Karlsruhe Institute of Technology

Particle Physics 1
Lecture 22: Dark Matter

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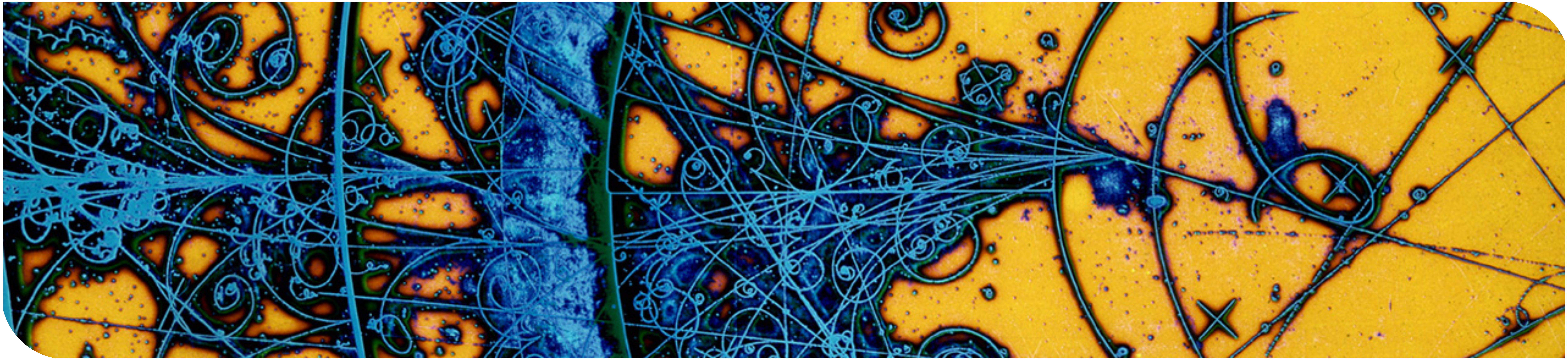
Wintersemester 2023/2024



Credit: CERN

Summary BSM from last lecture

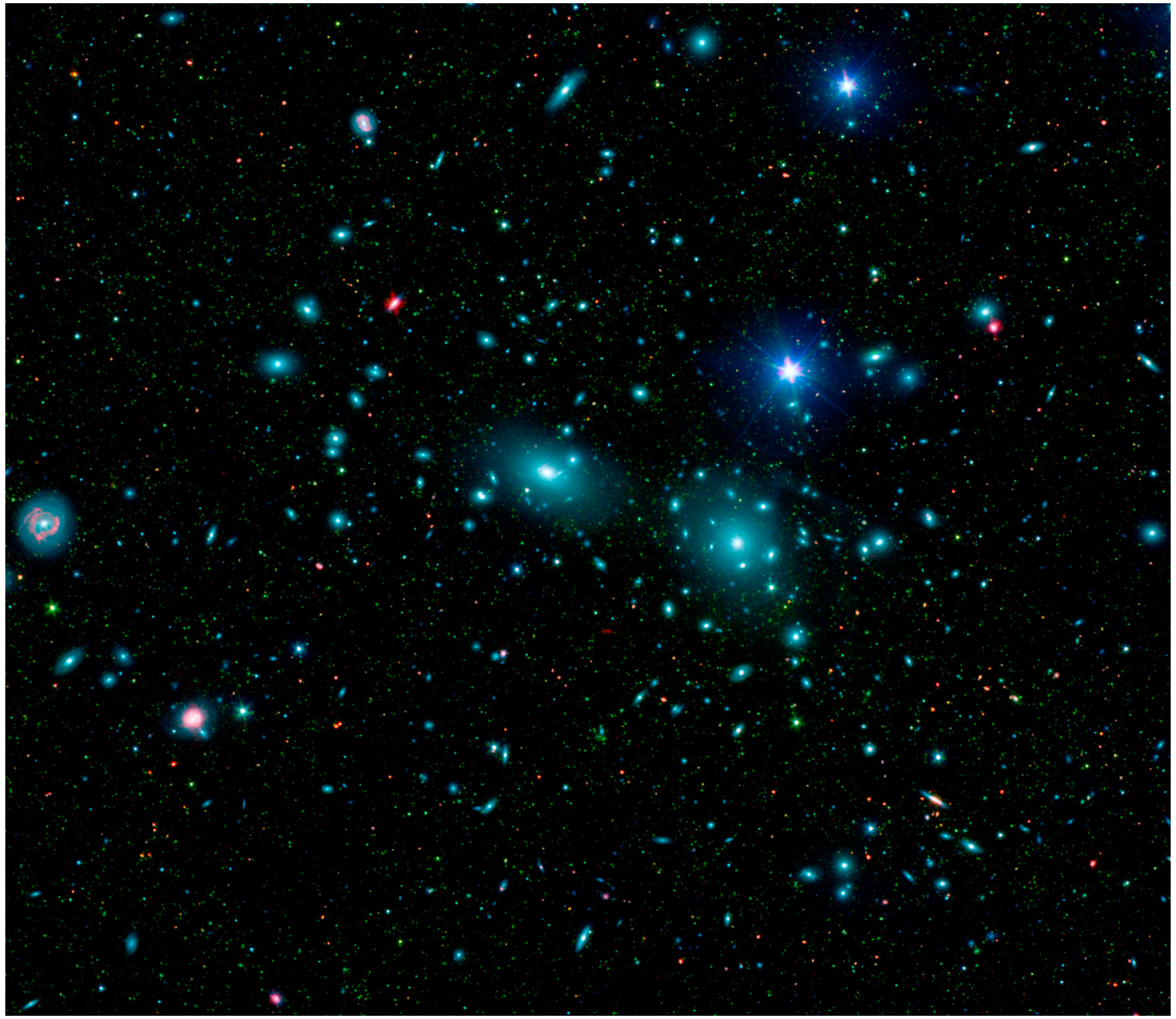
- $R(D^*)$: 3.5 σ (my best bet: experimental problem)
- P_5': 3.3 σ (my best bet: theory problem)
- $(g-2)_\mu$: 4.2 σ to standard theory (my best bet: ?)
- Neutrino anomalies (my best bet: experimental problems)
- W-mass (my best bet: experimental problem)
- **Dark Matter (my best bet: SM is very broken)**

Learning goals

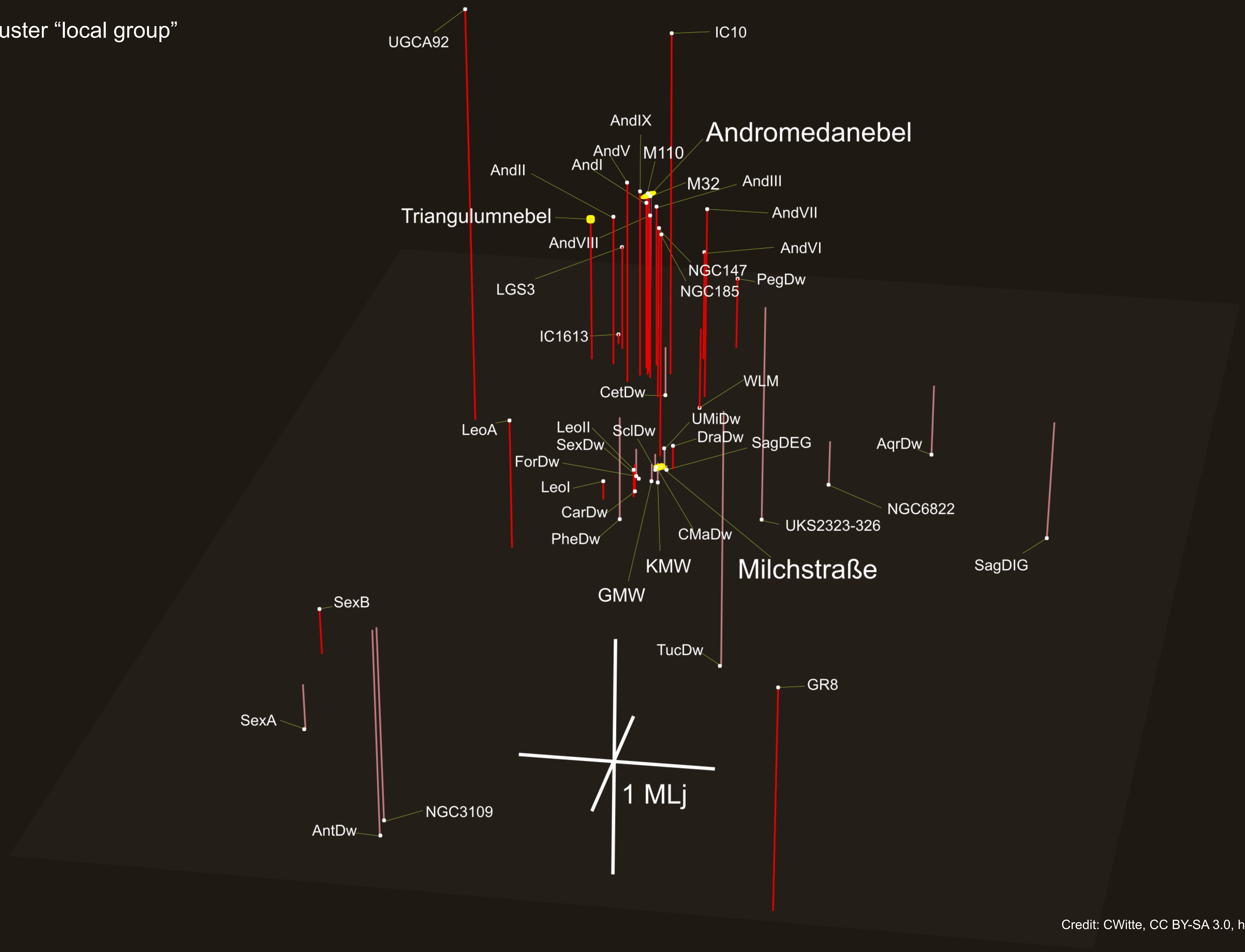
- What is the experimental evidence for Dark Matter?
- What are possible models that explain Dark Matter?
- How do we search for Dark Matter?

Experimental evidence: Virial theorem

- Pioneered by Fritz Zwicky in the 1930s, also coined the term “Dark Matter”
- Comparison of velocities of observed galaxies in the Coma-Cluster with their visible mass
- Violates Virial theorem that relates kinetic and potential energy: Need much more “dark” mass than what is observed

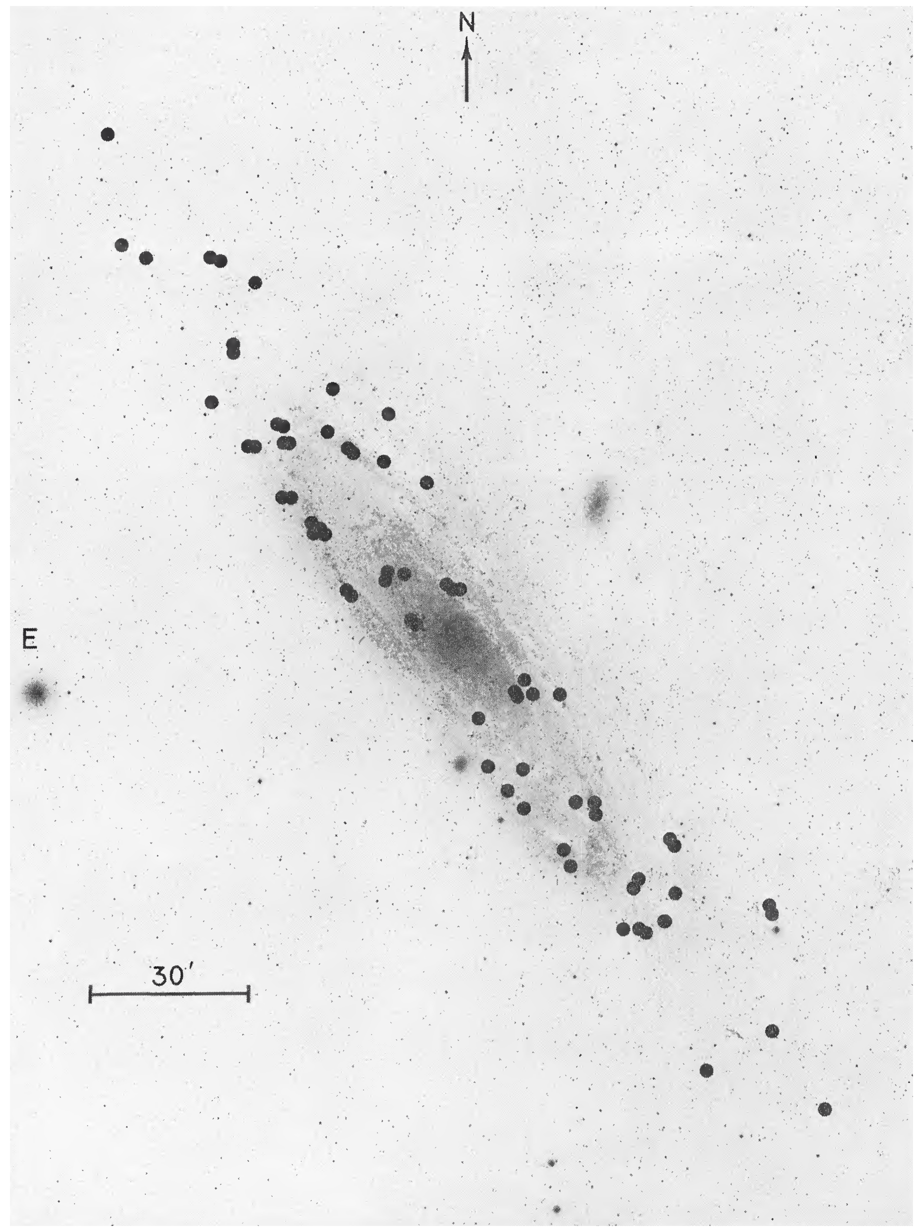


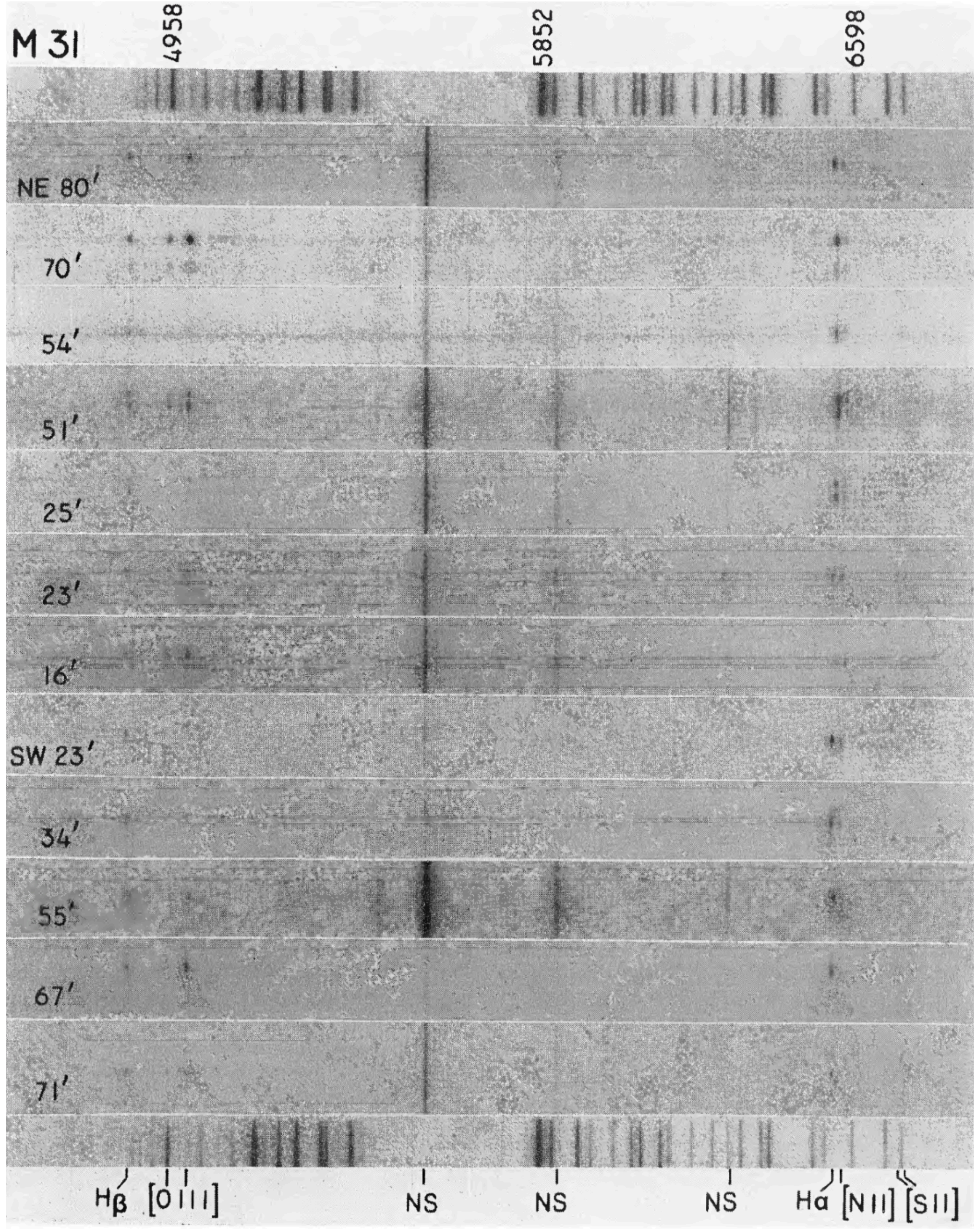
Credit: NASA / JPL-Caltech / L. Jenkins (GSFC) galaxy cluster “local group”



Experimental evidence: Galaxy rotation curves

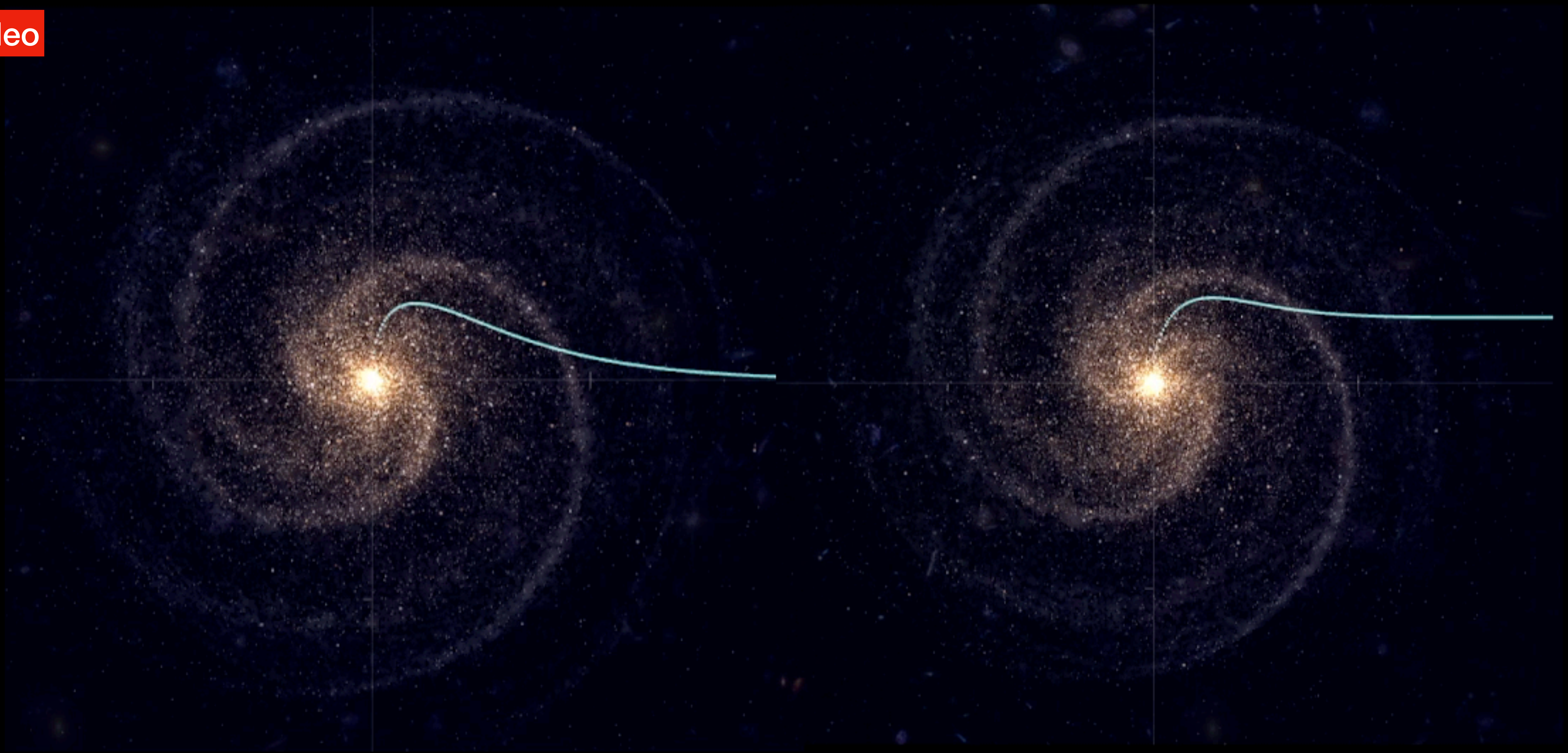
- Field pioneered by Vera Rubin in the early 1970
- Measured doppler shift of 21cm hydrogen line of various stars in the Andromeda galaxy





Credit: The Astrophysical Journal, Vol. 159, February 1970

Video



Credit: Ingo Berg, https://github.com/beltoforion/Galaxy-Renderer

Experimental evidence: Galaxy rotation curves

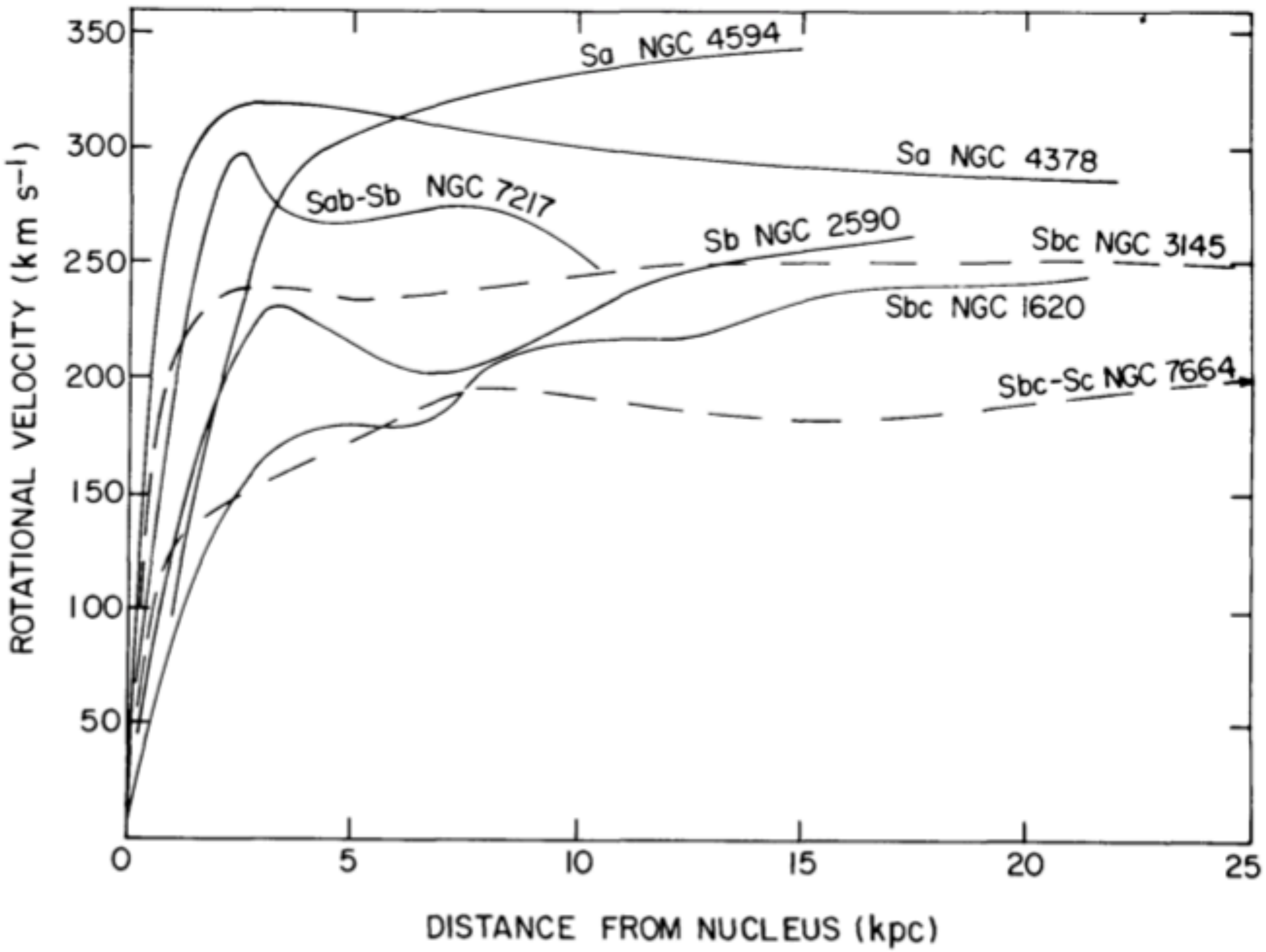
- Observation:

  Approximately flat rotational velocity

- Explanation:

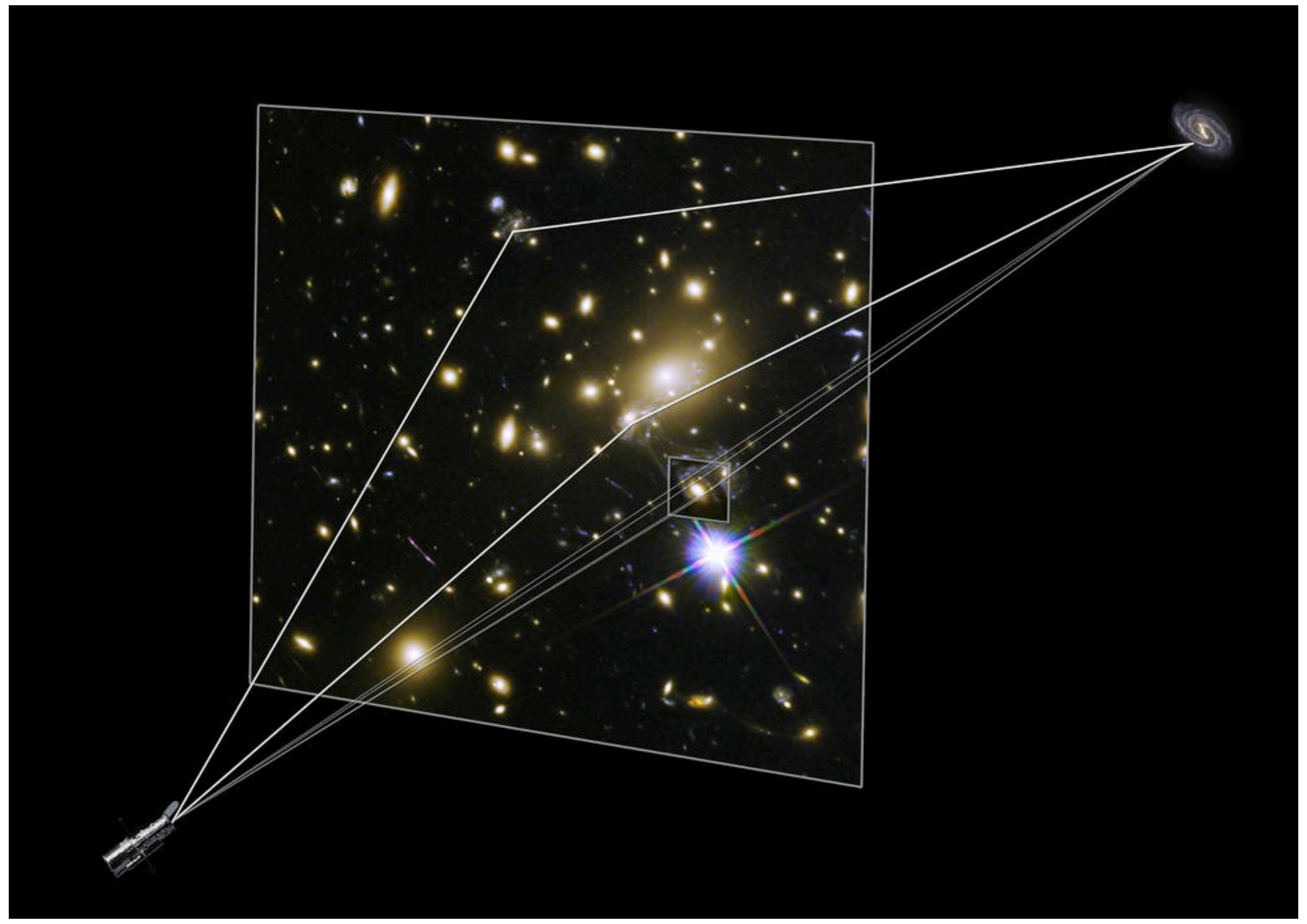
  A large mass with density $\propto 1/r^2$ in the center of the galaxies

Credit: The Astrophysical Journal, 225:L107-L111, 1978 November 1

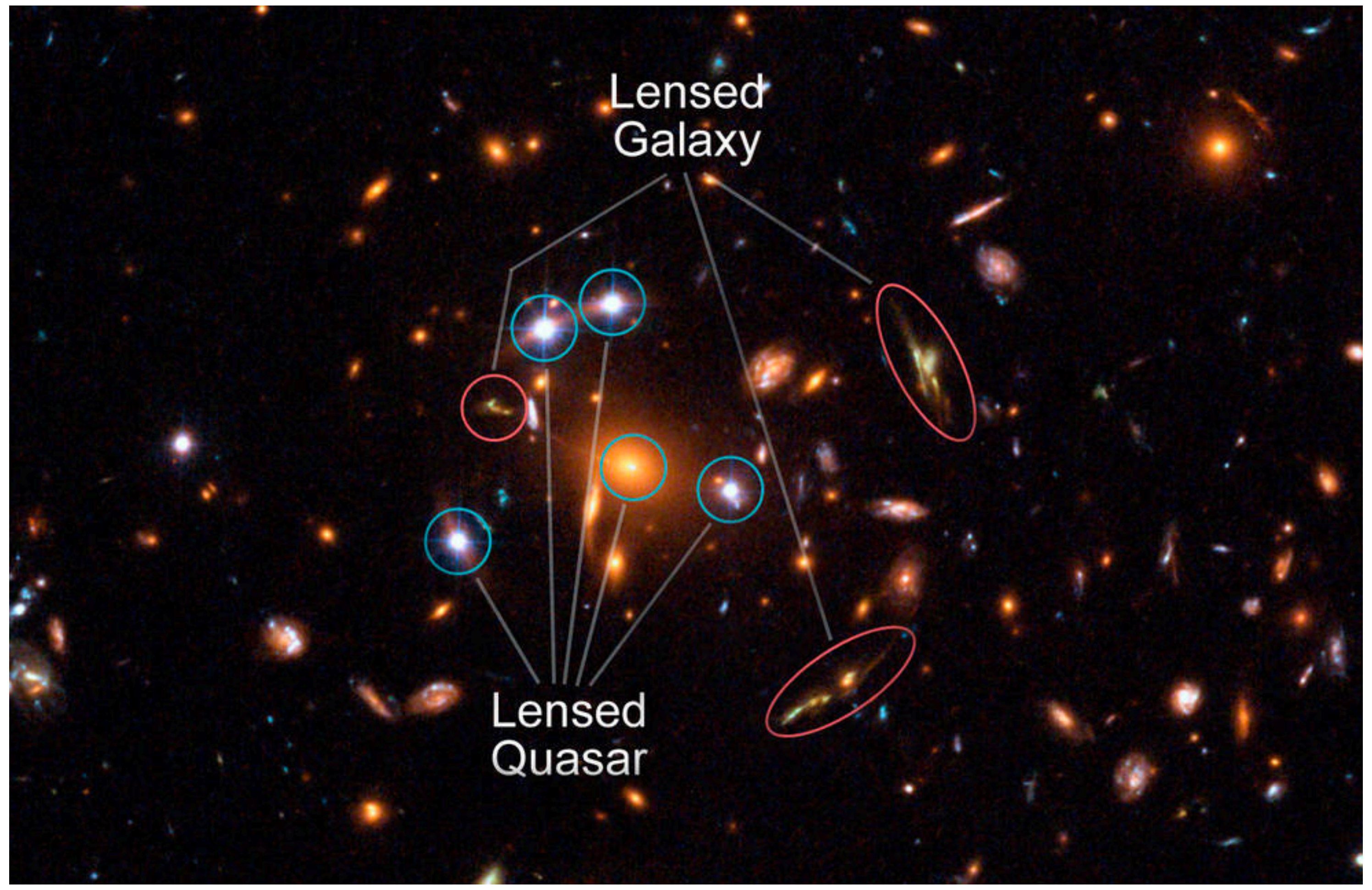


Experimental evidence: Gravitational lensing

- Deflection ("lensing") or fuzzy distortion of light by massive objects (black holes, galaxies) and large scale structures
  - Distinguish weak and strong lensing
- Total matter distribution can be reconstructed from deflection patterns
- Mass related to visible light and gas can not explain lensing results



Credits: NASA, ESA, M.J. Jee and H. Ford (Johns Hopkins University)

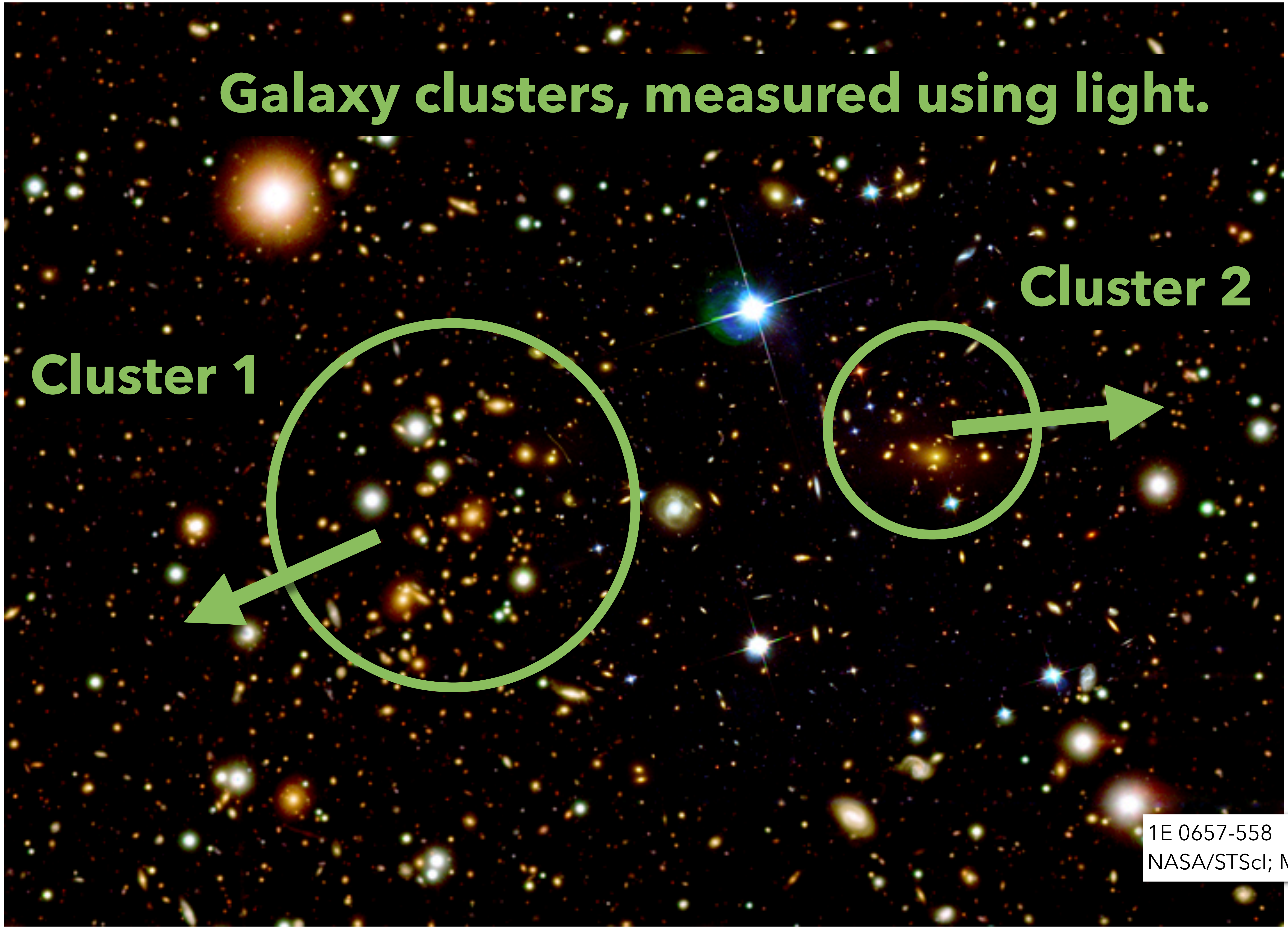


Credits: ESA, NASA, K. Sharon (Tel Aviv University) and E. Ofek (Caltech)

Experimental evidence: Galaxy cluster collisions

1E 0657-558
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

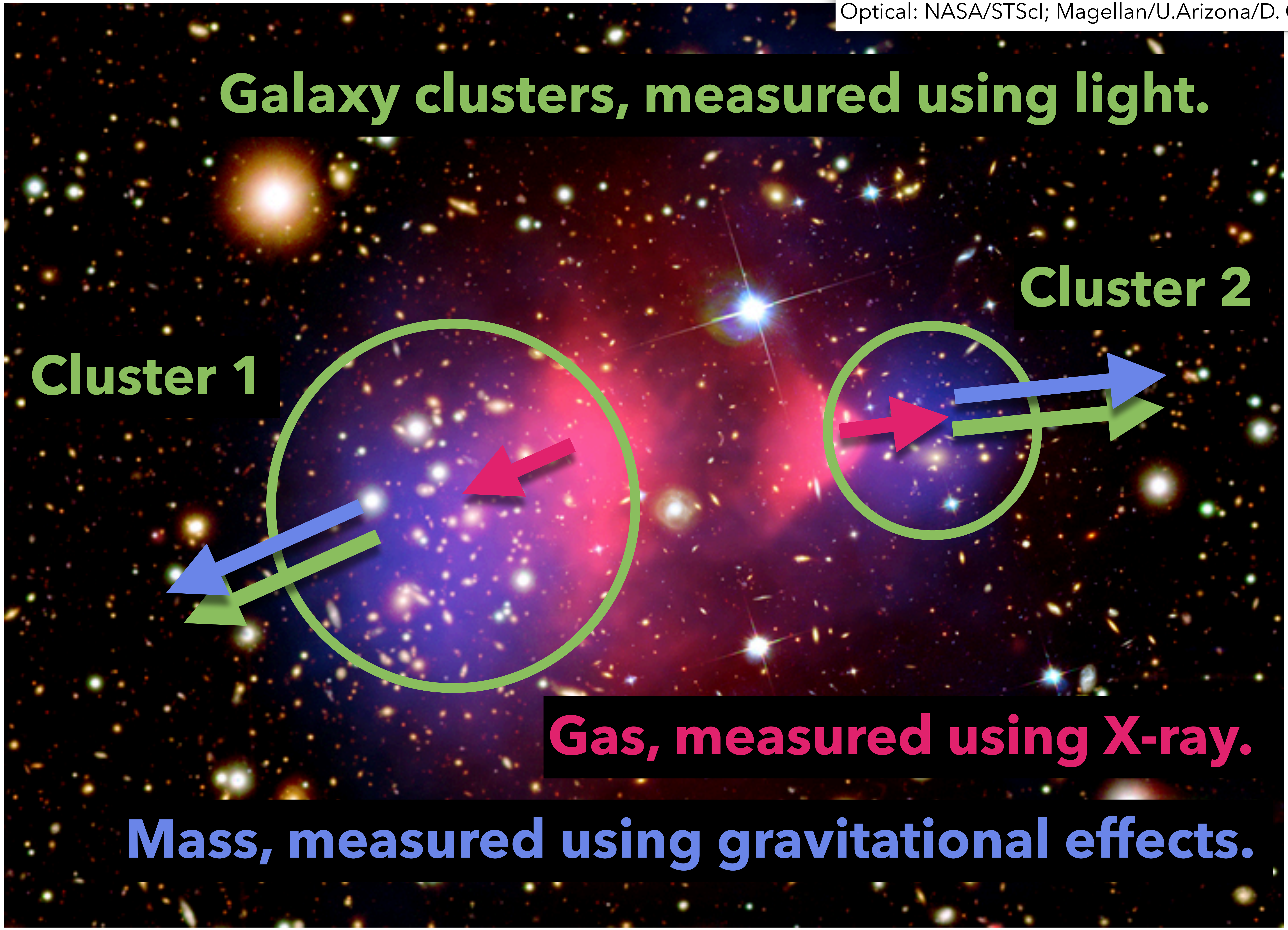
Experimental evidence: Galaxy cluster collisions



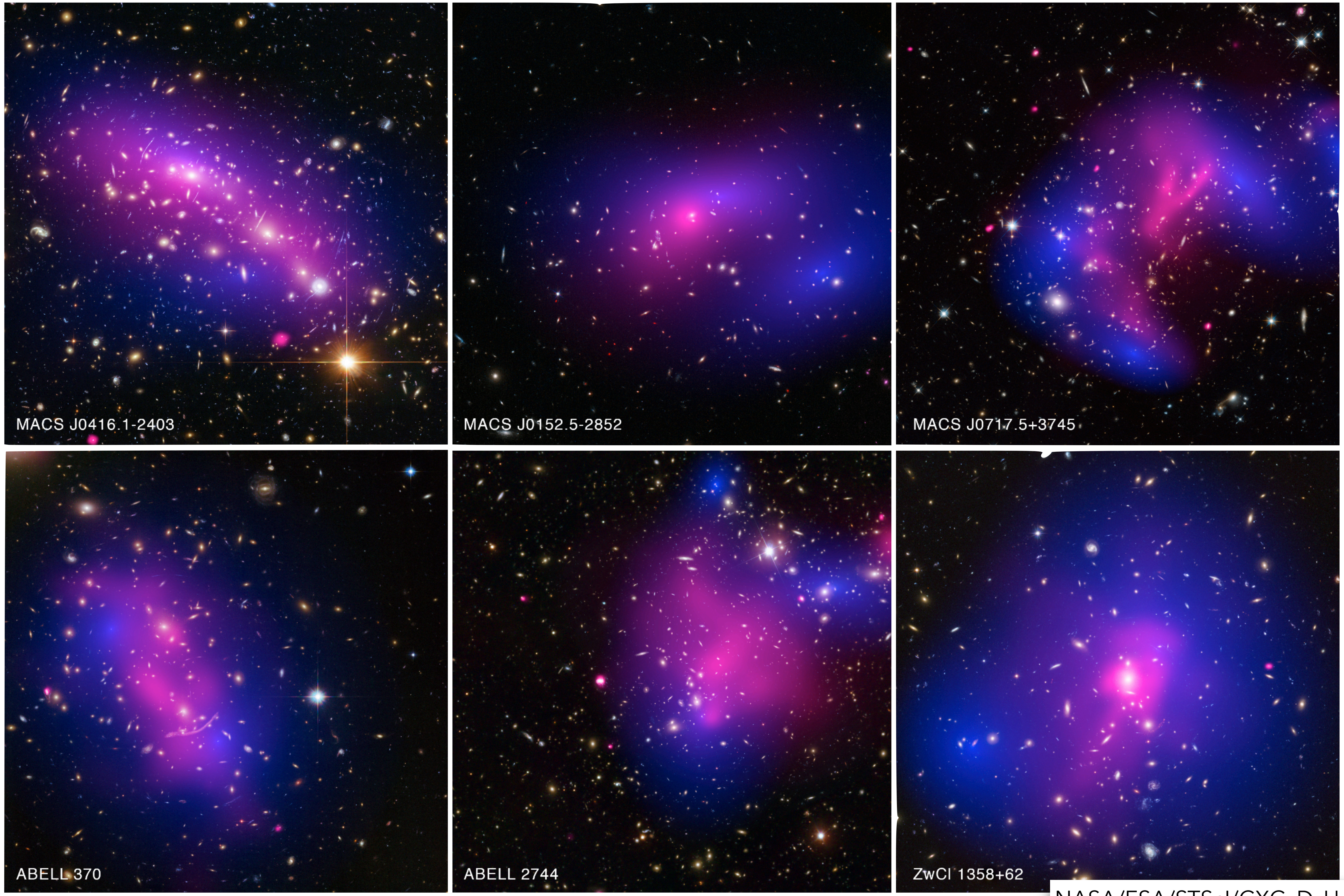
1E 0657-558
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

Experimental evidence: Galaxy cluster collisions

1E 0657-558
X-ray (red): NASA/CXC/CfA/ M. Markevitch et al.;
Lensing map (blue): NASA/STScl; ESO WFI; Magellan/U.Arizona/ D. Clowe et al.
Optical: NASA/STScl; Magellan/U.Arizona/D. Clowe et al.;



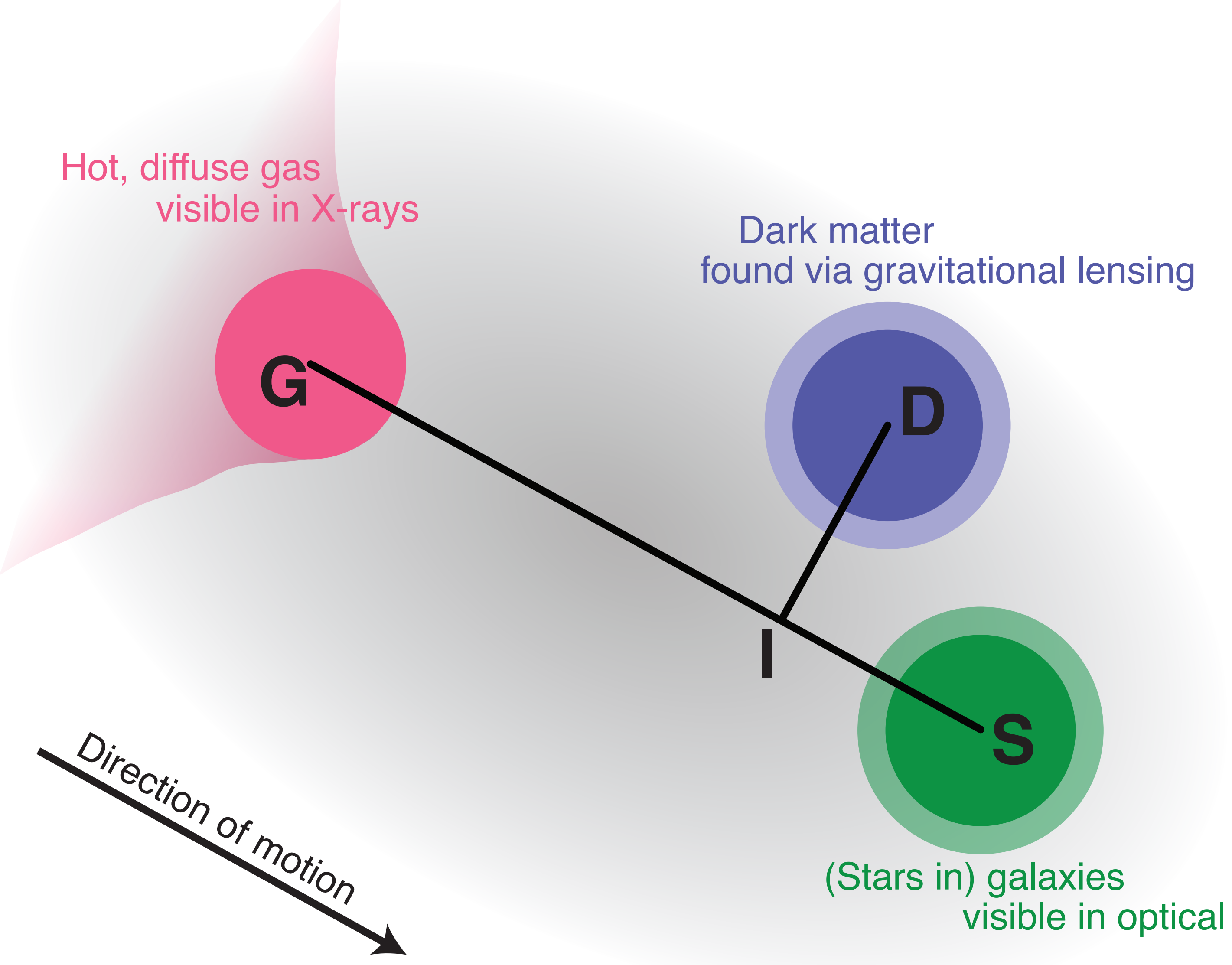
Experimental evidence: Galaxy cluster collisions

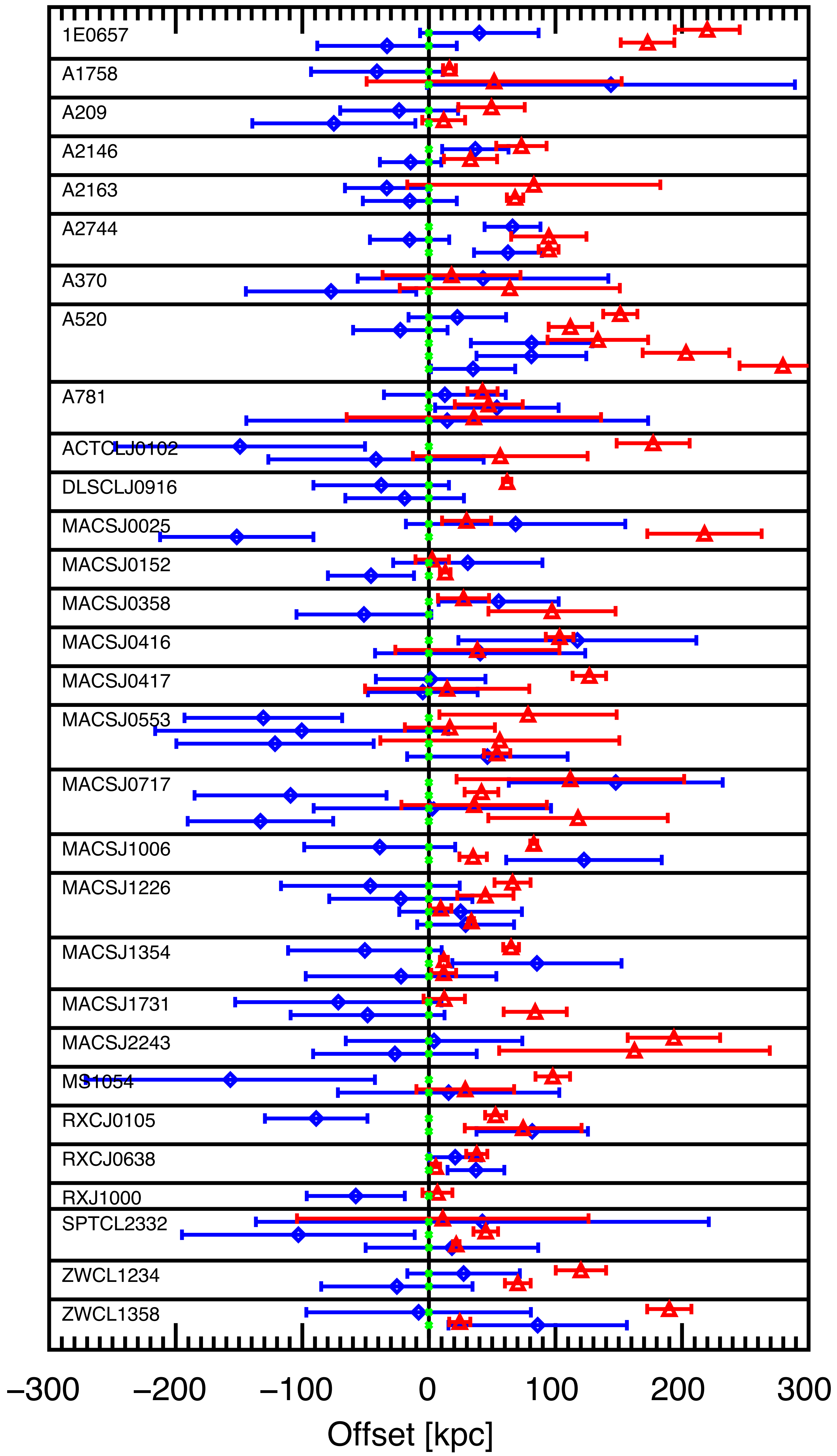


NASA/ESA/STScI/CXC, D. Harvey, R. Massey, A. Taylor, E. Tittley

Experimental evidence: Galaxy cluster collisions

- Galaxy clusters contain stars, gas clouds, and dark matter
- Measure average displacement of DM to baryonic matter
- Global analysis of Hubble data: >8σ evidence for the existing of a dark mass
- Also provides limits on DM-DM self interactions

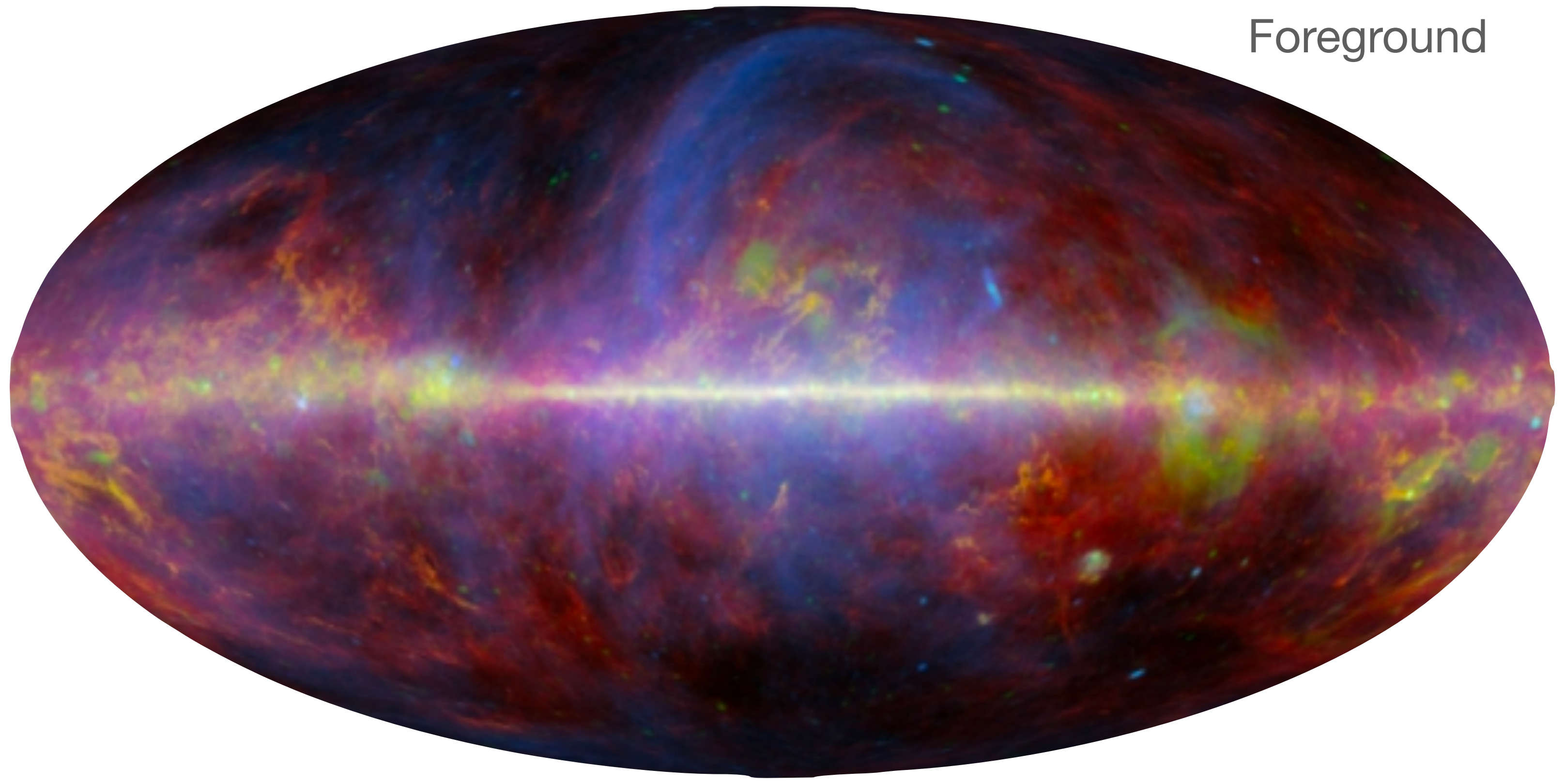


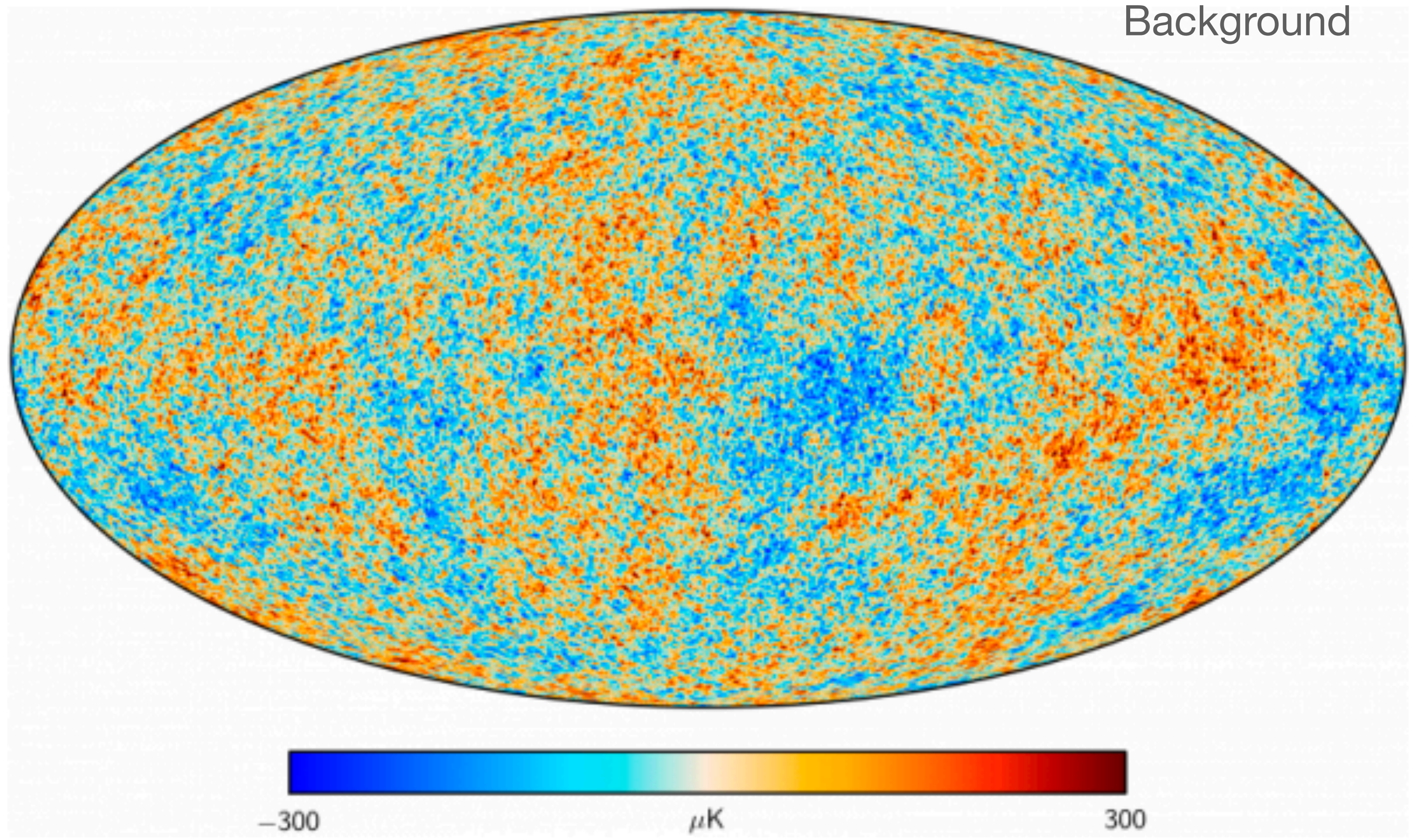


D. Harvey et al., Science, Vol. 347 no. 6229 pp. 1462-1465 (2015)

Experimental evidence: Cosmic microwave background

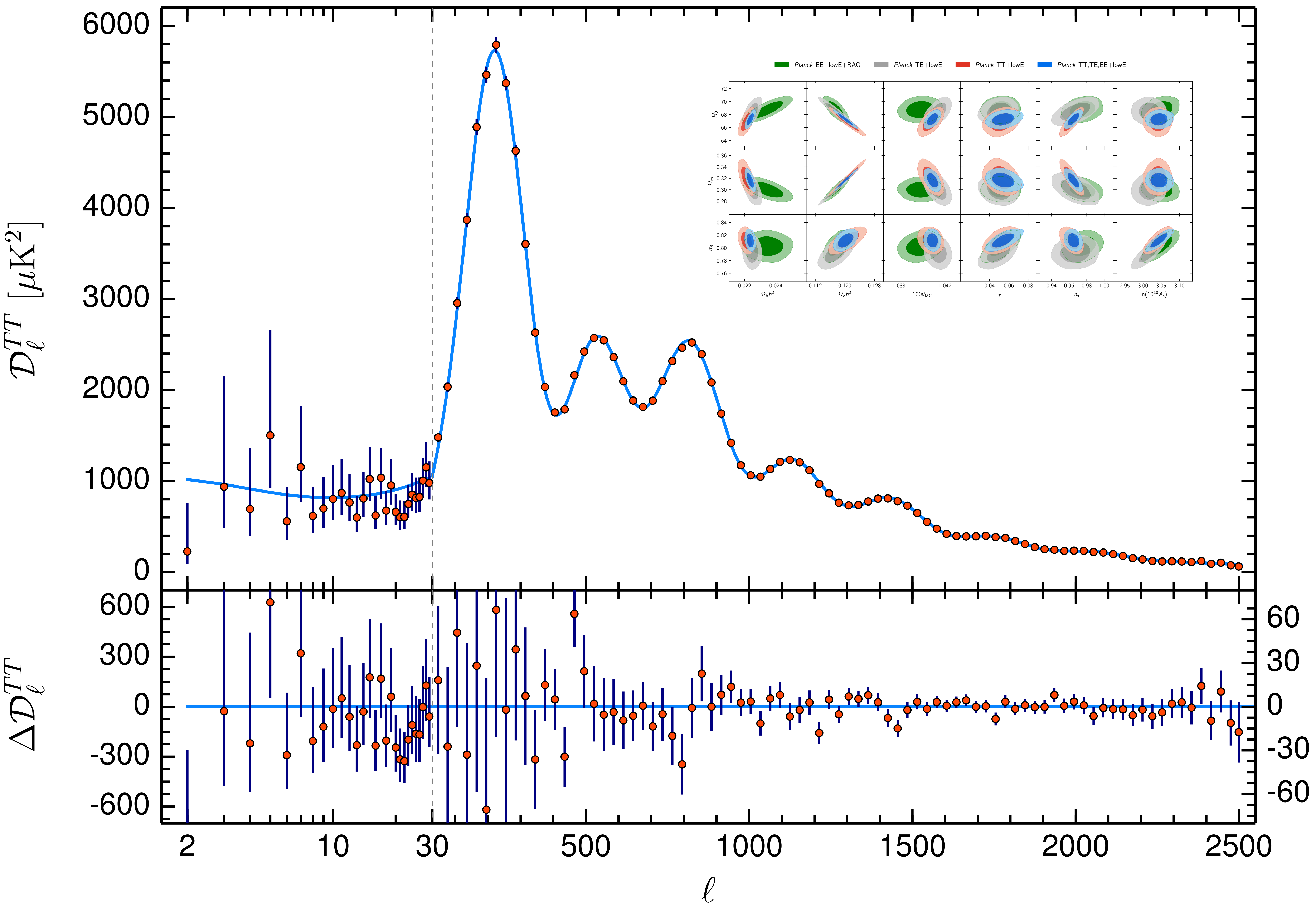
- CMB: thermal photon radiation emitted at the end of the recombination era
- Isotropic emission with a temperature of T = 2.7 K
- CMB anisotropies measured by COBE (1992) and measured with precision by WMAP and Planck satellites
- CMB power spectrum from correlation of temperature with respect to angular scale (full moon is ~1°)
- Spectrum fit with cosmological model suggests that DM is a fundamental ingredient
- Conclusion: 27% of total energy content in the Universe is dark matter





Credit: ESA and the Planck Collaboration

Experimental evidence: Cosmic microwave background

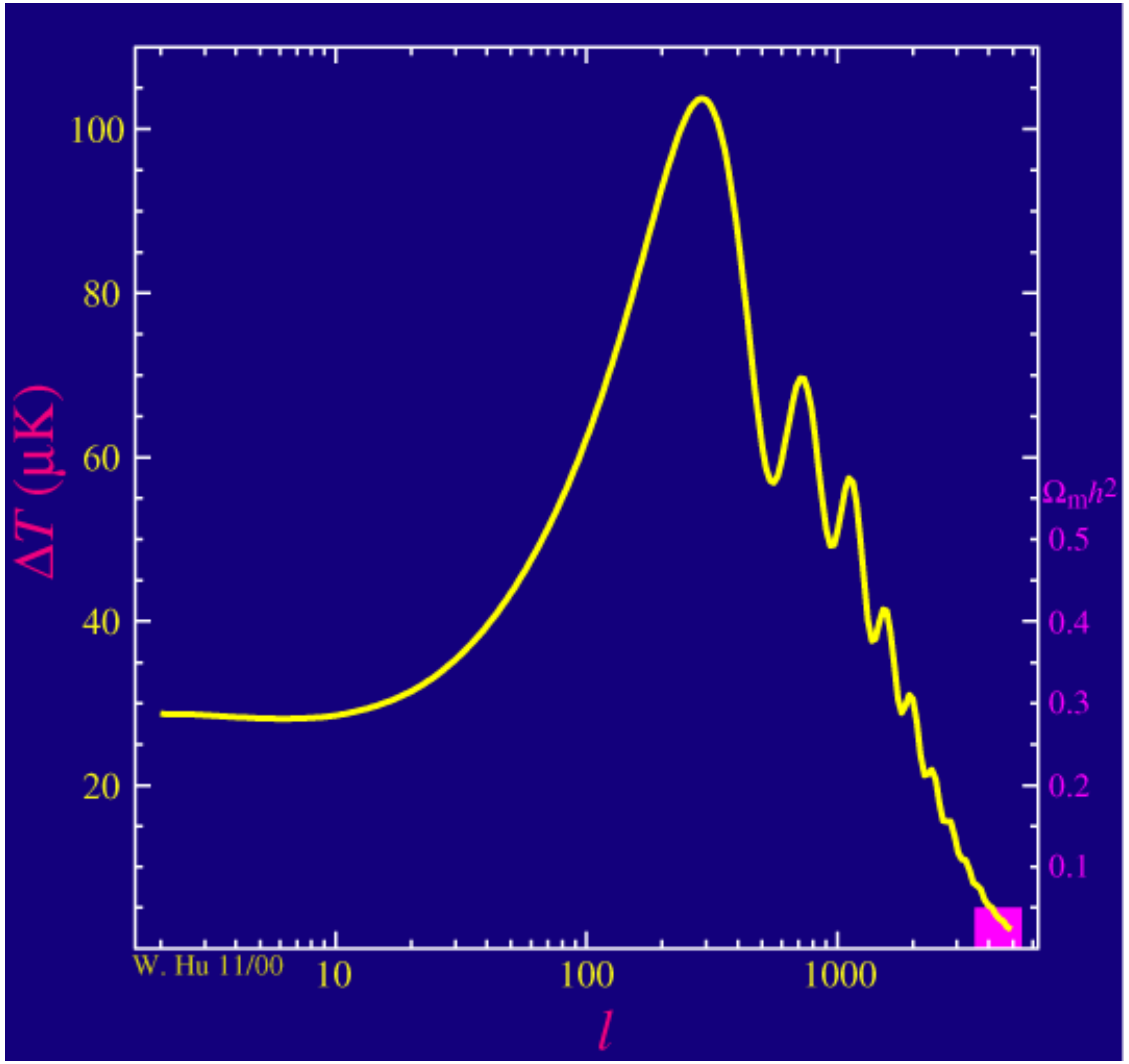


https://arxiv.org/abs/1807.06209

- Fit of ΛCDM model to Planck2018 temperature power spectrum extracted from CMB measurement: Excellent agreement (but many free parameters)

Experimental evidence: Cosmic microwave background

Video

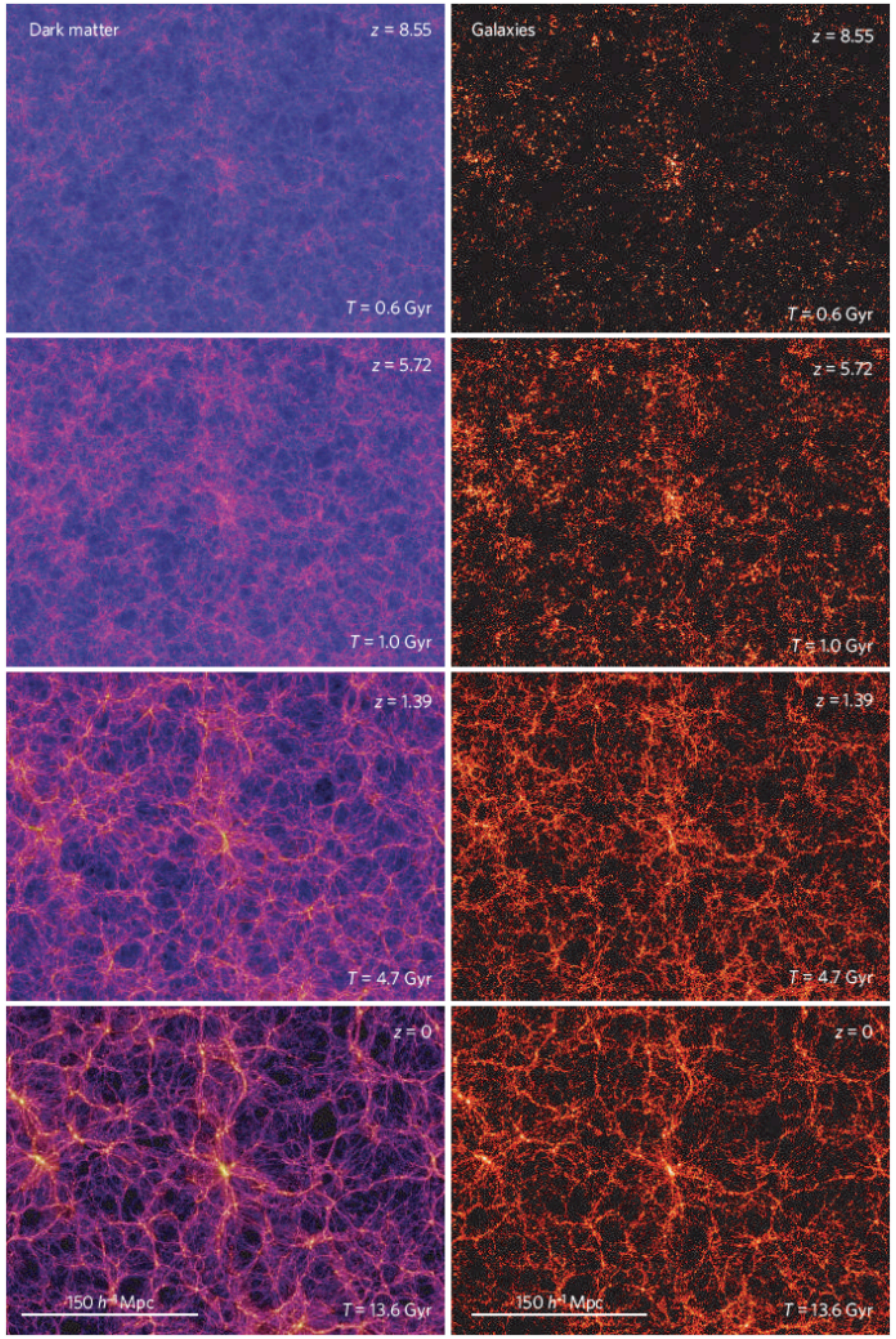


Source: http://background.uchicago.edu/~whu/animbut/anim1.html

- Dark matter increases the total matter content at fixed baryon (ordinary matter) density
- As the dark matter increases:
  - overall amplitude of the peaks decrease (due to the elimination of radiation driving)
  - prominence of the even-odd modulation from the baryons increases.

Experimental evidence: Large structure formation

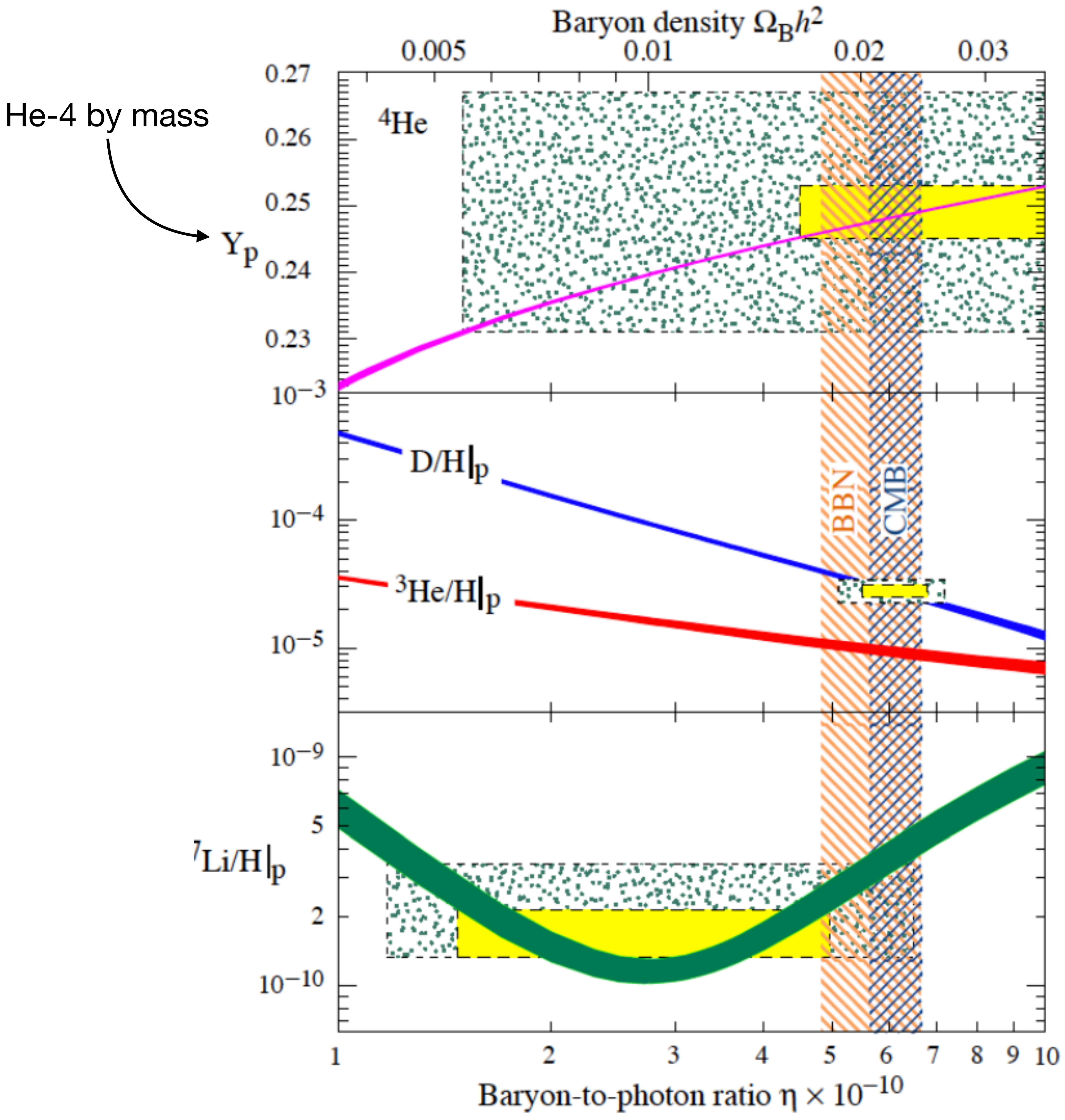
- Formation of large structures (galaxies, galaxy clusters, voids …) from early density fluctuations
- Computer simulations can produce the observed structures - if DM is added
- However: DM can not be relativistic or all large structures (that we observe today) are washed out or disappear



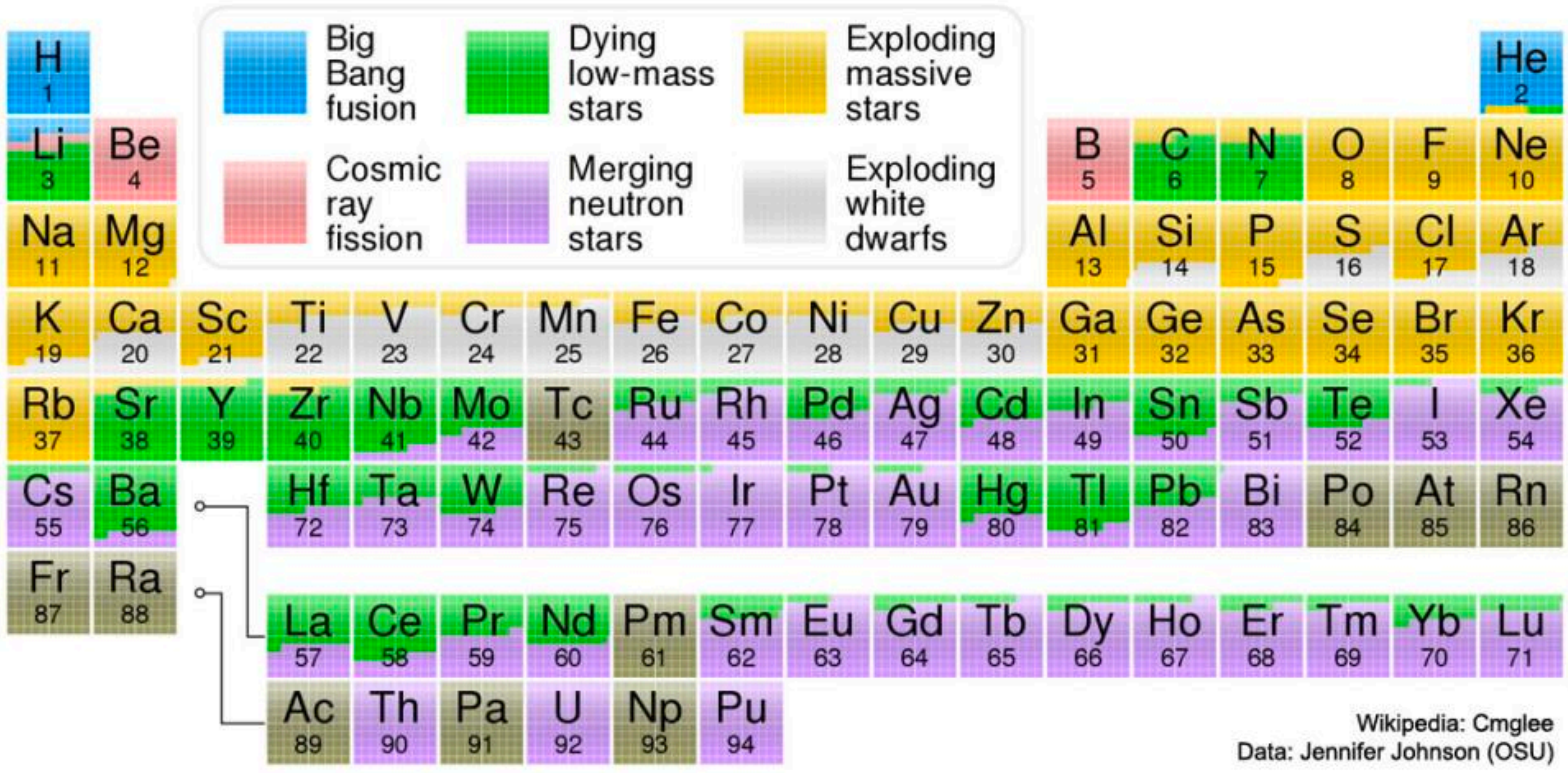
Nero (by F. Schwall)

Experimental evidence: Big Bang Nucleosynthesis

- BBN a few minutes after the BB
- Light nuclei are created: H, D, ^{4}He, a bit of ^{7}Li
  - ^{3}H and ^{7}Be are created but are unstable and decay
- Heavier elements are only created by stellar nucleosynthesis
- BBN predicts the abundance of elements as function of temperature, nucleon density, expansion rate and neutrino properties
- Baryon to photon ration is a key parameter as photons can disrupt deuterium
- If all mass of the universe was originally made up by protons and neutrons, the amount of deuterium would be much lower (since it burns into He-4)



Experimental evidence: Big Bang Nucleosynthesis



Possible explanation: Modified gravity

- Umbrella term for Beyond General Relativity theories
- These theories usually modifiy GR behavior at very small and/or very large distances (GR is extremely well tested on solar-system scale)
- Very simple Modified Newtonian Dynamics (MOND) theories proposed to explain galaxy rotation curves, have been experimentally ruled out
- More complicated models can explain some observed effects but have difficulties with others

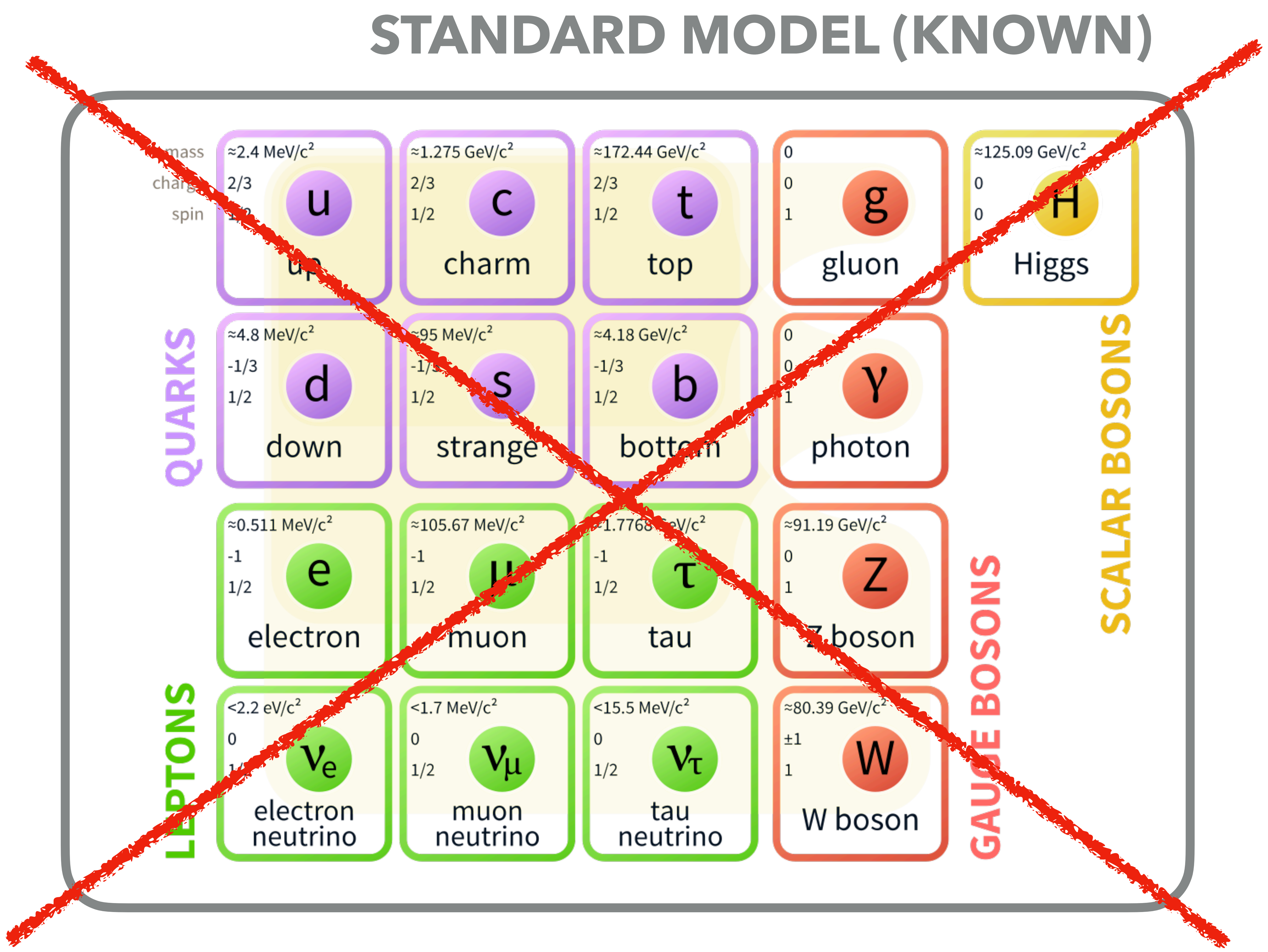
Possible explanation: Supermassive objects

- Massive astrophysical compact halo object (MACHO) are a class of non-luminous massive objects ((primordial) black holes, neutron stars, brown dwarfs, …)
  - Can be detected through gravitational micro-lensing (brightness of stars is reduced if a MACHO passes in front of it)
- LISA may measure merging primordial black holes
- Webb may observe light from very early stars near primordial black holes
- Under debate: They could make up some fraction (up to 20%) of the DM density in a galaxy

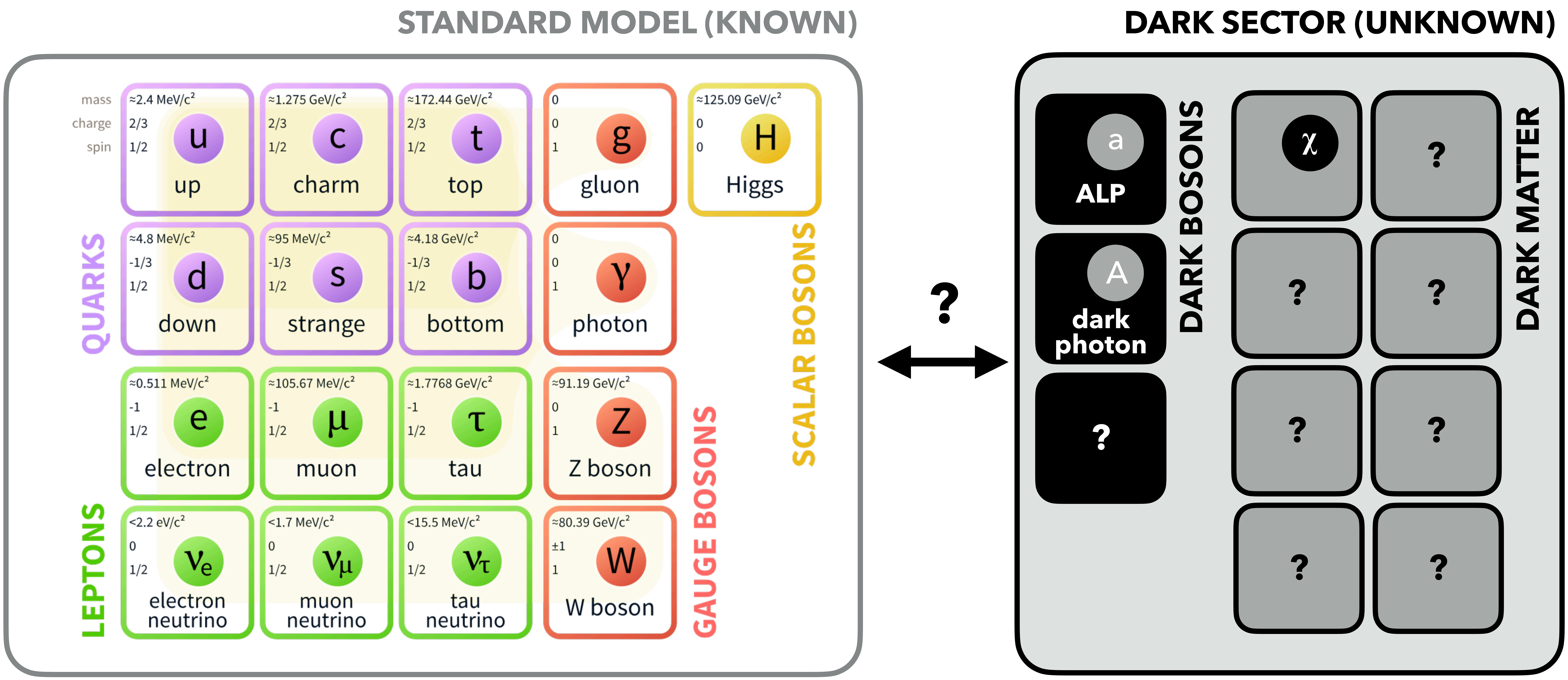
https://www.esa.int/Science_Exploration/Space_Science/LISA_factsheet

Possible explanation: Particles

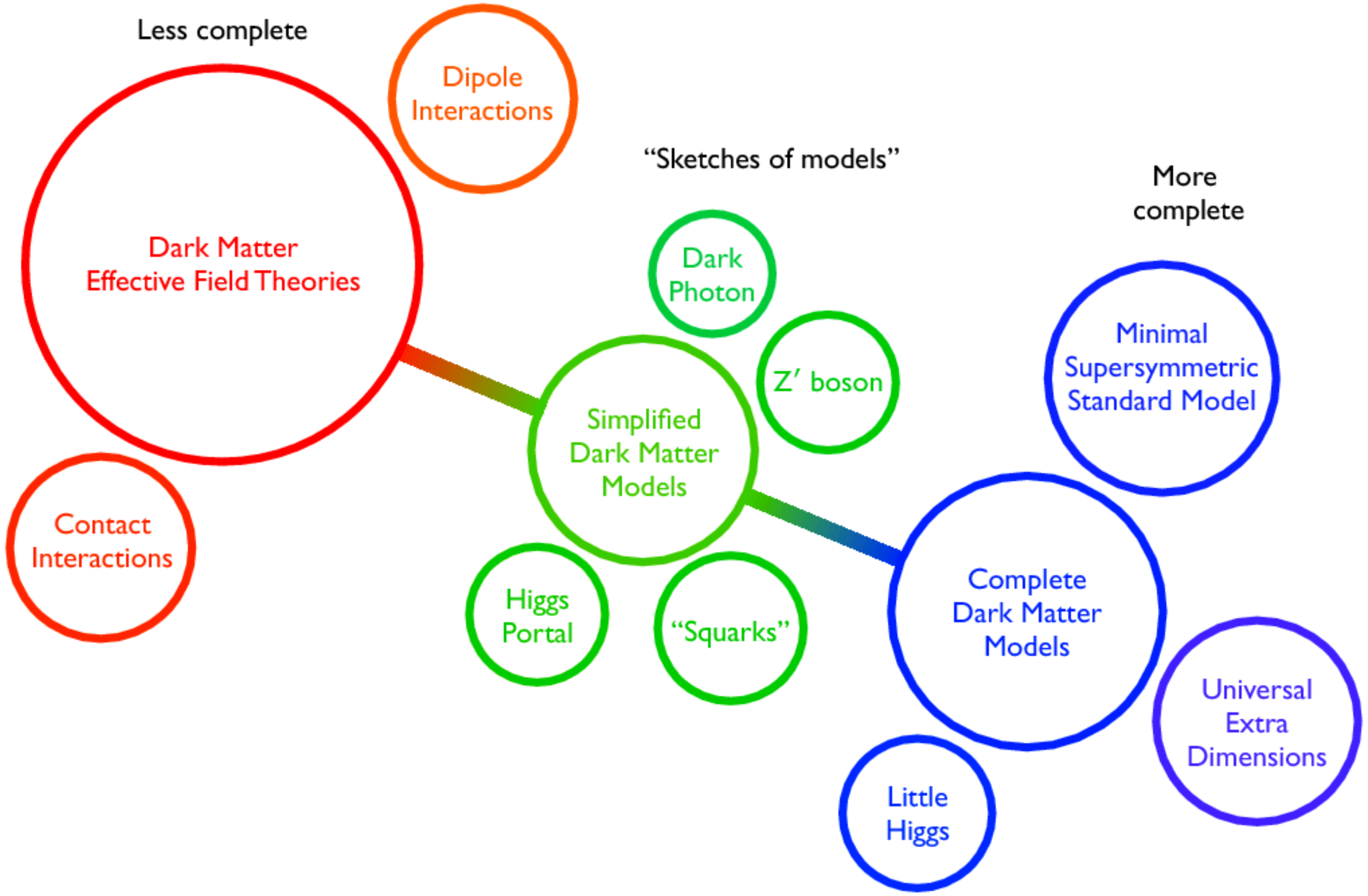
- If DM is an elementary (?) particle:
  - Massive to explain gravitational effects
  - Neutral particle, i.e. no EM interaction
  - At most weakly interacting
  - Stable or very long-lived (age of the universe)
  - Cold or warm (and not hot)
- Like modified GR, modified SM can not easily explain all DM observations simultaneously in simple models



Dark Matter Models



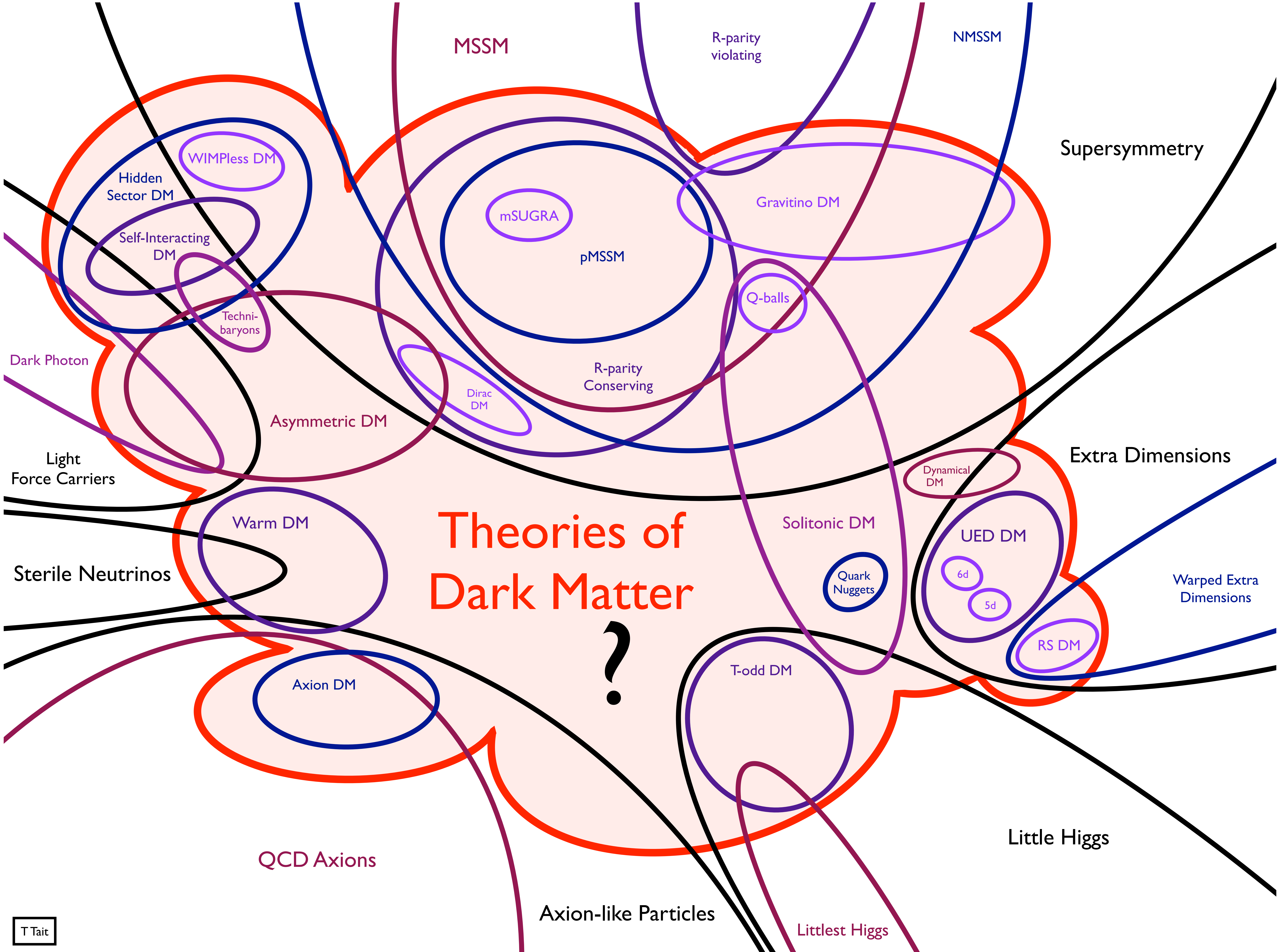
Dark Matter Models



	EFT	Simple	Complete
Complexity	(too?) low	medium	(too?) high
Free parameters	1	~5	20+
Exp. signatures	weak	some	clear

https://arxiv.org/pdf/1506.03116.pdf

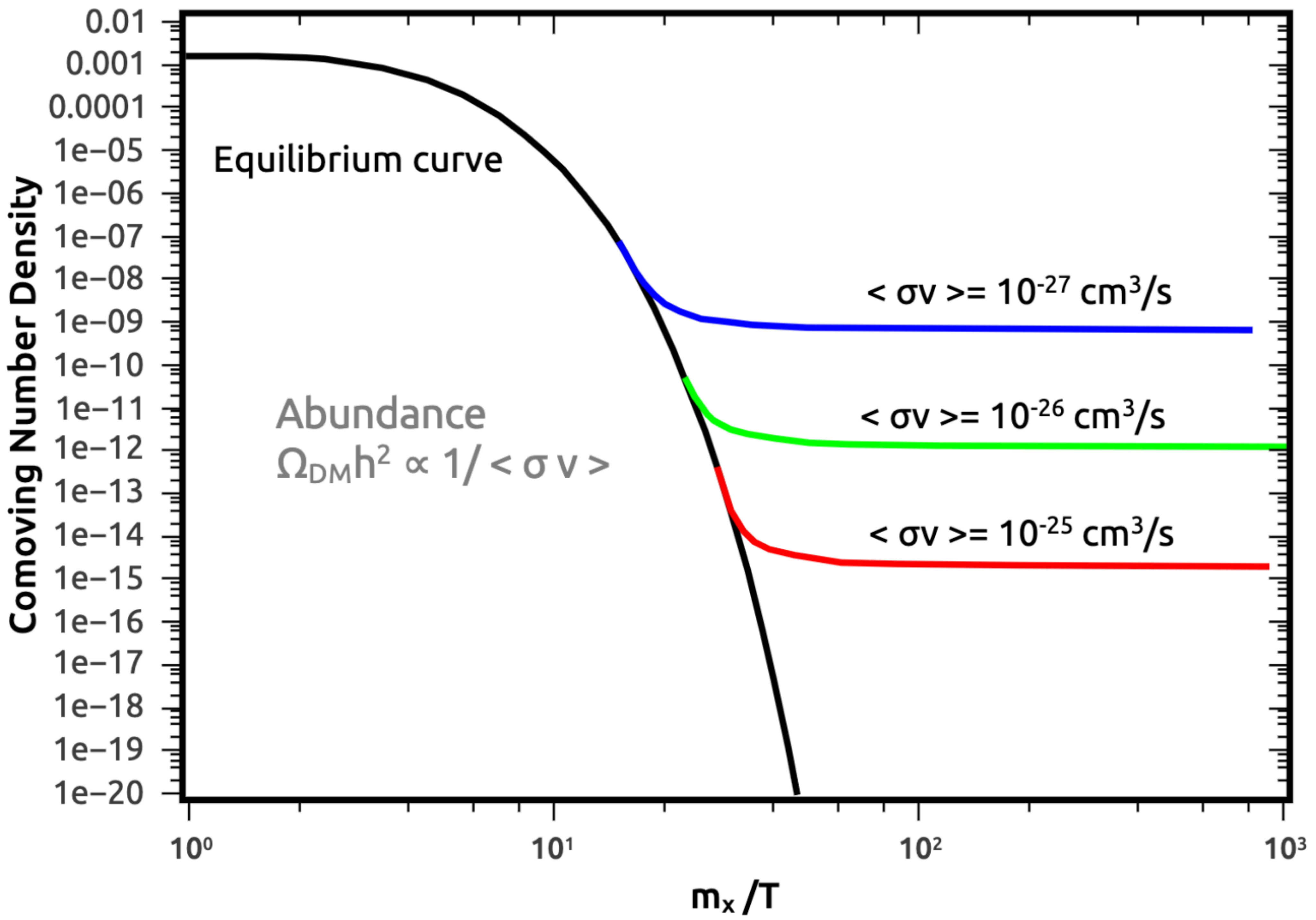
Dark Matter Models



Artist's impression of a spiral galaxy embedded in a dark matter halo (Credit: ESO / L. Calçada)

Possible BSM model: Weakly Interacting Massive Particles (WIMP)

- For high temperatures in the early Universe, WIMPs are in equilibrium with thermal plasma
- When the Universe expanded, the temperature of the plasma decreased and the number density of the created WIMPs also decreased
- The freezing out* of the number density depends on the interaction cross-section $\langle \sigma v \rangle$



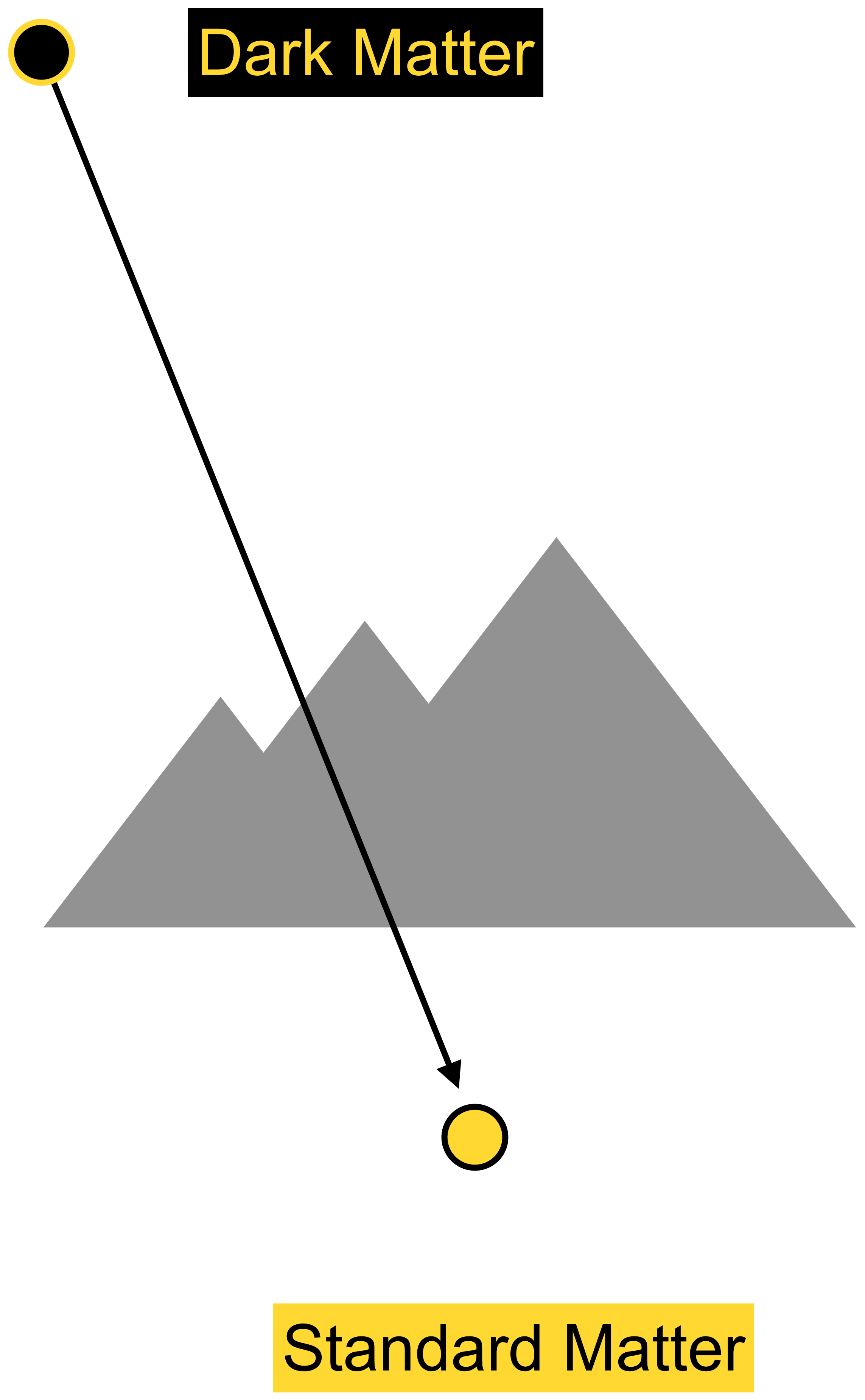
Source: https://arxiv.org/pdf/1703.07364.pdf

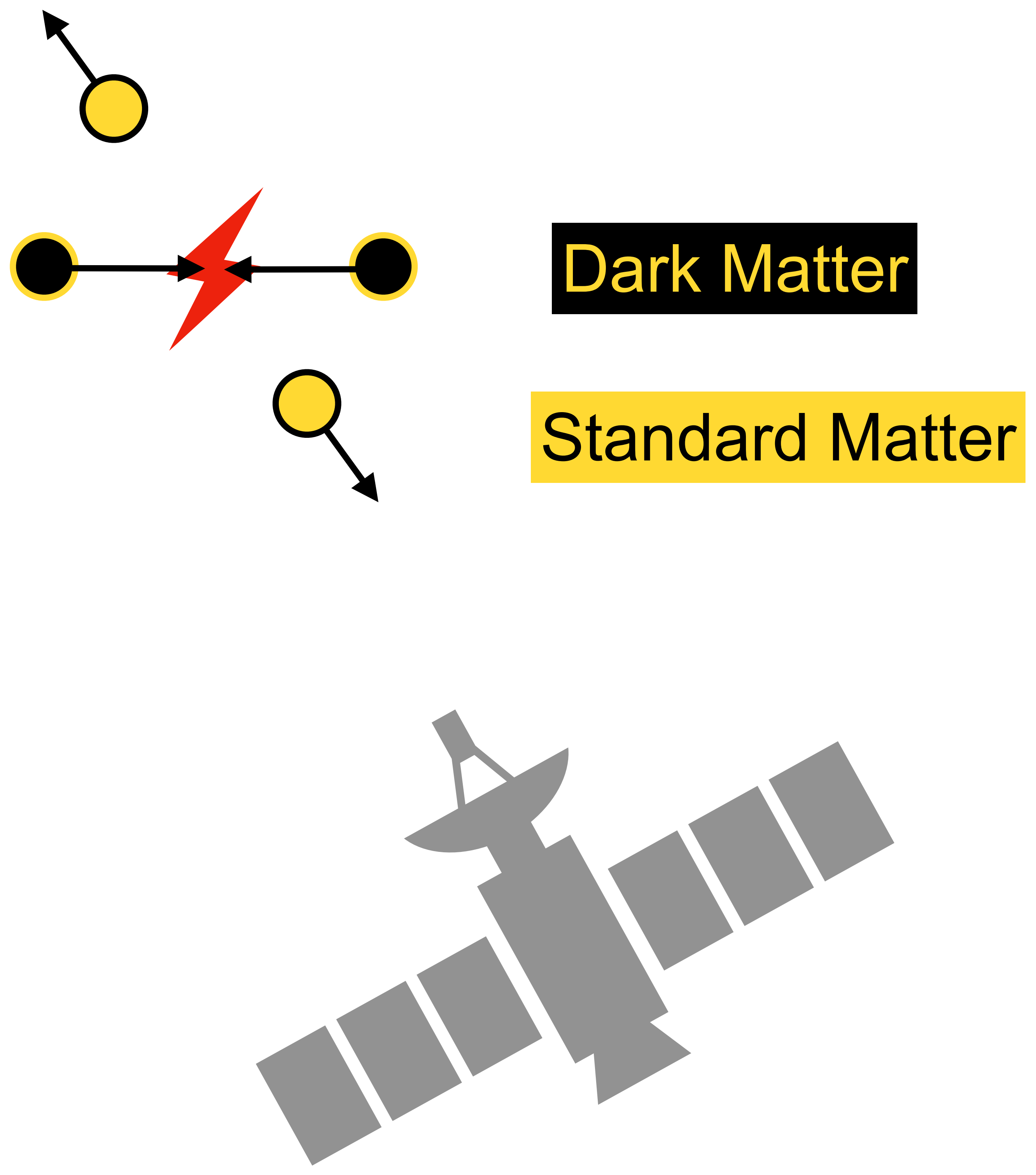
*Freeze out is just one possible scenario. It is very predictive and we love it. But maybe nature did something different.

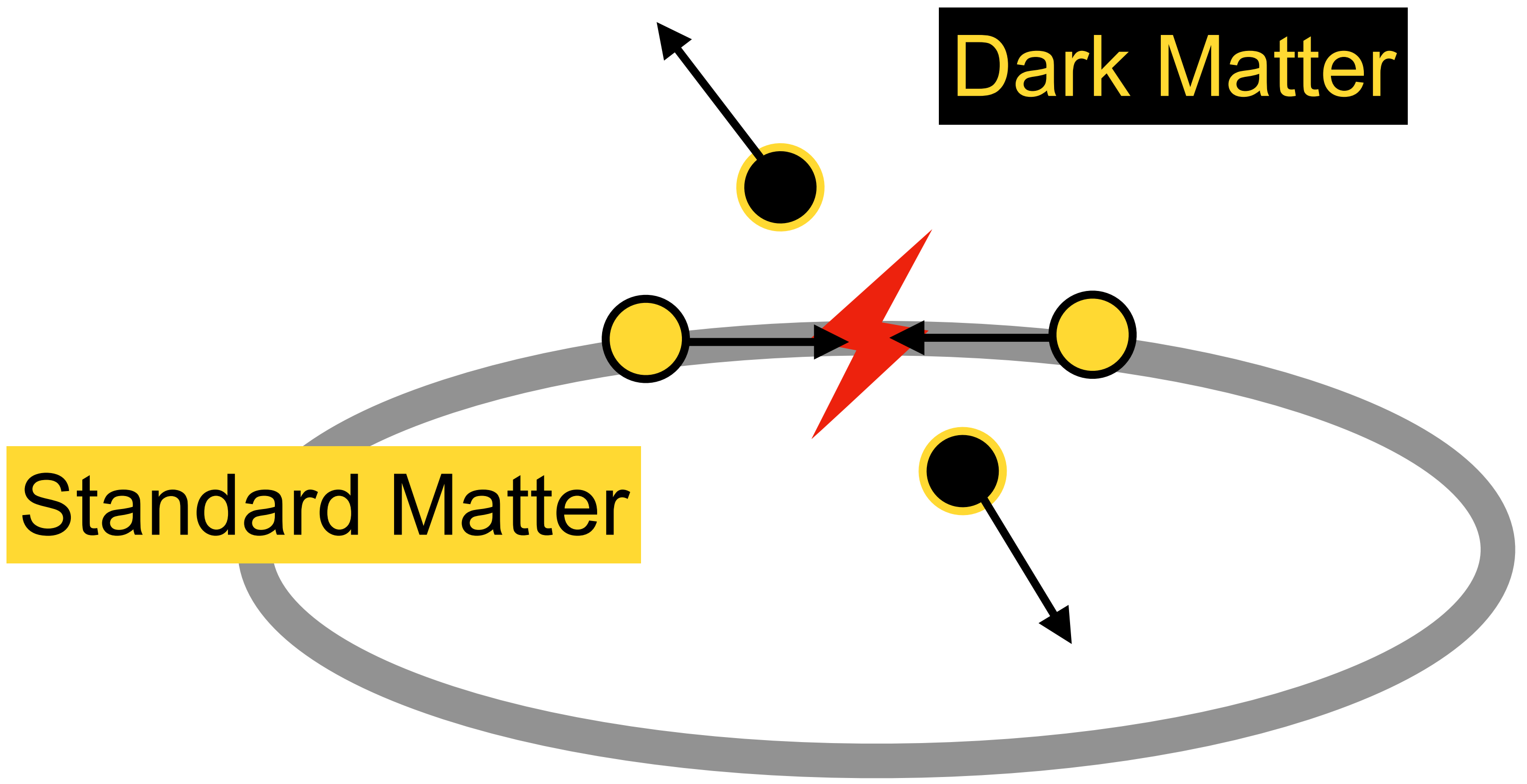
Possible BSM model: WIMP “Miracle”

- We know the DM density in the universe from Planck CMB data ($\Omega_{\mathrm{DM}}h^2 \approx 0.12$)
- The miracle is that this is compatible with an electroweak interactions:
  - Typical electroweak pair annihilation cross section $\sigma \sim G_F^2 T^2$
  - Typical freeze out temperature $T \sim m_{\mathrm{DM}}/20$
  - Typical electroweak mass scale of DM: $m_{\mathrm{DM}} \sim 100\,\mathrm{GeV}$
- **$\rightarrow$ thermal relic density matches the observed cosmological density**

How to detect the WIMP

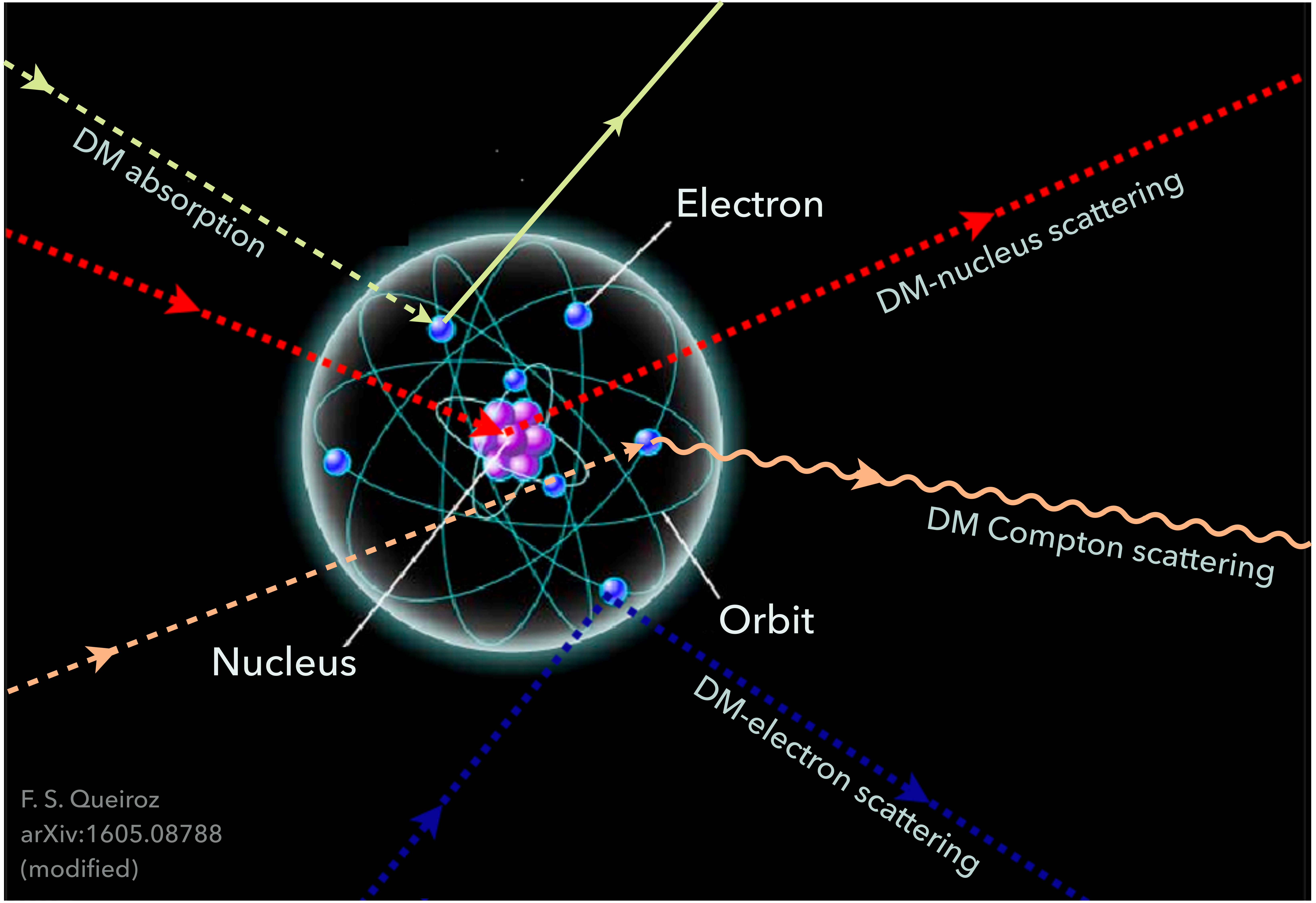




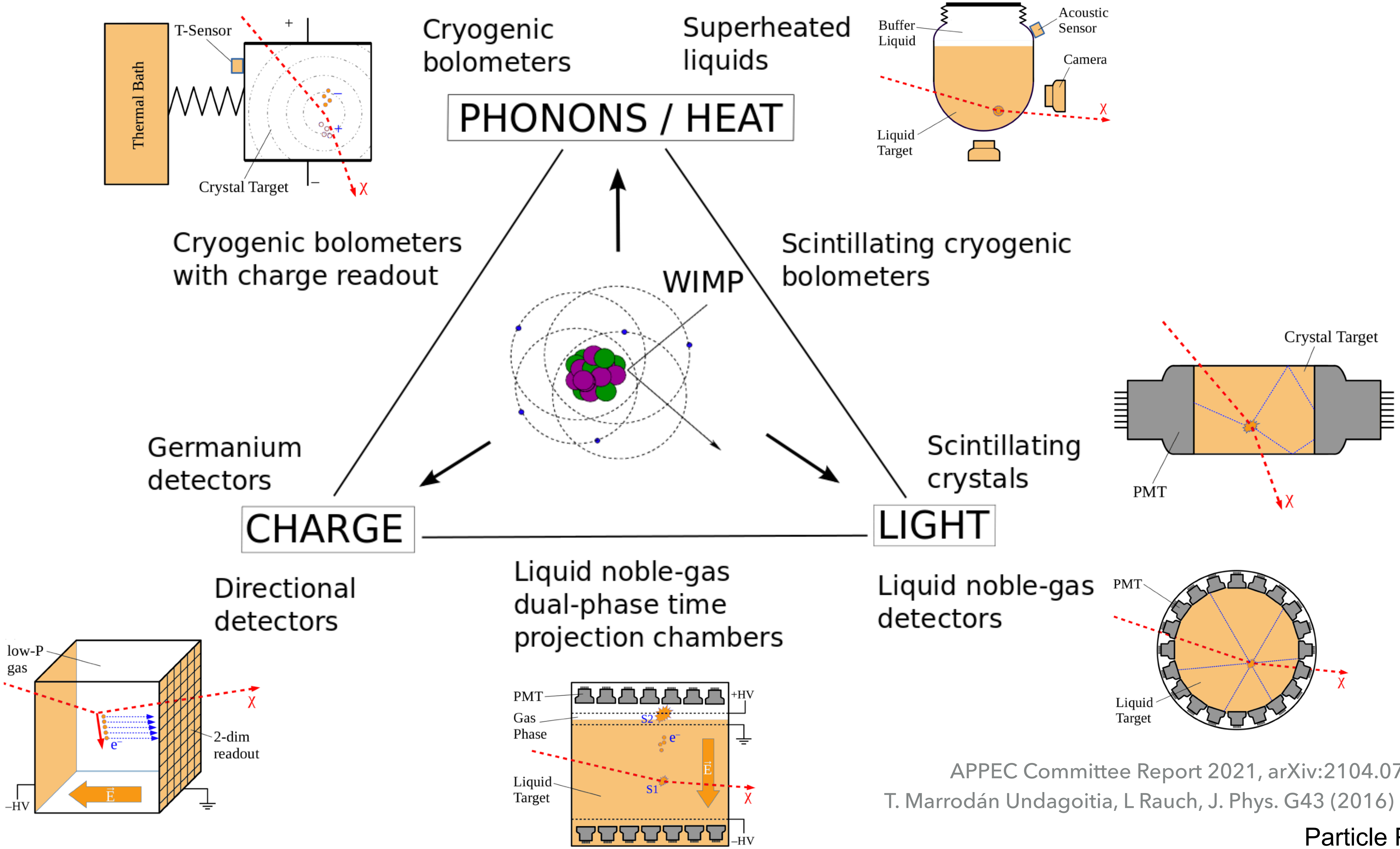


Direct detection

- Local DM density at earth is rather low:
  - $\rho \approx 0.3\ \text{GeV/cm}^3$
  - $v \approx 220\ \text{m/s}$
- Interaction cross section may dependent on target spin: “spin-dependent” vs “spin-independent” limits



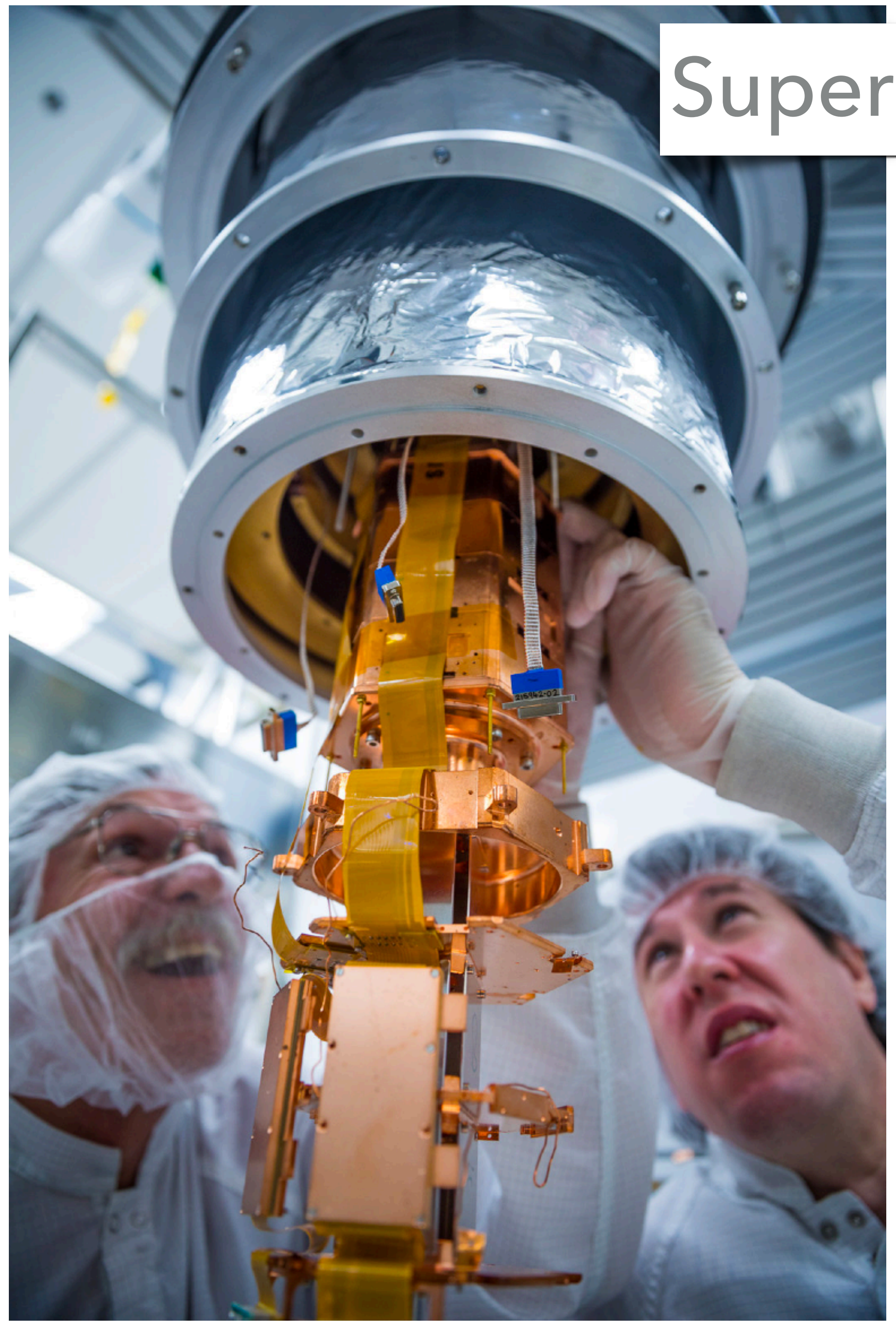
Dark Matter experiments



APPEC Committee Report 2021, arXiv:2104.07634 [hep-ex]
T. Marrodán Undagoitia, L Rauch, J. Phys. G43 (2016) no.1, 013001

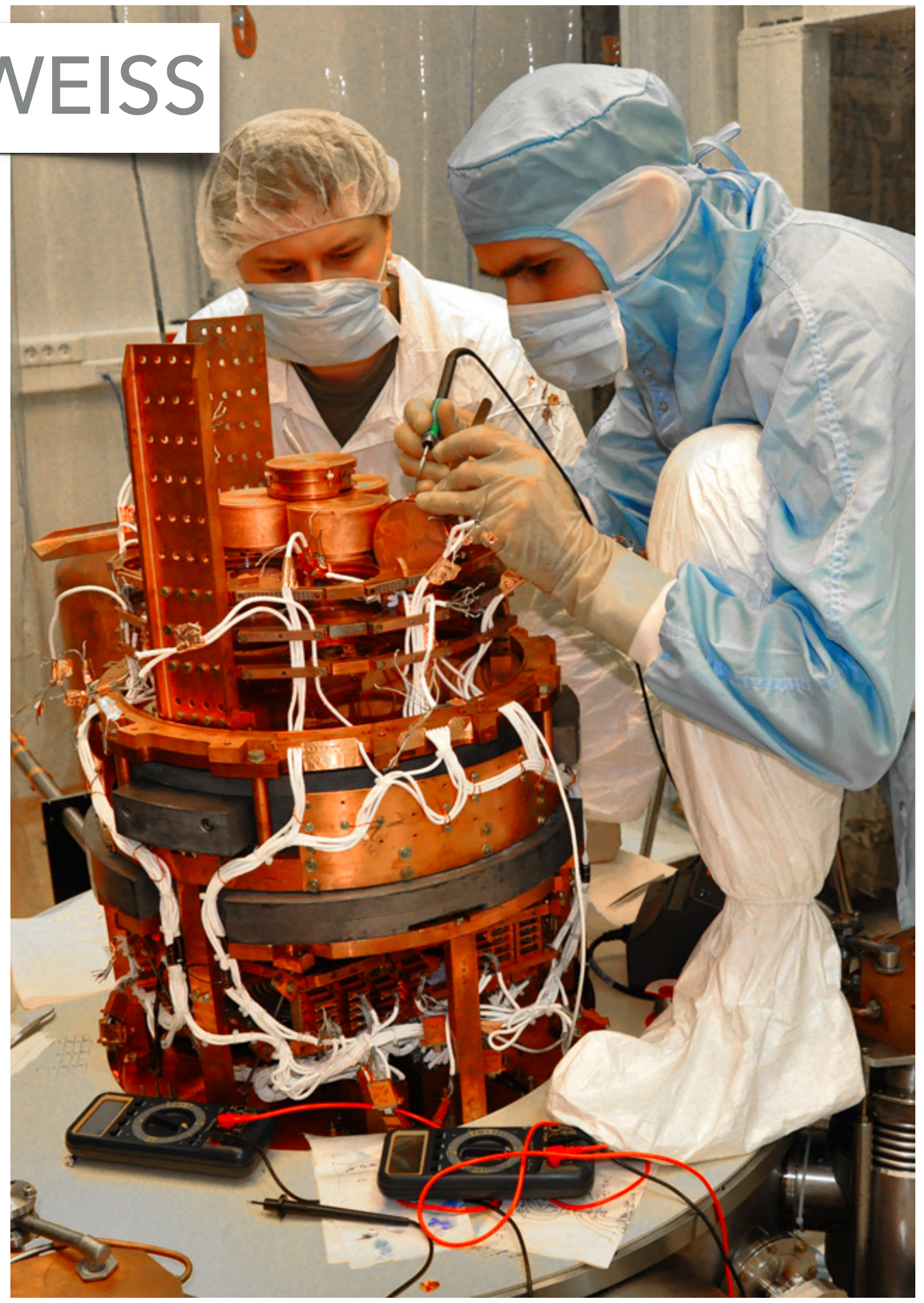
Dark Matter experiments: Cryogenic bolometers

Some examples

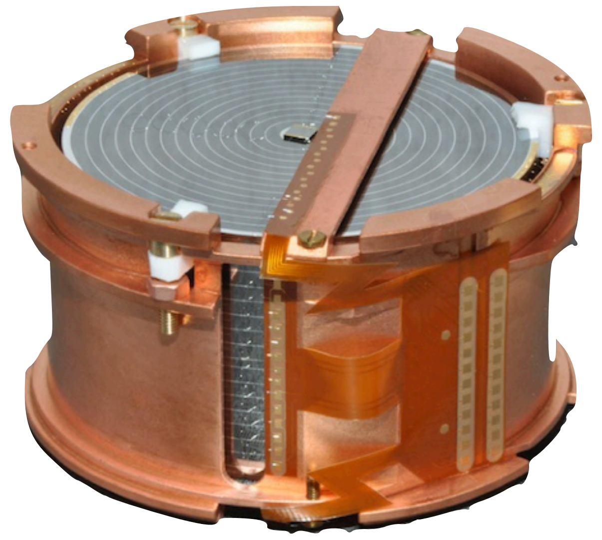


SuperCDMS

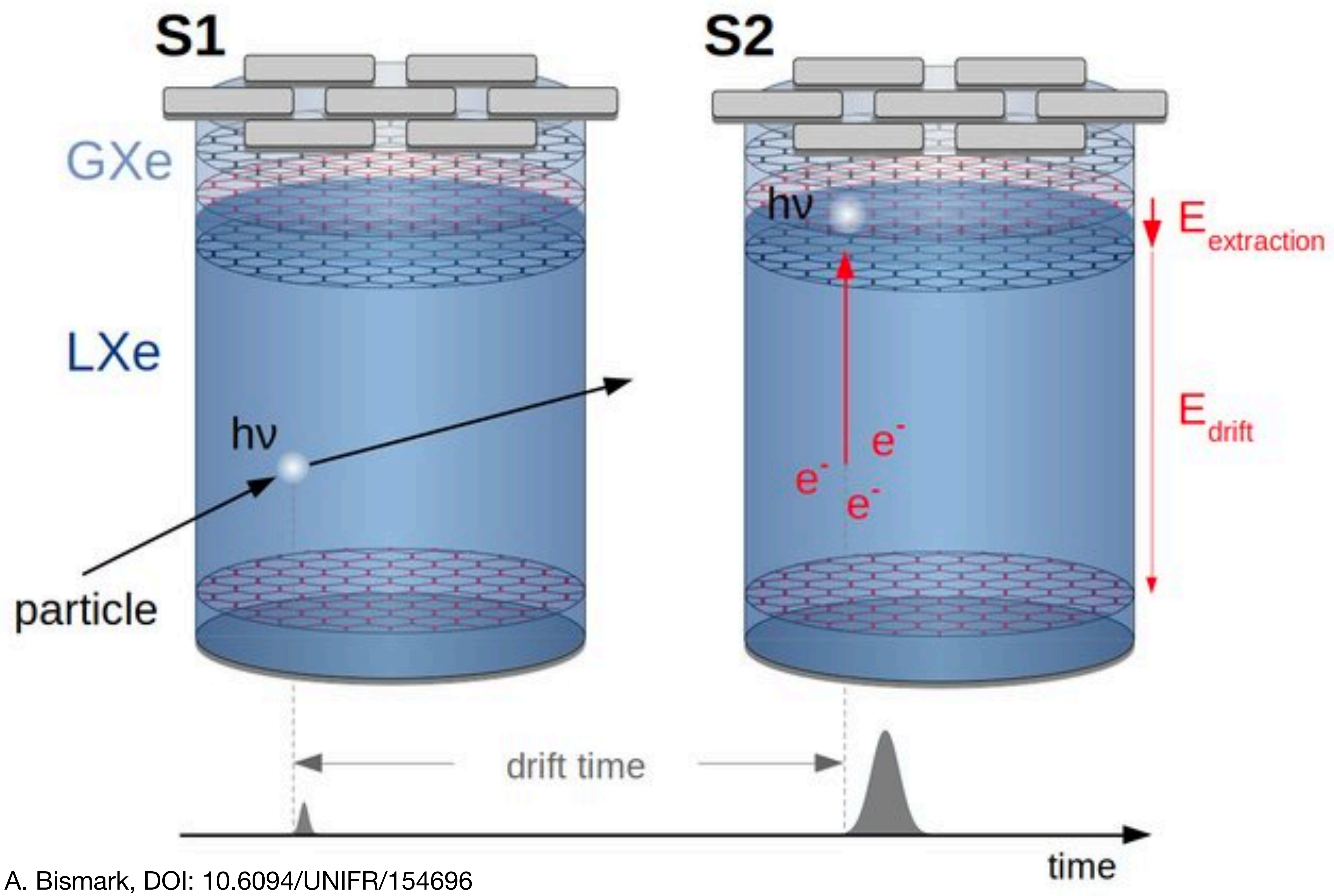
EDELWEISS



- Pro: Measurement of ~100% of deposited energy
- Pro: Low energy threshold
- Con: Difficult to increase target mass for large exposures

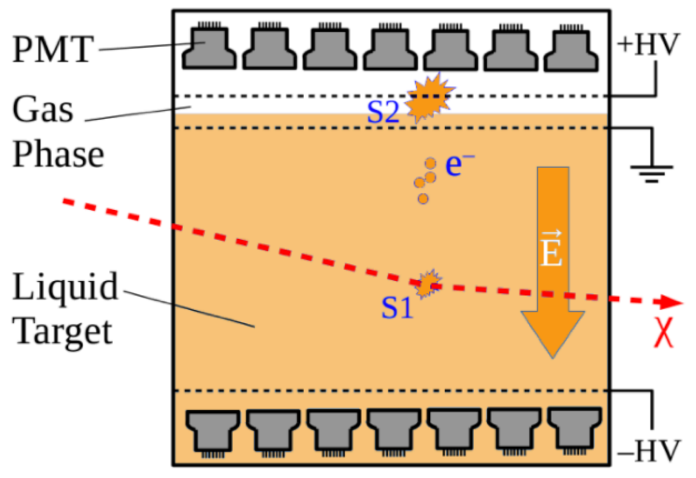


Dark Matter experiments: Dual-phase time projections chambers (TPC)



A. Bismark, DOI: 10.6094/UNIFR/154696

Light + Ionization

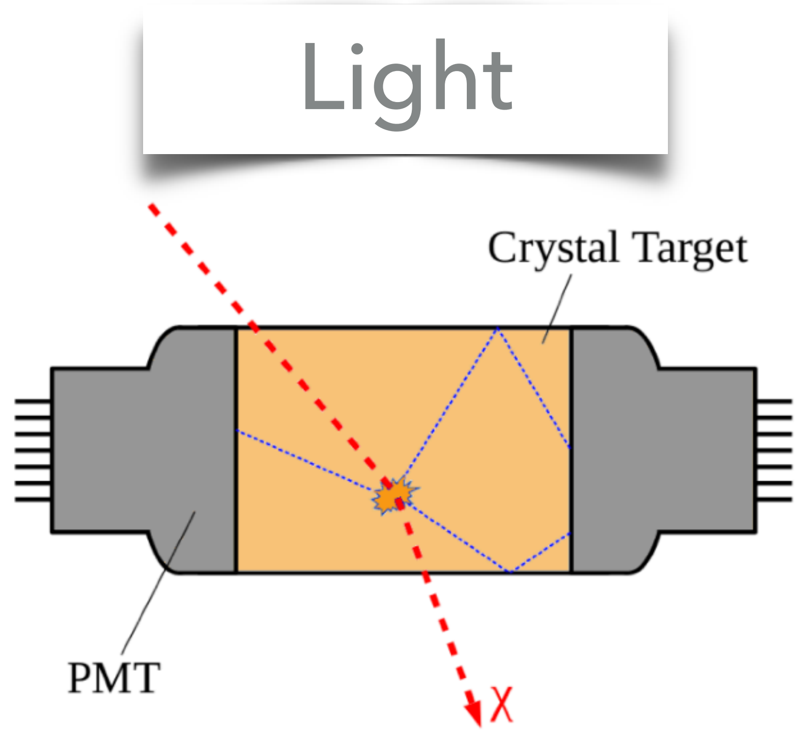


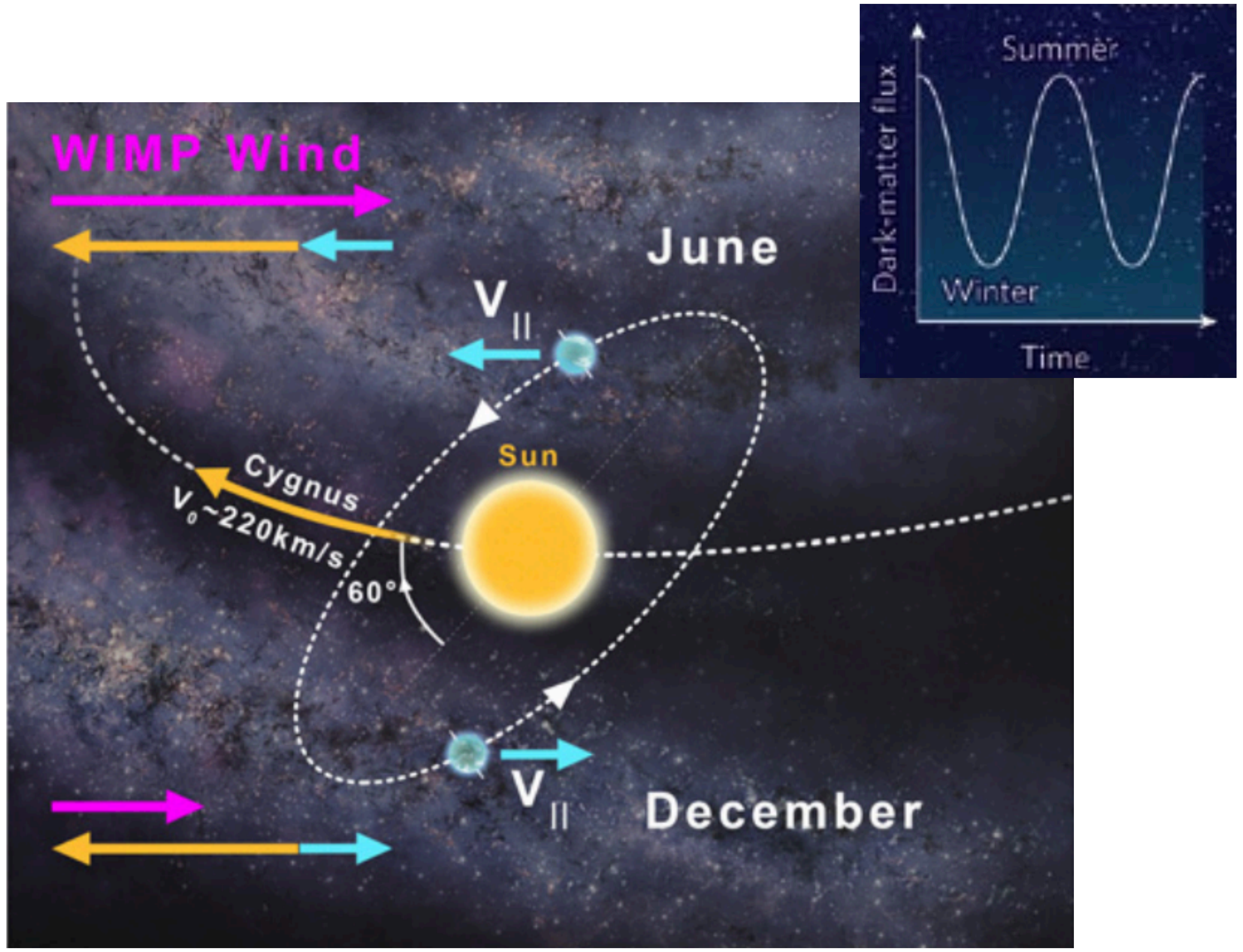
- Two signals (S1 and S2) with
  - different intensities
  - different shapes
  - variable time delay

F. Froborg, A.R. Duffy, J. Phys. G: Nucl. Part. Phys. 47 094002 (2020)
Artist’s impression of a spiral galaxy embedded in a dark matter halo (Credit: ESO / L. Calçada)

Dark Matter experiments: Scintillating crystals

- Only the scintillation light is measured
- Relatively high background level
- Focus on annual modulation search

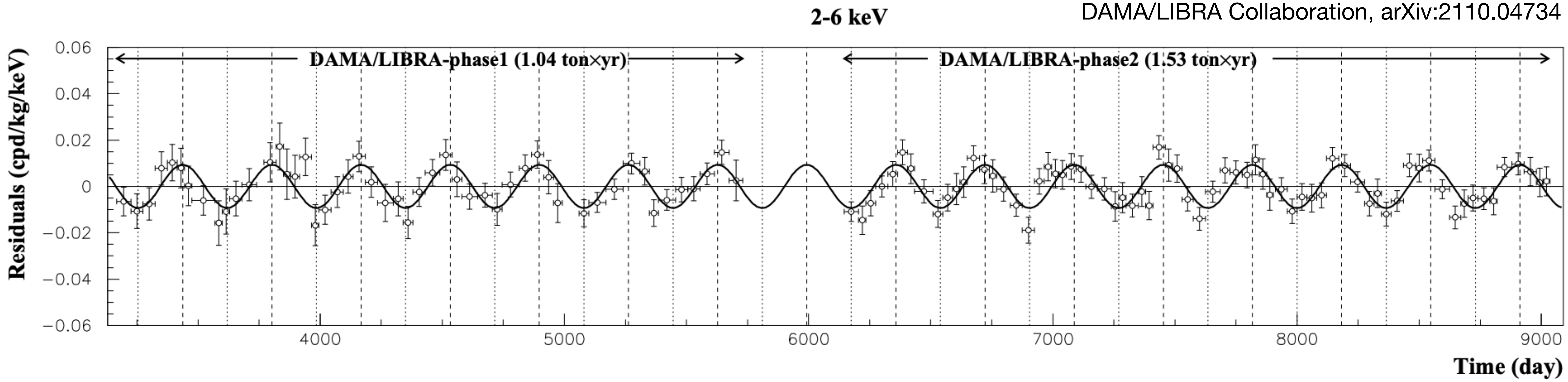




- Pro: Good background discrimination based on time dependence of Dark Matter model
- Con: signal prediction is model dependent

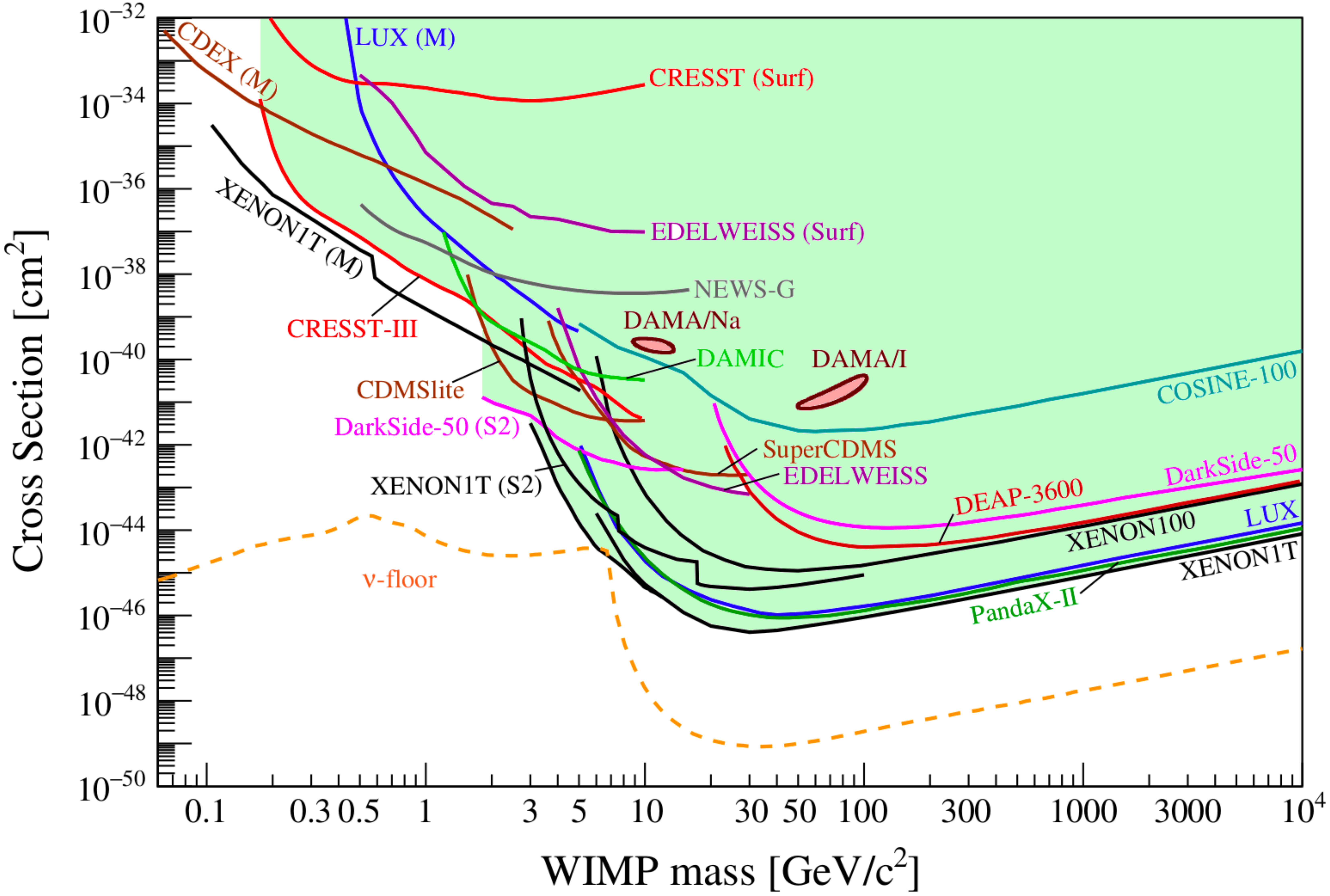
Dark Matter experiments: Scintillating crystals

DAMA/LIBRA Collaboration, arXiv:2110.04734



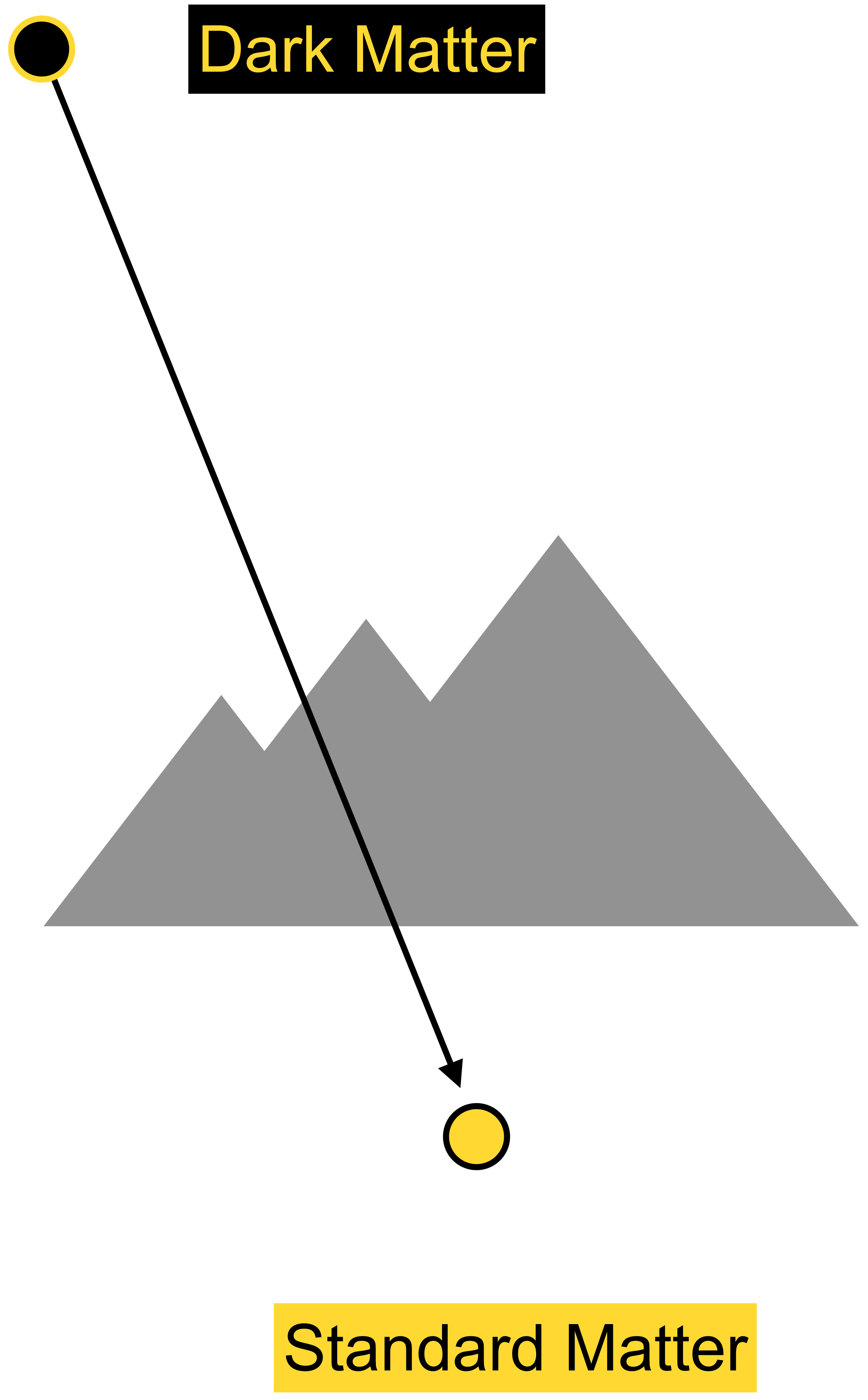
- 250 kg highly radio-pure NaI(Tl)
- 15 annual cycles
- Favors the Dark Matter annual modulation signal hypothesis at 13.7 σ C.L.
- But so far no confirmation by any other experiment (COSINE-100 and SABRE will probe the same parameter space soon)

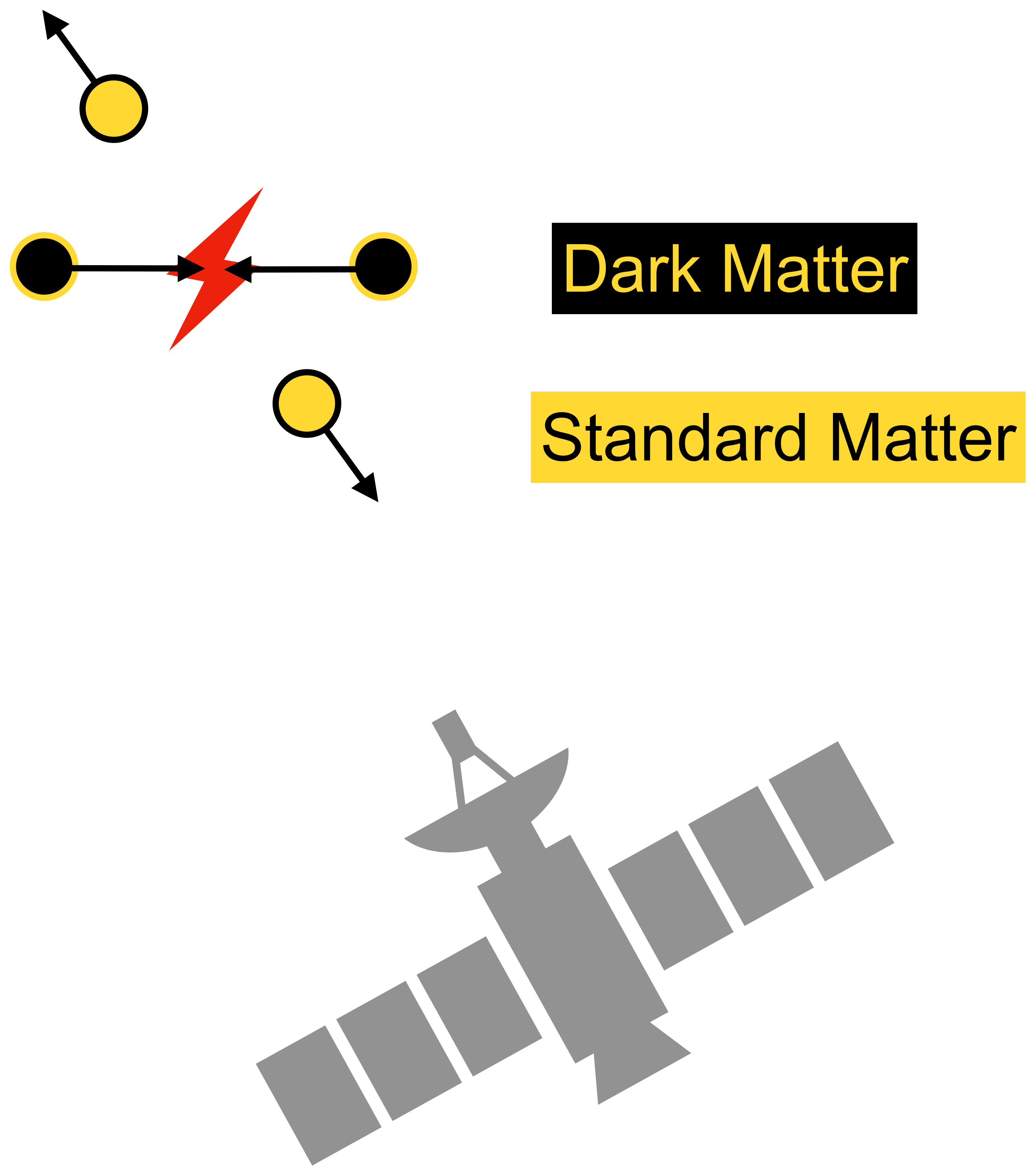
Direct detection limits

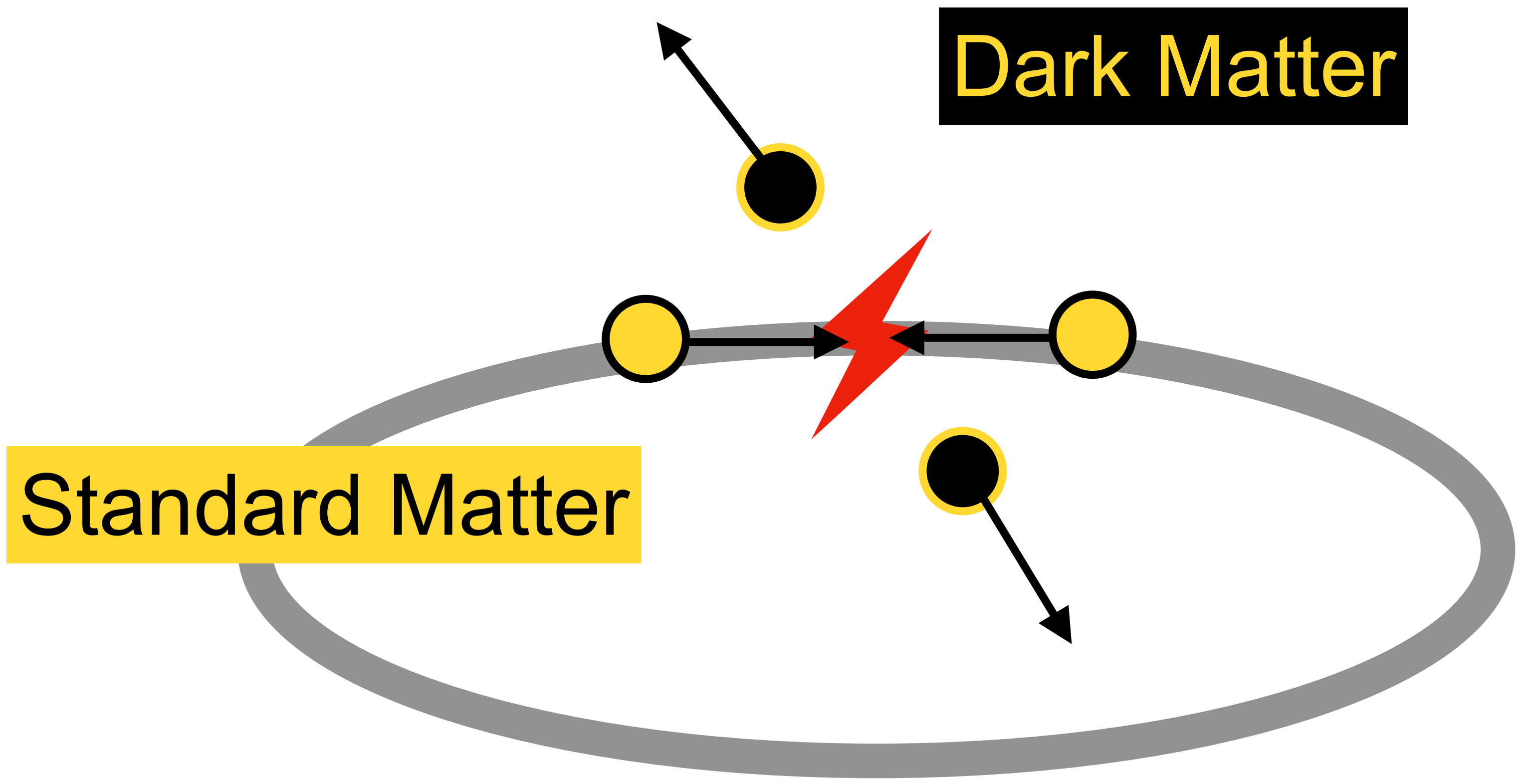


APPEC Committee Report 2021, arXiv:2104.07634 [hep-ex]

How to detect the WIMP







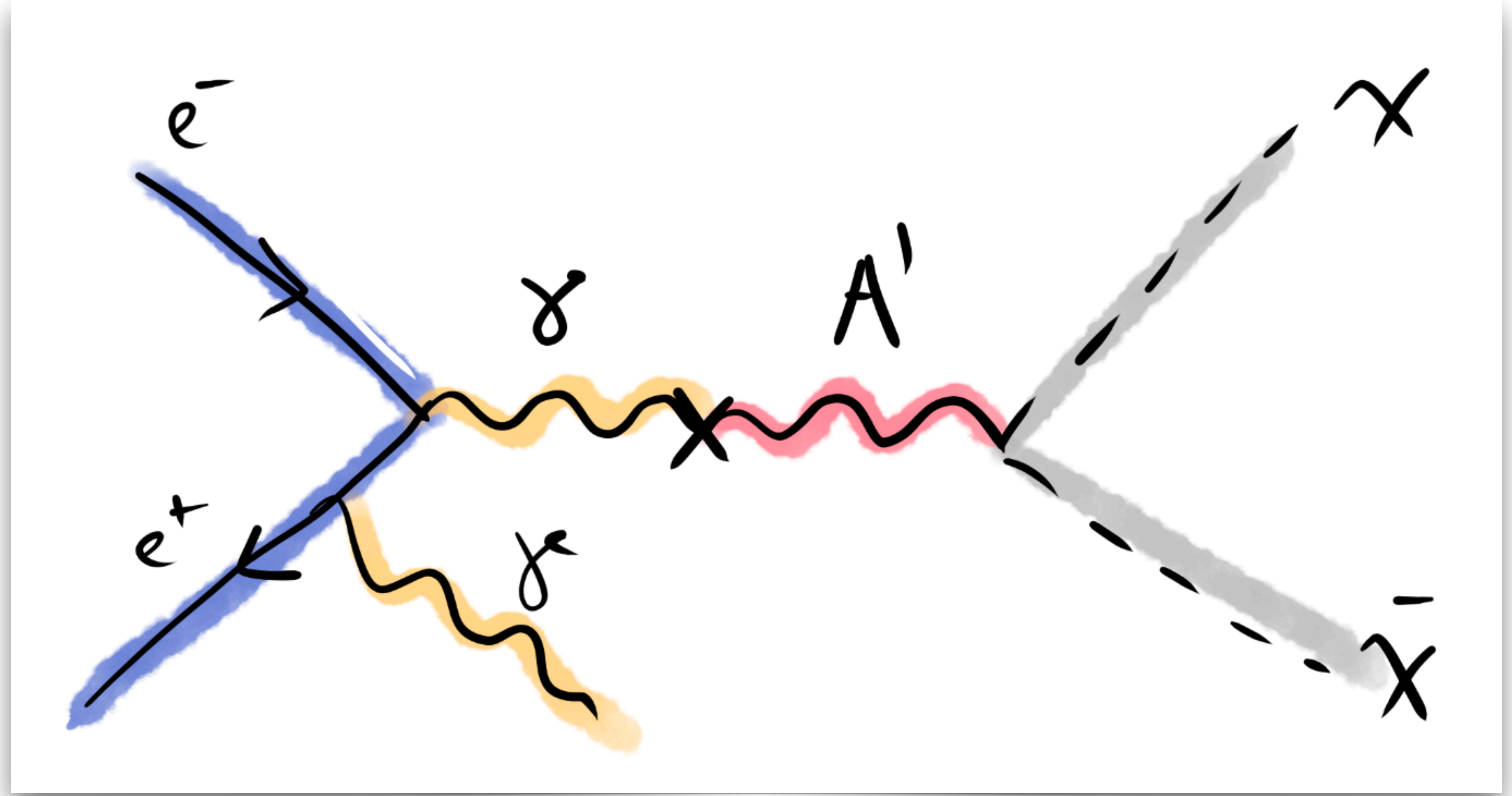
Dark Matter at colliders

- By definition: At colliders we may find new particles that are suitable DM candidates, but the actual DM discovery must come from direct or indirect detection
- There must be some interaction with the SM:
  - Via (new) Higgs bosons
  - Via Z-bosons
  - Via dark photons
  - Via axion-like particles
  - …
- If the DM mass is (much) lighter than the EW scale, typically around 5 GeV, new mediators are needed to provide the correct relic density: “Light Dark Matter” (LDM) instead of WIMPs

Possible BSM model: Dark Photons decaying to DM

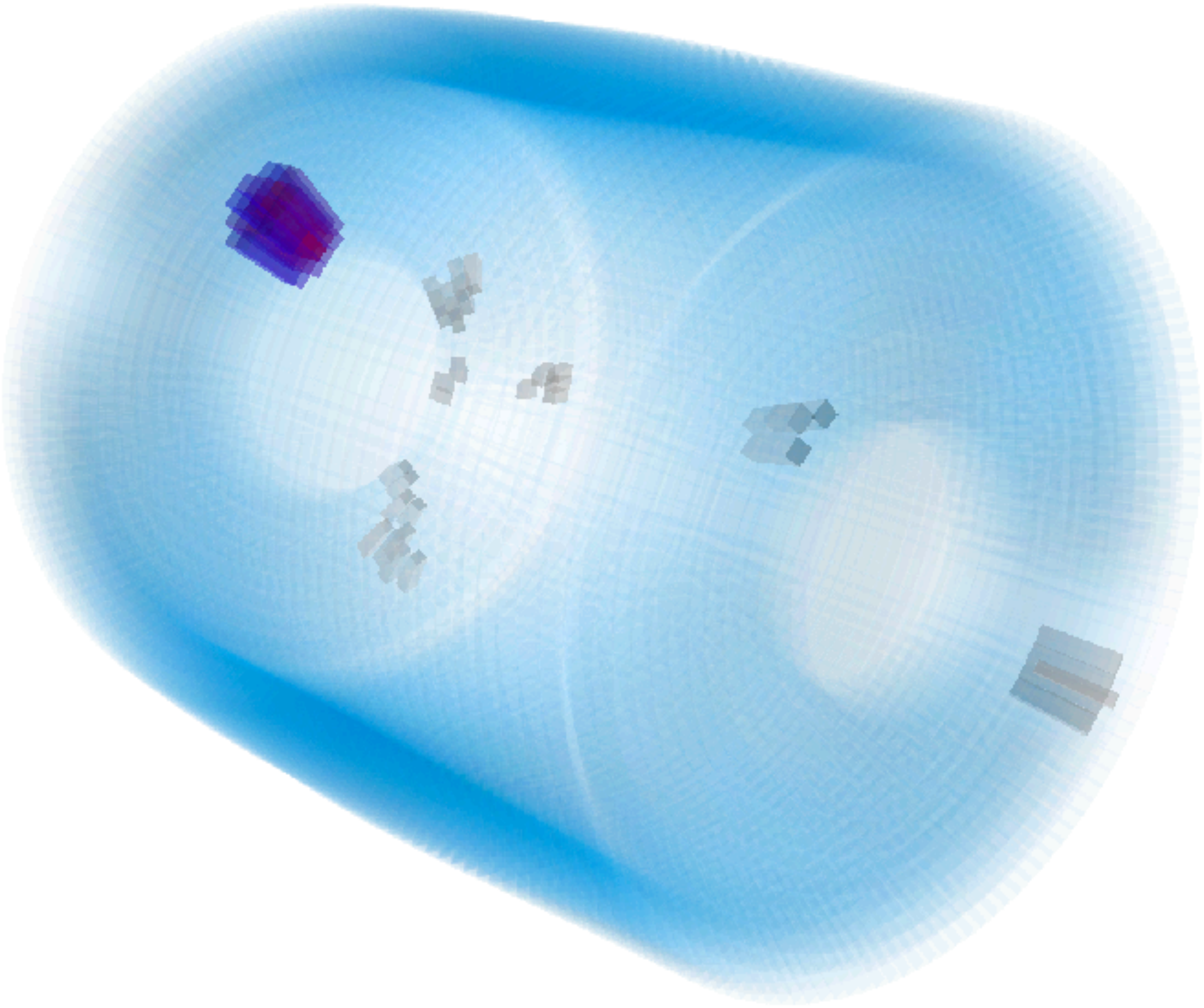
- Search for a single photon with unknown, but fixed energy an e^+e^- colliders:
  - initial electron and positron energy are known
  - Dark Photon mass is unknown
- Standard models backgrounds:
  - $ee \to Z\gamma(Z \to \nu\bar{\nu})$
  - $ee \to ee\gamma$ (miss both electrons)
  - $ee \to \gamma\gamma$ (miss one photon)

Vector portal (F is the dark photon field which couples to the hypercharge field B)	$-\dfrac{\epsilon}{2\cos(\theta_W)}F'_{\mu\nu}B^{\mu\nu}$

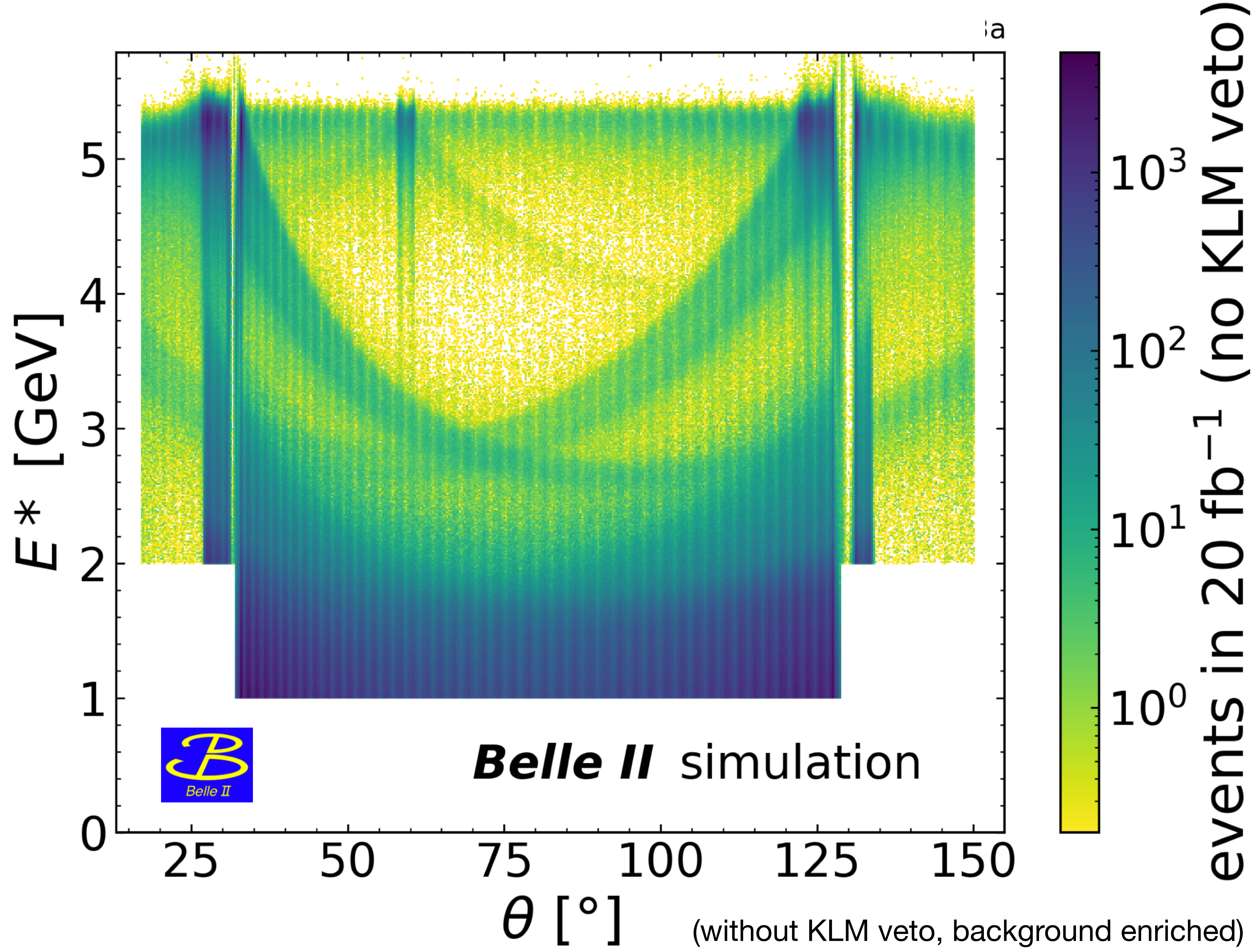


$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

Possible BSM model: Dark Photons at Belle II



Possible BSM model: Dark Photons at Belle II



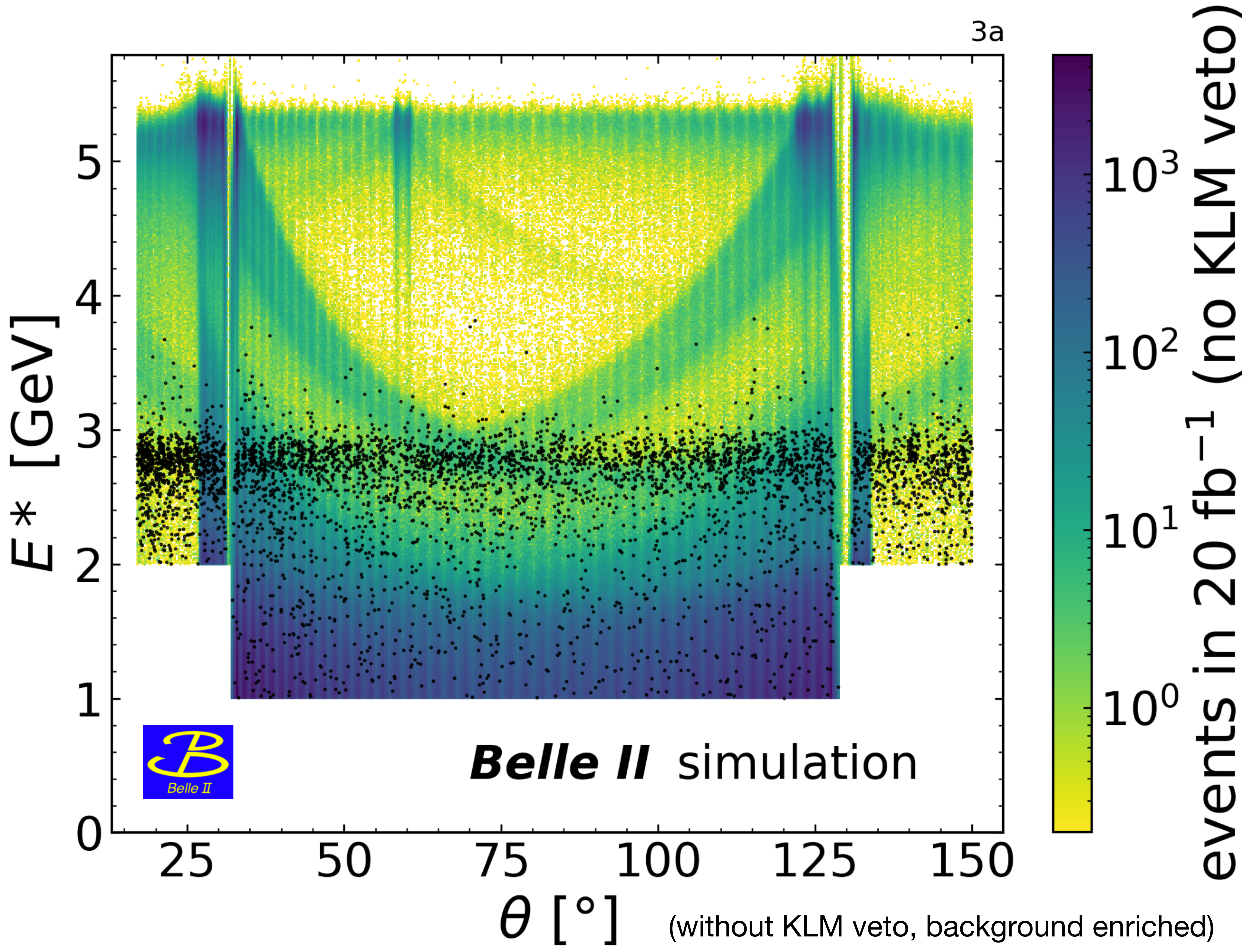
(without KLM veto, background enriched)

Possible BSM model: Dark Photons at Belle II

Simulated signal M=7.2 GeV/c²

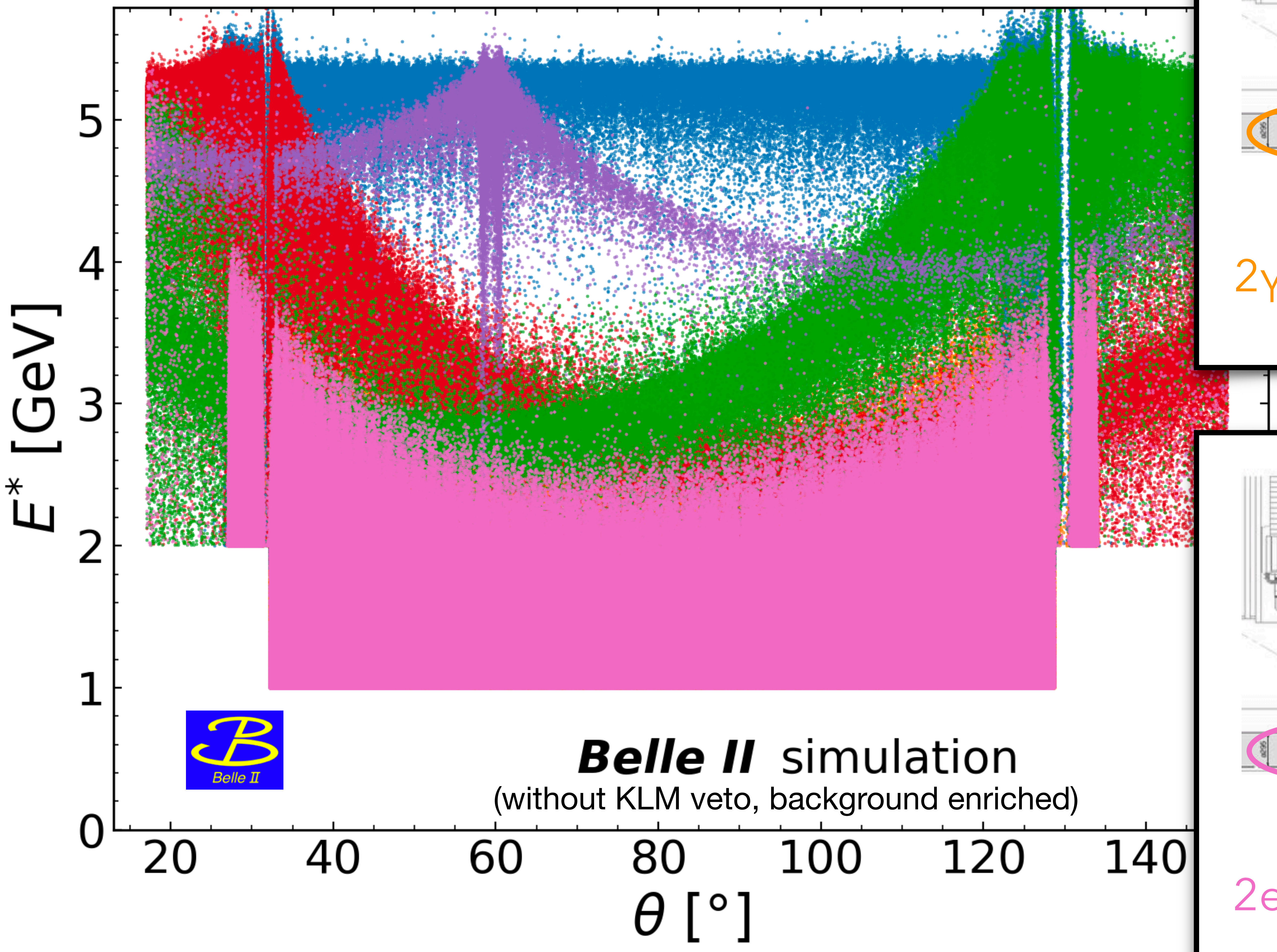
$$E^*_\gamma = \frac{s - M_X^2}{2\sqrt{s}}$$

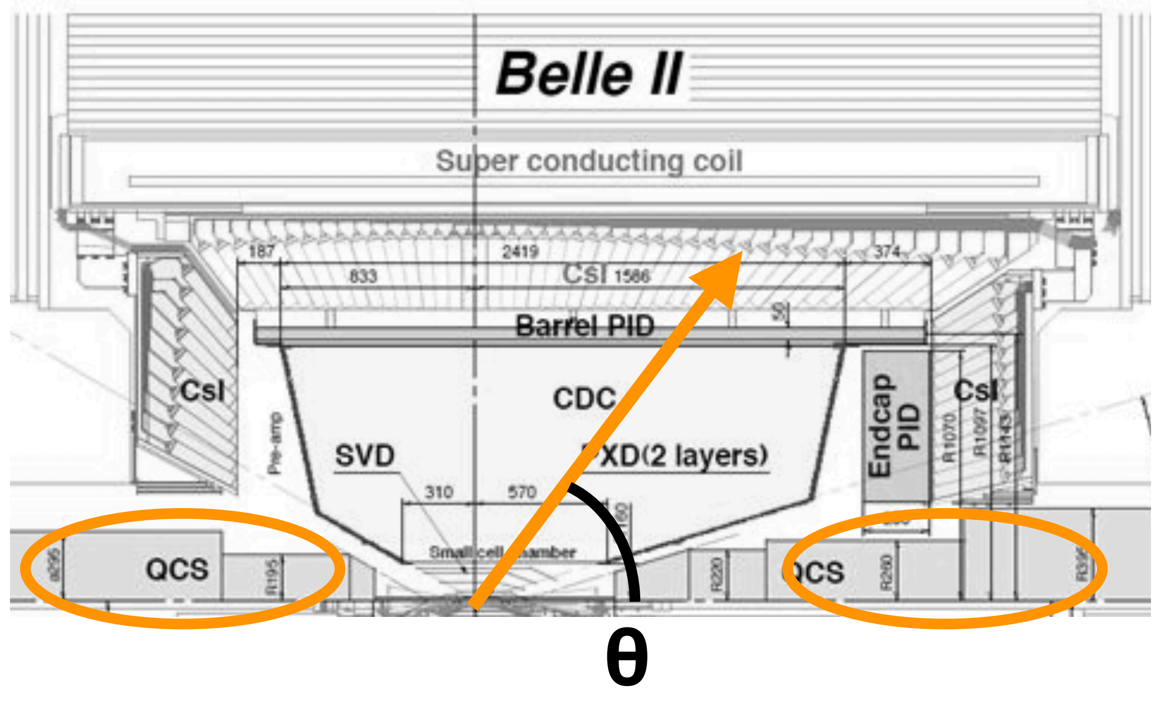
$\sqrt{s} = 10.58\,\mathrm{GeV/c^2}$



(without KLM veto, background enriched)

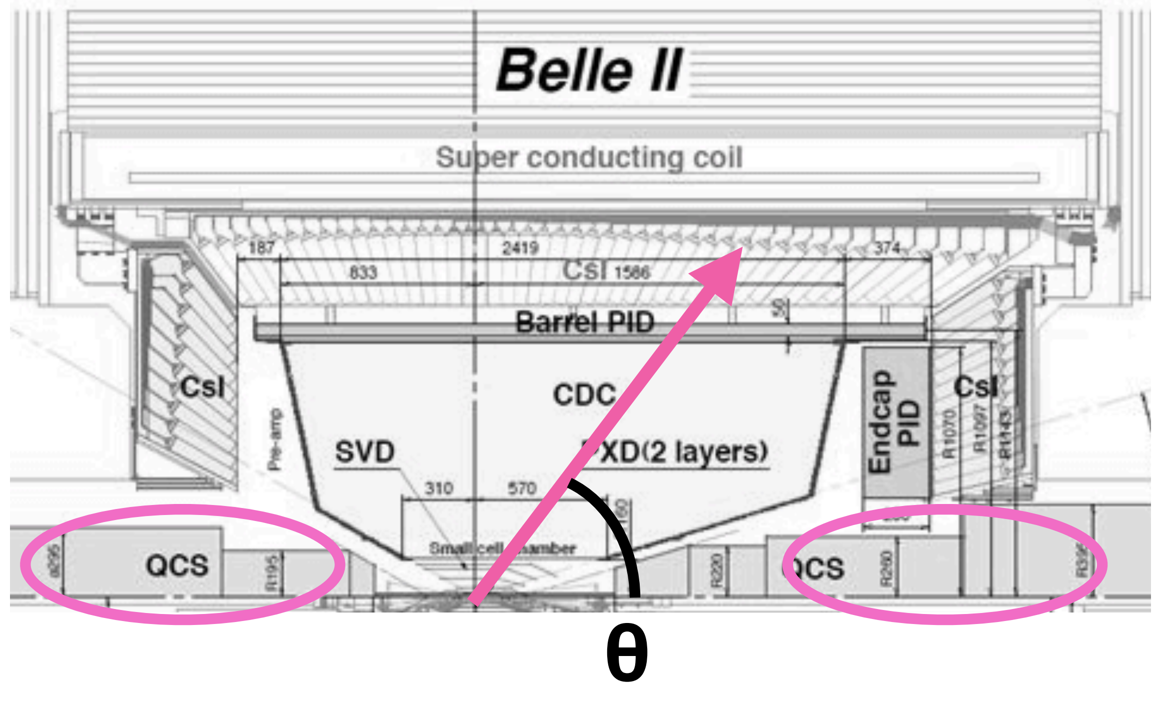
Possible BSM model: Dark Photons at Belle II





ee→γγγ

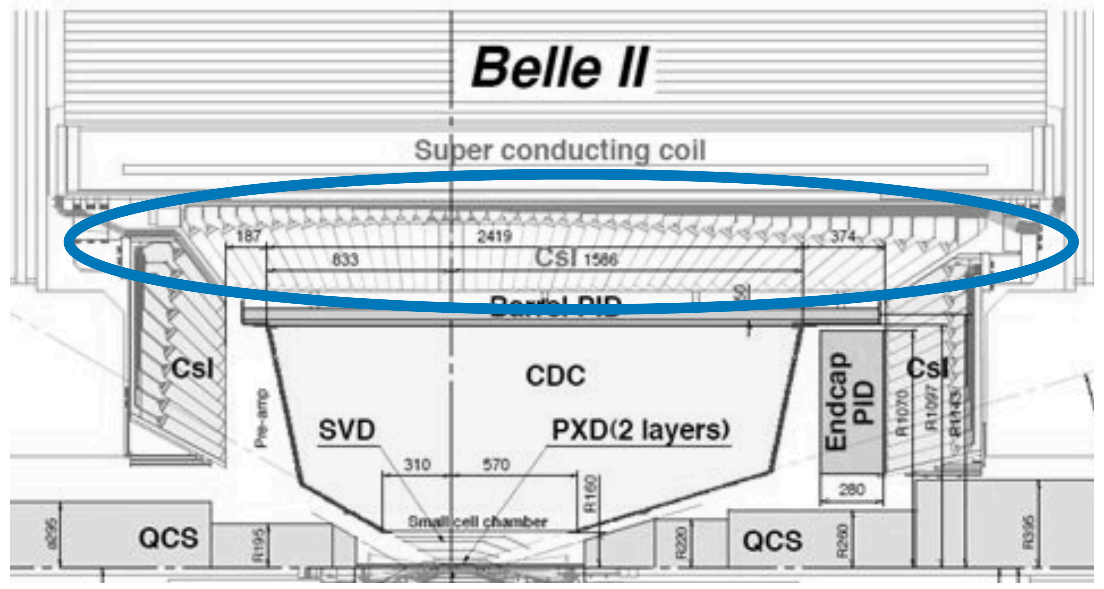
2γ out of ECL acceptance



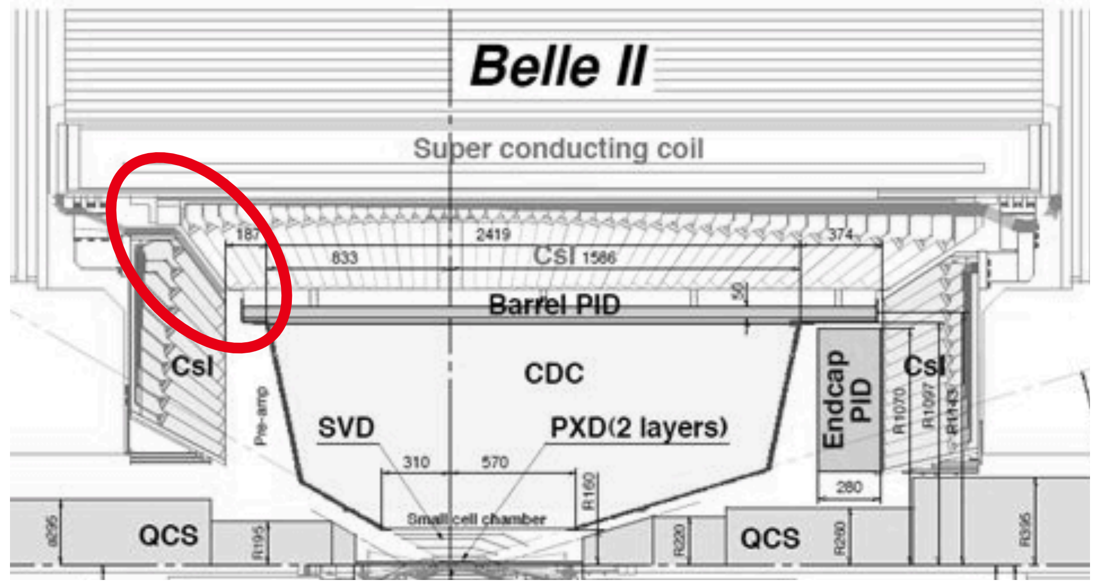
ee→eeγ

2e out of ECL acceptance

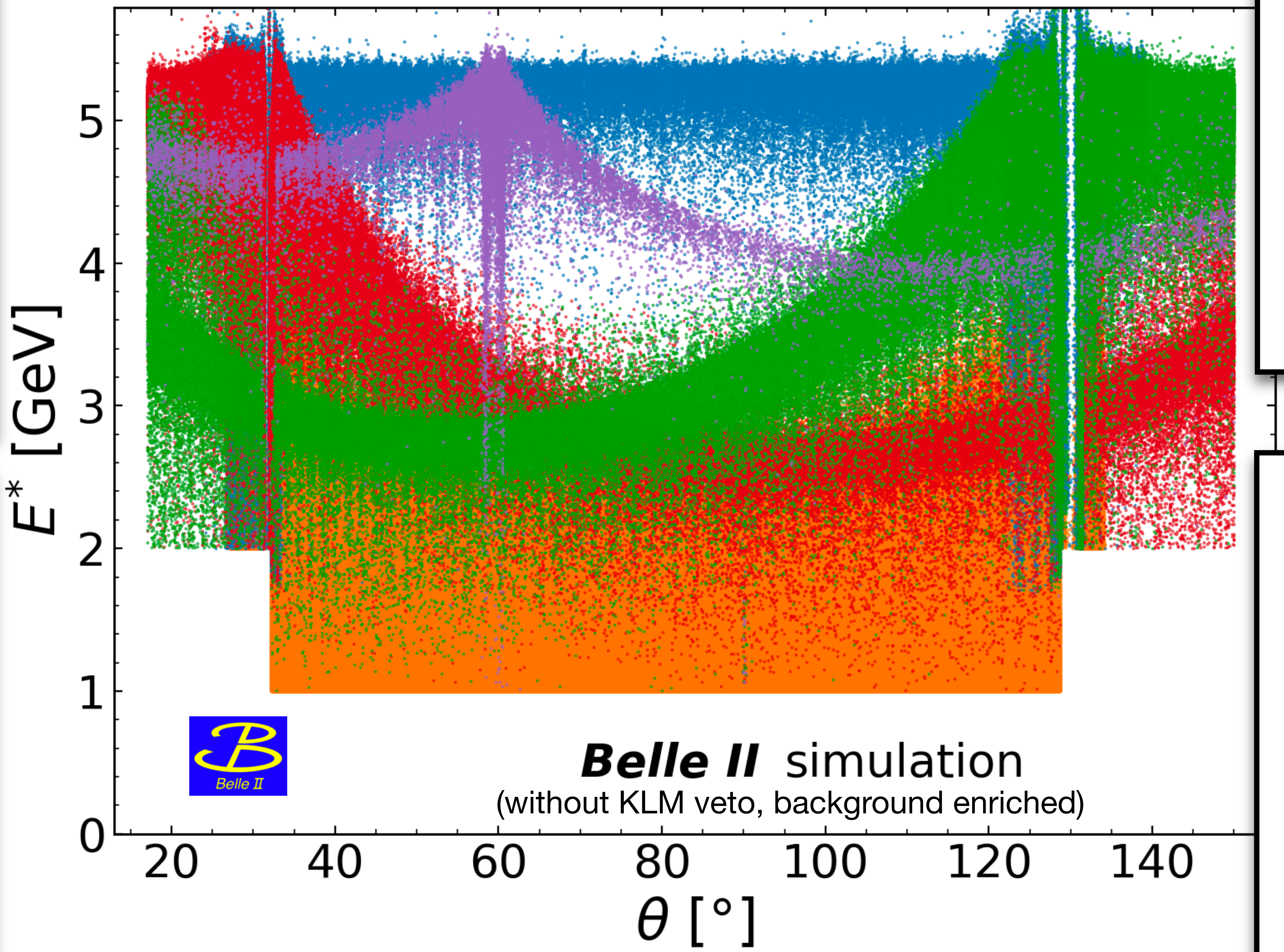
Possible BSM model: Dark Photons at Belle II

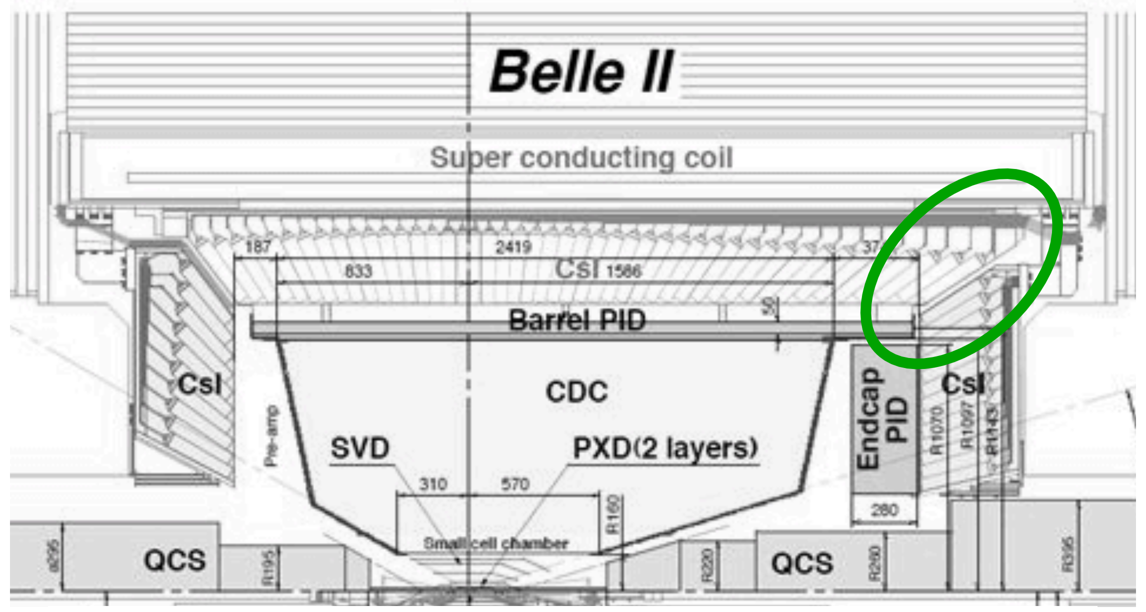


ee→2γ
1γ "punchthrough"

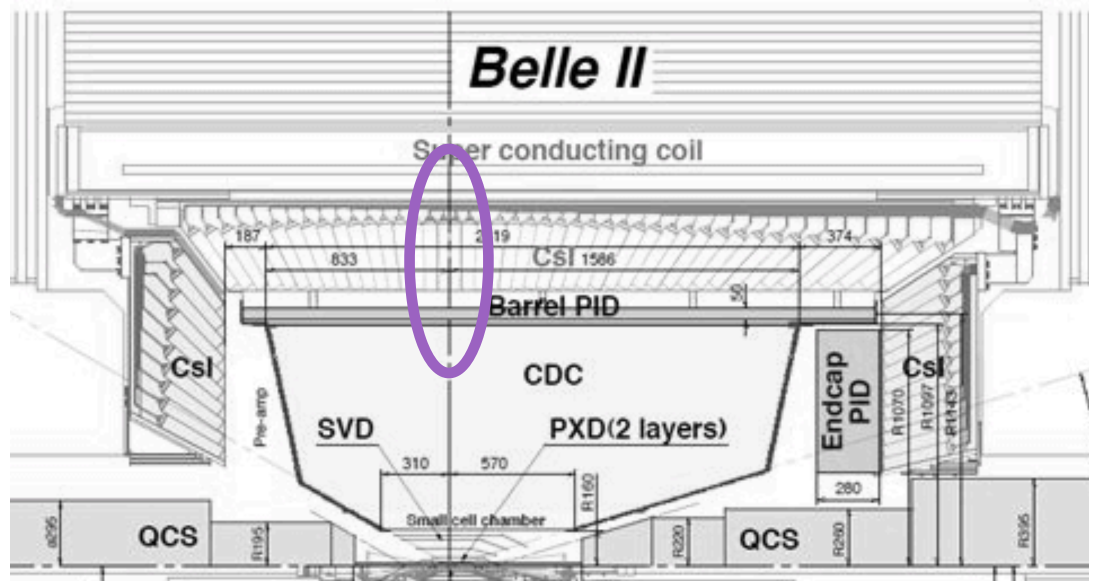


ee→2γ and 3γ
1γ in ECL BWD gap
(1γ out of ECL acceptance)





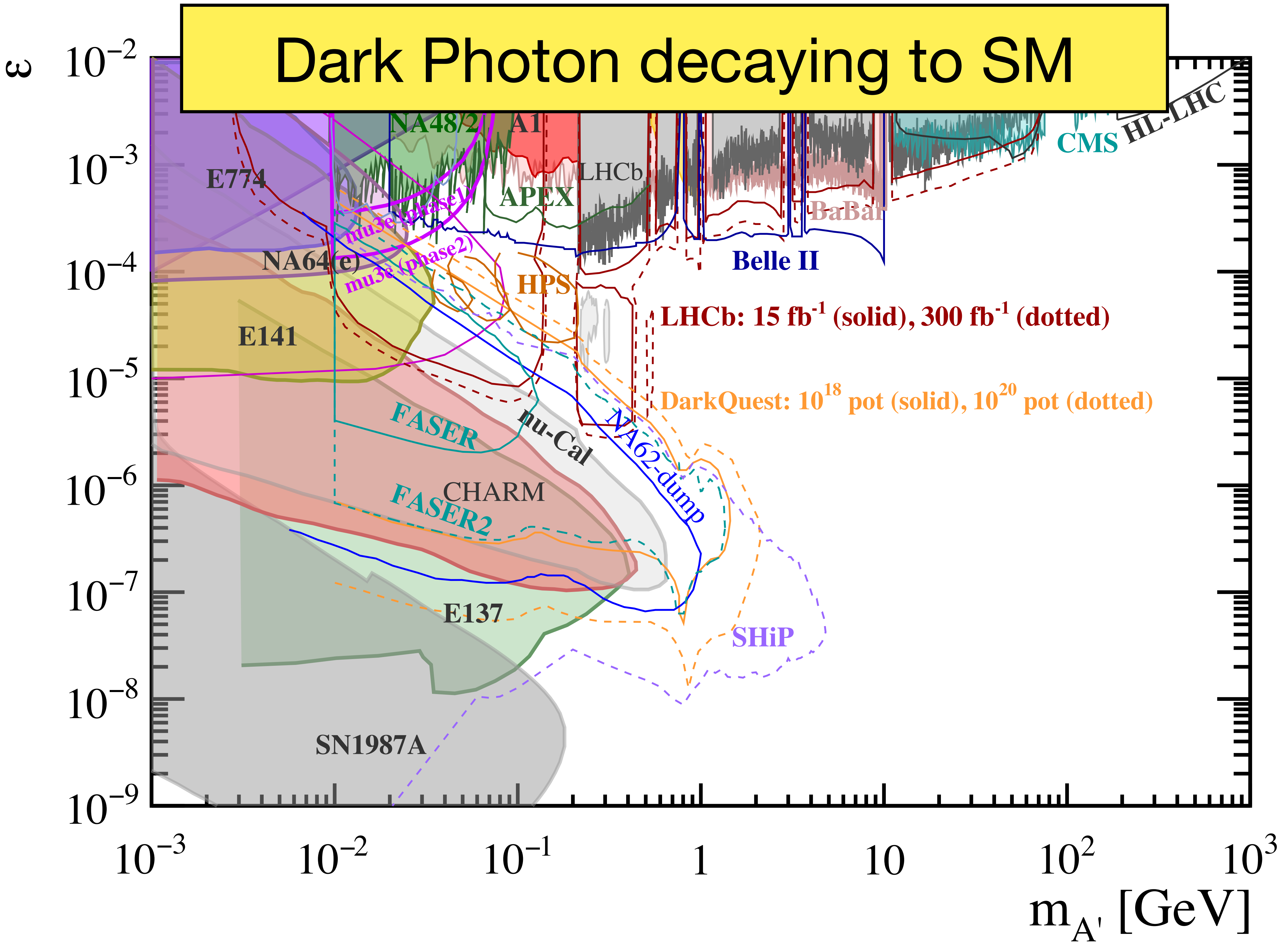
ee→2γ and 3γ
1γ in ECL FWD gap
(1γ out of ECL)acceptance

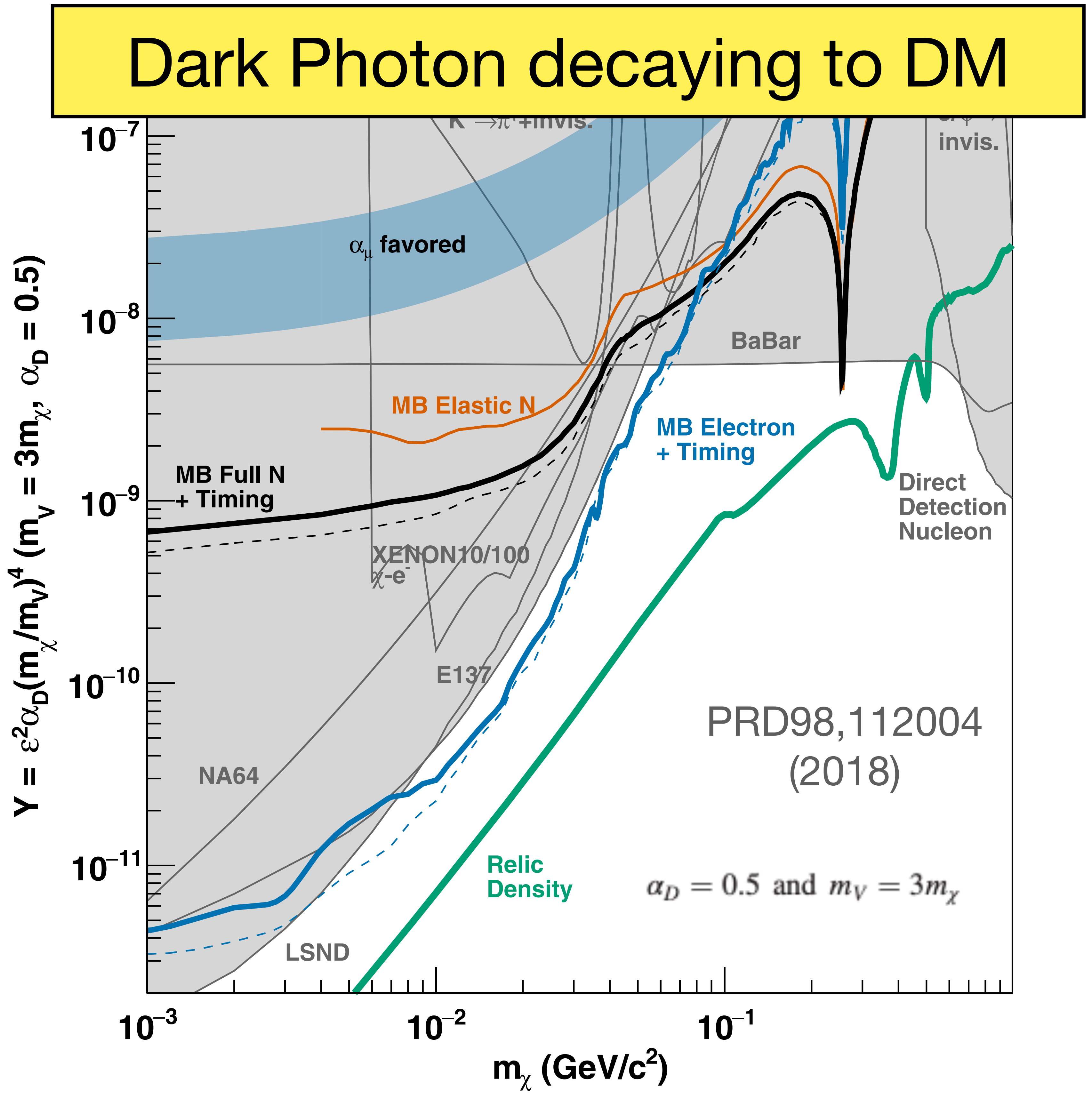


ee→2γ and 3γ
1γ in ECL 90° gap
(1γ out of ECL acceptance)

Light Dark Matter at colliders: Model dependent!

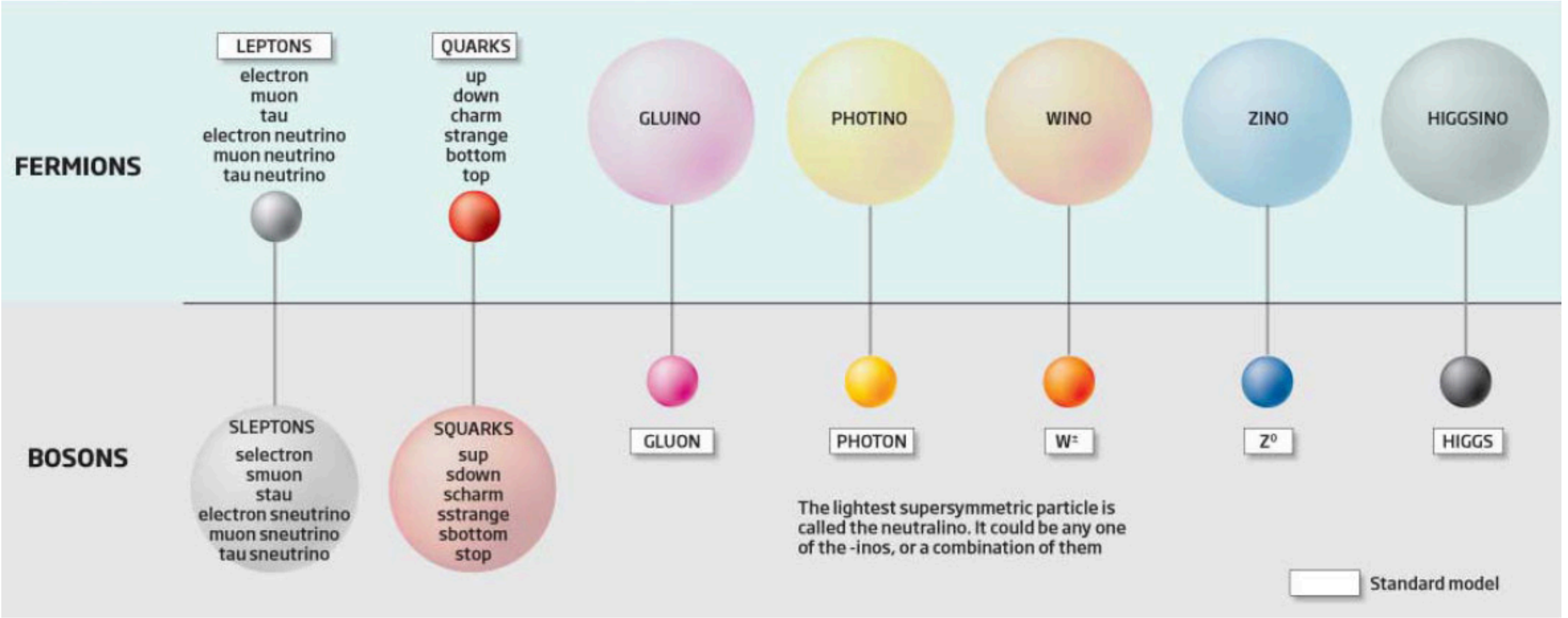
Examples:





Possible BSM model: SUSY

- Generalization of the space-time symmetries of QFT that transforms bosons and fermions and vice versa
- Provides a framework to answer many questions and puzzles in particle physics
- If SUSY were an exact symmetry of nature, particles and superpartners would differ in spin by 1/2 and degenerate in mass.



- Lightest SUSY particle is neutral and stable → DM candidate
- No SUSY particles have been observed at the LHC yet…

Theory problem example: CP violation in QCD

- The Standard Model in principle allows CP violating terms (here for two quarks, see [1]):

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \theta\frac{g^2}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - me^{e\theta'\gamma_5})\psi$$

[1]: https://www.osti.gov/servlets/purl/6260191

Possible BSM model: QCD axions

- Instead of setting θ to (a value very close to) zero, add a term to the Lagrangian that cancels the CP violating second term (Peccei and Quinn):

  $\mathscr{L} \propto -\frac{a}{f_a} G^a_{\mu\nu} G^{a\mu\nu}$ where a(x) is a new Pseudoscalar field that couples to the SM gluons with coupling strength $\frac{1}{f_a}$.

- Low-energy QCD effects generates an effective mass of the new particle: The Axion.

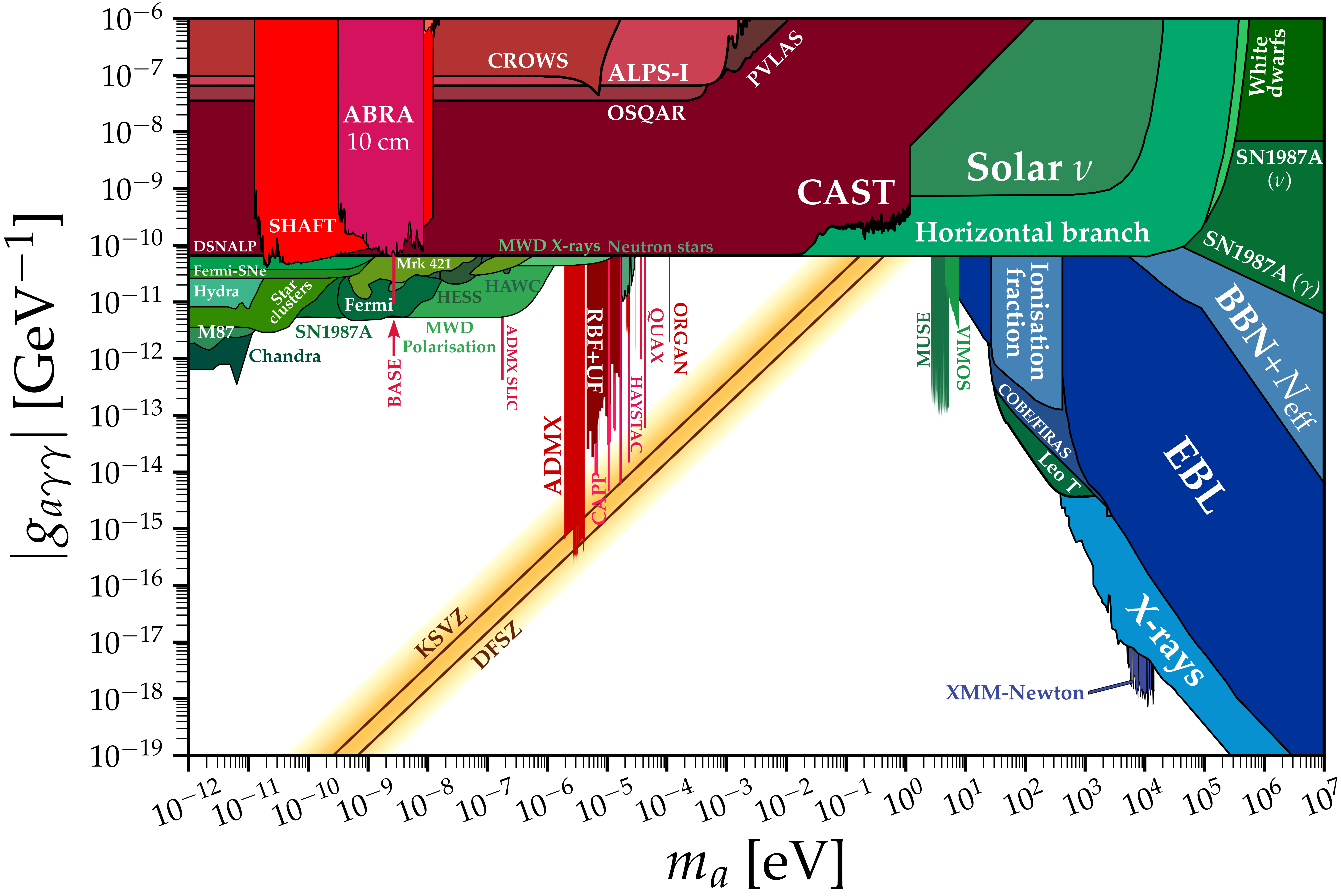
- In order to have exact cancellation (and hence no CP violation in QCD), there is a relation between axion mass and coupling: $m_a \approx \left(\frac{10^7\,\mathrm{GeV}}{f_a}\right)\mathrm{eV}$

Possible BSM model: QCD axions

- The simplest PQ axion is experimentally long ruled out, but with some modifications, variants of the "original" axion go under the name of e.g. "Kim-Shifman-Vainstein-Zakharov (KSVZ)" axion
- In general the axion couples to all bosons of the Standard Model and hence also to the massless photons [1]
- The lifetime of very light axion ($\lesssim$10 eV) however is longer than the lifetime of the universe and hence they are an **excellent dark matter** candidate (but unlike WIMPs they are not in thermal equilibrium)!

[1] https://arxiv.org/abs/0807.3125

Possible BSM model: QCD axions



Picture: https://github.com/cajohare/AxionLimits

Possible BSM models

- Extra dimensions
- String theory
- Supersymmetry (SUSY)
- Compositeness
- Leptoquarks
- Technicolor
- Magnetic monopoles
- W’, Z’, …
- Axions
- Dark Matter particles
- Modified gravity
- …

Possible strategies

- Model dependent searches
- EFTs
- Global fits
- Model independent anomaly detection
- Precision physics (low energy)
- New colliders
- New beam dump experiments
- …

What questions do you have?