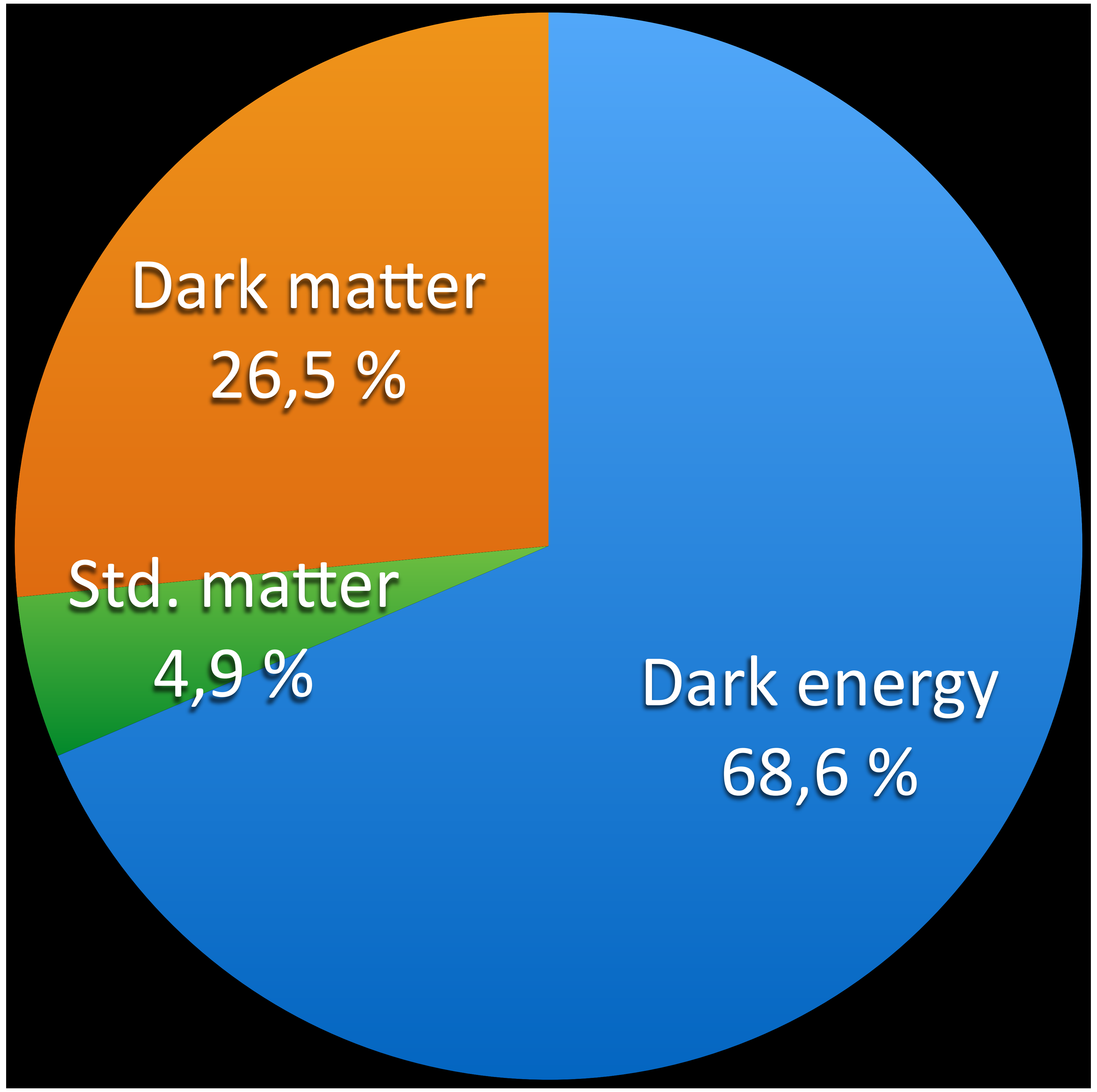
Třetí miniworkshop difrakce a ultraperiferálních srážek

An introduction to dark matter

Guillermo Contreras
Czech Technical University in Prague

Děčín
September 14, 2020

The current energy budget of the universe



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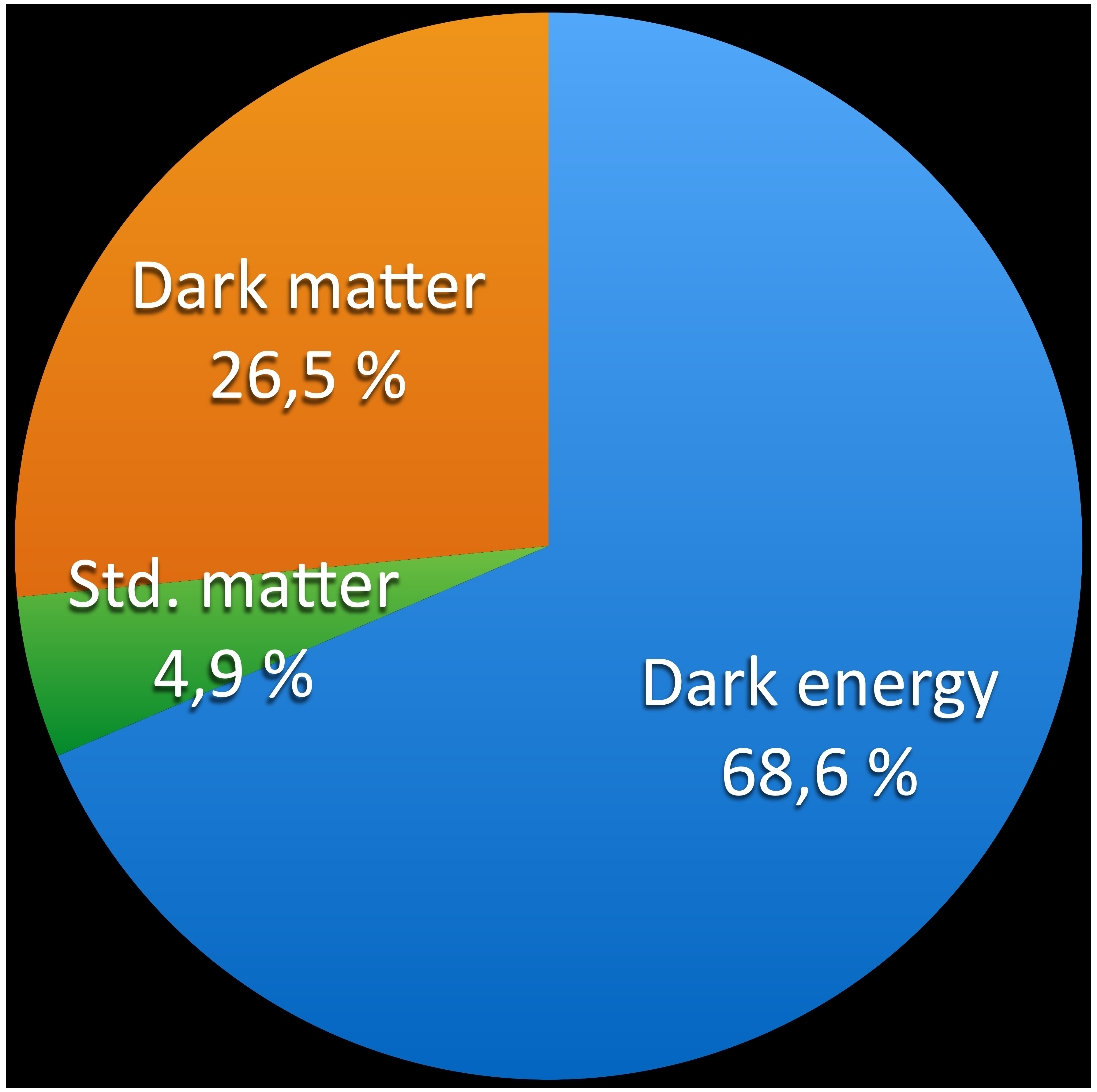
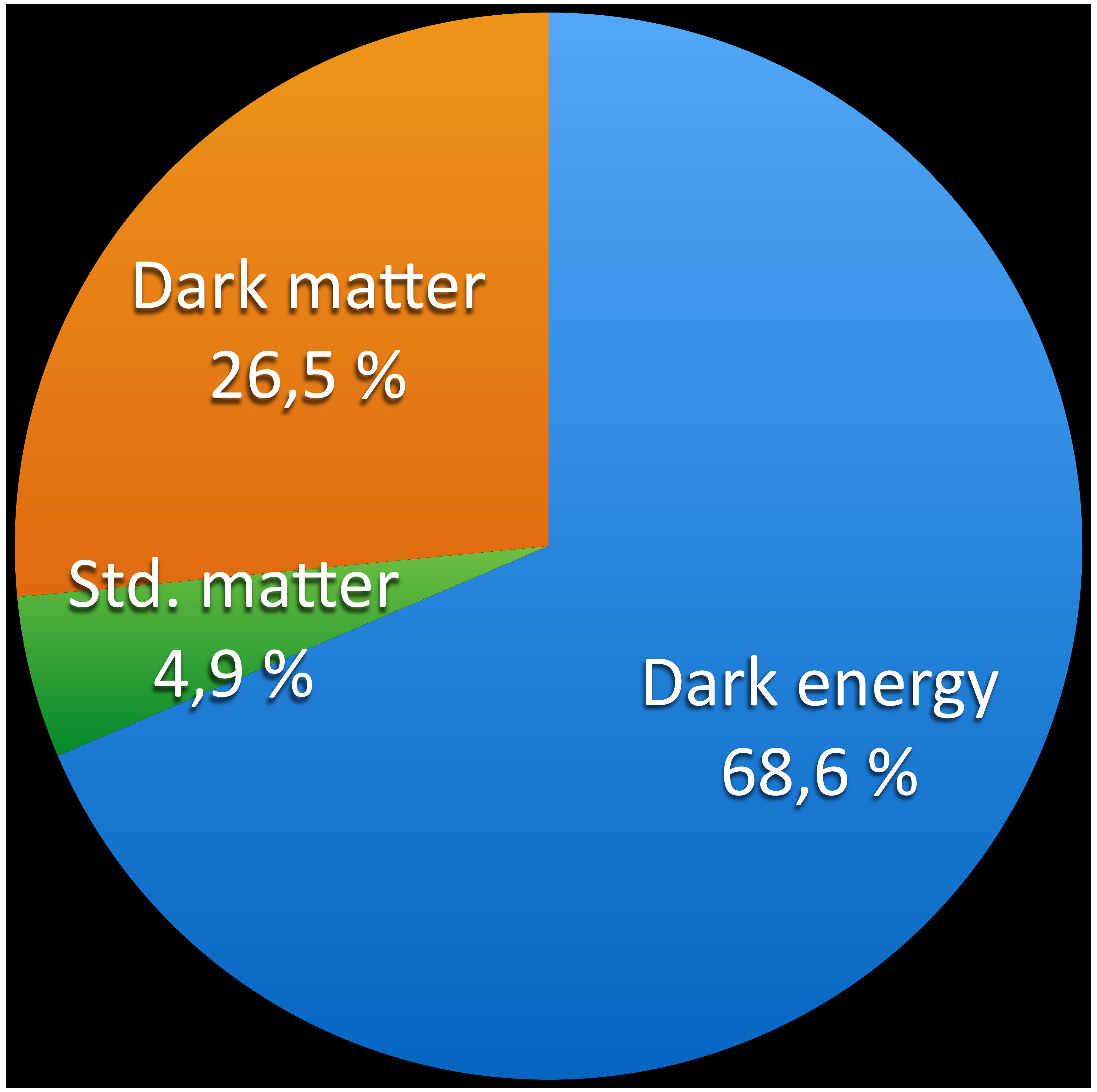


All of what we know off:
quarks, leptons, radiation, …
people, stars, …

The current energy budget of the universe

You are a very fine person, Mr. Baggins, and I am very fond of you; but you are only quite a little fellow in a wide world after all!

Gandalf in The Hobbit (J. R. R. Tolkien)



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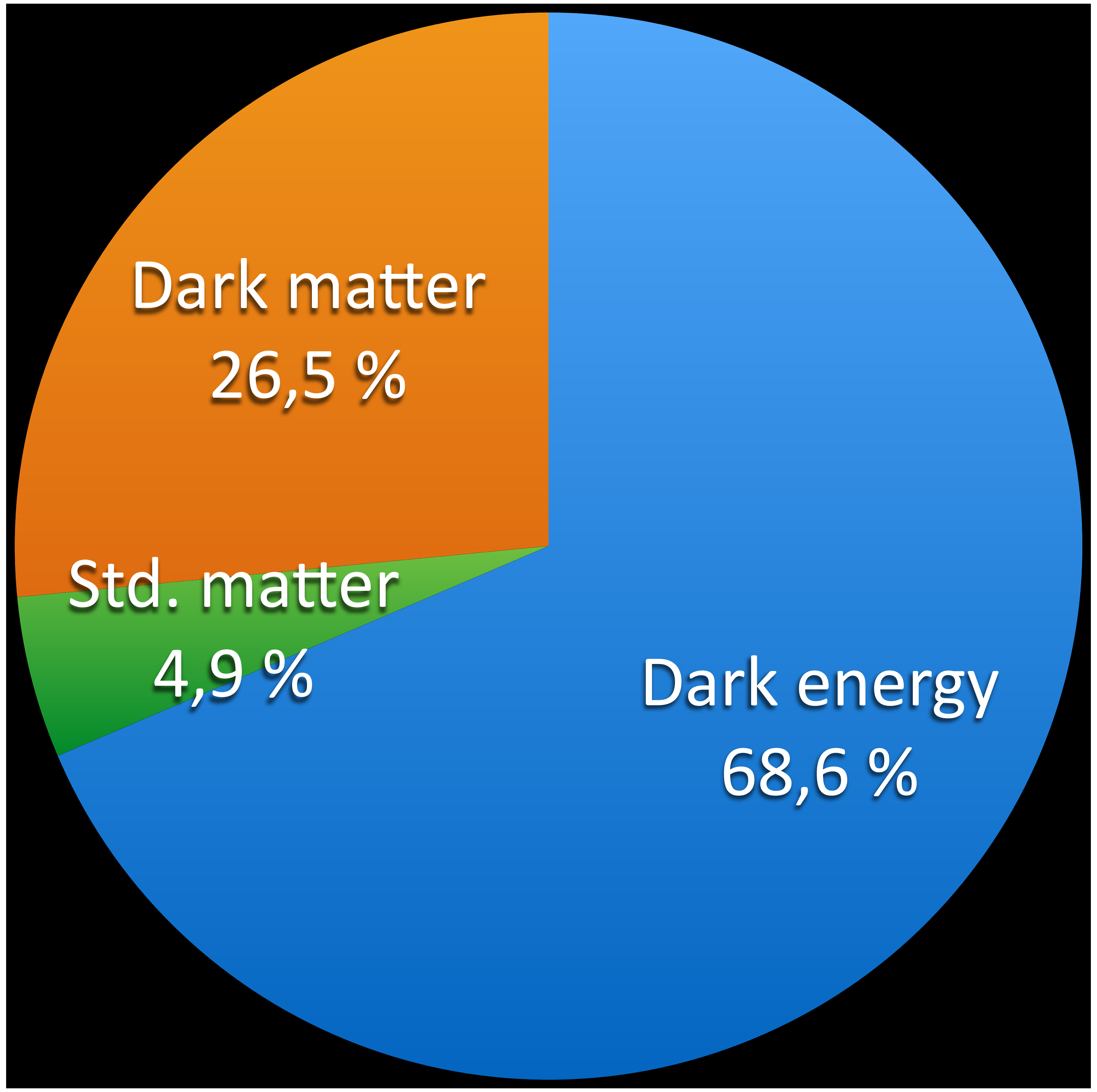
Today, we want to talk about this



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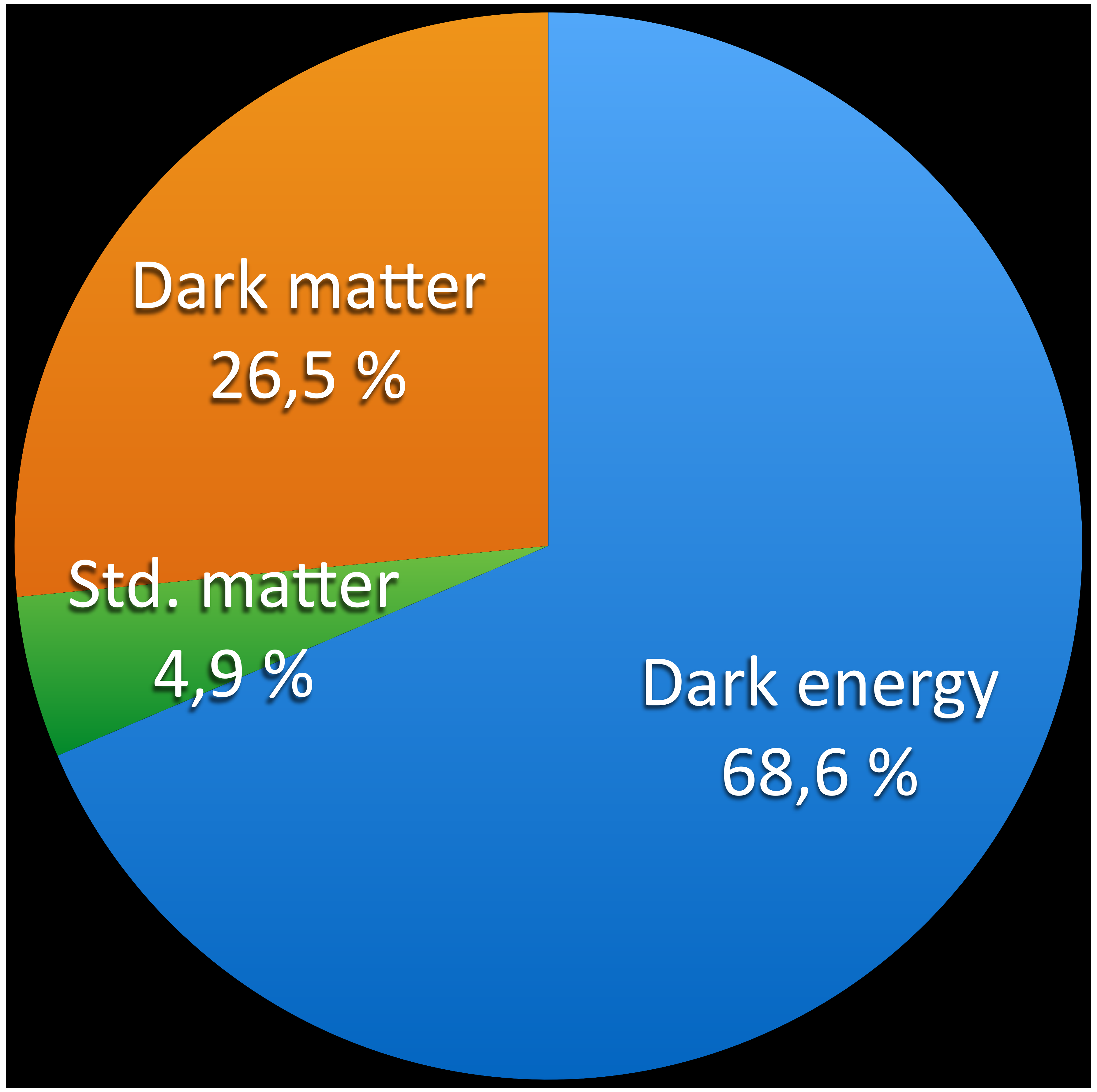
The current energy budget of the universe: main assumptions



Based on applications of gravity to astrophysical scales
(larger than 10 Mpc≈3 M light years≈ 3×10^{24} cm)

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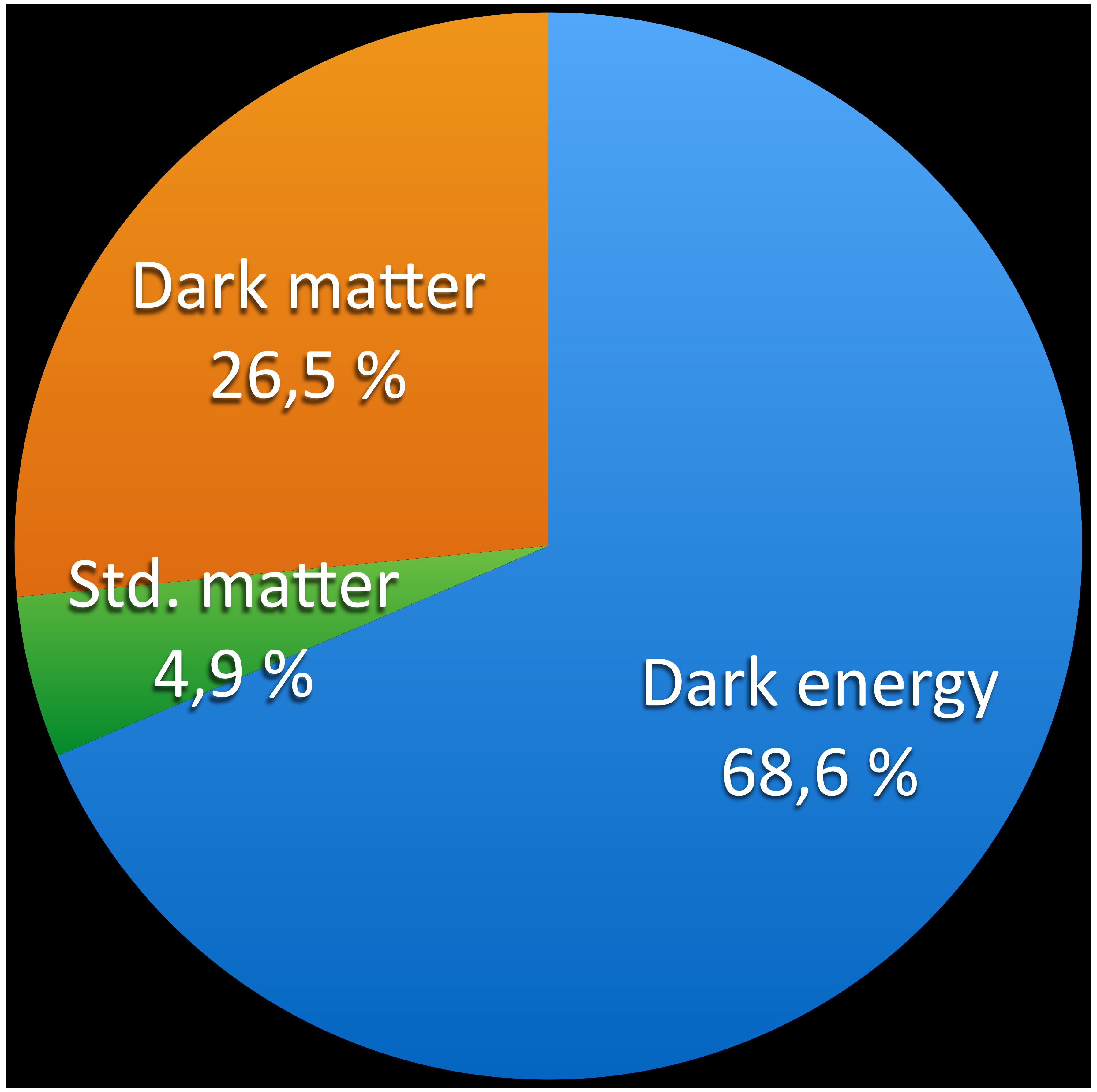

Based on applications of gravity to astrophysical scales (larger than 10 Mpc≈3 M light years≈ $3x10^{24}$ cm)

Assumes that all is ok with our use of gravity to build the cosmological model and assuming that all is ok with the related measurements

Do we understand gravity?

Gravity has been tested down to the mm scale, but there is no guarantee that it is still valid at smaller and smaller scales

Do we understand gravity?

https://inspirehep.net/literature/198135

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For example, MOND (modified Newtonian dynamics) postulates a 2nd law:
$F=ma^2/a_0$
in the limit of very low accelerations
($a \ll a_0 \approx 1.2 \times 10^{-10}$ m/s^2)

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

M. MILGROM
Department of Physics, The Weizmann Institute of Science, Rehovot, Israel; and
The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I consider the possibility that there is not, in fact, much hidden mass in galaxies and galaxy systems. If a certain modified version of the Newtonian dynamics is used to describe the motion of bodies in a gravitational field (of a galaxy, say), the observational results are reproduced with no need to assume hidden mass in appreciable quantities. Various characteristics of galaxies result with no further assumptions.

In the basis of the modification is the assumption that in the limit of small acceleration $a \ll a_0$, the acceleration of a particle at distance r from a mass M satisfies approximately $a^2/a_0 \approx MGr^{-2}$, where a_0 is a constant of the dimensions of an acceleration.

A success of this modified dynamics in explaining the data may be interpreted as implying a need to change the law of inertia in the limit of small accelerations or a more limited change of gravity alone.

I discuss various observational constraints on possible theories for the modified dynamics from data which exist already and suggest other systems which may provide useful constraints.

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The original model has problems with observations, but some of it s modifications are still around ...

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In some theories where gravity is an emergent phenomenon, dark matter is not needed

SciPost SciPost Phys. 2, 016 (2017)

Emergent gravity and the dark universe

Erik Verlinde

Delta-Institute for Theoretical Physics, Institute of Physics, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, The Netherlands

e.p.verlinde@uva.nl

Abstract

To Maria

Recent theoretical progress indicates that spacetime and gravity emerge together from the entanglement structure of an underlying microscopic theory. These ideas are best understood in Anti-de Sitter space, where they rely on the area law for entanglement entropy. The extension to de Sitter space requires taking into account the entropy and temperature associated with the cosmological horizon. Using insights from string theory, black hole physics and quantum information theory we argue that the positive dark energy leads to a thermal volume law contribution to the entropy that overtakes the area law precisely at the cosmological horizon. Due to the competition between area and volume law entanglement the microscopic de Sitter states do not thermalise at sub-Hubble scales: they exhibit memory effects in the form of an entropy displacement caused by matter. The emergent laws of gravity contain an additional ‘dark’ gravitational force describing the ‘elastic’ response due to the entropy displacement. We derive an estimate of the strength of this extra force in terms of the baryonic mass, Newton’s constant and the Hubble acceleration scale $a_0 = cH_0$, and provide evidence for the fact that this additional ‘dark gravity force’ explains the observed phenomena in galaxies and clusters currently attributed to dark matter.

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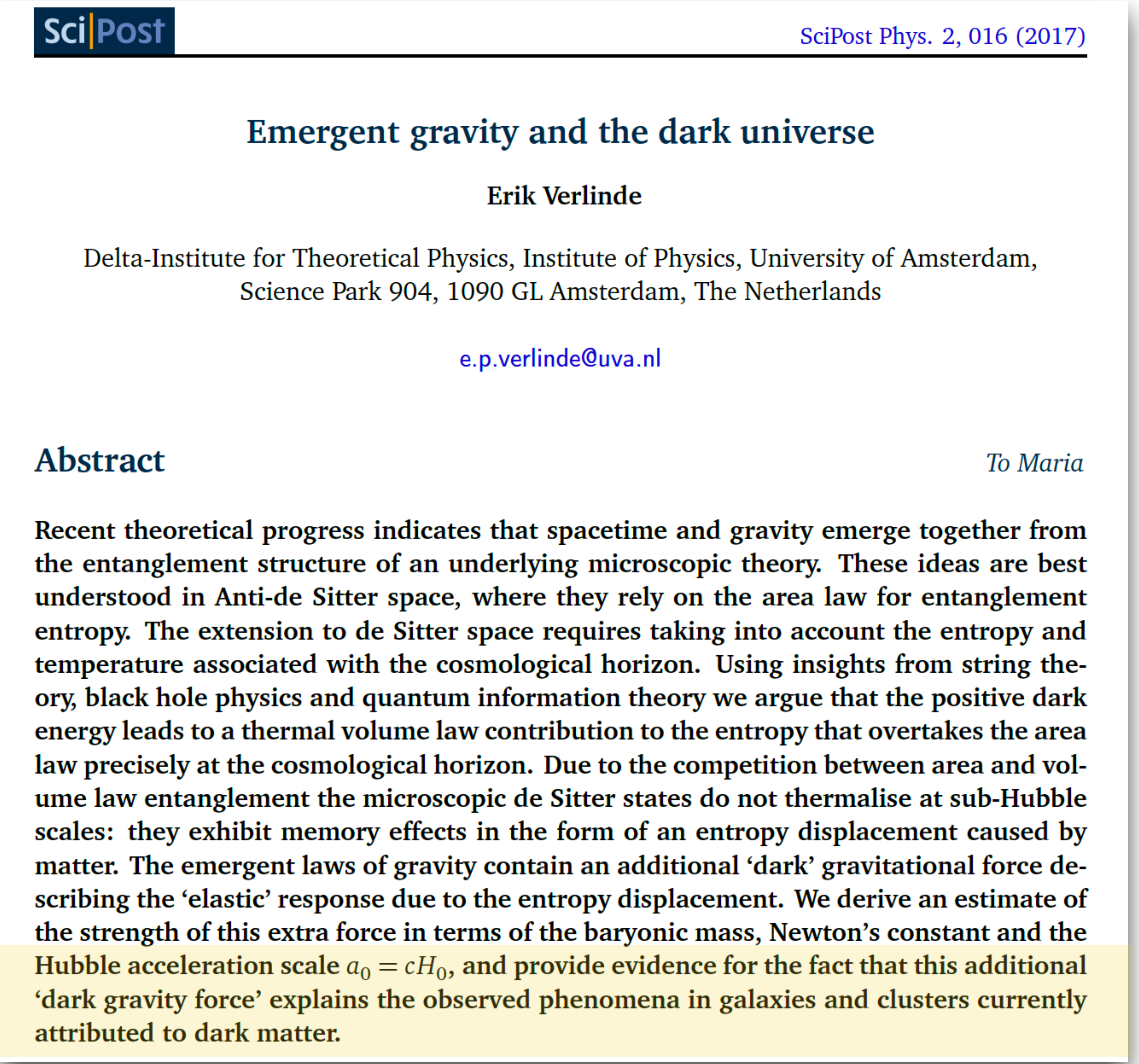

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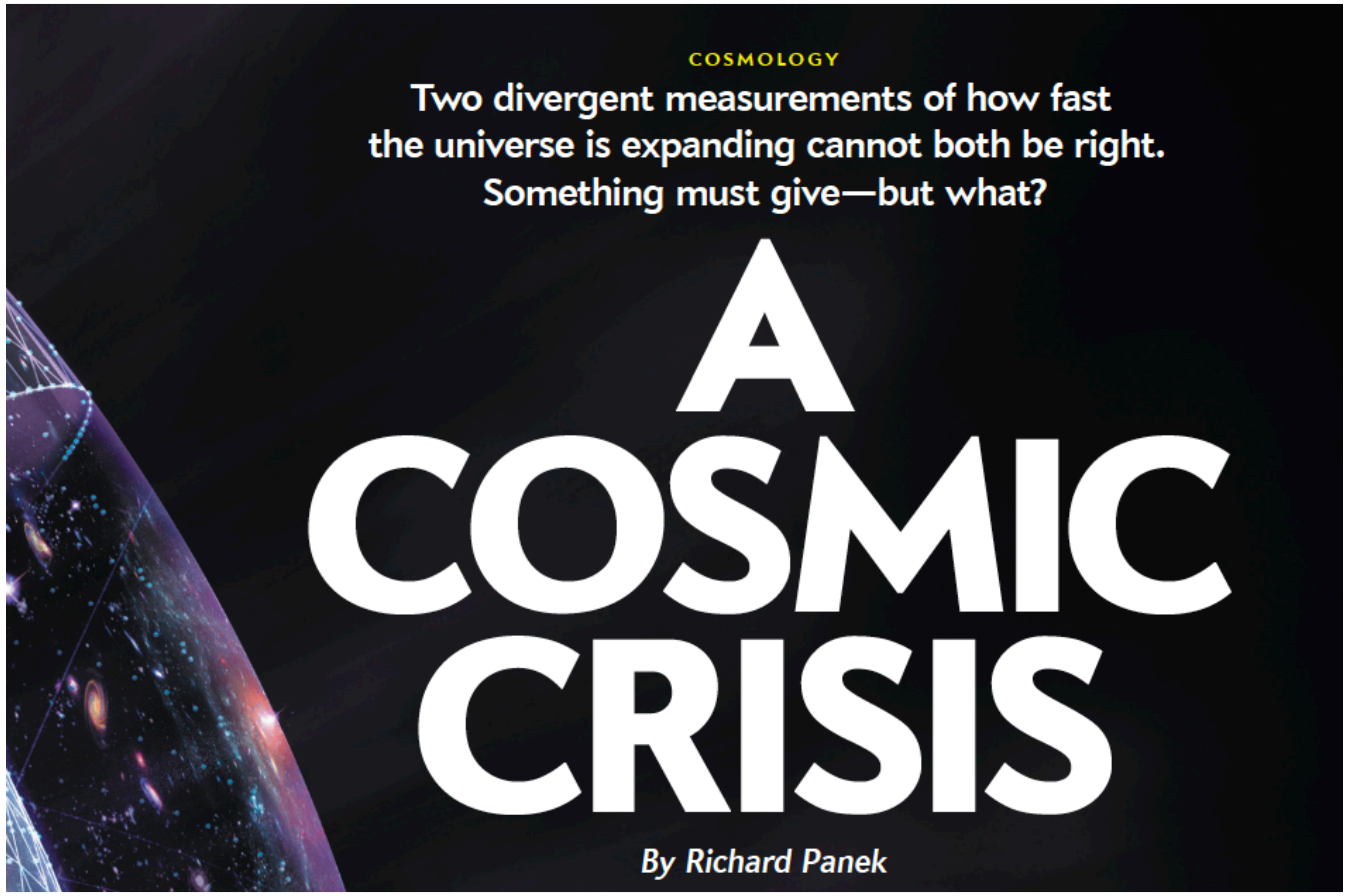
Nice interview with the author at https://cerncourier.com/a/doubting-darkness/

Is everything ok with our cosmology models and measurements?

https://www.scientificamerican.com/article/how-a-dispute-over-a-single-number-became-a-cosmological-crisis/



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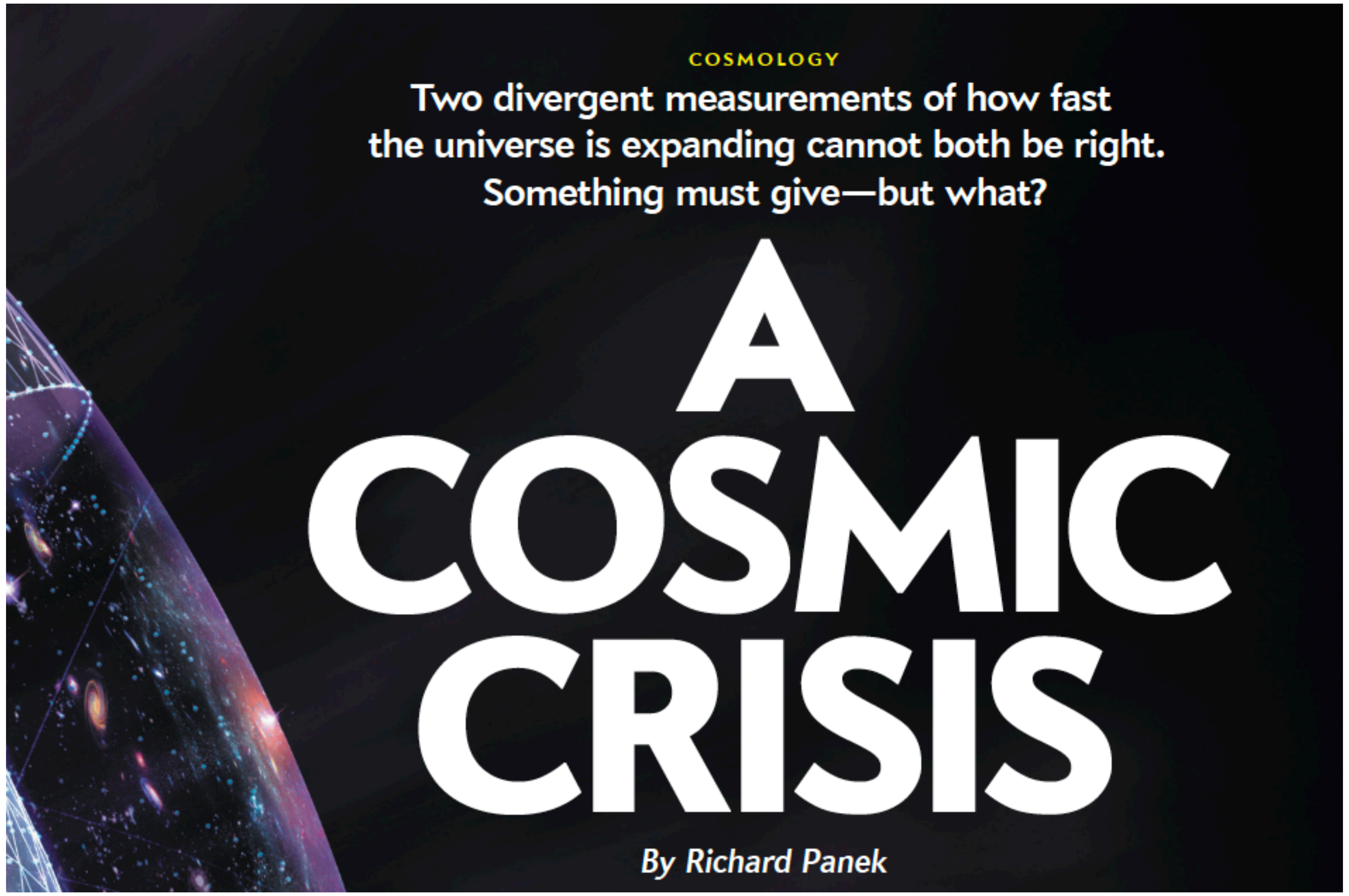
IN BRIEF

Astronomers have repeatedly calculated the rate of the universe's expansion—the Hubble constant—with two different techniques. These measurements have produced a seemingly intractable conflict.

One method, which involves measuring supernovae and stars in the relatively recent universe, arrives at one value. The other strategy, which uses light left over from shortly after the big bang, finds another.

Experimental problems could cause the discrepancy, but no one is sure what those problems would be. Another possibility is that the conflict points to undiscovered phenomena—"new physics."



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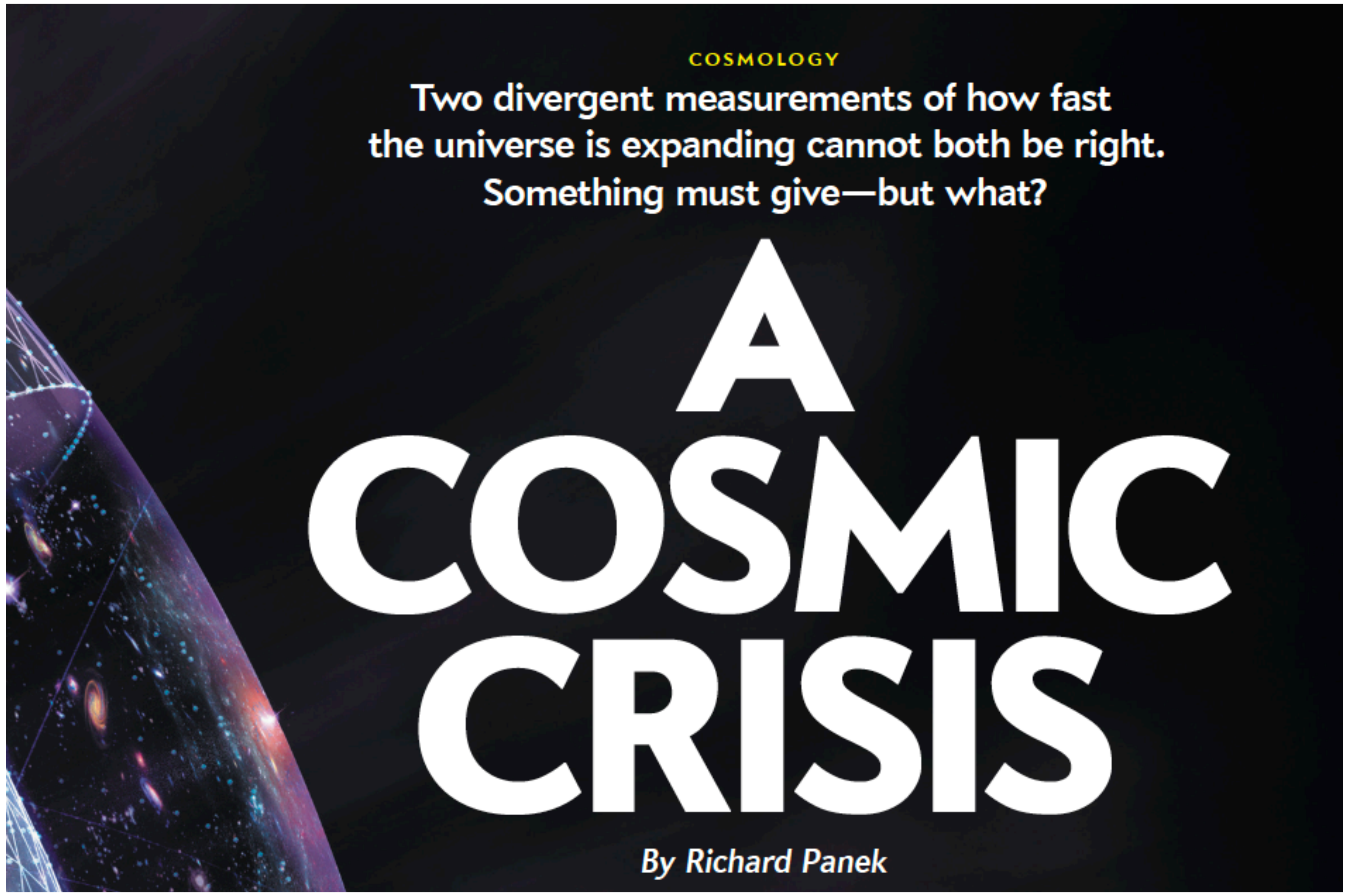

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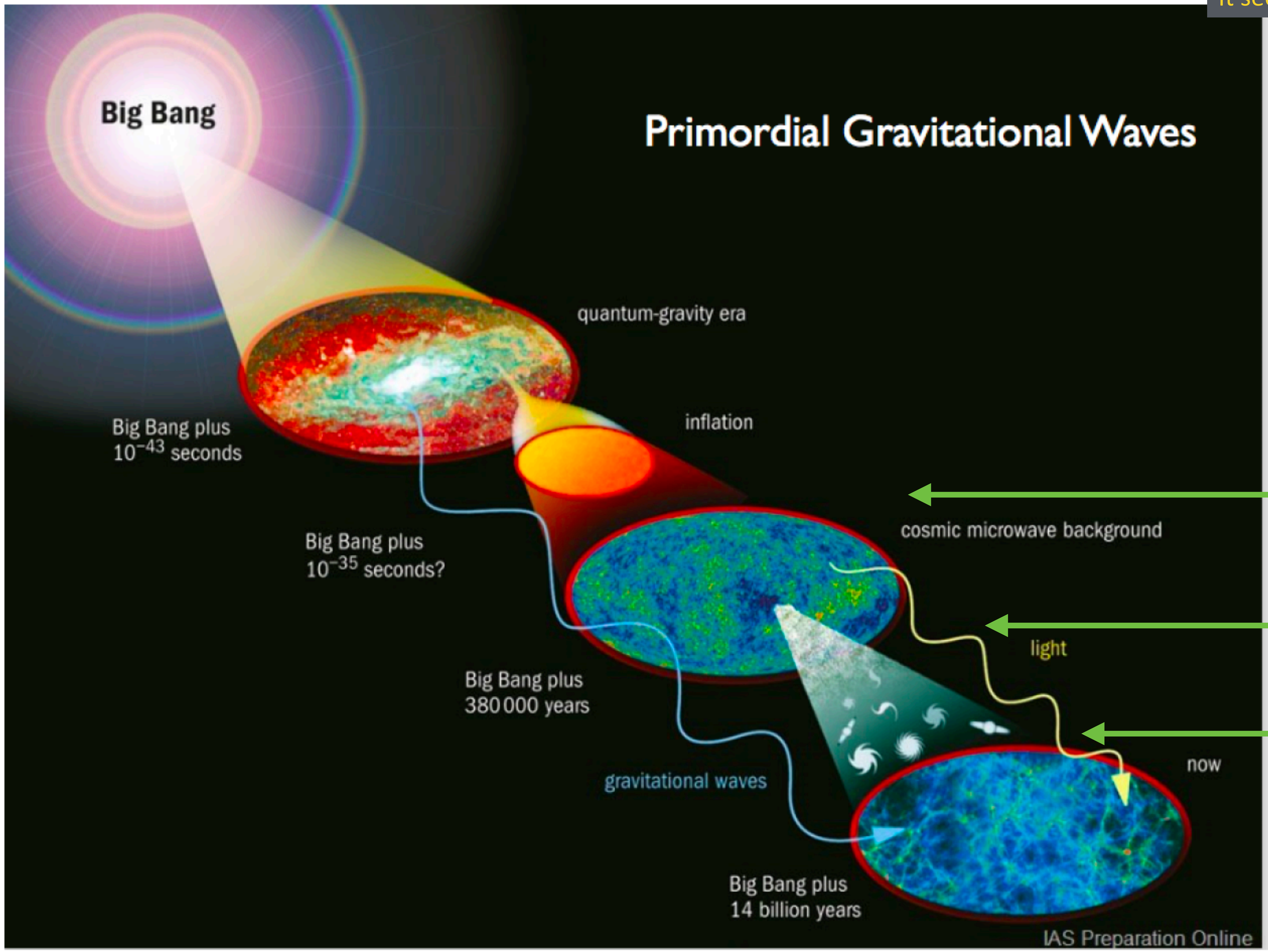
Bearing in mind that there are caveats,
Let's **assume** that the **current** energy budget is ok.

The history of the universe

https://www.iaspreparationonline.com/primordial-gravitational-waves/

It seems that this web page does not exist anymore …



Radiation dominated

Matter dominated

Dark energy dominated

Dark matter: Astronomical observations

Rotational curves of galaxies in the Coma cluster
(Zwicky, ~1930)

Velocities of stars in the Andromeda galaxy
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Bullet cluster: weak lensing vs X-ray maps (2006)

https://arxiv.org/abs/astro-ph/0608407

THE ASTROPHYSICAL JOURNAL, 648:L109–L113, 2006 September 10

A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER[1]

DOUGLAS CLOWE,[2] MARUŠA BRADAČ,[3] ANTHONY H. GONZALEZ,[4] MAXIM MARKEVITCH,[5,6]
SCOTT W. RANDALL,[5] CHRISTINE JONES,[5] AND DENNIS ZARITSKY[2]
Received 2006 June 6; accepted 2006 August 3; published 2006 August 30

ABSTRACT

We present new weak-lensing observations of 1E 0657−558 ($z = 0.296$), a unique cluster merger, that enable a direct detection of dark matter, independent of assumptions regarding the nature of the gravitational force law. Due to the collision of two clusters, the dissipationless stellar component and the fluid-like X-ray–emitting plasma are spatially segregated. By using both wide-field ground-based images and *HST*/ACS images of the cluster cores, we create gravitational lensing maps showing that the gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, but rather approximately traces the distribution of galaxies. An 8 σ significance spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law and thus proves that the majority of the matter in the system is unseen.

Subject headings: dark matter — galaxies: clusters: individual (1E 0657−558) — gravitational lensing

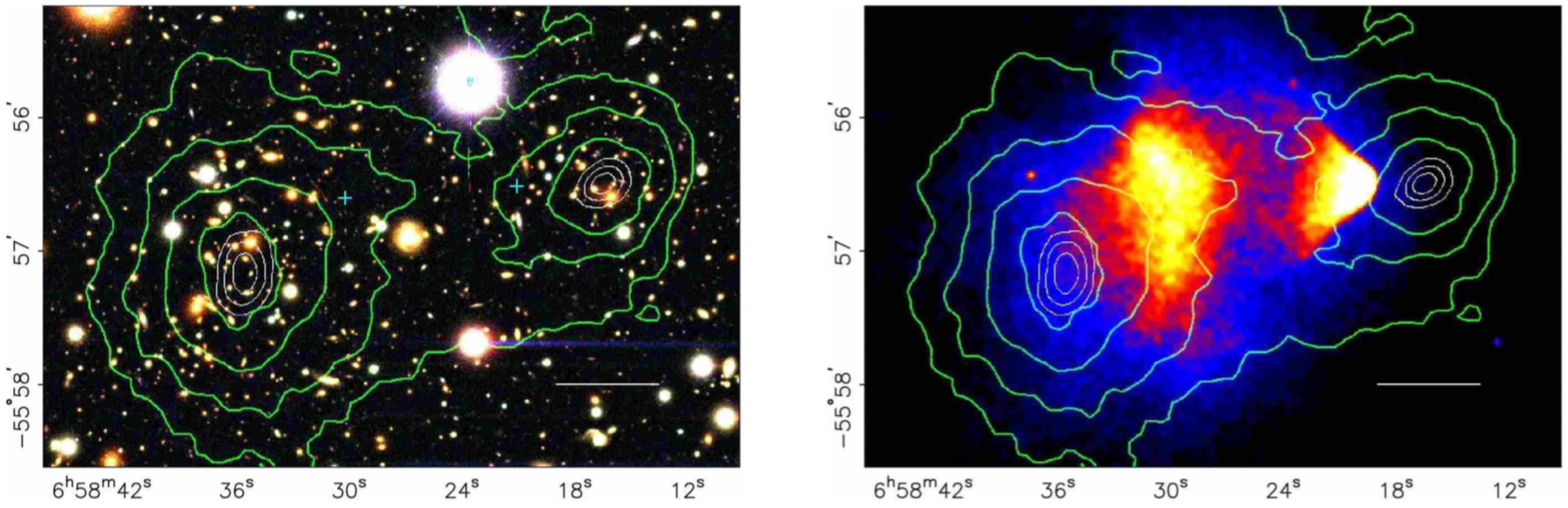
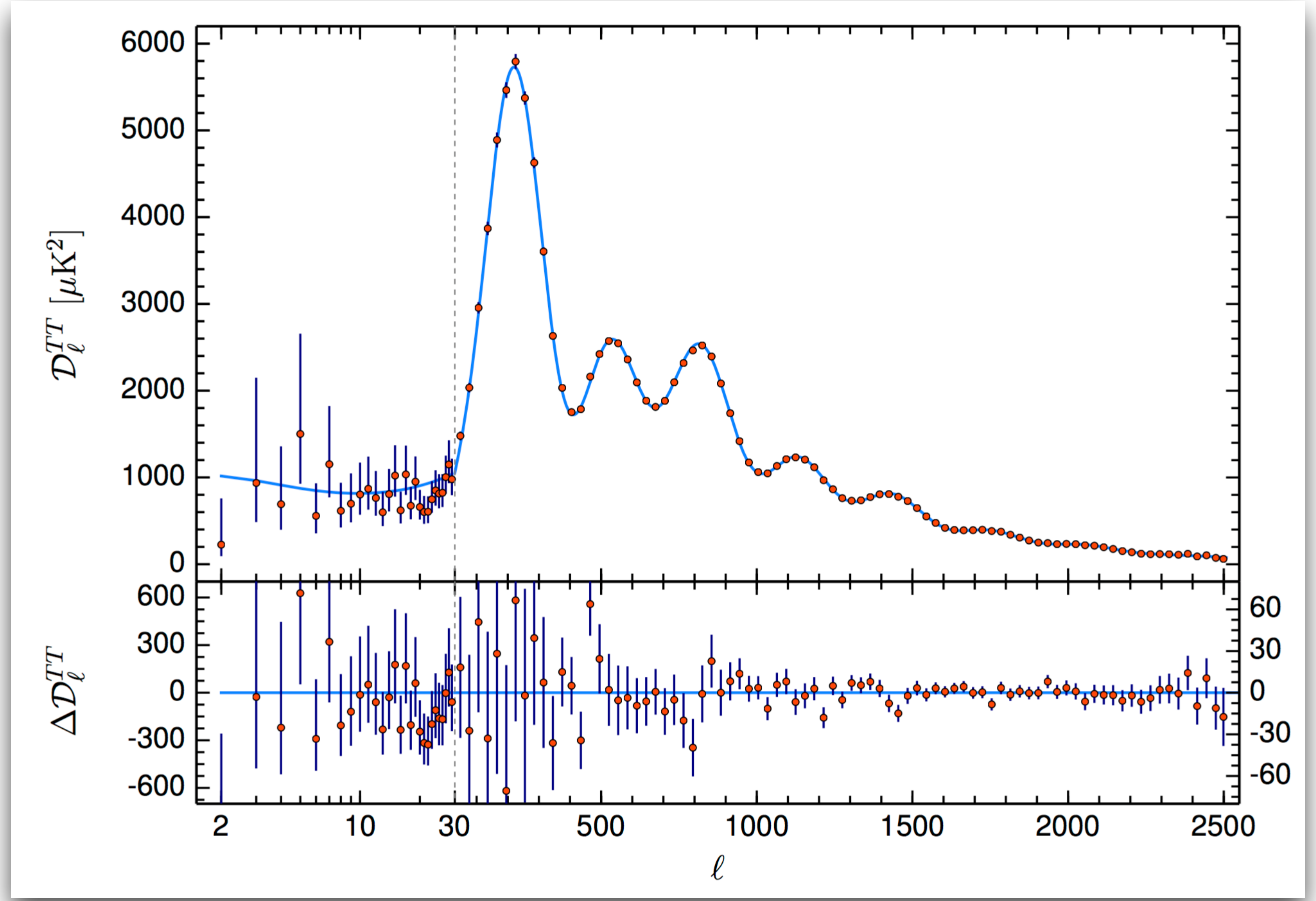


FIG. 1.— Shown above in the top panel is a color image from the Magellan images of the merging cluster 1E0657−558, with the white bar indicating 200 kpc at the distance of the cluster. In the bottom panel is a 500 ks Chandra image of the cluster. Shown in green contours in both panels are the weak lensing κ reconstruction with the outer contour level at $\kappa = 0.16$ and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68.3%, 95.5%, and 99.7% confidence levels. The blue +s show the location of the centers used to measure the masses of the plasma clouds in Table 2.

Any non-standard gravitational force that scales with baryonic mass will fail to reproduce these observations. The lensing peaks require unseen matter concentrations that are more massive than and offset from the plasma. While the existence of dark matter removes the primary motivation for alternative gravity models, it does not preclude non-standard gravity. The scaling relation

Dark matter: Planck 2018 results

Power spectrum of the CMB temperature anisotropies



Astronomy & Astrophysics manuscript no. ms
September 24, 2019

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***Planck* 2018 results. VI. Cosmological parameters**

https://arxiv.org/abs/1807.06209

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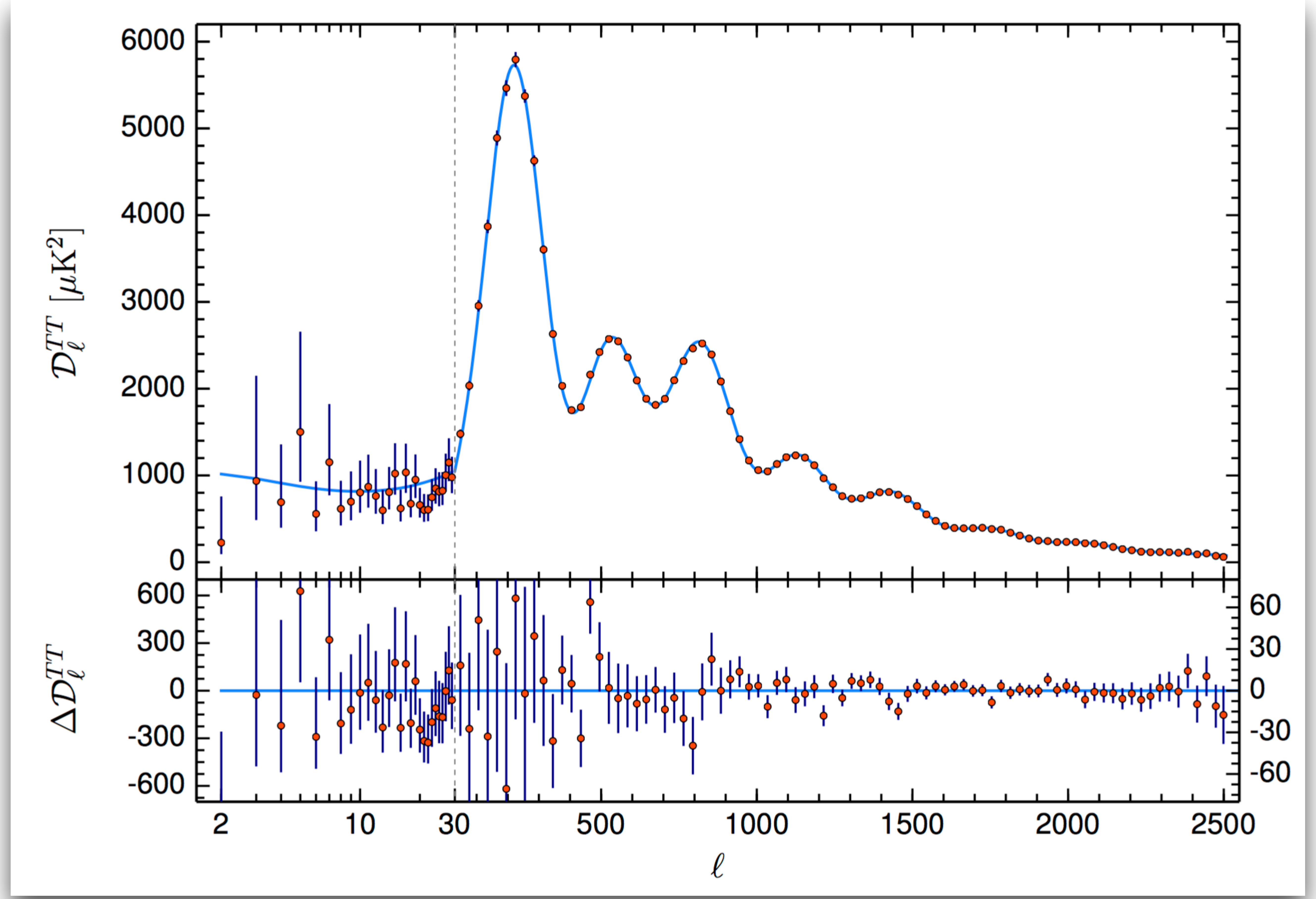

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Parameter	Plik best fit	Plik [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073
Age [Gyr]	13.7971	13.797 ± 0.023
σ_8	0.8120	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013
z_{re}	7.68	7.67 ± 0.73
$100\theta_*$	1.041085	1.04110 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26

Fit to the ΛCDM cosmology
(Six parameters!)

Dark matter: what do we know?

It is there ....

... and there is a lot of it

It interacts gravitationally

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It is stable

It is less interacting than SM particles

As it contributes to the formation of large structures in the universe (most of) it must be cold (i.e. non relativistic)

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WIMPs (weakly interacting massive particles)

Dark matter candidates

Neutrinos

They exists, but their density is too small.
Furthermore, they are relativistic.
(this would imply that big structures are formed before smaller ones … but this contradicts observations …)

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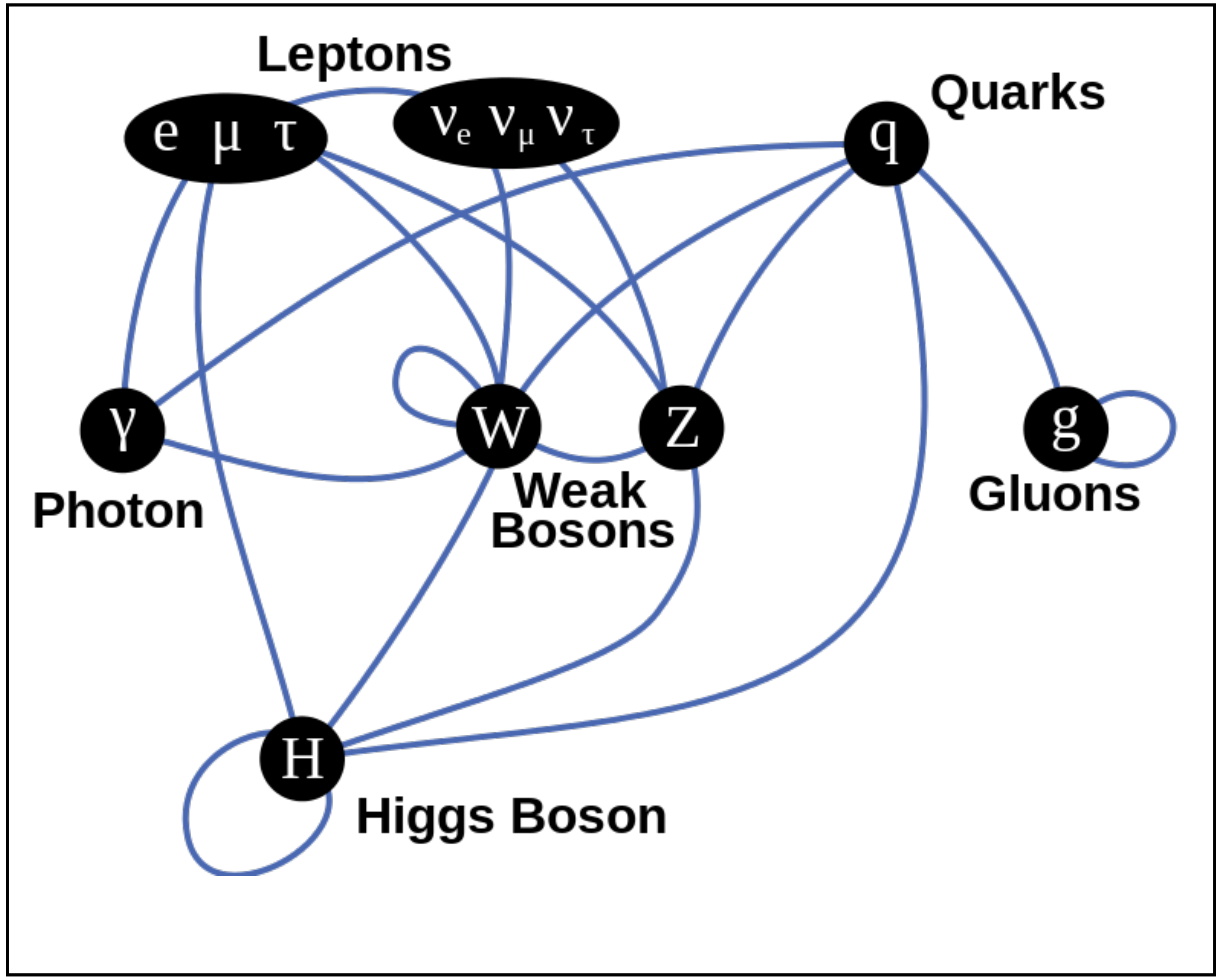
A quick look at the standard model

https://commons.wikimedia.org/wiki/File:Elementary_particle_interactions.svg



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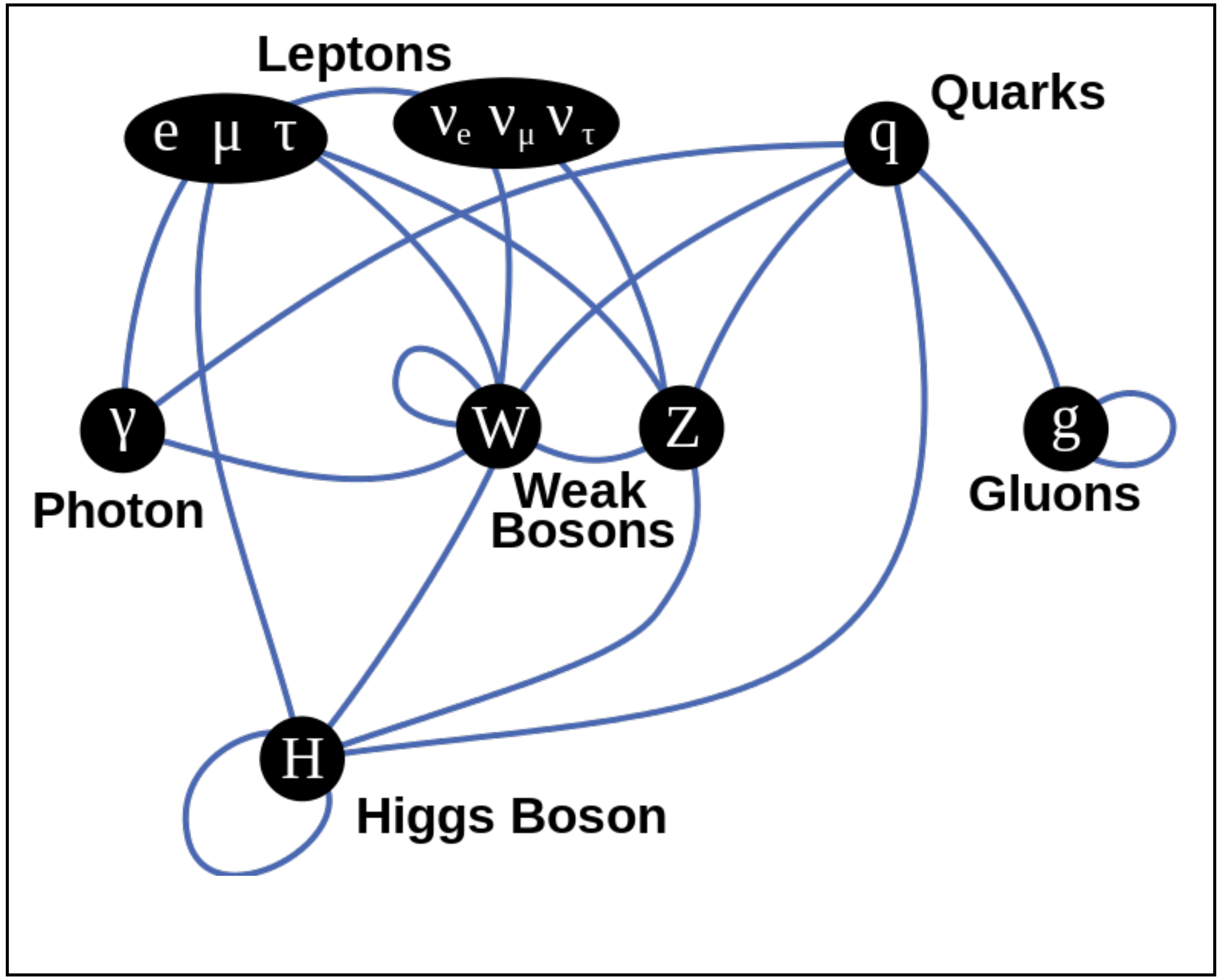

Quite rich structure

- ⇨ Different spins
- ⇨ Huge range in masses
- ⇨ Different lifetimes
- ⇨ Several families
- ⇨ Chiral structure
- ⇨ There are different types of charges.

  Not everybody talks to everybody …
  (at least not directly …)

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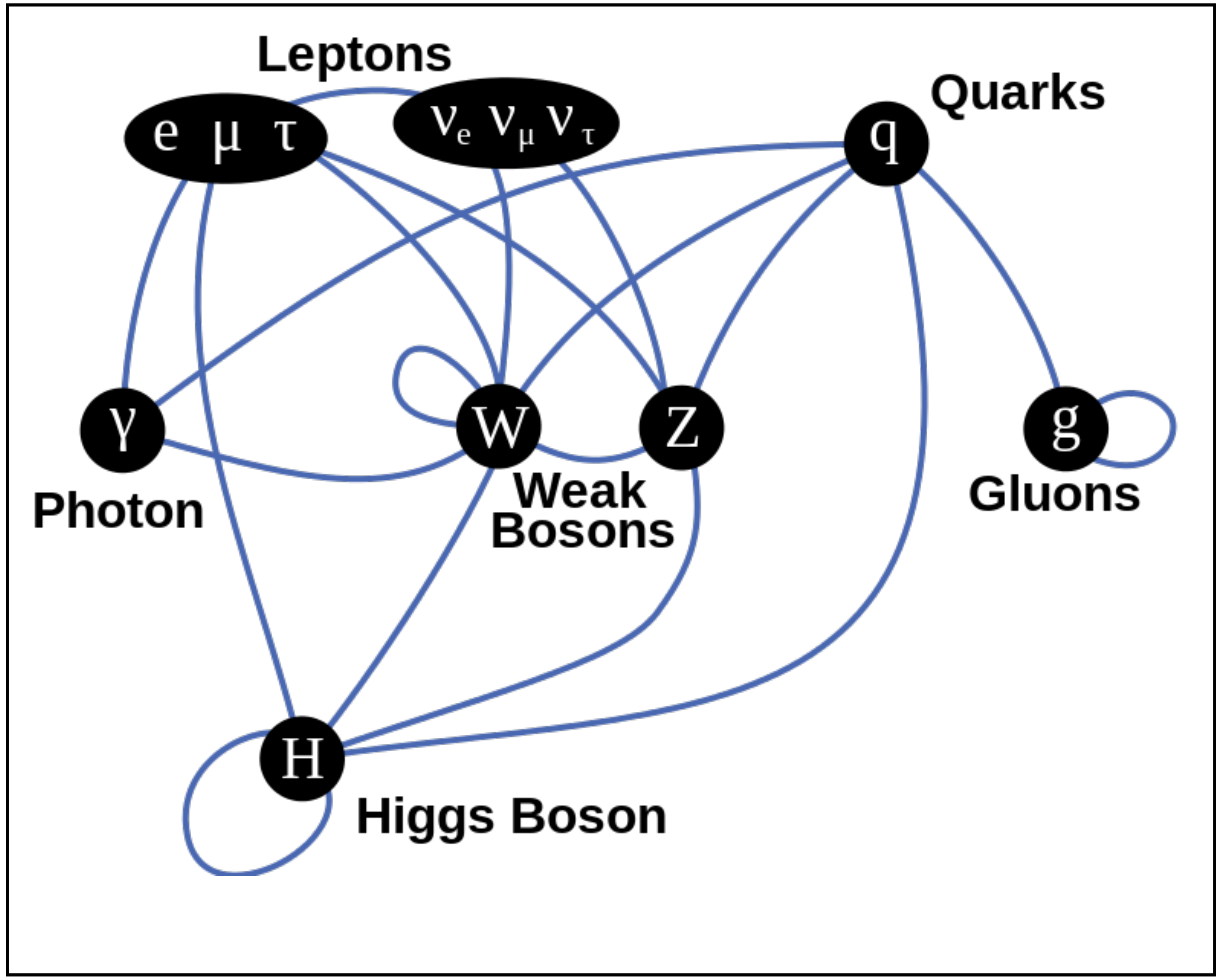

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Could it be that there is a dark sector equally rich (or richer!)?

How does the SM talks to the dark sector?

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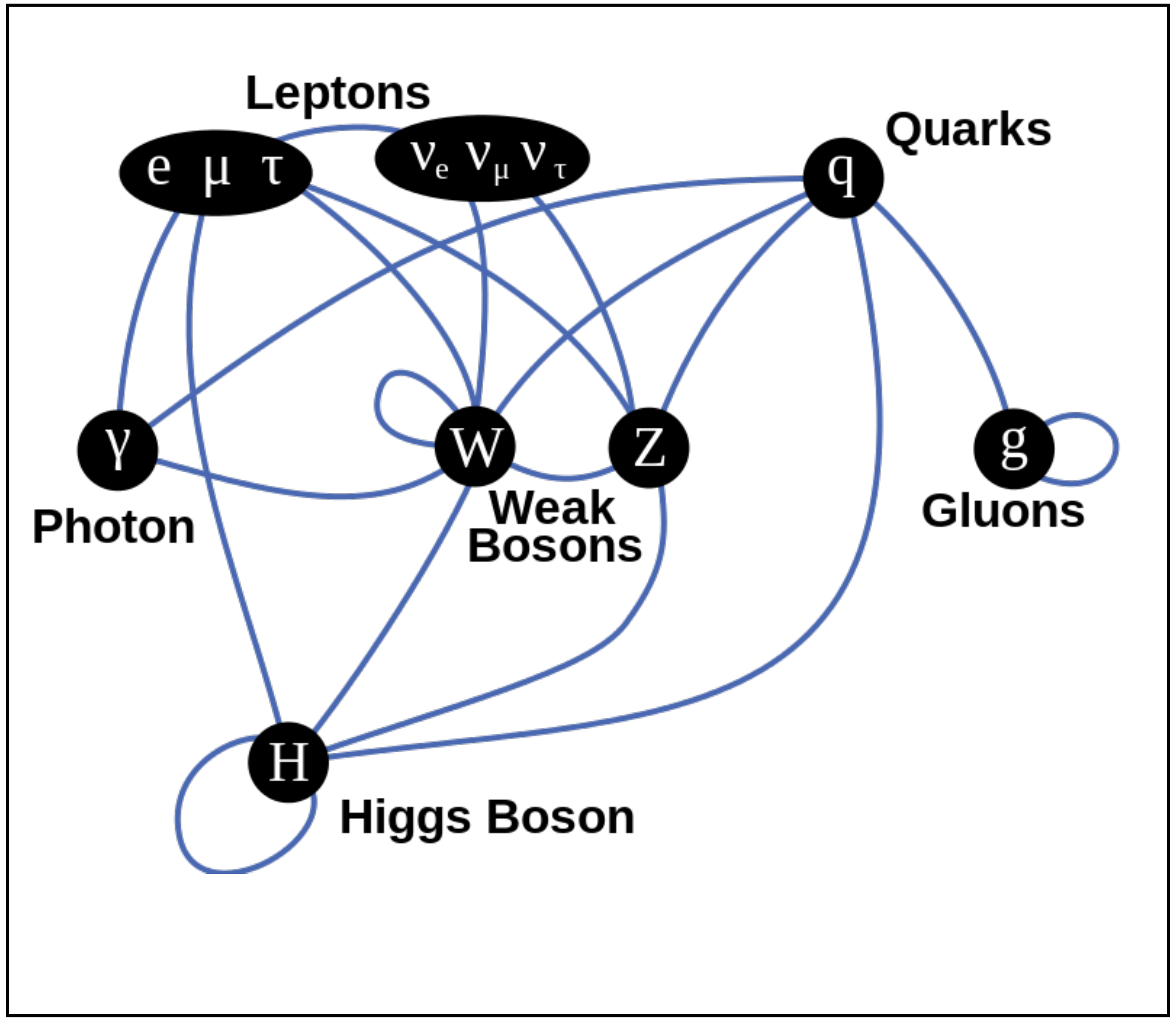

Arbitrarily complicated dark sector. It may contain DM, and also other particles, symmetries, …

DM sector

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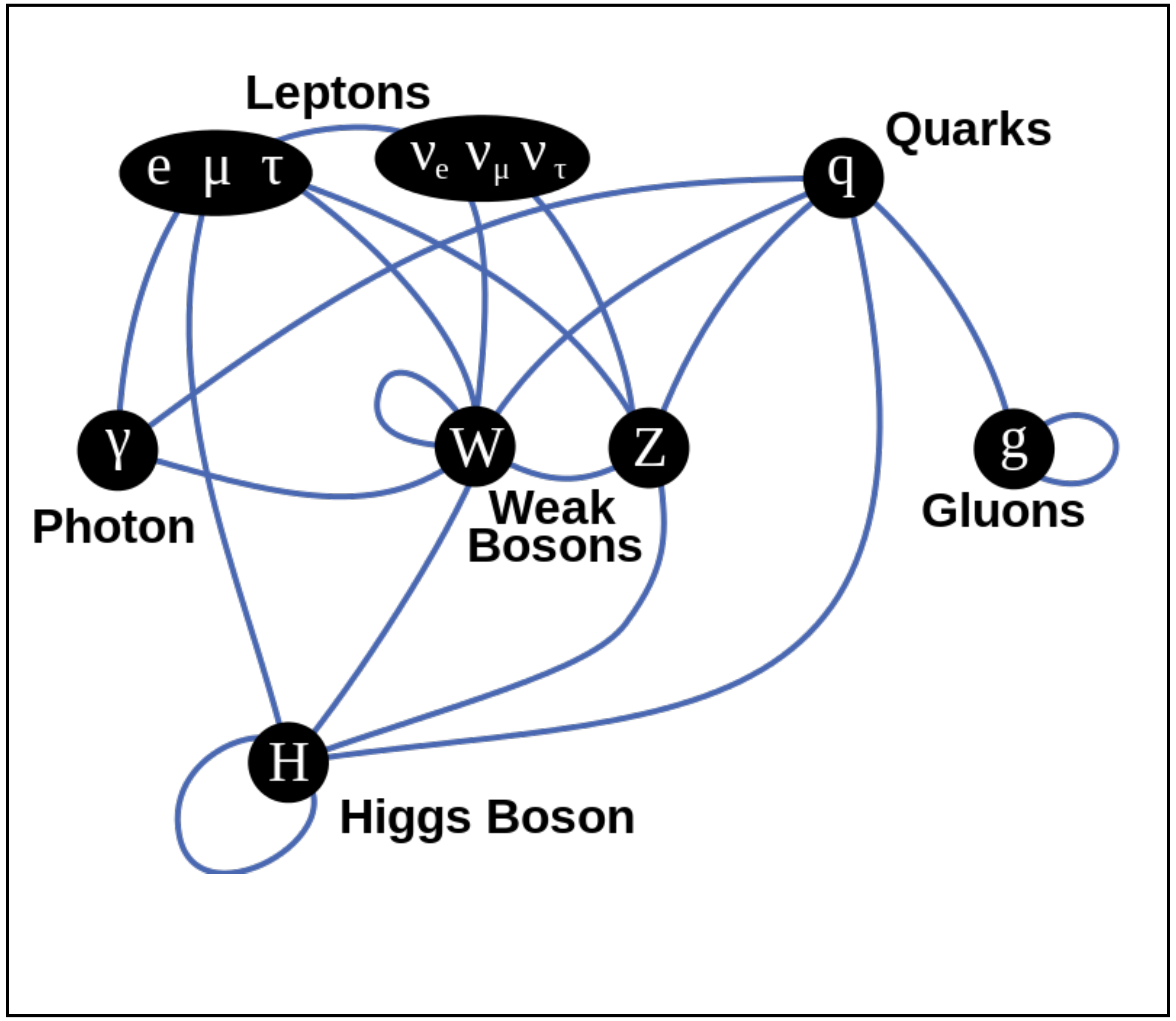


Mediator(s)
(Portals)

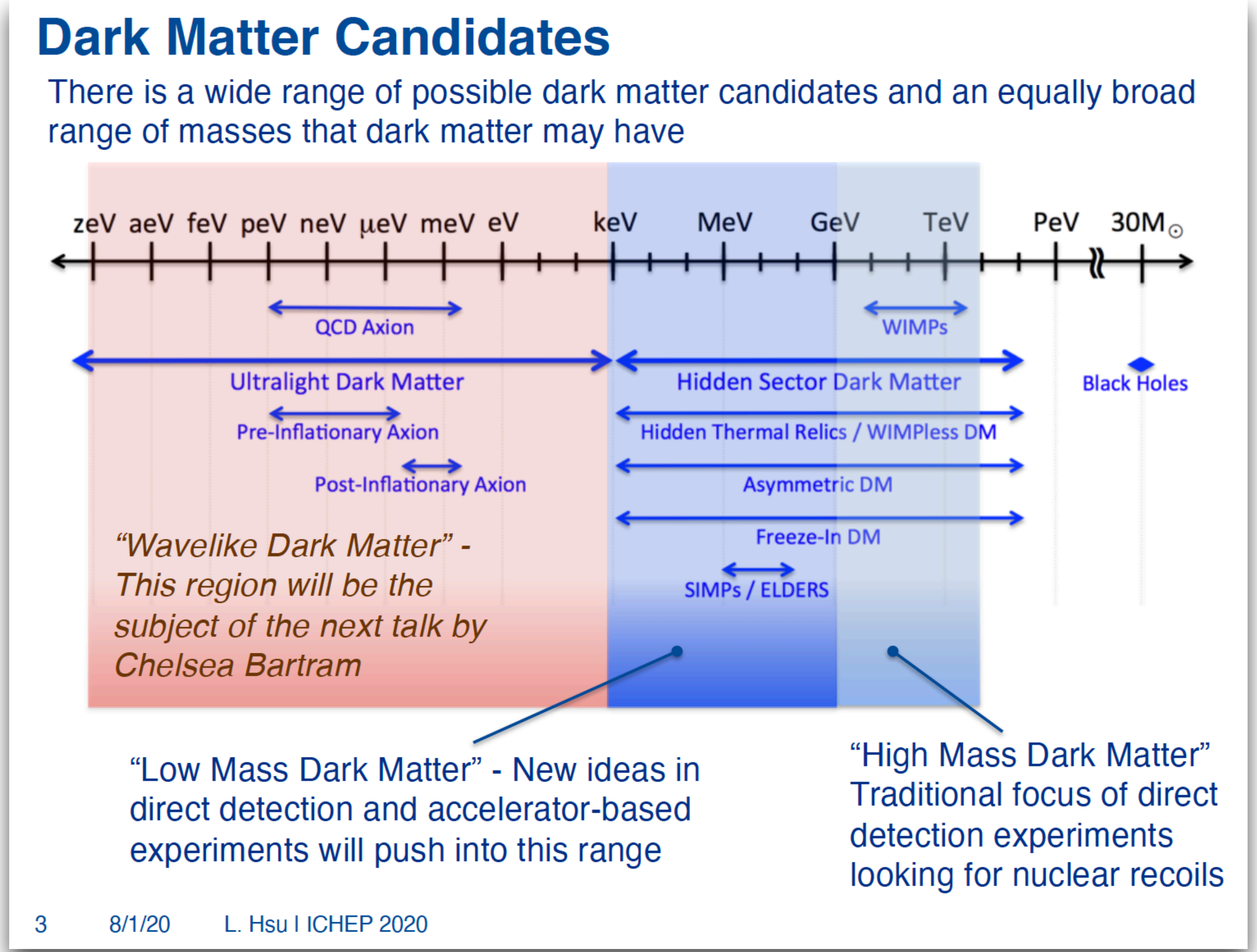
Vectorial: dark photons, …
Scalar: dark Higgs , …
Pseudoscalar: axions, ALP, …
Neutrino portal,
Gauge portal

Arbitrarily complicated dark sector. It may contain DM, and also other particles, symmetries, …

DM sector

Dark matter: what do we know?

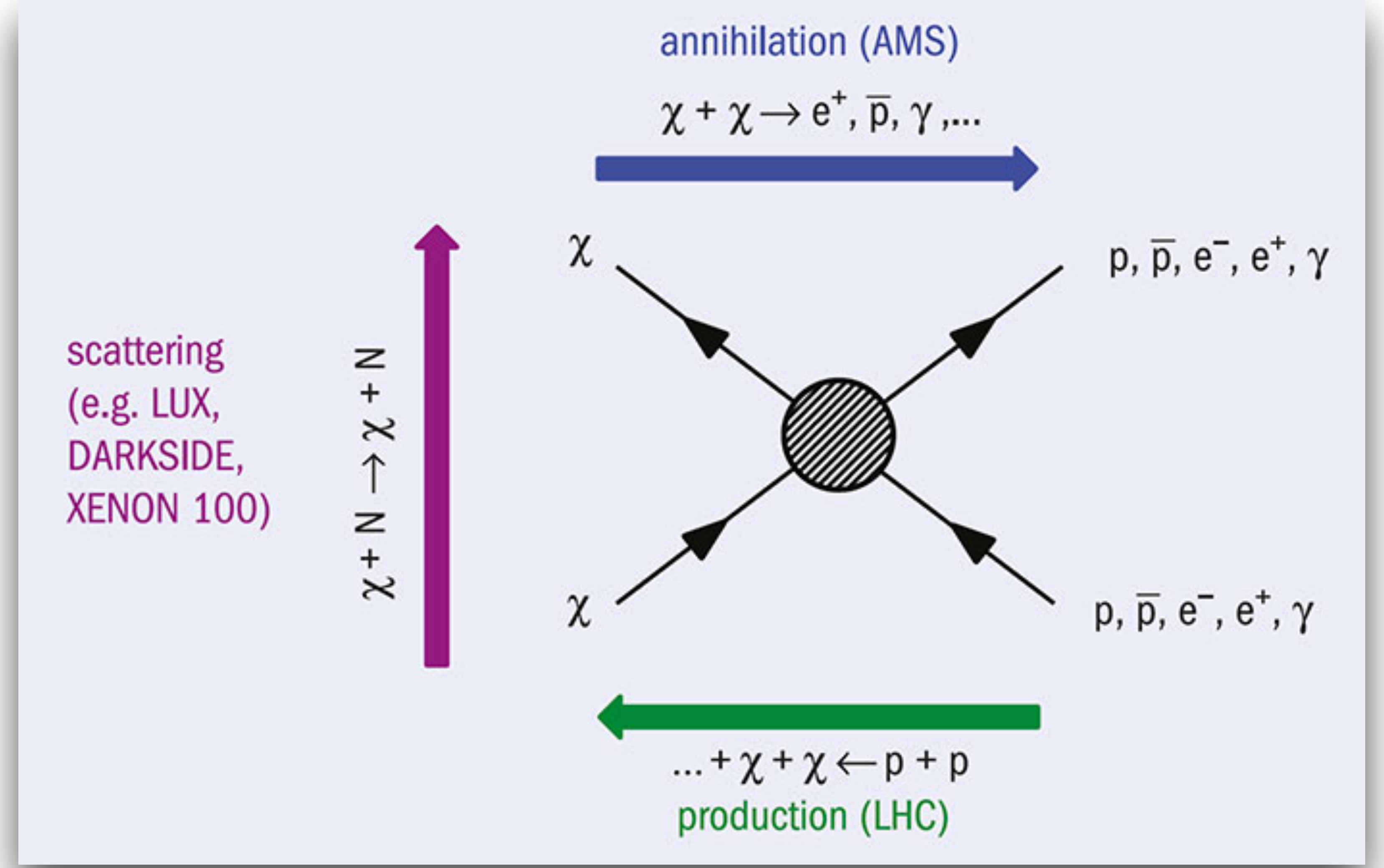
https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter



https://indico.cern.ch/event/868940/contributions/3905692/

How to search for dark matter

https://cerncourier.com/a/what-is-ams-telling-us/



https://inspirehep.net/literature/1375500

Physics of the Dark Universe 9–10 (2015) 8–23

Contents lists available at ScienceDirect

Physics of the Dark Universe

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

Simplified models for dark matter searches at the LHC

1. Introduction

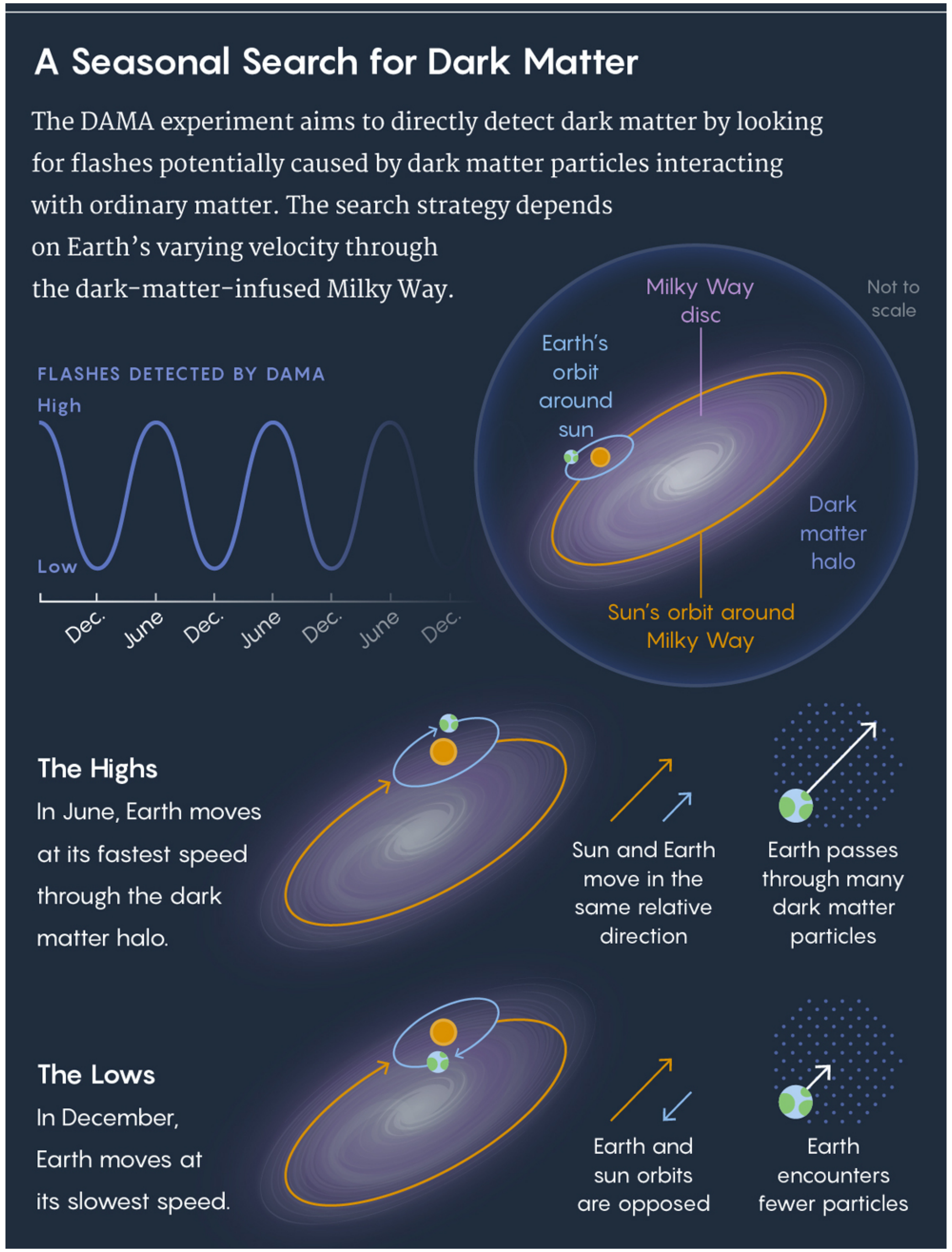
Gravitational effects on astrophysical scales give convincing evidence for the presence of dark matter (DM) in Nature, an observation that is strongly supported by the large-scale structure of the Universe and measurements of the cosmic microwave background [1]. While the existence of DM thus seems well established, very little is known about the properties of the DM particle(s). To shed light on this question, three classes of search strategies are being employed: (i) direct detection in shielded underground detectors; (ii) indirect detection with satellites, balloons, and ground-based telescopes looking for signals of DM annihilation; (iii) particle colliders aiming at direct DM production.

† Primary contributor.

[a] Summary of the discussions and conclusions following from *Dark Matter @ LHC 2014*, held at Merton College, Oxford, on September25–27, 2014.

Hints of dark matter: DAMA annual modulation

https://www.quantamagazine.org/trouble-detected-in-infamous-dark-matter-signal-20180412/



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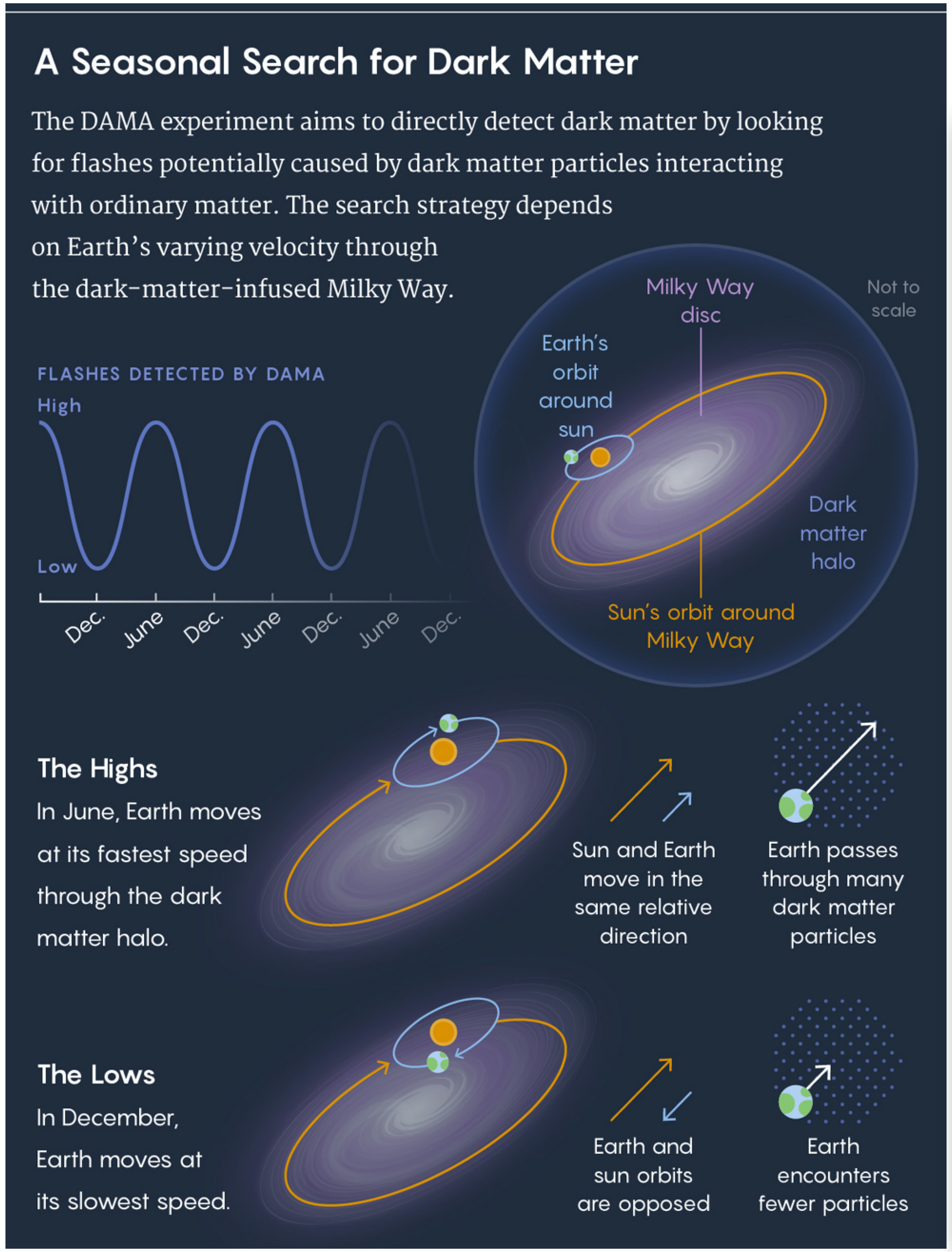
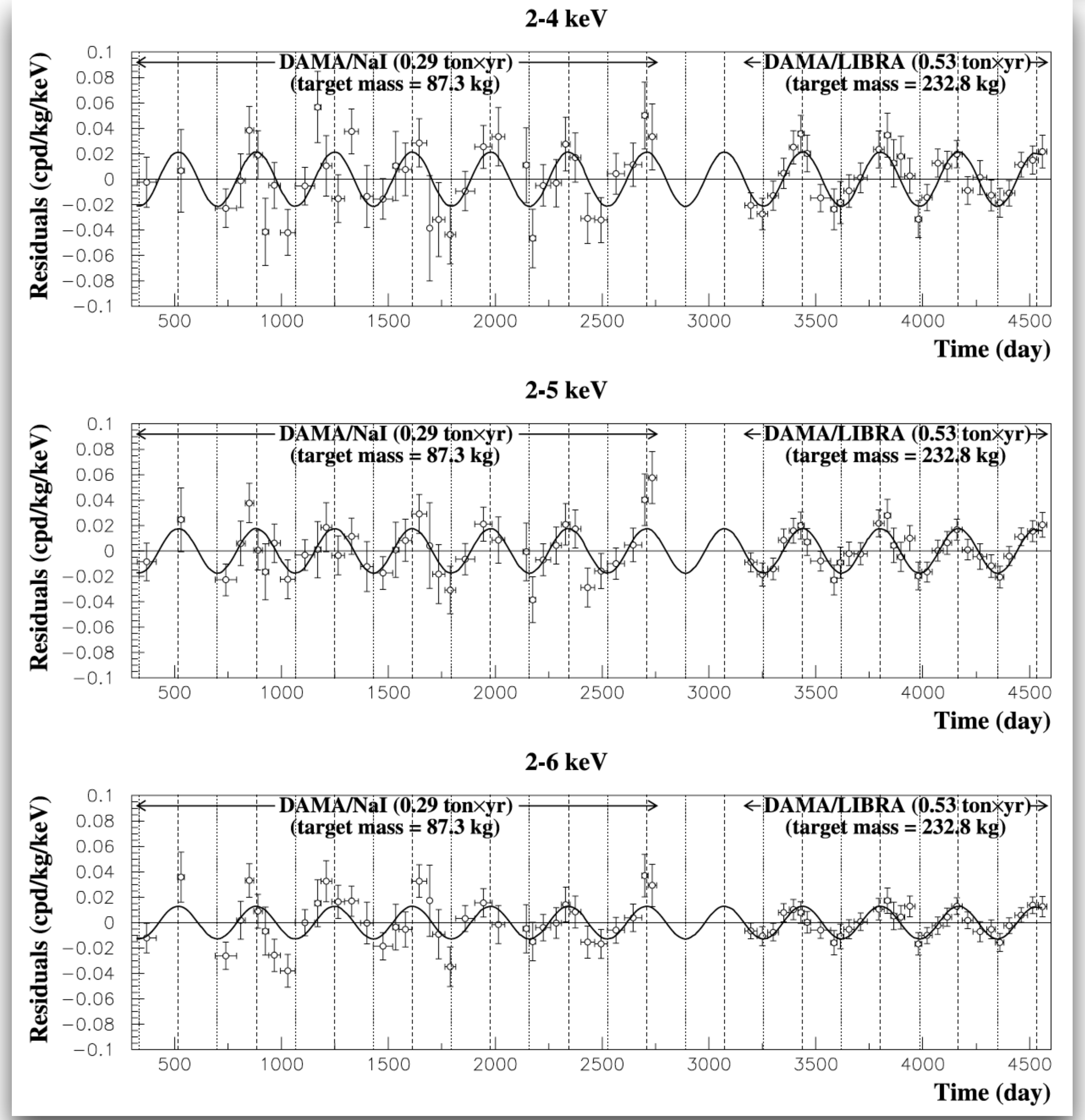
https://inspirehep.net/literature/783646

Eur. Phys. J. C (2008) 56: 333–355
DOI 10.1140/epjc/s10052-008-0662-y
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

First results from DAMA/LIBRA and the combined results with DAMA/NaI



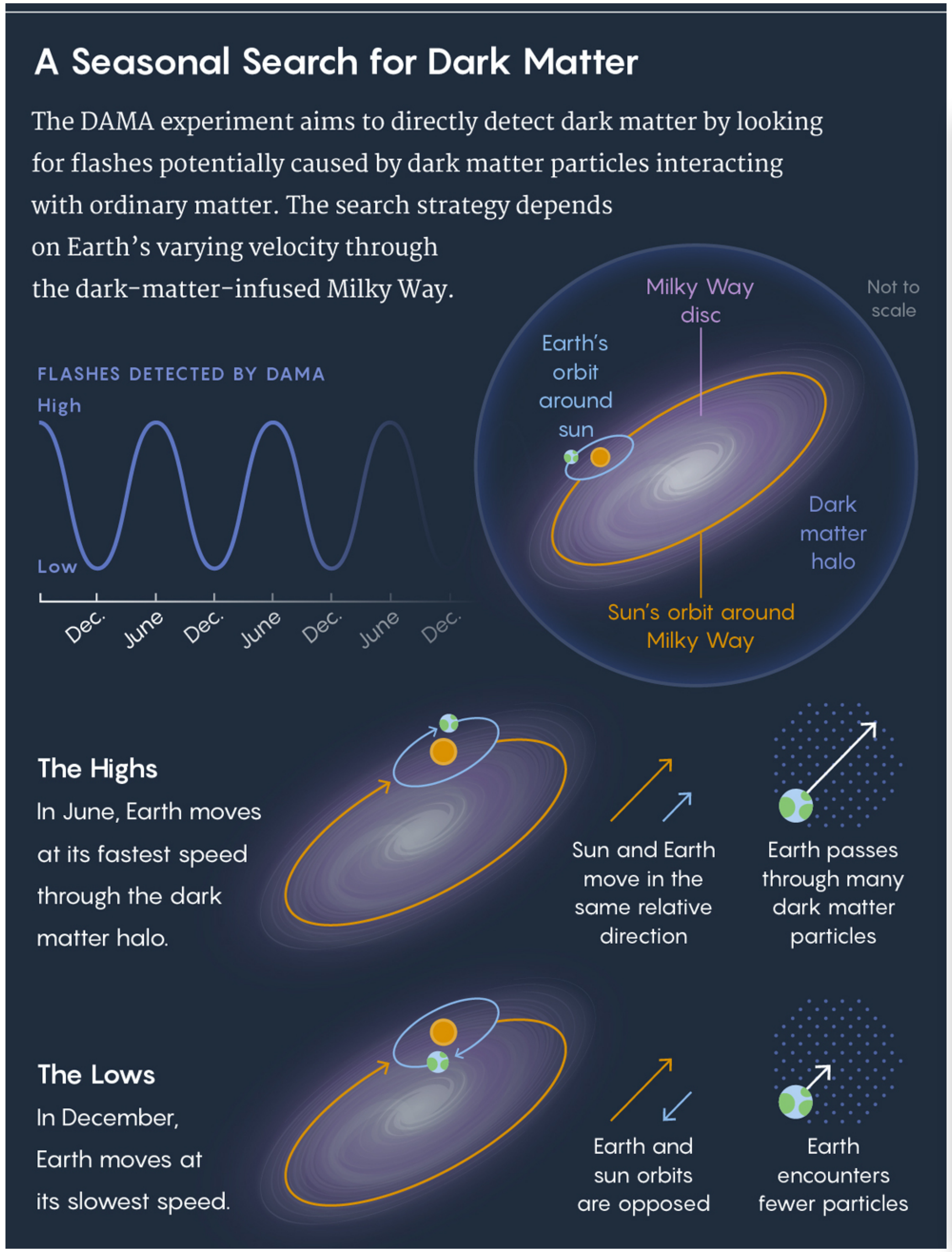


Scintillator light measured. Potentially produced by the interaction of DM with a nucleus.

Annual modulation observed.

Hints of dark matter: DAMA annual modulation

https://www.quantamagazine.org/trouble-detected-in-infamous-dark-matter-signal-20180412/



https://inspirehep.net/literature/783646

Eur. Phys. J. C (2008) 56: 333–355
DOI 10.1140/epjc/s10052-008-0662-y

THE EUROPEAN PHYSICAL JOURNAL C

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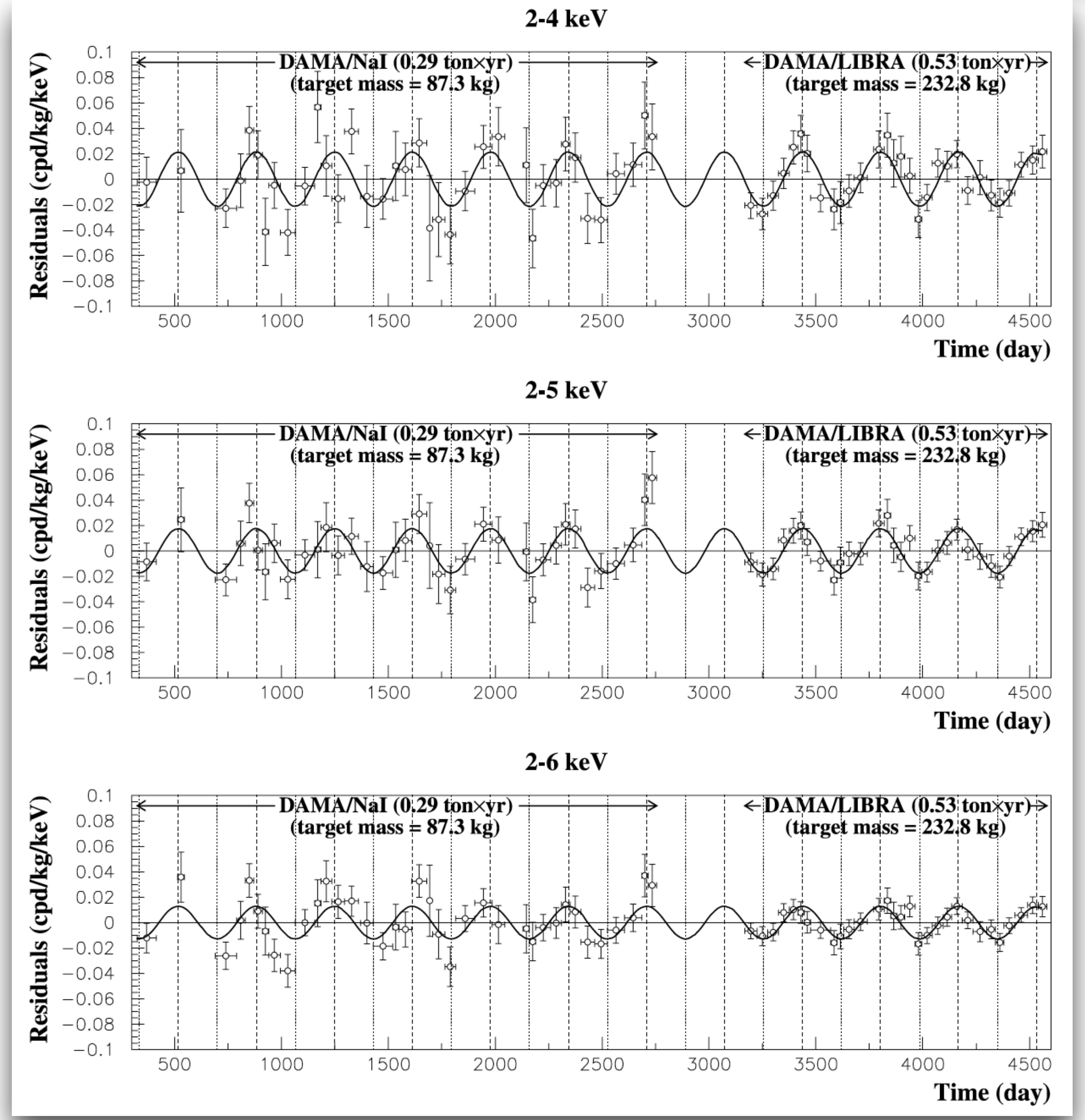


Scintillator light measured. Potentially produced by the interaction of DM with a nucleus.

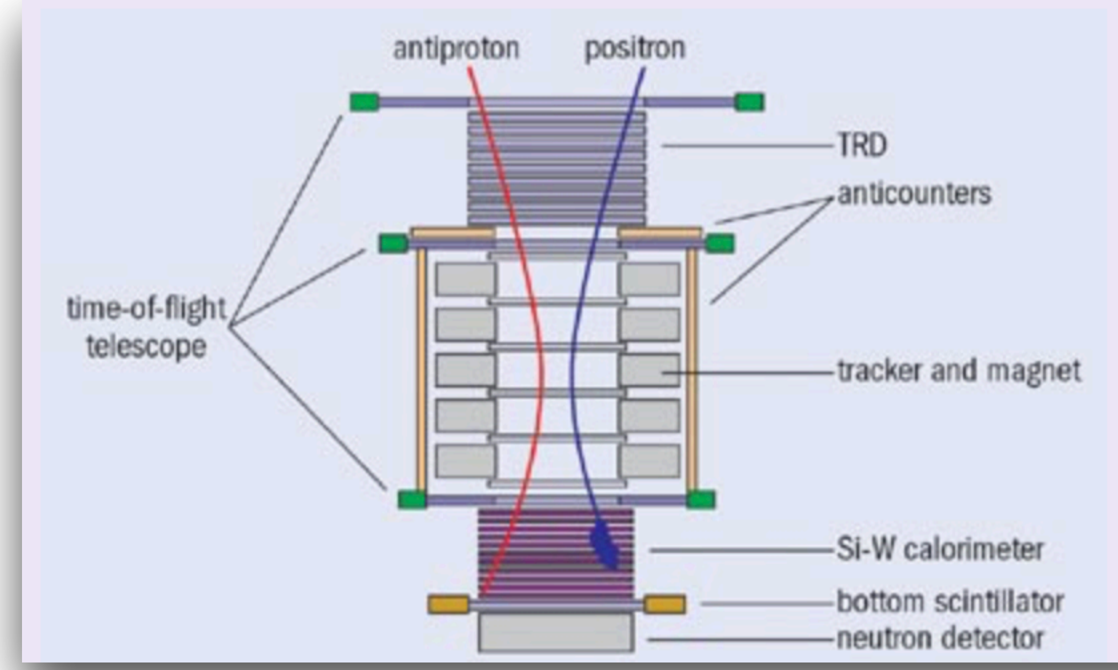
Annual modulation observed.

Results have not been reproduced in other independent experiments.

Results are in conflict with other experimental results.

Hints of dark matter: PAMELA's positron excess

Satellite born experiment.



Detection of antiprotons and positrons in PAMELA. The detector is approximately 1.2 m tall and weighs 470 kg. Its power consumption is only 360 W.

https://cerncourier.com/a/pamela-set-to-take-particle-physics-into-orbit/

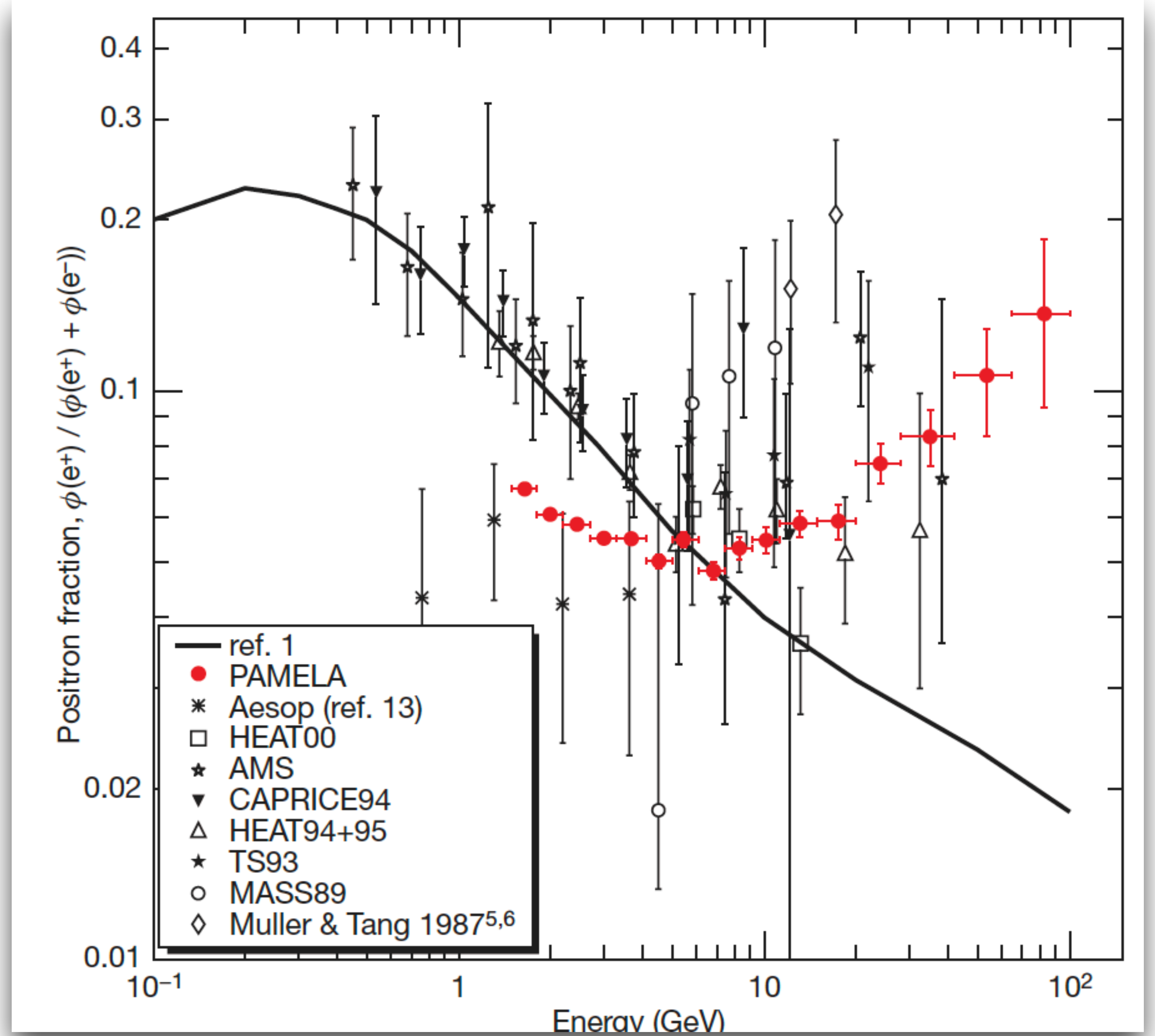
Hints of dark matter: PAMELA's positron excess

https://inspirehep.net/literature/800801

Vol 458 | 2 April 2009 | doi:10.1038/nature07942 nature

LETTERS

An anomalous positron abundance in cosmic rays with energies 1.5–100 GeV



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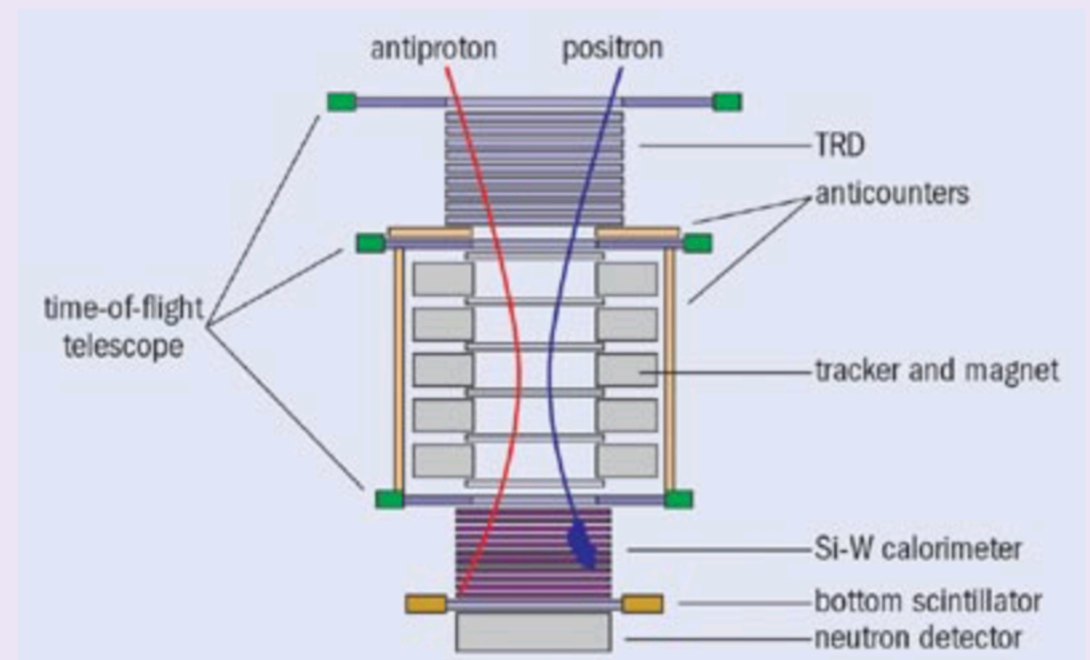

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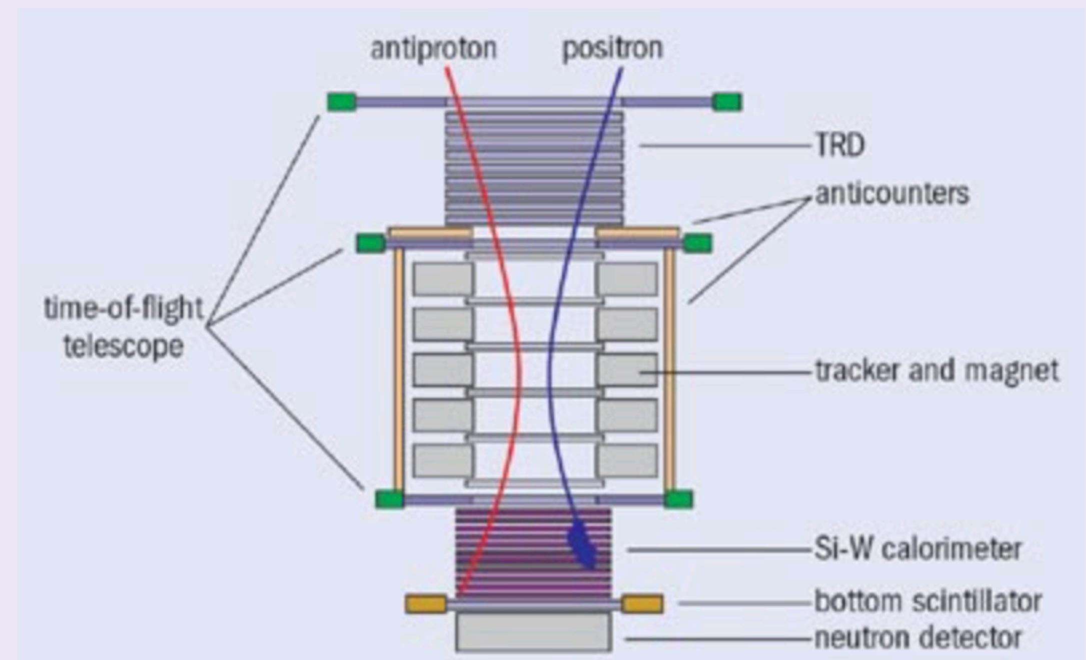

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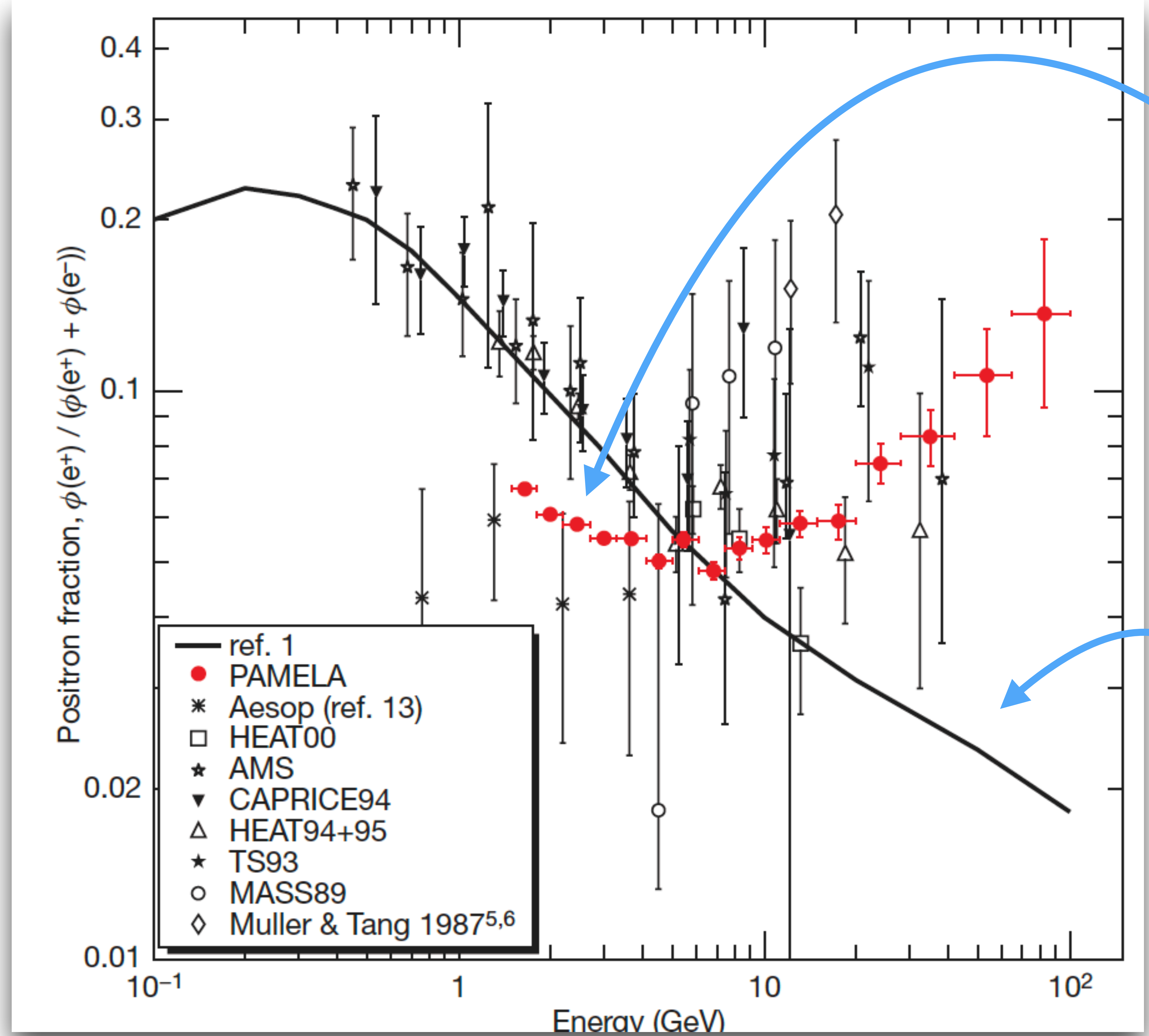

Solar modulation effect

Secondary sources(interactions between cosmic-ray nuclei and atoms in the interstellar medium

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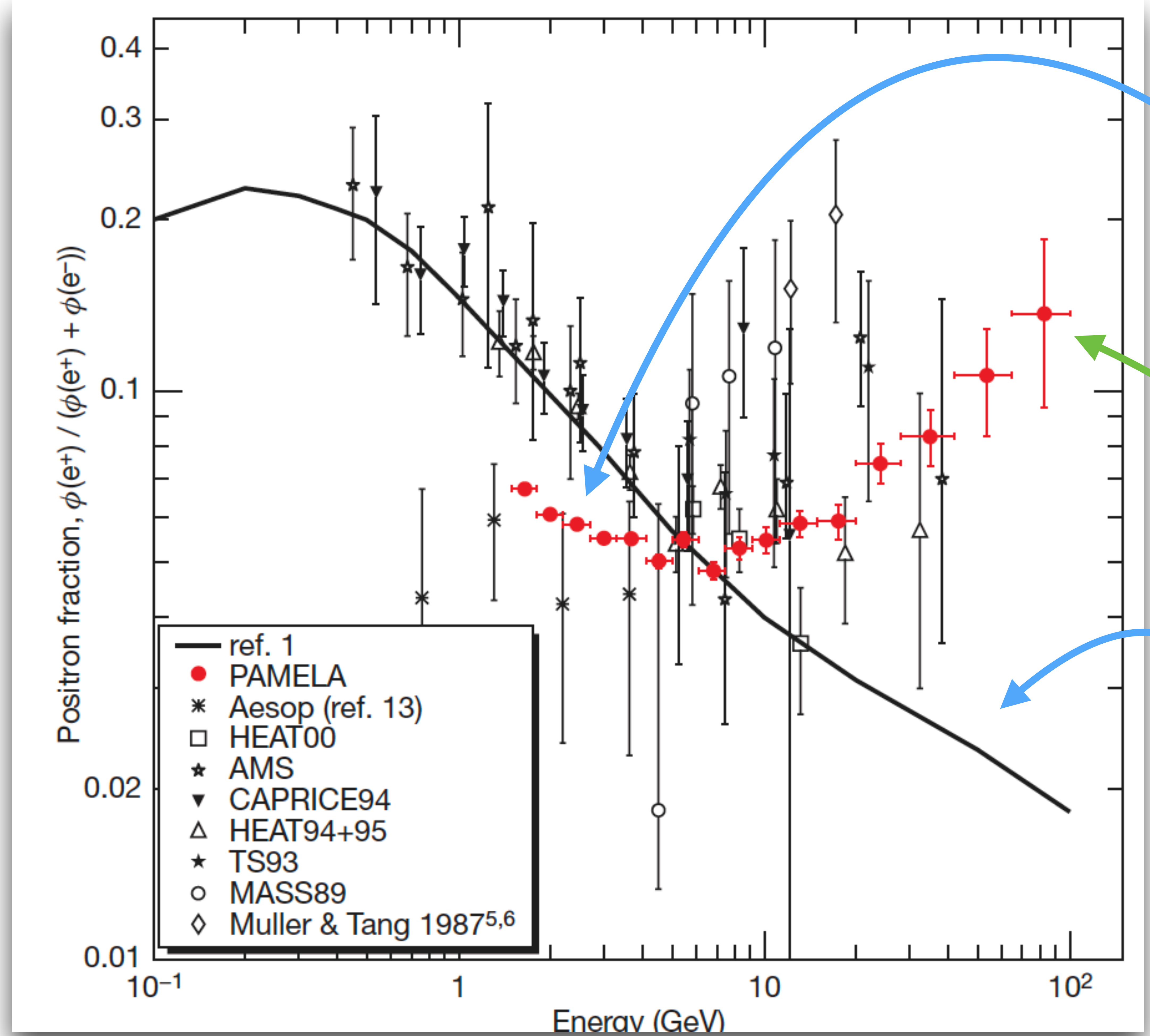

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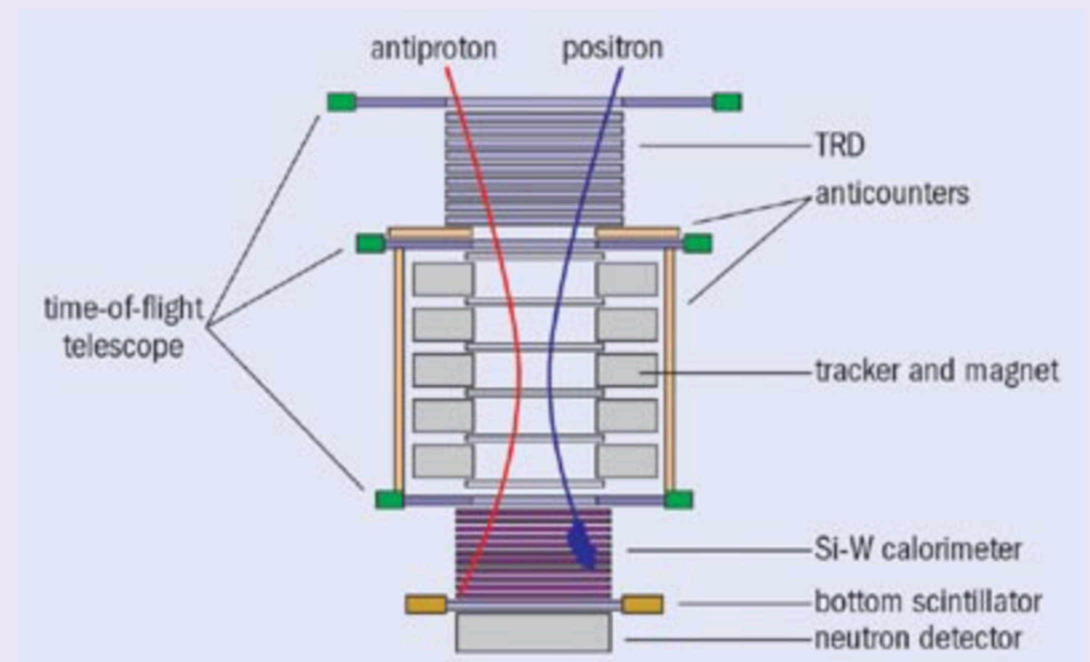

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Signal has to come from primary sources: astrophysical objects (pulsars, microquasar) or dark matter annhilation …

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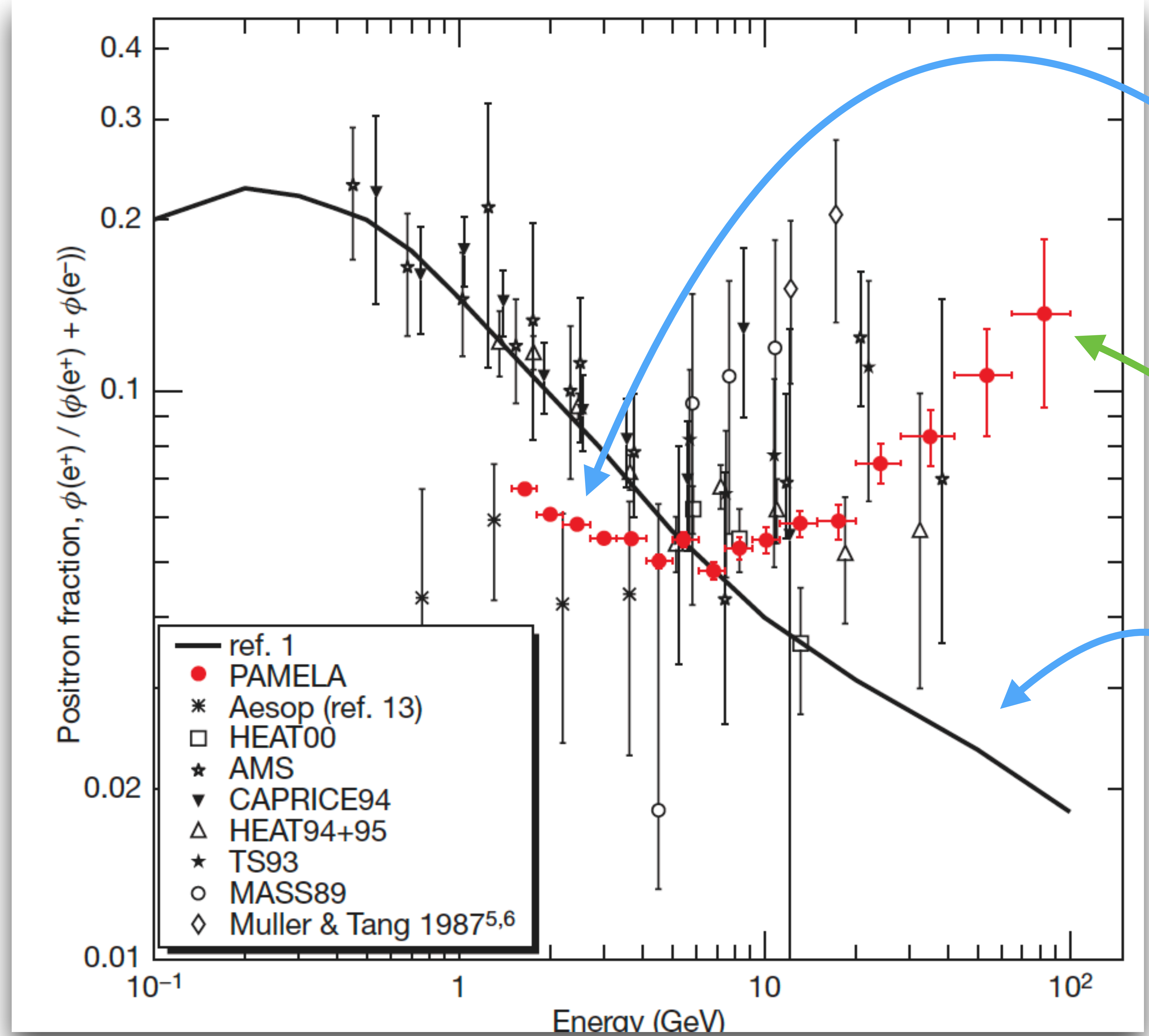

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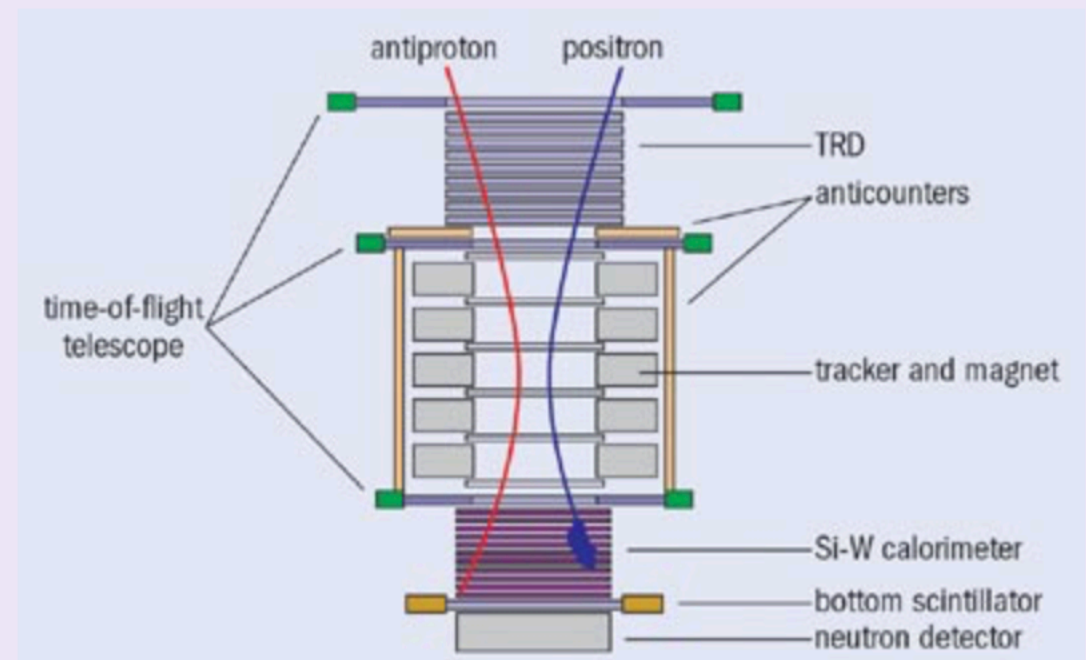

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Solar modulation effect

from secondary production calculations for antiprotons. Therefore, if the PAMELA positron results have a component due to dark matter this has to annihilate or decay into mostly leptonic final states. Furthermore, heavy WIMP candidates or large boost factors (see, for example, refs 22, 23) associated with non-uniform clumps in the dark matter distribution are required. It is worth pointing out that our antiproton-to-proton flux ratio data[21] limit significantly the boost factor for thermal WIMP candidates (ref. 24). WIMPs of non-thermal origin[25] can also be considered as explanations for both PAMELA positron and antiproton results. This model predicts a sharp decrease in the primary positron

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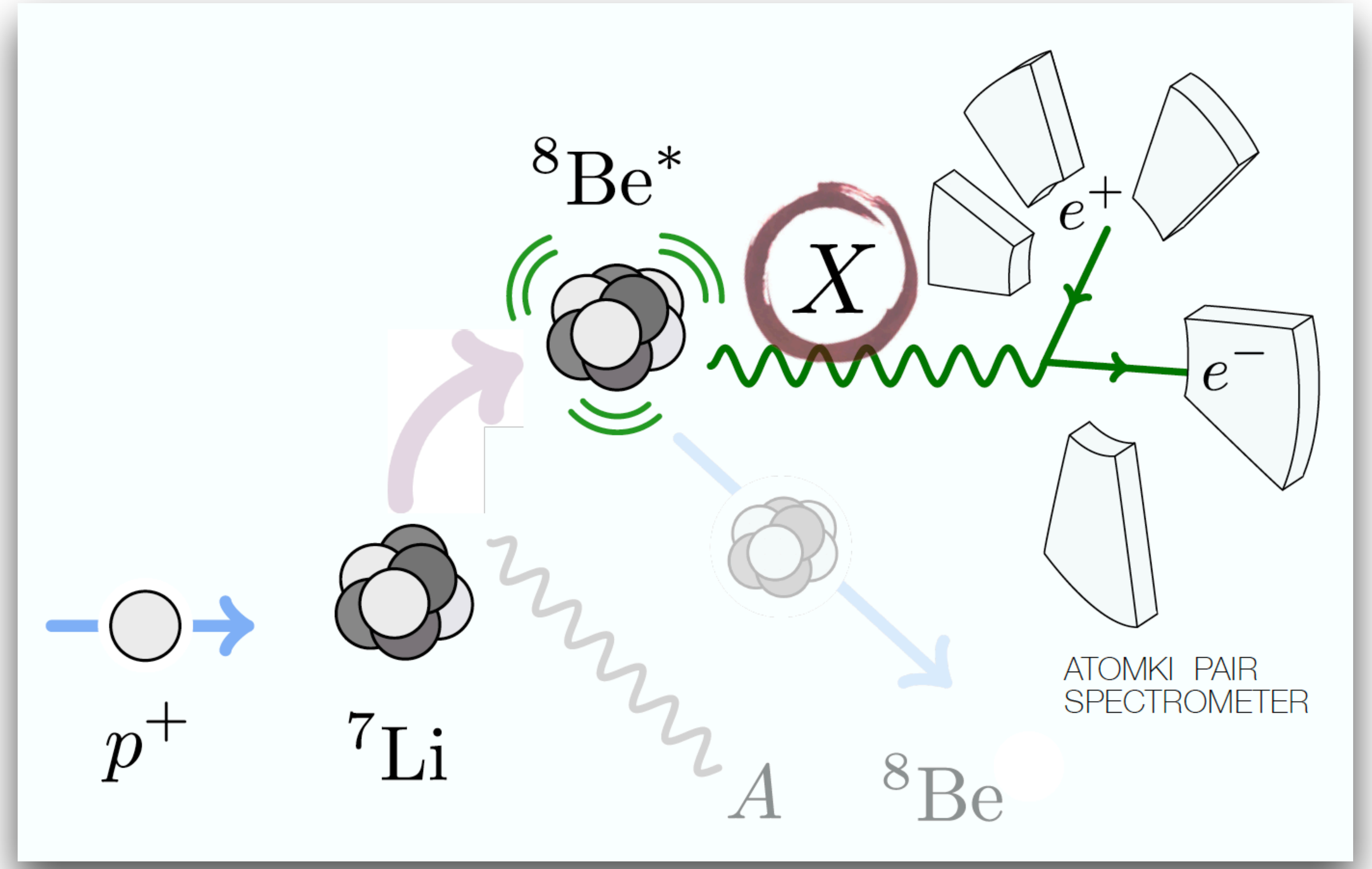
Hints of dark matter: pair creation in ^{8}Be

https://indico.cern.ch/event/507783/contributions/2151732/

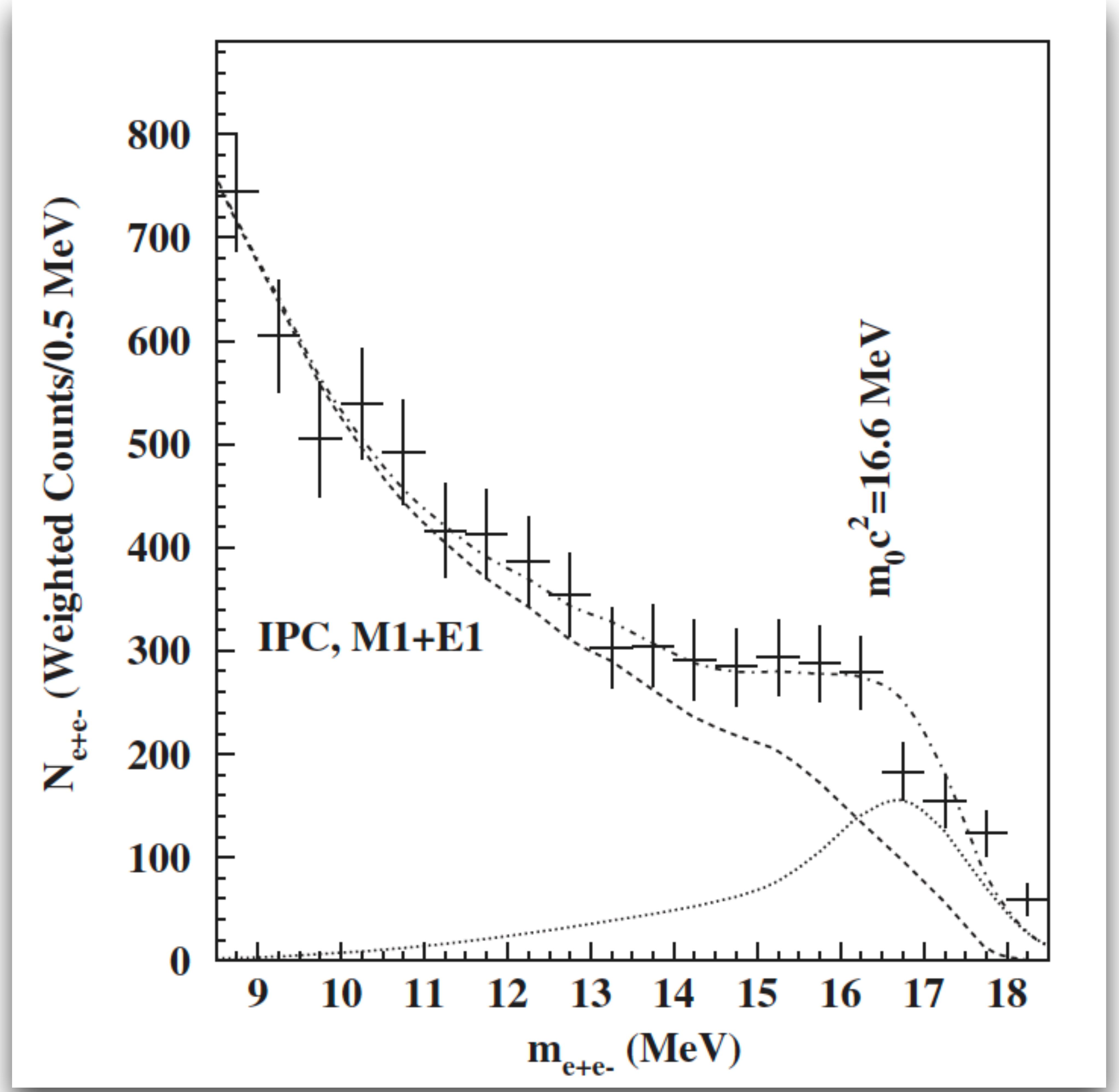


Hints of dark matter: pair creation in ^{8}Be

https://inspirehep.net/literature/1358248

PRL **116**, 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson



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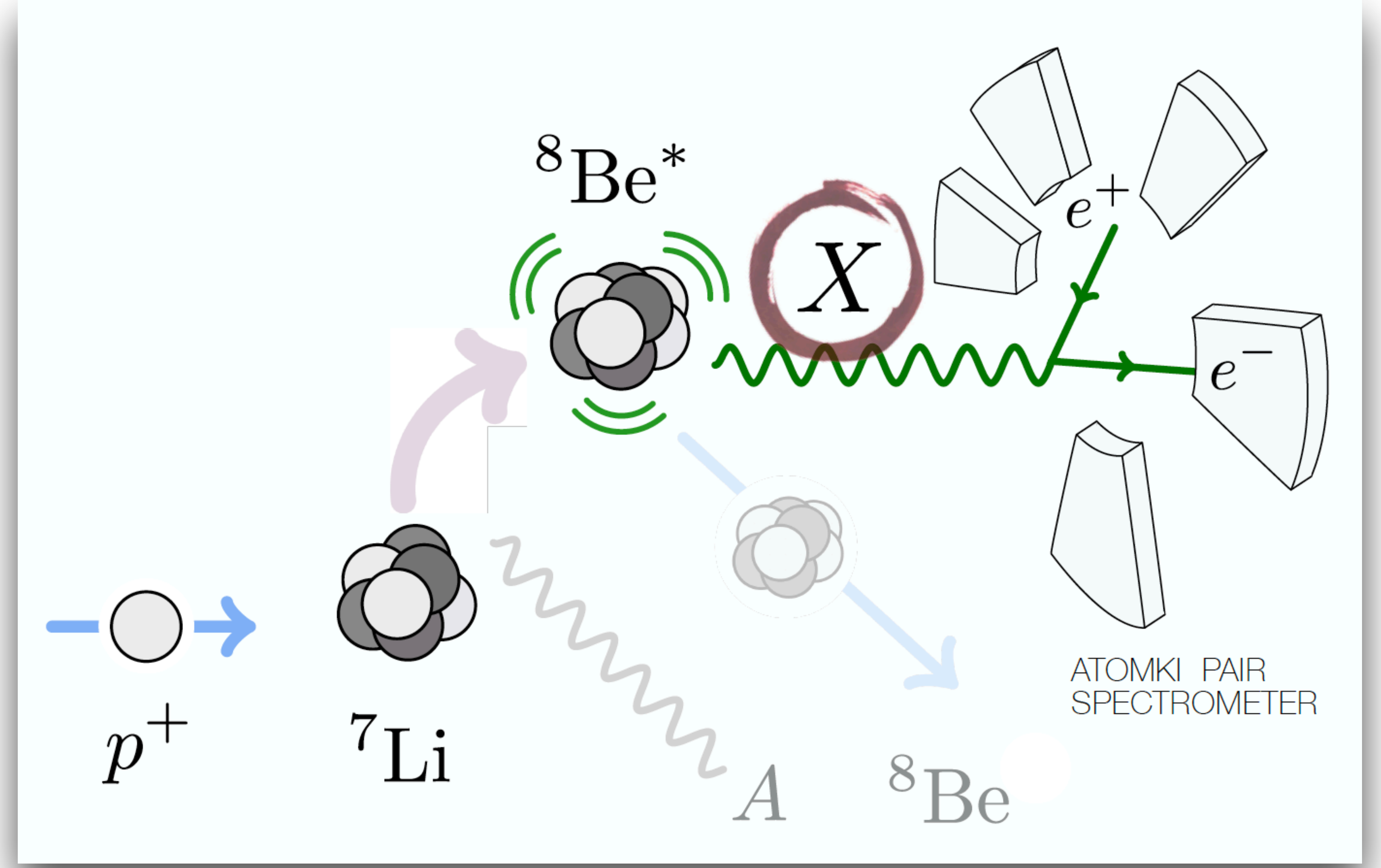

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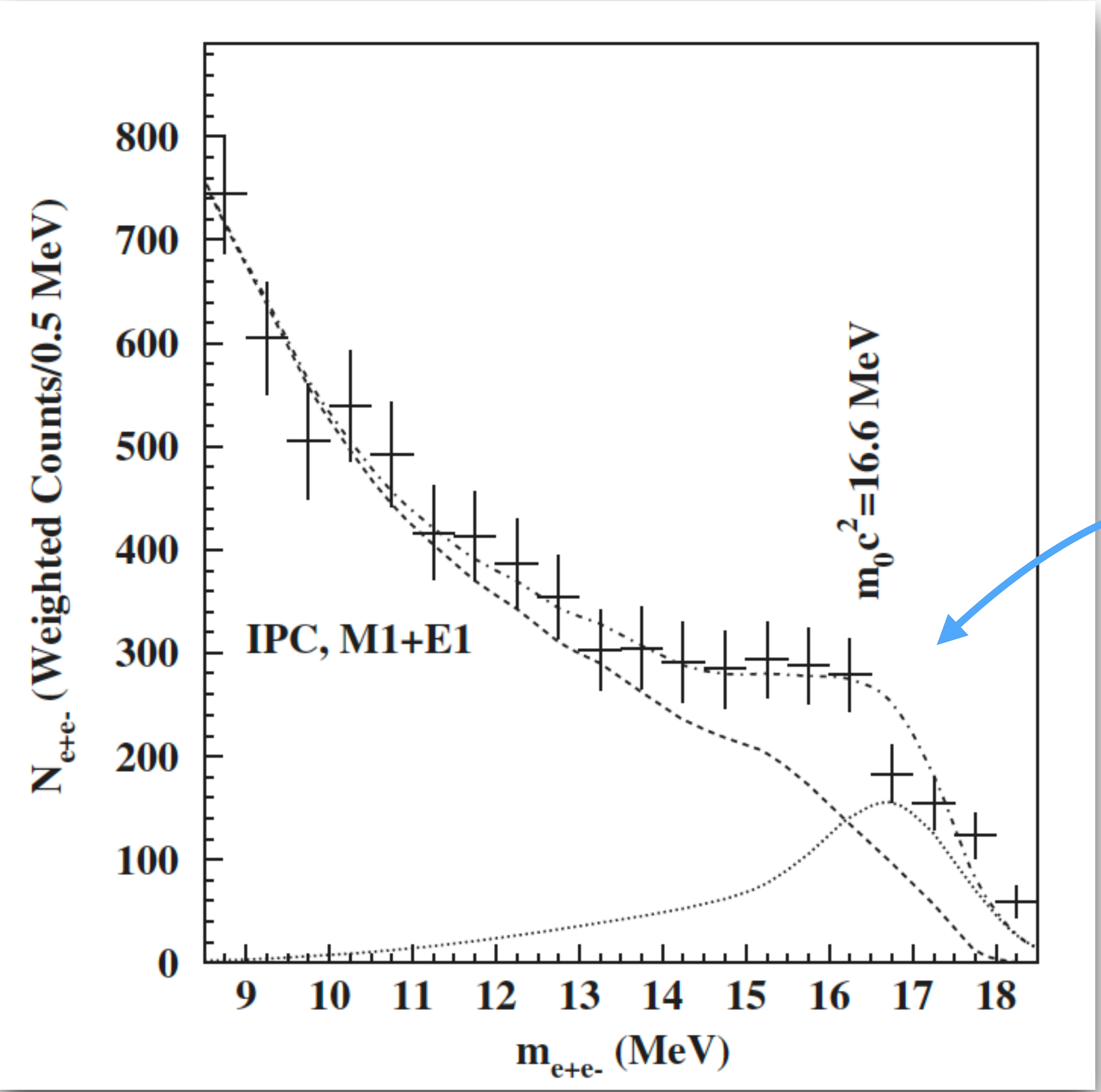

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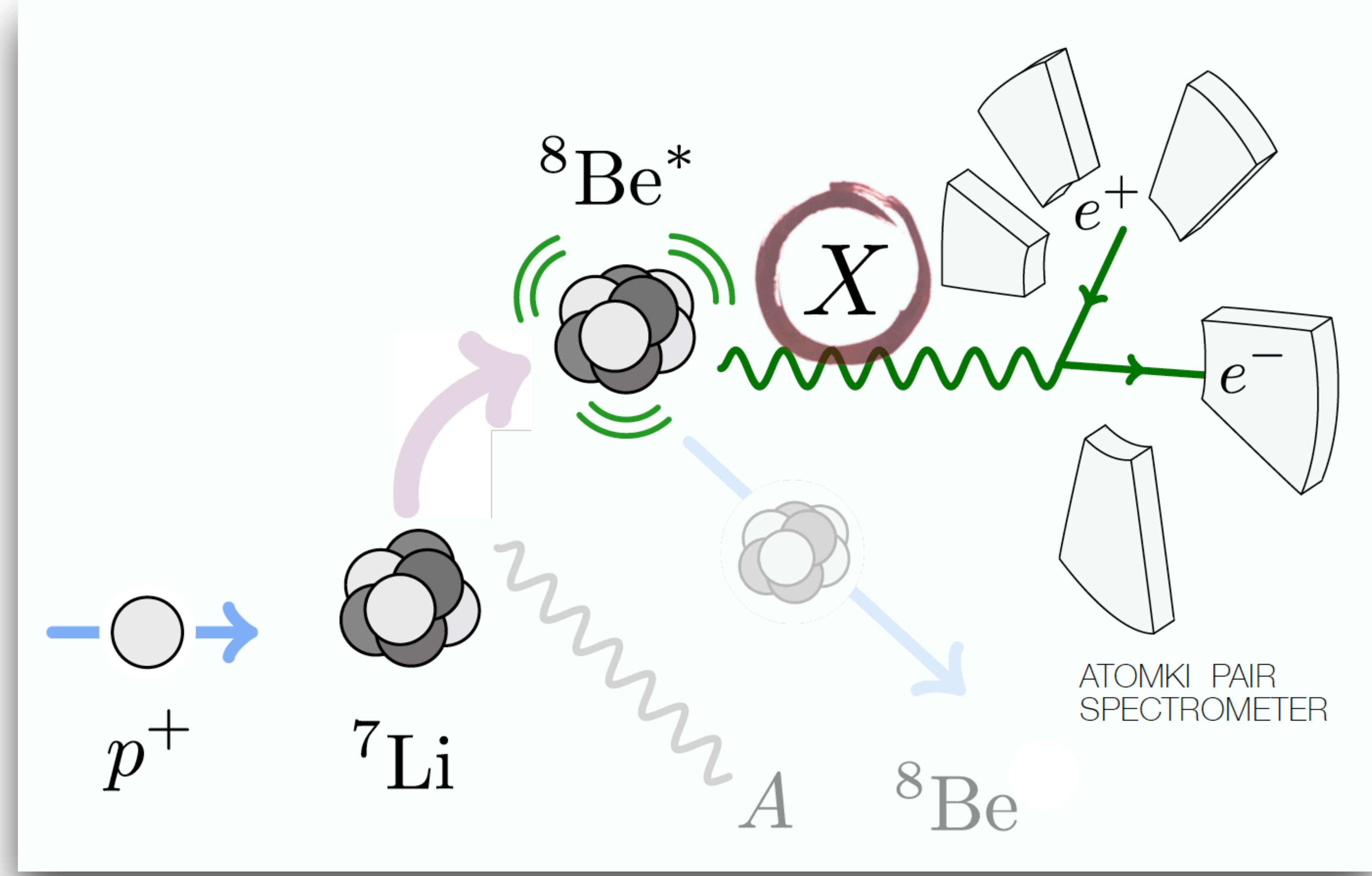

Authors claim that this is a 6.8 σ effect

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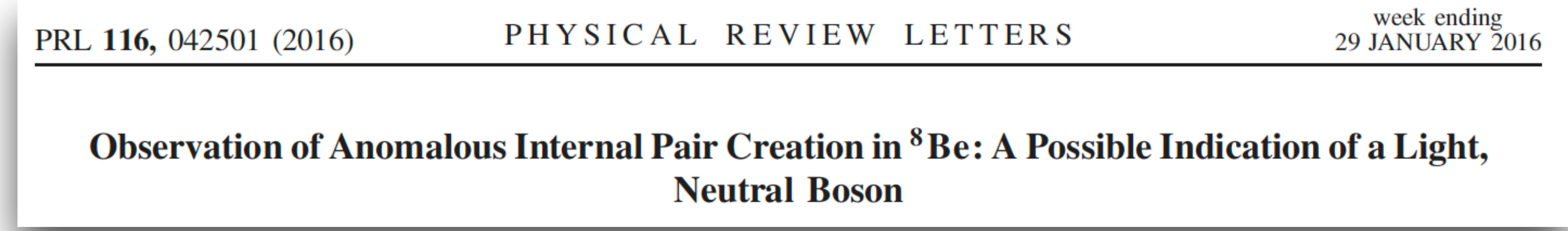
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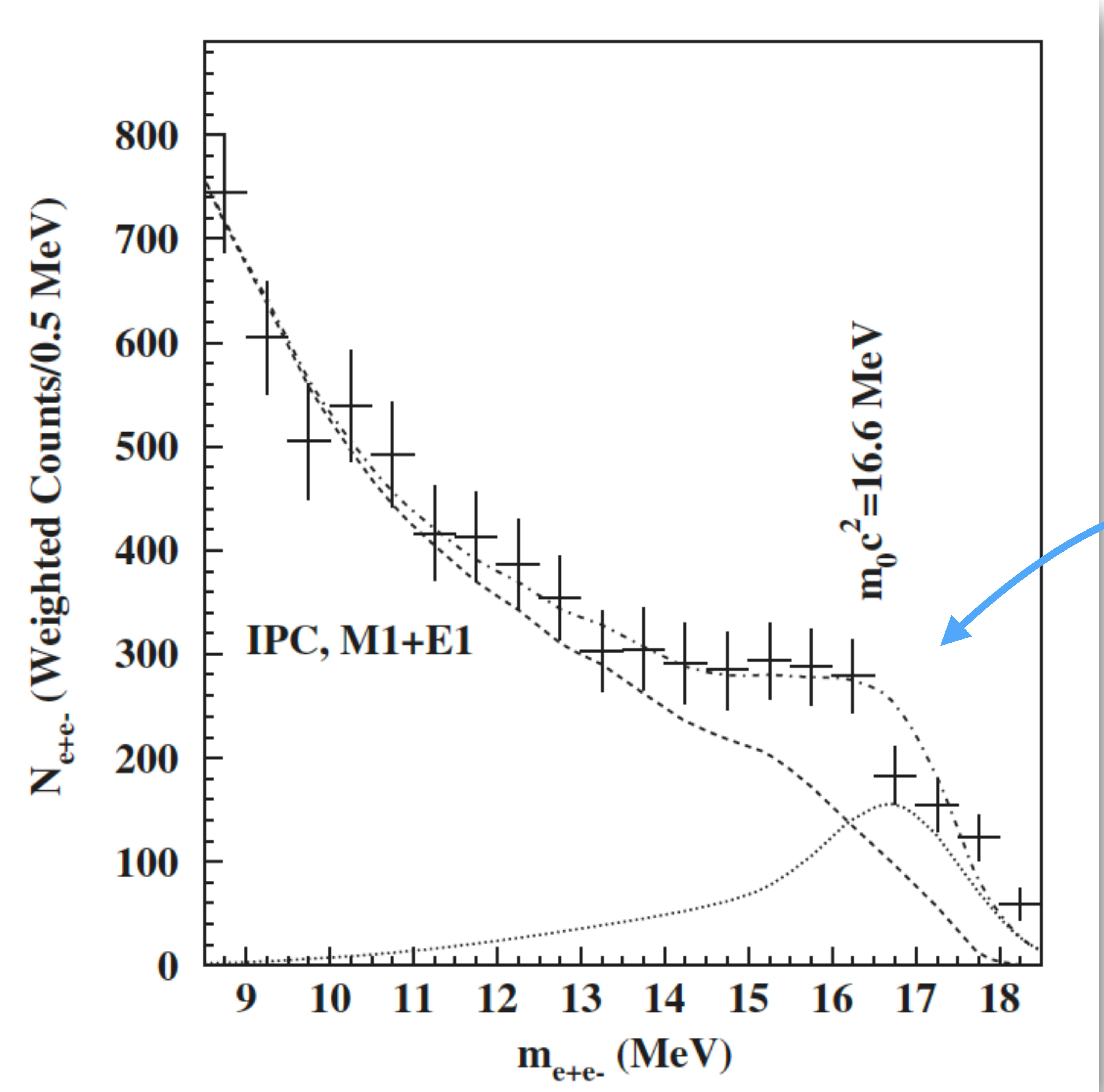

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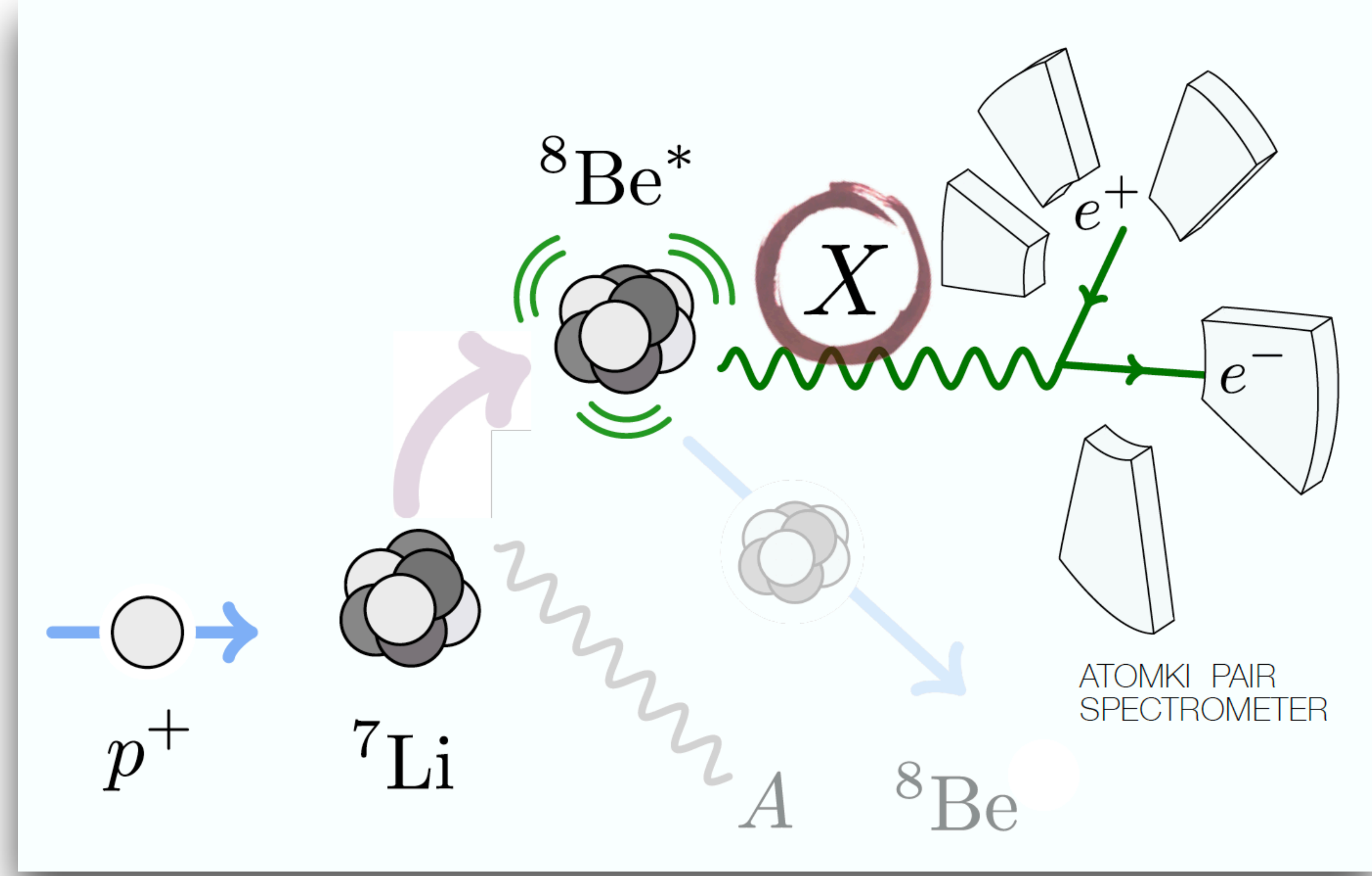

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Not clear what can be the origin:
Not compatible with dark Higgs (quantum numbers are wrong)
Not ALP (region ruled out by other experiments)
Not ‘standard’ dark photon …
May be a not so standard dark photon?

Hints of dark matter: Xenon 1T electron recoil

https://indico.cern.ch/event/868940/contributions/3814884

Time projection chamber
To measure scintillation light
from nuclear or electron recoil

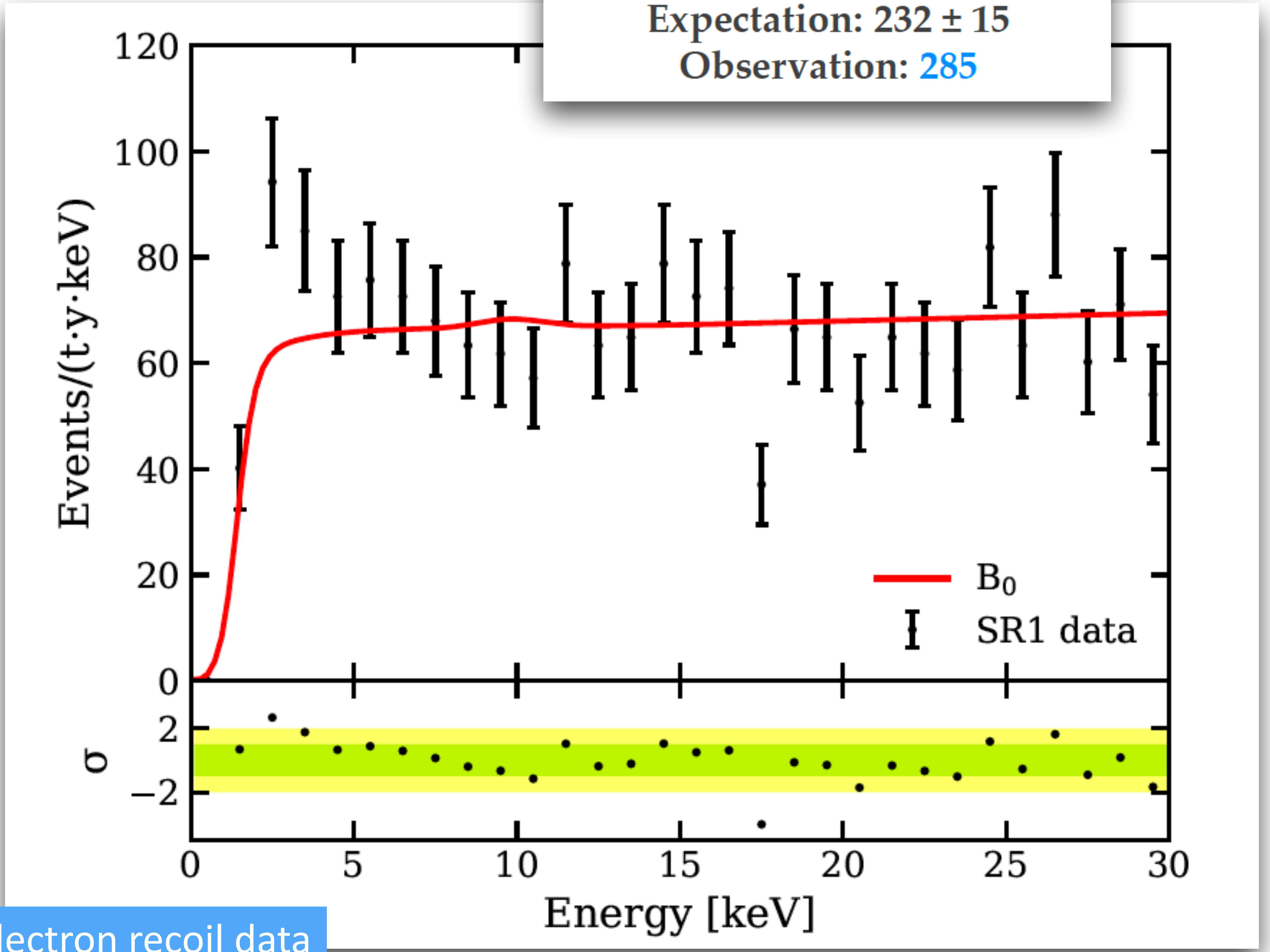
Hints of dark matter: Xenon 1T electron recoil

https://inspirehep.net/literature/1801701

https://indico.cern.ch/event/868940/contributions/3814884

Excess between 1 - 7 keV!

Expectation: 232 ± 15
Observation: 285



Electron recoil data

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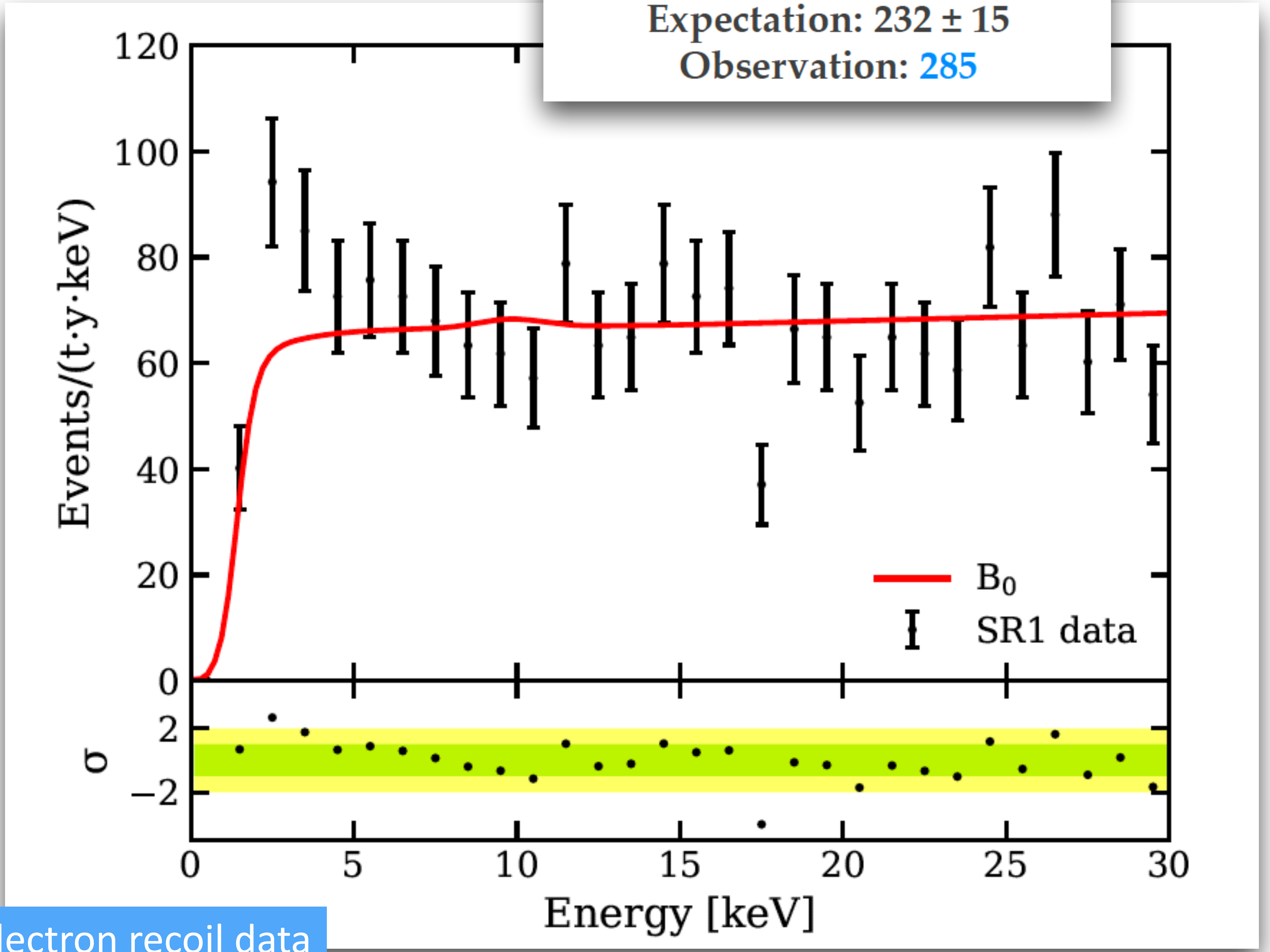

Electron recoil data

Authors explore the hypothesis of a solar axion, which fits, but is in conflict with stellar constraints.
Some experts (and the authors) point at a possible tritium contamination ….

Time projection chamber
To measure scintillation light
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Dark matter searches: axion-like particles at NA64

arXiv: 2005.02710

The $a - \gamma\gamma$ interaction is given by the Lagrangian

$$L_{int} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a, \quad (1)$$

where $g_{a\gamma\gamma}$ is the coupling constant, $F_{\mu\nu}$ is the photon field strength, $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$, and a is the axionlike particle field. For a generic axion, the coupling constant is

$$g_{a\gamma\gamma} = \left[0.203\frac{E}{N} - 0.39\right]\frac{m_a}{\mathrm{GeV}^2} \quad (2)$$

where E and N are the electromagnetic and color anomalies of the axial current associated with the axion [6–8]. In grand unified models such as DFSZ [3] and KSVZ [4], $E/N = 8/3$ and $E/N = 0$, respectively, while a broader range of E/N values is possible [7, 8]. For the scalar

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NA64: electron beam (100 GeV) dumped in a ECAL of Pb and Sc.
Looking for a single shower in ECAL and nothing else.
2.84 10e11 electrons … no candidates found.

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Using the Primakoff effect

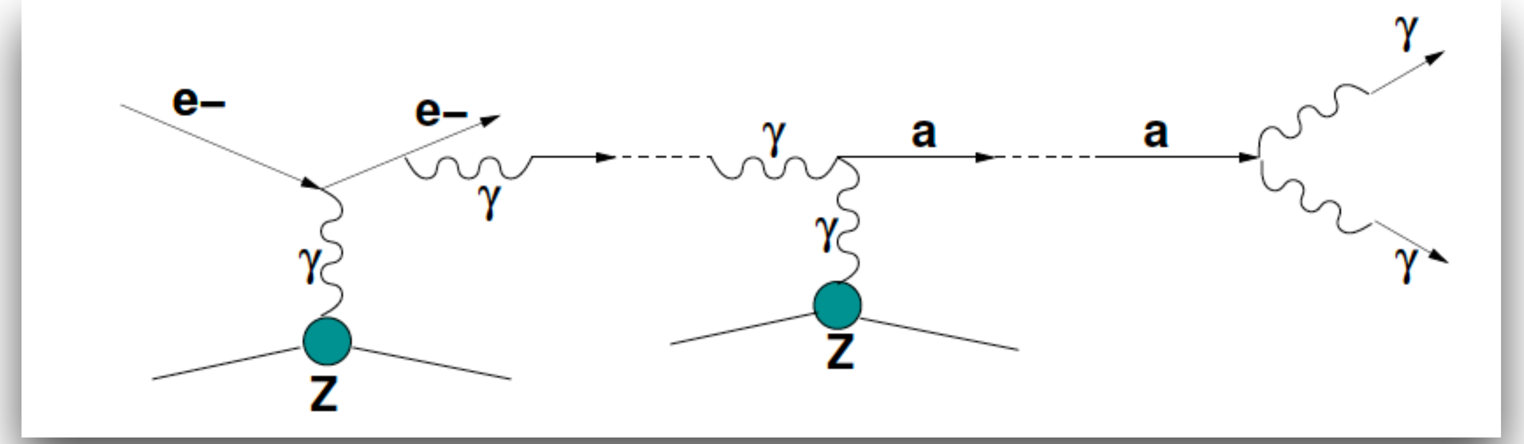

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TABLE I: Expected background for 2.84×10^{11} EOT.

Background source	Background, n_b
leading neutrons	0.02 ± 0.008
leading K^0 interactions and decays	0.14 ± 0.045
beam π, K charge exchange and decays	0.006 ± 0.002
dimuons	< 0.001
Total n_b	0.17 ± 0.046

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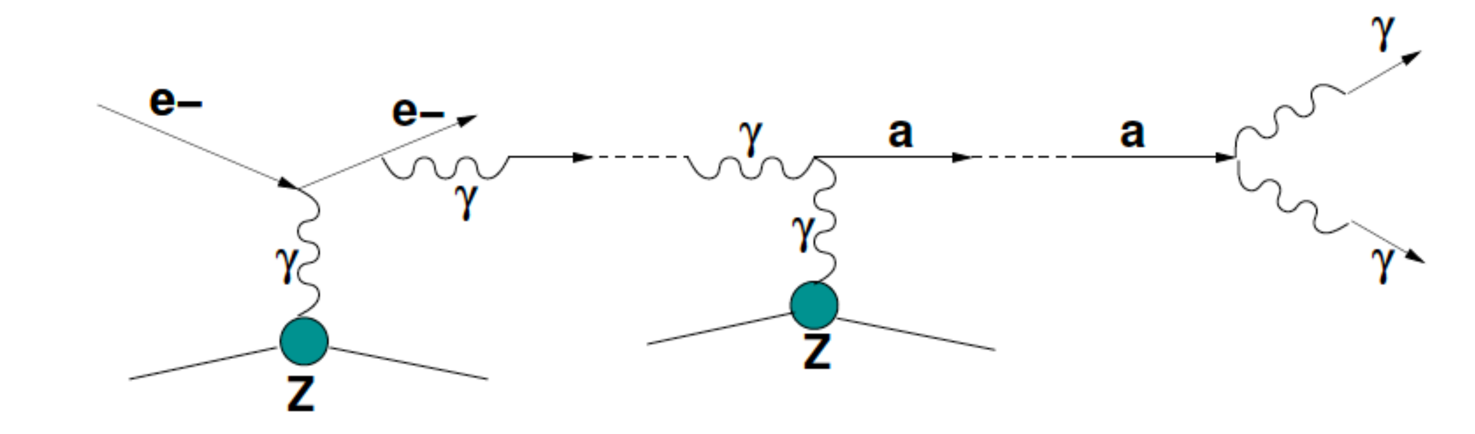

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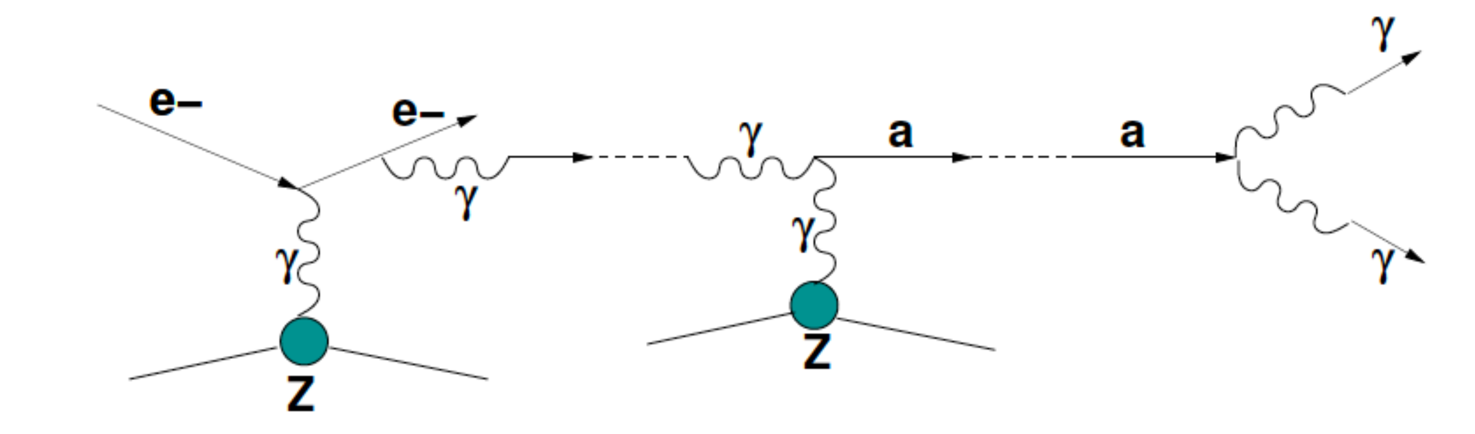

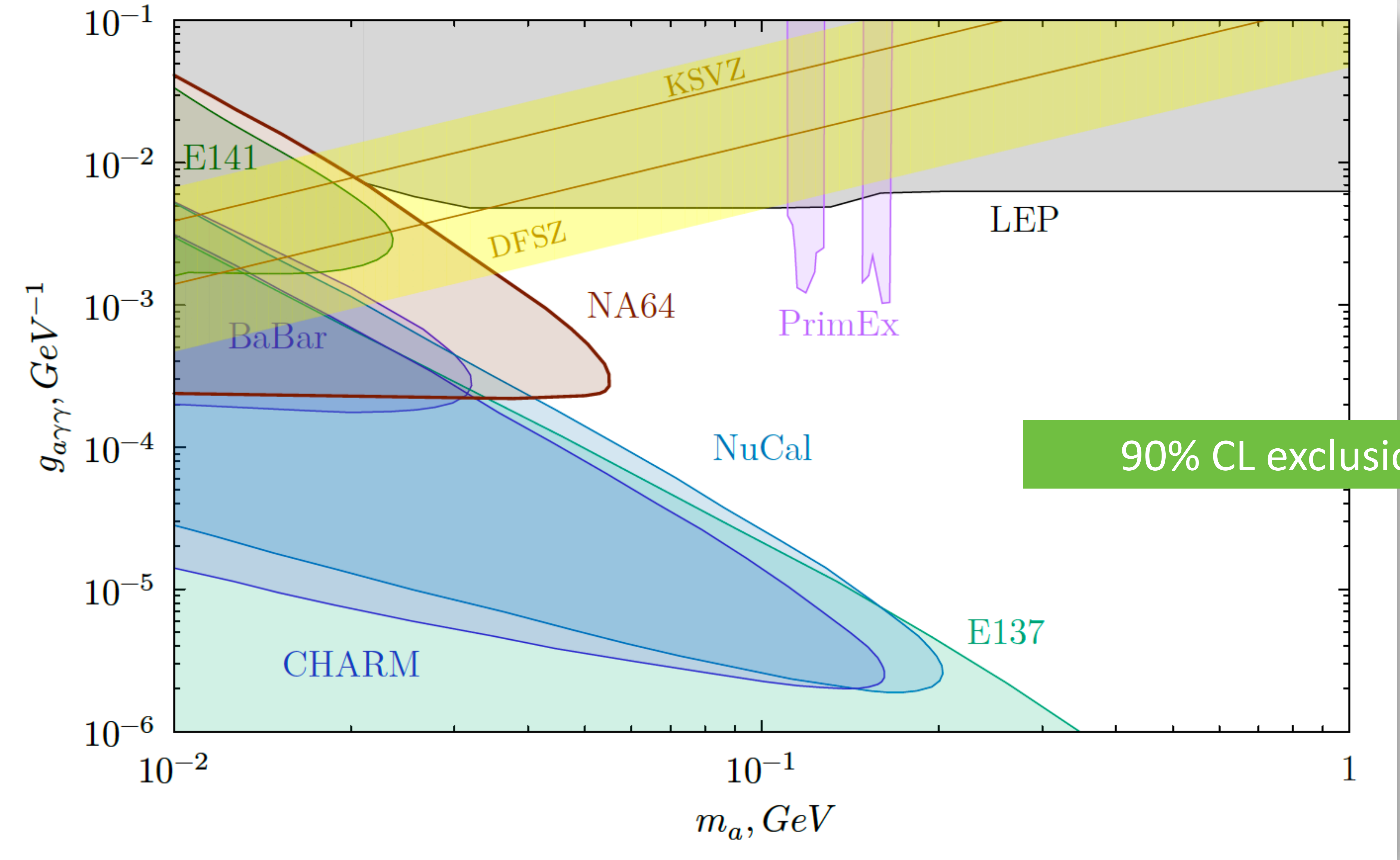

90% CL exclusion region

Dark matter searches: heavy neutral lepton at NA62

arXiv: 2005.09575

All Standard Model (SM) fermions except neutrinos are known to exhibit right-handed chirality. The existence of right-handed neutrinos, or heavy neutral leptons (HNLs), is hypothesised in many SM extensions in order to generate non-zero masses of the SM neutrinos via the seesaw mechanism [1]. For example, the Neutrino Minimal Standard Model [2] simultaneously accounts for dark matter, baryogenesis, and neutrino masses and oscillations by postulating two HNLs in the MeV–GeV mass range and a third HNL, a dark matter candidate, at the keV mass scale.

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NA62: kaon beam of 75 GeV/c

Decay of $K^+ \to e^+ N$

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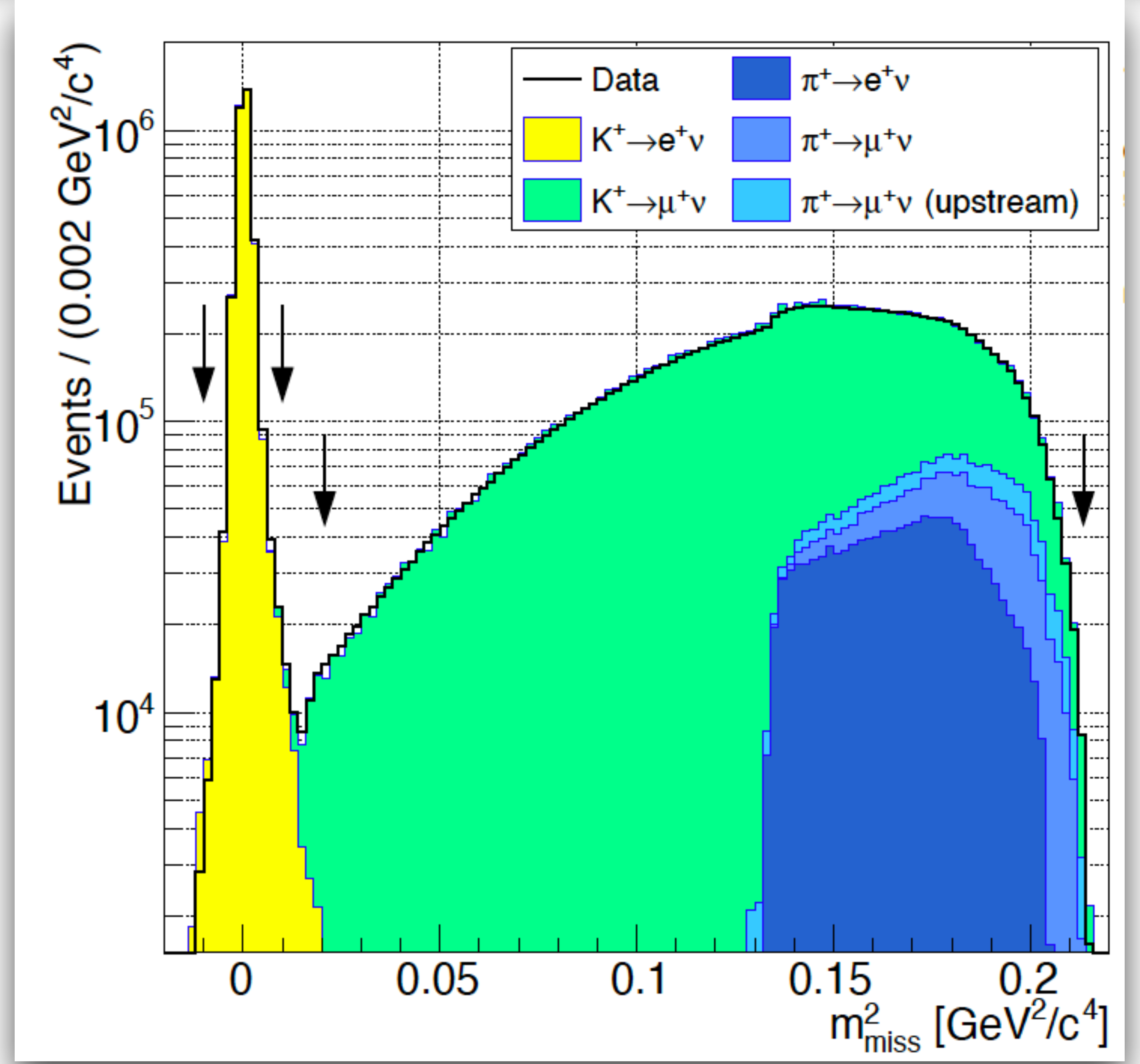

Upper arrows: SM region

Lower arrows: search region

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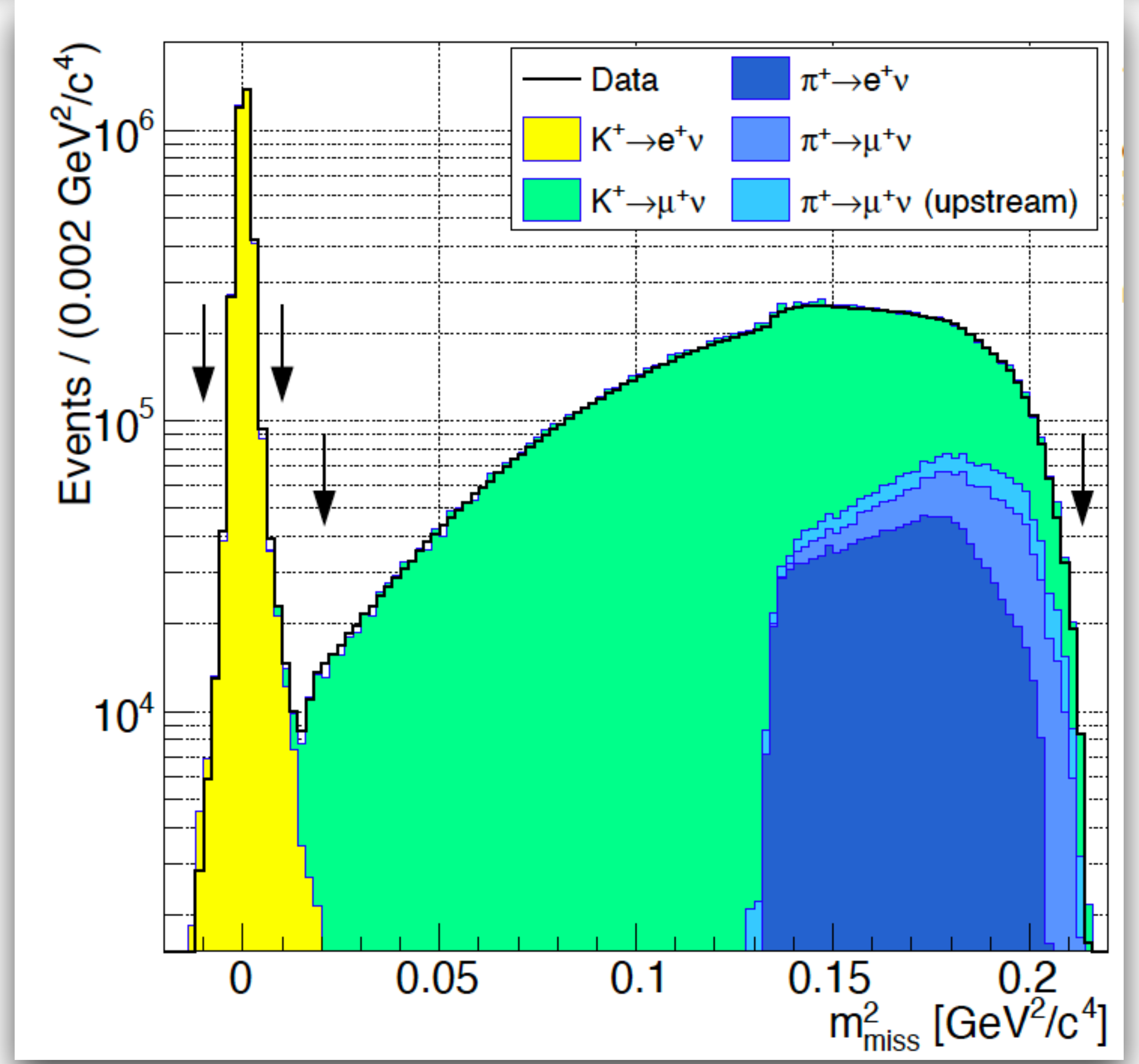

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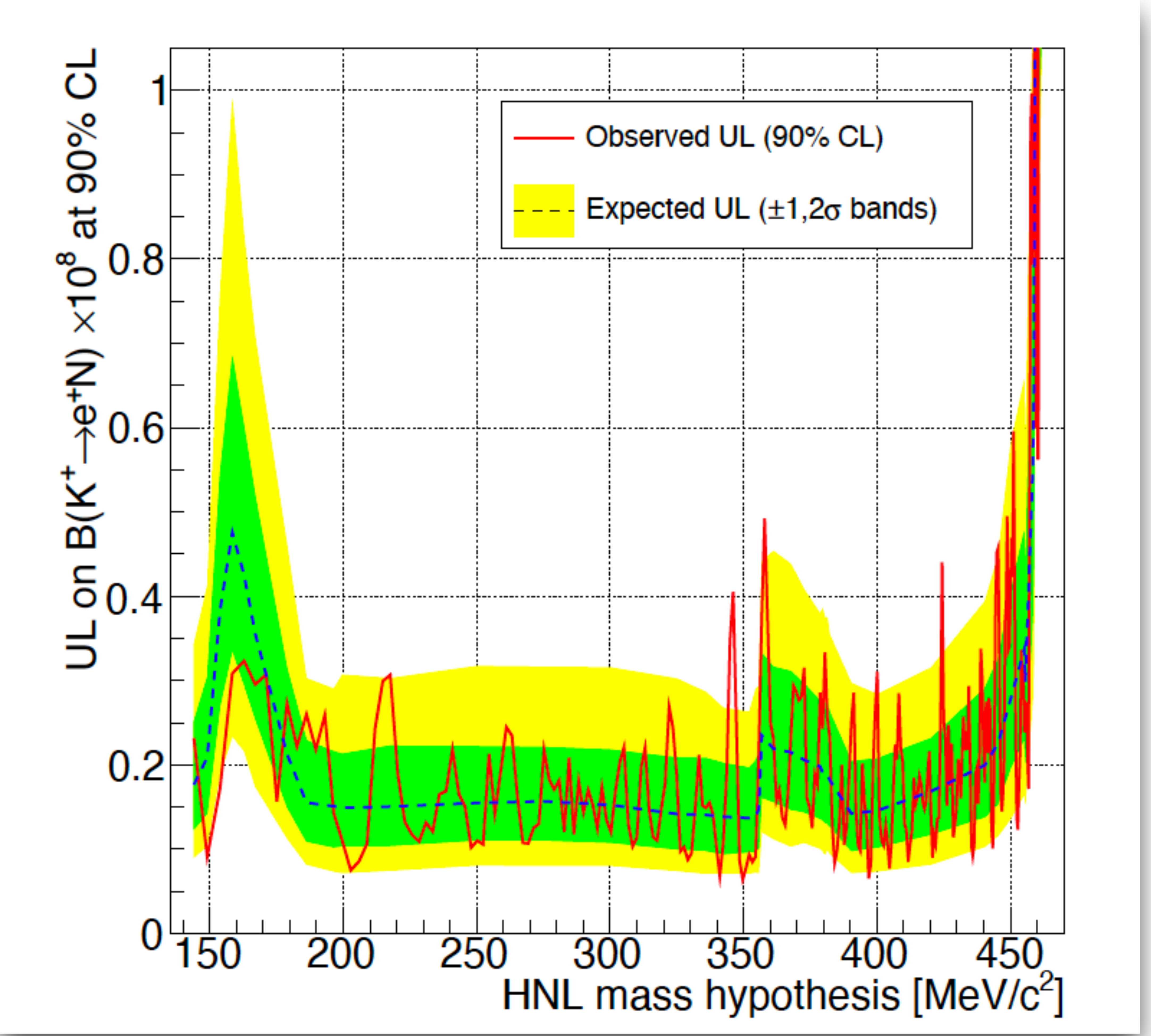


Dark matter searches: dark photon at NA62

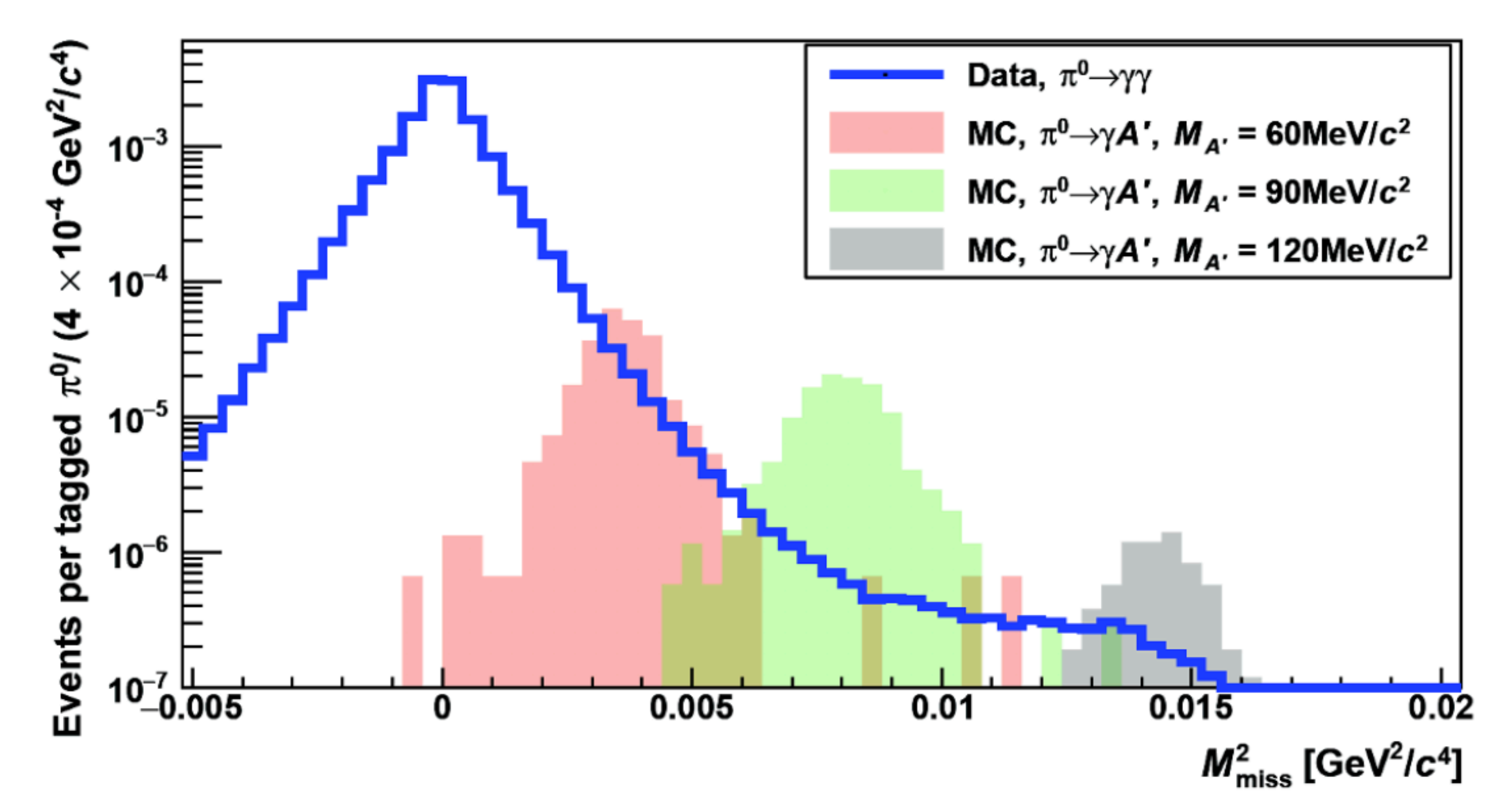
JHEP 05 (2019) 182

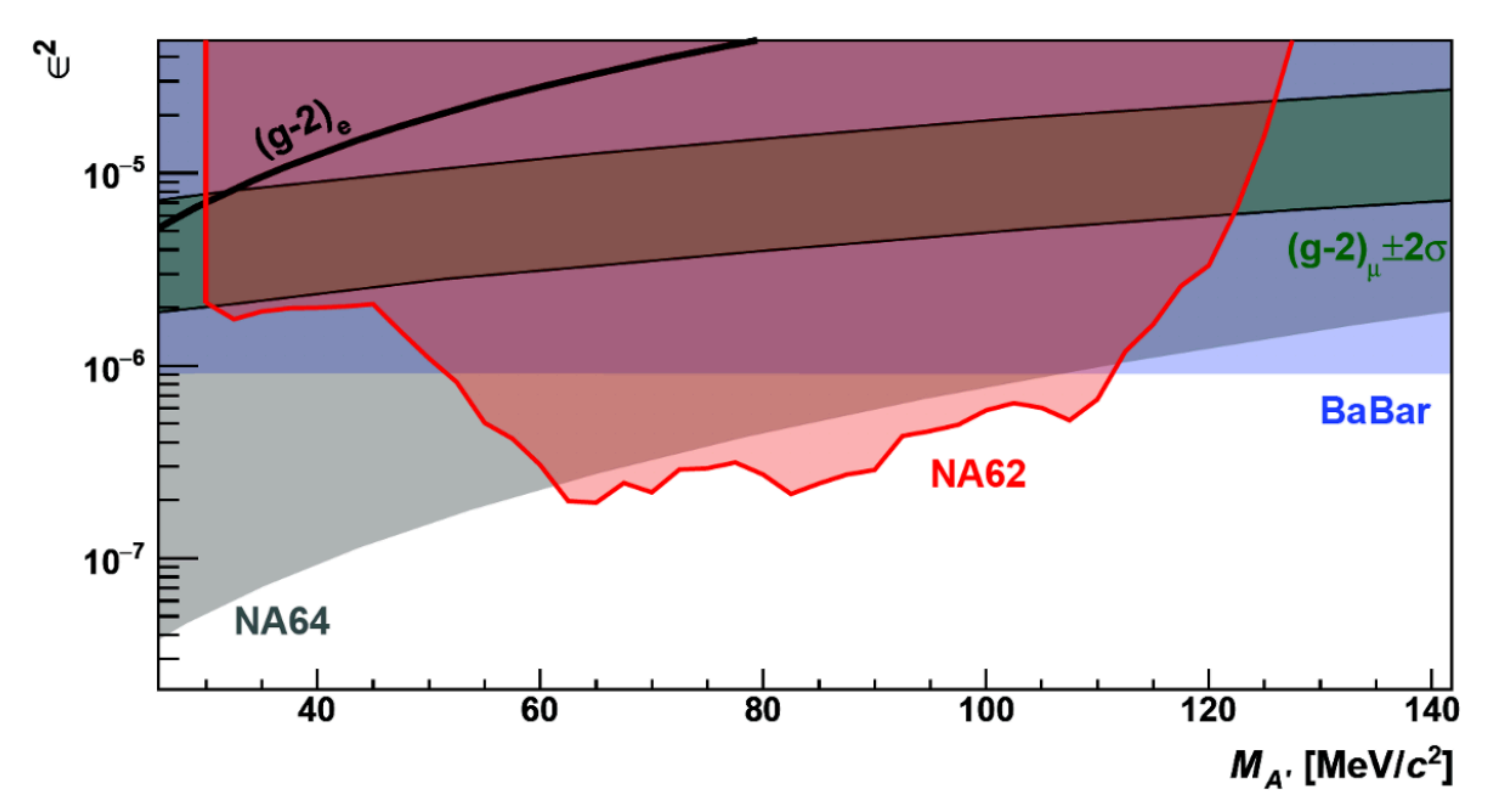
Select pure π0 sample from the K+ and π+
Search for a photon in this sample

$$M^2_{\text{miss}} = (P_K - P_\pi - P_\gamma)^2$$

NA62: kaon beam of 75 GeV/c

$$K^+ \to \pi^+\pi^0, \quad \pi^0 \to A'\gamma.$$





90% CL

Dark matter searches: ALP at Belle2

arXiv:2007.1307

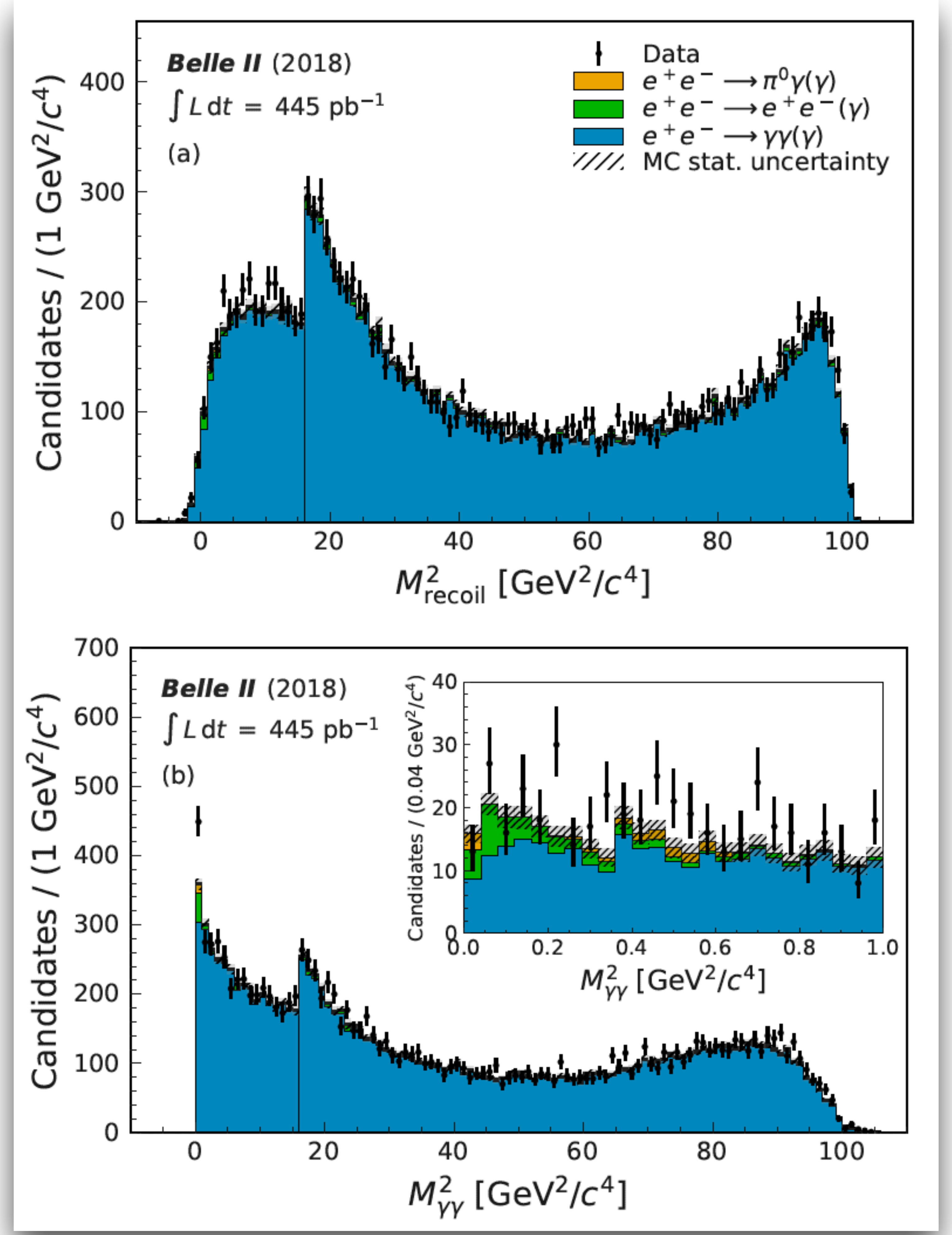
Belle 2: electron-positron collider at 10.58 GeV (mass of the Υ(4S) resonance)

$$e^+e^- \to \gamma a, a \to \gamma\gamma$$

Dark matter searches: ALP at Belle2

arXiv:2007.1307

Select events either with a single monoenergetic photon or reconstruct the invariant mass of the di-photon system



Belle 2: electron-positron collider at 10.58 GeV (mass of the Y(4S) resonance)

$$e^+e^- \to \gamma a,\ a \to \gamma\gamma$$

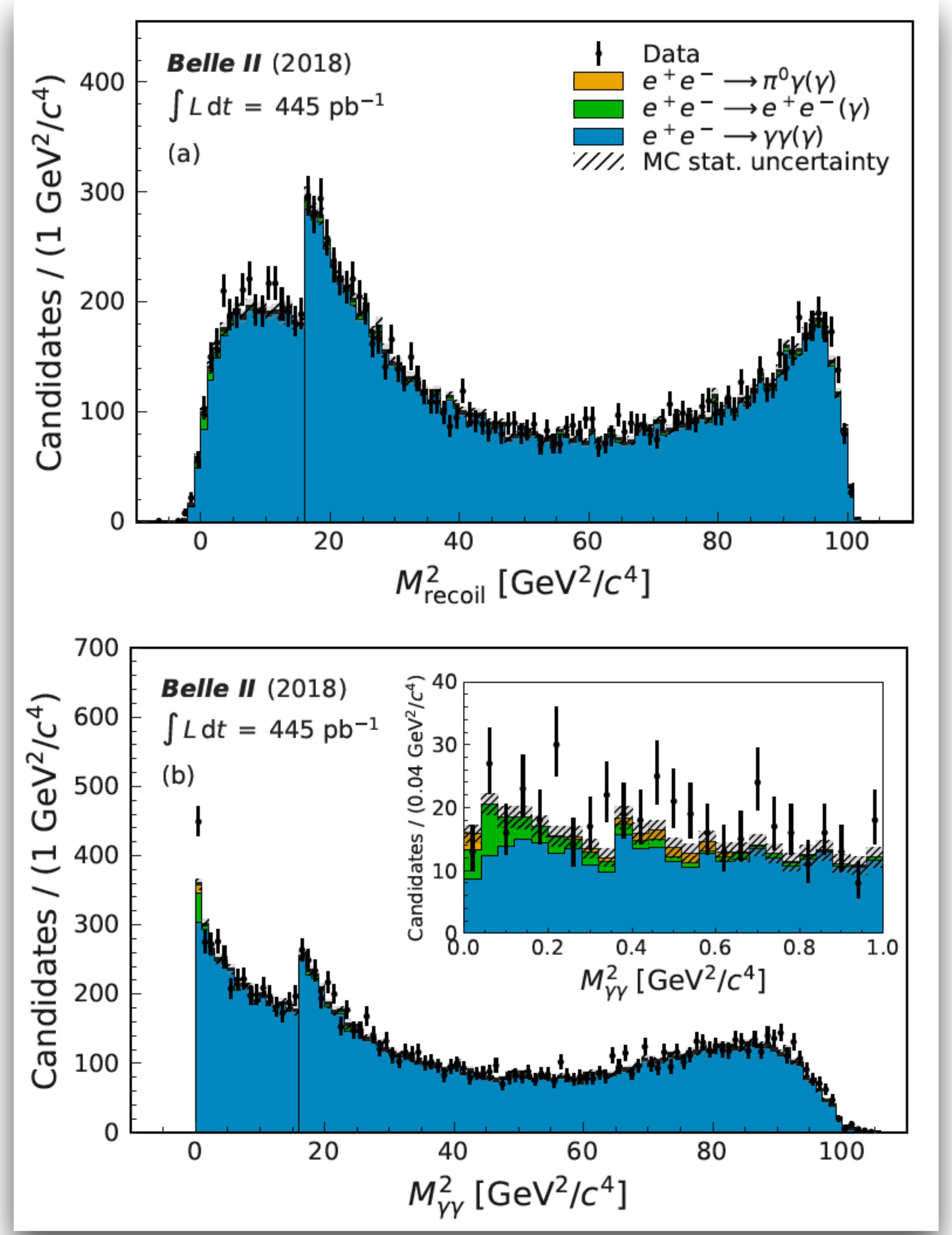
Dark matter searches: ALP at Belle2

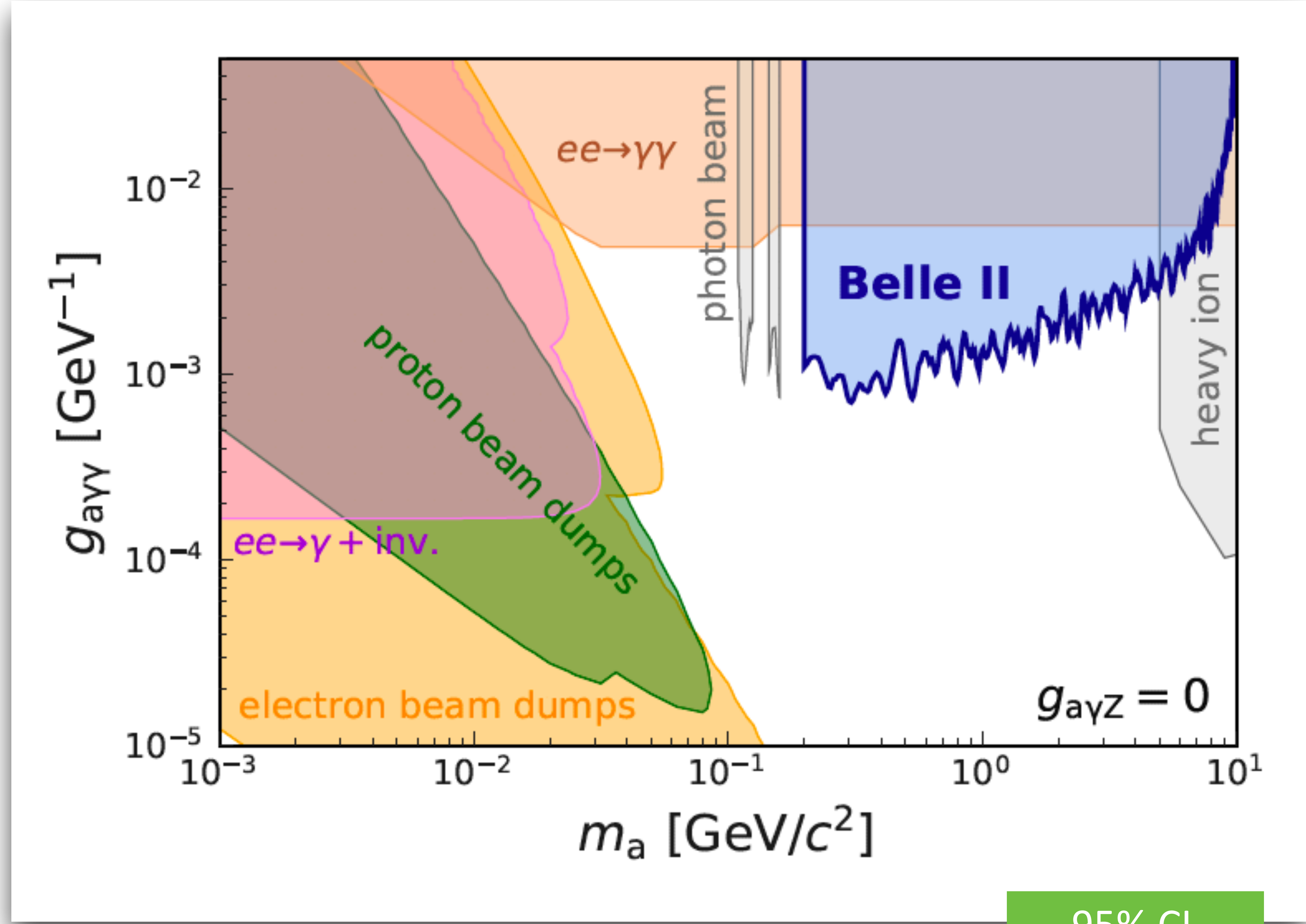
arXiv:2007.1307

Select events either with a single monoenergetic photon or reconstruct the invariant mass of the di-photon system

Belle 2: electron-positron collider at 10.58 GeV (mass of the Υ(4S) resonance)

$$e^+e^- \to \gamma a,\ a \to \gamma\gamma$$





95% CL

Dark matter searches: LHCb, A’→μ+μ-

PHYSICAL REVIEW LETTERS 124, 041801 (2020)

Search for prompt and long lived dark photons

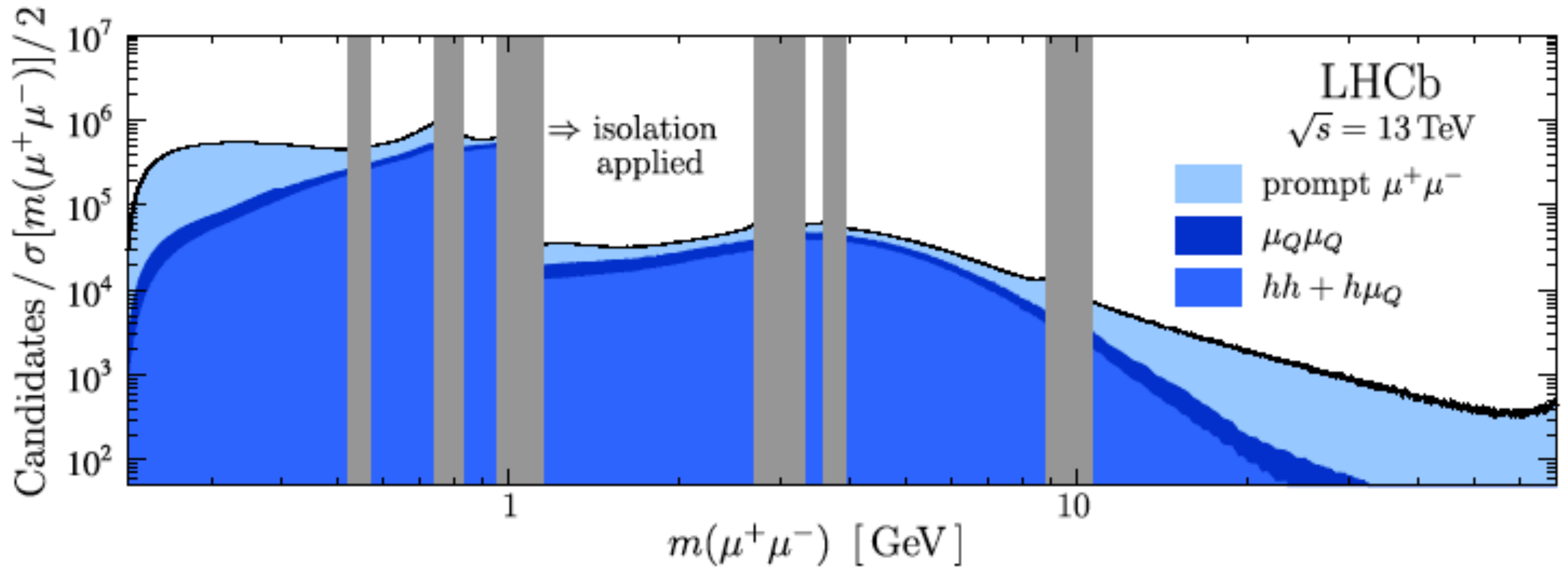


FIG. 1. Promptlike mass spectrum, where the categorization of the data as prompt $\mu^+\mu^-$, $\mu_Q\mu_Q$, and $hh + h\mu_Q$ is determined using the min$[\chi^2_{\rm IP}(\mu^\pm)]$ fits described in the text (examples of these fits are provided in the Supplemental Material [97]). The anti-k_T-based isolation requirement is applied for $m(A') > 1.1$ GeV.

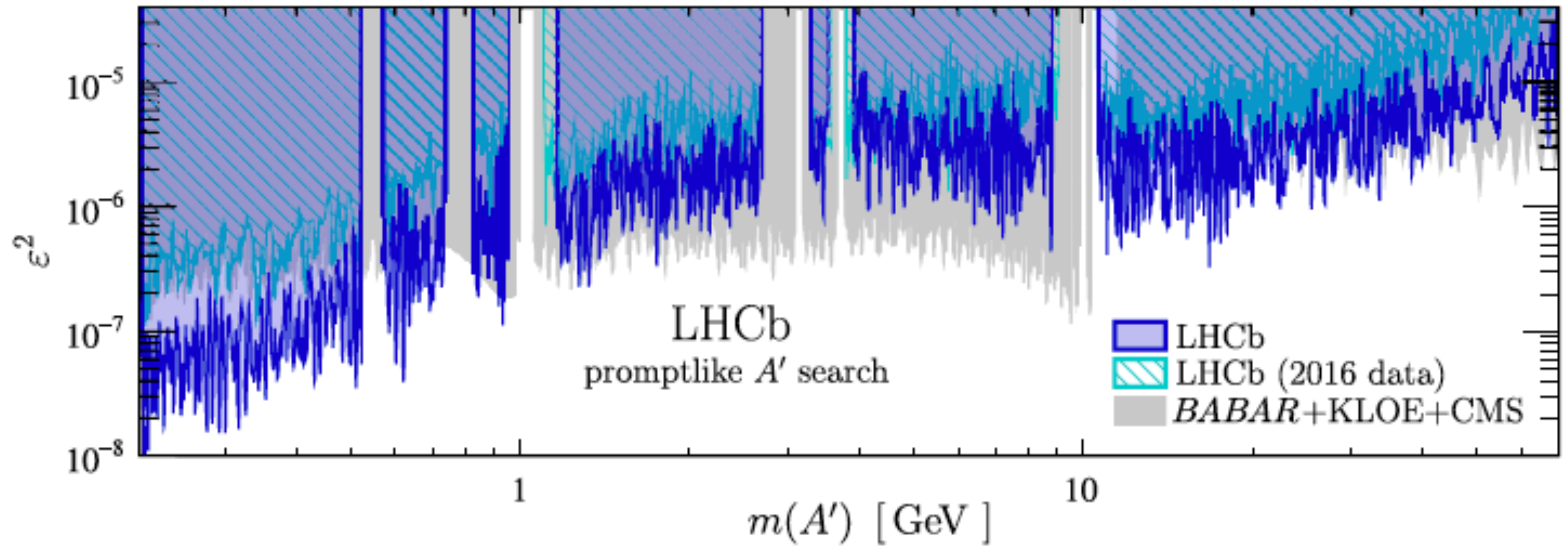
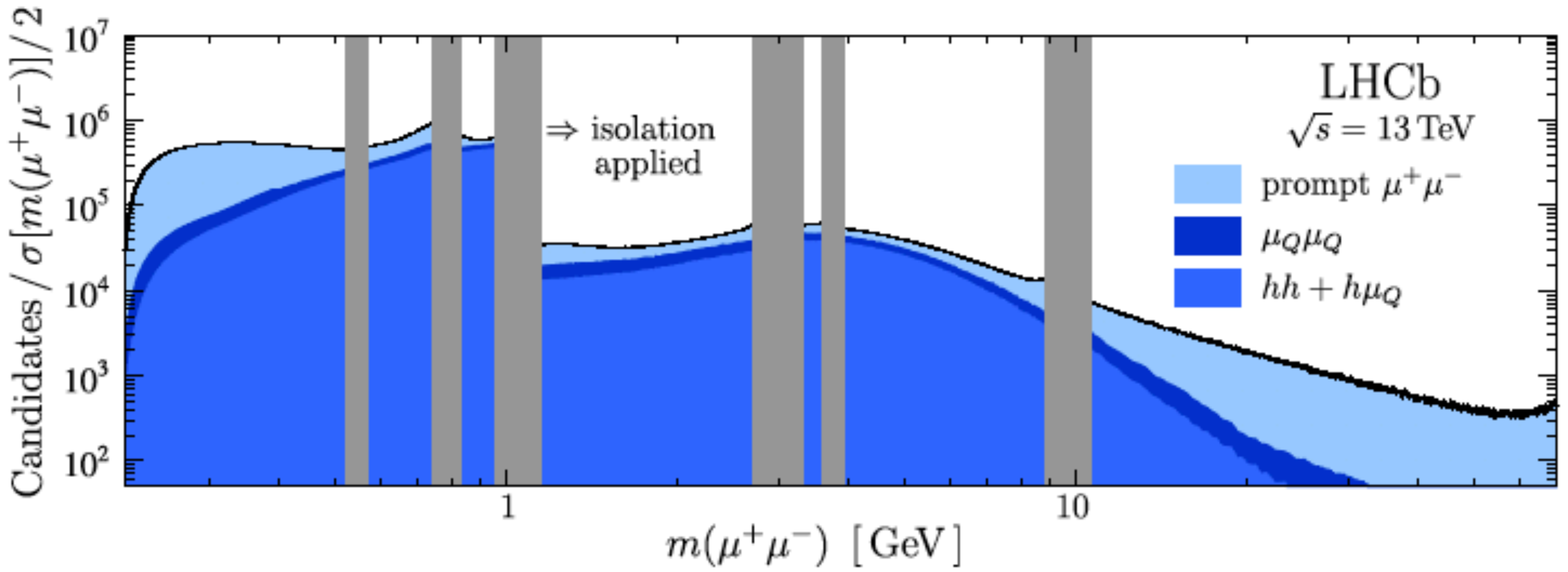


FIG. 2. Regions of the $[m(A'), \varepsilon^2]$ parameter space excluded at 90% C.L. by the promptlike A' search compared to the best published [35,38,83] and preliminary [102] limits.

Dark matter searches: LHCb, A'→μ+μ-

PHYSICAL REVIEW LETTERS 124, 041801 (2020)

Search for prompt and long lived dark photons



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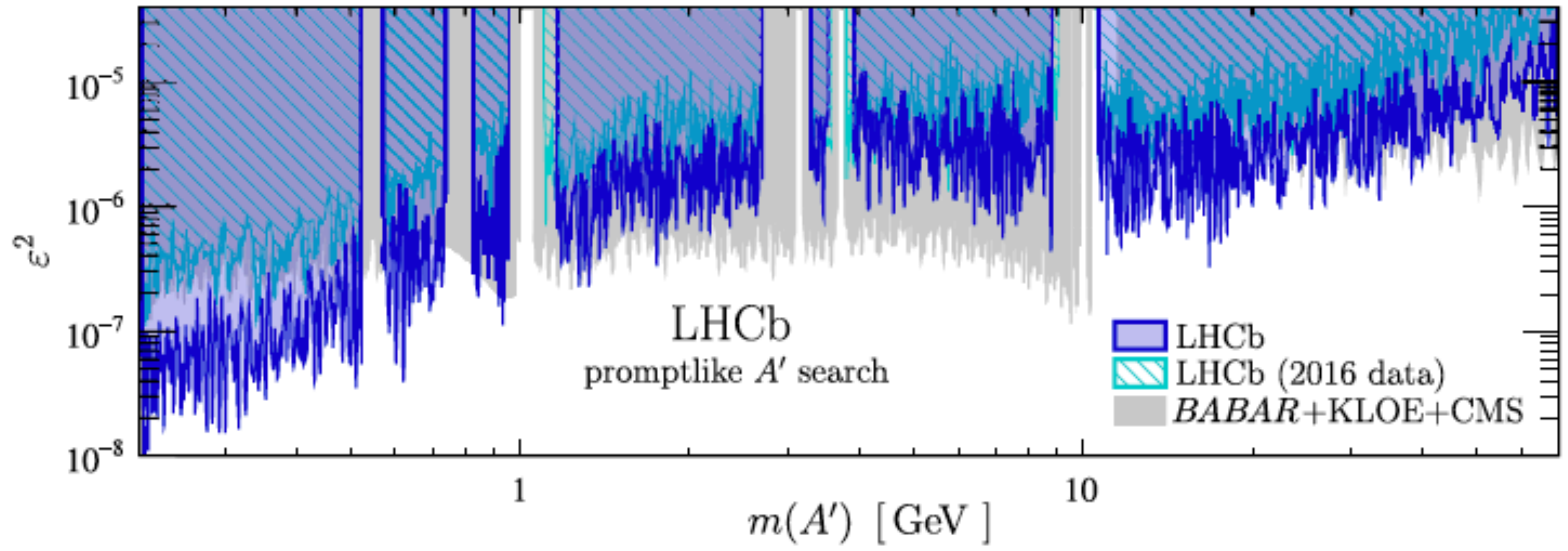
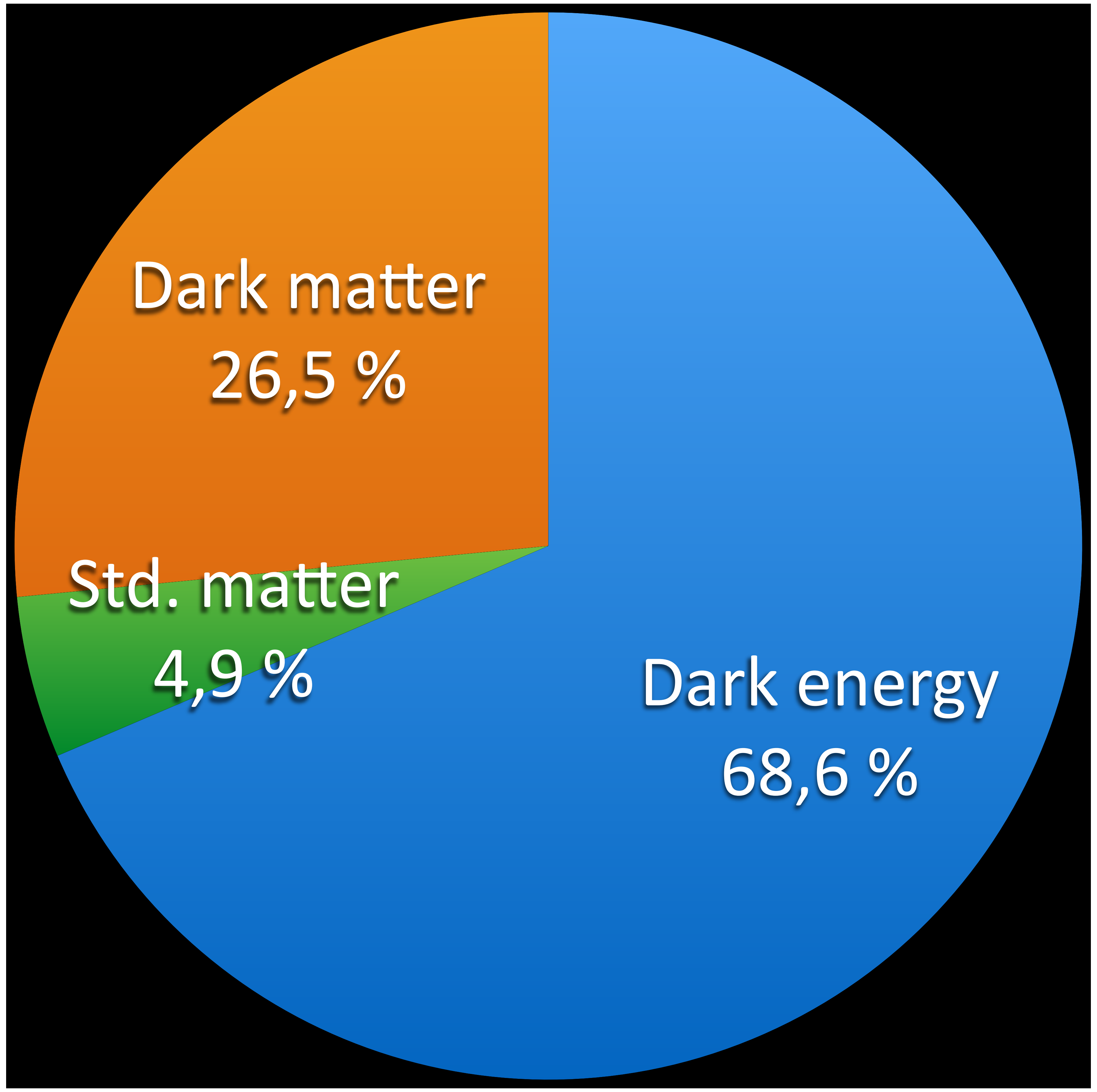


FIG. 2. Regions of the $[m(A'), \varepsilon^2]$ parameter space excluded at 90% C.L. by the promptlike A' search compared to the best published [35,38,83] and preliminary [102] limits.

90% CL

Instead of a summary ….



Based on applications of gravity to astrophysical scales (larger than 10 Mpc≈3 M light years≈ $3x10^{24}$ cm)

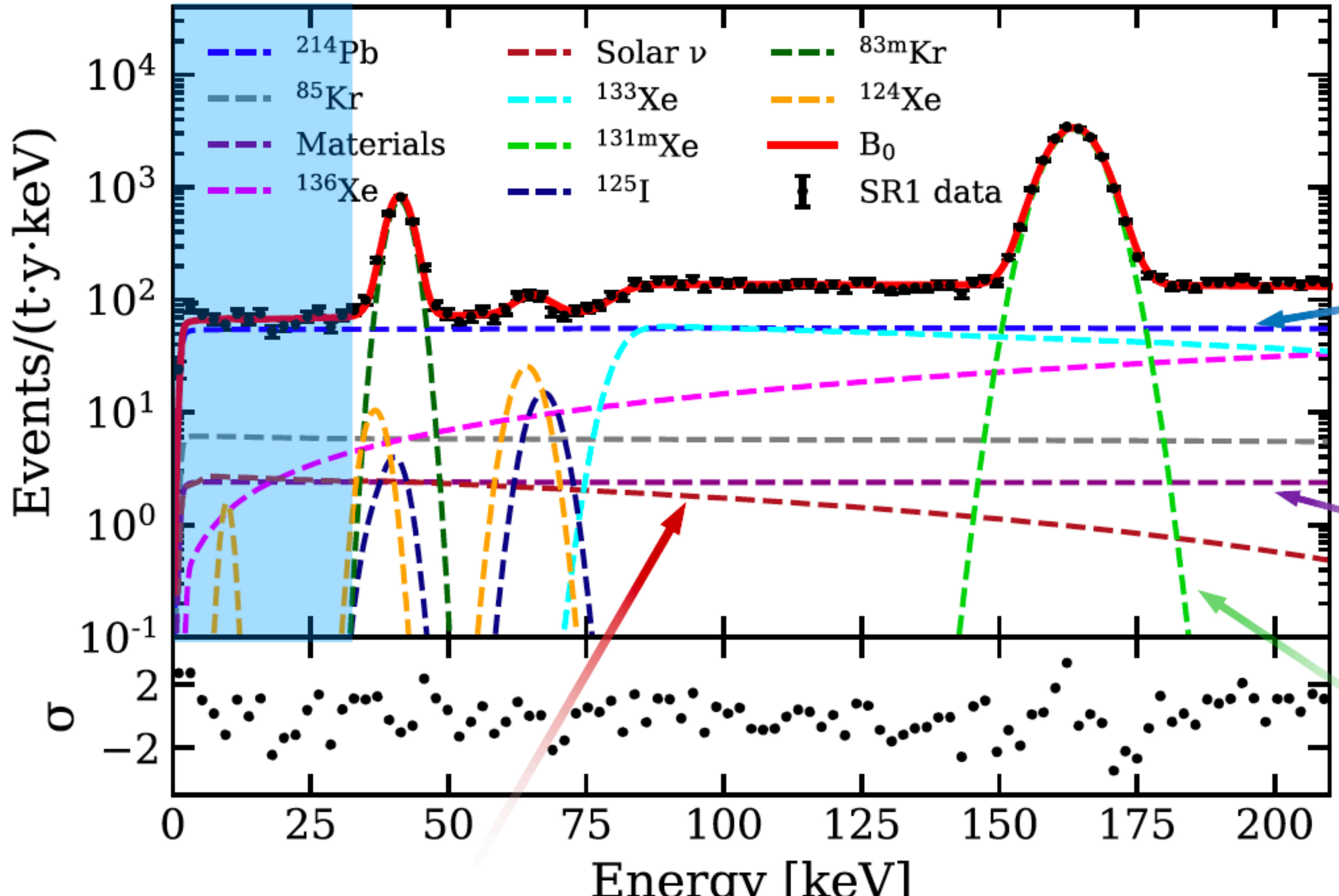
Assumes that all is ok with our use of gravity to build the cosmological model and assuming that all is ok with the related measurements

Beyond gravity there are hints of DM and many searches ….
… it is a very active field …

Extra slides

Hints of dark matter: Xenon 1T electron recoil

https://indico.cern.ch/event/868940/contributions/3814884



Solar neutrinos

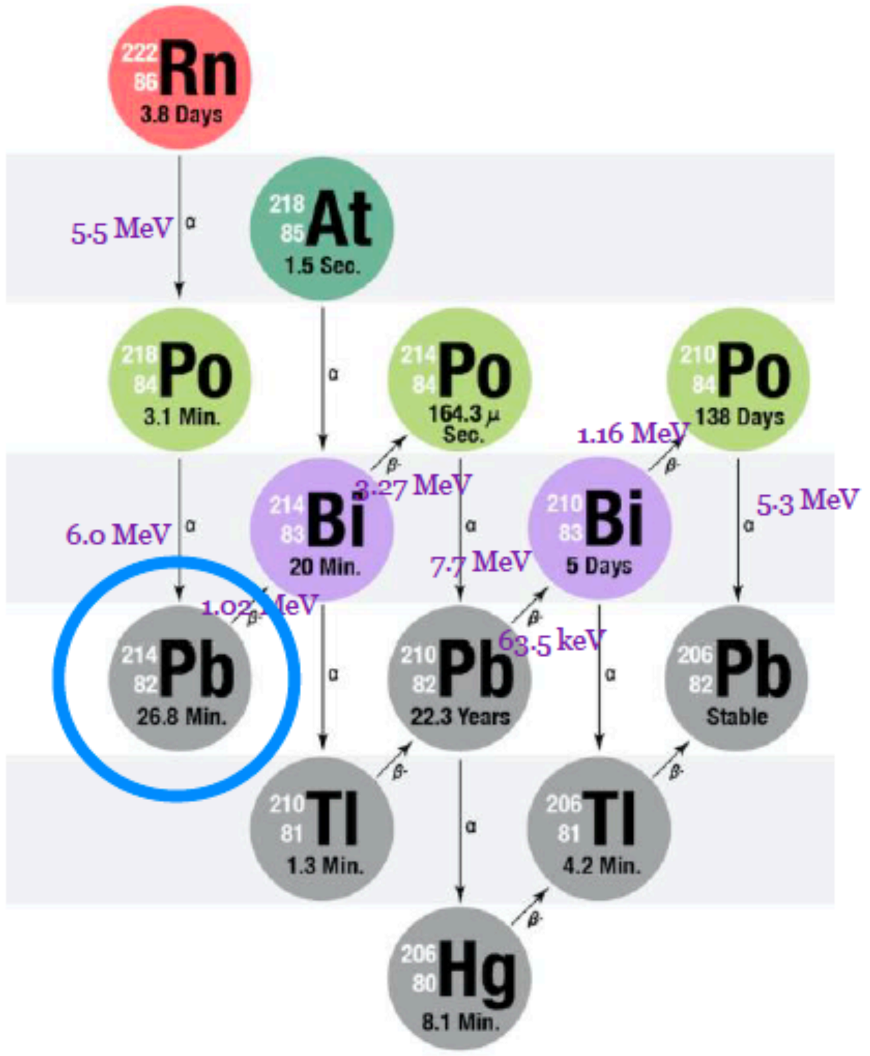
Intrinsic backgrounds

^{214}Pb, ^{136}Xe, ^{124}Xe, ^{83m}Kr, ^{85}Kr

Detector materials γ

Neutron activation

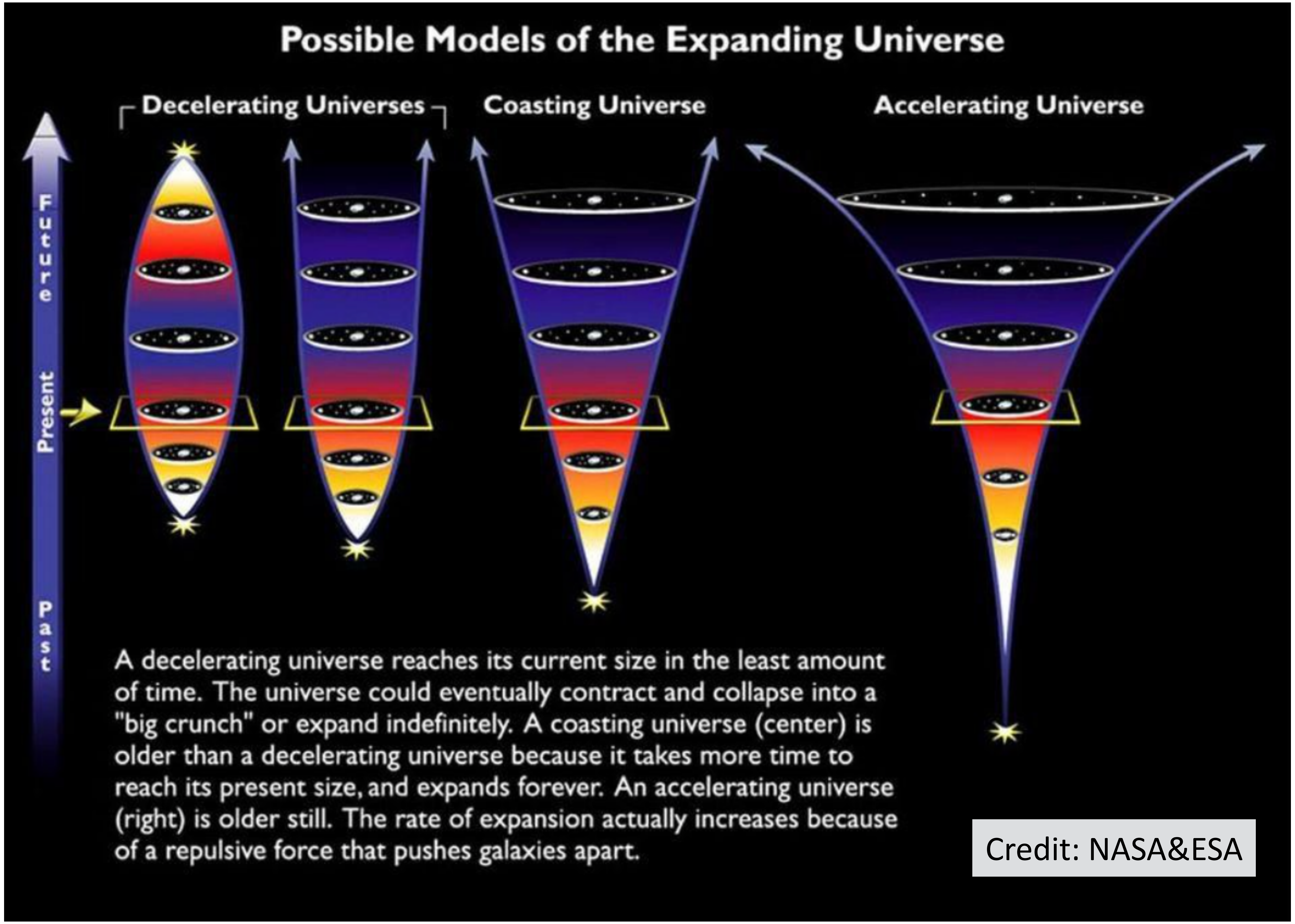
^{131m}Xe, ^{133}Xe, ^{125}I



- Good match between MC and data
- Predicted background spectra based on Geant4 simulations smeared with detector effects

Use lowest background rate ever achieved (76 +/- 2) events/(t·y·keV) in [1, 30] keV to search for excesses in the ER band!

Dark Energy



Credit: NASA&ESA

It does not clump
It seems to be homogeneous
It accounts for ≈68% of he energy budget of the universe

The density of dark energy remains constant while the universe expands!
(Matter/radiation density decays)
(at least in the last 9 billion years)

This behaviour is like a cosmological constant. We know this from baryon acoustic oscillations, (1±0.08, with one being a cosmological constant)

Universe is dominated by dark energy today, but some 9 billion years ago it was negligible, and some 6 billion years ago it was equal to the density of dark matter