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SEARCHING FOR LIGHT DARK MATTER PORTALS

in collaboration with PADME collaboration and G. Corcella, E. Nardi, L. delle Rose, M. Pruna
my results soon submitted

ASI
06 FEBRUARY 2020

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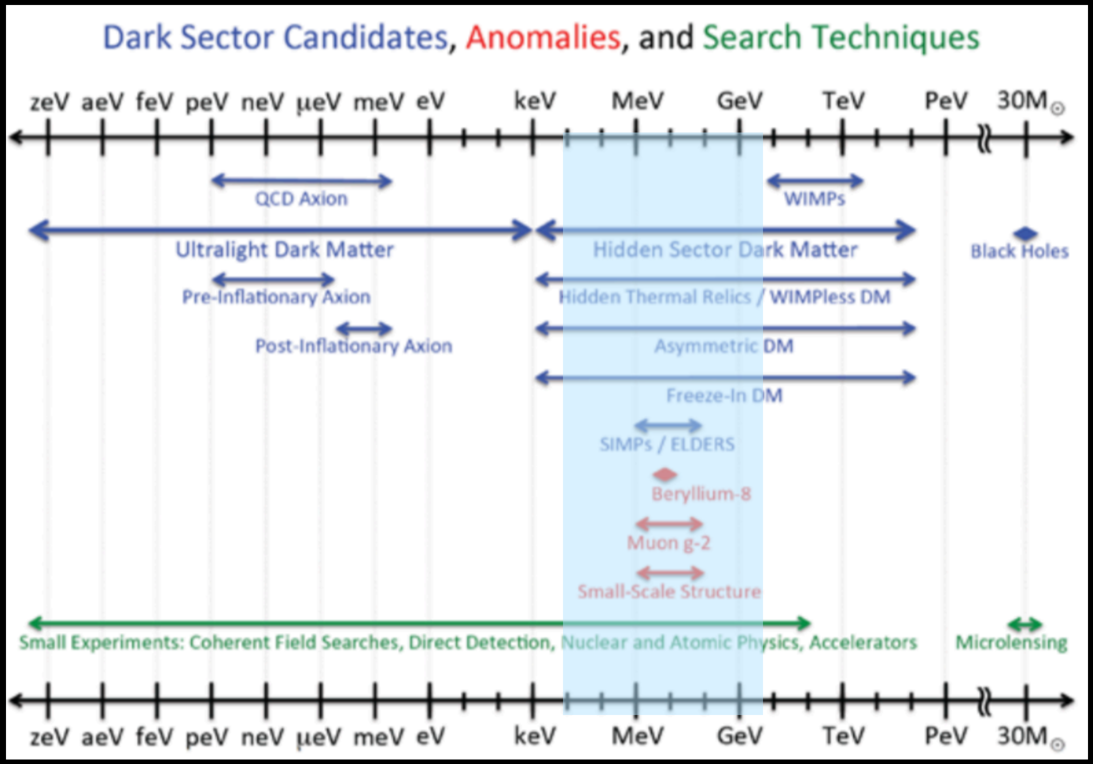

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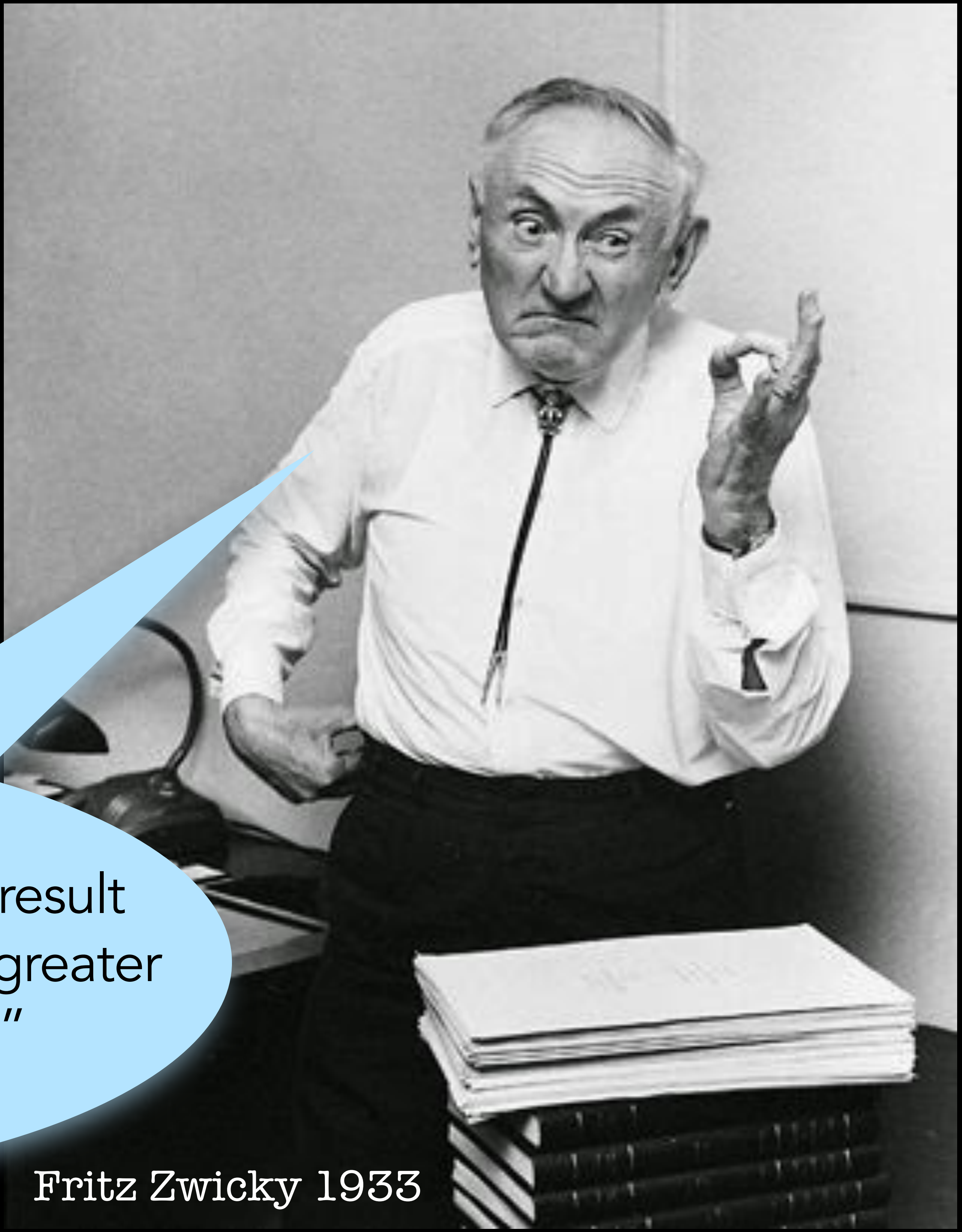
HOW DO WE KNOW THE DARK MATTER IS THERE?

HOW DO WE KNOW THE DARK MATTER IS THERE?

THANKS TO GRAVITY!

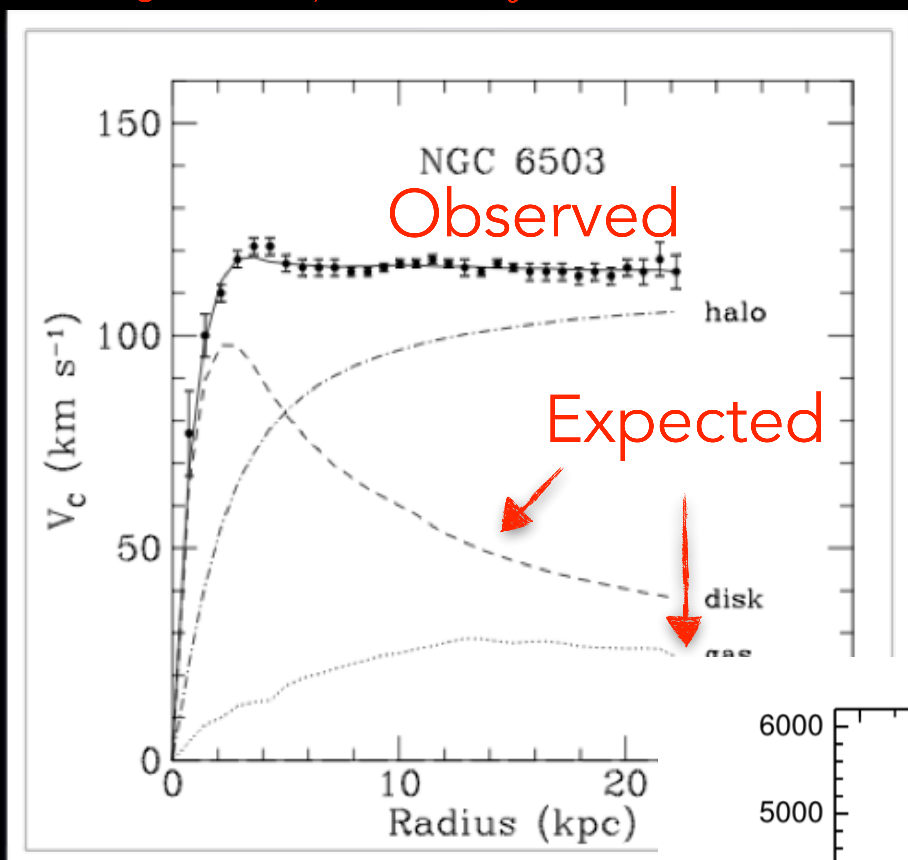
" [...] we would get the surprising result that dark matter is present in much greater amount than luminous matter."



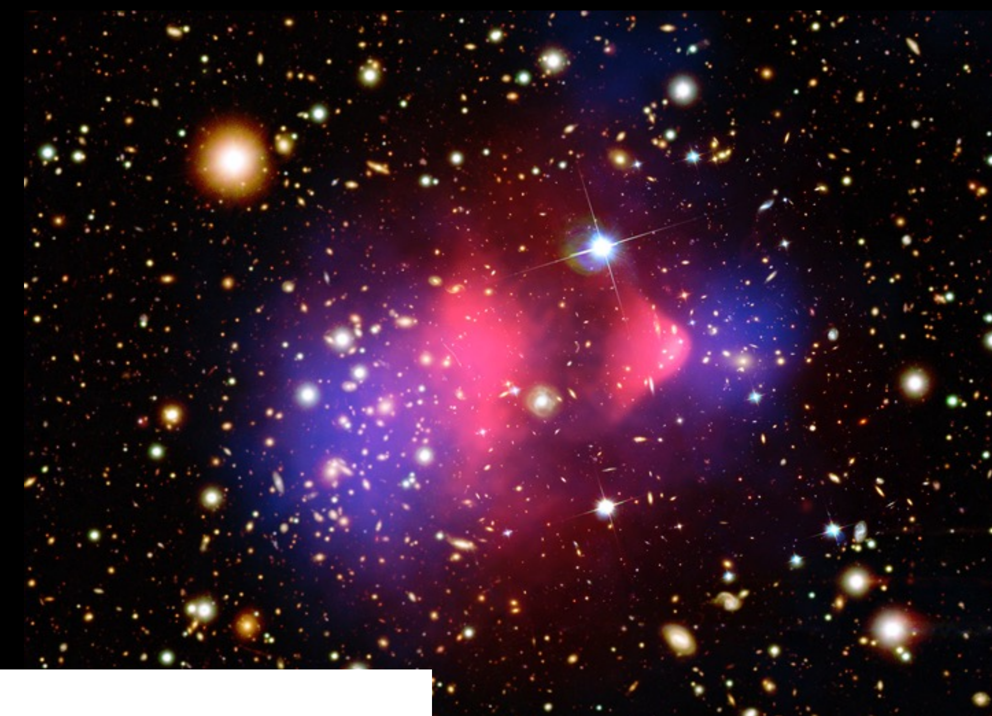
Fritz Zwicky 1933

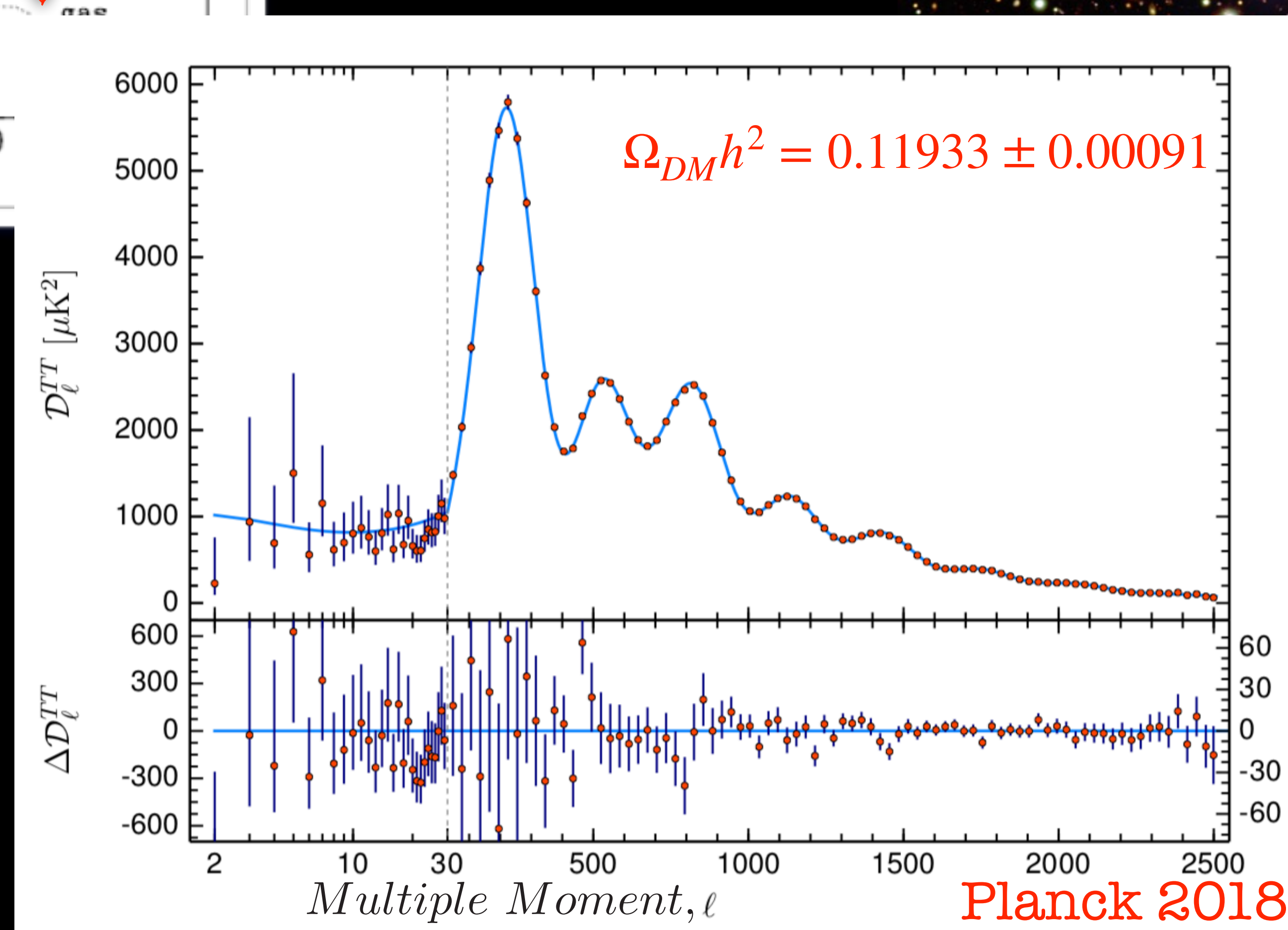
IN TIME GRAVITATIONAL EVIDENCE OF DARK MATTER WAS COLLECTED IN A WIDE RANGE OF DISTANCE SCALES: I.E.

K. G. Begeman et al, Mon.Not.Roy.Astron.Soc. 249



Clowe et al, ApJ 648:L109,2006





Planck 2018

SEEMS TO BE CONVINCING?!!!

…

SO, WHAT IS THE DARK MATTER?

… AND THEN

- IS IT A PARTICLE?
- HOW IS THE OBSERVED RELIC ABUNDANCE PRODUCED?
- INTERACTION WITH THE STANDARD MODEL?
- JUST ONE PARTICLE OR AN ENTIRE DARK SECTOR?

FIRST HYPOTHESIS:

IT IS PARTICLE.

WHAT IS THE DARK MATTER?

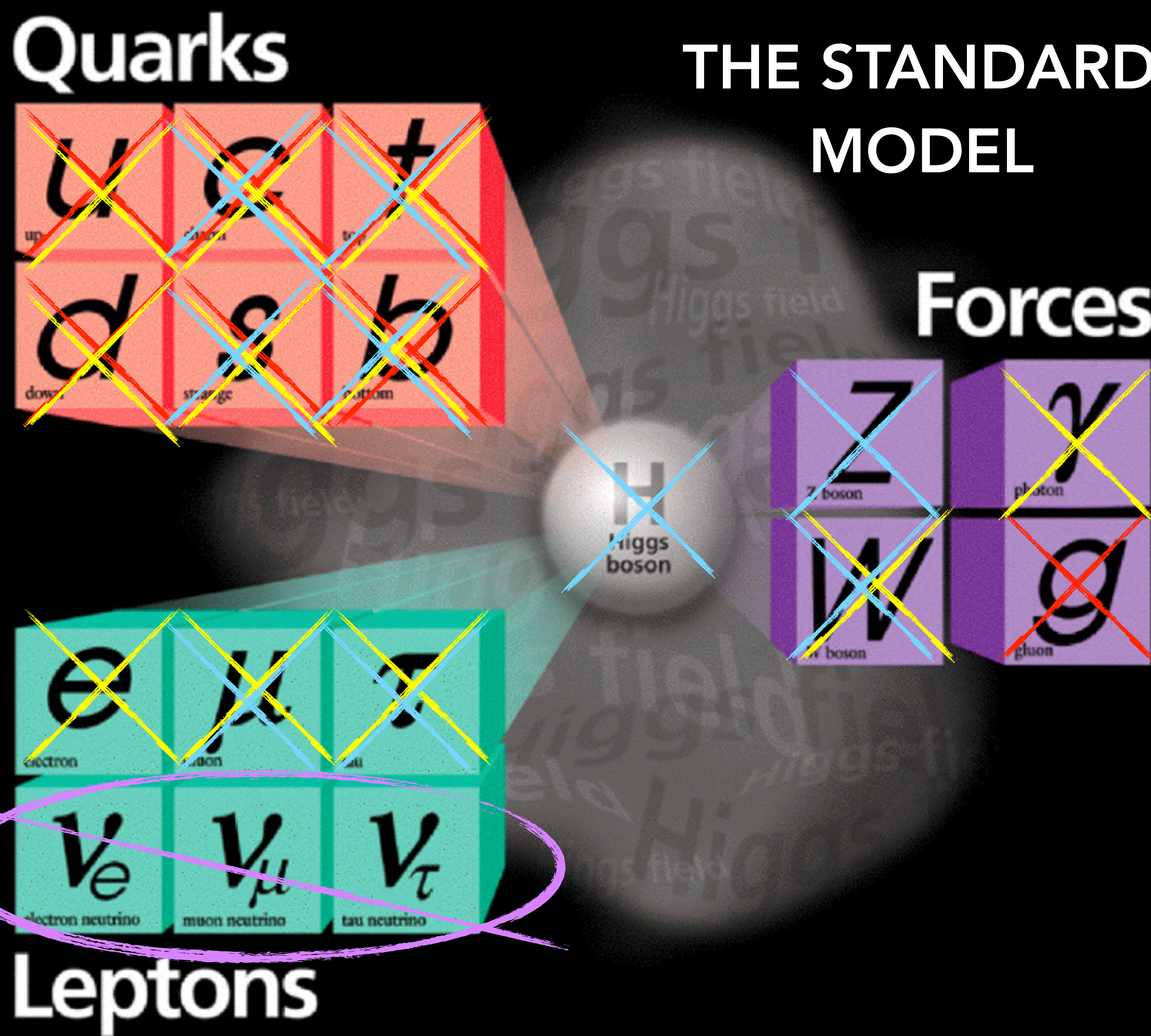
strong

electromagn.

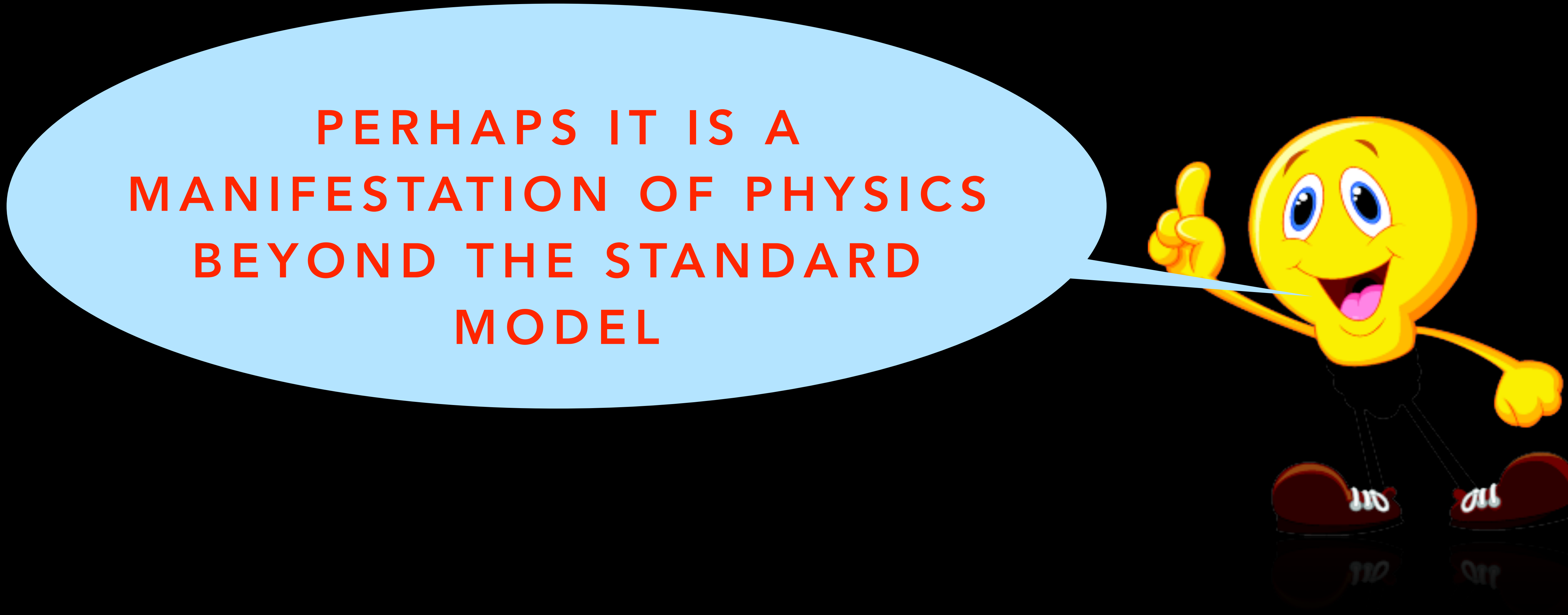
unstable

they move too fast (*hot dark matter*) to form the observed large scale structure

THE STANDARD MODEL



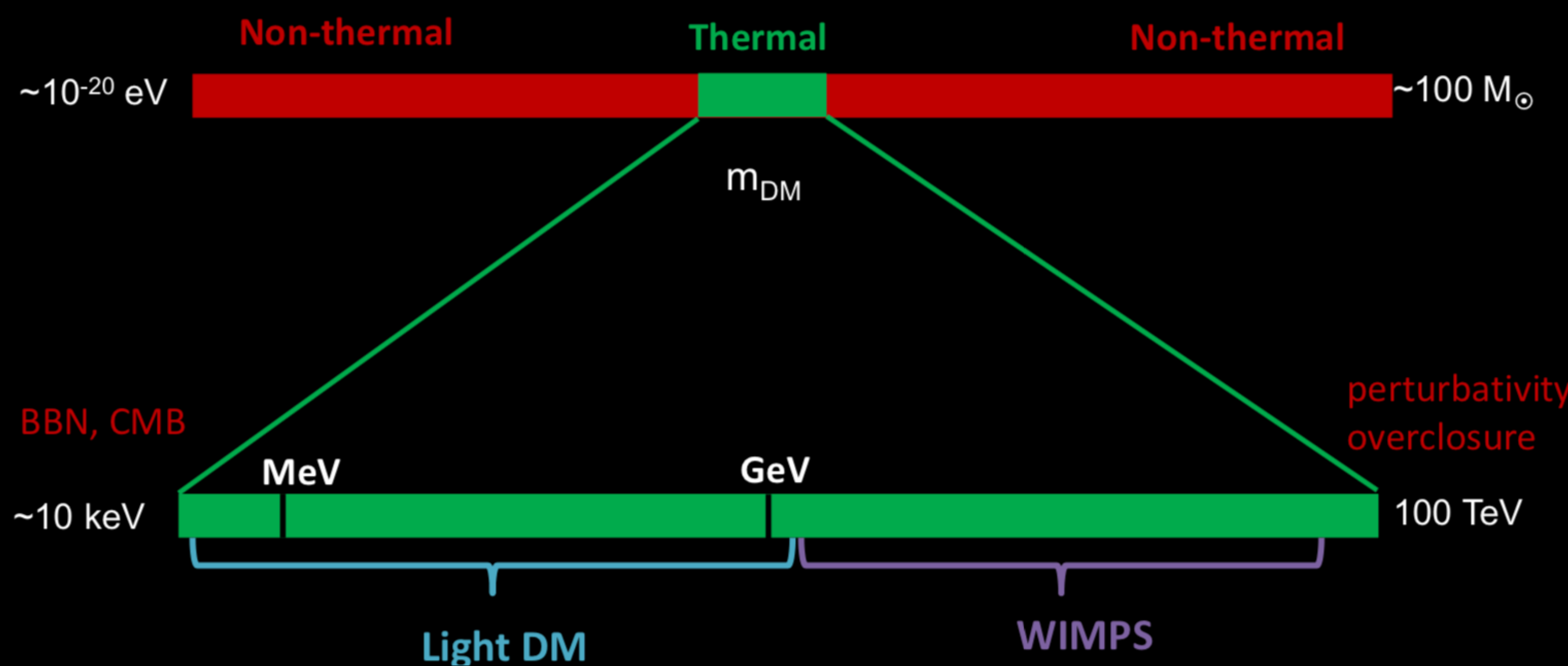
WE DON'T KNOW!!!



Unfortunately, gravity does not tell us what the underlying New Physics should be.

WHICH CANDIDATE?

WIDE RANGE OF POSSIBILITIES



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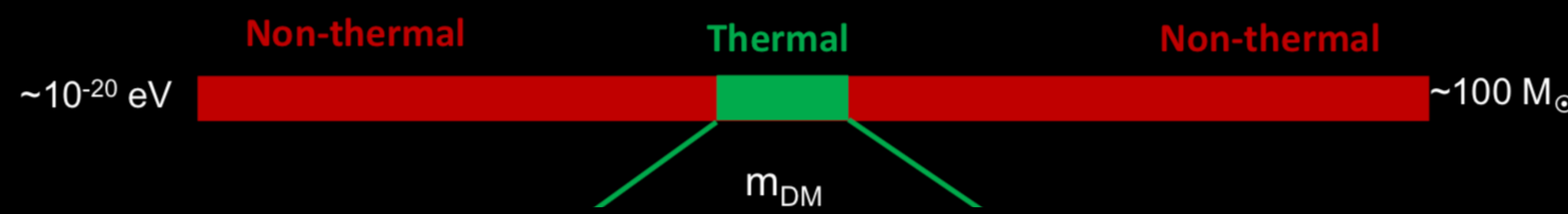
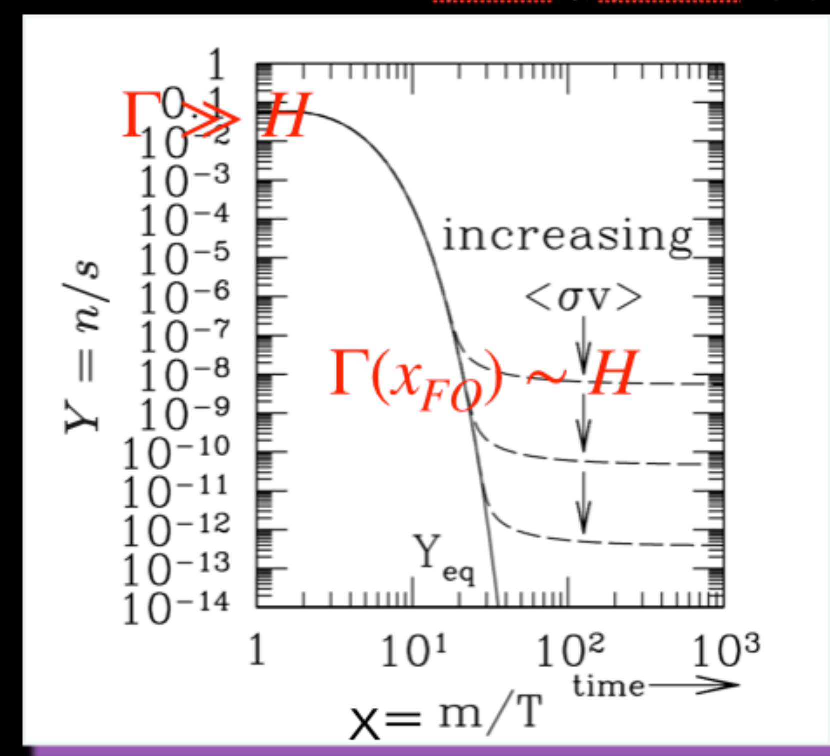


Gelmini & Gondolo 2010



Weakly Interactive Massive Particles

The ***freeze-out mechanism*** explains the abundance of DM:

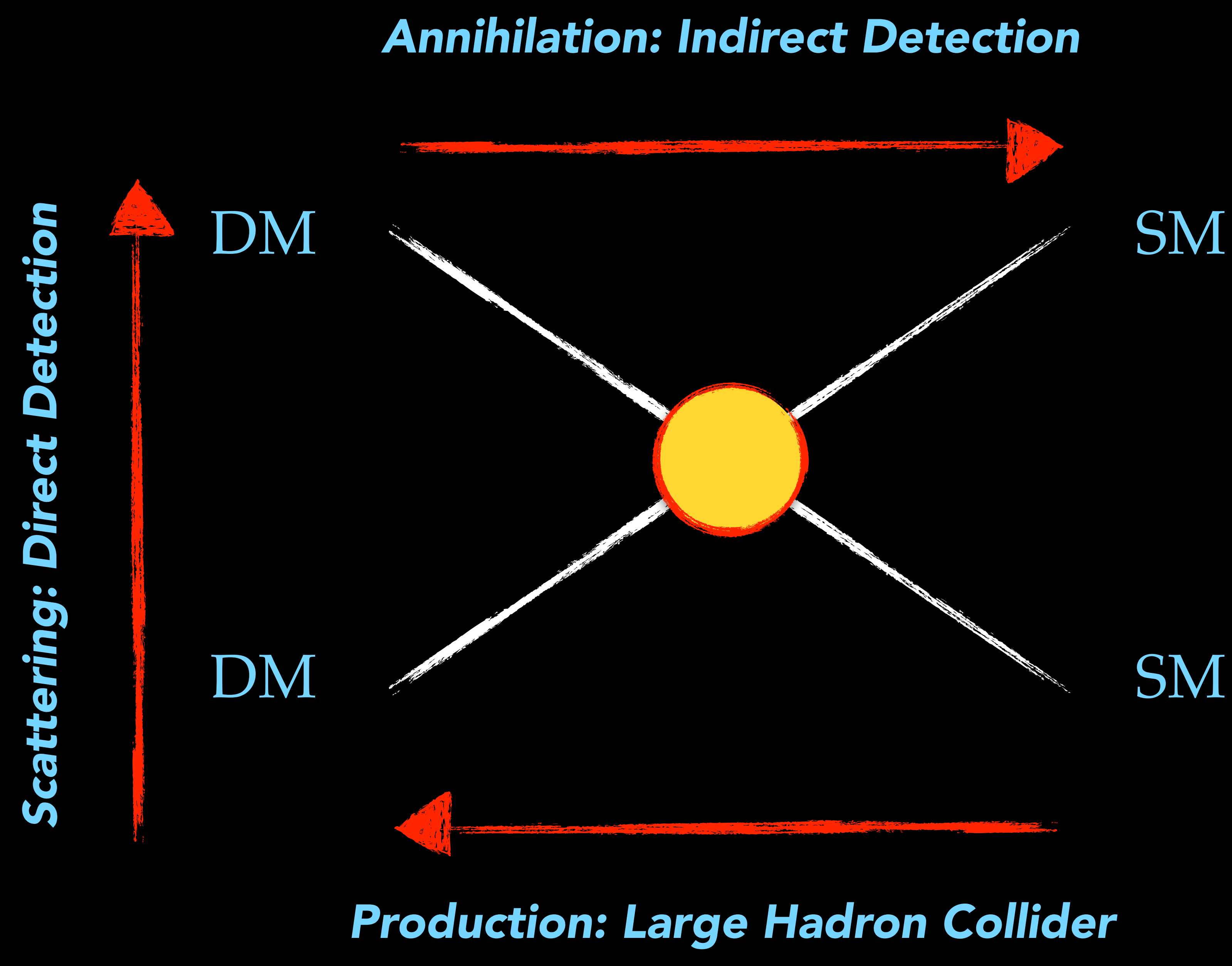
1) dark matter particles were in thermal equilibrium: $SM\ SM \leftrightarrow X\ X$
2) freeze-out as thermal relic
3) solving the Boltzmann eq.

$$\frac{dY_{DM}}{dx} = \frac{s\langle\sigma v\rangle}{Hx}\left(Y_{DM}^2 - Y_{DM,eq}^2\right)$$

$\Omega_{DM}h^2 \simeq \frac{3\times10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle_{f.o.}} \simeq 0.12$ where generally $\langle\sigma v\rangle_{f.o.} \propto \frac{g_X^4}{M_X^2}$

predicts an annihilation coupling of electroweak scale for particles of $M_{WIMP} \sim \mathcal{O}(GeV) - \mathcal{O}(TeV)$ scales → *opened an era of detection techniques*!

HOW CAN WE TEST IT?



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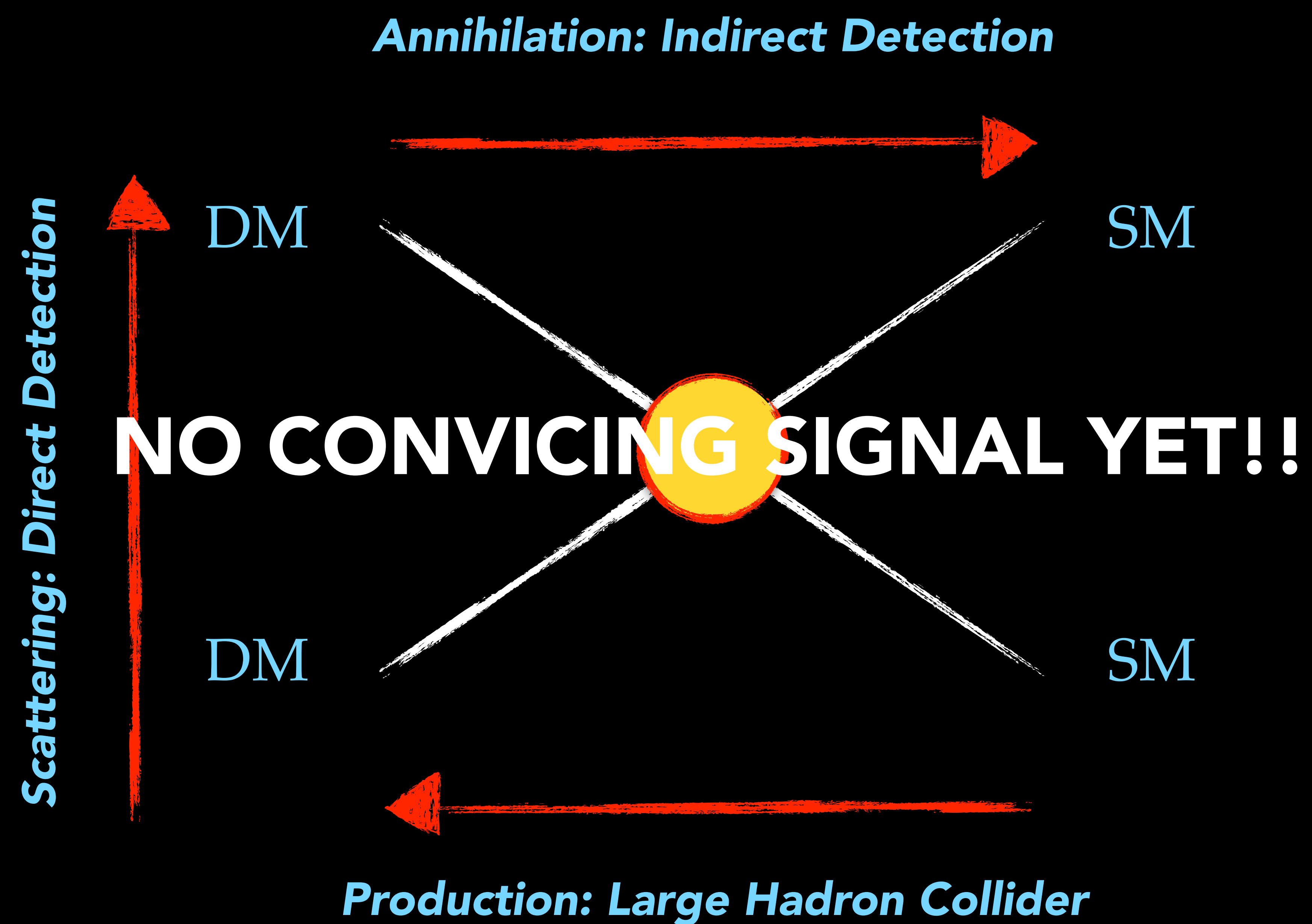

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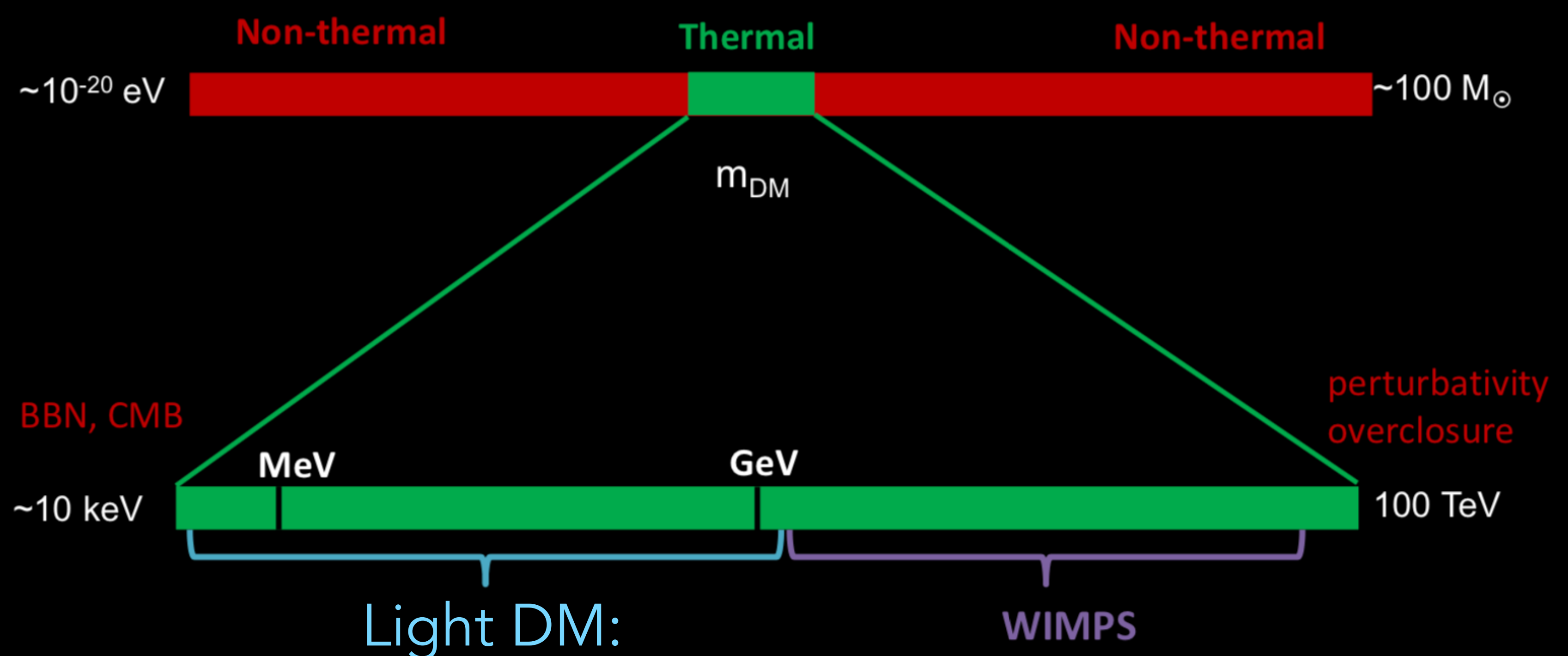
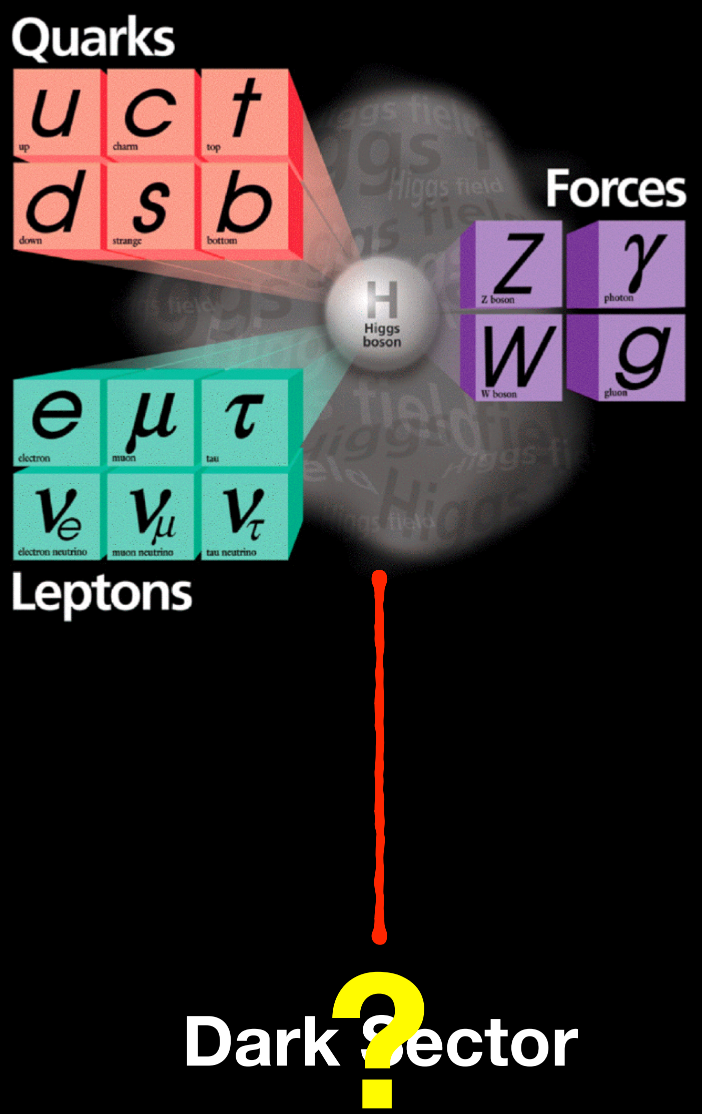


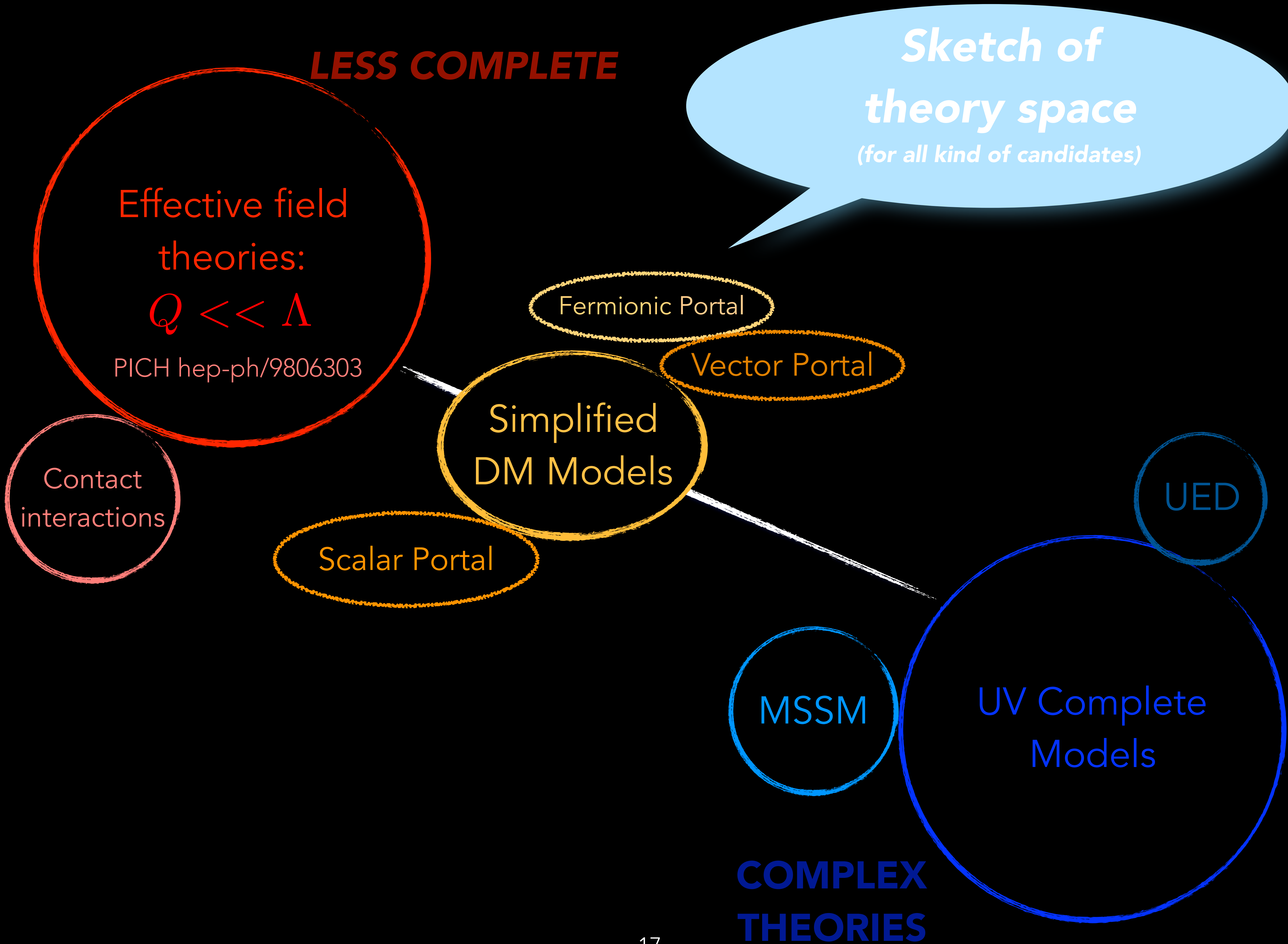
thermally produced too. For smaller mass range (sub-GeV), we need very weak (feeble) coupling in order to obtain the observed relic abundance. Often called *hidden or dark sector*.

WHY DARK SECTORS?

The Standard Model describes the known elementary particle content and three of the four fundamental forces which manage their physics.

- As the Standard Model we can suppose a Dark Sector composed by **new particles** not charged under SM gauge group and **new forces**: how is connected with Standard Model?




Sketch of theory space
(for all kind of candidates)
LESS COMPLETE
Effective field theories:
$Q << \Lambda$
PICH hep-ph/9806303
Contact interactions
Fermionic Portal
Vector Portal
Simplified DM Models
Scalar Portal
UED
MSSM
UV Complete Models
COMPLEX THEORIES

SIMPLIFIED MODELS

The Simplified Model concept (Abdallah '15, De Simone '16) lies in the description of a model in a simple way, following general prescriptions which summarise the properties of more complete models and EFT theories:

- few and relevant parameters adding in particular the **Portal** particle which, as bridge, mediates the interaction between hidden and visible sector
- the new terms in the Lagrangian should be renormalisable, respect the Lorentz invariance, SM gauge invariance and DM stability.
- the Portals (i.e. in the next slides) are representative of a broader class of well-motivated models and can easily be expanded to describe UV-complete theories.

Basically any other new physics is at much higher energies than the energy scale accessible to the experiment, so that only DM and the mediator appear in addition to SM particles.

SIMPLIFIED MODEL: LIGHT DARK MATTER PORTAL

Alternatively to WIMP portal, the *hidden-sector* portals are well-motived to explore. Parameter space of hidden-sector are largely invisible to WIMP searches. A high intensity source is necessary to produce LDM portals at a detectable rate: we need high-intensity accelerator beams. The search for new physics in low range of masses and couplings is currently called the *intensity frontier* (Jaeckel et al. 1002.0329, Beacham et al. 1901.09966v2).

Portals for sub-GeV DM are:

	Hidden Sector Portal	Coupling	
[Pospelov, Ritz, Voloshin] [Hooper, Zurek]	Dark Photon, A'_μ	$-\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$	$F'_{\mu\nu}$ dark photon field
[O'Connell, Ramsy-Musolf, Wise]	Scalar Singlet, S	$(\mu S + \lambda S^2)H^\dagger H$	H is the SM Higgs boson $(1,2,+\frac{1}{2})$
[Bertoni, Ipek, Nelson, McKeen] [Bohem, Fayet, Schaeffer]	Sterile Neutrino, N	$y_N LHN$	L is a lepton doublet $(1,2,-\frac{1}{2})$
→	Axion-like particle, a	$-\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}, g_{a\psi\psi}\partial_\mu a\bar{\psi}\gamma^\mu\gamma^5\psi$	$\tilde{F}_{\mu\nu}$ is the dual of $F_{\mu\nu}$

VECTOR PORTAL: DARK PHOTON

$$\mathcal{L}_{vector} = \mathcal{L}_{SM} + \mathcal{L}_{DS} + \mathcal{L}_{portal}$$

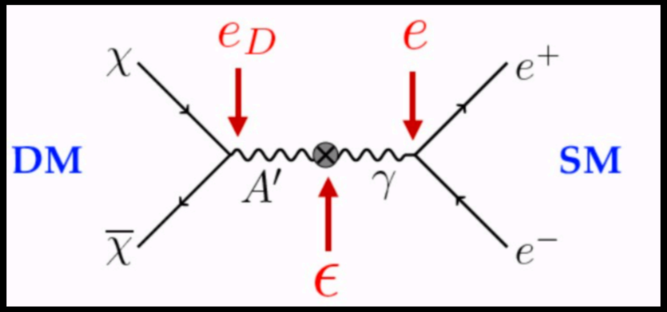
- Dark Sector: As QED photon, the vector boson A' is the gauge field of an extra abelian gauge symmetry U'(1). It is massive cause a spontaneous symmetry breaking of dark symmetry.

$$\mathcal{L}_{DS} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{M_{A'}^2}{2}A'^{\mu}A_{\mu} + \mathcal{L}_{DM}$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon field strength.

- The Portal interaction is described by a kinetic mixing **ε** (after EWSB):

$$\mathcal{L}_{portal} = -\frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$



- This introduces a dark photon-SM fermion coupling $\alpha' = \epsilon^2\alpha$ testable with accelerators: current constraints requiring the mixing parameter $\epsilon \leq 10^{-3}$

PSEUDOSCALAR PORTAL: AXION-LIKE PARTICLE

$$\mathscr{L}_{pseudoscalar} = \mathscr{L}_{SM} + \mathscr{L}_{DS} + \mathscr{L}_{portal}$$

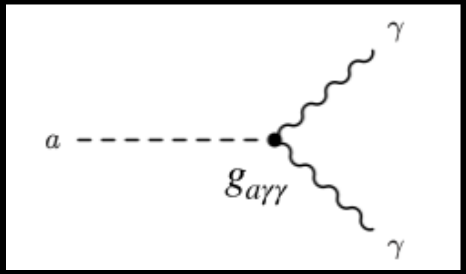
Ingredients of Minimal Model:

- **Dark Sector:** SM gauge symmetries + extra global symmetry ⟶ a light, pseudo-scalar particle and derivative coupling with SM particles can be produced: the axion-like particle ALP is a pNGB. ALP is not necessarily a QCD axion (so not solving the strong CP-problem) and for this reason mass and couplings are free and independent parameters. Region I: Very light ALP (from 10^{-22} eV to few keV scale) is dark matter itself and it is called WISP [1201.5902]. Region II: ALP with MeV-GeV masses can be produced at accelerator-based experiments and it could be a portal (since the lifetime of ALP in this mass range is shorter than age of the Universe)

$$\mathscr{L}_{DS} = \frac{1}{2}\partial^{\mu} a \partial_{\mu} a - \frac{1}{2} M_a^2 a^2 + \mathscr{L}_{dm}$$

- **Portal:** The Portal between visible and invisible sector is allowed by an interaction with photon ….

$$\mathscr{L}_{portal} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



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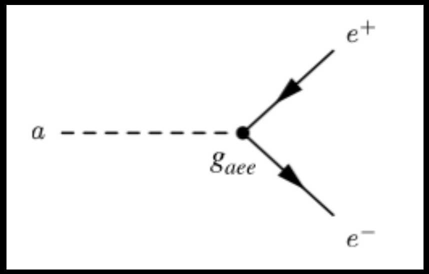
$$\mathscr{L}_{DS} = \frac{1}{2}\partial^{\mu}a\partial_{\mu}a - \frac{1}{2}M_a^2a^2 + \mathscr{L}_{dm}$$

- **Portal:** The Portal between visible and invisible sector is allowed by … and interaction with fermions

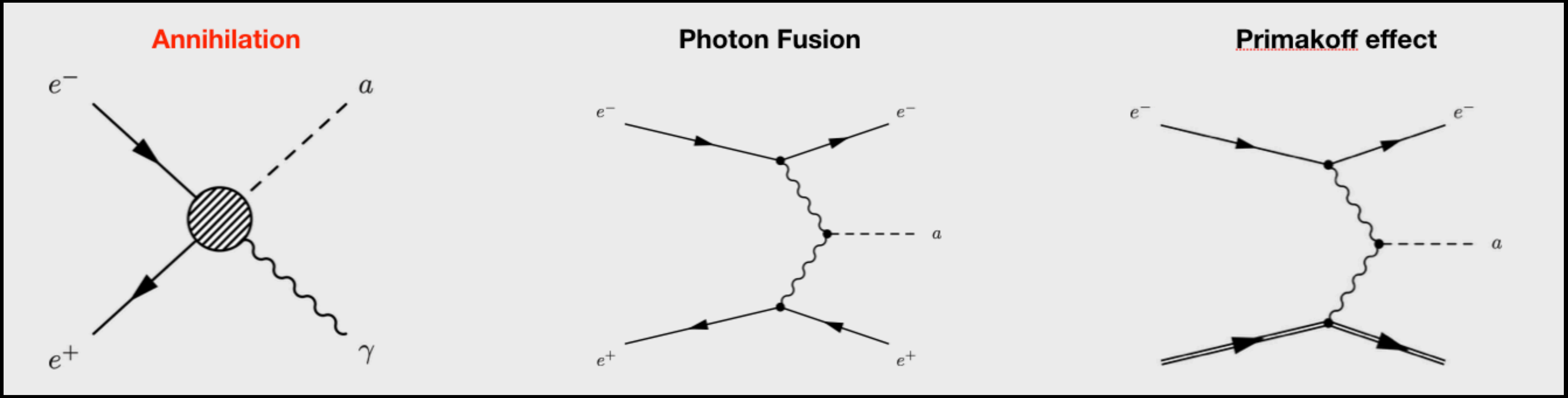
$$\mathscr{L}_{portal} = g_{a\psi\psi}\partial_{\mu}a\bar{\psi}\gamma_{\mu}\gamma_5\psi$$



AXION-LIKE PARTICLE PRODUCTION AT ACCELERATORS

Increasing interest for experimental searches at accelerators: assuming a leptophilic ALP ⇒ Lepton beam/fixed target, e.g. PADME, BDX,..

Lepton beam/Collider, e.g. Belle II, KLOE,..



$e^+e^- \rightarrow \gamma + a$

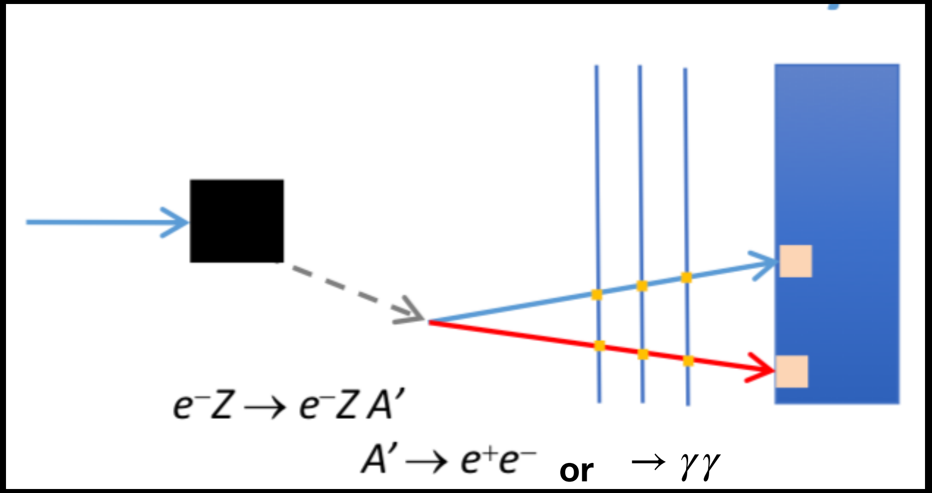
$e^+e^- \rightarrow e^+e^- + a$

$e^-Z \rightarrow e^-Z + a$

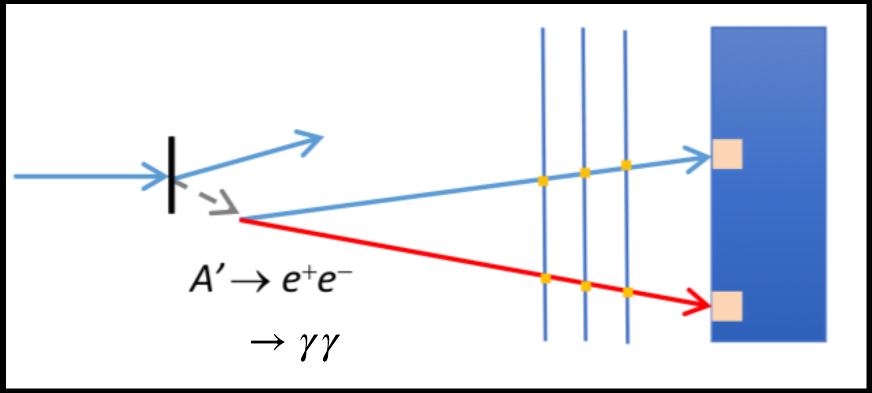
TWO POSSIBLE SIGNATURES FOR ALP (AND DARK PHOTON) IN ACCELERATOR:

VISIBLE: if $m_a/2 < M_{\chi}$, $a \to SM\, SM$

TECHNIQUES:



1. Beam dump (Primakoff effect) using a very intense electron beam + an high Z target + shield for SM absorption

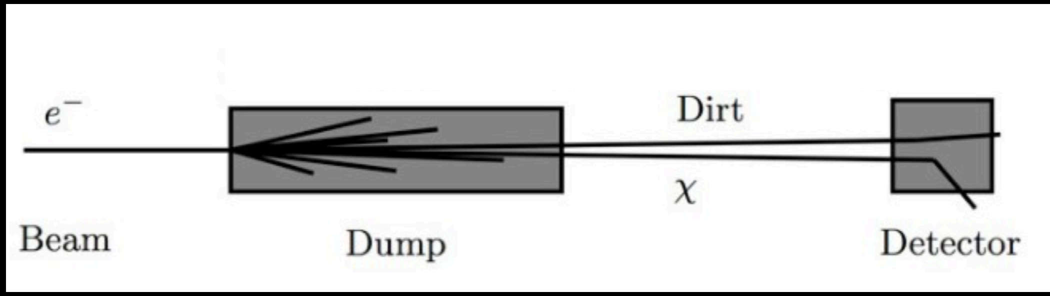


2. thin fixed target (annihilation)

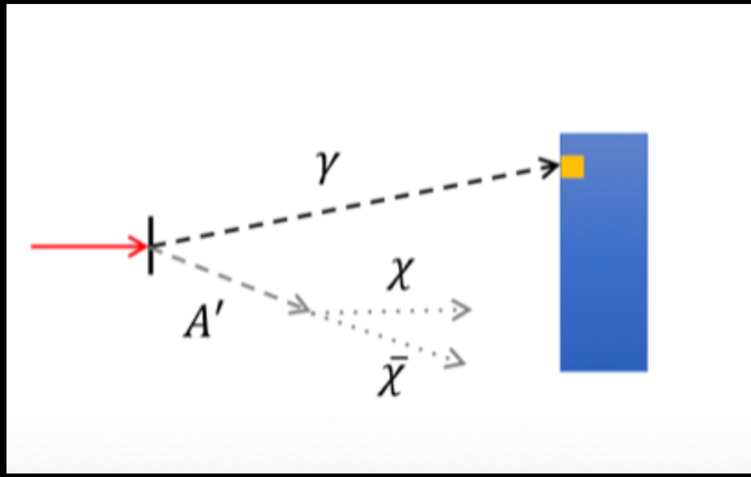
TWO POSSIBLE SIGNATURES FOR ALP (AND DARK PHOTON) IN ACCELERATOR:

INVISIBLE: long-lived or if $m_a/2 > M_\chi$, $a \to DM\,DM$ with likely $BR \simeq 1$

TECHNIQUES:



1. Dump (primakoff) + DM scattering

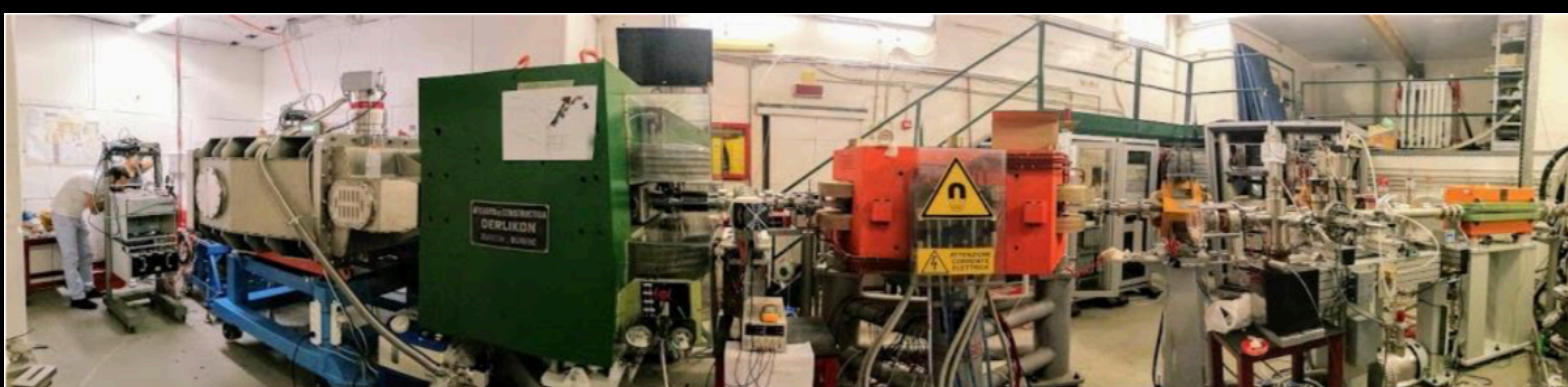


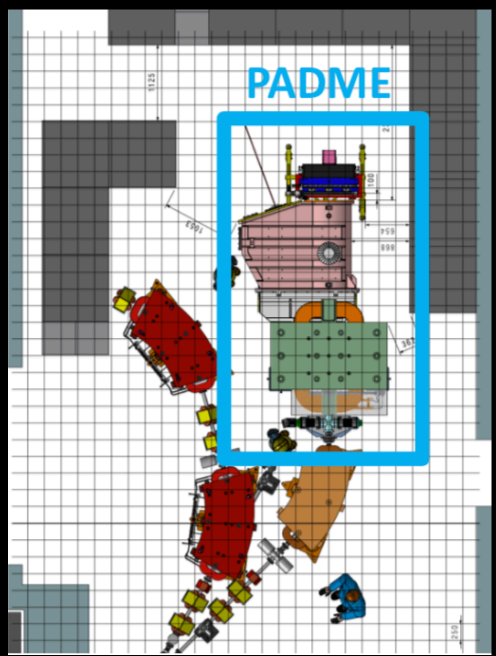
2. missing mass/energy/momentum search (annihilation)

PADME EXPERIMENT

PADME (Positron Annihilation into Dark Matter Experiment) is placed in the DAΦNE Beam Test Facility hall of the Laboratori Nazionali di Frascati.

~ 4,50 m

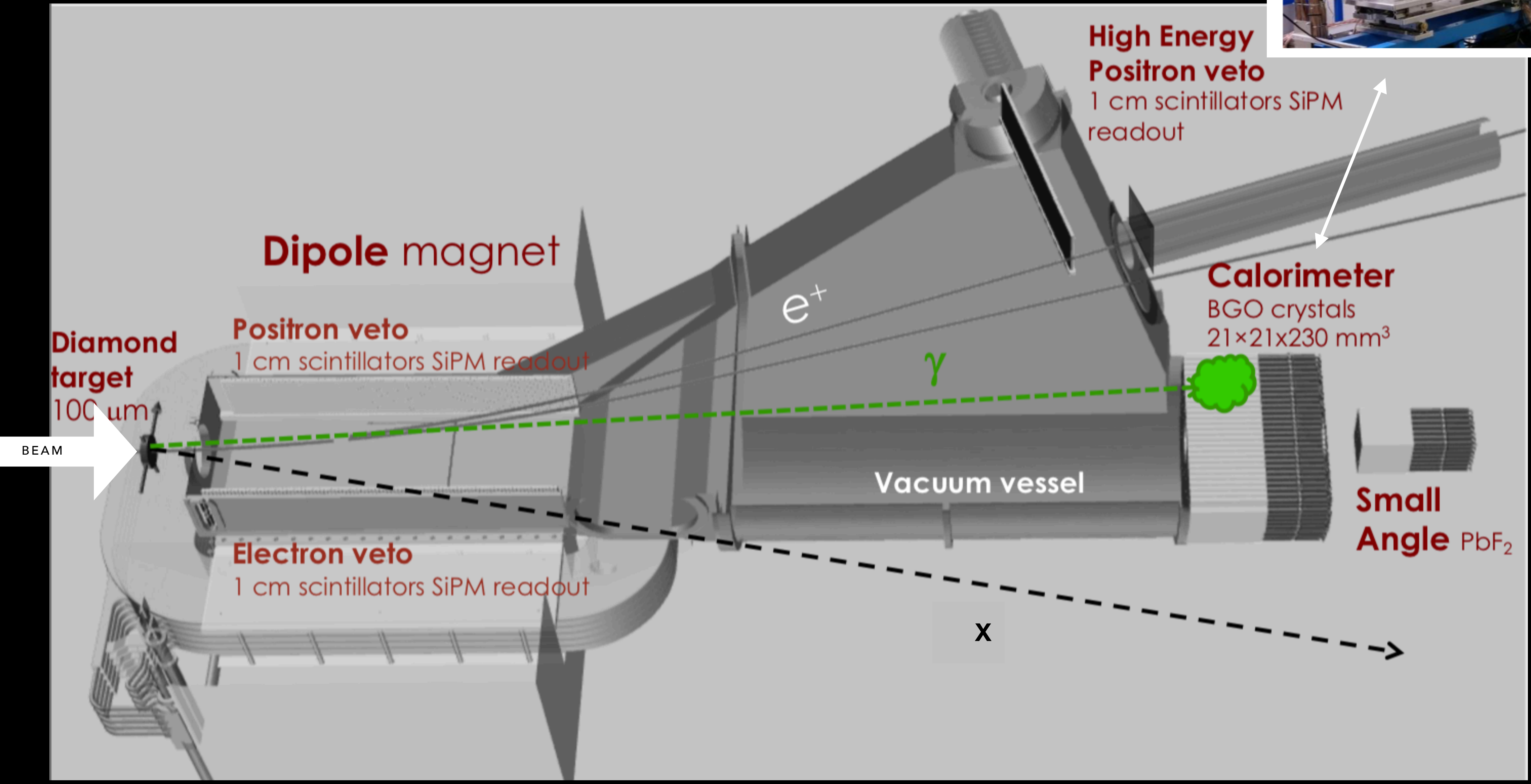


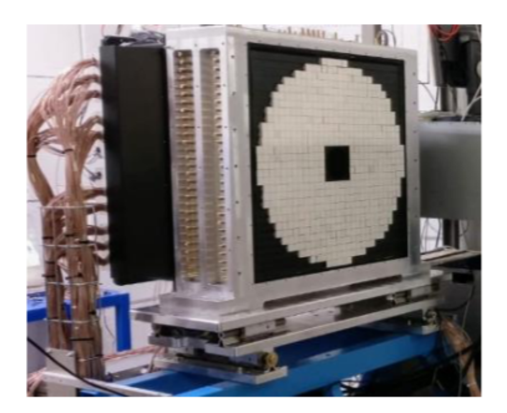


BTF

e^+ Beam from LINAC

EXPERIMENTAL SETUP

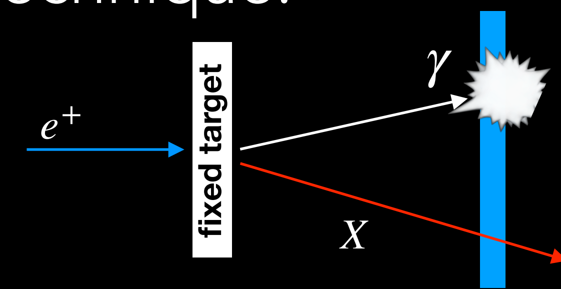




HOW PADME WORKS...

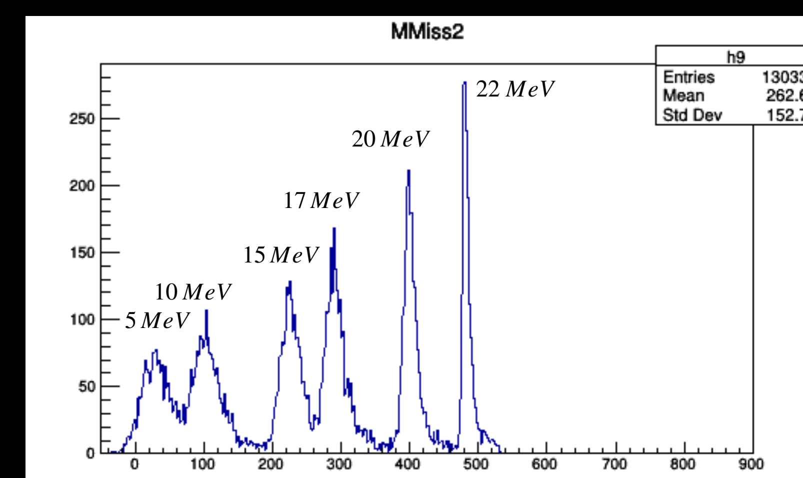
PADME is a fixed target experiment which looks at the **invisible decay** of X that could be *dark photon, dark Higgs, ALP* through the missing mass technique:

$$e^+e^- \rightarrow \gamma + X$$



well-known initial state and detectors with very good hermeticity that allow to detect all the other particles in the final state.

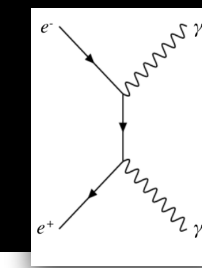
$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2$$

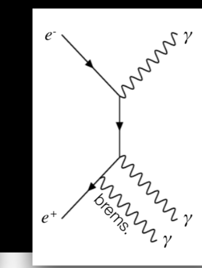


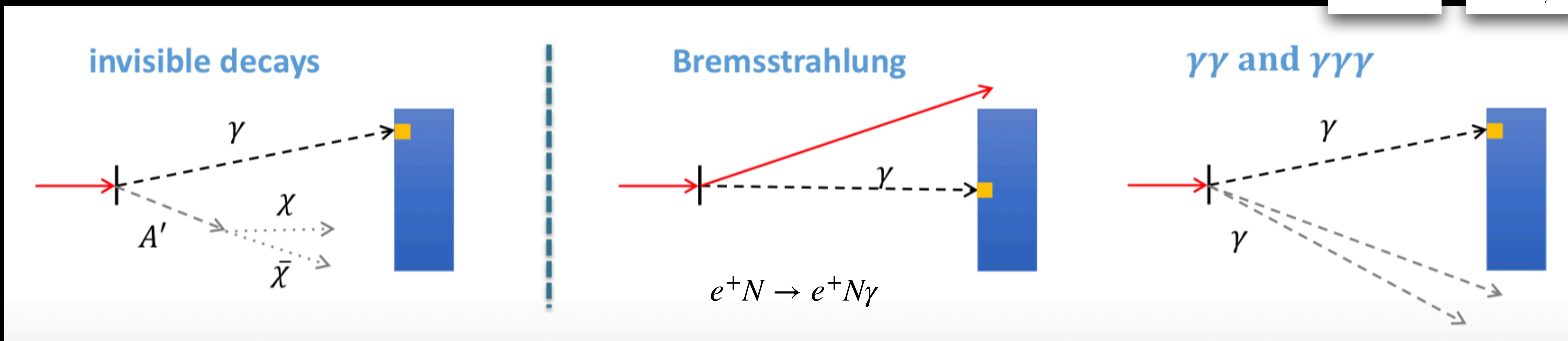
basically the characteristic signature of this process is the presence of a peak emerging over a smooth background in the distribution of the missing mass.

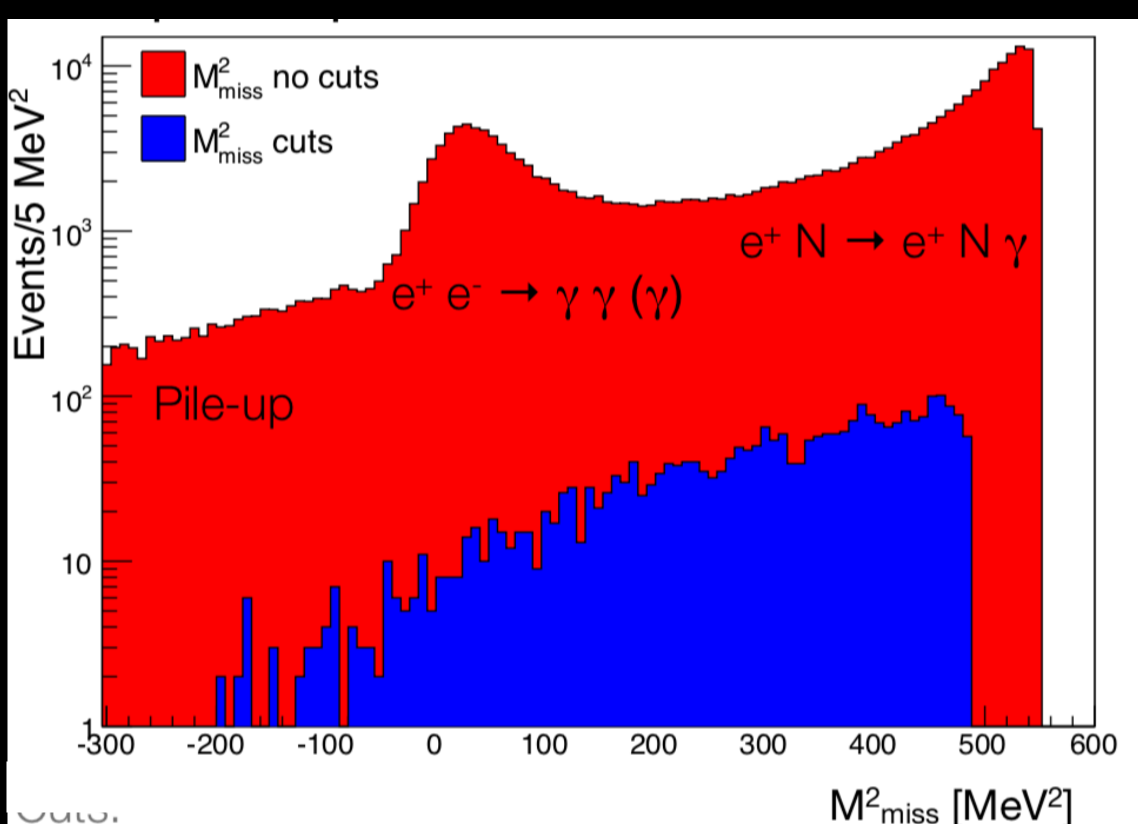
One assumption: *leptophilic dark particles*

BACKGROUND



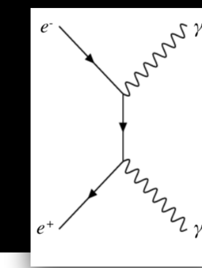


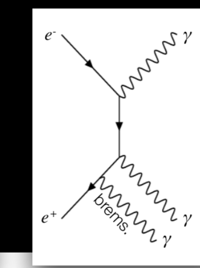


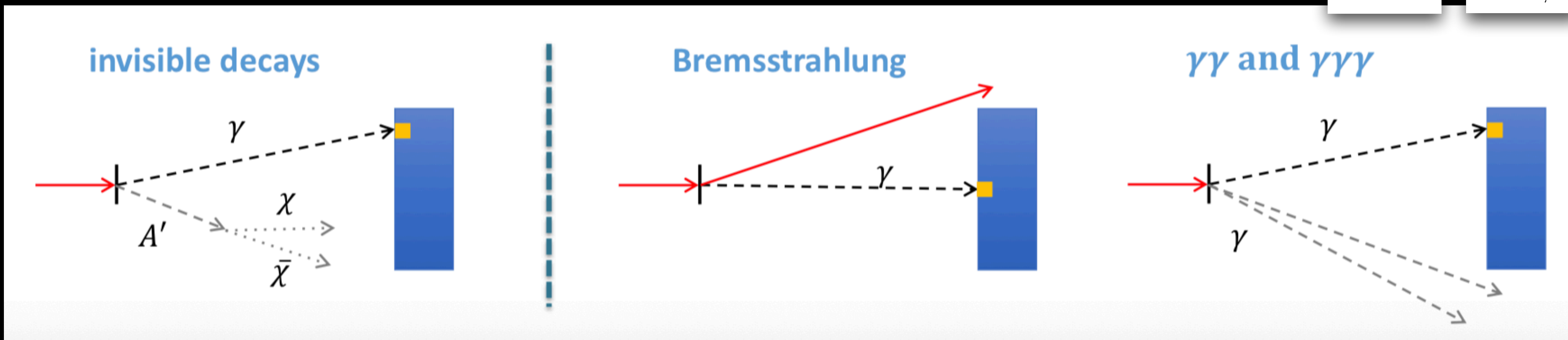


Background process	Cross section e⁺@550 MeV beam	Comment *Carbon target*
$e^+e^- \to \gamma\gamma$	1.55 mb	
$e^+ + N \to e^+ N \gamma$	4000 mb	Eγ > 1MeV
$e^+e^- \to \gamma\gamma\gamma$	0.16 mb	CalcHEP, Eγ > 1MeV
$e^+e^- \to e^+e^-\gamma$	180 mb	CalcHEP, Eγ > 1MeV

BACKGROUND







WORK IN PROGRESS ⚠️:

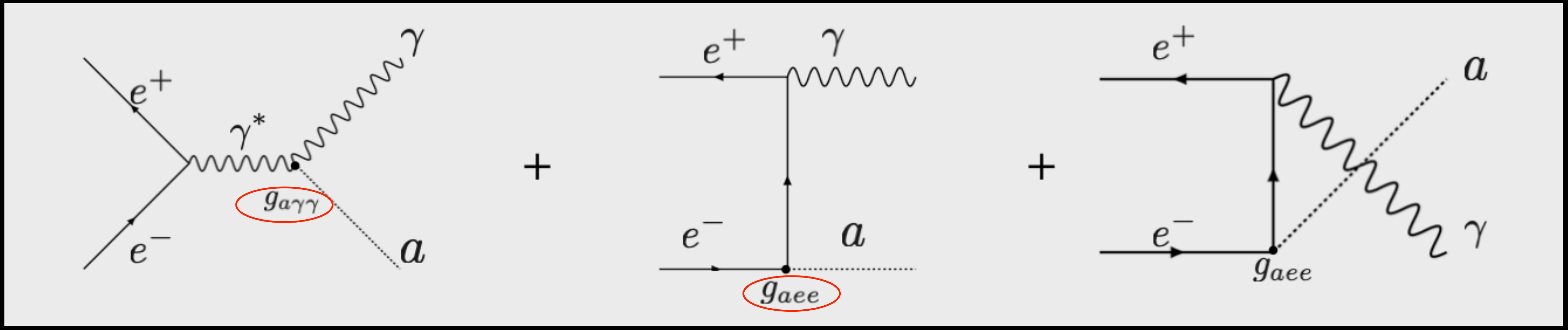
IN COLLABORATION WITH *MARCO PRUNA*, RADIATIVE CORRECTIONS FOR PROCESSES $e^+e^- \to 2\gamma, 3\gamma, 4\gamma$ USING ALSO A TOOL CALL RECOLA TO IMPLEMENT IN BABAYAGA.

TWO REASONS:

1. PERFORMING A GOOD ANALYSIS FOR INVISIBLE DECAY,
2. MAKE A MEASURE OF PHYSICS WITH ELEVATED PRECISION.

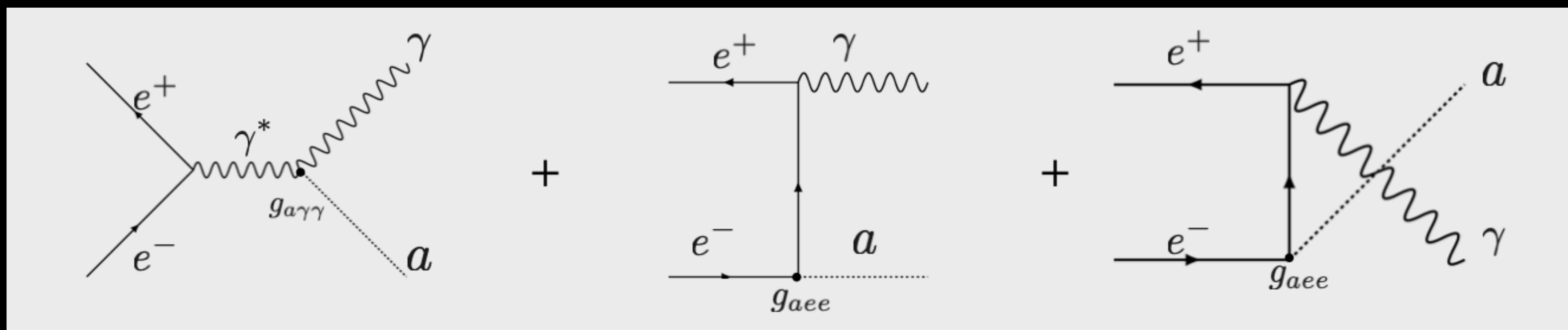
SEARCHING $e^+e^- \to a + \gamma$ IN PADME

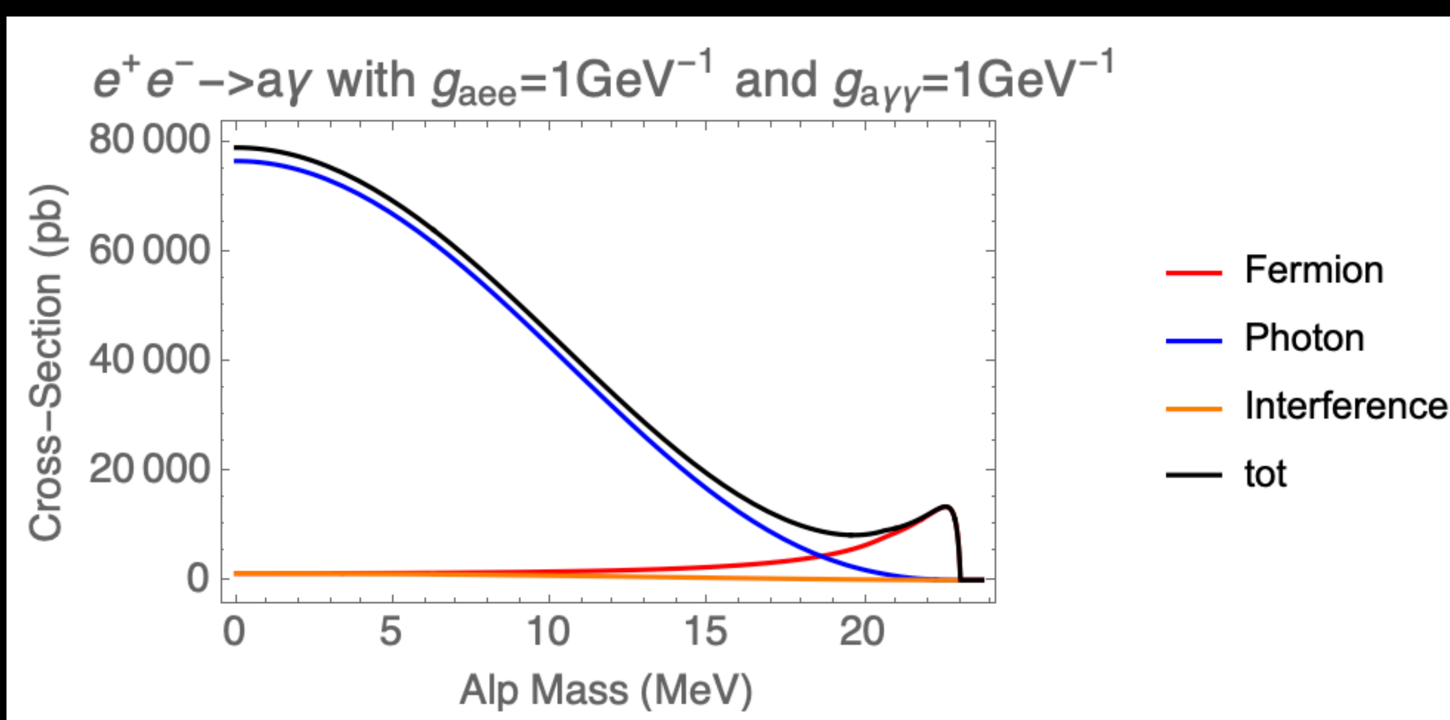
$$\mathscr{L}_{alp} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}M_a{}^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - i g_{aee} m_e a \bar{e}\gamma^5 e + \mathscr{L}_{DM}$$



$e^+e^- \to a + \gamma$ IN PADME

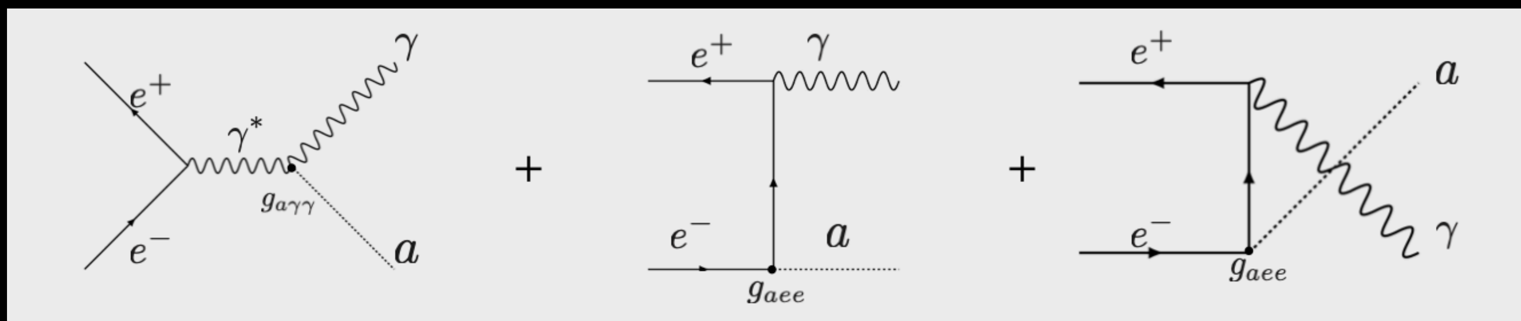
- angular coverage of ECAL ($15 < \theta < 84$ mrad),
- Energy beam of 550 MeV
- photon energy larger than ~ 30 MeV.

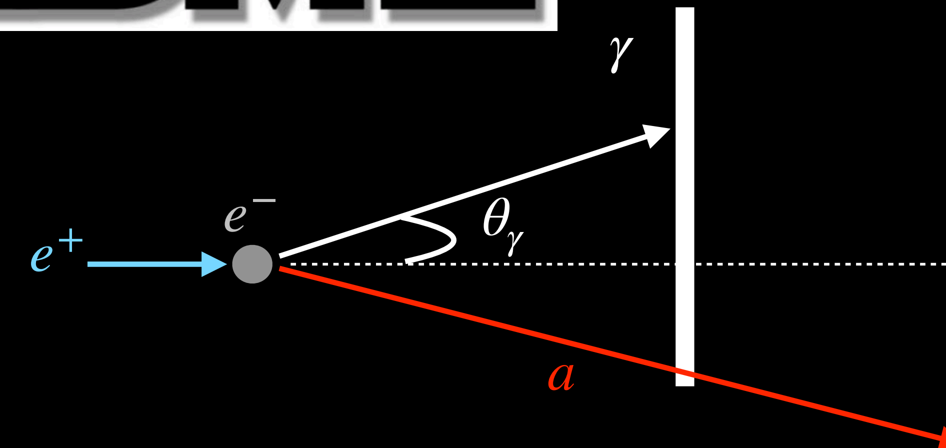


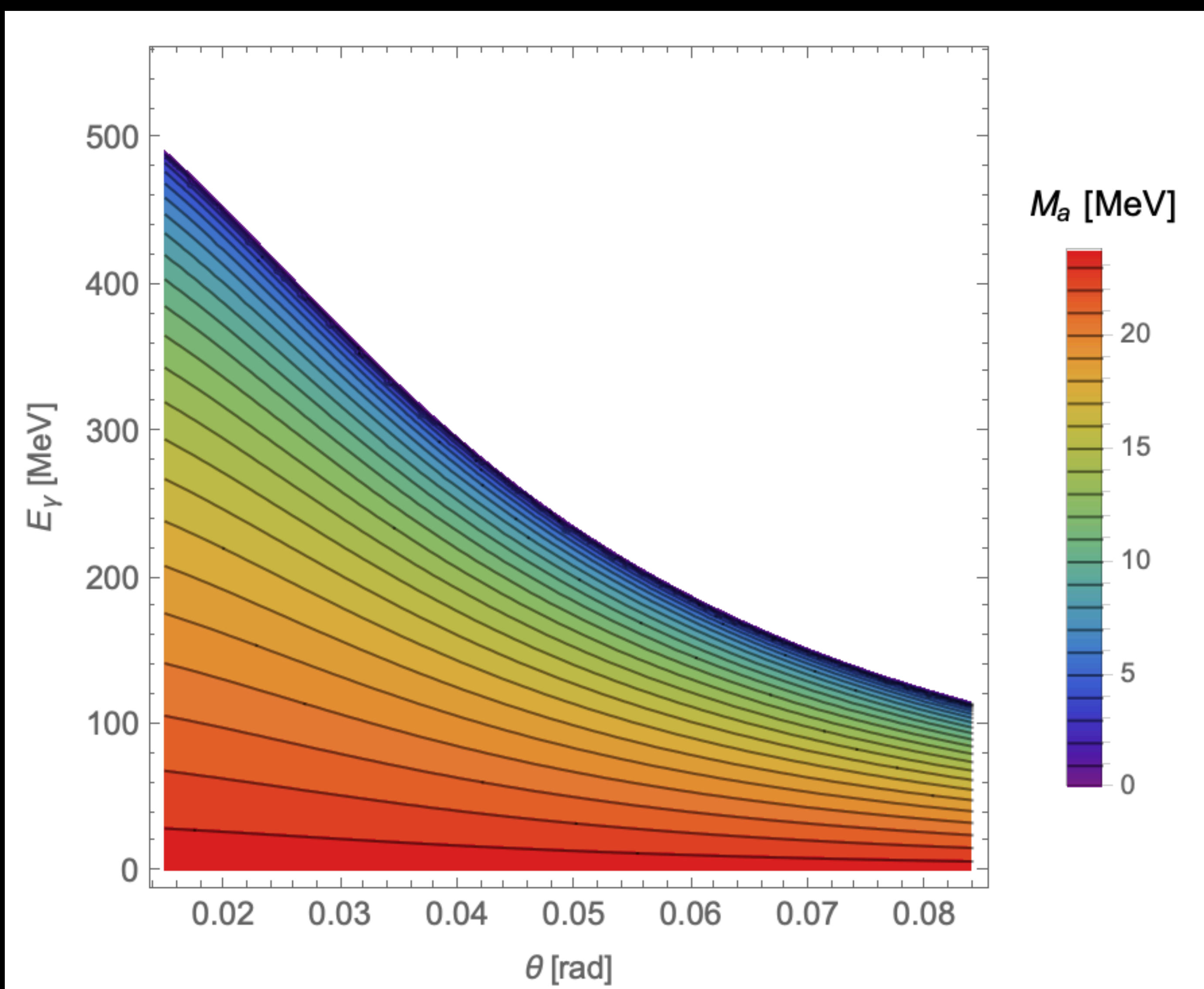


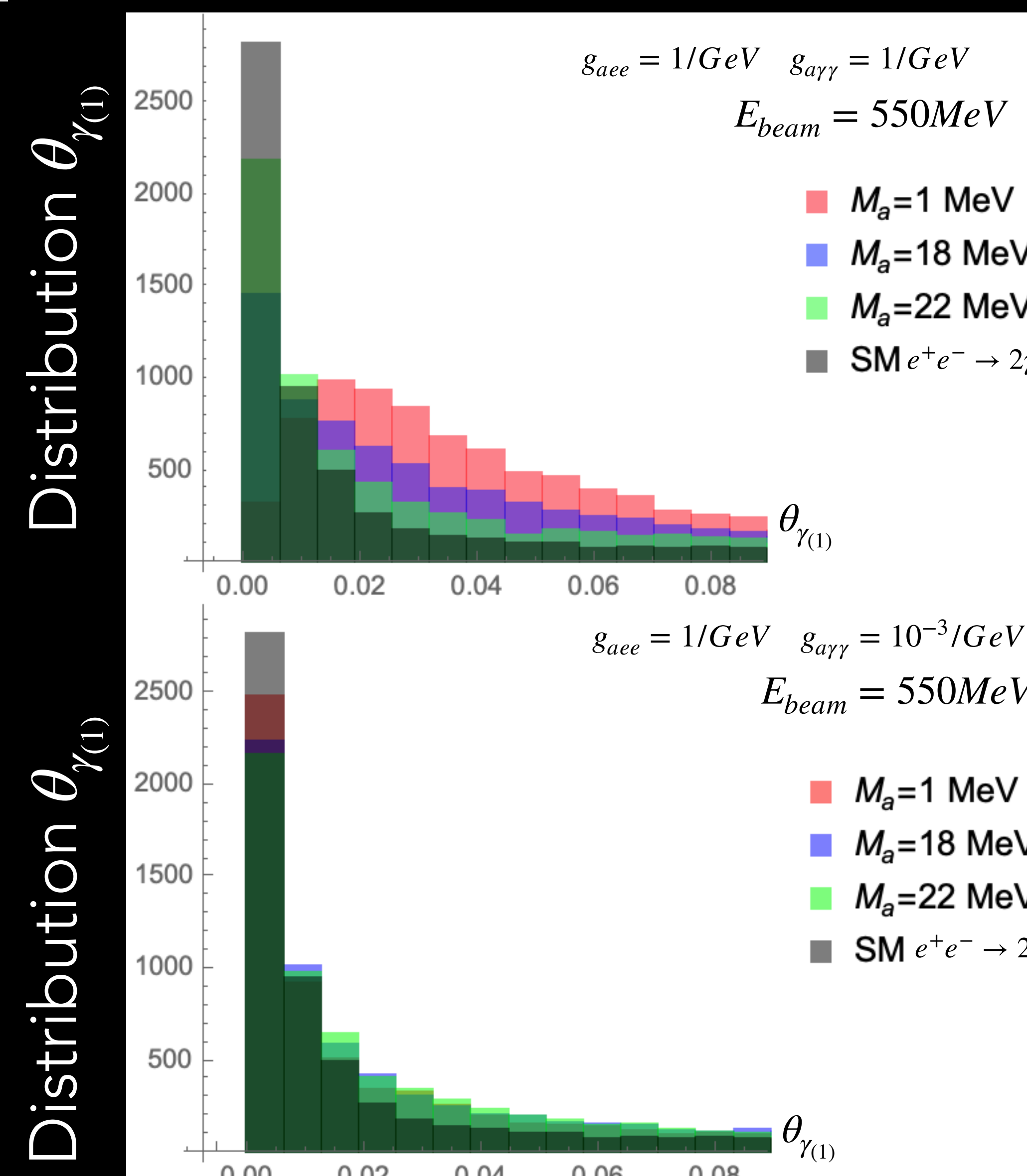
- photon mediator is relevant at small alp masses and fermion is relevant at larger alp masses
- In some regions of the parameter space, the total cross-section should take into account of the complete model

$e^+e^- \to a + \gamma$ IN PADME









Number of events of $e^+e^- \to \gamma + a$ in PADME

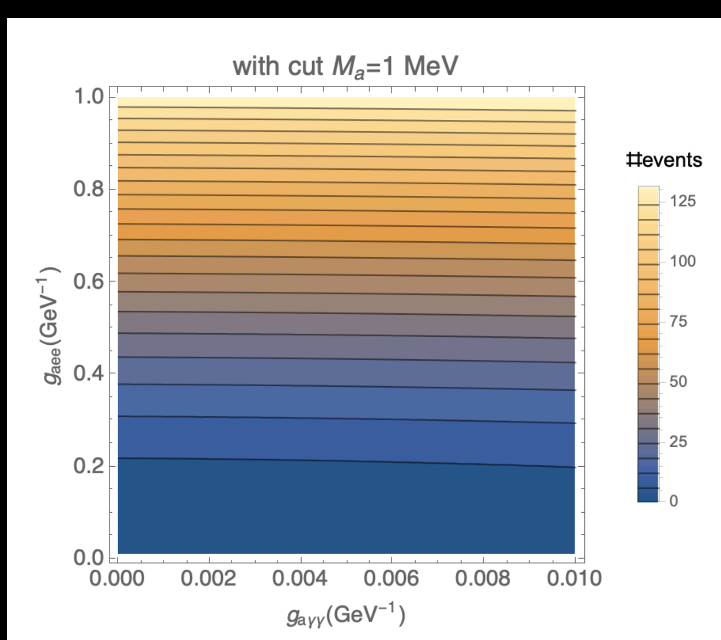
- angular coverage of ECAL ($15 < \theta < 84$ mrad),
- Energy beam of 550 MeV
- photon energy larger than ~ 30 MeV.

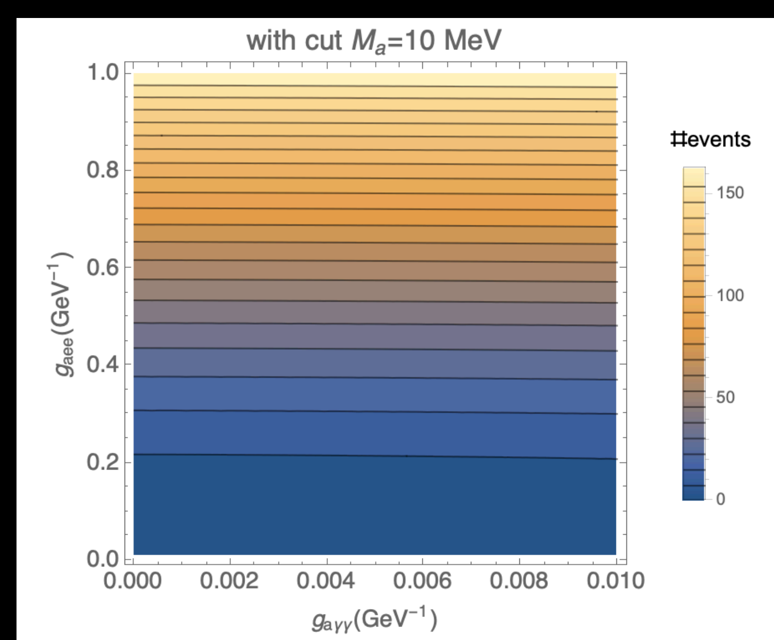
$$N_{events} = 10^{13} N_e \sigma_{e^+e^- \to a\gamma} = 6 d_{target} N_A \frac{\rho}{A} \sigma_{e^+e^- \to a\gamma}$$

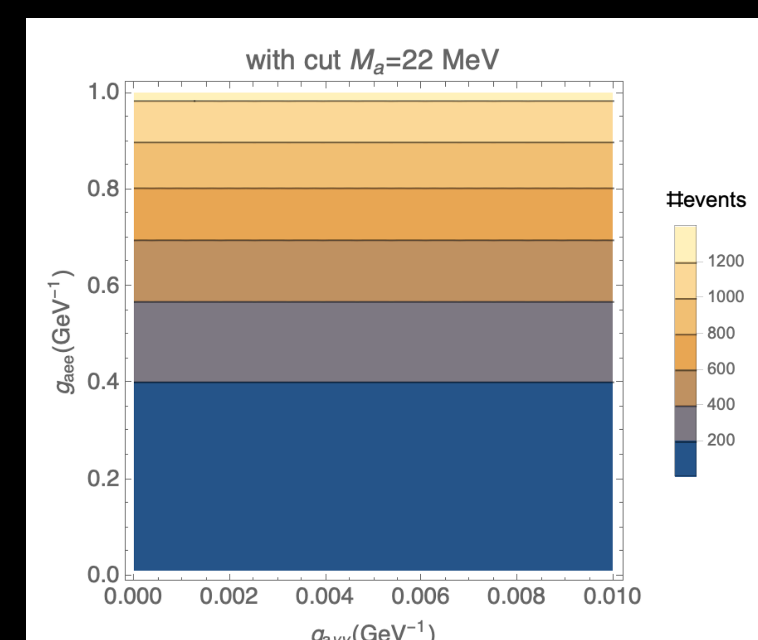
diamond density 3.5 g/cm^3

$\#_{tot}$ of e$^-$ on target per unit surface area

atomic mass = 12 g/mol

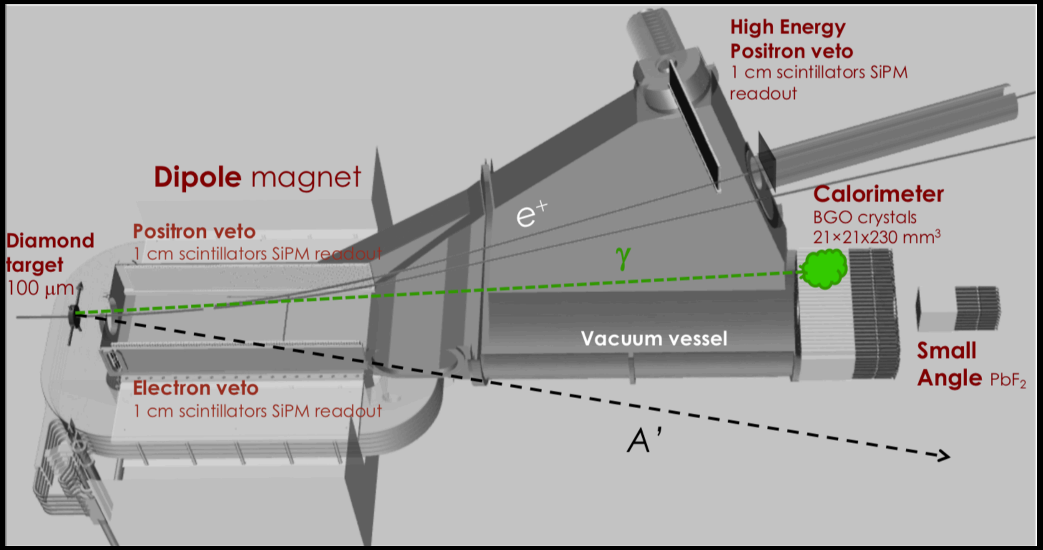






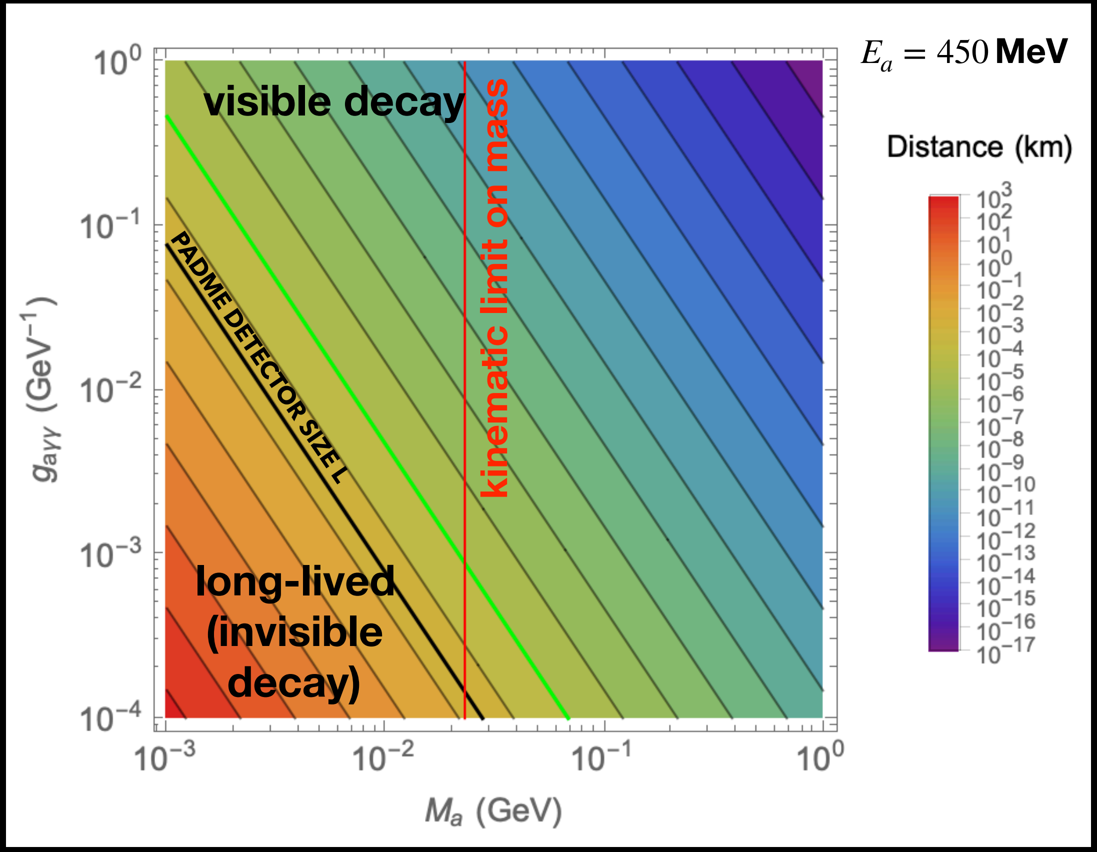
WHAT ABOUT VISIBLE DECAYS OF ALPS IN PADME?

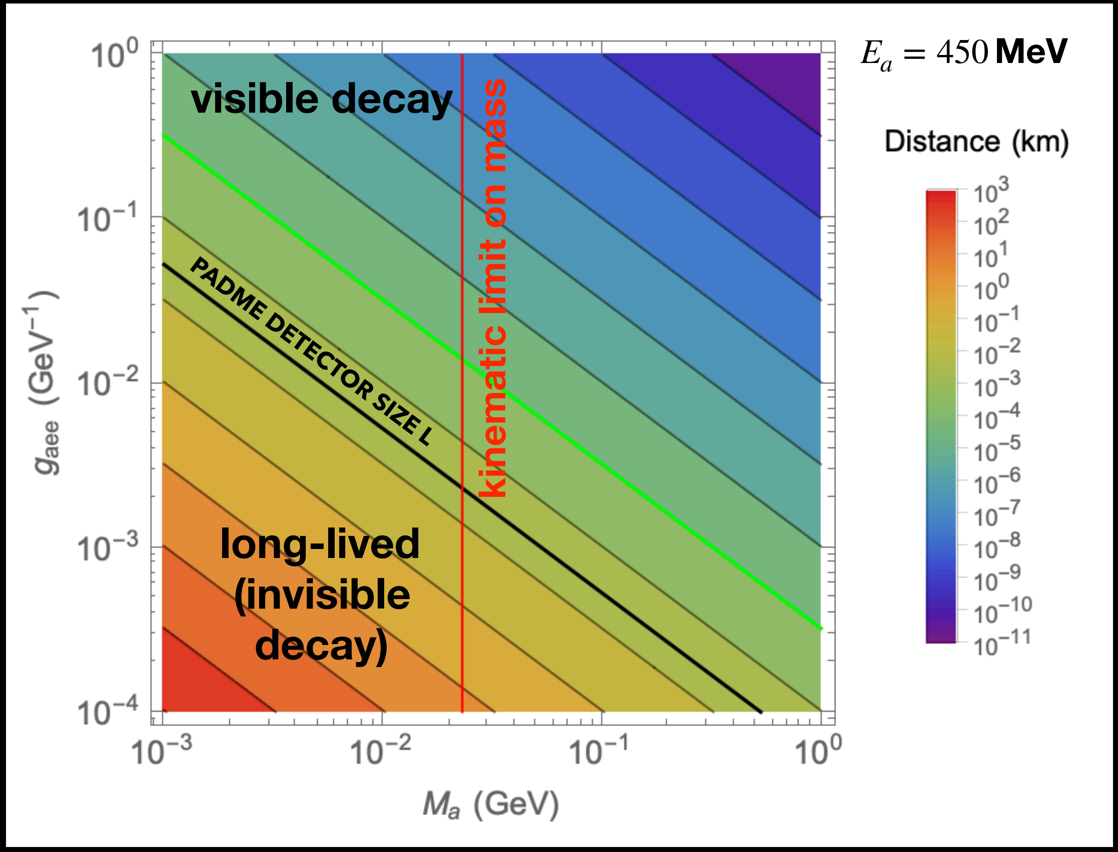
It depends on the ALP decay length relative to the size of the detector



$$L_{a\to\gamma\gamma} = \frac{64\pi c E_a \hbar}{g_{a\gamma\gamma}^2 M_a^4}$$

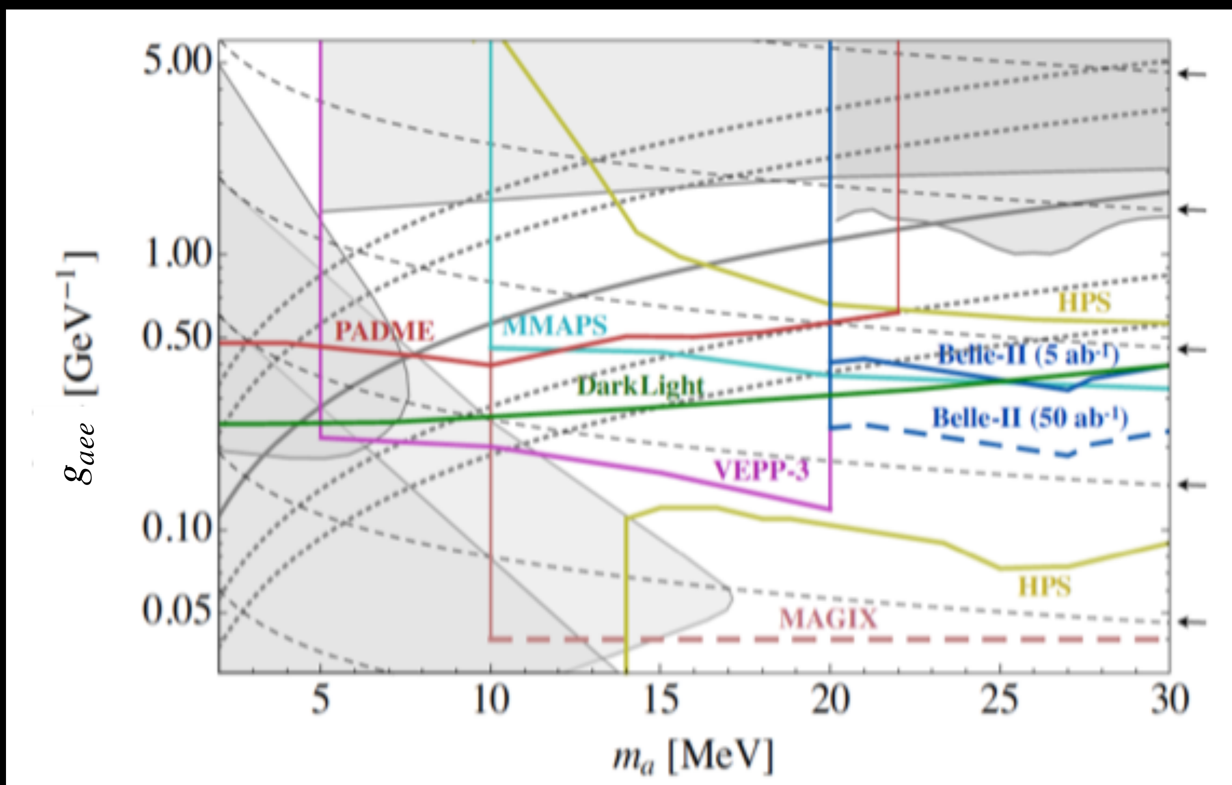
$$L_{a\to e^+e^-} \simeq \frac{8\pi c E_a \hbar}{g_{aee}^2 M_a^2 M_e^2}$$





CURRENT CONSTRAINTS OF ALP

Alves and Weiner JHEP07(2018)092



$$\frac{d\sigma}{d\cos\theta} = \frac{(1+\cos^2\theta)\pi\,\alpha^2\,\epsilon^2}{2\,\sin^2\theta\,E_{\rm beam}^2}\,, \tag{3.2}$$

where ϵ denotes the kinetic mixing parameter.[7] To convert a bound on ϵ for Dark Photons into a bound on $g_{a\gamma\gamma}$ for ALPs we therefore have to correct for the fact that the geometric acceptance will be very different in the two cases.

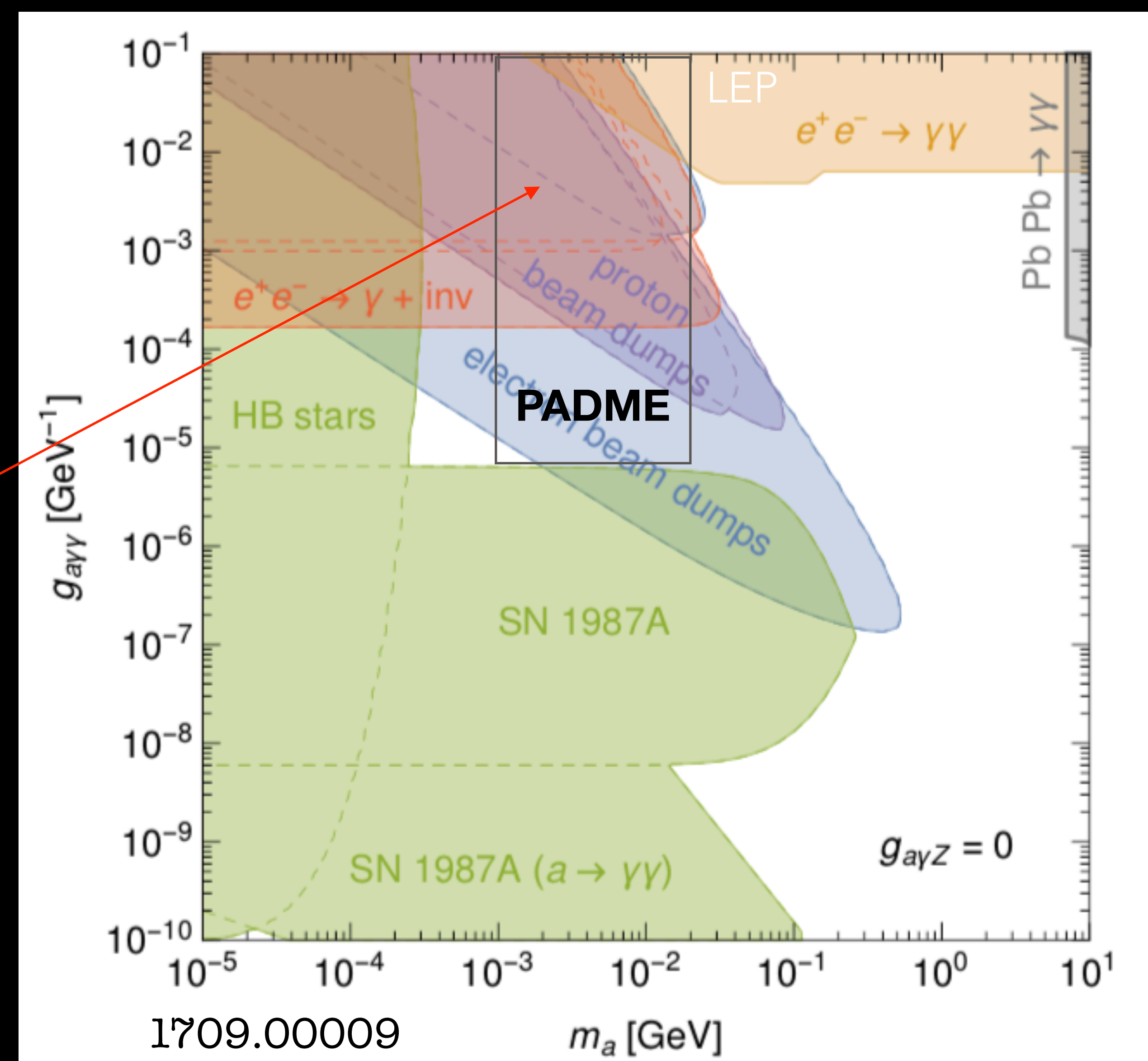
The BaBar analysis considers $-0.6 < \cos\theta < 0.6$ for $m_{A'} > 5.5\,$GeV and $-0.4 < \cos\theta < 0.6$ for $m_{A'} < 5.5\,$GeV. By integrating the respective differential cross sections for ALP production and Dark Photon production over these ranges we obtain the fiducial cross section including geometric acceptance. Using these numbers, we can translate bounds on Dark Photons into the ALP parameter space under the assumption that all other selection cuts have the same efficiency for the two models. For very small masses of the invisibly decaying particle, we find that the translation is given by

$$g_{a\gamma\gamma} = 1.8\times10^{-4}\,\text{GeV}^{-1}\left(\frac{\epsilon}{10^{-3}}\right)\,. \tag{3.3}$$

Repeating this calculation for finite ALP masses and taking into account the probability that the ALP decays before leaving the detector (see above) using a detector length of $L_D = 275\,$cm [59], we can then reinterpret the full BaBar bound in the context of ALPs.

RECAST

FUTURE PADME RESULTS ARE NOT A RECAST OF DARK PHOTON MEASUREMENTS, BUT IT IS EXPLORING DIRECTLY THESE REGIONS WITH A GENERAL MODEL



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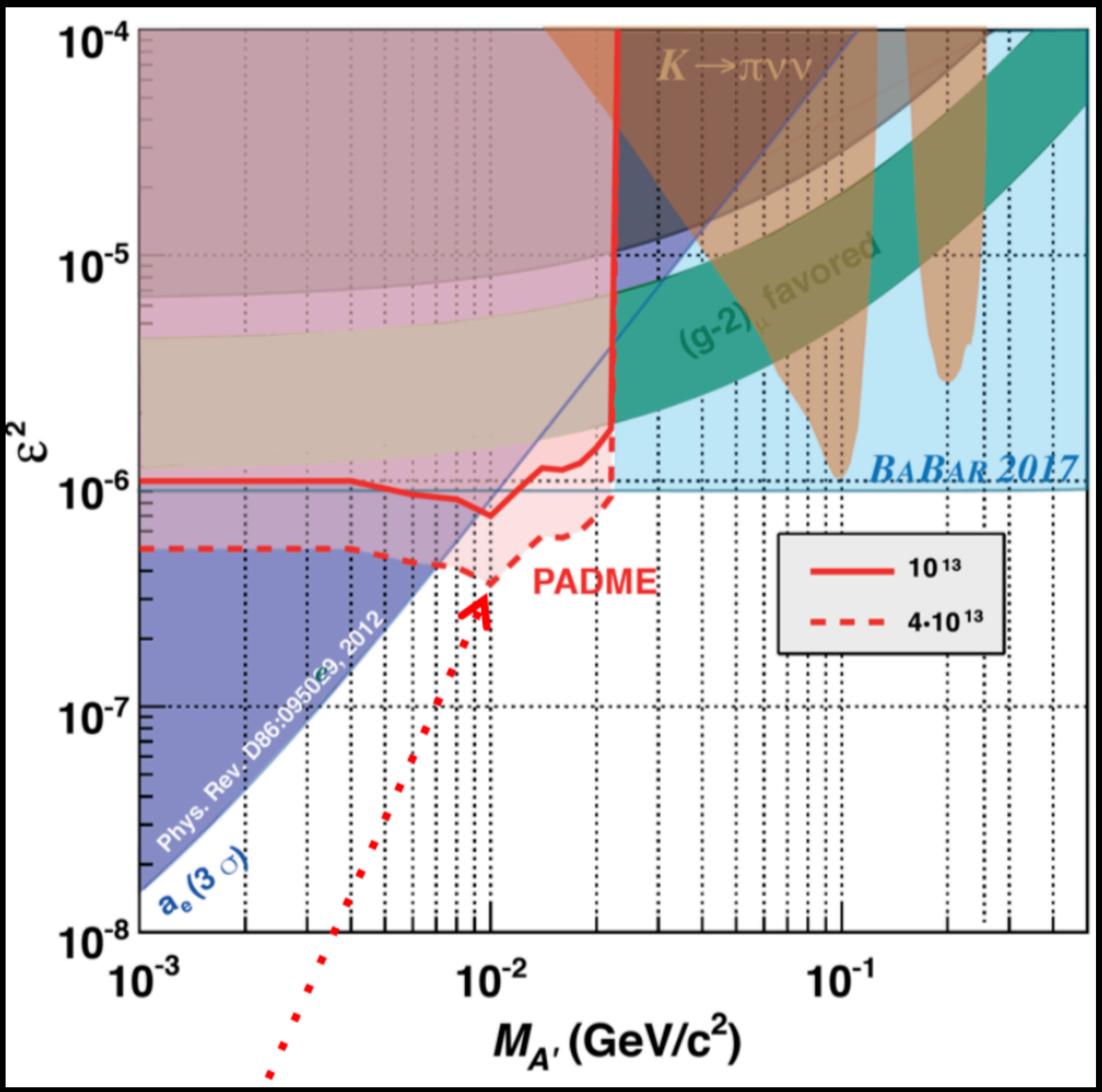
ANALYSIS STATUS OF DARK PHOTON IN PADME

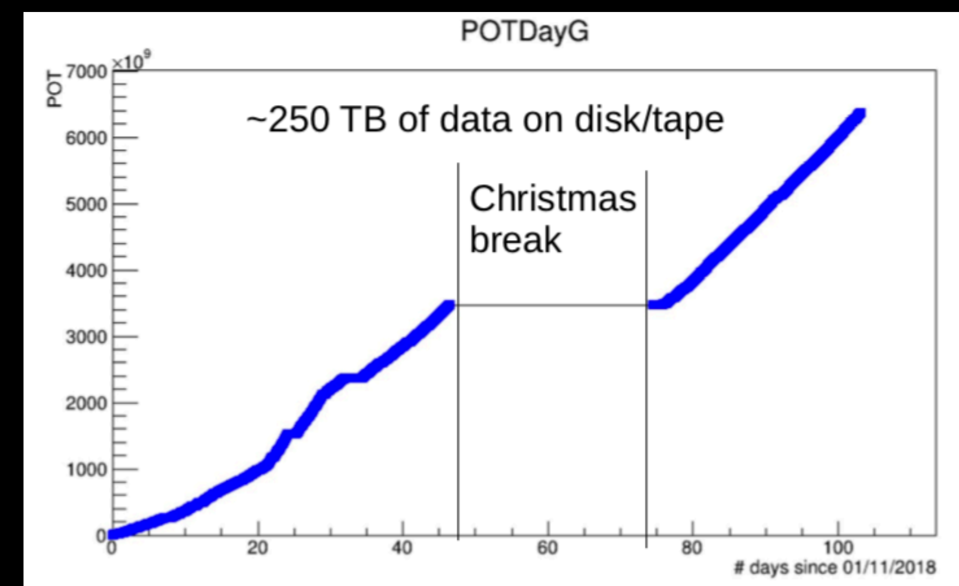


DP sensitivity is based on $2.5x10^{10}$ fully GEANT4 simulated 550 MeV e^+ on target events and BG events are extrapolated to 10^{13} POT on target

CURRENT STATUS OF PADME

PADME commissioning and Run-1 started in Autumn 2018 and ended on February 25th

- $\sim 7 \times 10^{12}$ positrons on target recorded
- Data quality and detector calibration in progress



In July Run-2 was where:

- few days of data
- detector performance/calibration check

Next, on March:

- Finalise detector absolute calibration
- Measure physics signals (bremsstrahlung and annihilation) from data
- Minimise beam background along the beam line
- Collecting the 10^{13} PoT that we want to reach.

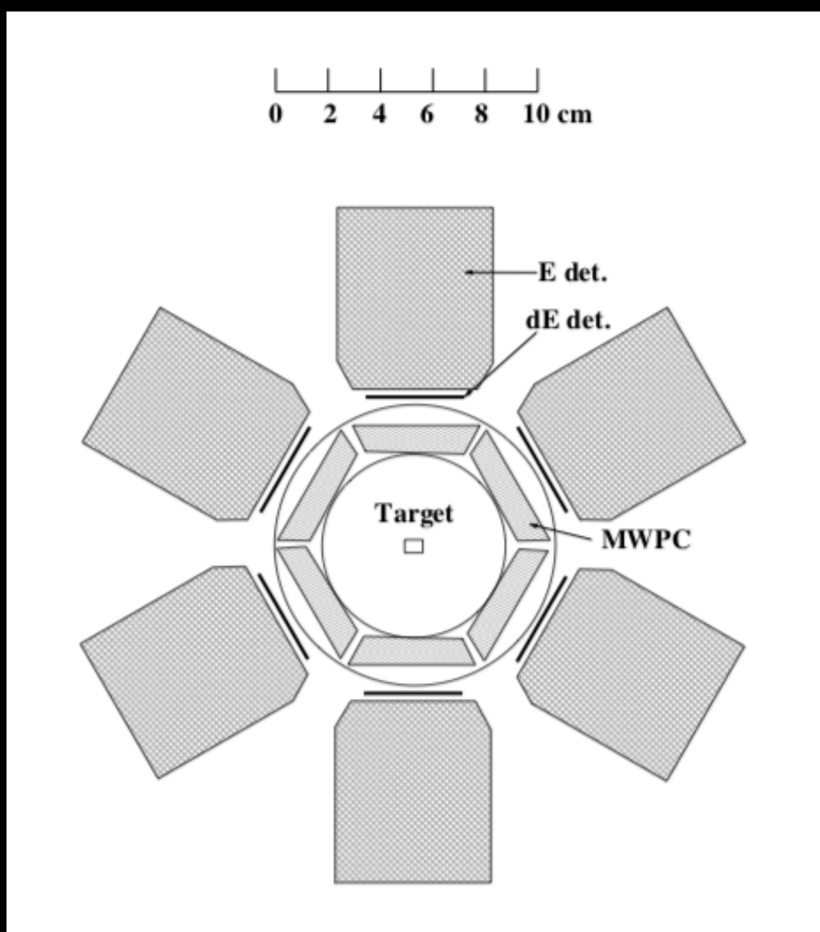
CONCLUSION

- Not only WIMP searches, but also Light Dark Matter (sub-GeV) is really interesting.
- *Intensity Frontier* experiment are increasing the interest.
- PADME is a promising (from data analysis ongoing and the detector performance reaching design parameters) and simple experiment which can look at new physics. In particular, not only dark photon, but ALP parameter space is testable with an interesting phenomenology to study.
- Complete analysis of background in order to measure the sensitivity of PADME.
- Other phenomenology is going to study: probing the anomaly at *17 MeV* observed in ATOMKI experiment [1504.01527].
- Expanding the model including $\mathscr{L}_{DM}$, I will study the parameter space from cosmological analysis.

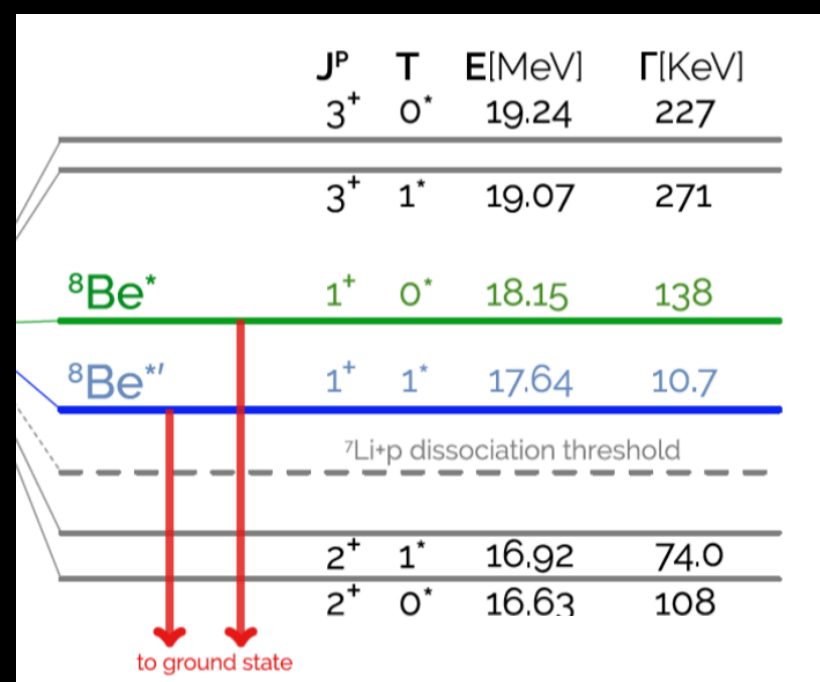
BACKUP SLIDE

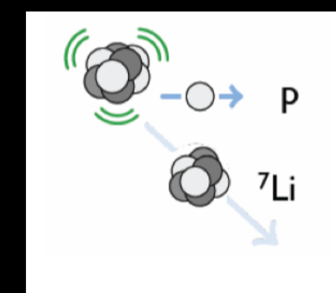
BERYLLIUM (&HELIUM) ANOMALY: EXISTENCE OF NEW PARTICLE AT 17 MEV?

The ATMOKI collaboration [1504.01527] has found “something”, let’s say anomaly, on angular correlation distribution of e+e- internal pair creation (IPC) process of Beryllium 8: ${}^{8}Be^{*} \rightarrow Be\, e^{+}e^{-}$

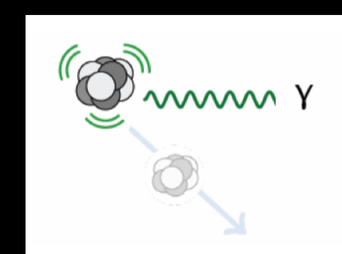


$$p^{+} + {}^{7}Li \rightarrow {}^{8}Be^{*}$$





BR~1



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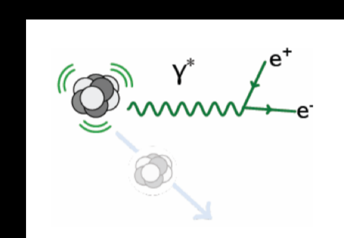
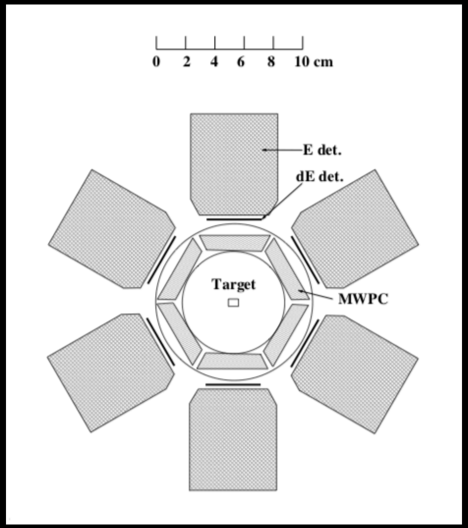


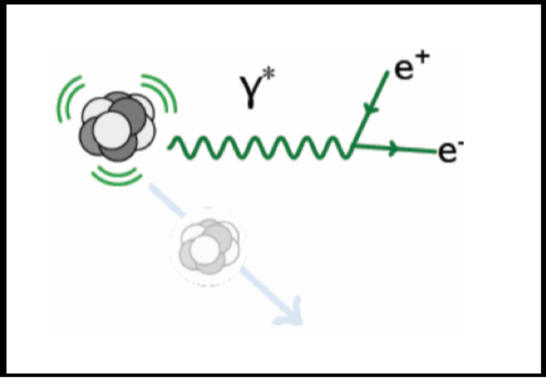
BR~10-8

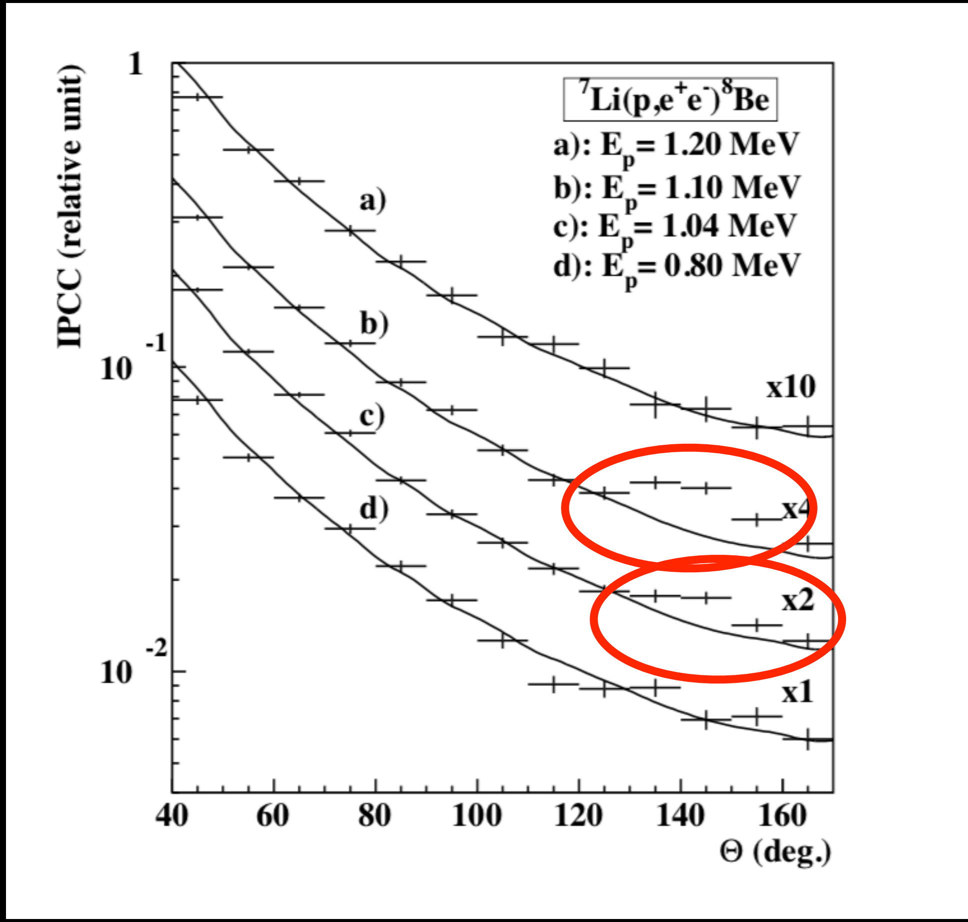
BERYLLIUM (&HELIUM) ANOMALY: EXISTENCE OF NEW PARTICLE AT 17 MEV?

The ATMOKI collaboration [1504.01527] has found "something", let's say anomaly, on angular correlation distribution of e+e- internal pair creation (IPC) process of Beryllium 8: $^8Be* \rightarrow Be\, e^+e^-$



- The e^+e^- pair produced by a virtual photon (IPC), we expect having an angular correlation distribution monotonically decreasing with θ, but for a particular energy beam they found a sharp peak at low θ.
- Moreover the excess is confined to event with symmetric energies, $|y| = \frac{E_{e^+} - E_{e^-}}{E_{e^+} + E_{e^-}} < 0.5$, and large summed energies, $E_{e^+} + E_{e^-} \sim 18MeV$





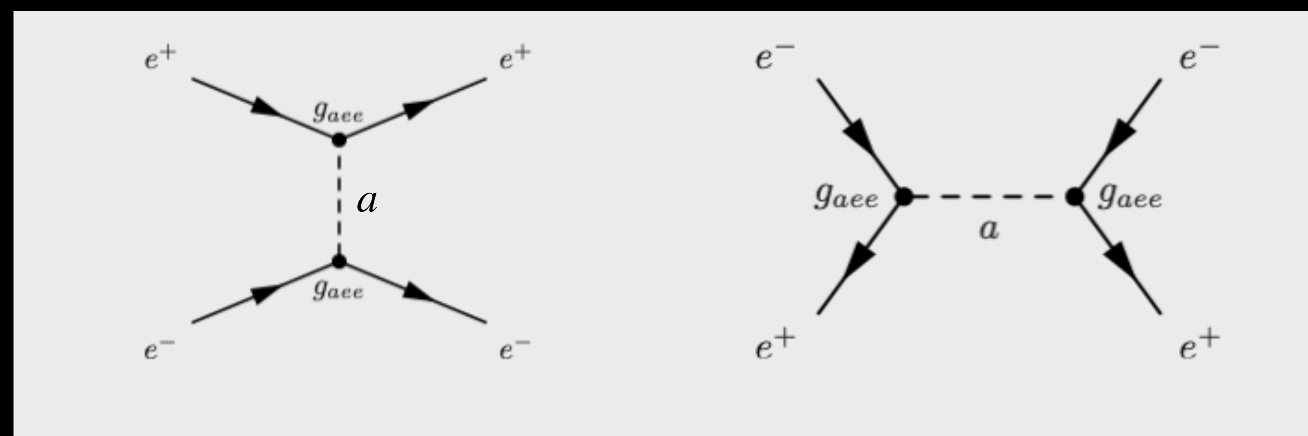
Three possibilities:

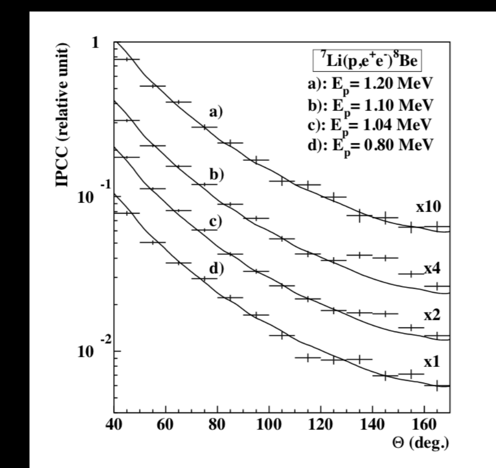
(1) an as-yet-unidentified nuclear experimental problem
(2) an as-yet-unidentified nuclear theory effect
(3) new particle physics

[Feng et al. '16,'17] **[Nardi et al. '18]**

BERYLLIUM (&HELIUM) ANOMALY: EXISTENCE OF NEW PARTICLE AT 17 MEV?

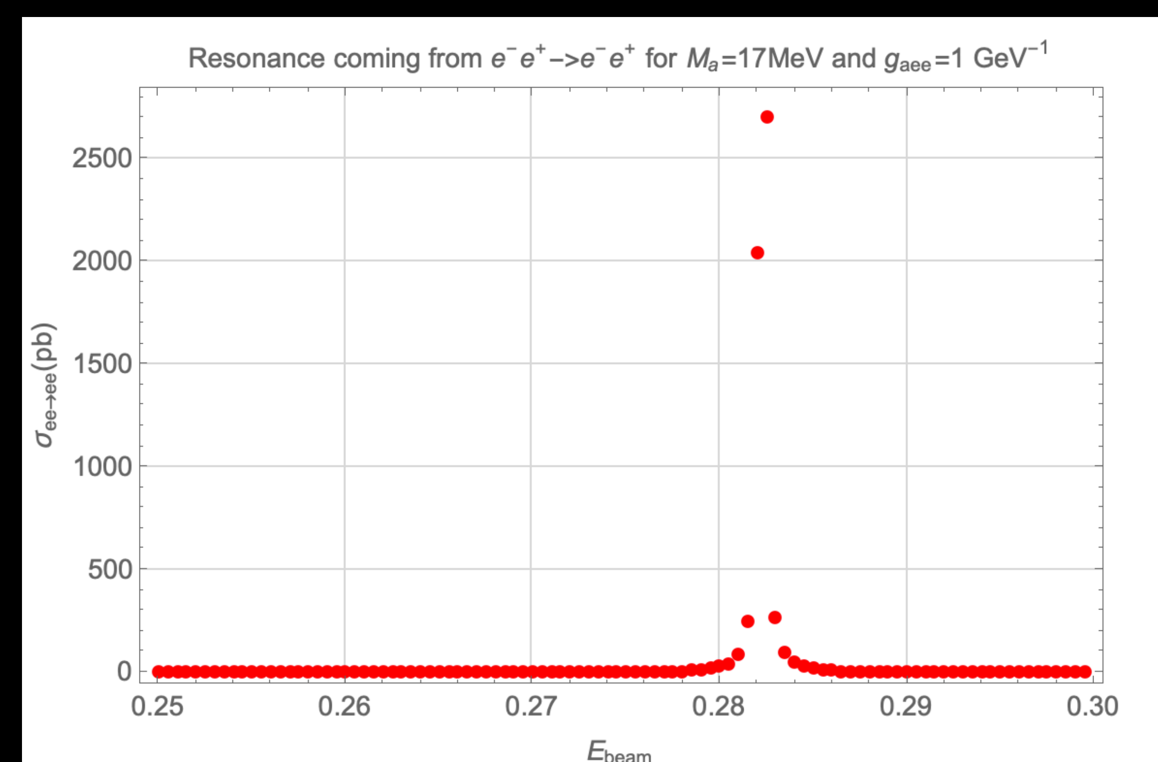
Anomaly observed in excited $^{8}B_{e}$ nuclear decays by Atomki collaboration is particularly relevant for PADME because it could be involved by a new particle at $M_a \sim 17\,MeV$ so really in a parameter space that PADME are testing. Exploiting the process $e^- e^+ \rightarrow X \rightarrow e^- e^+$ where X = ALP





The resonant annihilation produce a very narrowed resonance ($width \simeq 10^{-10}\,GeV$):

$$\sigma_{res} = \sigma_{peak}\frac{\Gamma_{ee}^2/4}{(\sqrt{s} - Ma)^2 + \Gamma_{ee}^2/4} \rightarrow E_{beam} \simeq 0.282268 \text{ at } M_a = 17MeV$$



How many event we have with a thin target of PADME?

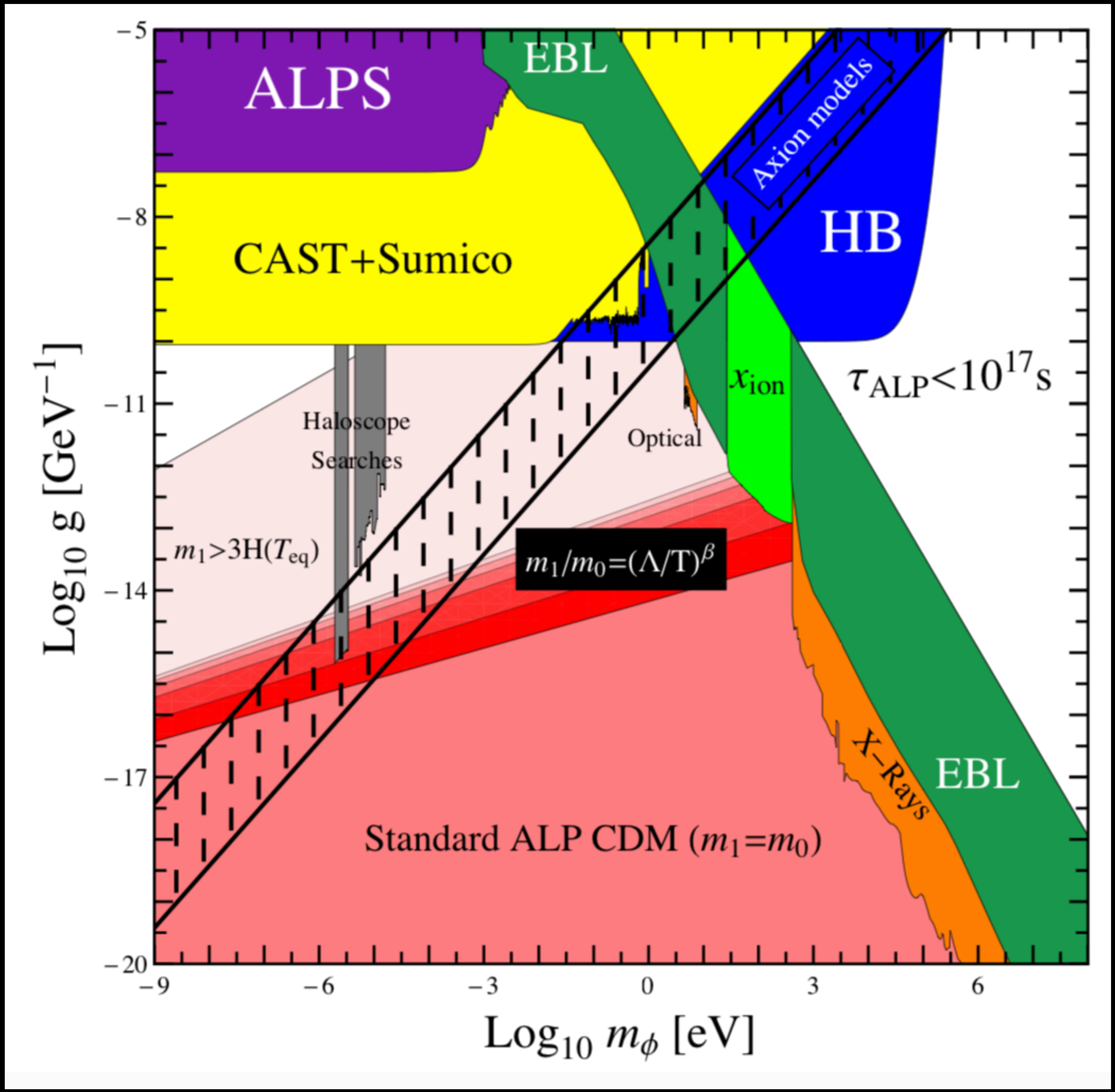
- at the resonance around 10^{14} particles (unless spread beam energy) for 10^{13} PoT

And how reduce the background (Bhabha scattering)?

WORK IN PROGRESS

PARAMETER SPACE FOR AXIONS AND AXION-LIKE PARTICLES

- Red Region represent where ALP could form CDM
- The exclusion regions labelled "ALPS", "CAST+Sumico" and "HB" arise from experiments and astrophysical observations that do not require ALP dark matter.
- The remaining constraints are based on axion being DM.
- ALPs with a lifetime shorter than the age of the universe, ~ 13.7 Gyr, cannot account for the DM observed in galaxies.



Arias et al. JCAP 1206 (2012) 013