Beyond Standard Model Theories

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האוניברסיטה העברית בירושלים
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New Ideas for Old Puzzles

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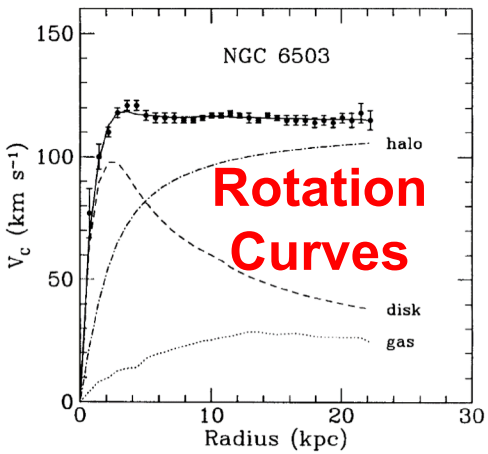
Outline

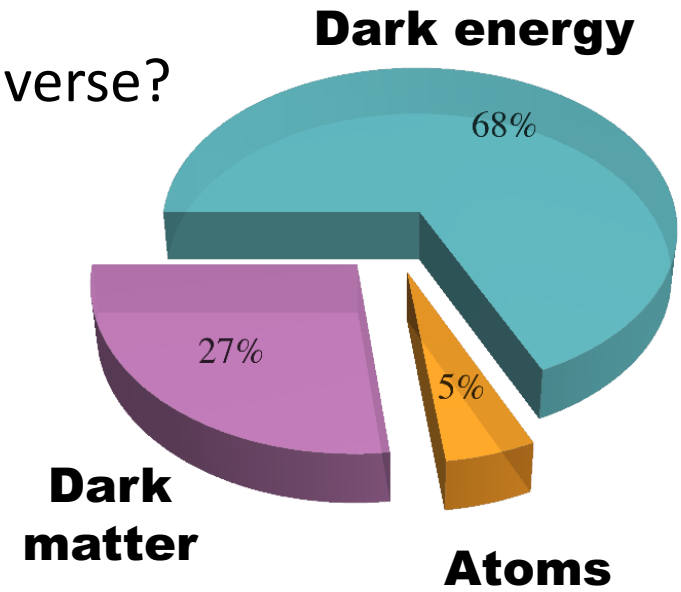
Dark matter & Naturalness

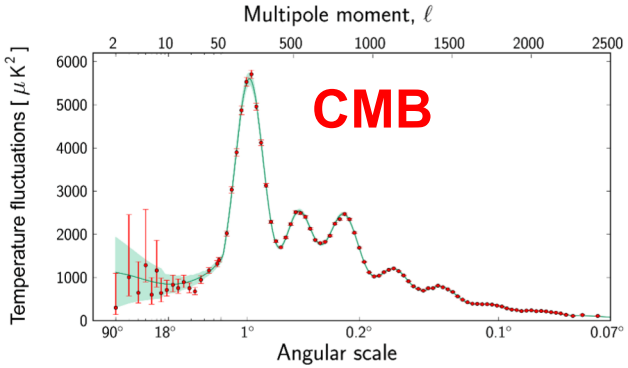
Setting the Stage

Dark Matter

What is the dark matter (DM) of our universe?







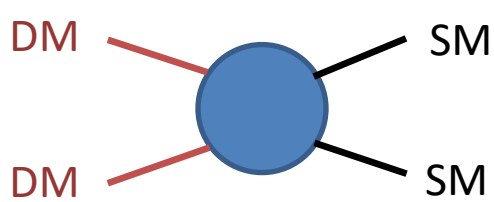
Classic Solution*

Correct thermal relic abundance:

$$m_{\rm DM} \sim \alpha \times 30 \ \ {\rm TeV}$$

For weak coupling, weak scale emerges.

WIMP = Weakly Interacting Massive Particle



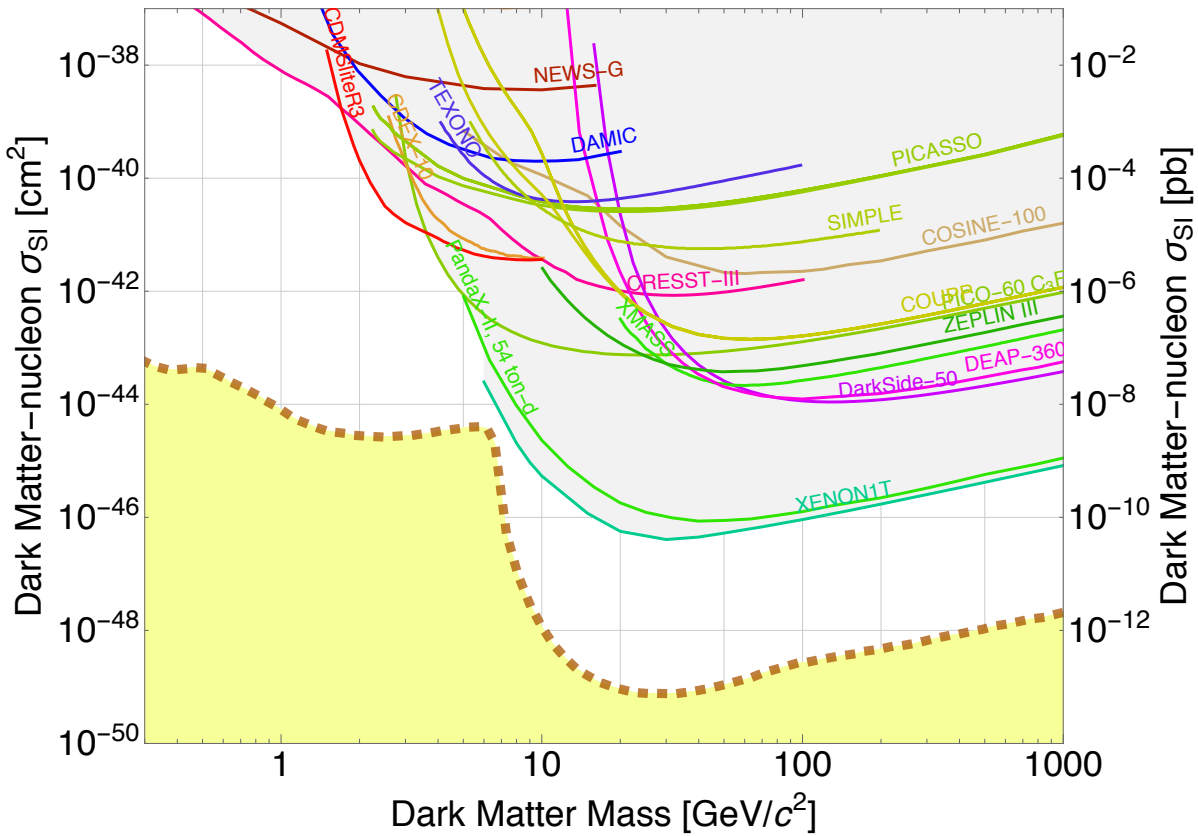
annihilation

$$\langle \sigma_{\rm ann} v \rangle = \frac{\alpha^2}{m_{\rm DM}^2}$$

*of course also axion

Experimental Status

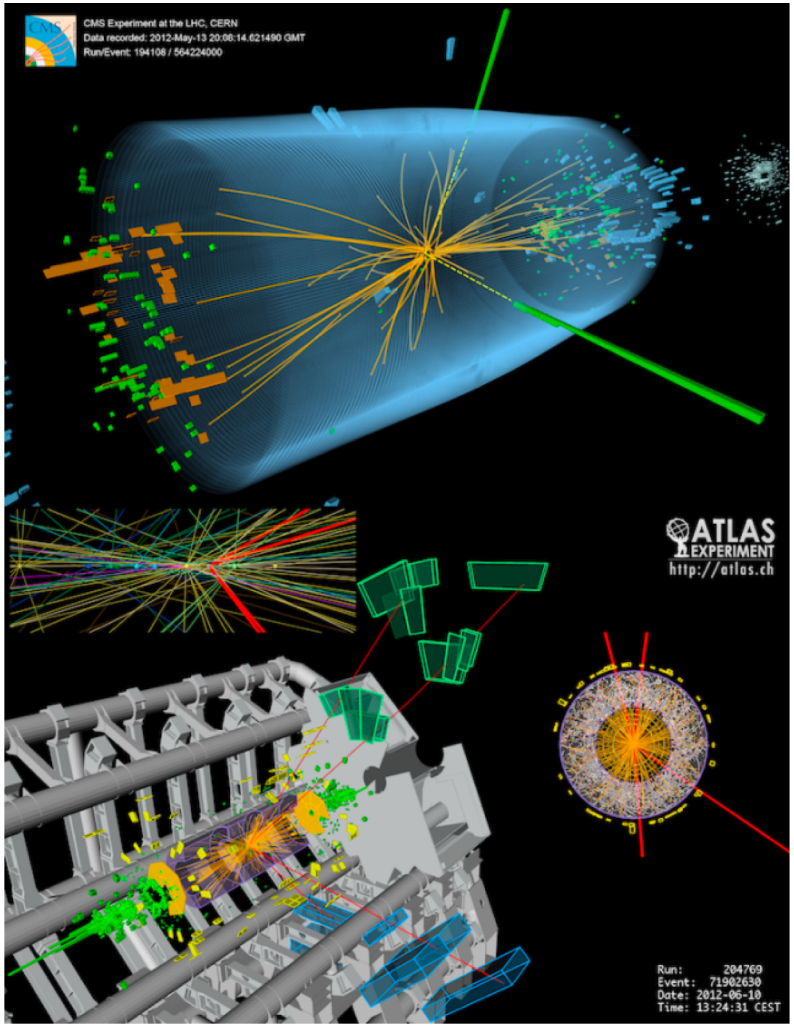
E.g. Direct Detection



[*website*: supercdms.slac.stanford.edu/dark-matter-limit-plotter]

(Similarly strengthening limits for direct production and indirect detection)

Naturalness



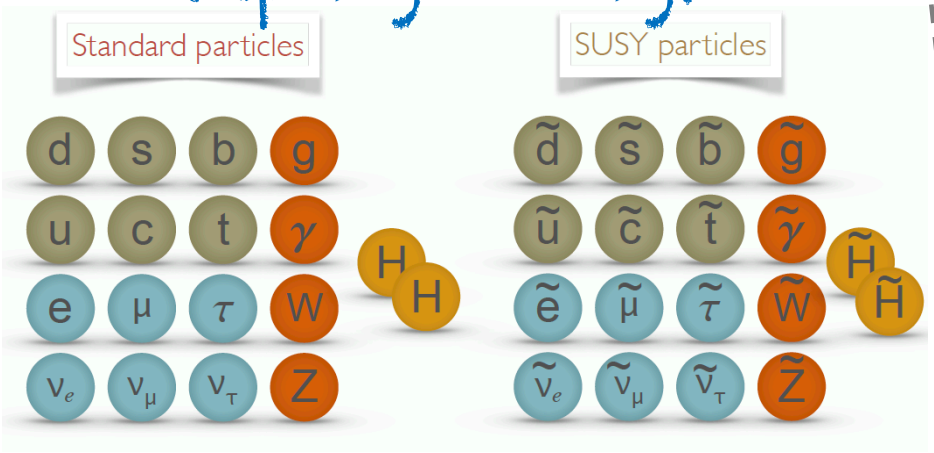
Why is the Higgs mass so light compared to the scale of gravity?

H^0 $\quad J = 0$

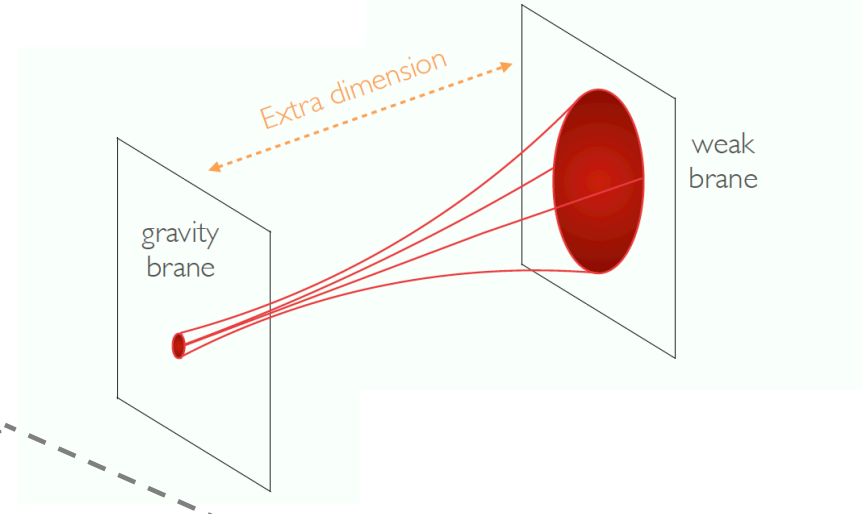
Mass $m = 125.10 \pm 0.14$ GeV

Classic Solutions

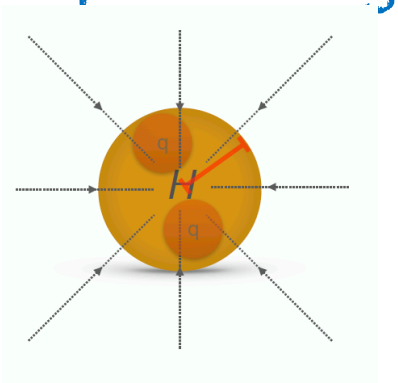
Supersymmetry?



Extra dimensions?

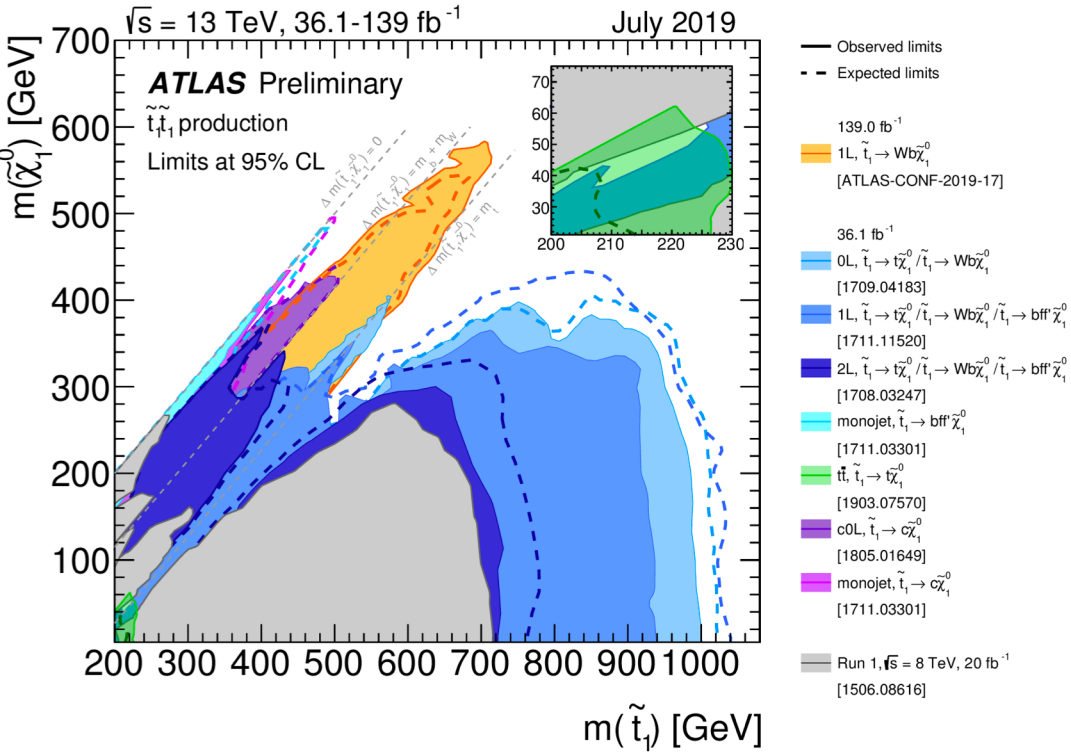


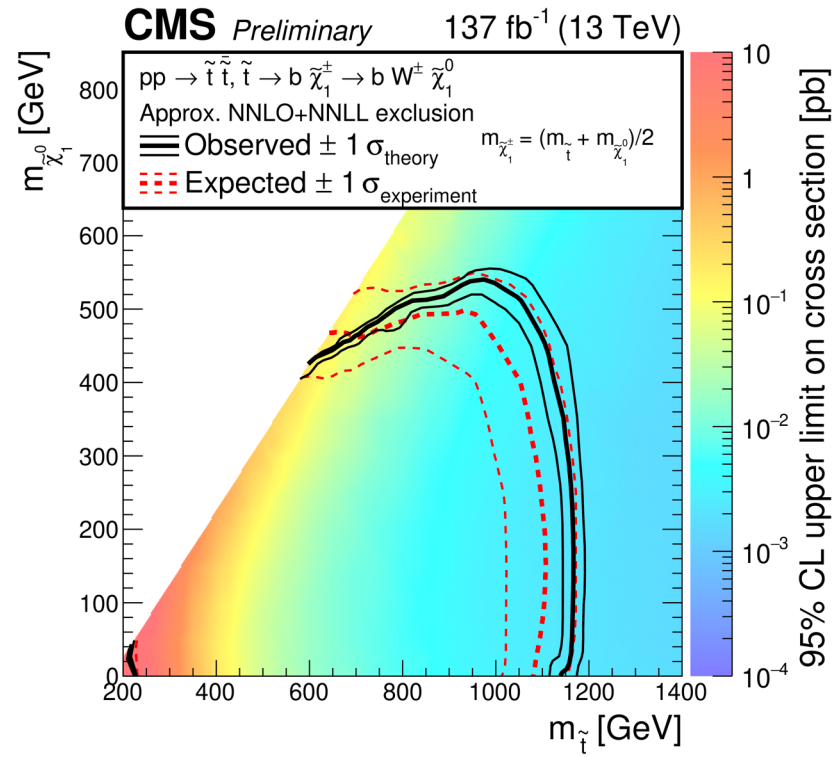
Composite Higgs?



Experimental status

E.g. supersymmetry





(Similarly strengthening limits in other channels)

Dominant ideas are being challenged.

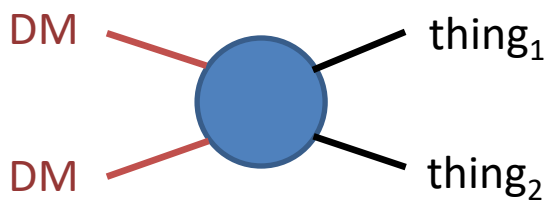
Great opportunity for creativity!

Dark Matter

New Ideas Abundant

- ……
- Weakly coupled WIMPs [Pospelov, Ritz, Voloshin 2007; Feng, Kumar 2008]
- Asymmetric dark matter [Kaplan, Luty, Zurek, 2009]
- Freeze-in dark matter [Hall, Jedamzik, March-Russell, West, 2009]
- SIMPs [**YH**, Kuflik, Volansky, Wacker, 2014 ; **YH**, Kuflik, Murayama, Volansky, Wacker, 2015]
- ELDERs [Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]
- Forbidden dark matter [Griest, Seckall, 1991; D'Agnolo, Ruderman, 2015]
- Co-decaying dark matter [Dror, Kuflik, Ng, 2016]
- Co-scattering dark matter [D'Agnolo, Pappadopulo, Ruderman, 2017]
- ……

Ex. #1: Forbidden Channels



$$2m_{\rm DM} < m_{\rm thing_1} + m_{\rm thing_2}$$

$$m_{\rm DM} \sim \alpha \times (30\ {\rm TeV}) \times e^{-x_F \Delta}$$

freezeout temp'

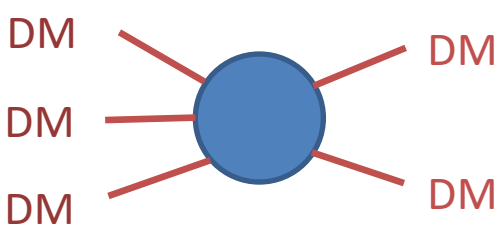
mass difference

Forbidden @ T=0;
Boltzmann suppressed @ finite T

[Griest, Seckel, 1991; D'Agnolo, Ruderman, 2015]

Ex. #2: SIMPs

What if dark matter mostly interacted with itself?



$$\langle \sigma v^2 \rangle_{3\to 2} \equiv \frac{\alpha^3}{m_{\rm DM}^5}$$

$$m_{\rm DM} \sim \alpha \times 100 \text{ MeV}$$

3 → 2 self-annihilations

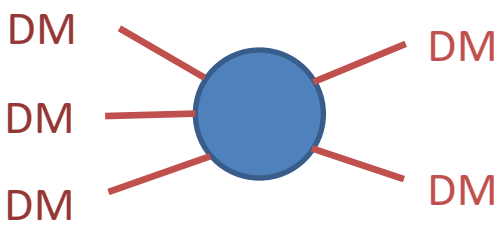
For strong coupling, the strong scale emerges.

SIMP = Strongly (self) Interacting Massive Particle

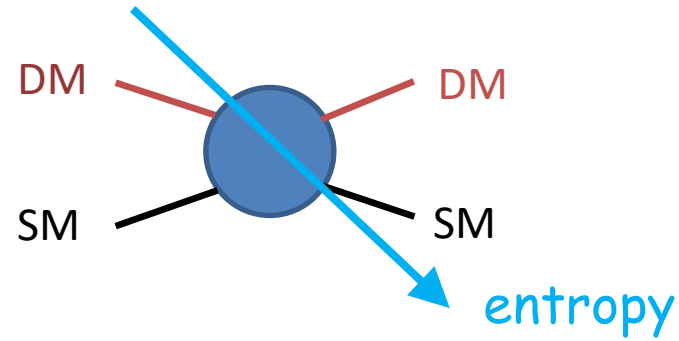
[Carlson, Hall, Machacek, 1992;
YH, Kuflik, Volansky, Wacker, 2014]

Ex. #2: SIMPs

Pumps heat into the system: need to shed the heat



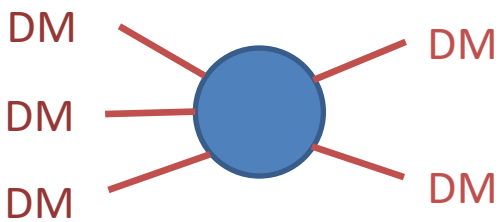
3 → 2 self-annihilations



thermalize with
light SM species
(active during freeze-out)

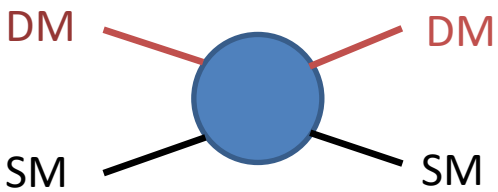
[**YH**, Kuflik, Volansky, Wacker, 2014]

Ex. #2: SIMPs



decouples 1st

Determines
DM relic density

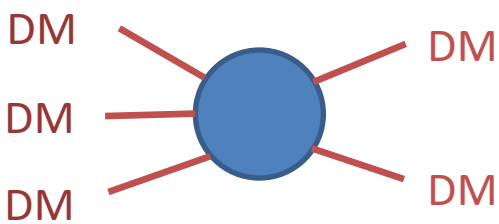


decouples 2nd

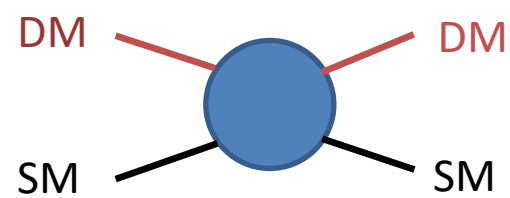
What if the order was reversed?

Ex. #3: ELDERs

ELastically DEcoupling Relic (ELDER)



decouples 2nd



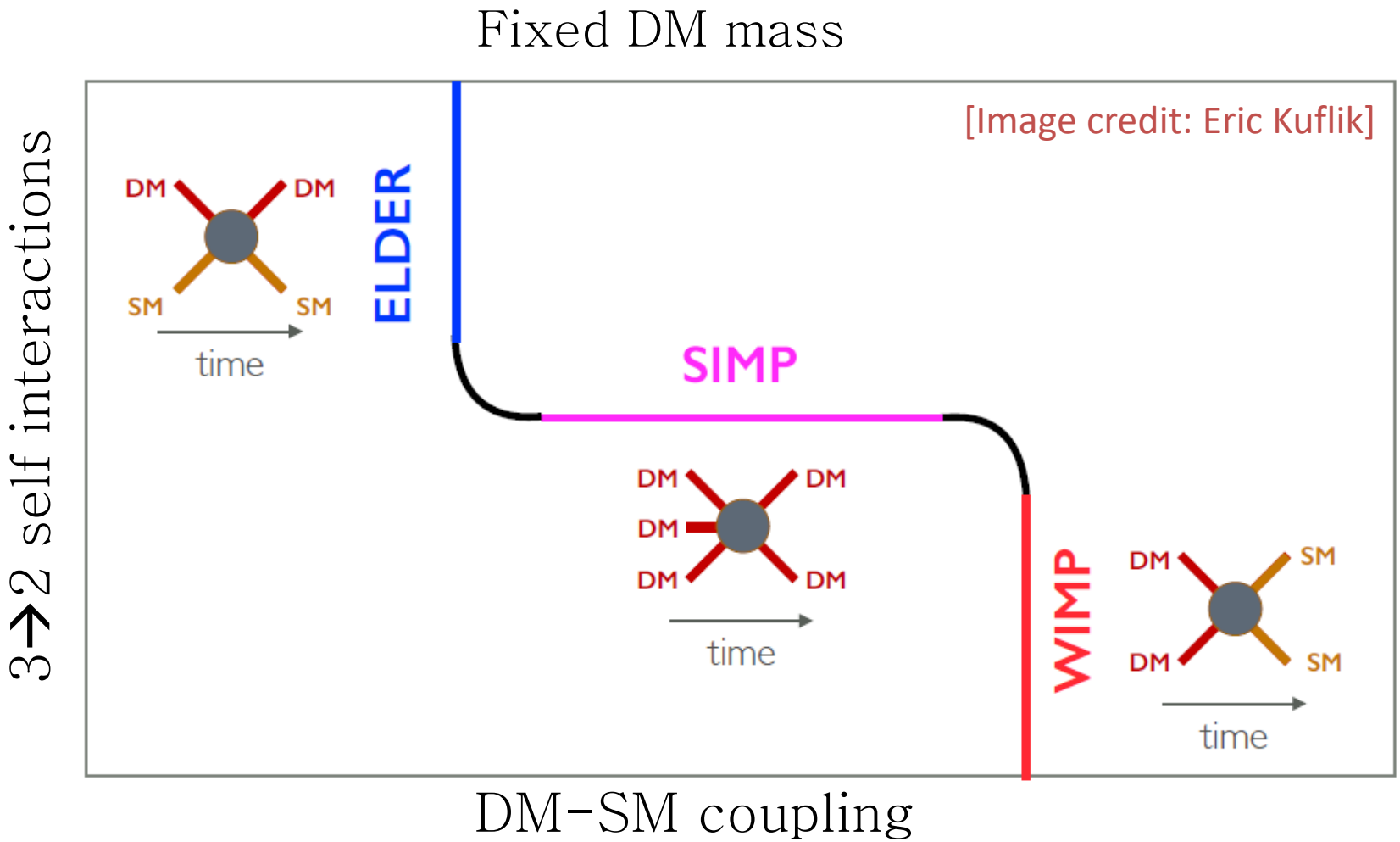
decouples 1st

Determines
DM relic density

$$\text{DM relic abundance} \propto e^{-\langle \sigma v \rangle_{\rm el} \#}$$

[Kuflik, Perelstein, Rey-Le Lorier, Tsai, 2016 & 2017]

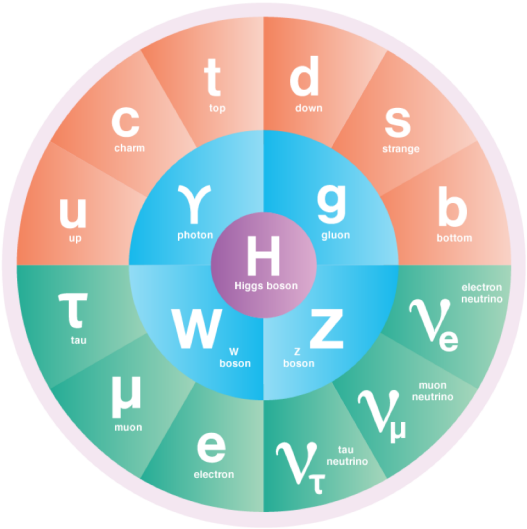
WIMP/SIMP/ELDER



Generic in complex rich dark sectors.

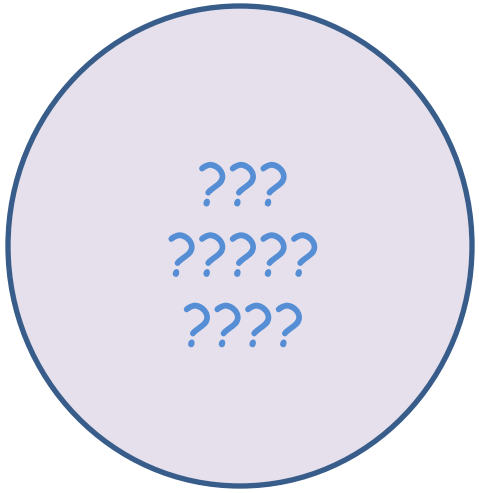
Dark Sectors

Visible sector



Zoo of particles
w/structure
$SU(3)_c \times SU(2)_L \times U(1)_Y$

Dark sector



Why not in the
dark sector too?
New gauge symmetries?

Dark Sectors

Think Standard Model!

Strongly coupled gauge theories

E.g. $SU(3)_{dark} \times U(1)_{dark}$

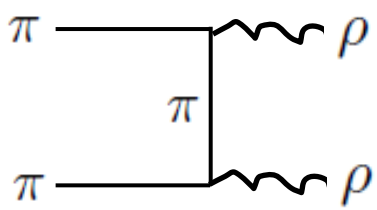
$Sp(N_c)$, $SU(N_c)$, $SO(N_c)$

Kinetically mixed hidden photon (V)

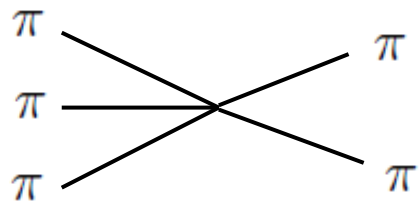
QCD-like theories, pions = dark matter

Many processes, many dark matter mechanisms.

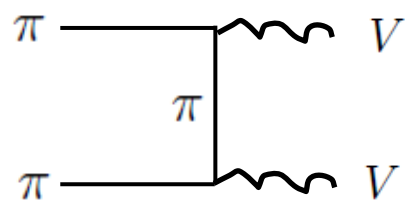
Dark Sectors



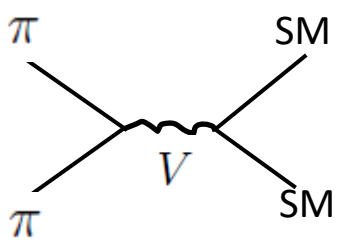
forbidden annihilations



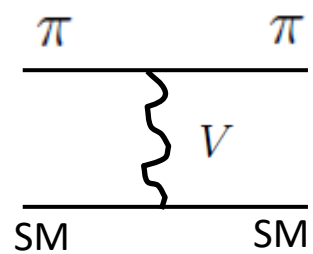
3→ 2 annihilations



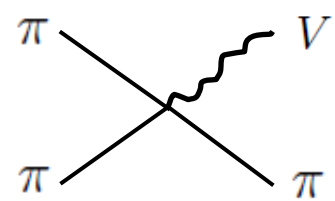
2→2 annihilations



2→ 2 annihilations



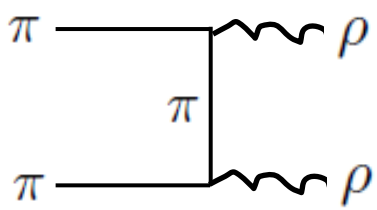
elastic scattering



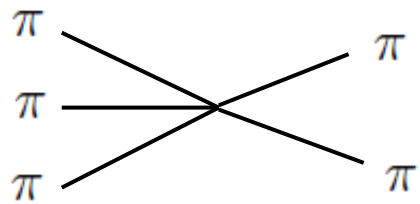
semi-annihilations

[**YH**, Kuflik, Murayama, Volansky, Wacker, 2015; Lee, Seo, 2015;
YH, Kuflik, Murayama, 2016; Harigaya, Nomura, 2016; Berlin, Blinov, Schuster, Toro, 2017;...]

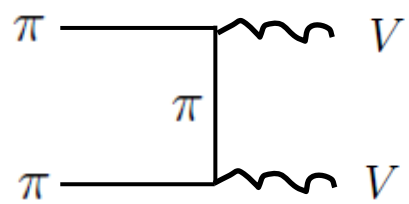
Dark Sectors



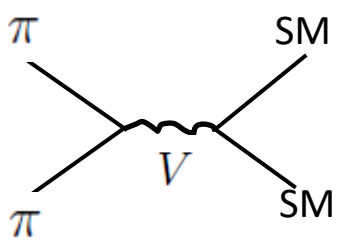
forbidden annihilations



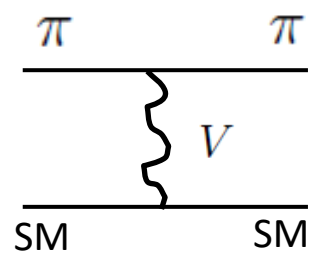
3→ 2 annihilations



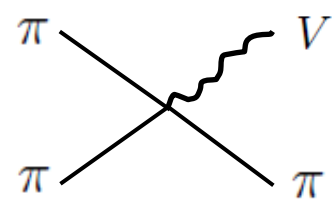
2→2 annihilations



2→ 2 annihilations



elastic scattering



semi-annihilations

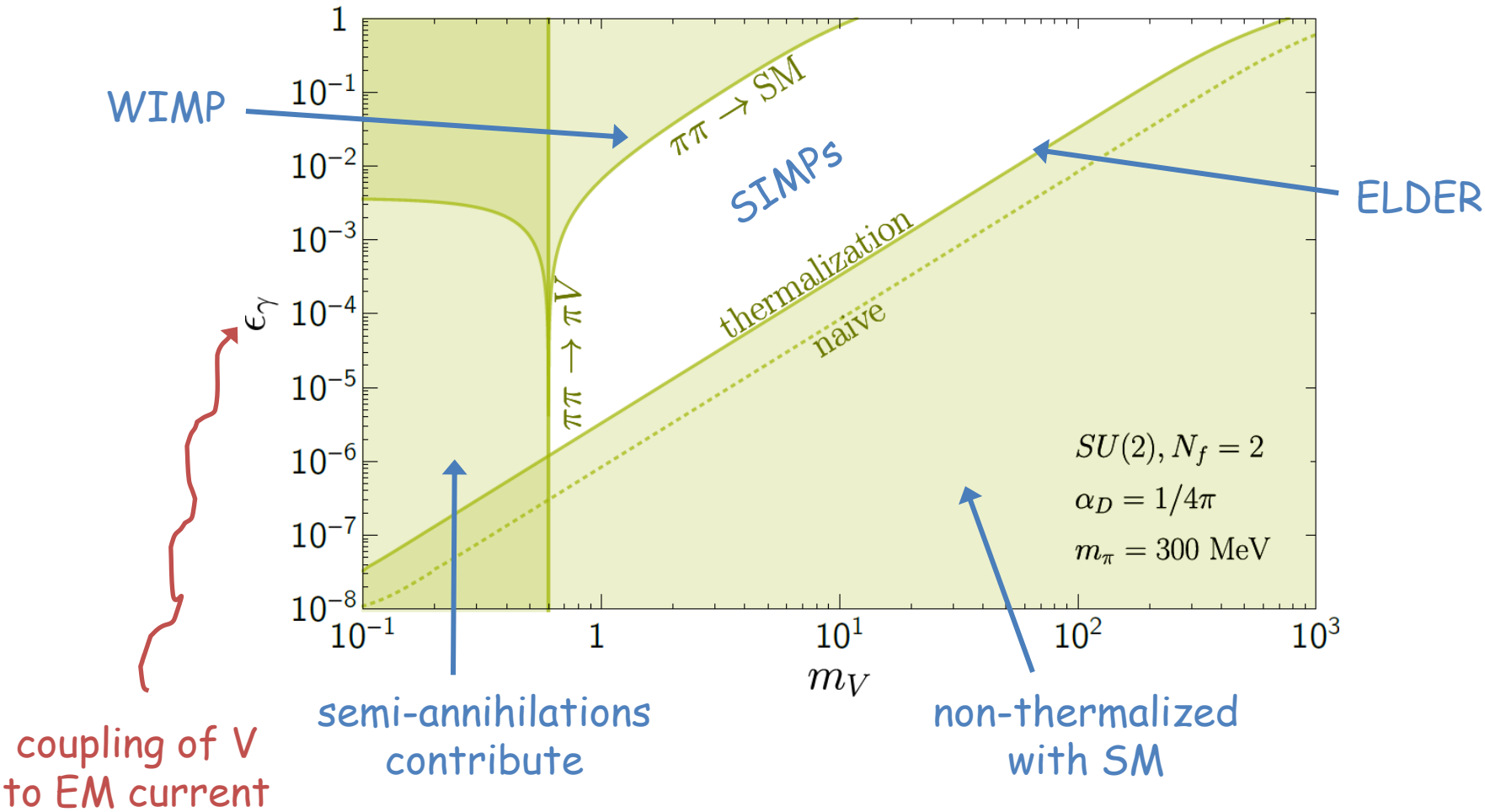
3→ 2 dark glueballs:
E.g. Carelson, Hall, Machacek, 1992; Soni, Zhang, 2016; Forestell, Morrissey, Sigurdson, 2017

Dark nuclei:
E.g. Krnjaic, Sigurdson, 2014; Detmold, Pochinsky, McCullough, 2015

Predictive.

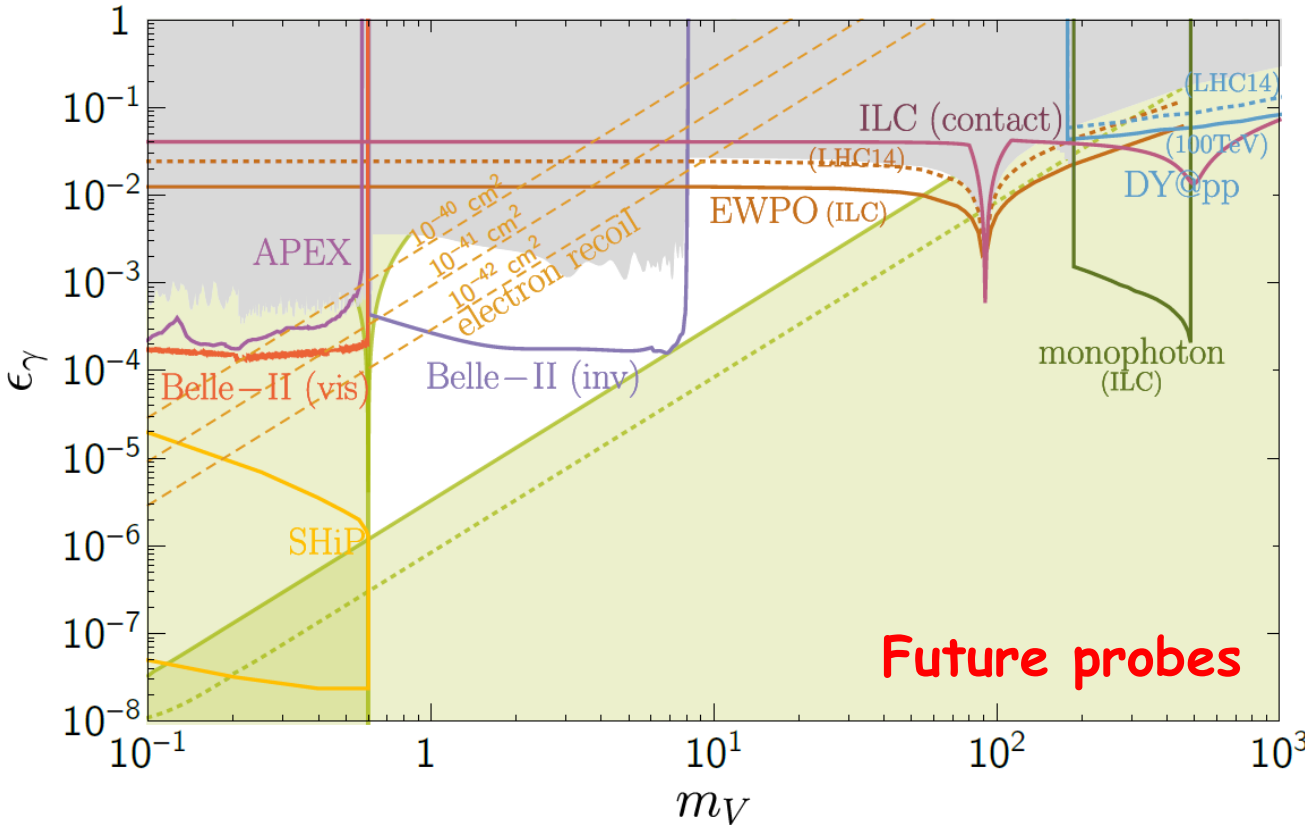
Predictive

E.g. **Kinetically Mixed U(1)**



Experimental Probes

E.g. **Kinetically Mixed U(1)**



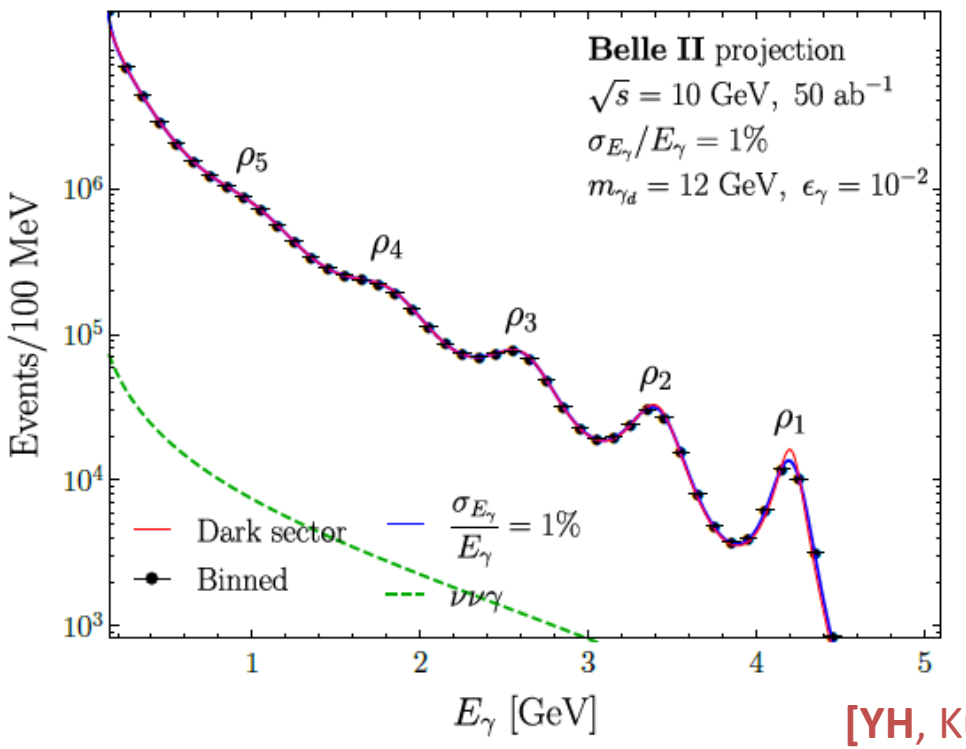
[Plot: **YH**, Kuflik, Murayama, 2016]

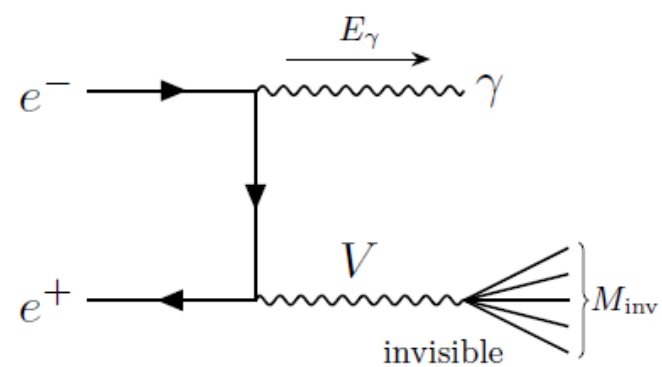
Experimental Probes

***E.g.* Dark Spectroscopy @ Lepton Colliders**

$$e^+e^- \to \gamma + \text{inv}:$$

Mono-photon traces the resonance structure of the dark sector



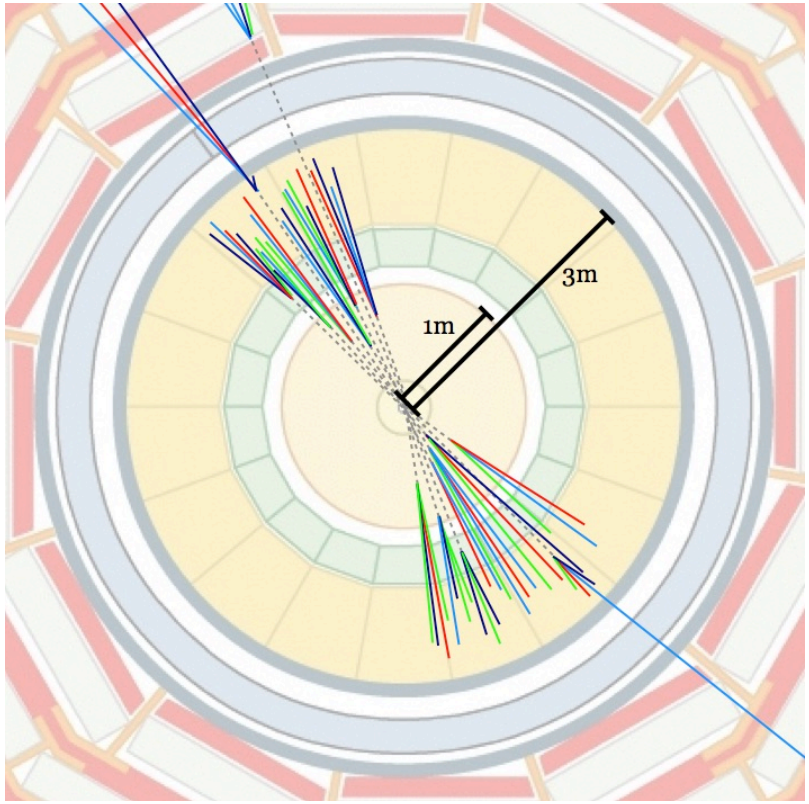


$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\text{inv}}^2}{s}\right)$$

[**YH**, Kuflik and Murayama, 2016 & 2017]

Experimental Probes

E.g. **Dark Showers @ LHC**



[Schwaller, Stolarski, Weiler, 2015; CMS 2018]
Emerging Jets

[Cohen, Lisanti, Lou, 2015; + w/ Mishra-Sharma, 2017]
Semi-visible Jets

[Strassler, Zurek, 2006]
Hidden Valleys

Experimental Probes

E.g. Long Lived Particles

Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case

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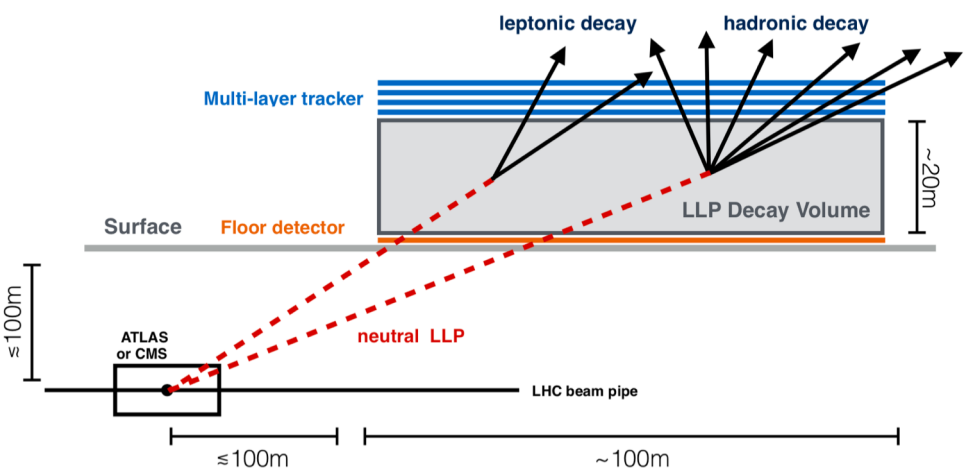
[arXiv:1806.07396]

MATHUSLA



Experimental Probes

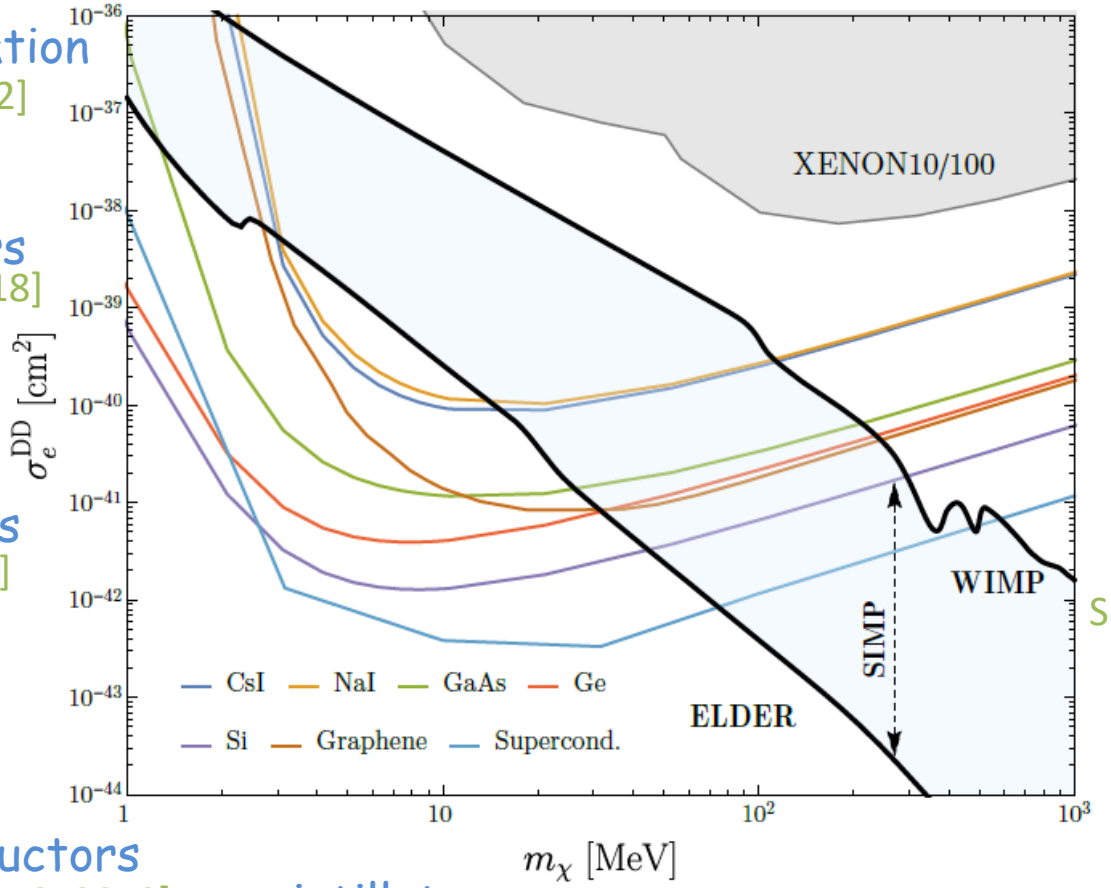
E.g. **Direct Detection, such as**

atomic ionization
[Essig et al, 2012]

color centers
[Budnik et al, 2018]

semi-metals
[**YH** et al, 2017]

superconductors
[**YH** et al, 2015 x 2, 2019]



scintillators
[Derenzo et al, 2016]

2D targets (graphene)
[**YH** et al, 2016; Cavoto et al, 2018]

[Plot:
Kuflik, Perelstein,
Rey-Le Lorier,
Tsai, 2017]

Polar materials
[**Griffin** et al, 2018]

semiconductors
[Essig et al, 2012;
SuperCDMS & SENSEI 2018;
Kurinsky et al, 2019]

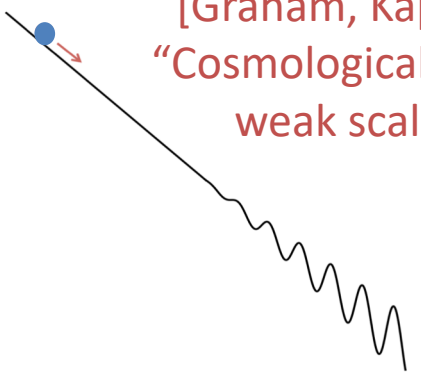
superfluid helium
[Schutz, Zurek, 2016;
Hertel et al 2018;
Acanfora et al 2019]

Naturalness

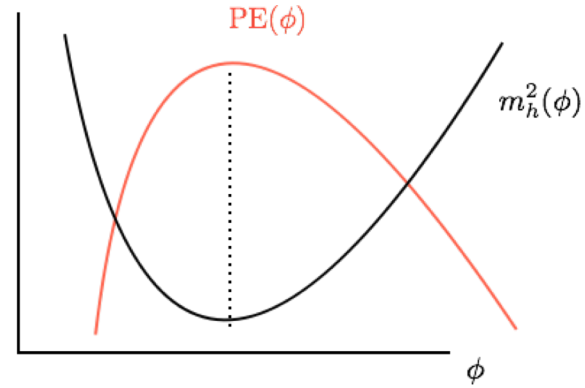
Cosmological Dynamics

The Relaxion

[Graham, Kaplan, Rajendran, "Cosmological relaxation of the weak scale", PRL 2015]

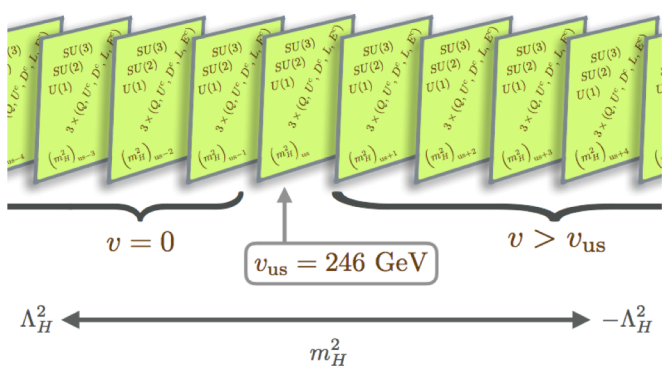


The Fluctuon



[Geller, **YH**, Kuflik, "Inflating to the weak scale", PRL 2019]

N-naturalness

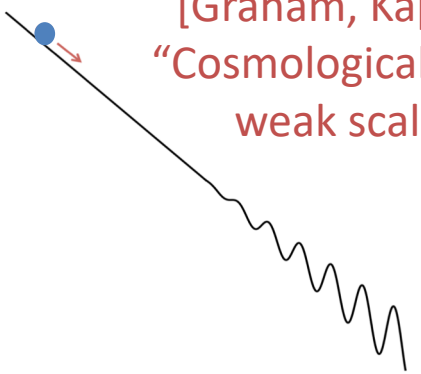


[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner, "Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom", PRL 2016]

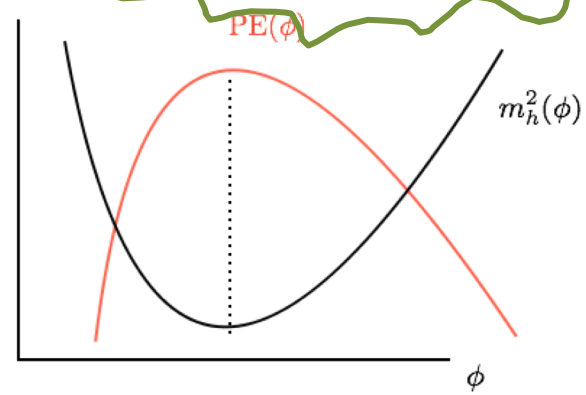
Cosmological Dynamics

The Relaxion

[Graham, Kaplan, Rajendran, "Cosmological relaxation of the weak scale", PRL 2015]

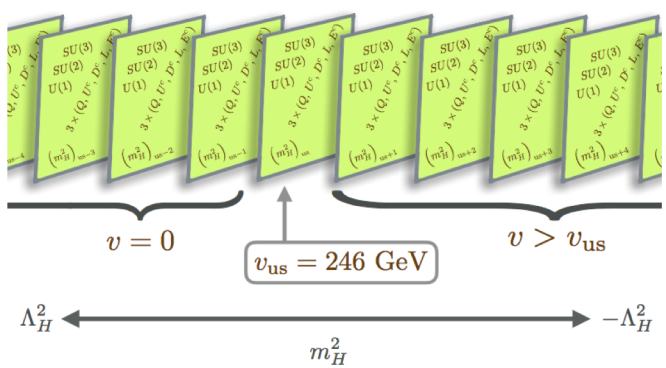


The Fluctuon



[Geller, **YH**, Kuflik, "Inflating to the weak scale", PRL 2019]

N-naturalness

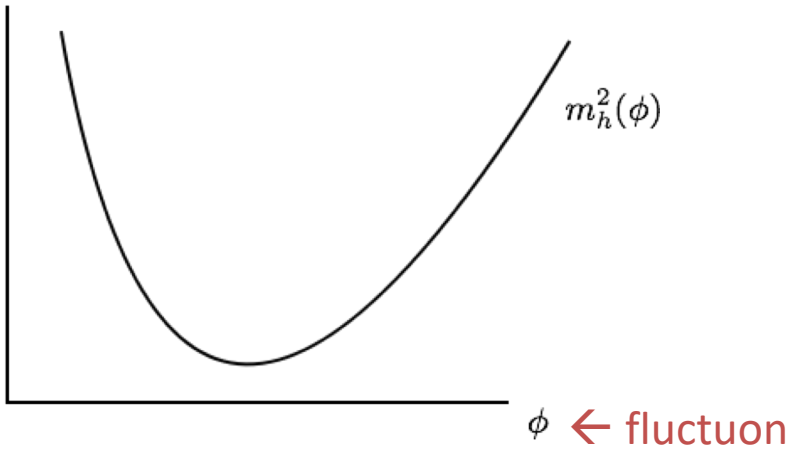


[Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner, "Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom", PRL 2016]

Basic Idea

The Higgs mass is at observed value
because such a patch inflates the most
in the early universe.

Basic Idea

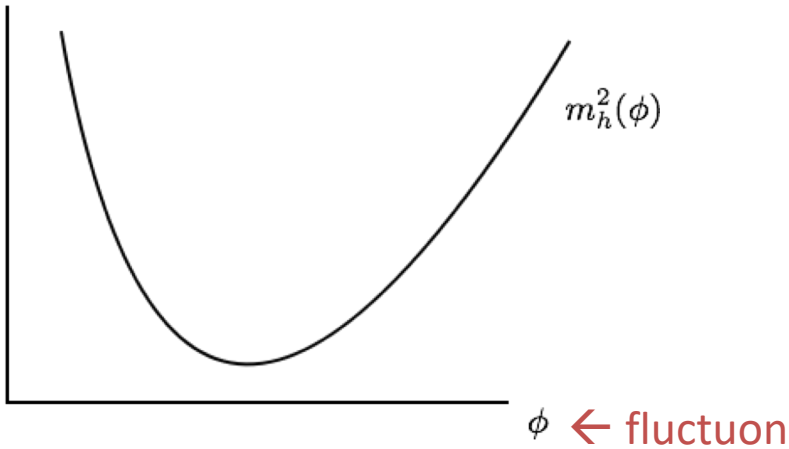


$$V \supset -m_h(\phi)^2|h|^2 + \lambda|h|^4$$

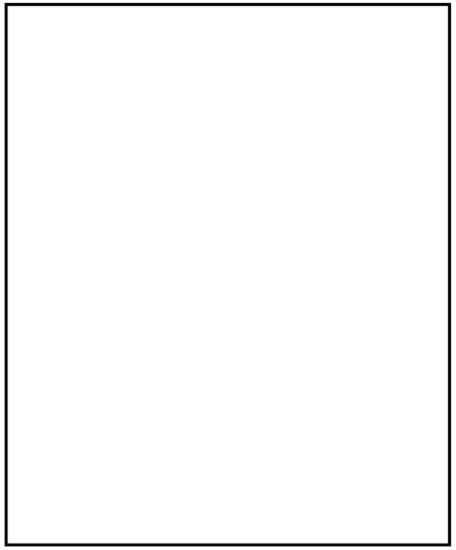
e.g. $m_h^2(\phi) = (M^2 - \phi^2)$

$M \gg$ weak scale

Basic Idea



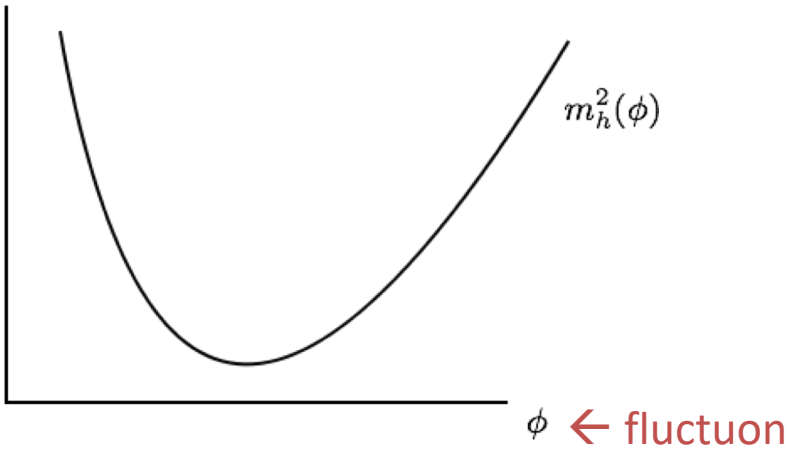
the universe



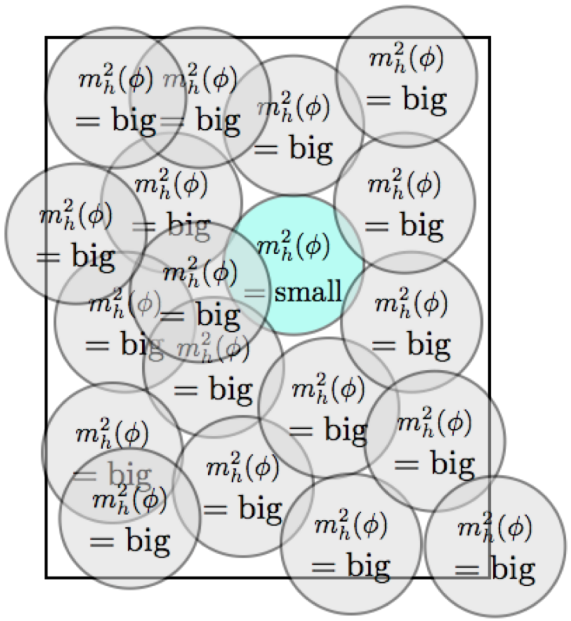
During inflation, ϕ has a very flat potential.

ϕ fluctuates →
spread in Higgs mass in the universe

Basic Idea



the universe



*universe not drawn to scale

During inflation, ϕ has a very flat potential.

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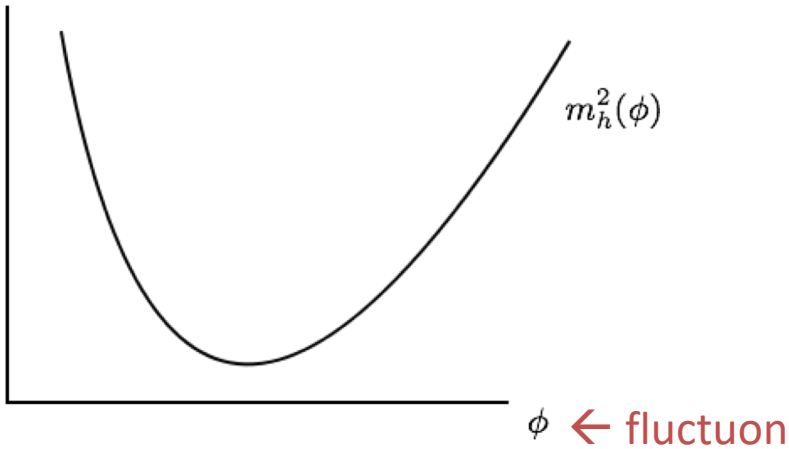
Basic Idea



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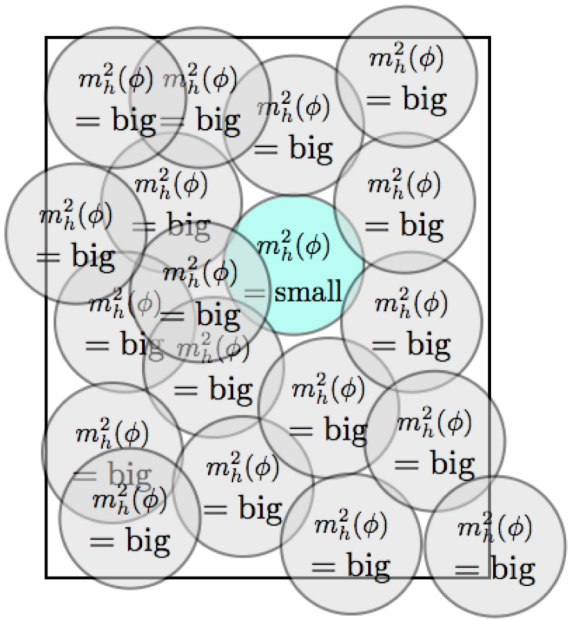
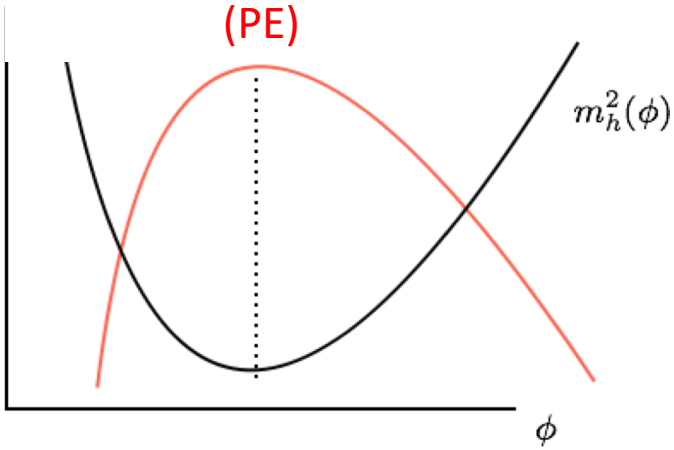


Why do we live in a seemingly unlikely patch of small Higgs mass?

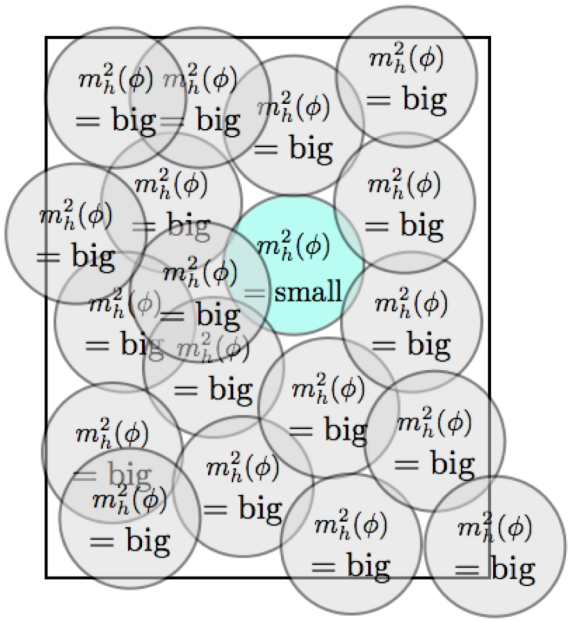
*universe not drawn to scale

Basic Idea

Potential Energy (PE)



the universe



*universe not drawn to scale

During inflation

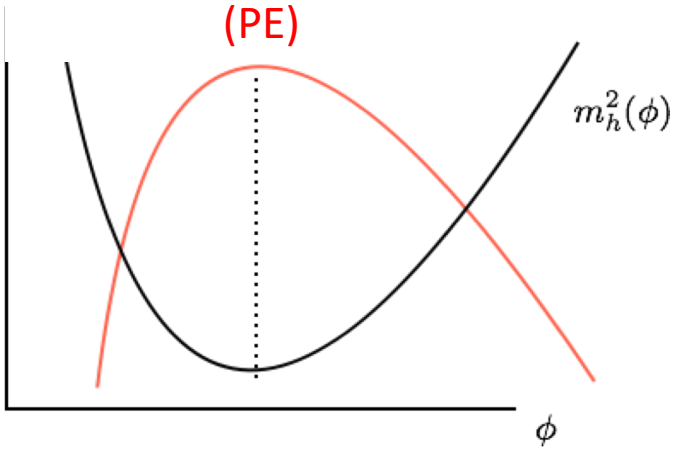
$$\text{Volume} \propto e^{\text{PE}(\phi)\times t}$$

If PE is max when m_h is small

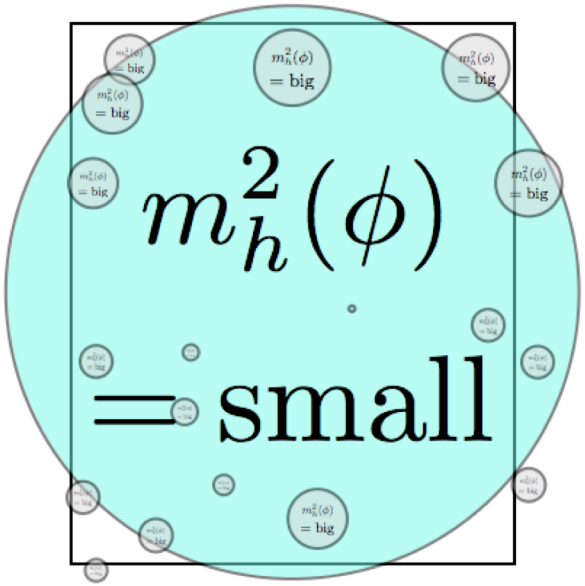
→ the universe will be filled with small m_h

Basic Idea

Potential Energy (PE)



the universe



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$$\text{Volume} \propto e^{\text{PE}(\phi)\times t}$$

*universe not drawn to scale

If PE is max when m_h is small
→ the universe will be filled with small m_h

Inflating to the weak scale

Toy Model

<u>Fields:</u> ϕ fluctuon (axion-like PNGB)

a axion

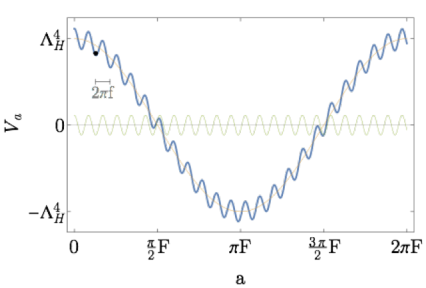
h Higgs

<u>Parameters:</u> M cutoff

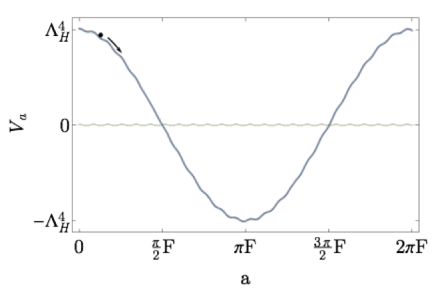
y spurion

$$V = M^3 y\phi + M^2 y^2 \phi^2 + \ldots$$
$$(M^2 + yM\phi + \ldots)h^2 + \lambda h^4$$
$$\frac{a}{f} G\tilde{G} + \Lambda_H^4 \cos\frac{a}{F}$$

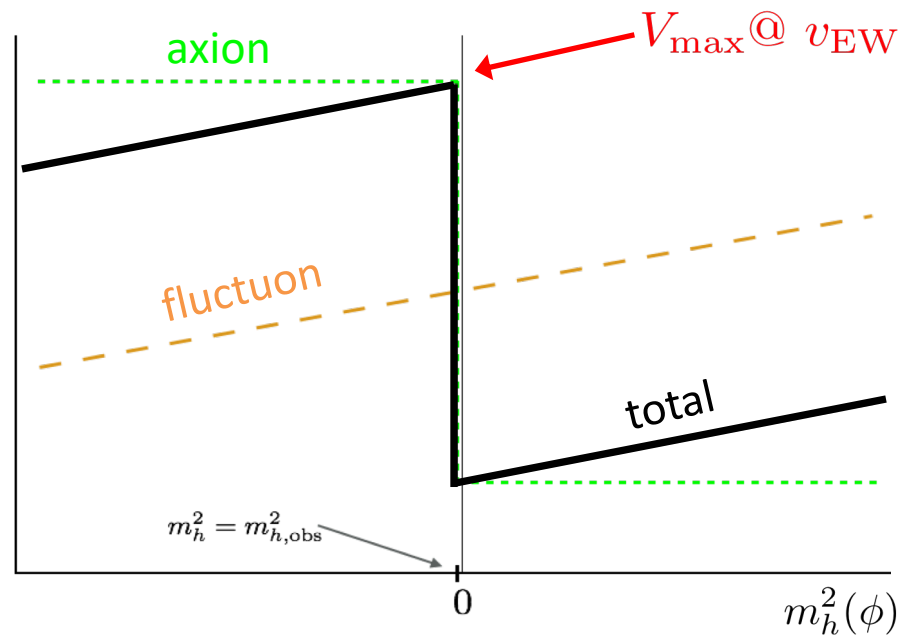
$v(\phi) \sim$ large



$v(\phi) \simeq v_{\rm EW}$



Full potential



Ideas still in Infancy

- Possible pheno':
  - Dark matter [e.g. Banerjee, Kim, Perez, 2018]
  - Higgs-mixing [e.g. Flacke, Frugiuele, Fuchs, Gupta, Perez, 2016]
  - Spatial and temporal changes in Higgs mass
  - ….
- Model building just at a start

[e.g. Gupta, Komargodski, Perez, 2015; Espinosa et al, 2015; McAllister et al, 2016; Hook, Marquese-Tavares, 2016; and many more…]

[e.g. Cheung, Saraswat, 2019]

Summary

- Experimental progress sourcing creativity in theoryland

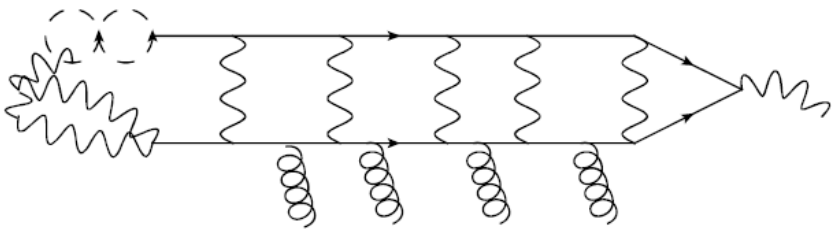
Innovative new ideas for the
driving puzzles of the field

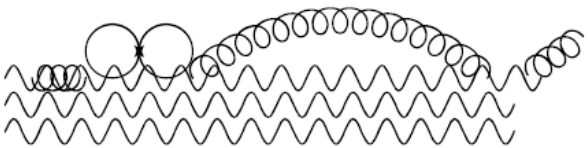
Naturalness & dark matter

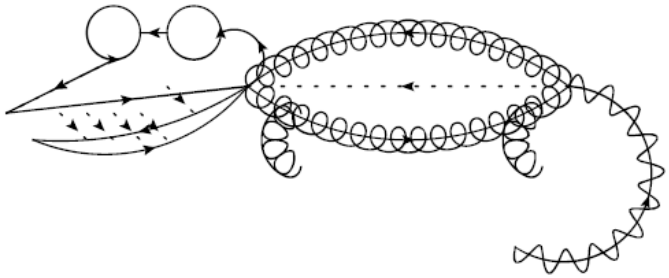
- Exciting time for particle physics

- Only just begun :-)

Thanks!







Backup

Requirements

- Inflaton drives inflation
- Axion moves fast and classically down the potential once barriers released
- Fluctuon fluctuates (up the potential)
- Most of the universe is filled with EW scale
- Things stay the same after inflation