Higgs, Dark Matter and beyond

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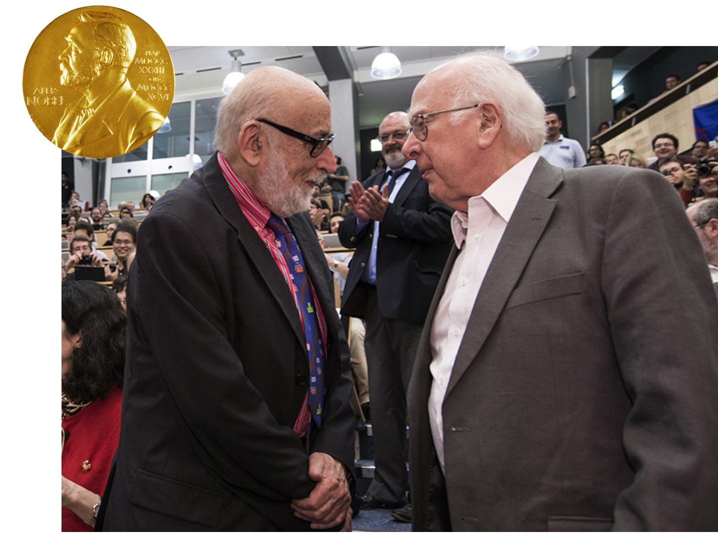
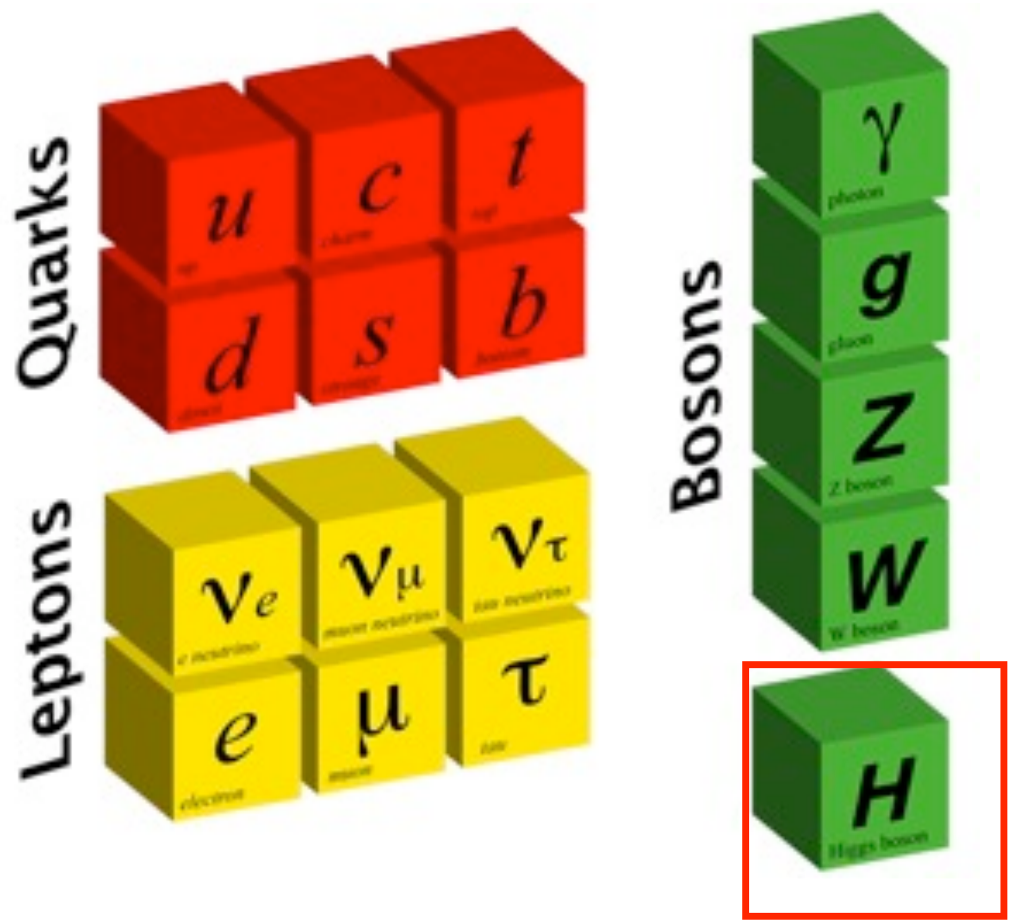
It has been 10 years.



The Standard Model is complete.

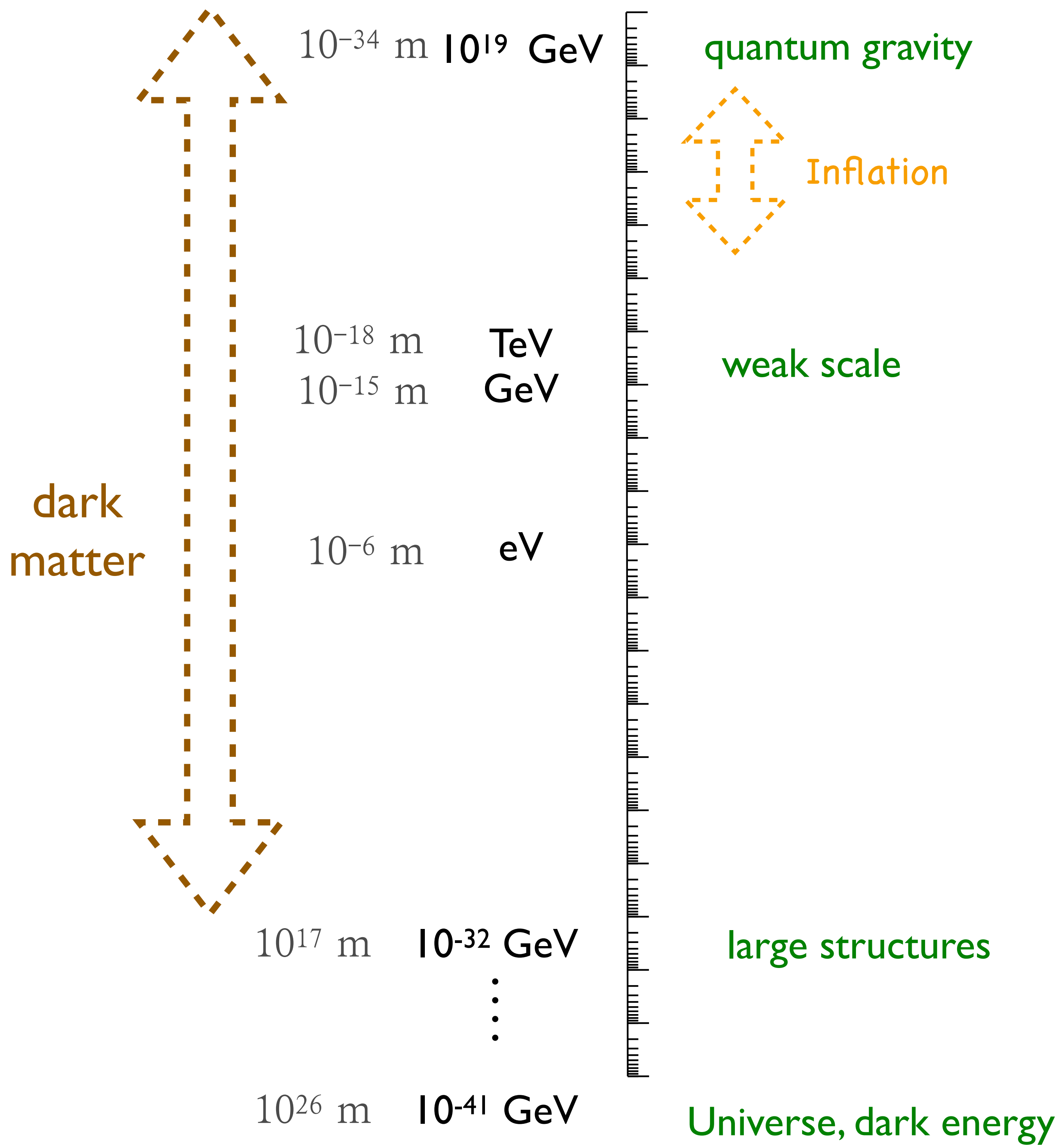


1961–1968

The Standard Model is very successful.

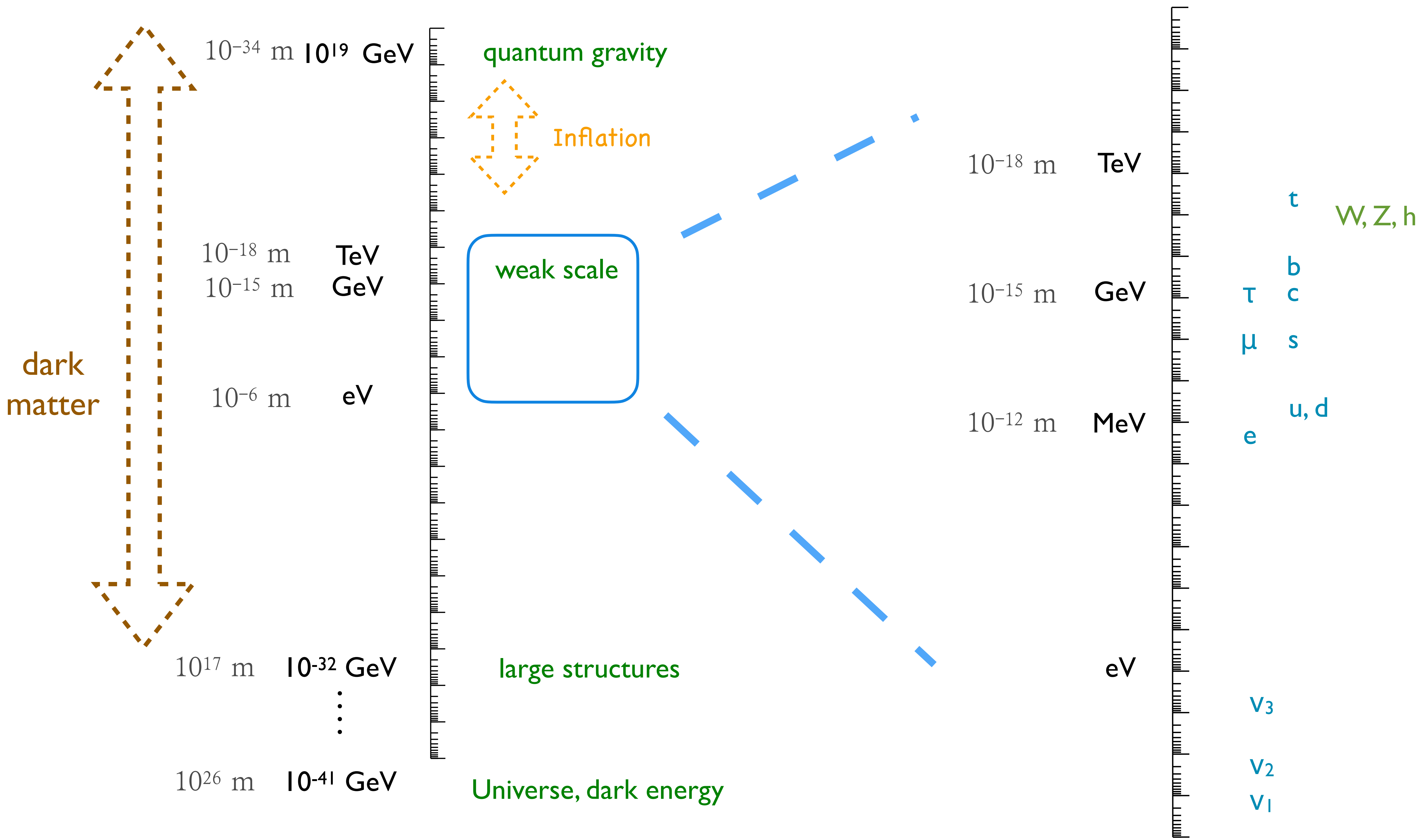
Many experimental tests. No cracks yet.

Our world



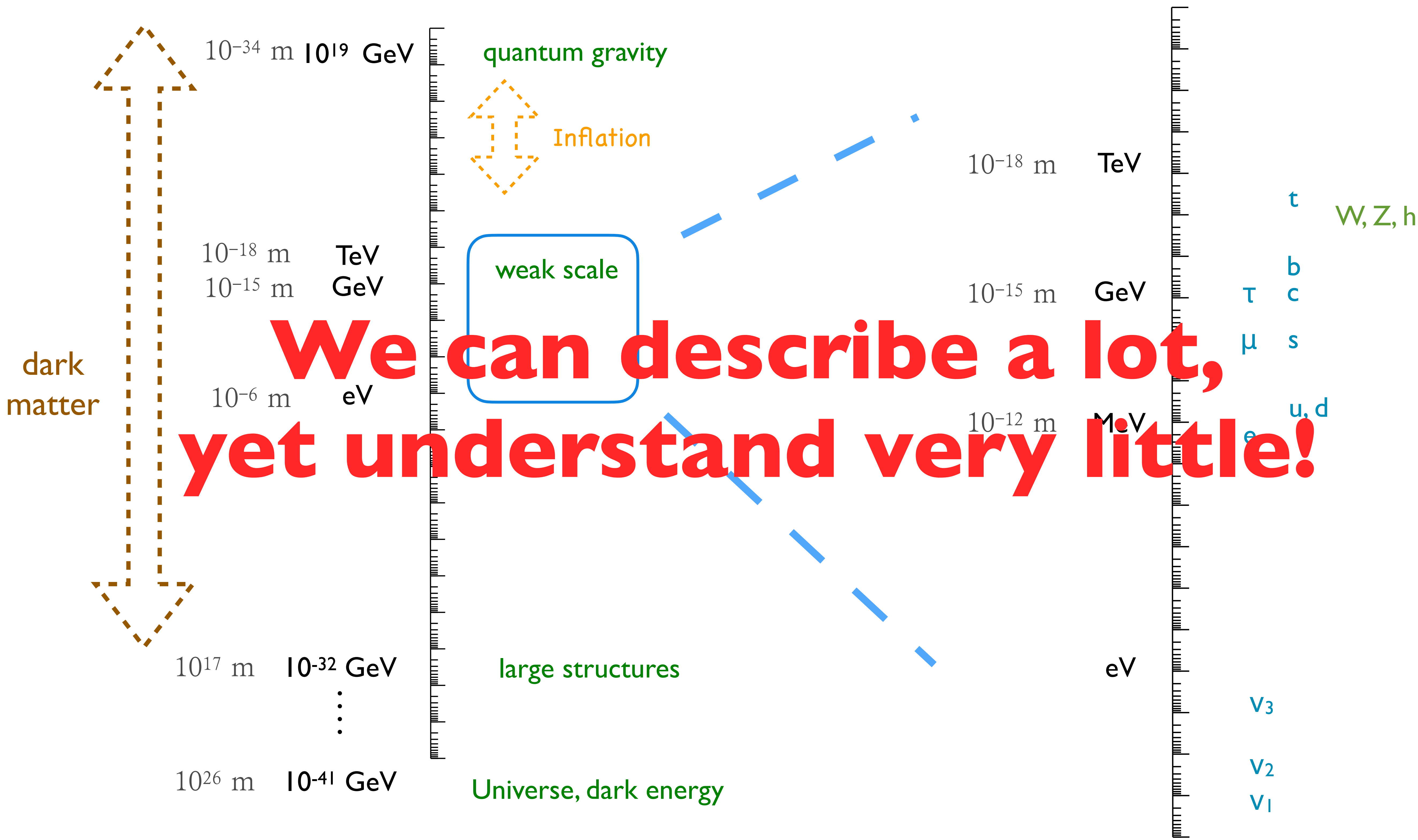
Amazing progresses in the last ~100 years

Our world



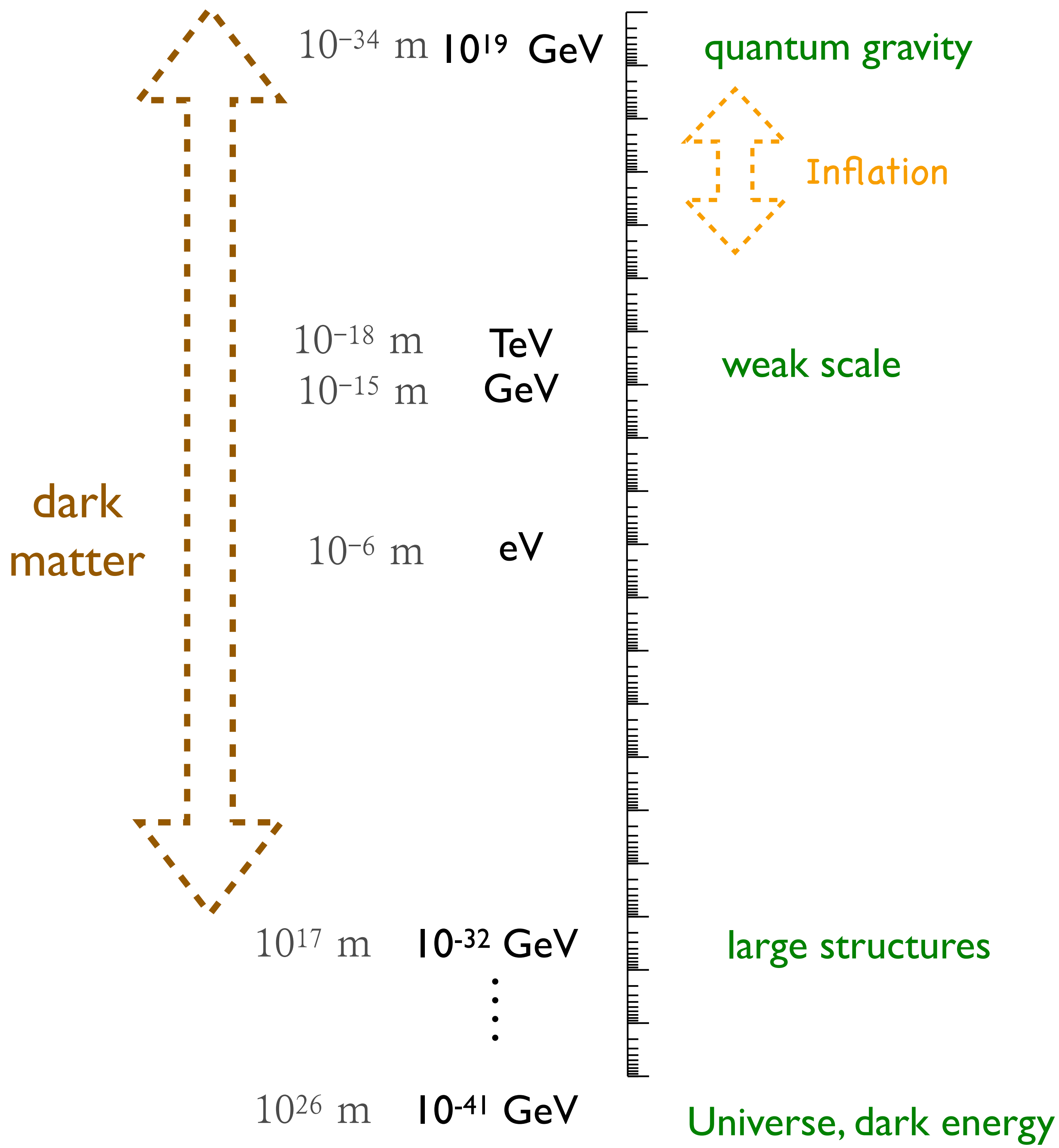
A lot of structure, multitudes of scales, but why?

Our world



We can describe a lot, yet understand very little!

Beginning of an new era



In particular

Why all the different scales?

Why are there 4 interactions?
Why are they so different?

Why 3 families?
why are they so different?

Why more matter than anti-matter?

Dark matter?

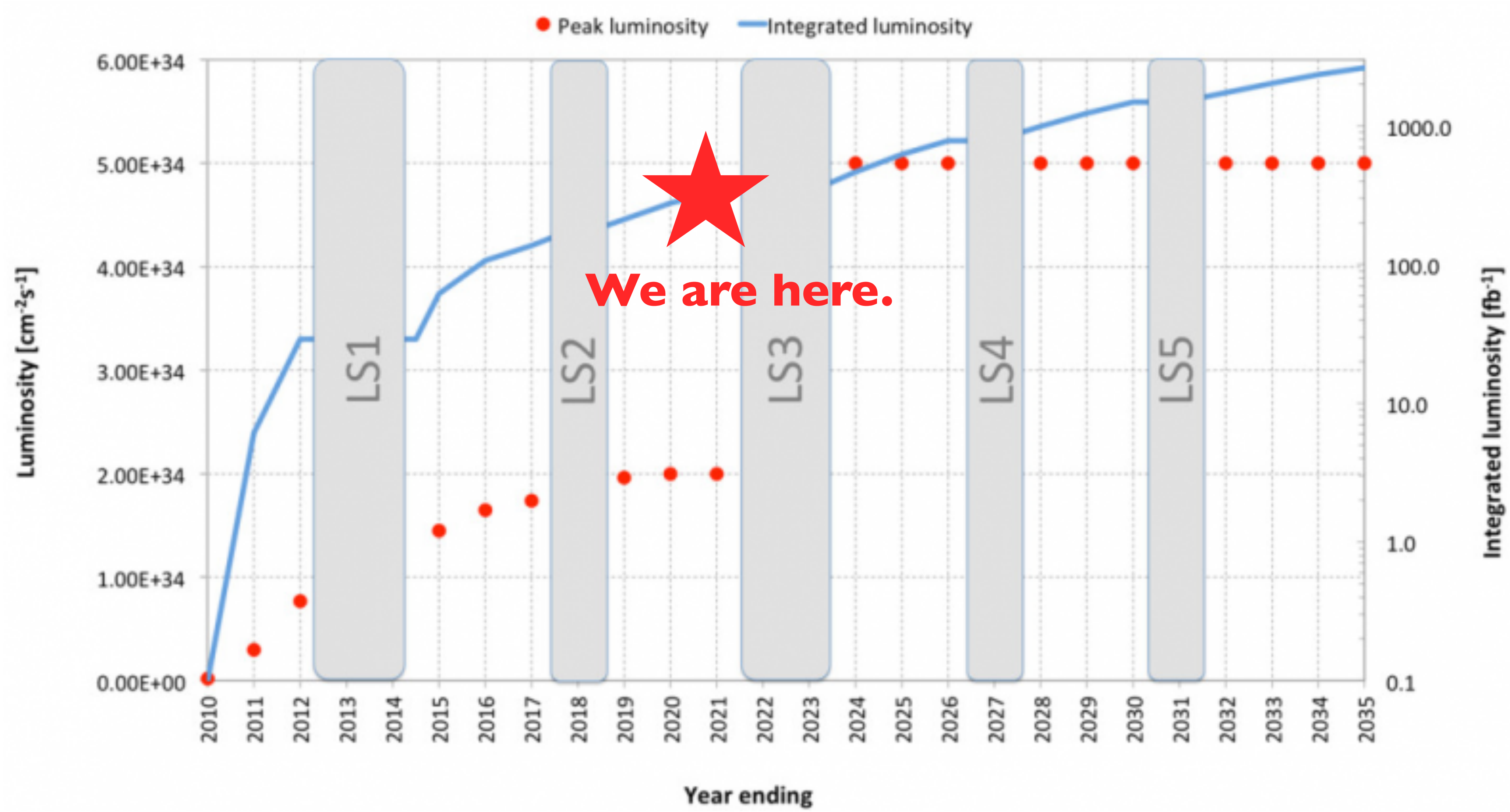
Inflation?

Dark energy? ...

This talk:

- Origin of electroweak symmetry breaking.
- What is Dark matter?

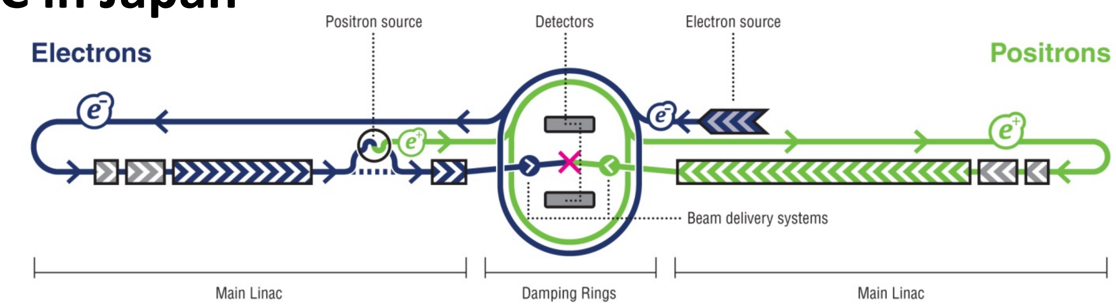
Our immediate future

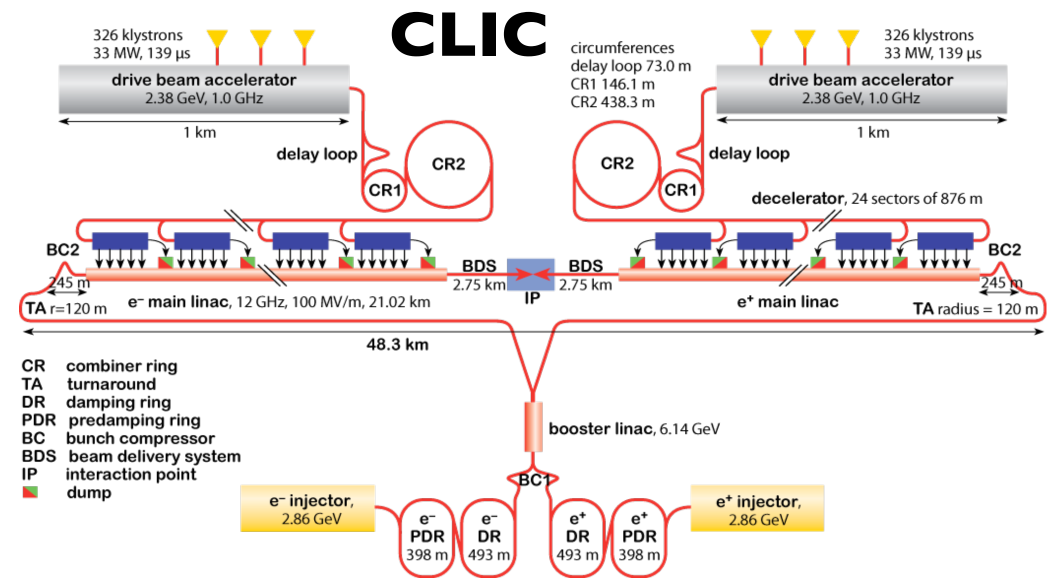


Still about 10 times amount of data to come.

Future Colliders

ILC in Japan





pp collider ~100 TeV

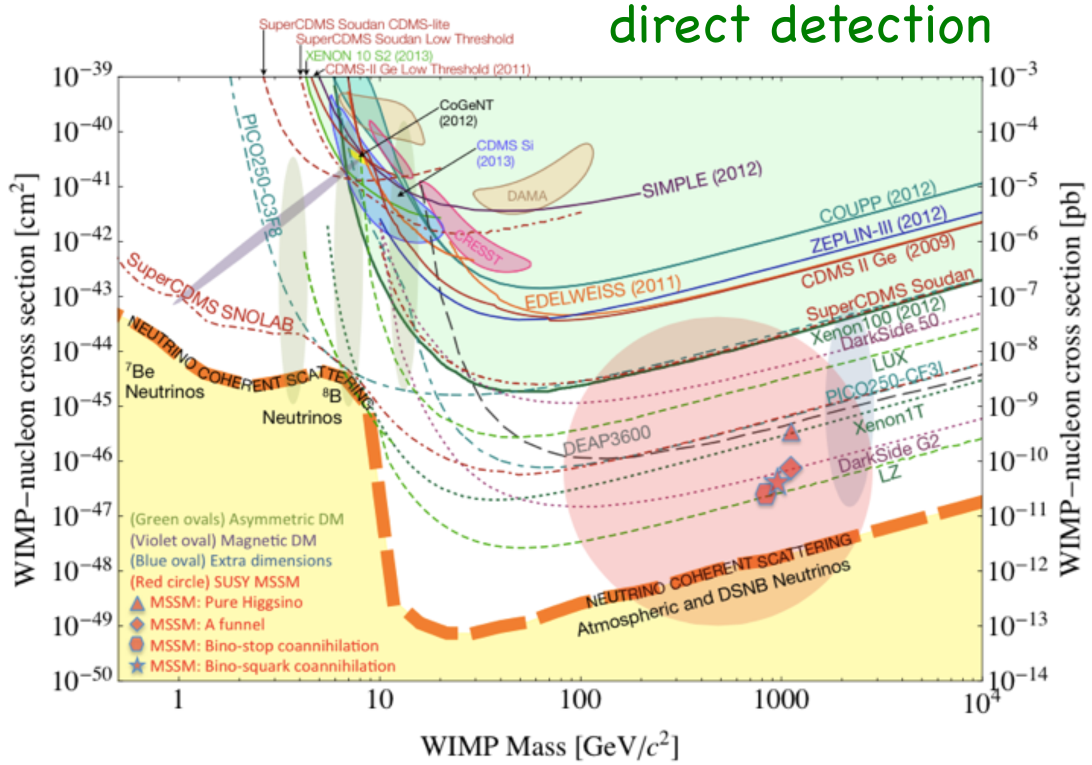
FCC-hh (CERN), SppC(China)

e^-e^+ Higgs Factory 250 GeV

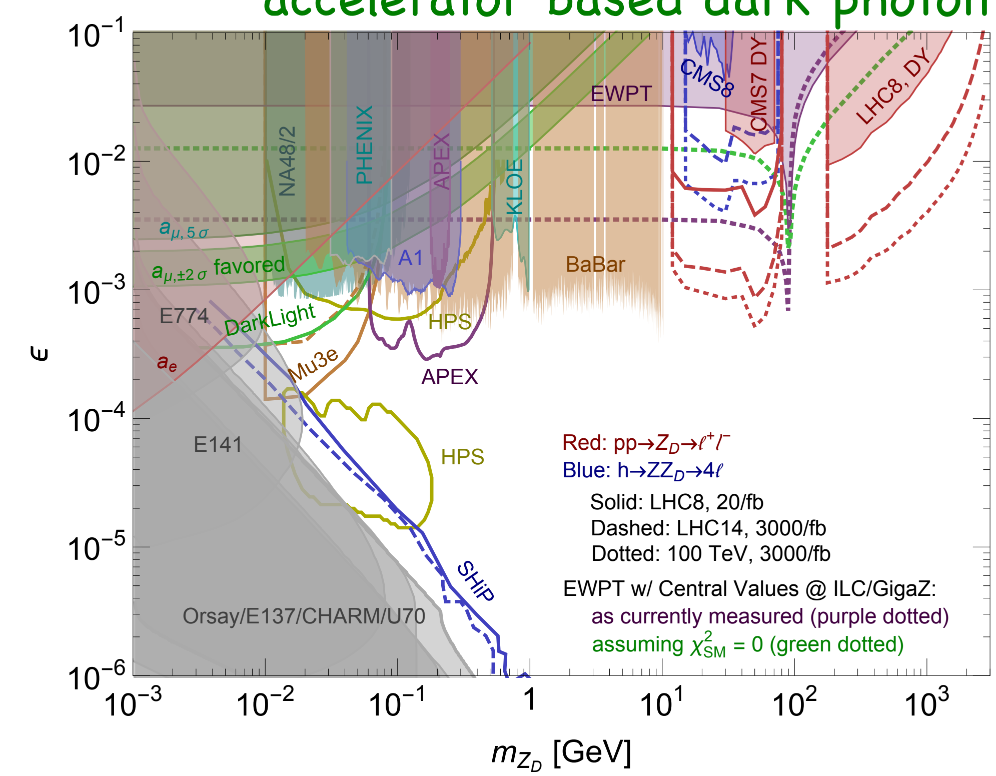
FCC-ee (CERN), CEPC(China)

Search for dark matter

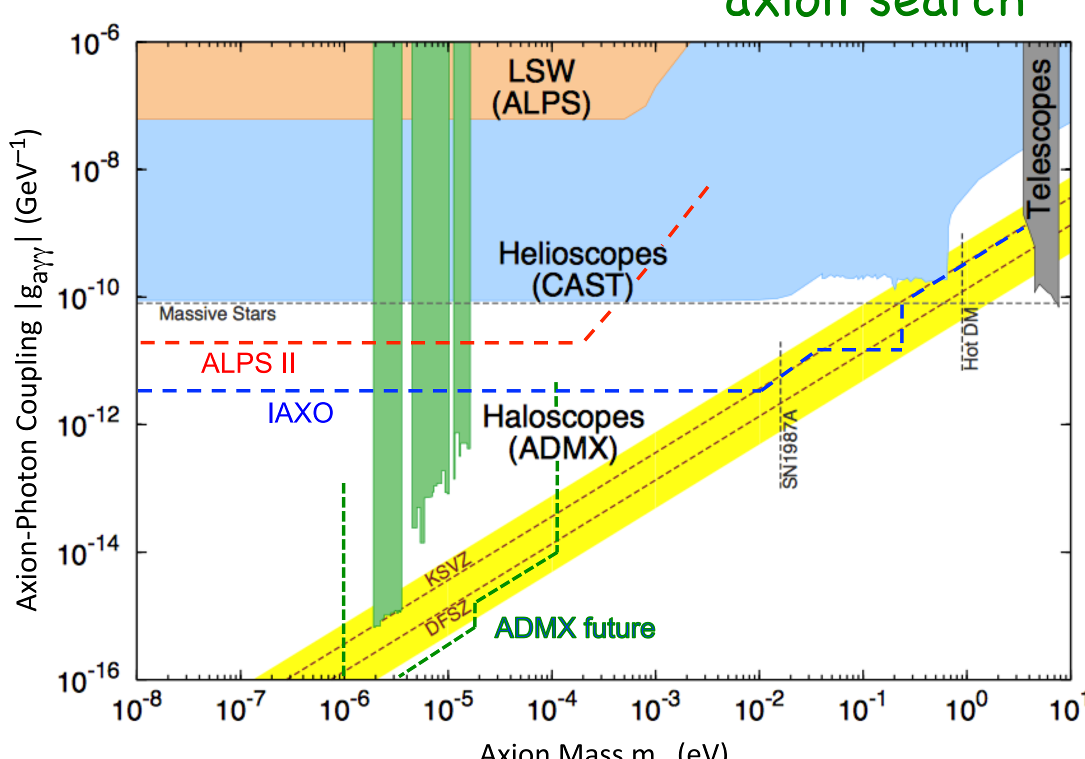
direct detection



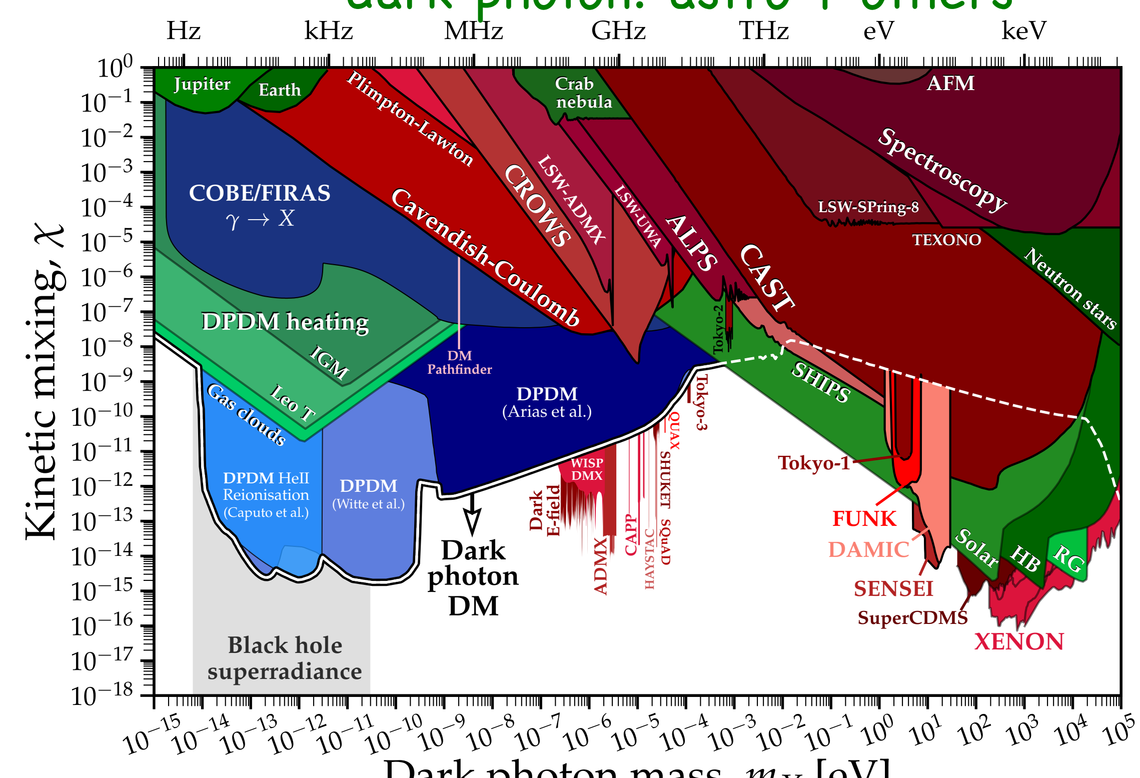
accelerator based dark photon



axion search



dark photon: astro + others



Lots of experiments, searches. New data to come in the next decades.

So, what are we looking for?

Electroweak symmetry breaking

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \frac{\alpha}{r}$

QCD: confinement $\sim r$

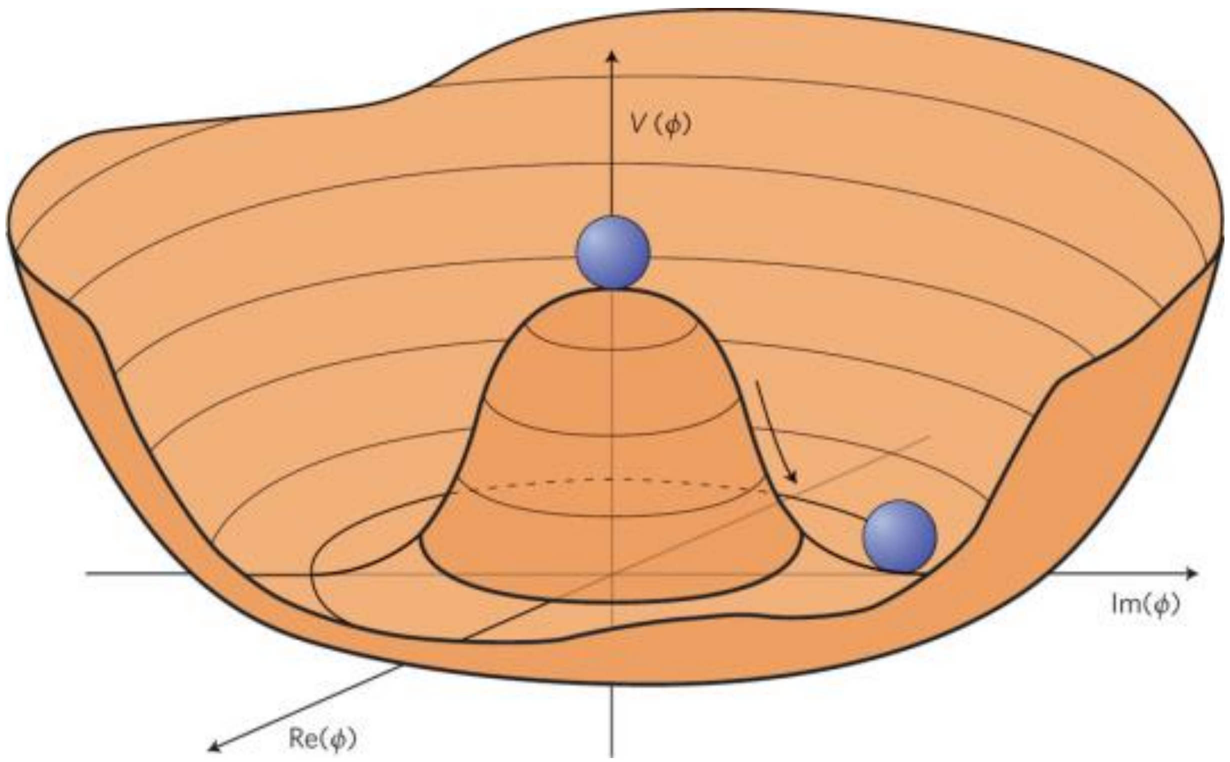
Well understood with many decades of exp study.

Lead to numerous breakthroughs, including the establishing QM and QFT

Weak interaction: Higgs $\sim \frac{e^{-m_W \cdot r}}{r}$

A very different type of interaction.
With a spin-0 Higgs boson, different from all other particles.
We have just barely started to study it, much to learn.

"Simple" picture:



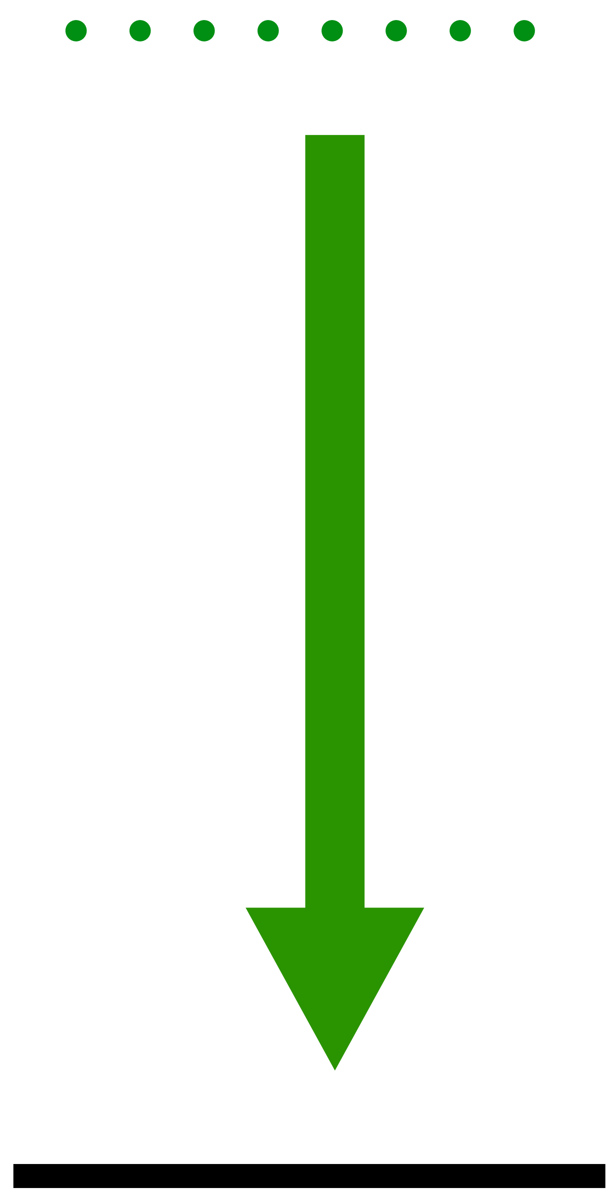
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

How to predict Higgs mass?



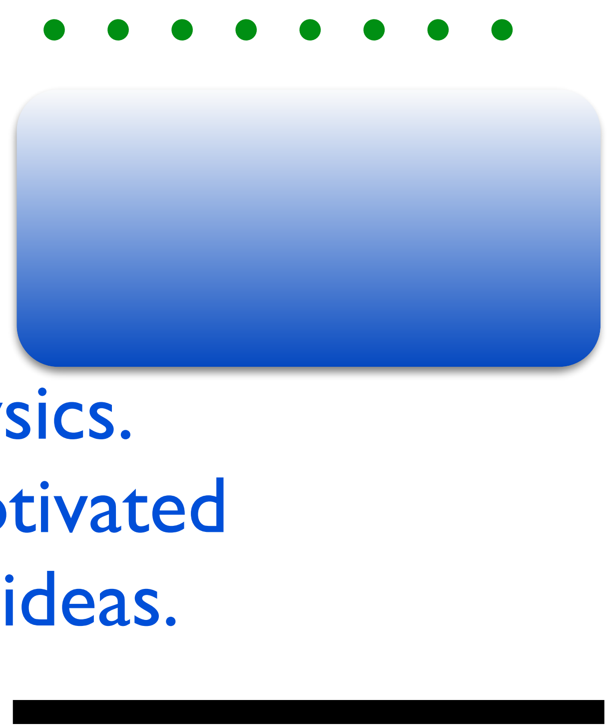
The energy scale of new physics
responsible for EWSB

What is this energy scale?
$M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking



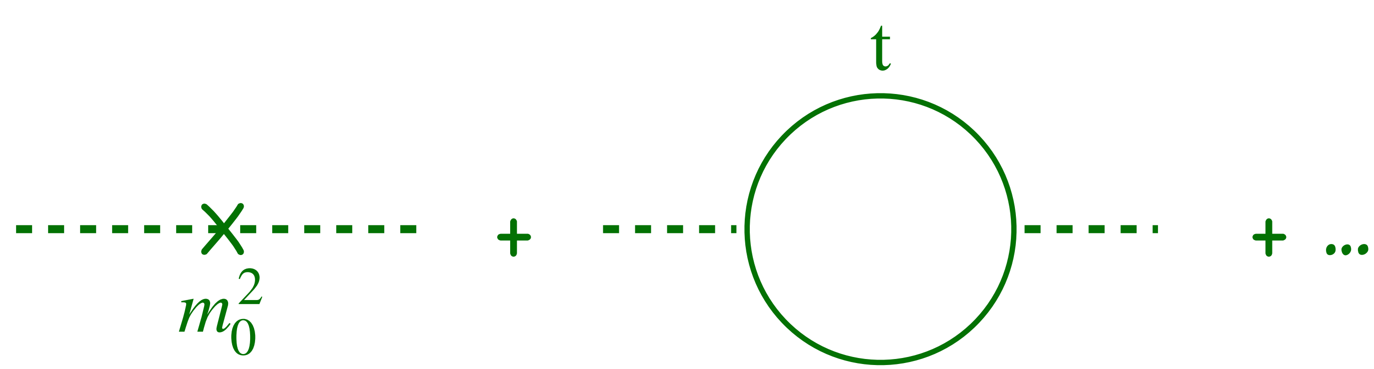
The energy scale of new physics
responsible for EWSB

TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W ...

How to generate the electroweak scale?

- The Higgs mass is not calculable in the Standard Model. It is a parameter.



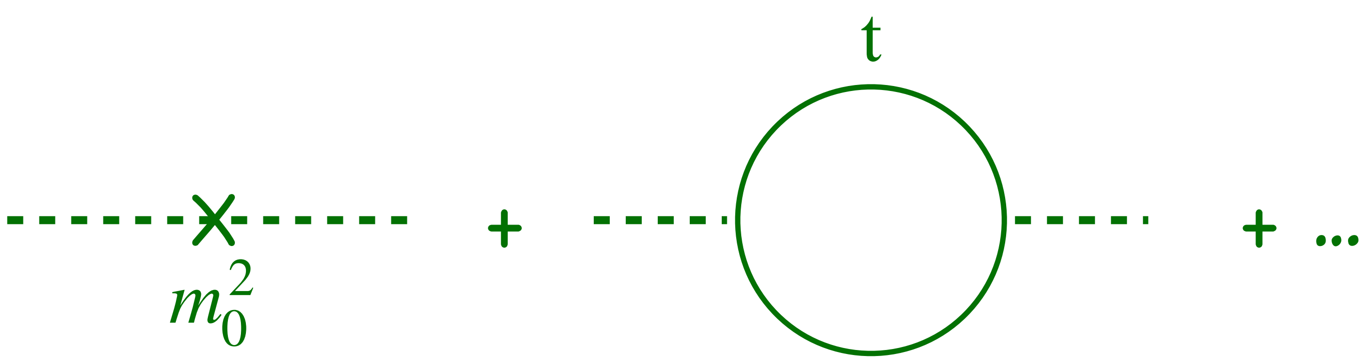
$$m_h^2 = m_0^2 - \frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$$

Λ: mass scale of UV (more fundamental) physics

M_0^2 : bare mass term

We can use m_h^2 to calculate other observables.
However, SM can't predict m_h^2 itself.

How to generate the electroweak scale?



$$m_h^2 = m_0^2 - \frac{6y_t^2}{16\pi^2}\Lambda^2 + \dots$$

- A more fundamental theory to predict Higgs mass
  - With its own scale M.
  - No dependence on arbitrary (unknown) UV scale Λ, or a fudge bare mass term m_0.
  - Then, in this model,

$$m_h^2 = cM^2$$

c: couplings, loops...

Toy model of scale generation

Scalar ϕ coupling to fermions

$$\mathscr{L} \supset M_\Psi(\bar{\Psi}_1\Psi_1 + \bar{\Psi}_2\Psi_2) + y\phi\bar{\Psi}_1\Psi_2 + \text{ h.c.}$$

Generating scalar potential:

$$V^\Psi(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \underbrace{bM_\Psi^2 y^2\phi^2}_{\text{mass}} + \underbrace{cy^4\phi^4}_{\text{quartic}}\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

$a,\ b,\ c \sim \mathcal{O}(1)$, calculable

Coupling to another scalar, similar story

$$\mathscr{L} \supset \frac{M_\Phi^2}{2}\Phi^2 + \frac{\kappa}{2}\phi^2\Phi^2$$

$$V^\Phi(\phi) \simeq \frac{1}{16\pi^2}\left(a' M_\Phi^4 + \underbrace{b'\kappa^2 M_\Phi^2\phi^2}_{\text{mass}} + \underbrace{c'\kappa^4\phi^4}_{\text{quartic}}\right)\left(\log\frac{M_\Phi^2}{\mu^2} + \ldots\right)$$

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \boxed{by^2M_\Psi^2\phi^2} + cy^4\phi^4\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

⇩

$$V_{\rm eff}(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4}\phi^4, \qquad m_\phi^2 = -\frac{b}{16\pi^2}M_\Psi^2$$

Difficult to generate: $m_\phi \ll M_\Psi$

Expectation: new physics scale close to scalar mass

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_{\Psi}^4 + by^2M_{\Psi}^2\phi^2 + cy^4\phi^4\right) \times \left(\log\frac{M_{\Psi}^2}{\mu^2} - \ldots\right)$$

$$V^{\Phi}(\phi) \simeq \frac{1}{16\pi^2}\left(a'M_{\Phi}^4 + b'\kappa^2M_{\Phi}^2\phi^2 + c'\kappa^4\phi^4\right)\left(\log\frac{M_{\Phi}^2}{\mu^2} + \ldots\right)$$

$$\square + \square \Rightarrow \quad m_{\phi}^2 = \frac{1}{16\pi^2}(-aM_{\Psi}^2 + bM_{\Phi}^2)$$

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \boxed{by^2M_\Psi^2\phi^2} + cy^4\phi^4\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

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$$\Box + \Box \;\Rightarrow\; m_\phi^2 = \frac{1}{16\pi^2}(-aM_\Psi^2 + bM_\Phi^2)$$

Possible to have $m_\phi \ll M_{\Psi,\Phi}$ However,

need cancellation : $\sim \mathcal{O}\left(16\pi^2\frac{m_\phi^2}{M_{\Psi,\Phi}^2}\right)$ fine-tuning

tuning $\propto M_{\rm NP}^{-2}$ is bad if $m_\phi \ll M_{\rm NP}$

Back to the Higgs mass

$$m_h^2 = cM^2 \qquad c \sim \frac{(\text{coupling})^2}{16\pi^2}$$

- Coupling is about O(0.1-1).
- Without large cancellation: M $\lesssim$ TeV.
  - New physics near weak scale!
- In particular:
  - Since top quark gives largest contribution to Higgs mass, we expect some "top-partner" to be around TeV scale.

TeV Supersymmetry (SUSY)

- Supersymmetry, $|\text{boson}\rangle \Leftrightarrow |\text{fermion}\rangle$
- An extension of spacetime symmetry.

A beautiful quantum field theory!

- New states: "Partners"

	spin			spin
gluon, g	1	gluino	$\tilde{g}$	1/2
$W^{\pm}$, Z	1	gaugino	$\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark	1/2	squark	$\tilde{q}$	0
....		....		
Standard Model particles		superpartners		

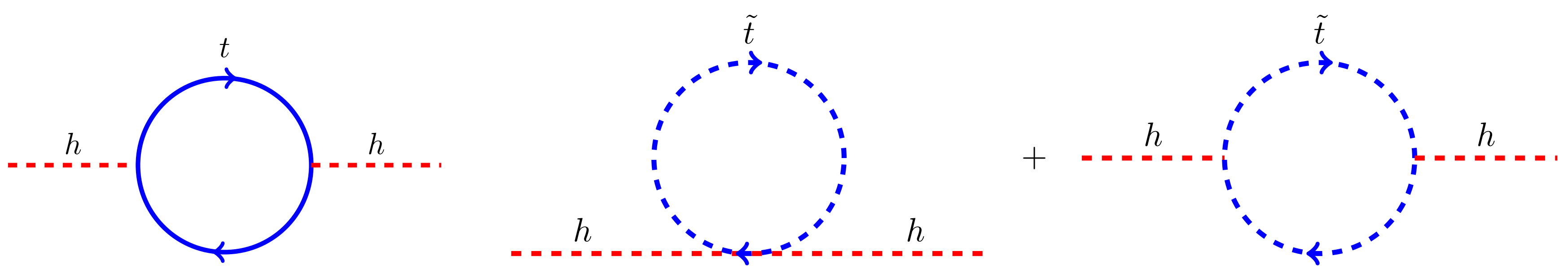
- Mass of superpartners $\sim$TeV.

Electroweak scale in Supersymmetry

A unique property of supersymmetry:

No Λ^2 dependence.

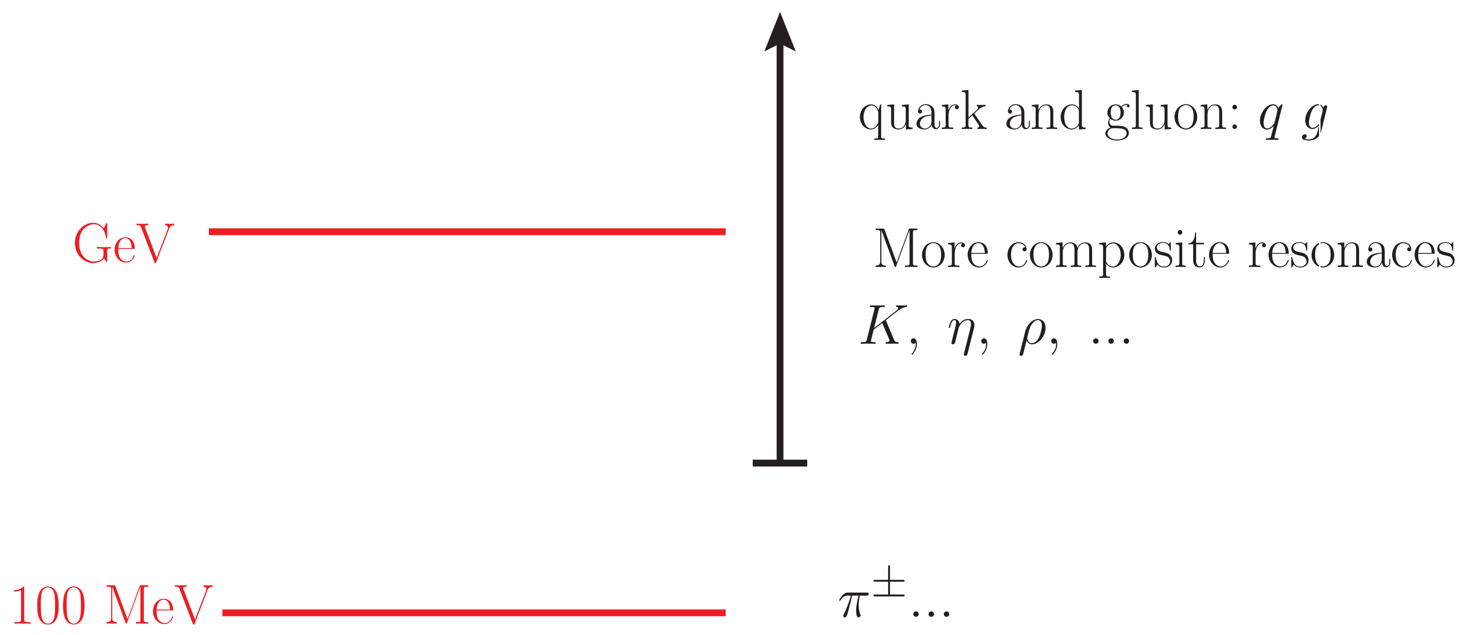
Mass parameters evolves slowly, generating large scale separation.



$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\text{TeV}}.$$

Prefer light superpartners $\quad m_{\text{SUSY}} \sim 1\ \text{TeV}$

"Learning" from QCD



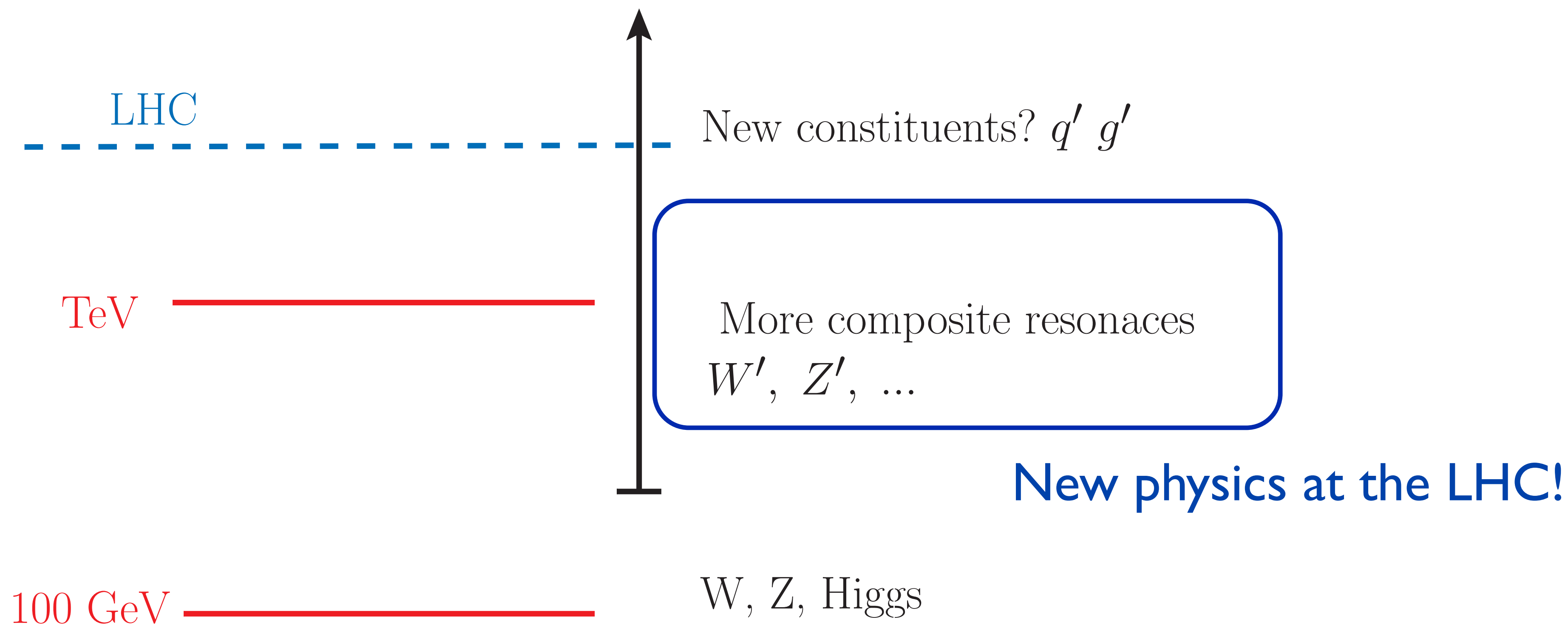
$\Rightarrow$ new strong dynamics, symmetry breaking

$\Rightarrow$ SM Higgs

- Construct a new strong dynamics in which the low lying states will be the SM Higgs.

- Composite Higgs models. Still a natural theory.

Composite Higgs



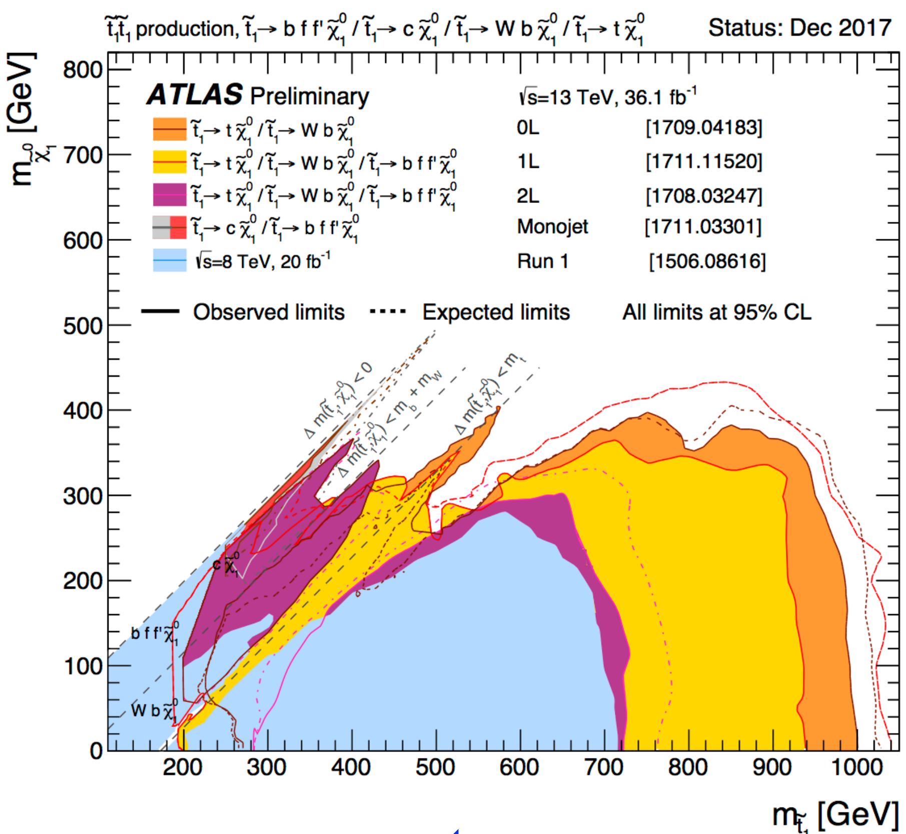
- Many many scenarios, models in this class.
- Little, fat, twin, holographic .... Higgs

– Similar scenarios: Randall-Sundrum, UED...

- Theories with Higgs + resonances.

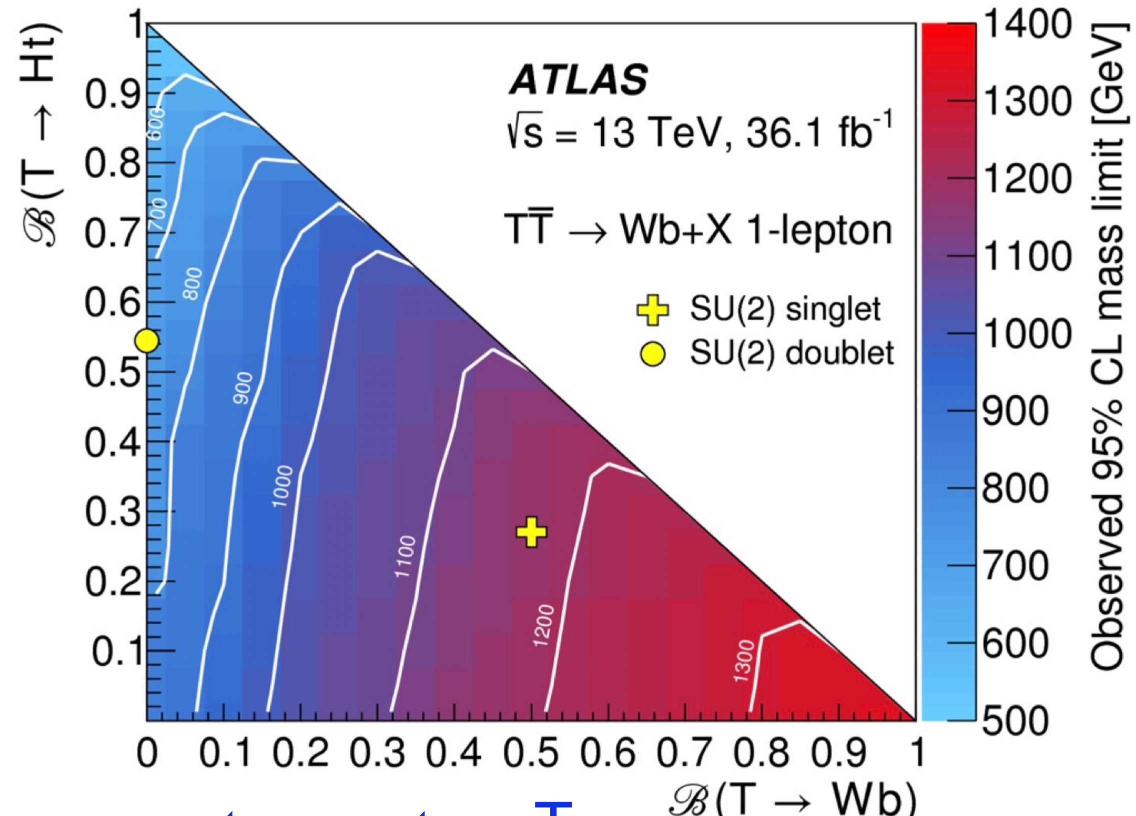
All eyes on these searches

Supersymmetry



stop

Composite Higgs



top partner, T

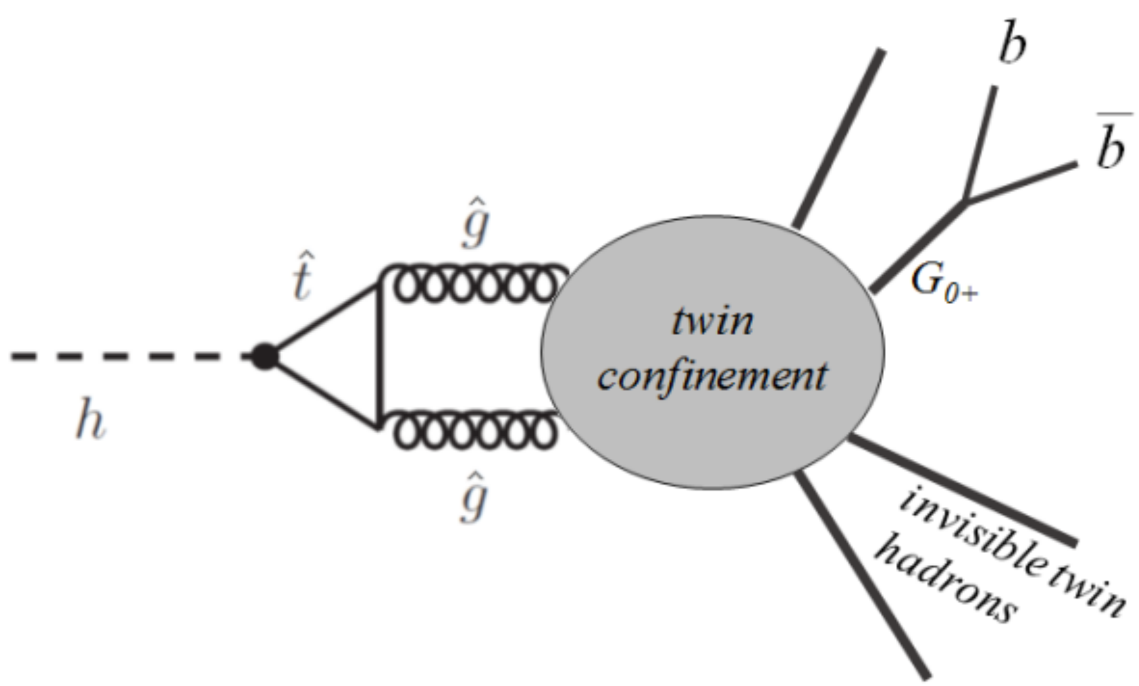
fine-tuning = comparison: $$\frac{1}{16\pi^2} m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$$

current limit: $$m_{\mathrm{T}} \sim 1\ \mathrm{TeV}$$

Stealthy top partner. "twin"

Chacko, Goh, Harnik

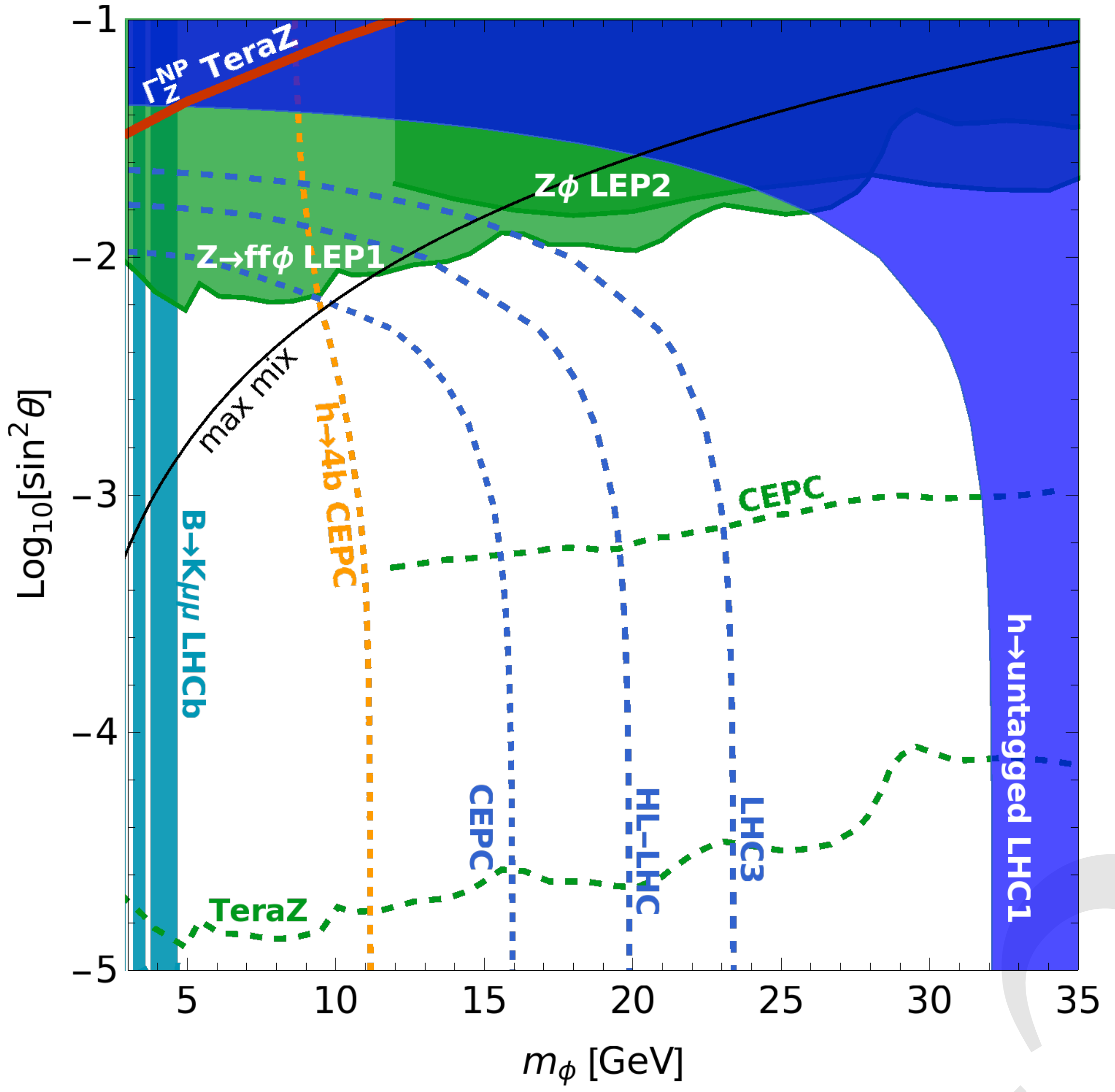
Craig, Katz, Strassler, Sundrum



- Top partner not colored. Higgs decay through hidden world and back.

- Can lead to Higgs rare decays.

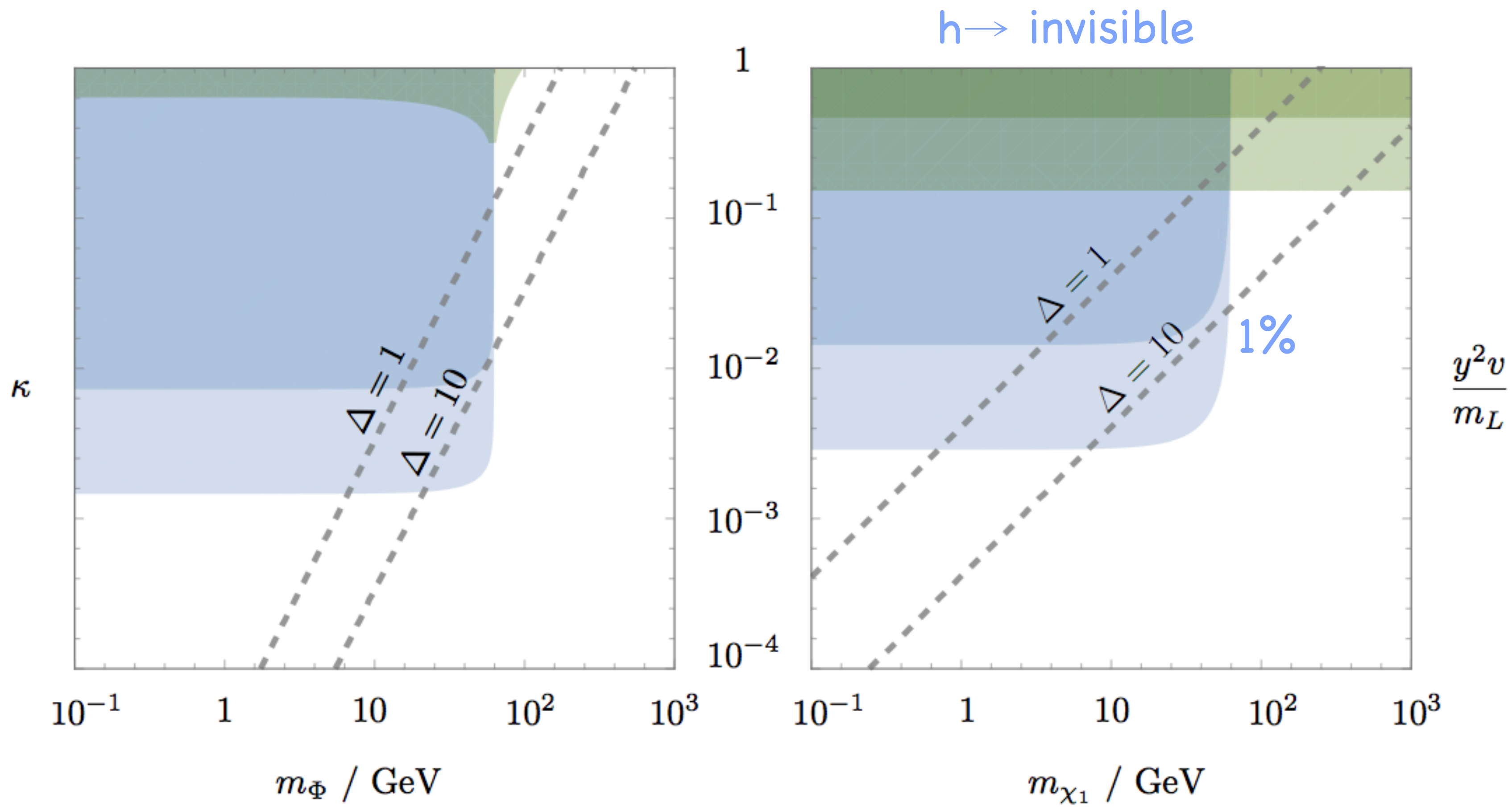
Relaxion



Cosmological evolution of a light scalar, the relaxion, sets the weak scale

Signal from relaxin-Higgs mixing,
and Higgs rare decay, $h \to \phi\phi \to 4b$ and rare Z decay

Weak gravity conjecture



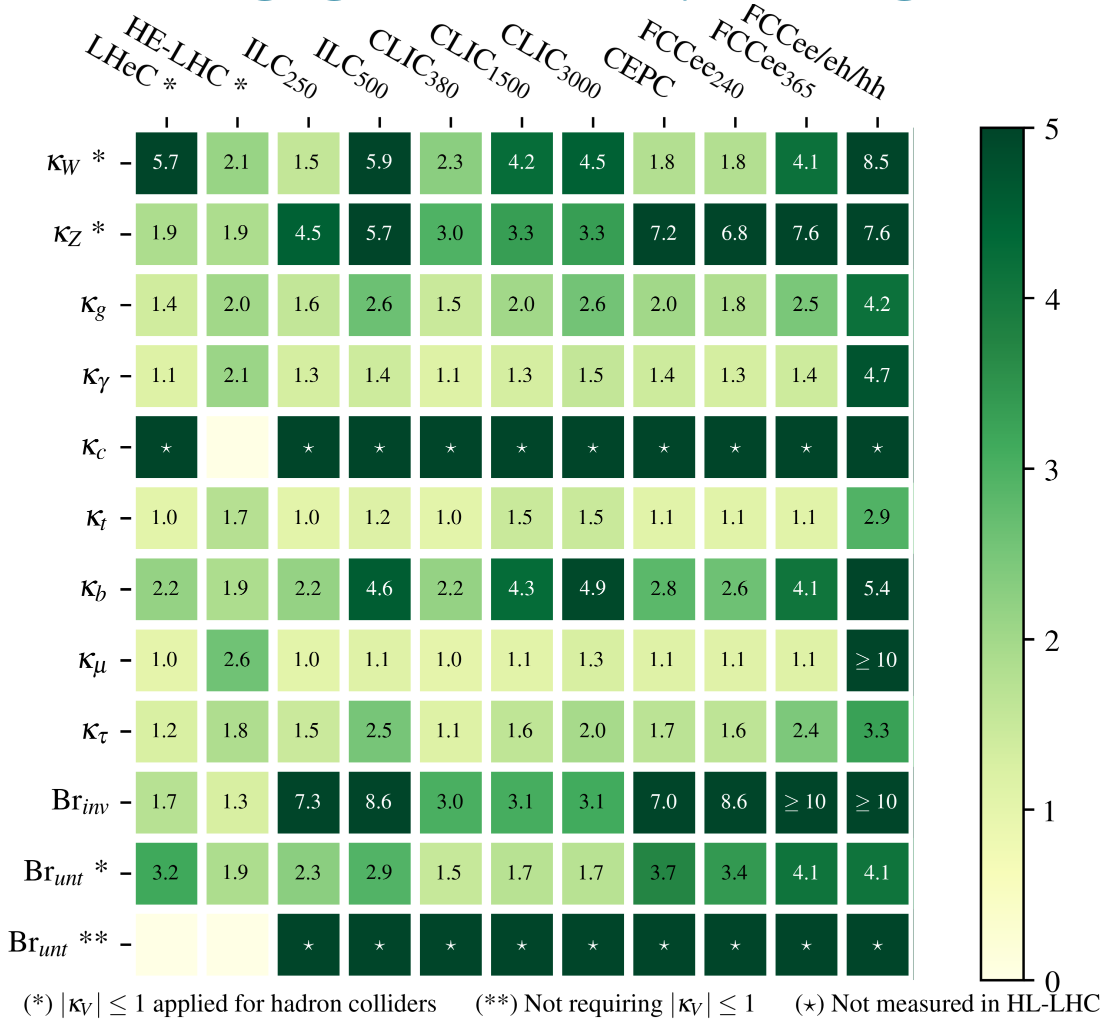
- For a U(1) gauge theory, new physics at scale $gM_{Pl.}$ If g<<1, responsible for weak scale? Cheung

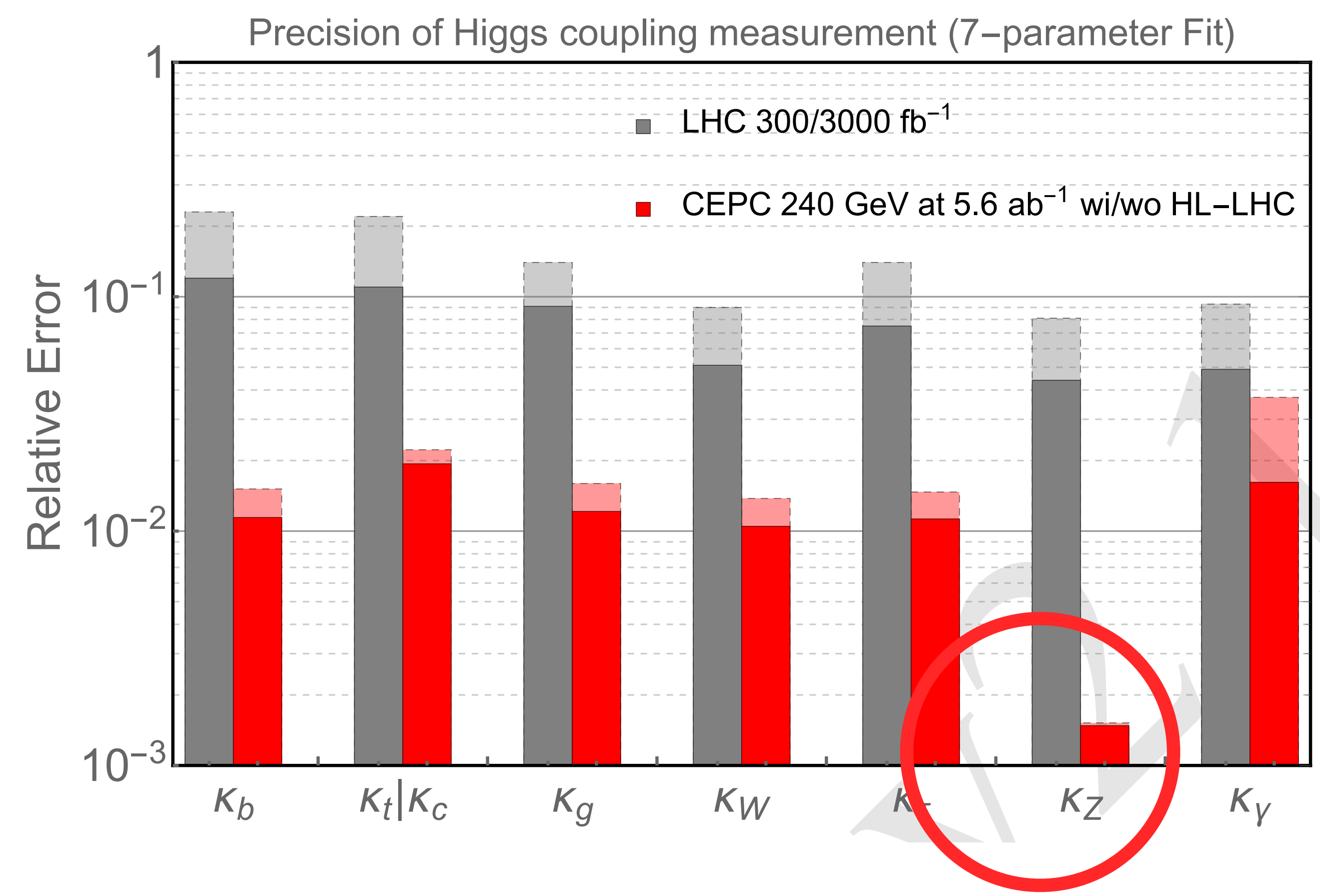
- This requires new physics close to weak scale couples to the Higgs boson. Craig, Garcia, Koren

Why is Higgs measurement crucial?

- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

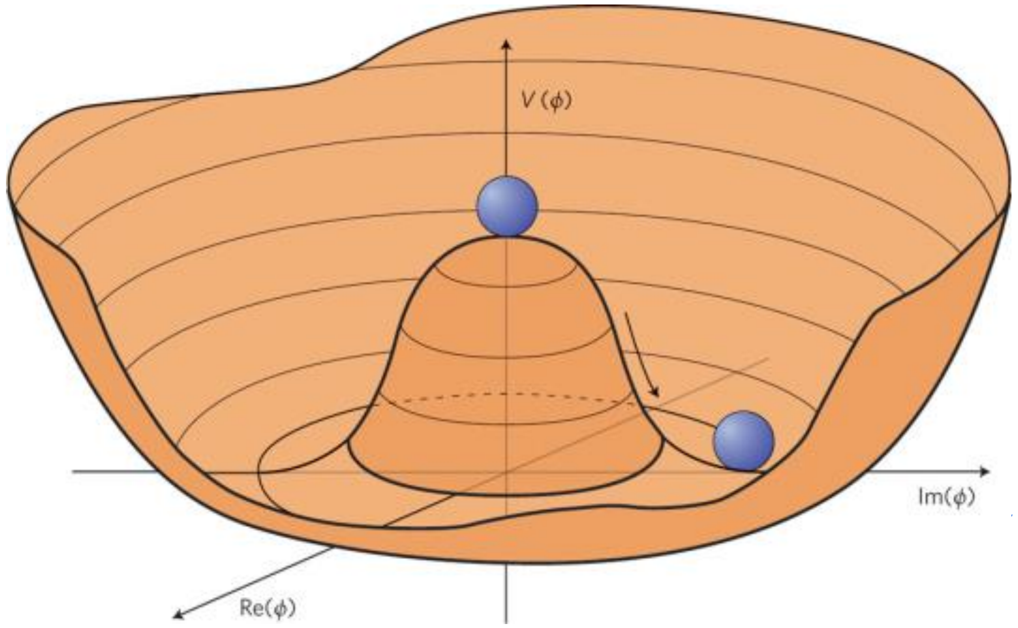
Higgs coupling at future colliders





- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

Mysteries of the electroweak scale.



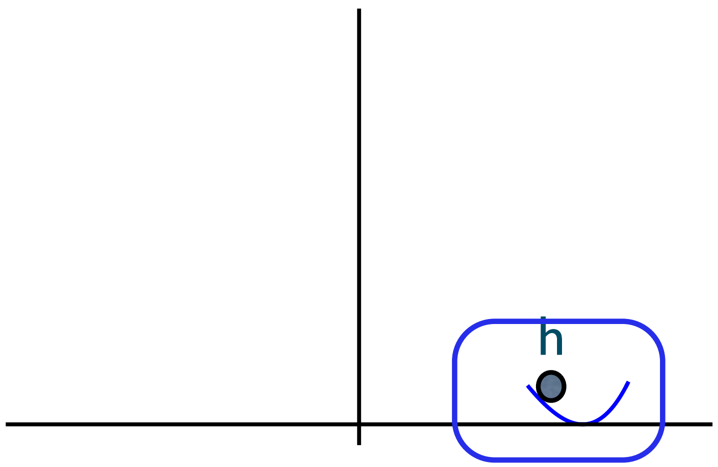
$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

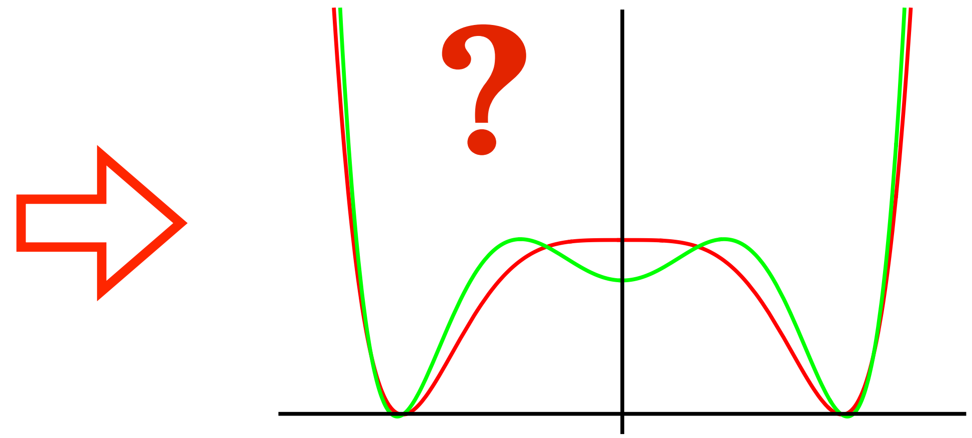
$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.

- Is it connected to the matter anti-matter asymmetry?

Nature of EW phase transition





What we know from LHC
LHC upgrades won't go much further

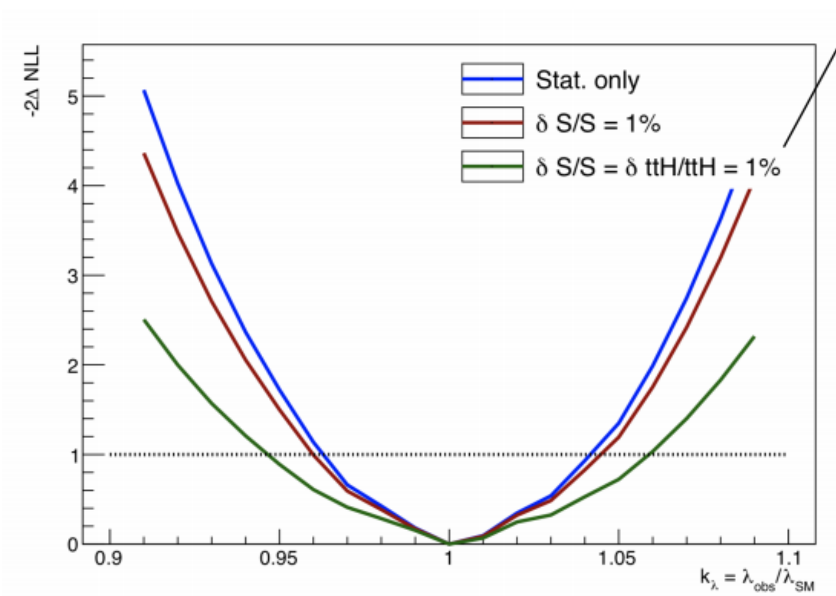
"wiggles" in Higgs potential

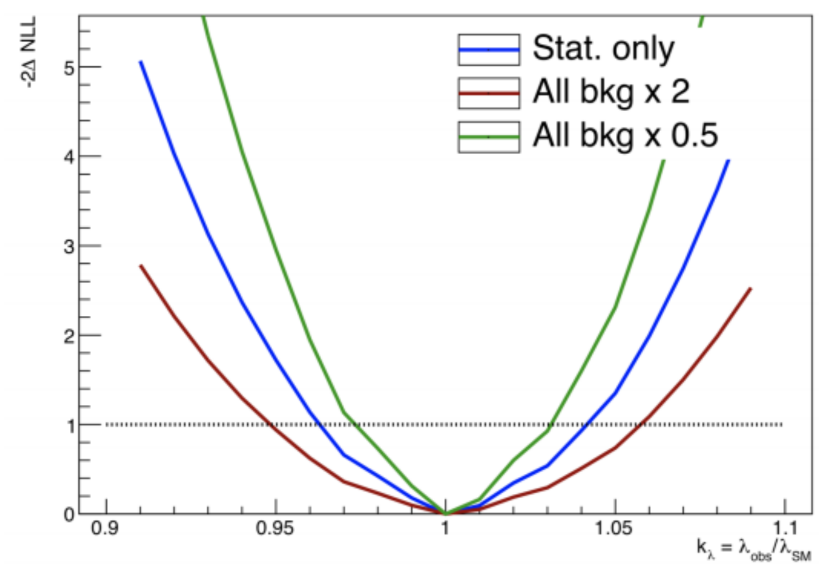
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda$(stat) ≈ 3.5 %
$\delta\kappa_\lambda$(stat + syst) ≈ 6 %

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda$(stat) ≈ 3 - 5 %

Talk by Michele Selvaggi at 2nd FCC physics workshop

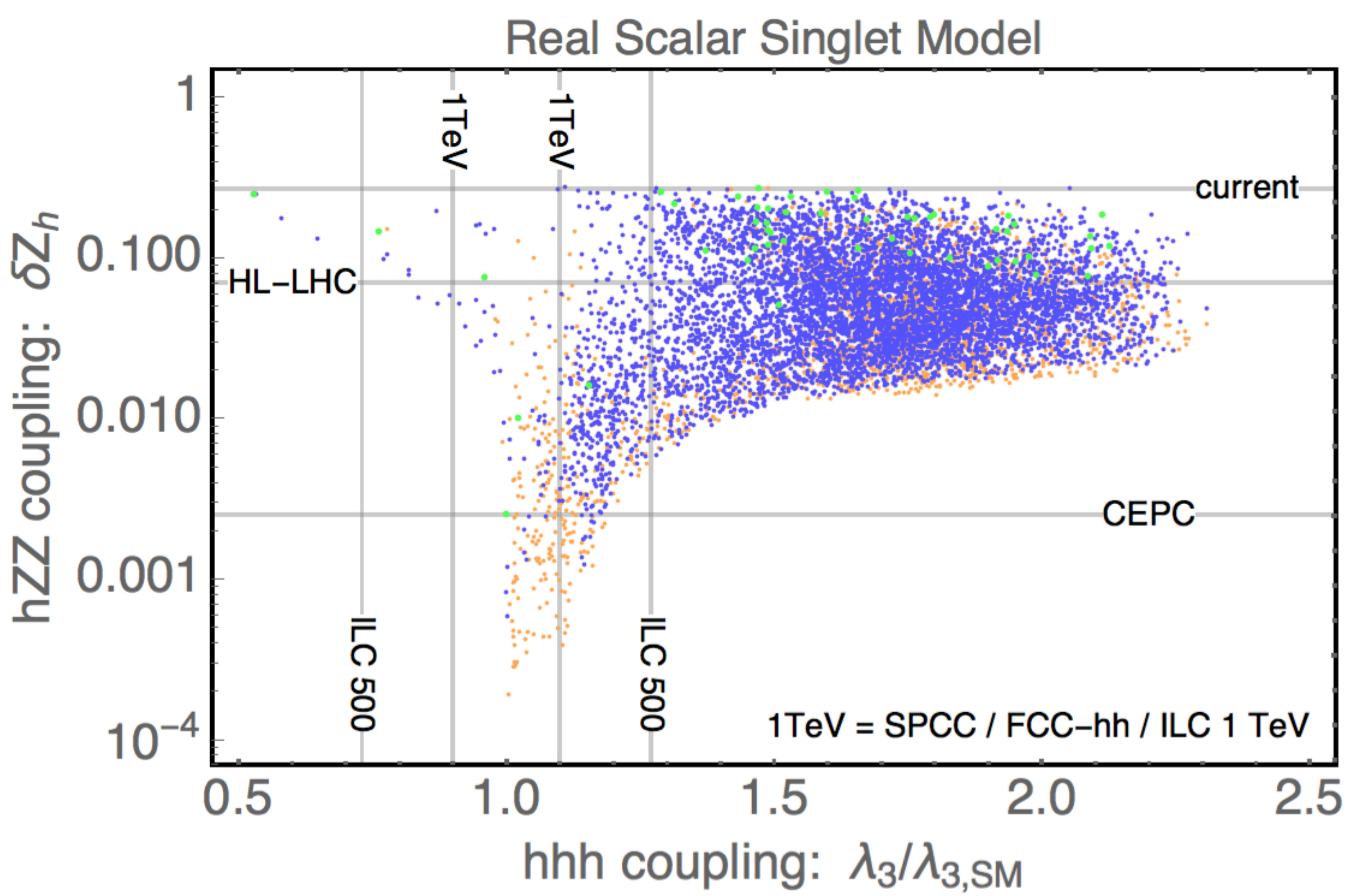
But, there should be more

$$V(h) = \frac{m^2}{2}h^2 + \lambda h^4 + \frac{1}{\Lambda^2}h^6 + \ldots$$

- Large deviation in the Higgs potential means there is new physics close to the weak scale.
- Will leave more signature in Higgs coupling.

For example: $$\frac{[\partial(HH^\dagger)]^2}{\Lambda^2} \rightarrow \delta_{Zh} \sim \frac{v^2}{\Lambda^2}$$

Probing EWSB at higgs factories



Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Huang, Long, LTW, 1608.06619

Good coverage in model space

Higgs portal

- Dark sector
  - Does not carry SM quantum number.
- Dark sector coupling to the SM

$$O_{\mathrm{SM}} \cdot O_{\mathrm{dark}}$$

O_{SM}: gauge inv. SM operator O_{dark}: dark sector operator

- More relevant coupling ⇔ lowest dim operator
  - Lowest dimension $O_{SM} = HH^\dagger$. Higgs portal.
  - A unique gateway to dark sector.

Higgs portal

$$\lambda O_{\rm SM} \cdot O_{\rm dark} \to \left(\lambda \frac{m_W}{g}\right) h \cdot O_{\rm dark}$$

- Producing dark sector particles through the Higgs portal.

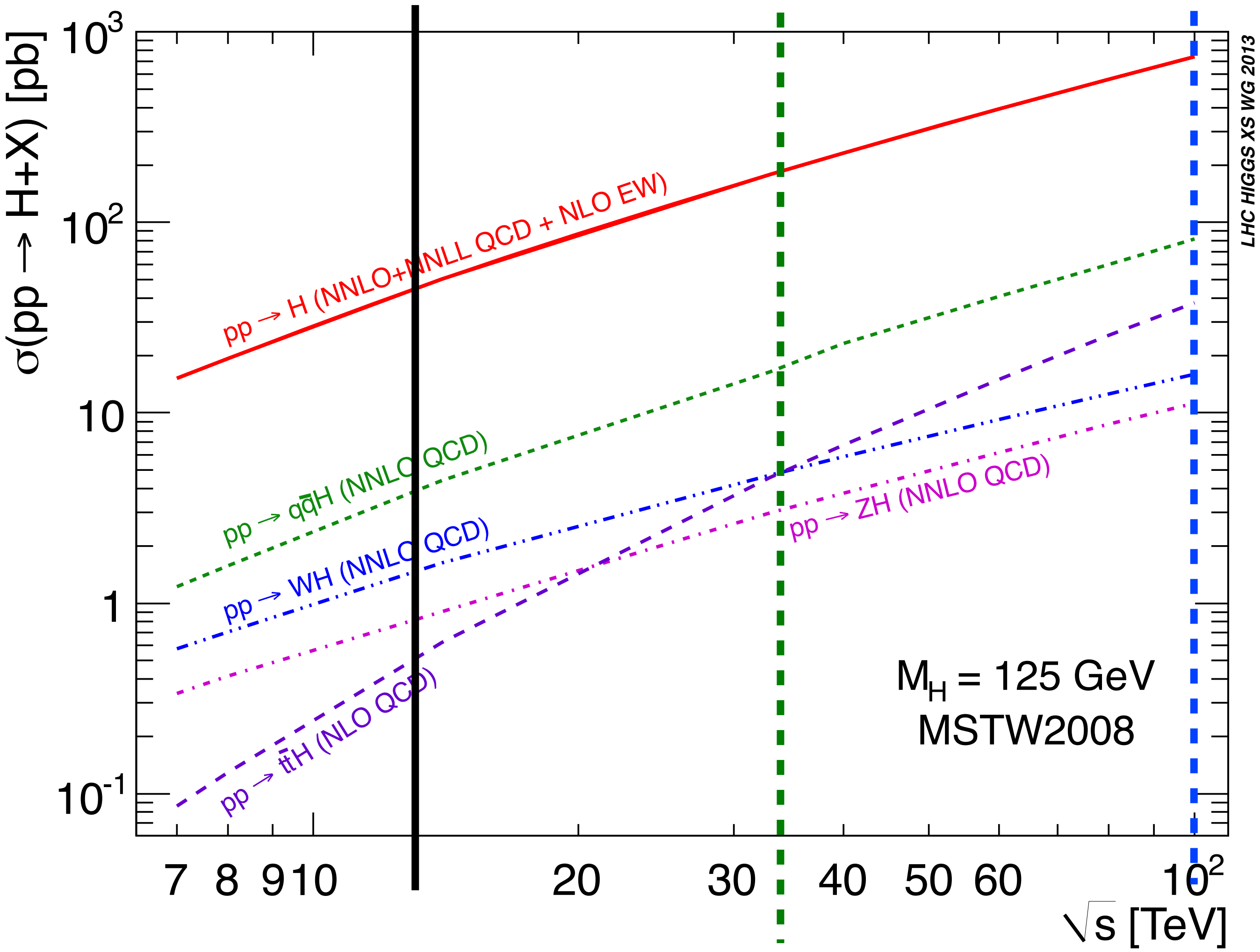
- Higgs rare decays:
  - Higgs $\to$ invisible at LHC can constrain down to a few percent.
  - A lot of room for exotic decay:

$$O_{\rm dark} = \bar{\psi}_{\rm dark}\psi_{\rm dark}, \quad \lambda = \frac{1}{\Lambda}$$

$$\Lambda \sim 10 \text{ TeV} \quad \to \quad \text{BR}(h \to \bar{\psi}_{\rm dark}\psi_{\rm dark}) \leq 10^{-2}$$

Hadron collider

- The "ultimate" Higgs factories



# of Higgses in 3 ab^{-1}

14 TeV > 150 million

33 TeV > 500 million

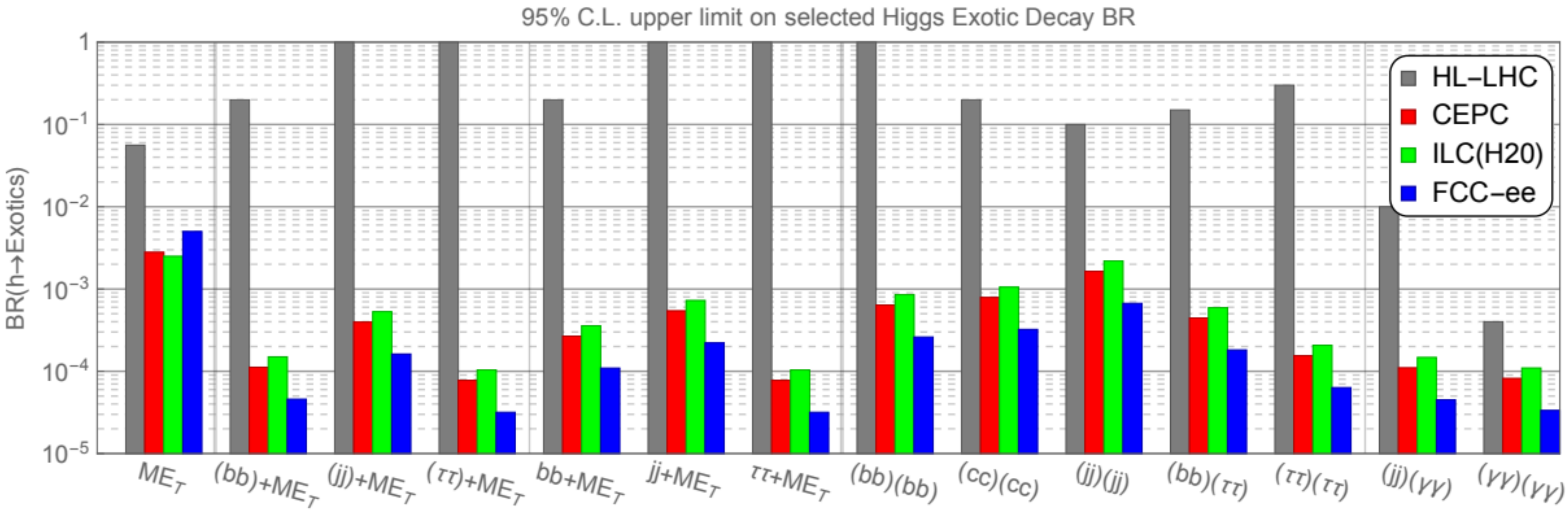
100 TeV > 2 billion

In comparison, O(million) Higgs at ee Higgs factories

Hadron collider good for rare but clean signal

In principle, can be sensitive to BR ≈ 10^{-7}

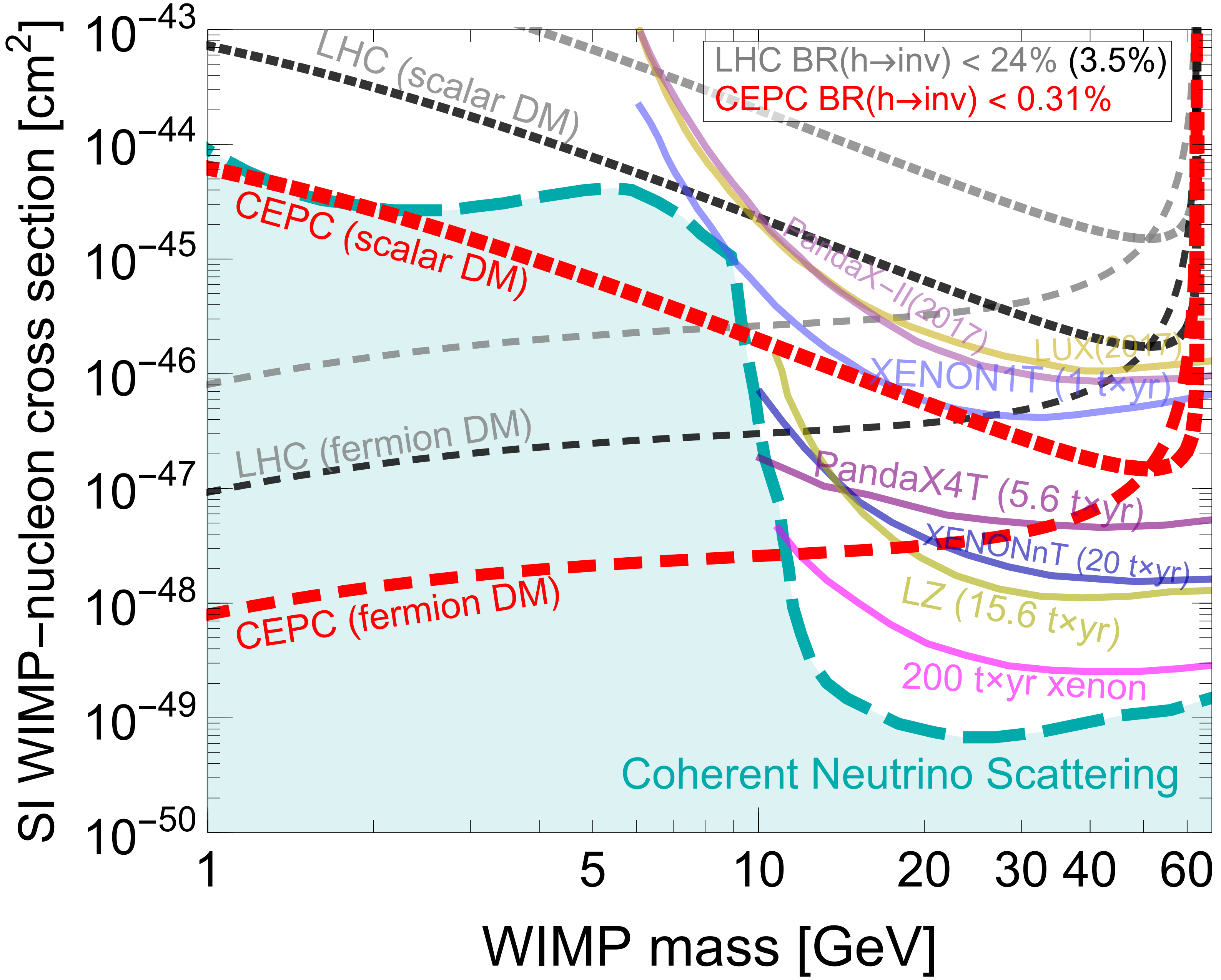
Higgs exotic decay at e^+e^- colliders



Complementary to hadron collider searches

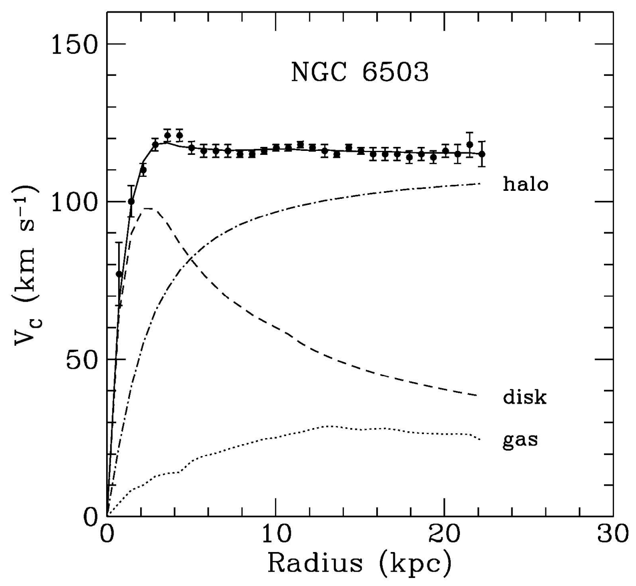
Higgs portal dark matter

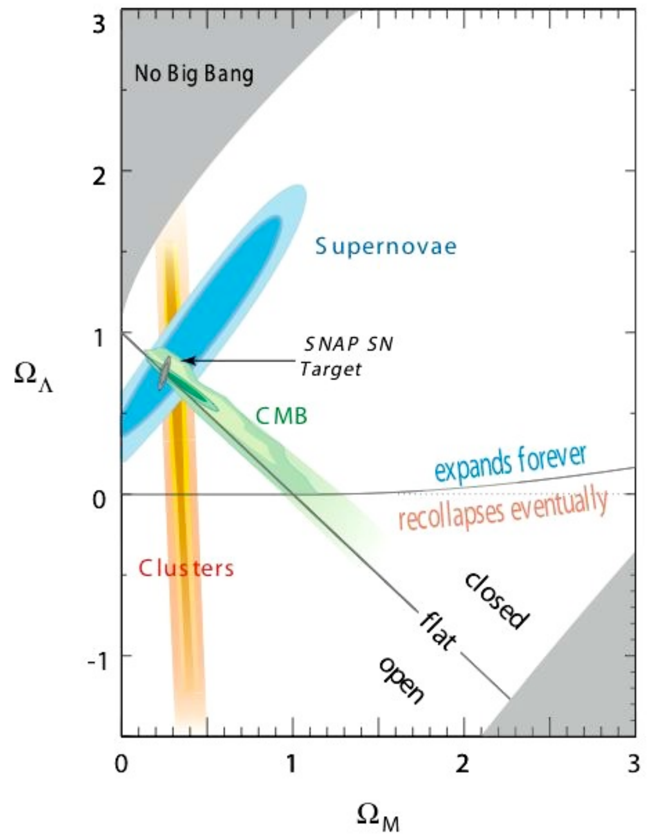
$$\mathcal{O} = H^\dagger H X_{\rm dm} X_{\rm dm} \quad \Rightarrow \quad h \to X_{\rm dm} X_{\rm dm}$$



Dark Matter

We have solid evidence for dark matter:





Our goal:
Understand the properties of dark matter.

What do we know about dark matter

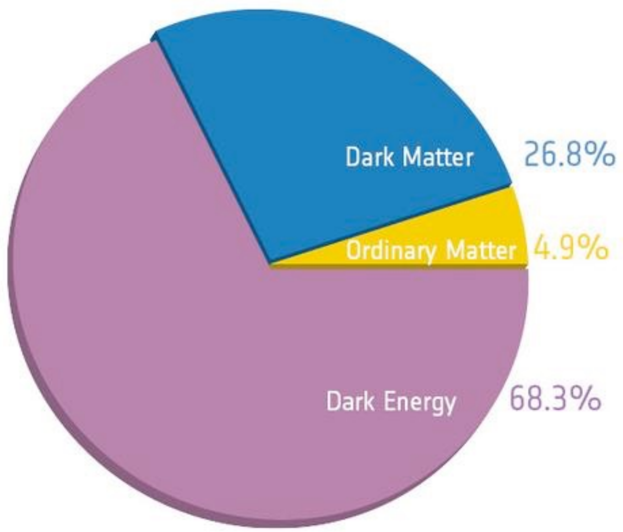
- Stable.
  - If it decays, lifetime much longer than the age of universe $\approx 10^{17}$ sec.

What do we know about dark matter

- Stable.
  - If it decays, lifetime much longer than the age of universe $\approx 10^{17}$ sec.
- Dark. Does not emit/absorb/reflect light.
  - Does not have electric charge

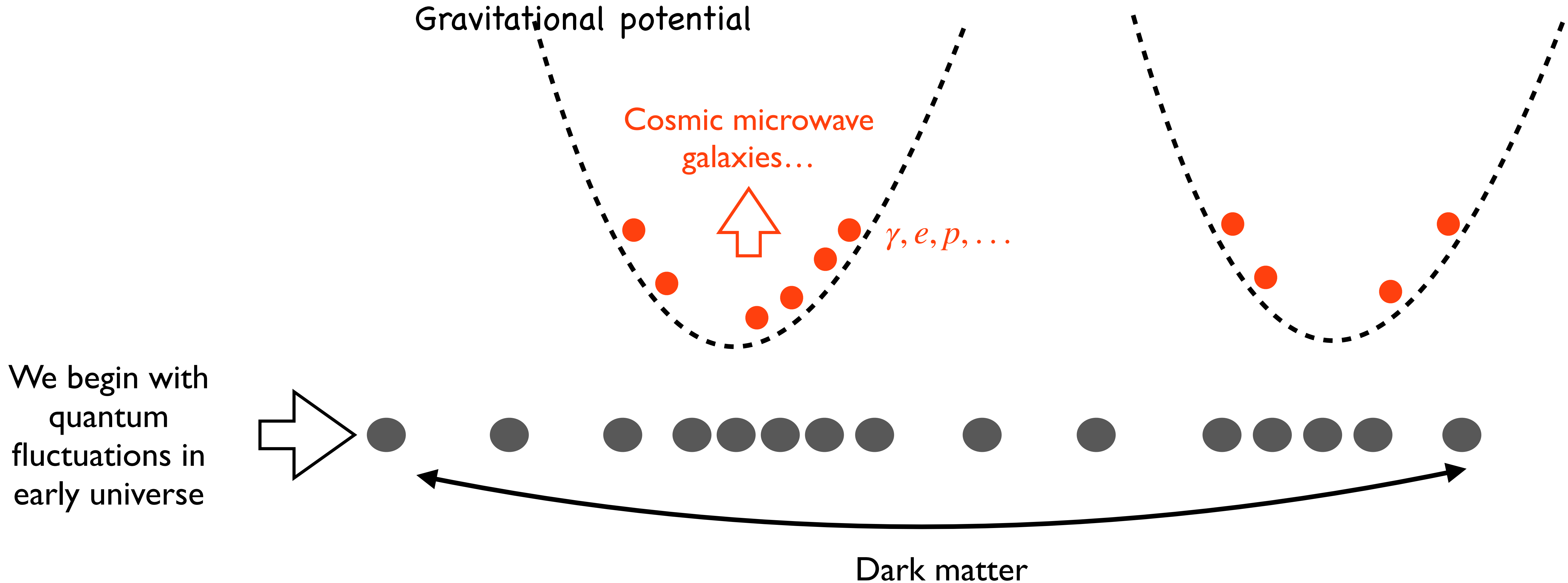
What do we know about dark matter

- Stable.
  - If it decays, lifetime much longer than the age of universe ≈ 10^{17} sec.
- Dark. Does not emit/absorb/reflect light.
  - Does not have electric charge.
- Produced in the early universe with the right amount. Right “relic abundance”



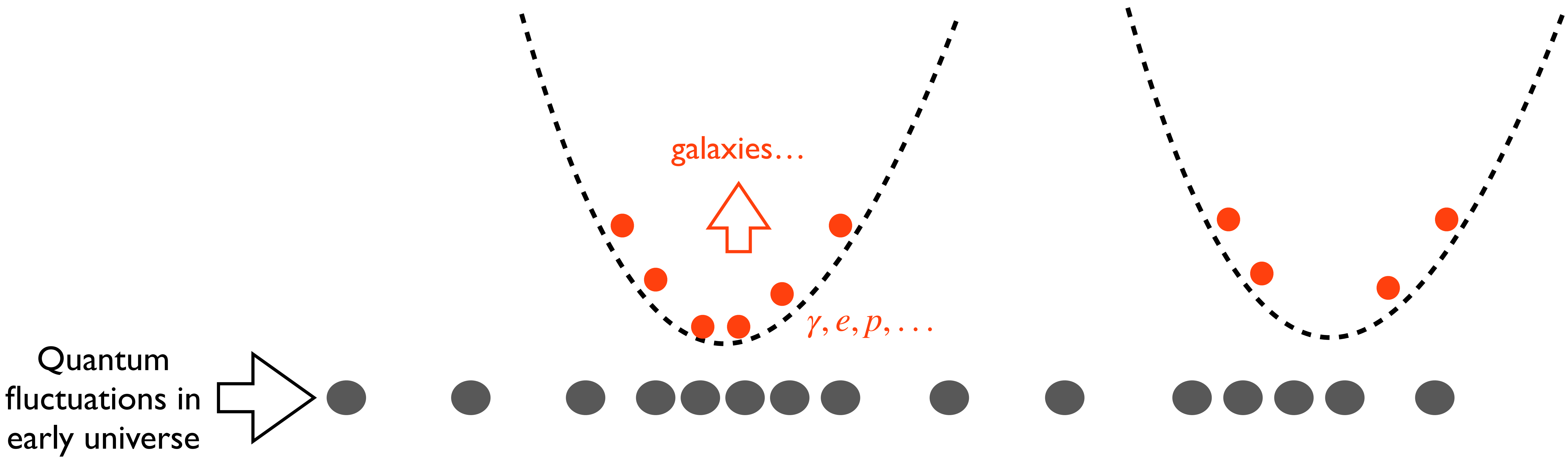
What do we know about dark matter

- Seed structures in the universe.



Dark matter needs to be "primordial", be there in early universe.

What do we know about dark matter



– "Collisionless". No long range interaction, except gravity.

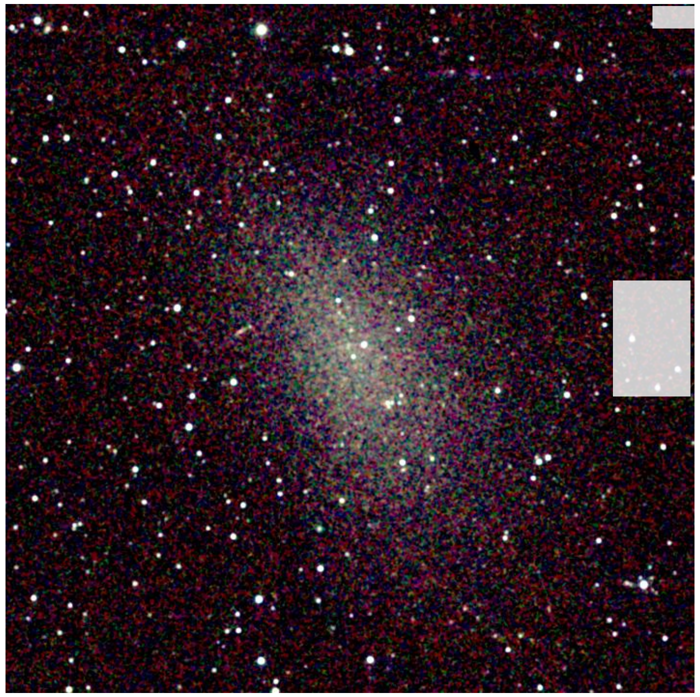
– Cold. Non-relativistic: kinetic energy ≪ mass

Mass of dark matter

DM needs to seed structures

Mass of dark matter

DM needs to seed structures



NGC147

Smallest structure DM seeded:
Dwarf spheroidal galaxy, size ≈ 1 kpc (3000 lyr)

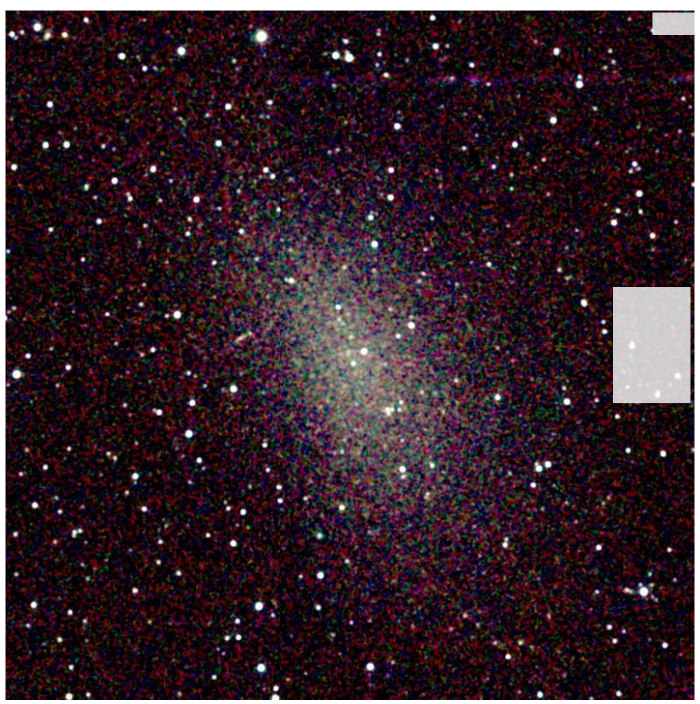
Dark matter particle wave packet must be smaller,
Lightest ⇔ largest de Broglie wave length

$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM} v} \approx 0.4 \text{ kpc} \left(\frac{10^{-22}\text{eV}}{m_{\rm DM}}\right)$$

"Fuzzy dark matter"

Mass of dark matter

DM needs to seed structures



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"Fuzzy dark matter"

Mass of dark matter

Upper bound? Large primordial blackholes (PBH) formed in early universe.

Mass of dark matter

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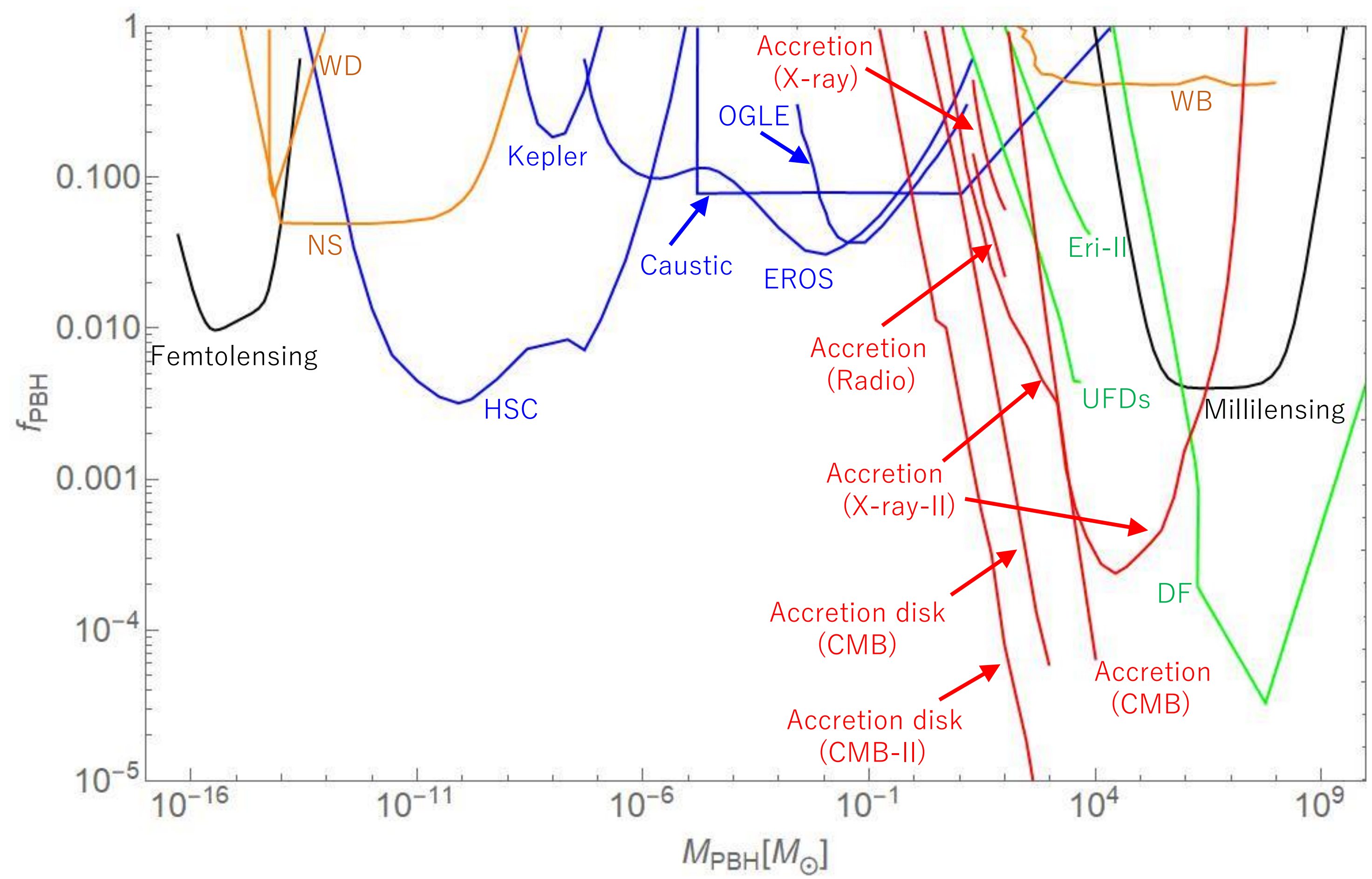
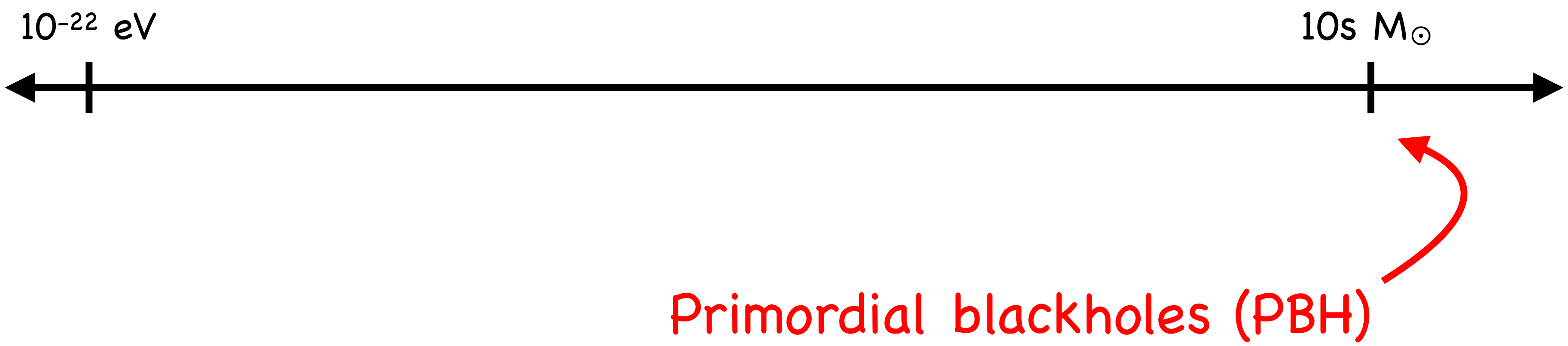
Very heavy BH accrete matter, too much ionizing radiation, CMB constraints $M_{PBH} < 10s\ M_\odot$

Blackhole lighter than $10^{-17}\ M_\odot$ will evaporate in the age of universe, not dark.

Other searches…



Mass of dark matter



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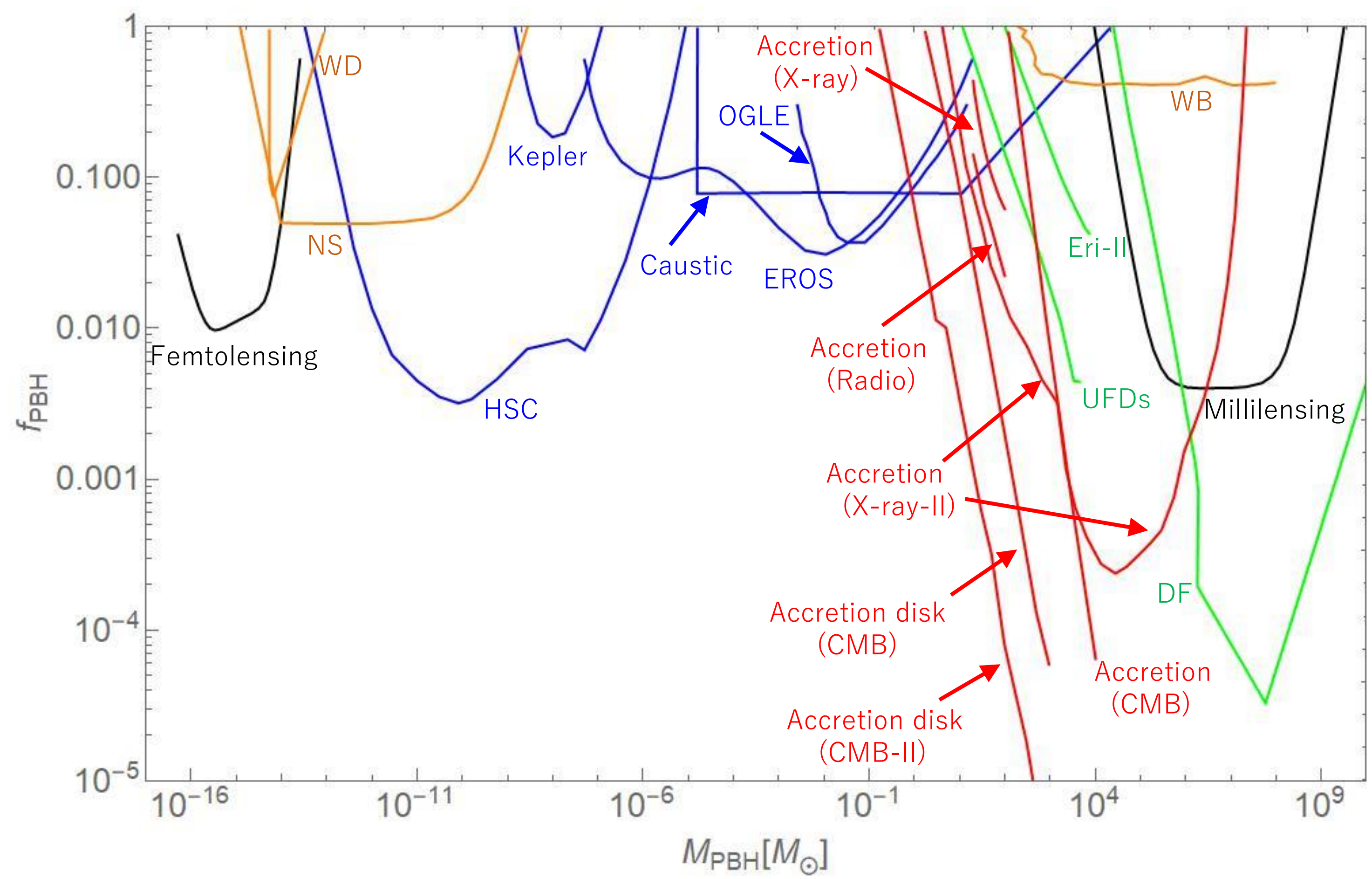
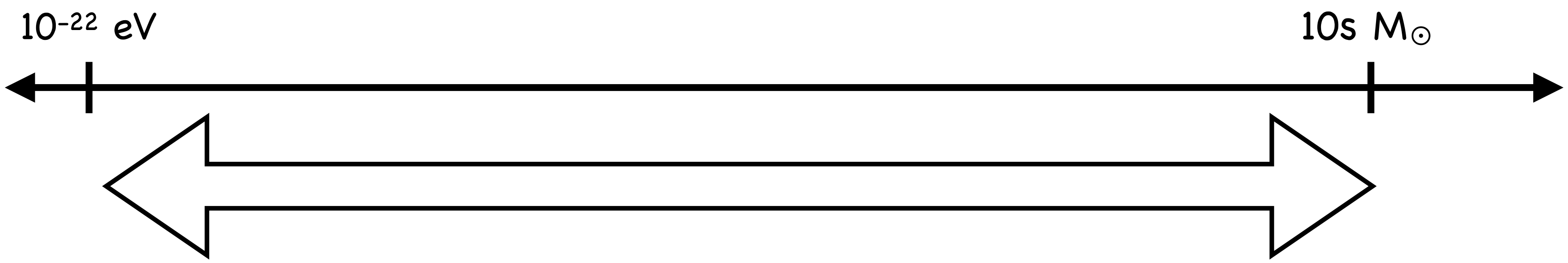


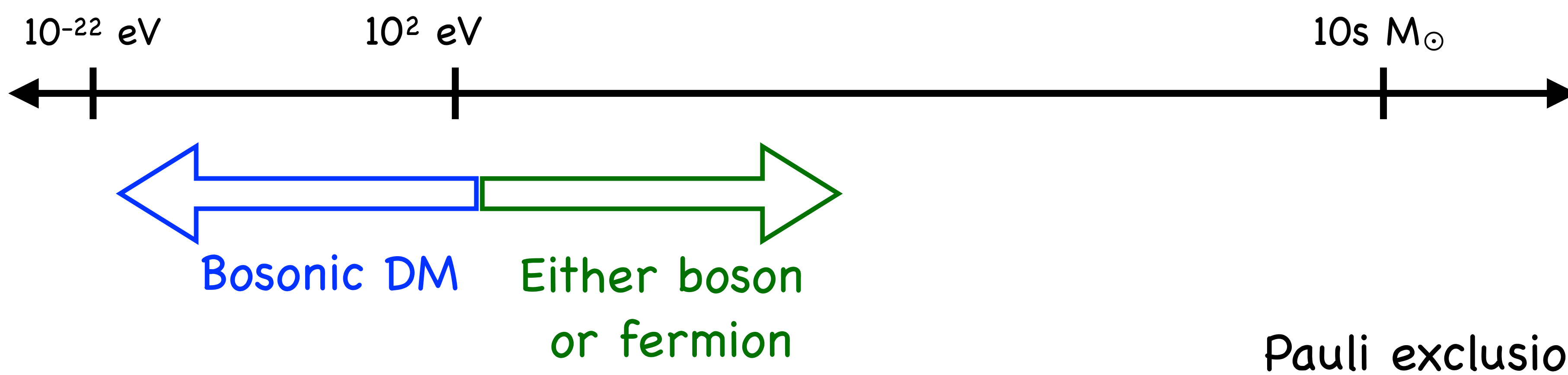
Mass of dark matter



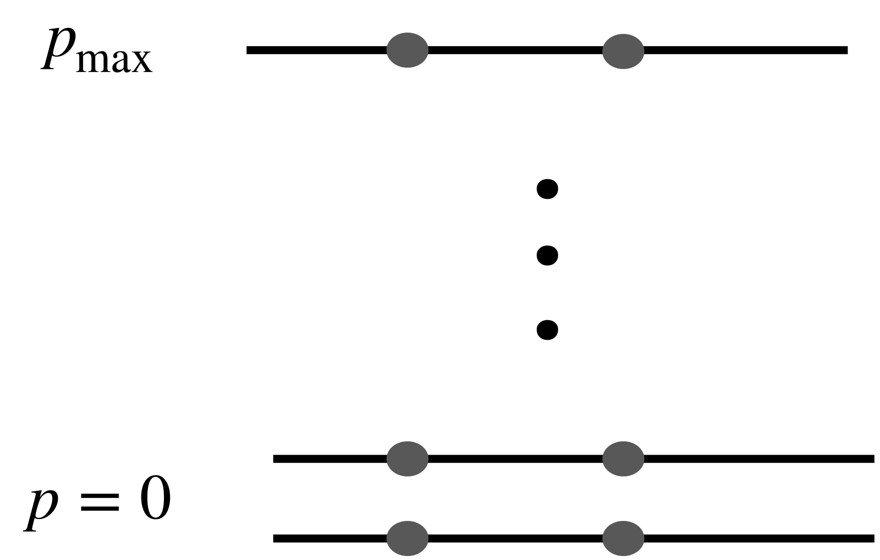
> 80 order of magnitudes!

What else can we say?

Mass of dark matter



Pauli exclusion principle



Fermionic dark matter

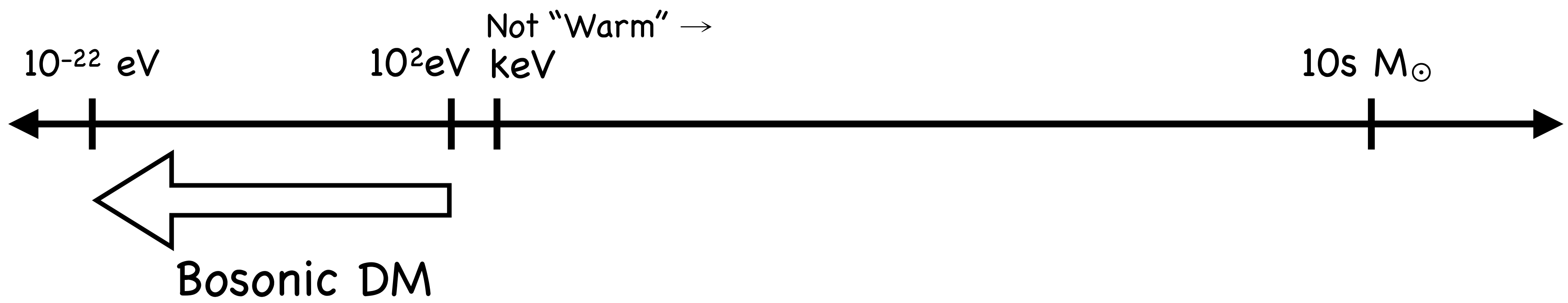
Since dark matter forms local bound structures such as galaxies

$$p_{\rm max} \simeq m_{\rm DM} \times v_{\rm esc}$$

$v_{\rm esc}$: escape velocity

DM abundance → $m_{\rm DM} > 10s$ eV

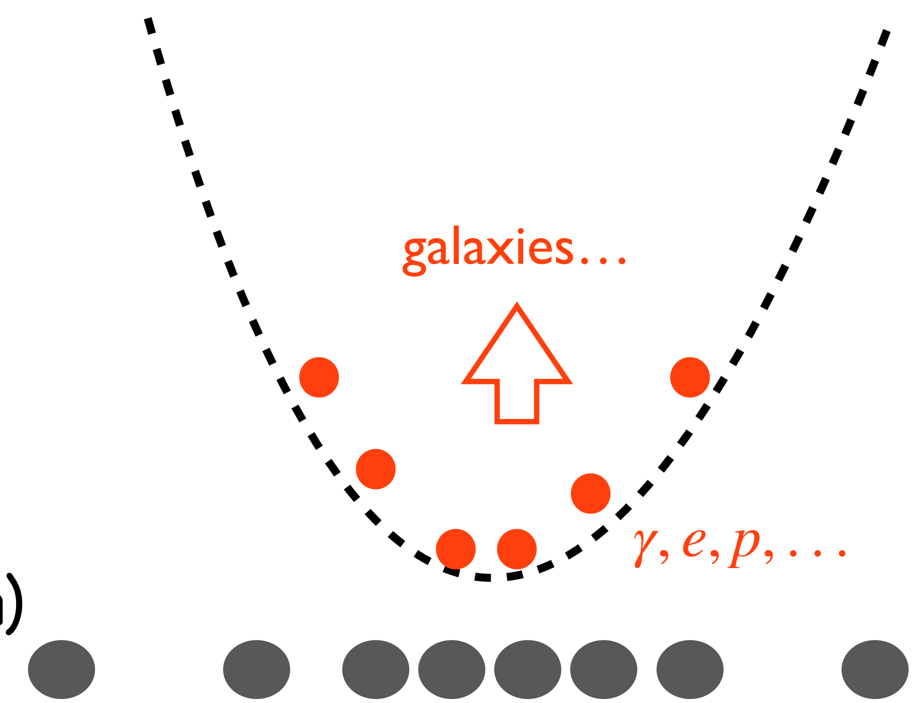
Mass of dark matter



Warm dark matter limit:

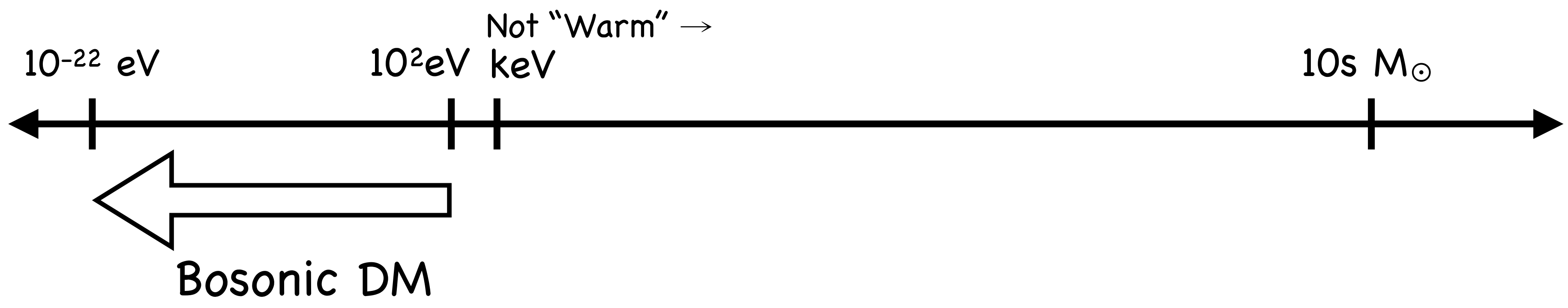
Dark matter needs to be cold (non-relativistic) for the smallest structure it can seed.

For dark matter particle (in thermal equilibrium)



m_{DM} > keV (10^3 eV)

Mass of dark matter



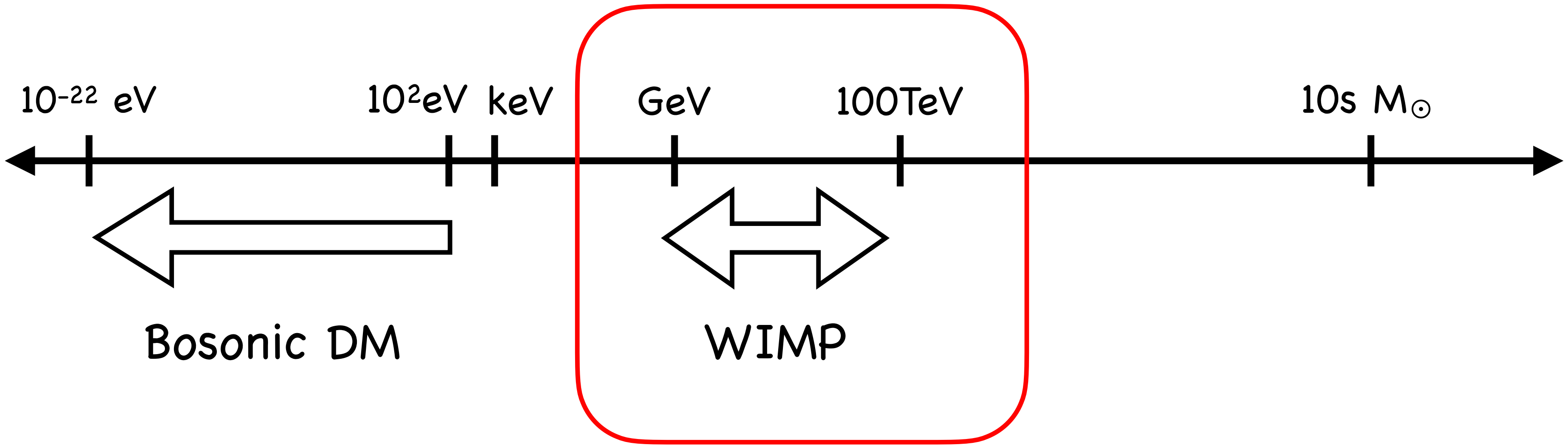
Going further.
How do we guide our searches? We need theories (stories).

A theory should give
1) The property of dark matter: spin, mass, couplings, etc.
2) How is dark matter produced in the early universe?

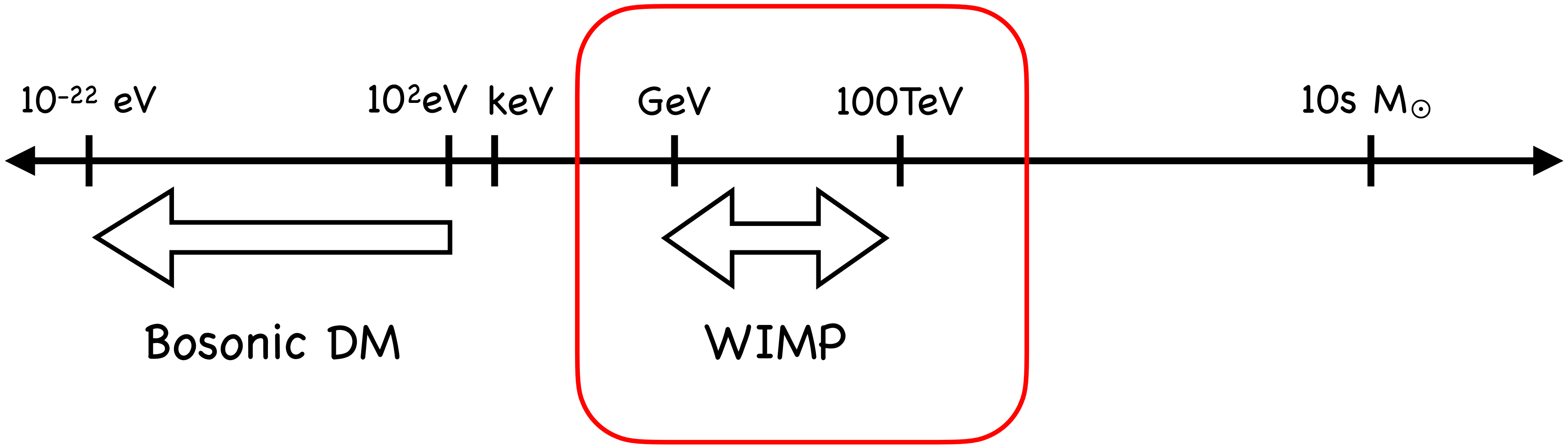
A good theory should be
1) A detailed and reasonable (without too many miracles) story.
2) Have a good chance to be tested.

Vast number of models, only a few good theories.

Mass of dark matter

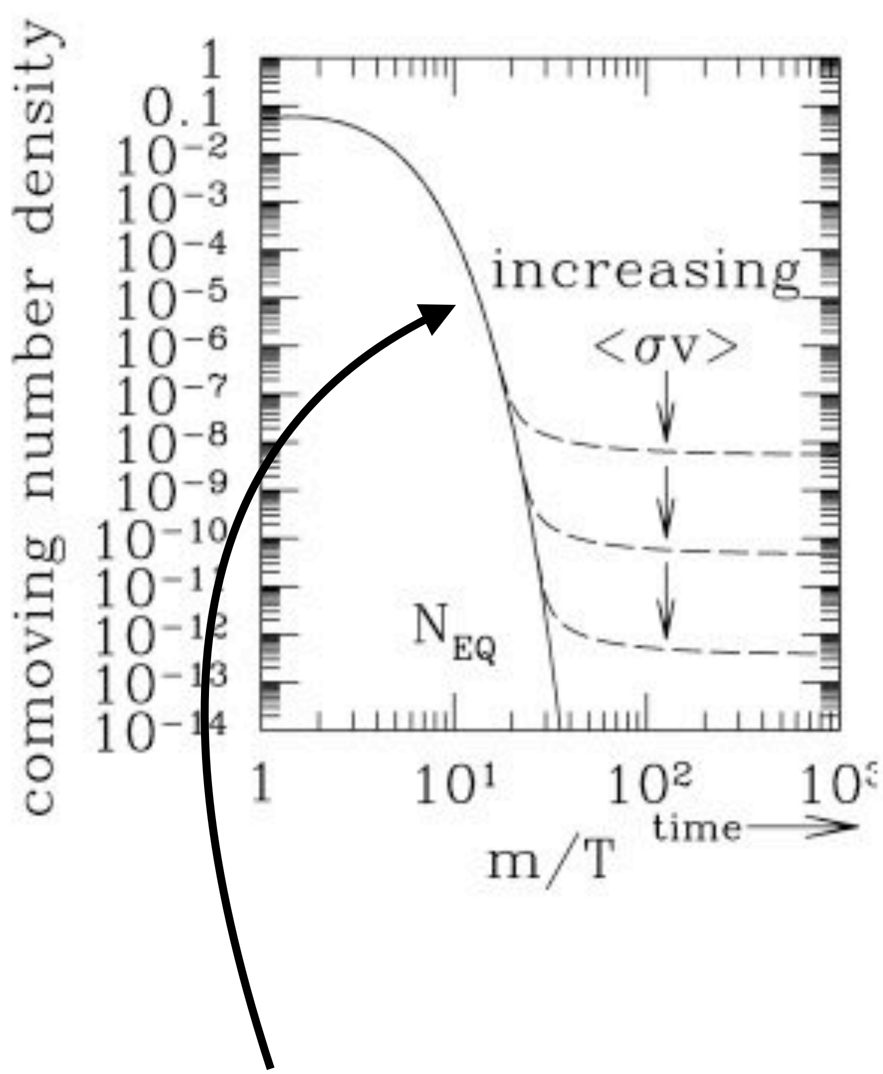


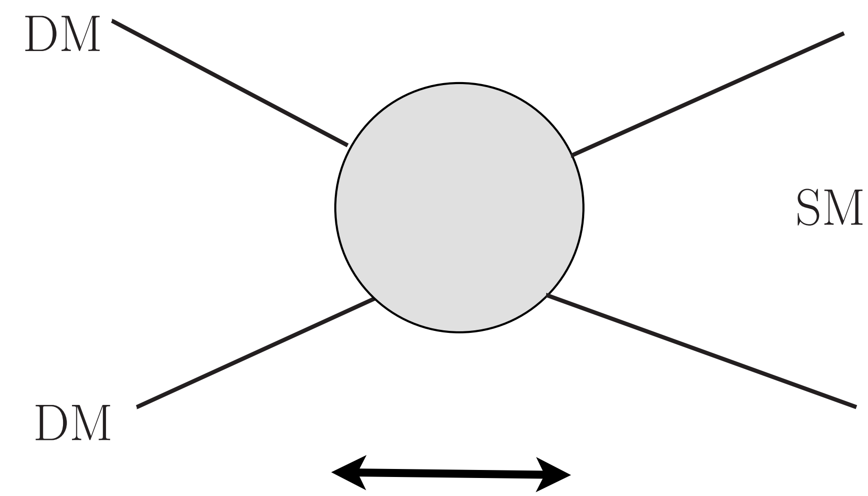
Mass of dark matter



A lamppost.
A tiny window in the full mass range.
A good lamppost.

WIMP (weakly interacting massive particle)



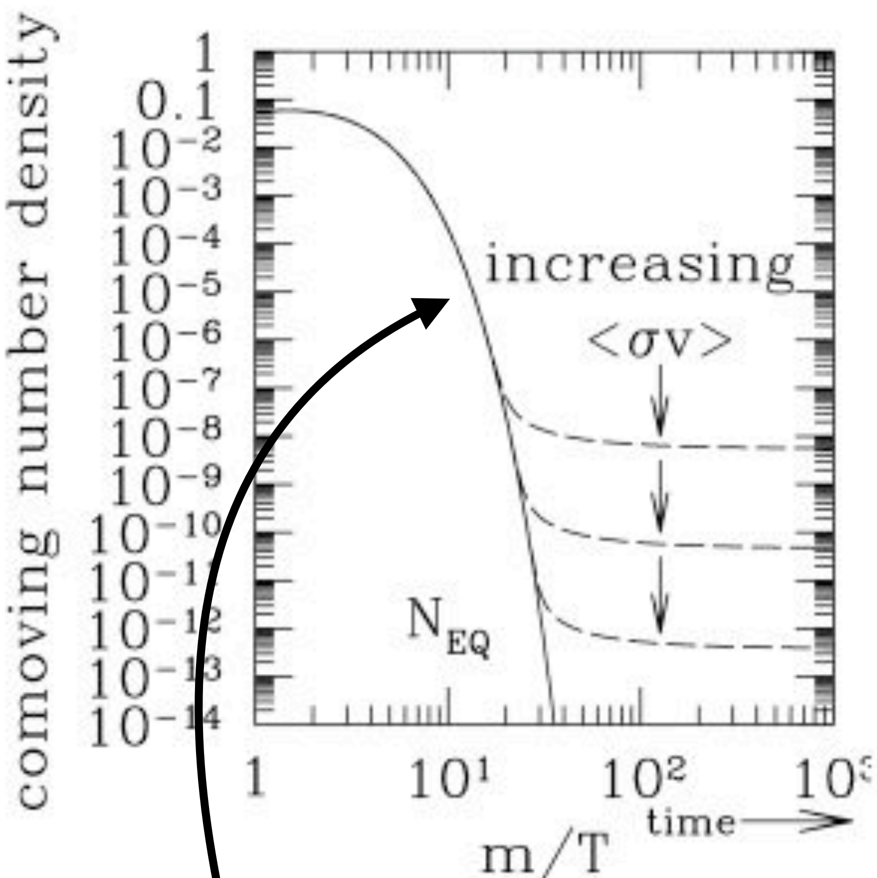


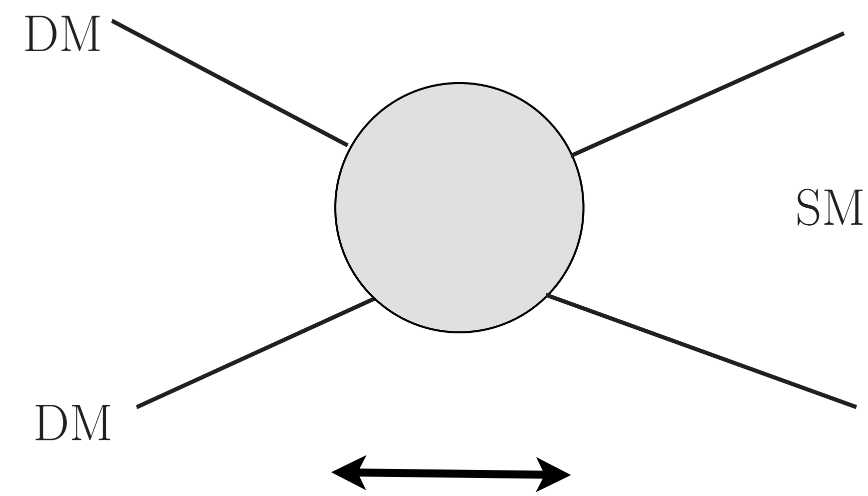
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

Dark matter in thermal equilibrium with the known (Standard Model) particles in the early universe.

Interaction rate faster than the expansion of the universe

WIMP (weakly interacting massive particle)



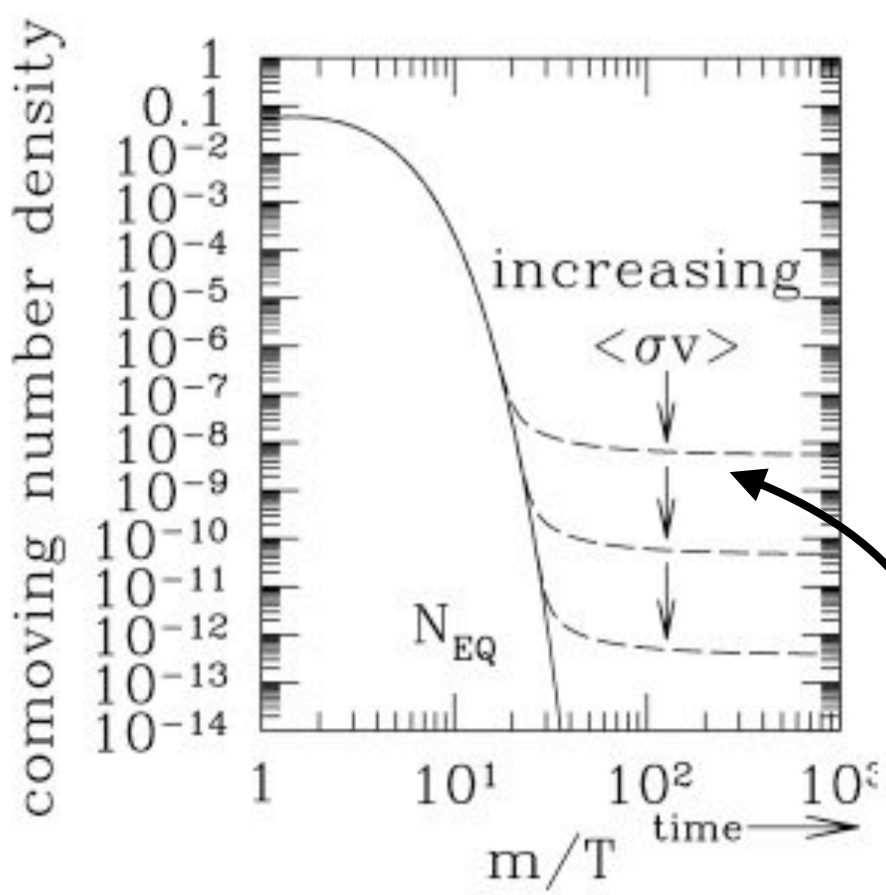


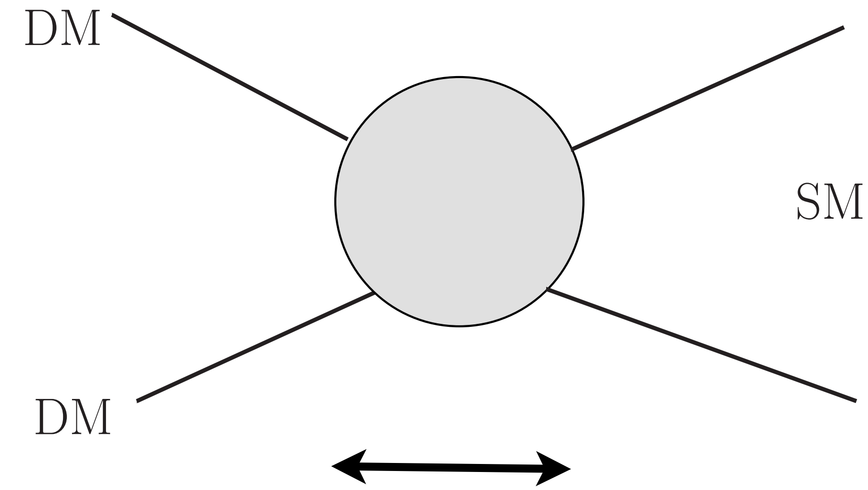
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

Dark matter in thermal equilibrium with the known (Standard Model) particles in the early universe.

Dark matter number density predicted by thermal eq: N_{EQ}

WIMP (weakly interacting massive particle)



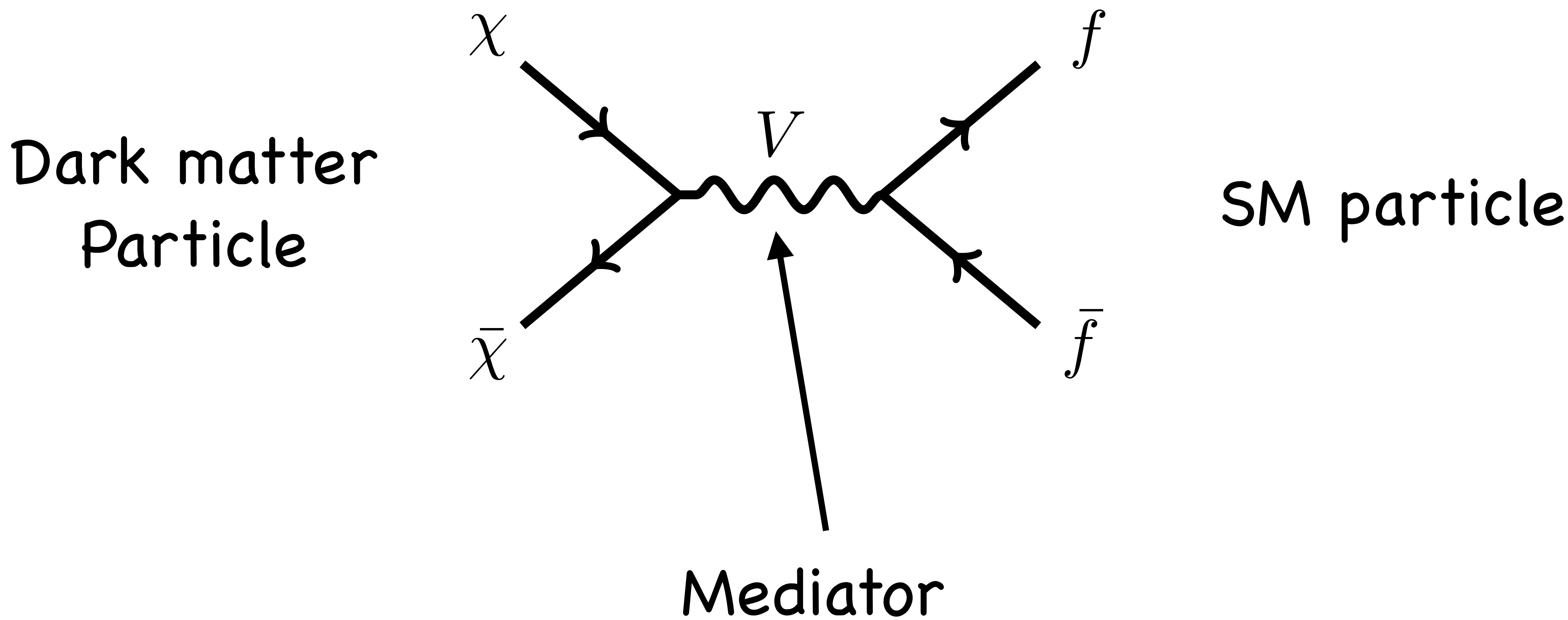


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

As universe expands, dark matter become rare. The DM-SM interaction rate can't keep up. DM drops out thermal eq.

Dark matter density become fixed, "Freeze-out"

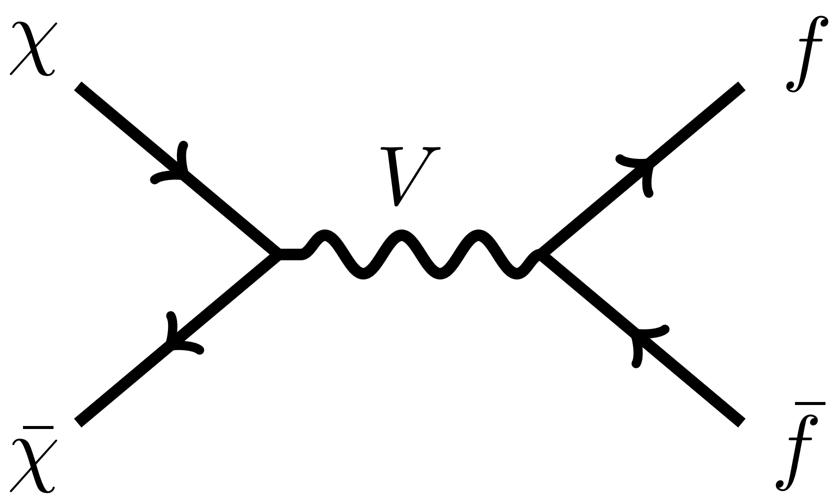
A simple picture of interaction



To get the correct relic abundance:

$$\langle \sigma v \rangle \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

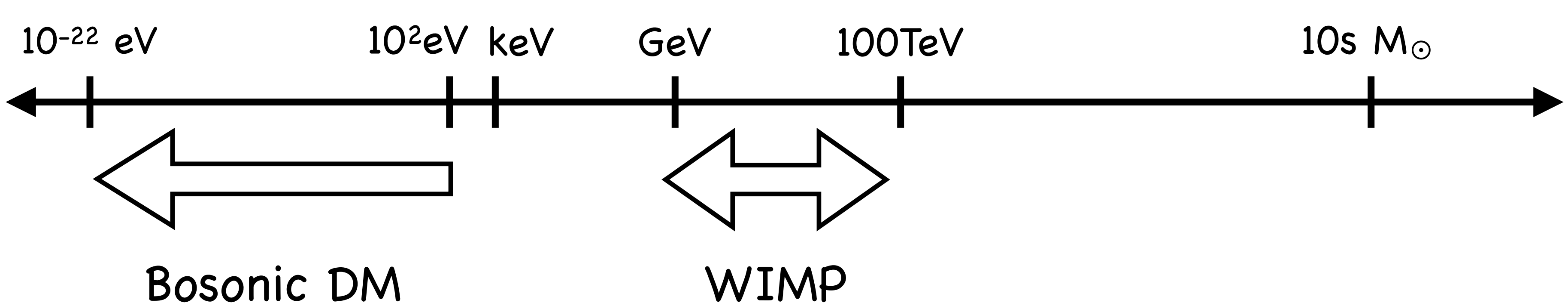
Two limits



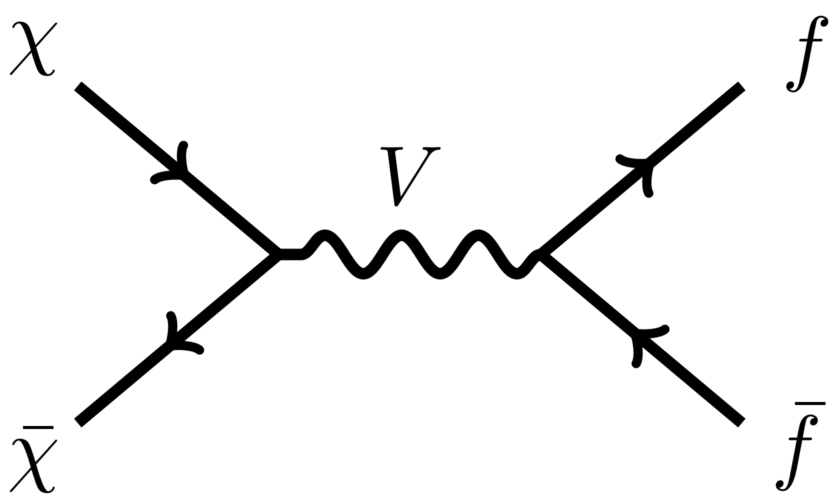
$$m_{\rm DM} > m_V, \quad \sigma v \sim \frac{g^4}{4\pi}\frac{1}{m_{\rm DM}^2}$$

g: coupling

Limit on coupling: $g < 4\pi \Rightarrow M_{DM} < 100\text{s TeV}$



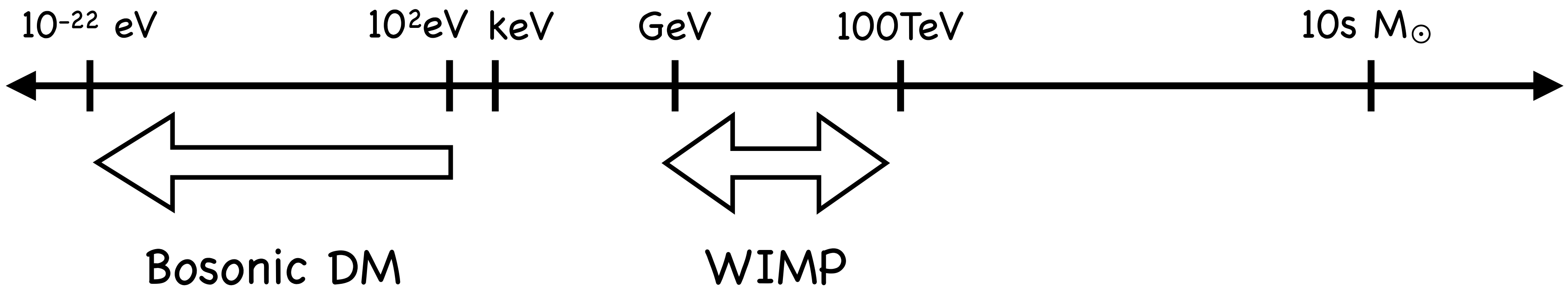
Two limits



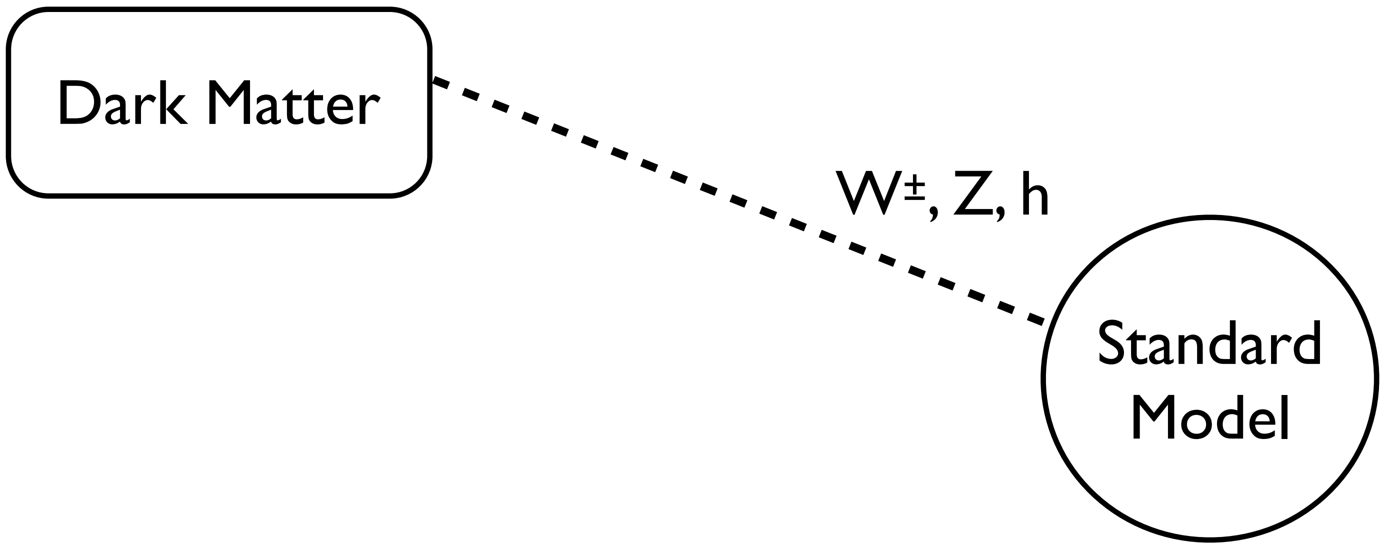
$$m_{\rm DM} < m_V, \quad \sigma v \sim \frac{g^4}{4\pi}\frac{m_{\rm DM}^2}{m_V^4}$$

g: coupling

$m_V \approx 10^2$ GeV $\Rightarrow$ m_{DM} > GeV



Simple WIMP model

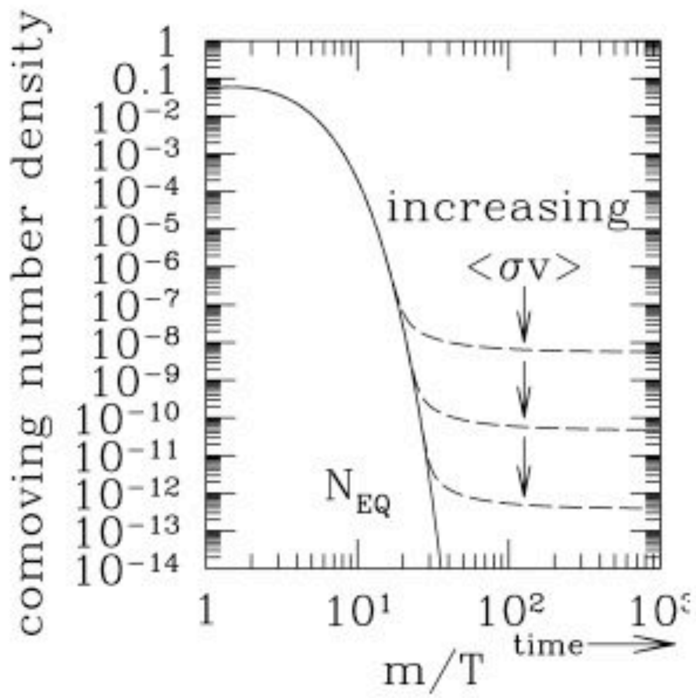


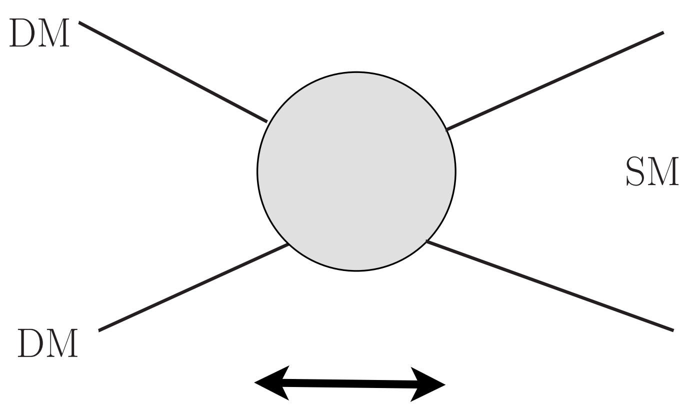
Mediated by a known interaction:

The weak interaction in the Standard Model

Mediator mass: 10^2 GeV

Why is WIMP a good theory?





$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

Reasonable:

Early universe (hot) is in thermal equilibrium. Don't need to know too much detail beyond (before) that.

Can be linked to other motivations for electroweak scale new physics.

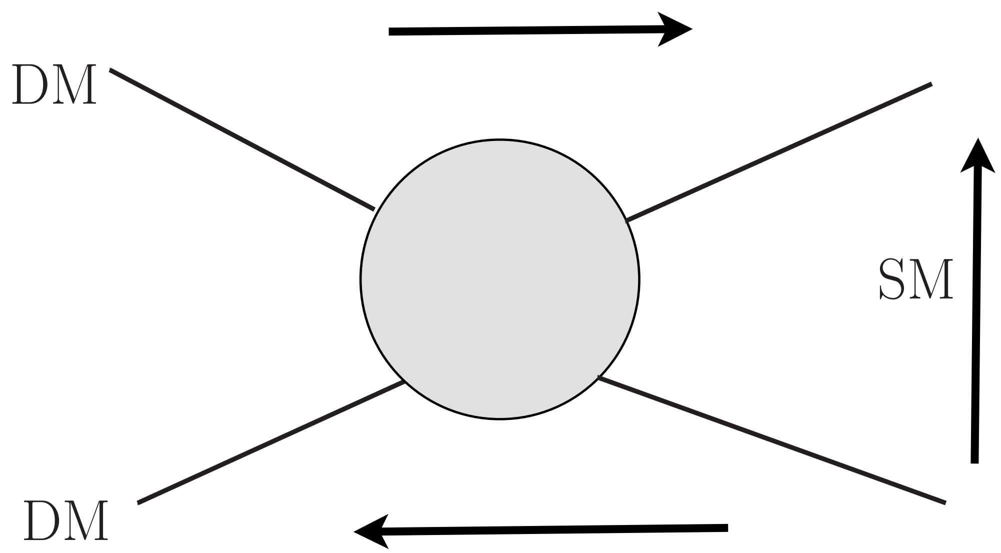
Present in many models: SUSY, extra dimension...

Testable:

With a sizable coupling to the known (SM) particle, WIMP can be searched in labs.

Looking around the lamppost

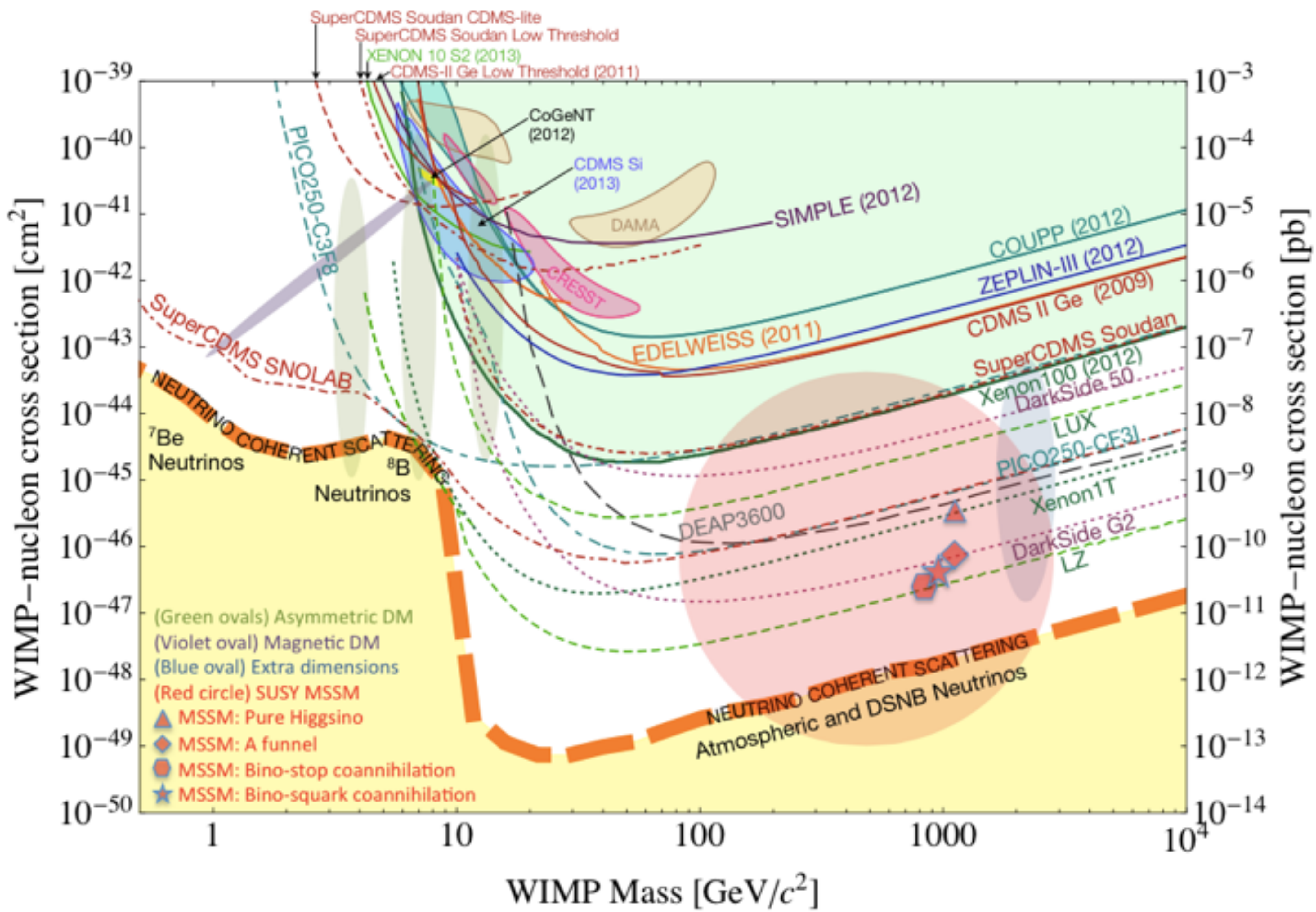
Indirect detection:
AMS2, PAMELA, Fermi-LAT
Cosmology



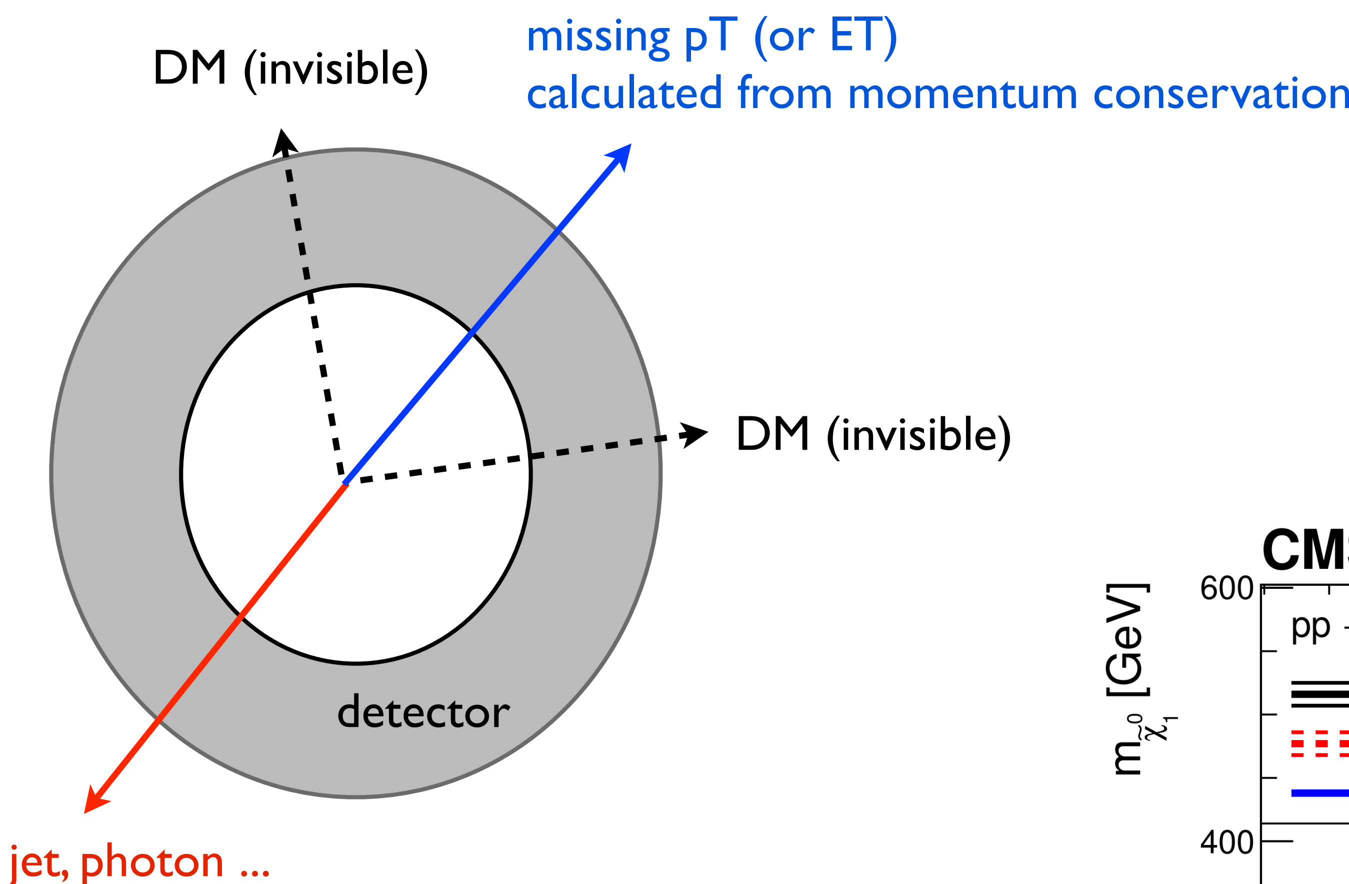
Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
Lux
.....

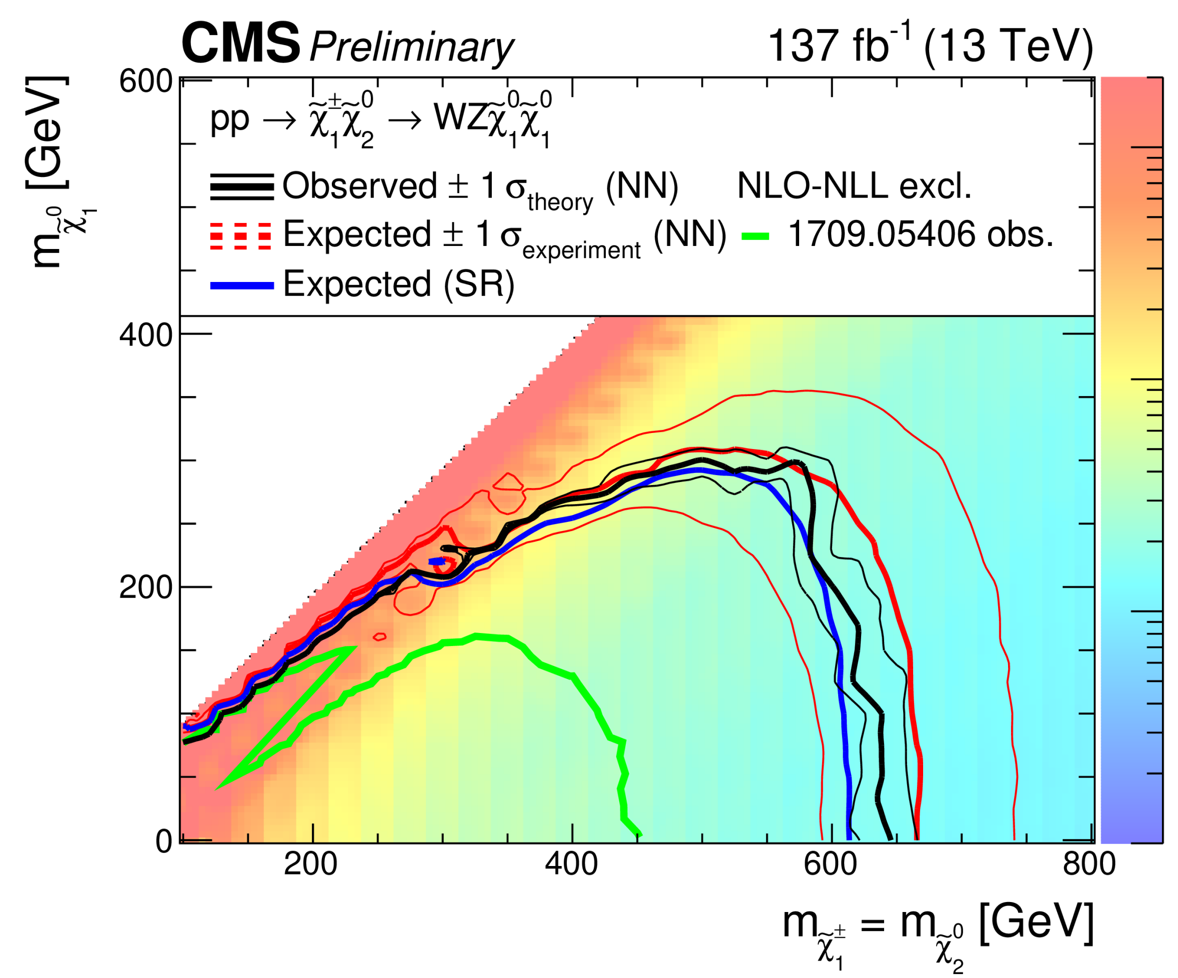
Collider searches:
LHC, ...

Direct detection

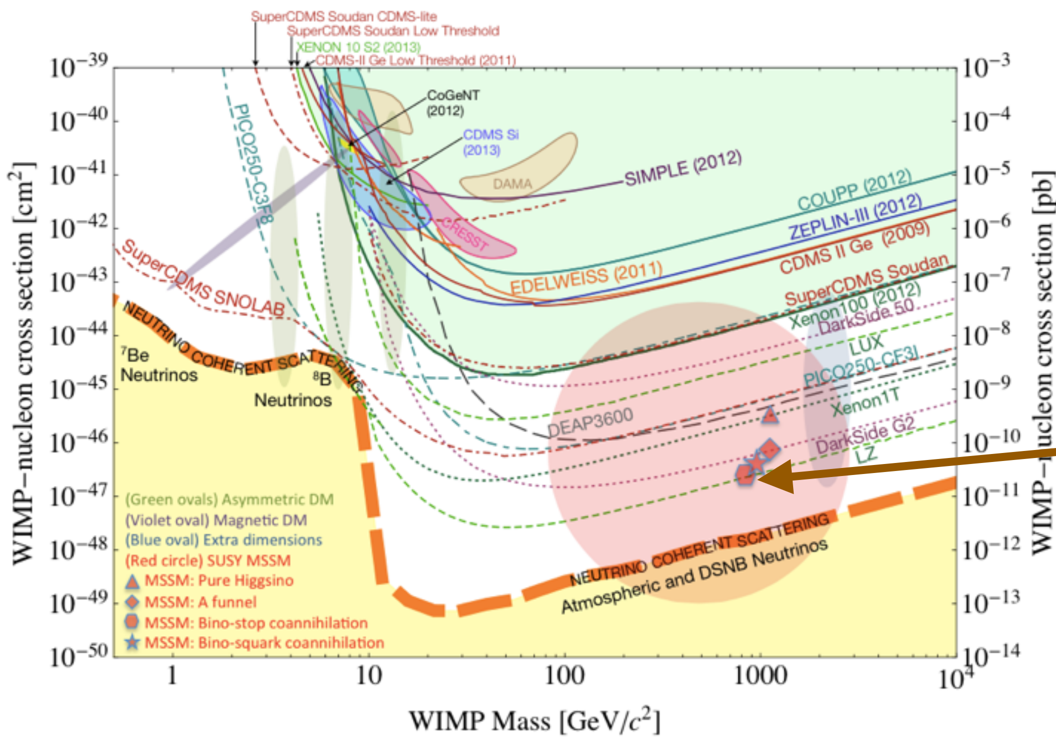


At colliders

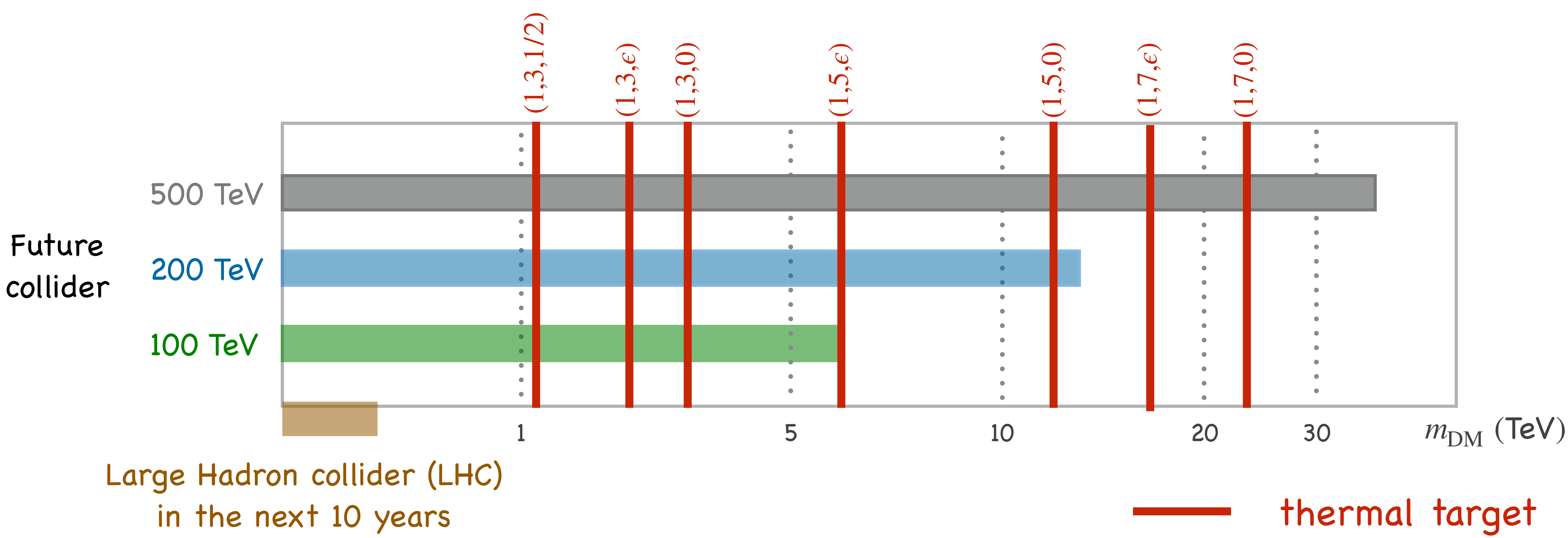




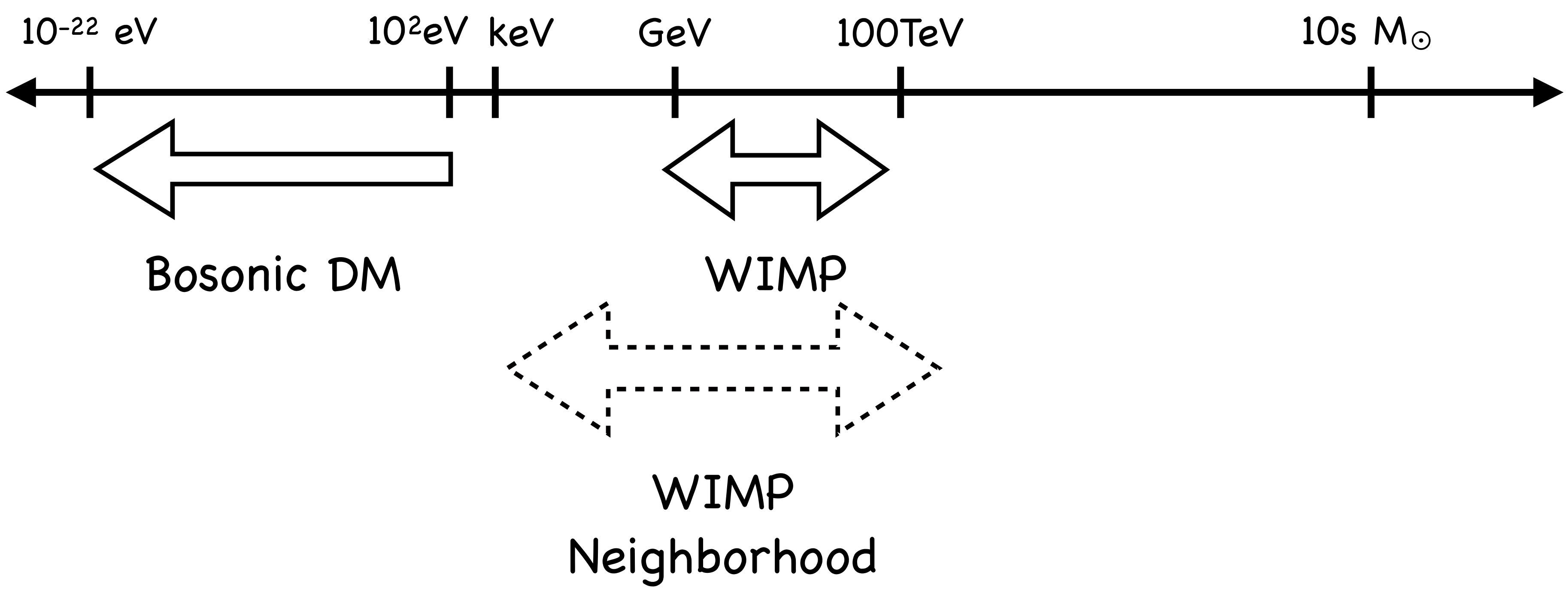
Still a lot to be done



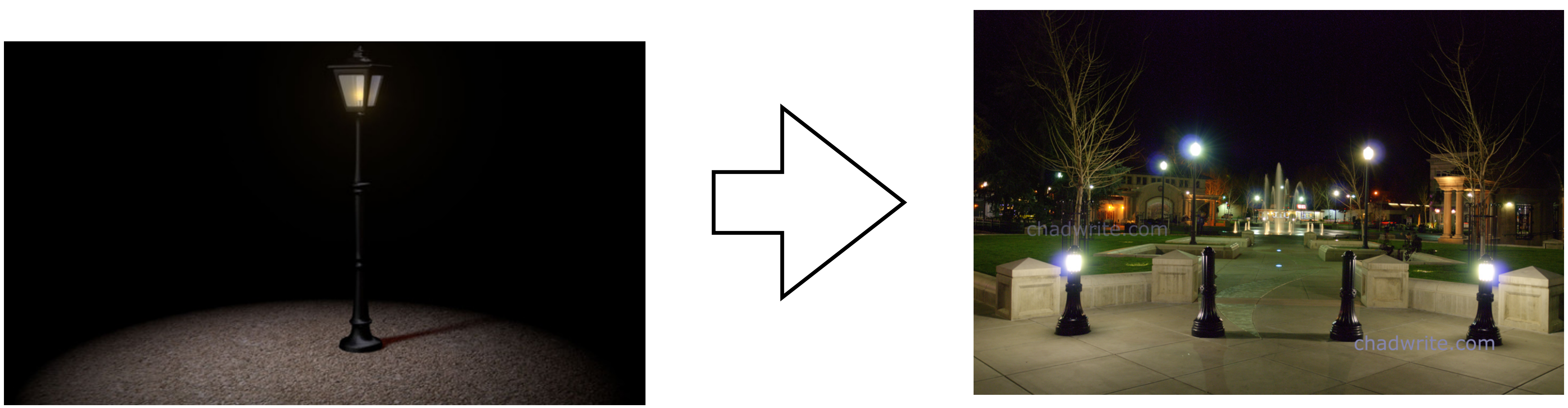
Simplest case yet to be probed



Beyond WIMP

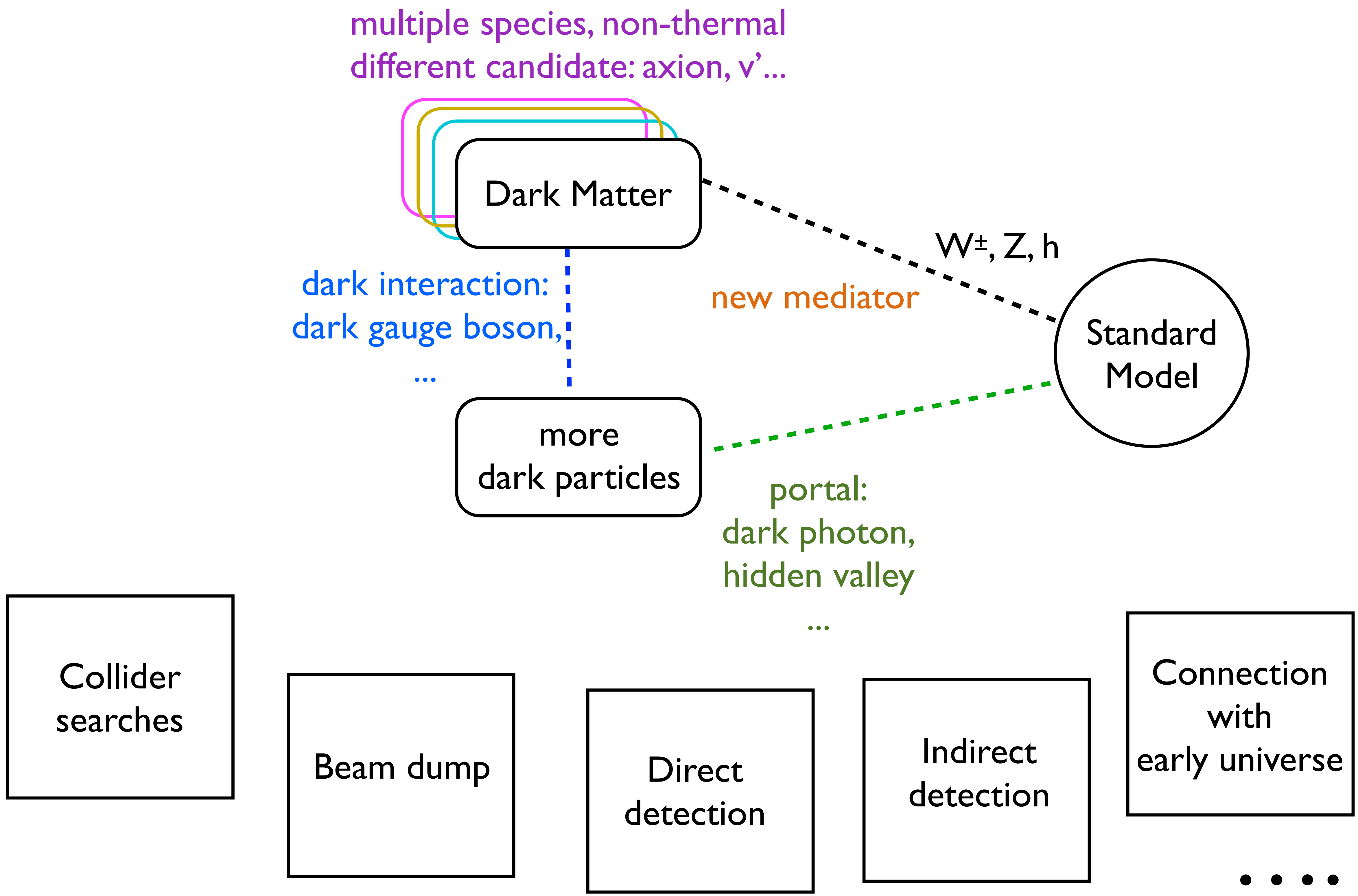


10^{-22} eV
10^{2}eV
keV
GeV
100TeV
10s $M_{\odot}$
Bosonic DM
WIMP
WIMP Neighborhood



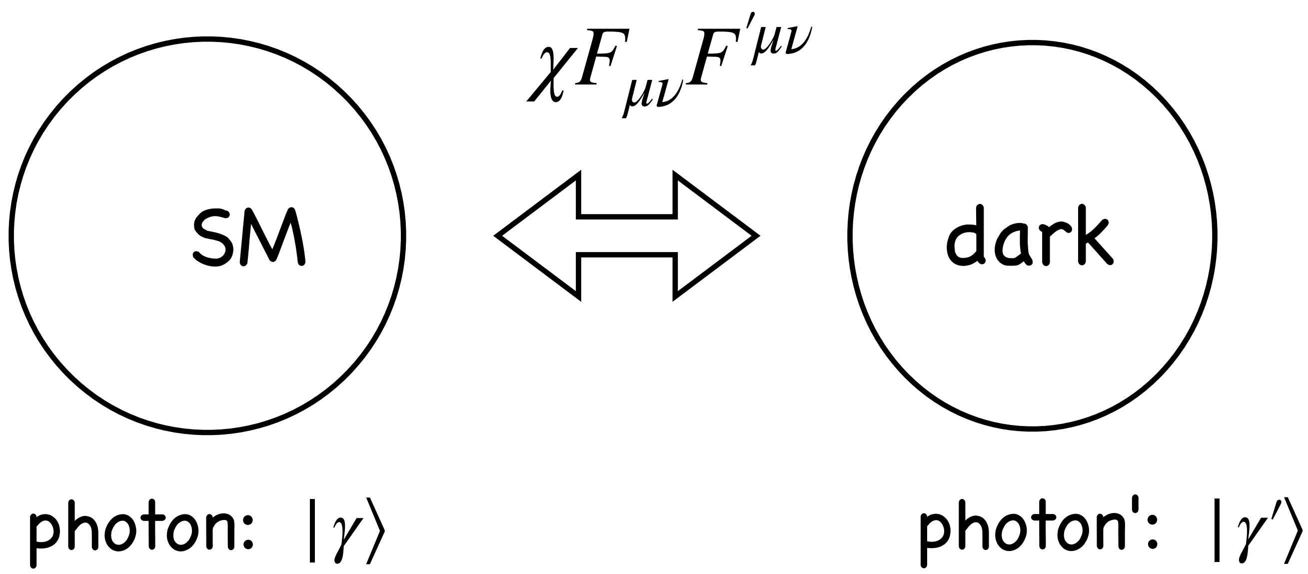
chadwrite.com
chadwrite.com

Beyond the simple WIMPs



New signals. DM may not be the first dark sector discovery.

Dark photon



dark photon: a quantum superposition of γ and γ'

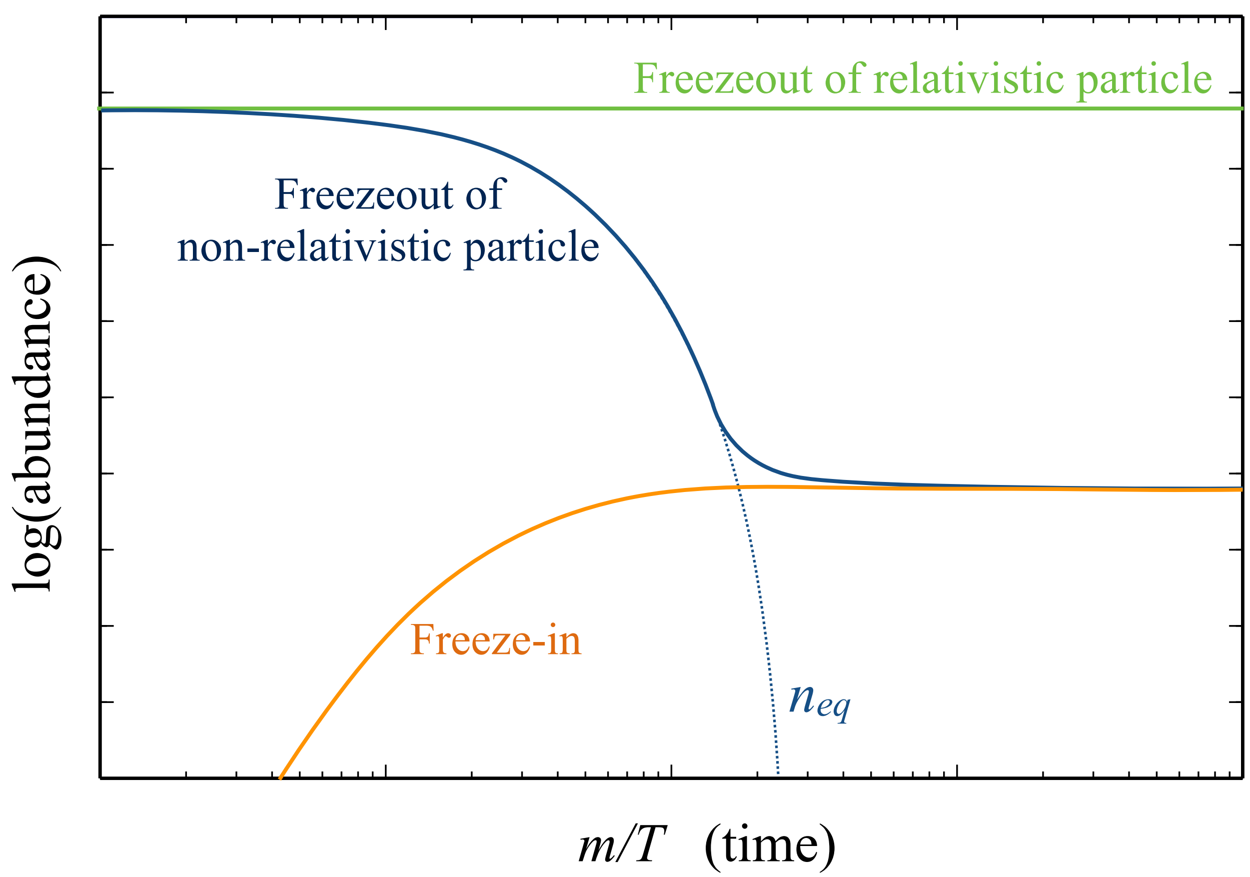
$$|\gamma_{\text{dark}}\rangle = |\gamma'\rangle + \chi|\gamma\rangle$$

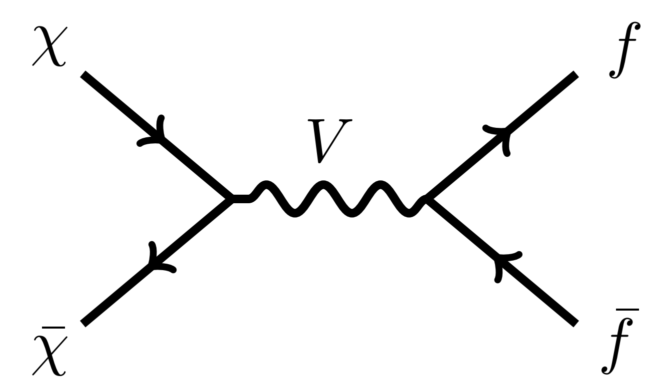
Mediates an interaction with strength $\propto \chi$

Roles of dark photon

As mediator for thermal freeze out. (Discussed earlier)

Freeze-in





Weak coupling, dark matter not in thermal eq.
It approaches the correct relic abundance.

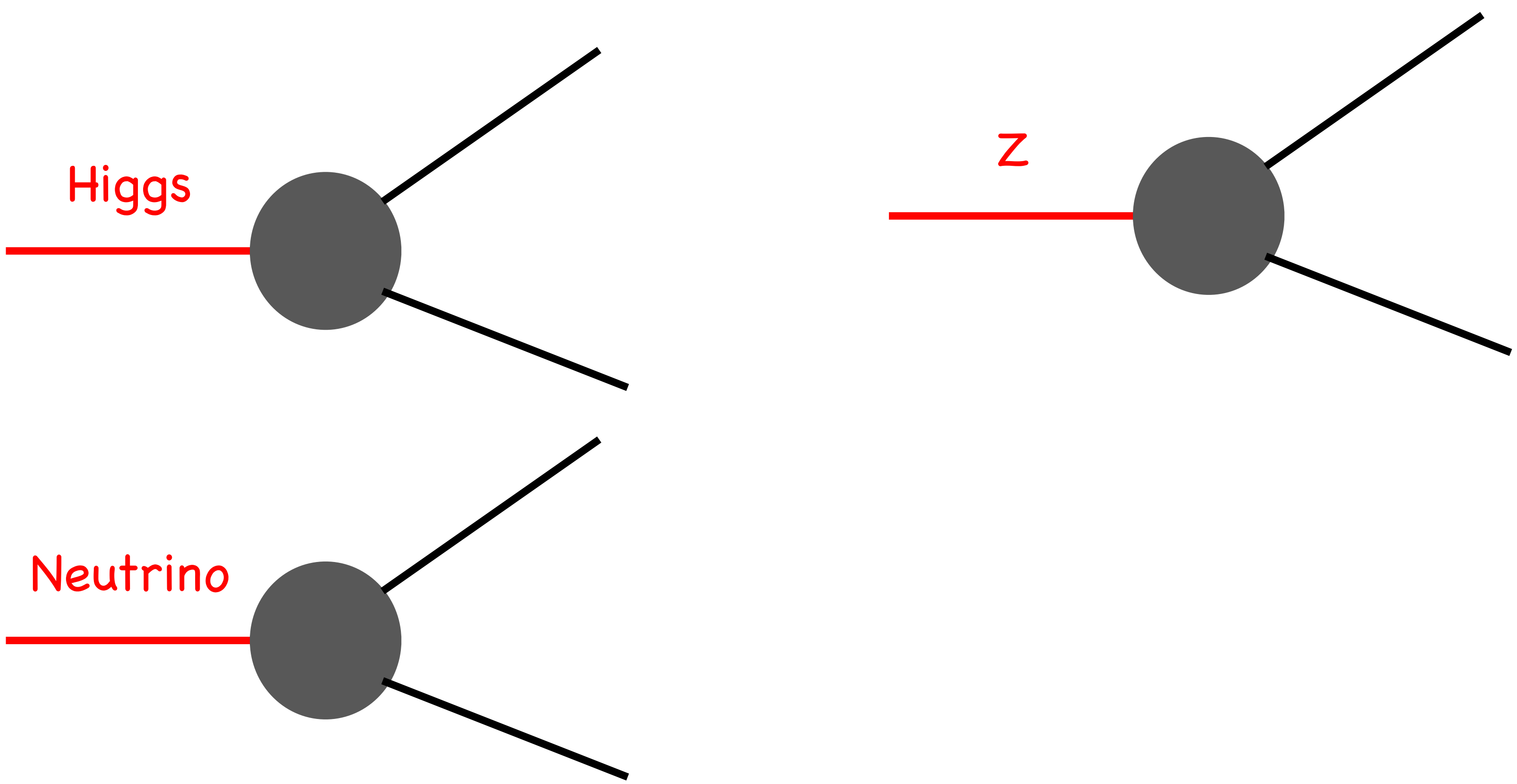
Examples

Thermal freeze out: $m_{\rm DM} = 10$ MeV, $m_V = 30$ MeV, $\chi \simeq 10^{-4}$

Freeze in: $m_{\rm DM} = 1$ MeV, $m_V = 10^{-12}$ eV, $\chi \simeq 10^{-6}$

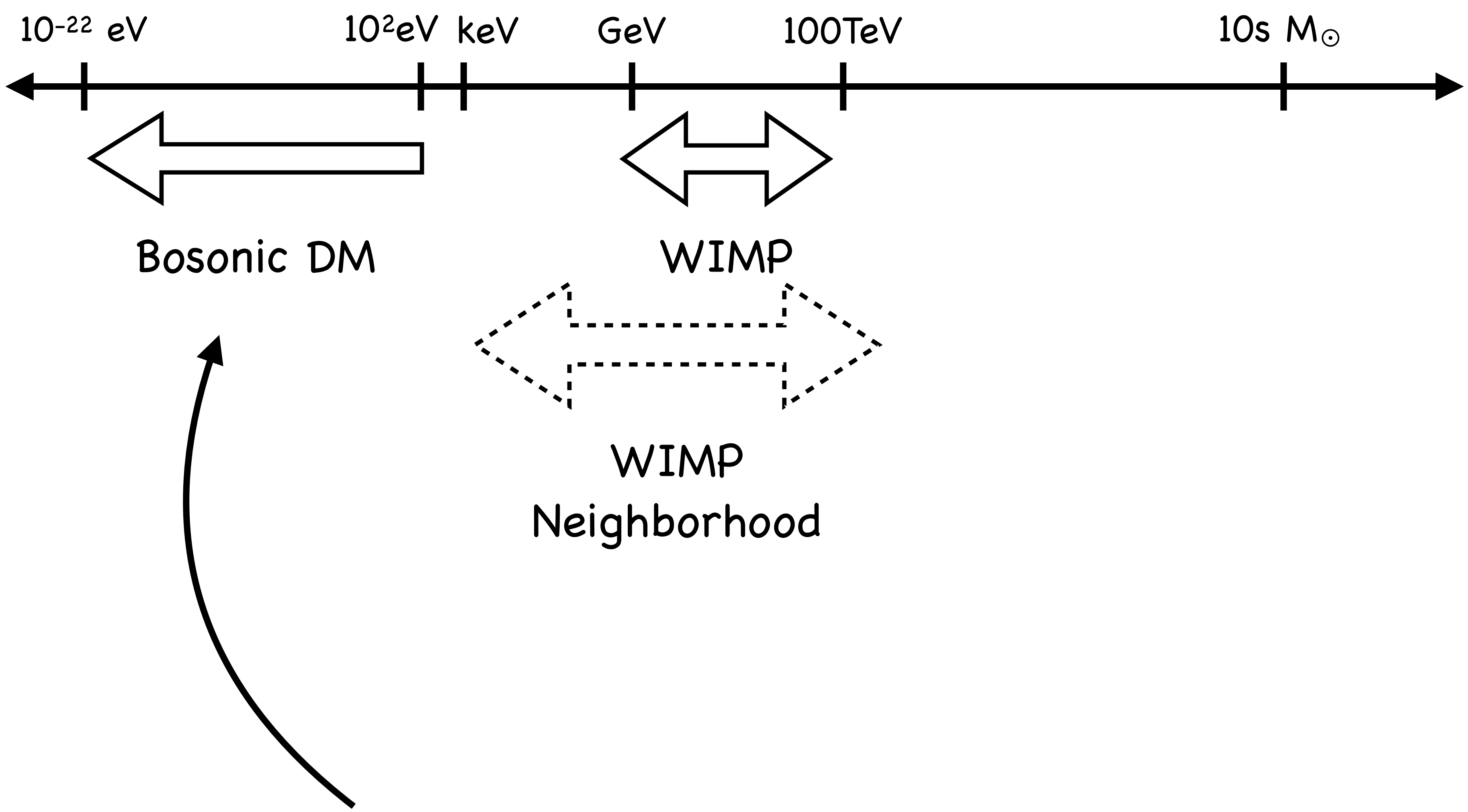
Windows into dark sector: portals

- Any known (SM) particle can in principle have small couplings to dark matter/dark sector.



Higgs/Z factories, such as CEPC
Neutrino facilities, fixed target experiments...

Theories of dark matter



Axion, dark photon

Not single particle-like.

Dark matter = classical wave

$$n_{\text{occupation}} \simeq \frac{\rho_{\text{DM}}}{M_{\text{DM}}} \times \lambda_{dB}^3 = 10^{94} \left(\frac{10^{-22}\text{eV}}{M_{\text{DM}}} \right)^4$$

$$\lambda_{dB} \sim \text{kpc} \left(\frac{10^{-22}\text{eV}}{M_{\text{DM}}} \right) \qquad \rho_{\text{DM}} \simeq 0.4\ \text{GeV/cm}^3$$

- Huge occupation number within a de Broglie wavelength.
  - Collective motion →classical waves, not a single particle
  - similar to sound, waves on the ocean or traveling on a string...

Classical field in expanding universe

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Expansion of universe
"Viscosity"

Hubble: $H \equiv \frac{\dot{a}}{a}$

$$V'(\phi) = m^2\phi + \cdots$$

Mass + interactions

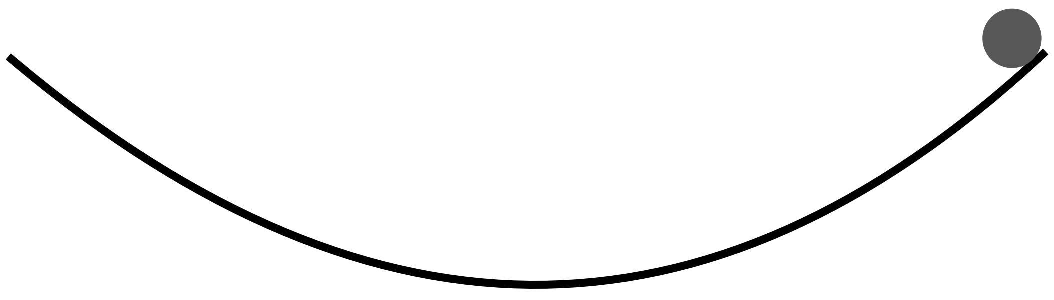
Classical field in two limits

$H > m_\phi$ $\quad \ddot{\phi} + 3H\dot{\phi} + \cancel{V'}(\phi) = 0$

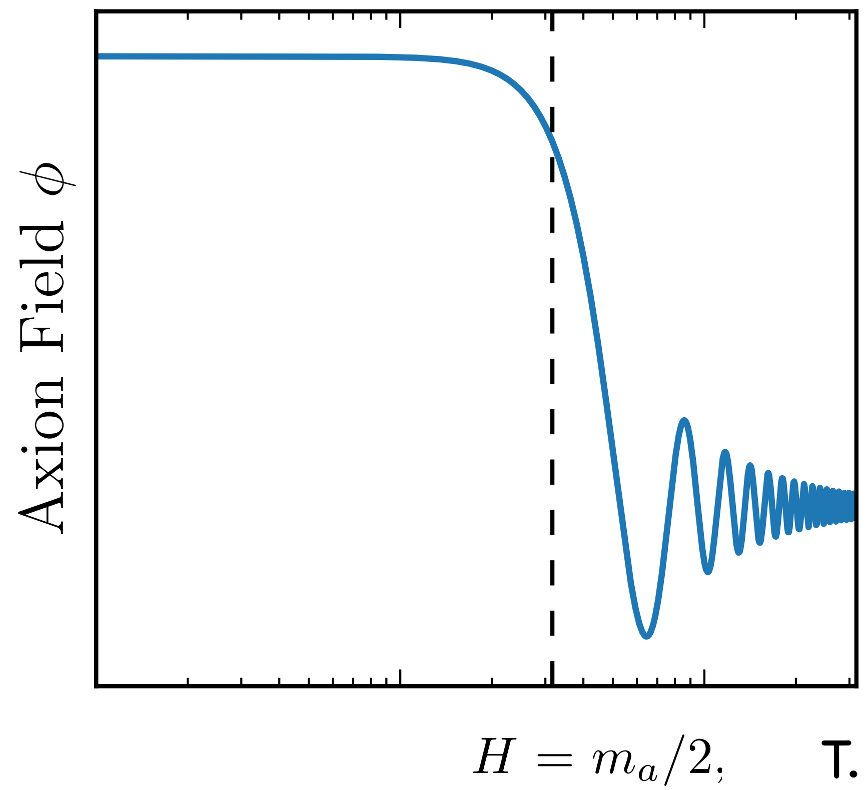
Hubble expansion more important

$H < m_\phi$ $\quad \ddot{\phi} + 3\cancel{H}\dot{\phi} + V'(\phi) = 0$

mass more important



$$\phi(t) \propto \frac{1}{a^{3/2}(t)} \sin(m_\phi t + \phi_0)$$

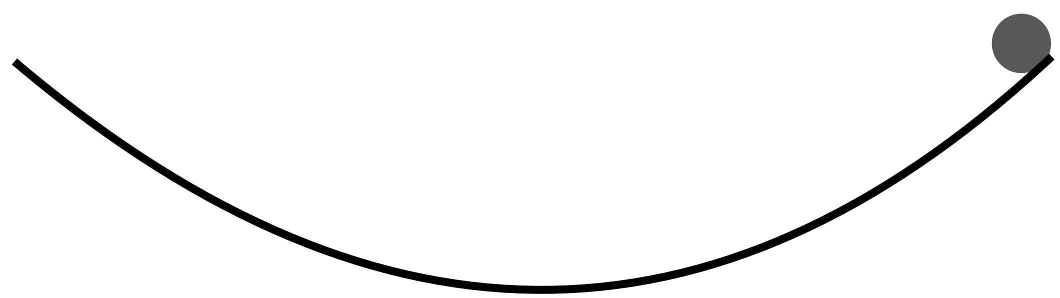


T. Lin 2018 TASI lecture

Classical field as DM

$$H < m_\phi \qquad \ddot{\phi} + 3H\dot{\phi} + \cancel{V'}(\phi) = 0$$

mass more important



$$\phi(t) \propto \frac{1}{a^{3/2}(t)} \sin(m_\phi t + \phi_0)$$

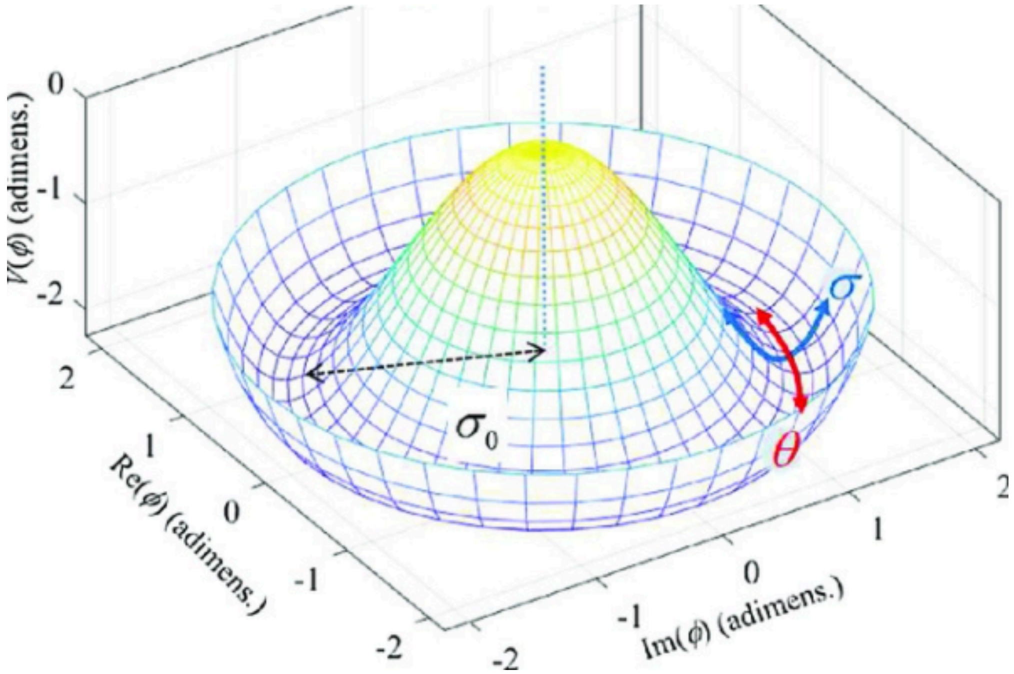
$$\rho \propto m_\phi^2 \phi^2(t) \propto \frac{1}{a^3(t)}$$

On large scales, behave same as particle-like matter.

Will similarly cluster, form structure, etc.

Why is axion light?

Potential of a symmetry breaking



A very common phenomenon:
1) Standard Model electroweak symmetry breaking. Strong interaction.
2) Condensed matter system: phonon, magnets, BCS...

Excitation in θ direction massless. "Goldstone" boson.

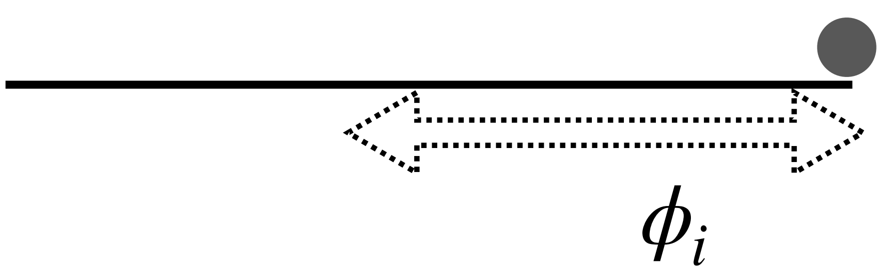
Symmetry $\theta \rightarrow \theta$ + c $\Rightarrow \theta$ is massless.

Small mass can then be generated by a small coupling.

Production: misalignment

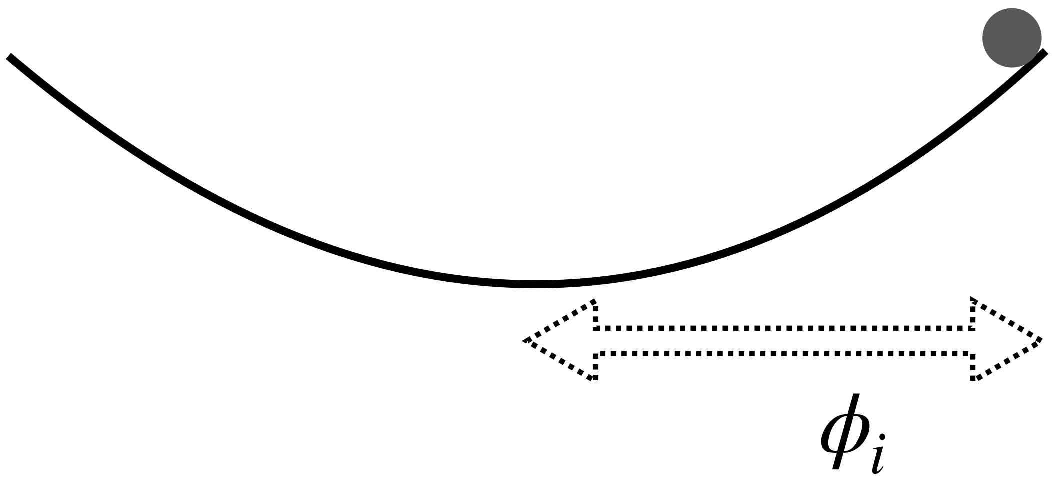
$H > m_\phi$

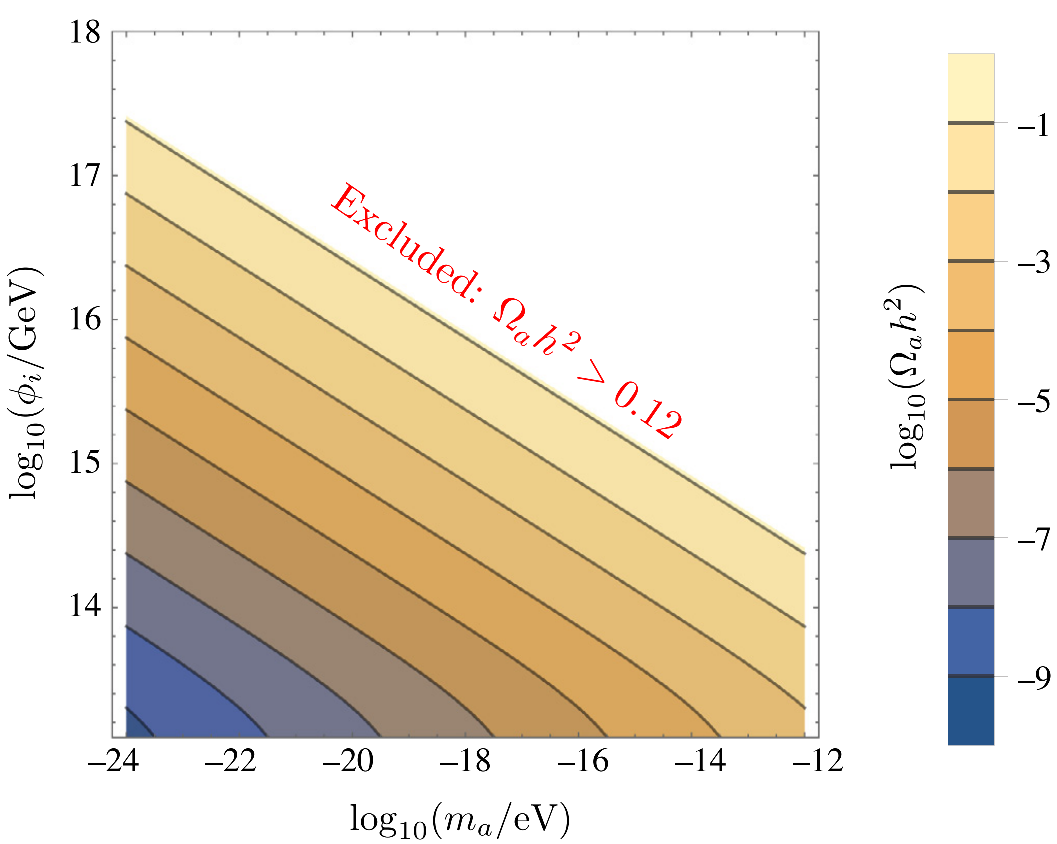
Hubble expansion more important



$H < m_\phi$

mass more important





$$\phi(t) = \frac{\phi_i}{a^{3/2}(t)} \sin(m_\phi t + \phi_0)$$

$$\rho = m_a^2 \phi^2(t) \propto \phi_i^2$$

Need large initial value
Possible during inflation.

“The axion” and ALP

QCD (strong interaction) axion: the axion

Axion from breaking of a U(1) global symmetry.
Axion mass generated by small non-perturbative effect of strong interaction.

Motivation: QCD strong CP problem.

The neutron electric dipole moment expected from QCD is wrong by at least 9 orders of magnitude.

Axion gives a dynamical solution to this problem.

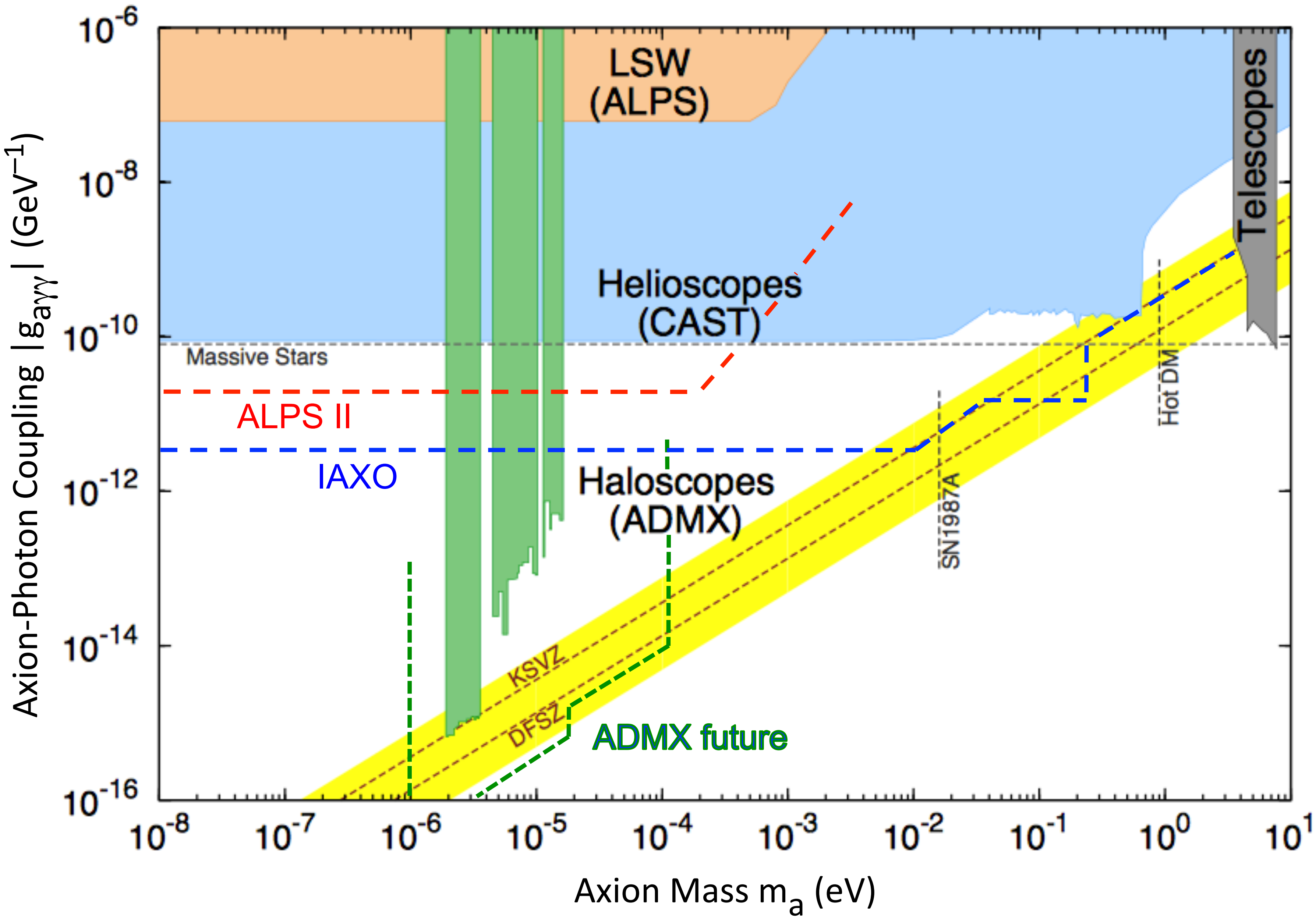
Axion like particles: ALPs

Similar light scalar particles.
The property is not dictated by the strong interaction. More general scenarios than the QCD axion.

Axion coupling to the known particles

Main detection channel relies on axion photon coupling

$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

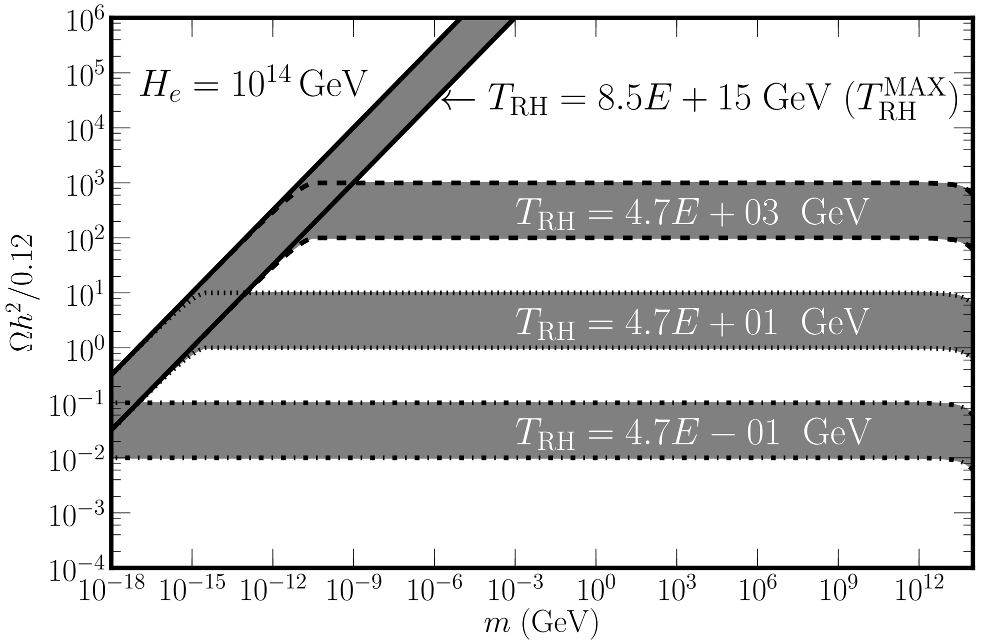


Dark photon dark matter

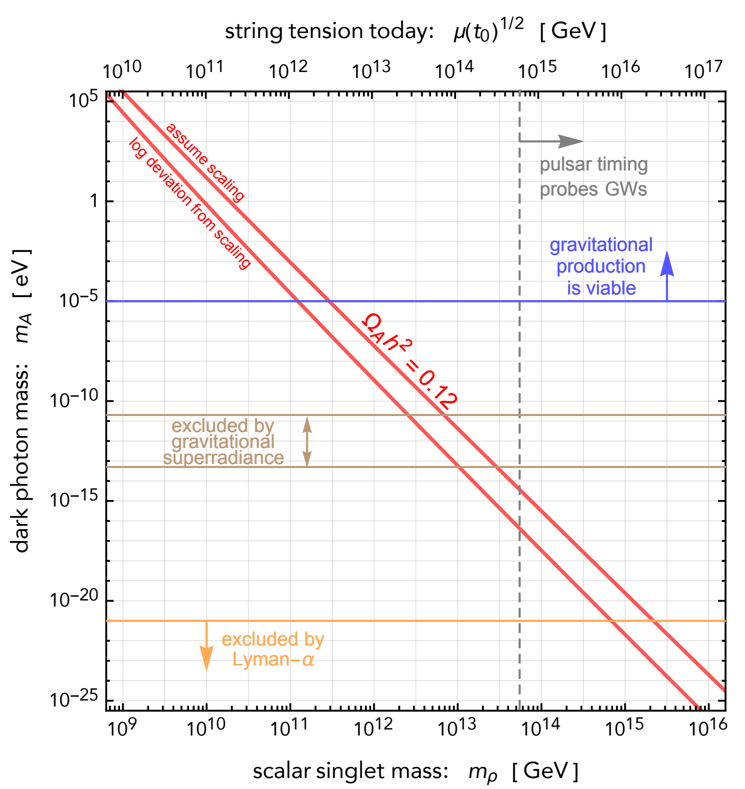
Multiple production mechanisms:

Produced gravitationally during inflation and reheating

Similar to Hawking radiation, but applied to expanding universe.

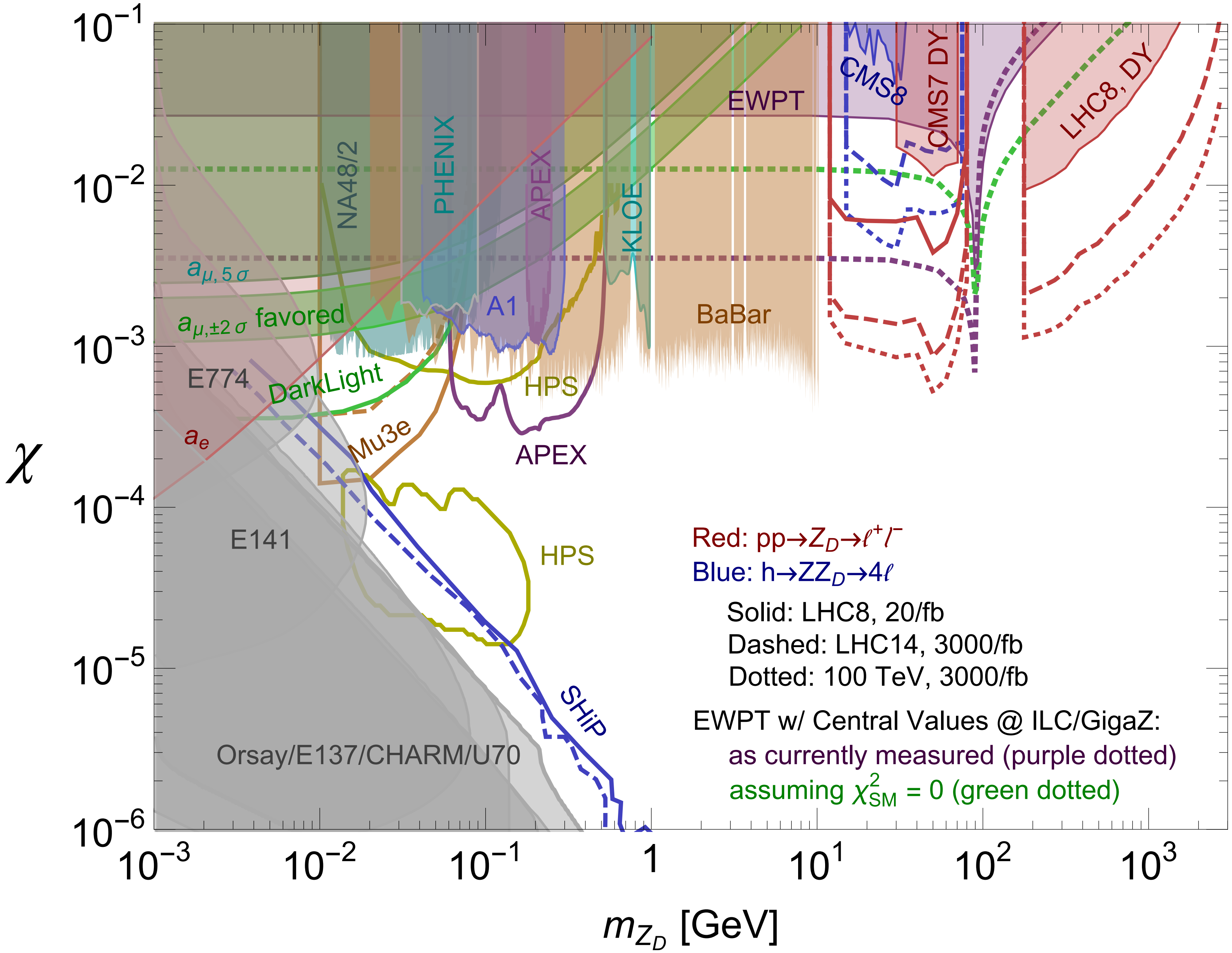


From topological defects (such as cosmic strings) radiation



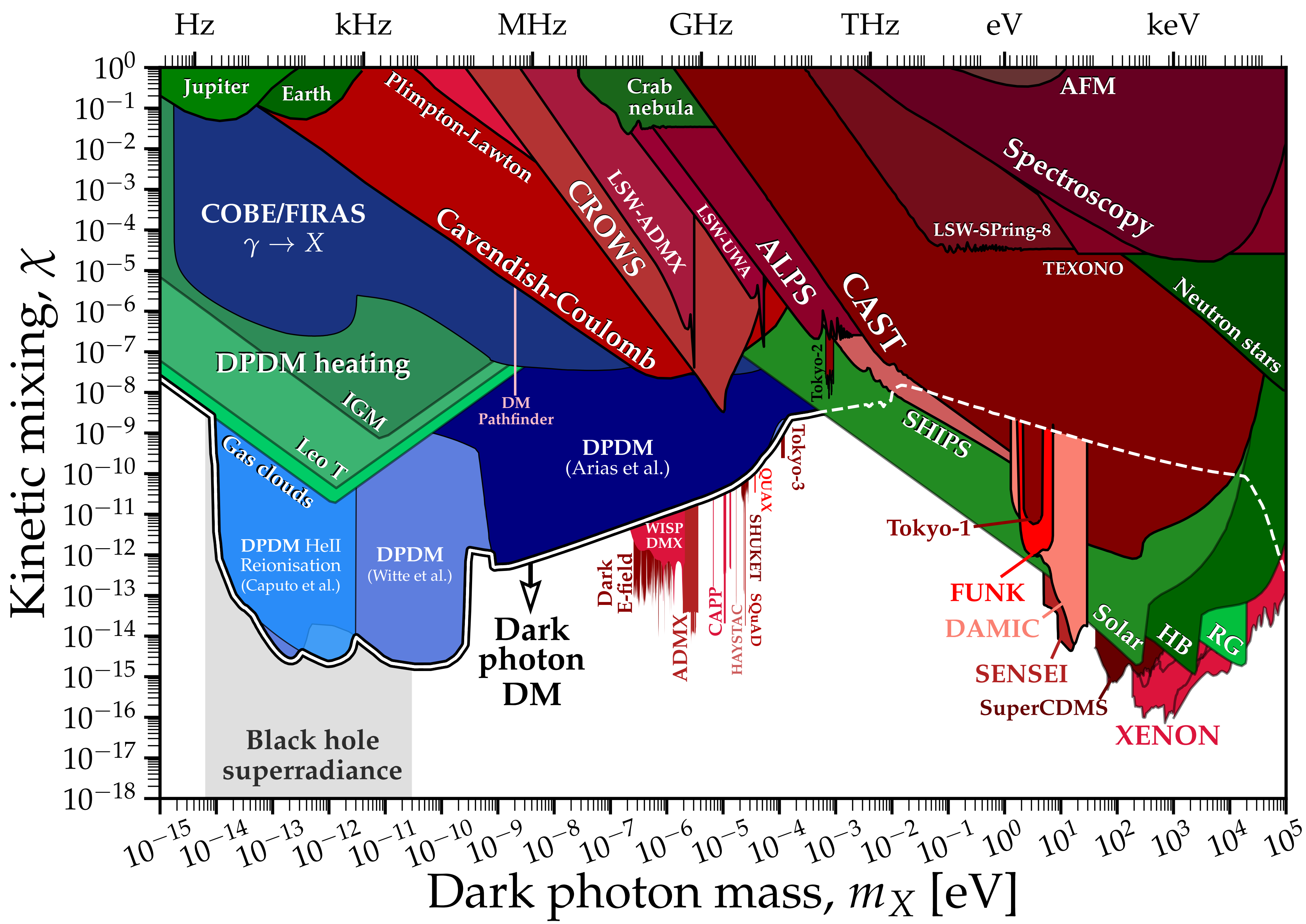
+ from misalignment, coupling to axions, …

Dark photon searches



Heavier dark photon: Colliders, fixed target experiments

Dark photon searches



Lighter dark photon: Terrestrial/table top detectors, astrophysical, ...

Many new ideas still emerging. 赵悦的讲座

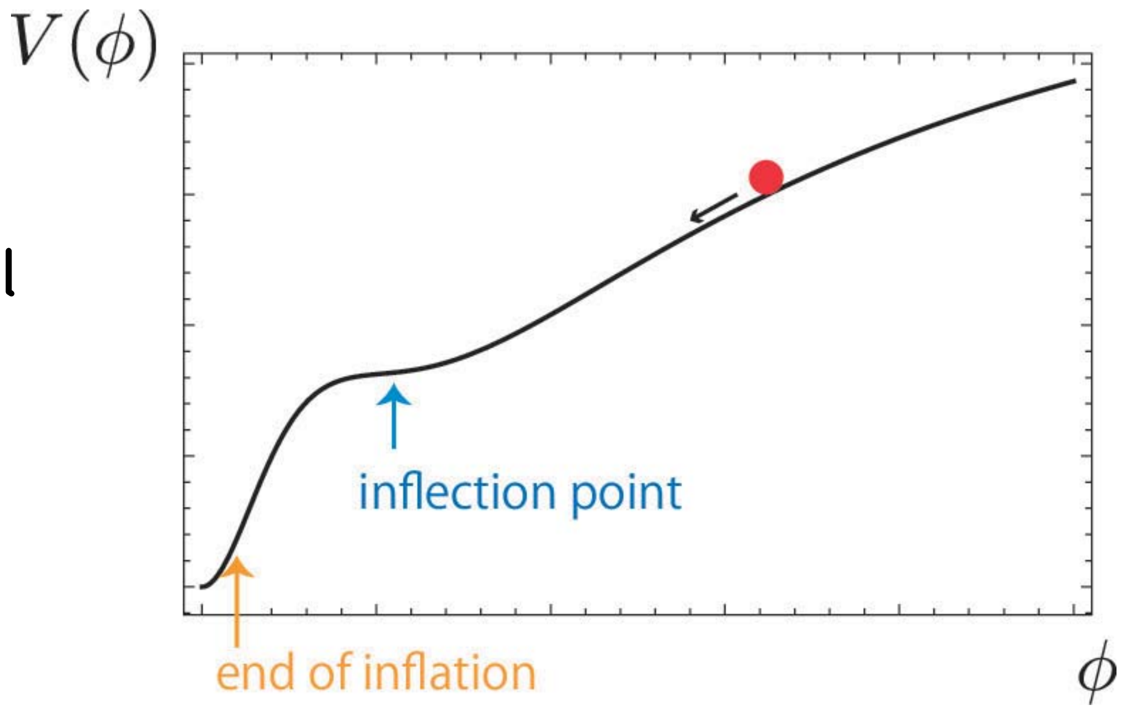
Are axion/dark photon good theories?

- Quite reasonable:
  - Based on well known physics (such as Goldstone boson and symmetry breaking).
  - QCD axion can solve strong CP problem.
- Testable:
  - Simple coupling to the Standard Model. Large possible region of coupling strength.
  - Many new development for new techniques.

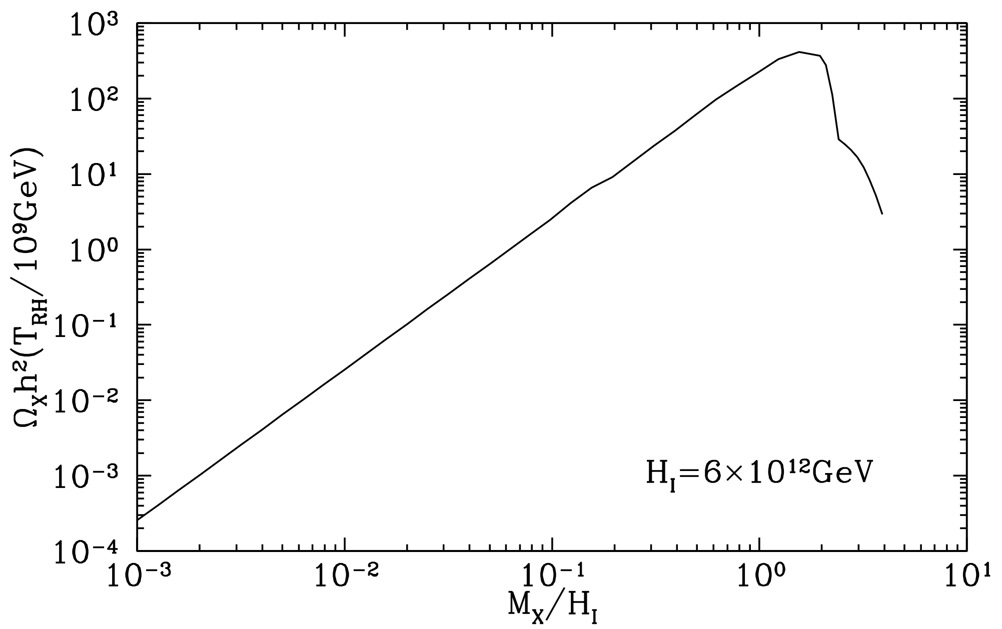
Pretty good theories. Good guide for experiments.

Other stories

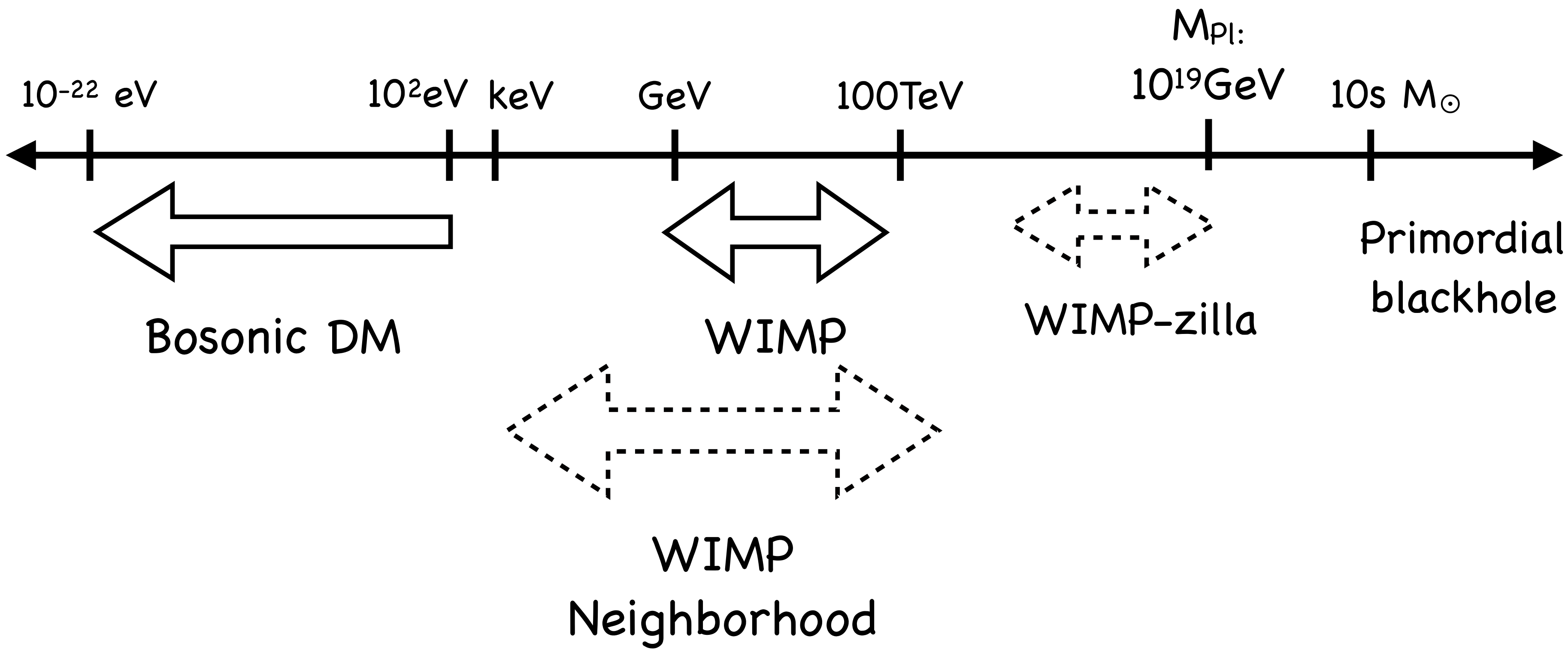
A special feature on the inflaton potential gives large fluctuations
⇒ primordial blackhole production



Gravitational effect during inflation and reheating can produce (very) heavy particles "WIMP-zillars" (10^{12-15} GeV)



The gaps in our stories



- Still, many orders of magnitudes empty.

More gaps

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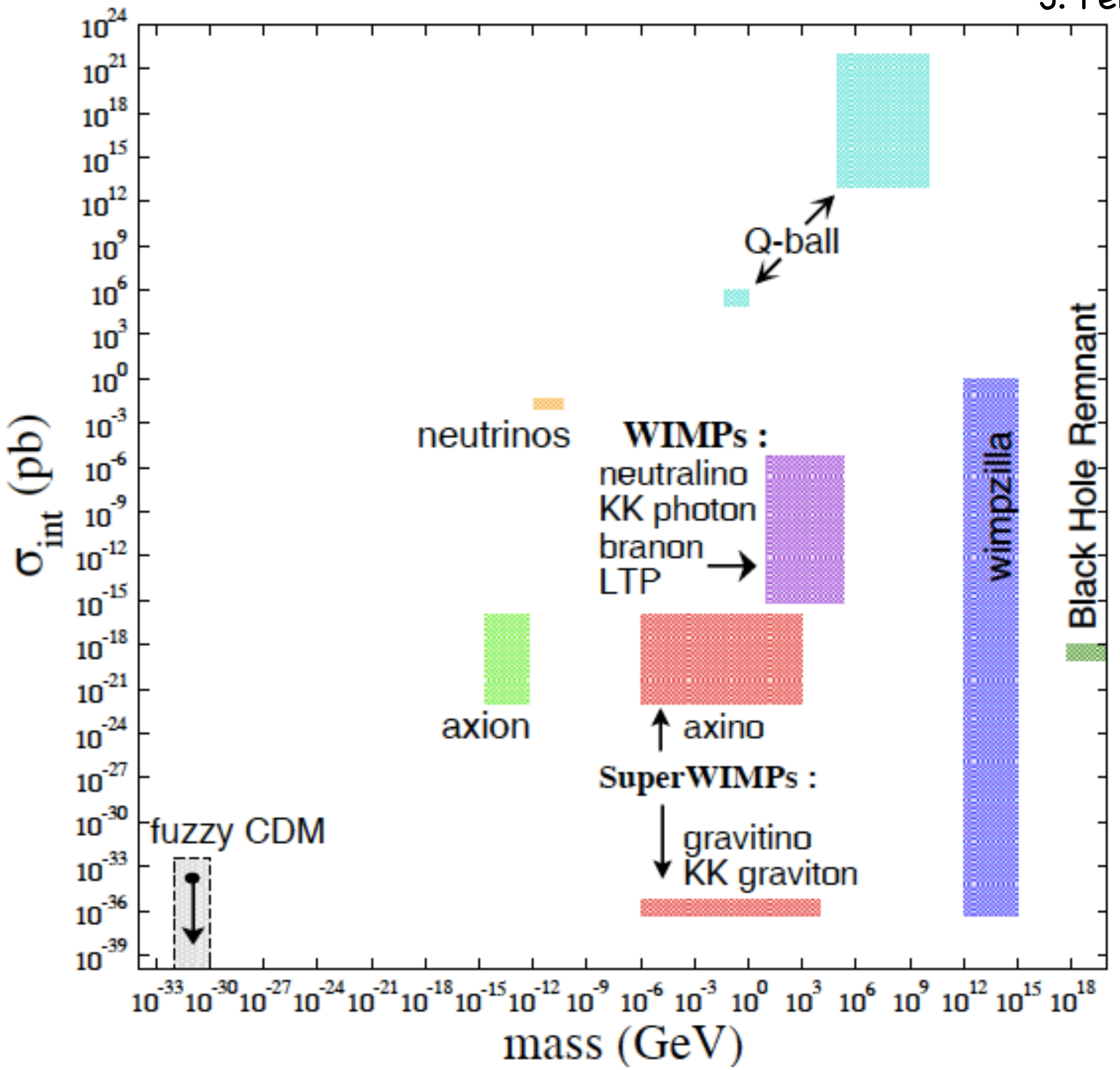

Challenge: can we find good models to fill these gaps?
Really necessary to guide searches!

Conclusions

- We are in an era with data coming from many directions
  - Colliders, underground detectors, table top experiments, astro/cosmo observations...
- We also face a lot of uncertainties
  - Many open questions.
    - EWSB, dark matter, inflation, flavor...
  - Not clear where the next breakthrough will come from.
- This is a perfect opportunity to make progress.

Enjoy this rest of the school!