NEW PHYSICS PERSPECTIVE FROM THE HIGHEST ENERGY COLLISIONS

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3rd Heavy-ion meeting (HIM): Researches on the future accelerators and colliders, PKNU
Nov. 23, 2024

What is new physics?

Why do we need it (or need to see it)?

STANDARD MODEL

The most successful description of elementary particles

Quantum Field Theory + Gauge Theory

describing Strong, Weak, and EM interactions but no Gravity

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Quantum Chromodynamics:
quarks and gluons

Vectorlike theory:
L & R same int.

Electroweak interaction:
all fermions, W, Z, ν

Chiral theory:
L & R diff int.

no mass terms allowed,
but from the Higgs mechanism

HIGGS MECHANISM

A scalar field charged under SU(2) x U(1)

$$V(\phi) = \lambda(|\phi|^2 - v^2)^2$$

Spontaneous Electroweak Symmetry Breaking

(or SU(2) x U(1) is hidden)

All fermions (except neutrinos) W, Z bosons become massive

SATISFYING?

We understand some physics phenomena with "scale"

Why is the higgs (or weak) scale much smaller than the Planck scale?

$$m_h \ll m_{\mathrm{Pl}}$$

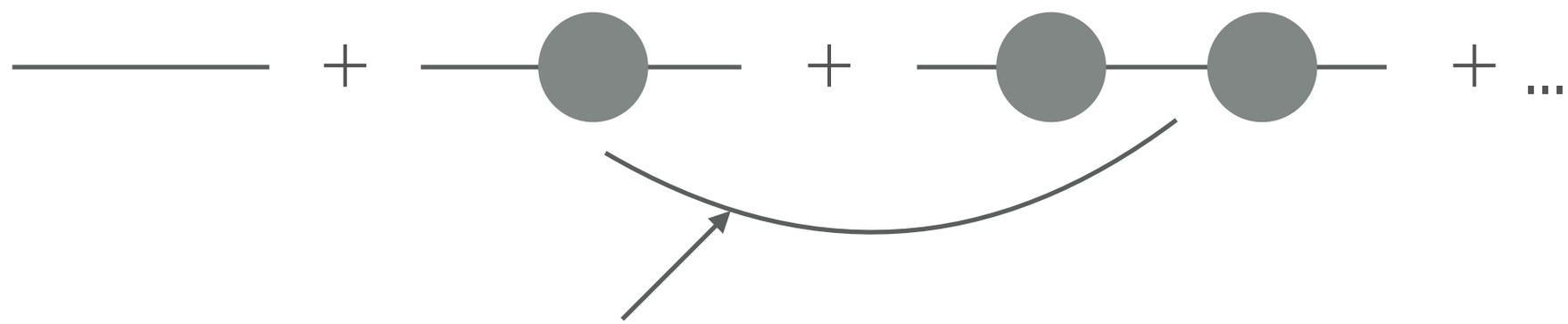
or why is the gravity much weaker than the other interactions?

We call this a fine-tuning problem.

WHY SO SERIOUS?

In QFT, fermion masses $m_\psi \bar{\psi}\psi$

propagator =



Quantum Corrections $\propto m_\psi$

In limit of $m_\psi \to 0$ QC don't induce mass contributions

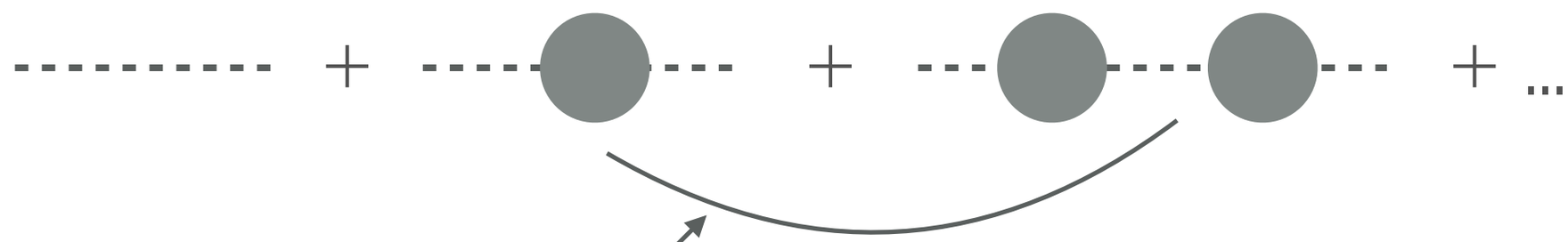
Therefore, we can endure

$$m_\nu < 0.1 \text{ eV} \qquad \ll \qquad m_t \sim 170 \text{ GeV}$$

WHY SO SERIOUS?

Scalar masses $m_\phi^2|\phi|^2$

propagator =



Quantum Corrections $\propto \Lambda^2$

unknown high energy scale, $m_{\rm GUT}$? $m_{\rm Pl}$?

and do not vanish even for $m_\phi \to 0$

We couldn't tolerate this ...

NEW PHYSICS?

Many ideas are raised:

Supersymmetry, (Warped) Extra Dimensions, Technicolor

Higgsless solution

geometric solution

(theoretically) most reliable solution,

and most promising (before the LHC era ...)

and others ...

OUTLINE

1. Introduction
2. Supersymmetry
3. Alternatives
4. Pheno study (diverges)
5. Conclusion

Supersymmetry

BASIC IDEA

Symmetry between F $\longleftrightarrow$ B

means the same mass and interaction, only spin-1/2 difference

Quantum Corrections by F and B cancel

$\simeq 0$ no Λ^2

But we do not see scalar counterparts of $e,\ q,\ \gamma,\ \cdots$

SUSY BREAKING

SUSY is slightly broken:

counterparts are heavier but should not be so much heavier

$$\sim m^2 \log\left(\frac{\Lambda^2}{m^2}\right)$$

mild log-dependence arises

So we strongly believed in new particles "near us"

MINIMAL MODEL

Standard Model ⟷ SUSY partners

mass scale ~ O(100) GeV slightly heavier

Again, we believed we can get them soon.

EARLY STUDY

$N = 1$ SUPERGRAVITY, THE WEAK SCALE AND THE LOW-ENERGY PARTICLE SPECTRUM

Nucl.Phys.B 233 (1984) 511-544

my first study on SUSY in 2005

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CERN, Geneva, Switzerland

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Received 8 August 1983

right after W discovery (25 January 1983)

We consider in detail the radiative SU(2) × U(1) breaking induced by broken $N = 1$ supergravity. We include in this study some parameters (b-quark Yukawas, mixed Higgs mass terms) neglected in a previous analysis. We show that there are essentially two types of mechanisms leading to radiative SU(2) × U(1) breaking. The first of them occurs for a t-quark mass $m_t \gtrsim 60$ GeV. The second one appears for arbitrary small values of m_t (without using a large A). These two mechanisms correspond to two different classes of local SUSY GUTs. We present results for the low-energy supersymmetric particle spectrum. In some of the possible scenarios presented, squarks, sleptons and/or gauginos are accessible to present accelerator energies. In other scenarios, the scalar neutrinos may be the lightest R-odd particles. We finally remark that the SU(5) prediction for m_b/m_τ is substantially suppressed for a very heavy t-quark.

EARLY STUDY

TABLE 1
Seven examples of low-energy spectra; the masses are in GeV

	a	b	c	d	e	f	g
m_t	29	29	30	63	111	111	160
m	25	50	100	50	200	50	150
M	17	5	71	141	108	49	6
A	1	1	1	1	0.5	1	1
$\sin 2\theta(M_X)$	0.787	0.679	0.779	0.76	0.195	0.038	0.187
$\sin 2\theta(M_W)$	0.999	0.999	0.996	0.42	0.43	0.43	0.45
$\tilde{q}$	50–52	51–52	215–220	380–396	300–363	120–150 67–75	143–160
$\tilde{\ell}$	26–28	49–50	105–114	84–122	207–219	$\tilde{\nu}_L \sim 16$	138–156
$\tilde{g}$	50	15	214	423	324	147	19
$\tilde{W}$	14	4	58	115	88	40	5
$\tilde{B}$	7	2	29	57	44	20	3
$H^{\pm}$	86	104	170	136	230	81	163
H_a	96	112	173	118	219	89	147
H_b	5	7	23	80	83	23	81
H_c	37	69	151	112	217	24	143

One big prediction: $m_h^2 < m_Z^2 + \text{loops}$

FOR 2 DECADES

Tevatron discovered top quark $m_t \sim 170 \text{ GeV}$

LEP no Higgs boson discovery,

but precision test for W & Z bosons

putting Higgs mass bound $m_h > 114 \text{ GeV}$

$\downarrow$

large correction to m_h^2 requires $m_{\tilde{t}} \sim 1 \text{ TeV}$

not as good as things we expected

We may tolerate this..., not so bad ...

PRE-LHC ERA

LHC (14 TeV) will discover SUSY (or plethora of particles).

We will see the era of model building in the zoo of new particles like 50's - 60's

Dark Matter physics also emerges:

weak scale new particles can be "perfect" candidates

cosmological history,
(in)direct detection,
LHC test

SUSY CONFERENCE 2008

Supersymmetry: the final countdown

Hans Peter Nilles

Bethe Center for Theoretical Physics

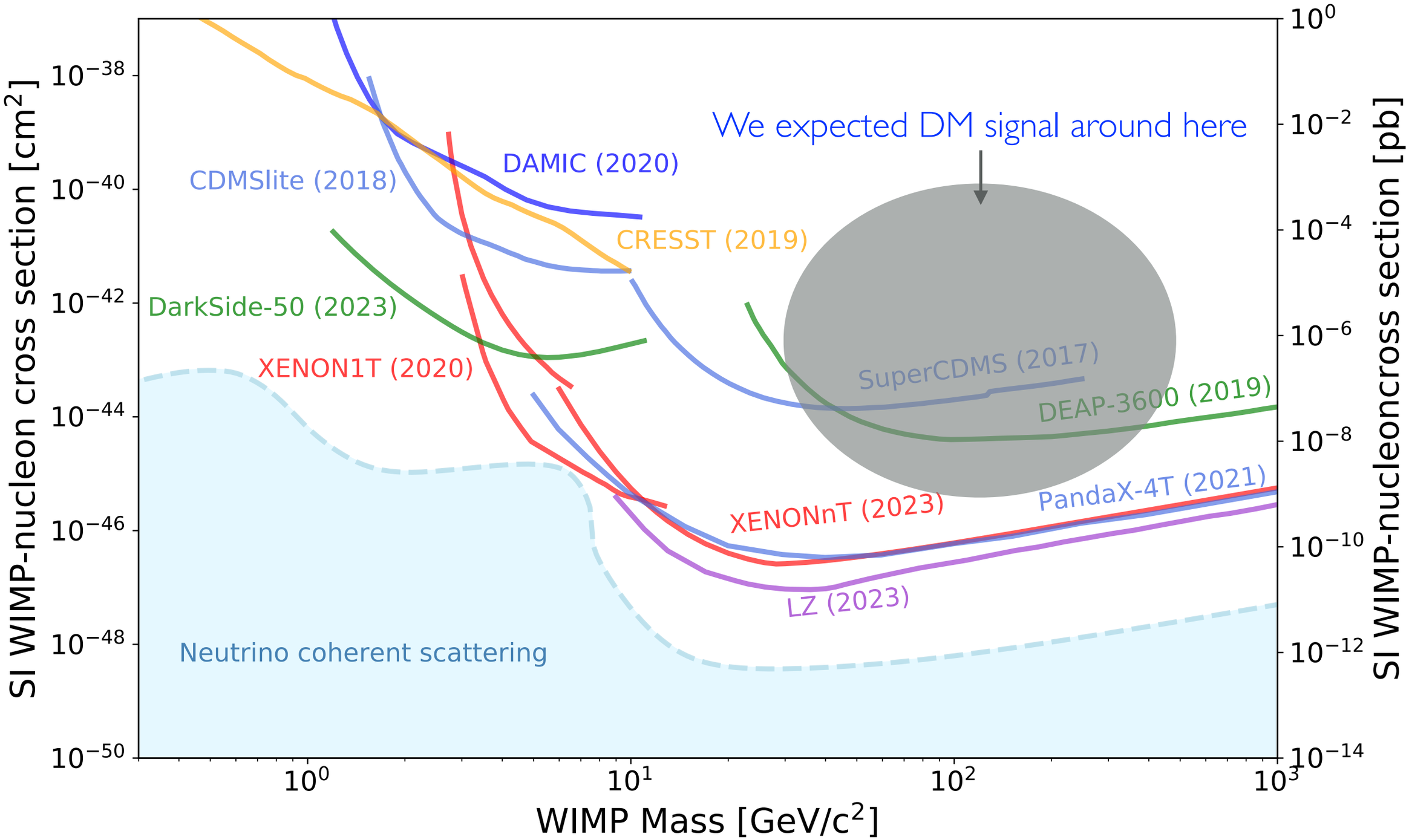
Universität Bonn

LHC 'SEEKS & DESTROYS' SUSY...

SUSY particle bounds

> 2 TeV

DM IN THE CORNER



from PDG review

Alternatives

NEUTRAL NATURALNESS

SUSY particles are charged (colored) under SM

What if new particles are neutral under SM?

studied a lot 2013 - 2014 (after RUN1)

Introducing mirror (or twin) world charge neutral under SM

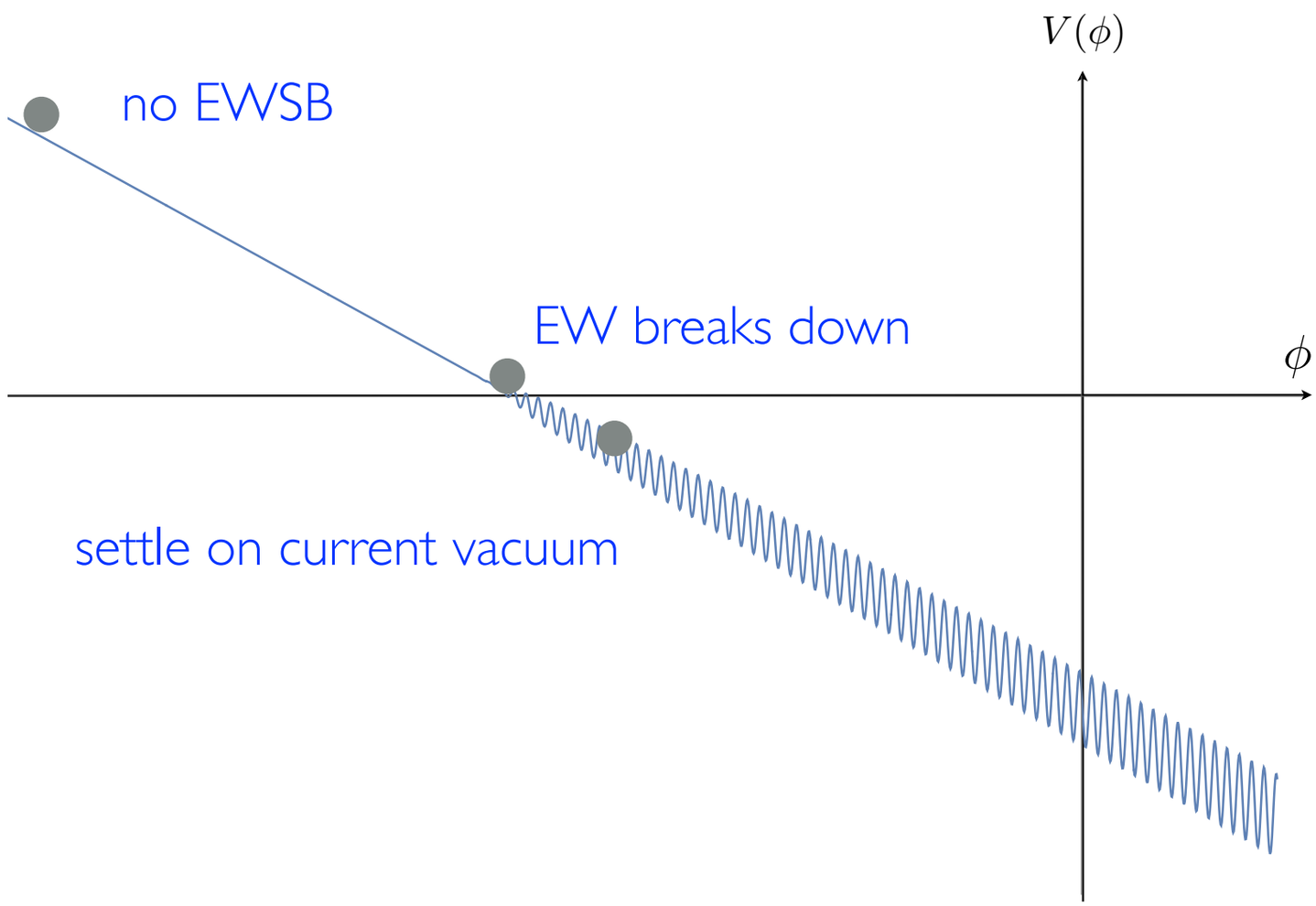
- communicating only through higgs
- cancels QC from SM

COSMOLOGICAL RELAXATION

Graham, Kaplan, Rajendran 2015

$$\mathcal{L} \supset (-M^2 + g\phi)|h|^2 + V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

fundamental scale



Pheno study diverges

POST LHC (RUN1 OR 2) STUDY

Pushing up the SUSY scale:

loosing the motivation of SUSY

no clear signal expected at LHC

Or finding loopholes in the SUSY search

POST LHC (RUN1 OR 2) STUDY

More challenging study:

feeble interactions

rare events

long-lived particle searches

Triggering another particle research (in experiments)

intensity frontier (low energy)

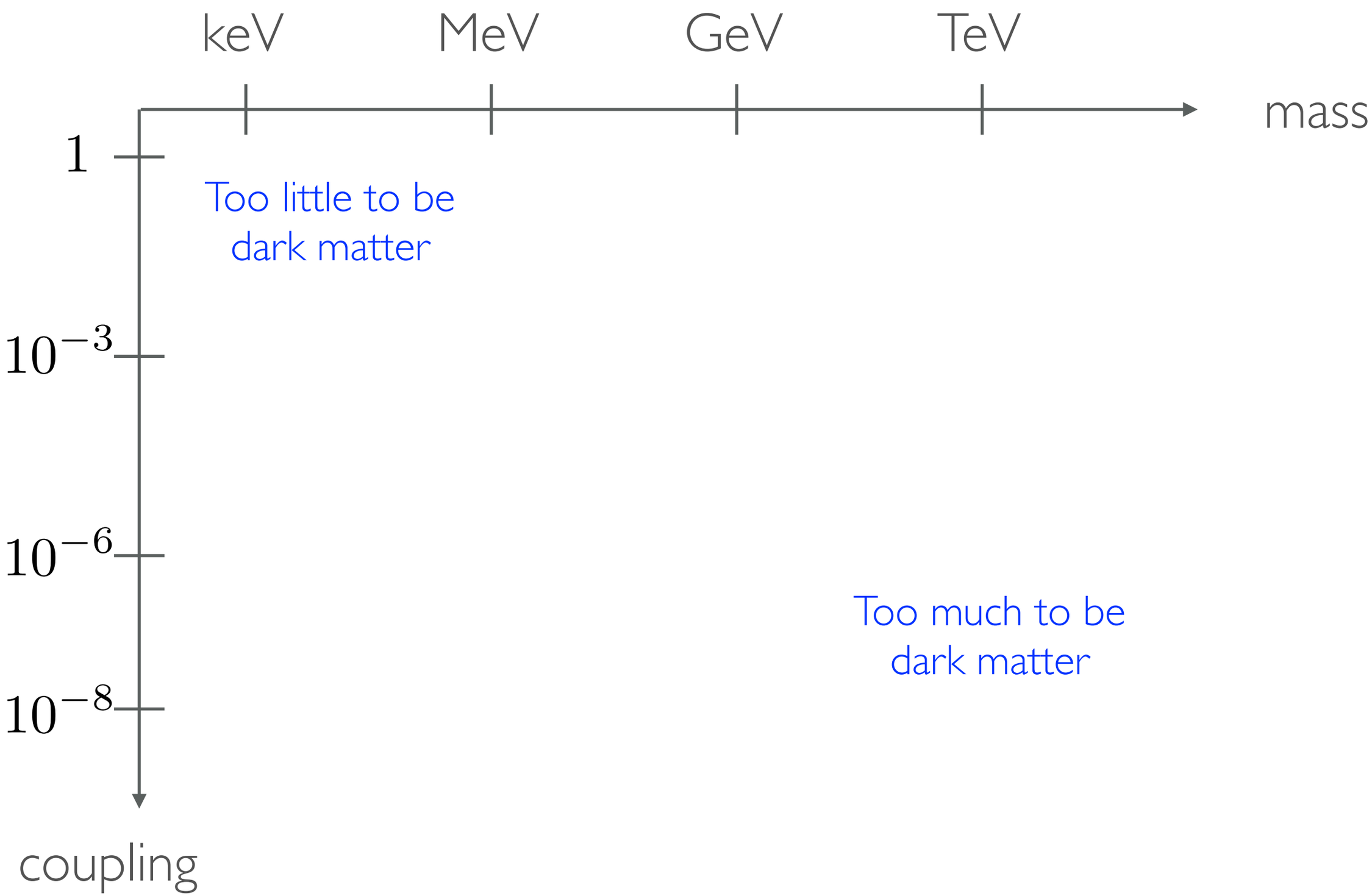
- flavor physics
- neutrino physics
- hidden particles

cosmic frontier

- non-WIMP dark matter
- structure formation
- cosmic ray

Long-lived Particles and Dark Matter

LONG-LIVED PARTICLE (DM)



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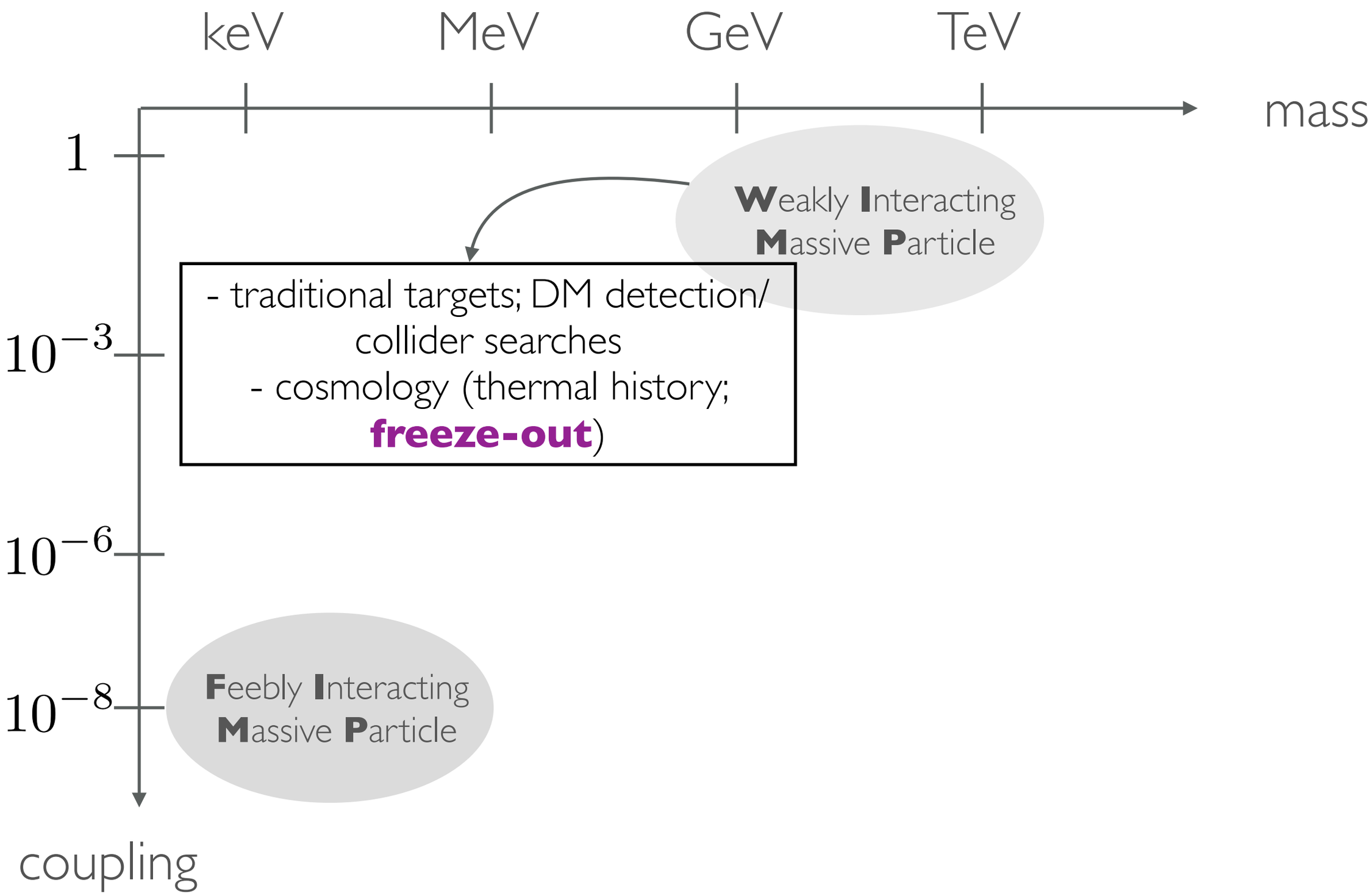
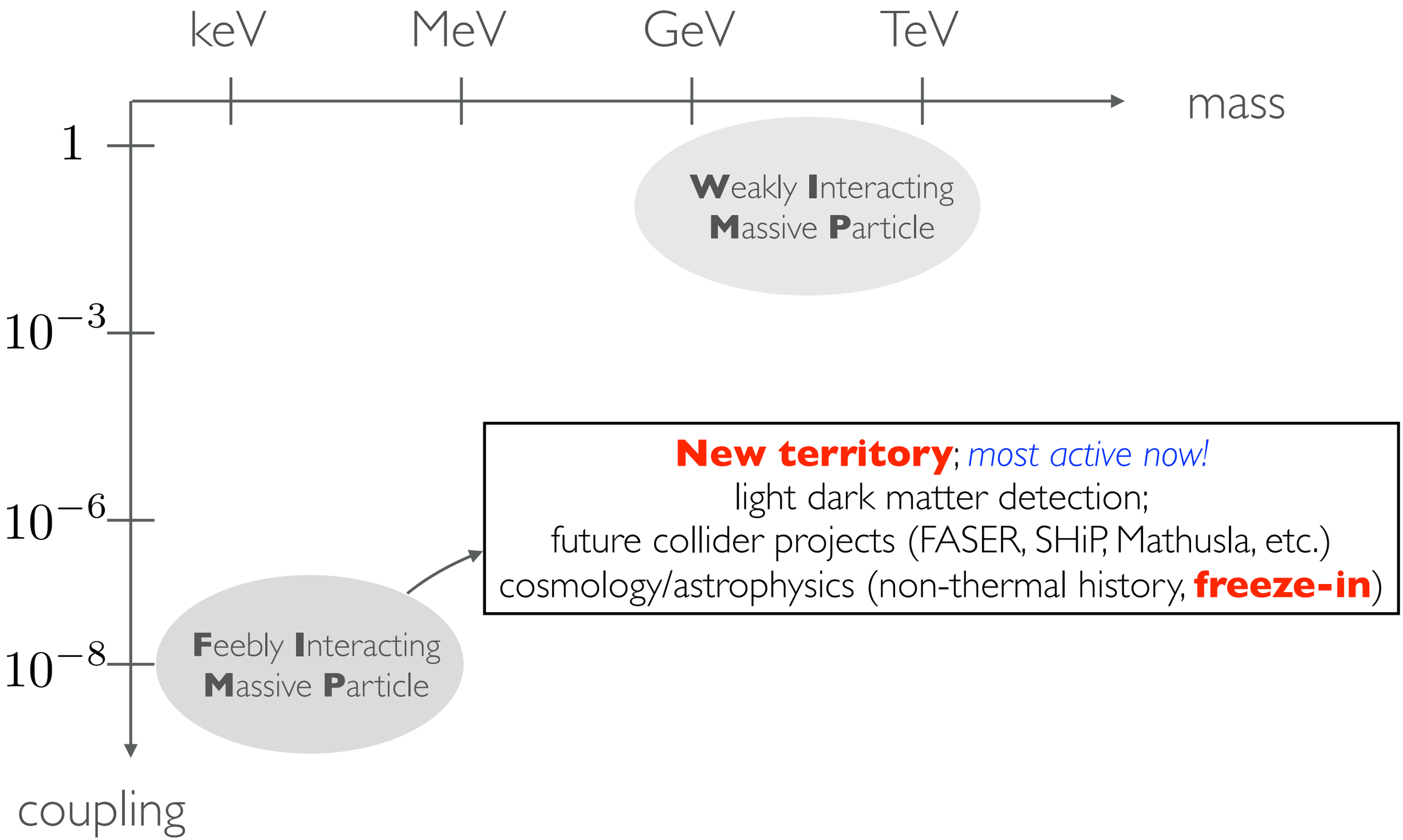


LONG-LIVED PARTICLE (DM)



STUDY ON DARK MATTER

Freeze-out

produced from *equilibrium*

O(weak) coupling

accessible at LAB

relic abundance

(in)direct detection

mono-X: spectral decomposition

Freeze-in

non-*equilibrium*

feeble coupling

long-lived particle

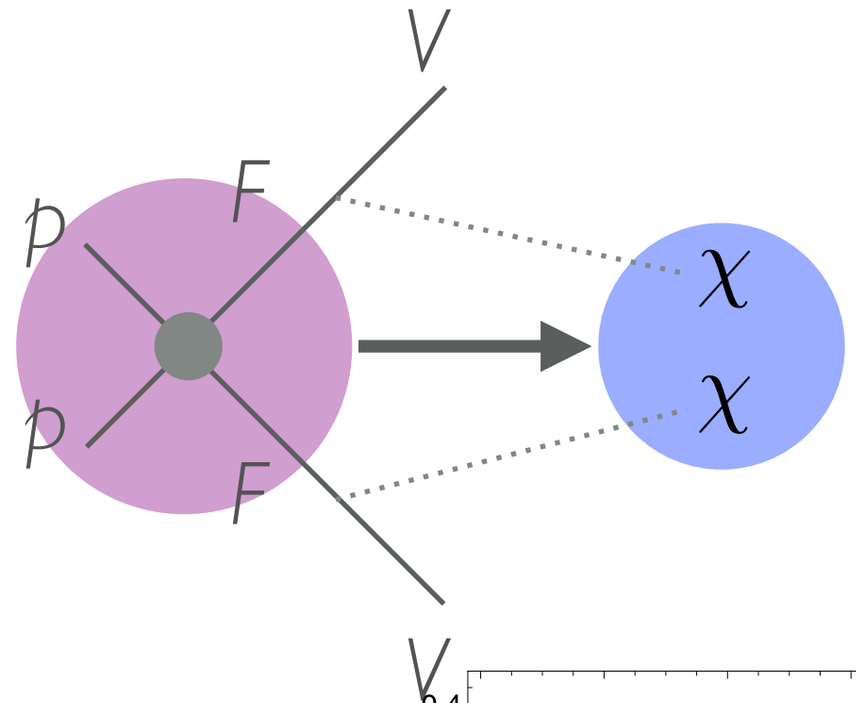
relic abundance: non-thermal dist.

Astrophysical observation: neural network

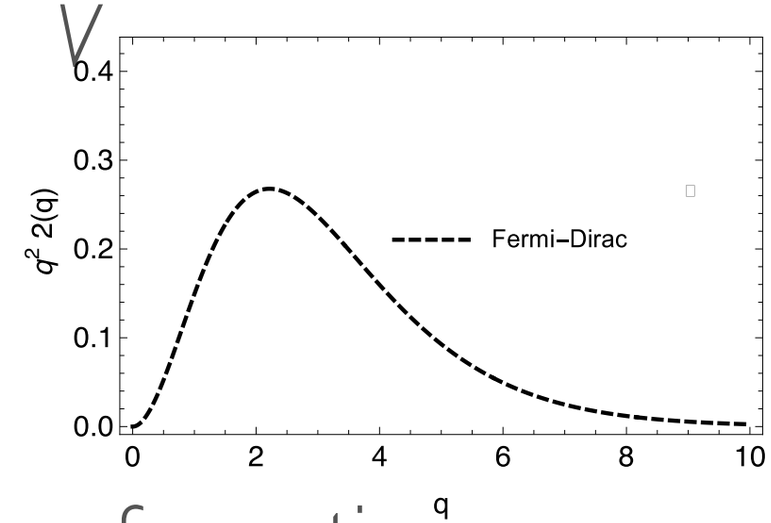
LHC search: displaced vertex

FREEZE-**IN** DM SEARCH

- Feeble interaction
  - correct abundance, $\lambda \lesssim 10^{-8}$
  - collider search (displaced vertex)



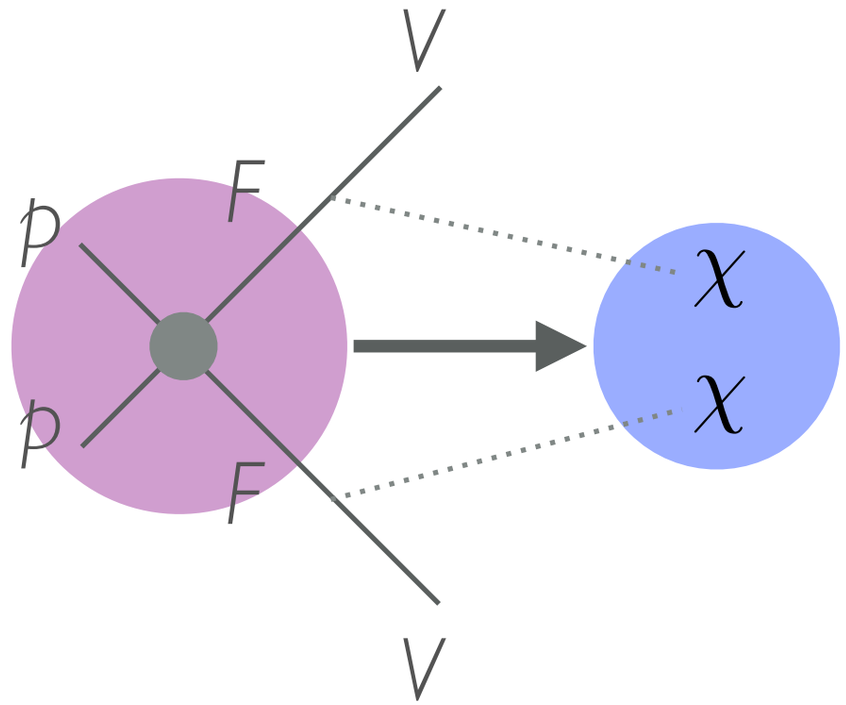
- Non-thermal nature
  - thermal WIMP: thermal dist. (e.g. Fermi-Dirac)



  - Freeze-in DM never be in thermal eq.
  - preserve its dist. leaving footprints in structure formation

- Model Construction
  - Do we have any motivated model?

DISPLACED VERTEX



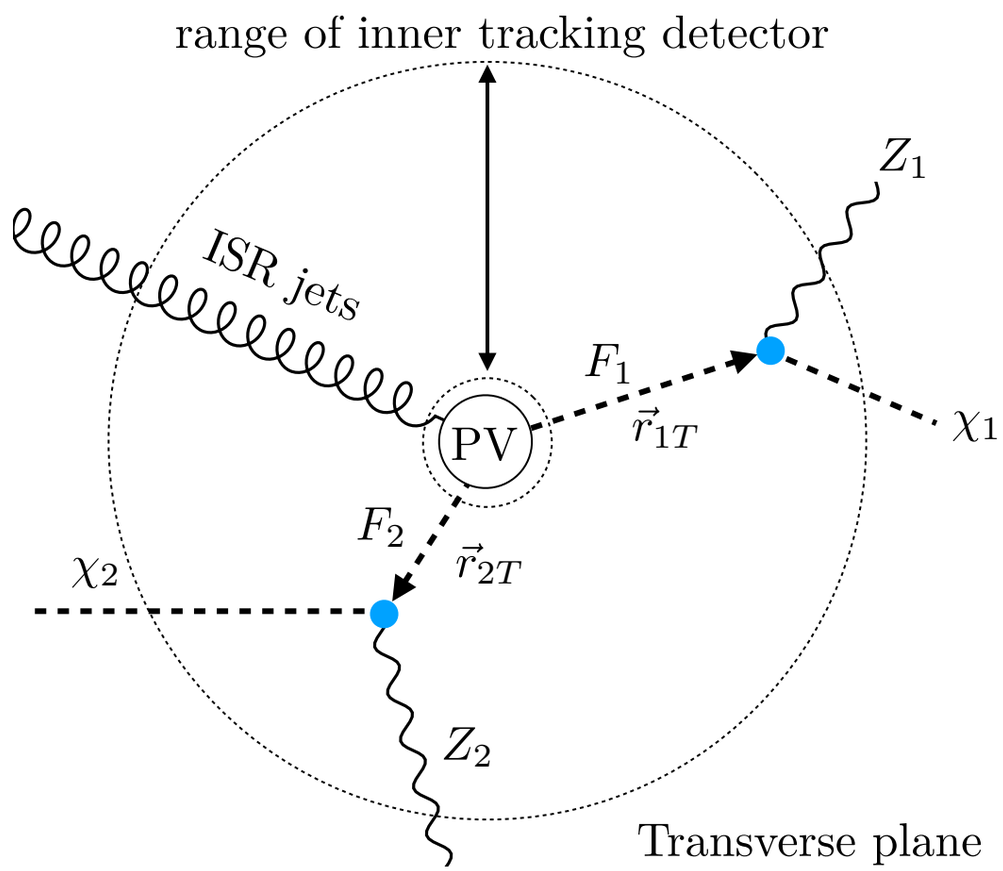
small coupling with visible sector

visible particle becomes long-lived

searching for displaced vertex signal

EVENT-BY-EVENT RECONSTRUCTION

KJB, Park, Zhang

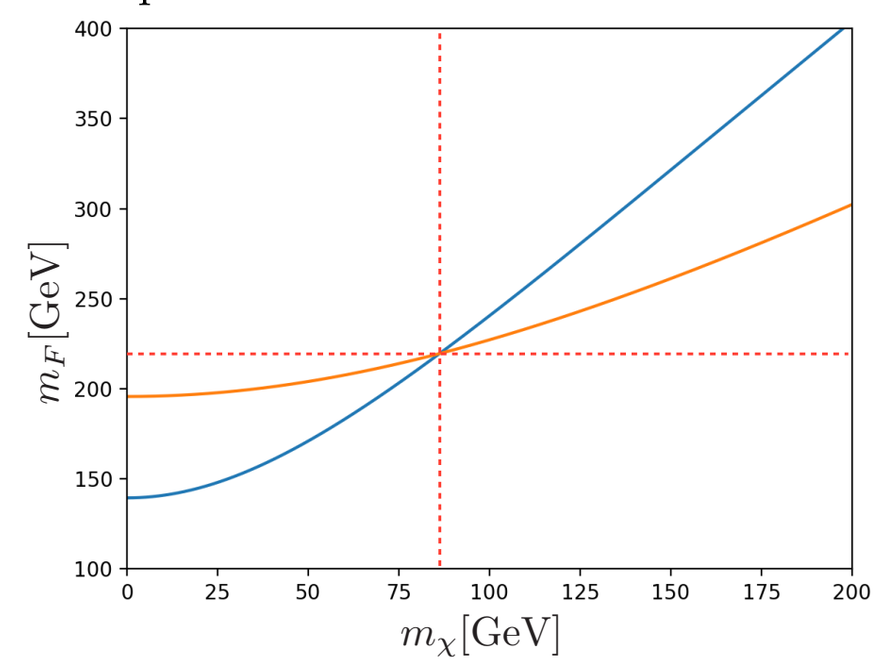


on-shell conditions

$$m_F^{(1)}(m_\chi) = \sqrt{\left(\sqrt{|\vec{p}_1|^2 + m_Z^2} + \sqrt{||\vec{q}_1|\hat{\vec{r}}_1 - \vec{p}_1|^2 + m_\chi^2}\right)^2 - |\vec{q}_1|^2},$$

$$m_F^{(2)}(m_\chi) = \sqrt{\left(\sqrt{|\vec{p}_2|^2 + m_Z^2} + \sqrt{||\vec{q}_2|\hat{\vec{r}}_2 - \vec{p}_2|^2 + m_\chi^2}\right)^2 - |\vec{q}_2|^2}$$

$$|\vec{q}_1| = p_{\rm ISR}\frac{\sin(\phi_2 - \phi_3)}{\sin\theta_1 \sin(\phi_1 - \phi_2)}\ ,\ |\vec{q}_2| = p_{\rm ISR}\frac{\sin(\phi_3 - \phi_1)}{\sin\theta_2 \sin(\phi_1 - \phi_2)},$$



MASS DETERMINATION

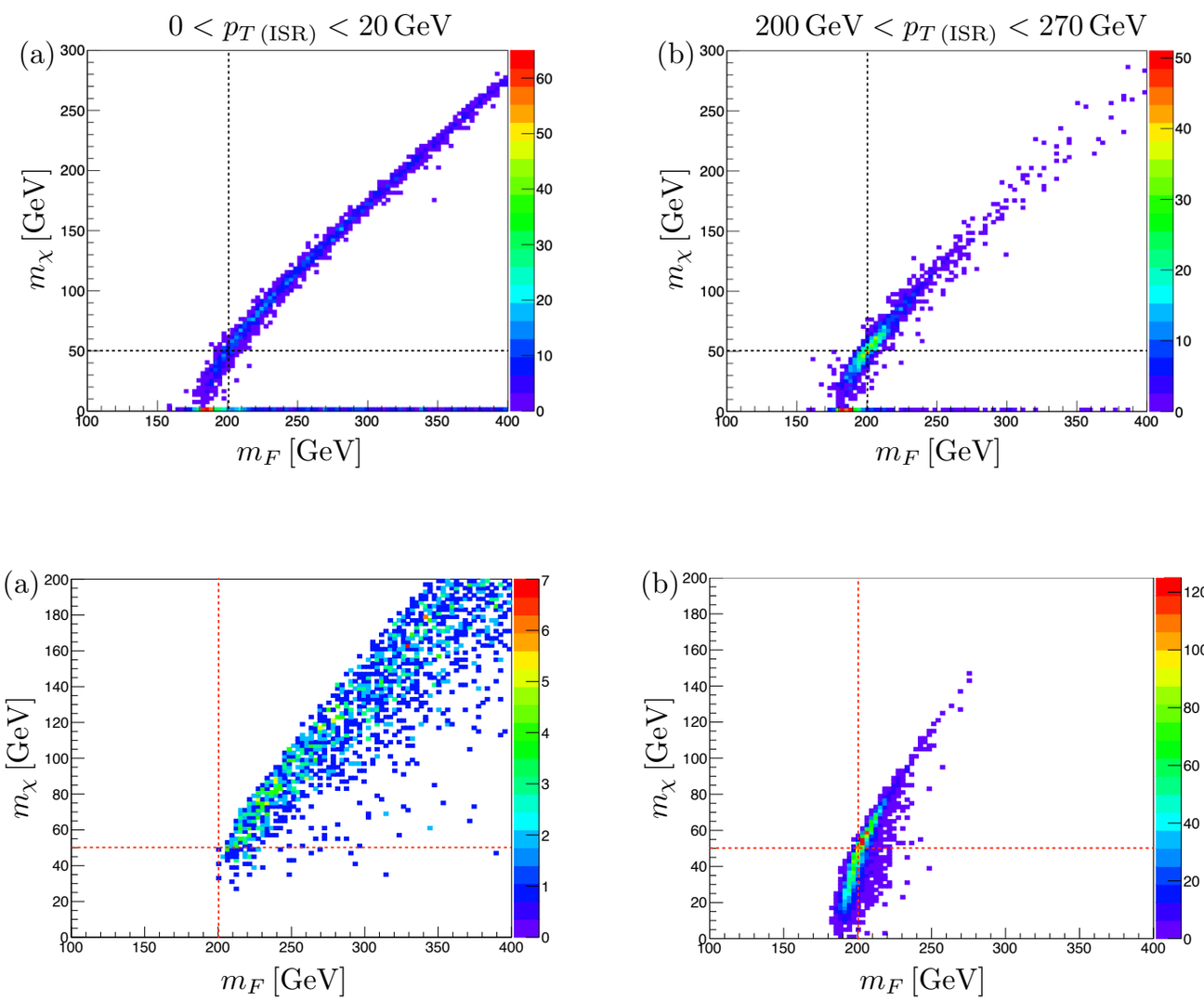
KJB, Park, Zhang

HL-LHC

$$pp \to FF + j \to \underline{ZZ}\chi\chi + j$$

$$l^+l^-l'^+l'^-$$

B. P.	m_F [GeV]	m_χ [GeV]	$c\tau$ (mm)	N_{events}@ HL-LHC
A	200	0	100	30
B	200	108	100	20
C	800	0	100	12
D	800	708	100	24



- Kinematics determines "warmness" of freeze-in dark matter.
- Checking cosmology at collider

Quo vadis, Domine?

FUTURE COLLIDER

Our naive wish for weak scale new physics has gone.

Nothing new? Is SM alright?

Looking at the nature of Higgs scalar, I believe that

something must reside above our territory, or

our QFT description for the particle physics is totally wrong.

To make the answer, or approach to the answer

we need the high energy collider

FUTURE COLLIDER

FCC: higher energy & larger luminosity will show us

how much tuned our world is, or

new physics above us

Muon collider: next generation lepton collider

precision higgs physics (direct production possible)

new signal from leptons

collision of unstable particles

CONCLUSIONS

- We hope for new physics once we established the SM
- (weak scale) SUSY seemed promising.
- LHC destroys almost everything, but triggers many new ideas: neutral naturalness, cosmological relaxation, light DM, ...
- Without high energy collisions, we cannot judge what is wrong, what is right.
- Future collider will be a frontier, triggering new ideas and paradigm.