Karlsruhe Institute of Technology

Searches for new physics

JENNIFER2 summer school (virtual) 26 July 2021

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to search (verb):

“to look somewhere carefully in order to find something”

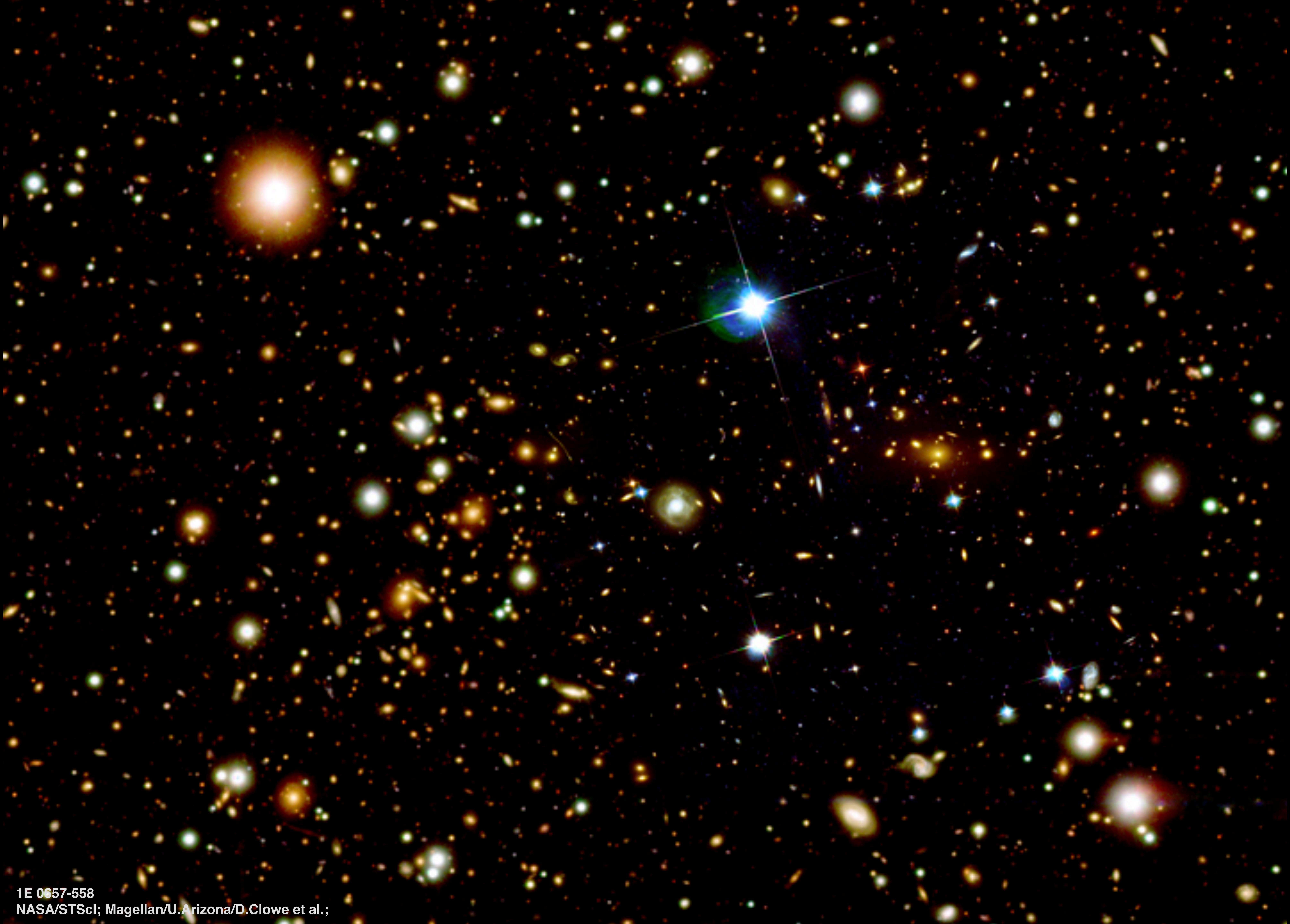
(Cambridge Dictionary)

Overview

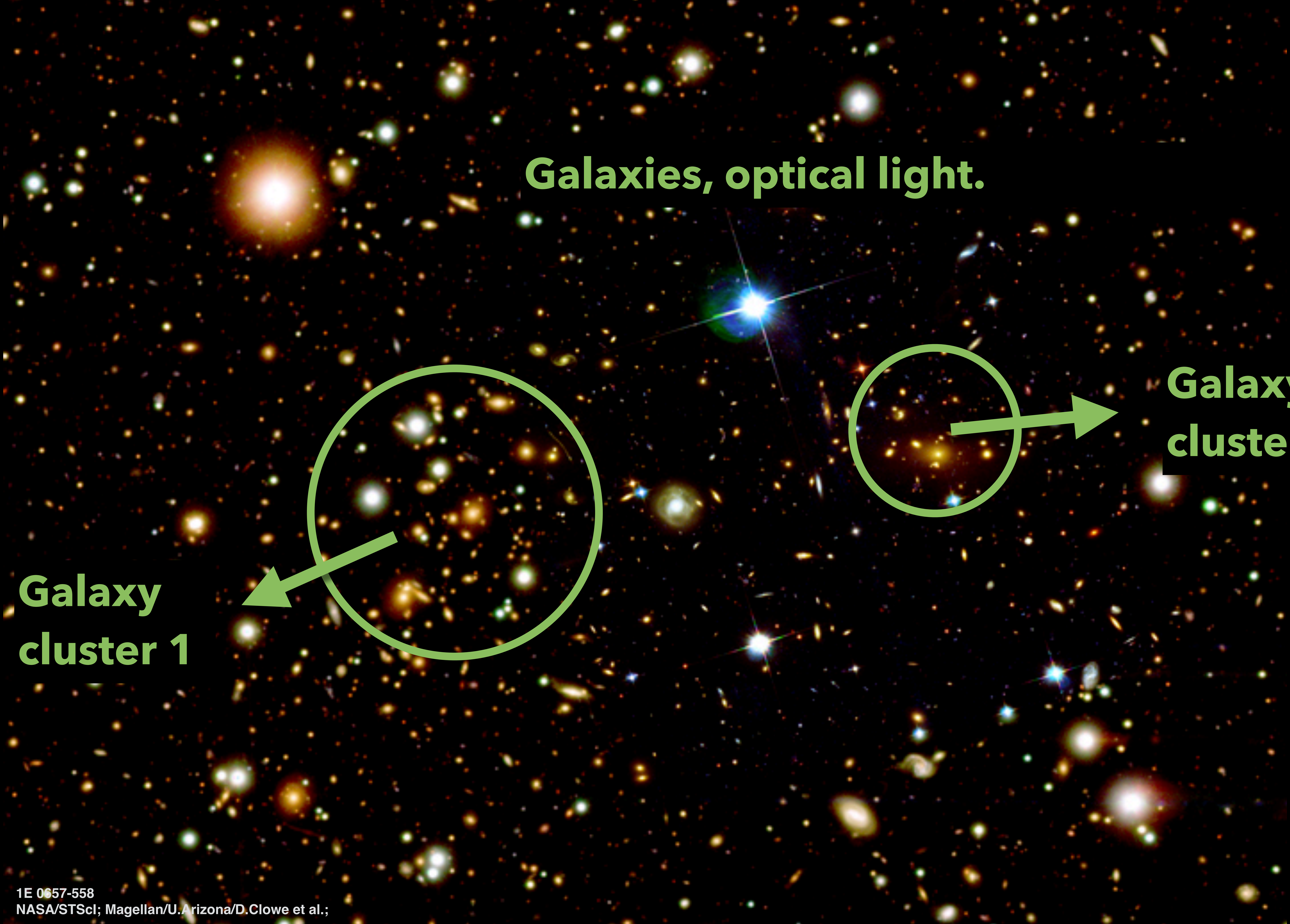
- Motivation:
  - Dark Matter
  - g-2
- Searches 101
- Portal models
  - Dark Photons
- Beyond searches 101

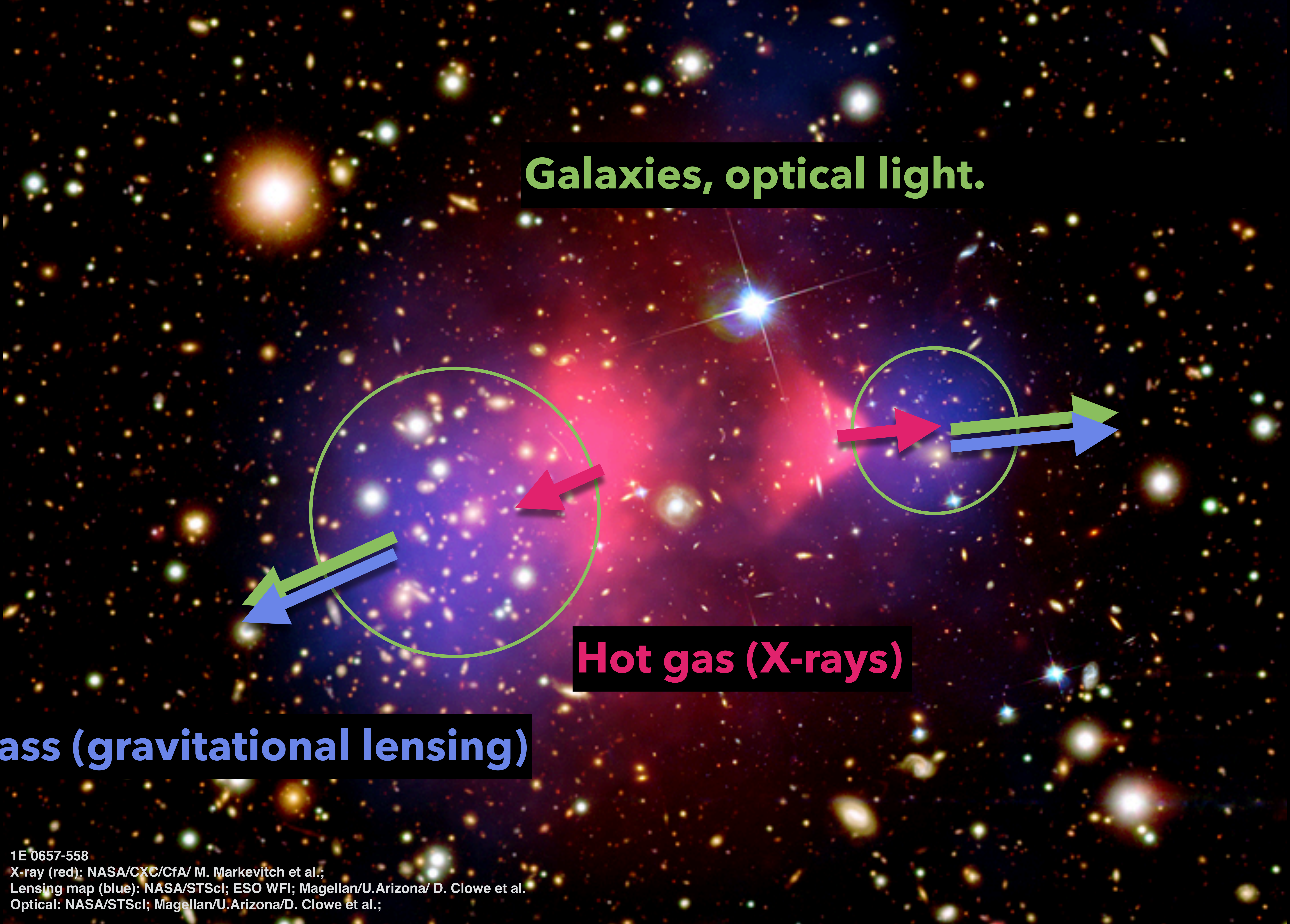
Motivation

- The Standard Model of particle physics is complete
  - Only non-zero neutrino masses remain unexplained
- Reasons to go beyond our Standard Model:
  - **Dark Matter** (and Dark Energy)
  - “Anomalies” at the 3-4σ level (in B decays, **muon anomalous moment g-2**, …)
  - “Unsatisfying” theory answers: Matter/Antimatter asymmetry, three generations, fine-tuning, …
  - …
  - “Analyse everything” in an ideally model-independent approach



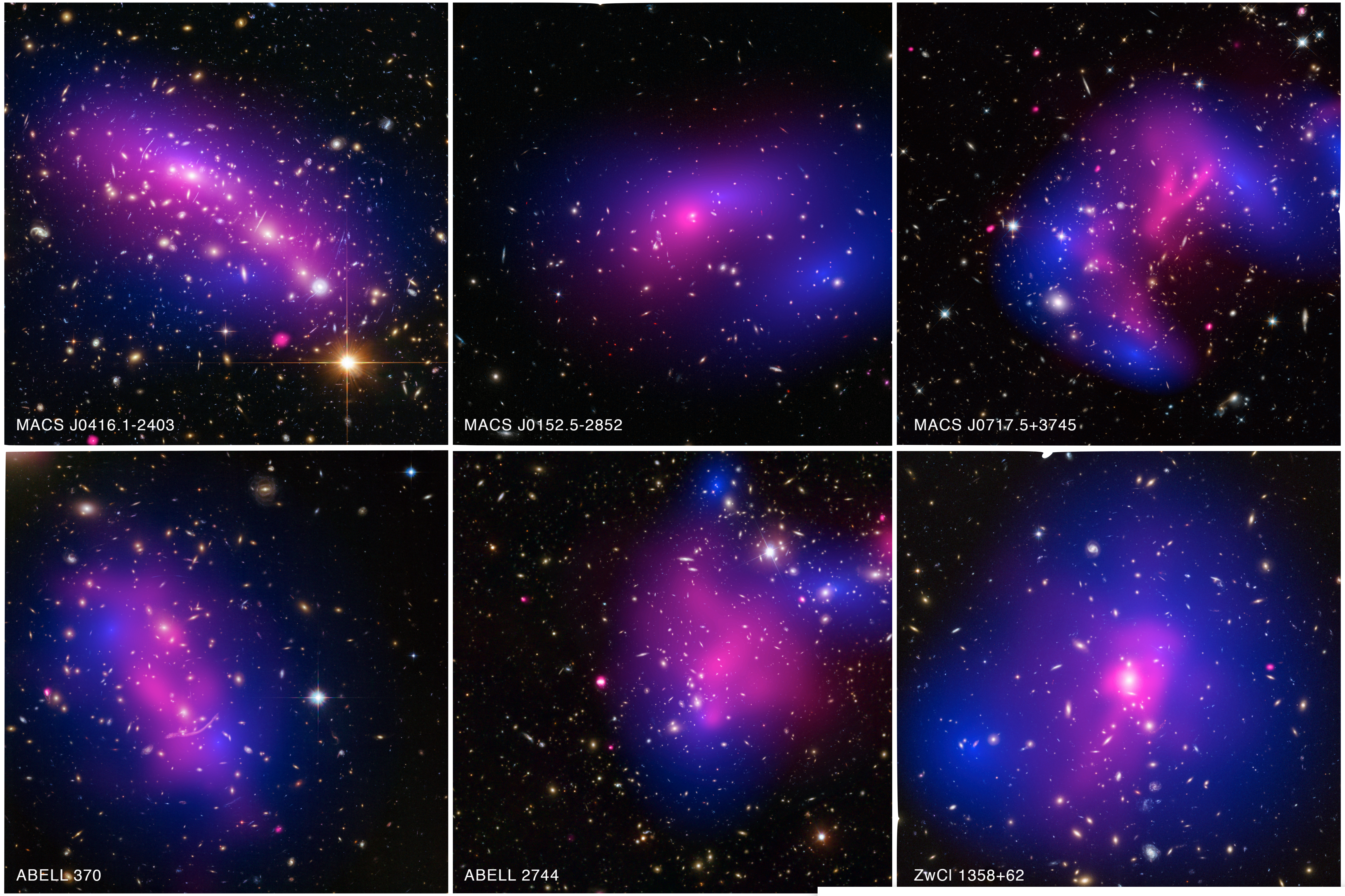
1E 0657-558
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;


Galaxies, optical light.
Galaxy cluster 2
Galaxy cluster 1
1E 0657-558
NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;


Galaxies, optical light.
Hot gas (X-rays)
Mass (gravitational lensing)
1E 0657-558
X-ray (red): NASA/CXC/CfA/ M. Markevitch et al.;
Lensing map (blue): NASA/STScI; ESO WFI; Magellan/U.Arizona/ D. Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D. Clowe et al.;

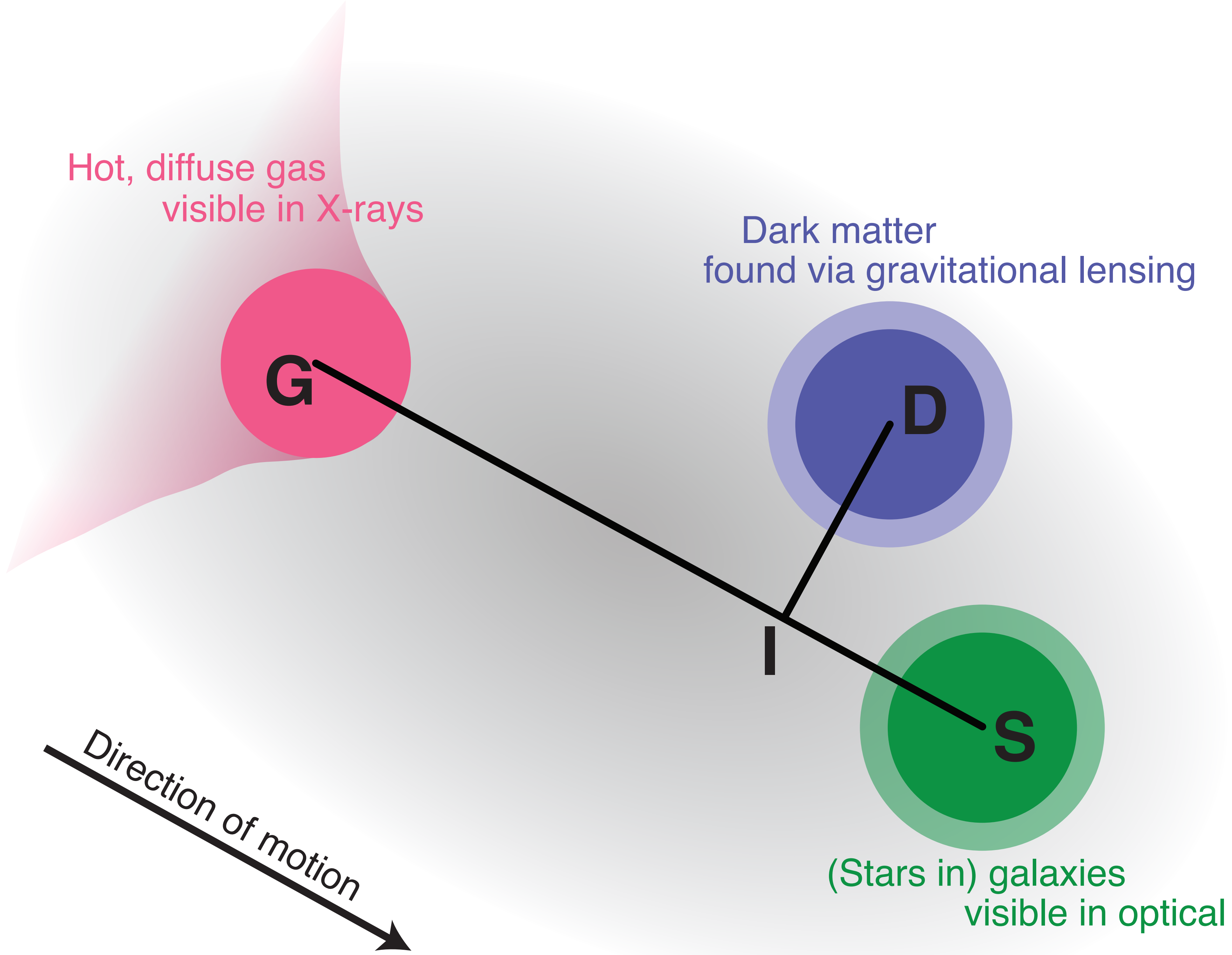

80%
of all matter is dark.

Dark matter: Galaxy cluster collisions



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

Dark matter: Galaxy cluster collisions

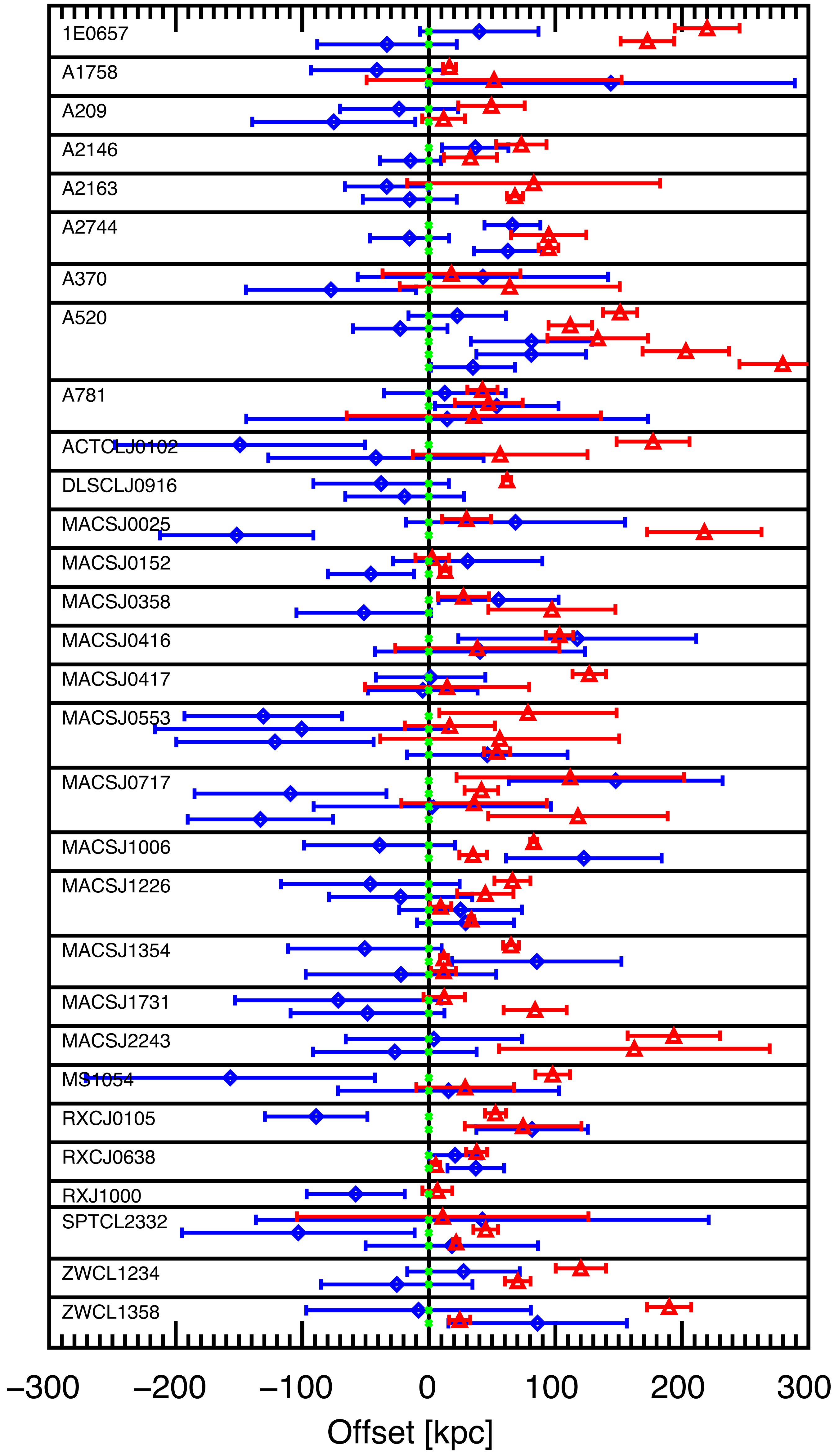


D. Harvey et al., Science, Vol. 347 no. 6229 pp. 1462-1465 (2015)

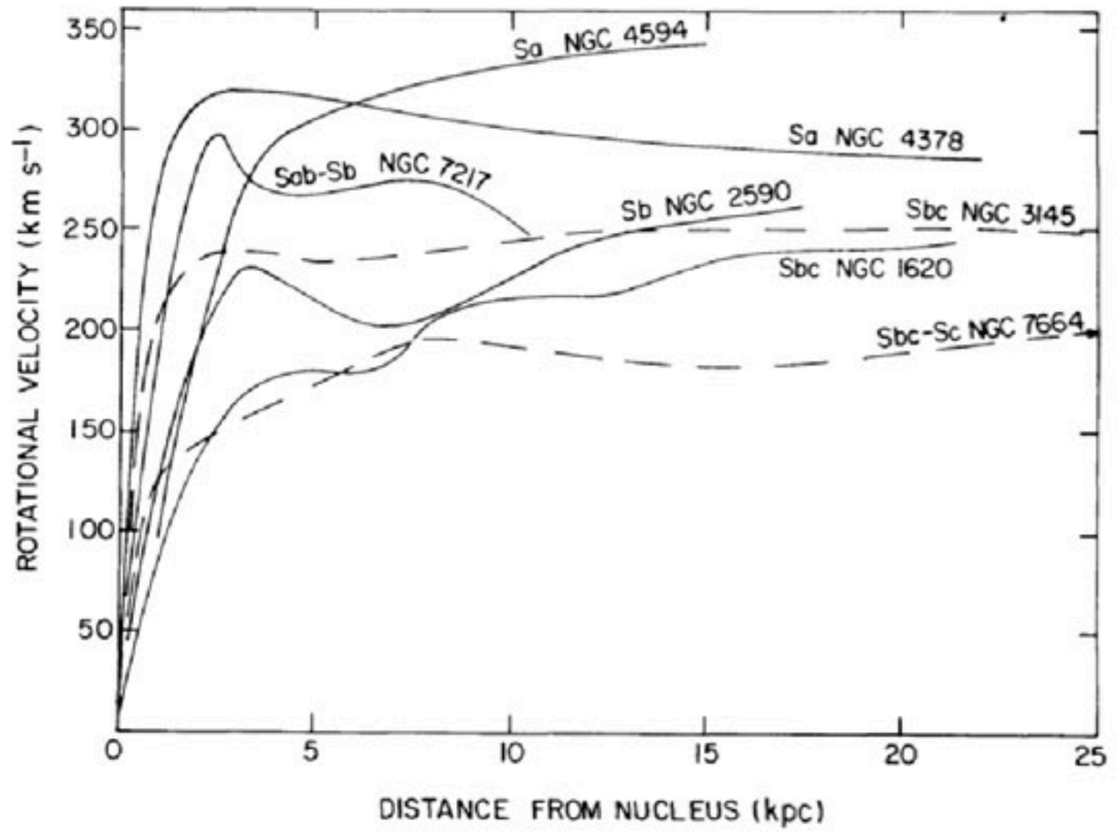
"(…), we detect the existence of dark mass at

7.6 σ

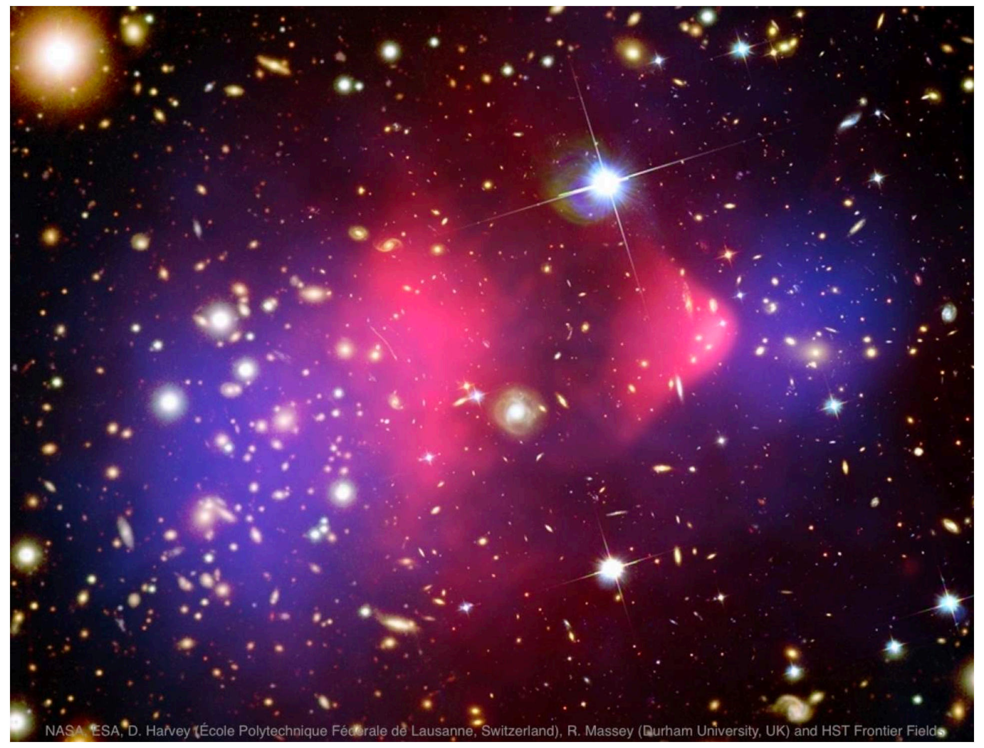
significance."



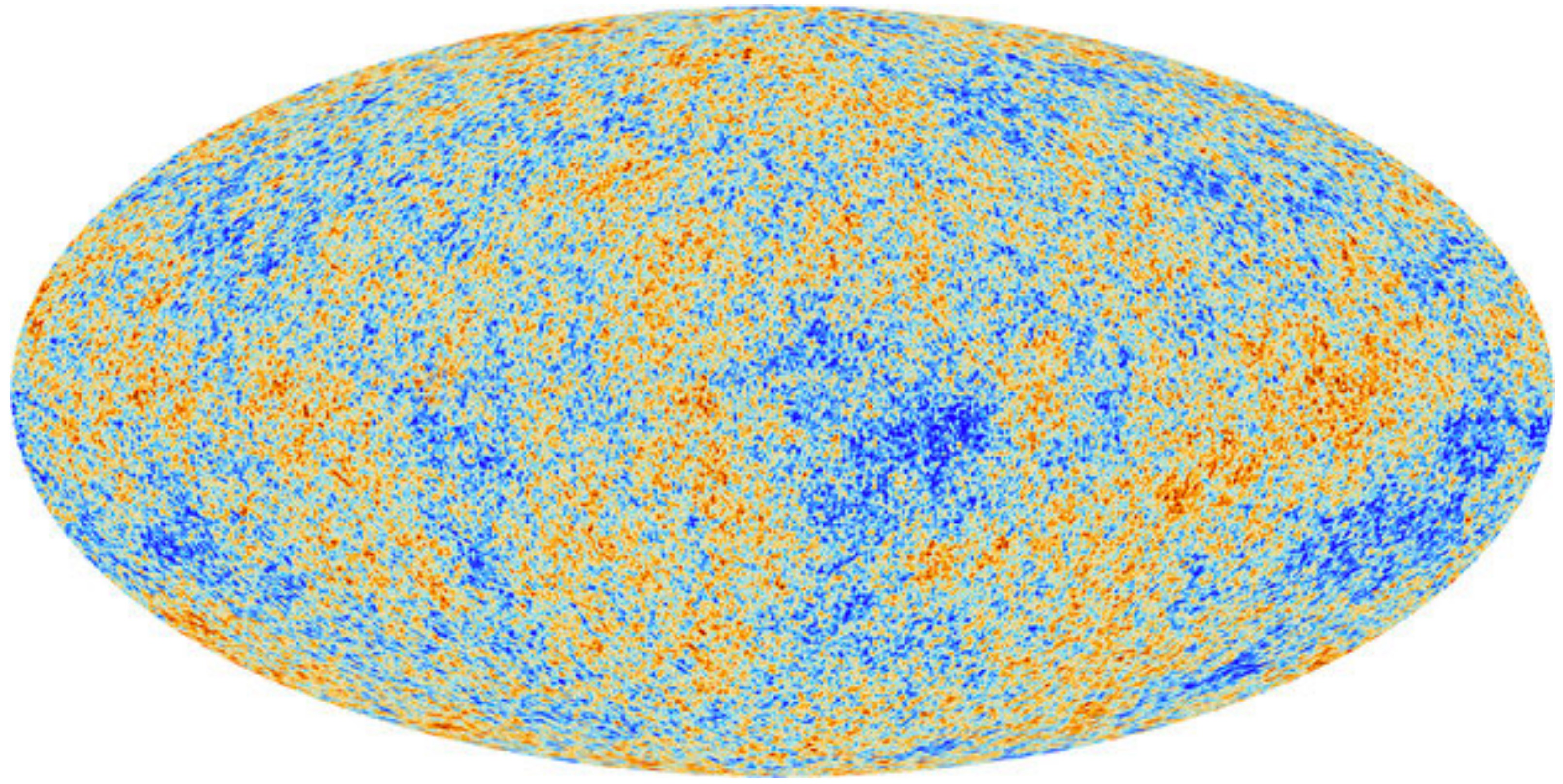
Dark matter: Overwhelming evidence



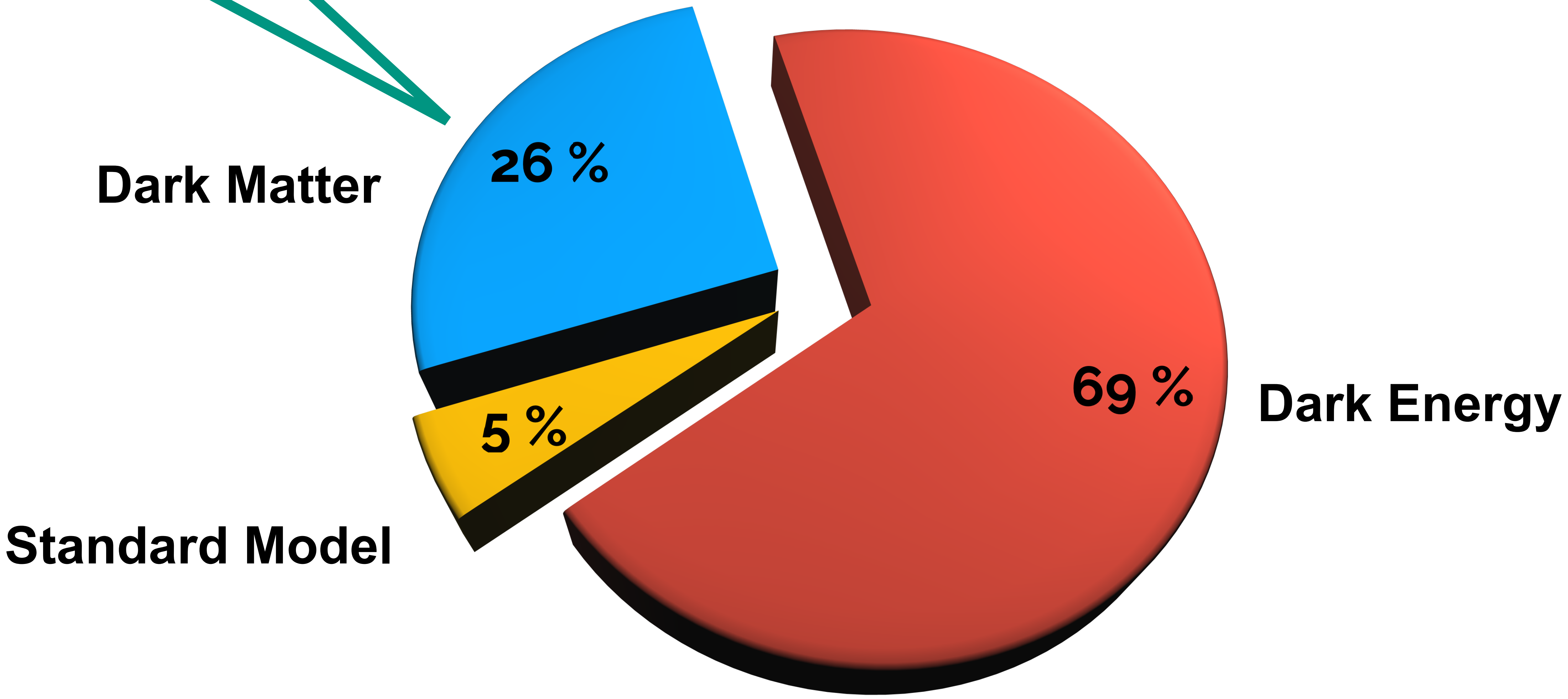
Galactic Rotation Curves



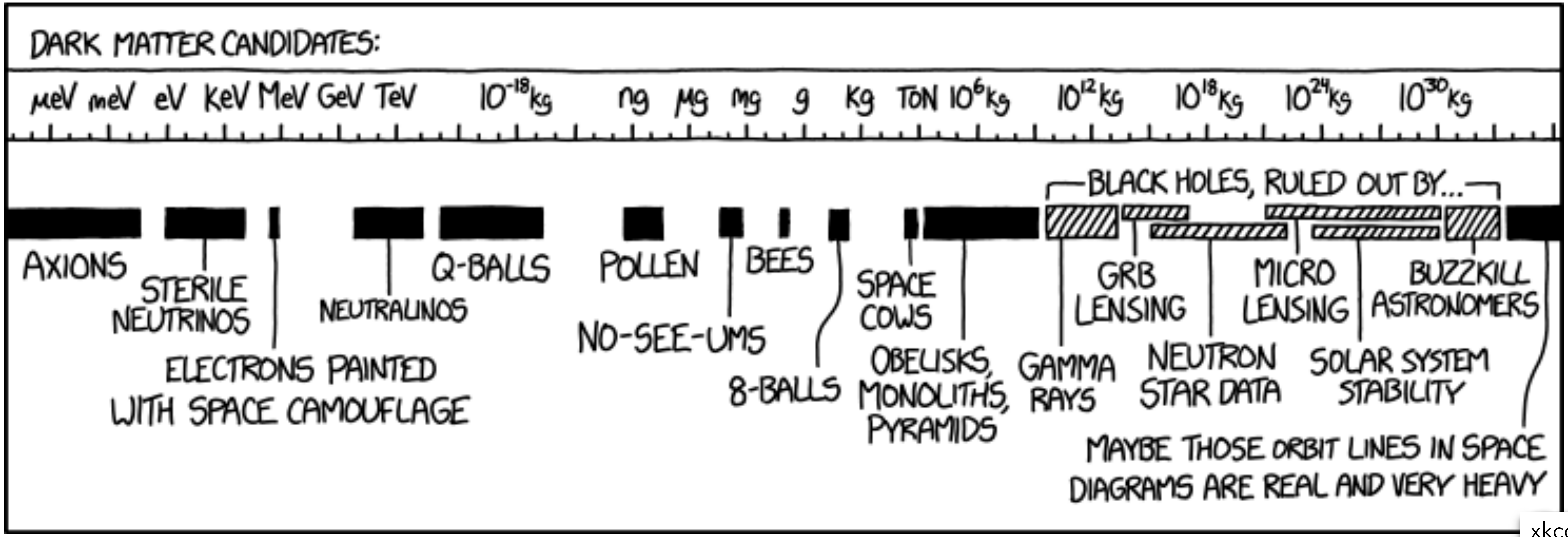
Gravitational Lensing



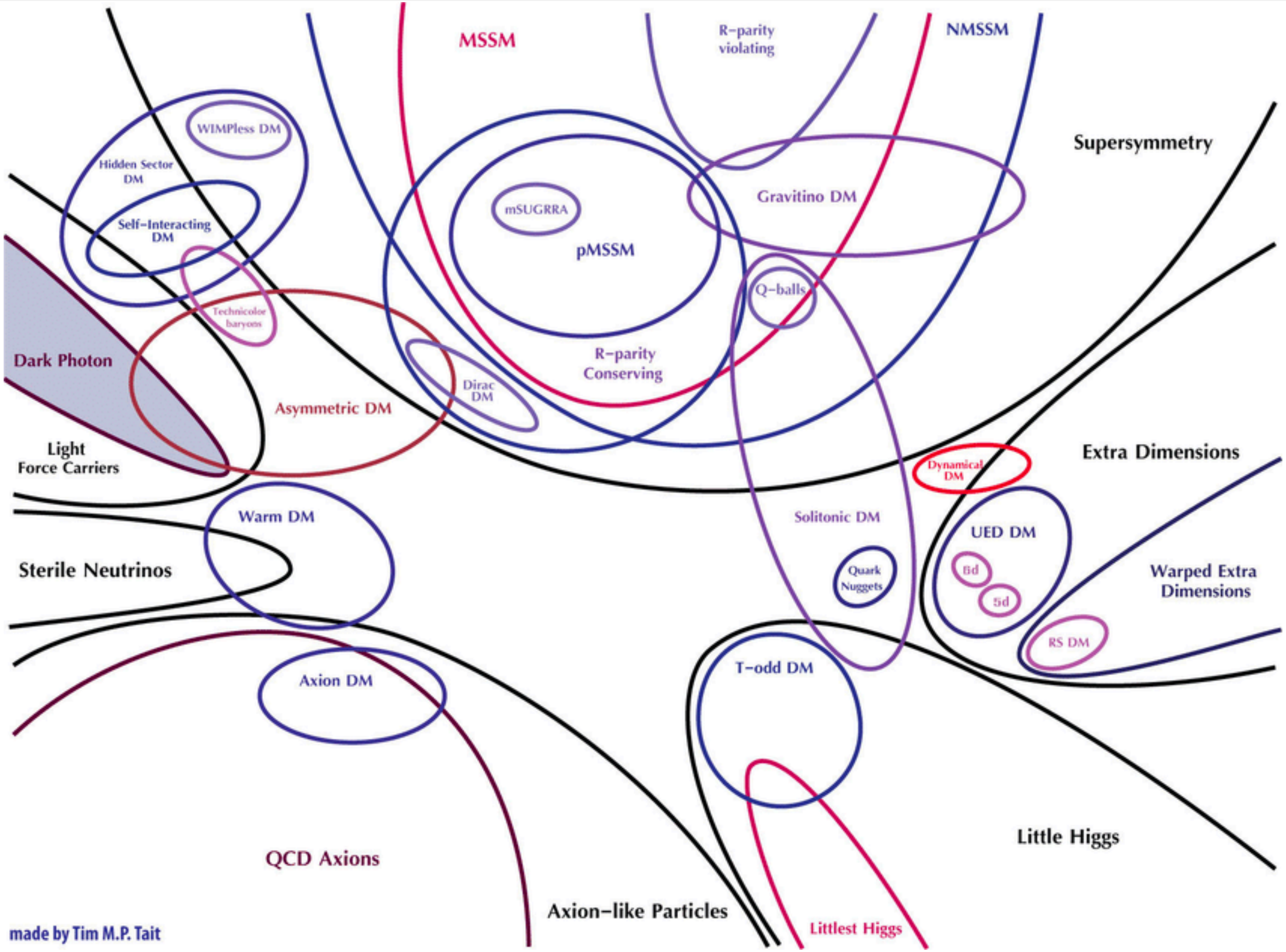
Cosmic Microwave Background



Dark matter: Candidates



xkcd



MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
Technicolor baryons
mSUGRRA
pMSSM
Gravitino DM
Q-balls
R-parity Conserving
Dark Photon
Asymmetric DM
Dirac DM
Light Force Carriers
Dynamical DM
Extra Dimensions
Warm DM
Solitonic DM
UED DM
Sterile Neutrinos
Quark Nuggets
6d
5d
Warped Extra Dimensions
RS DM
T-odd DM
Axion DM
Little Higgs
QCD Axions
Axion-like Particles
made by Tim M.P. Tait
Littlest Higgs

Dark matter: Candidates

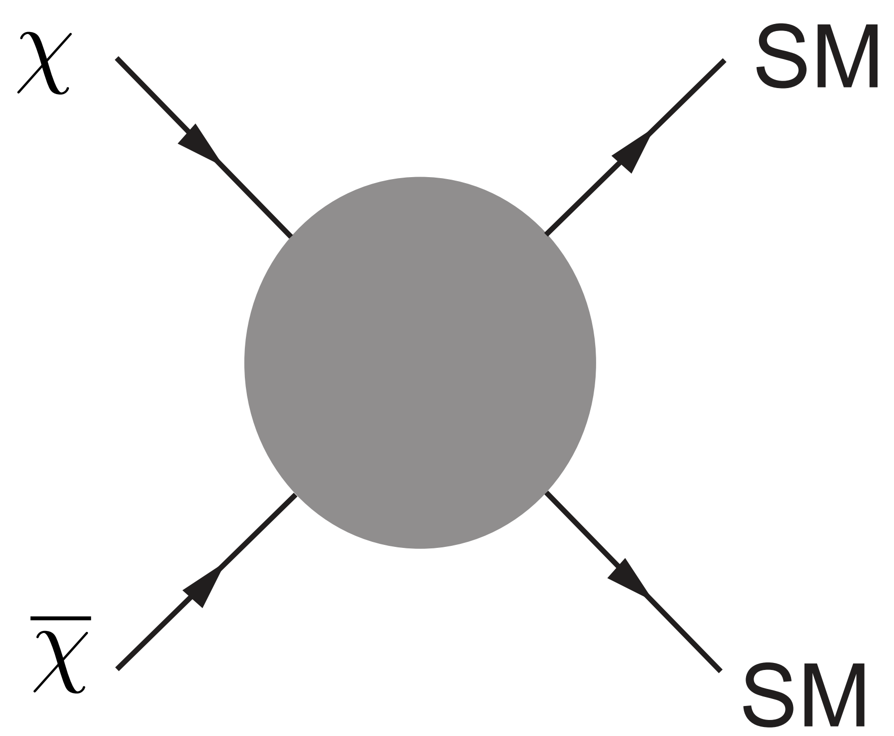
- What we know:
  - Does interact gravitationally
  - Does not interact via electromagnetic or strong force
  - Is non-relativistic (or cold)
  - Local density (at earth): $\rho_{local} \approx 0.4$ GeV/cm^3
- What we do not know:
  - Collision-less (assumed in ΛCDM model)
  - Maybe interacts via the weak force (WIMPs) or via the SM Higgs mechanism
  - Mass between 10^{-22} eV and 5 $M_\odot$

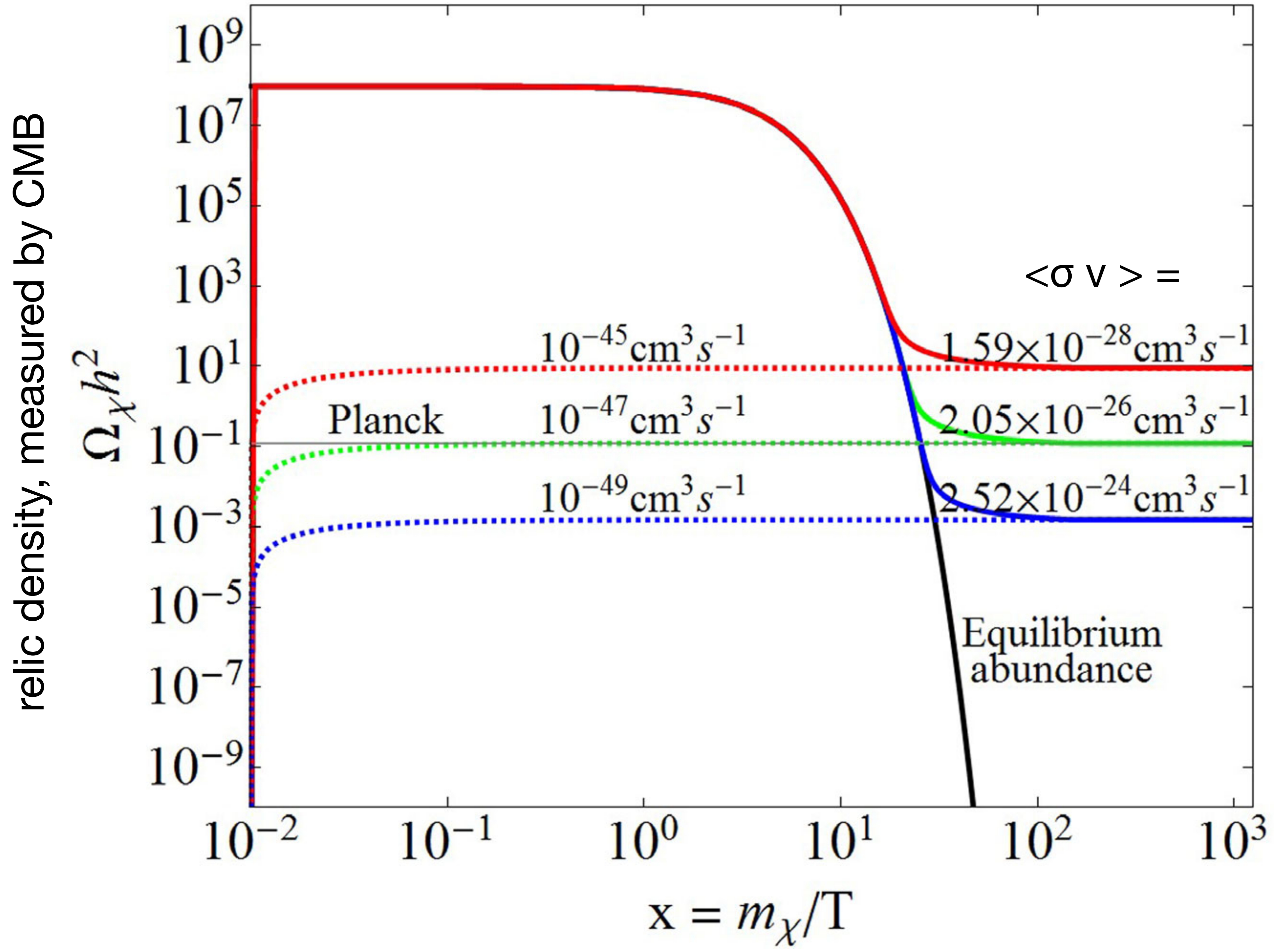
Local DM density:
1 DM squirrel compared to the mass of the earth

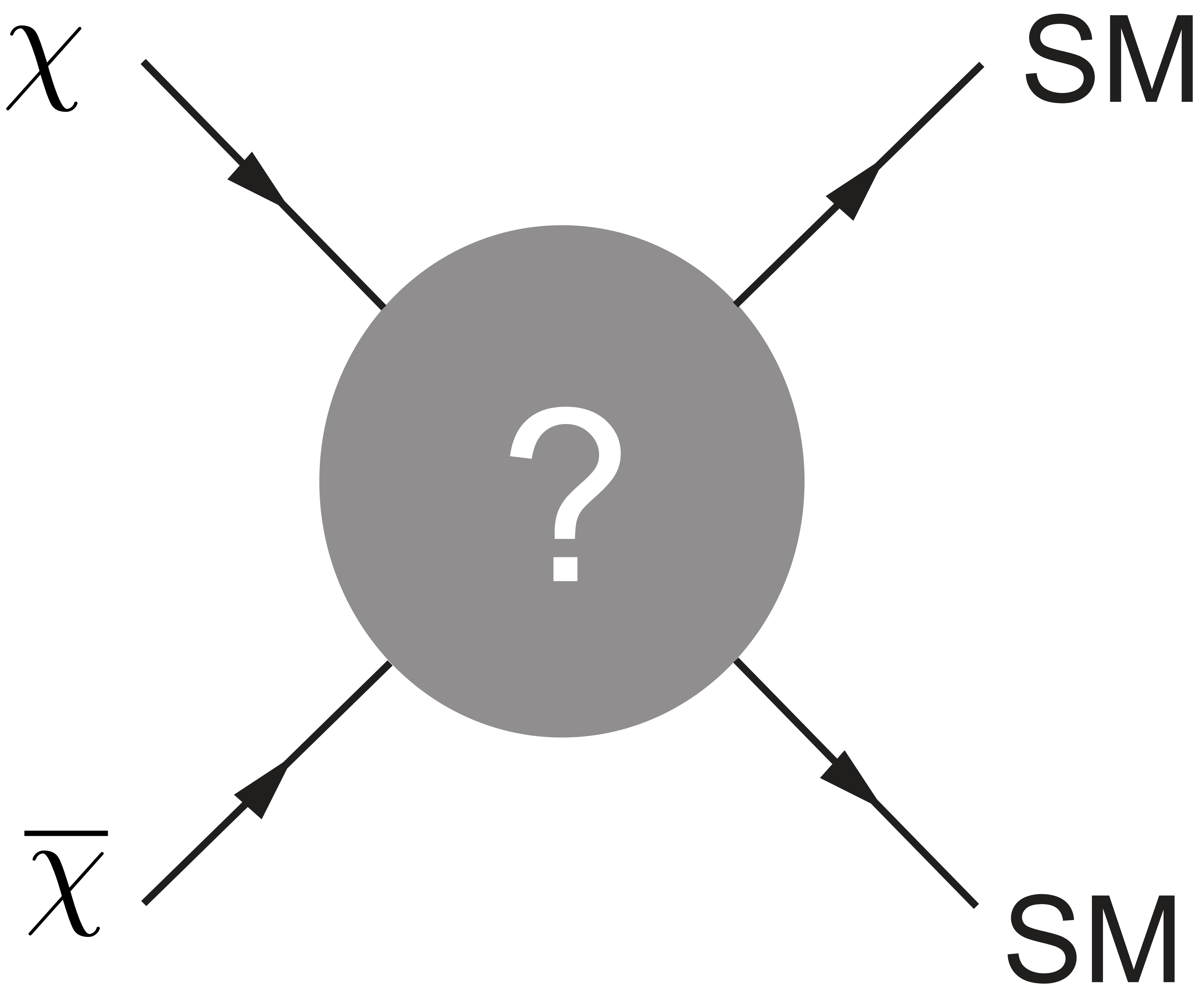
Dark matter: Thermal freeze out

- Early universe (x→0):
  - DM annihilation (DM+DM→SM+SM) and production (SM+SM→DM+DM) are possible
- Universe expands (=T decreases):
  - DM production is kinematically disfavoured (Boltzmann tails)
  - DM annihilation still possible for a while…
- Once the annihilation is smaller than the hubble rate, DM annihilation too rare: Freeze out!
- **Relic abundance** observed today:

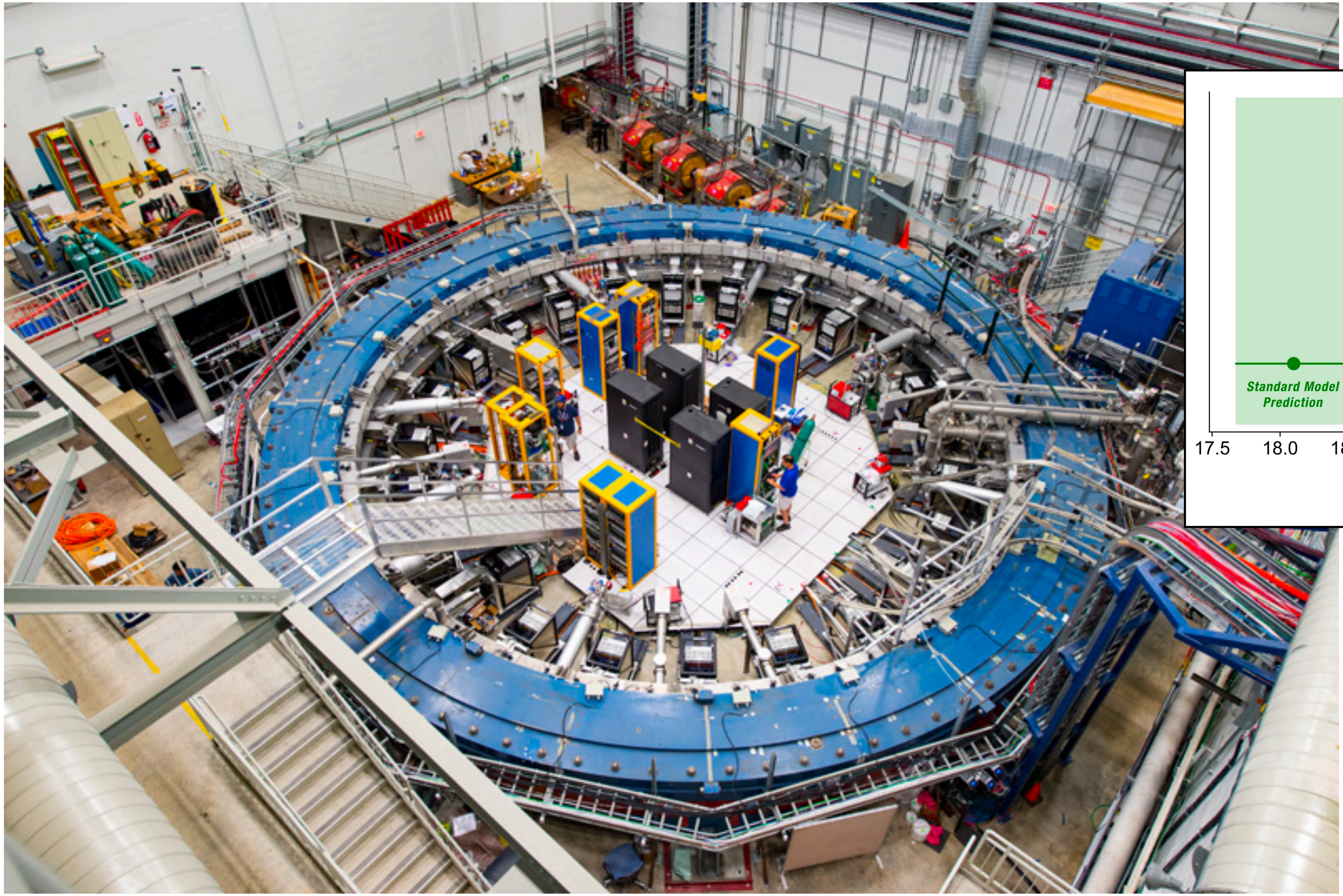
$$\Omega_\chi h^2 \sim 0.1 \left(\frac{\text{pb}}{\langle \sigma v \rangle}\right)$$






χ
SM
?
$\bar{\chi}$
SM

Anomalous magnetic moment of the muon $(g\text{-}2)_\mu$



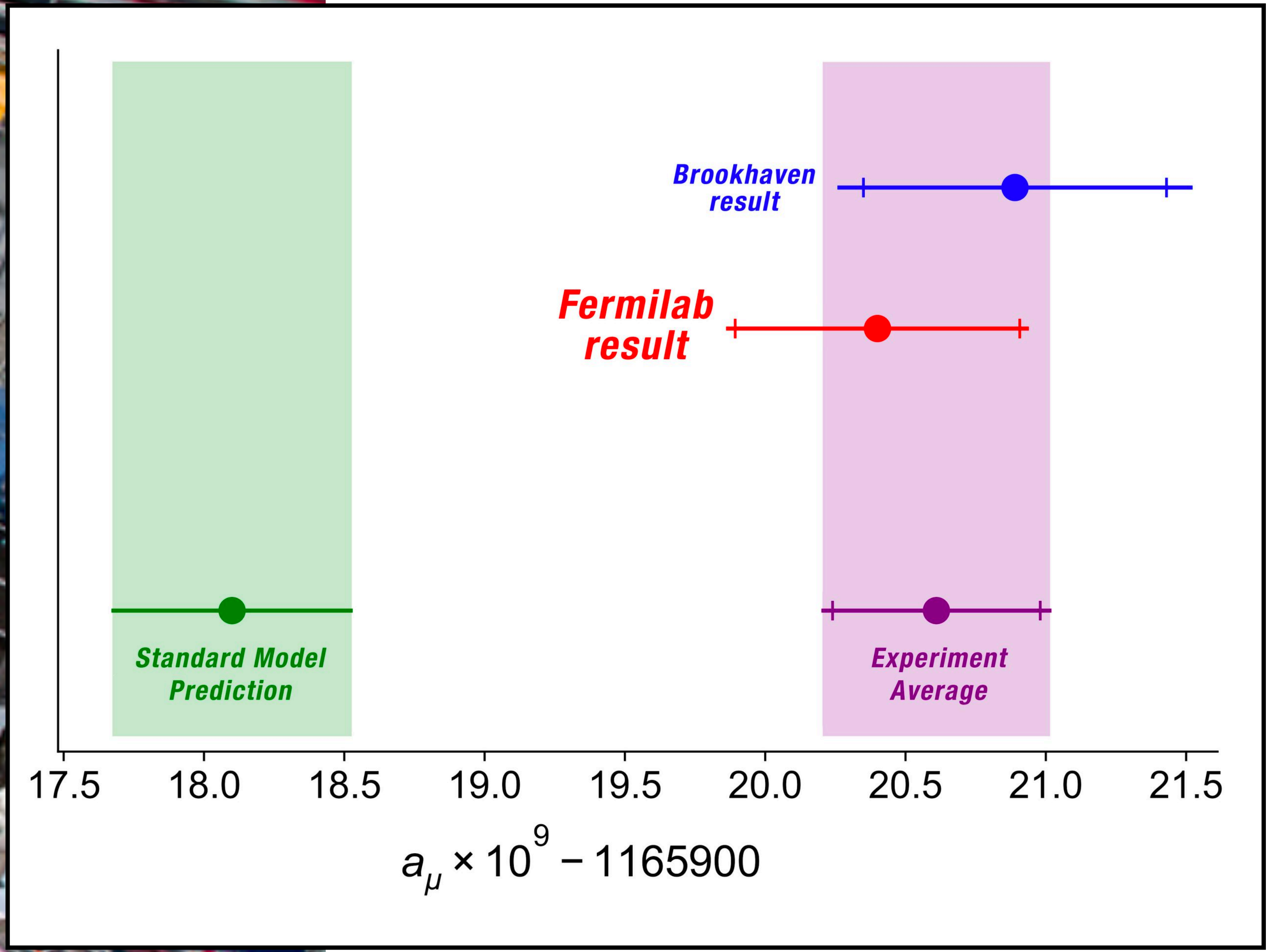
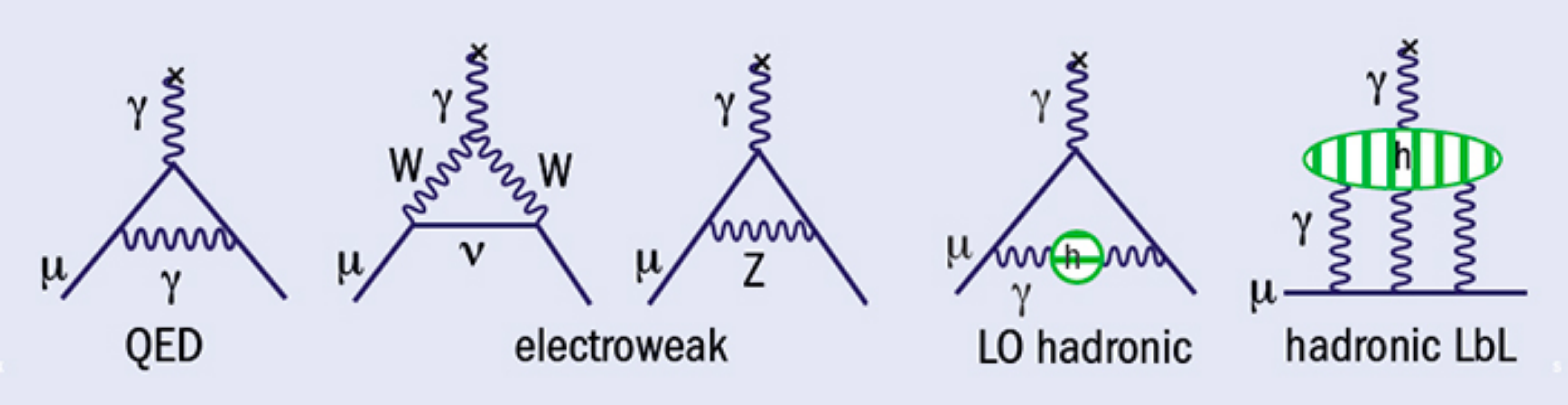


Photo: Reidar Hahn, Fermilab

Anomalous magnetic moment of the muon $(g\text{-}2)_\mu$

- anomalous magnetic moment $a = (g-2)/2$

Anomalous magnetic moment of the muon $(g\text{-}2)_\mu$



$$a_\mu^{\mathrm{QED}}(\alpha(\mathrm{Cs})) = 116\,584\,718.931(104) \times 10^{-11}$$
$$a_\mu^{\mathrm{EW}} = 153.6(1.0) \times 10^{-11}$$
$$a_\mu^{\mathrm{HVP,\,LO}} = 6931(40) \times 10^{-11}$$
$$a_\mu^{\mathrm{HLbL}} = 92(19) \times 10^{-11}$$

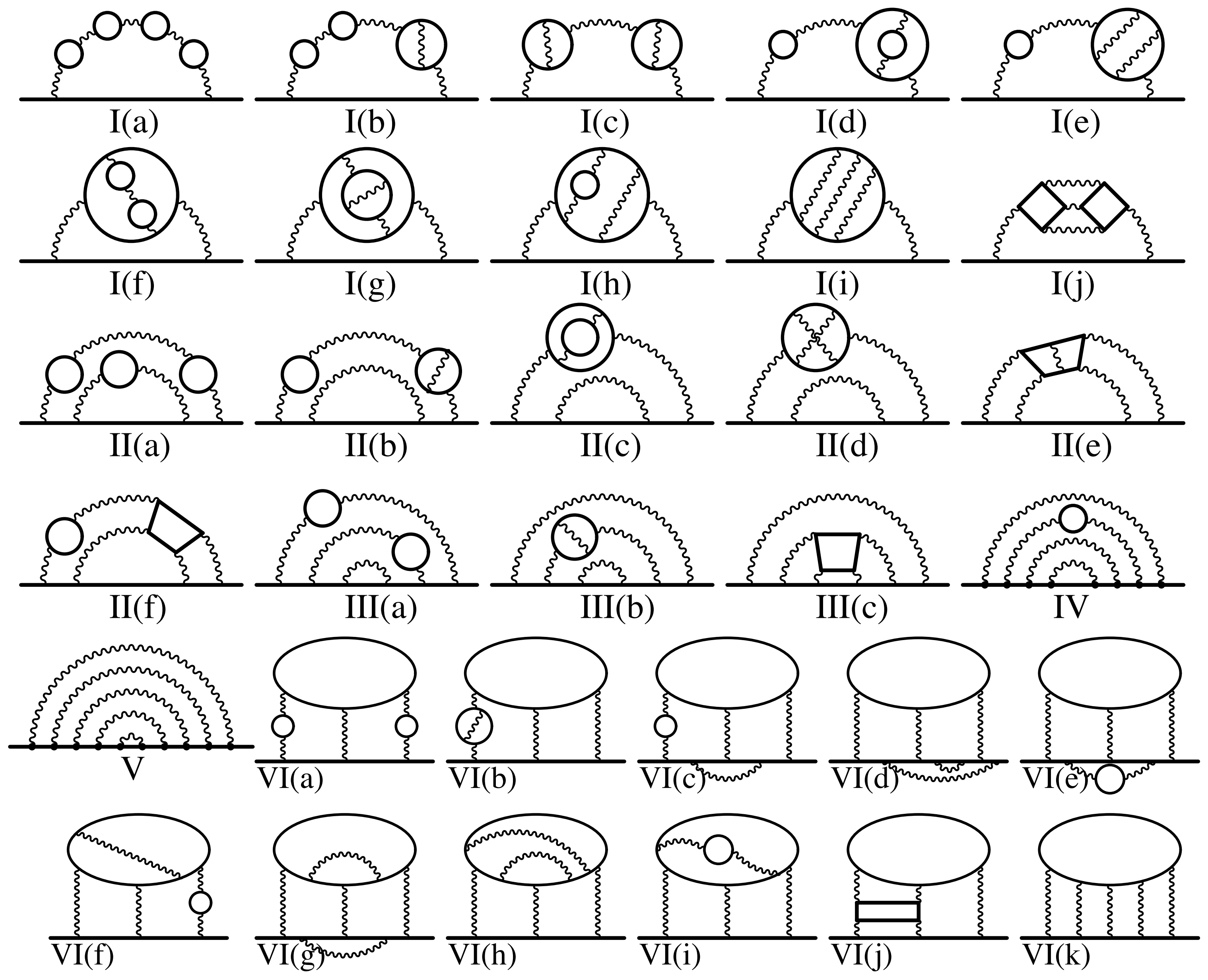
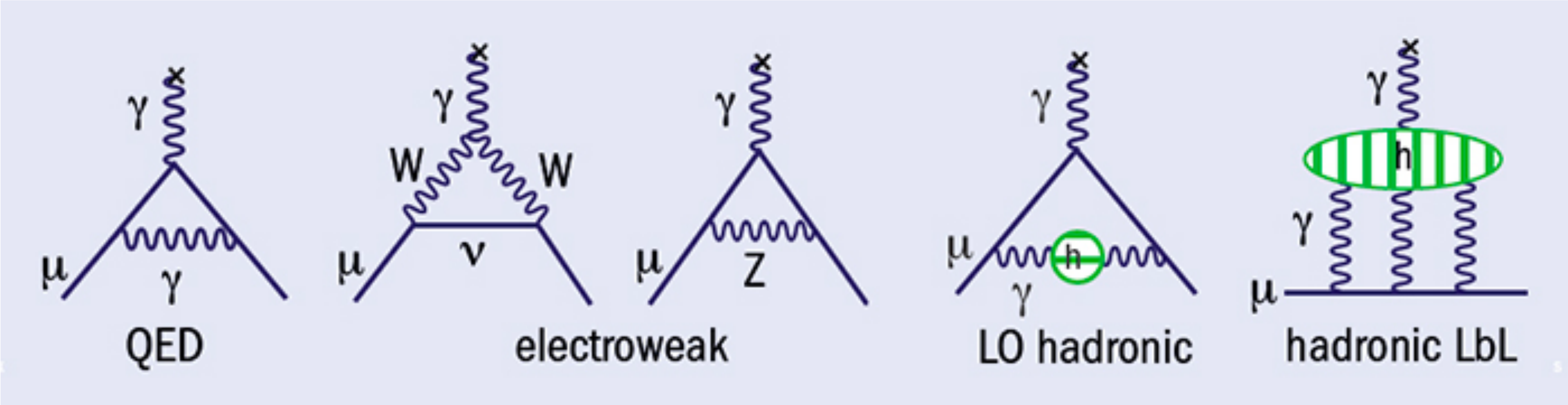
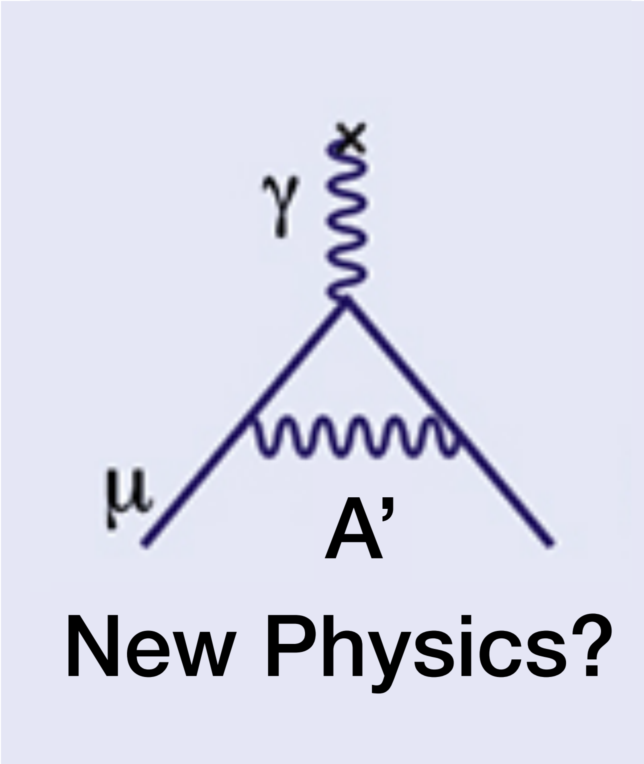


Figure 99: Tenth-order vertex diagrams. There are 12 672 diagrams in total, and they are divided into 32 gauge-invariant subsets over six super sets. Typical diagrams of each subsets are shown as I(a)–(j), II(a)–(f), III(a)–(c), IV, V, and VI(a)–(k). There are 208 Set I diagrams (1 for I(a), 9 for I(b), 9 for I(c), 6 for I(d), 30 for I(e), 3 for I(f), 9 for I(g), 30 for I(h), 105 for I(i), and 6 for I(j)), 600 Set II diagrams (24 for II(a), 108 for II(b), 36 for II(c), 180 for II(d), 180 for II(e), and 72 for II(f)), 1140 Set III diagrams (300 for III(a), 450 for III(b), and 390 for III(c)), 2072 Set IV diagrams, 6354 Set V diagrams, and 2298 Set VI diagrams (36 for VI(a), 54 for VI(b), 144 for VI(c), 492 for VI(d), 48 for VI(e), 180 for VI(f), 480 for VI(g), 630 for VI(h), 60 for VI(i), 54 for VI(j), and 120 for VI(k)). The straight and wavy lines represent lepton and photon propagators, respectively. The external photon vertex is omitted for simplicity and can be attached to one of the lepton propagators of the bottom straight line in super sets I–V or the large ellipse in super set VI. Reprinted from Ref. [773].

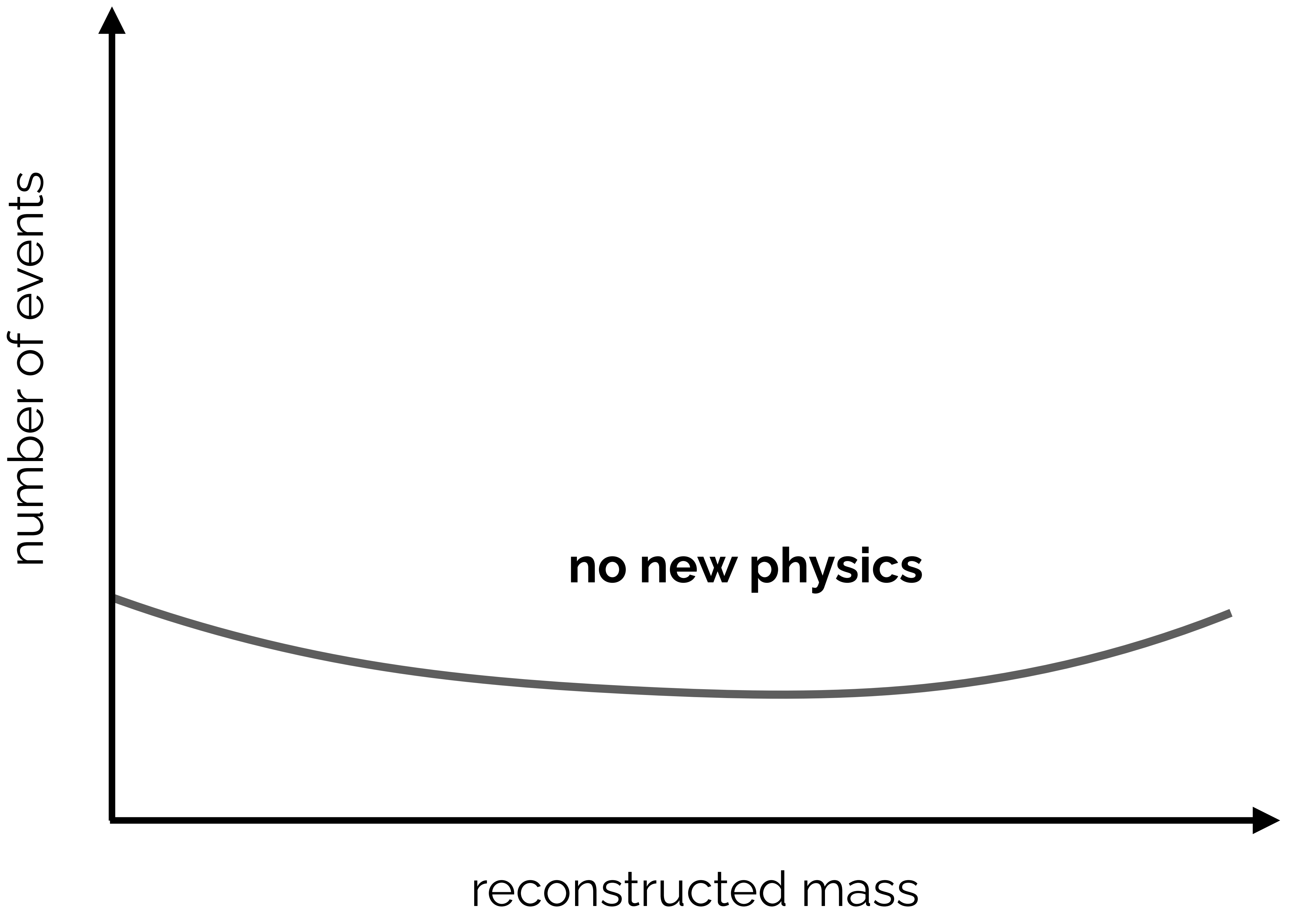
Anomalous magnetic moment of the muon $(g\text{-}2)_\mu$

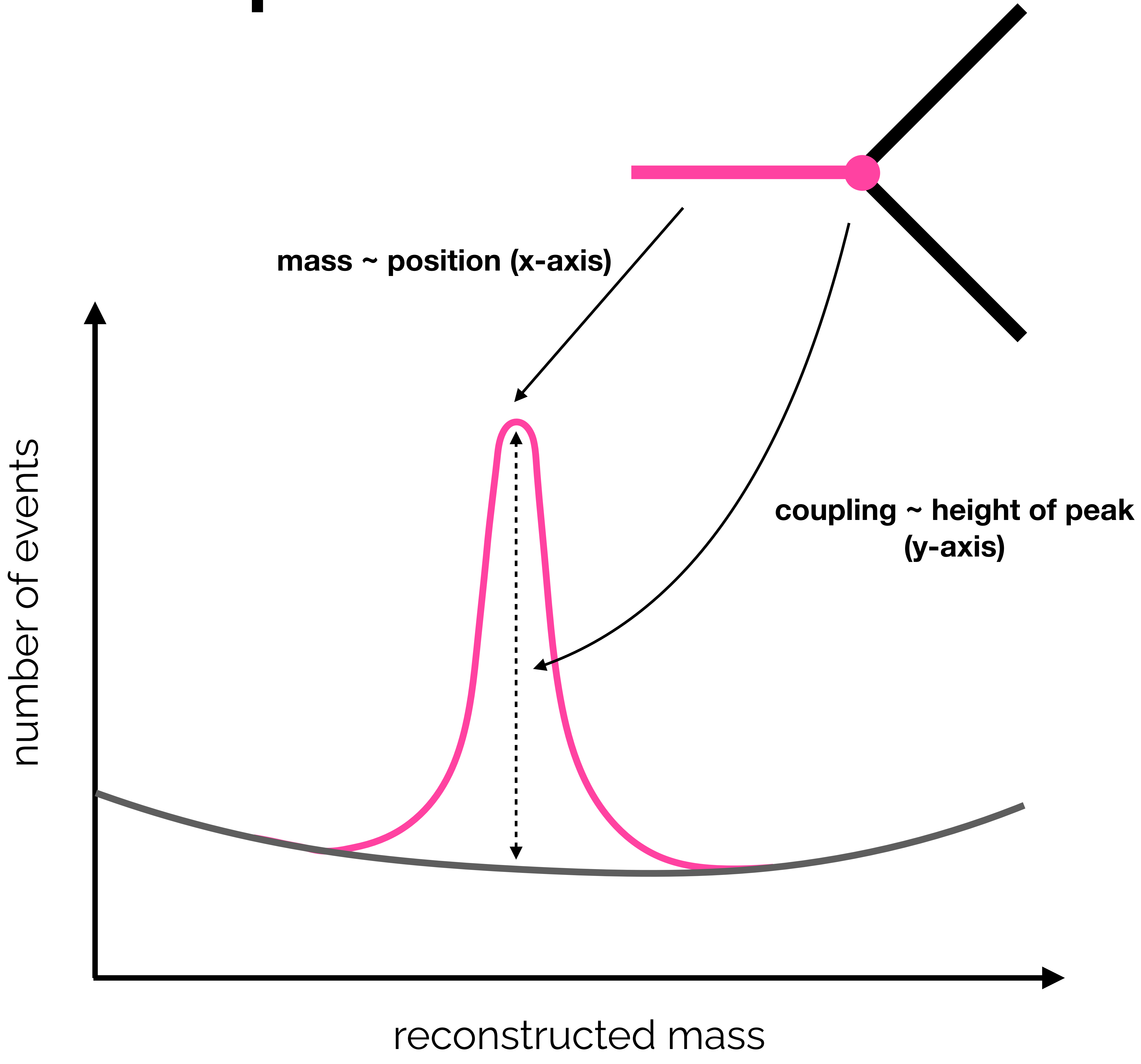


+



Search 101: NP mediator decaying to SM particles





Search 101

- “Closed box” analysis
- Signal and background
- Trigger
- Event selection
  - signal efficiency and background rejection
- Search for an excess
  - Prepare for the case that you actually find an excess
- Set limits

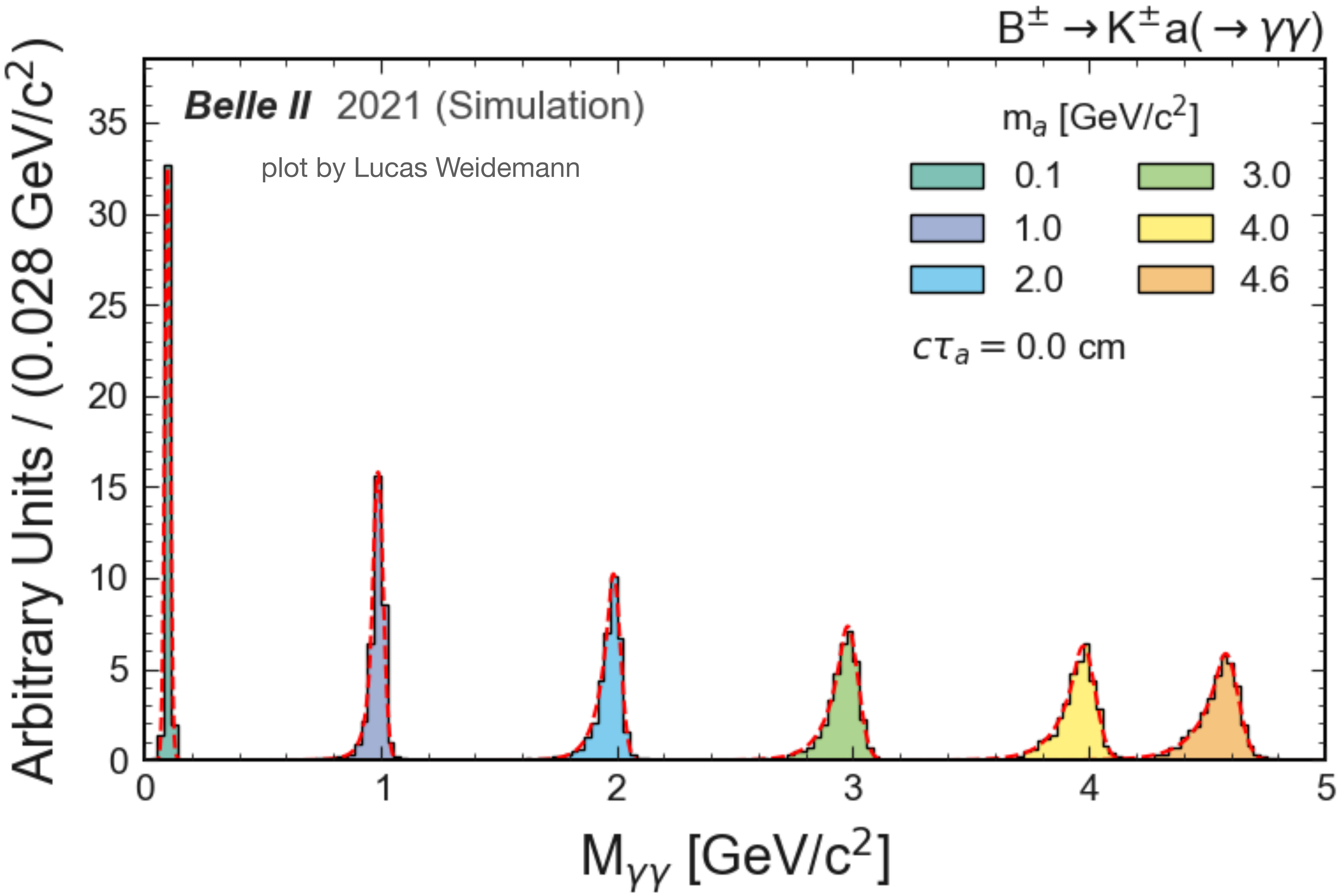
There is no “one size fits all”!

This is a simplified typical analysis workflow with some real life recipes.

Search 101: Closed box

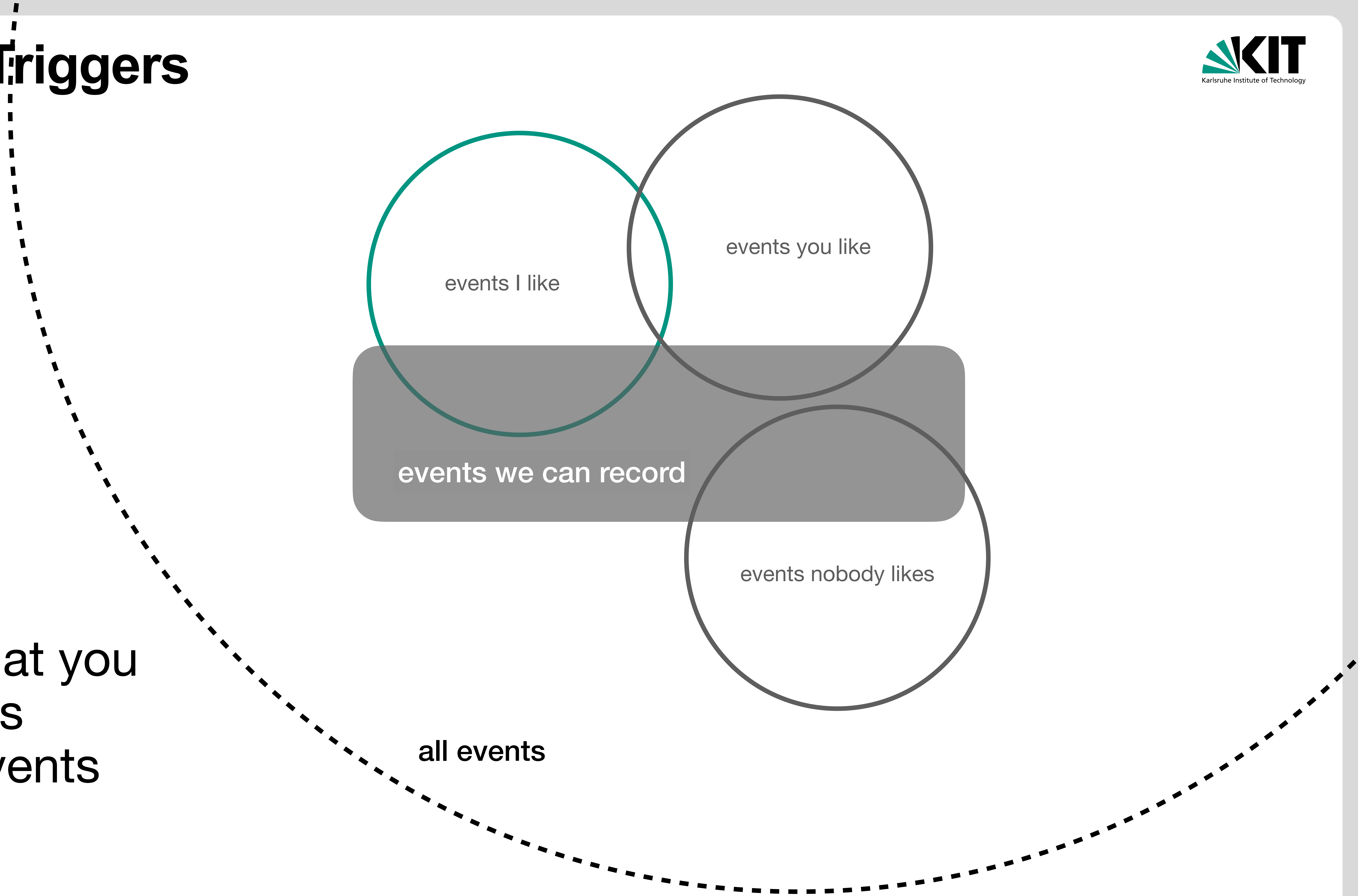
- Never forget: You are searching for physics beyond the standard model. If you find anything, this is the greatest news in (particle) physics for decades.
- We used to call these analysis “blind”: **Do not look at any data** until the full analysis is established on simulation and convenors have given you green light (your collaboration has very clear rules).
- We do this to not (unintentionally) bias ourself to finding (or not finding) anything in data.
  - Be aware that machine learning methods must be unbiased, too!

Search 101: Signal



- Produce MC samples for hundreds of mediator masses
- Parametrise signal shape (“signal PDF”) so that you can use this in a fit to data later (only the signal yield will be a free parameter)
- You often also need the mass resolution for a later step in “Search 101”…

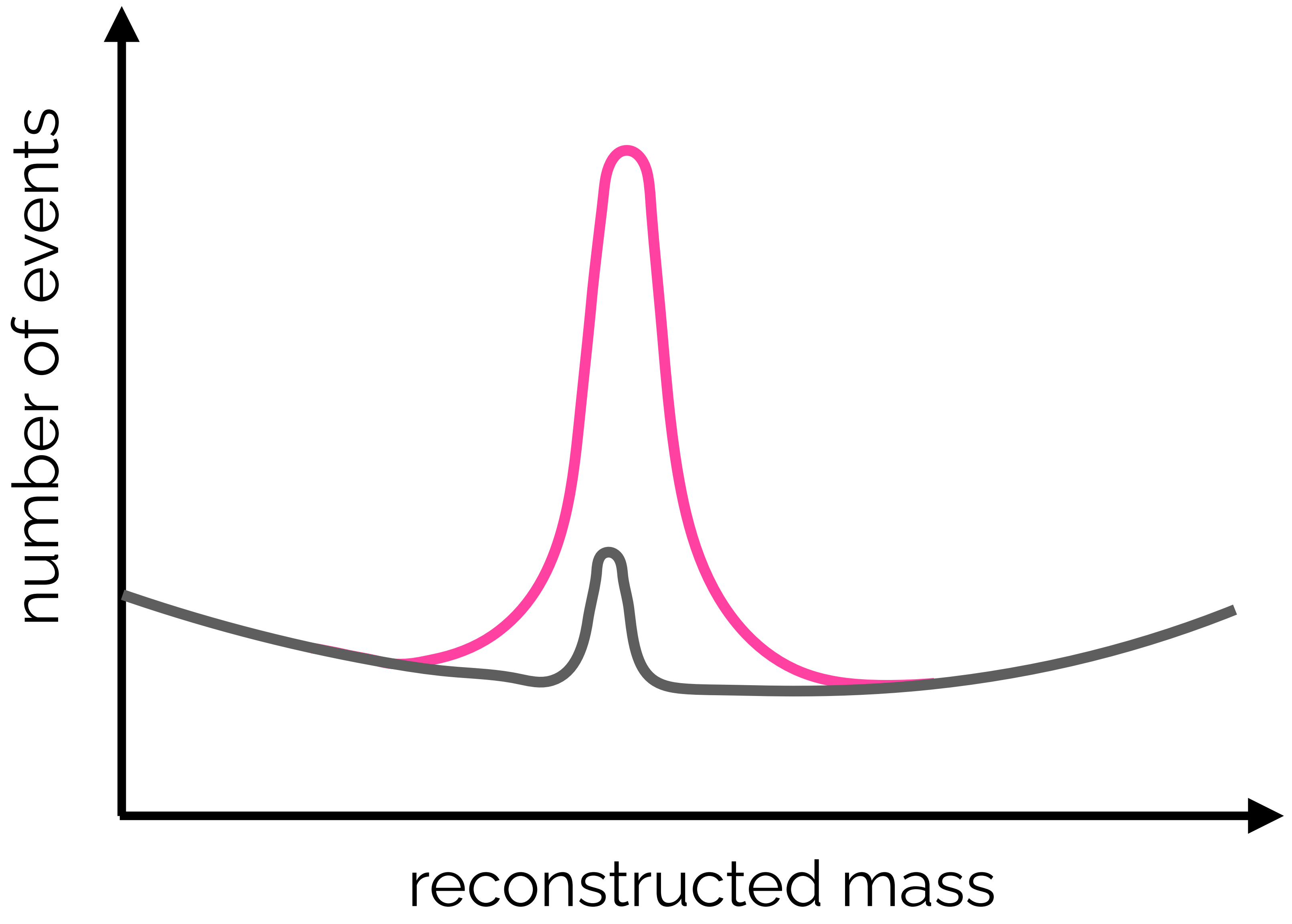
Search 101: Triggers



- Make sure that you detector does record the events you like!

Search 101: Background

- Everything that looks like your signal is your background
- If you are looking for a peak, you are particularly worried about "peaking backgrounds"
  - J/Ψ decaying to leptons (looks like dark photons)
  - Neutral mesons (π0, η, η') decaying to photons (look like ALPs)
    - Sometimes the peak is less obvious: e.g. in a search with three photons: $ee \to \gamma\omega$, $\omega \to \pi^0\gamma$
  - Experience helps a lot here, so talk to your supervisor and peers!
- You usually would like to reduce your background as much as possible.



Search 101: Punzi figure of merit

- You can spend a lot of time optimizing your selection:

$$PFM = \frac{\epsilon_S}{\frac{a}{2} + \sqrt{B}}$$

ε_S: signal efficiency in the "signal region"

B = number of background events in the "signal region"

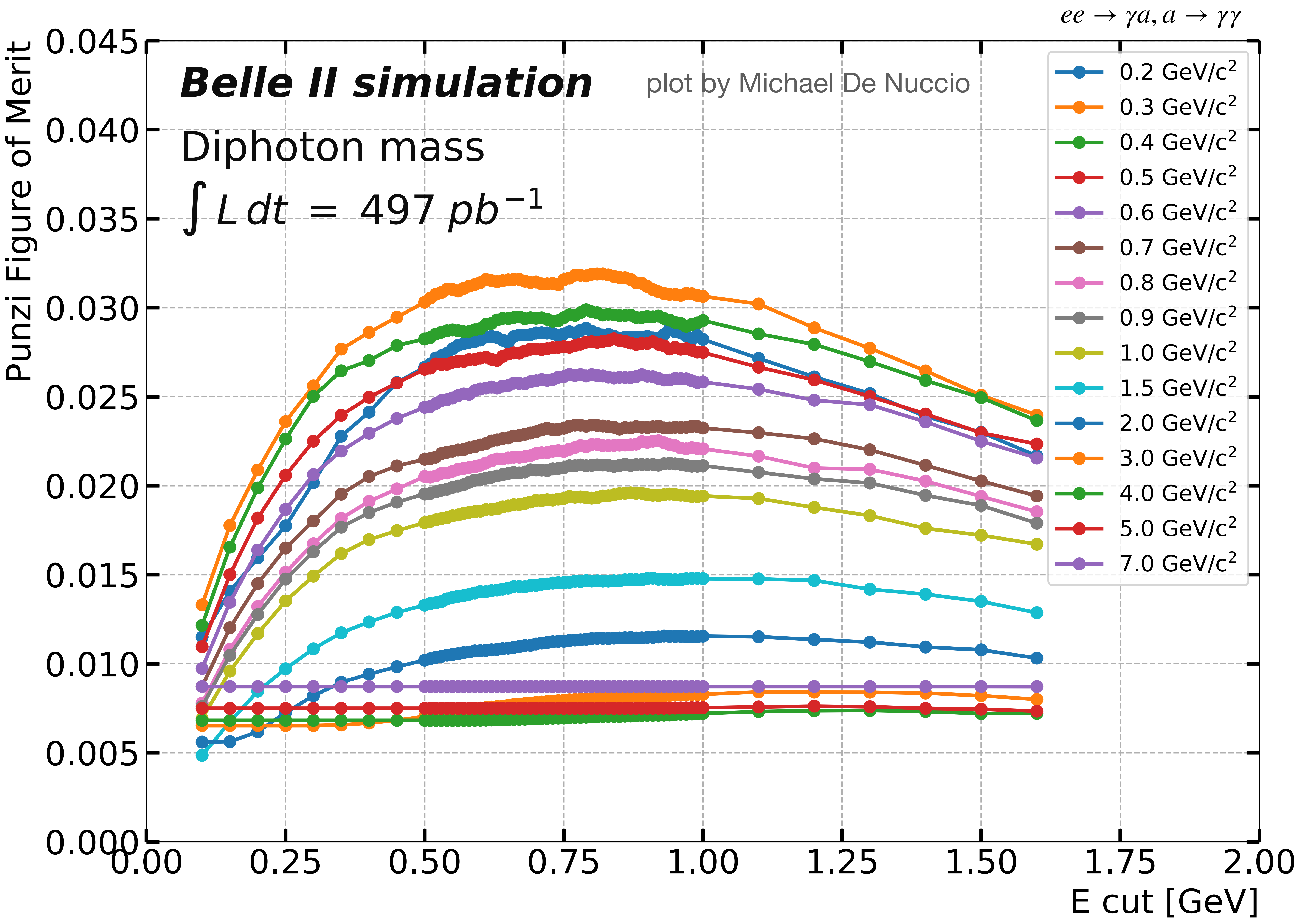
https://arxiv.org/pdf/physics/0308063.pdf

  - a=5 (==5σ) when optimizing a discovery
  - Note that you only need the signal efficiency, not the signal yield!
- Your selection can (and often will) depend on the unknown mass of the mediator
- Rules of thumb:
  - "Cut hard, finish early"
  - Apply the strongest (and mass-independent) selection first

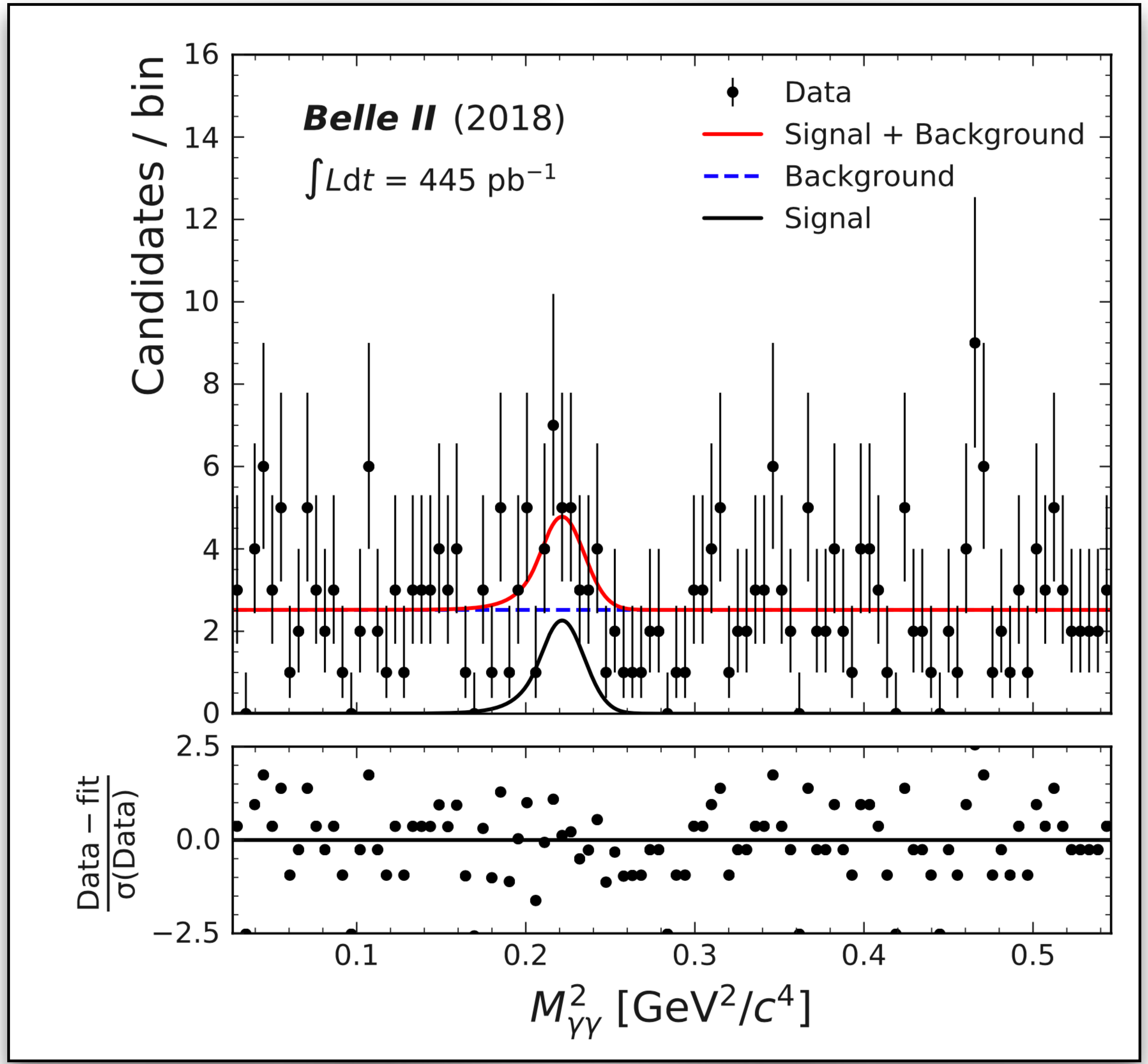
Search 101: Punzi figure of merit

good

bad



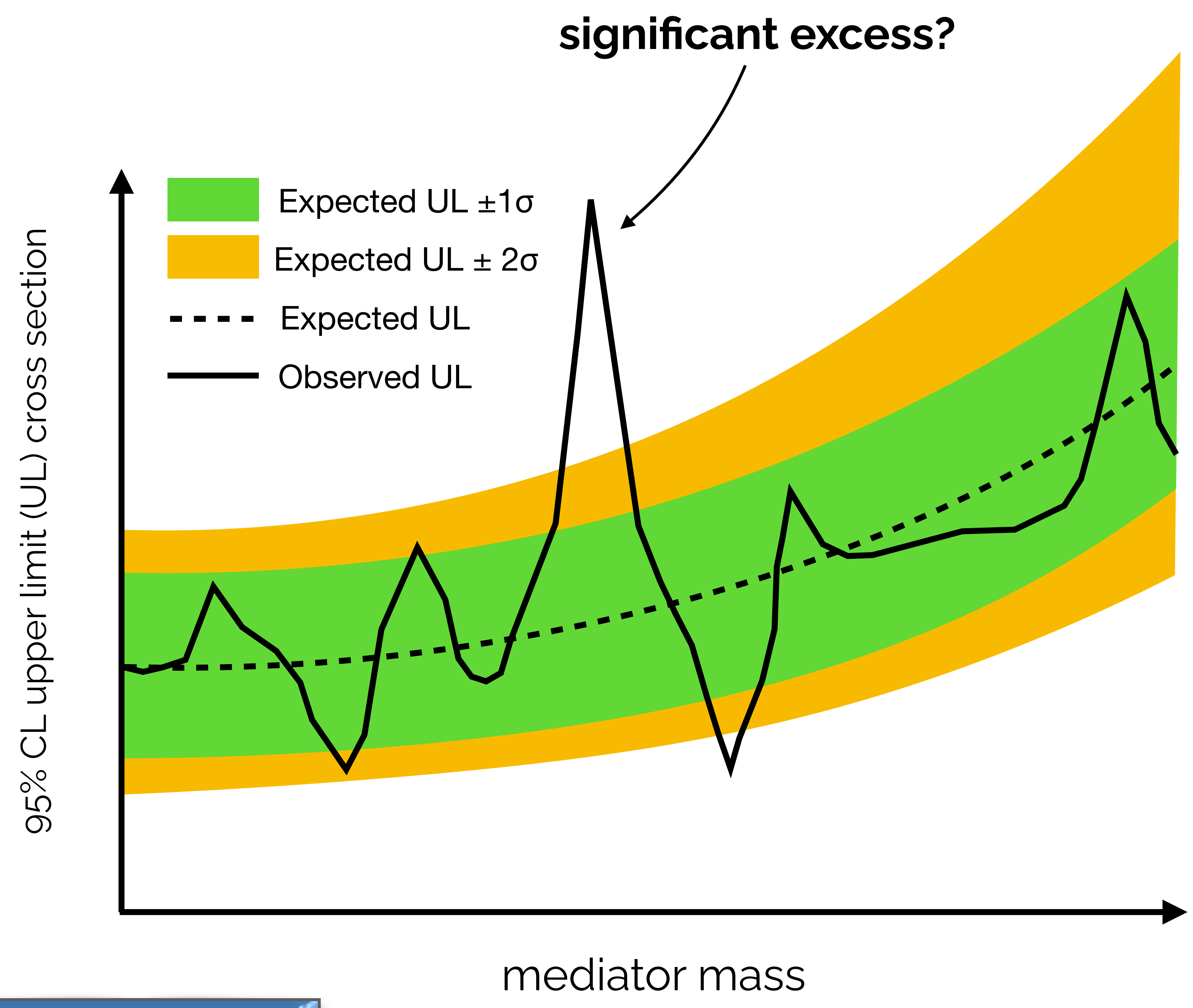
Search 101: Fits to data



- Rule of thumb: Fit in steps of at most half the signal resolution (can easily be hundreds of fits for a 1D search)
- Calculate the local significance using signal+background and background only fits
- Typically (and you must decide this before unblinding!): If more than $3\sigma_{global^*}$ you will claim discovery

*We are searching for a signal anywhere, not a specific mass, you must take into account the "look-elsewhere-effect"

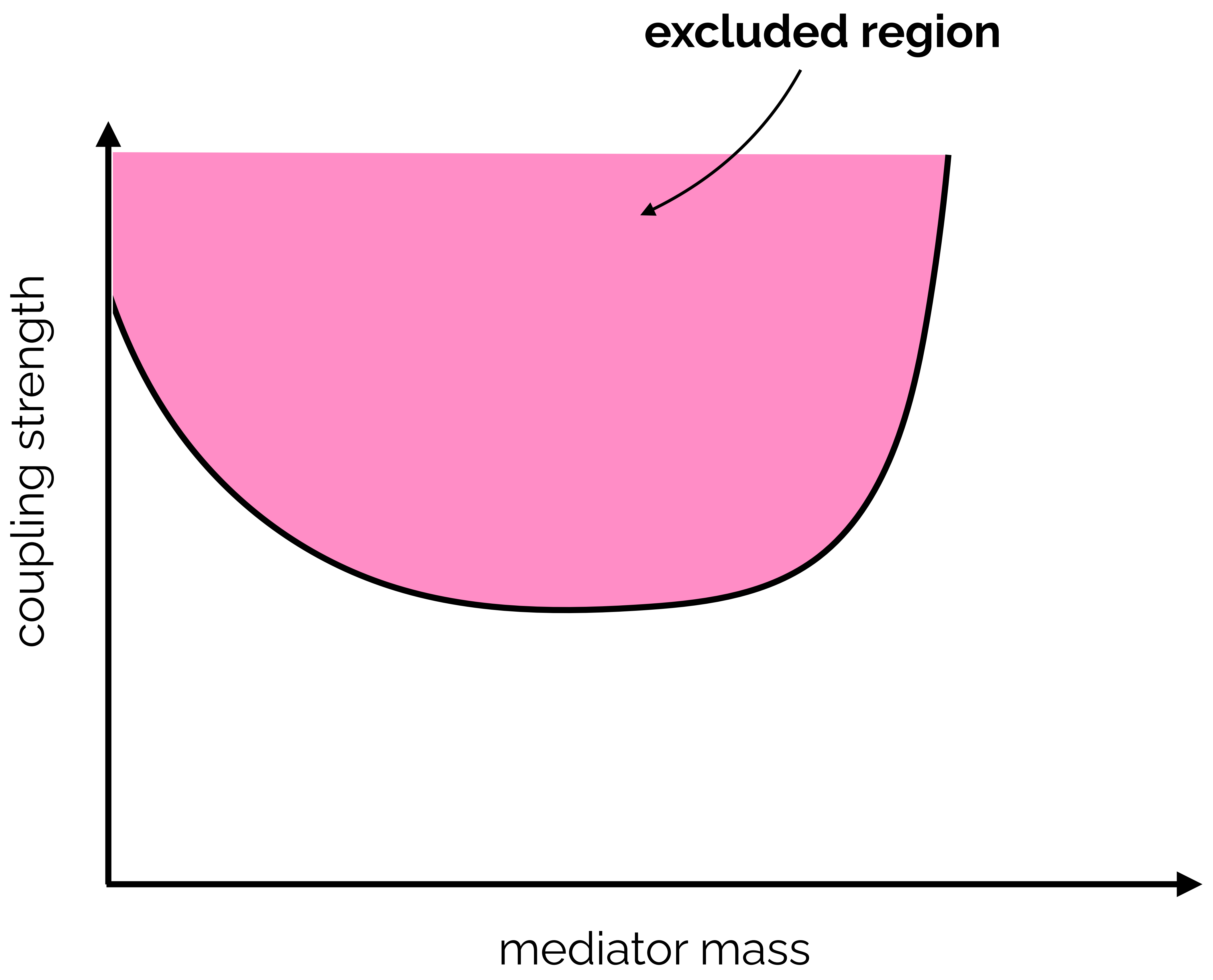
Search 101: Brazil bands

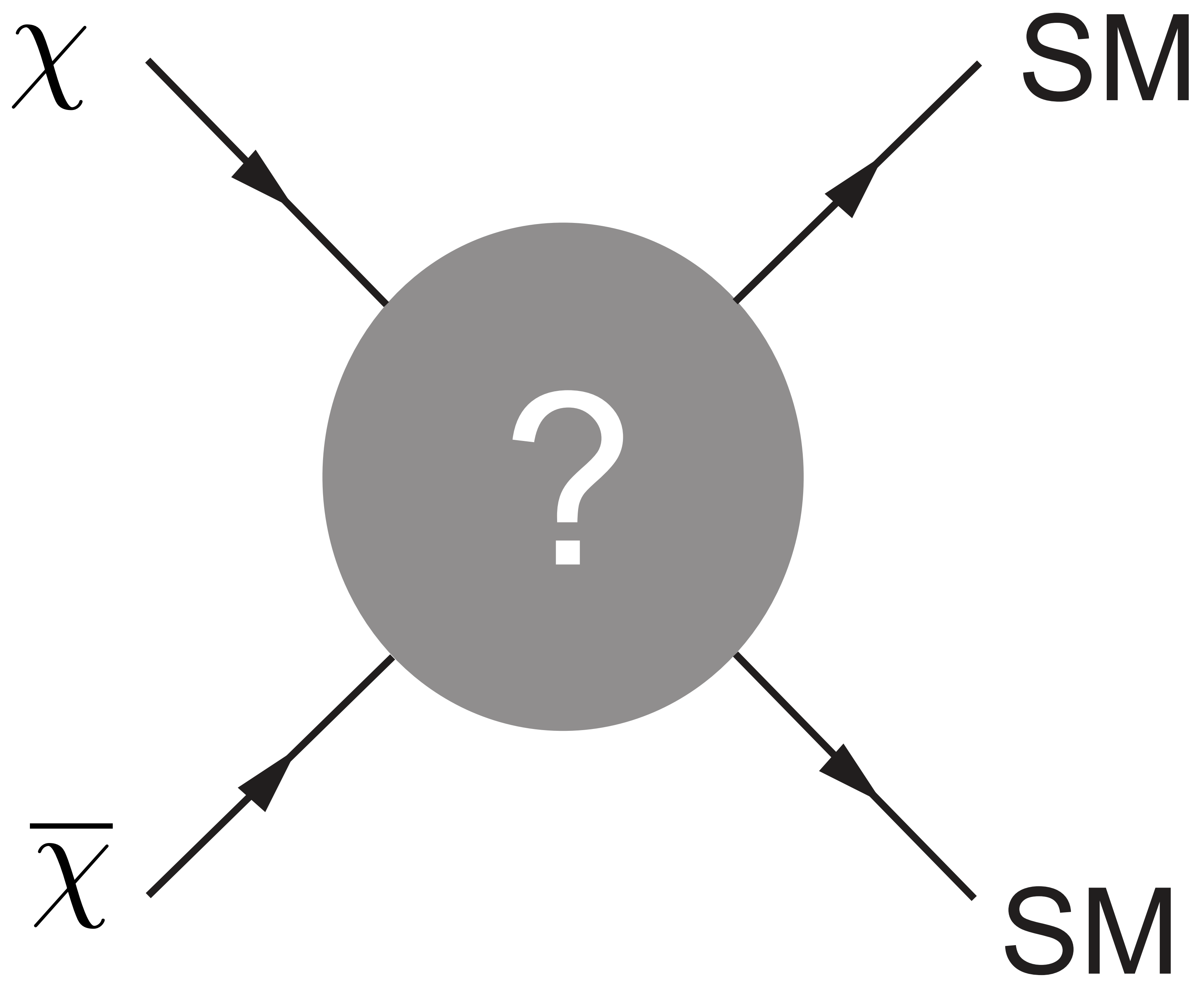


Search 101: Set limits

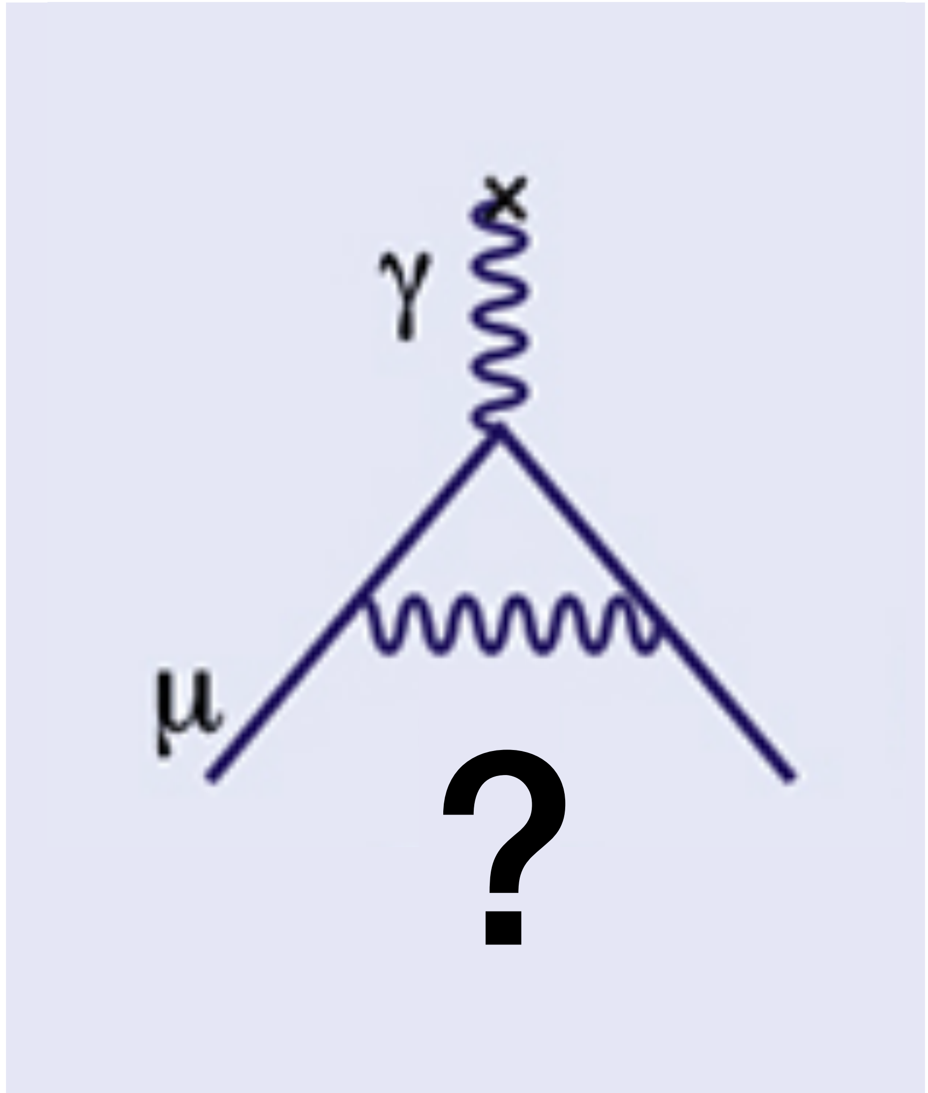
(careful: sometimes log-scale or linear scale)

(careful: sometimes cross section, branching fractions, couplings or any combination thereof…)

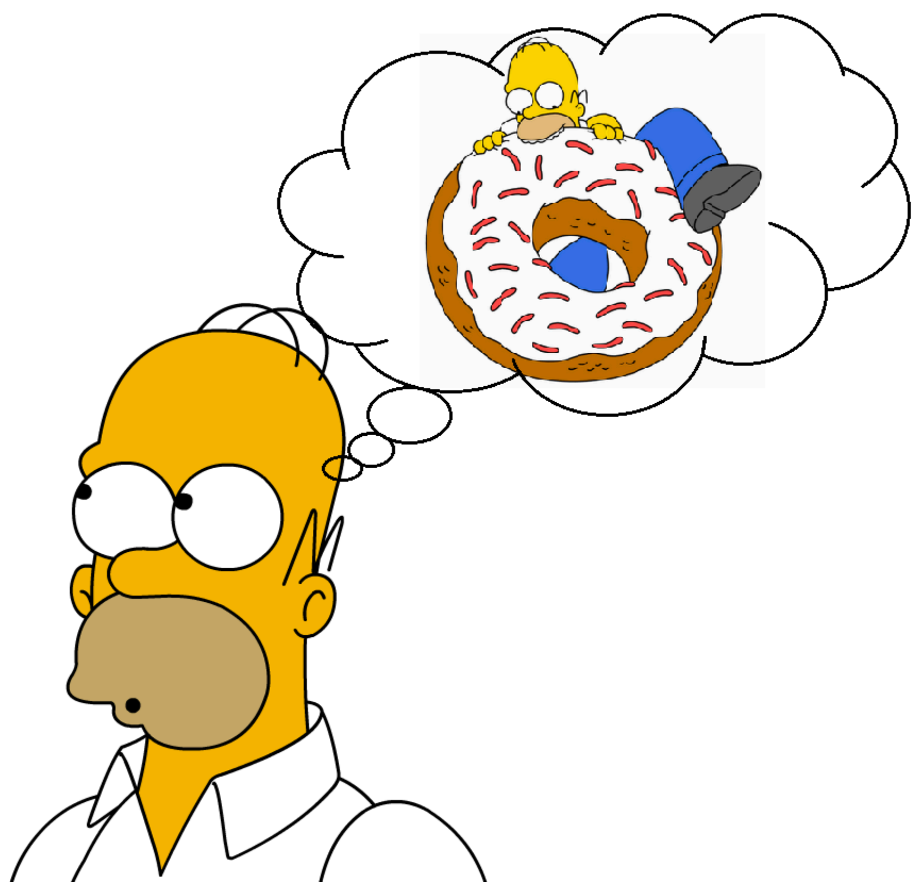




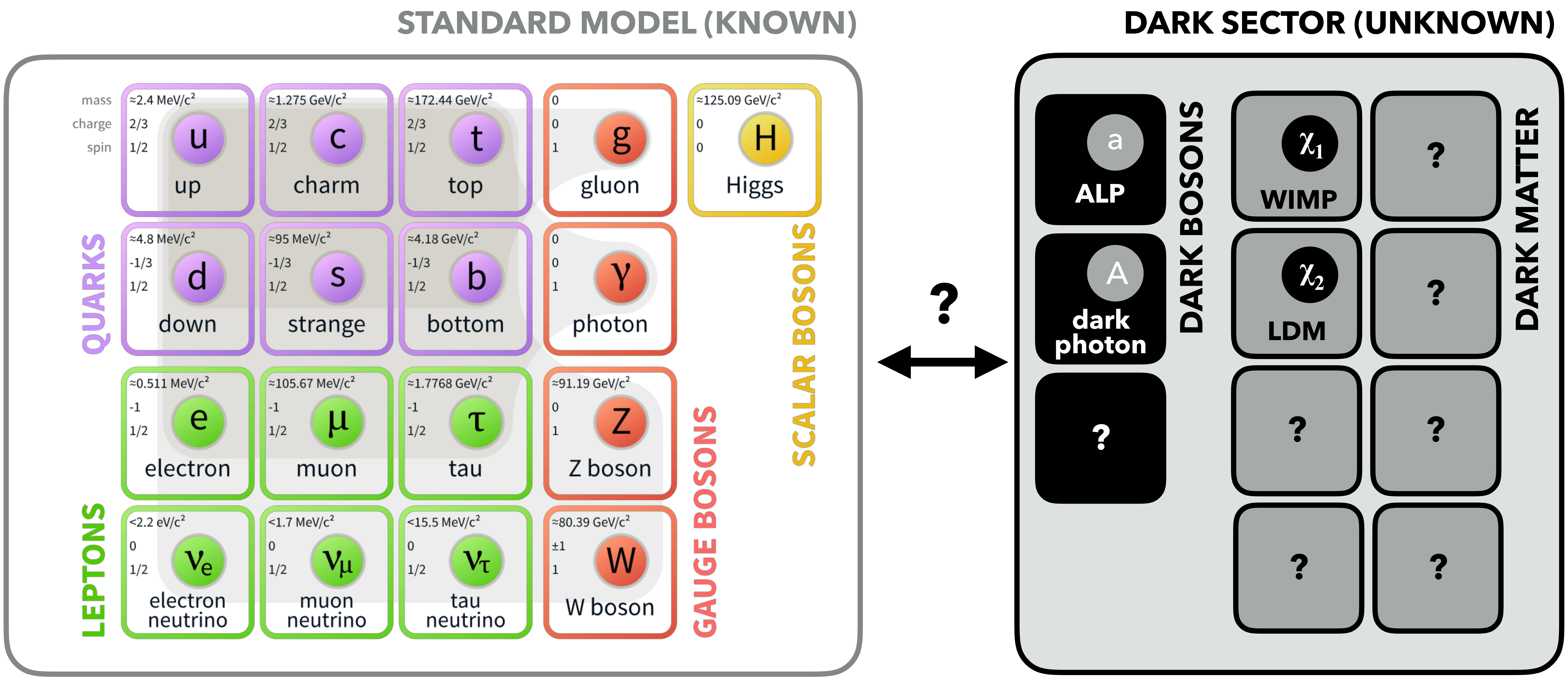
χ
SM
?
$\bar{\chi}$
SM



γ
μ
?



Portal models



Portal models: What to search for?

$$\mathcal{L} = \sum_{n=k+l-4} \frac{c_n}{\Lambda^n} \mathcal{O}_k^{(\mathrm{SM})} \mathcal{O}_l^{(\mathrm{med})} = \mathcal{L}_{\mathrm{portals}} + \mathcal{O}\left(\frac{1}{\Lambda}\right)$$

$$= \boxed{-\frac{\epsilon}{2} B^{\mu\nu} A'_{\mu\nu}} - \boxed{H^\dagger H (AS + \lambda S^2)} - \boxed{Y_N^{ij} \bar{L}_i H N_j} + \boxed{\mathcal{O}\left(\frac{1}{\Lambda}\right)}$$

Vector Portal: massive dark photon A' mixes with SM γ with strength ε

Scalar Portal: Additional dark Higgs(es)

Neutrino Portal: Sterile Neutrinos, heavy neutral leptons (HNLs)

T2K: https://arxiv.org/abs/1902.07598v2, Belle: https://arxiv.org/abs/1301.1105

e.g. Axion Portal: Massive ALPs with couplings to SM bosons

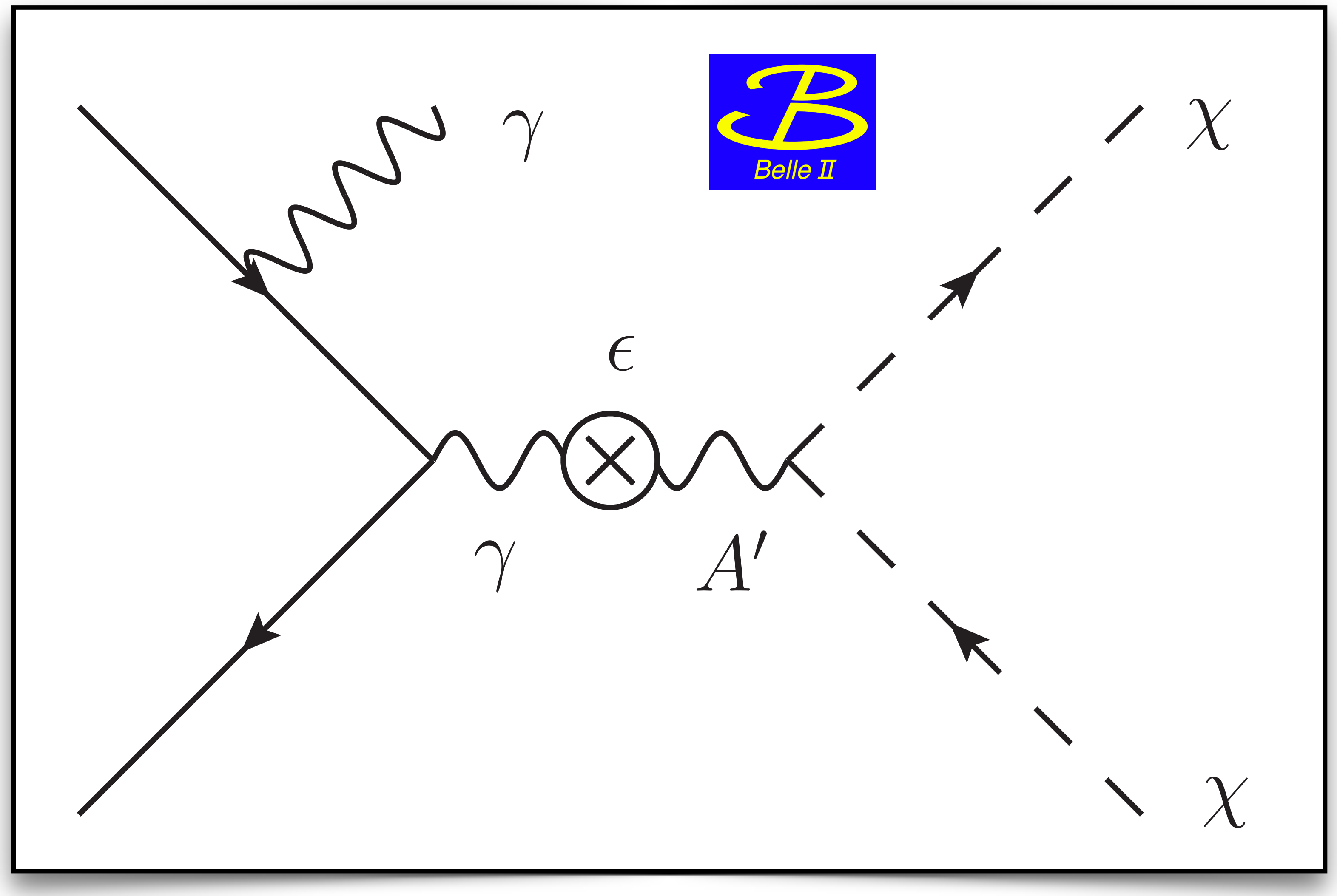
Belle II: https://arxiv.org/abs/2007.13071

Dark photons: A'

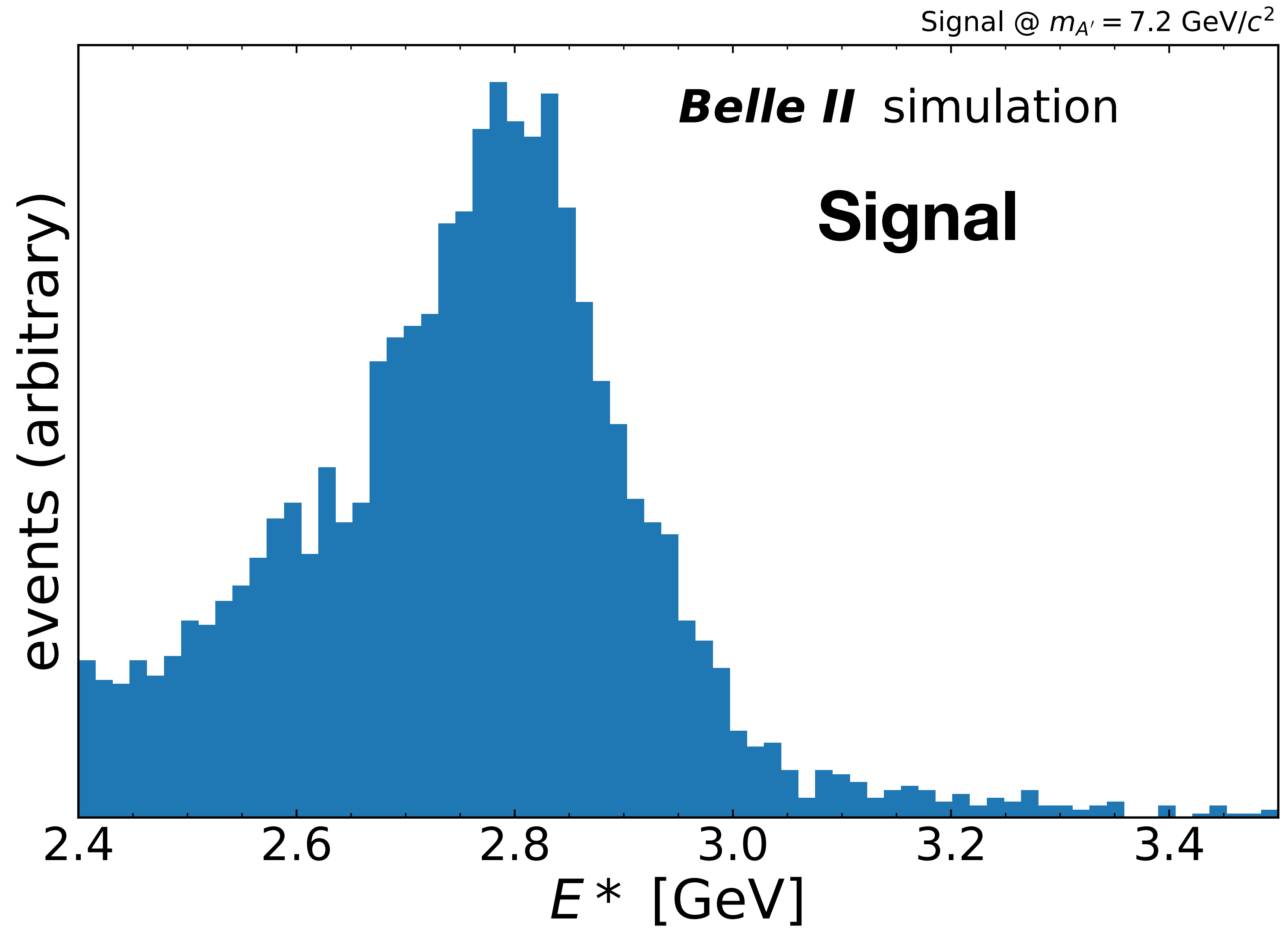
- Probably **THE** benchmark model for portal model searches
- Not a Dark Matter candidate itself (unless $m_{A'} \ll 2m_e$), but an excellent mediator
- Comes in two experimentally very different versions:
  - $m_{A'} > 2m_\chi$: Decays to invisible NP particle χ kinematically allowed, χ could be DM! ("invisible dark photons")
  - $m_{A'} < 2m_\chi$: Only decays back to SM particles kinematically possible ("visible dark photons")

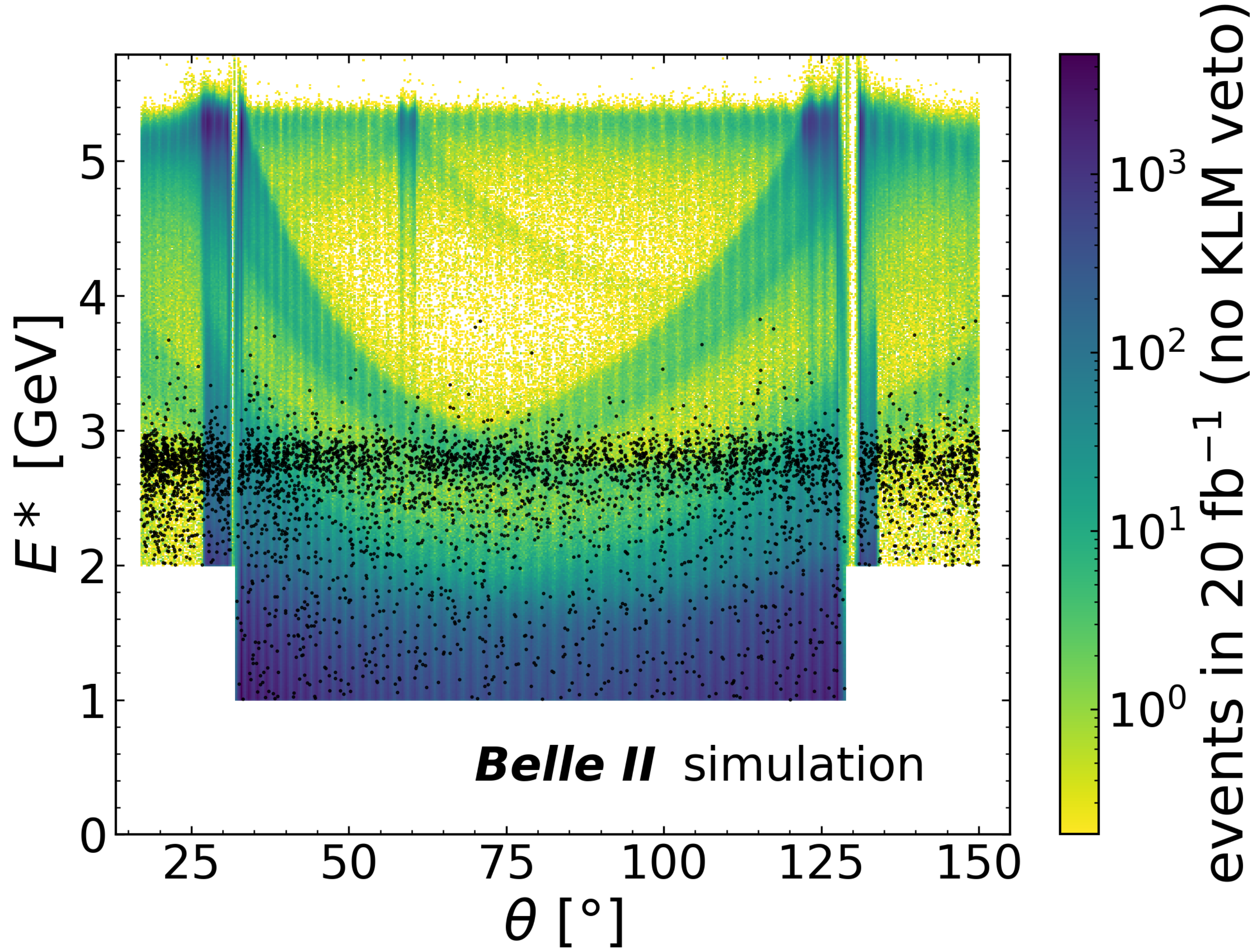
four free parameters:
- dark photon mass $m_{A'}$
- χ mass (dark matter candidate)
- dark coupling α_D
- kinetic mixing parameter ε

Dark photons: Invisible

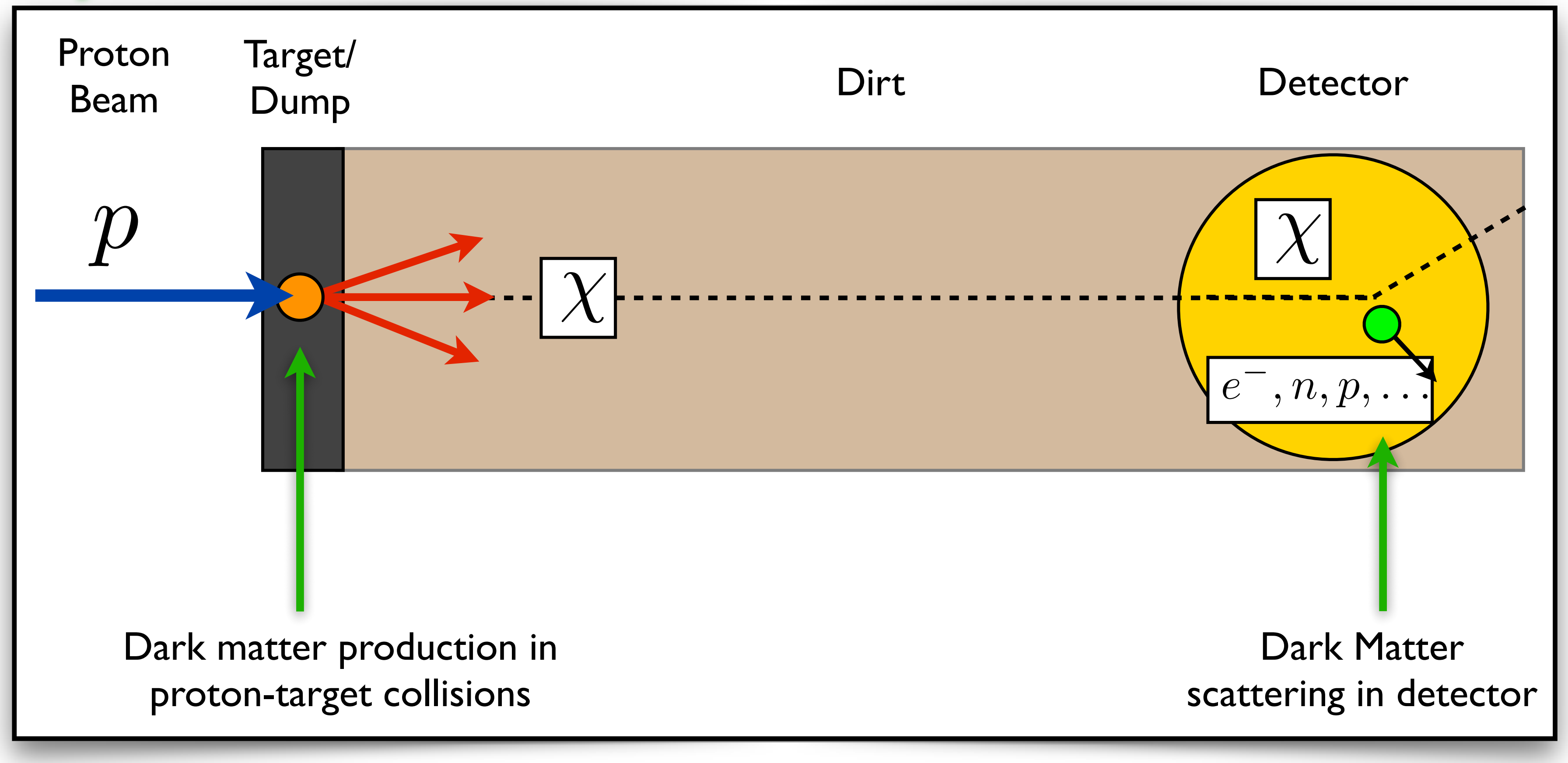


$$E_\gamma = \frac{s - M_{A'}^2}{2\sqrt{s}}$$

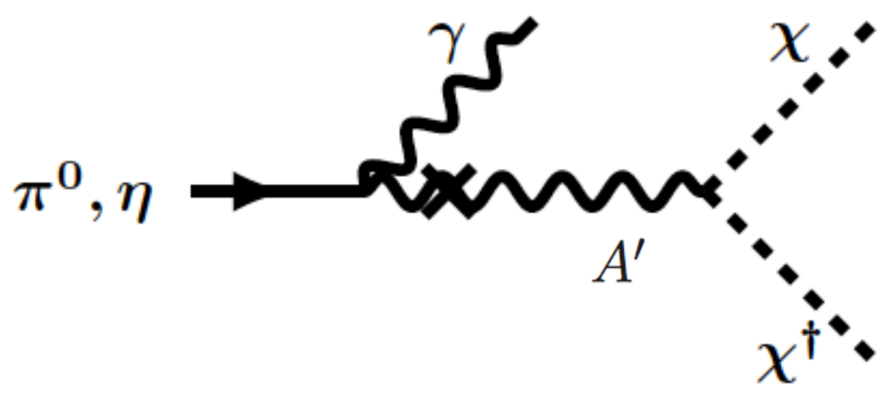




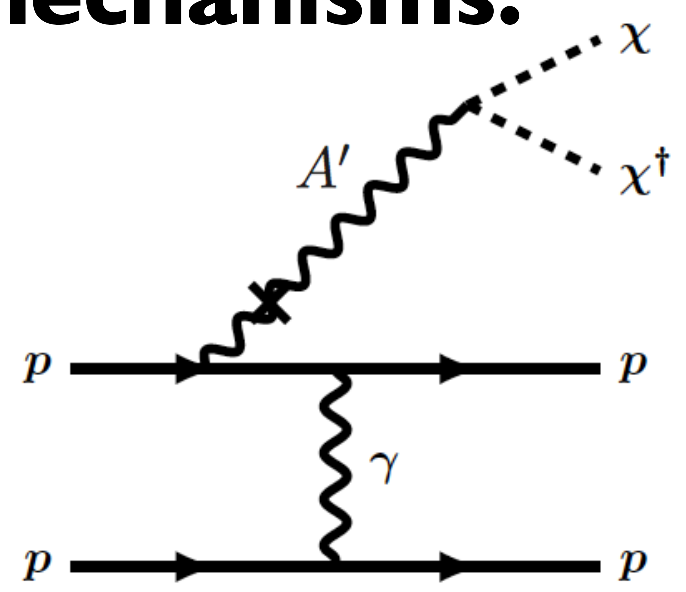
Dark photons: Invisible



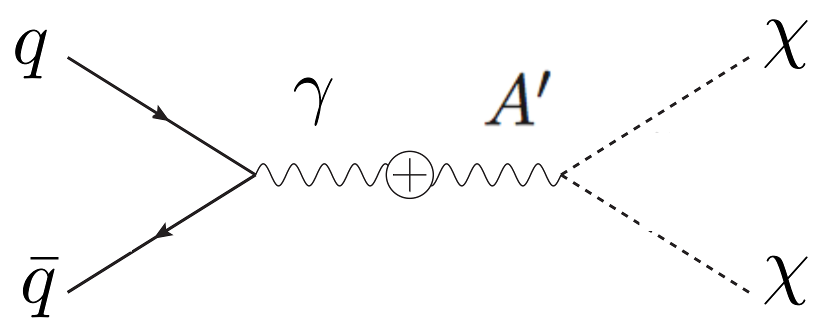
Dark matter production mechanisms:



Neutral mesons decays

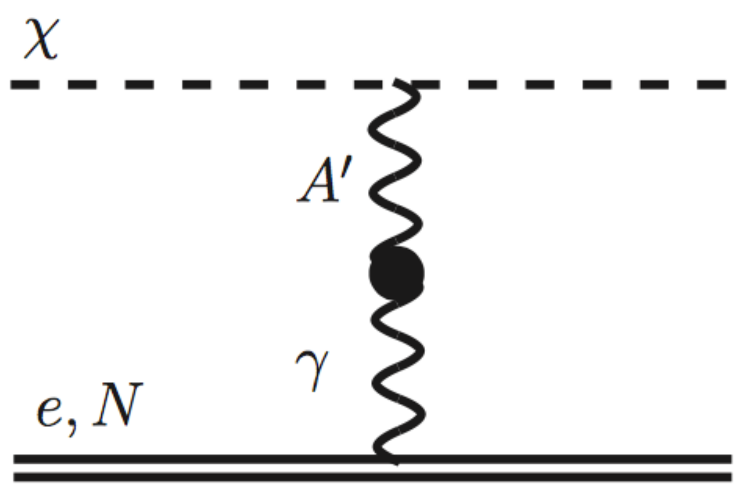


Bremsstrahlung + vector meson mixing

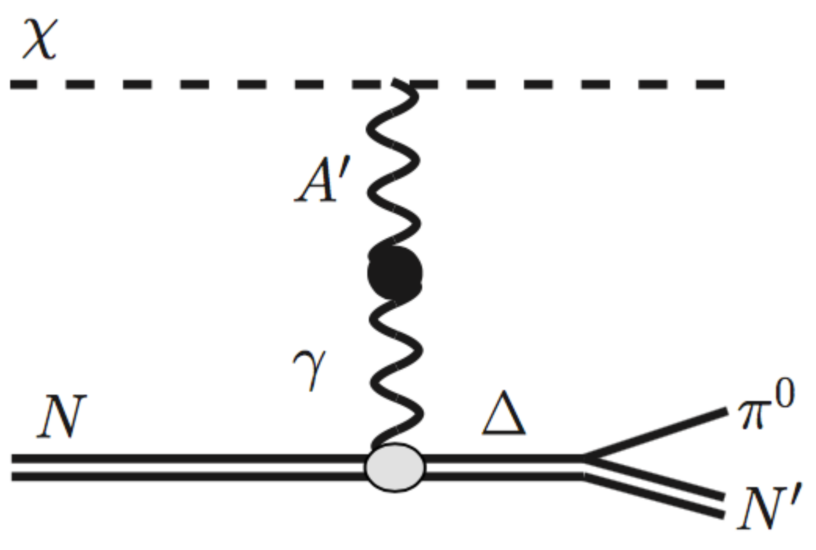


Direct production

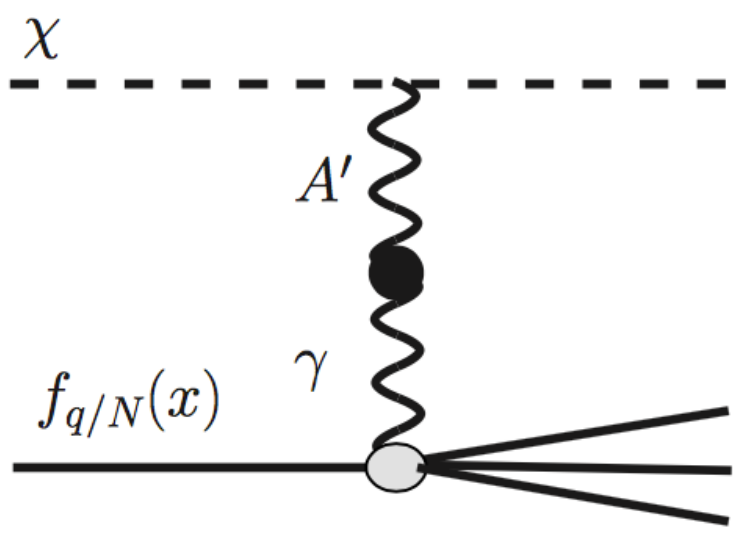
Dark matter detection via scattering:



Elastic electron, nucleon , nucleus (coherent) scattering



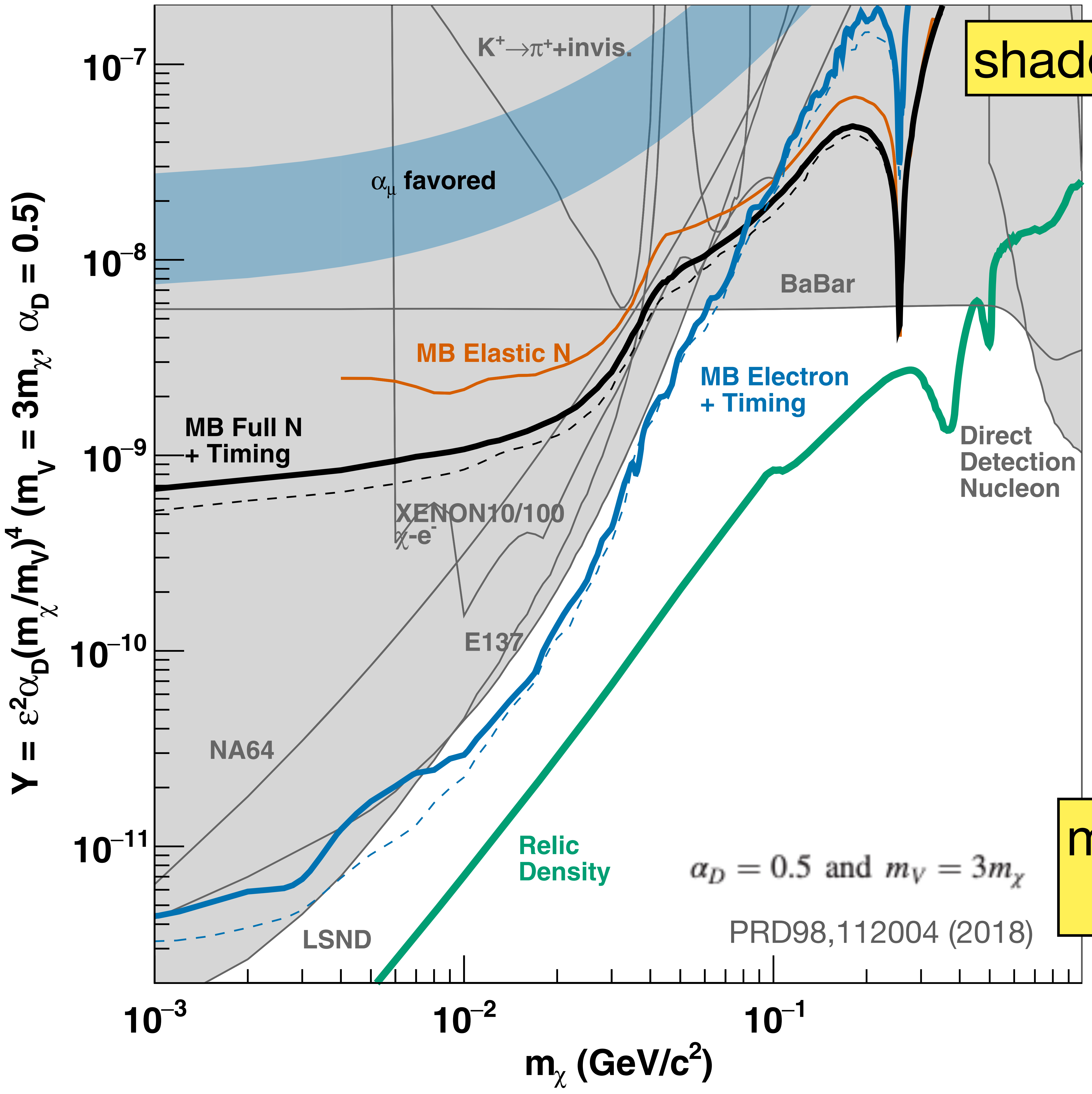
Inelastic neutral pion production



Deep inelastic scattering

from. B. Batell

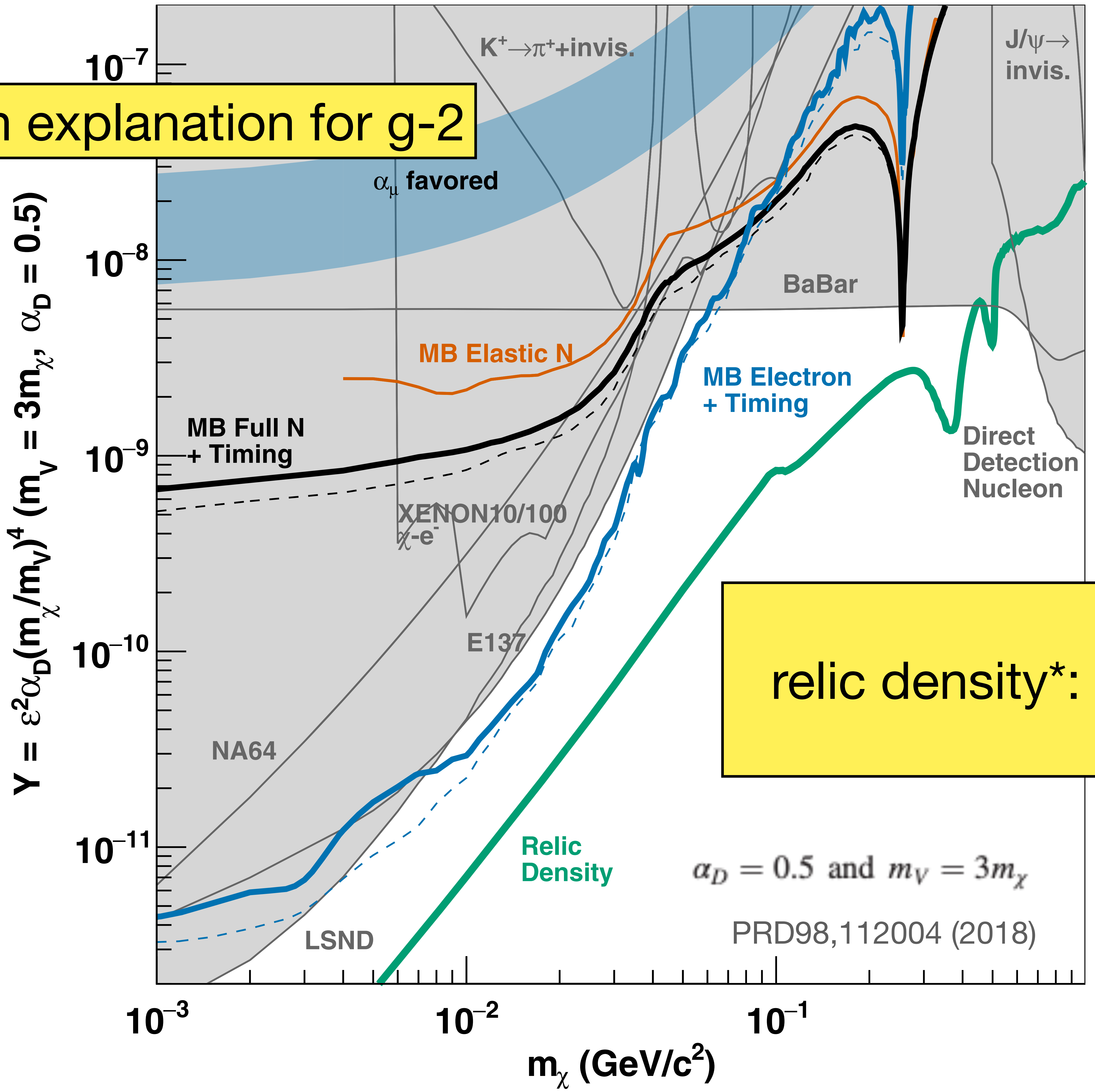
Dark photons: Invisible



shaded regions are excluded at 90% C.L.

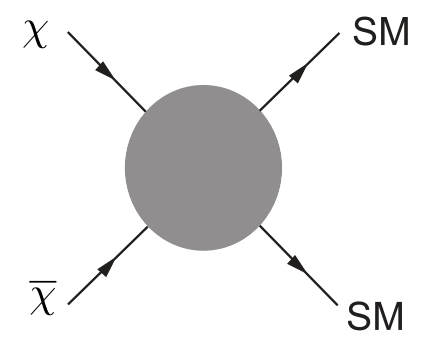
model has four free parameters → fix two of them

Dark photons: Invisible



dark photon explanation for g-2

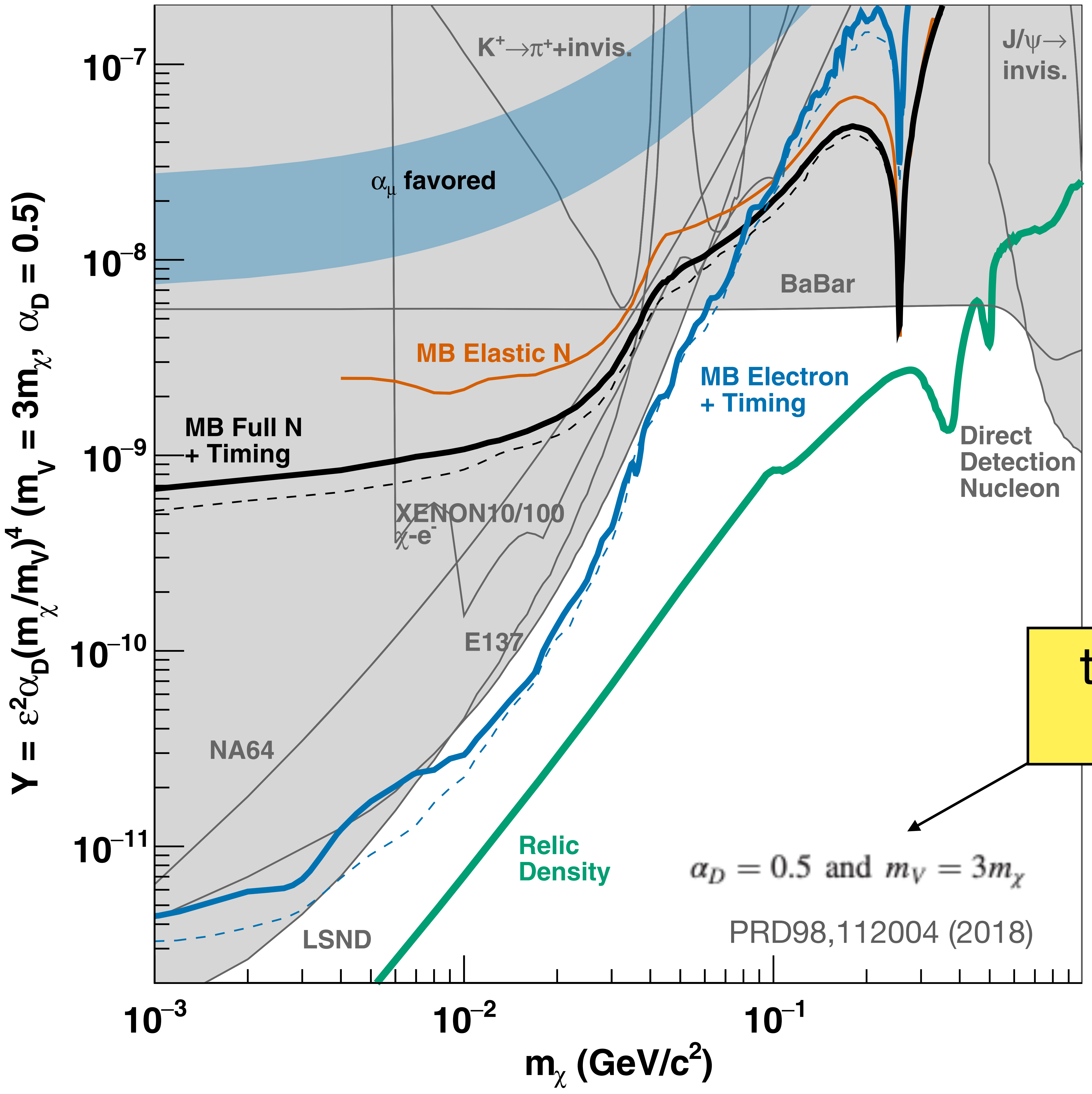
relic density*: $\langle \sigma v \rangle \sim \dfrac{\epsilon^2 \alpha_D \alpha m_\chi^2}{m_{A'}^4} \sim \dfrac{y}{m_\chi^2}$

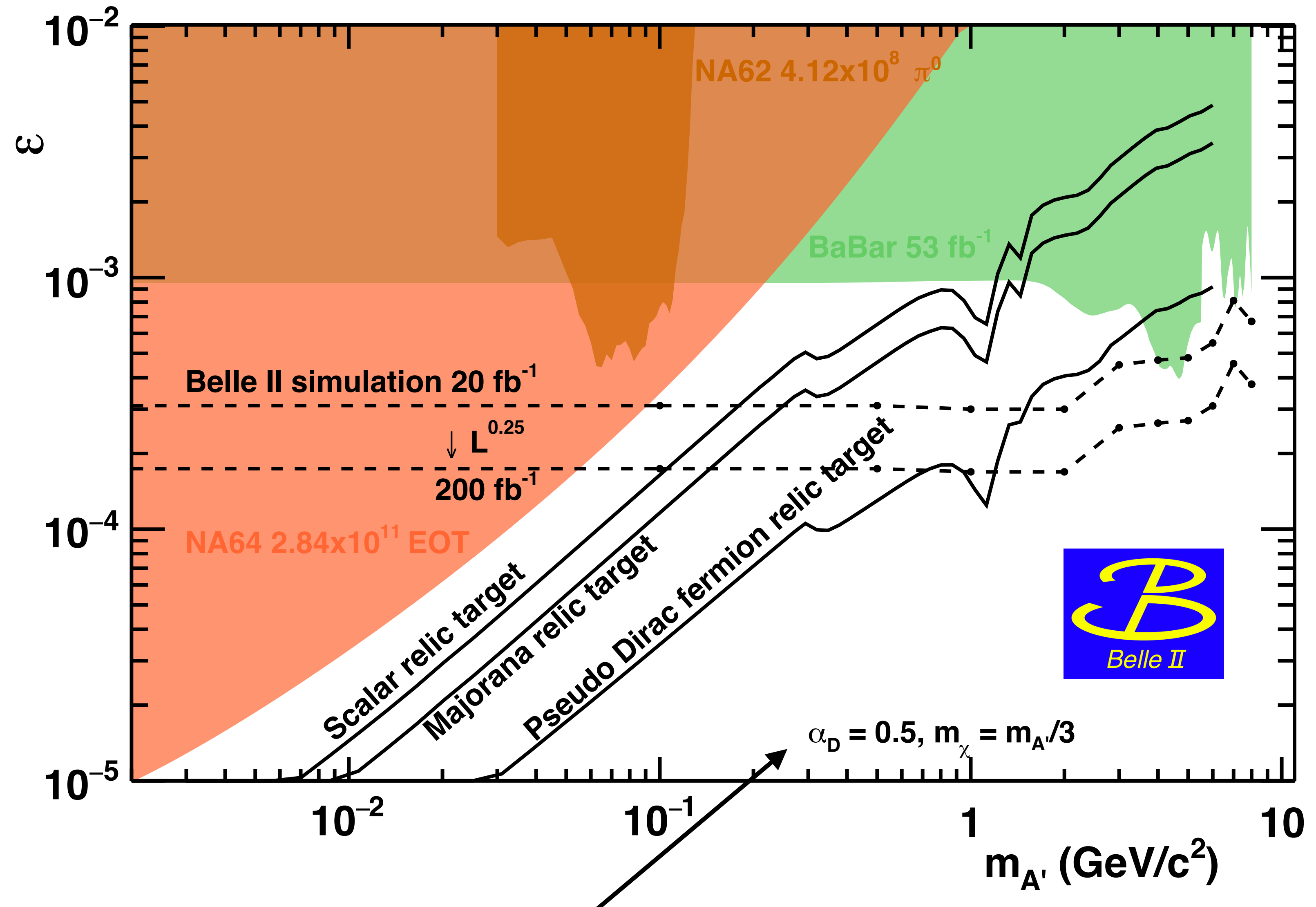


* The relic density calculation os untrivial with many (published) mistakes in the past, more details:

Duerr, TF, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney, *J. High Energ. Phys. 2020, 39 (2020)*, arXiv:1911.03176

Dark photons: Invisible

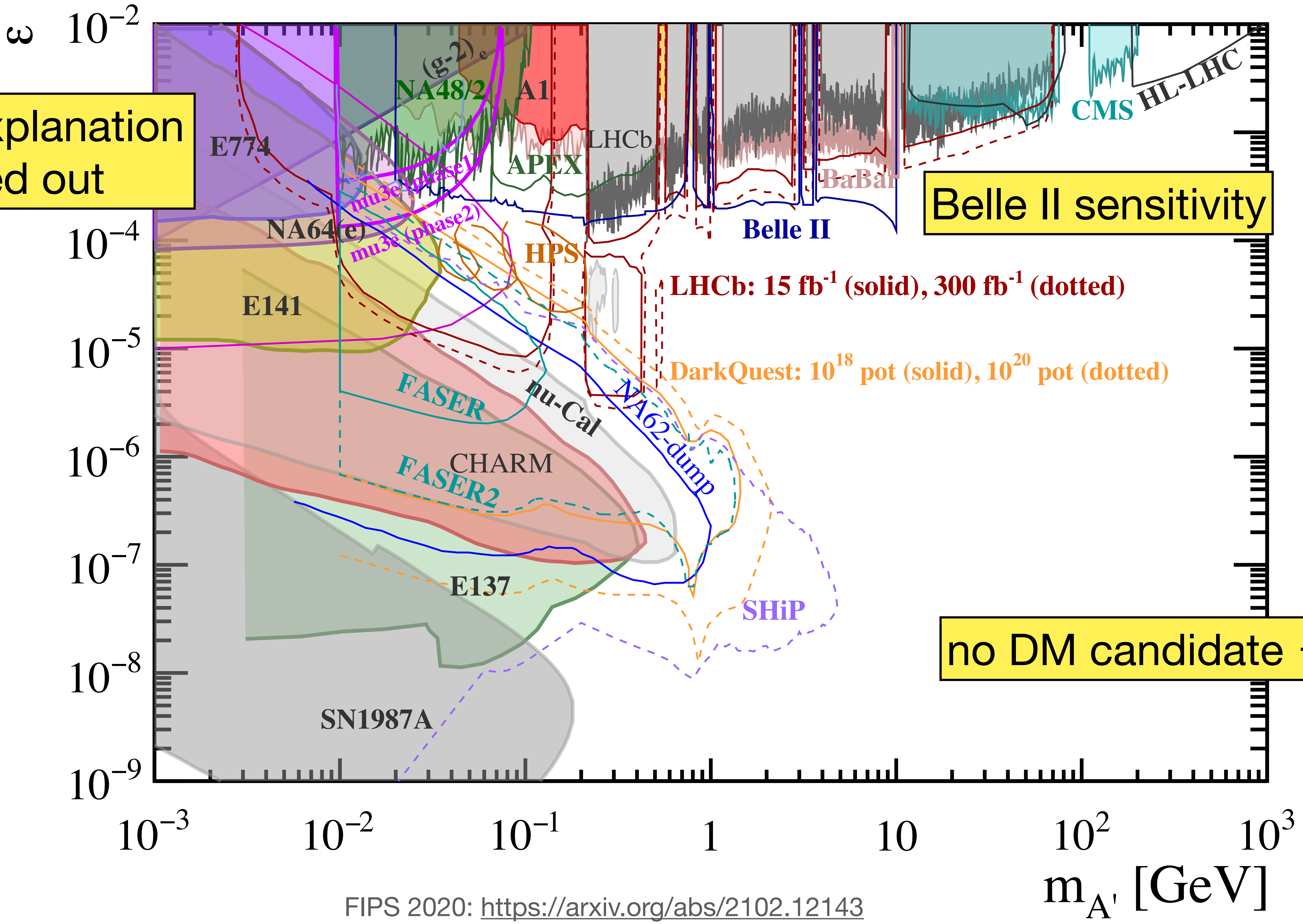




the community has adopted some “benchmark” values

Dark photons: Visible

dark photon explanation for g-2 ruled out



Belle II sensitivity

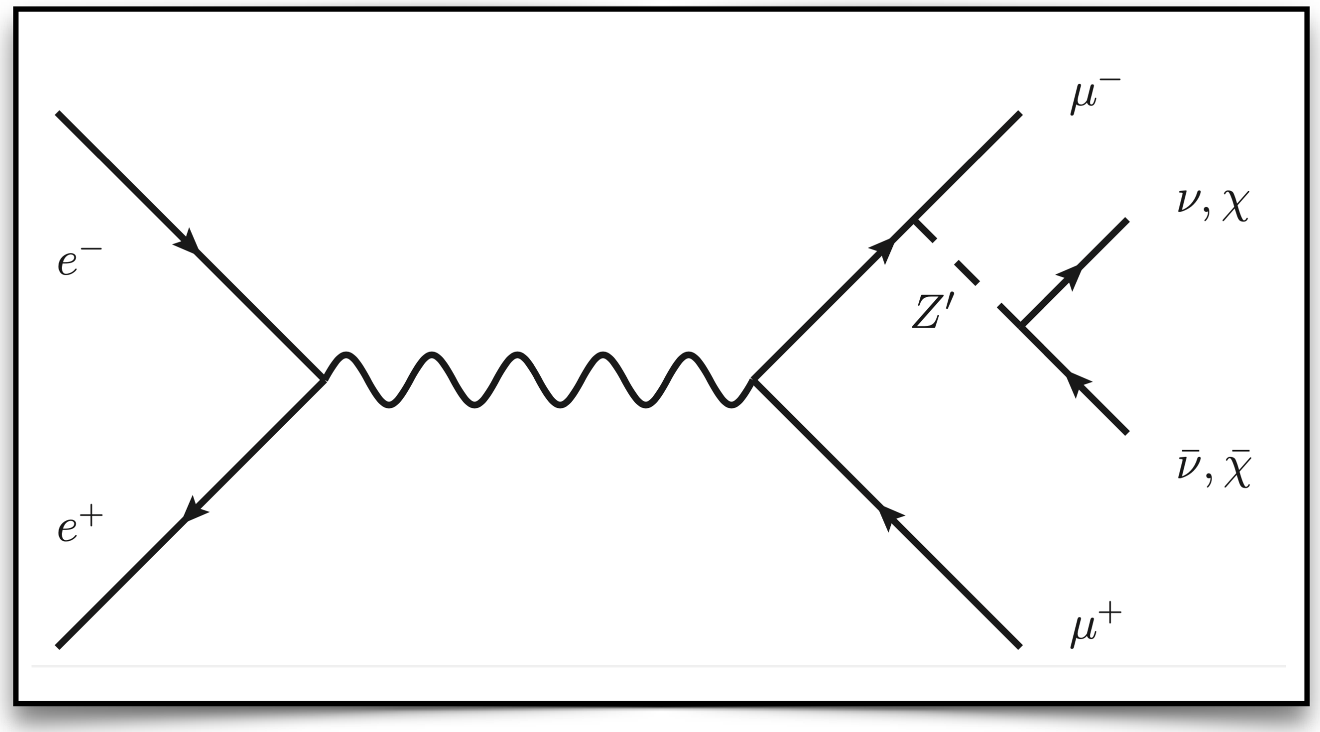
no DM candidate → no relic targets

FIPS 2020: https://arxiv.org/abs/2102.12143

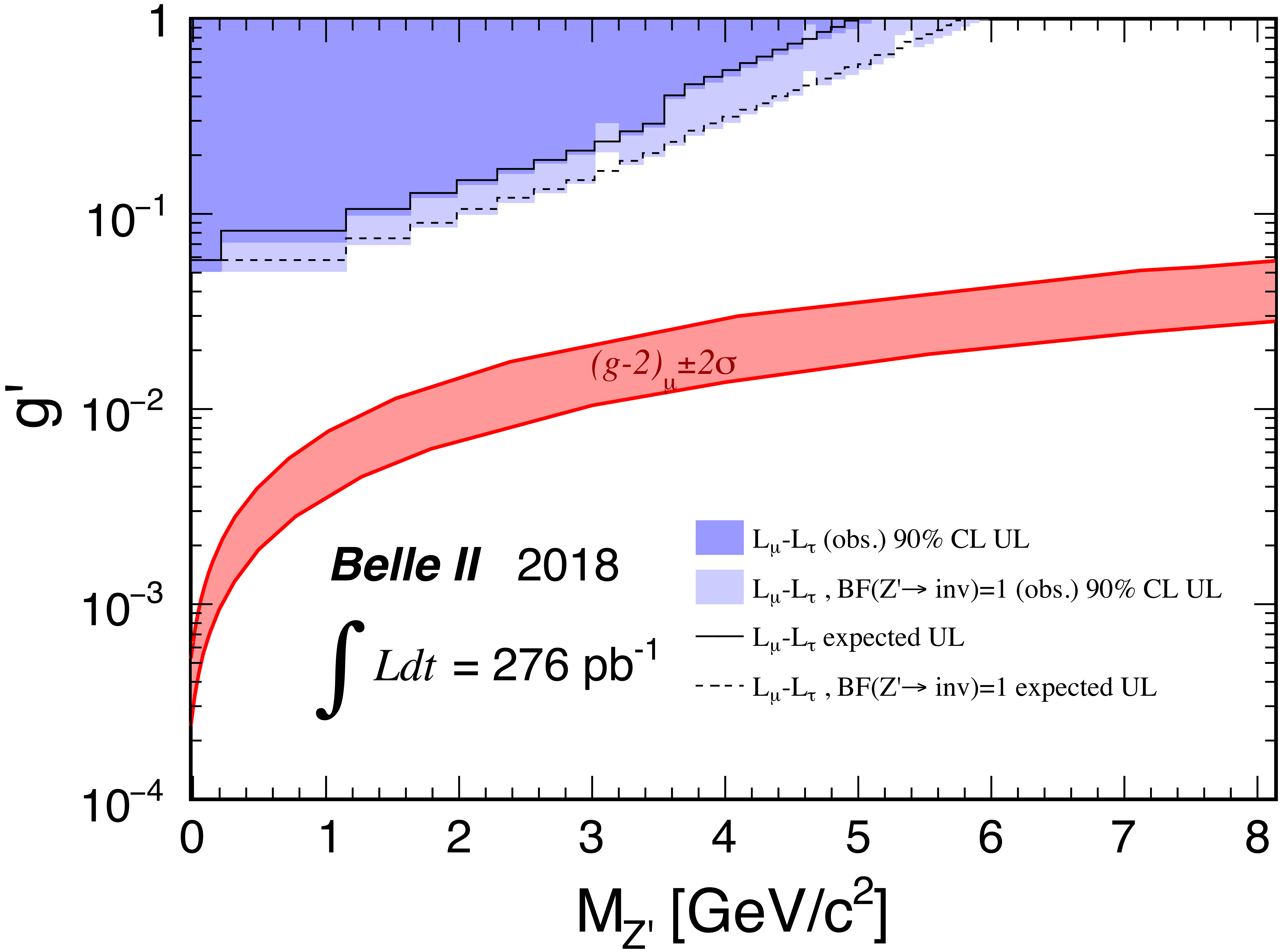
Dark photons with a twist: Z’

dark photon explanation for g-2 ruled out?

What if the Z’ is electrophobic?

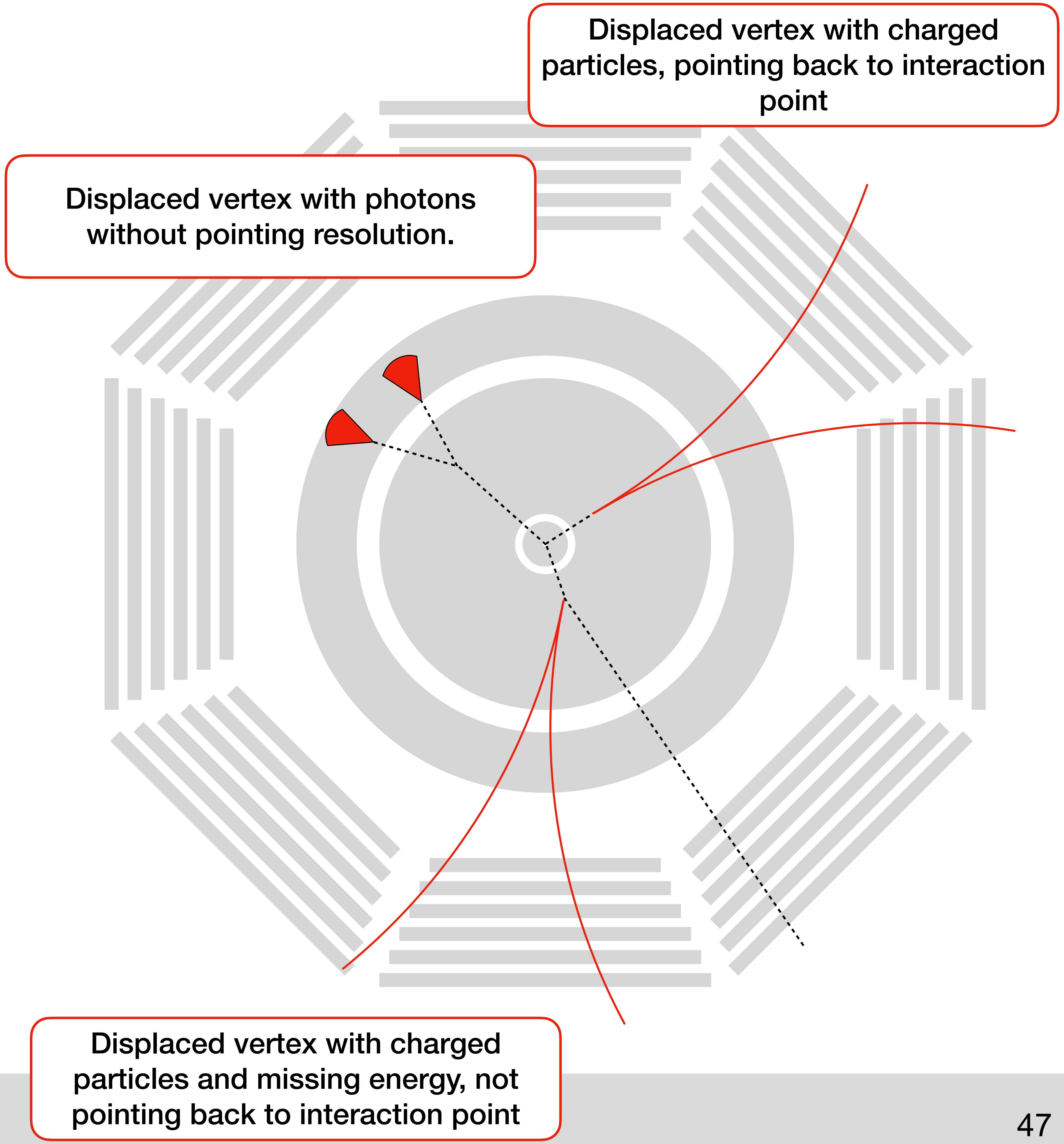


Belle II: https://arxiv.org/abs/1912.11276

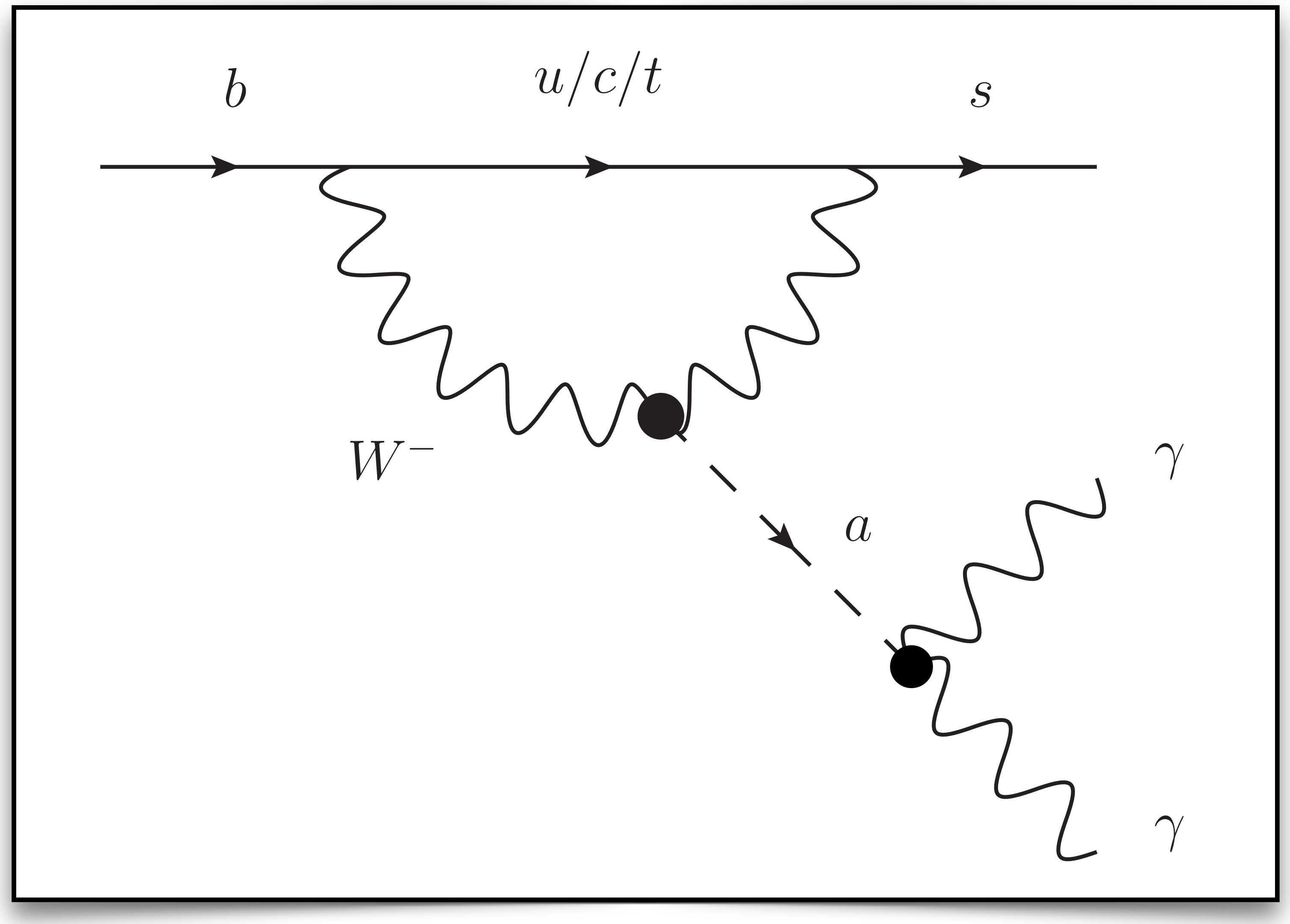


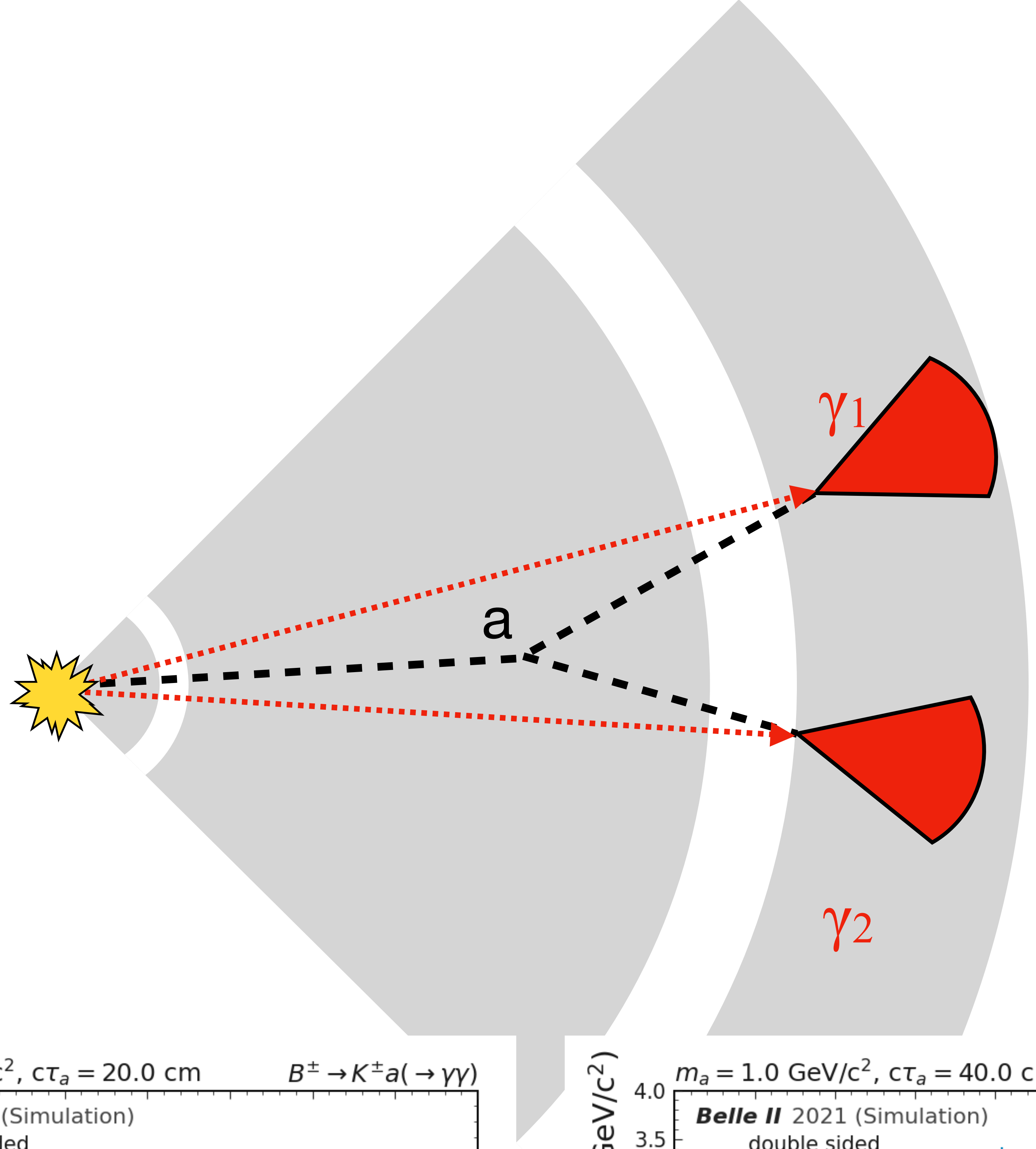
Beyond searches 101: Long-lived particles

- Long-lived particles appear naturally for small couplings
- Exploited in beam dumps (neutrino near detectors)
- But: Collider detectors (and software) optimized for particles from the collision points!
  - Triggers, reconstruction, simulation, …

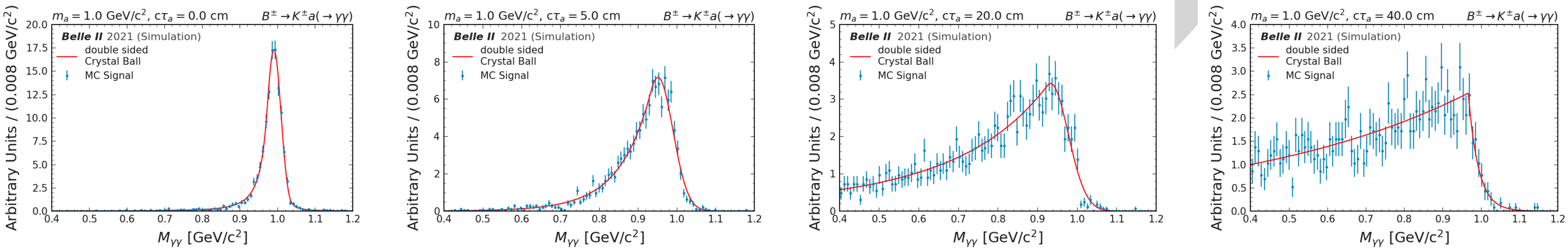


Beyond searches 101: Long lived particles



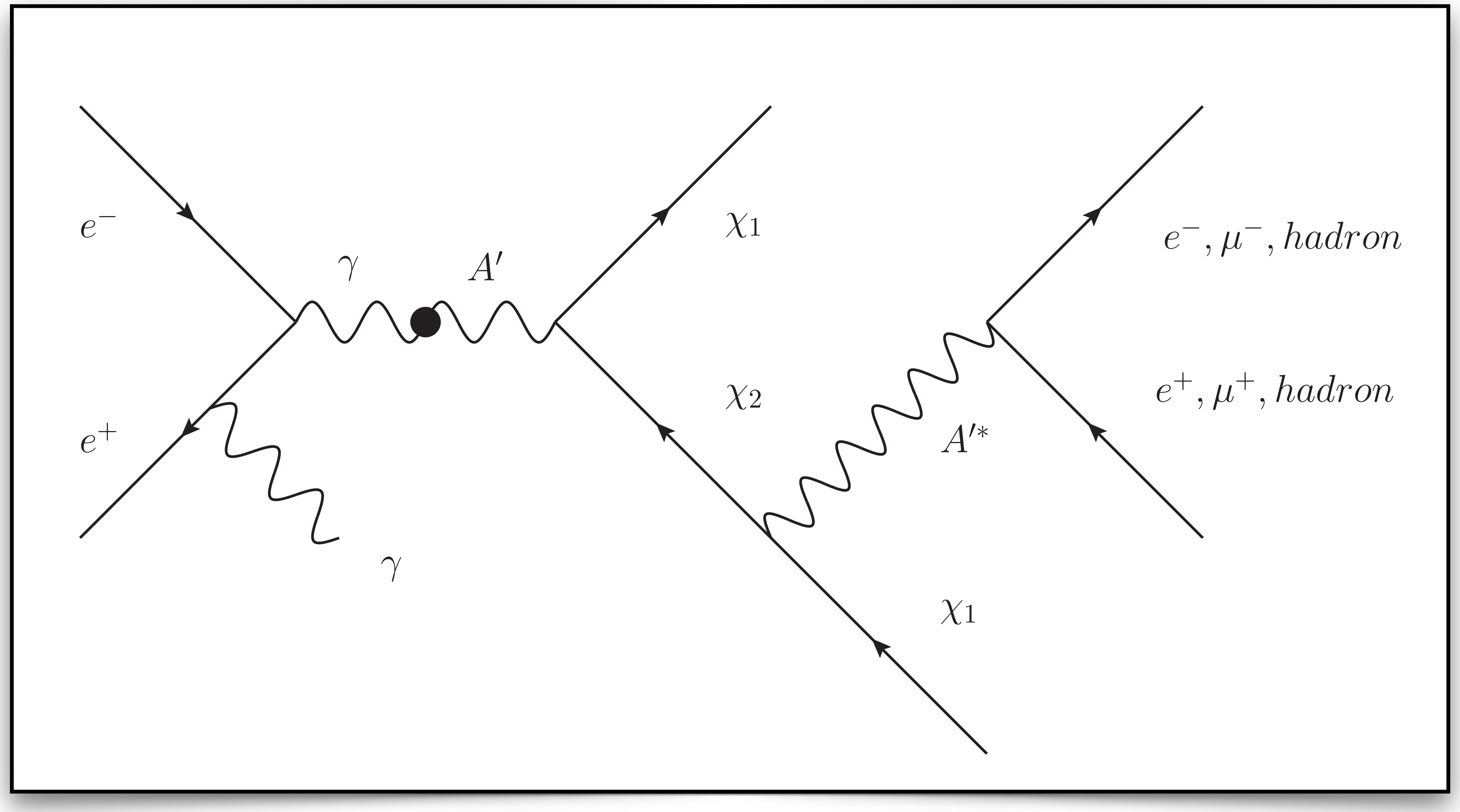


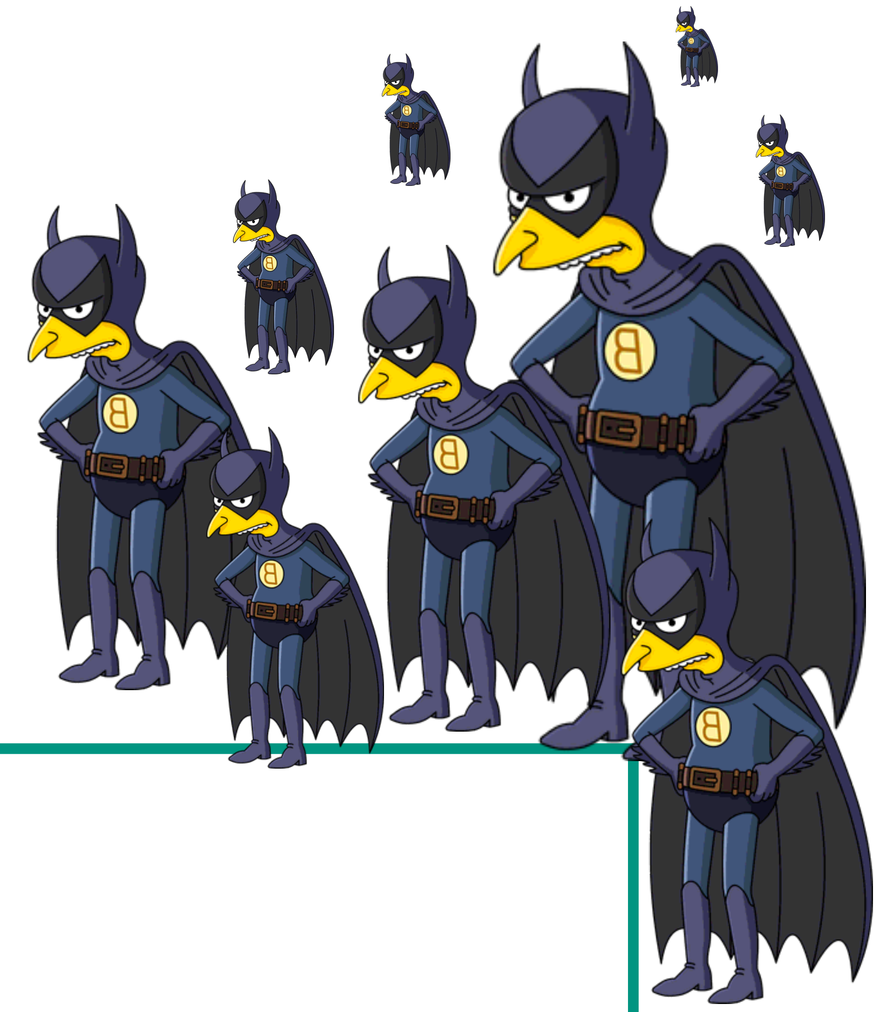
plots by Alex Heidelbach



Beyond searches 101: Complex dark sectors

Inelastic dark matter, $m_{\chi 2} > m_{\chi 1}$





five free parameters:

- dark photon mass $m_{A'}$
- χ_1 mass (stable dark matter candidate)
- mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$
- dark coupling α_D
- kinetic mixing parameter ε

Beyond searches 101: Complex dark sectors

two parameters fixed: α_D and $m_{A'}/m_{\chi 1}$

displaced search

invisible search

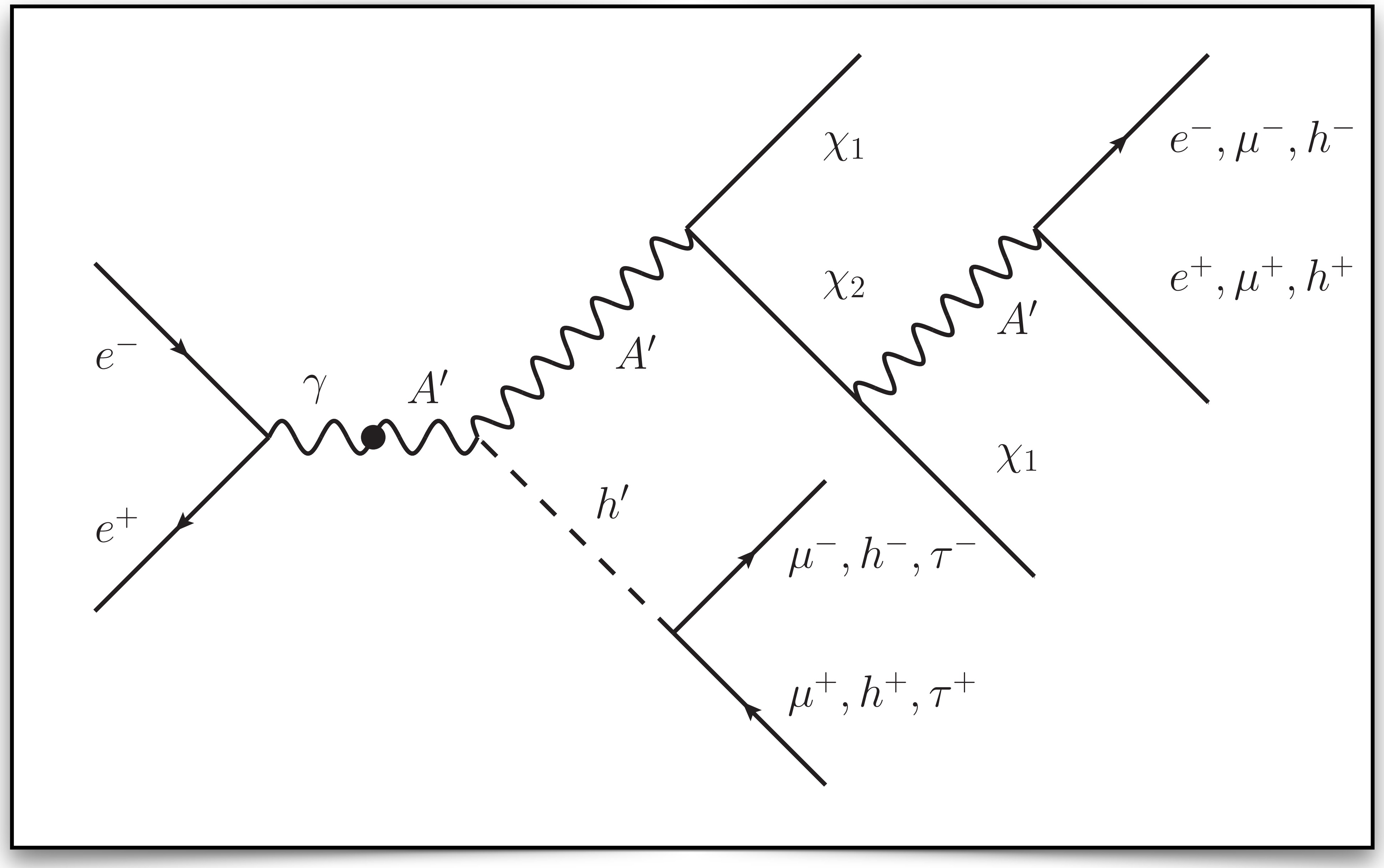
$m_{\chi 1} \approx m_{\chi 2}$ → $m_{\chi 1} \ll m_{\chi 2}$

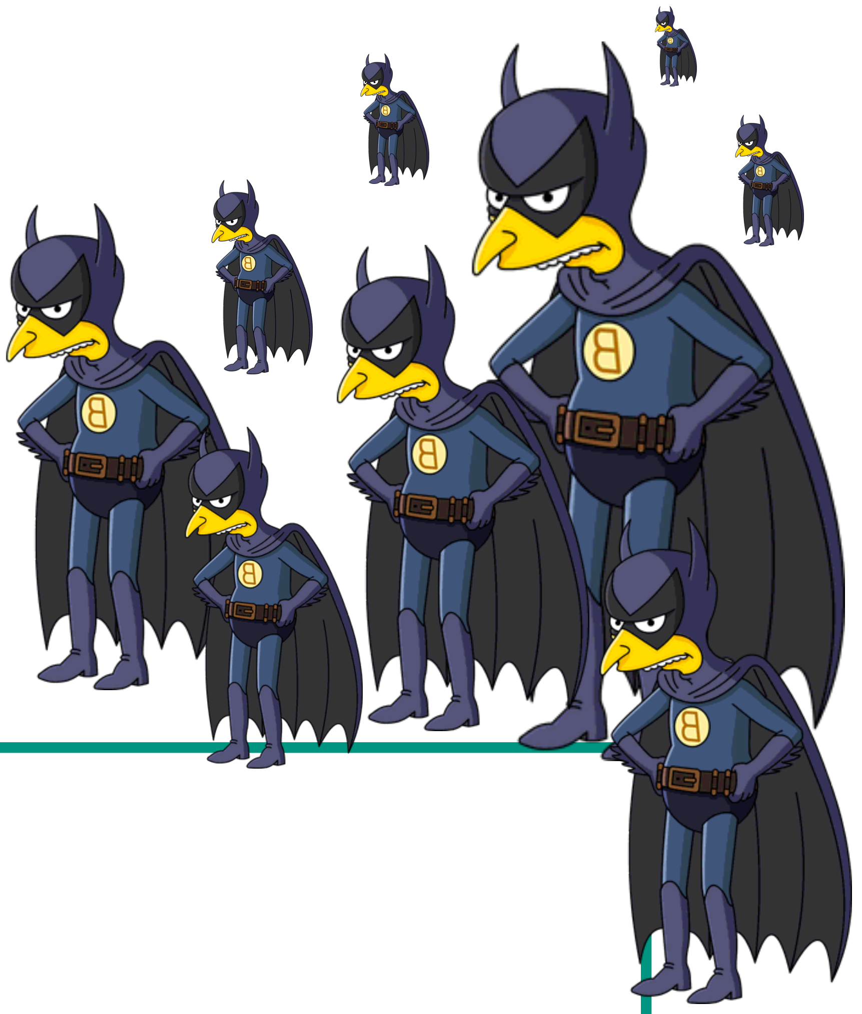
one parameter changed per plot: Δ

Duerr, **TF**, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney, *J. High Energ. Phys. 2020, 39 (2020)*, arXiv:1911.03176

Beyond searches 101: Multiple mediators

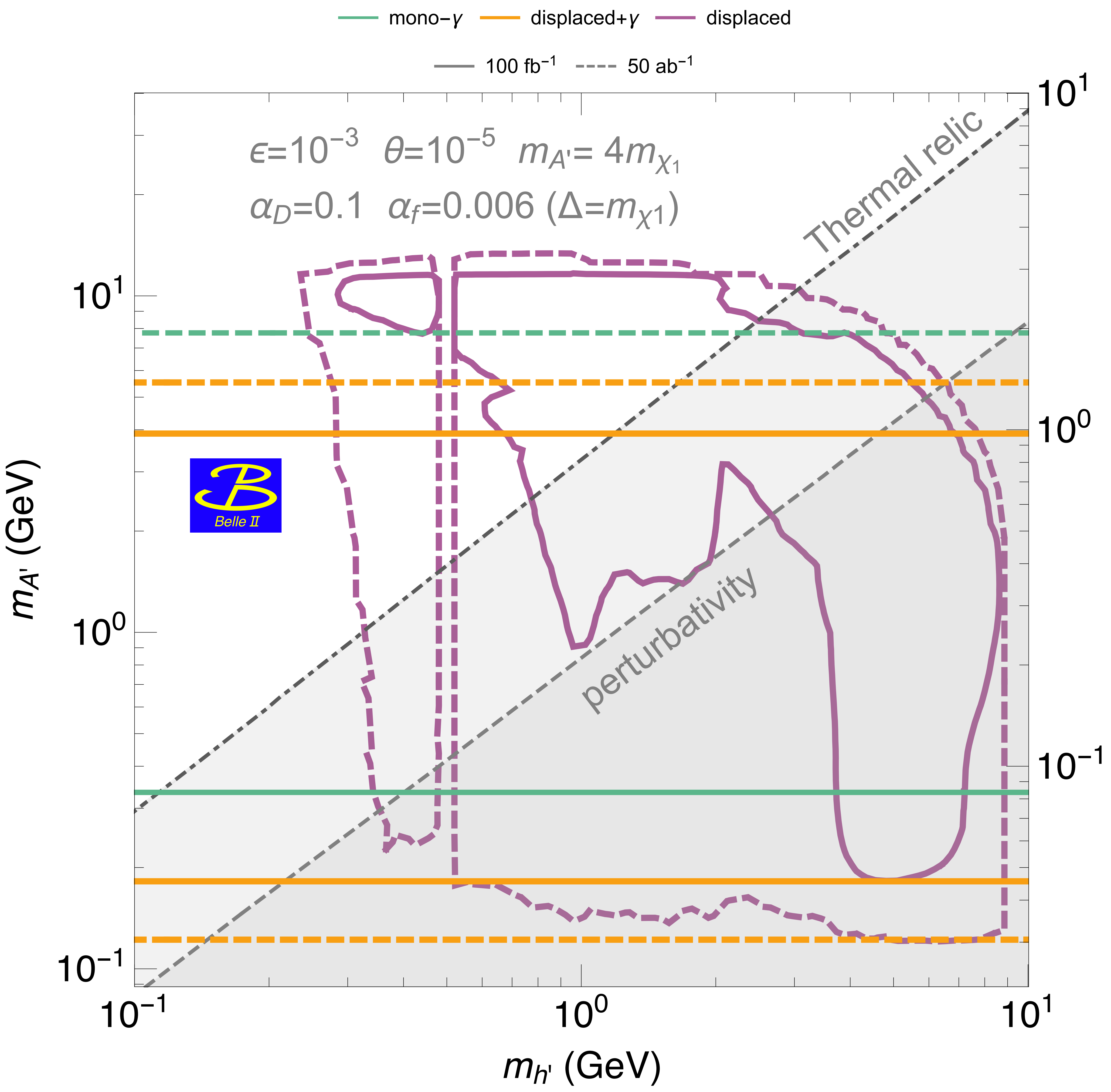
Inelastic dark matter and dark higgs





seven free parameters:
- dark photon mass $m_{A'}$
- χ_1 mass (stable dark matter candidate)
- mass difference $\Delta = m_{\chi_2} - m_{\chi_1}$
- dark coupling α_D
- kinetic mixing parameter ε
- dark higgs mass $m_{h'}$
- dark higgs mixing angle θ

Beyond searches 101: Multiple mediators



five parameters fixed

Duerr, TF, Garcia-Cely, Hearty, Schmidt-Hoberg, *J. High Energ. Phys.* **2021,** 146 (2021), arXiv:2012.08595

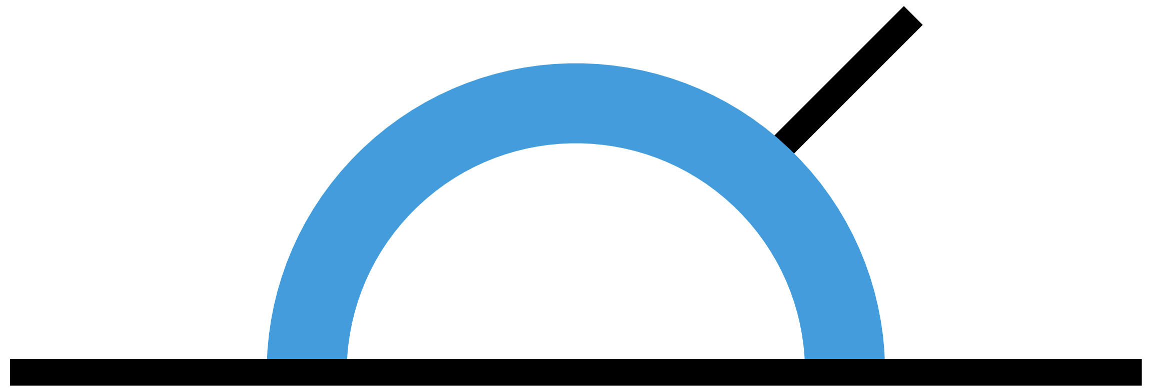
Take home messages

- Dark Matter is here to stay
  → promising scenarios testable with current experiments!
- $(g\text{-}2)_\mu$ is the largest single anomaly in particle physics
  → very predictive and testable!
- We barely started to exclude parameter space in simple DM models only
  → get involved now!
- More information:
  Feebly Interacting Particles Physics Centre
  https://pbc.web.cern.ch/fpc-mandate

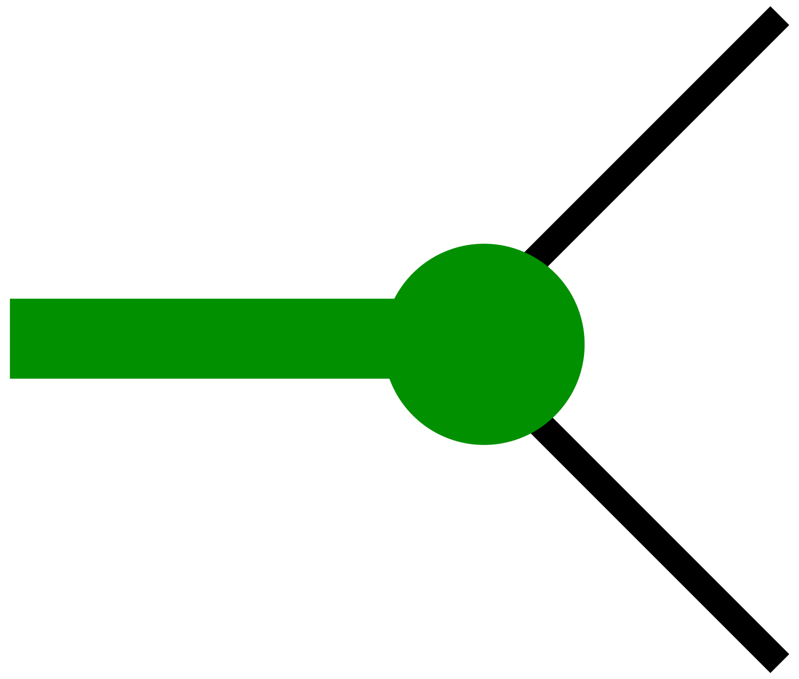
Beyond searches 101

- No background model → no discovery potential
  - typical for direct detection experiments, but also a problem if you have peaking backgrounds
- Model independent searches
  - often weaker limits for specific models, but wider applicability to different models
  - theorists often recast model-dependent searches if we provide enough information
- Bump-hunts only work in specific kinematic configurations
  - heavy mediator searches or interference effects can drastically change search strategy
- …

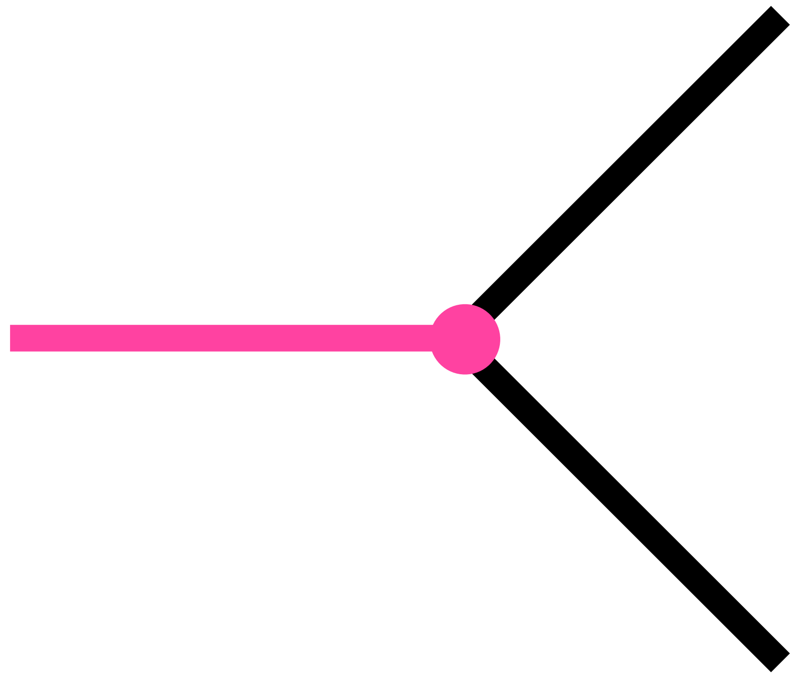
Searches for new physics: Three options



“Heavy” new physics in loop corrections



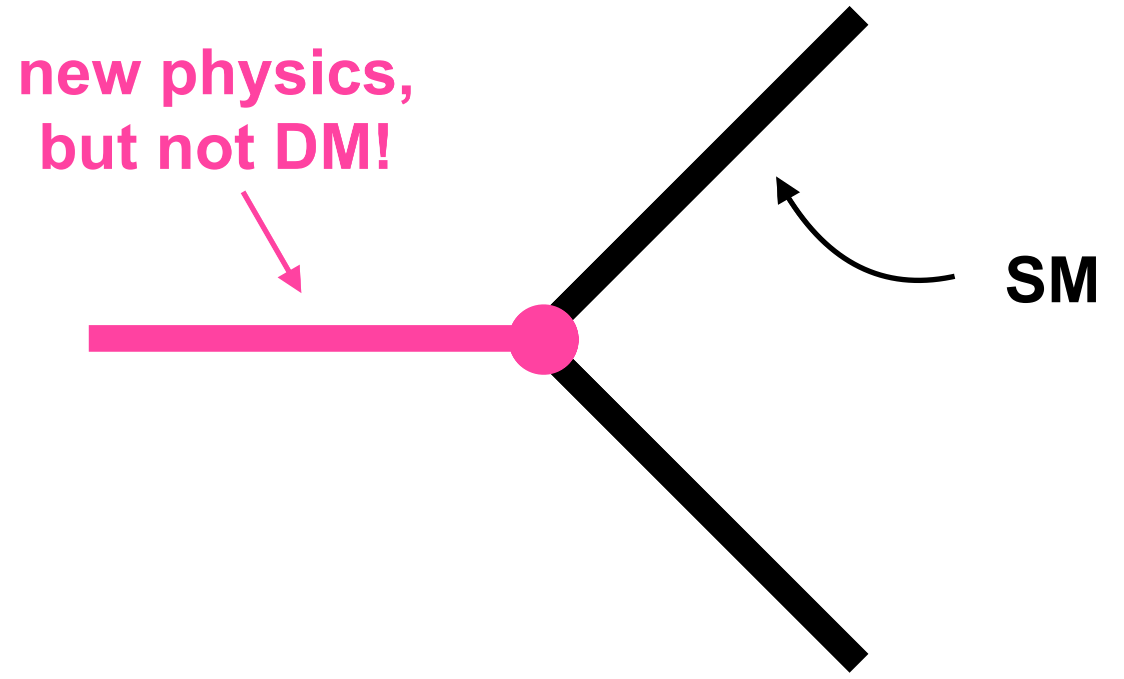
Heavy new mediators with large couplings



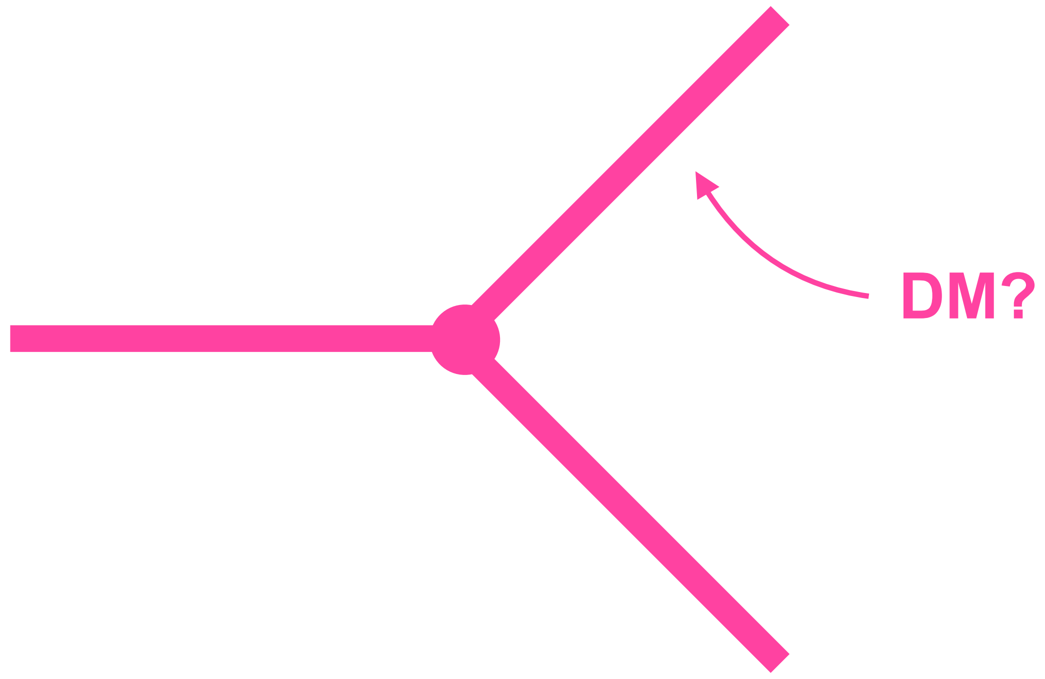
Light mediators with small couplings

Searches for new physics: Light mediators

- Experiments can measure stable (on detector timescales) final state particles like leptons, hadrons, or photons
  - New physics particles can not be stable and (QED) charged or we would have seen them already.



- At lepton colliders (e.g. SuperKEKB) missing energy and momentum allows searches for invisible final state (the full initial state is known)



- At hadron colliders (e.g. LHC) missing transverse energy allows searches for invisible final state

Search 101: NP mediator decaying to SM particles