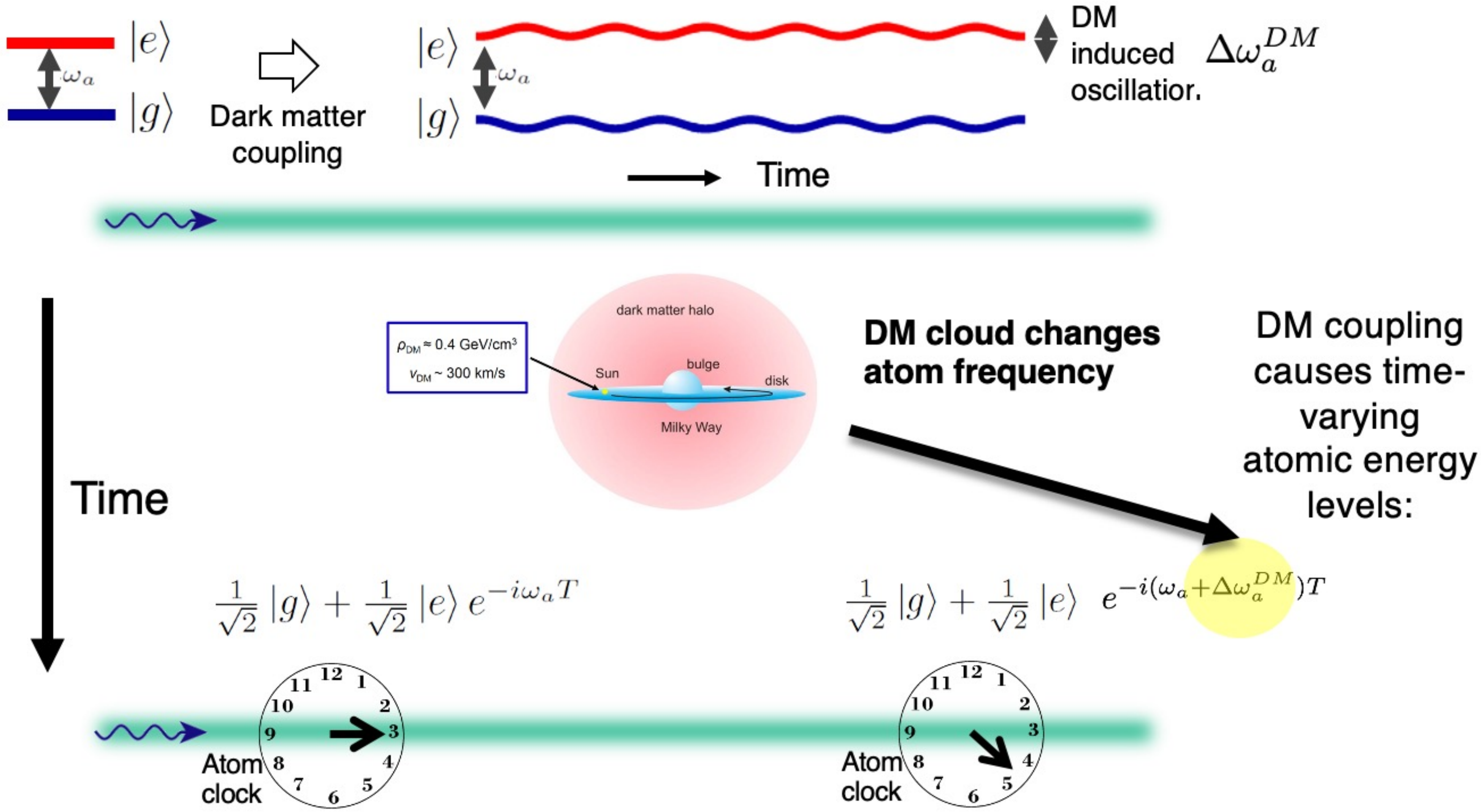


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

Interference between atoms following different paths



Effect of Dark Matter on Atom Interferometer



AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], A Beniwal[1],
D. Bortoletto[3], T. Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman[5], J. Carlton[1],
G. Elertas[5], J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
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P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3],
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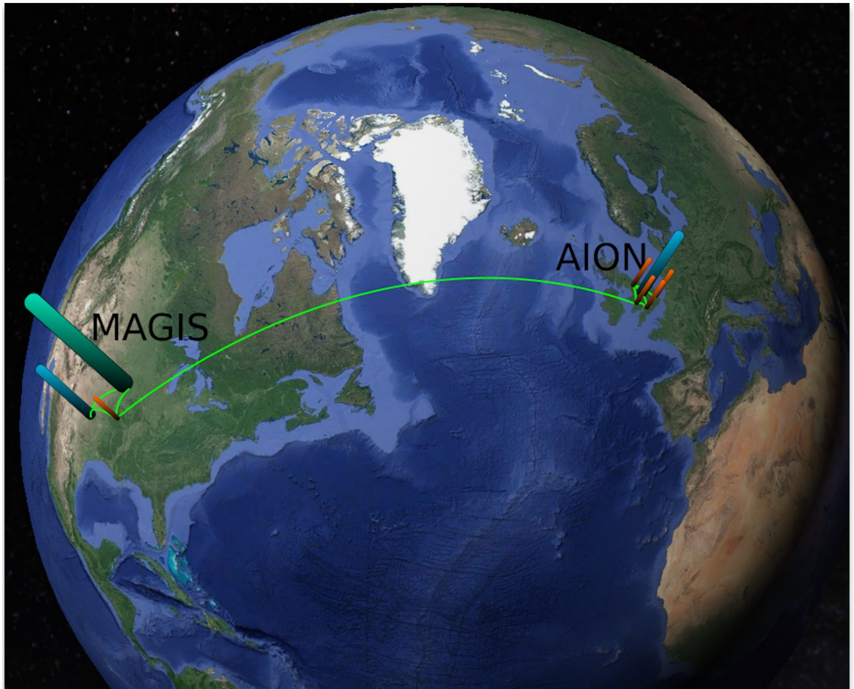


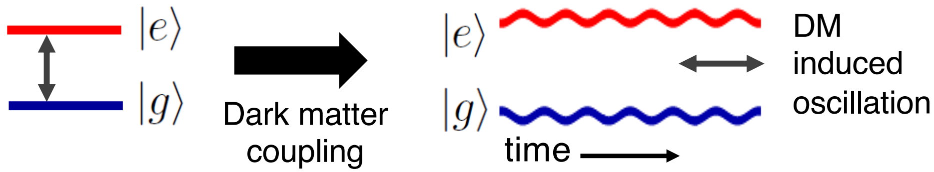
Network with MAGIS project in US

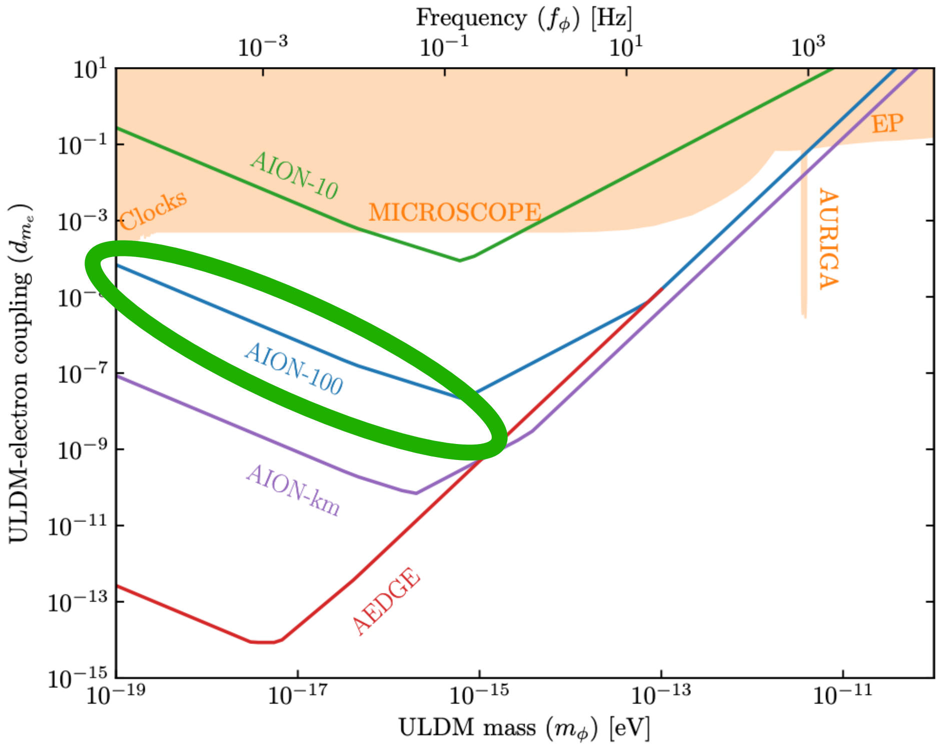
MAGIS Collaboration (Abe et al): arXiv:2104.02835

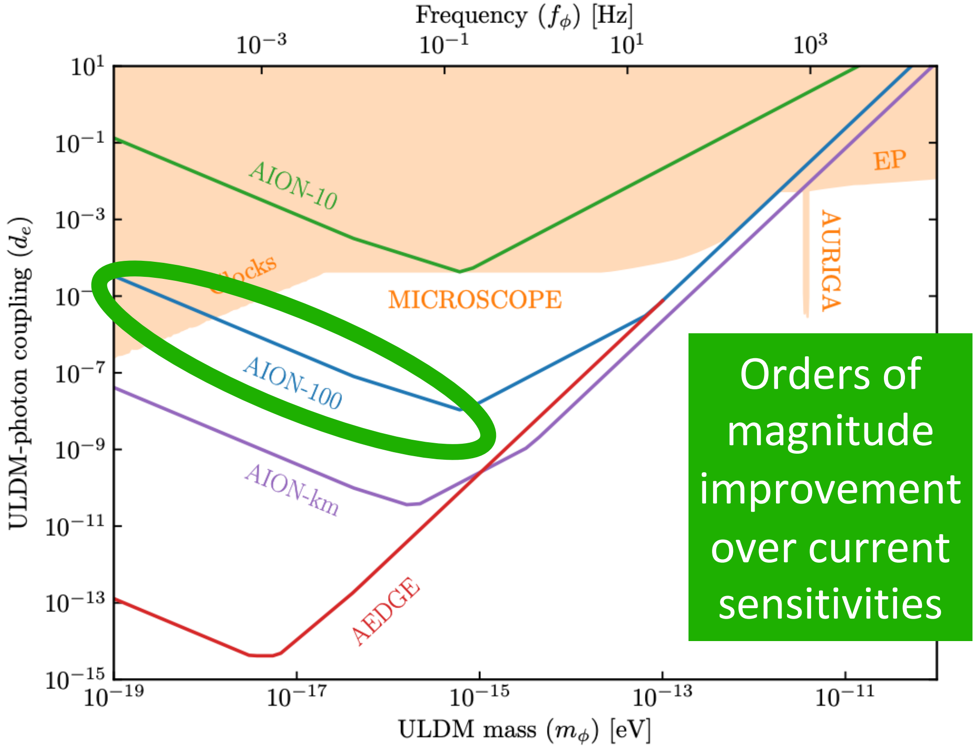
Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

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







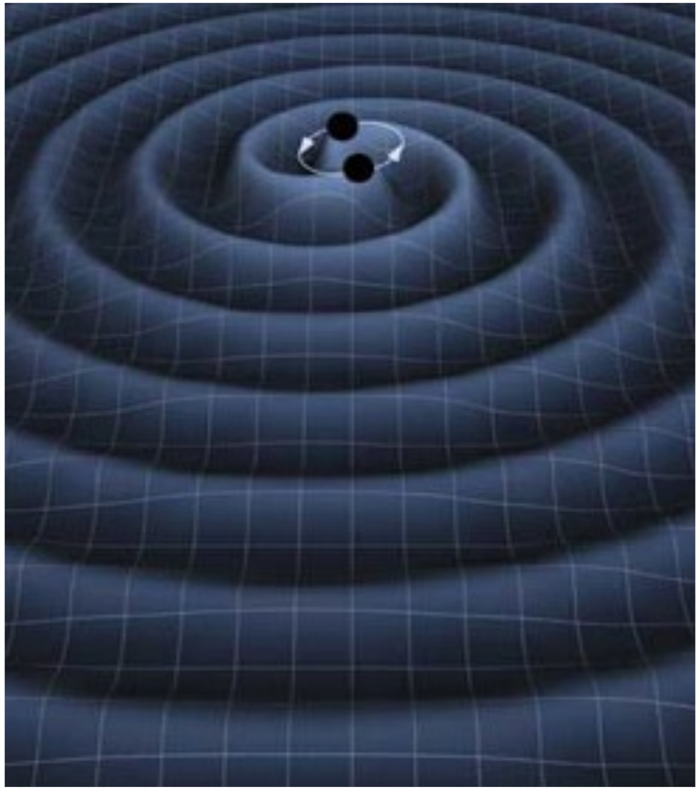
Orders of magnitude improvement over current sensitivities

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

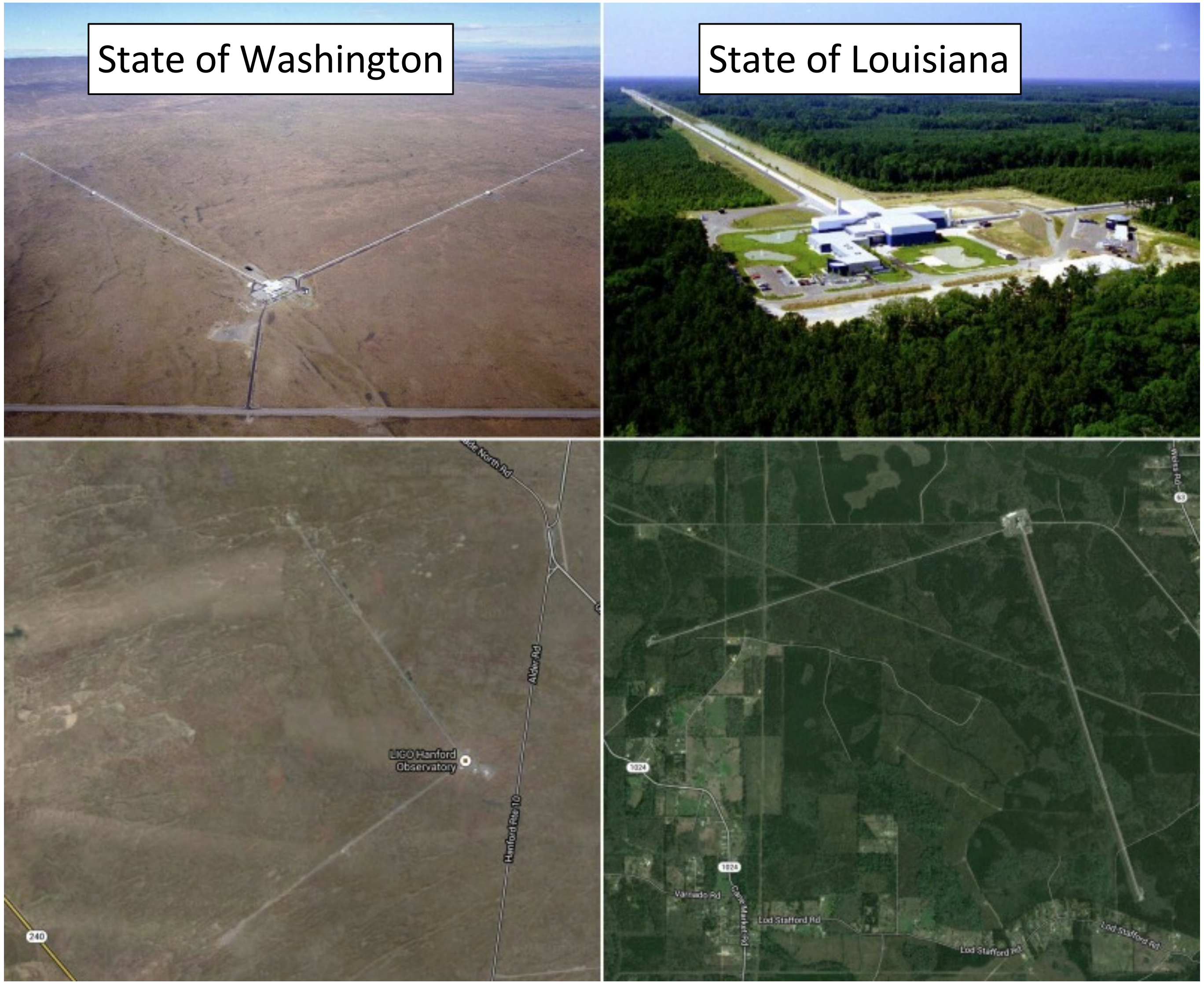
Albert Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, 22.6.Berlin 1916



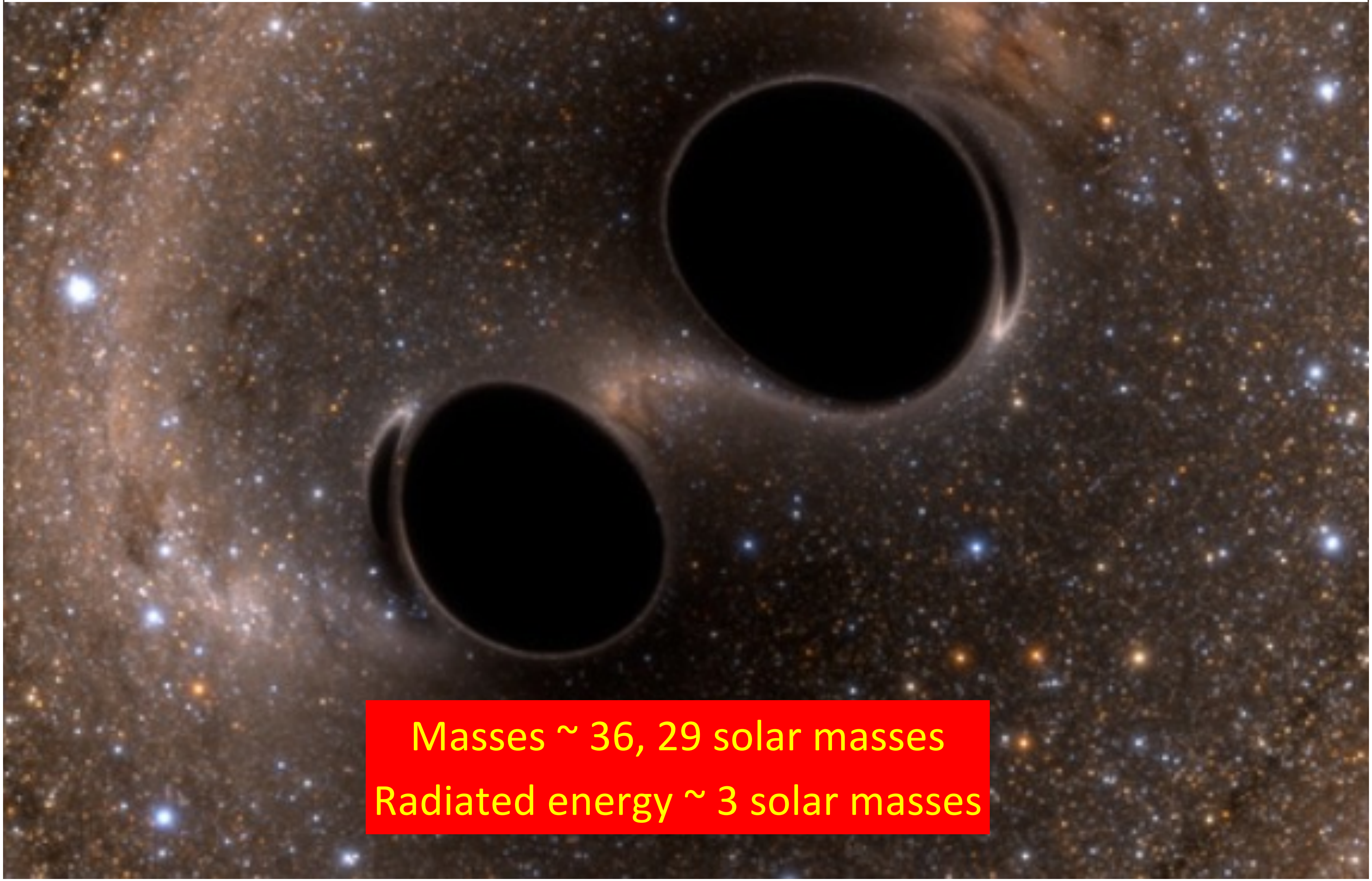
- Tried to retract prediction in 1936!

Direct Discovery of Gravitational Waves

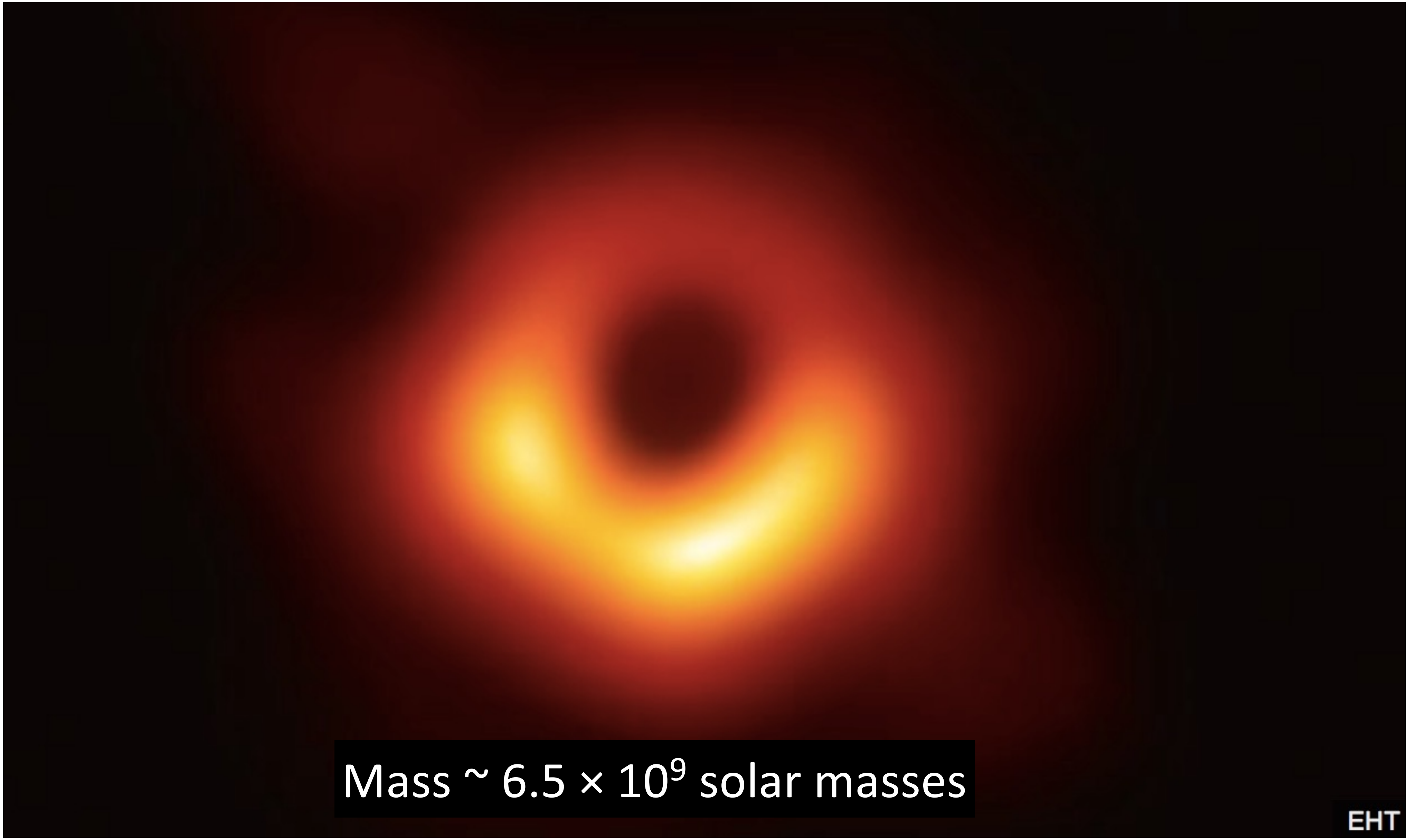
- Measu



Fusion of two massive black holes

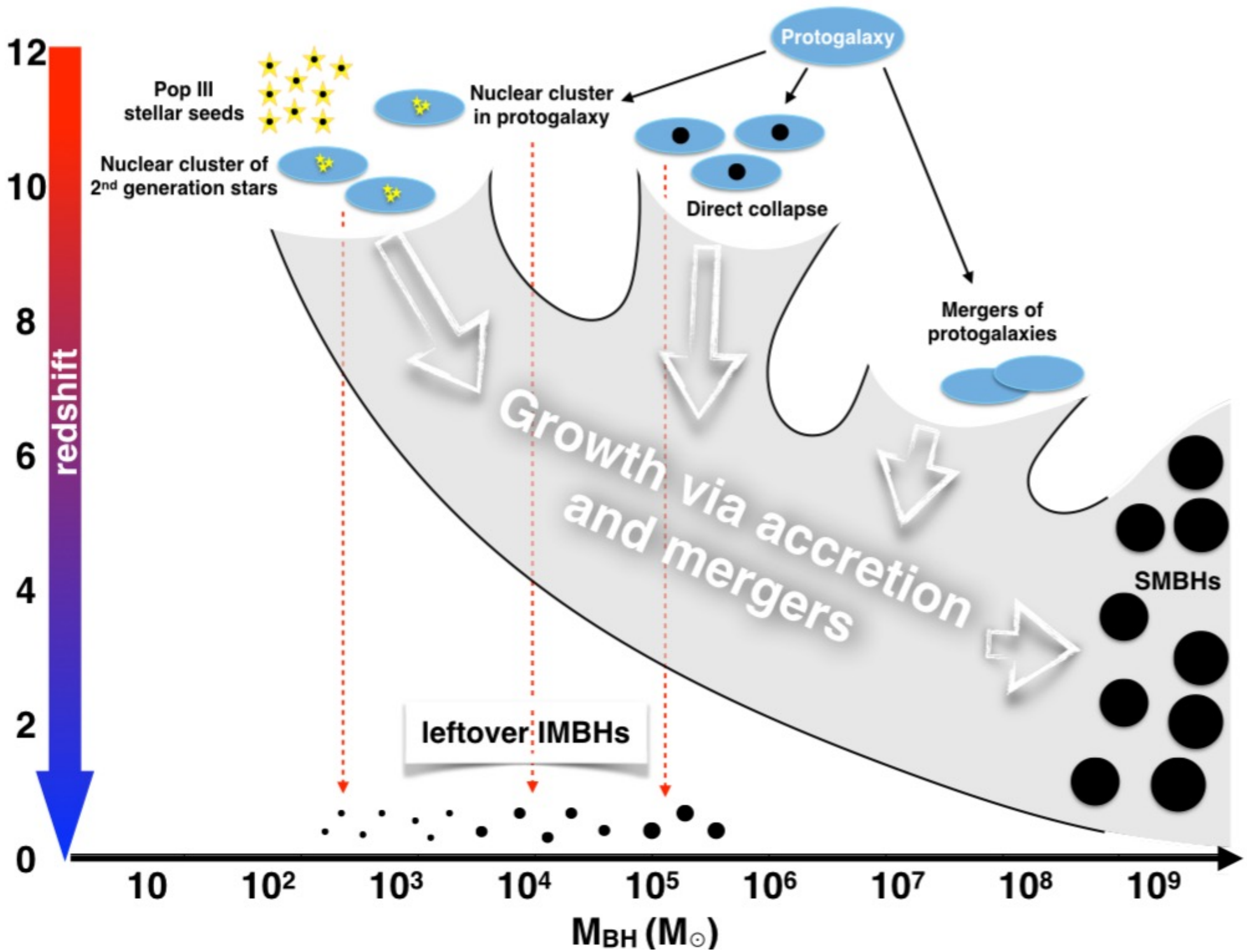


Supermassive Black Holes in Active Galactic Nuclei: Image of M87

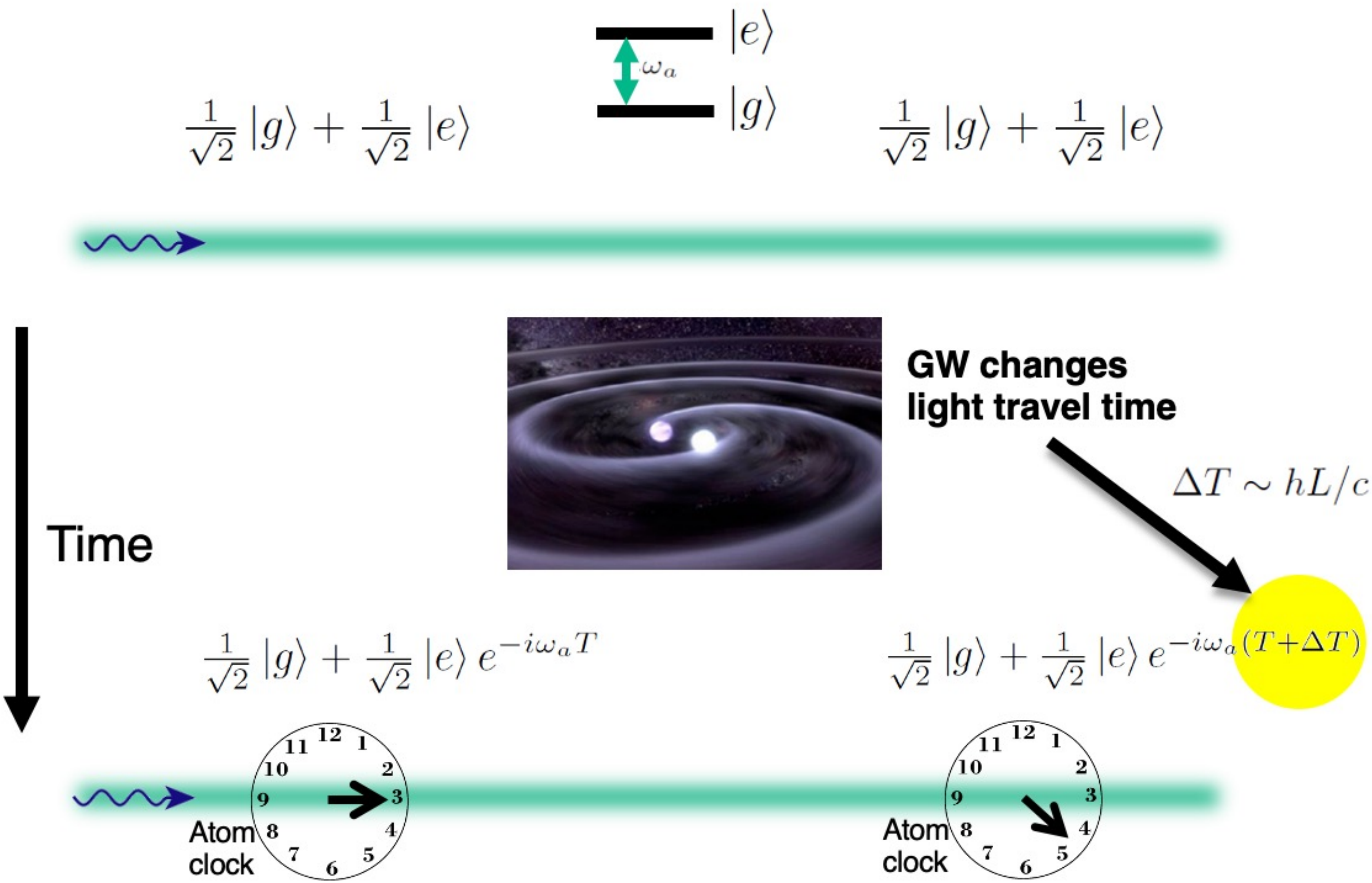


How to Make a Supermassive BH?

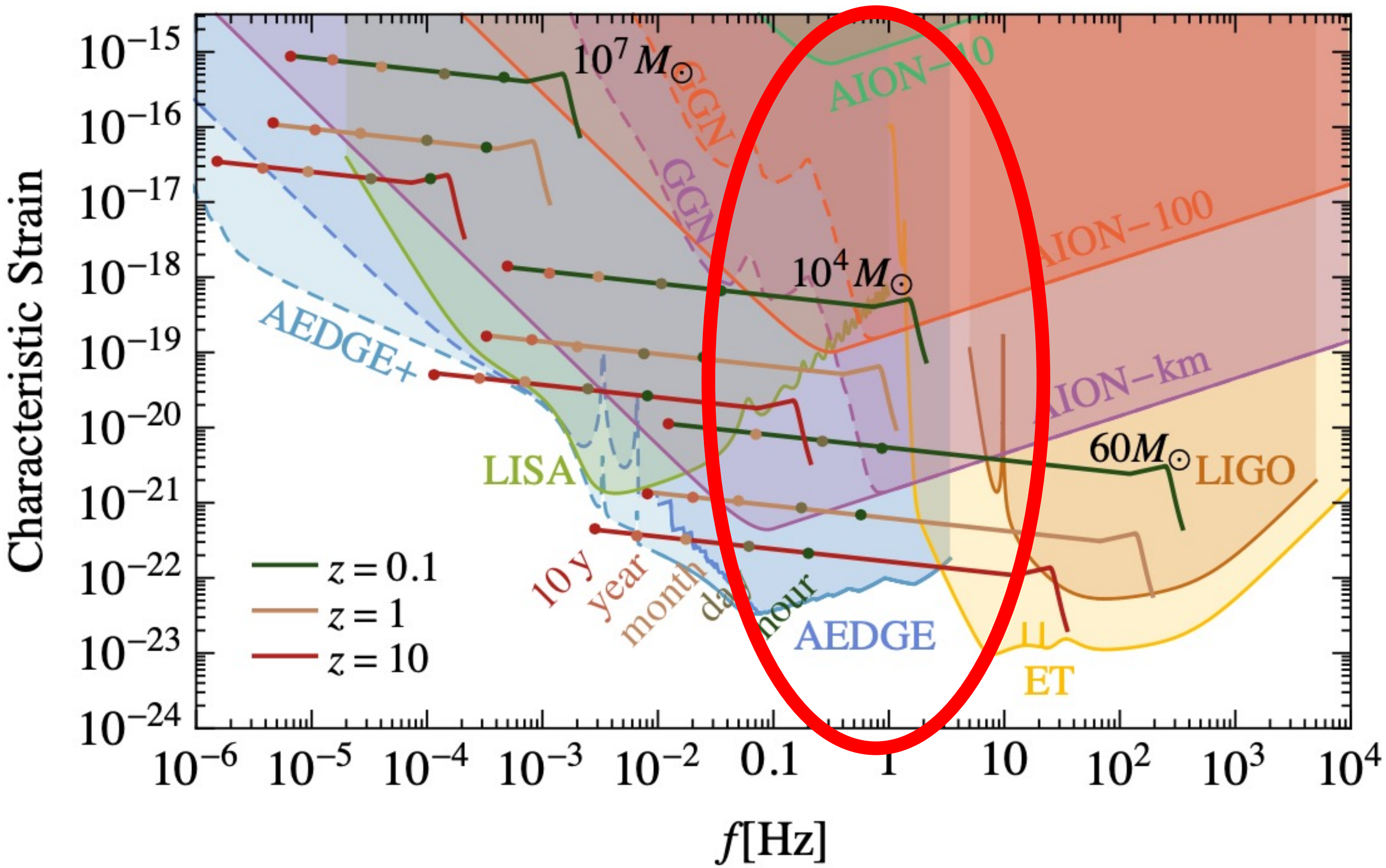
SMBHs from mergers of intermediate-mass BHs (IMBHs)?



Effect of Gravitational Wave on Atom Interferometer



Gravitational Waves from IMBH Mergers

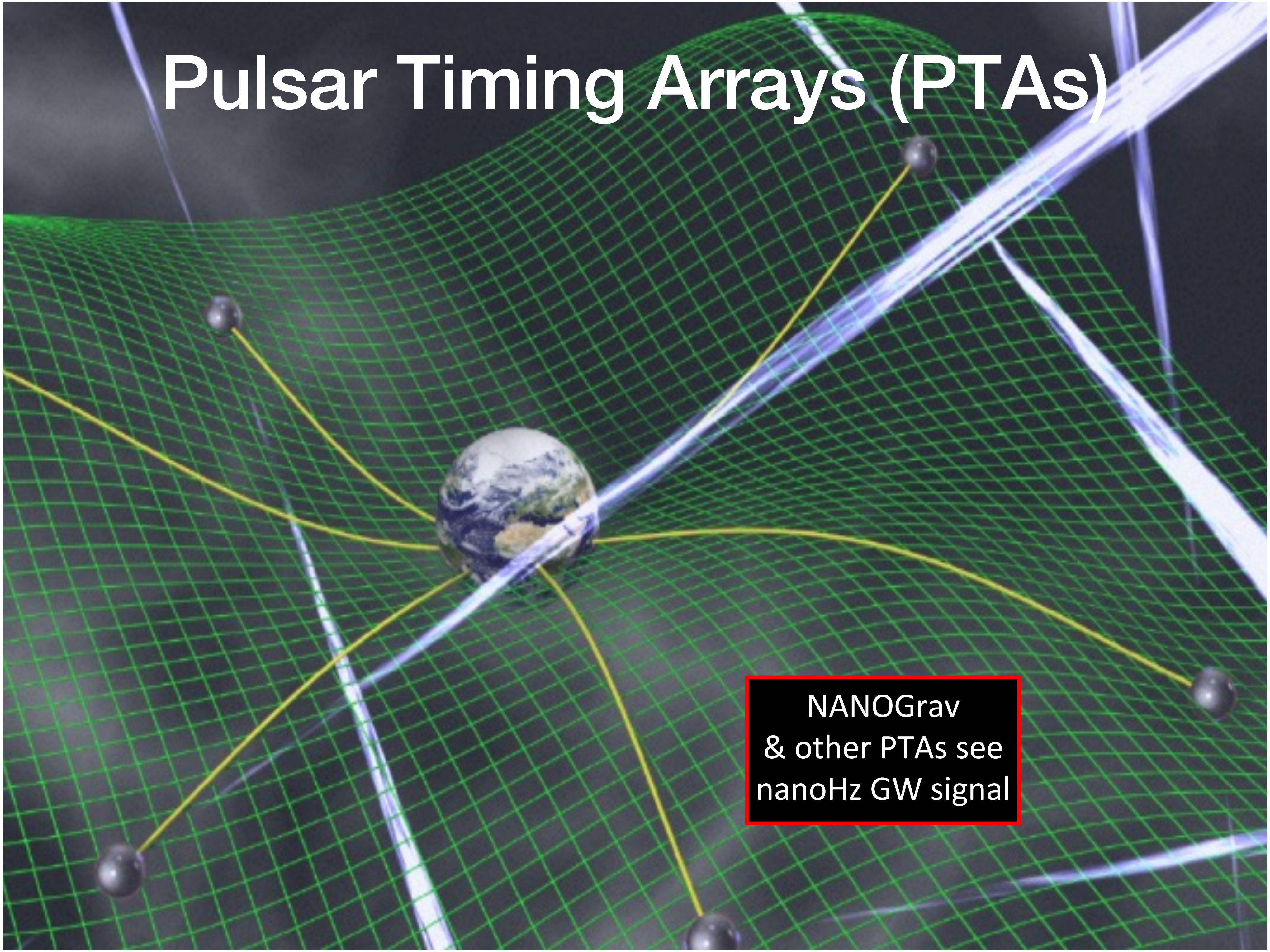


Probe formation of SMBHs

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

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

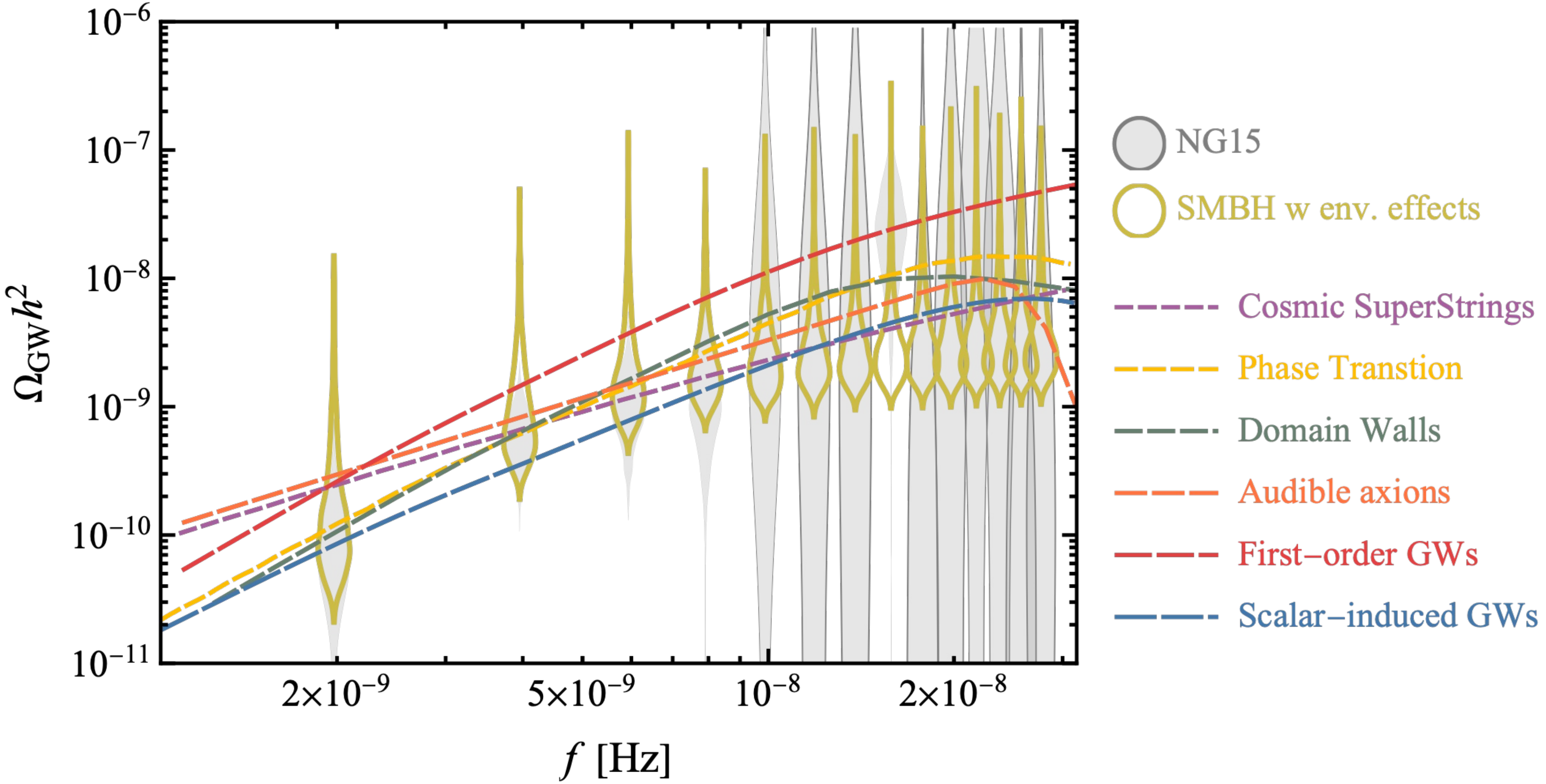
Pulsar Timing Arrays (PTAs)



The Biggest Bangs since the Big Bang

Fits to NANOGrav

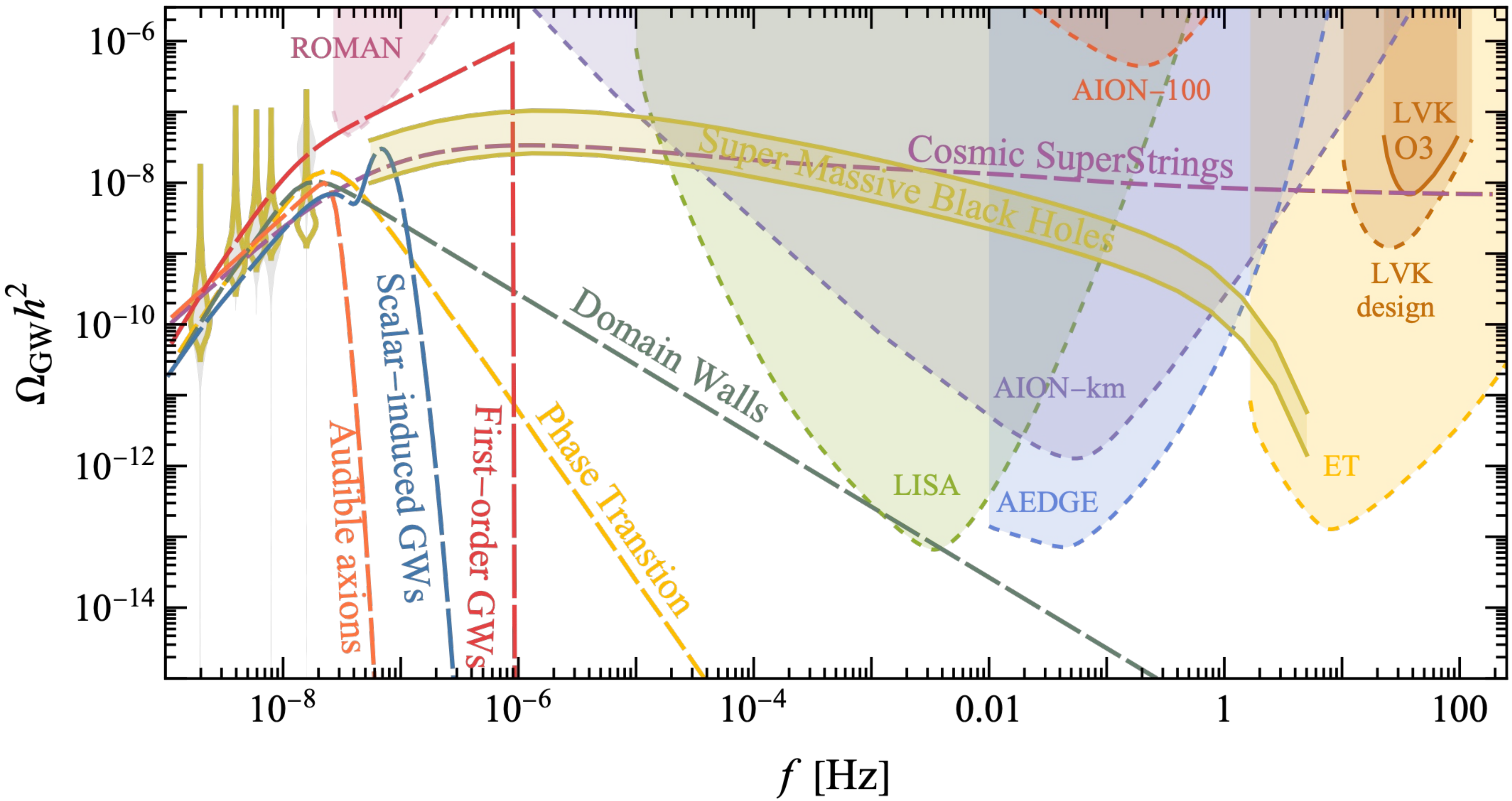
AION



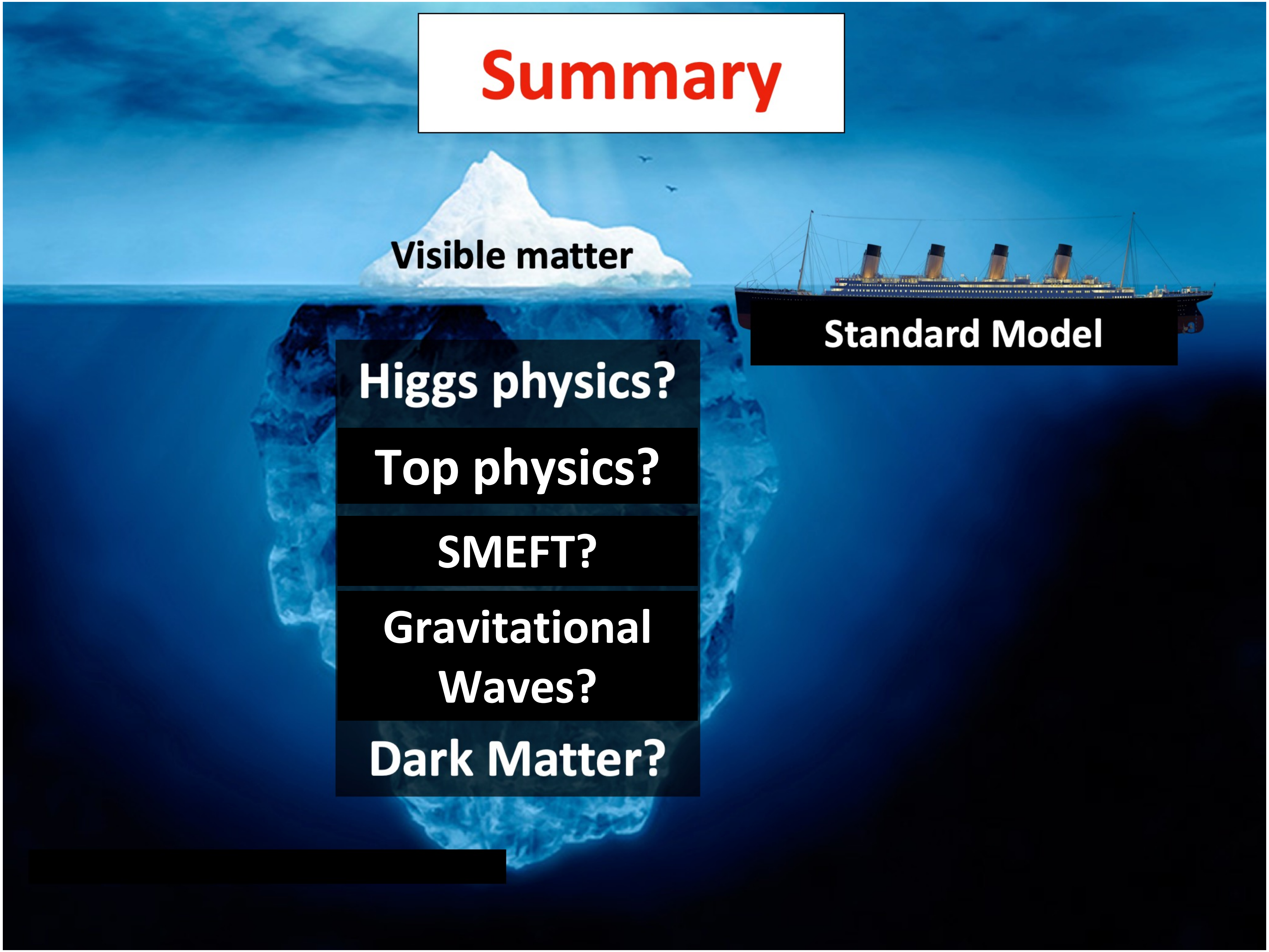
JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, arXiv:2308.08546

Extension of Fits to Higher Frequencies

AION



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


Summary
Visible matter
Standard Model
Higgs physics?
Top physics?
SMEFT?
Gravitational Waves?
Dark Matter?
[redacted]