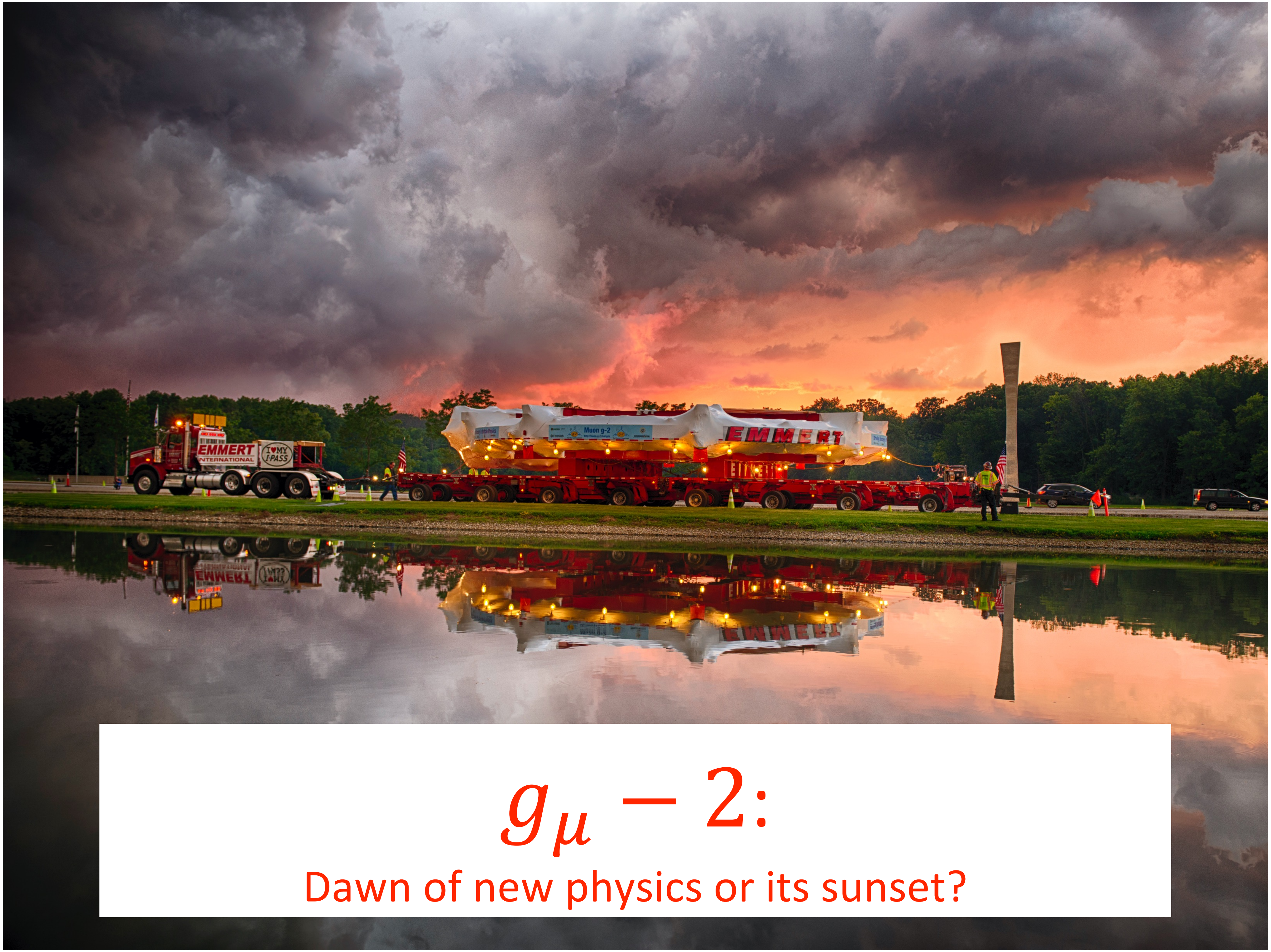
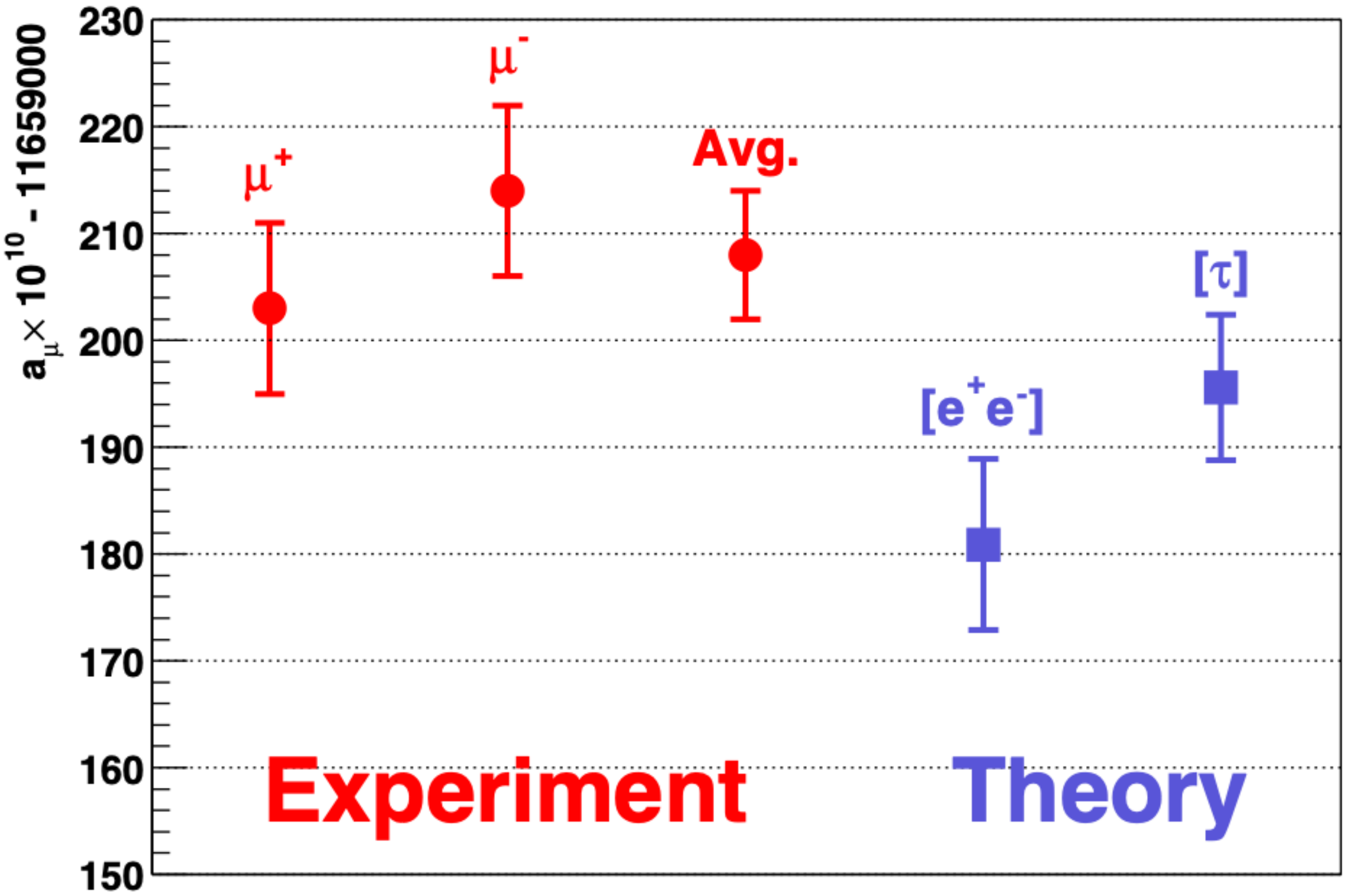


$g_\mu - 2$:

Dawn of new physics or its sunset?

Possible Discrepancy with Theory?

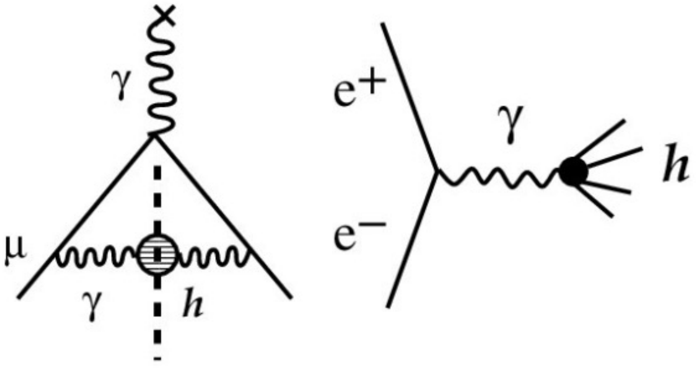


$$\delta a = \pm 0.47\text{ppm}$$

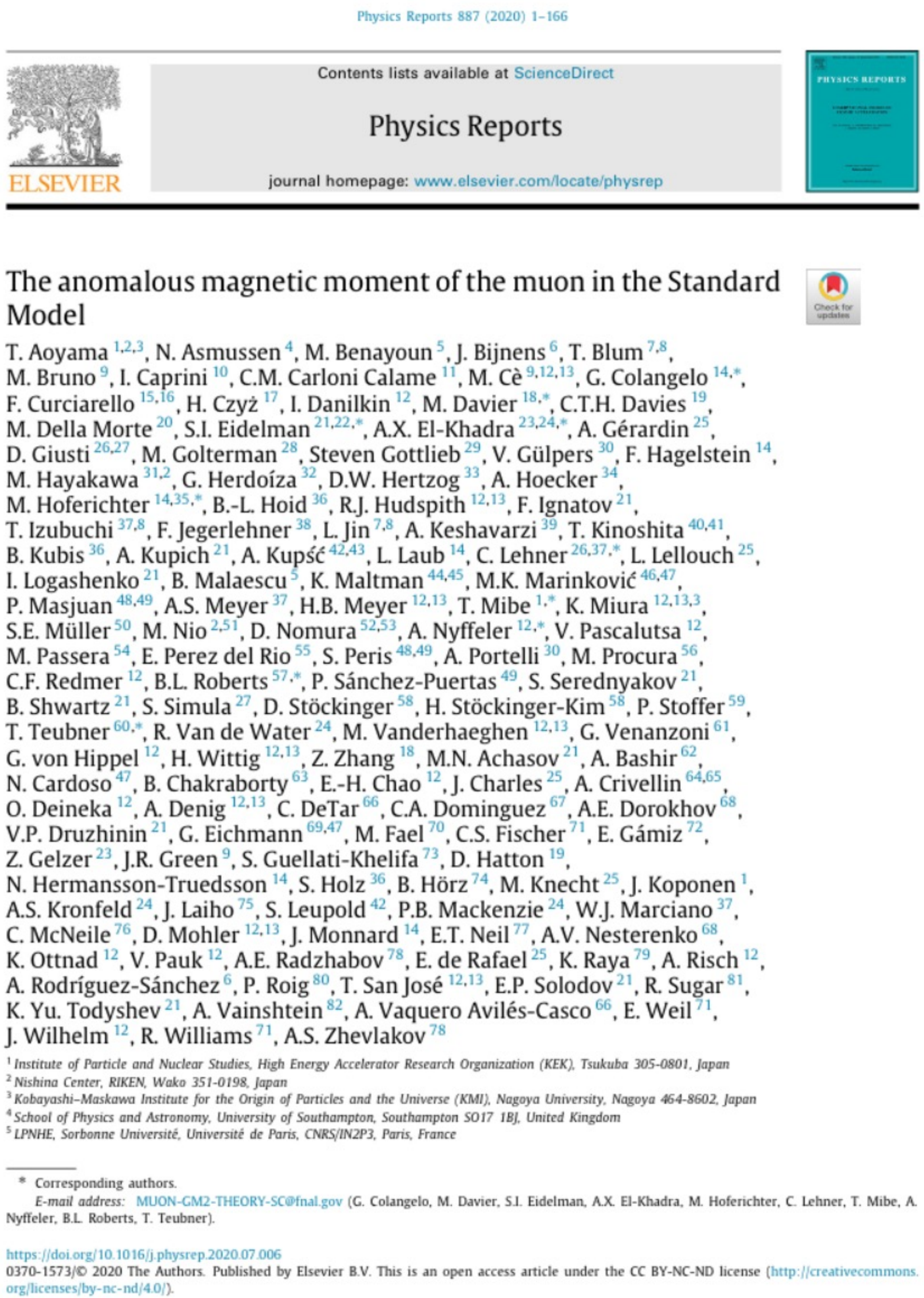
BNL E821 experiment, 2001 - 2006

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

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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*

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[*] 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

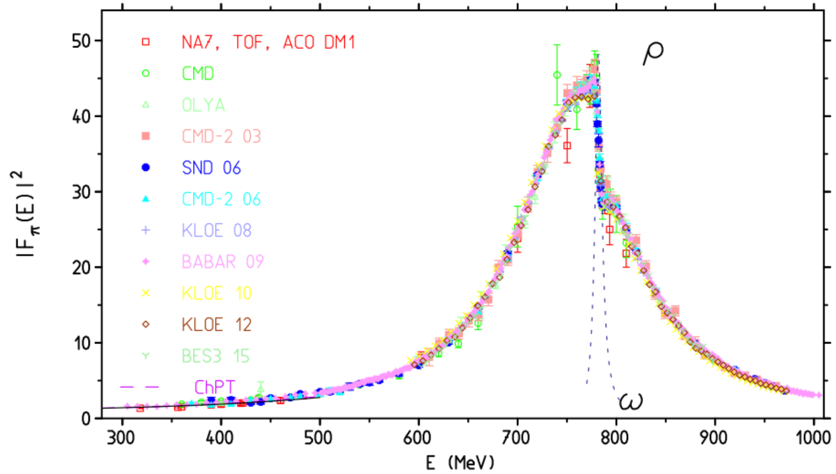
- Most important contribution is from low energies $\lesssim 1$ GeV, dominated by ρ and ω peaks, taking account of interference effects

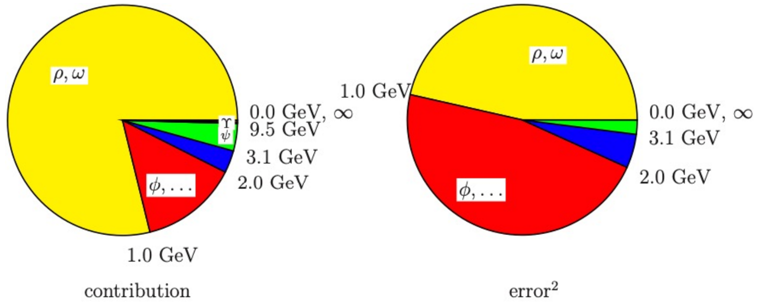
- Uncertainties dominated by ρ and ω region, and by region between 1 and 2 GeV (ϕ, etc.)

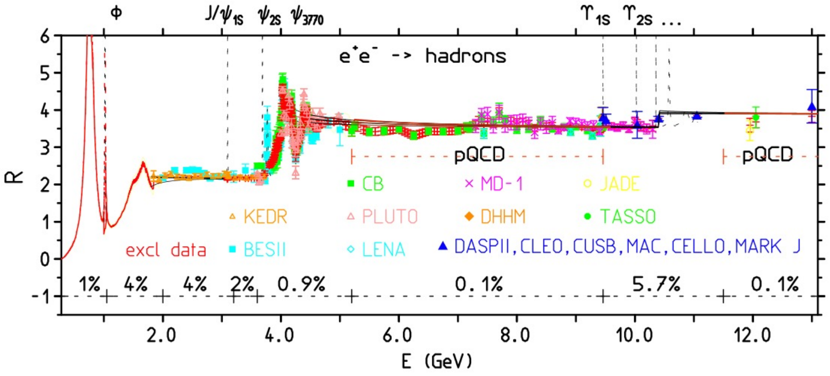
- High energies under good control from

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

Aoyama et al, arXiv:2006.04822





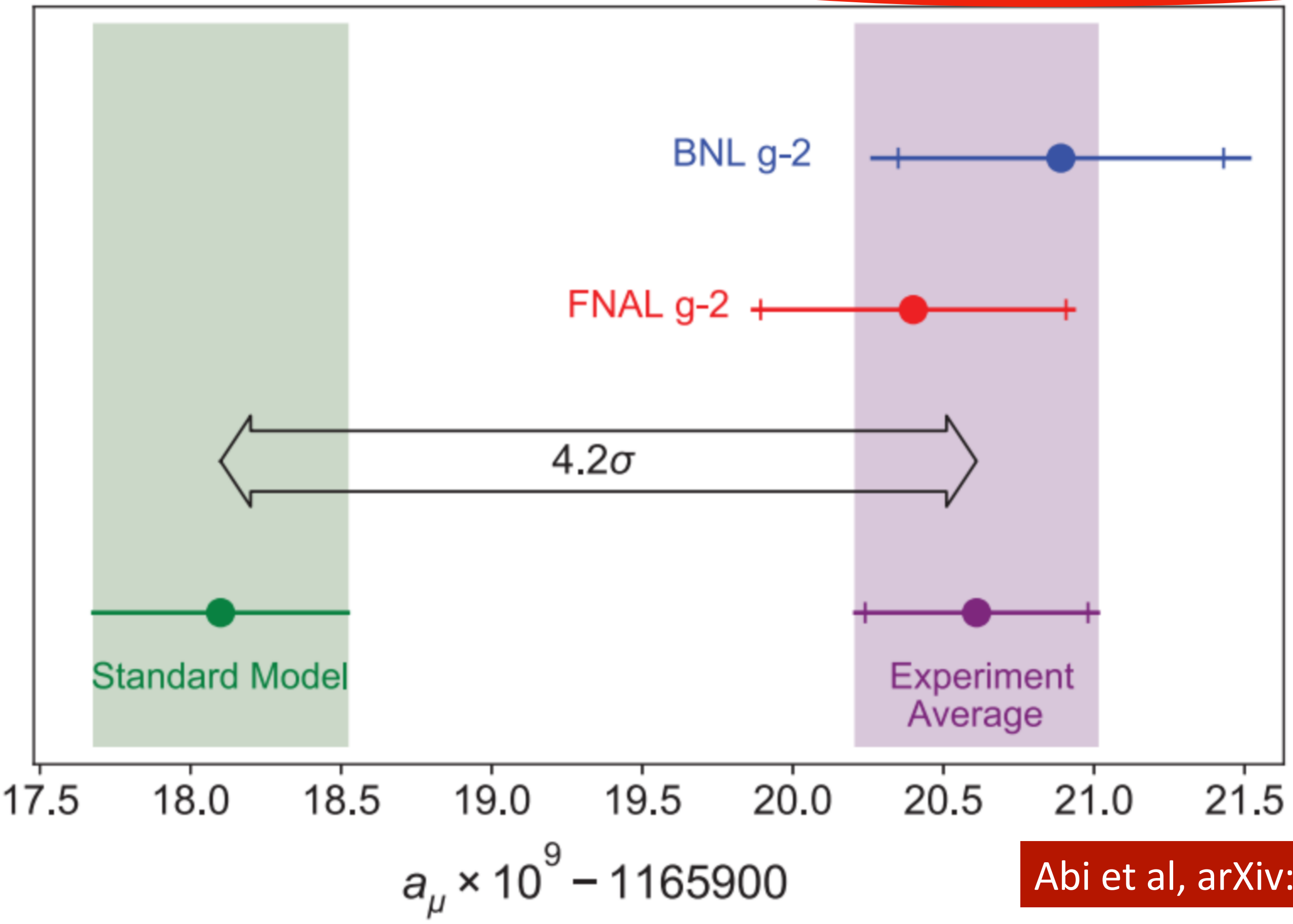


Fermilab Measurement

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

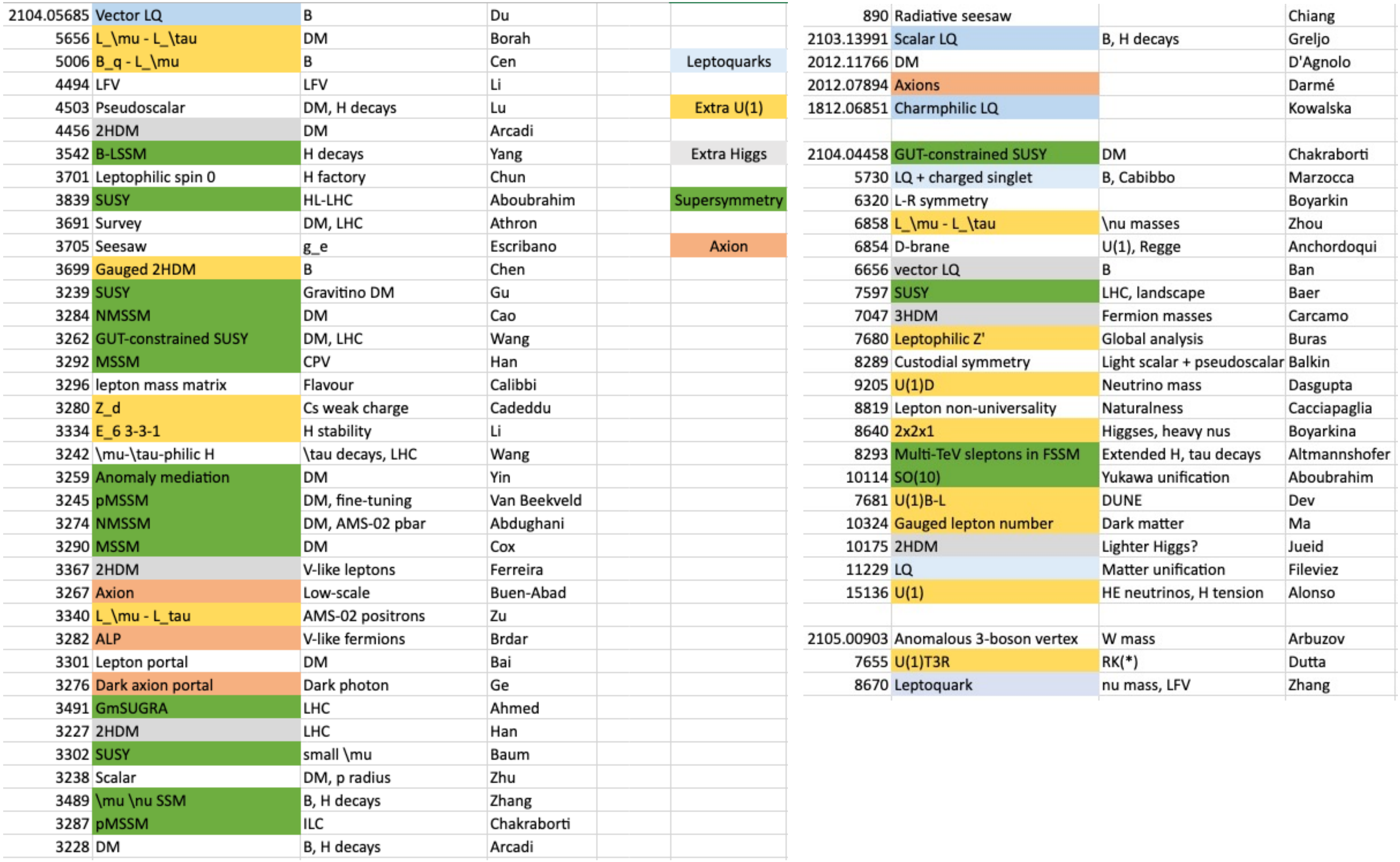
Combined result: $a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$

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



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

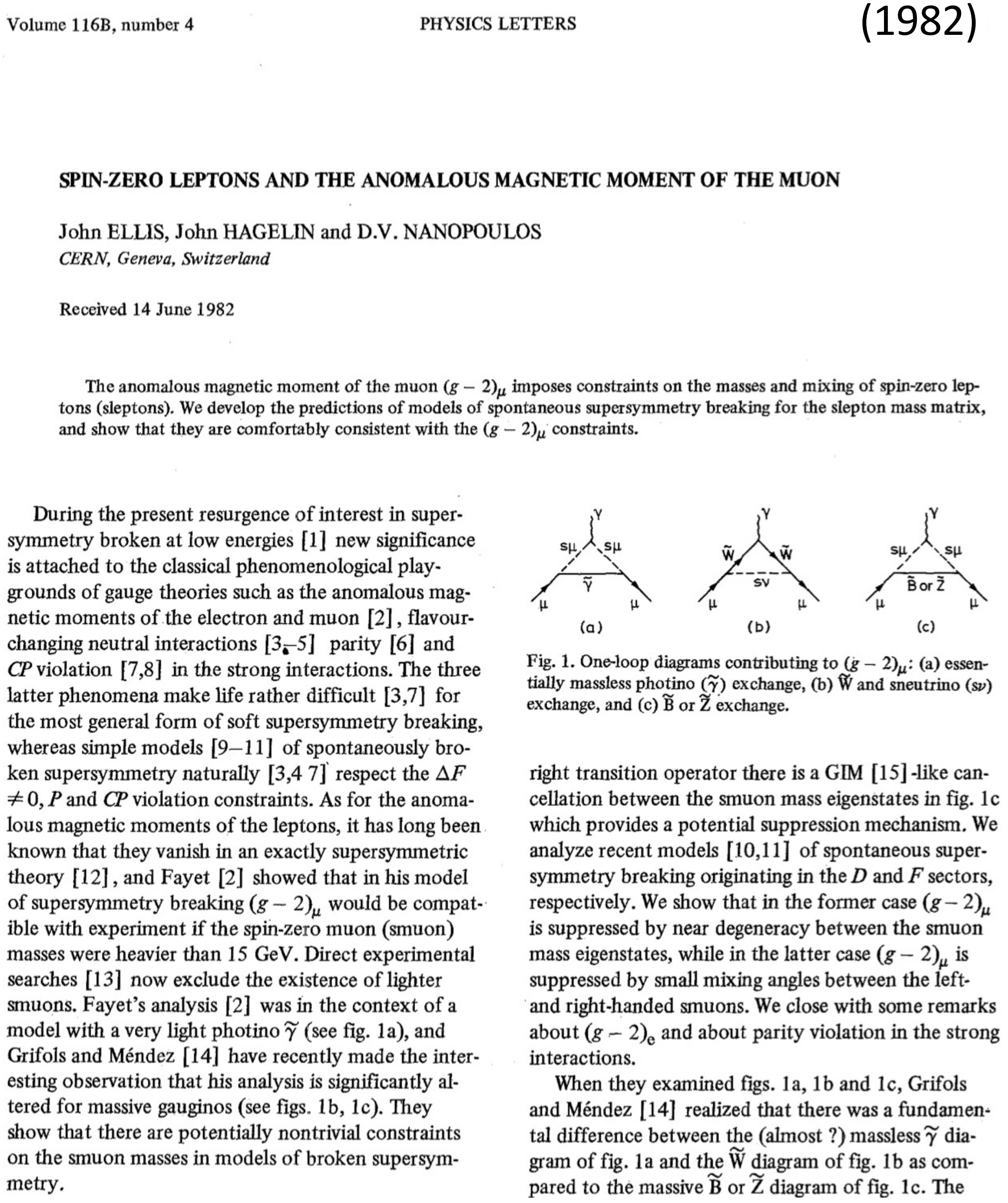
$g_\mu - 2$ in Supersymmetry

- One-loop contribution from smuon/neutralino loop

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

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

(1982)



Volume 116B, number 4 PHYSICS LETTERS

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 $\widetilde{\gamma}$ (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.

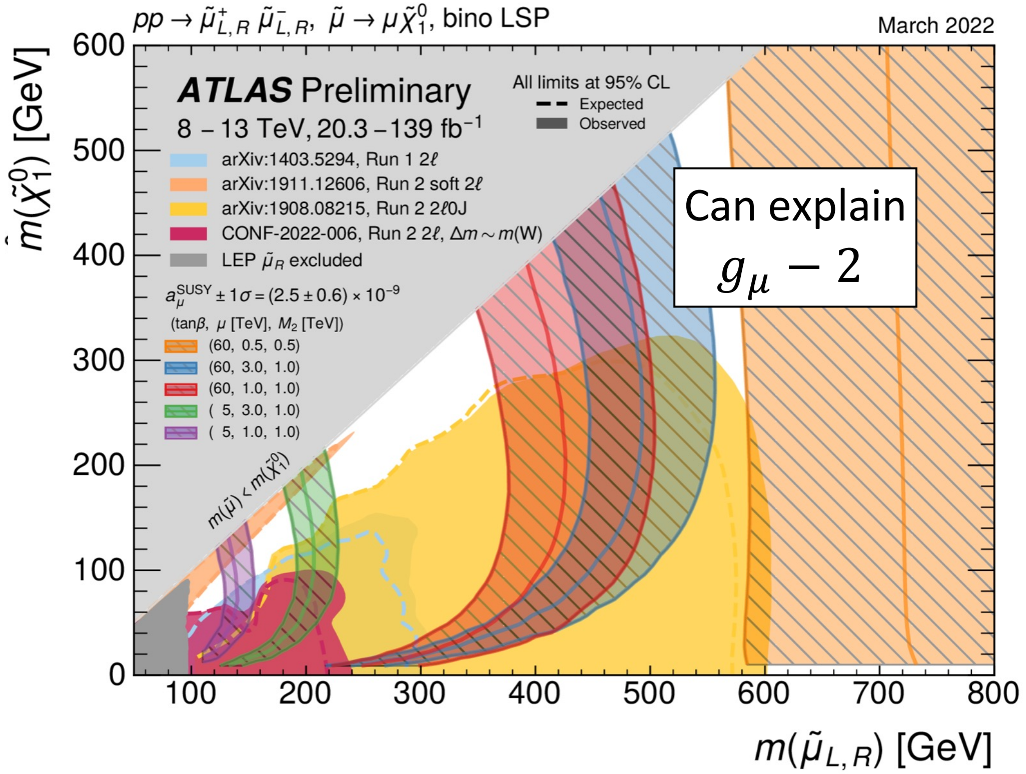
Fig. 1. One-loop diagrams contributing to $(g-2)_\mu$: (a) essentially massless photino $(\widetilde{\gamma})$ exchange, (b) $\widetilde{W}$ and sneutrino ($s\nu$) exchange, and (c) $\widetilde{B}$ or $\widetilde{Z}$ exchange.

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.

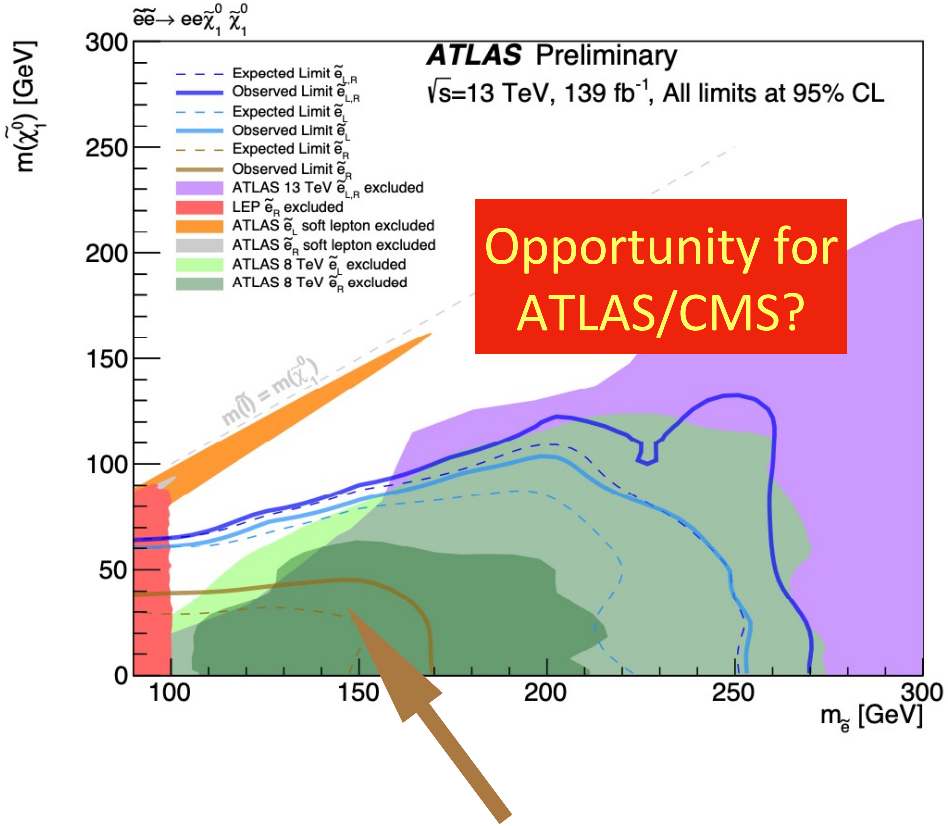
When they examined figs. 1a, 1b and 1c, Grifols and Méndez [14] realized that there was a fundamental difference between the (almost ?) massless $\widetilde{\gamma}$ diagram of fig. 1a and the $\widetilde{W}$ diagram of fig. 1b as compared to the massive $\widetilde{B}$ or $\widetilde{Z}$ diagram of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

LHC vs Supersymmetry

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



Can explain $g_\mu - 2$

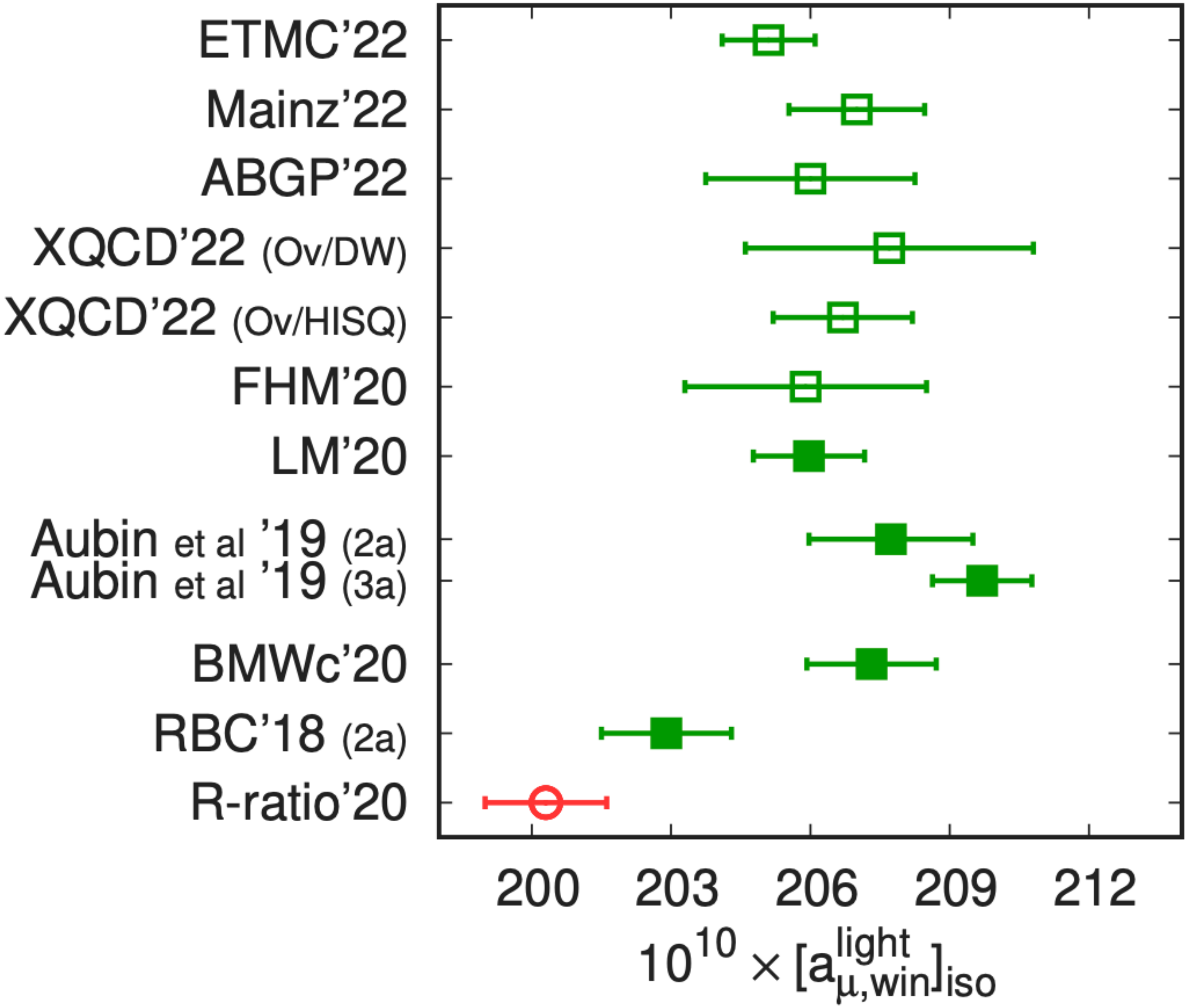


Opportunity for ATLAS/CMS?

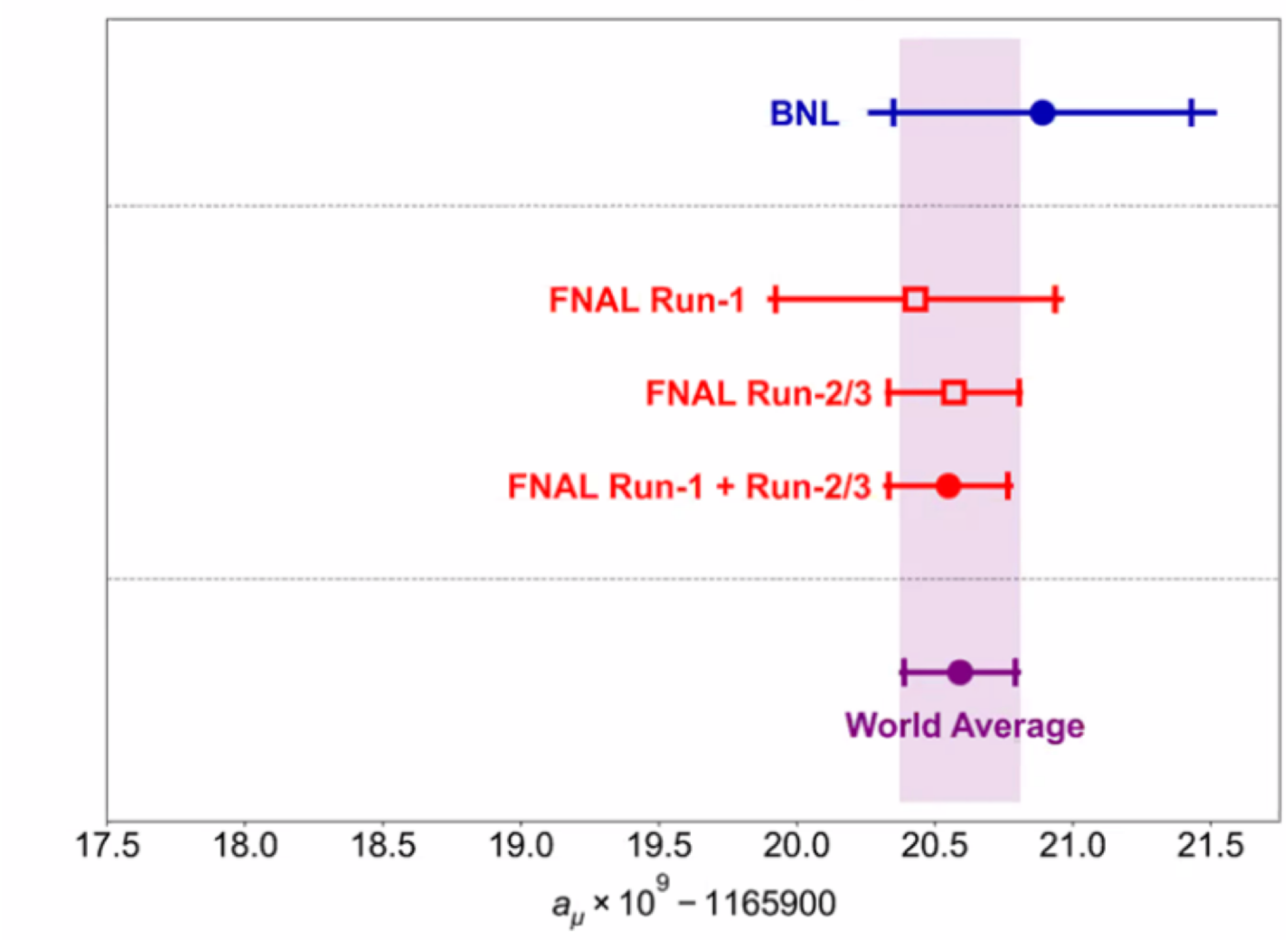
- Most models have $m_{\tilde\mu_L} > m_{\tilde\mu_R}$ but $m_{\tilde\mu_R} \simeq m_{\tilde e_R}$: **relevant constraint**

ATLAS Collaboration

Recent Lattice Calculations



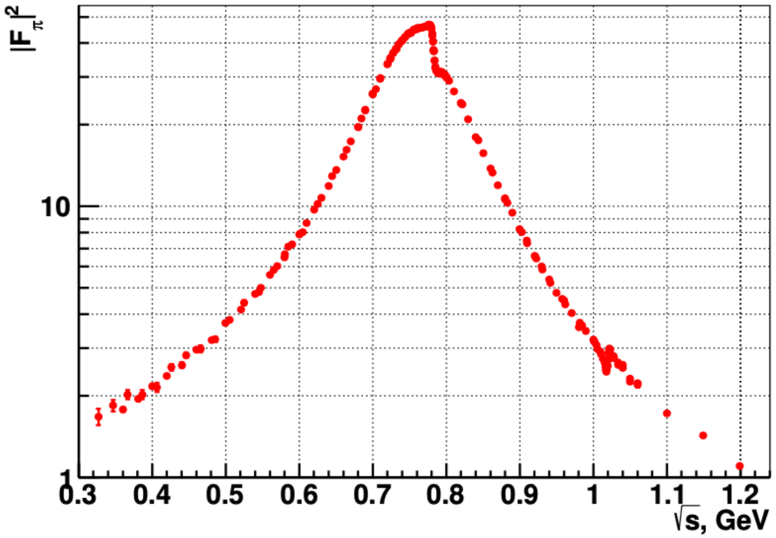
Quo Vadis $g_\mu - 2$?



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

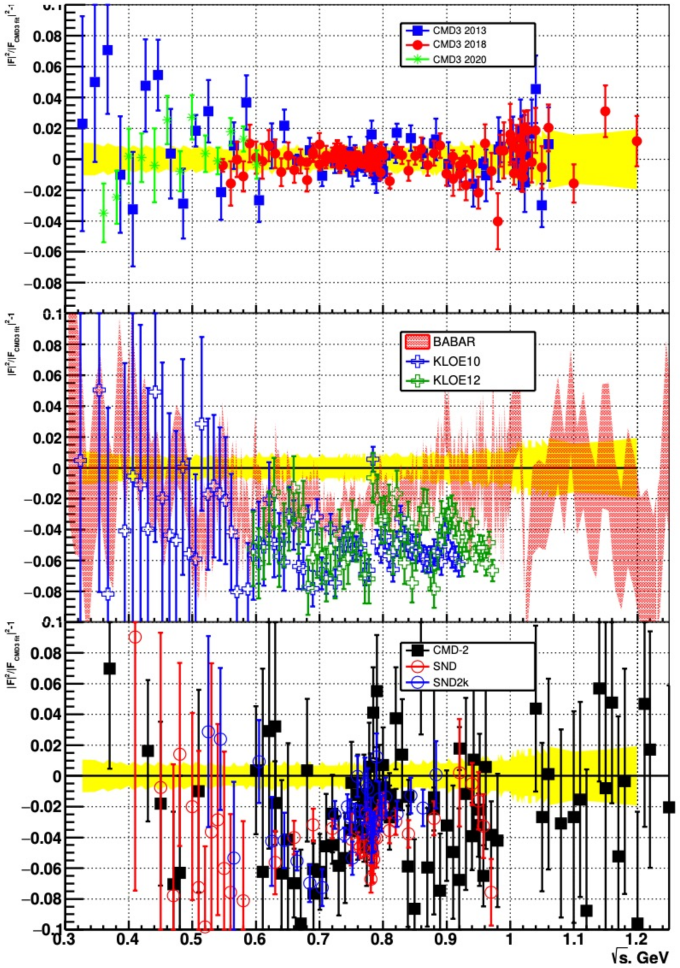
Updated CMD-3 Measurement of HVP

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



CMD-3 Collaboration, arXiv:2309.12910

Comparison with previous results



$(g_\mu - 2)$ −HVP discrepancy

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

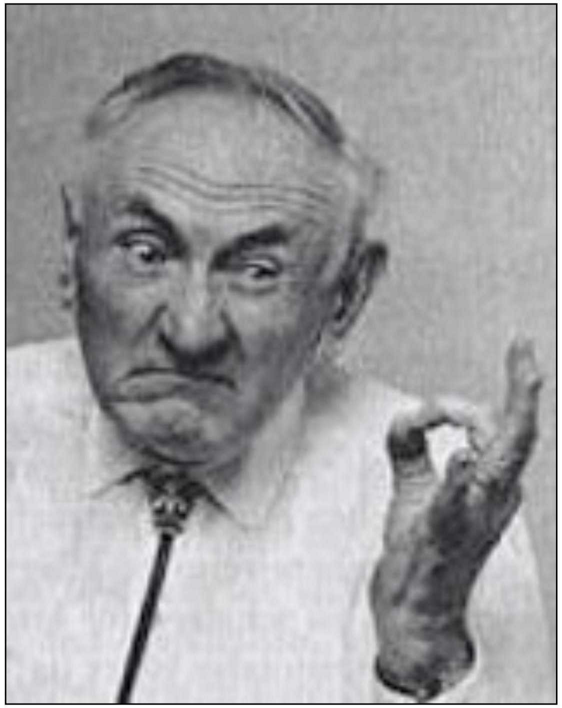
Consistent with no BSM signal

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?**

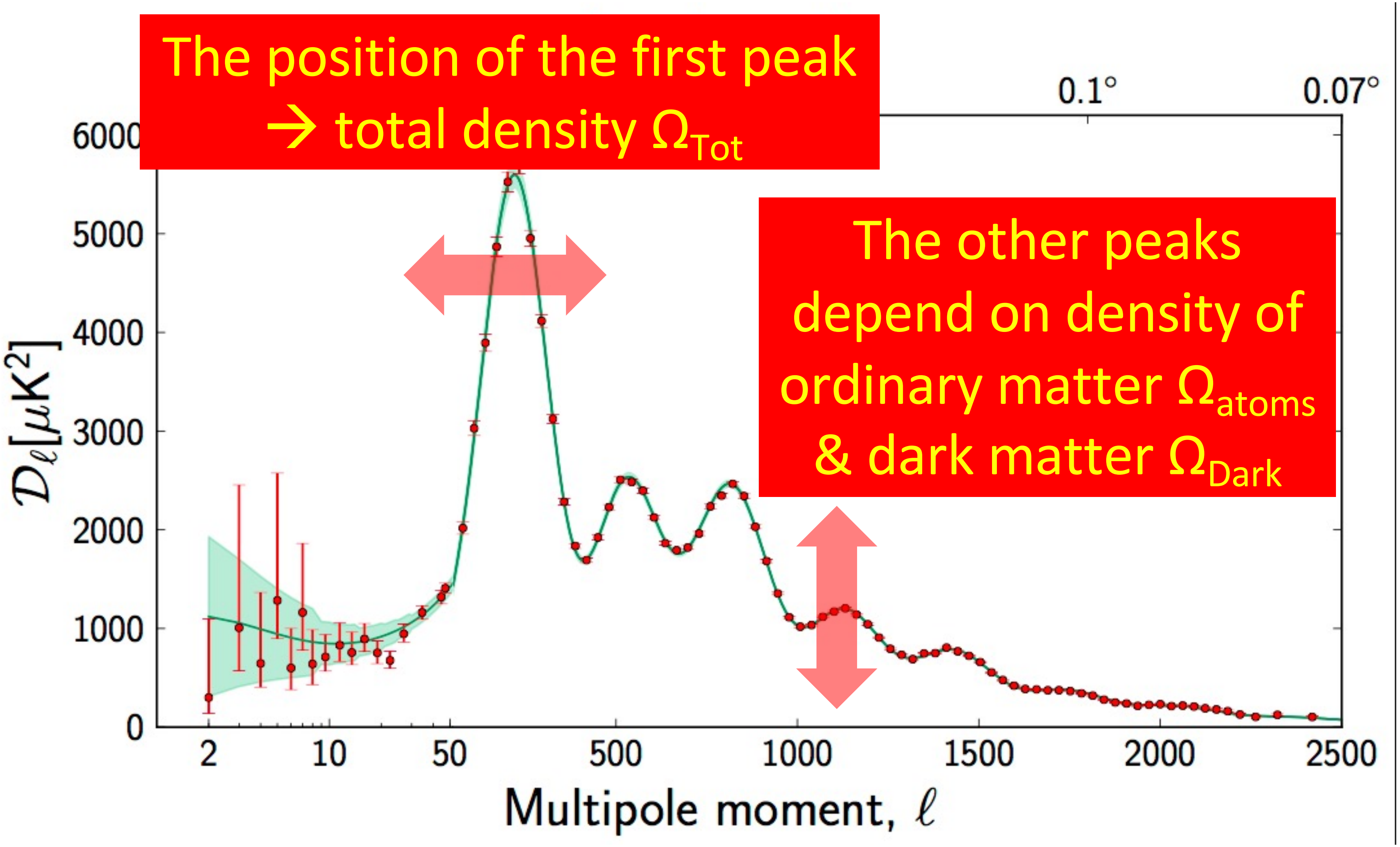


The Rotation Curves of Galaxies


Scanned at the American Institute of Physics

- 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, …

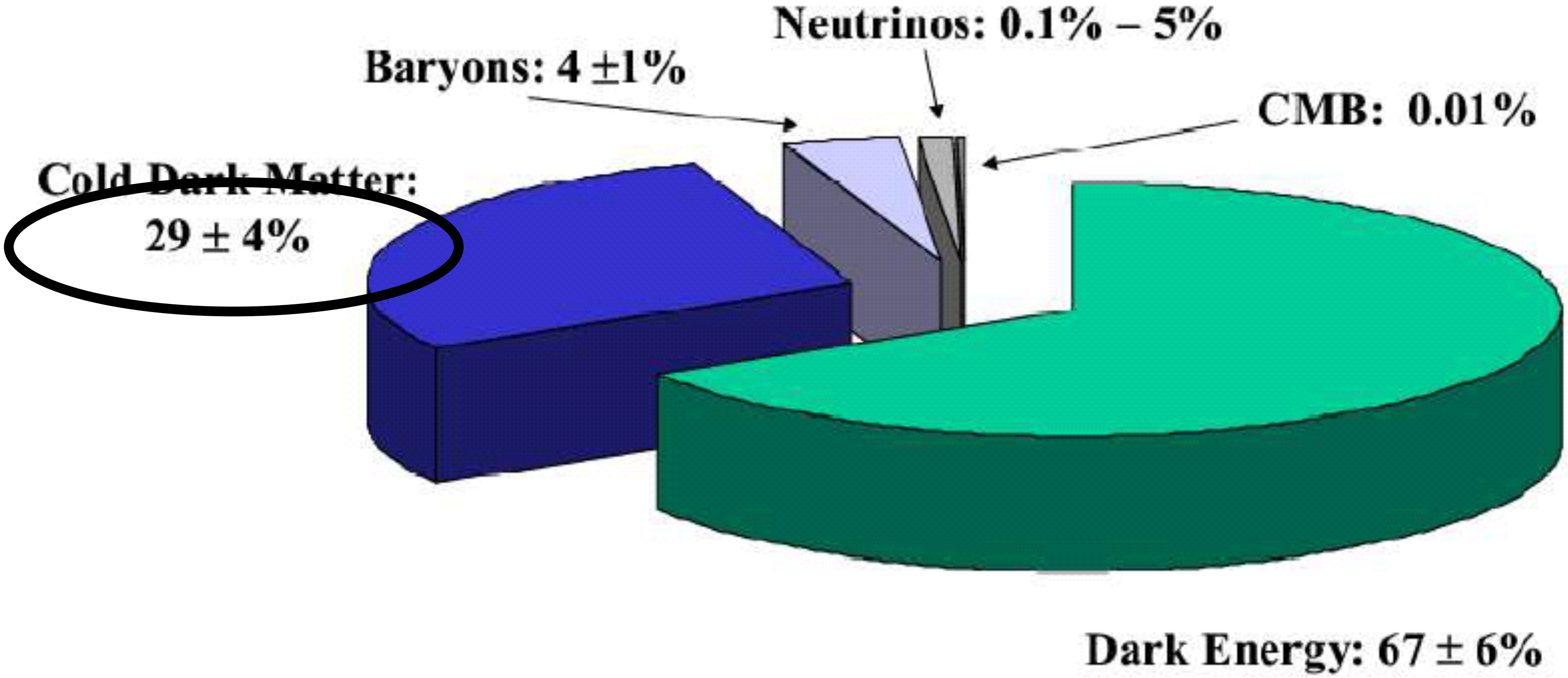
The Spectrum of Fluctuations in the Cosmic Microwave Background



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

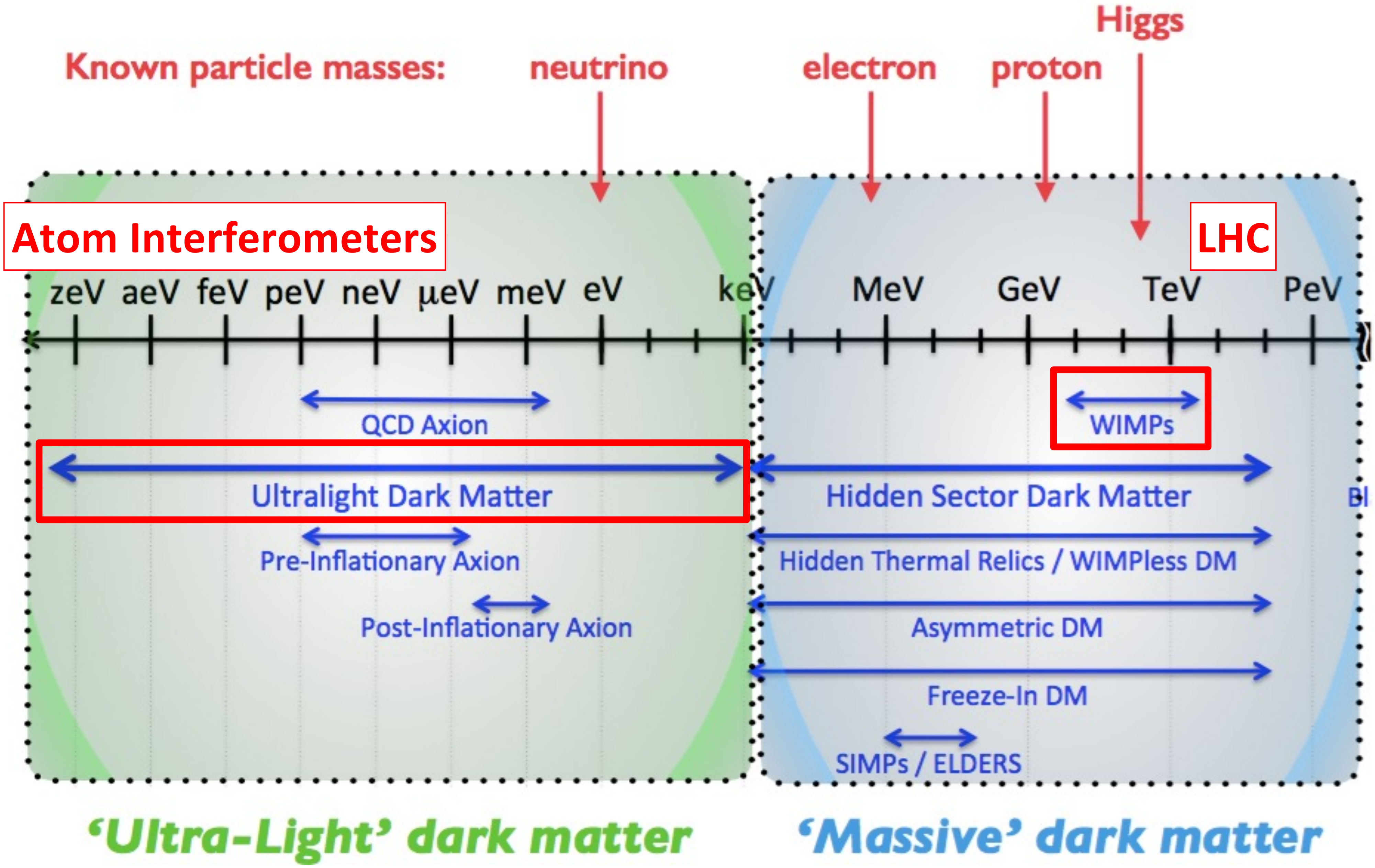
Properties of Dark Matter

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

Neutrinos

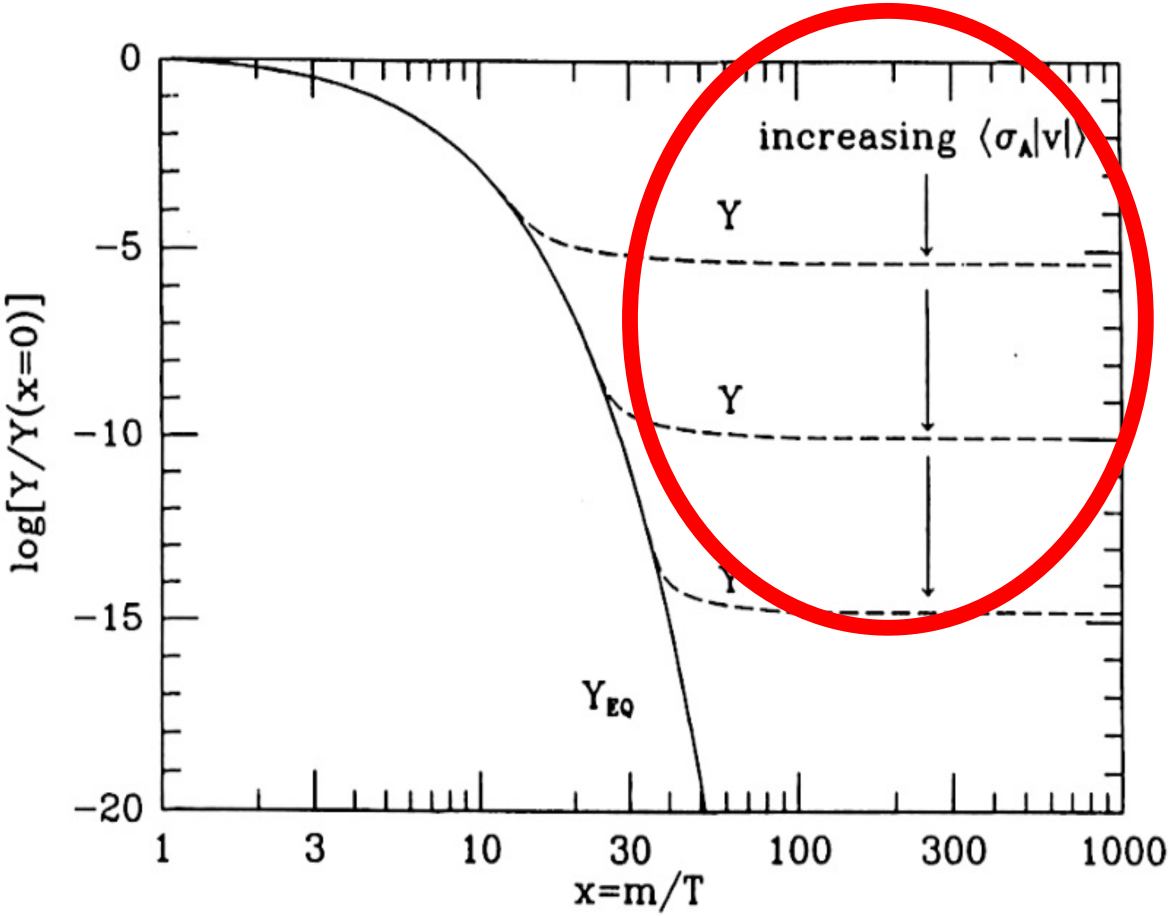
- They exist! ☺
- They have weak interactions ☺
- They have masses ☺
  - As indicated by neutrino oscillations
- But their masses are very small ☹
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹
  - (run away from small structures)
- Maybe some other neutrinos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

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



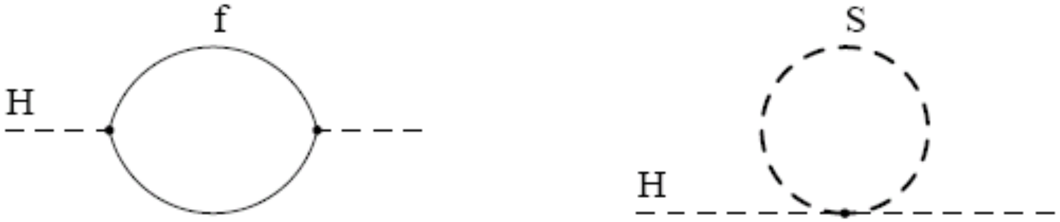
WIMP Candidates

- 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**

Naturalness of hierarchy of mass scales

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



2

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

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

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

- Leading divergence cancelled if $\lambda_S = y_f^2$ x 2 **Supersymmetry!**

What lies beyond the Standard Model?

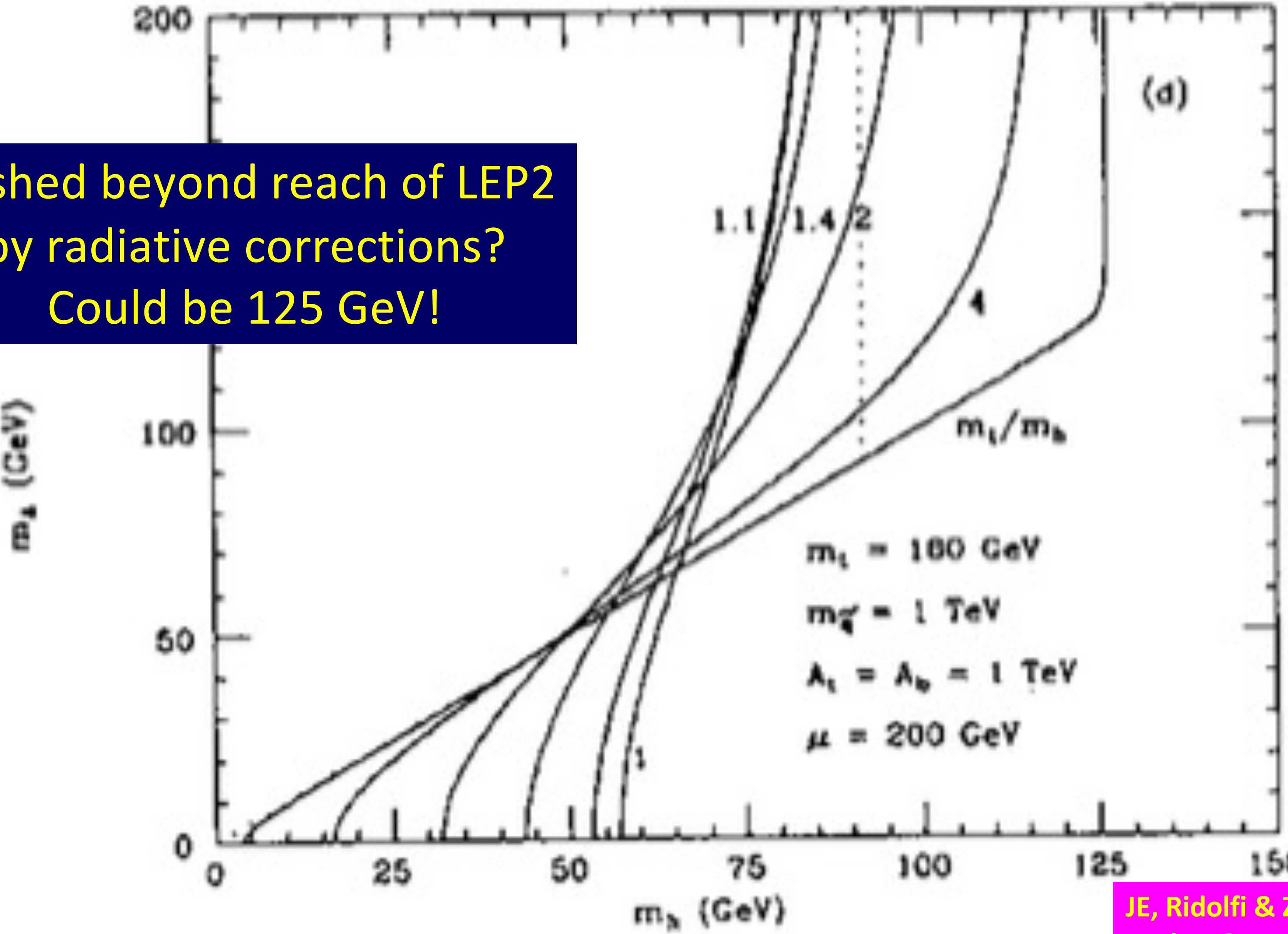
Supersymmetry

New motivations from LHC

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, **dark matter**, $g_\mu - 2$, …

1990/1

Higgs Mass in Supersymmetry



Pushed beyond reach of LEP2
by radiative corrections?
Could be 125 GeV!

JE, Ridolfi & Zwirner;
Haber & Hempfling

1991

Grand Unification

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

$$b_i = \begin{pmatrix} 0 \\ -\frac{22}{3} \\ -11 \end{pmatrix} + N_g \begin{pmatrix} \frac{4}{3} \\ \frac{4}{3} \\ \frac{4}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix} \quad \boxed{b_i = \begin{pmatrix} 0 \\ -6 \\ -9 \end{pmatrix} + N_g \begin{pmatrix} 2 \\ 2 \\ 2 \end{pmatrix} + N_H \begin{pmatrix} \frac{3}{10} \\ frac12 \\ 0 \end{pmatrix}}$$

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

$$b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -\frac{136}{3} & 0 \\ 0 & 0 & -102 \end{pmatrix} + N_g \begin{pmatrix} \frac{19}{15} & \frac{3}{5} & \frac{44}{15} \\ \frac{1}{5} & \frac{49}{3} & 4 \\ \frac{4}{30} & \frac{3}{2} & \frac{76}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{13}{6} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \boxed{b_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & -24 & 0 \\ 0 & 0 & -54 \end{pmatrix} + N_g \begin{pmatrix} \frac{38}{15} & \frac{6}{5} & \frac{88}{15} \\ \frac{2}{5} & 14 & 8 \\ \frac{11}{5} & 3 & \frac{68}{3} \end{pmatrix} + N_H \begin{pmatrix} \frac{9}{50} & \frac{9}{10} & 0 \\ \frac{3}{10} & \frac{7}{2} & 0 \\ 0 & 0 & 0 \end{pmatrix}}$$

- At three-loop order …

Dimopoulos, Raby & Wilczek,
Ibanez & Ross, 1982

1991

LEP Data Consistent with Supersymmetric Grand Unification

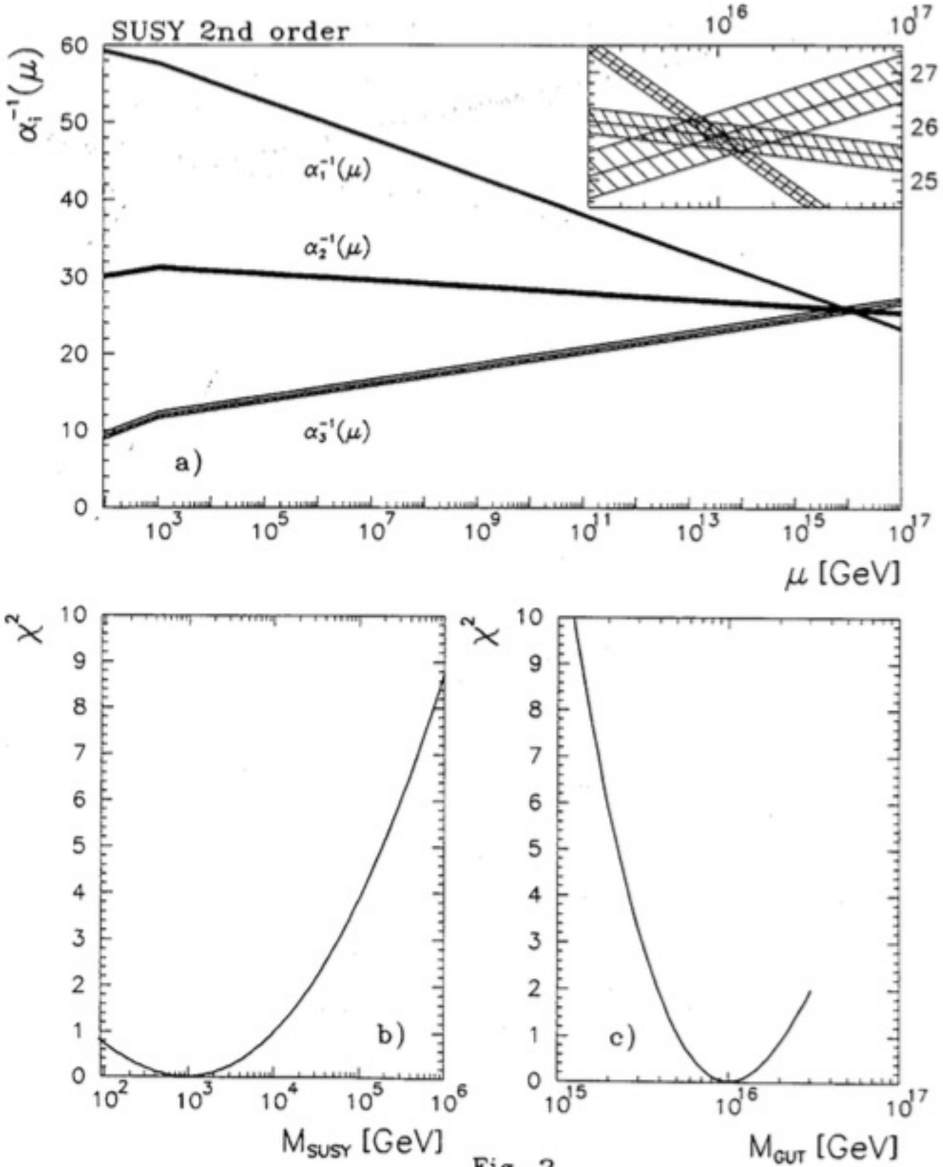
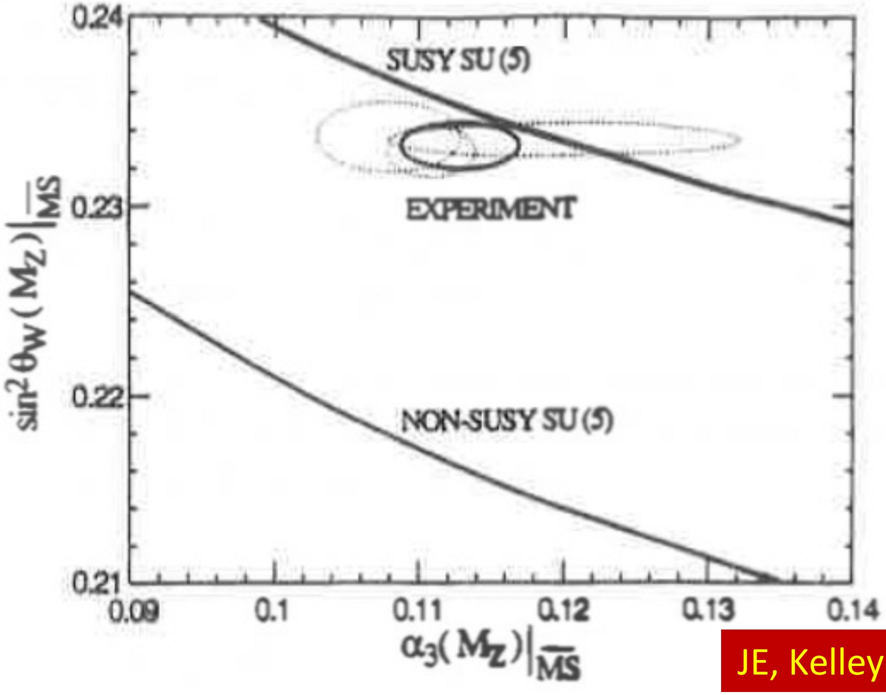


Fig. 2

Amaldi, de Boer & Furstenau



JE, Kelley & Nanopoulos

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

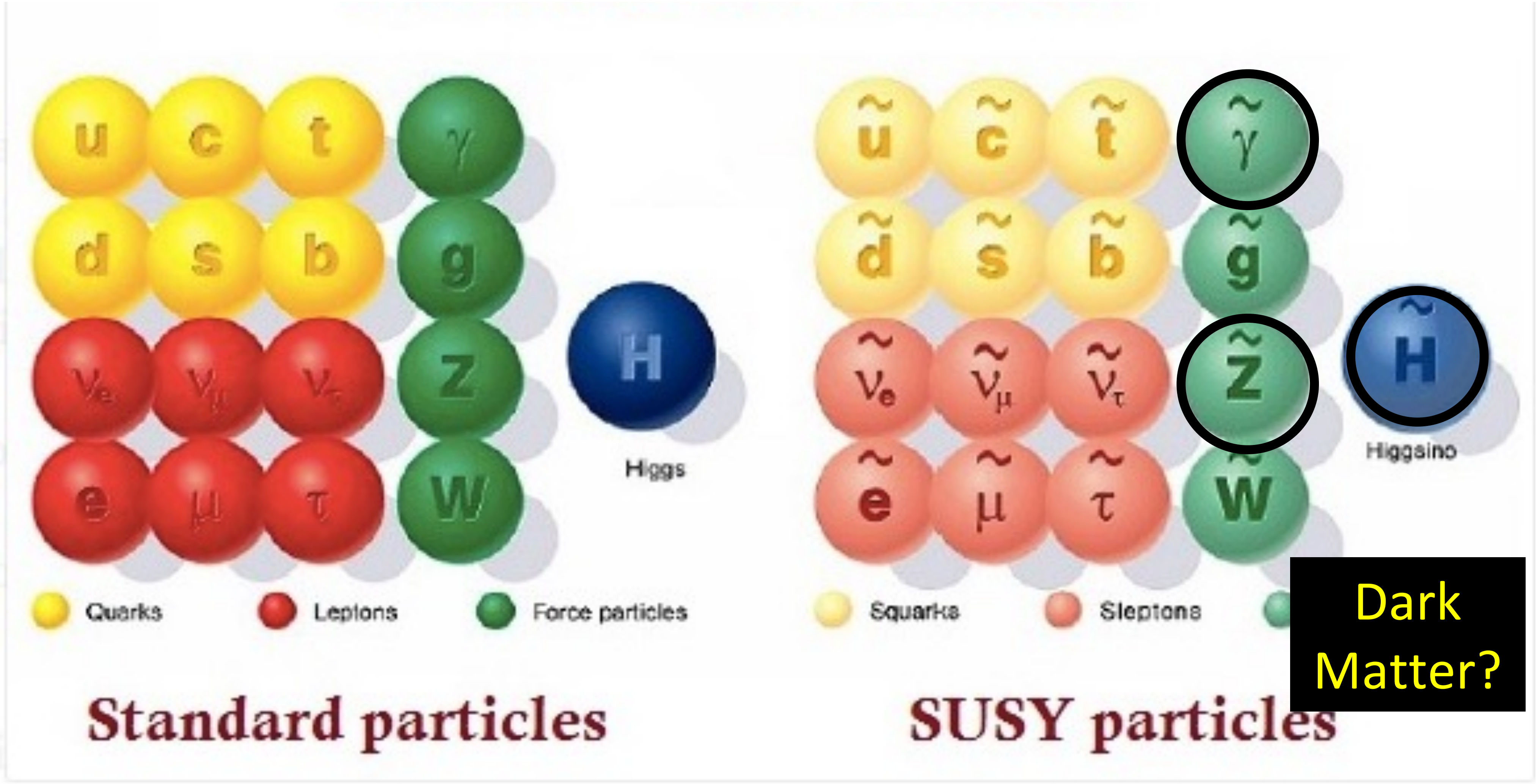
(Excluded by LEP, direct searches)

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

Gravitino

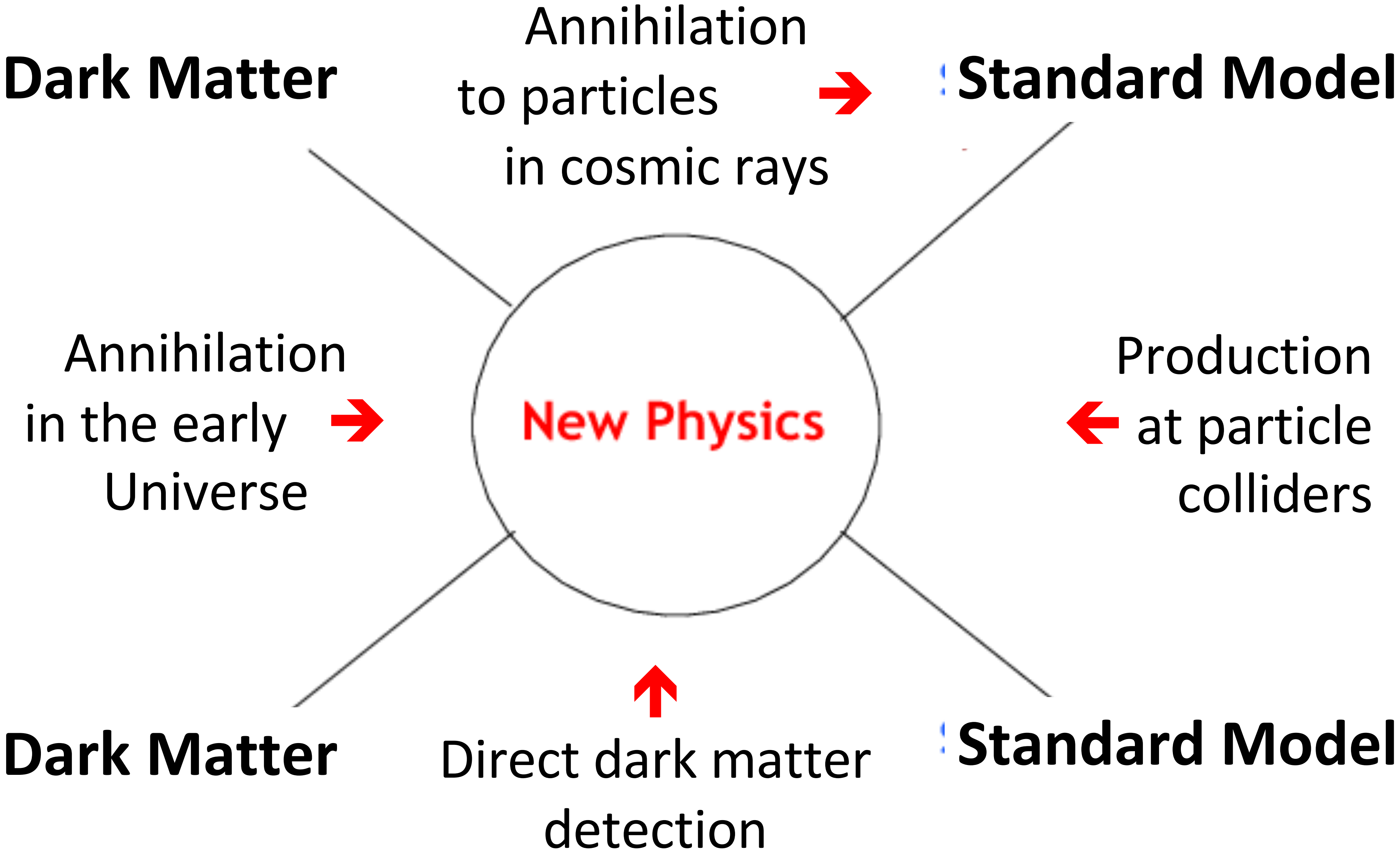
(nightmare for detection)

Minimal Supersymmetric Extension of the Standard Model



Dark Matter?

Searches for Dark Matter



Dark Matter

Annihilation to particles in cosmic rays →

Standard Model

Annihilation in the early Universe →

New Physics

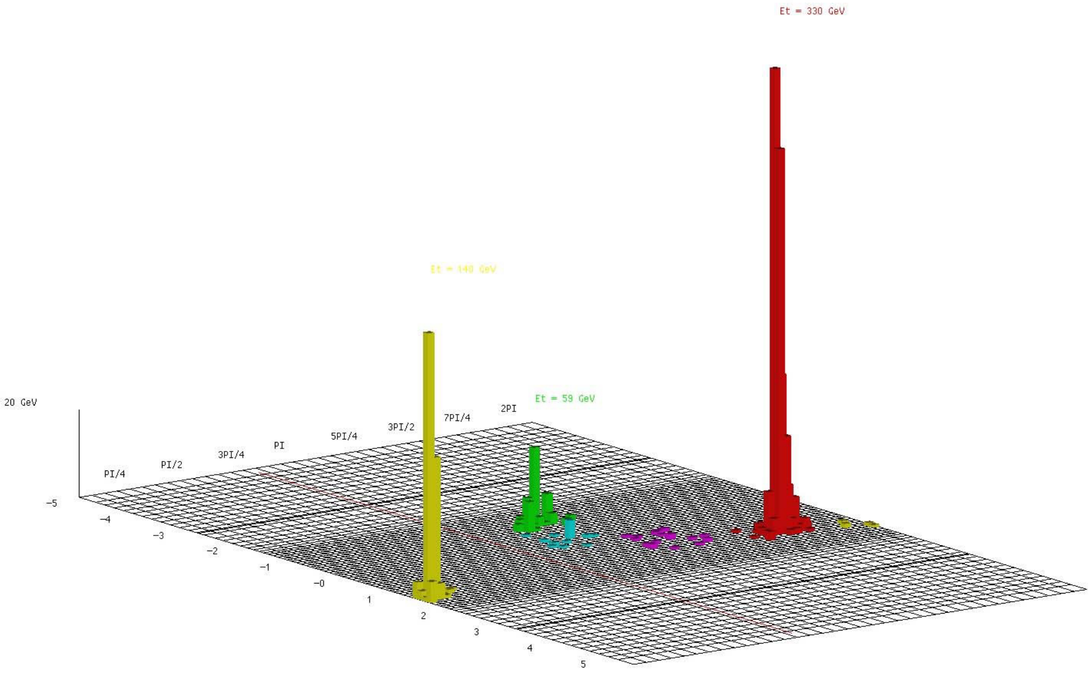
← Production at particle colliders

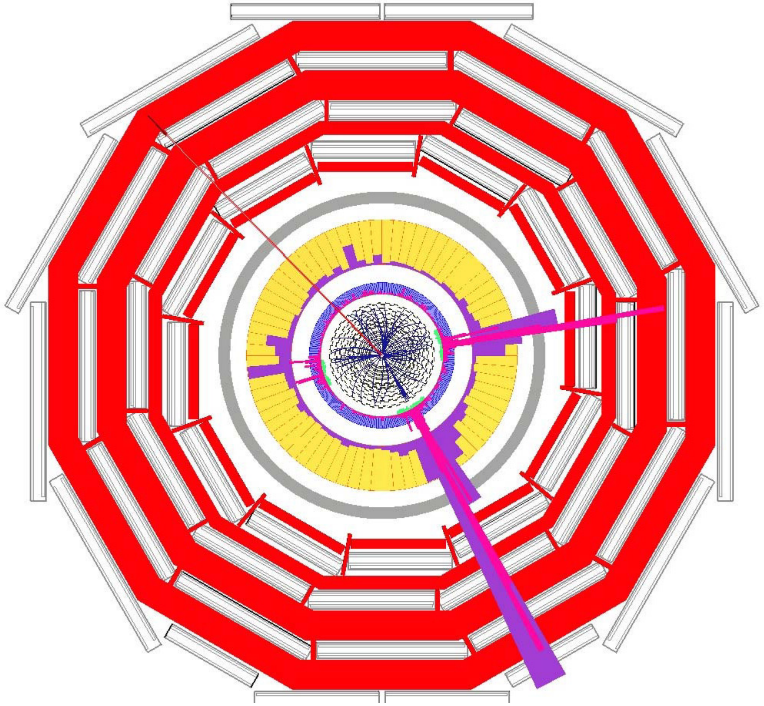
Dark Matter

↑ Direct dark matter detection

Standard Model

Classic Dark Matter Signature



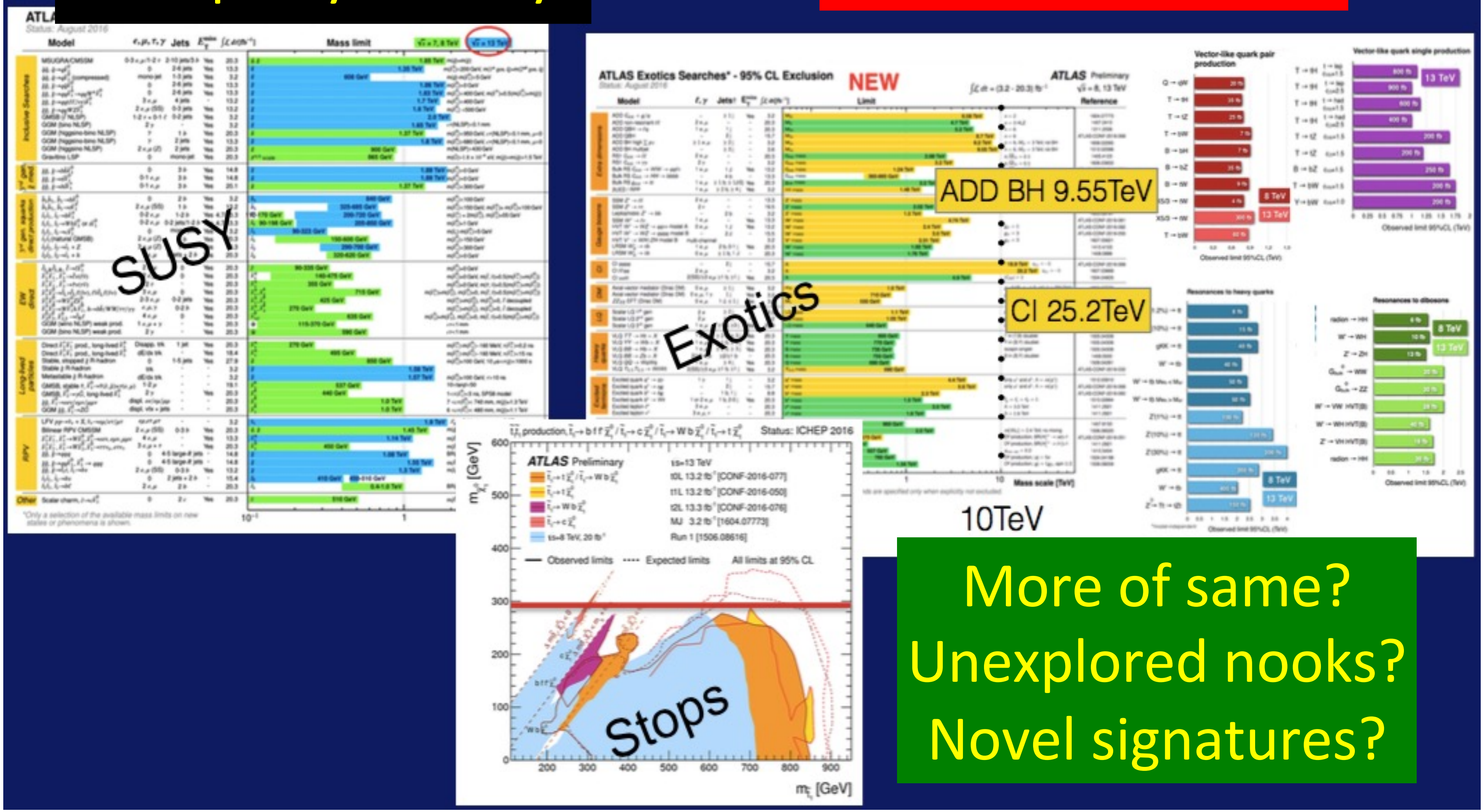


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



More of same?
Unexplored nooks?
Novel signatures?

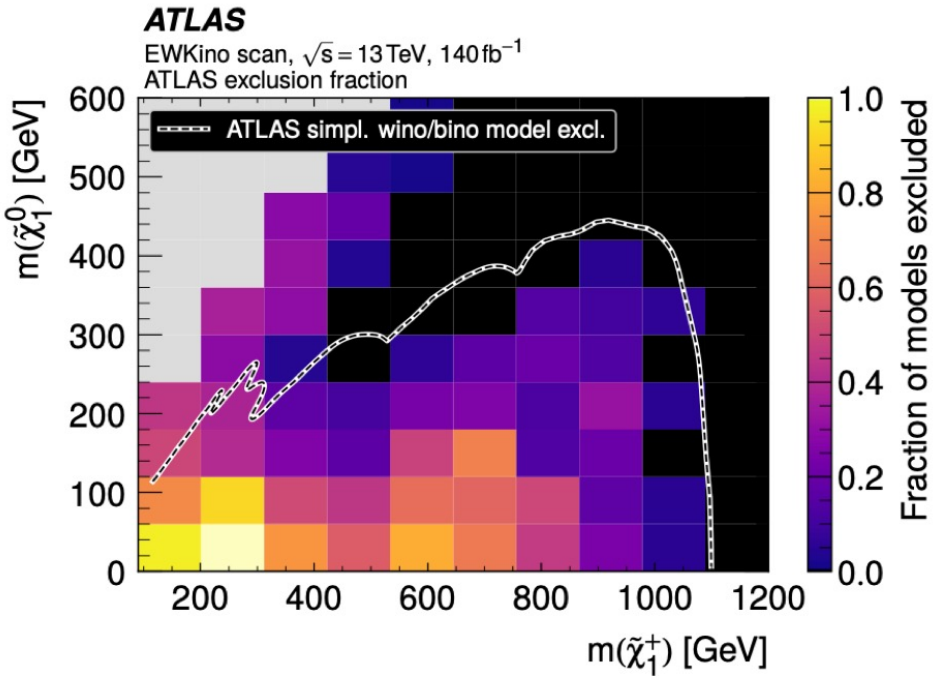
Fraction of Models Excluded

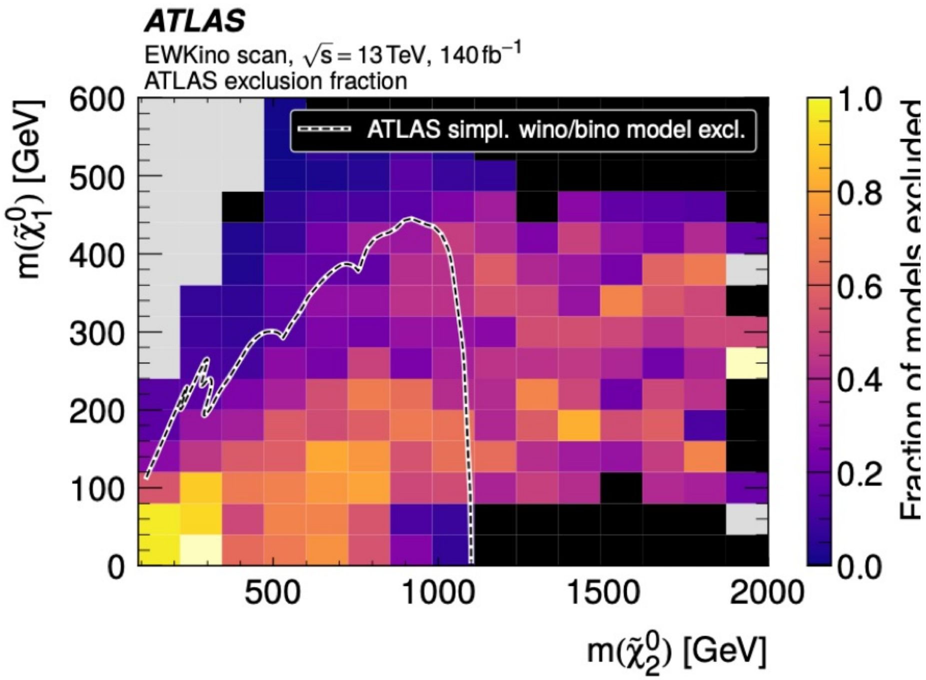
Exclusions not 100%, not as strong as often stated

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

Black = < 10% of pMSSM models excluded

Cream = > 90% of pMSSM models excluded

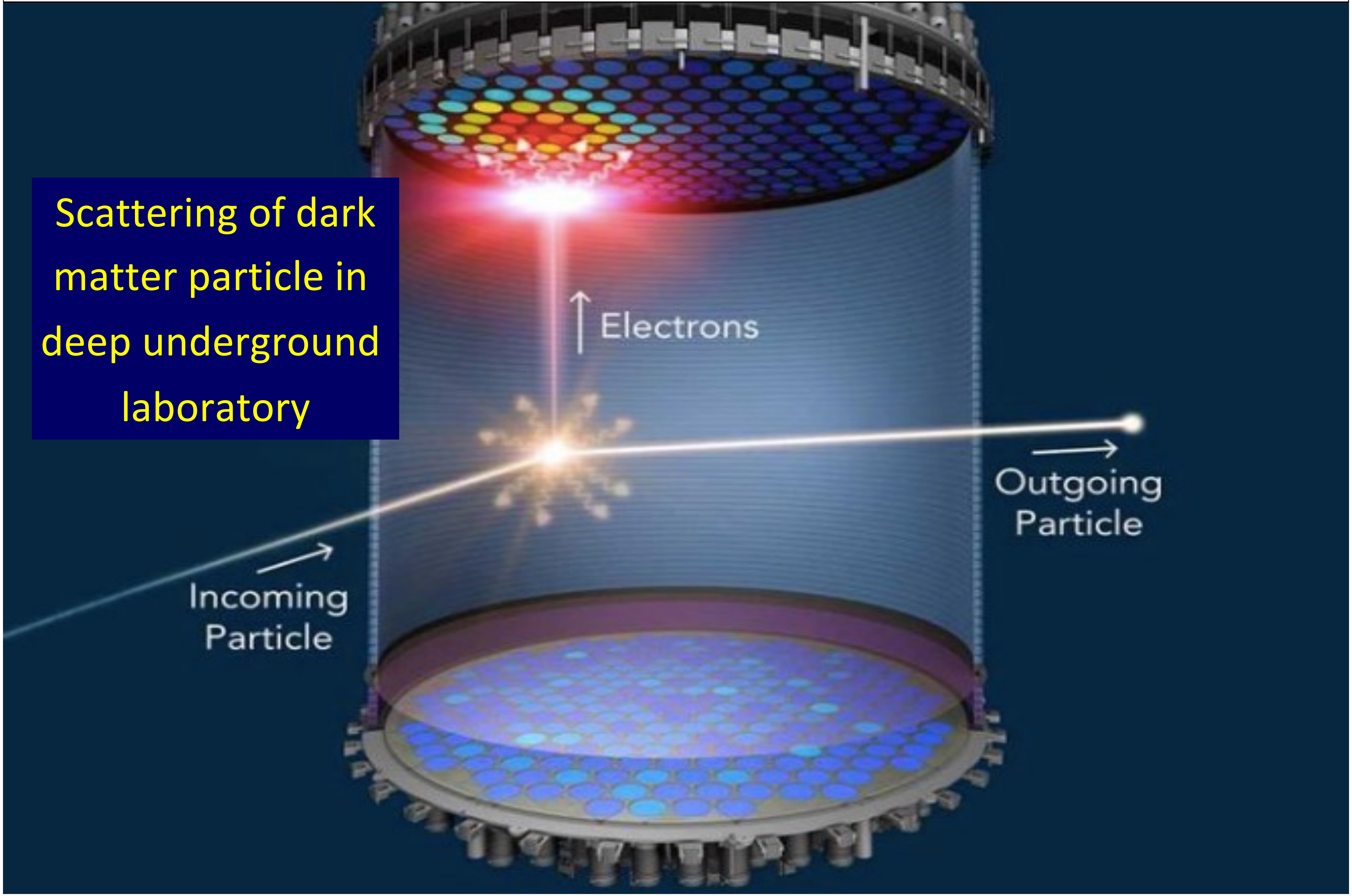




Many low-mass pMSSM models consistent with constraints

Hope springs eternal!

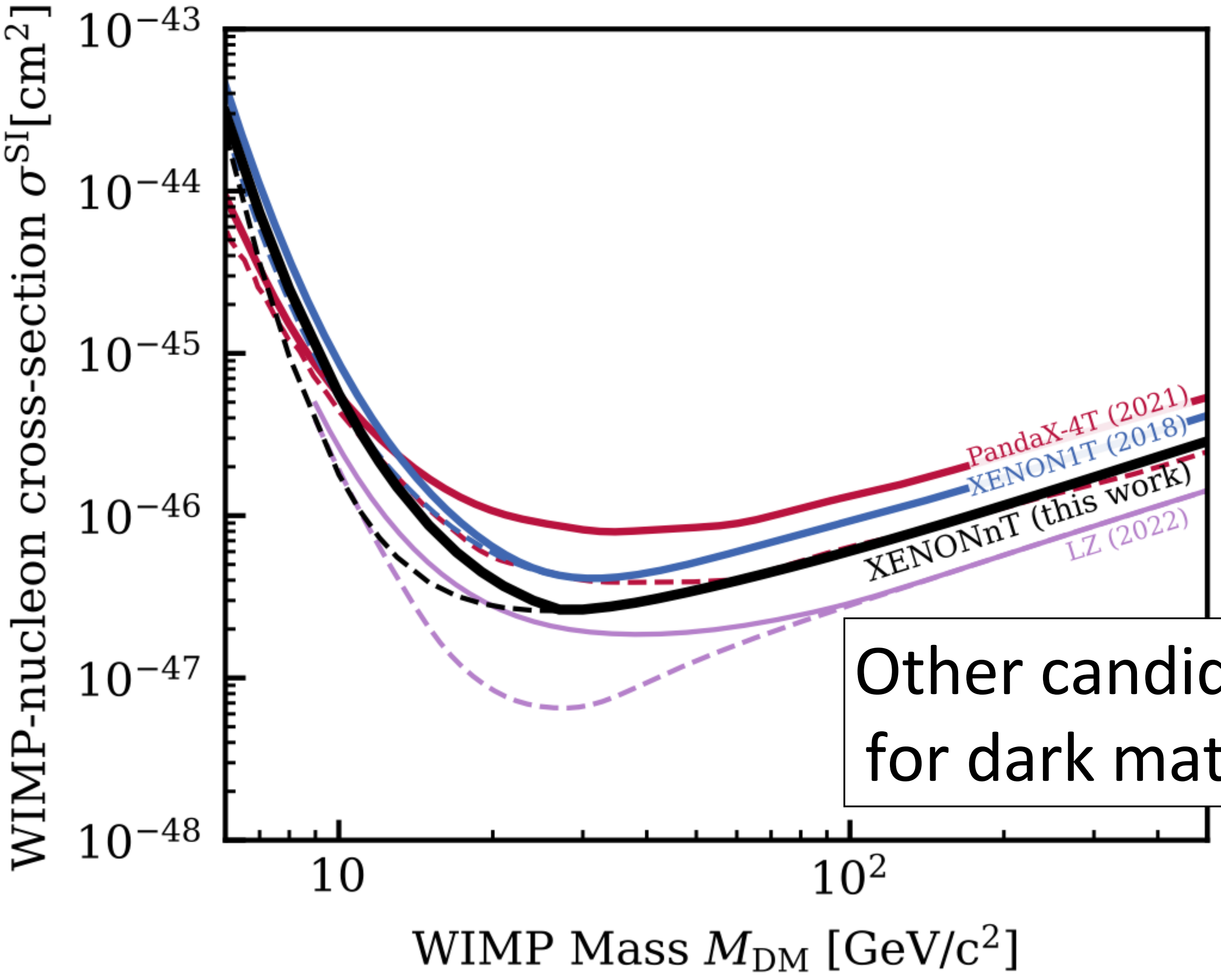
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

Direct Dark Matter Searches

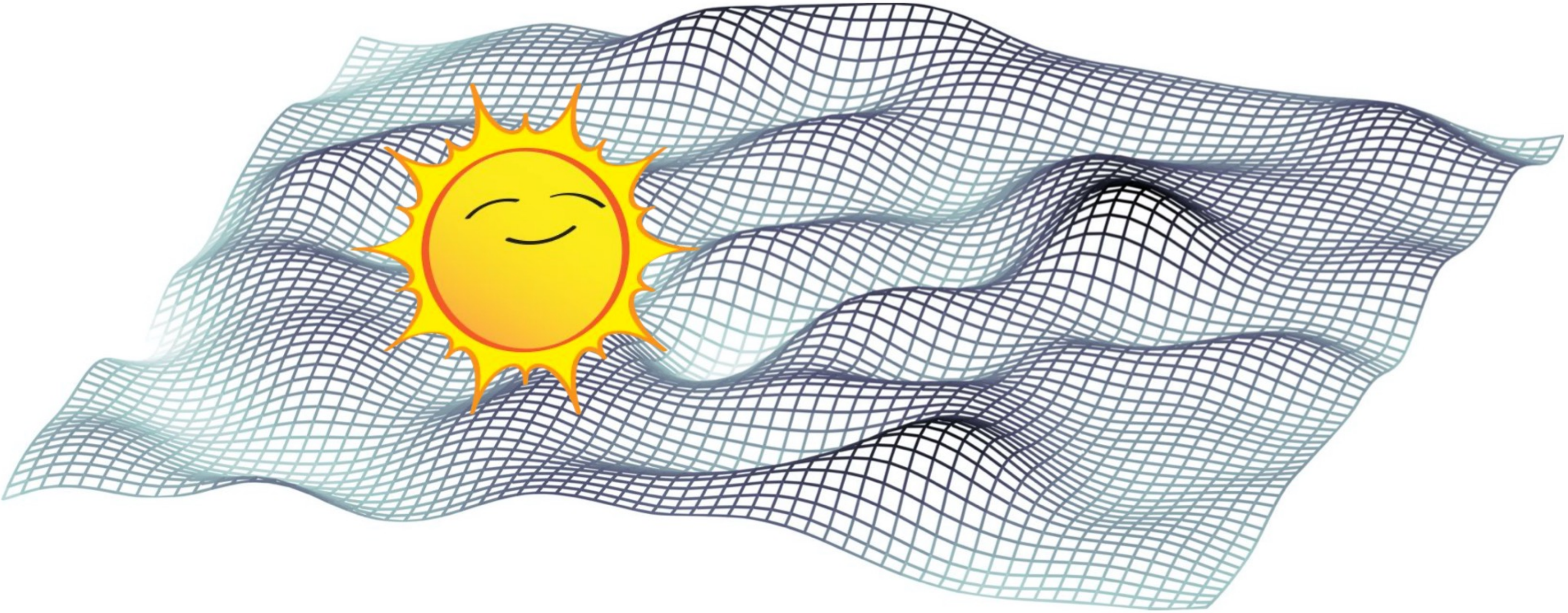
Latest experimental results



Other candidates for dark matter?

Ultralight Dark Matter

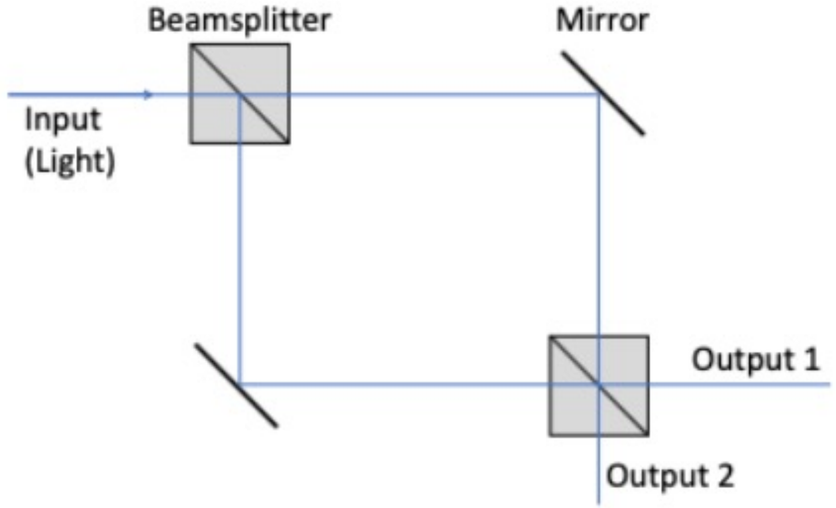
A scalar ULDM $\boldsymbol{\phi}(\mathbf{x}, t)$ field would be present throughout the Solar System



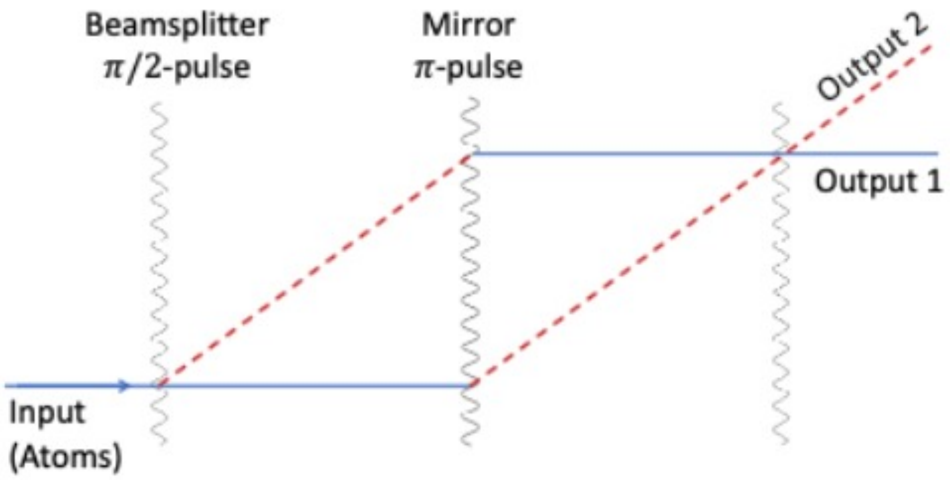
The wavelength depends on the ULDM mass: $\lambda \sim 10^8\,\mathrm{km}\left(\frac{10^{-15}\,\mathrm{eV}}{m_\phi}\right)$

Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

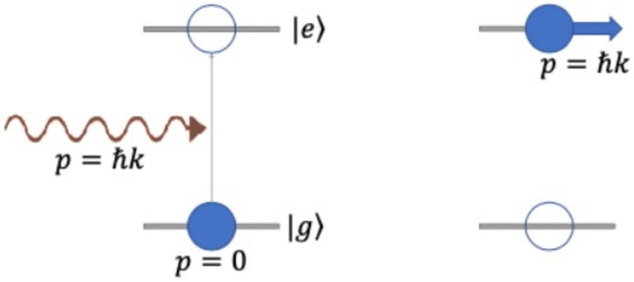


Atom Interferometer

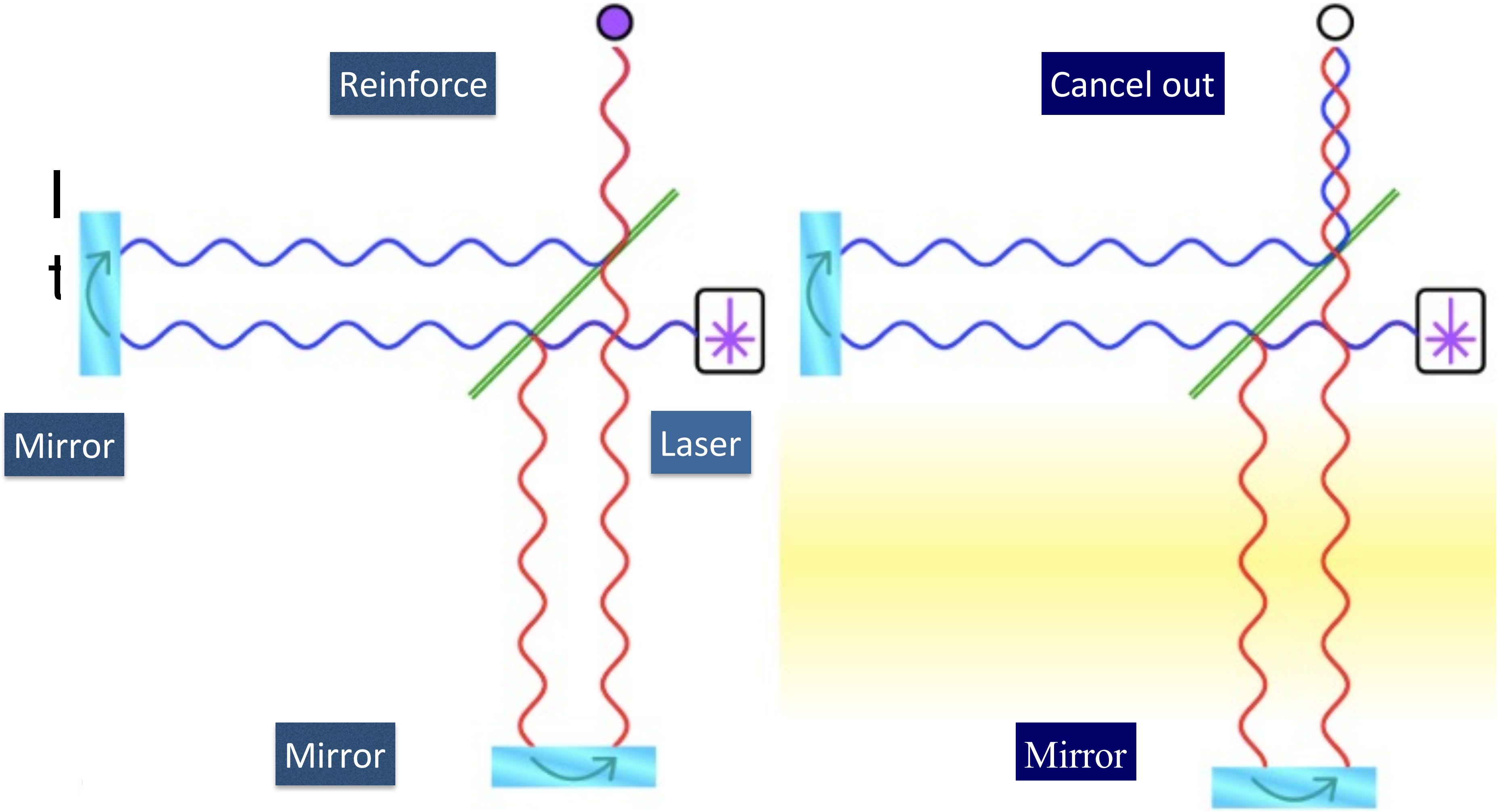


Laser excitation gives momentum kick to excited atom, which follows separated space-time path

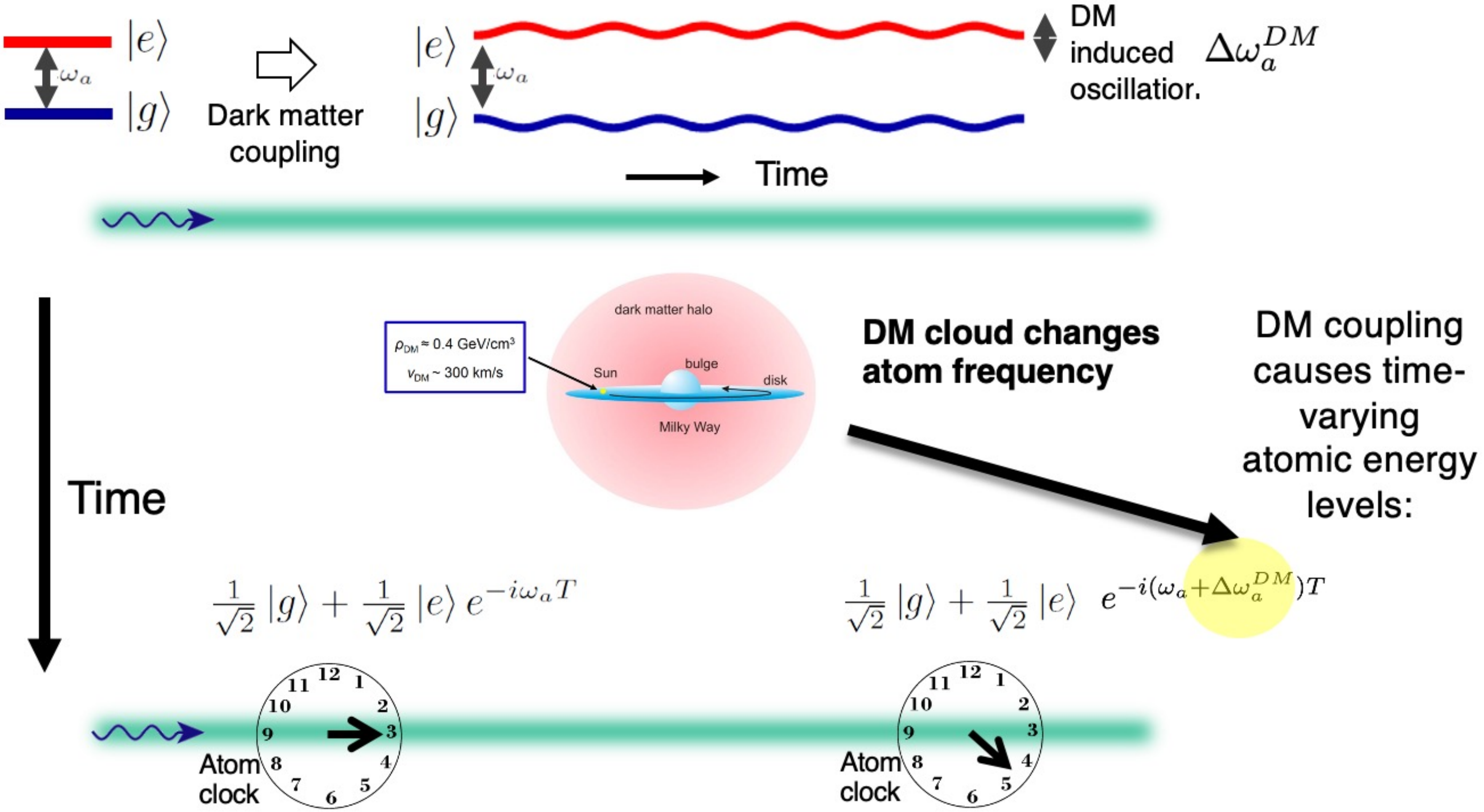
Interference between atoms following different paths



Principle of Laser Interferometers



Effect of Dark Matter on Atom Interferometer



Dark matter coupling

DM induced oscillatior. $\Delta\omega_a^{DM}$

Time

Time

DM cloud changes atom frequency

DM coupling causes time-varying atomic energy levels:

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\, e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}}\,|g\rangle + \frac{1}{\sqrt{2}}\,|e\rangle\;\; e^{-i(\omega_a + \Delta\omega_a^{DM})T}$$

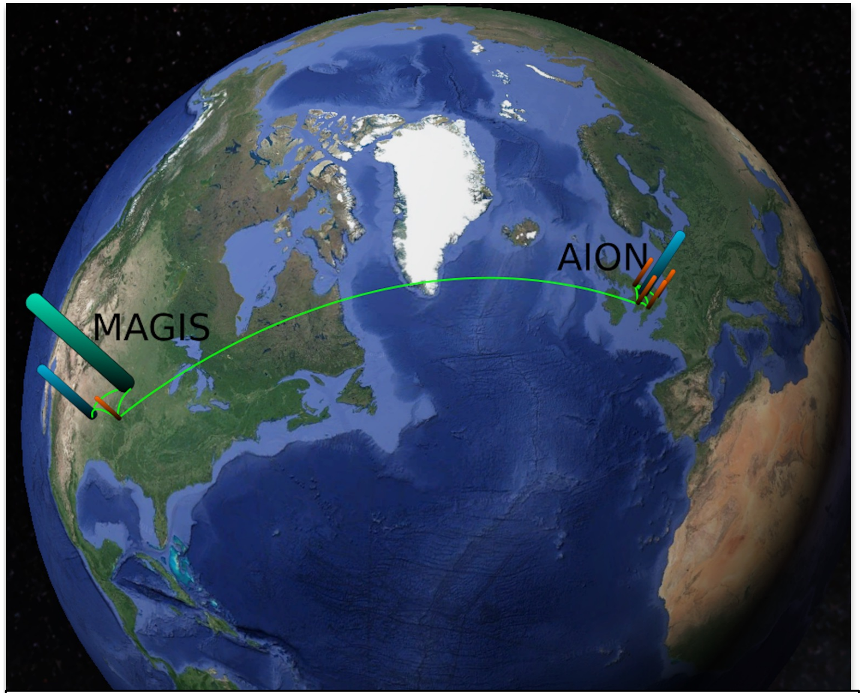
Atom clock

Atom clock

AION Collaboration

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1]
D. Bortoletto, Bowcock[5], W. Bowden[6,*], C. Brew[2], O. Buchmueller[6], J. Coleman, J. Carlton
G. Elertas, J. Ellis[1,&], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6,*],
M. Holynski, A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7],
P. Majewski[2], S. Malik[6], J. March-Russell, C. McCabe, D. Newbold[2], R. Preece[3],
B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh, 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



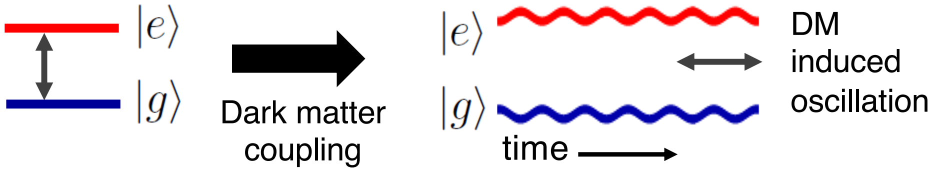
Network with MAGIS project in US

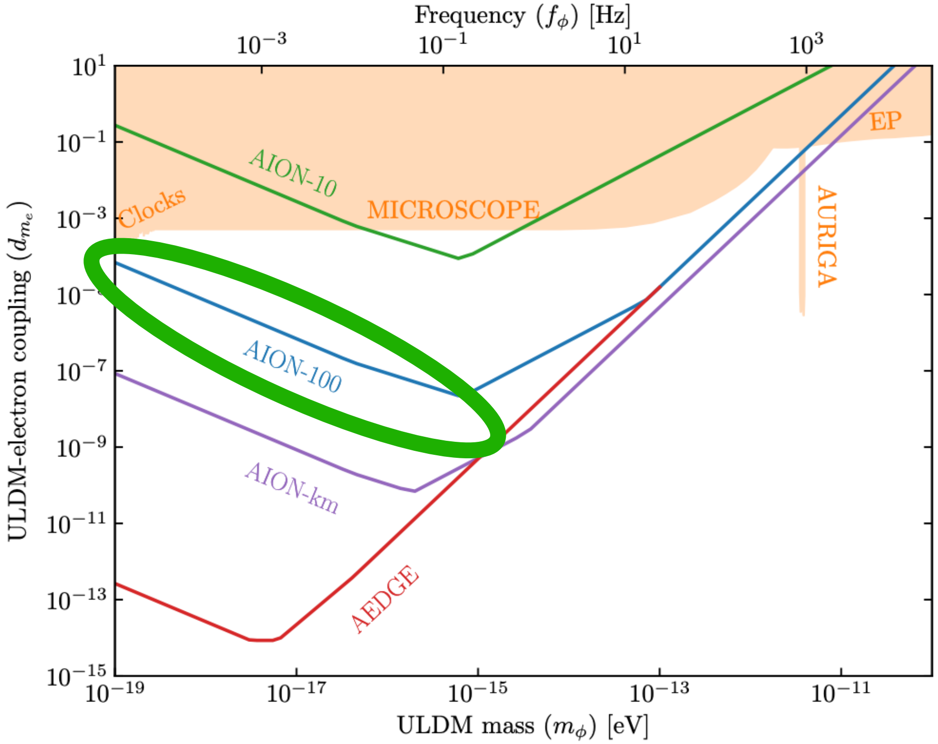
MAGIS Collaboration (Abe et al): arXiv:2104.02835

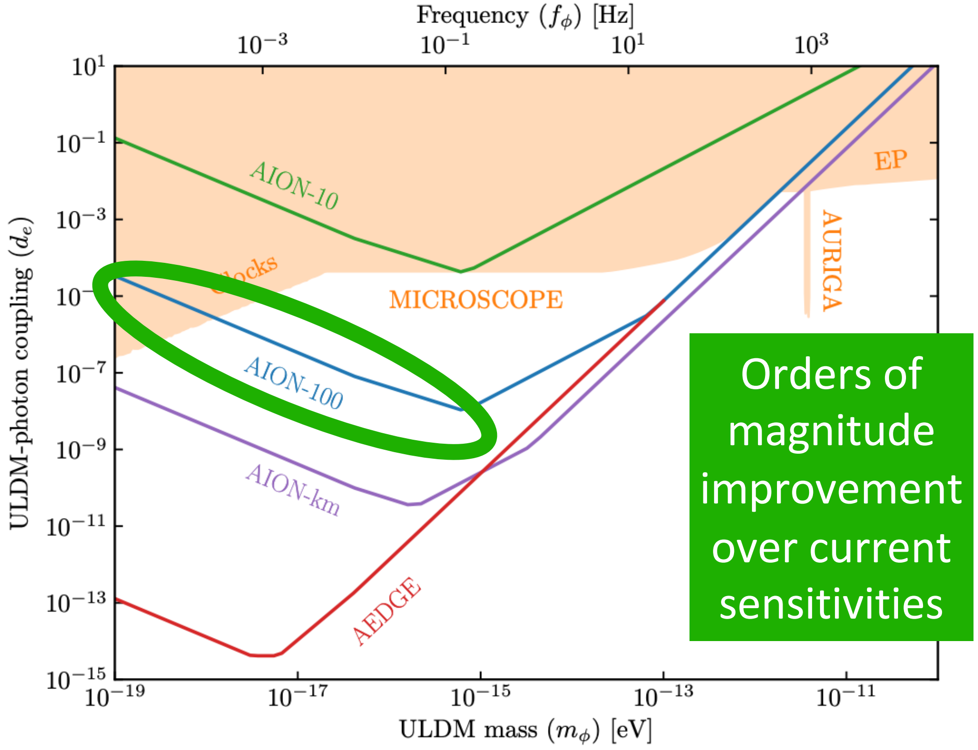
Searches for Light Dark Matter

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

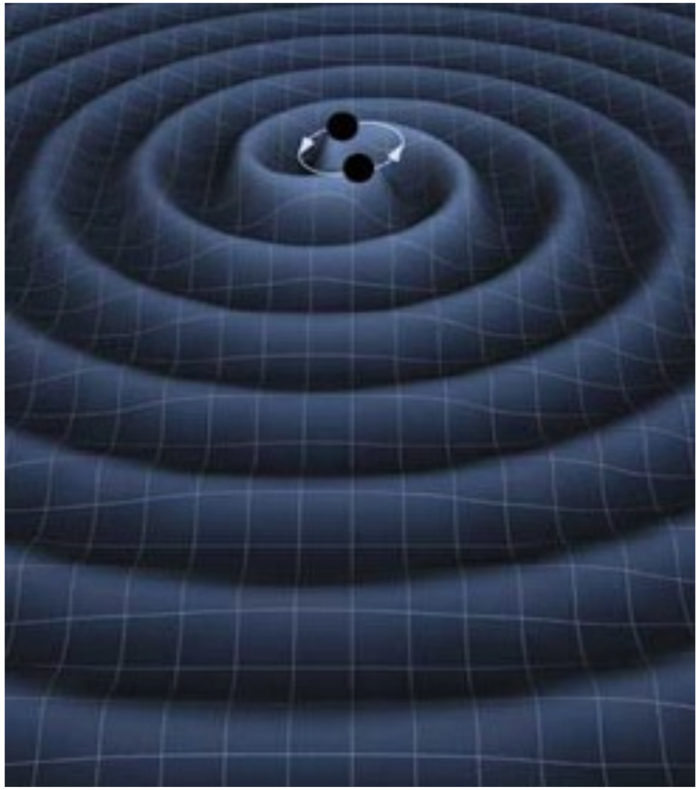
Näherungsweise Integration der Feldgleichungen
der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Prob
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

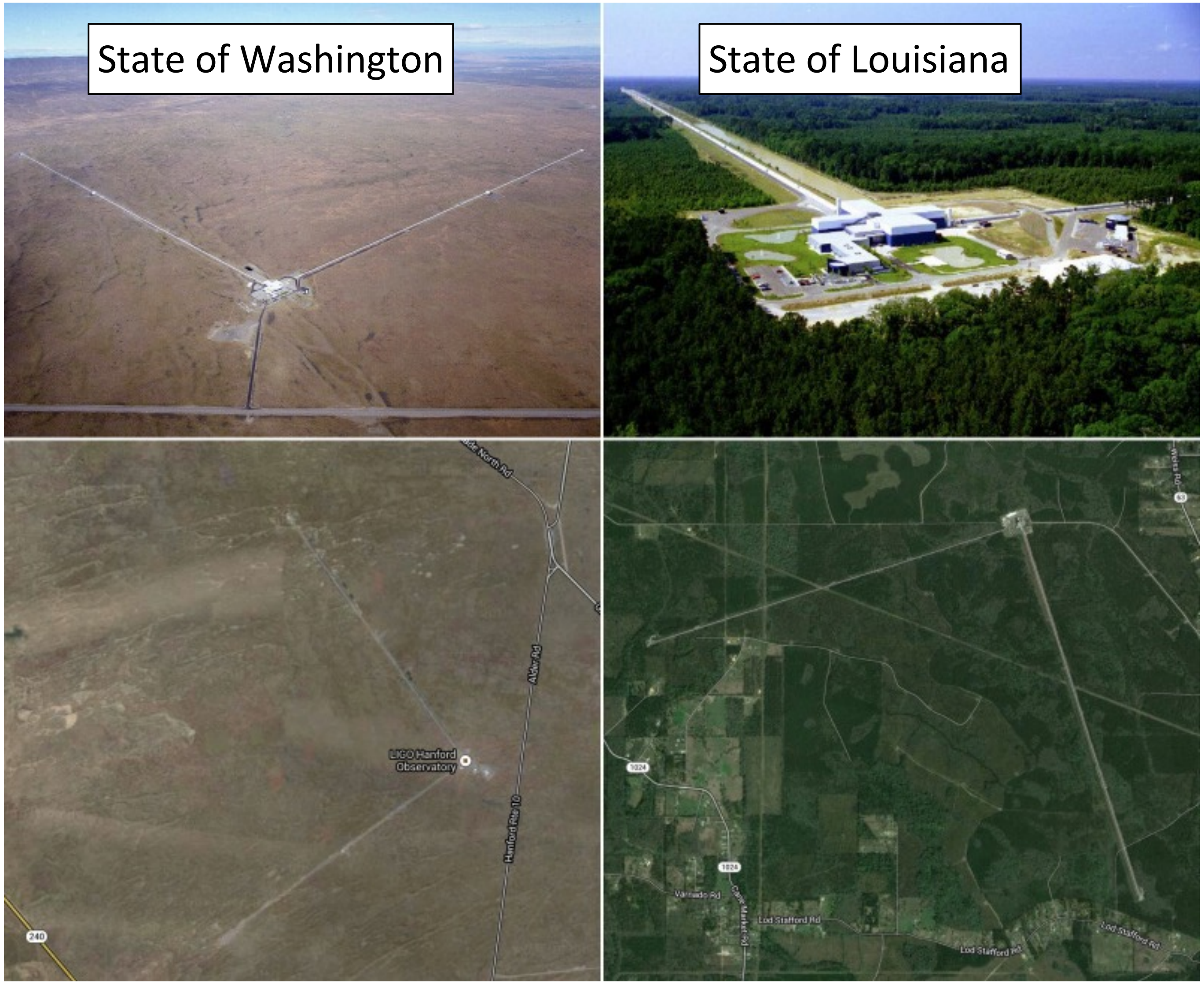
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}$$

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



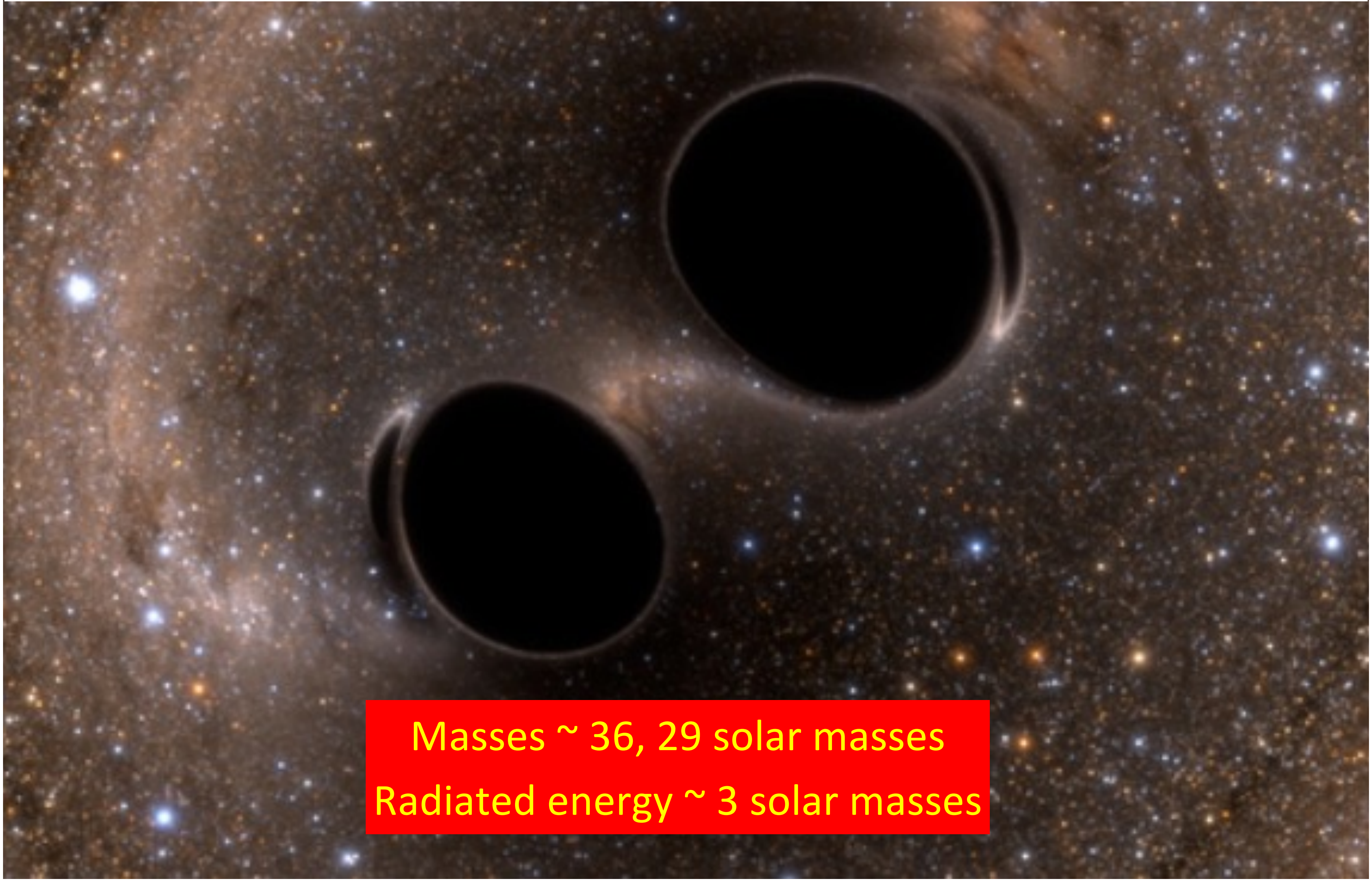
- Tried to retract prediction in 1936!

Direct Discovery of Gravitational Waves



- Measu

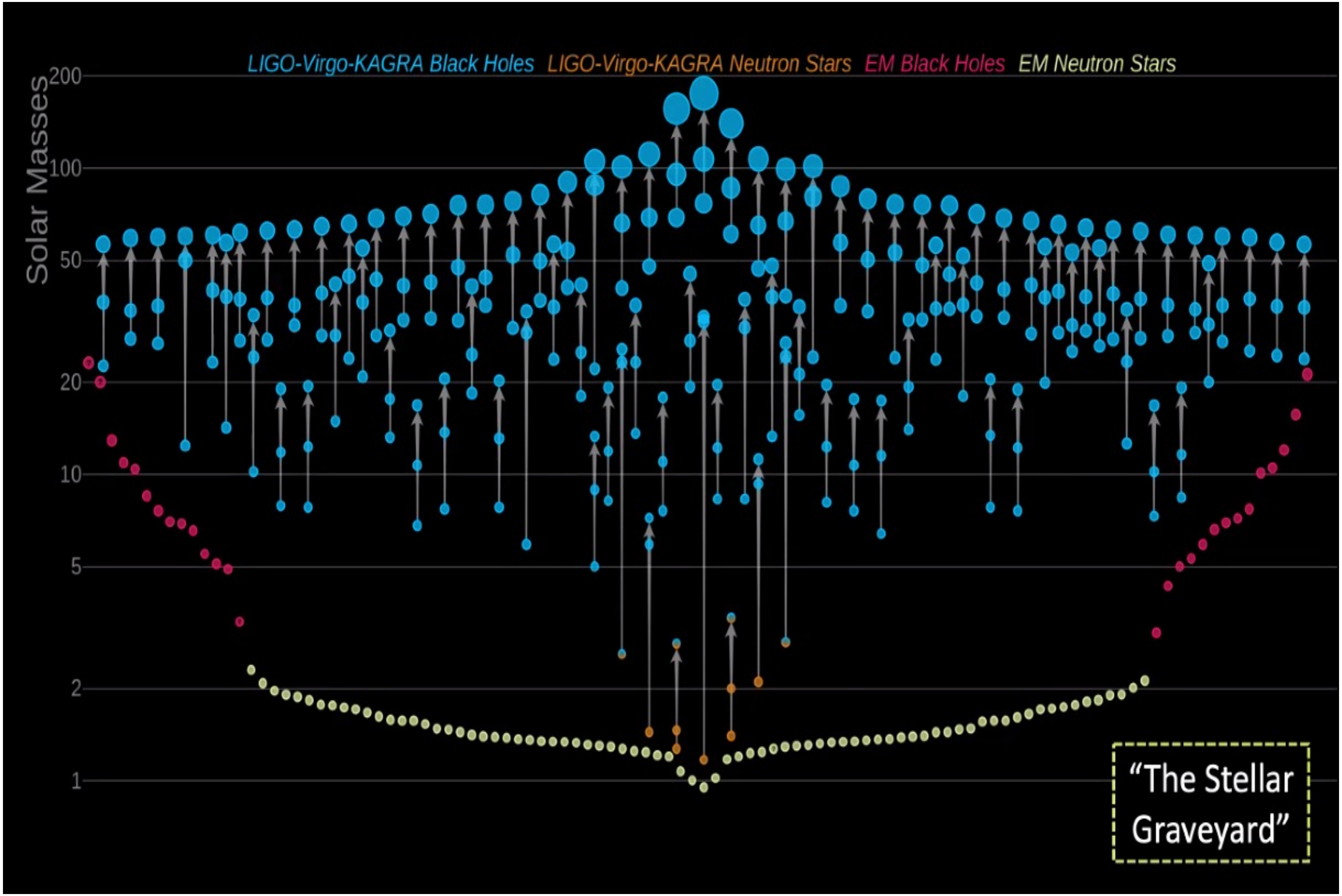
Fusion of two massive black holes



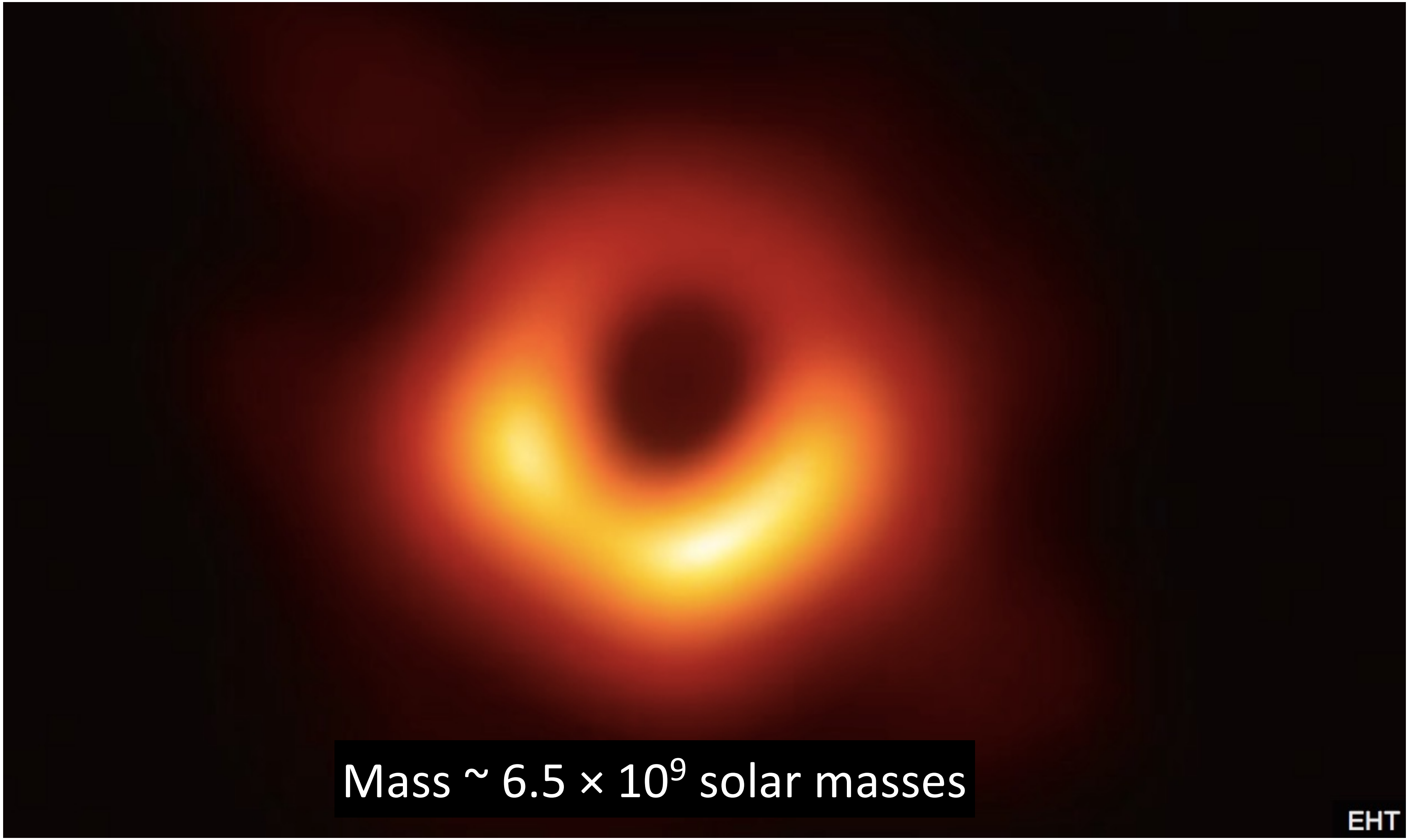
Masses ~ 36, 29 solar masses

Radiated energy ~ 3 solar masses

LIGO-Virgo-KAGRA Black Holes & Neutron Stars



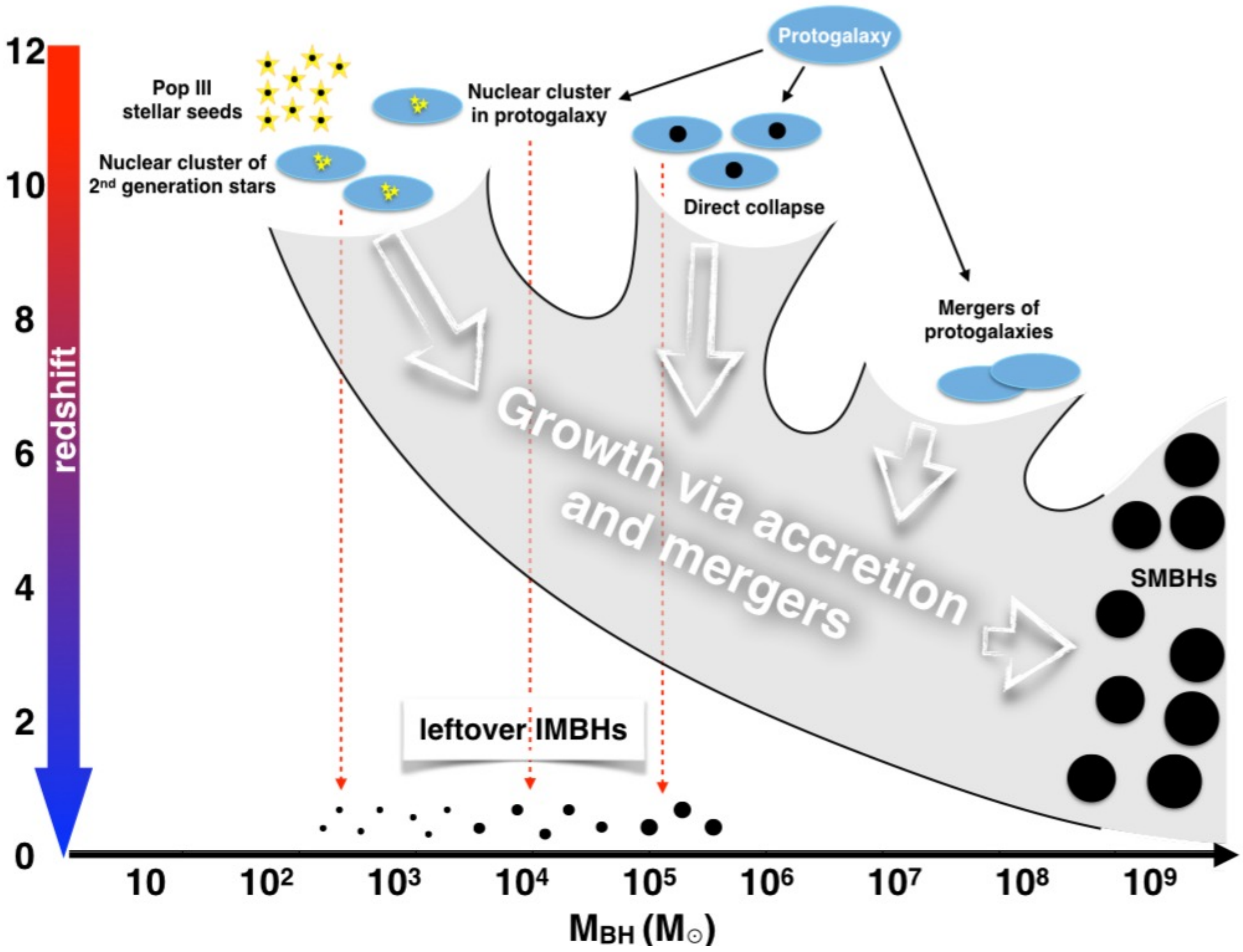
Supermassive Black Holes in Active Galactic Nuclei: Image of M87



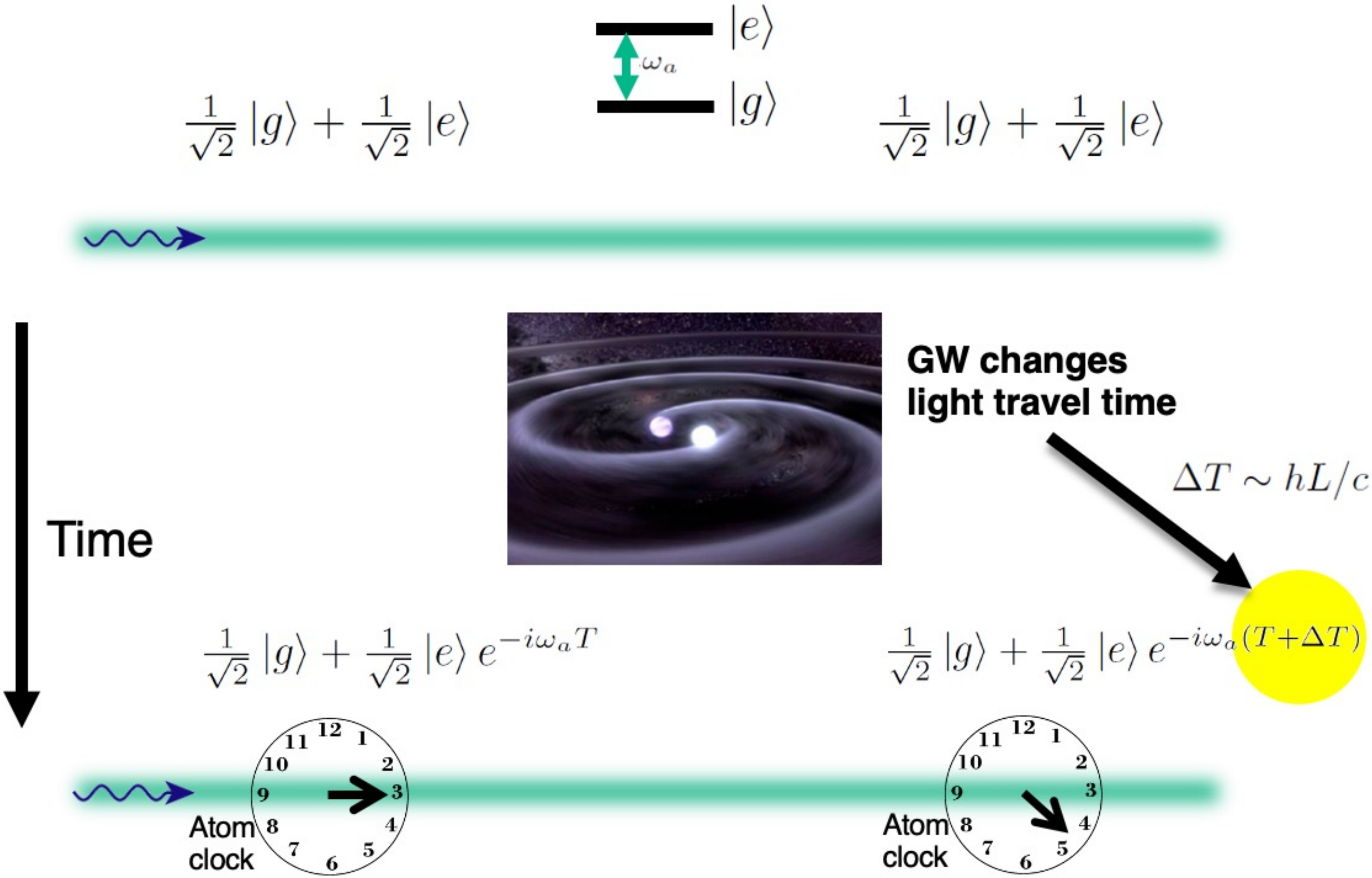
Mass ~ 6.5×10^9 solar masses

How to Make a Supermassive BH?

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



Effect of Gravitational Wave on Atom Interferometer



$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

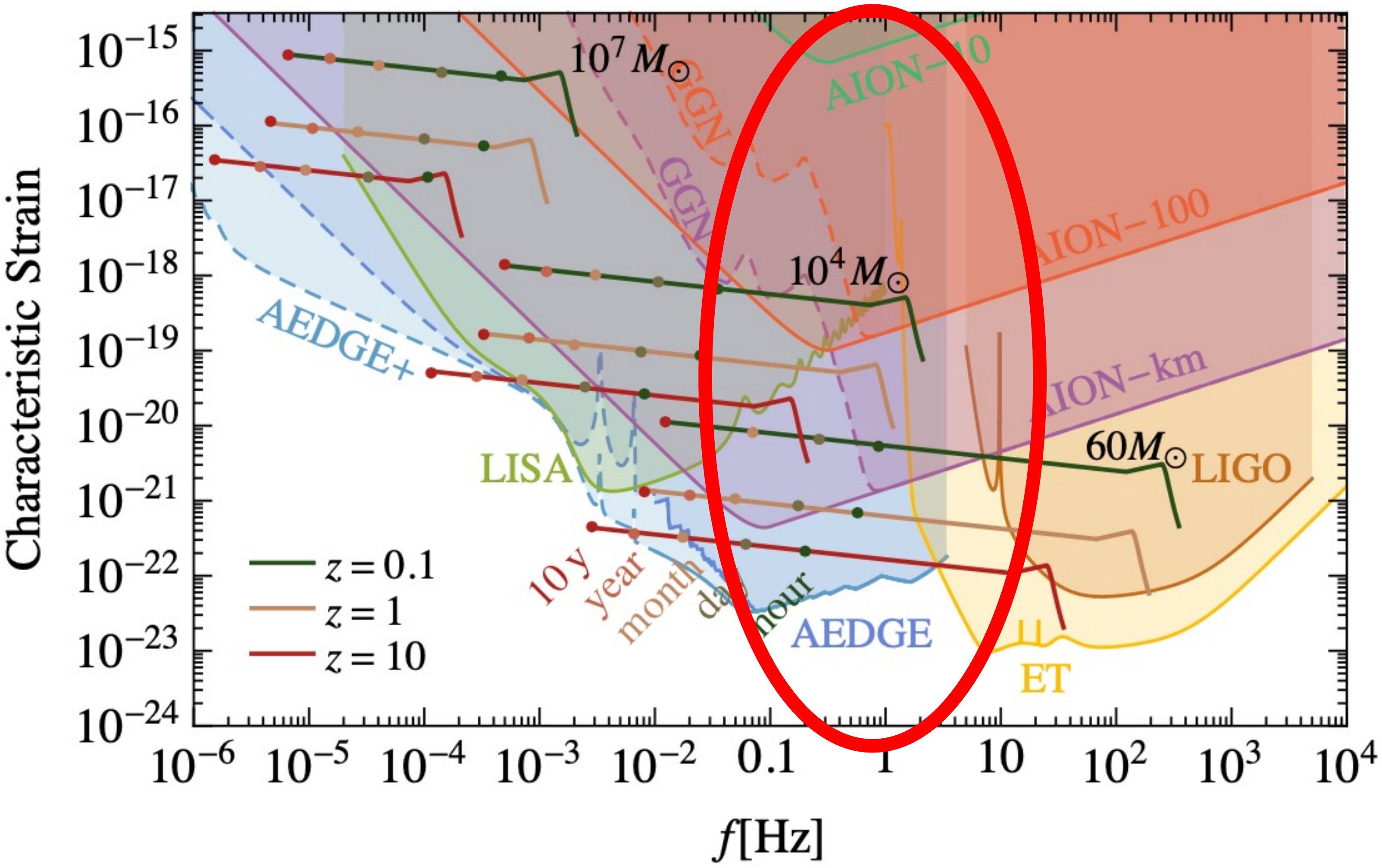
GW changes light travel time

$\Delta T \sim hL/c$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$

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

The Biggest Bangs since the Big Bang

STELIOS THOUKIDIDES

Home > Bureau of Oceans and International Environmental and Scientific Affairs > Remarks & Releases > Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

★ ★ ★

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

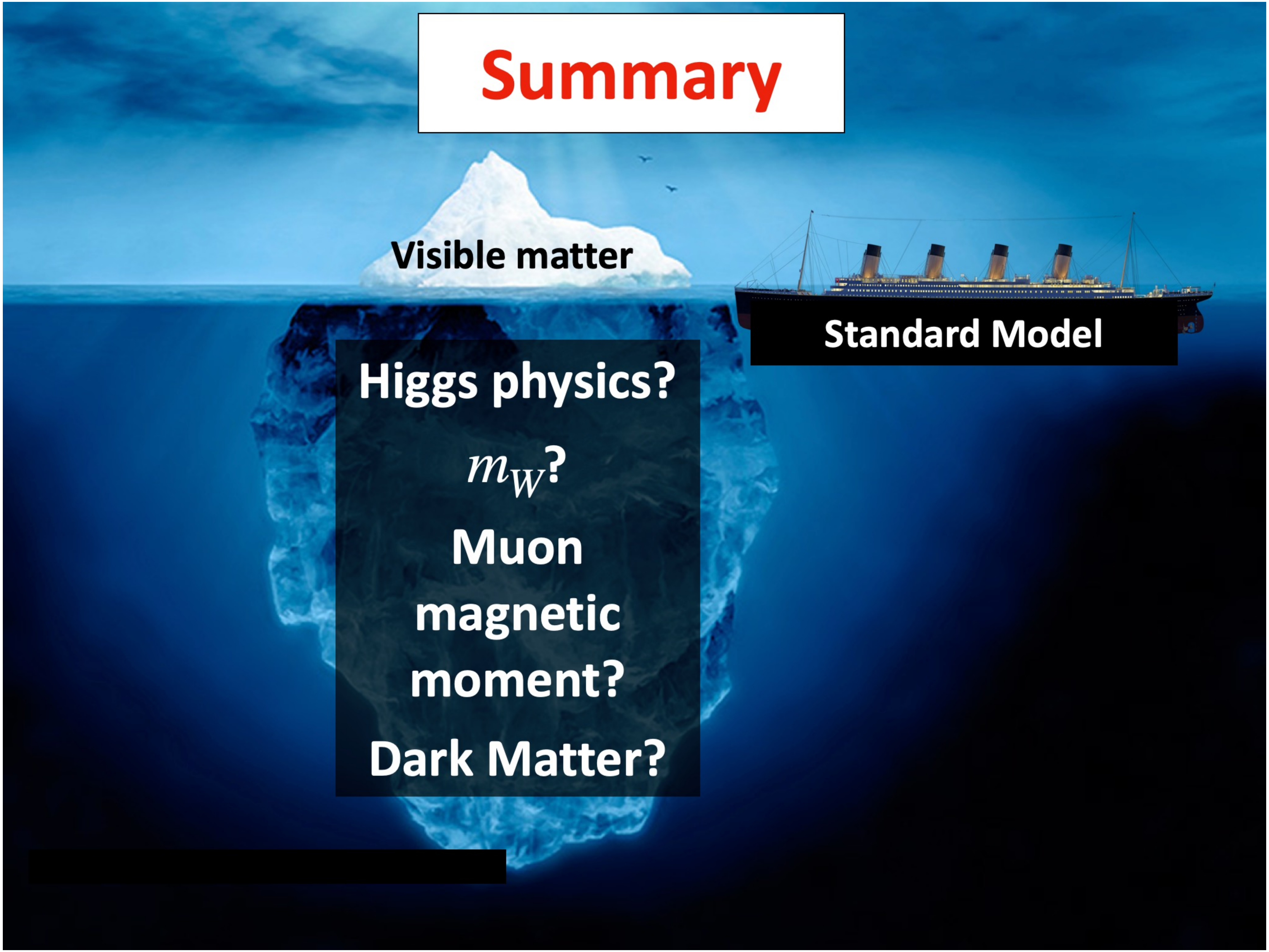
OTHER RELEASE

BUREAU OF OCEANS AND INTERNATIONAL ENVIRONMENTAL AND SCIENTIFIC AFFAIRS

APRIL 26, 2024

“Should the CERN Member States determine the FCC-ee is likely to be CERN’s next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.”

Summary



Higgs physics?

m_W?

Muon magnetic moment?

Dark Matter?

[redacted]