ACCELERATING THE SEARCH FOR DARK MATTER WITH MACHINE LEARNING

INTRO TO THEORY MODELS FOR DARK MATTER

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DM Physicists

ML Experts

DM Physicists

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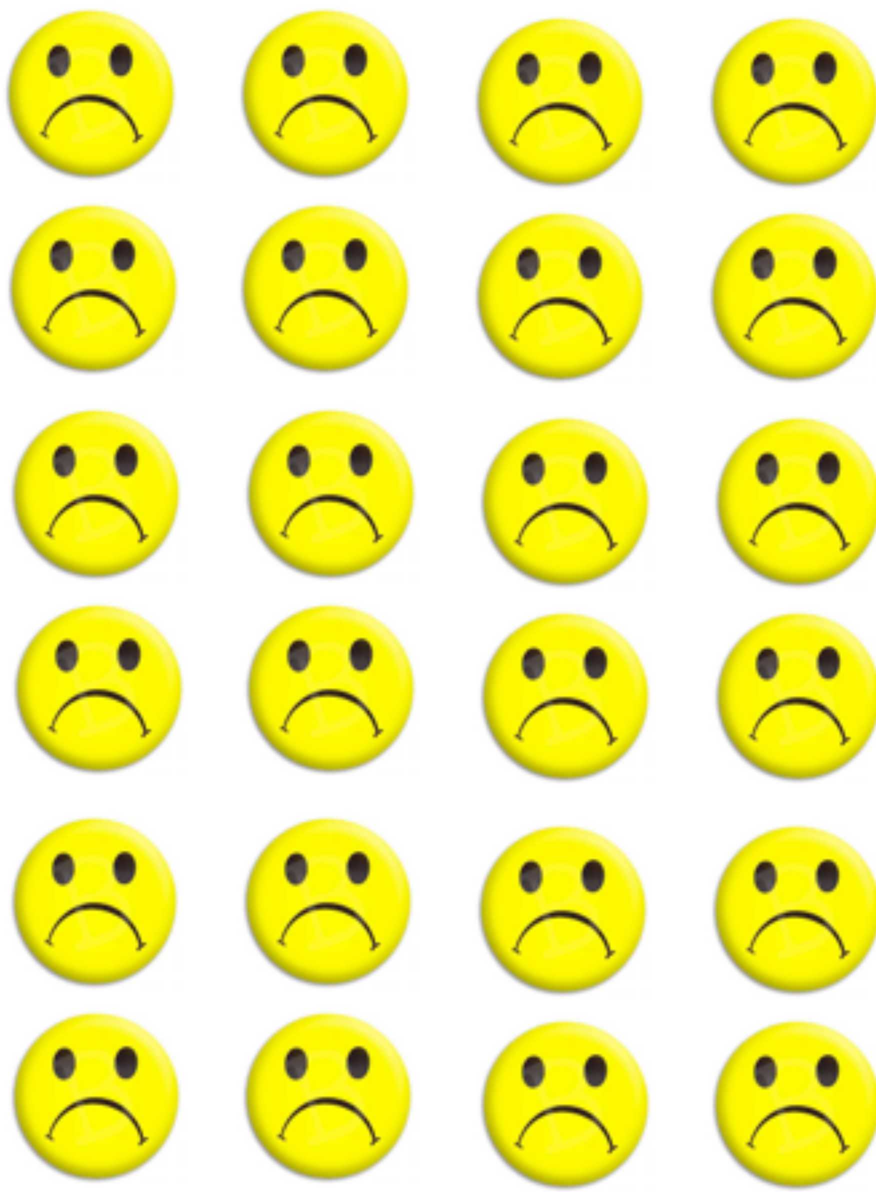
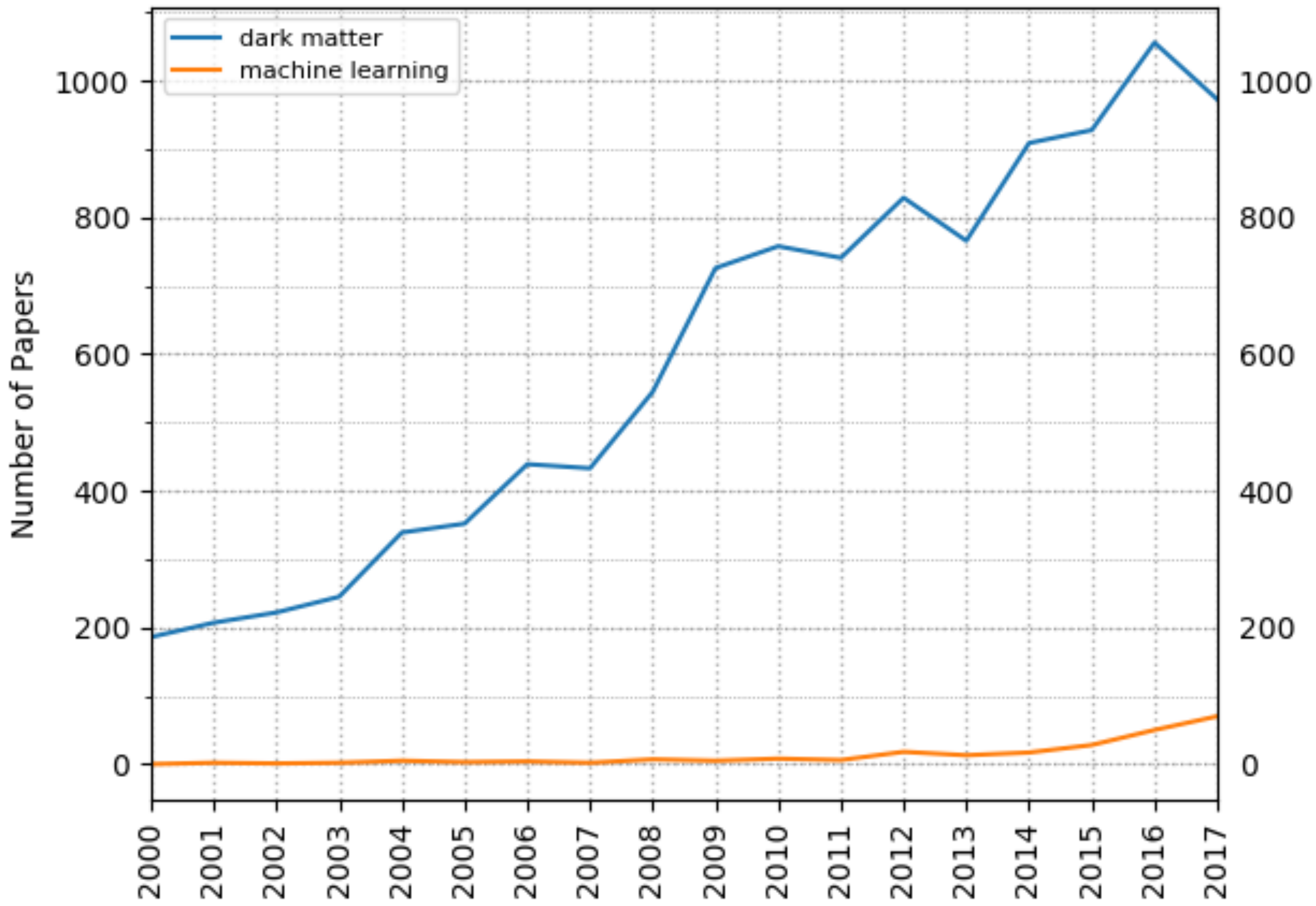
DM Physicists



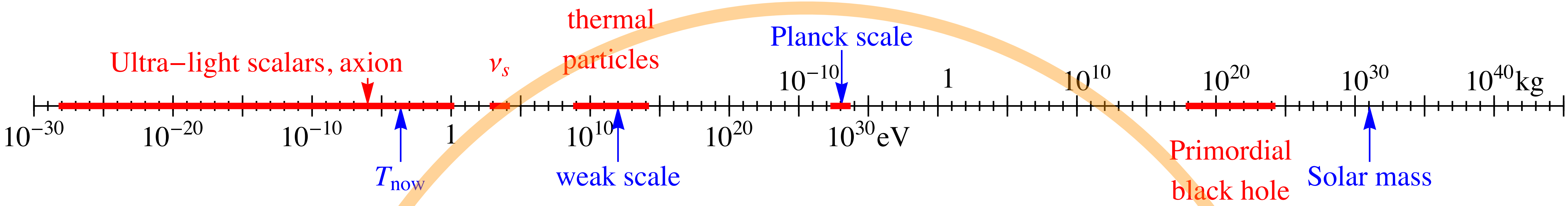
ML Experts

../ Research Trends



[source: InSpire]

../ Landscape of DM theories



[courtesy of A.Strumia]

Dark Matter
Models

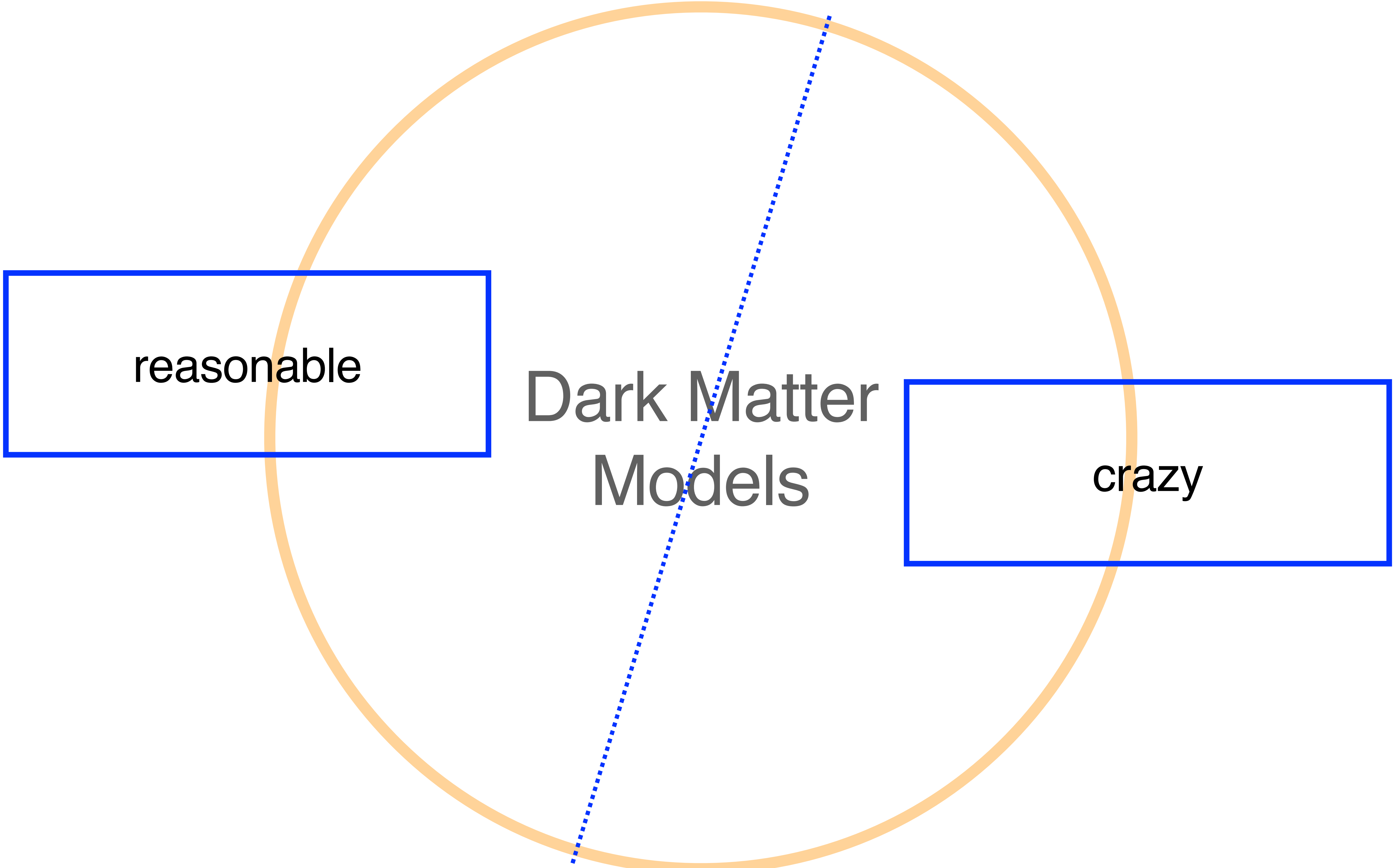
Wide landscape of DM models

DM masses spanning several orders of magnitude

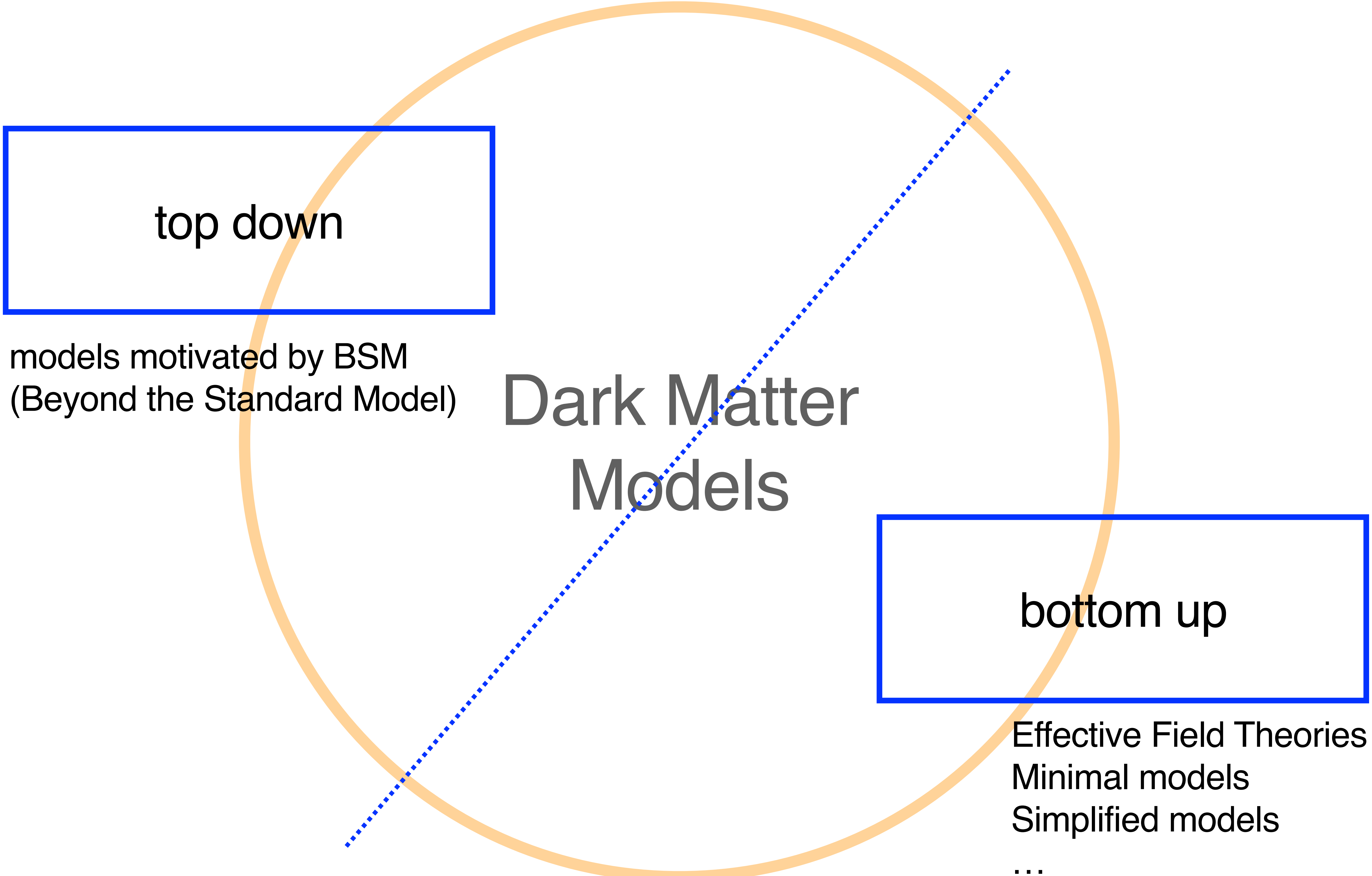
No preferred mass scale

we are not sure where to look for DM (unlike e.g. the Higgs)

../ Landscape of DM theories



../ Landscape of DM theories

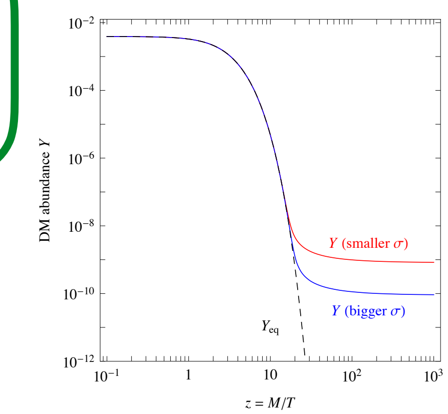


../ Landscape of DM theories

standard cosmology

thermal production

WIMP
(Weakly Interacting
Massive Particles)



Dark Matter
Models

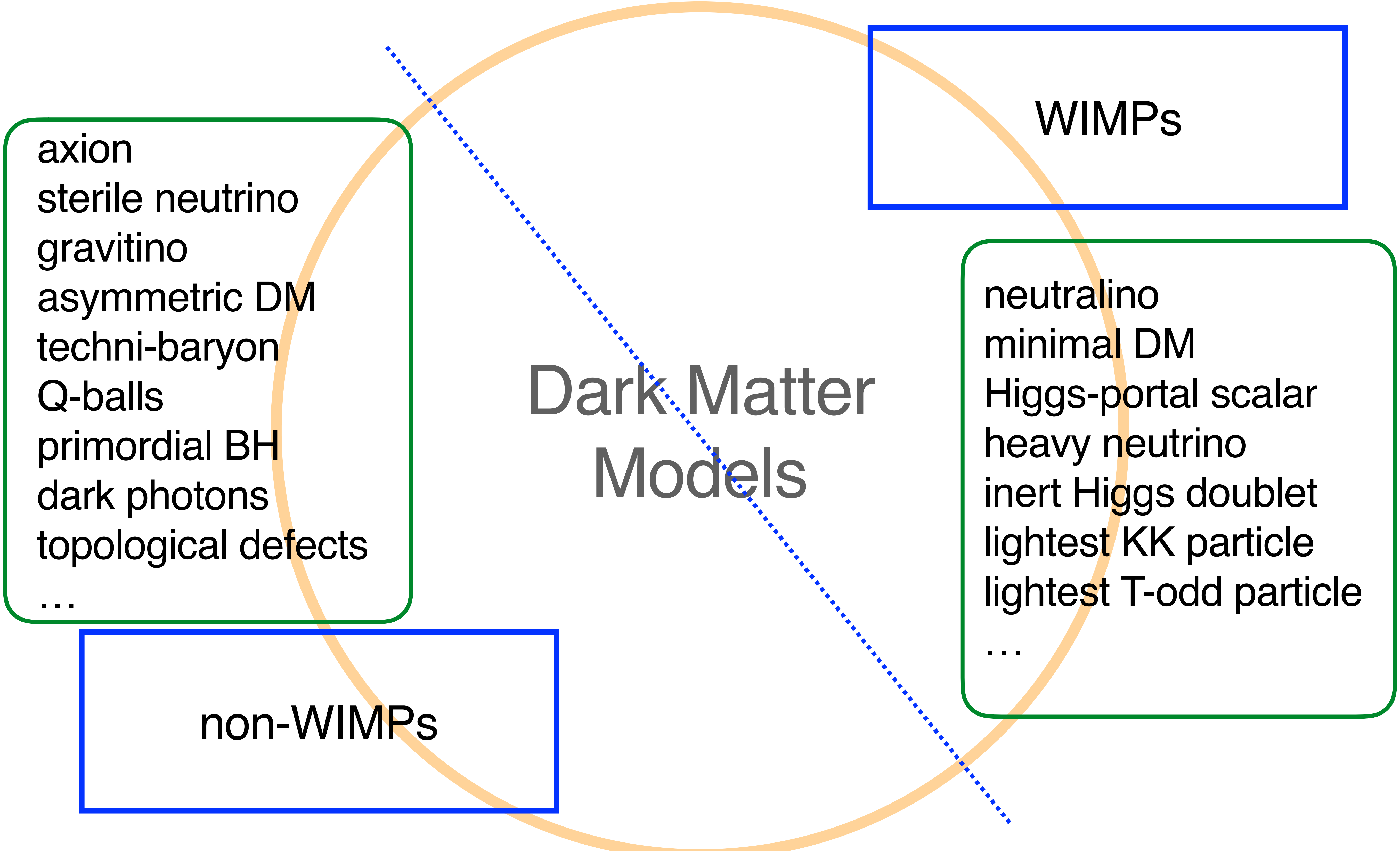
non-thermal production

out-of-eq. decay of heavier particles (gravitinos)
vacuum misalignment (axions)
oscillations (sterile nu)
gravitational mechanism (WIMPzillas)
…

non-standard
cosmology

low reheating T
modification of H

../ Landscape of DM theories



../ Outline

1. Full-fledged models:

- for WIMPs
  - SUSY
  - Composite Higgs
- for non-WIMPs
  - Axions
  - Sterile Neutrinos

disclaimer: personal picks

2. Simpler models (for WIMPs)

3. Machine learning mumbo jumbo

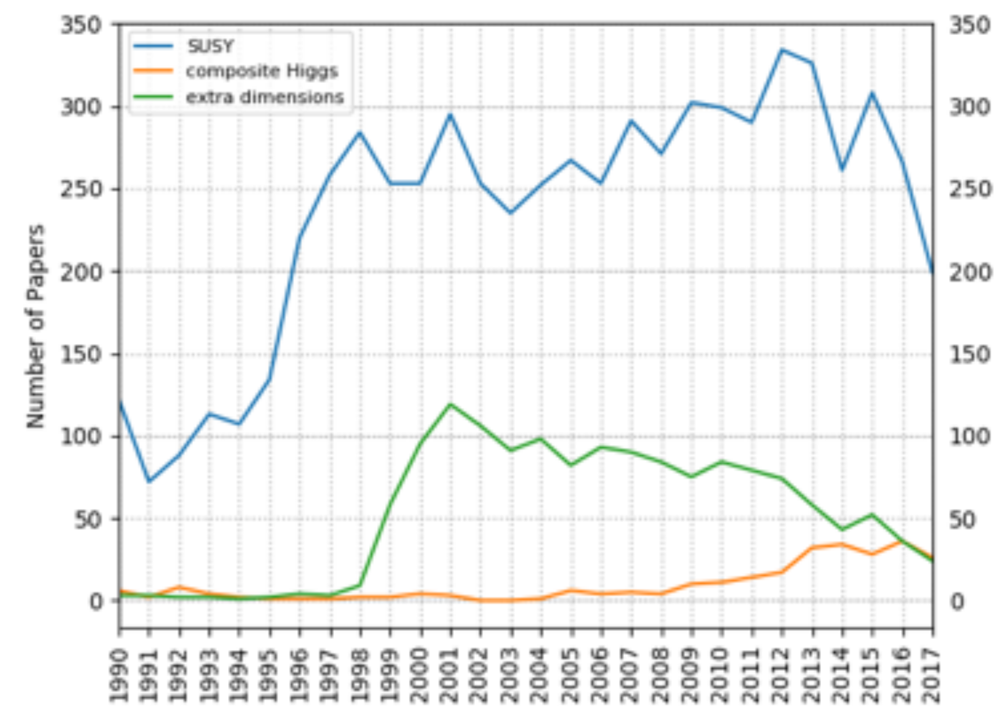
Ingredients for a WIMP recipe:

- massive particle in 1 GeV — 100 TeV range
- weak interactions with the SM
- thermal freeze-out in the early universe

Motivated by hierarchy problem

[Van Beekveld's talk]

Supersymmetry, composite Higgs, extra dimensions, …



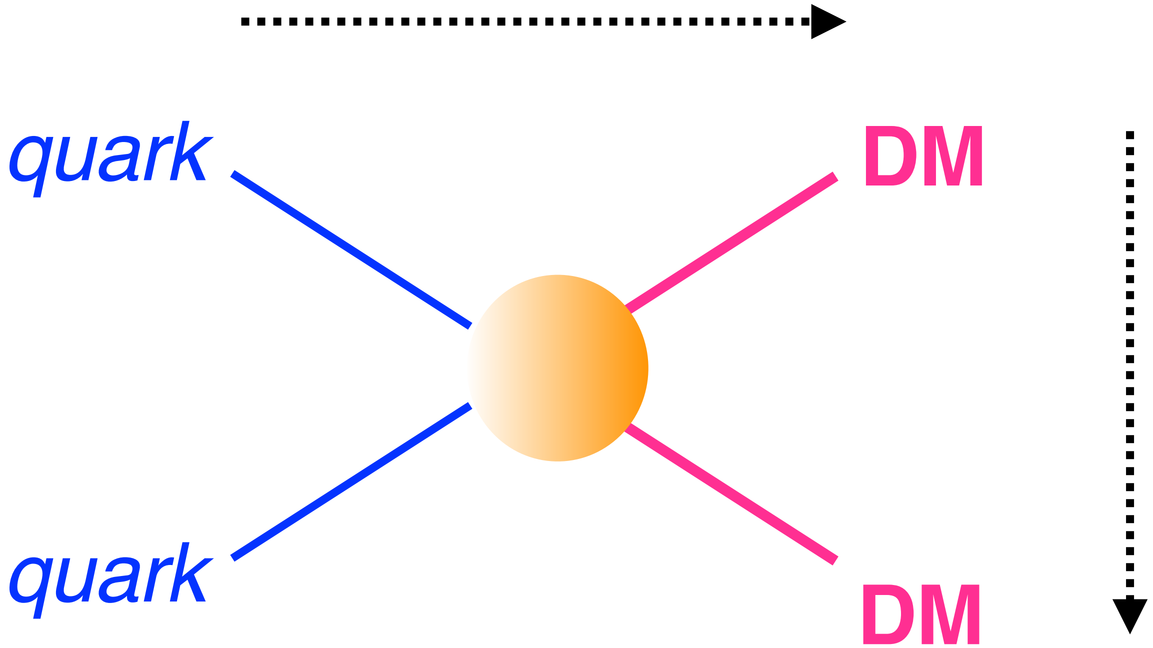
[source: InSpire]

Minimality rescued!

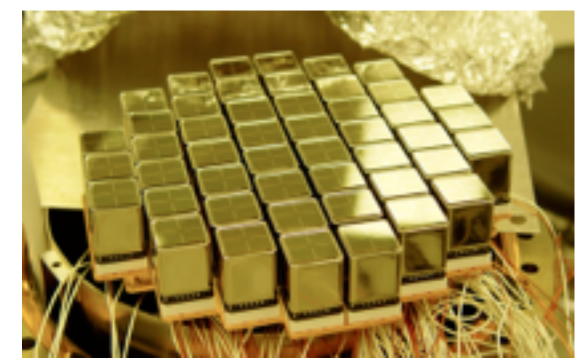
minimal DM, Higgs-portal scalar, inert doublet, simplified models, …

../ Searches for WIMPs

collider detection



direct
detection



indirect detection

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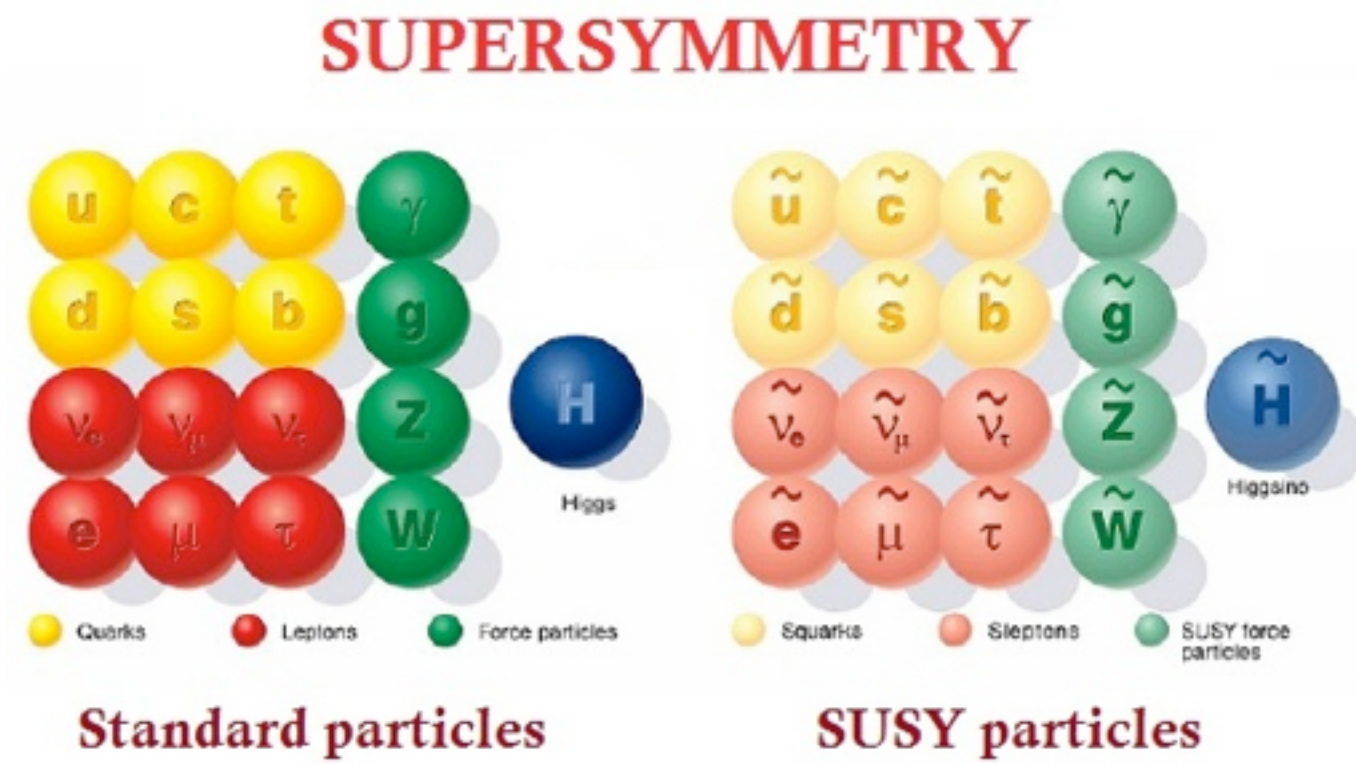
SUSY is beautiful

- ✓ (elegant)
- ✓ hierarchy problem
- ✓ gauge coupling unification
- ✓ EWSB mechanism
- ✓ DM candidate
- ✘ fine-tuning
- ✘ not found!



Which SUSY?

MSSM, NMSSM, cMSSM, pMSSM, flavourful SUSY, split SUSY, stealth SUSY, mSUGRA, natural SUSY, twisted SUSY, gauge mediation, gaugino mediation, gravity mediation, focus-point SUSY, leptogenic SUSY, clockwork SUSY, SUSY seesaw, SUSY GUT…

../ SuperSymmetry

MSSM: 124 parameters

matter fields

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
($\times 3$ families)	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	$(\overline{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
sleptons, leptons	L	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
($\times 3$ families)	$\bar{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ H_u^0)$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	H_d	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

gauge fields

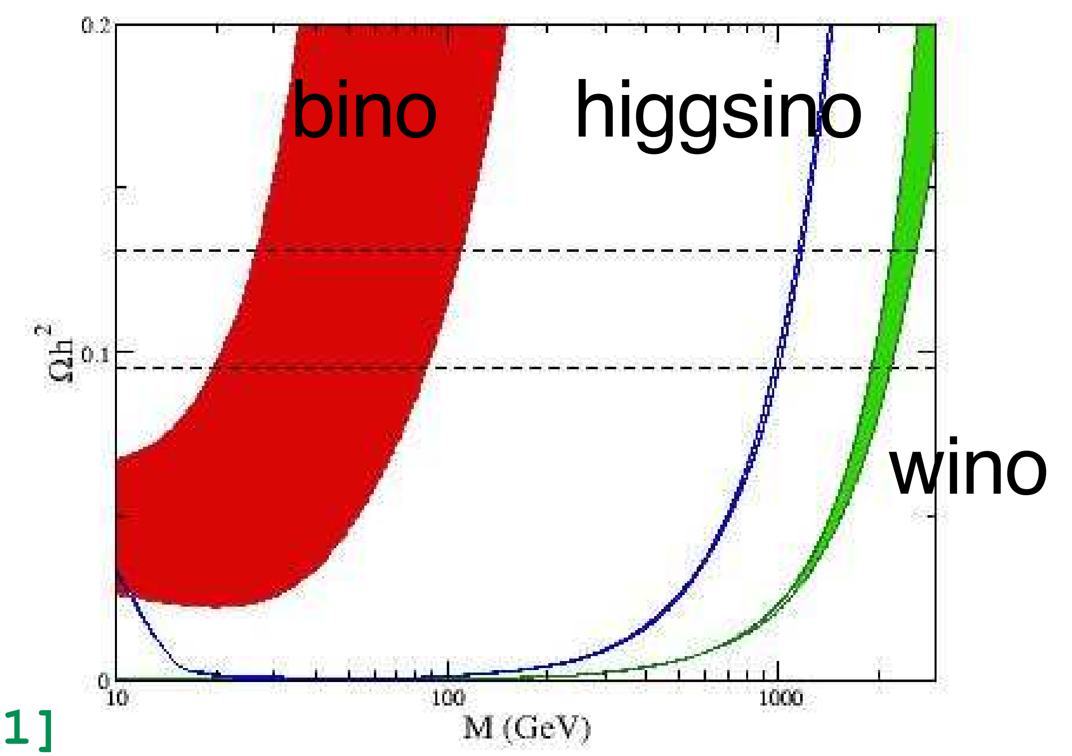
Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \widetilde{W}^0$	$W^\pm \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

R-parity $R = (-1)^{3(B-L)+2s}$

to avoid proton decay

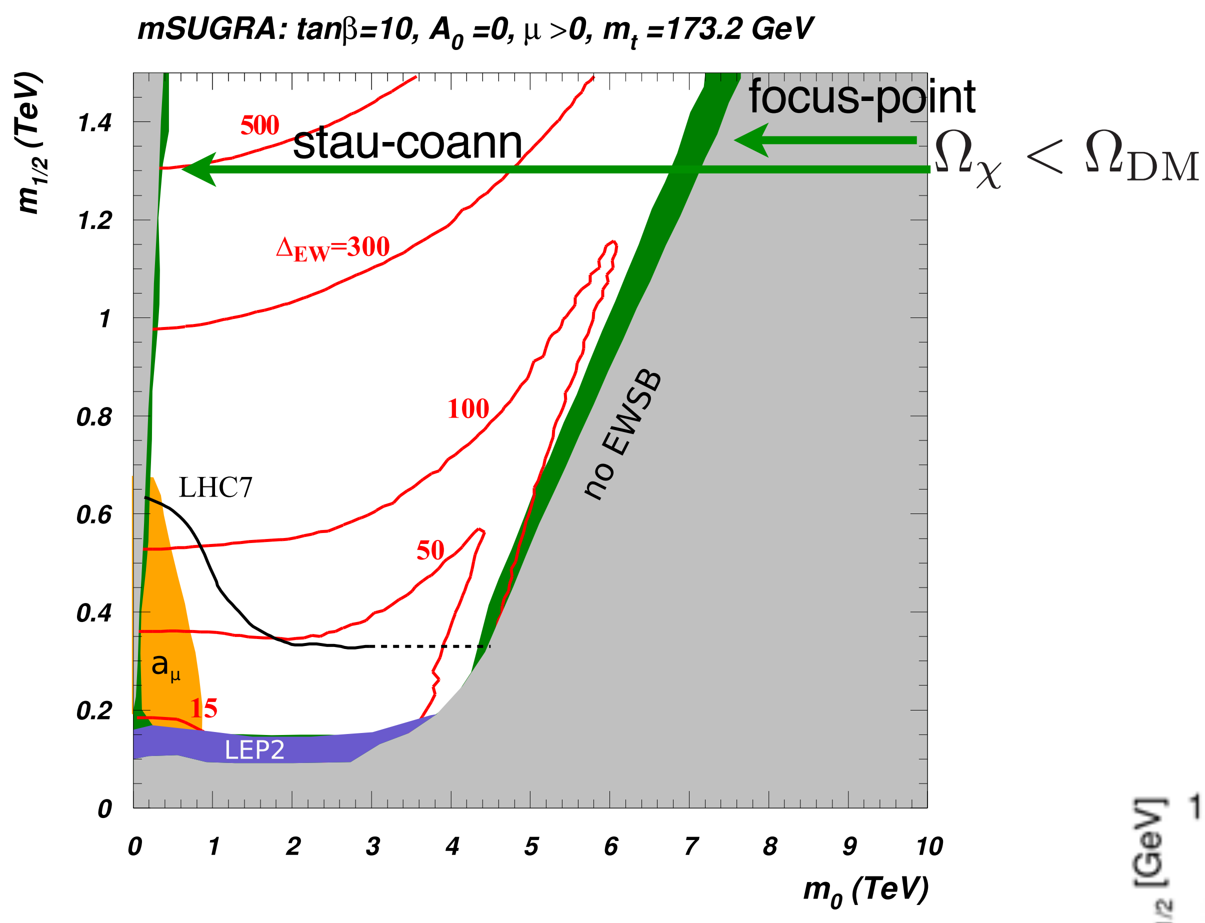
R-parity makes Lightest SUSY Particle (LSP) stable!

$$\chi_i^0 = N_{1i}\tilde{B} + N_{2i}\tilde{W}^3 + N_{3i}\tilde{H}_u^0 + N_{4i}\tilde{H}_d^0 \qquad (i = 1, \ldots, 4)$$



[hep-ph/0601041]

../ SuperSymmetry



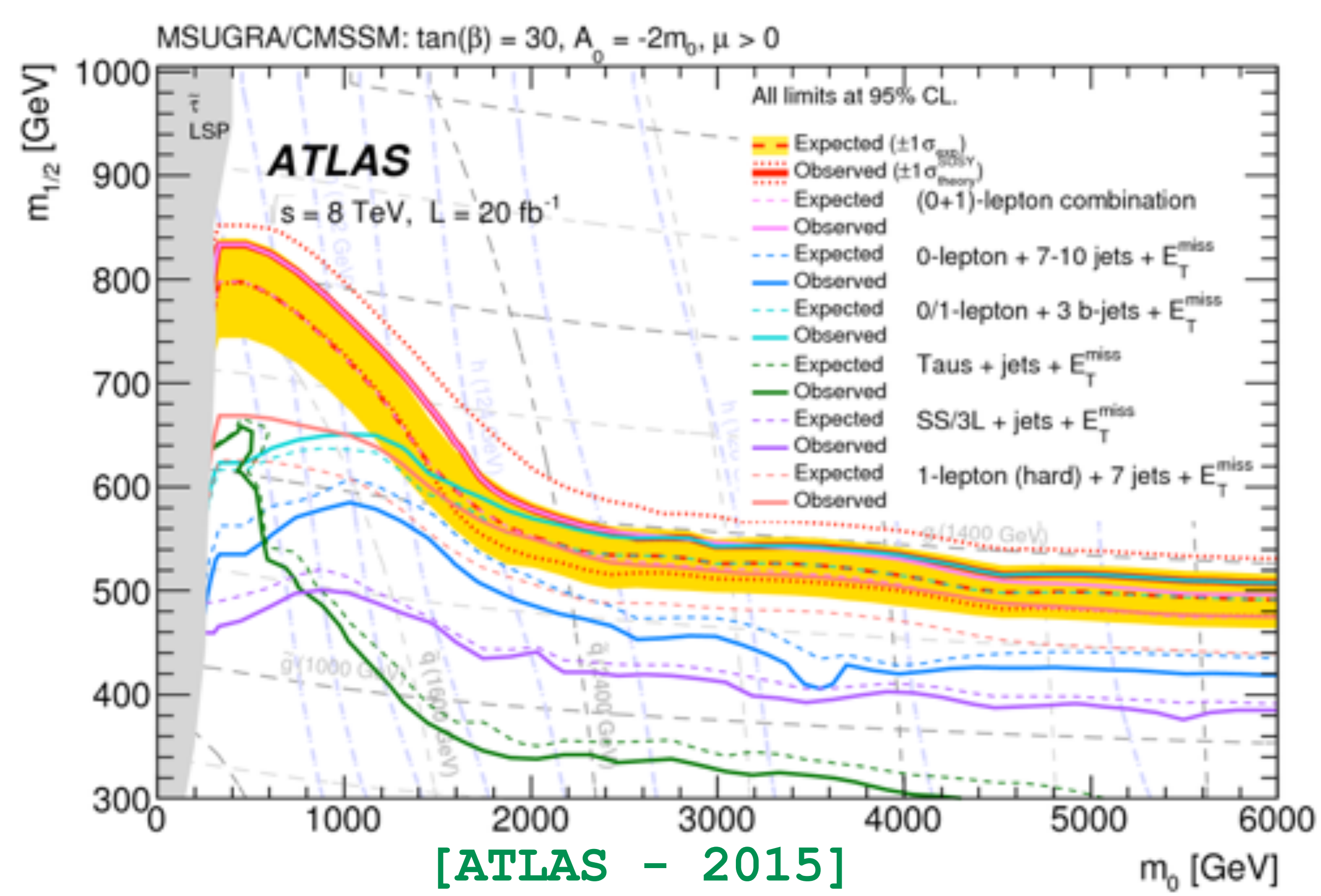
[Baer et al - 1210.3019]

mSUGRA

$$\{m_{H_u}^2, m_{H_d}^2, \mu, B, m_{1/2}, m_0, A\}$$

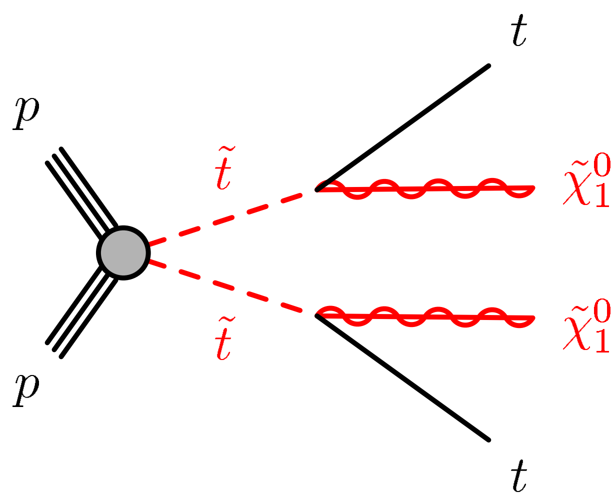
CMSSM

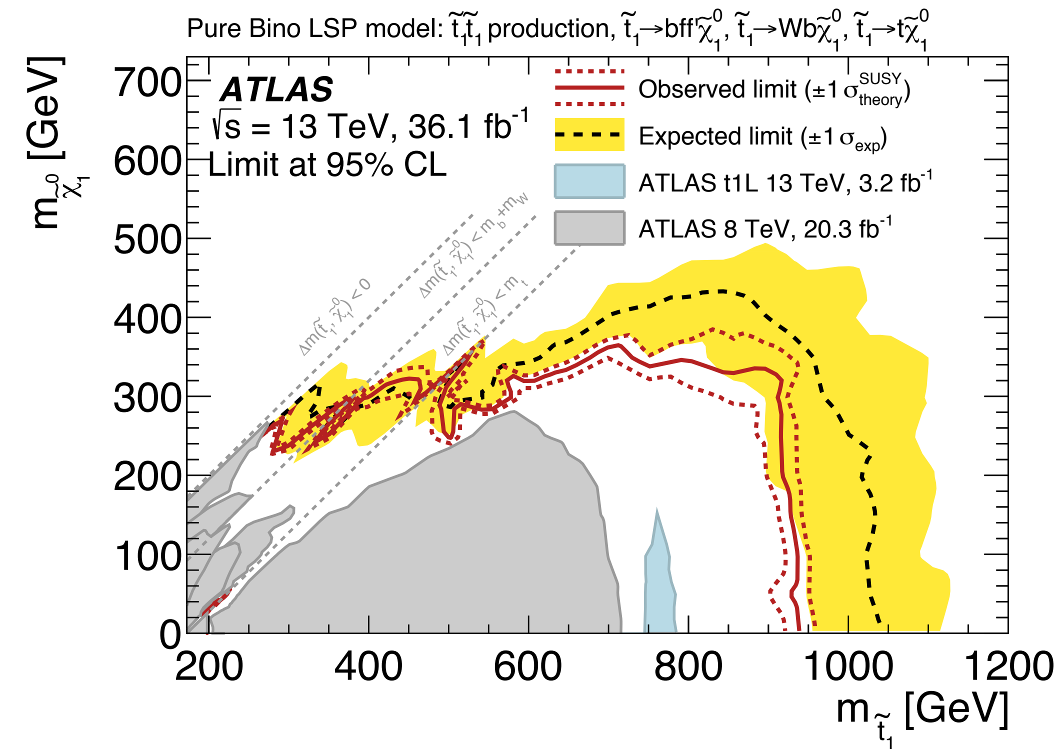
$$\{m_{1/2}^2, m_0^2, A, \tan\beta, \mathrm{sign}(\mu)\}$$



[ATLAS - 2015]

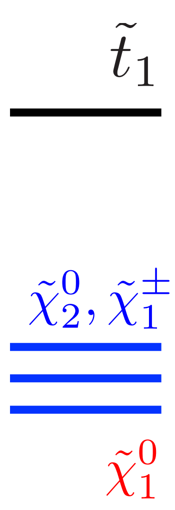
LSP-stop

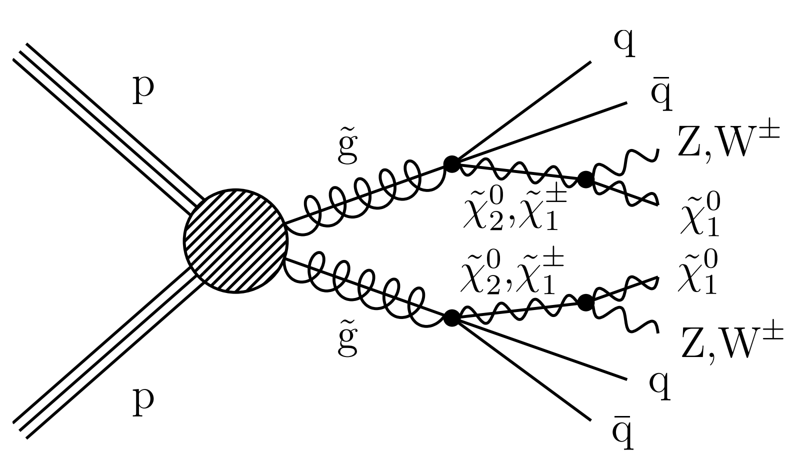


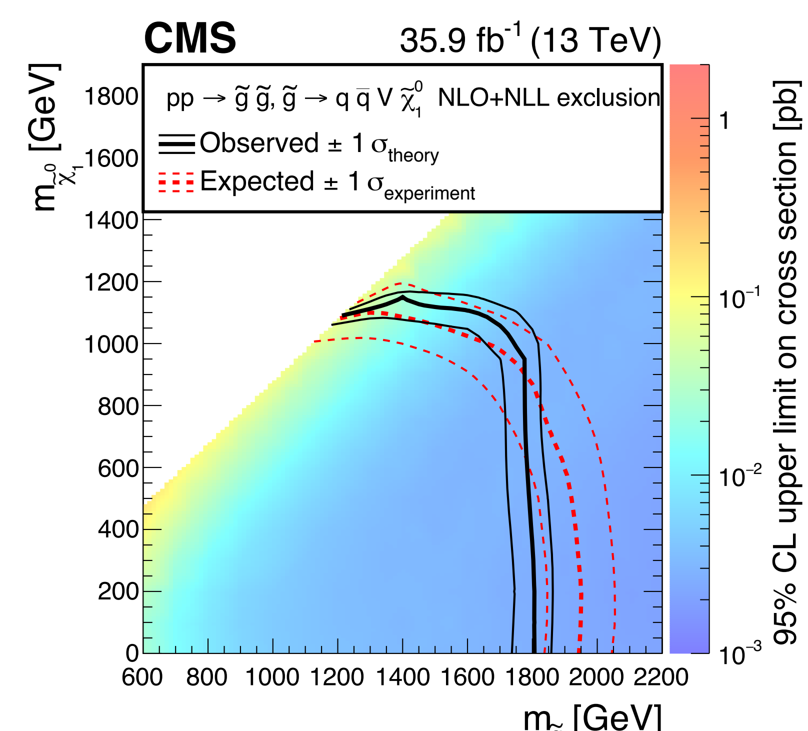


[ATLAS - 1711.11520]

LSP-chargino-gluino







[CMS - 1704.07781]

1. Full-fledged models:

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2. Simpler models (for WIMPs)

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Higgs as a pseudo-NG boson

[Kaplan, Georgi - 1984]
[Giudice, Grojean, Pomarol, Rattazzi - 2007]

- Strongly-coupled sector symmetric under the global sym G

- *G* spontaneously broken to *H* at a scale *f*
(cf. QCD chiral sym. breaking).

Elementary Sector

$SU(2)_L \times U(1)_Y$

- SM fermions
- gauge bosons

mixings

Composite Sector

G/H

- Higgs
- (top)
- top partners

$$\mathcal{L} = \mathcal{L}_{\rm elem} + \mathcal{L}_{\rm comp} + \mathcal{L}_{\rm mix}$$

Linear mixing
(*partial compositeness*)

$$\mathcal{L}_{\rm mix} \propto \Psi_{\rm elem} \cdot \mathcal{O}_{\rm comp}$$

breaks G explicitly → Higgs pNGB acquires potential

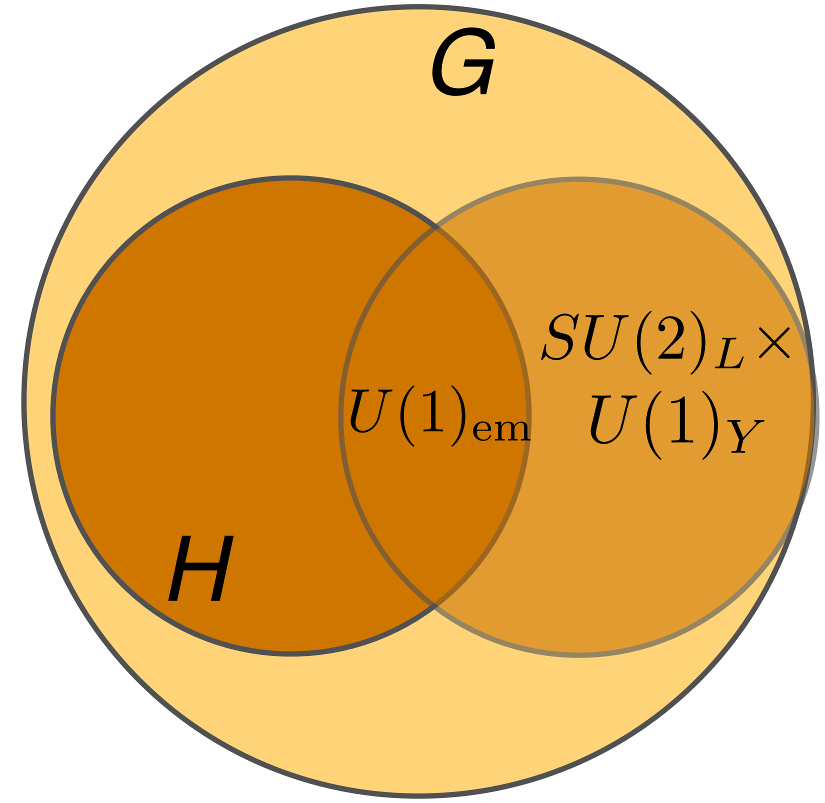
Hierarchy problem solved

Higgs mass UV-screened (cf. QCD pion)

../ Composite Higgs models

Require custodial symmetry

$$H \supset SO(4) \sim SU(2)_L \times SU(2)_R$$



Minimal choice: *G* = *SO(5)*, *H* = *SO(4)*
delivering 4 NG-bosons: h + 3 W,Z // pol.

minimal CH model

h+real scalar (DM)

h+complex scalar (DM)

2HDM

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2) \times \mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5} = (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4_{+2}} + \mathbf{\bar{4}_{-2}} = 2 \times (\mathbf{2}, \mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6} = 2 \times (\mathbf{1}, \mathbf{1}) + (\mathbf{2}, \mathbf{2})$
SO(7)	G_2	7	$\mathbf{7} = (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10_0} = (\mathbf{3}, \mathbf{1}) + (\mathbf{1}, \mathbf{3}) + (\mathbf{2}, \mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2}, \mathbf{2}, \mathbf{3}) = 3 \times (\mathbf{2}, \mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4}, \mathbf{2}) = 2 \times (\mathbf{2}, \mathbf{2}), (\mathbf{2}, \mathbf{2}) + 2 \times (\mathbf{2}, \mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4_{-5}} + \mathbf{\bar{4}_{+5}} = 2 \times (\mathbf{2}, \mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer - 1105.5403]

Sym. breaking pattern $SO(6) \to SO(5)$

[Frigerio, Pomarol, Riva, Urbano - 1204.2808]

[Marzocca, Urbano - 1404.7419]

- Add extra Z_2-parity to stabilize DM (effectively *O(6)/O(5)*).
- Almost excluded by direct detection

Sym. breaking pattern $SO(7) \to SO(6)$

[Balkin, Ruhdorfer, Salvioni, Weiler - 1707.07685]

DM charged under exact global $U(1)_{\rm DM} \subset SO(6)$ ensuring stabilization

$$\mathcal{L}_{\rm eff} = \underbrace{\mathcal{L}_{\rm GB} + \mathcal{L}_t}_{\rm tree} \underbrace{- V_{\rm eff}}_{\rm 1\text{-}loop}$$

$$\mathcal{L}_{\rm GB} = \frac{1}{2}(\partial_\mu h)^2\left(1 + 2\,a_{hhh}\frac{h}{v} + 2\,a_{hh\chi\chi}\frac{\chi^*\chi}{v^2}\right) + \partial_\mu\chi\partial^\mu\chi^* + \frac{1}{v}\partial_\mu h\,\partial^\mu(\chi^*\chi)\left(b_{h\chi\chi} + b_{hh\chi\chi}\frac{h}{v}\right)$$
$$+ 2\,a_{hVV}\frac{h}{v}\left(m_W^2 W_\mu^+ W^{-\mu} + \frac{m_Z^2}{2}Z_\mu Z^\mu\right).$$

$$\mathcal{L}_t = i\bar{t}\partial\!\!\!/ t - m_t\bar{t}t\left(1 + c_{tth}\frac{h}{v} + 2\,c_{tt\chi\chi}\frac{\chi^*\chi}{v^2}\right)$$

coefficients functions of top-partner masses

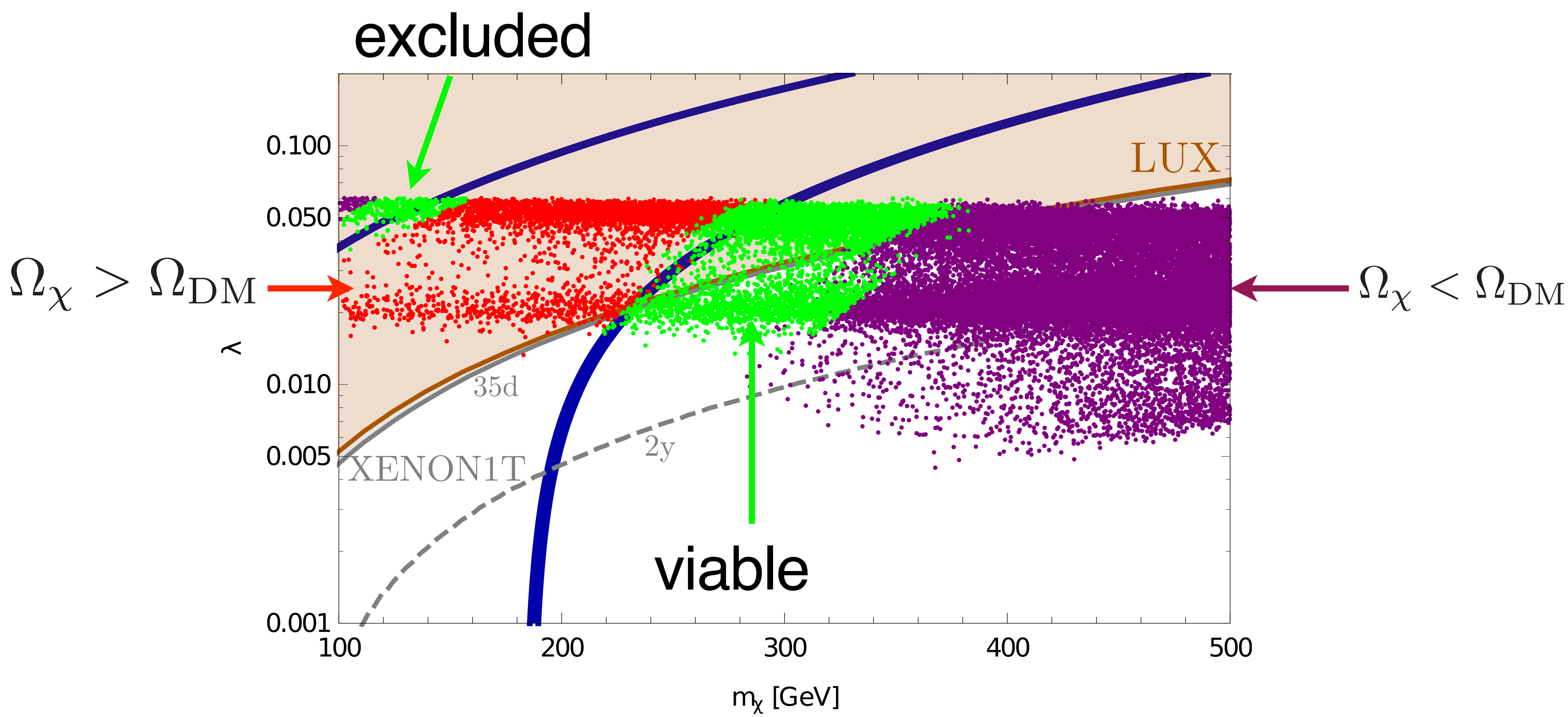
$$V_{\rm eff} = \frac{1}{2}m_h^2 h^2 + d_{hhh}\frac{m_h^2}{2v}h^3 + m_\chi^2\chi^*\chi + 2\,d_{h\chi\chi}v\lambda h\chi^*\chi + d_{hh\chi\chi}\lambda h^2\chi^*\chi$$

coefficients functions of $\xi \equiv \frac{v}{f}$

../ Composite Higgs models

Parameter set: $\{f, m_\chi, \lambda\}$ + top-partner masses

f = 1.4 TeV



[Balkin, Ruhdorfer, Salvioni, Weiler - 1707.07685]

Viable window to be closed by direct detection

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Most general QCD lagrangian

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \overline{q}\,(i\gamma_\mu D^\mu - \mathcal{M}_q)\,q - \frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

Topological term $G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$ violates P and T, thus CP

Observable effect: neutron EDM: $d_n \sim \frac{\theta}{(4\pi)^2} e \frac{m_\pi}{m_N^2} \sim 10^{-16}\theta\, e\cdot {\rm cm}$

$$|d_n| \lesssim 10^{-26} e\ {\rm cm} \longrightarrow \theta \lesssim 10^{-10}.$$

"strong-CP problem"

Axion solution of strong-CP problem

A global U(1)$_{PQ}$ symmetry is broken spontaneously and by anomaly

The **axion** is the pseudo-NG boson of this symmetry

Triangle anomaly: $\mathcal{L} \supset \left(\theta + \frac{a(x)}{f_a}\right) \frac{g_s^2}{32\pi^2} G\tilde{G}$ [f_a ~ PQ-breaking vev]

The CP-violating term relaxes dynamically to zero.

Axion Properties

Mass: $m_a \simeq 6 \times 10^{-6}\ \text{eV} \left(\frac{10^{12}\ \text{GeV}}{f_a}\right)$ f_a : free parameter

Effective Couplings to SM:

to photons: $\mathcal{L} \supset -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} = g_{a\gamma\gamma}\, a\, \vec{E} \cdot \vec{B}$

from PQ anomaly

to fermions: $\mathcal{L} \supset \frac{C_{aff}}{f_a} (\partial_\mu a) \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f$

largely model-dependent

“invisible axion” models:

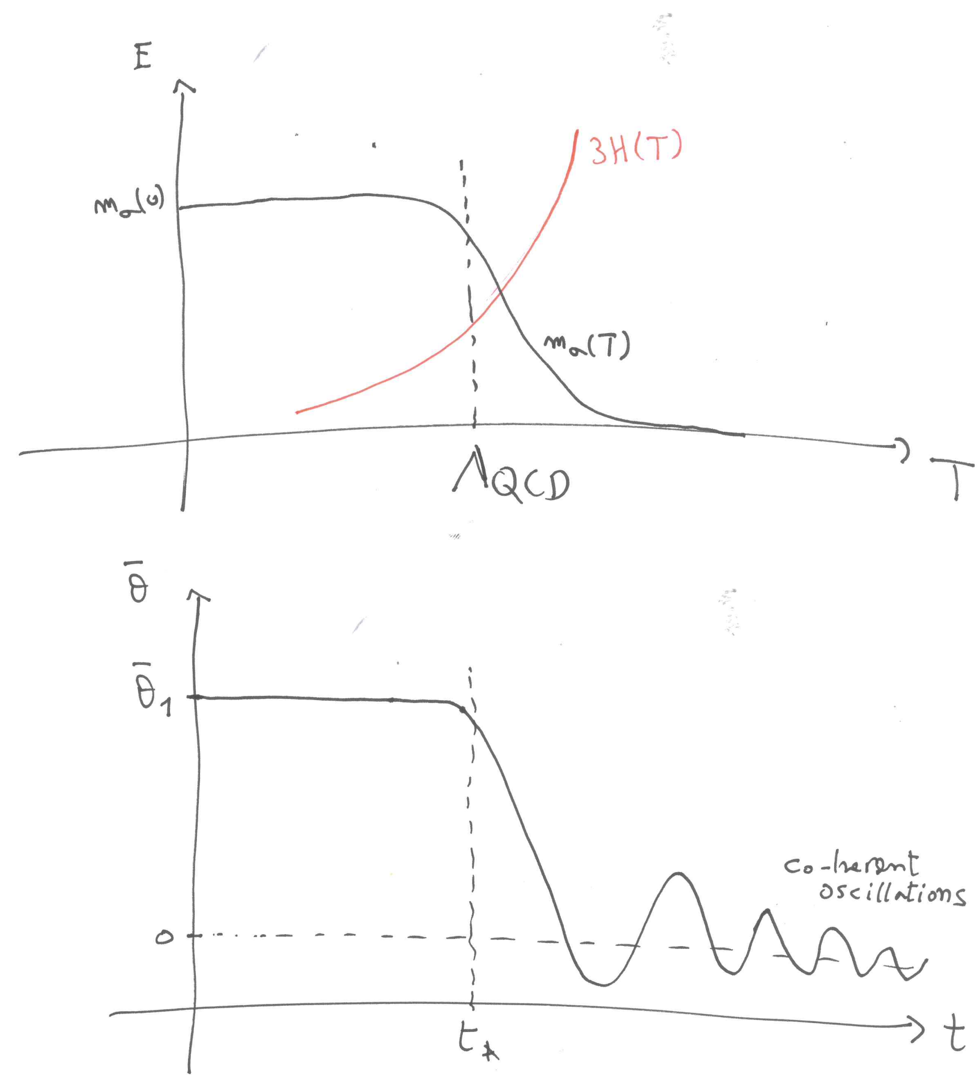
KSVZ: axion + heavy quarks [Kim, Shifman, Vainshtein, Zakharov - 1979/80]

DFSZ: axion + extra Higgs [Dine, Fischler, Srednicki, Zhitnitsky - 1980/81]

Axions as cold DM

Solve EOM

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0$$

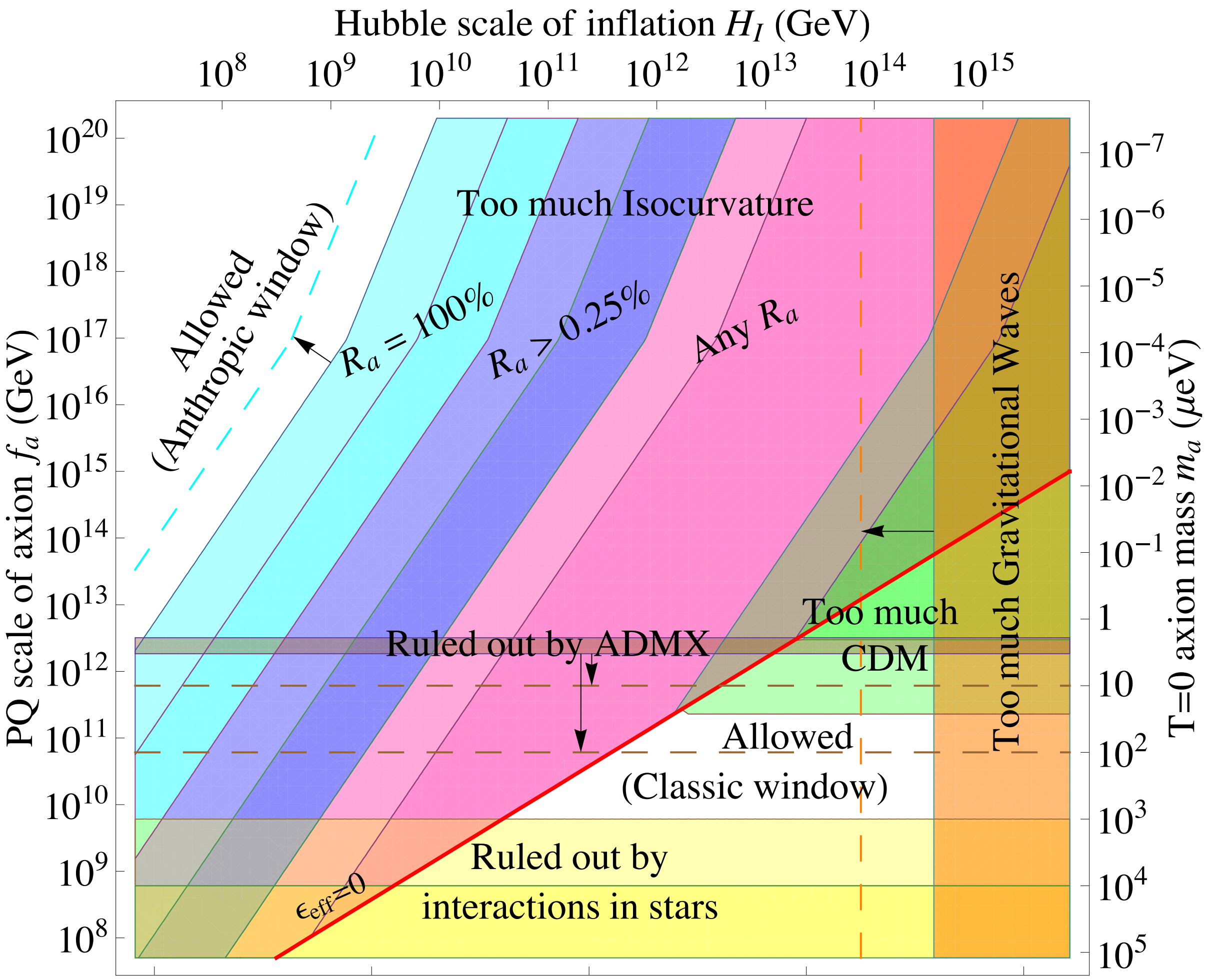


Axions redshift as NR (cold) matter

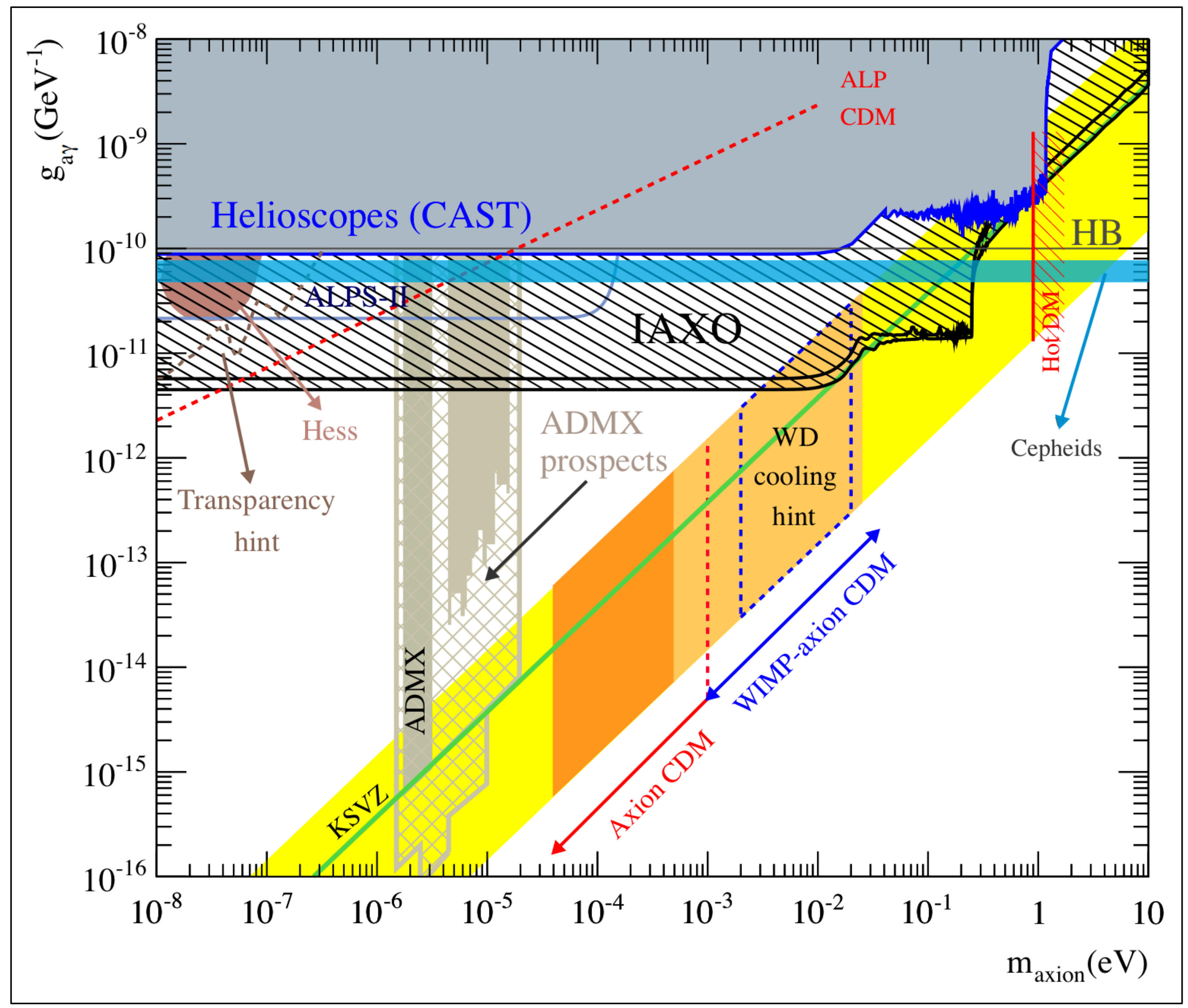
$$\rho_a(T) \propto \frac{m(T)}{a(T)^3}$$

Relic density $\quad \Omega_a \simeq 0.7 \left(\frac{f_a}{10^{12}\ \text{GeV}} \right)^{7/6} \bar{\theta}^2$

../ Axions



[Hertzberg, Tegmark, Wilczek, 0807.1726]



[ADMX 2016]

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../ Sterile Neutrinos

Motivation

[Asaka, Blanchet, Shaposhnikov, hep-ph/0503065]
[Boyarski, Ruchayskiy, Shaposhnikov - [0901.0011]

Origin of neutrino masses/mixings

The Model

SM + 3 Majorana fermions N_I

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_I \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I H - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

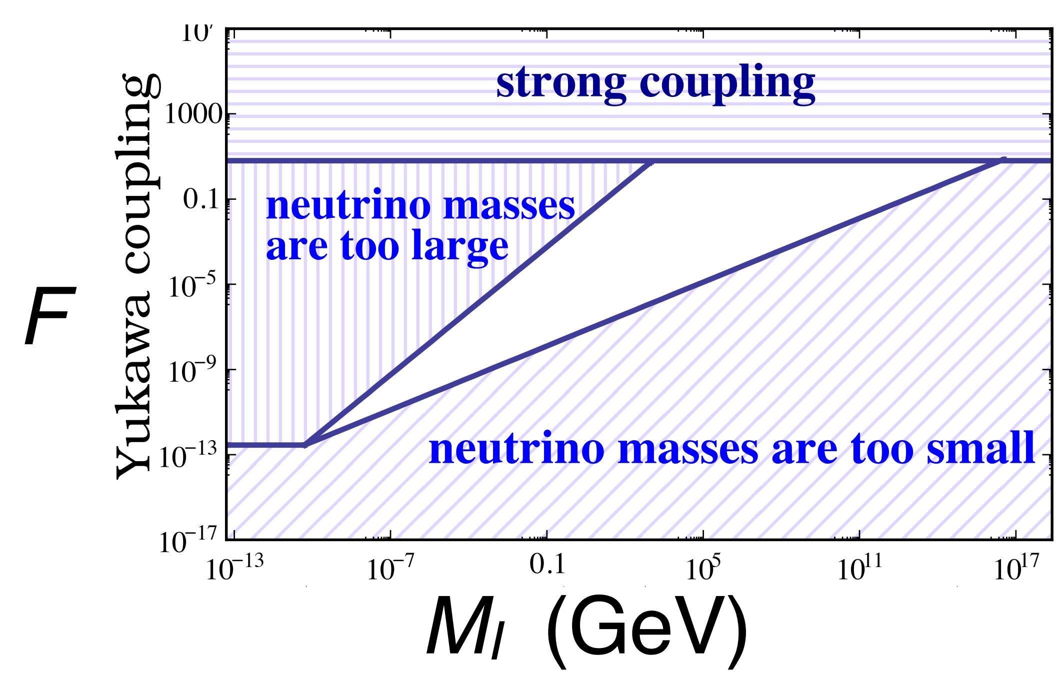
active-sterile mixing angle $\theta_{\alpha 1} = F_{\alpha 1} v / M_1$

$$|\nu_\alpha\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle,$$
$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle,$$

Dirac neutrino mass $m_{\rm Dirac} = Fv$

See-Saw

$$m_\nu \sim \frac{m_{\rm Dirac}^2}{M_I} \longrightarrow F \sim \left(\frac{M_I m_\nu}{v^2}\right)^{1/2}$$



Bonuses: Baryon Asymmetry + Dark Matter

- N_2, N_3 are heavy (> 10^2 GeV) to generate
  - > **Neutrino Masses** (see-saw)
  - > **Baryon Asymmetry** (leptogenesis)

- Sterile N_1 is light (~ keV) to make **Dark Matter**

DM Production

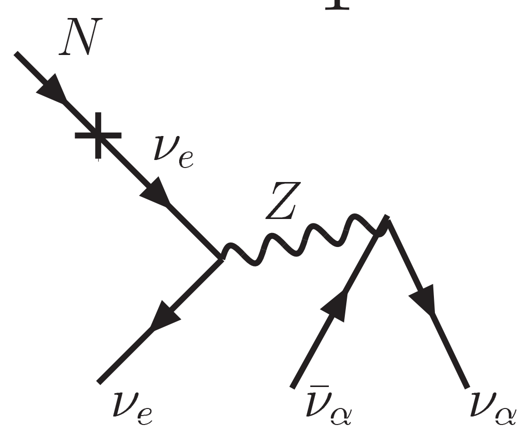
- thermal production via mixing
  (never in thermal eq., “freeze-in”)

- non-thermal production via decay of heavy particles
  (inflaton, scalar singlet…)

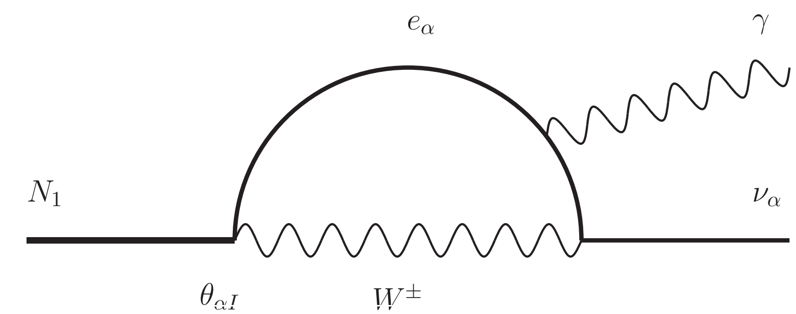
../ Sterile Neutrinos

Decays

tree-level $N_1 \to 3\nu$



radiative $N_1 \to \nu\gamma$

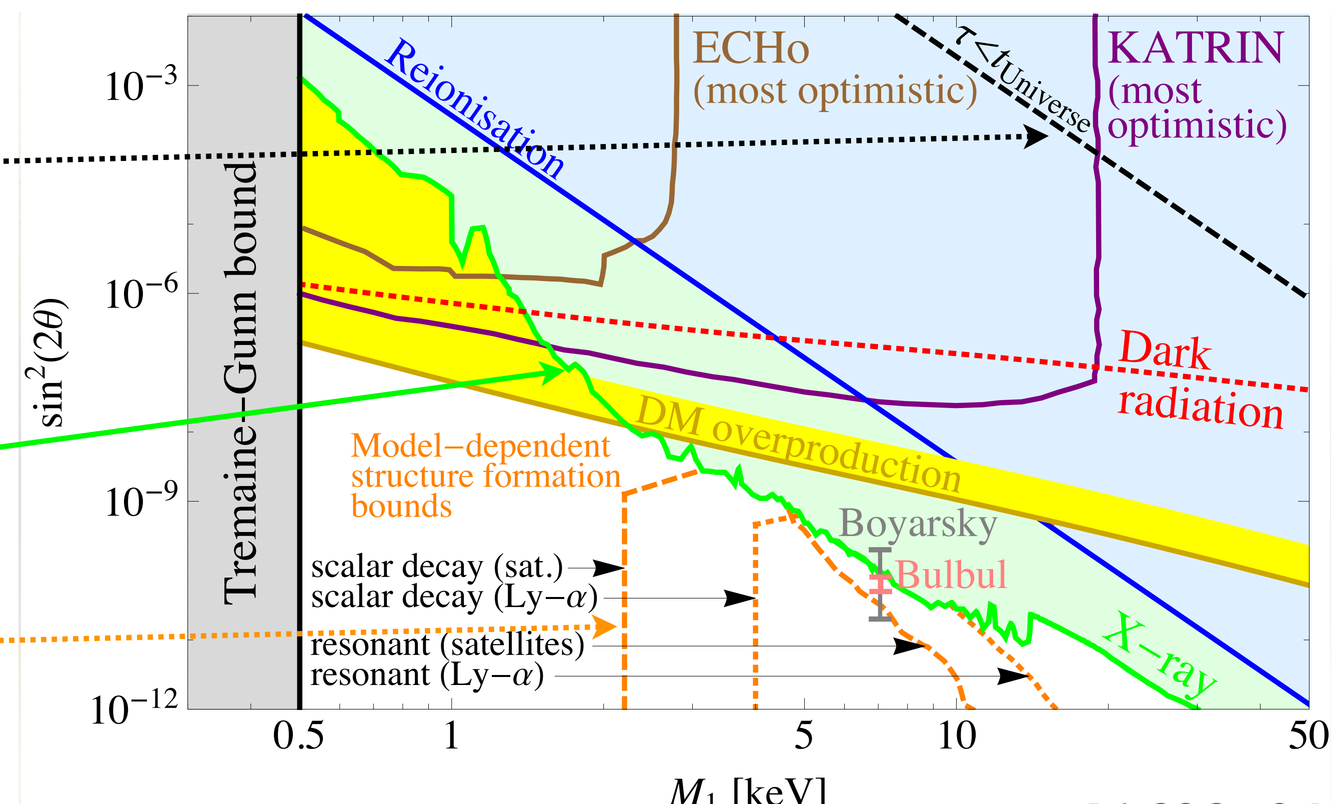


mixing small enough for stable DM

$$\left(\frac{M_1}{10\text{keV}}\right)^5 \left(\frac{\theta_1^2}{10^{-4}}\right) \lesssim 1$$

stronger limits from X-ray

and Lyman-alpha



[1602.04816]

other constraints on nuMSM from: KATRIN, T2HK, SHiP, …

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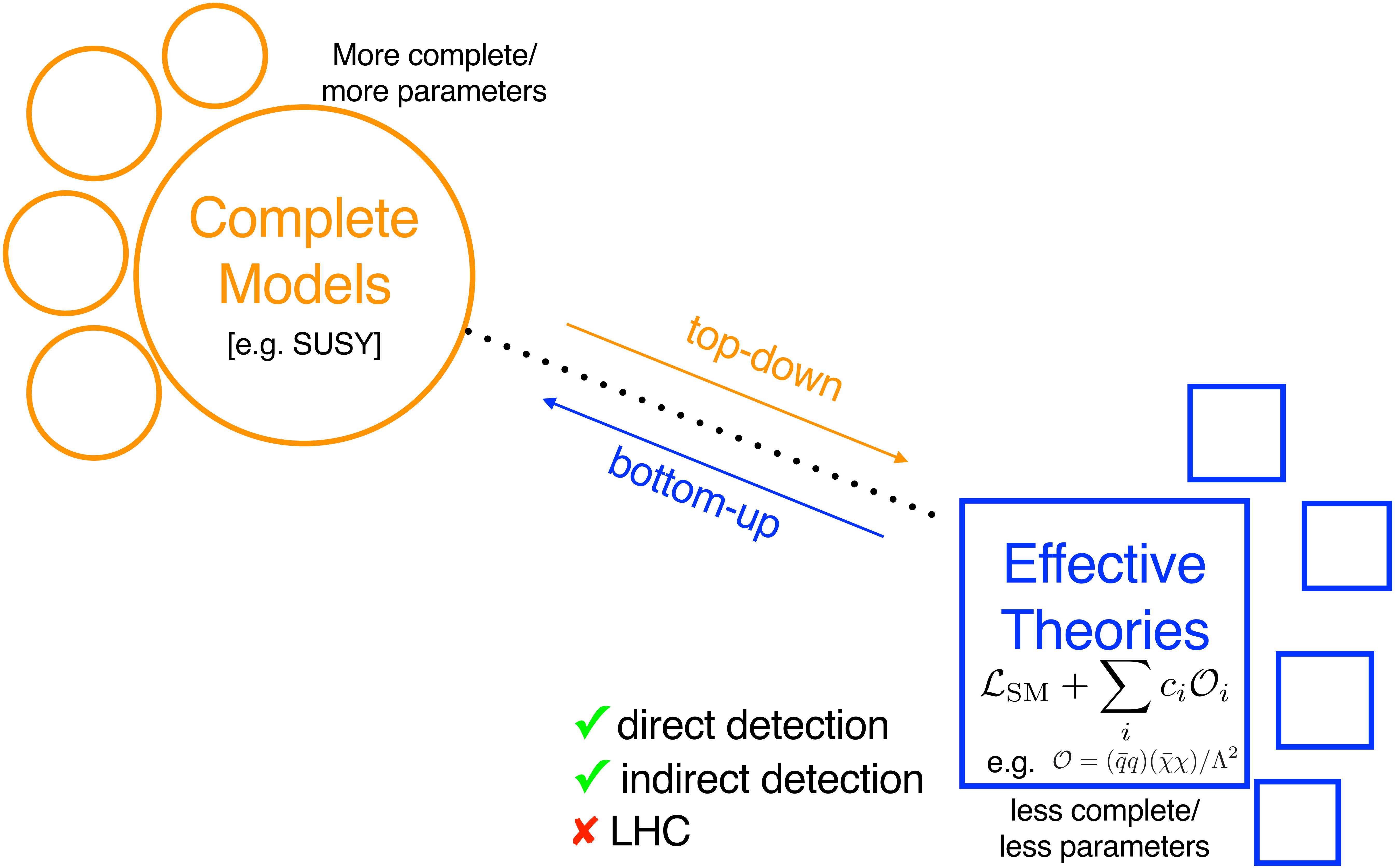
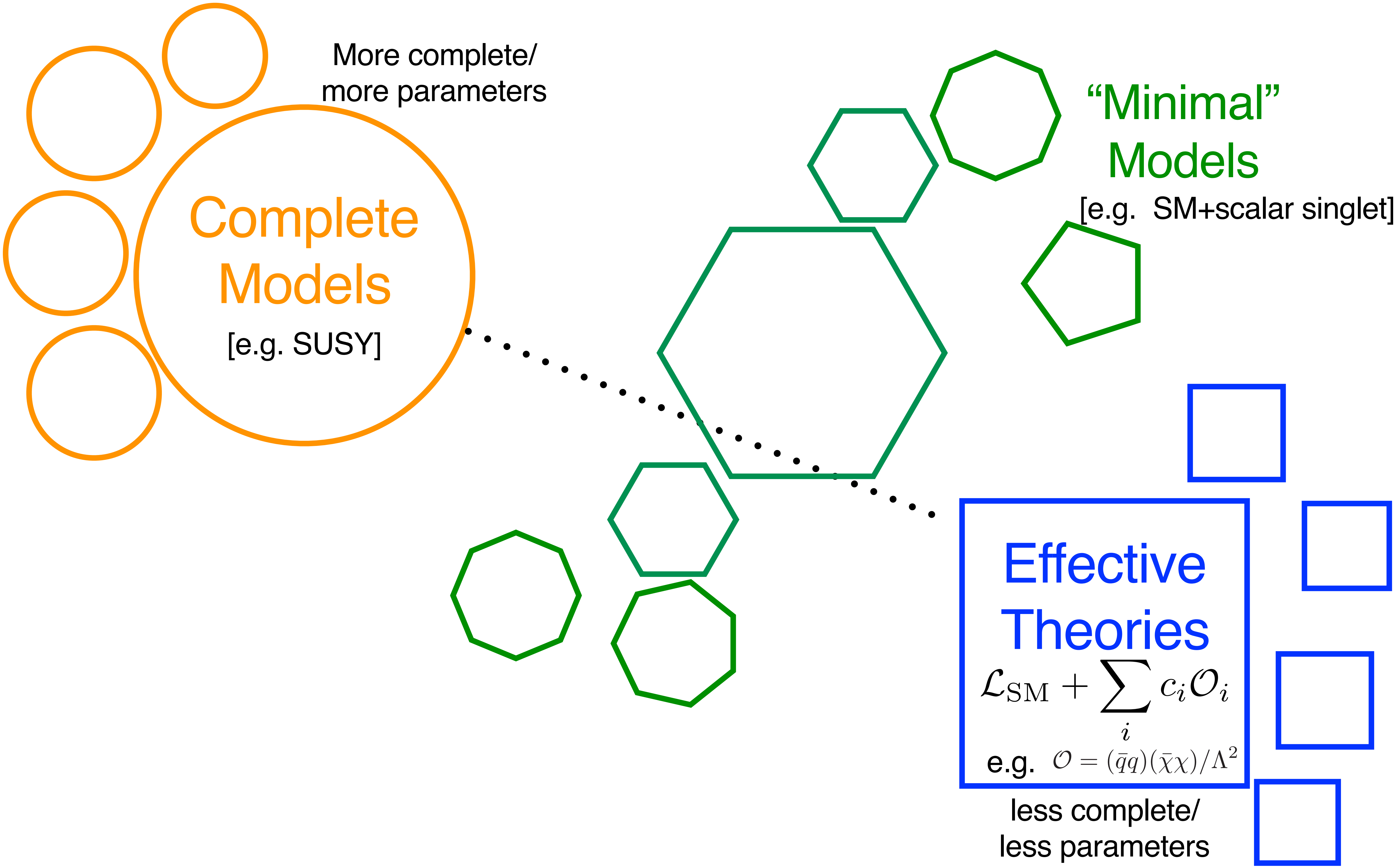
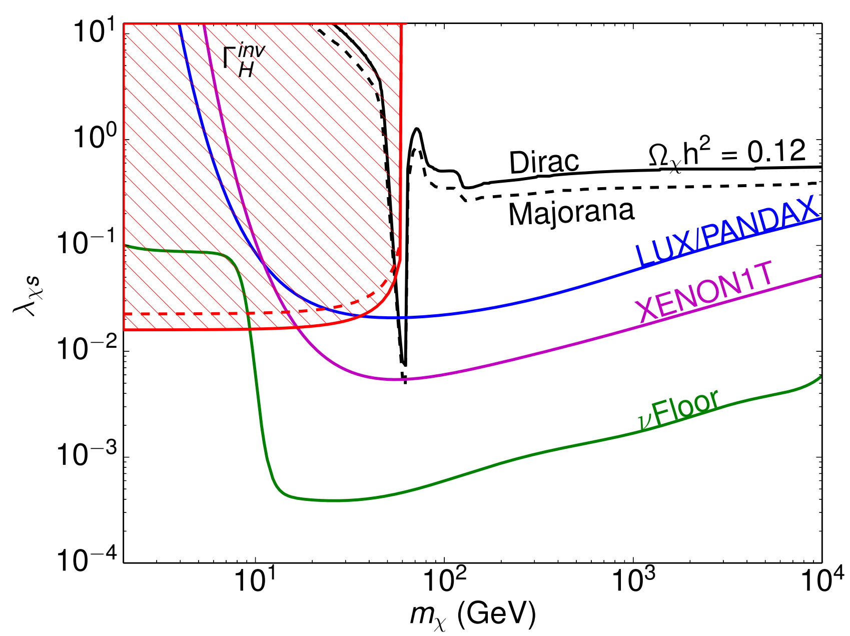
../ Simpler (WIMP) Models

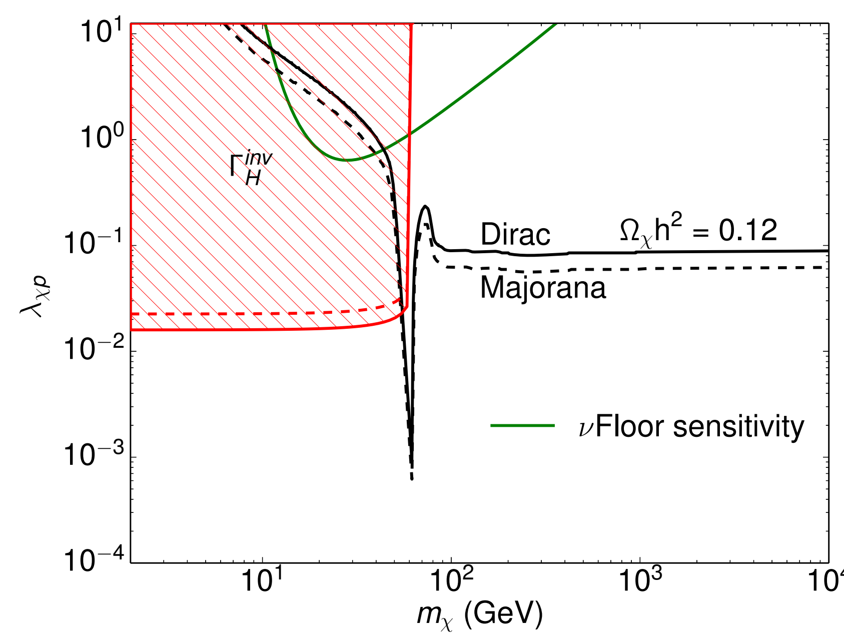



More complete/
more parameters
Complete
Models
[e.g. SUSY]
"Minimal"
Models
[e.g. SM+scalar singlet]
Effective
Theories
$\mathcal{L}_{\rm SM} + \sum_i c_i \mathcal{O}_i$
e.g. $\mathcal{O} = (\bar{q}q)(\bar{\chi}\chi)/\Lambda^2$
less complete/
less parameters

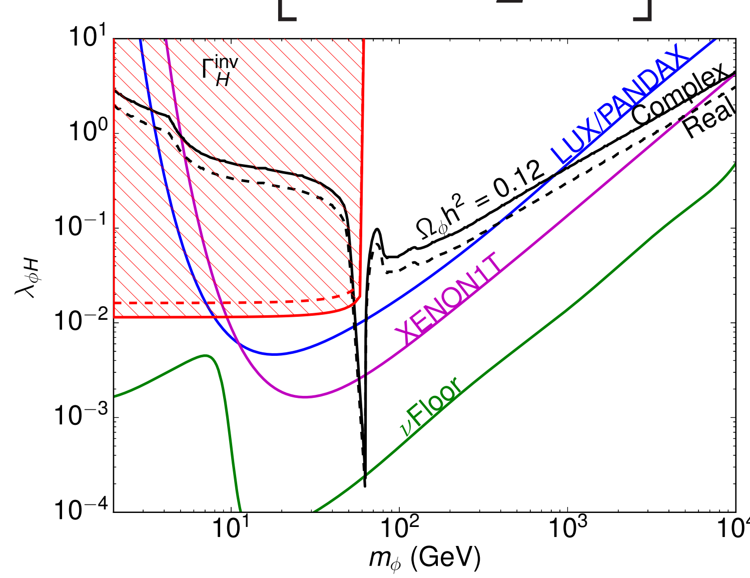
Higgs-mediator

Fermion DM $\mathcal{L} \supset \bar{\chi}(\lambda_{\chi s} + i\gamma^5 \lambda_{\chi p})\chi H$





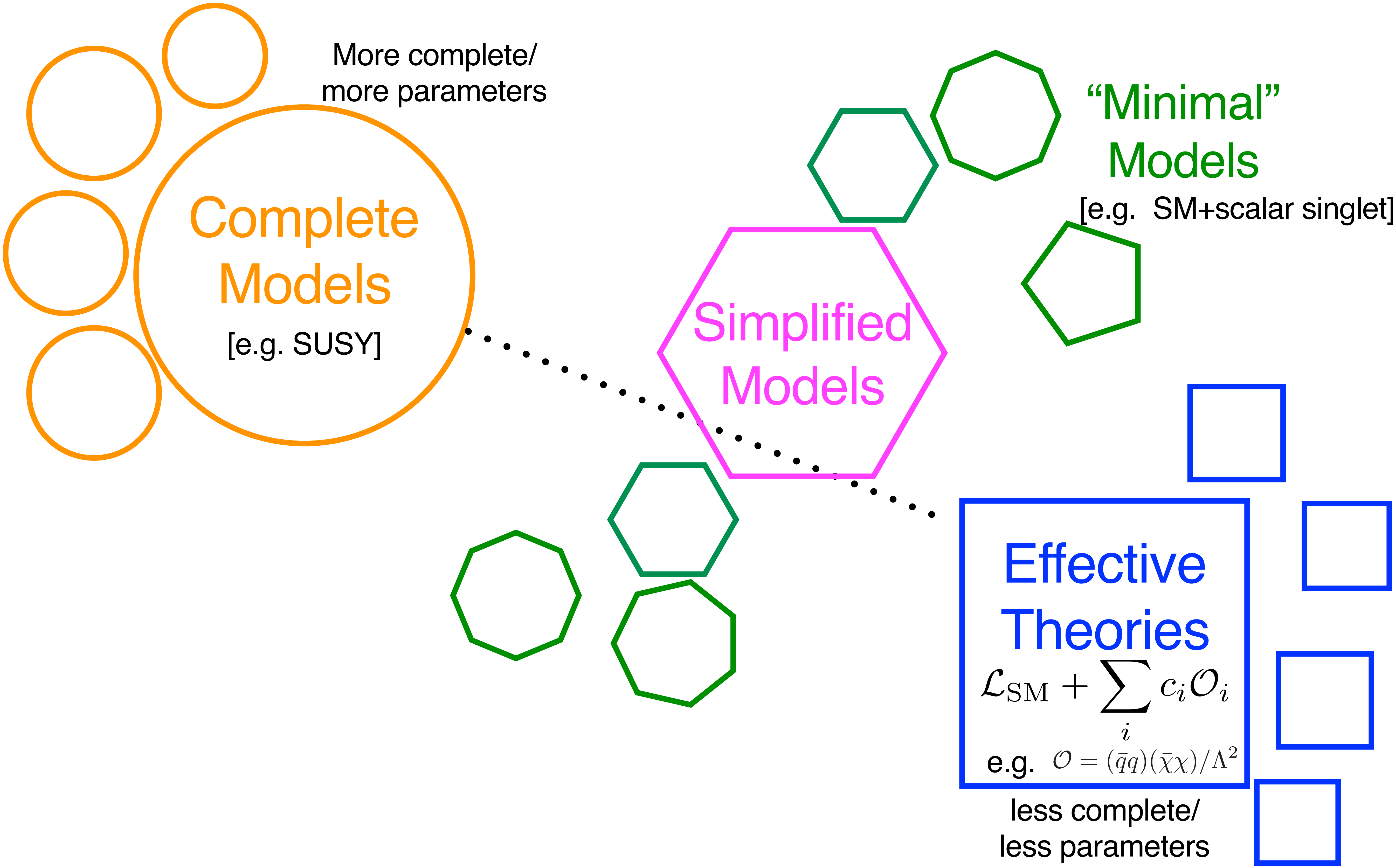
Scalar DM $\mathcal{L} \supset \lambda_{\phi H}\left[vH + \frac{1}{2}H^2\right]\phi^2$



[DS, Giudice, Strumia - 1402.6287]

[Escudero, Berlin, Hooper, Lin - 1609.09079]

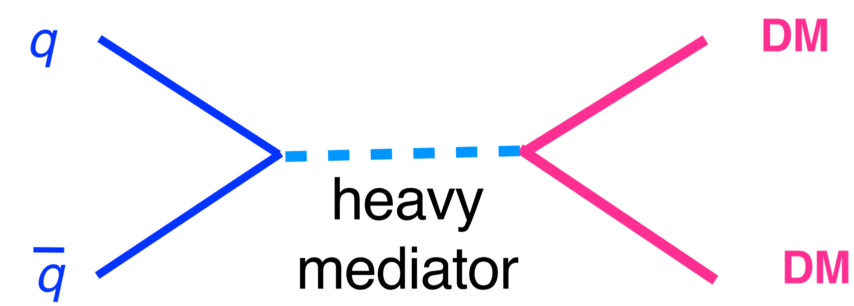
../ Simplified Models



../ Simplified Models

... just means extending the SM with:

- 1 Dark Matter particle
- 1 Mediator particle connecting DM-SM



just another parametrization of unknown high-energy physics

✘ more parameters (*g*'s)

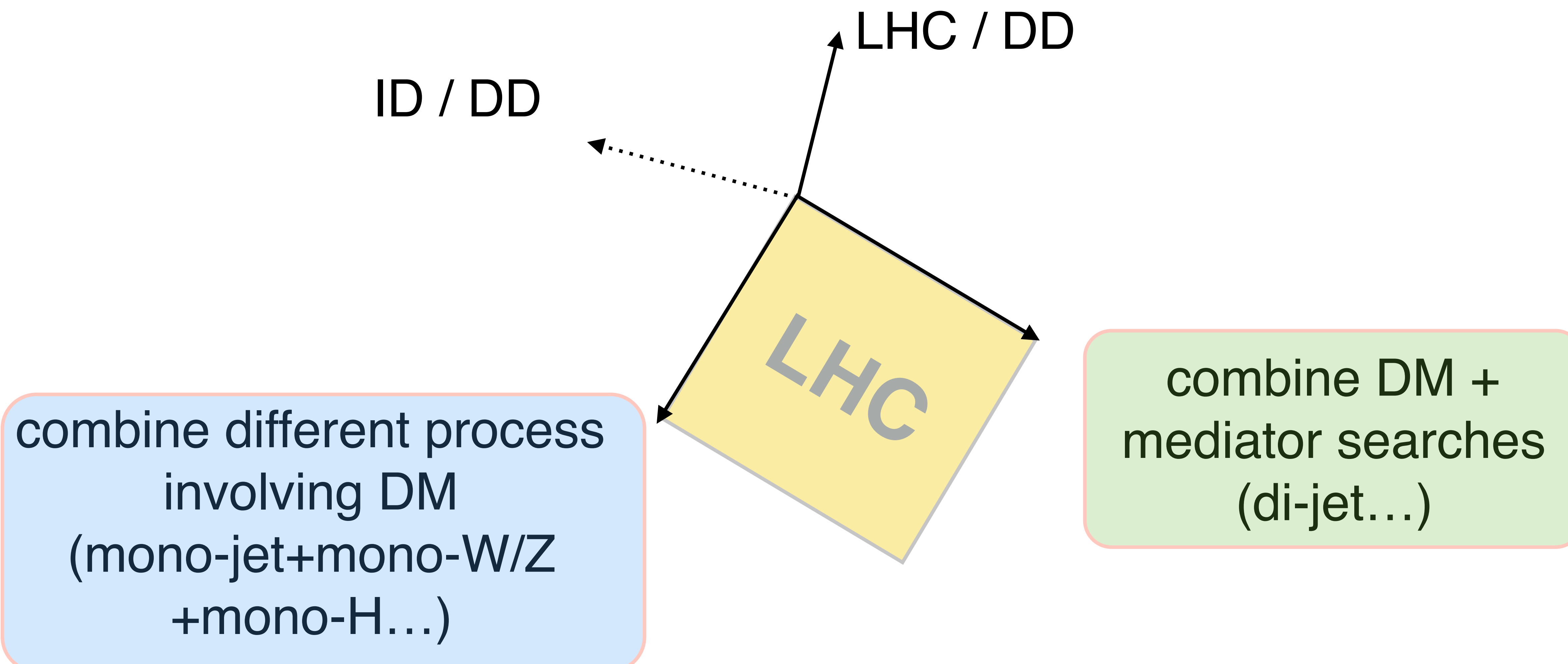
✓ exploit other searches for mediators (e.g. di-jet), complementary to mono-jet

✓ theoretically consistent, no worries about EFT, widths, etc.

from DM search to MEDIATOR search

../ Simplified Models

multi-dimensional exploration



../ Simplified Models

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

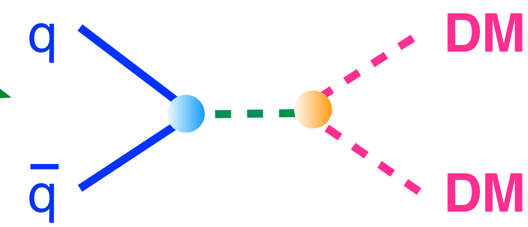
[DS, Jacques - 1603.08002]

[see also Wang's talk]

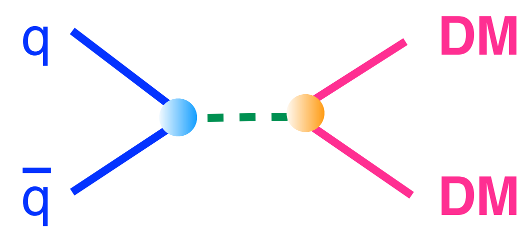
../ Simplified Models

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

s-channel models



scalar DM



fermion DM

$$\mathcal{L}_{\text{scalar}} = -g_{\text{DM}}\,\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q\,,$$

$$\mathcal{L}_{\text{pseudo-scalar}} = -i g_{\text{DM}}\,\phi\bar{\chi}\gamma_5\chi - i g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q}\gamma_5 q\,,$$

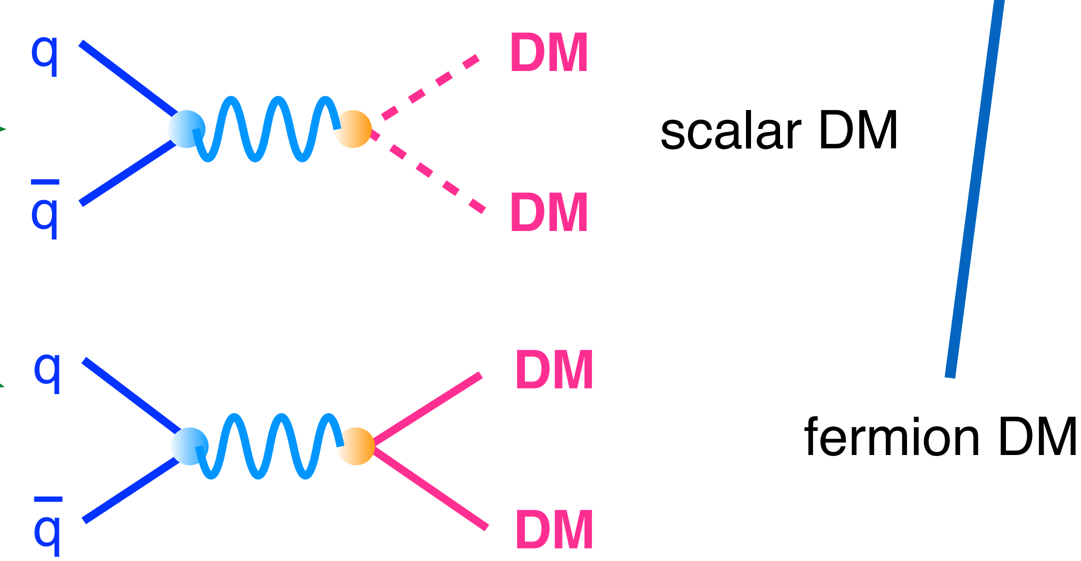
../ Simplified Models

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

s-channel models

$$\mathcal{L}_{\text{vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu q\,,$$

$$\mathcal{L}_{\text{axial-vector}} = -g_{\text{DM}} Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu \bar{q}\gamma^\mu \gamma_5 q\,.$$

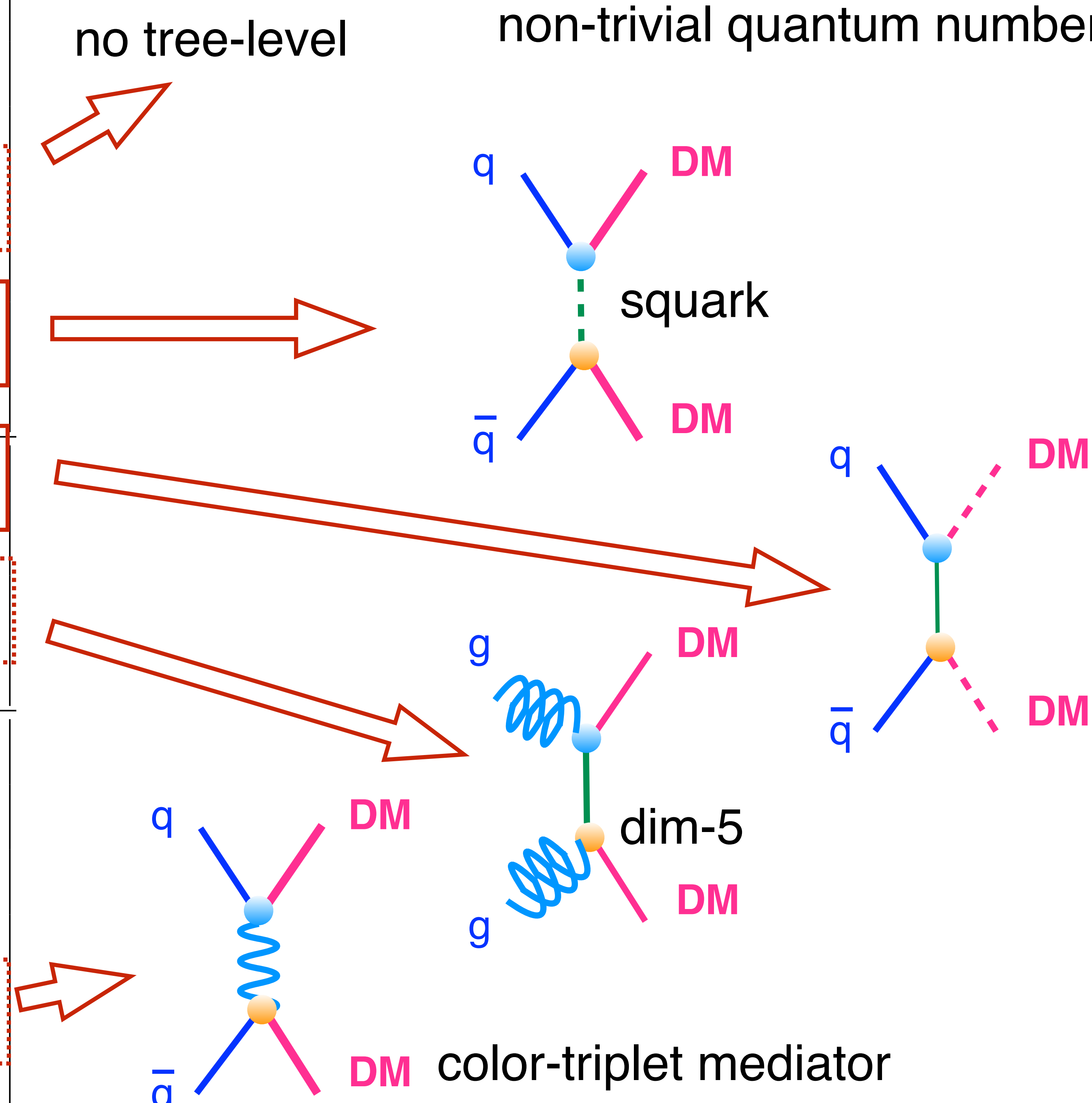


../ Simplified Models

Mediator spin	Channel	DM spin	Model Name
0	s	0	$0s0$
0	s	$\frac{1}{2}$	$0s\frac{1}{2}$
0	t	0	$0t0$
0	t	$\frac{1}{2}$	$0t\frac{1}{2}$
$\frac{1}{2}$	t	0	$\frac{1}{2}t0$
$\frac{1}{2}$	t	$\frac{1}{2}$	$\frac{1}{2}t\frac{1}{2}$
1	s	0	$1s0$
1	s	$\frac{1}{2}$	$1s\frac{1}{2}$
1	t	$\frac{1}{2}$	$1t\frac{1}{2}$

t-channel models

Leitmotiv: mediator carries non-trivial quantum numbers



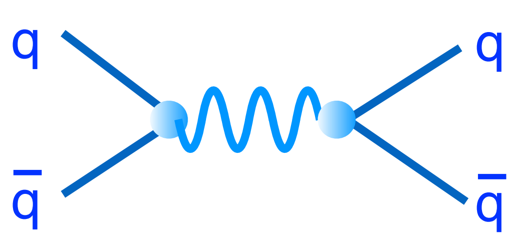
4-dimensional parameter space

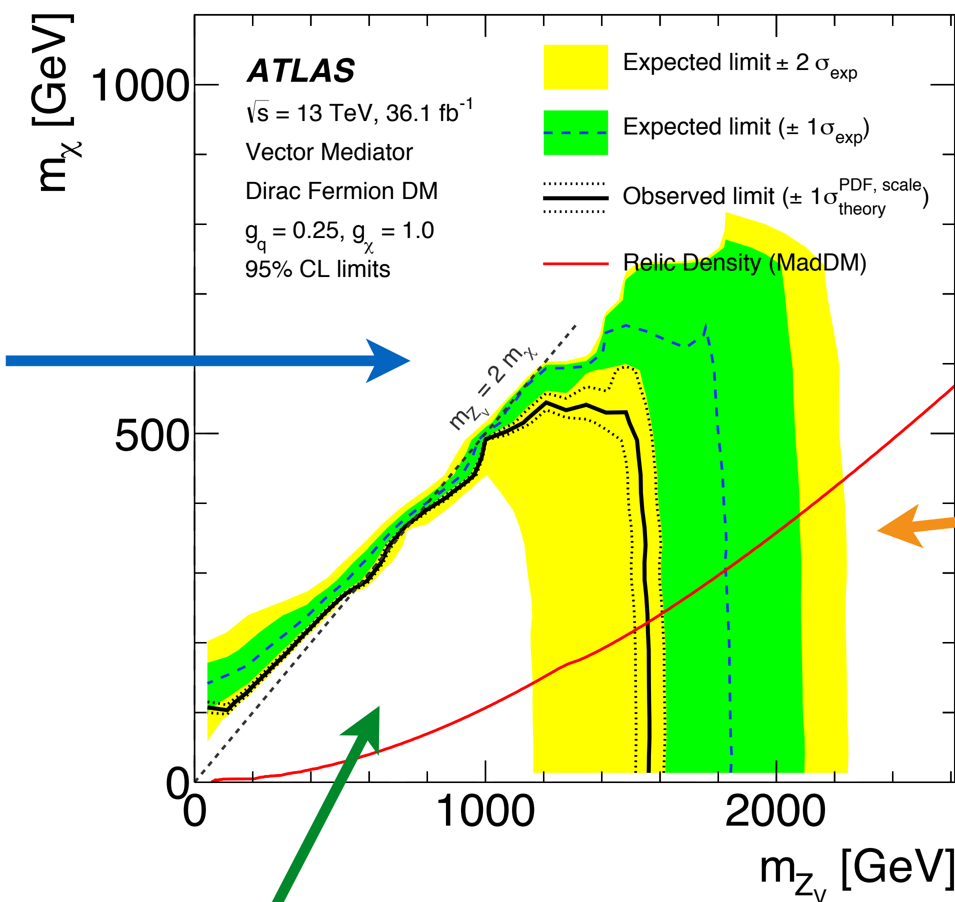
$$\{m_{\rm DM}, M_{\rm med}, g_{\rm DM}, g_q\}$$

Mass-mass plane

slice of parameter space with fixed couplings

off-shell ($M_{\rm med} < 2m_{\rm DM}$)
(use e.g. di-jet)





vector mediator

EFT
(large $M_{\rm med}$)

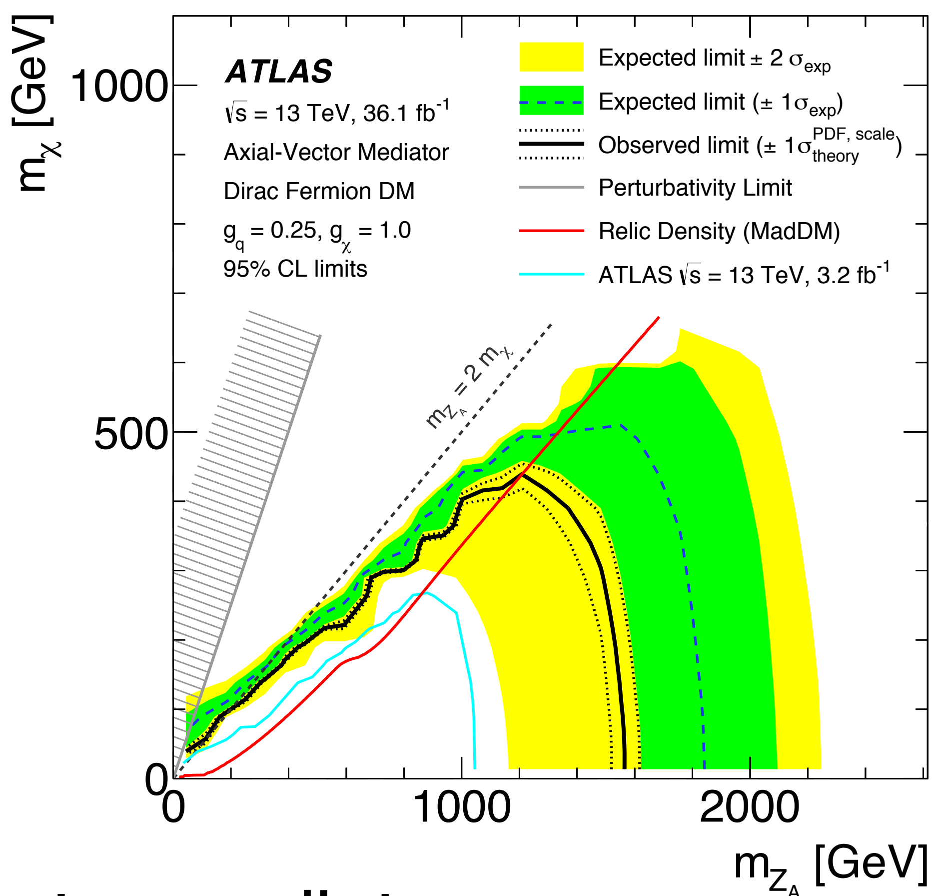
on-shell ($M_{\rm med} > 2m_{\rm DM}$)

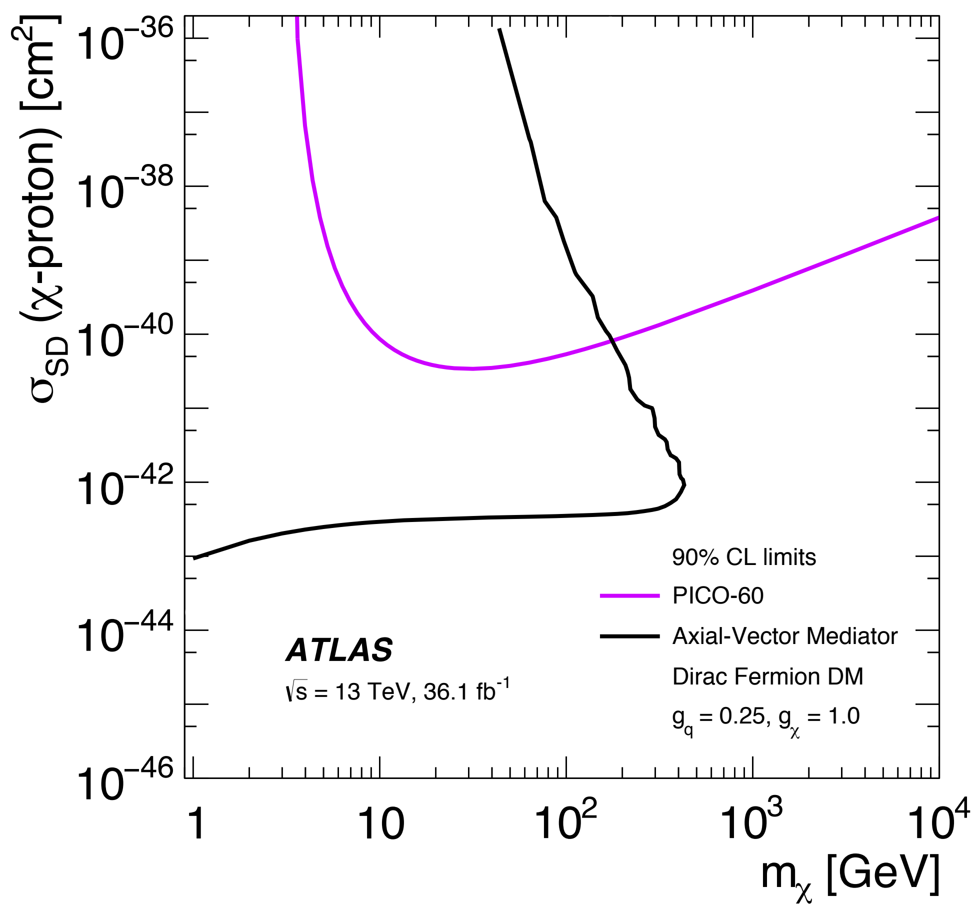
[ATLAS - 1711.03301]

../ Simplified Models

Link to direct detection: $$\sigma_{\mathrm{SI,SD}} \propto \frac{(g_q g_{\mathrm{DM}})^2}{M_{\mathrm{med}}^4}$$

plug in M_{med} from the mass-mass plane



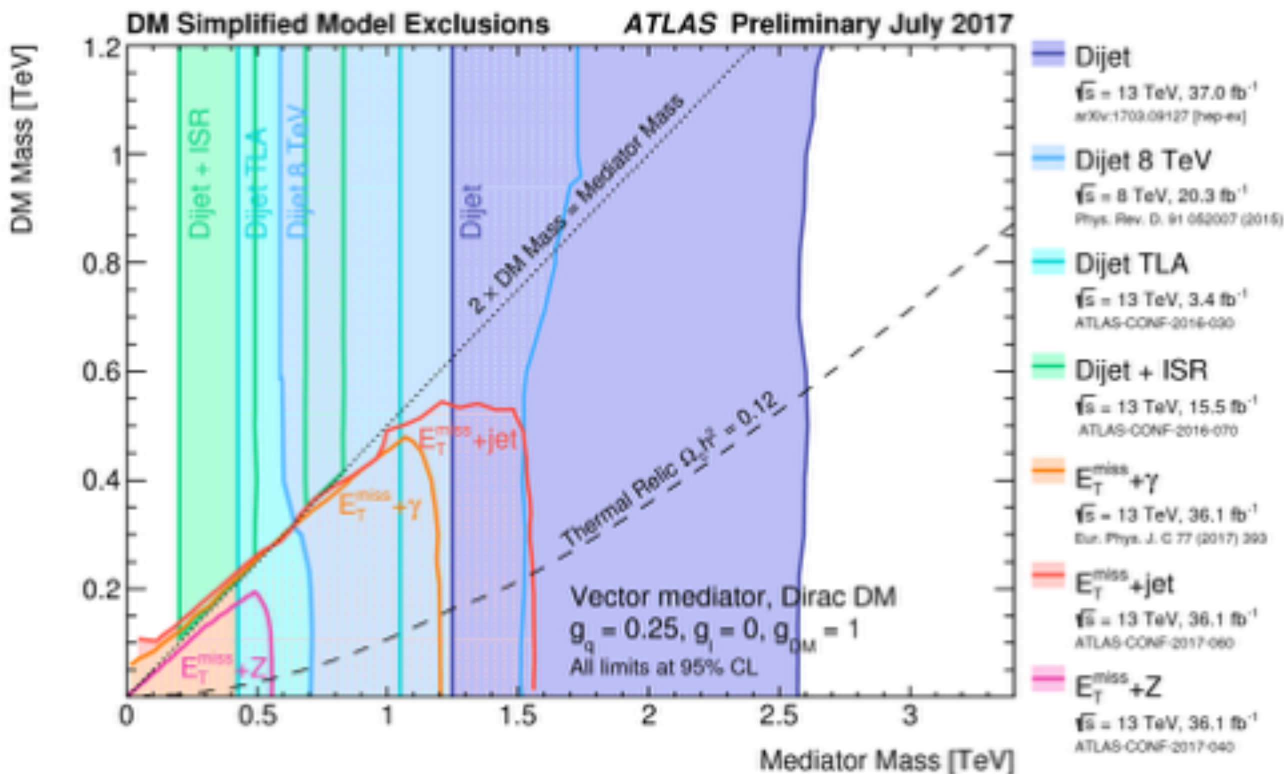


axial-vector mediator

[ATLAS - 1711.03301]

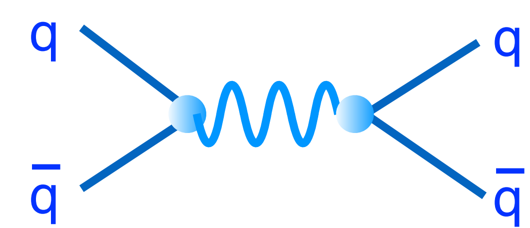
[CMS - 1722.02345]

../ Simplified Models



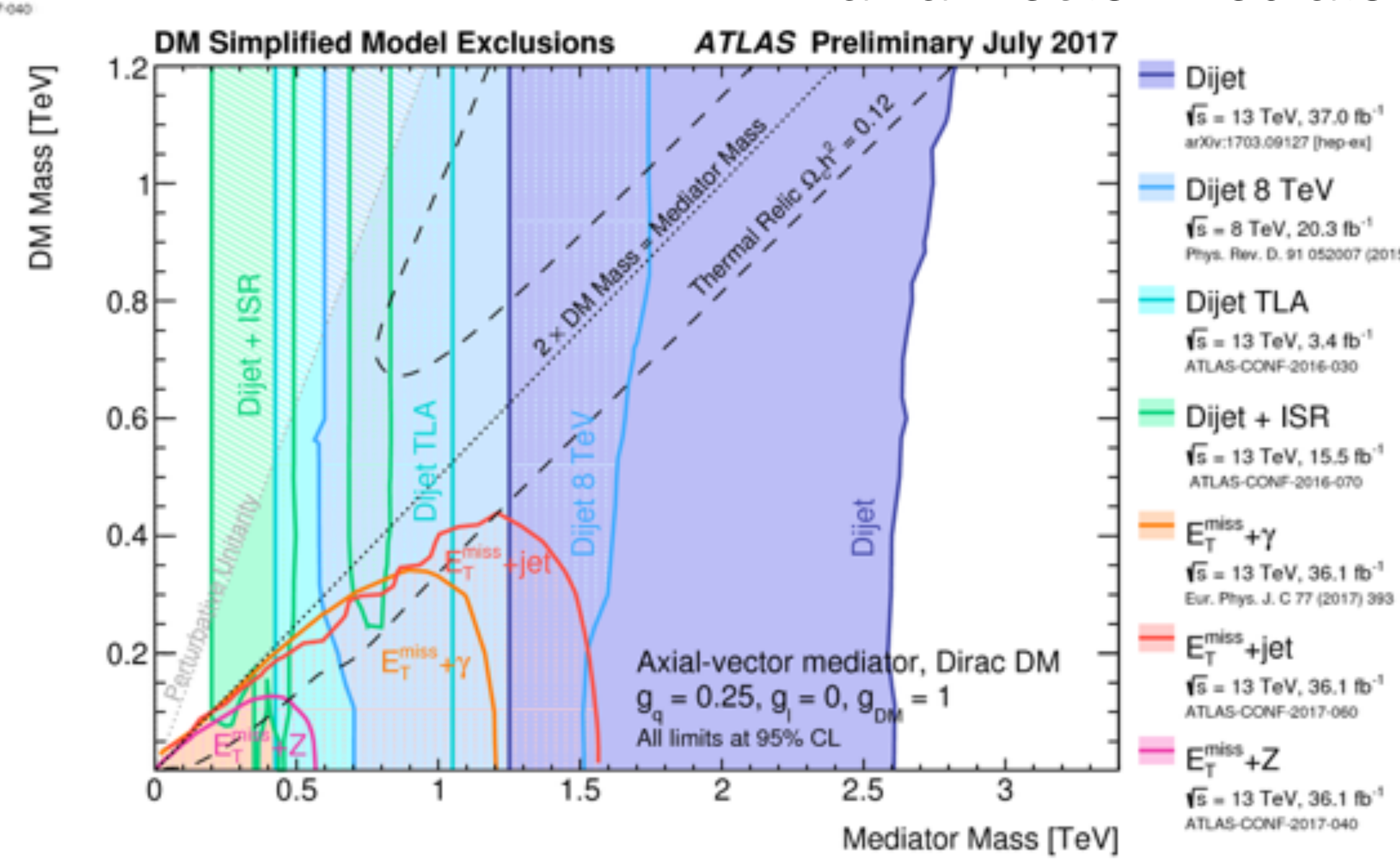
vector mediator

Combine with mediator searches



di-jet

axial-vector mediator



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

[see also Wang's talk]

Is this the whole story?

“ if all you have is a hammer,
everything looks like a nail… ”

Need to look for <u>other tools</u>*

* less conventional / unexplored phenomenology
* data-driven approaches (ML)
* new/deeper views into data (ML)

../ Scoreboard

WIMP	non-WIMP
✓ simple	
✓ BSM-motivation (for some)	✓ more and more expt. data
✓ common production (freeze-out)	✓ BSM-motivation (for some)
✓ testable, in many ways	✗ case-by-case production
✗ ad-hoc stabilization (for some)	
✗ window is closing (insist/desist?)	

../ Outline

1. **Full-fledged models:**

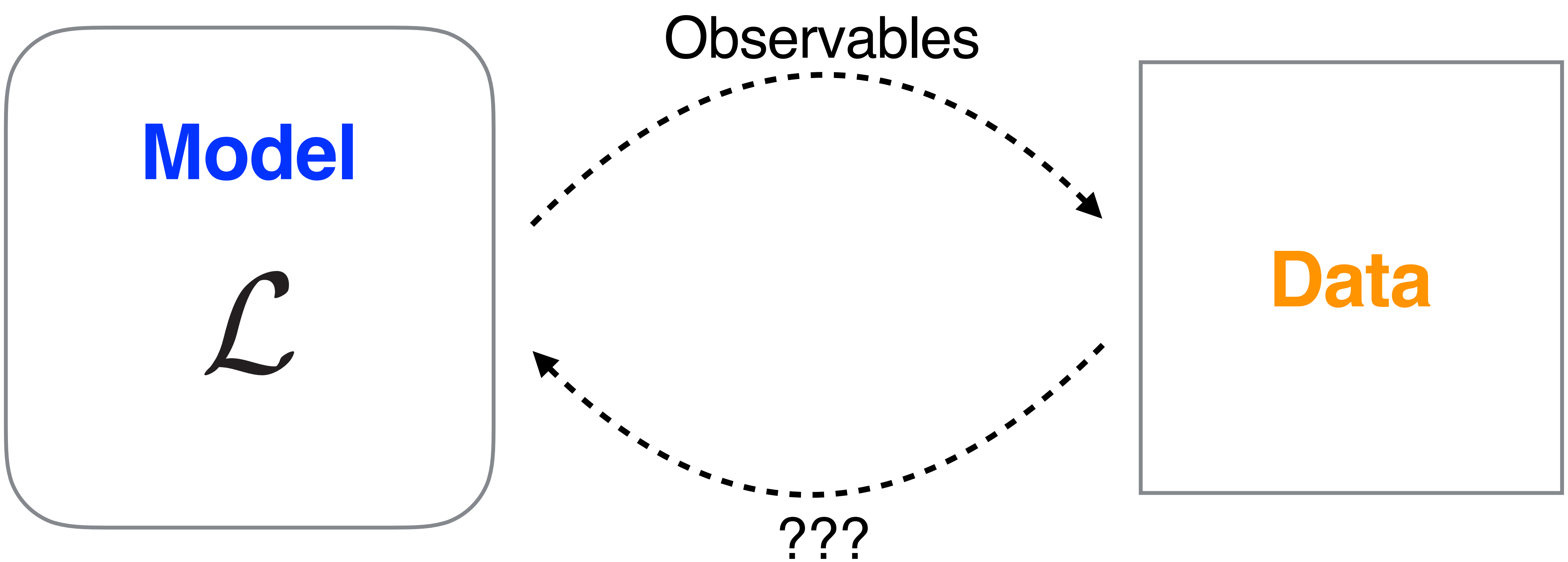
   - **for WIMPs**
     - SUSY
     - Composite Higgs

   - **for non-WIMPs**
     - Axions
     - Sterile Neutrinos

2. **Simpler models (for WIMPs)**

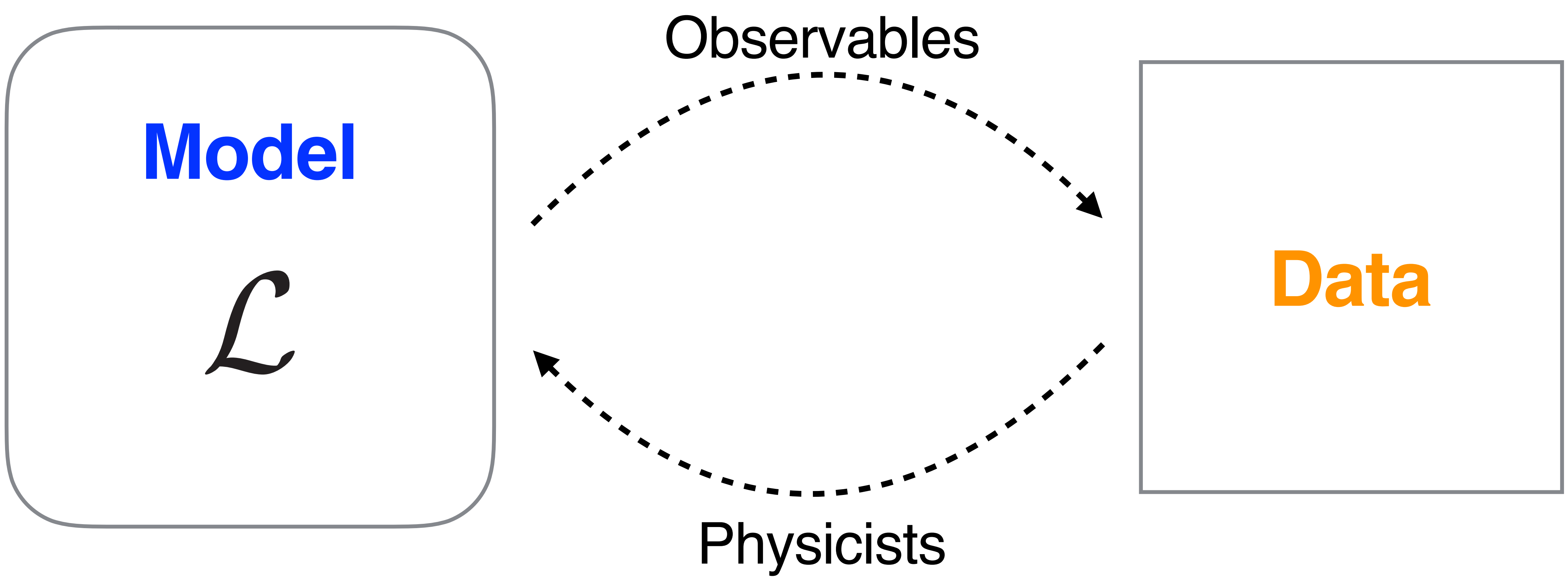
3. **Machine learning mumbo jumbo**

../ Inverse Problem

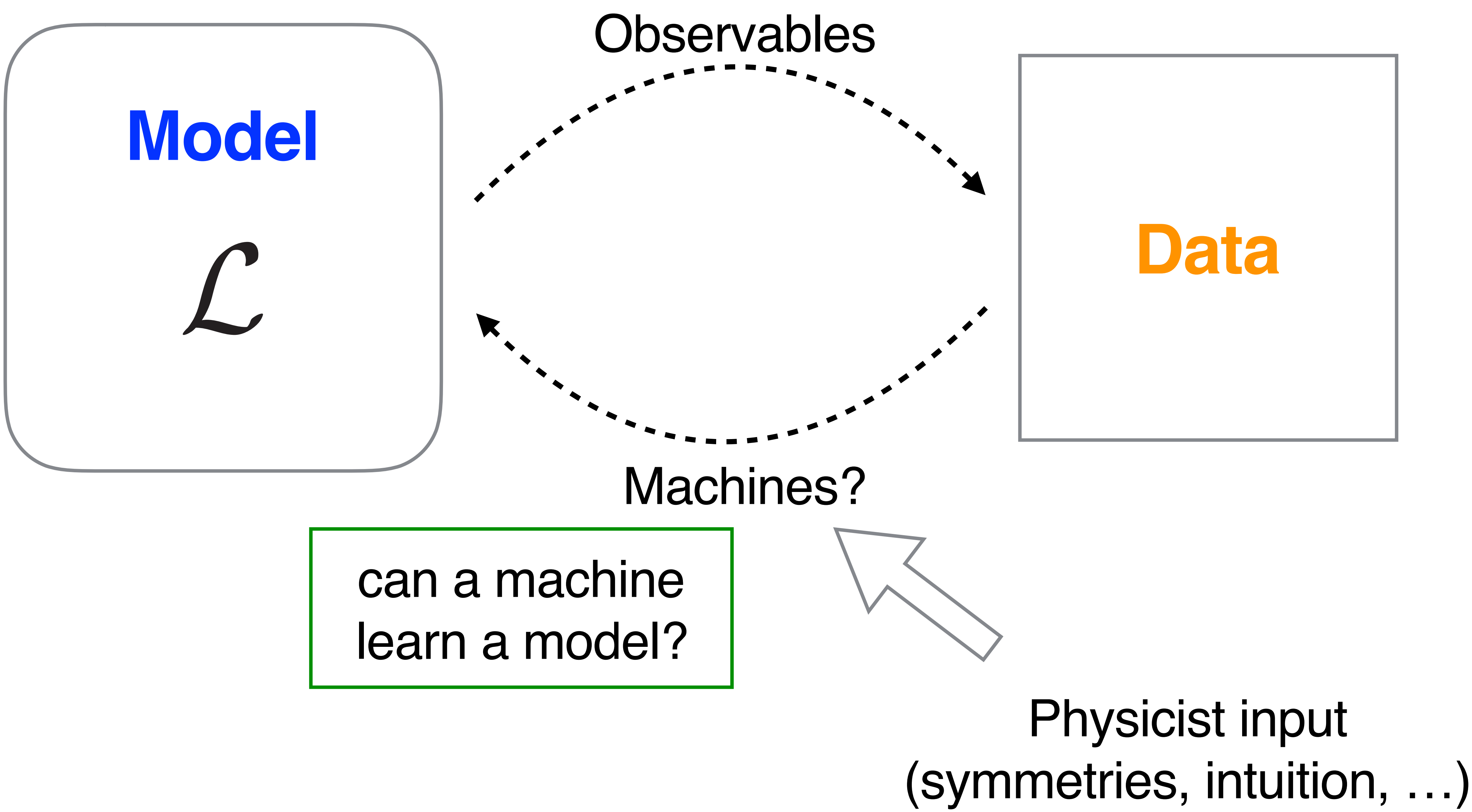


[see also Hendrick's talk]

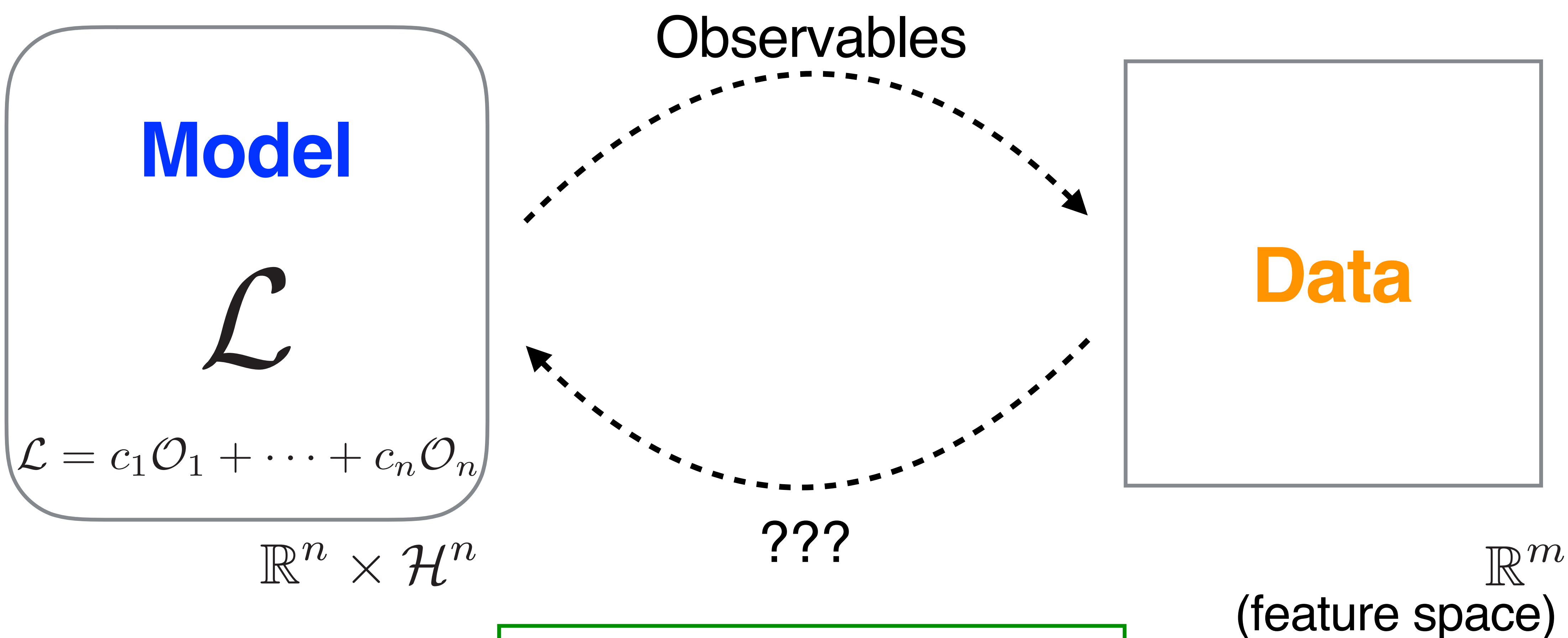
../ Inverse Problem



../ Inverse Problem

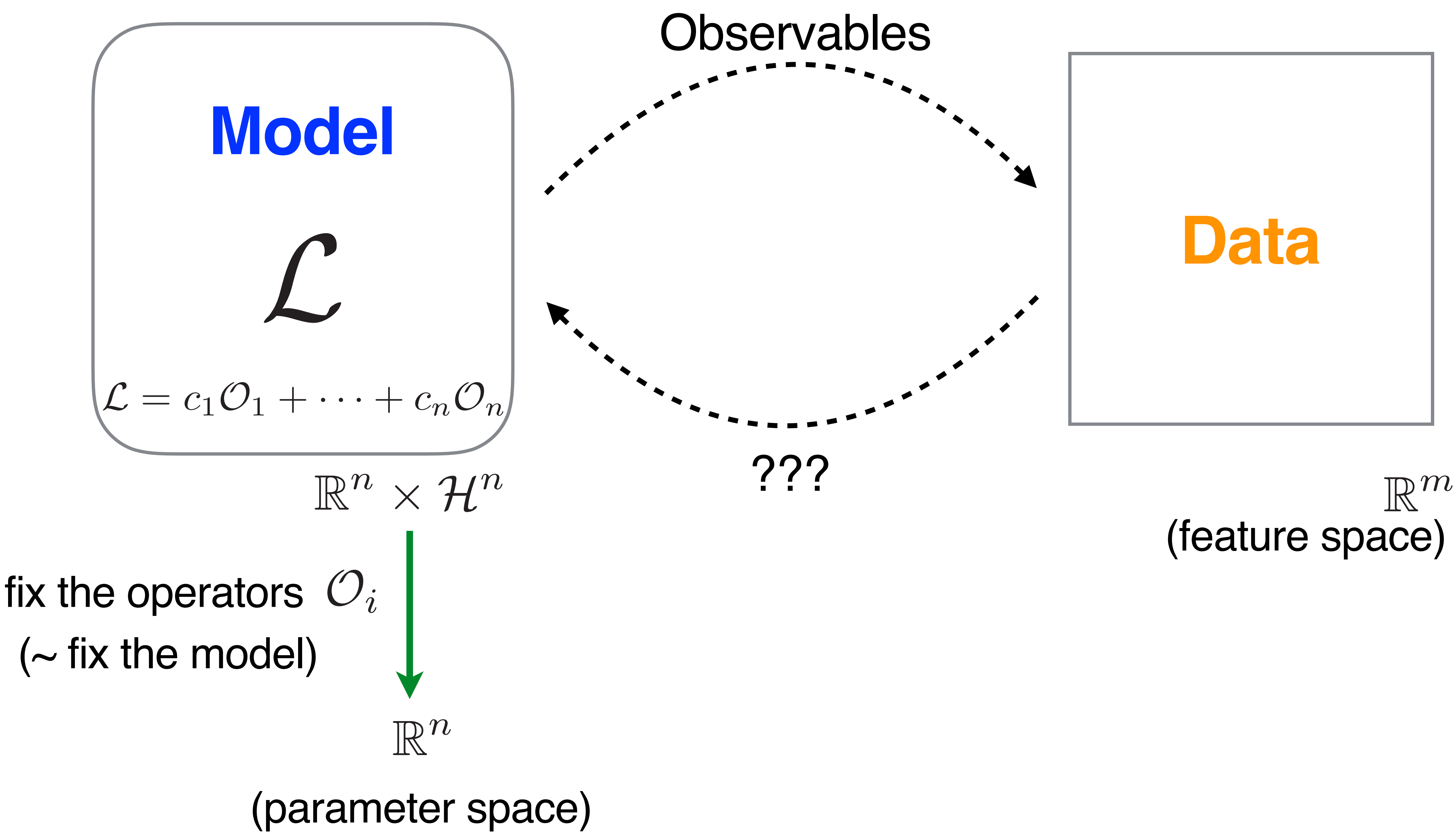


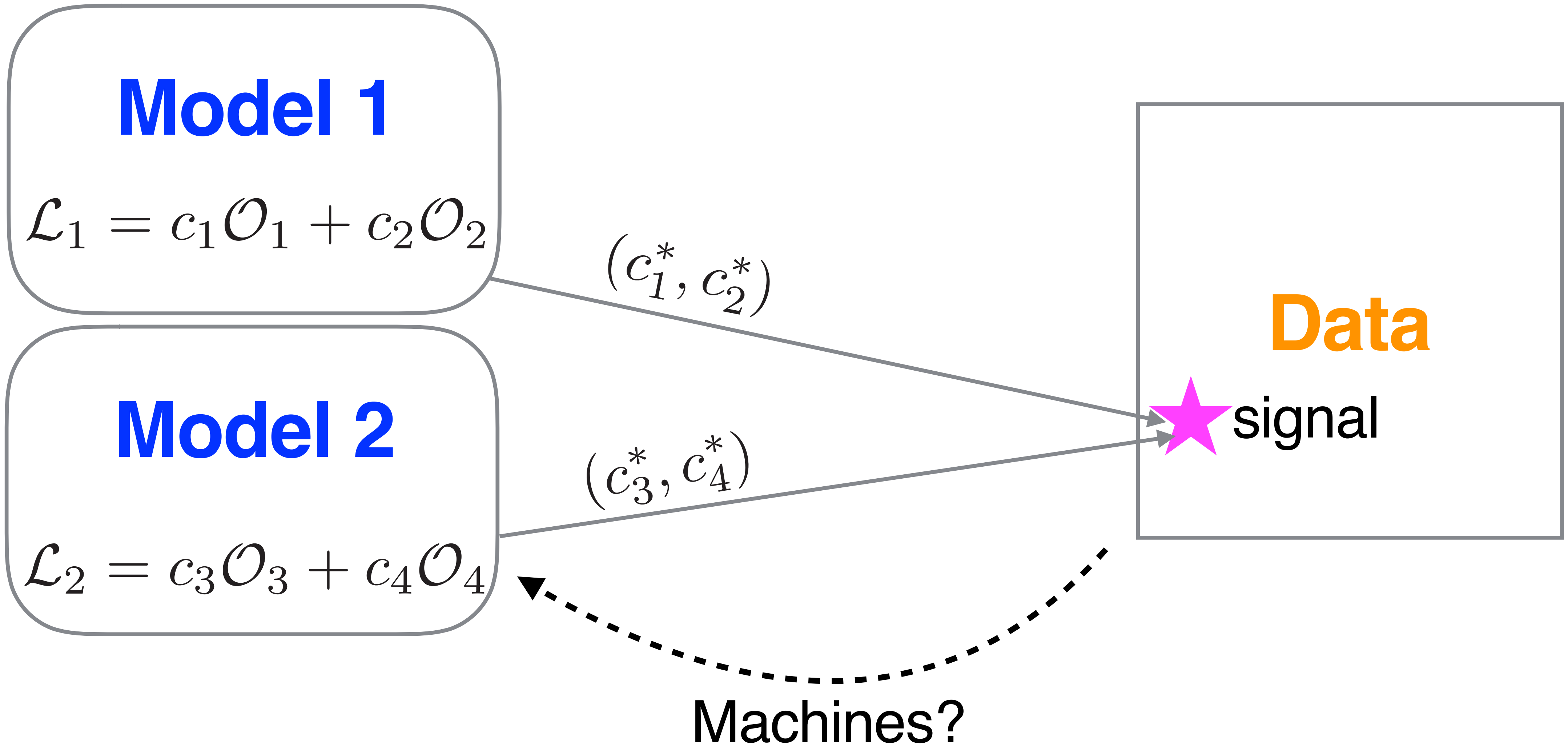
../ Inverse Problem



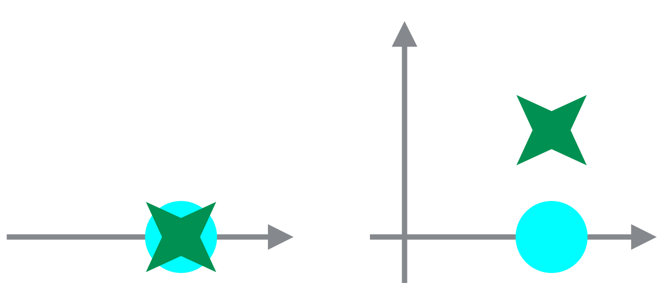
From feature space to functional space

../ Inverse Problem





disentangle $\mathcal{L}_1$ from $\mathcal{L}_2$



enlarge **features** space
to reduce/remove degeneracy?

clustering?

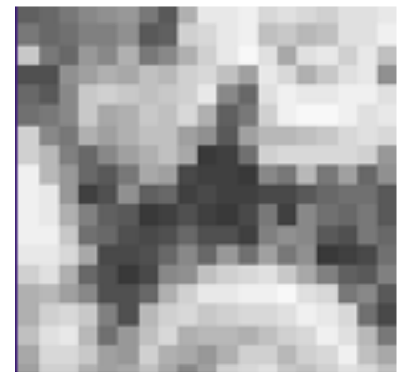
[Merényi's talk]

../ Inverse Problem

Energy ←

high-res.

New degrees of freedom



low-res.

"The" Model

$\mathcal{L}_{\text{full}}$

Physicist

Machines?

Model 1

$\mathcal{L}_{\text{simple}}$

Observables

Machines?

Data

$\mathcal{L}_{\text{simple}} = c_1 \mathcal{O}_1 + c_2 \mathcal{O}_2$

$\mathcal{L}_{\text{full}} = c_3 \mathcal{O}_3 + \cdots + c_N \mathcal{O}_N$

RIM? [Welling's talk]

../ ML and DM models

disclaimer: personal picks

- Improve speed/power of param. scans?

from models to data
more accuracy with less training data (active learning?)

- Reduce degeneracies?

from data to models   (inverse problem)

- Learn a model?

from param space to functional space (inverse problem)

../ Take-Home Messages

- WIMP land is rich

SUSY, composite Higgs,
minimal models, simplified models, …

- DM-models land is even richer!

a great deal of possibilities outside WIMPs

- ML can help

DM Physicists

ML Experts