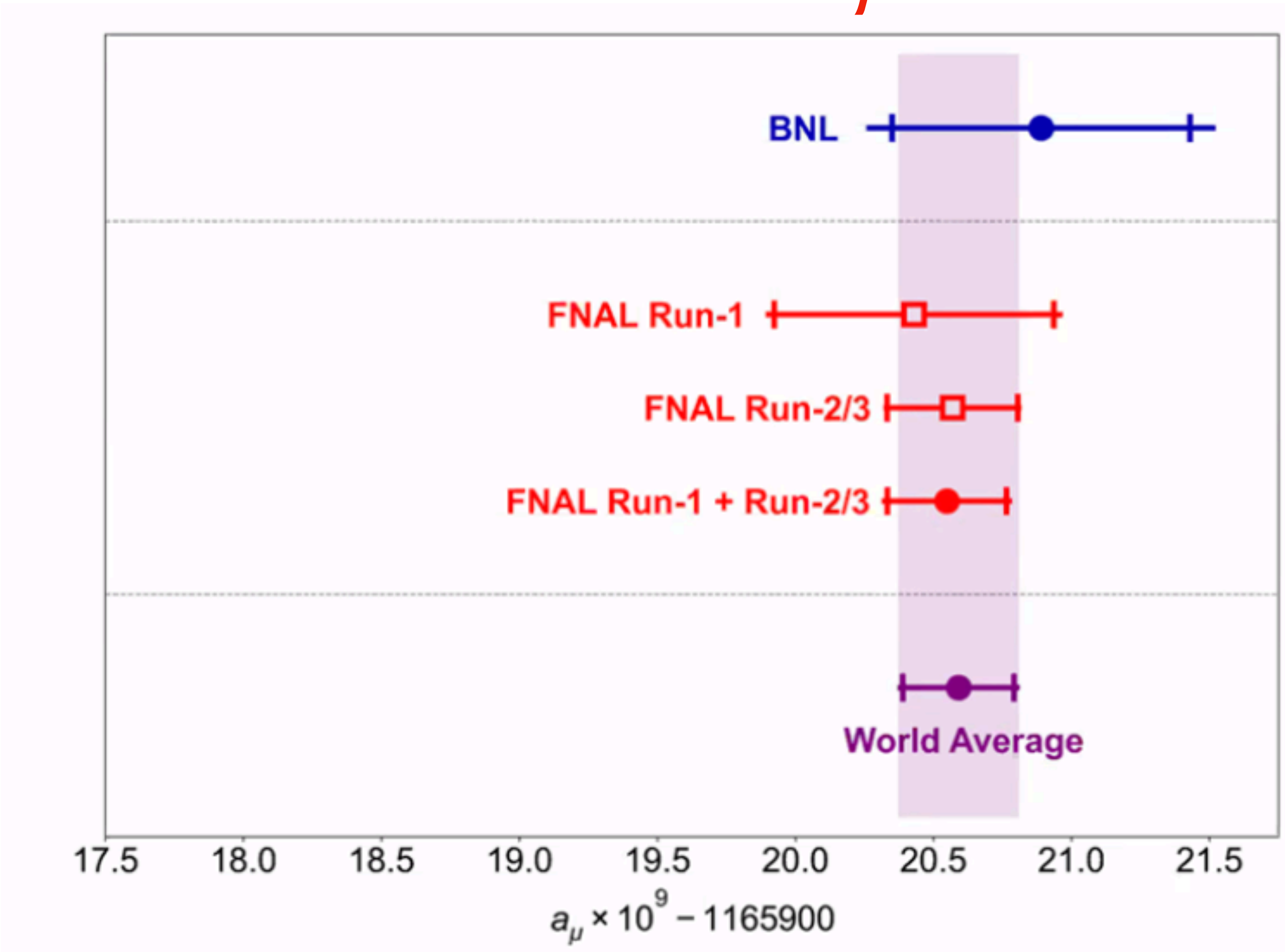
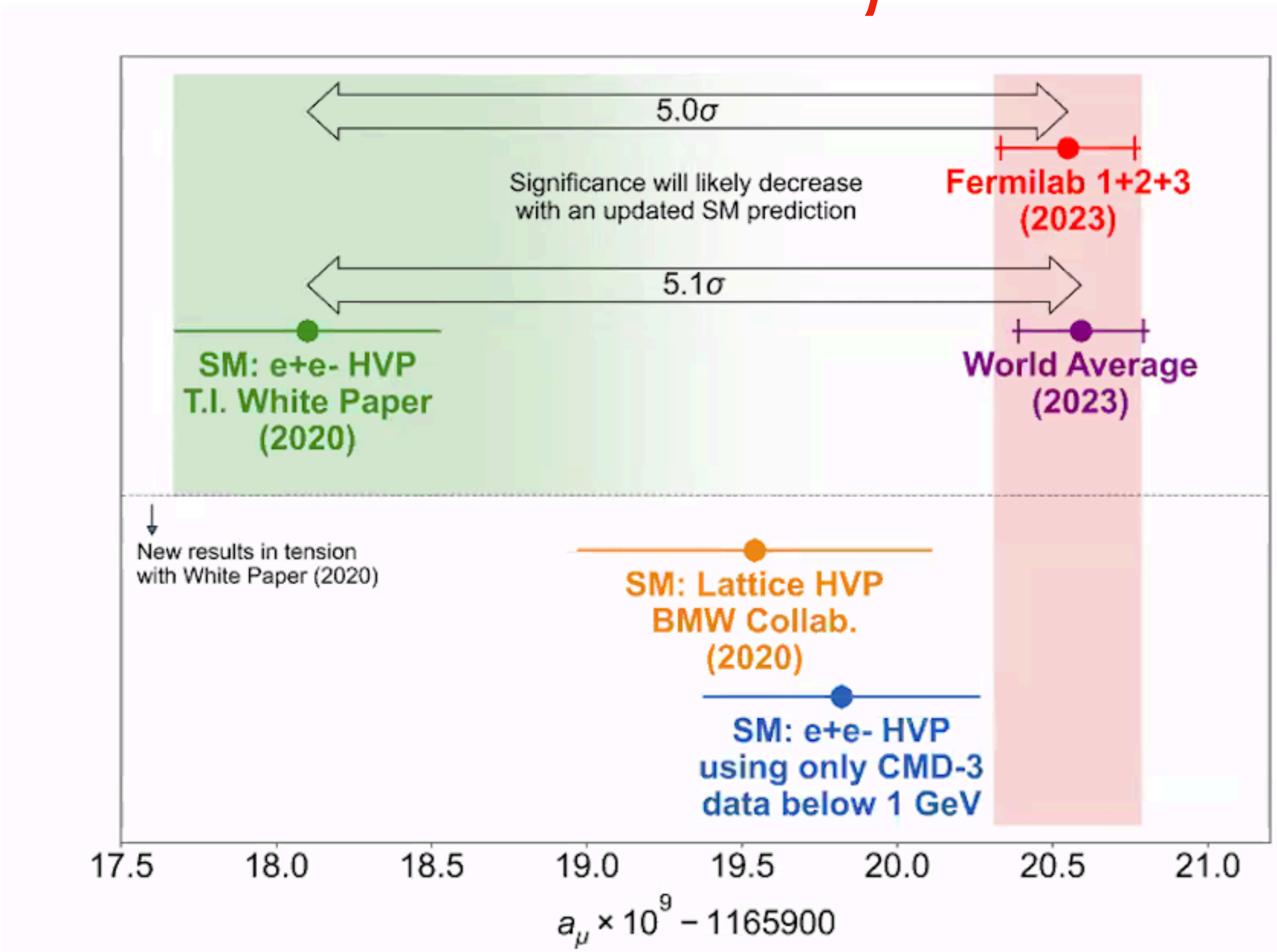
Quo Vadis $g_\mu - 2$?



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

Quo Vadis $g_\mu - 2$?



- Theoretical situation still confused: watch this space!

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

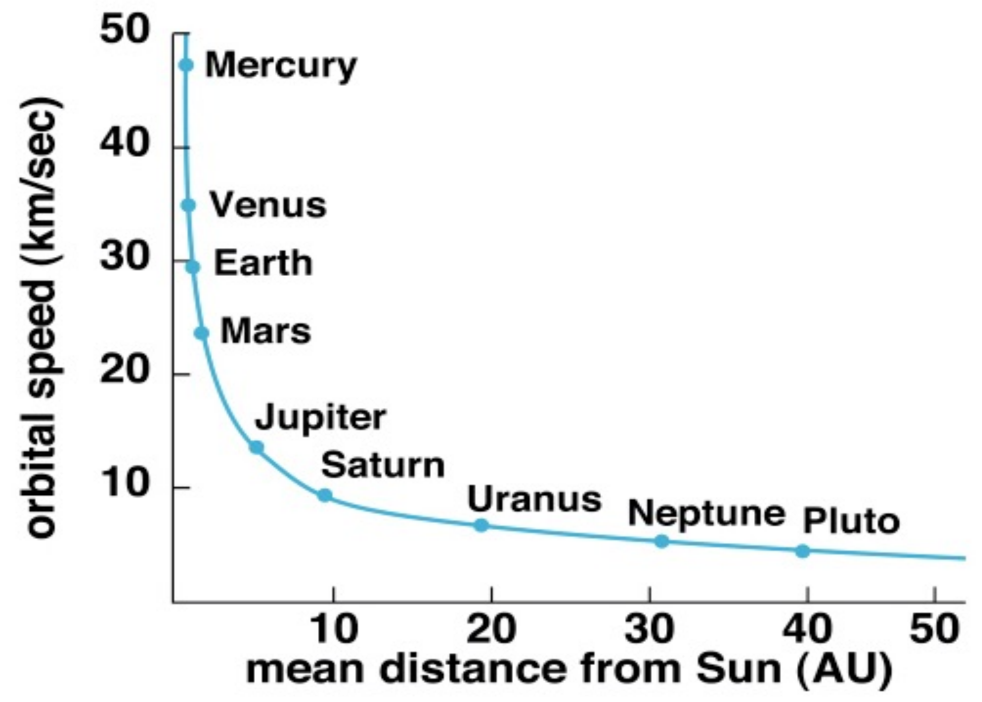
- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter

Scanned at the American Institute of Physics

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

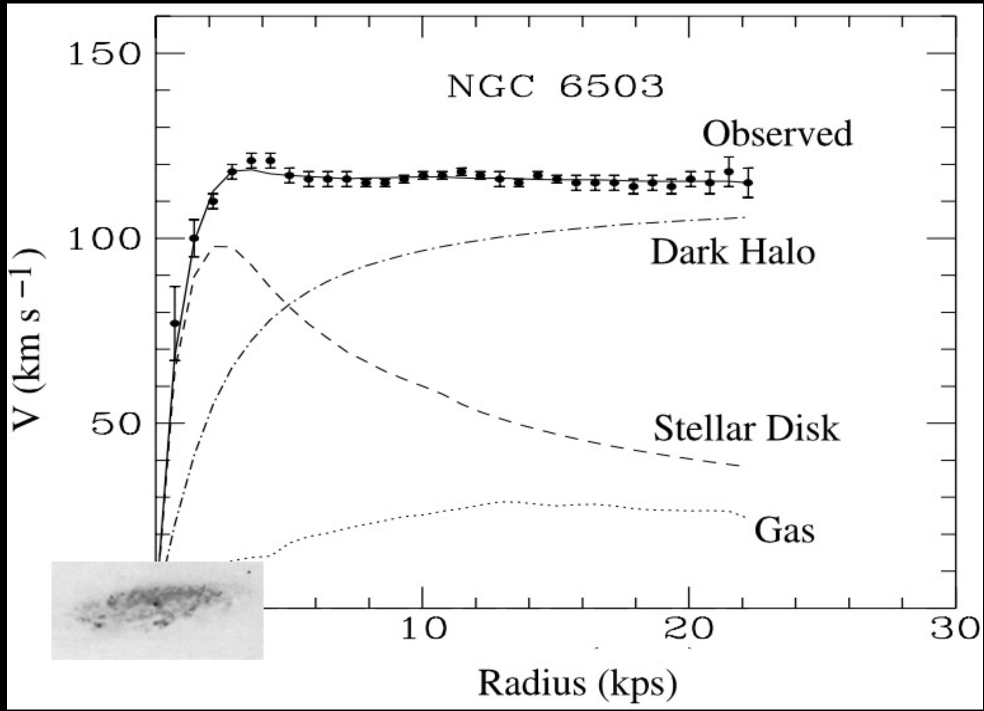
Galactic Rotation Curves

- In the Solar System



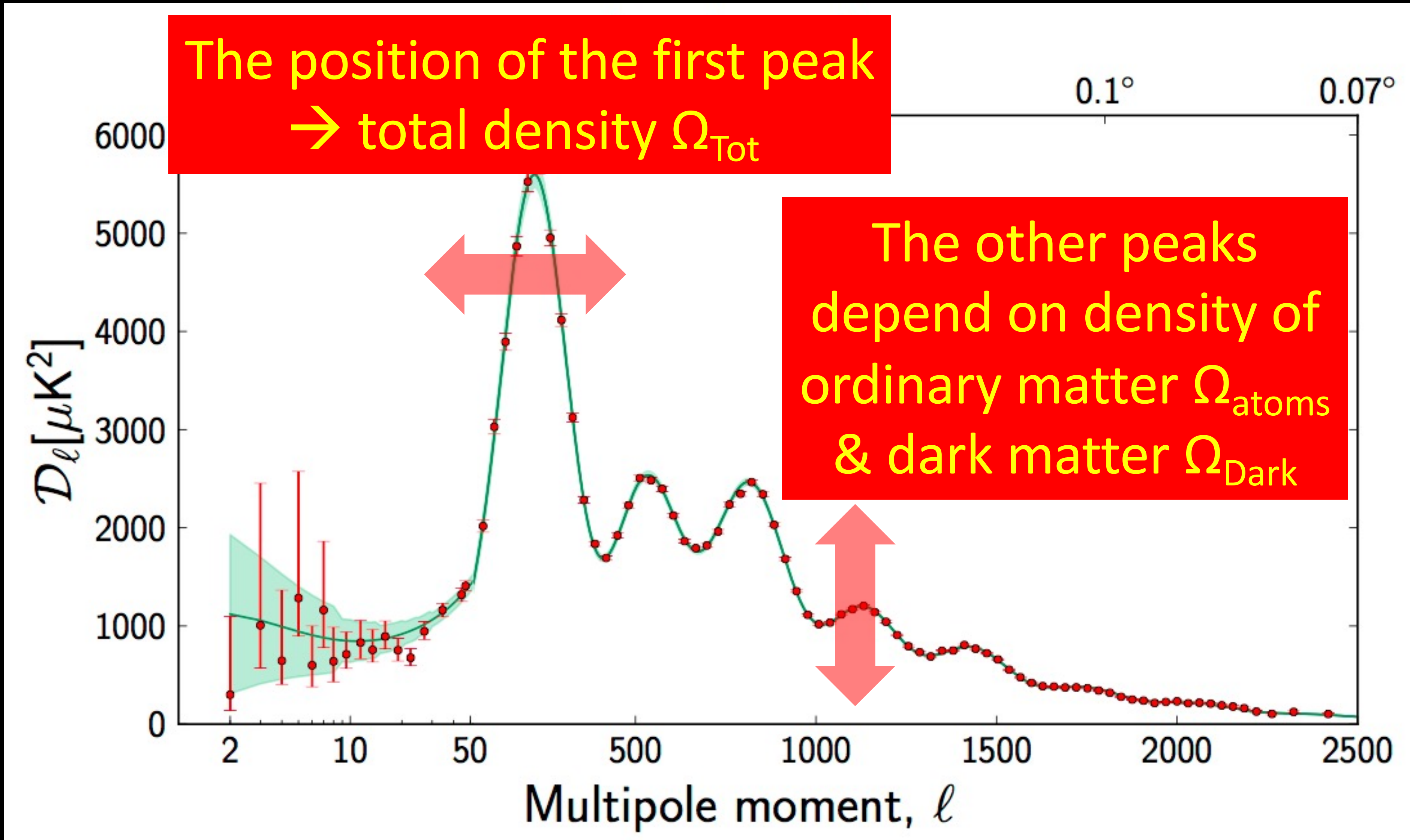
- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies



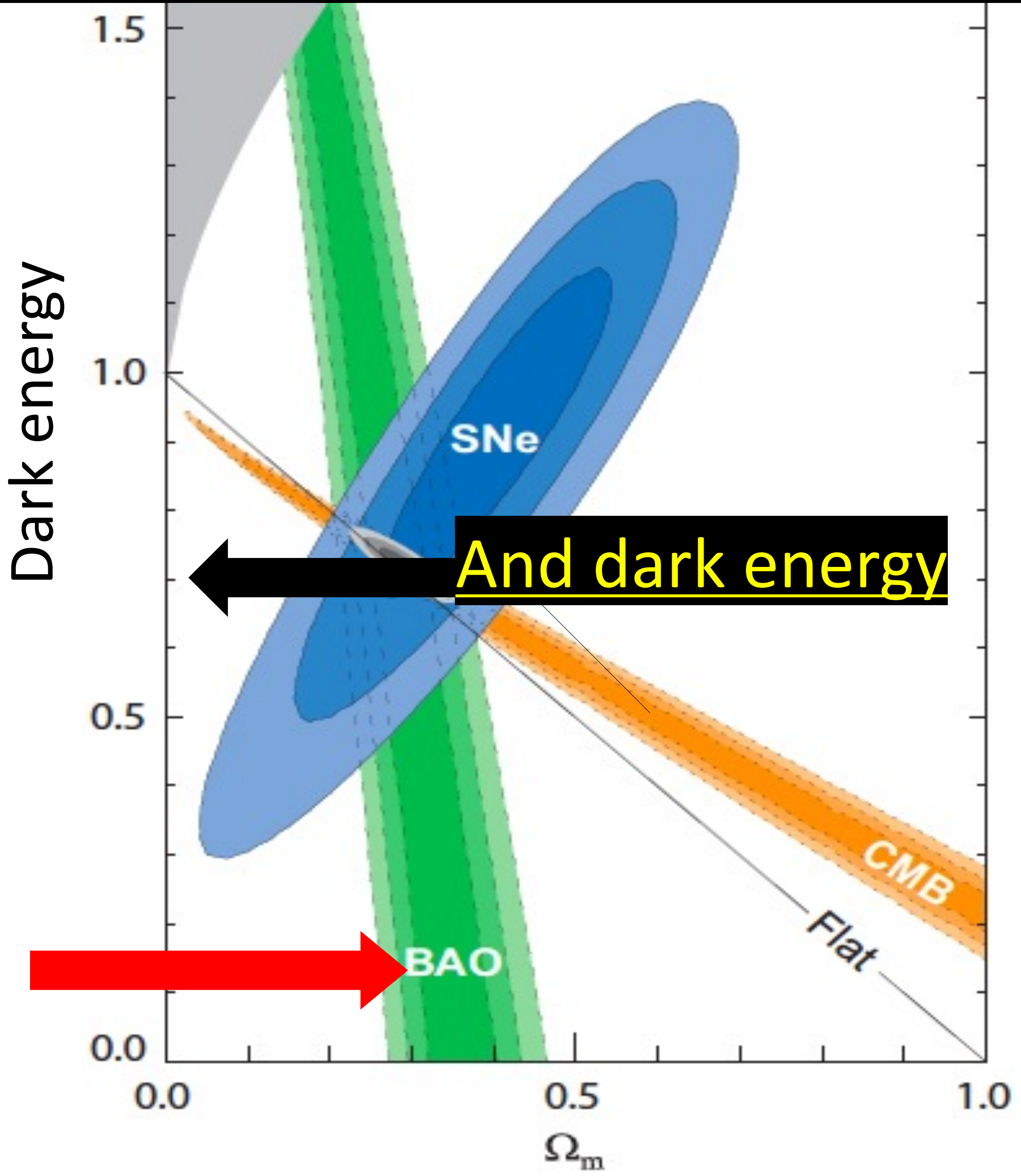
- The velocities do not decrease with distance
- Dark matter spread out

The Spectrum of Fluctuations in the Cosmic Microwave Background



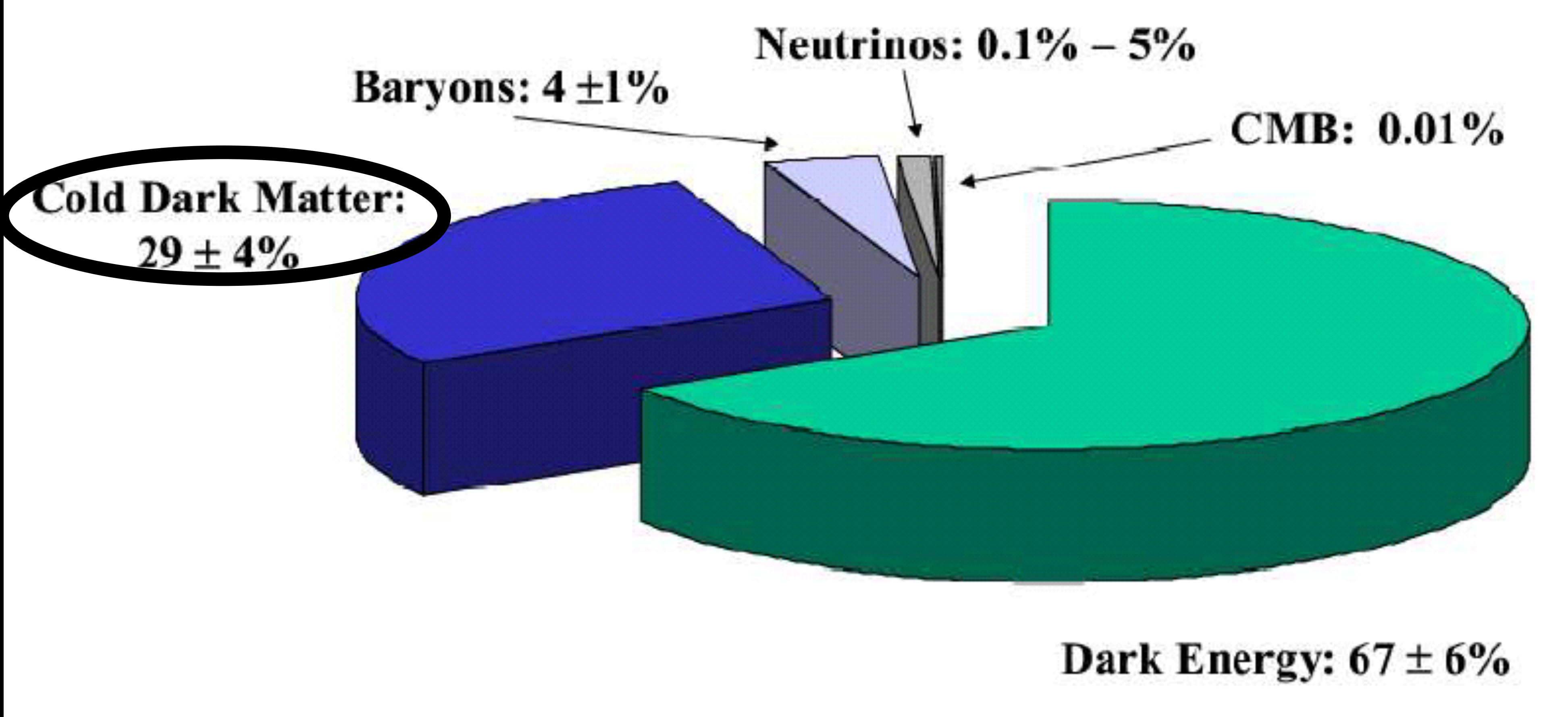
The Content of the Universe

- According to
  - Microwave background
  - Supernovae
  - Structures (galaxies, clusters, …) in the the Universe



There is dark matter

Strange Recipe for a Universe

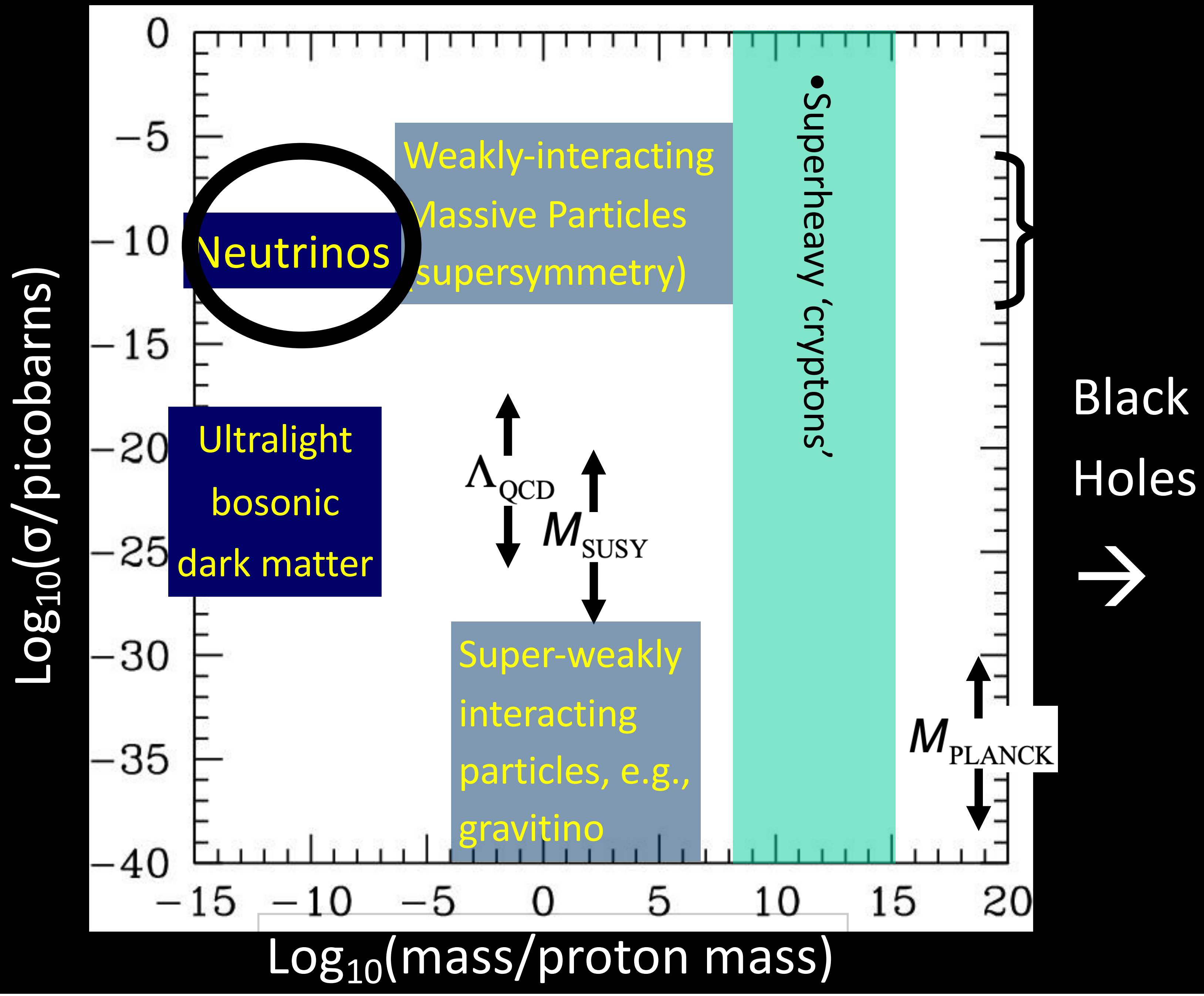


The 'Standard Model' of the Universe indicated by astrophysics and cosmology

Properties of Dark Matter

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

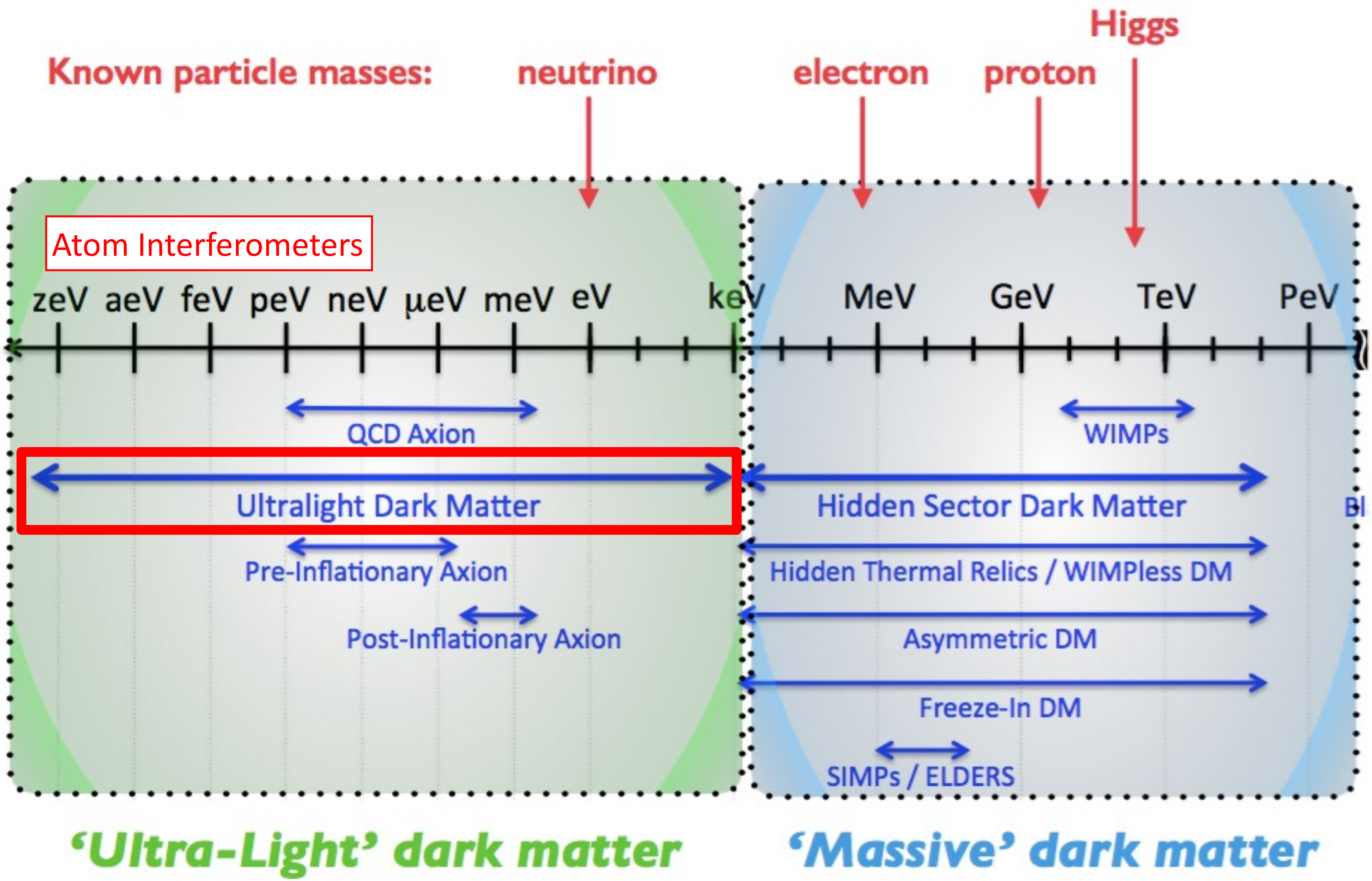
Particle Dark Matter Candidates



Neutrinos

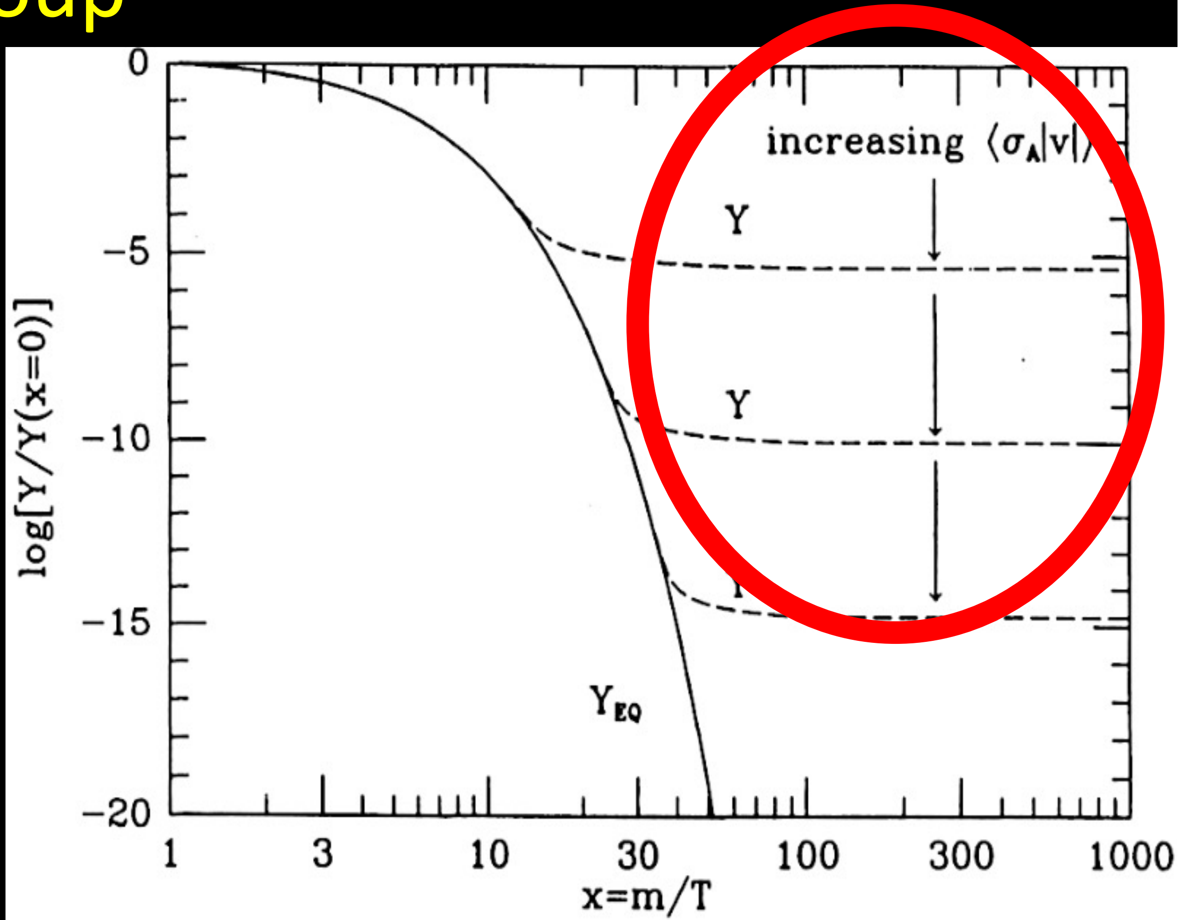
- They exist! ☺️
- They have weak interactions ☺️
- They have masses ☺️
  - As indicated by neutrino oscillations
- But their masses are very small ☹️
  - < 1 eV (= 1/1000,000,000 of proton mass)
- Not able to grow all structures in Universe ☹️
  - (run away from small structures)
- Maybe some other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



The WIMP 'Miracle'

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

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

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

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

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

- Putting the numbers in:

$$m \lesssim \tfrac{1}{2}\sqrt{10C}\;\mathrm{TeV} \lesssim 5\;\mathrm{TeV}$$

Dimopoulos, PLB246, 347 (1990)

WIMP Candidates

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

What lies beyond the Standard Model?

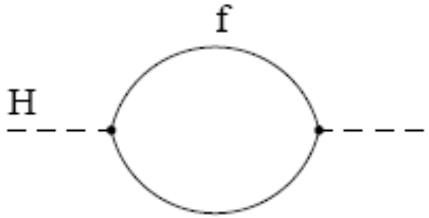
Supersymmetry

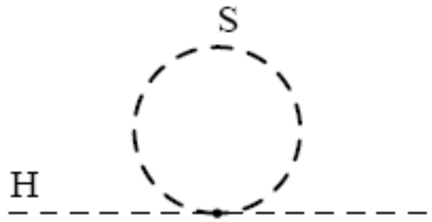
New motivations
From LHC Run 1

- 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**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:





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

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

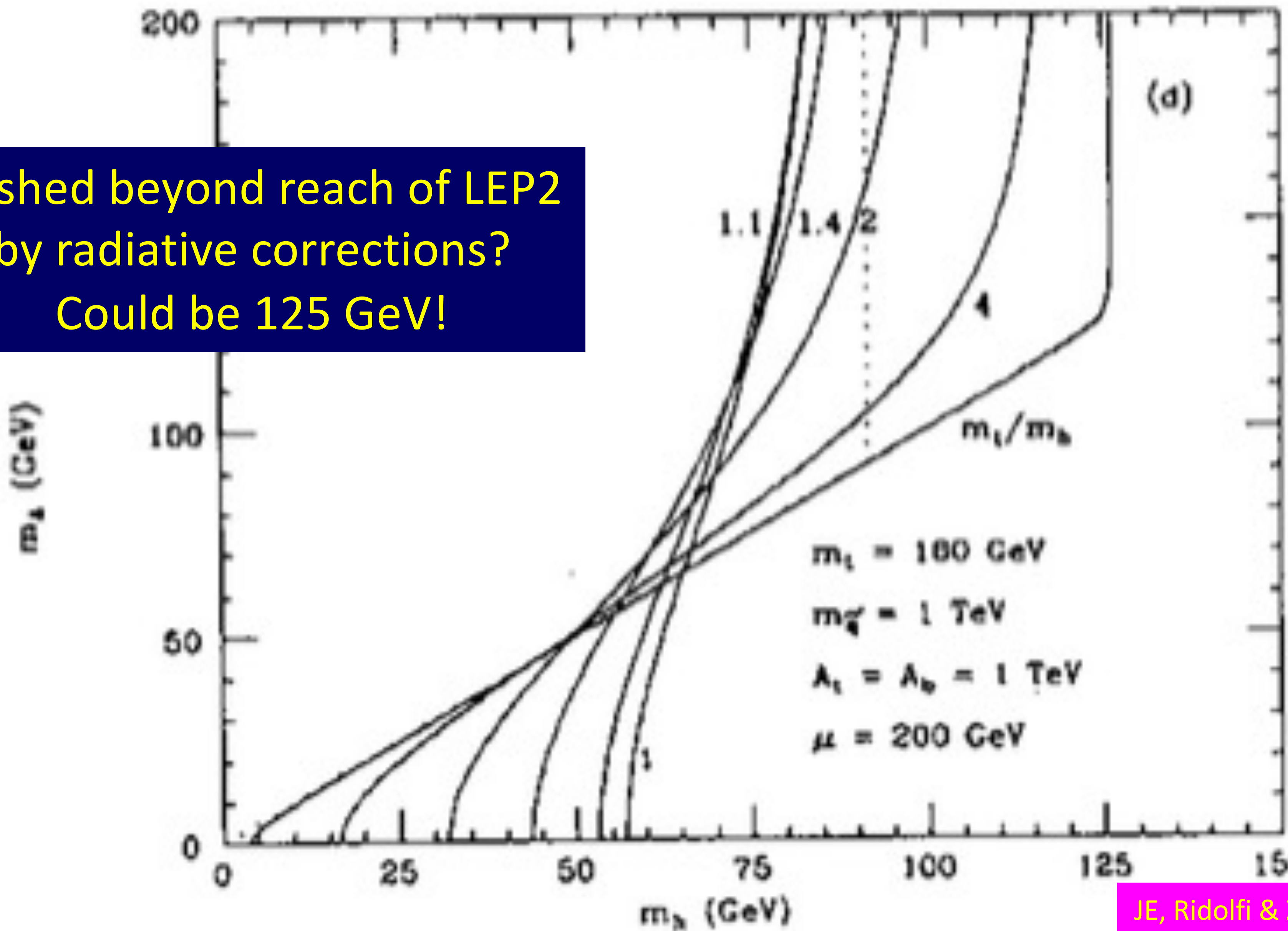
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

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

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:

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

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

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

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

Dimopoulos, Raby & Wilczek,
Ibanez & Ross, 1982

1991

LEP Data Consistent with Supersymmetric Grand Unification

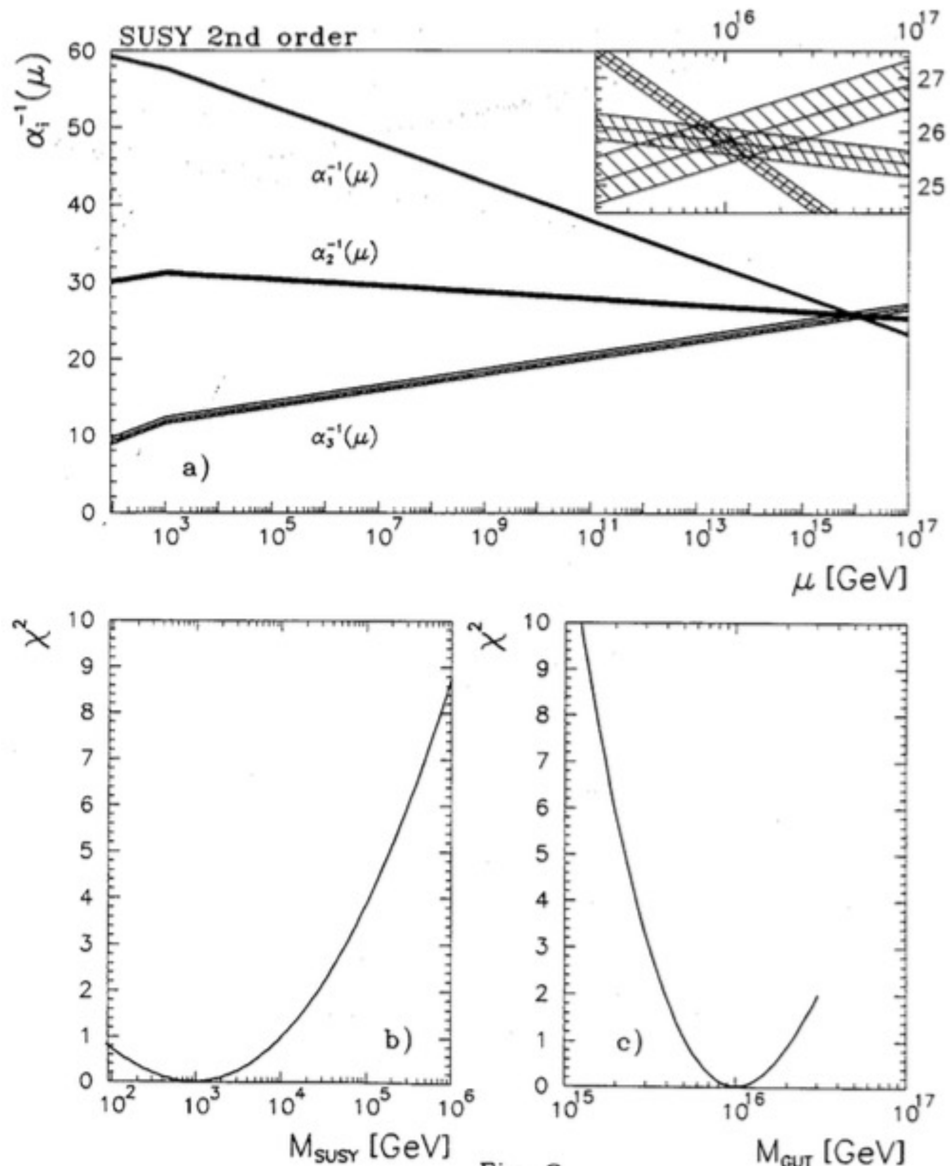
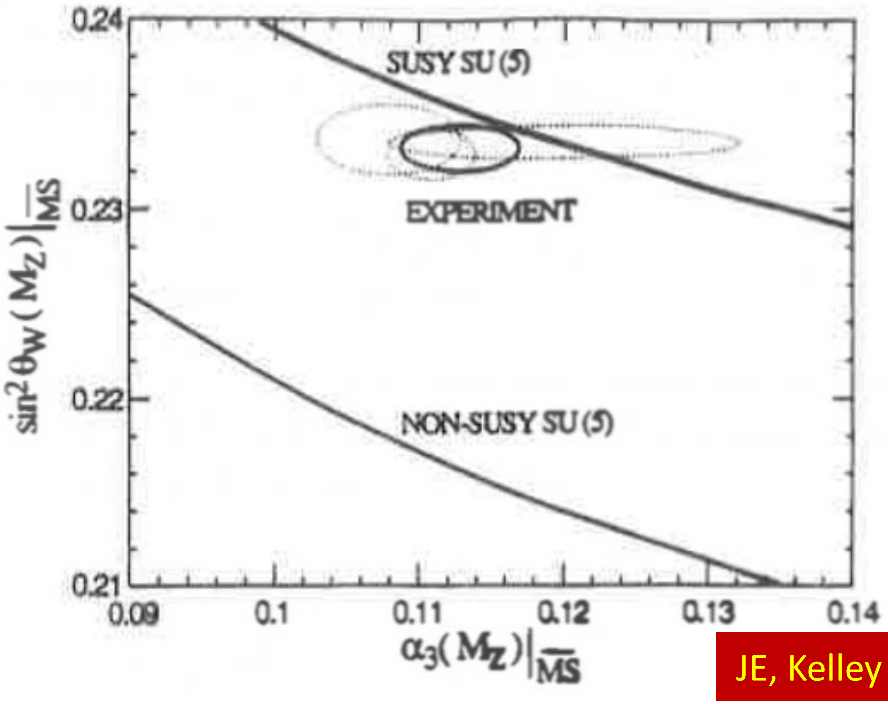


Fig. 2

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

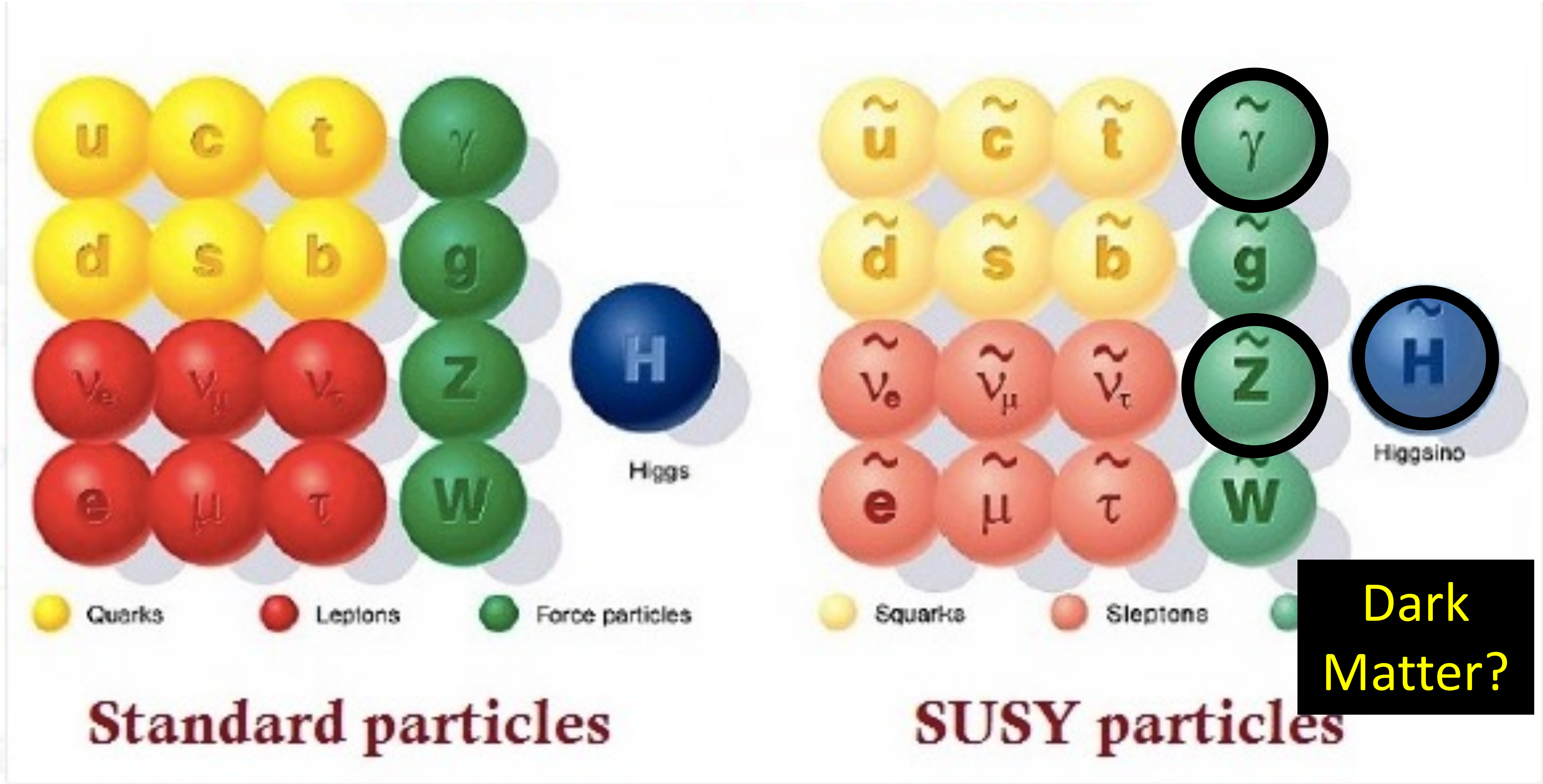
  (Excluded by LEP, direct searches)

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

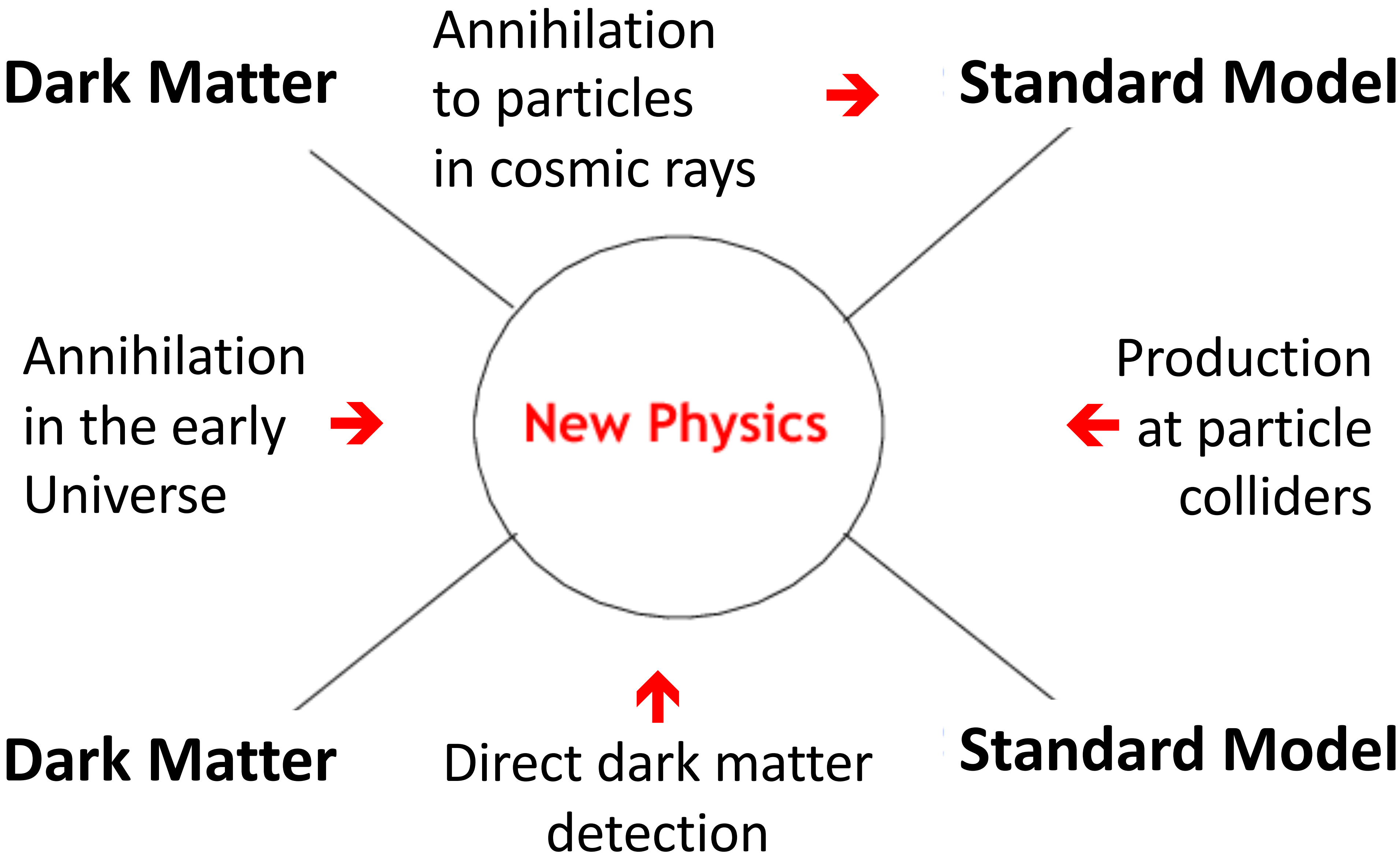
  Gravitino

  (nightmare for detection)

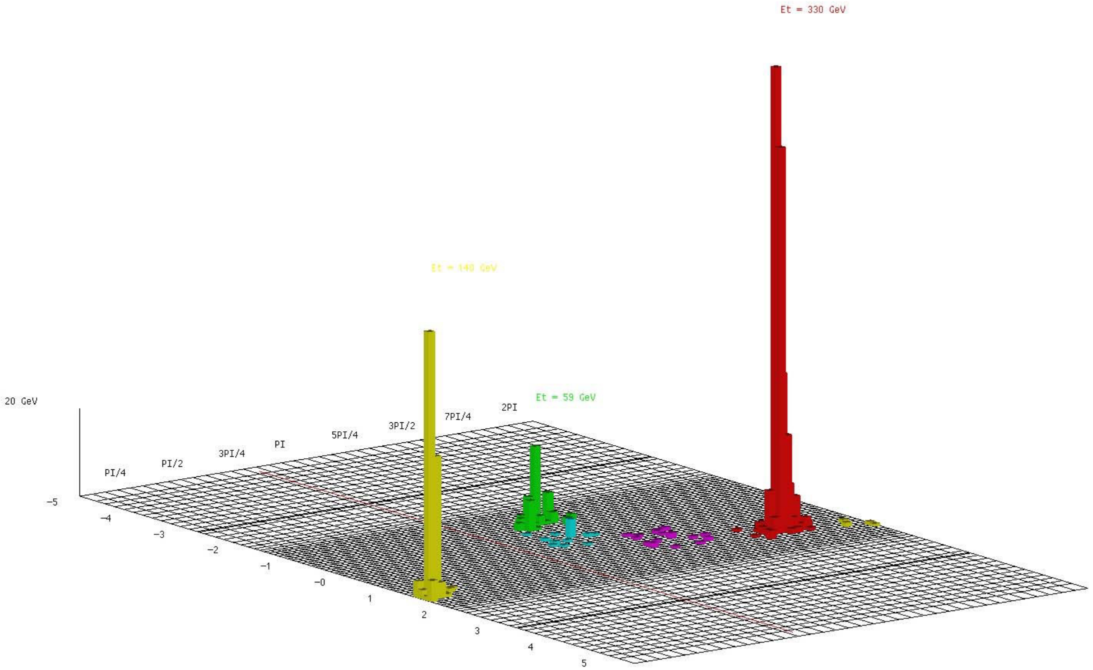
Minimal Supersymmetric Extension of the Standard Model

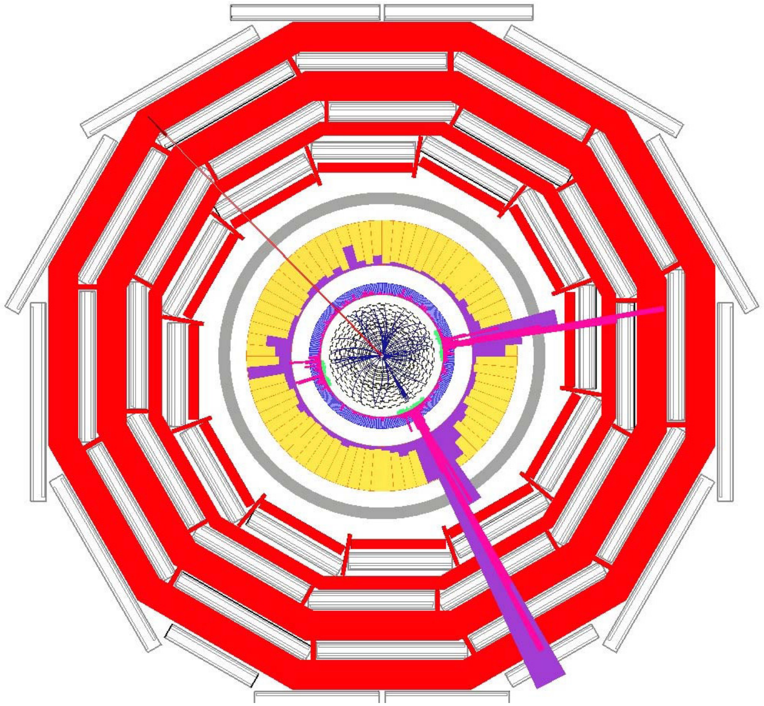


Searches for Dark Matter



Classic Dark Matter Signature



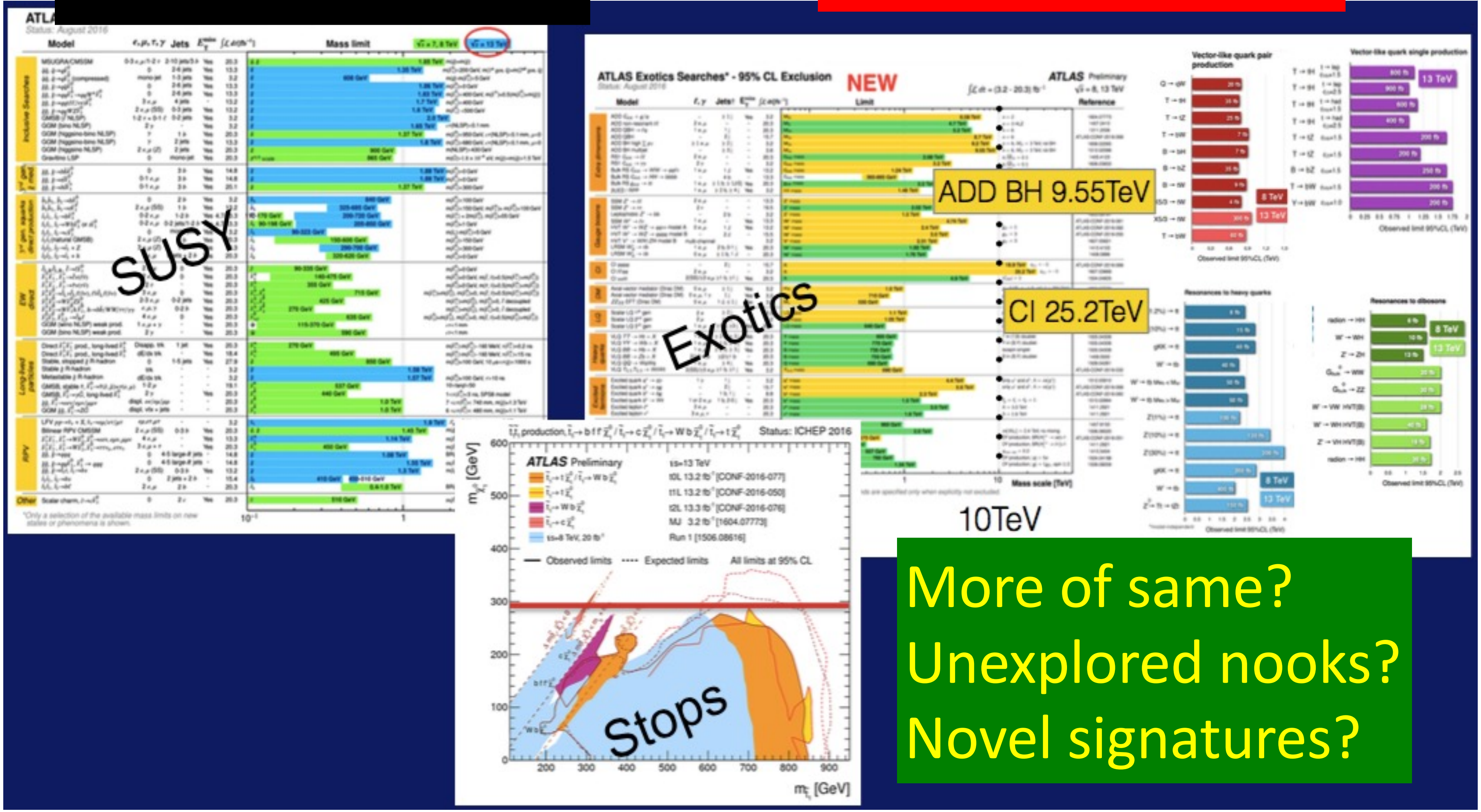


Missing transverse energy
carried away by dark matter particles

Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



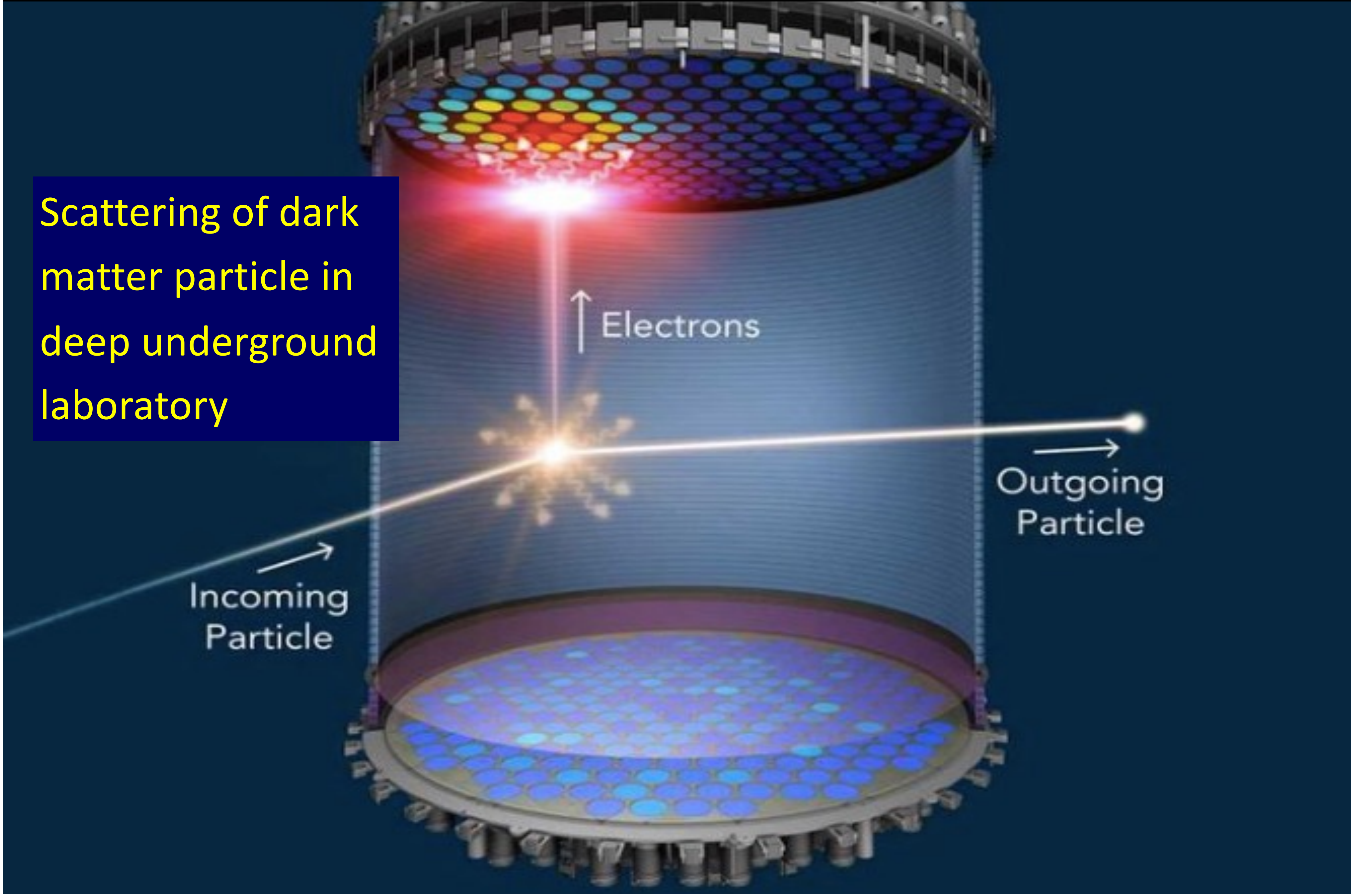
More of same?

Unexplored nooks?

Novel signatures?

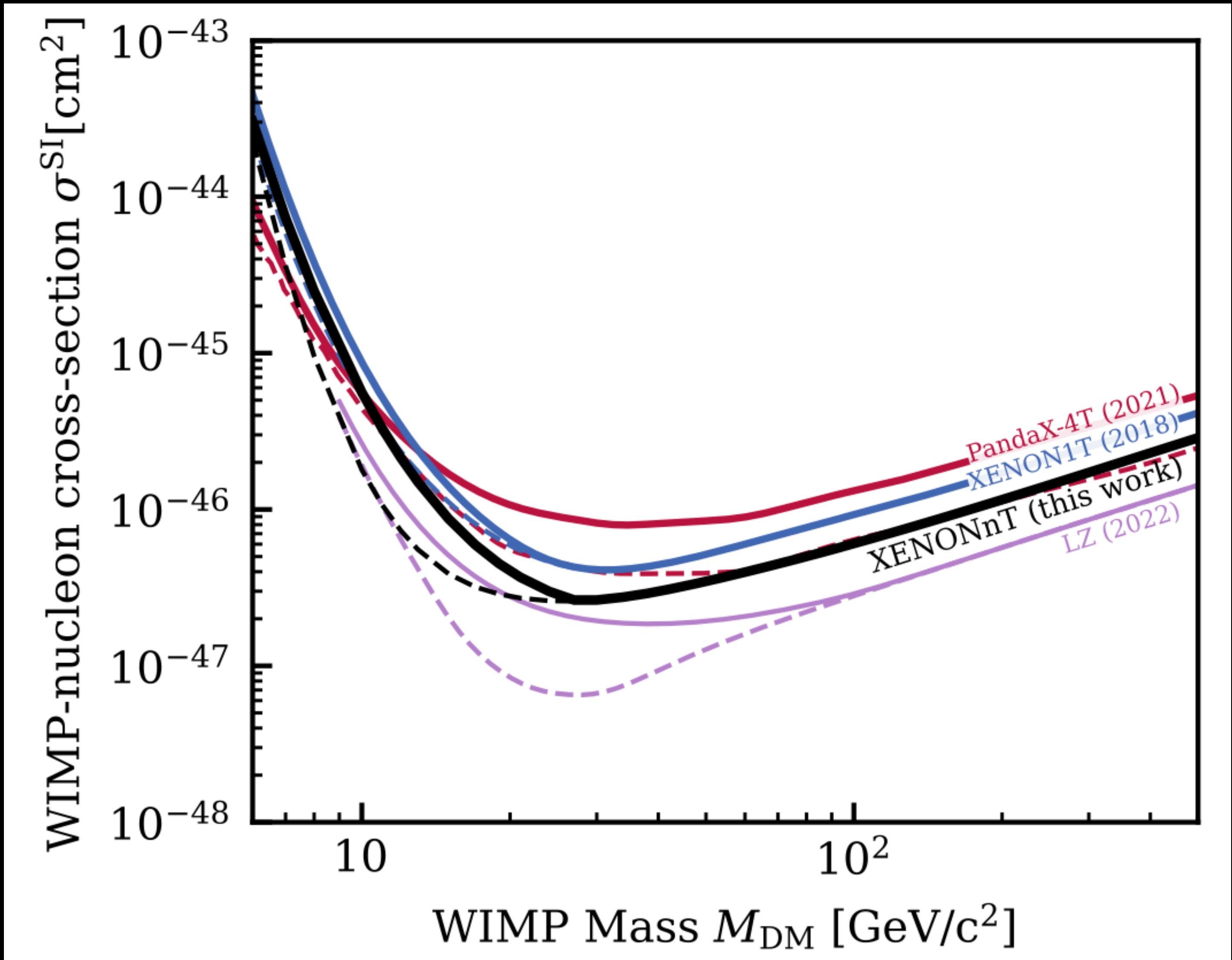
Direct Dark Matter Detection

Scattering of dark matter particle in deep underground laboratory

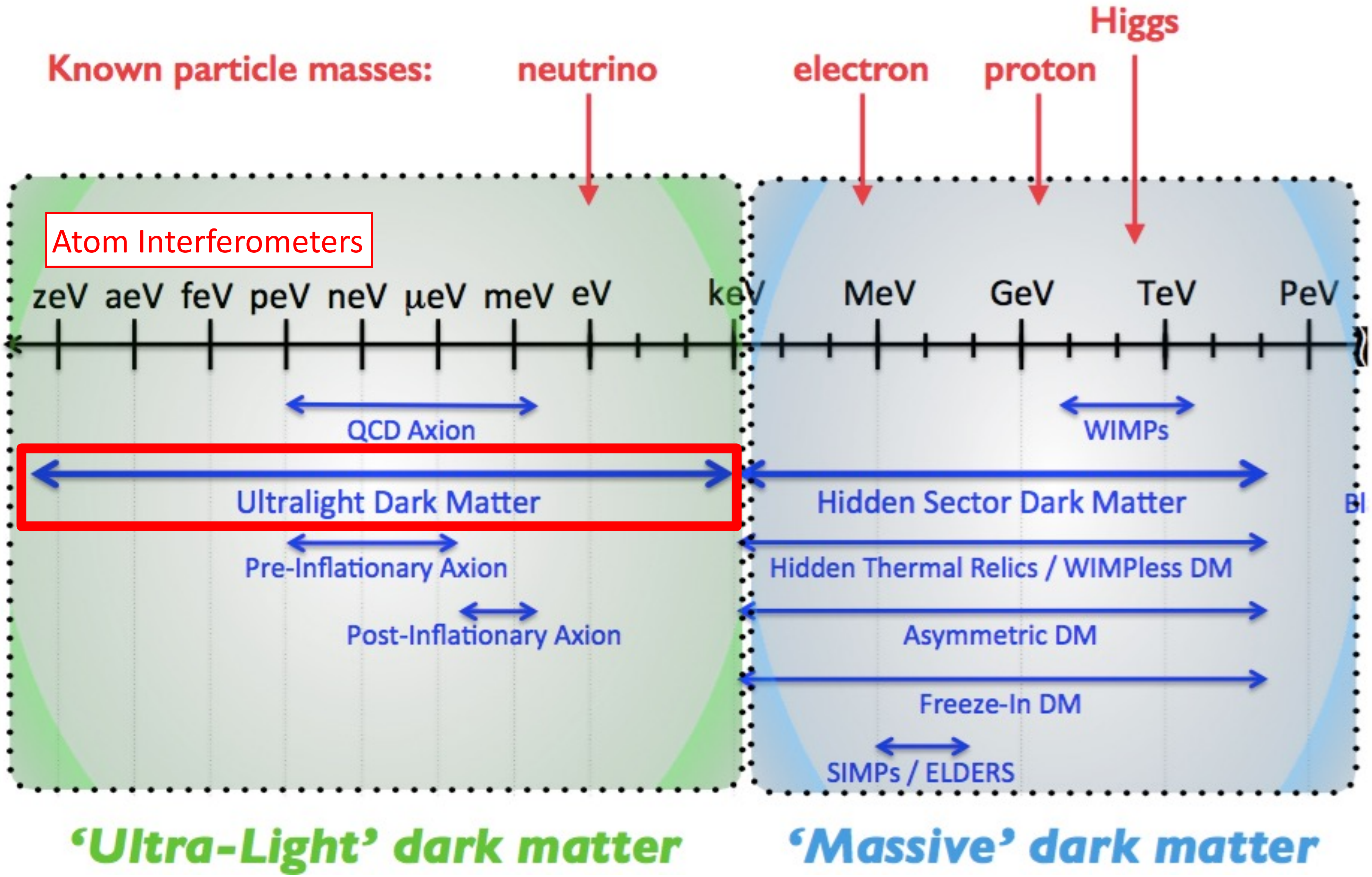


Direct Dark Matter Searches

- Latest experimental results

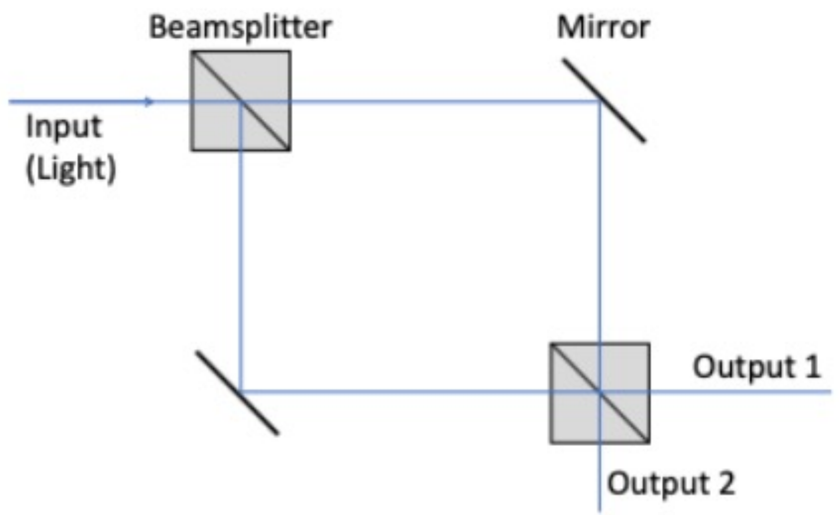


Candidates for Dark Matter

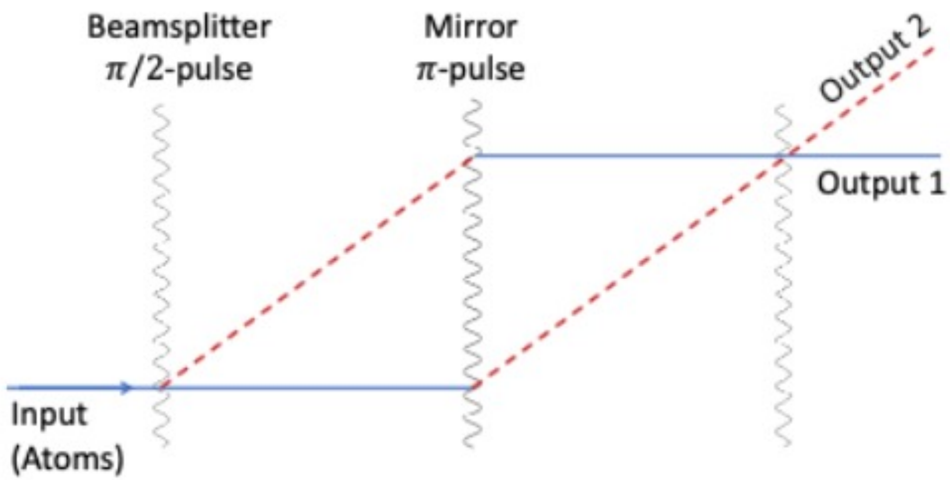


Principle of Atom Interferometry

Mach-Zehnder Laser Interferometer

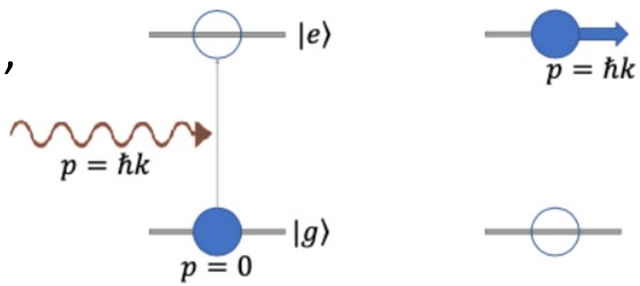


Atom Interferometer



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

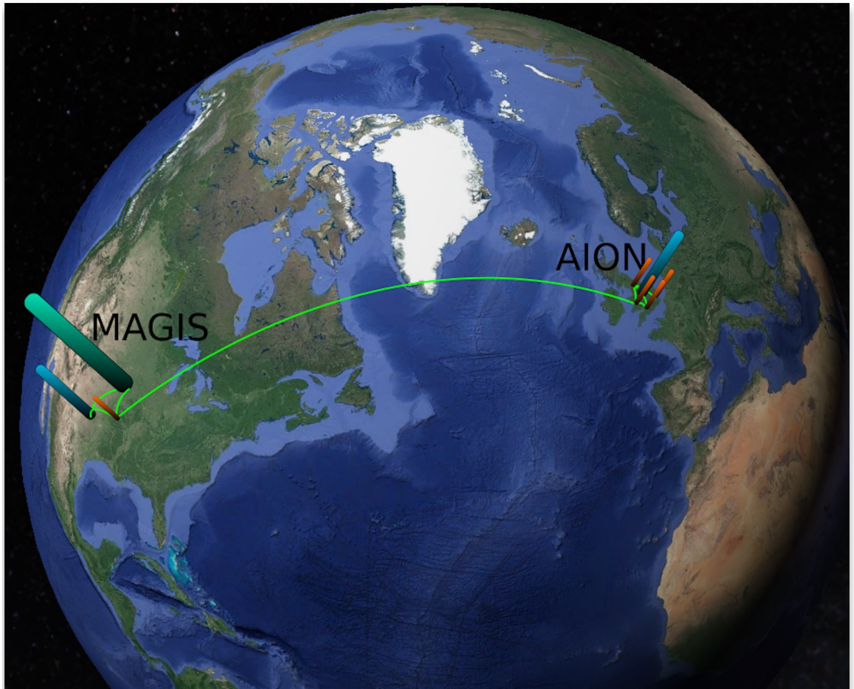
Interference between atoms following different paths



AION Collaboration

L. Badurina, S. Balashov[2], E. Bentine, D. Blas[1], J. Boehm[2], K. Bongs, A Beniwal[1]
D. Bortoletto, T. Bowcock[5], W. Bowden[6,*], C. Brew, O. Buchmueller[6], J. Coleman, J. Carlton
G. Elertas, J. Ellis, 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

AION – Staged Programme

AION

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

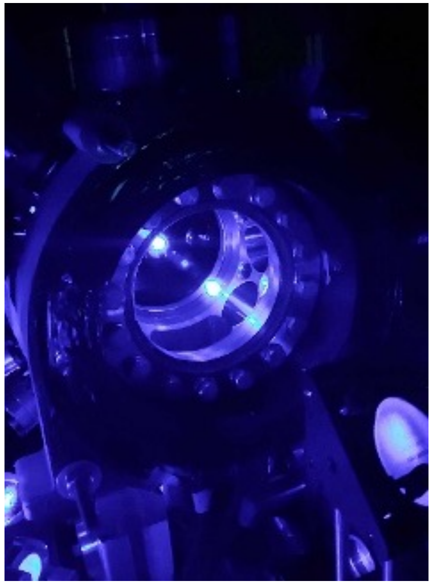
Initial funding from UK STFC

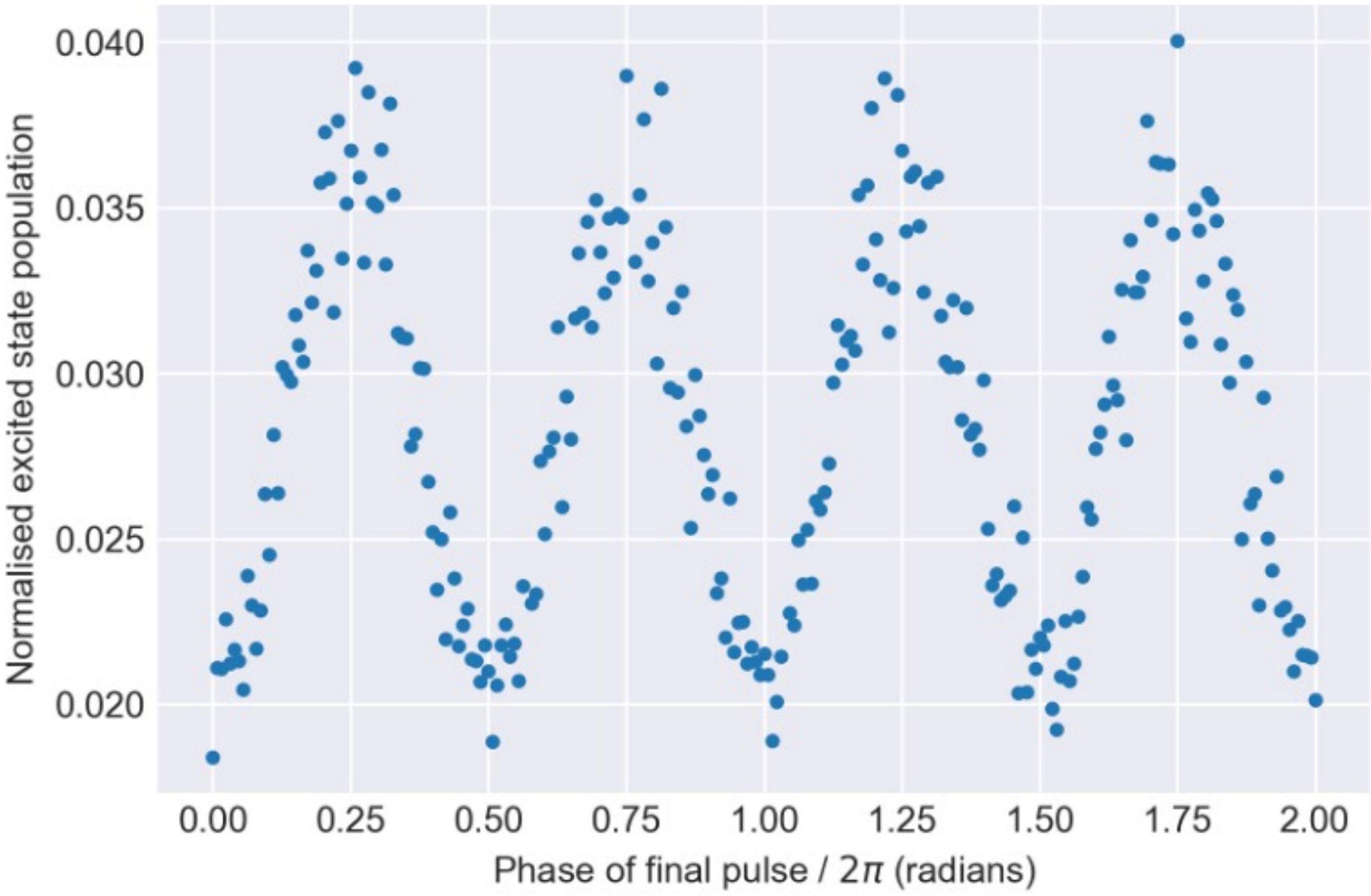
- AION-100: Stage 2 [year 3 to 6]
  - 100m Construction & commissioning
- AION-KM: Stage 3 [> year 6]
  - Operating AION-100 and planning for 1 km & beyond
- AION-SPACE (AEDGE): Stage 4 [after AION-km]
  - Space-based version

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

Atom Interference Fringes

Atomic analogue of Mach-Zehnder optical interferometer





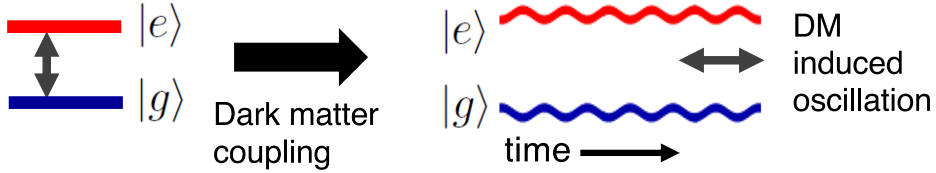
Using 689 nm transition in Sr

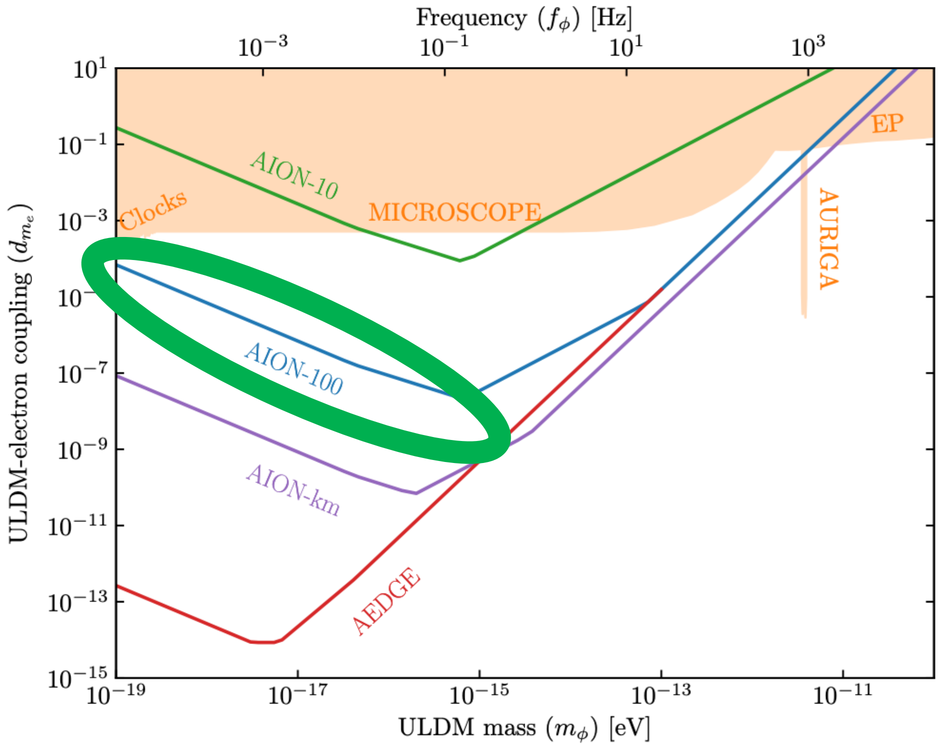
AION Collaboration

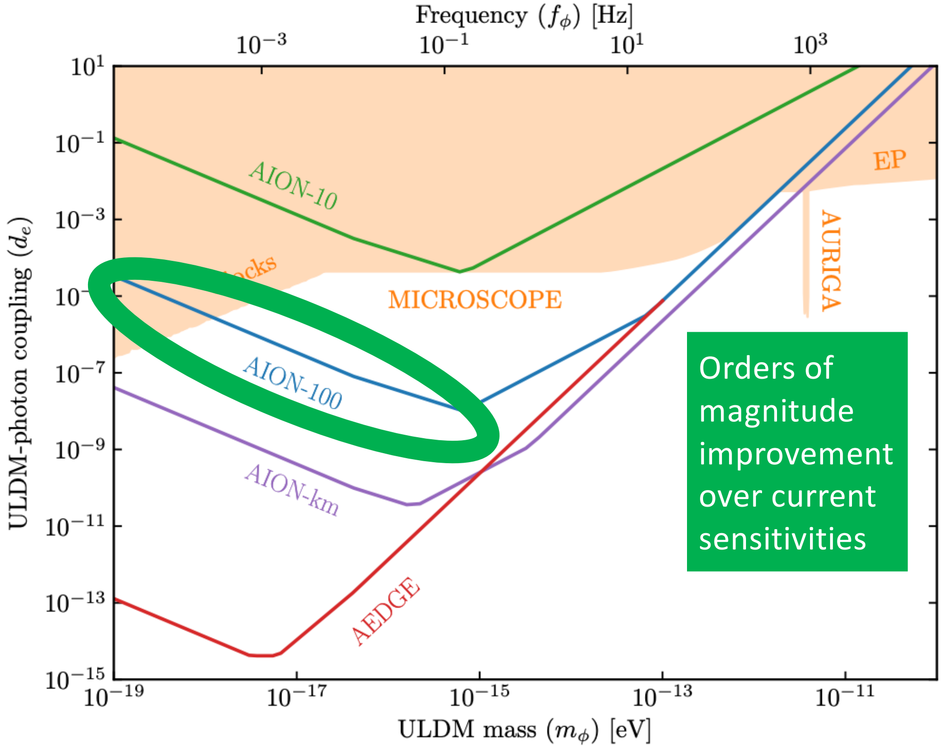
Searches for Light Dark Matter

Linear couplings to gauge fields and matter fermions

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

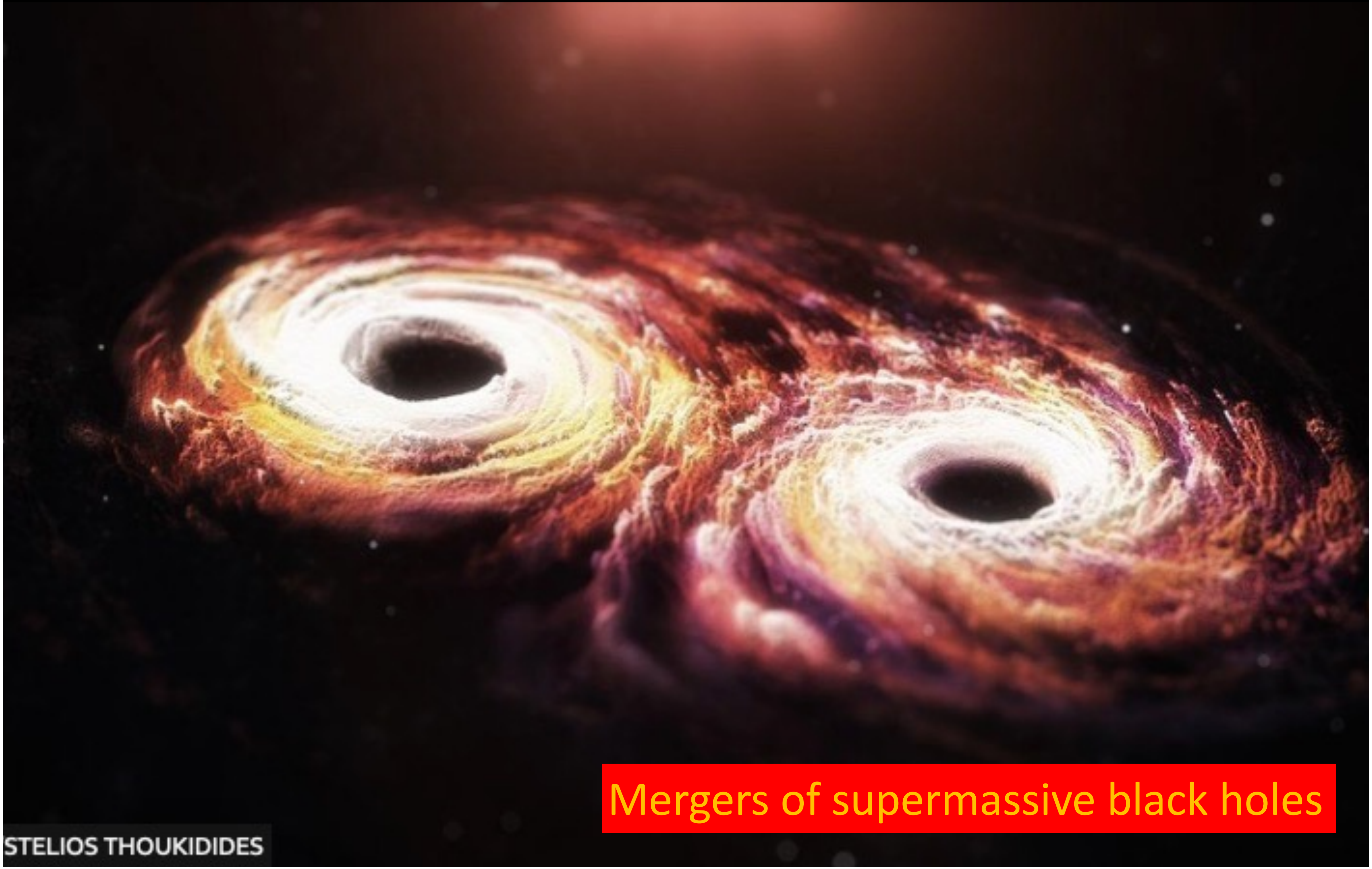




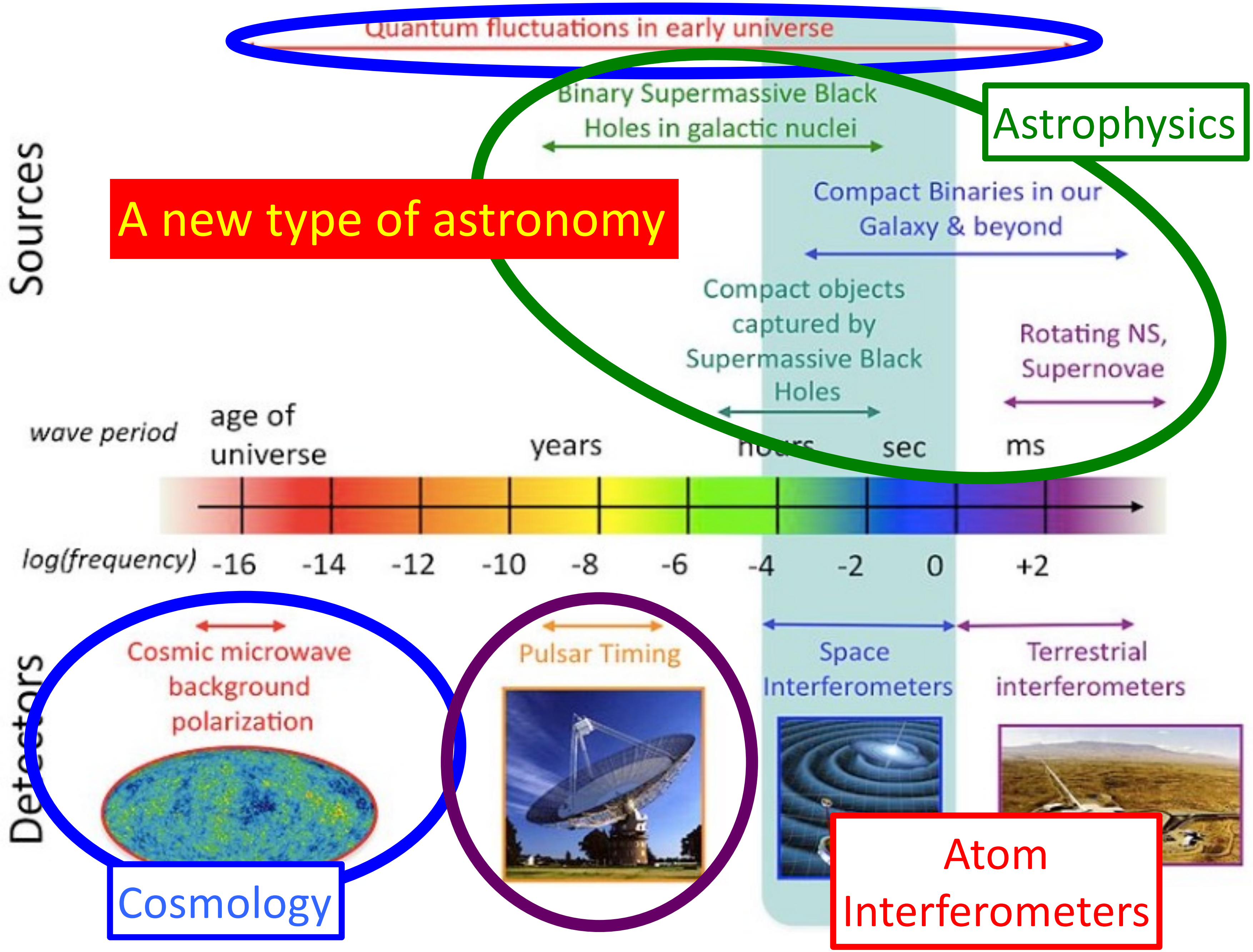


AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

The Biggest Bangs since the Big Bang

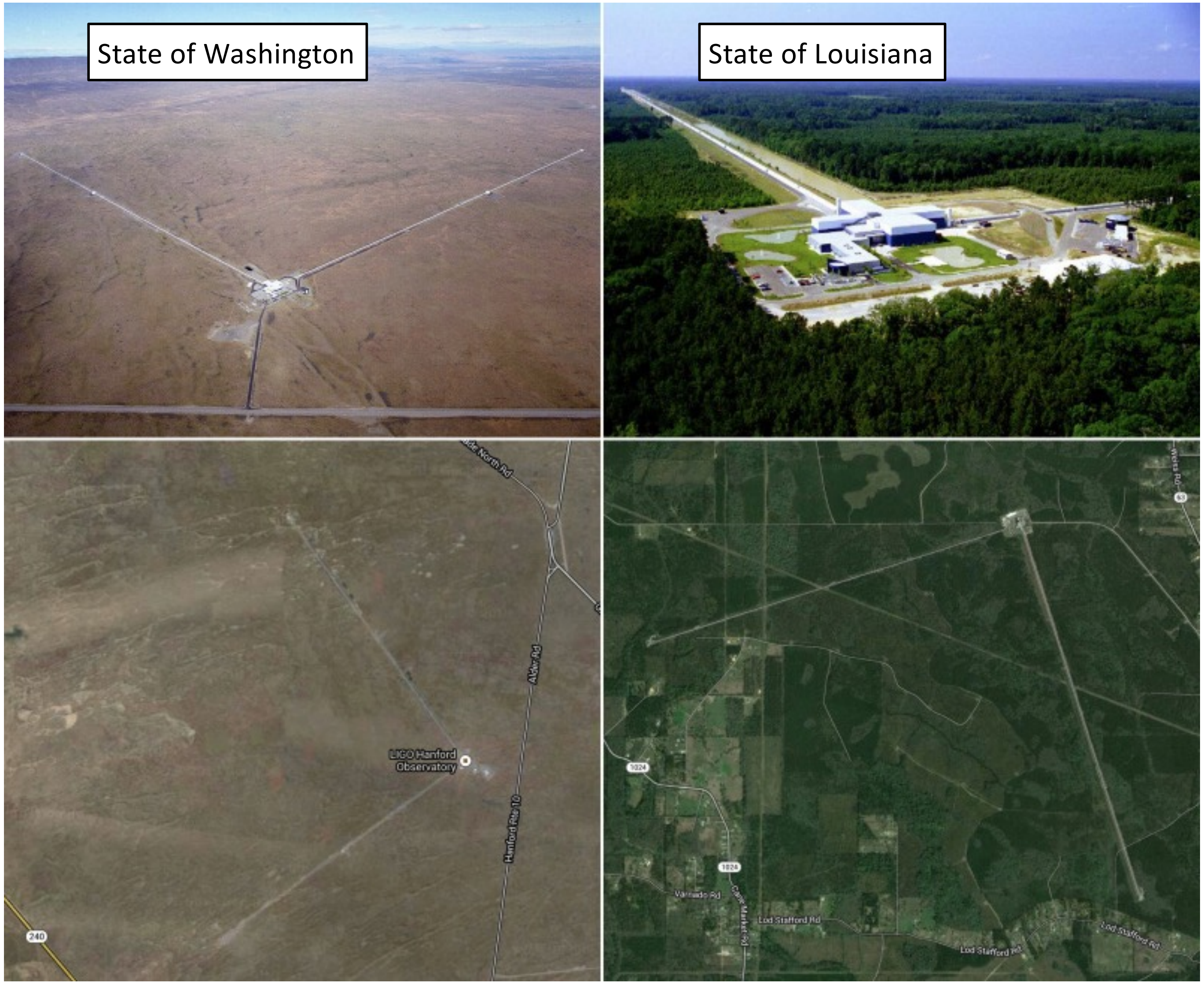


Gravitational Wave Spectrum

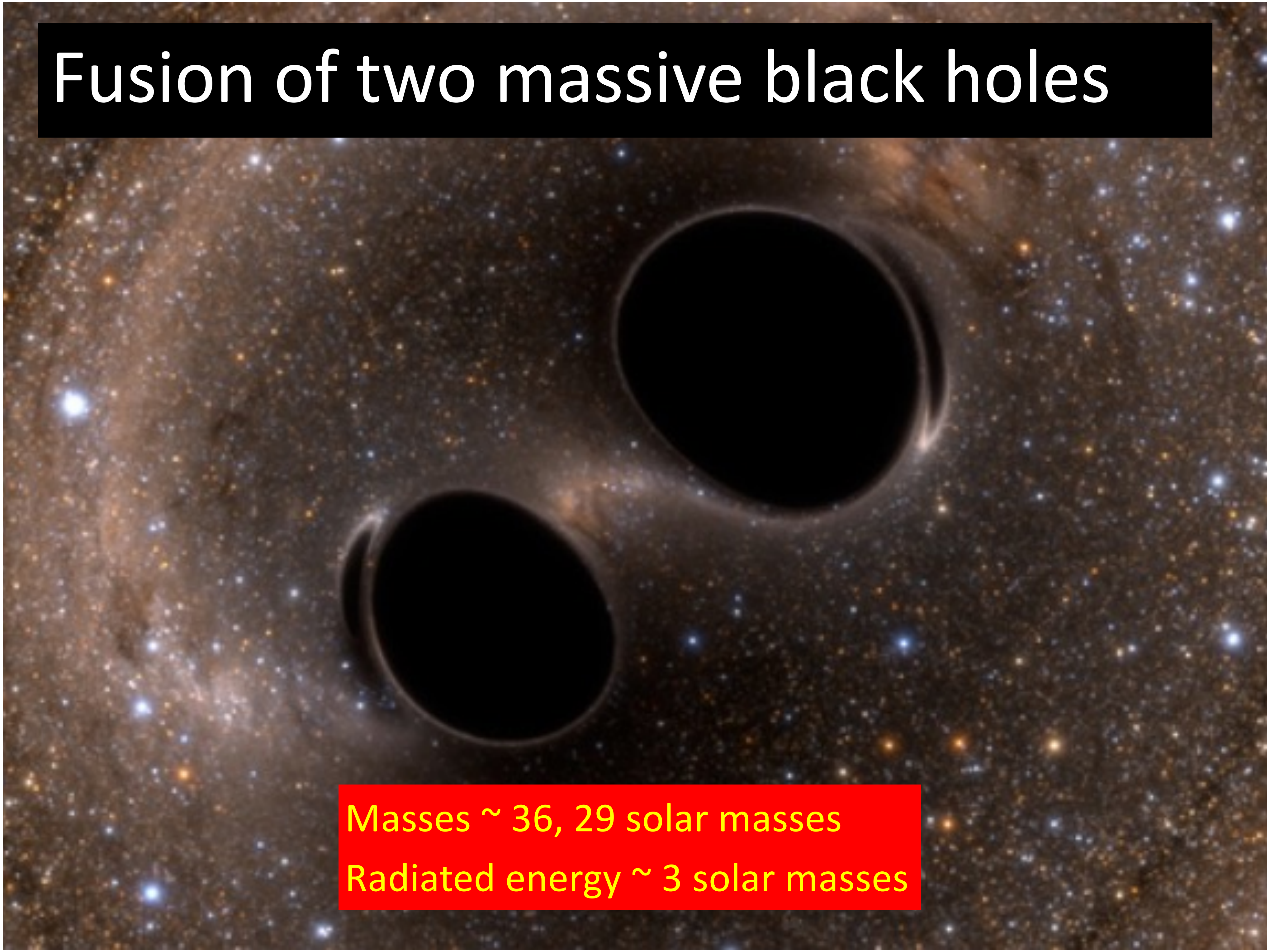


Direct Discovery of Gravitational Waves

- Measured by the LIGO experiment in 2 locations



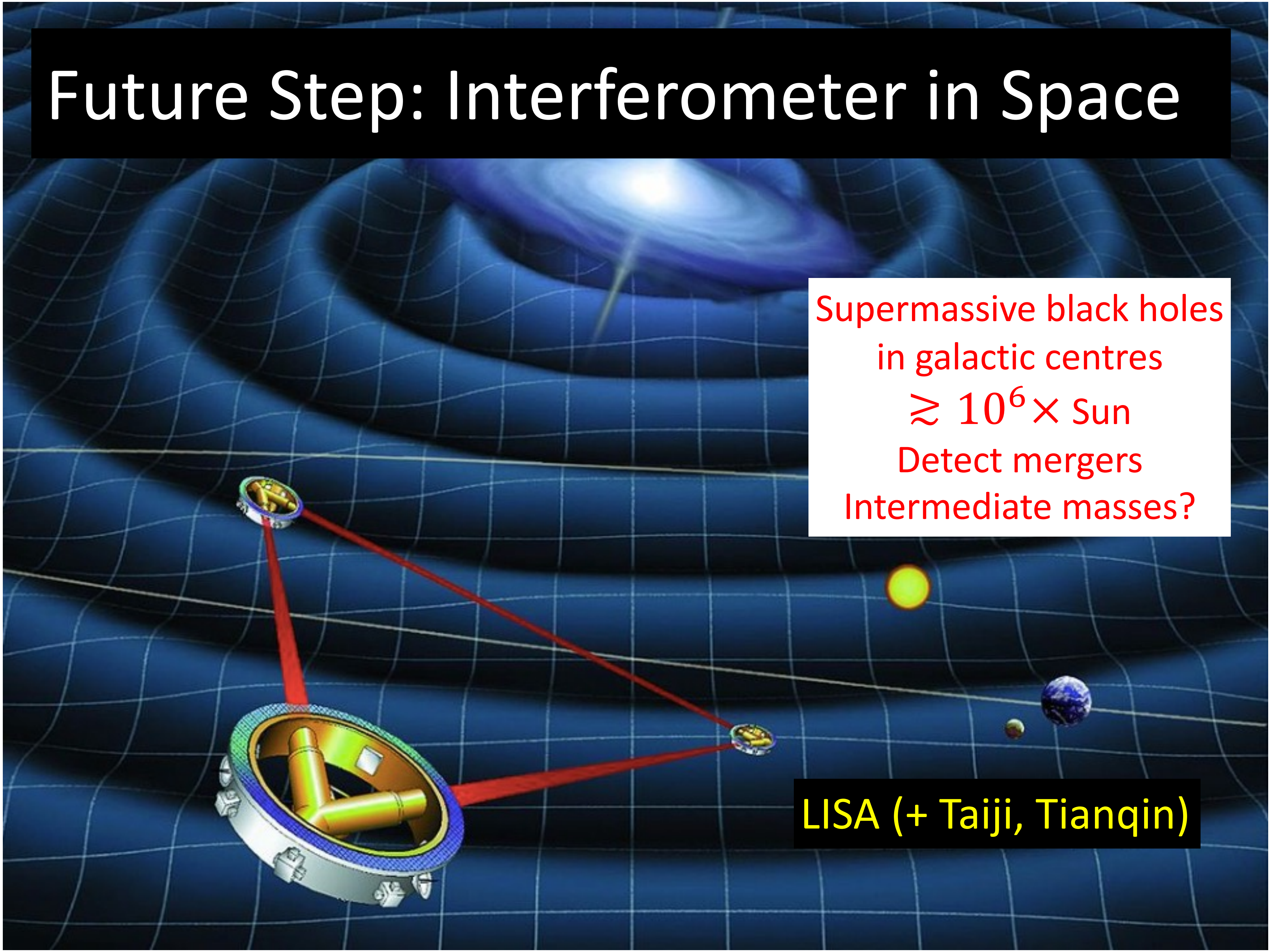
Fusion of two massive black holes



Masses ~ 36, 29 solar masses

Radiated energy ~ 3 solar masses

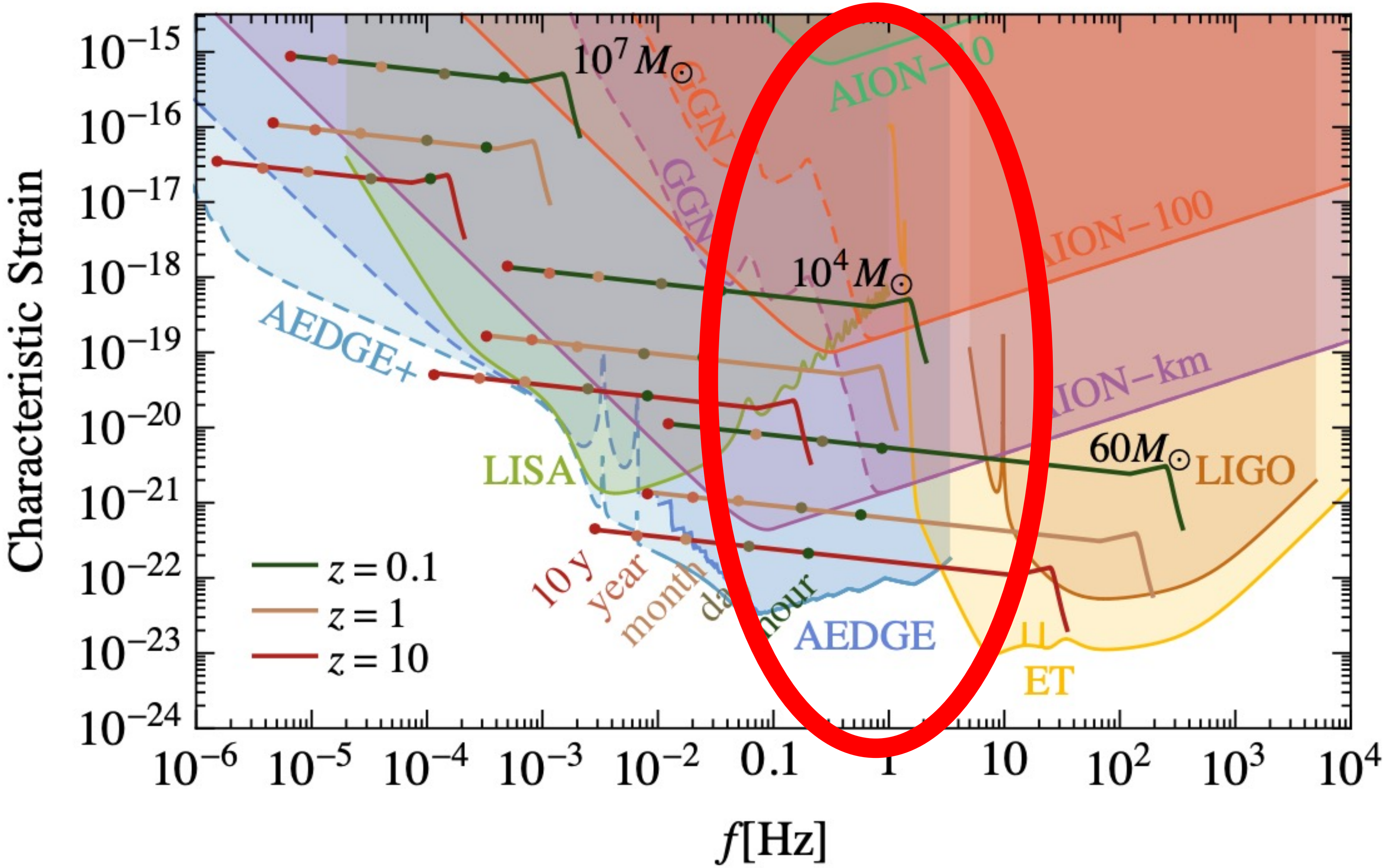
Future Step: Interferometer in Space



Supermassive black holes
in galactic centres
$\gtrsim 10^6 \times$ Sun
Detect mergers
Intermediate masses?

LISA (+ Taiji, Tianqin)

Gravitational Waves from IMBH Mergers

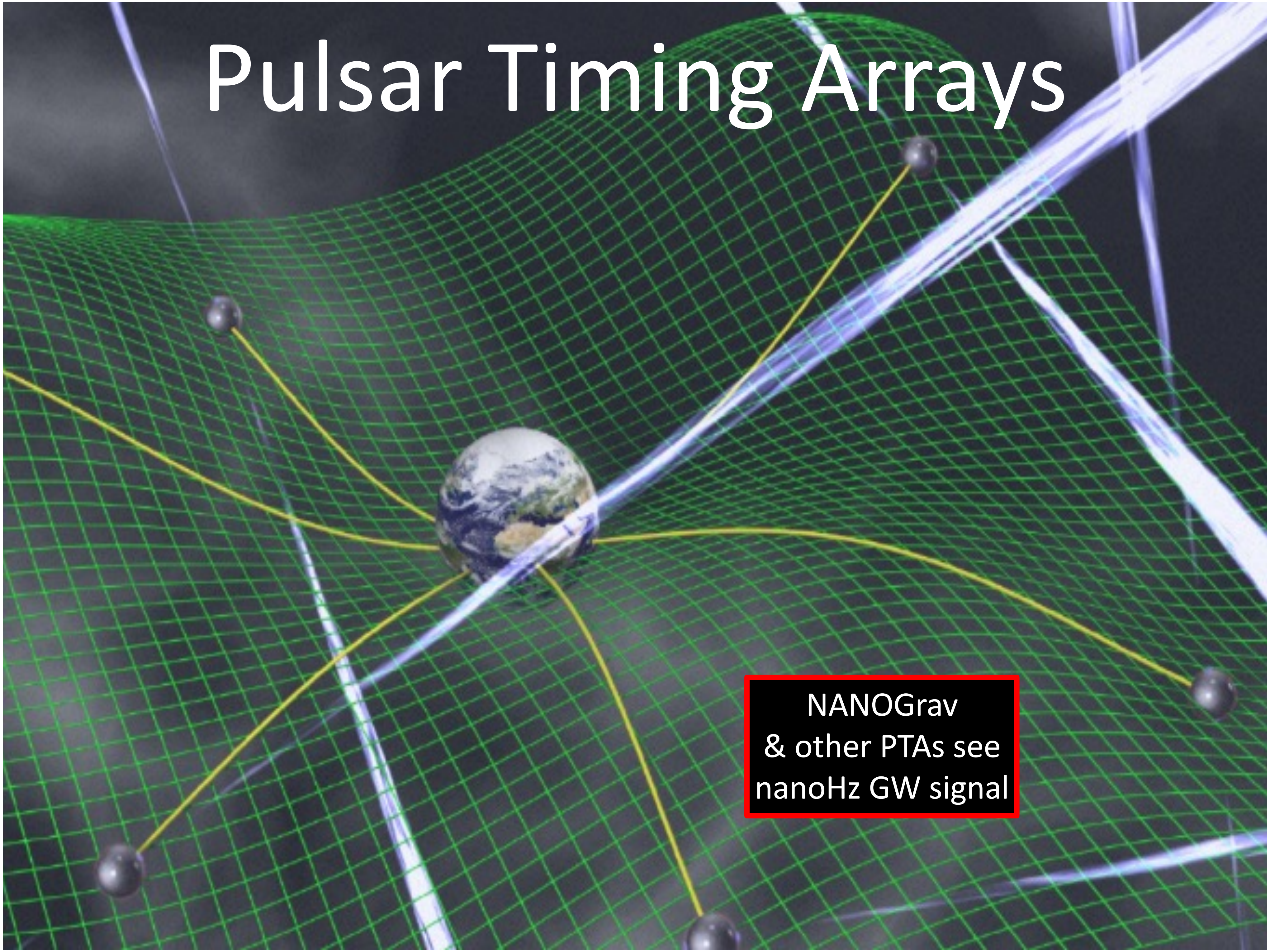


Probe formation of SMBHs

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

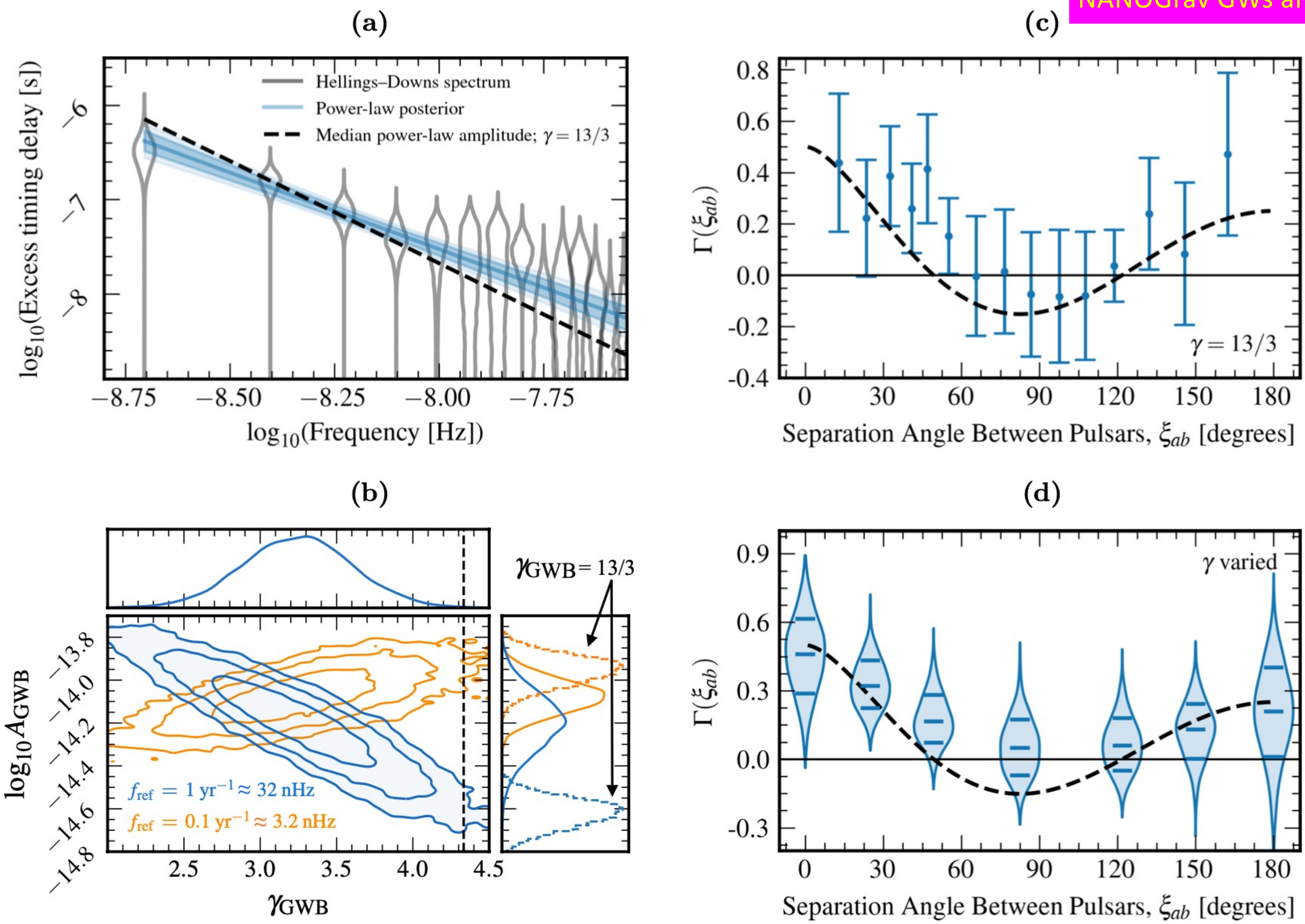
Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

Pulsar Timing Arrays



NANOGrav 15-Year Data

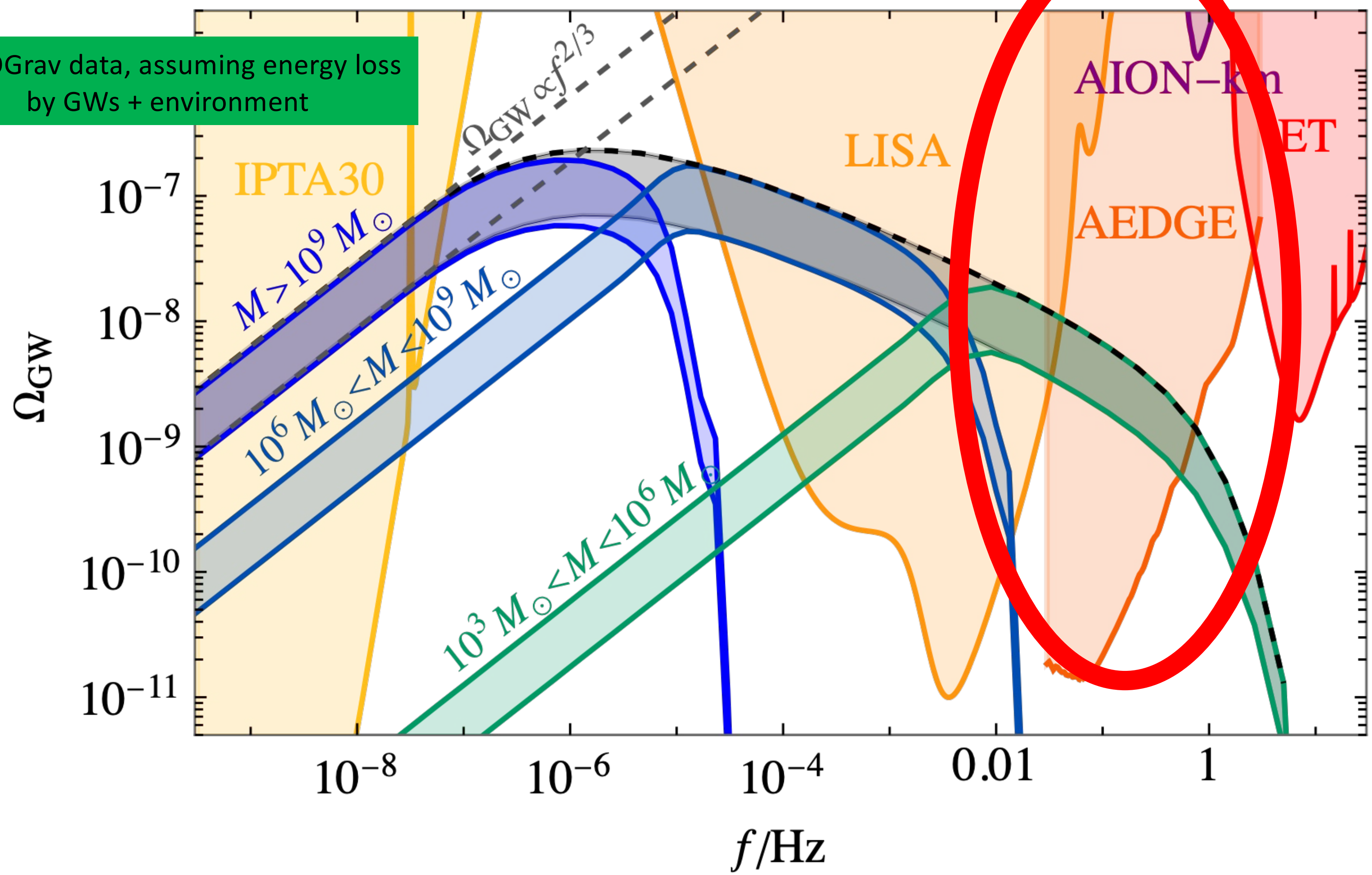
NANOGrav GWs arXiv:2306.16213



Evidence for GWs: Hellings-Downs angular correlation Bayes factor$\sim$ 200

Stochastic GW Background from BH Mergers

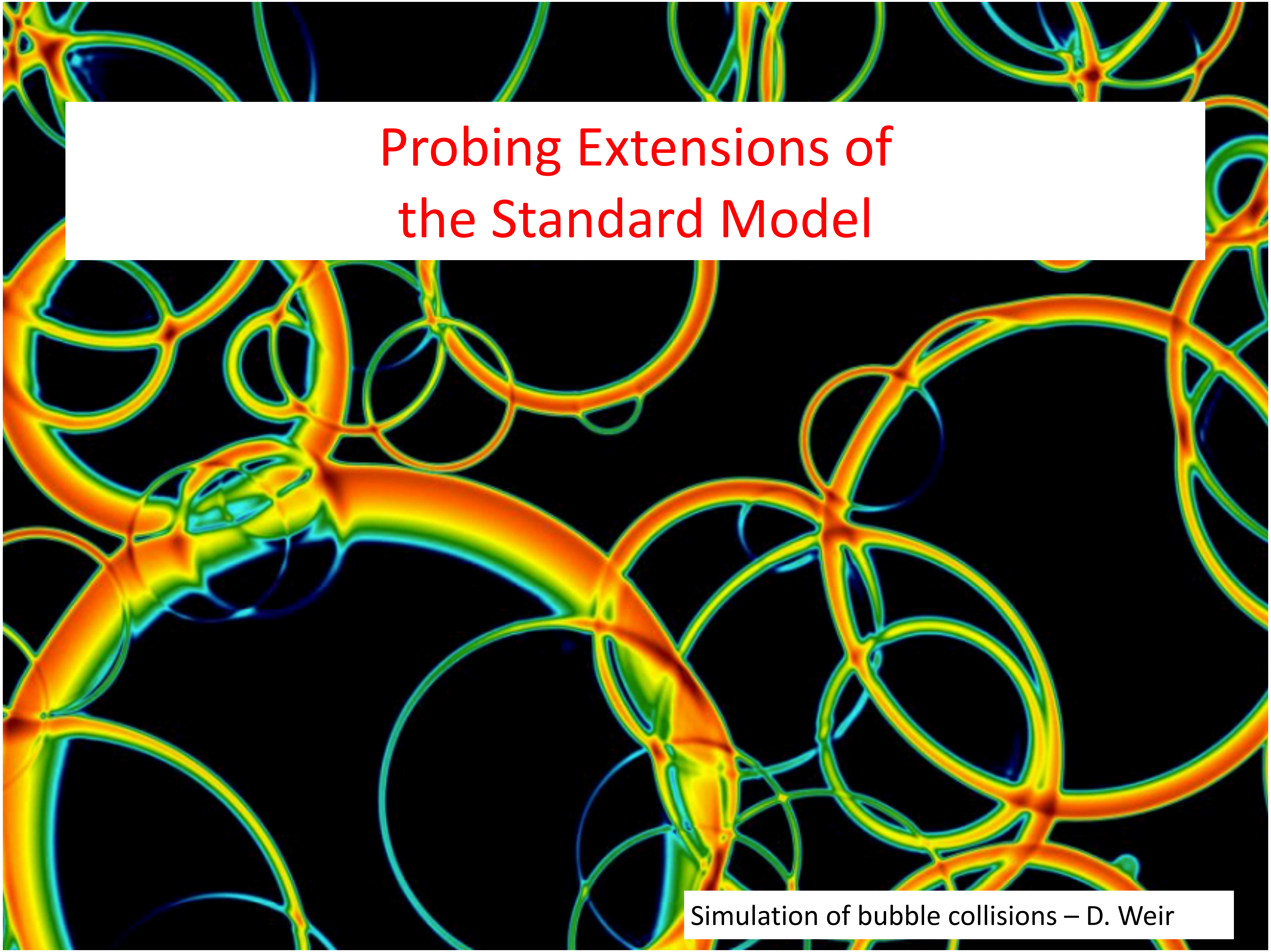
NANOGrav data, assuming energy loss by GWs + environment



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

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

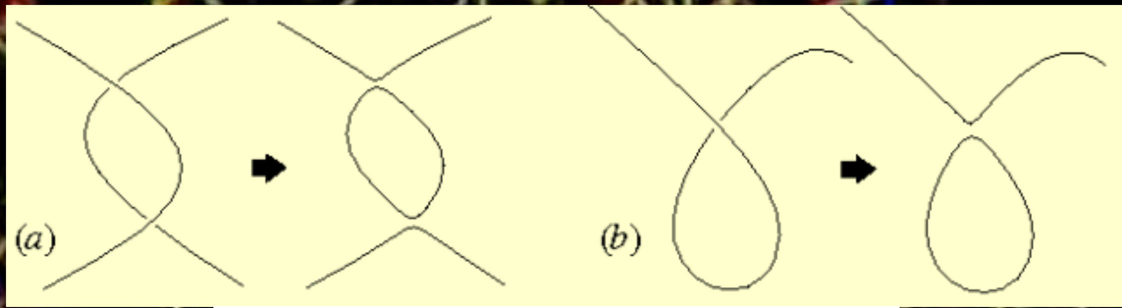
Probing Extensions of the Standard Model



Simulation of bubble collisions – D. Weir

Probing Cosmic Strings

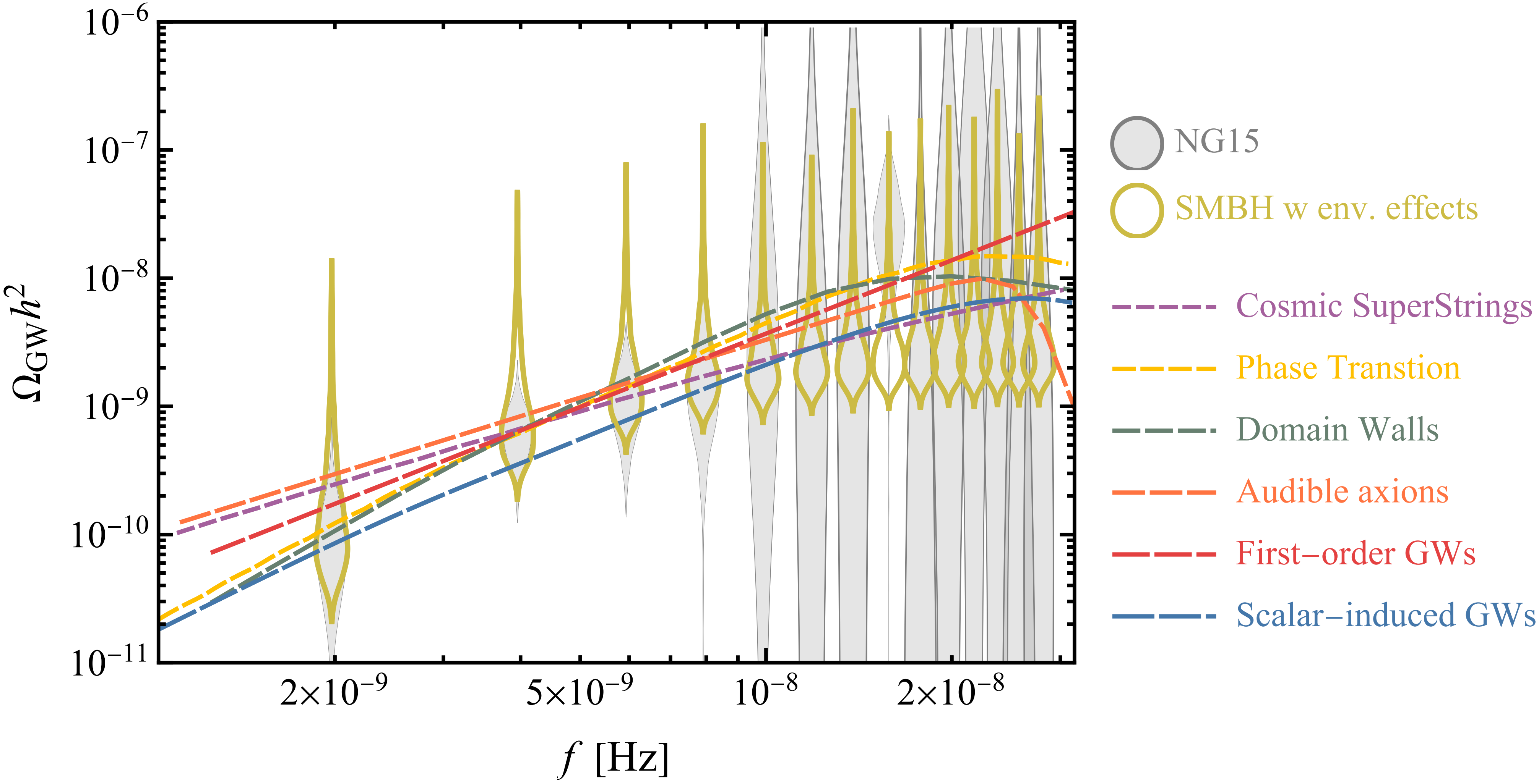
Hint from the NANOGrav pulsar timing array?



GW emission from string loops

Simulation of cosmic string network – Cambridge cosmology group

BSM Model Fits to NANOGrav



All better than GW-driven SMBH binaries: phase transition and domain walls best

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, in preparation

BSM Model Fits to NANOGrav

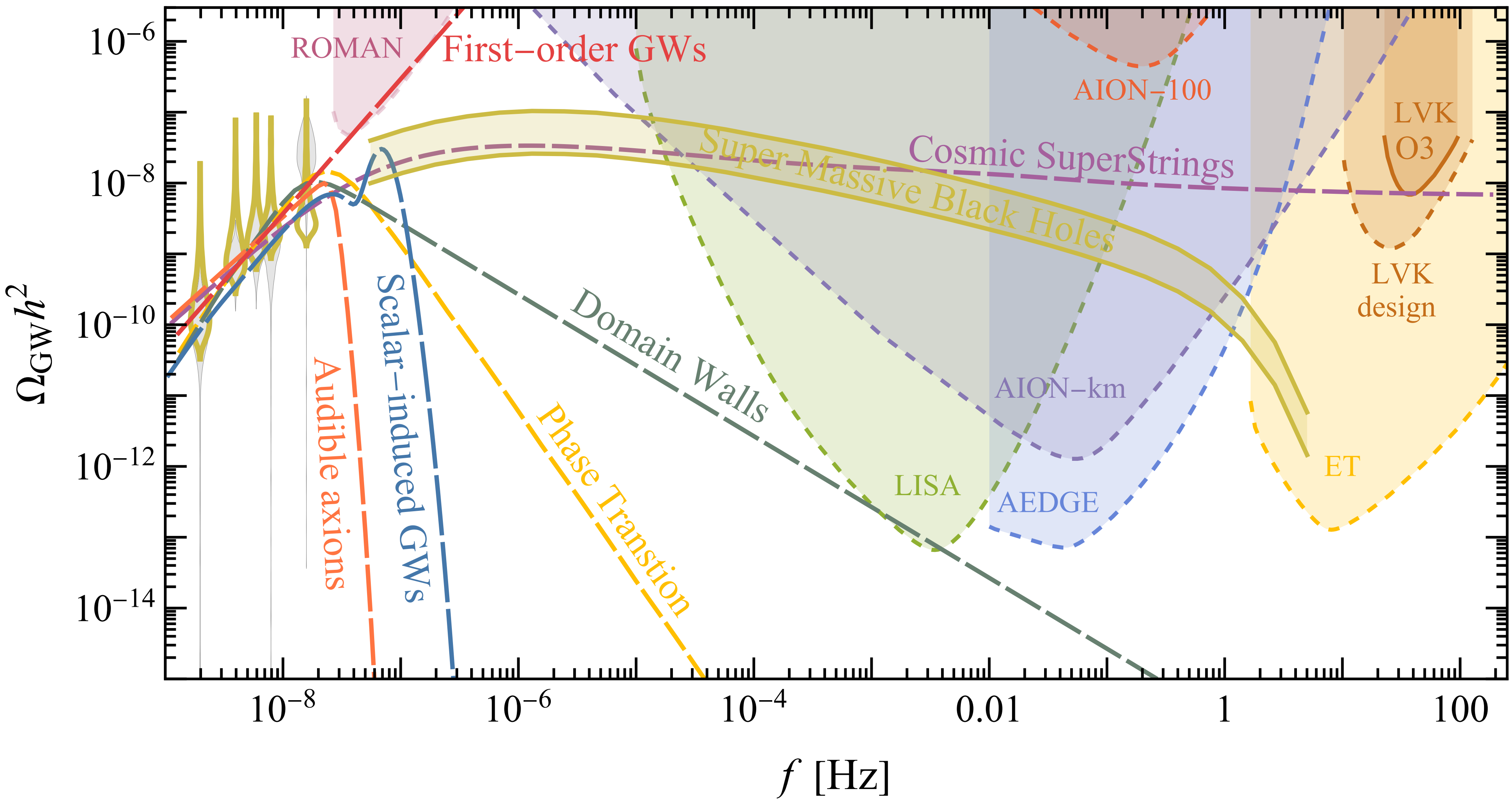
Results from Multi-Model Analysis (MMA)

Scenario	Best-fit parameters	$\Delta\chi^2$	Favoured by	Signatures
GW-driven SMBH binaries	$p_{\rm BH} = 0.25$	10.5	$-2.9\,\sigma$	FAPS, LISA, mid-f, ~~LVK, ET~~
GW + environment-driven SMBH binaries	$p_{\rm BH} = 1$ $\alpha = 3.8$ $f_{\rm ref} = 12$ nHz	Baseline ($\chi^2 = 49.4$)	Baseline	FAPS, LISA, mid-f, ~~LVK, ET~~
Cosmic (super)strings (CS)	$G\mu = 2 \times 10^{-12}$ $p = 6.3 \times 10^{-3}$	-1.7	$2.5\,\sigma$	~~FAPS~~, LISA, mid-f, LVK, ET
Phase transition (PT)	$T_* = 0.24$ GeV $\beta/H = 6.0$	-6.3	$2.5\,\sigma$	~~FAPS, LISA, mid-f, LVK, ET~~
Domain walls (DWs)	$T_{\rm ann} = 0.79$ GeV $\alpha_* = 0.026$	-6.2	$2.5\,\sigma$	~~FAPS~~, LISA?, ~~mid-f, LVK, ET~~
Scalar-induced GWs (SIGWs)	$k_* = 10^{7.6}/{\rm Mpc}^{-1}$ $A = 10^{-1.1}$ $\Delta = 0.28$	-5.4	$2.3\,\sigma$	~~FAPS, LISA, mid-f, LVK, ET~~
First-order GWs (FOGWs)	$\log_{10} r = -14.75$ $n_t = 2.7$ $\log_{10} T_{\rm rh} = -0.015$	-8.5	$2.9\,\sigma$	~~FAPS, LISA, mid-f, LVK, ET~~
"Audible" axions and Axion-Like Particles (ALPs)	$m_a = 1.3 \times 10^{-11}$ MeV $f_a = 0.17 M_{\rm P}$	-3.7	$1.9\,\sigma$	~~FAPS, LISA, mid-f, LVK, ET~~

All better than GW-driven SMBH binaries: phase transition and domain walls best

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, in preparation

BSM Model Fits to NANOGrav



Supermassive black hole binaries and cosmic (super)strings offer signatures at higher frequencies

JE, Fairbairn, Franciolini, Hütsi, Iovino, Lewicki, Raidal, Urrutia, Vaskonen & Veermäe, in preparation

Still Waiting for BSM Physics