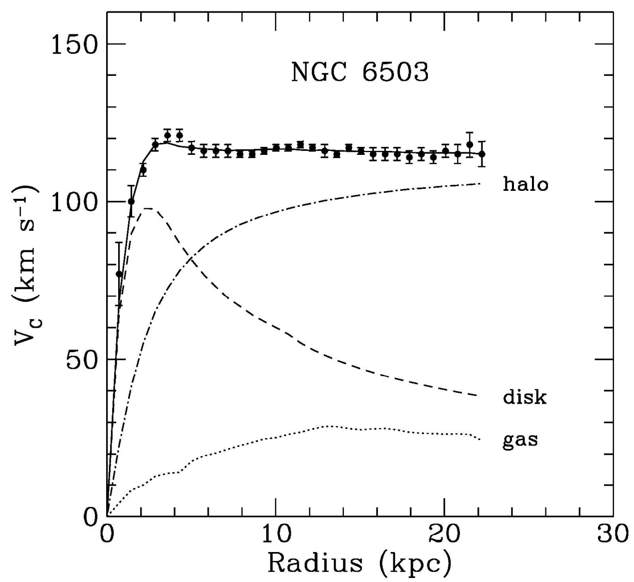
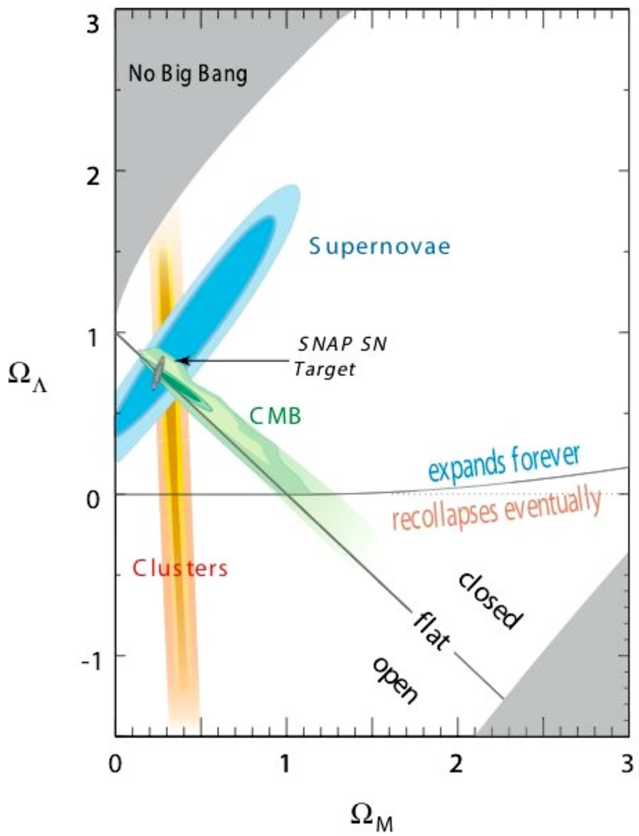
Theories of dark matter

Lian-Tao Wang
University of Chicago

Peking University, May 27, 2021

We have solid evidence for dark matter:





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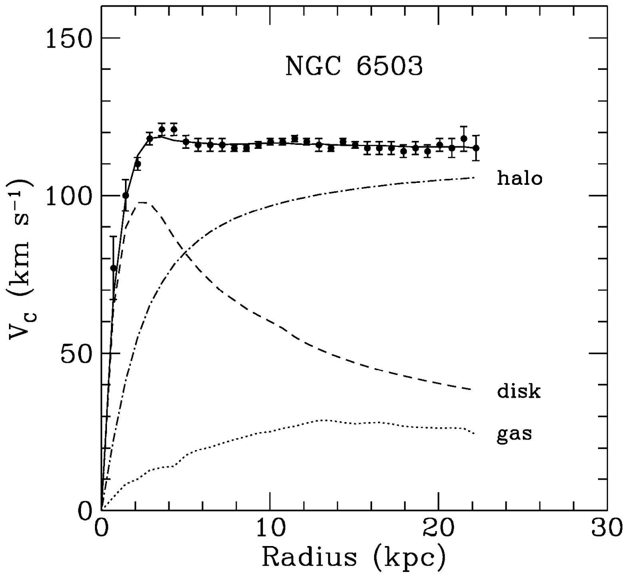

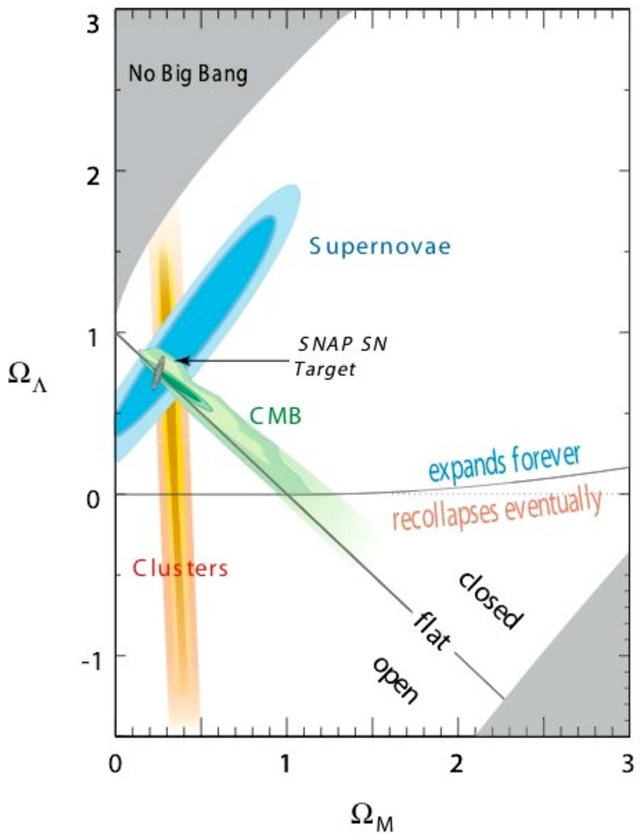

Our goal:
Understand the properties of dark matter.

This talk

- Going over our basic understanding and main scenarios of dark matter.

- Focusing on theoretical aspects of dark matter models

- It is a HUGE subject.
  - This talk is only an overview and glossing over many details.

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

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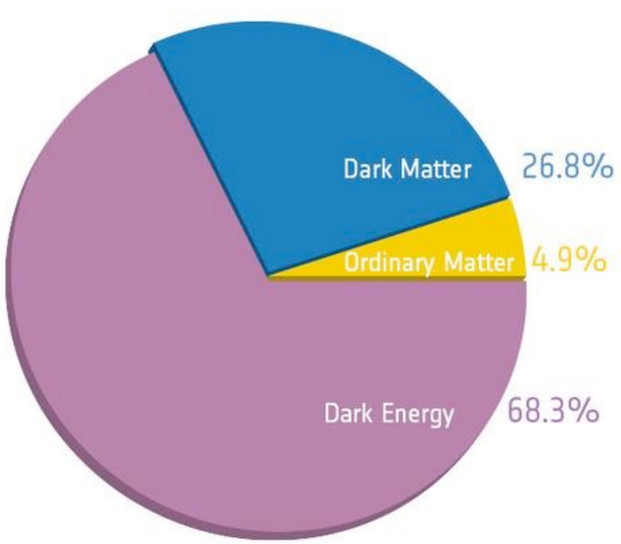
- Stable.
  - If it decays, lifetime much longer than the age of universe ≈ 10^{17} sec.
- Dark. Does not emit/absorb/reflect light.
  - Does not have electric charge.
- Produced in the early universe with the right amount. Right "relic abundance"



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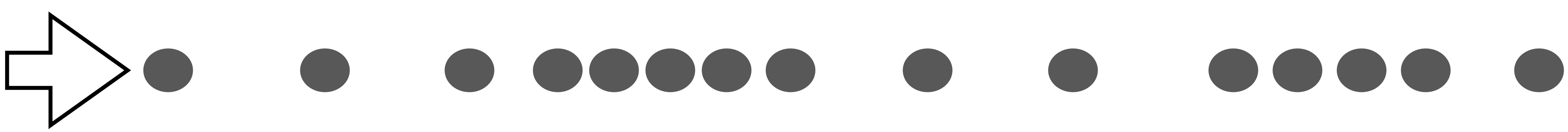

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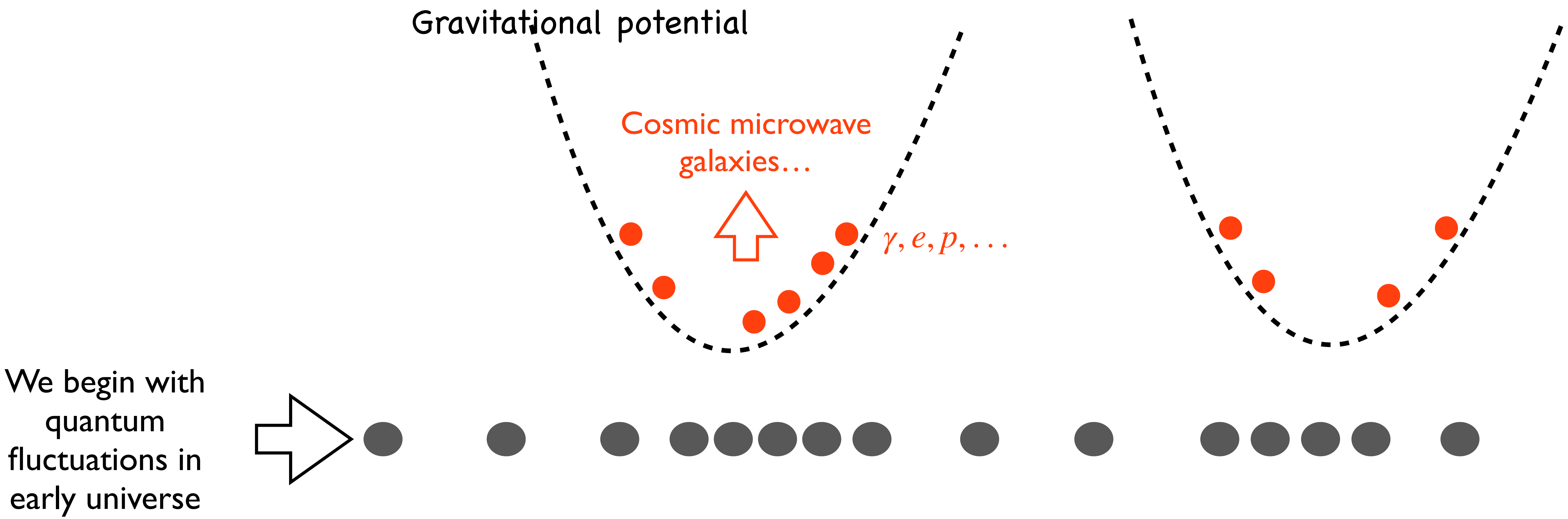

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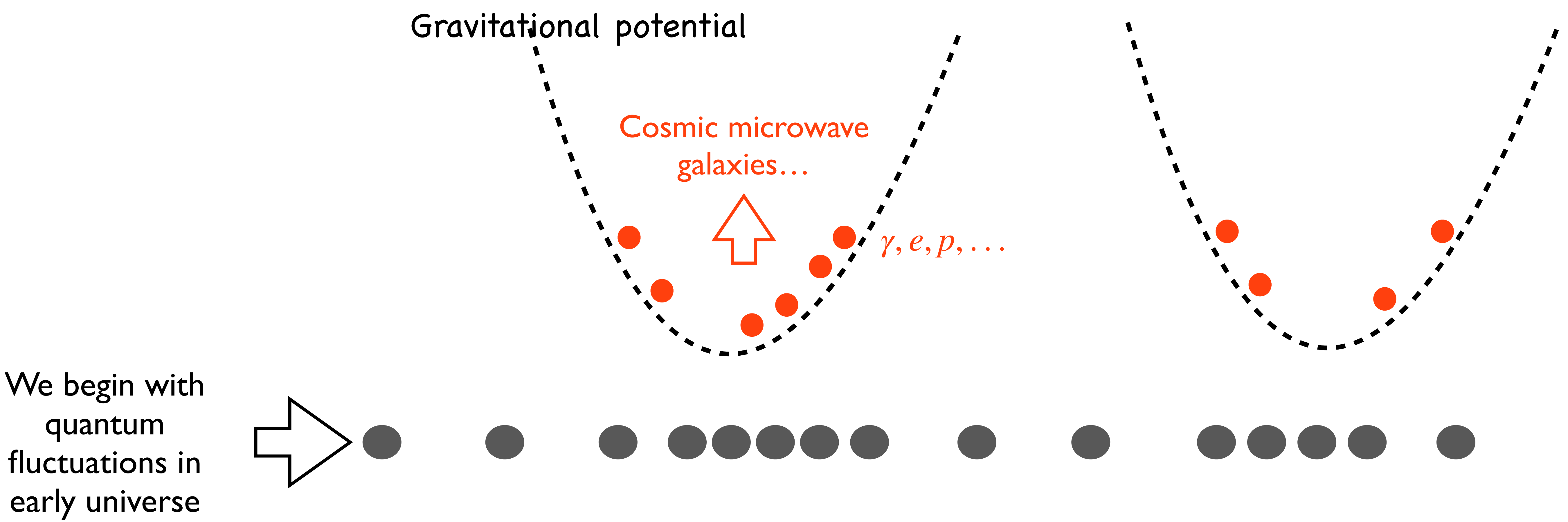
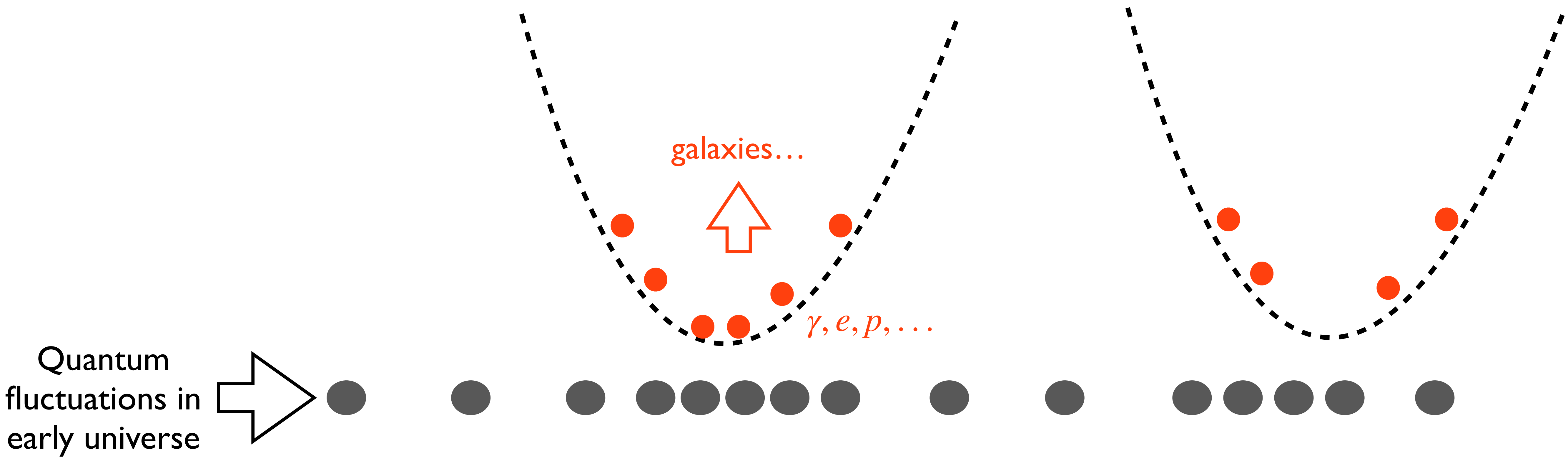


Dark matter needs to be "primordial", be there in early universe.

What do we know about dark matter



- "Collisionless". No long range interaction, except gravity.
- Cold. Non-relativistic: kinetic energy $\ll$ mass

Mass of dark matter

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DM needs to seed structures

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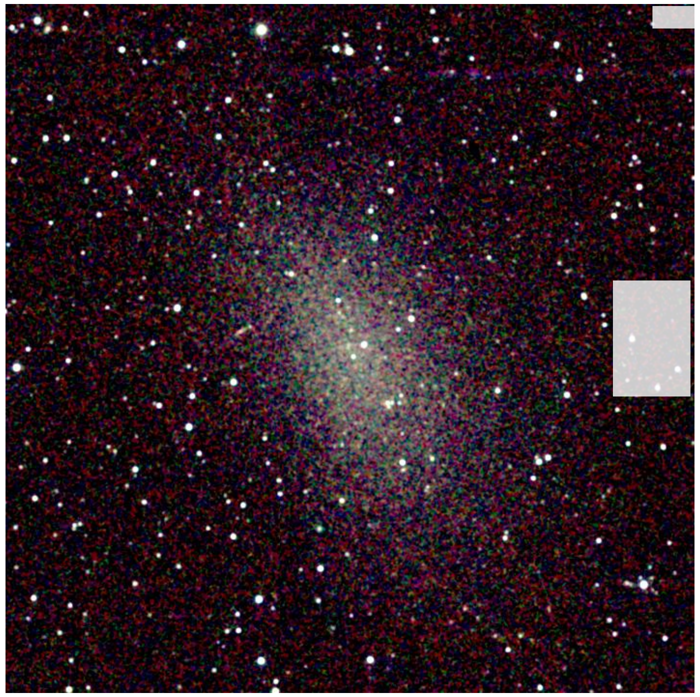
DM needs to seed structures



NGC147

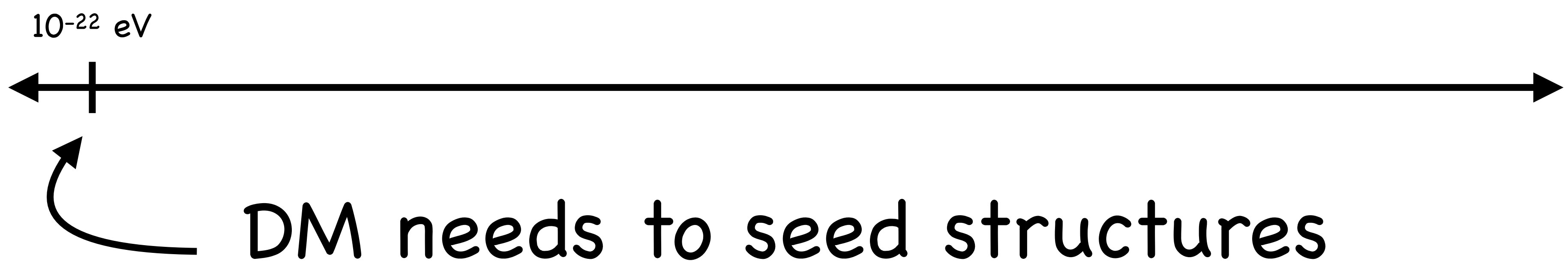
Smallest structure DM seeded:
Dwarf spheroidal galaxy, size ≈ 1 kpc (3000 lyr)

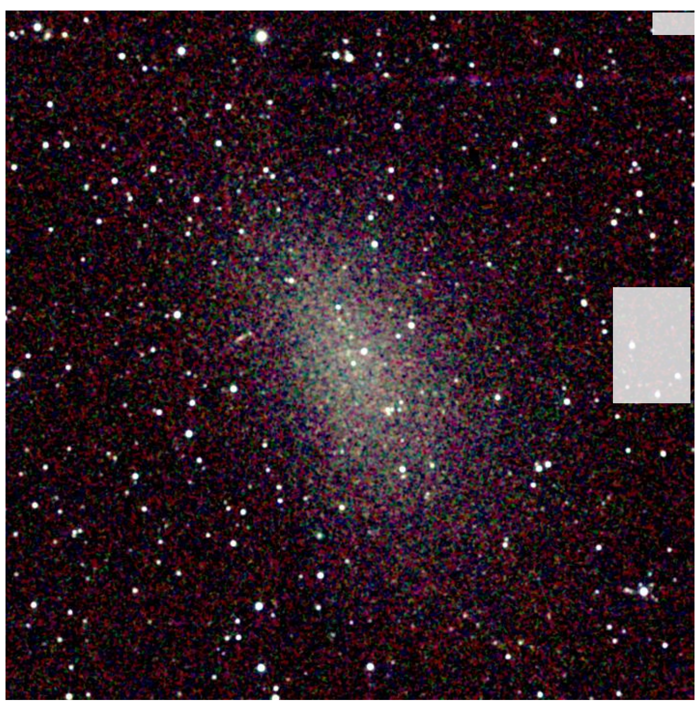
Dark matter particle wave packet must be smaller,
Lightest ⇔ largest de Broglie wave length

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

"Fuzzy dark matter"

Mass of dark matter





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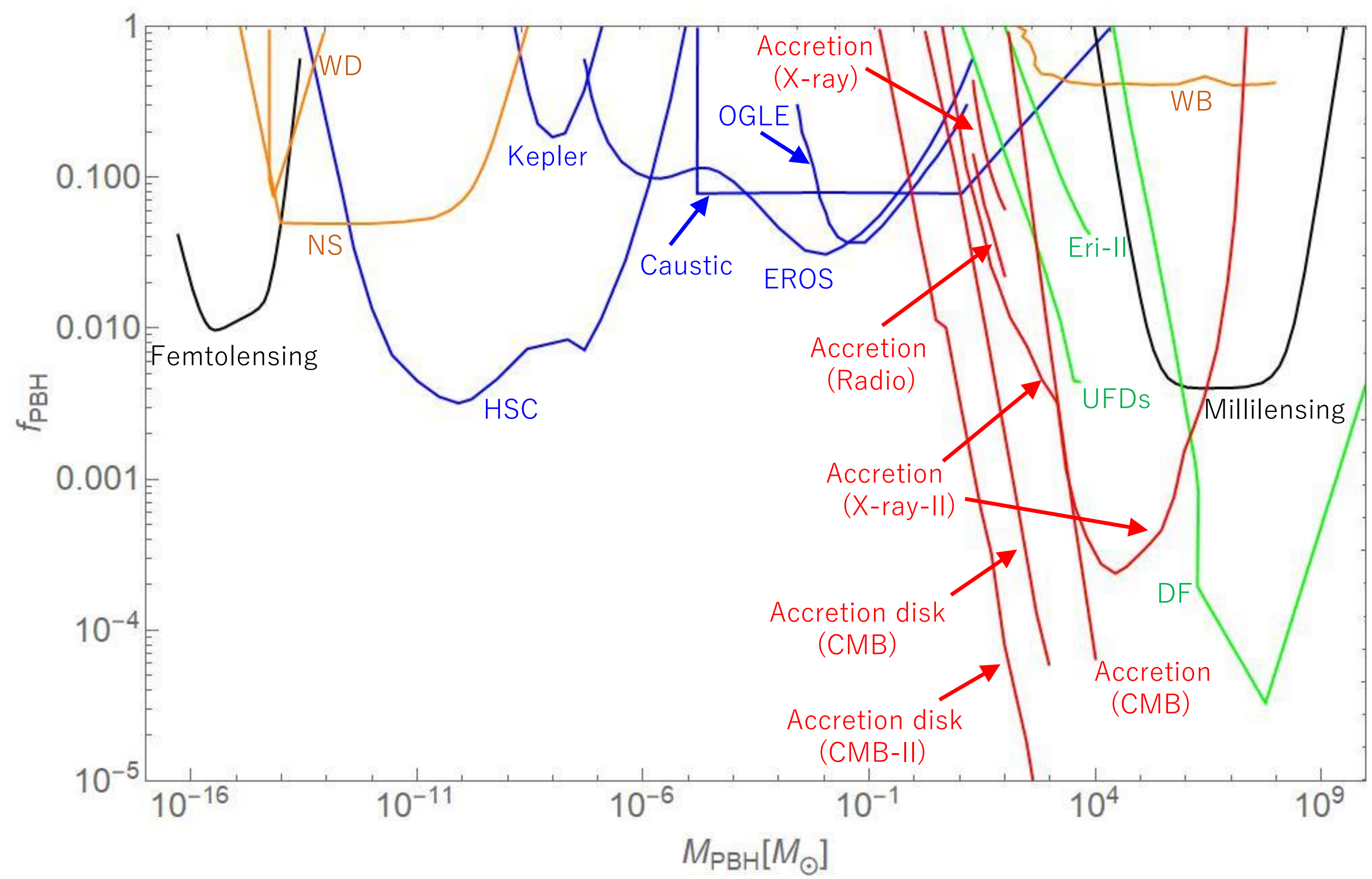
Very heavy BH accrete matter, too much ionizing radiation, CMB constraints $M_{PBH} < 10s\ M_\odot$

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

Other searches…



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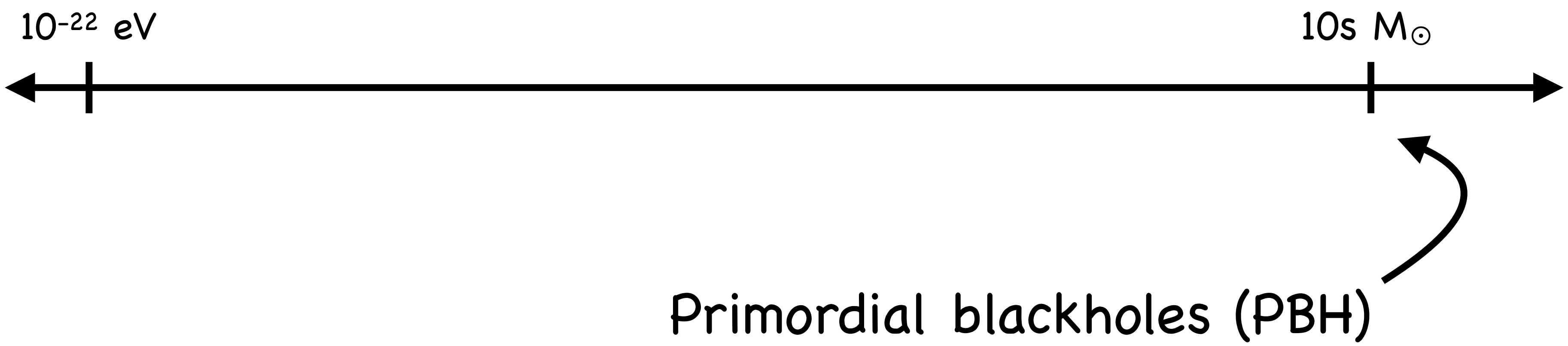

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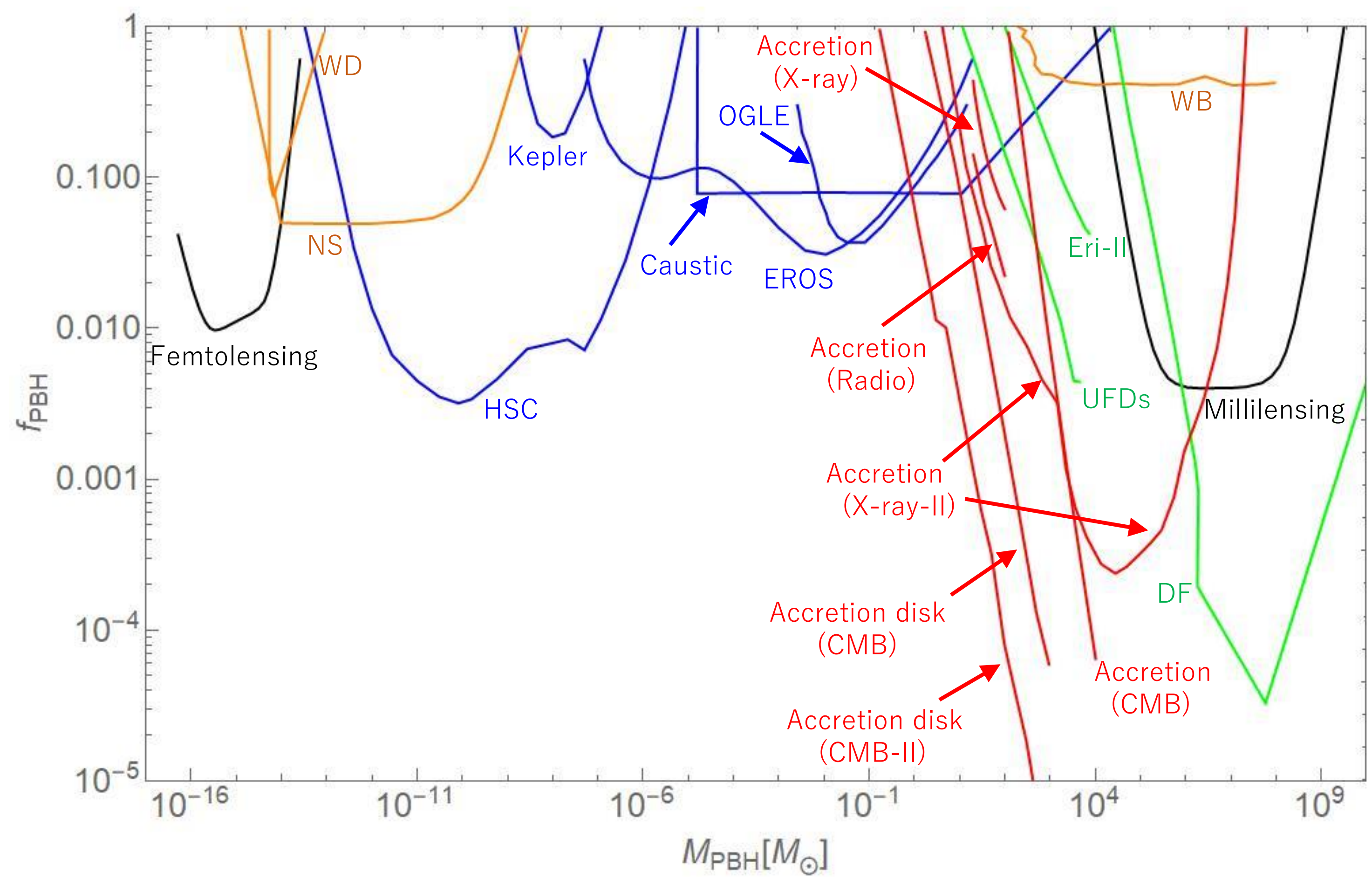
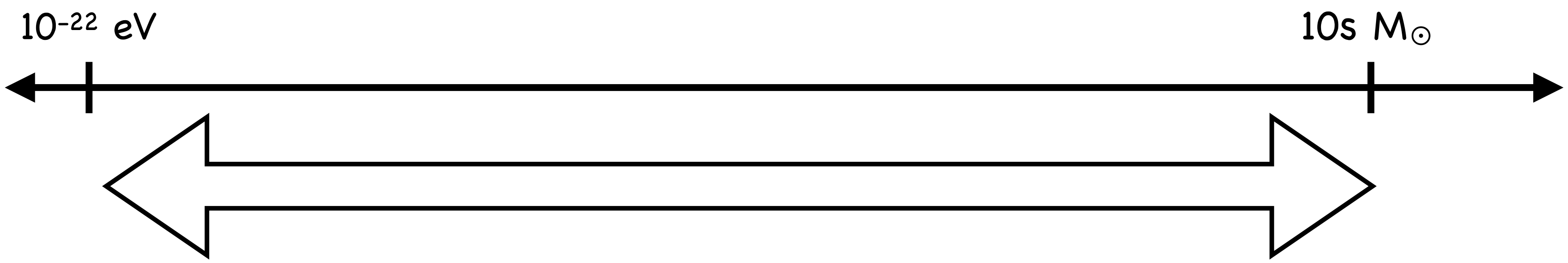


Mass of dark matter



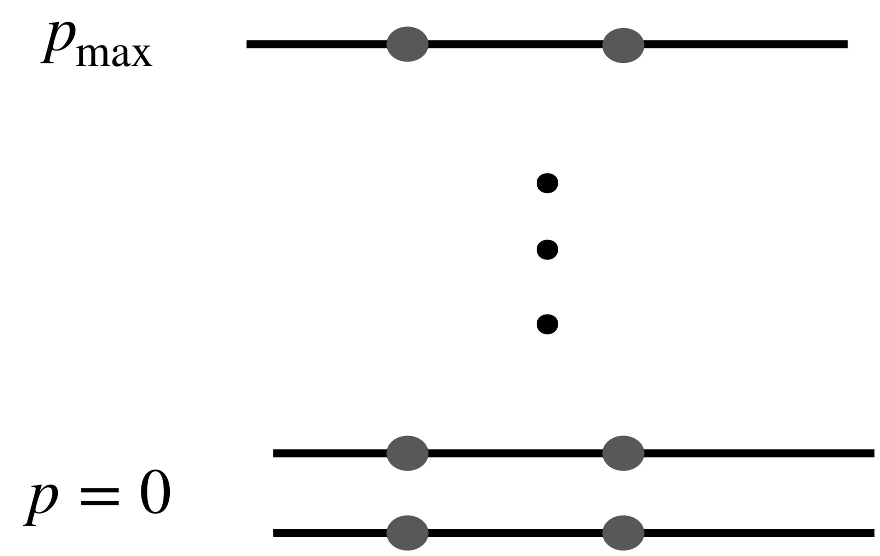
> 80 order of magnitudes!

What else can we say?

Mass of dark matter

Pauli exclusion principle

Fermionic dark matter



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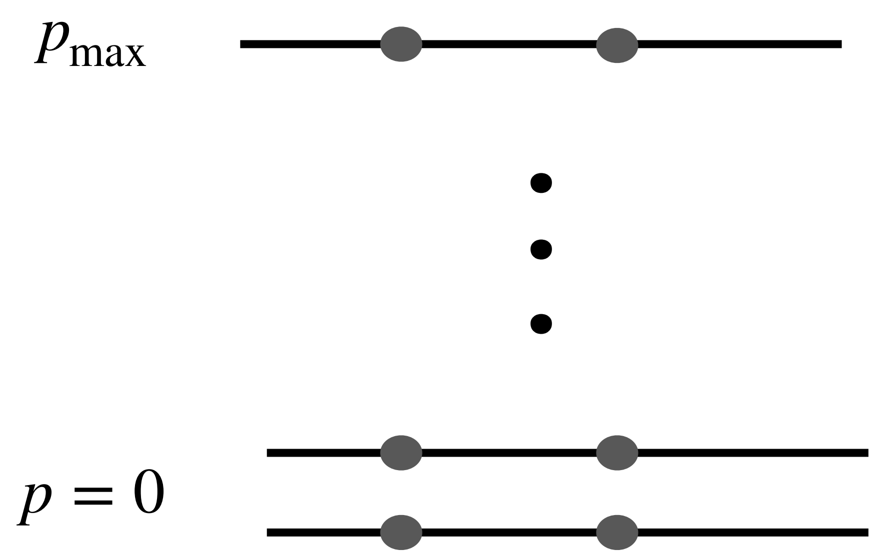


Fermionic dark matter

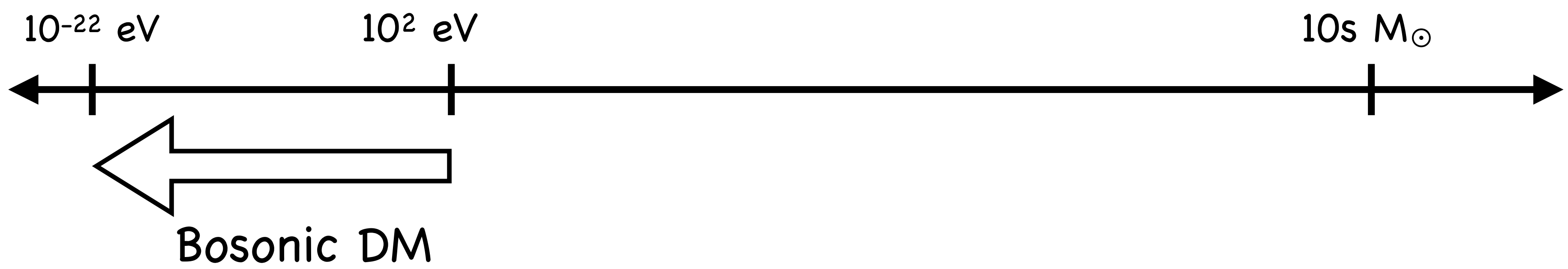
Since dark matter forms local bound structures such as galaxies

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

$v_{\rm esc}$: escape velocity

$$m_{\rm DM} > 10s \text{ eV}$$

Mass of dark matter



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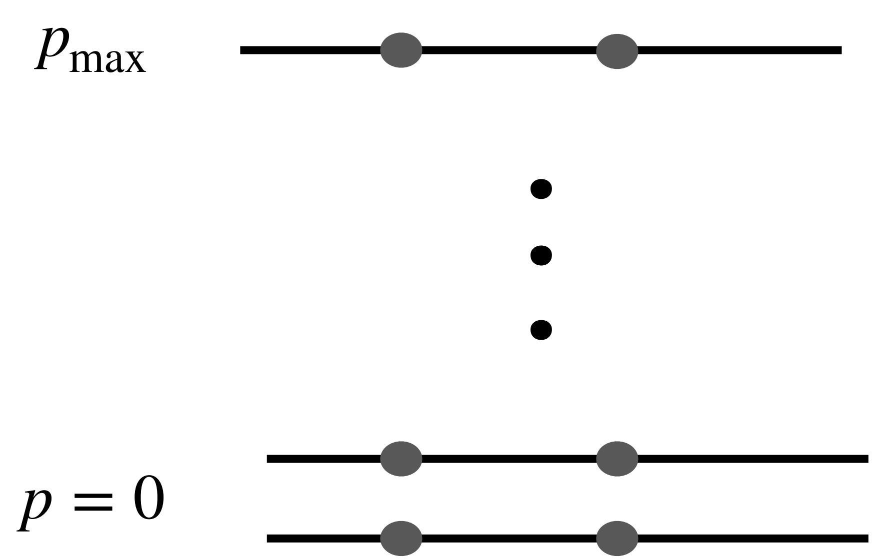

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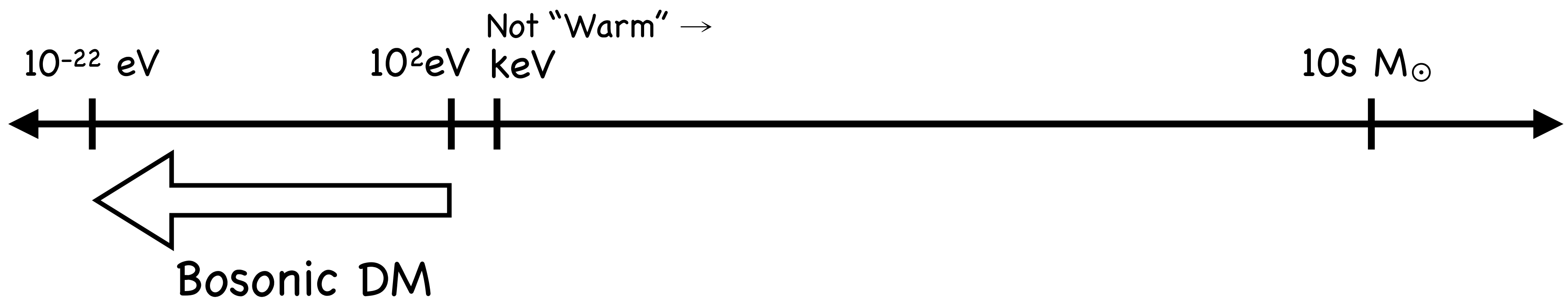
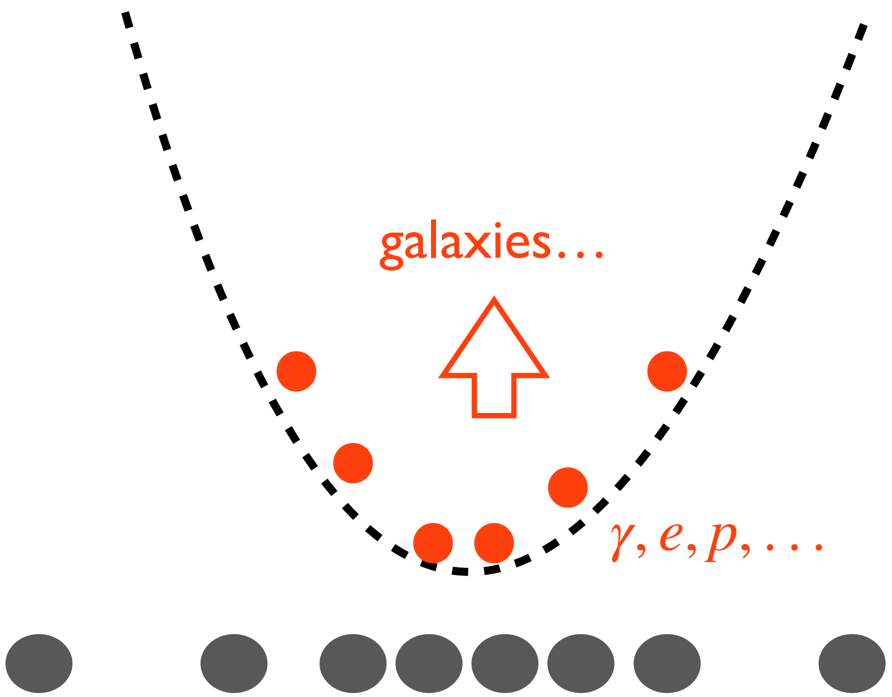


Warm dark matter limit:

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)



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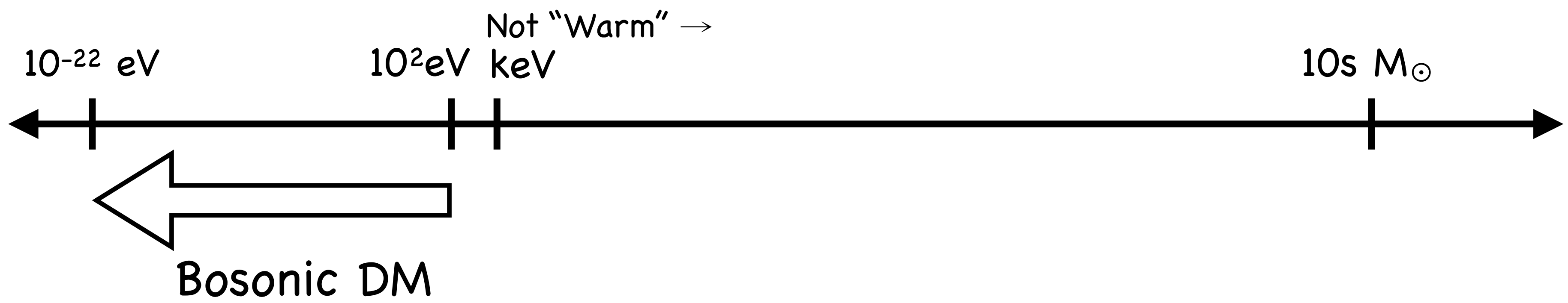

How do we guide our searches? We need theories (stories).

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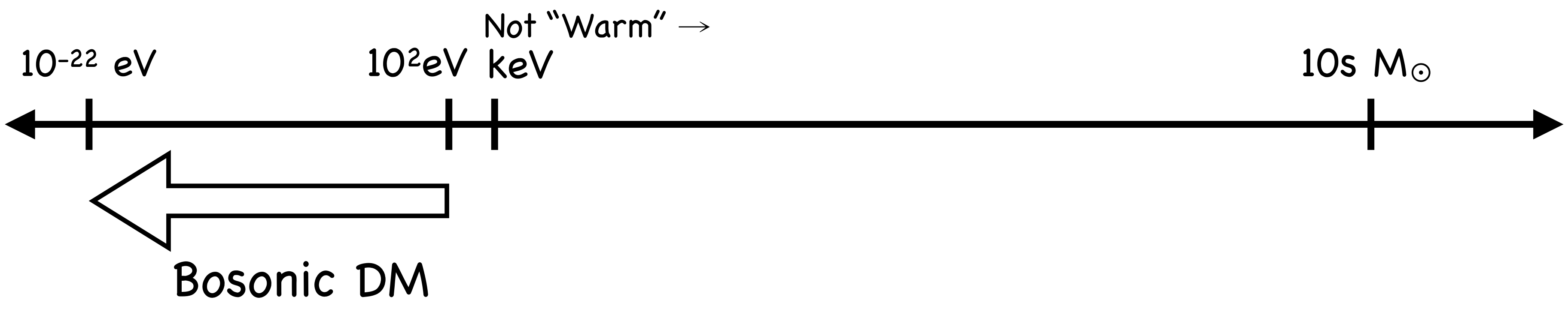

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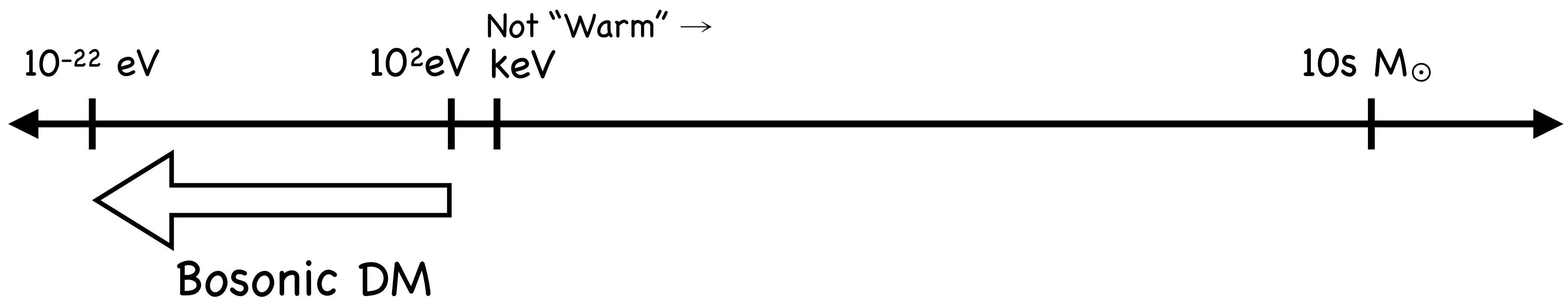

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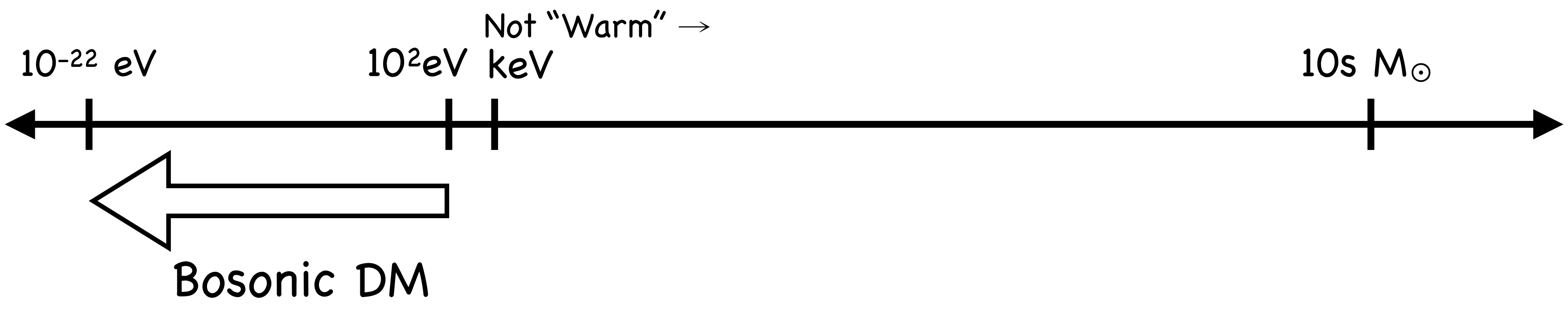

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Vast number of models, only a few good theories.

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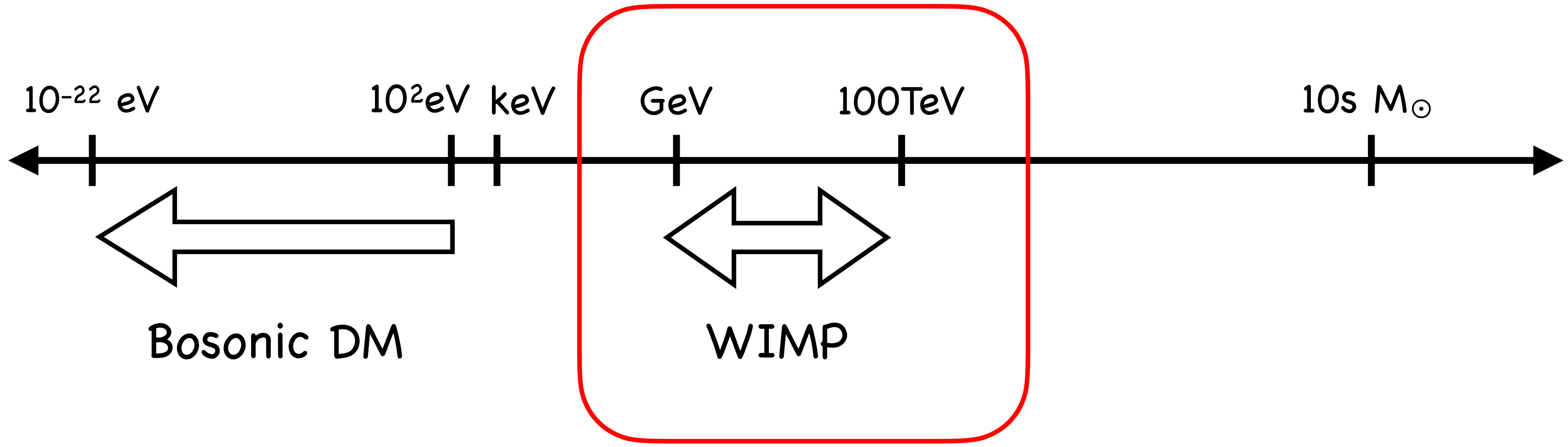

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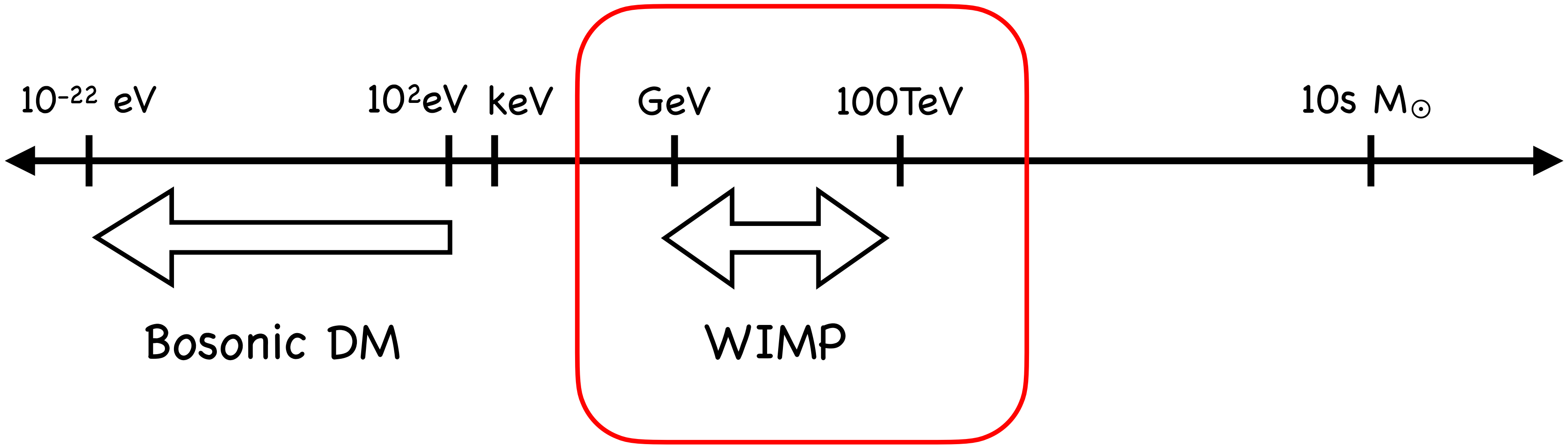
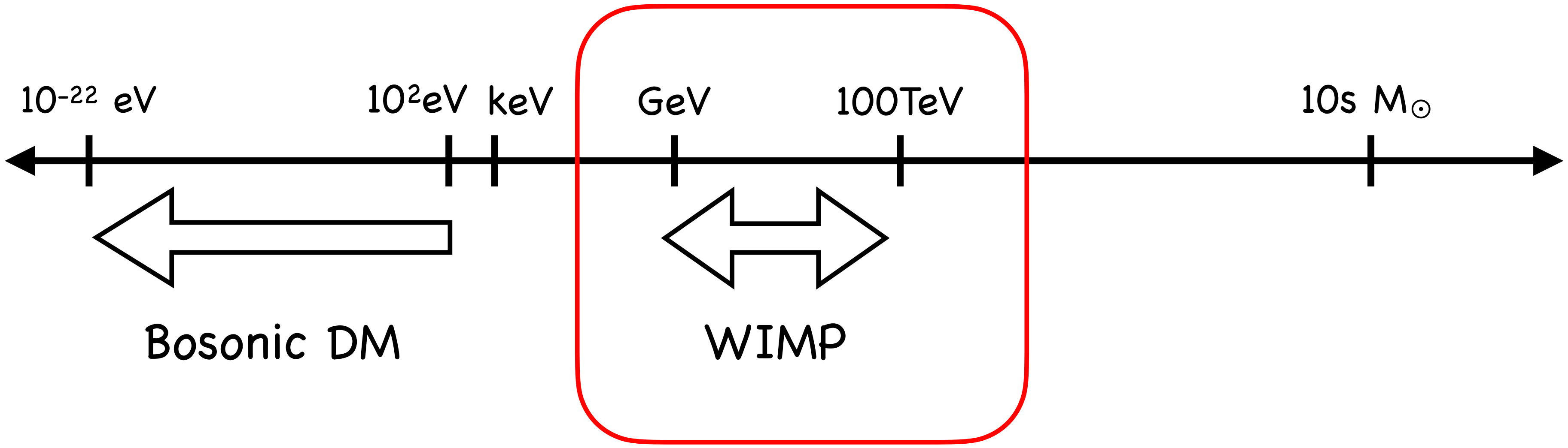


A lamppost.

A tiny window in the full mass range.

A good lamppost.

Mass of dark matter



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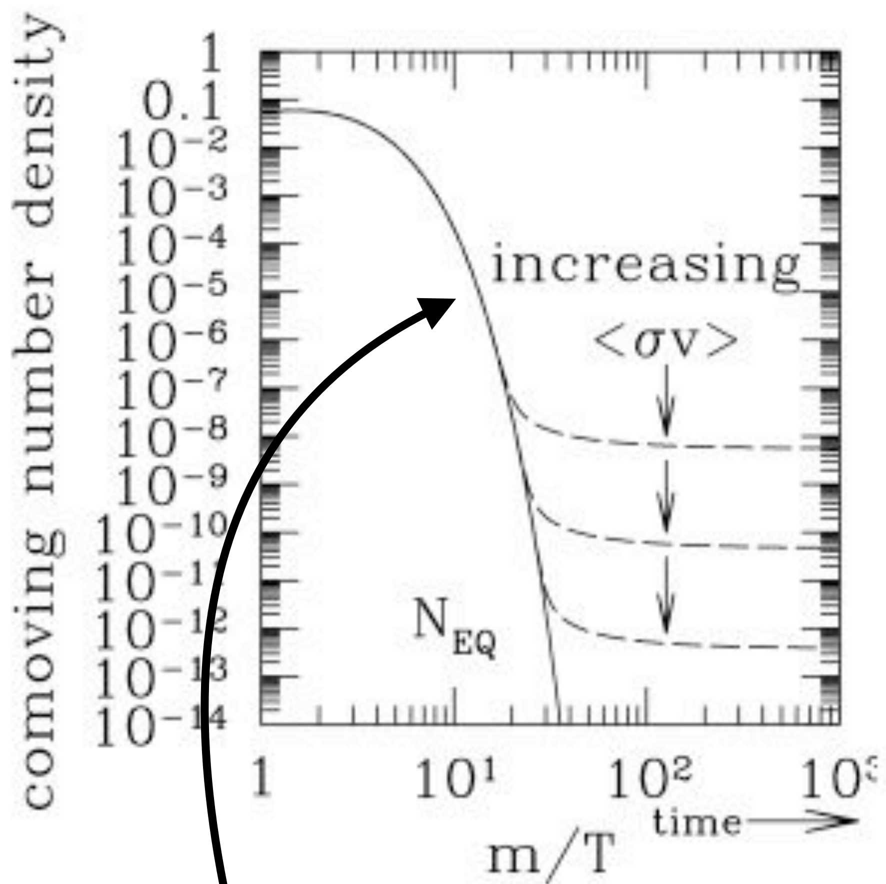
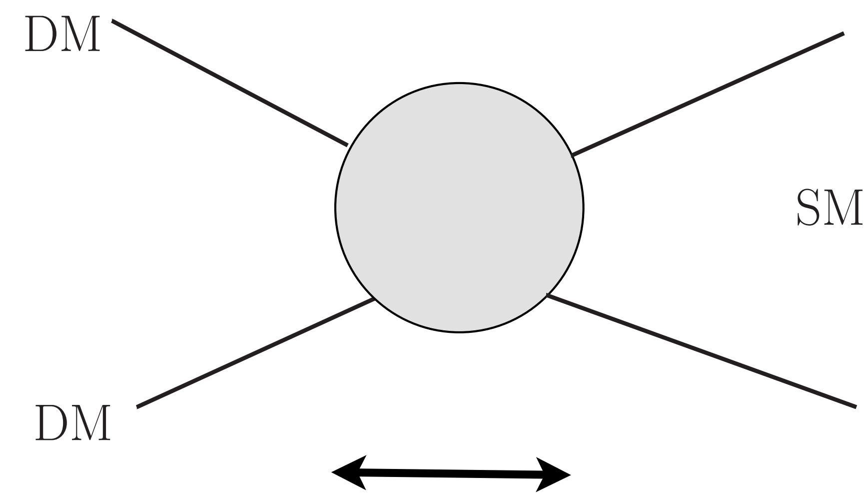
WIMP (weakly interacting massive particle)



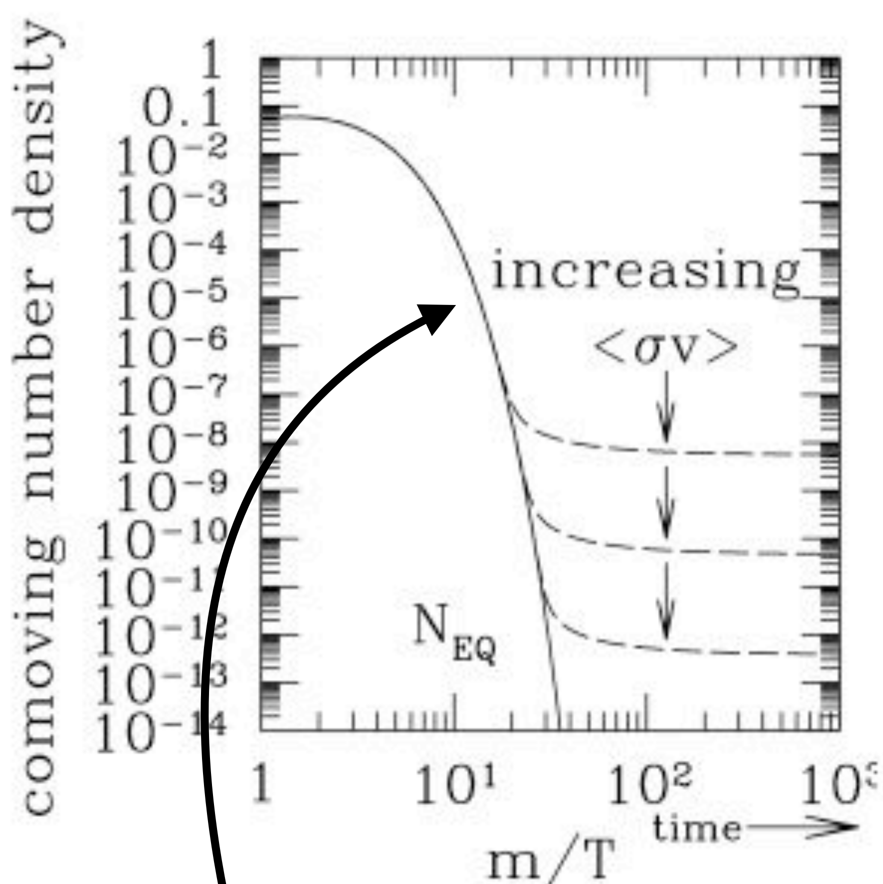


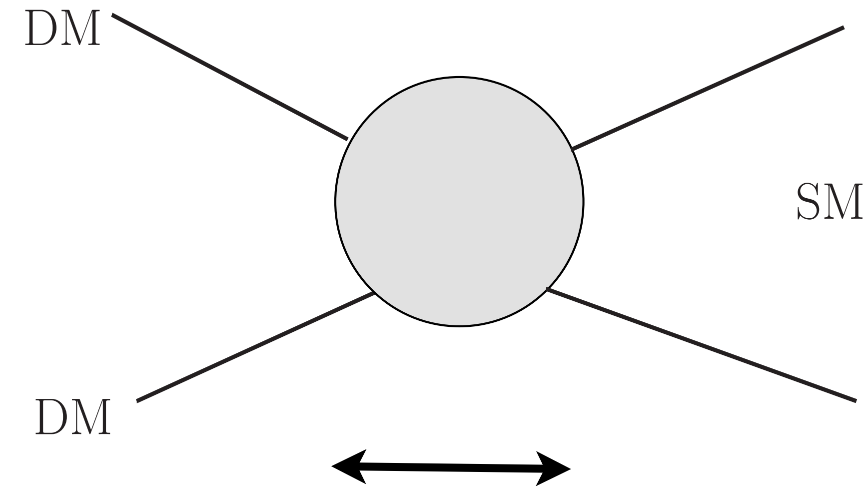
$$\langle \sigma v \rangle \sim \frac{g_{\rm D}^4}{m_{\rm DM}^2}$$

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)





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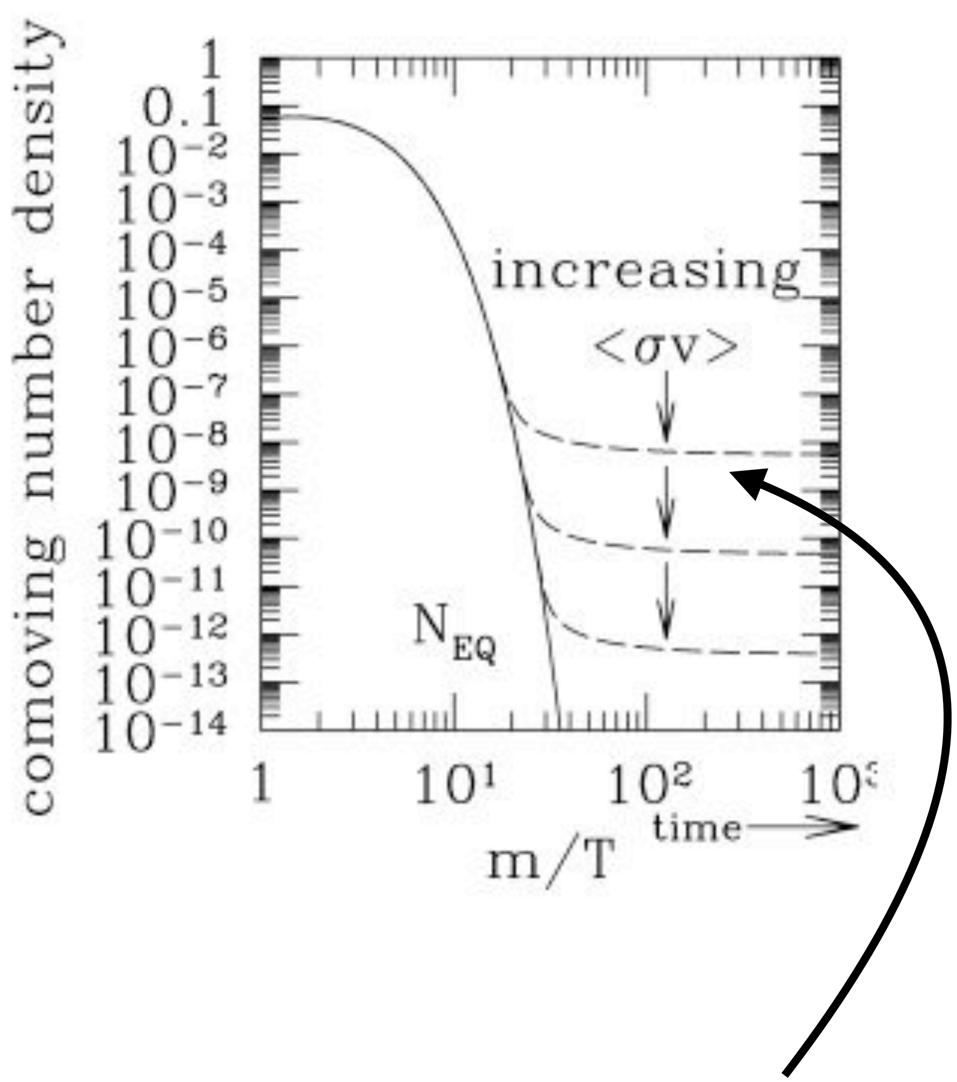
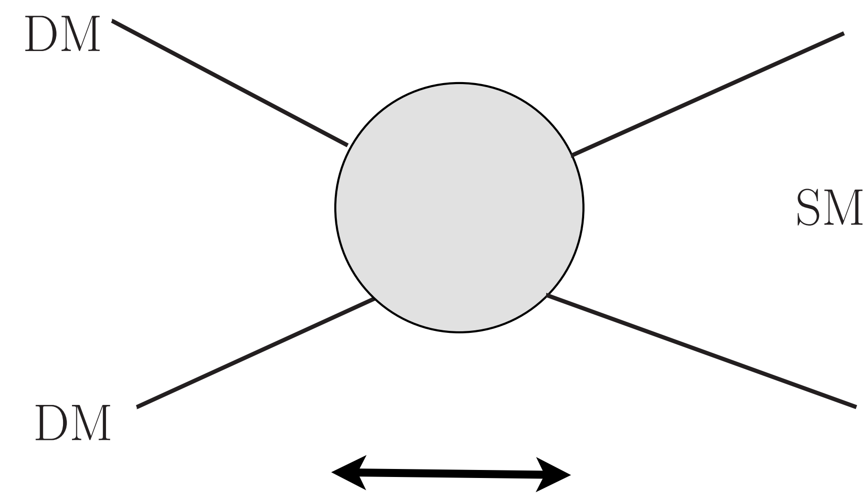
Dark matter in thermal equilibrium with the known (Standard Model) particles in the early universe.

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

WIMP (weakly interacting massive particle)



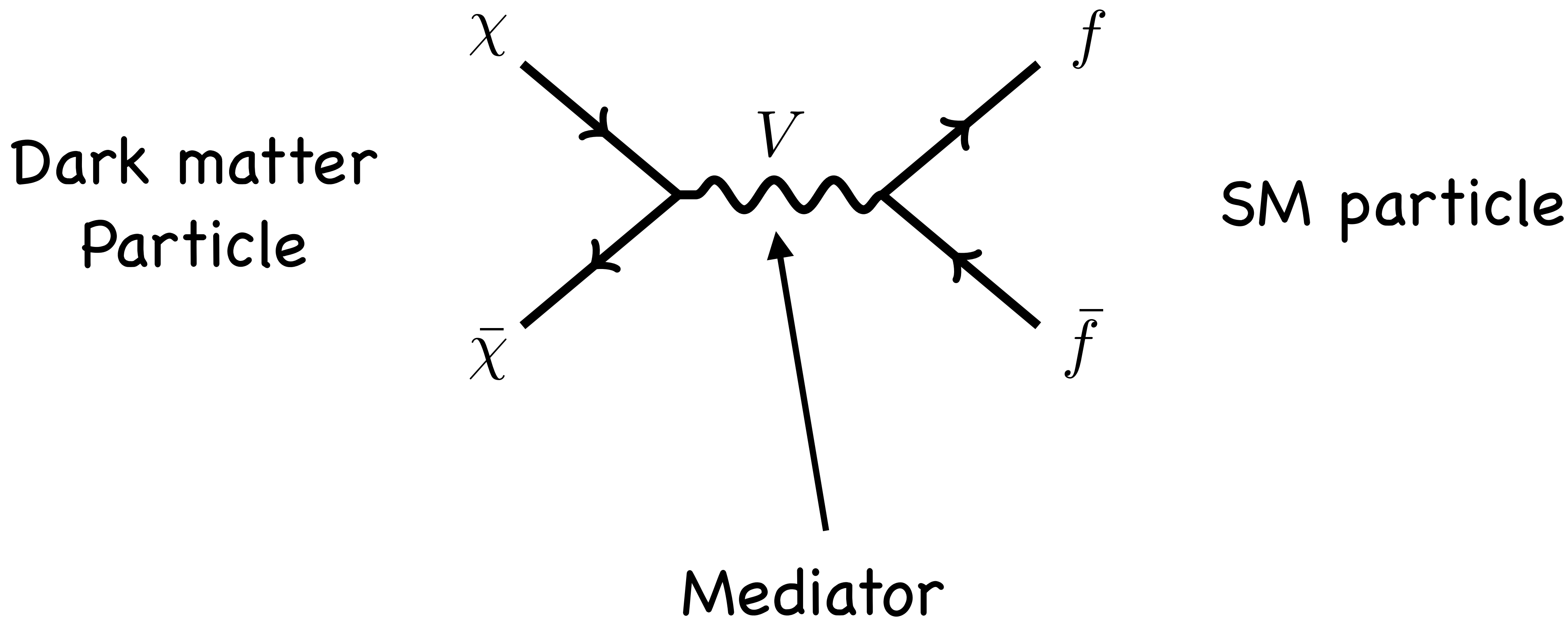


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

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"

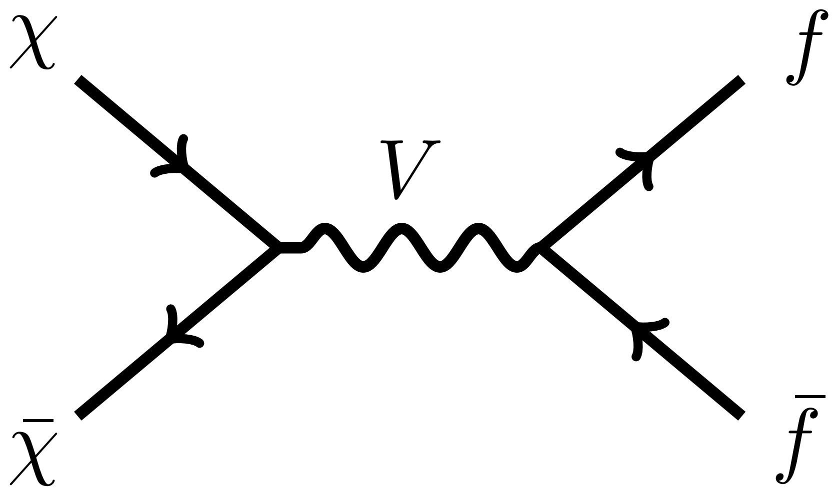
A simple picture of interaction



To get the correct relic abundance:

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

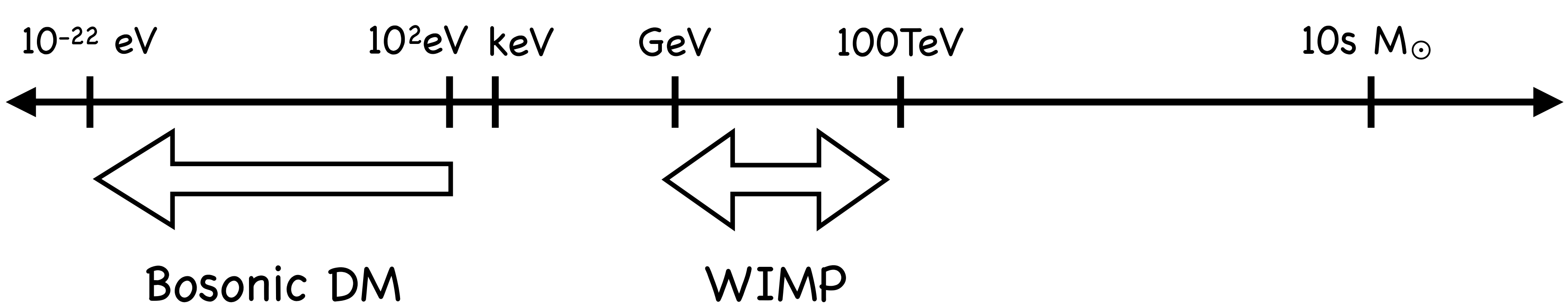
Two limits



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

g: coupling

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



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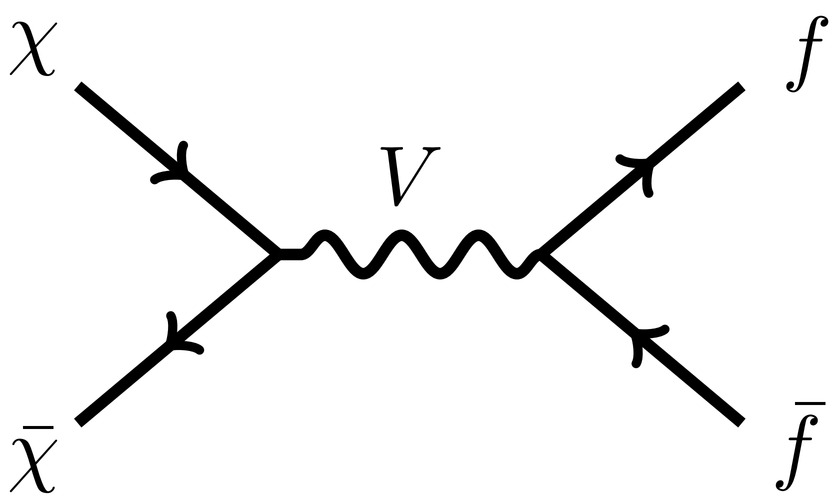
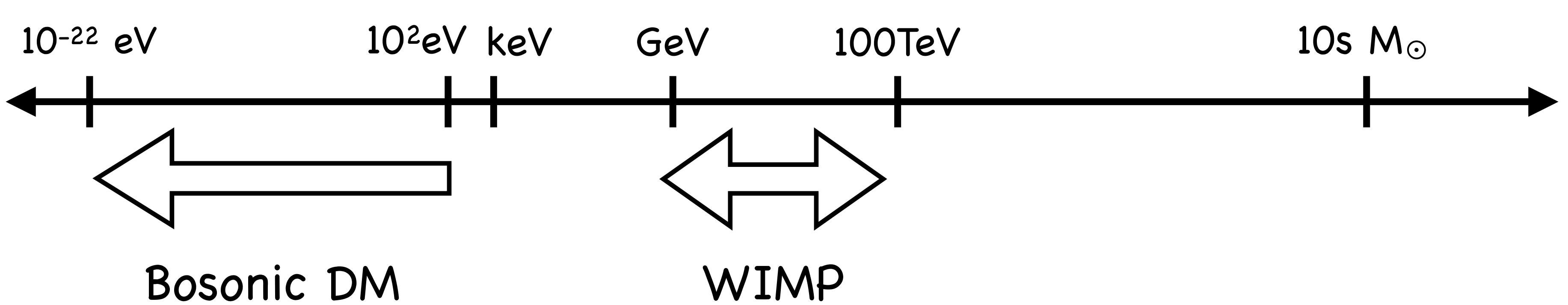


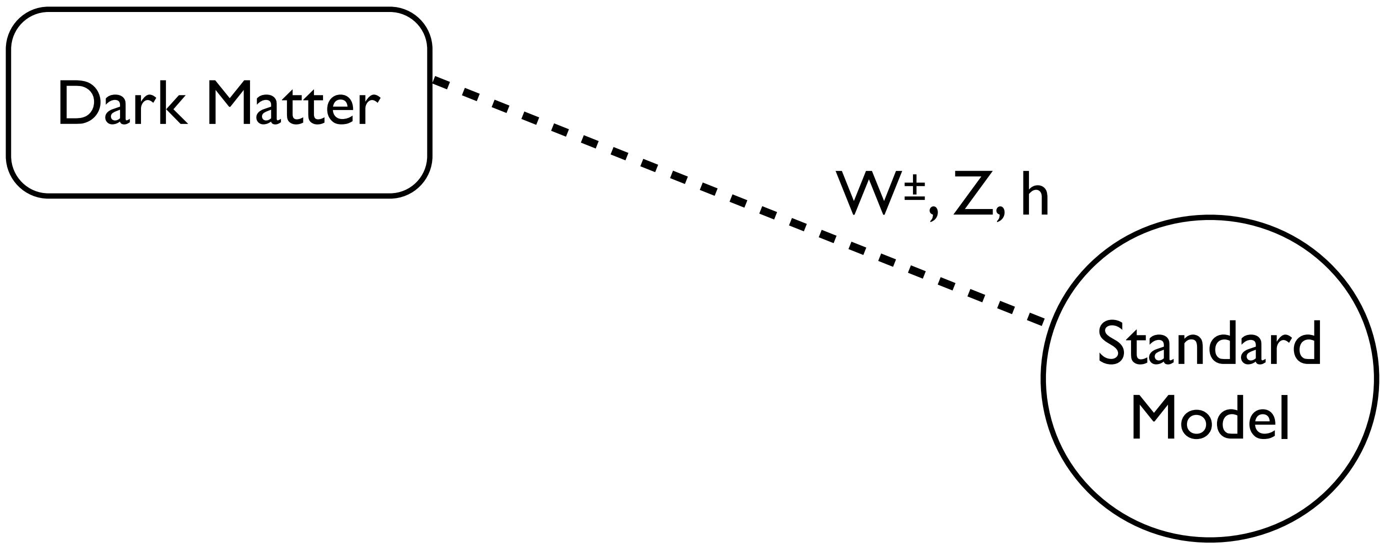
$$m_{\rm DM} < m_V, \quad \sigma v \sim \frac{g^4}{4\pi}\frac{m_{\rm DM}^2}{m_V^4}$$

g: coupling

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



Simple WIMP model

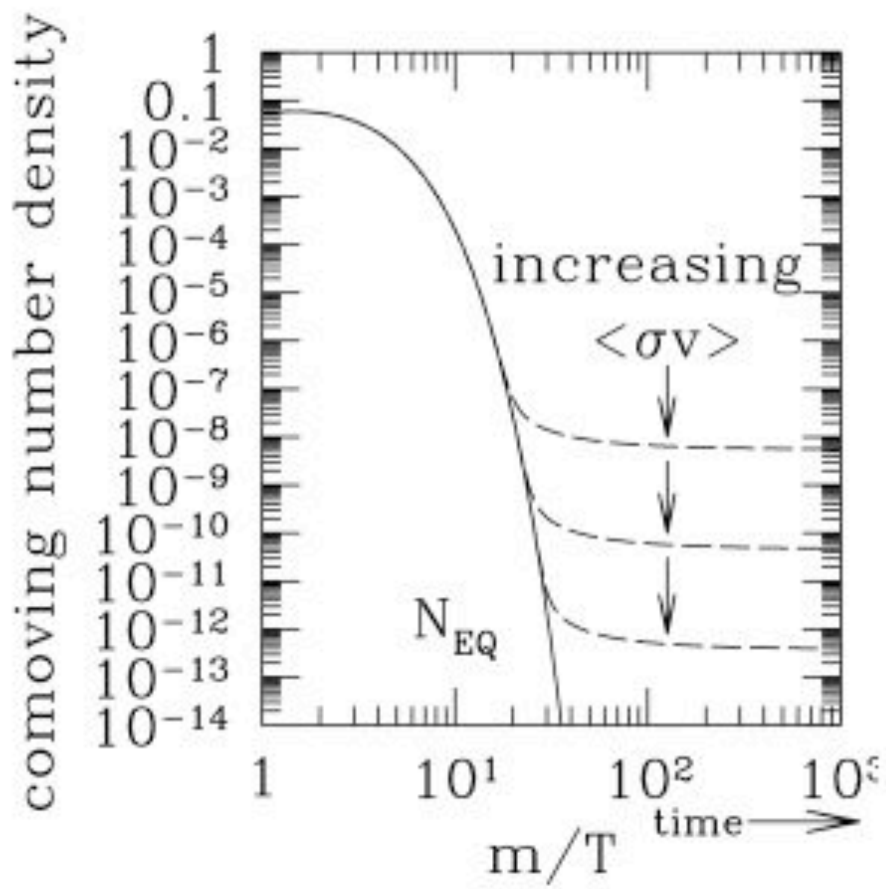


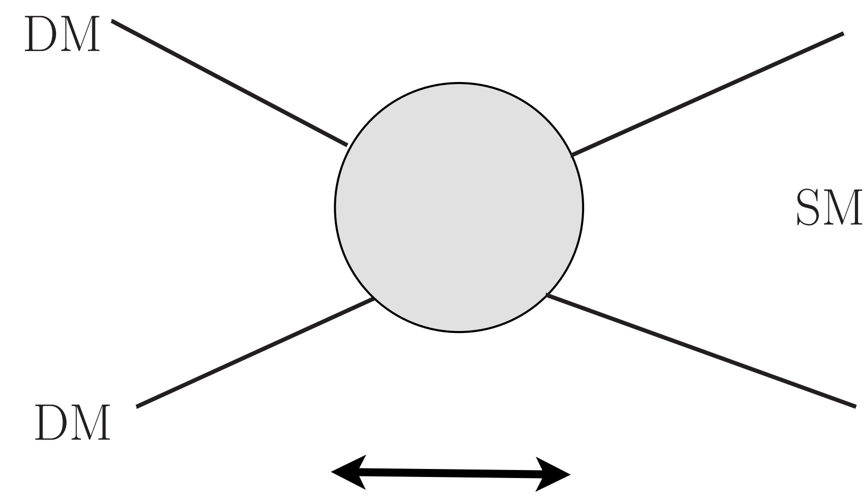
Mediated by a known interaction:

The weak interaction in the Standard Model

Mediator mass: 10^2 GeV

WIMP "miracle"

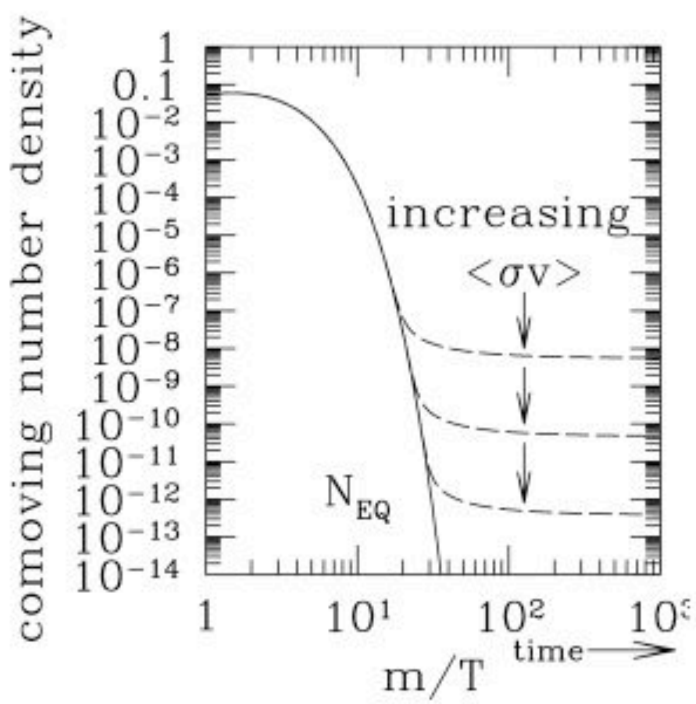


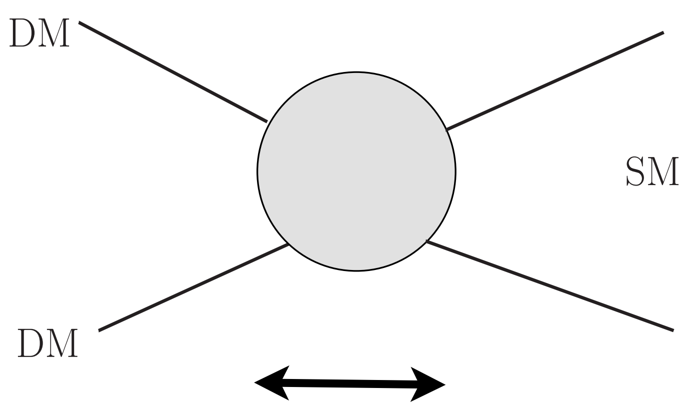


$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.
- Coincide with our expectation for weak(±) scale new physics!

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.

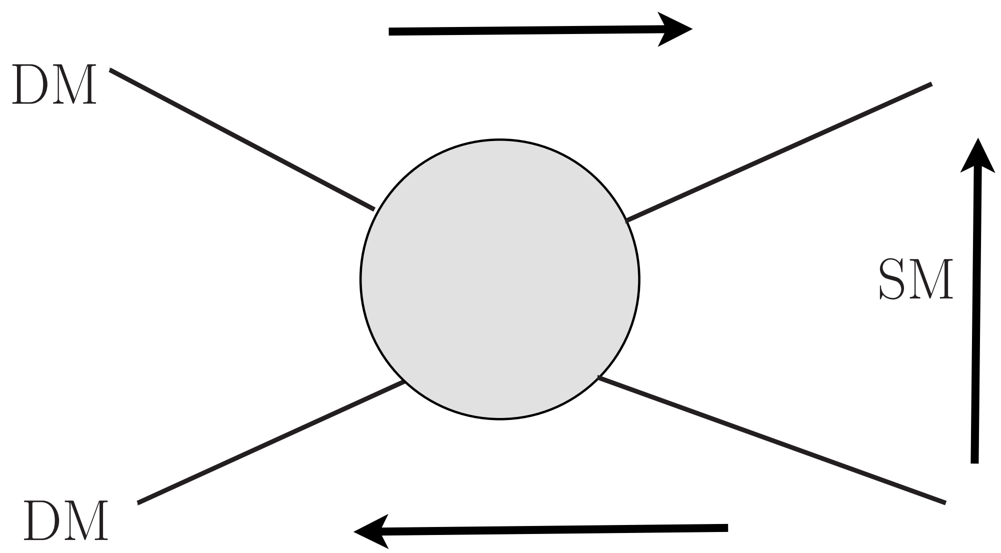
Present in many models: SUSY, extra dimension...

Testable:

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

Looking around the lamppost

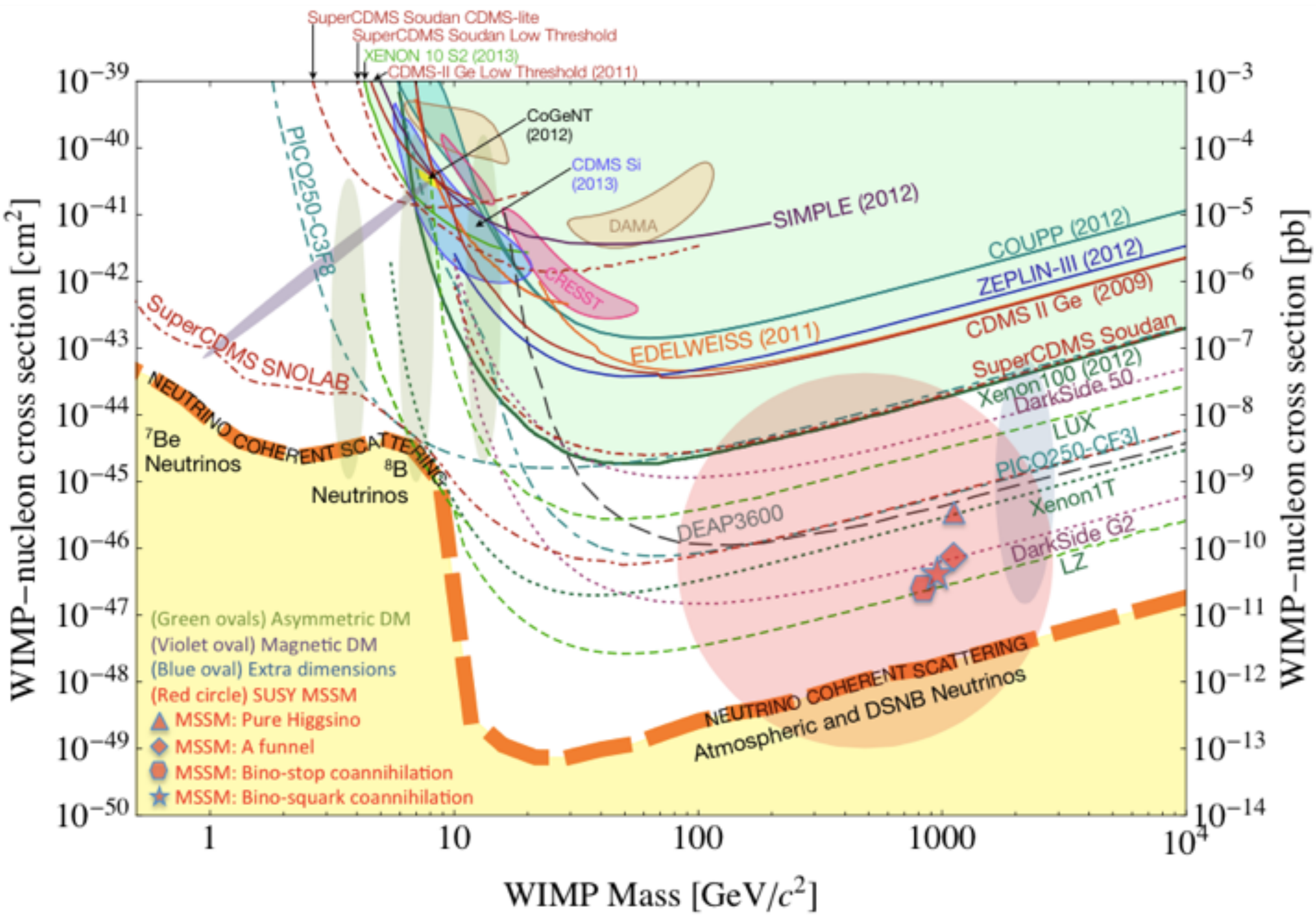
Indirect detection:
AMS2, PAMELA, Fermi-LAT
Cosmology



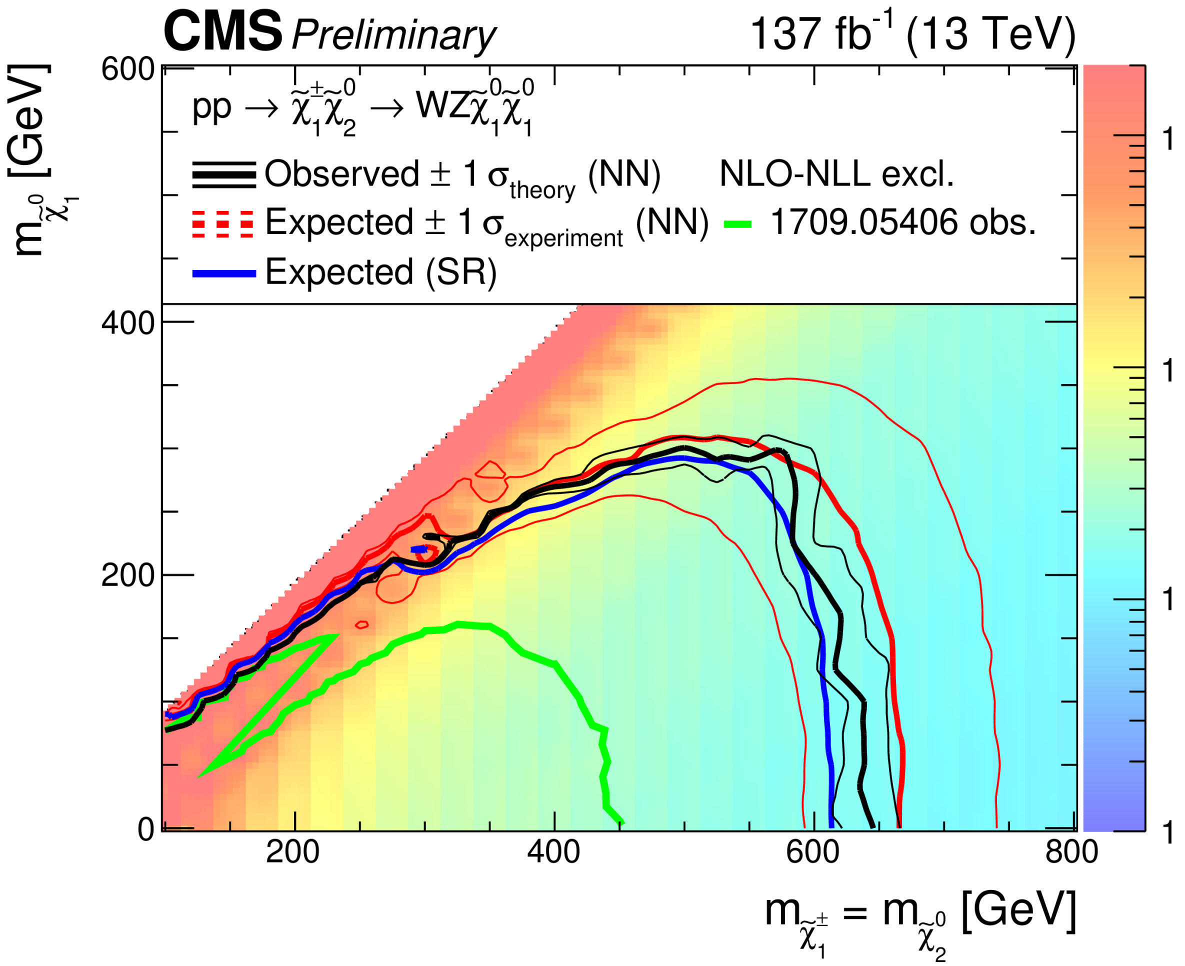
Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
Lux
.....

Collider searches:
LHC, ...

Direct detection



At colliders



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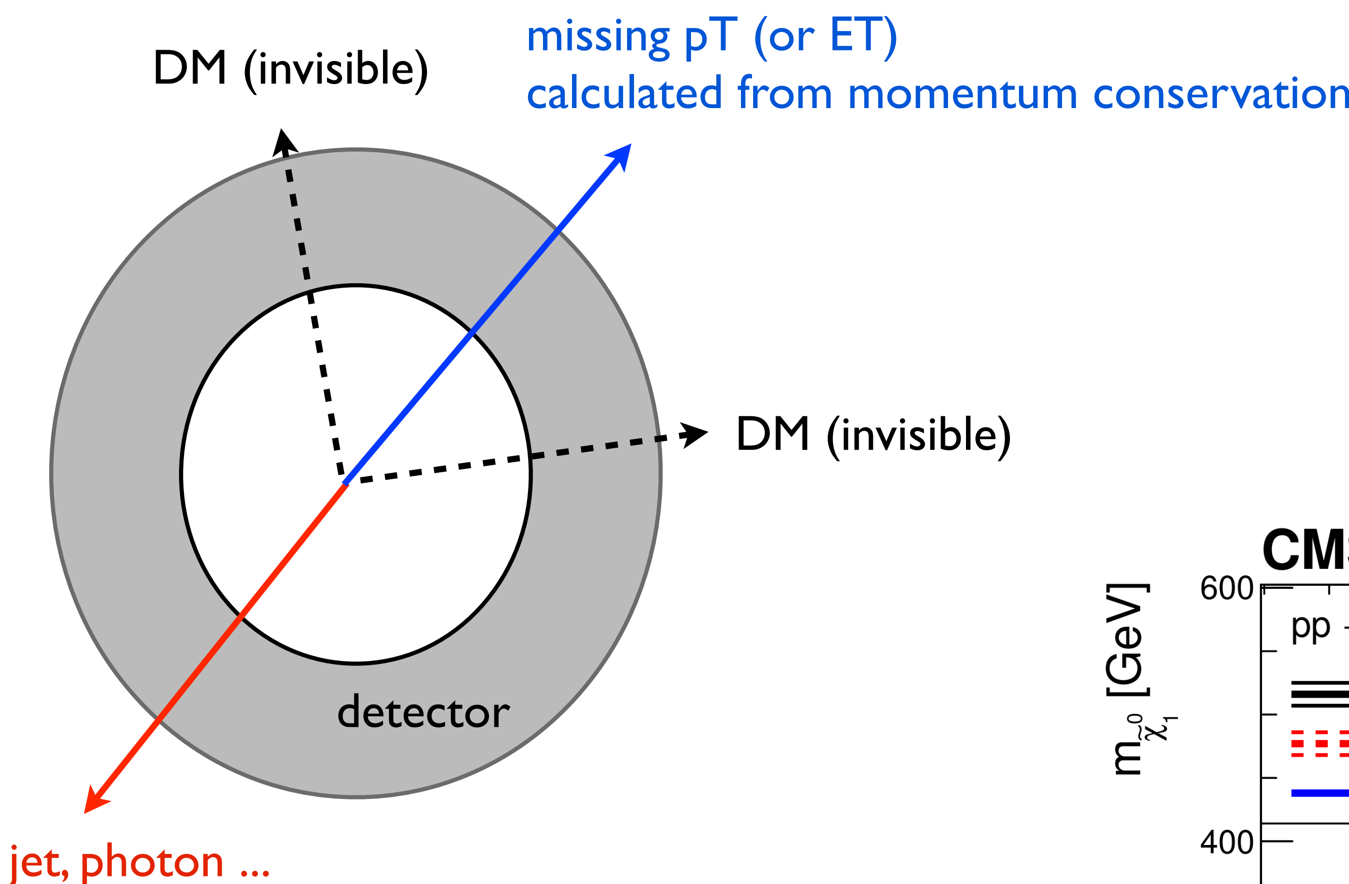
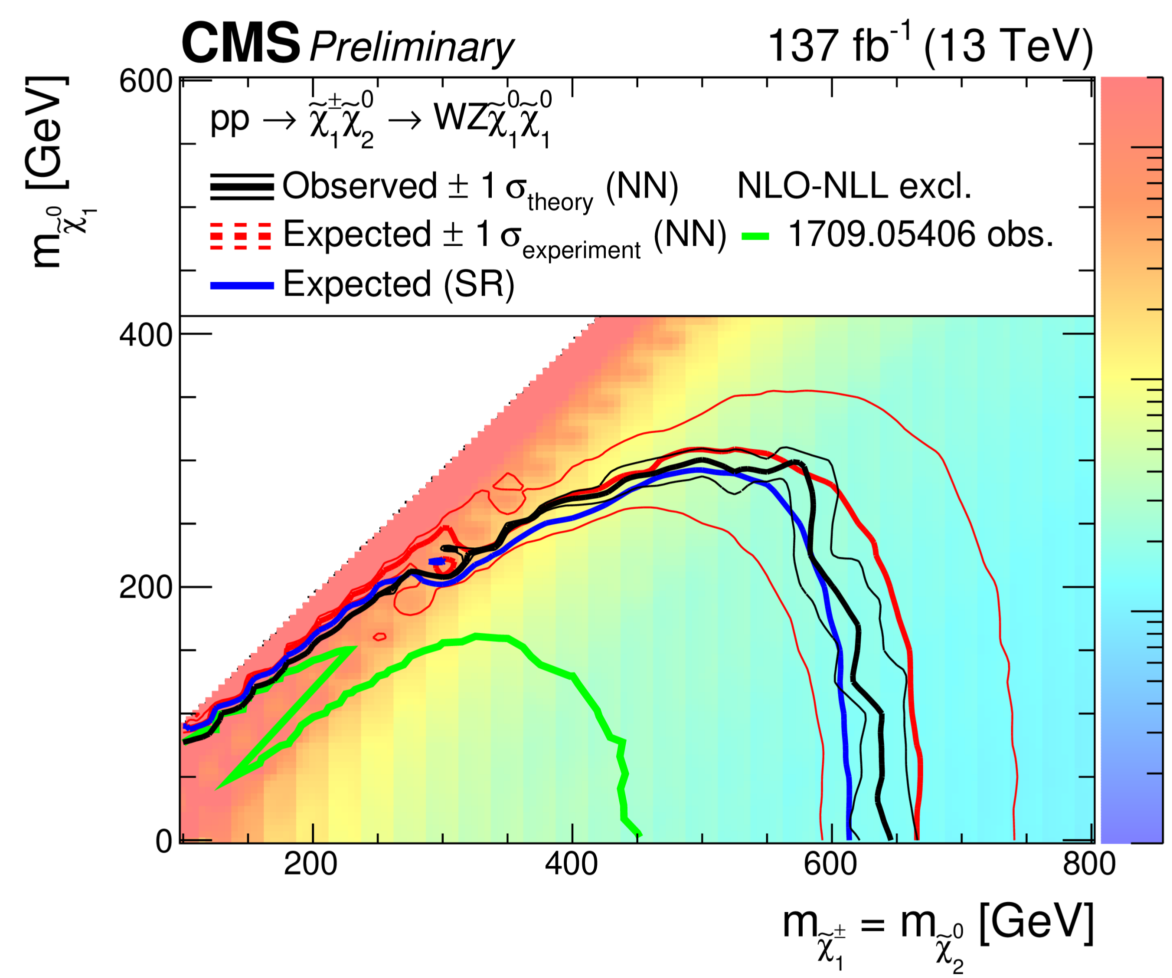
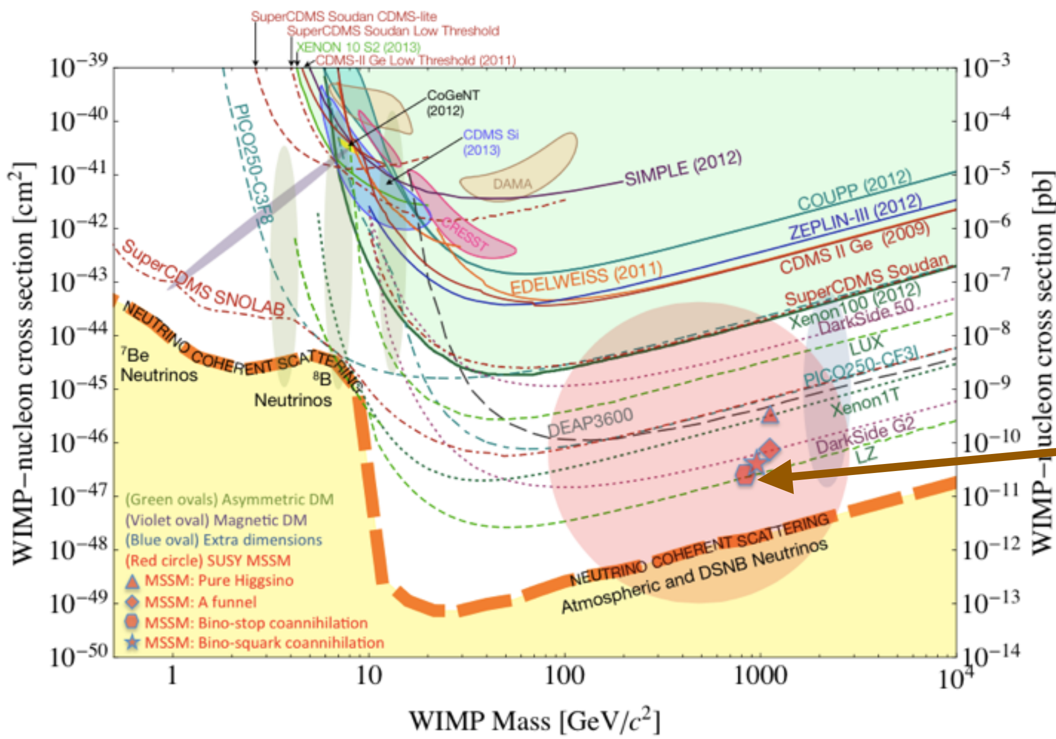
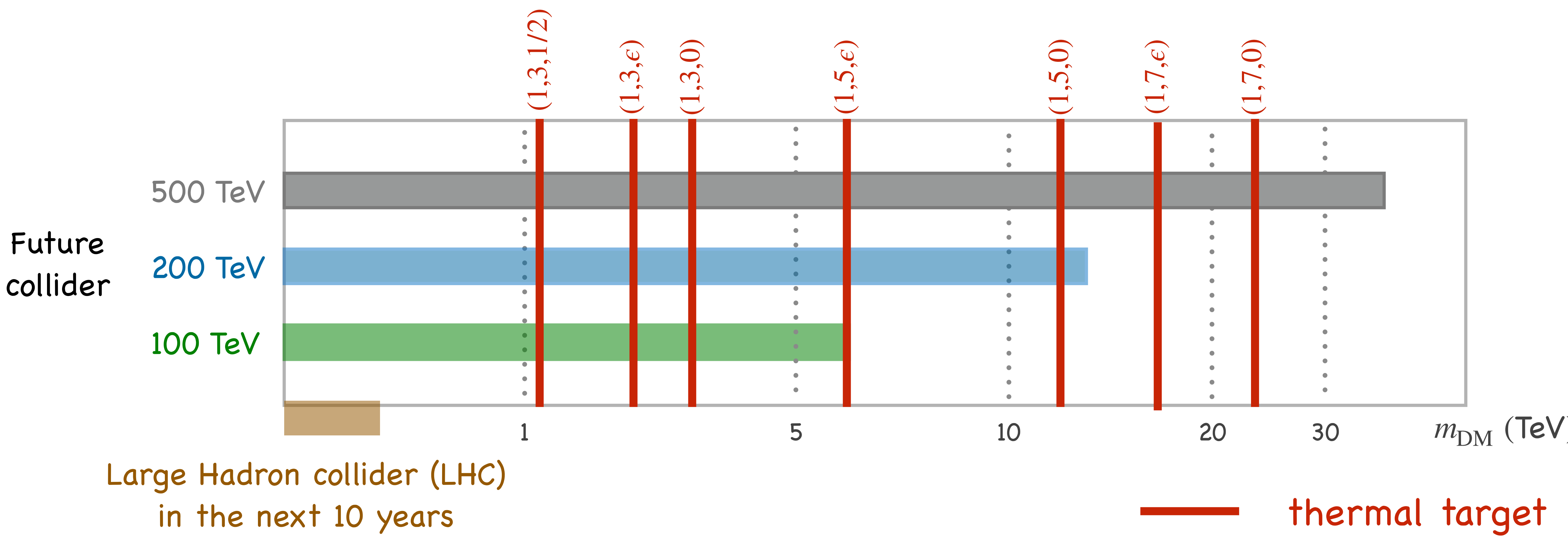




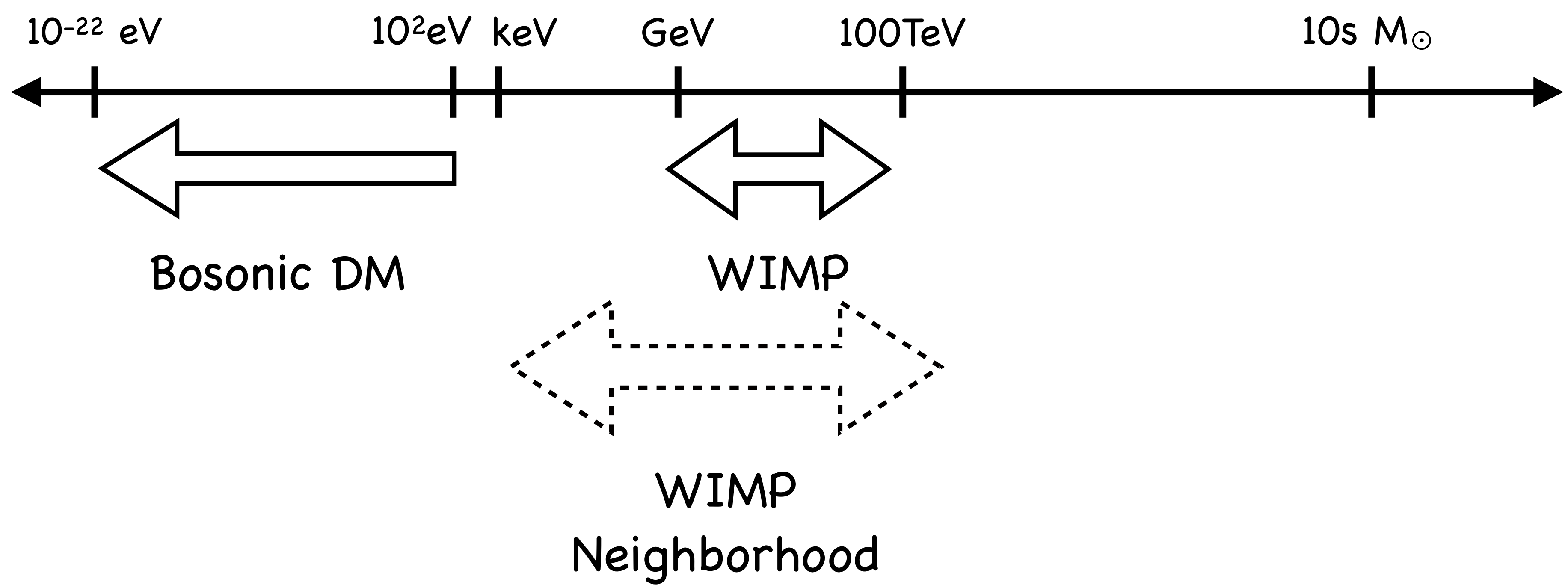
Still a lot to be done

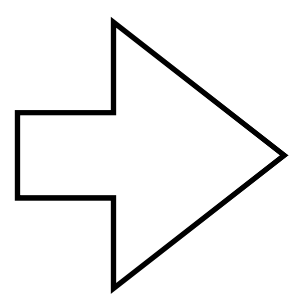


Simplest case yet to be probed



Beyond WIMP


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



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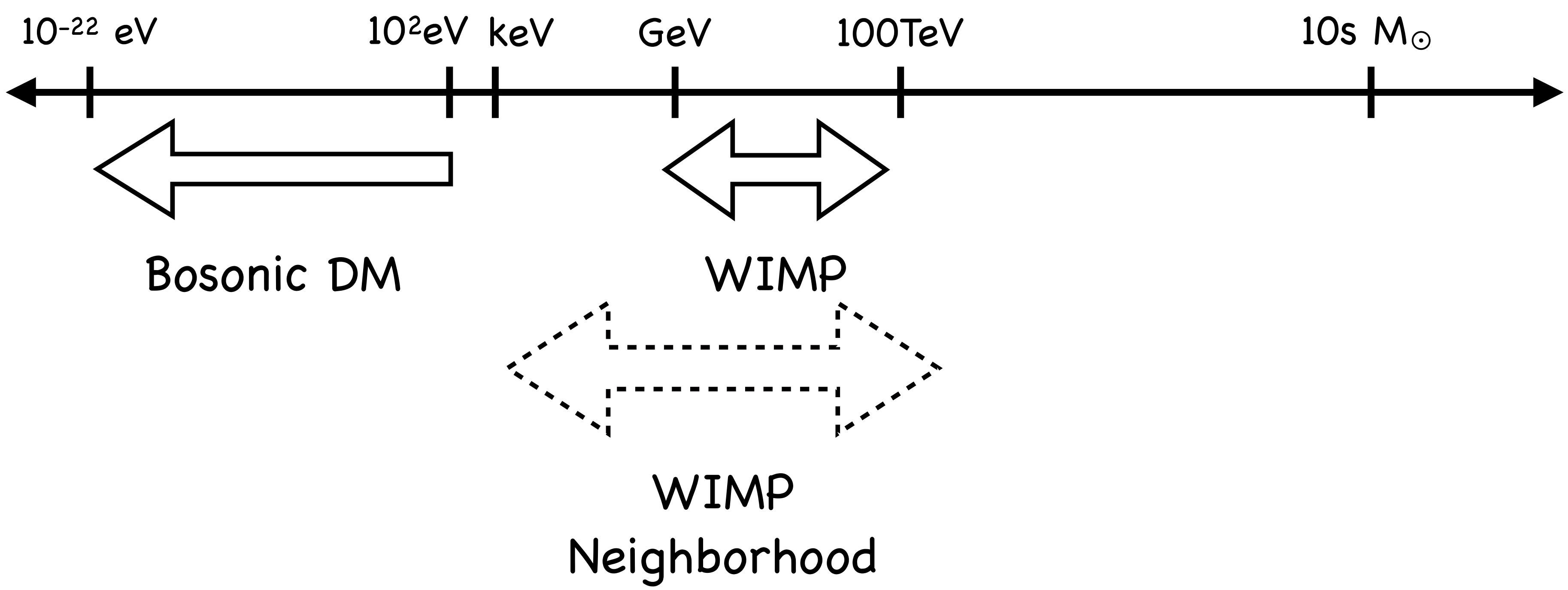
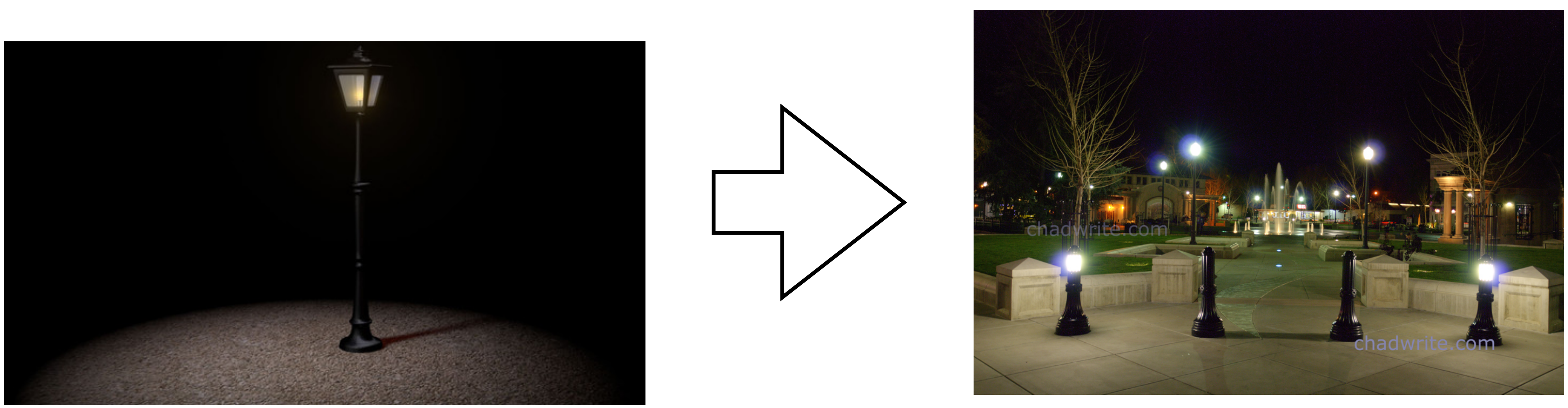

10^{-22} eV
10^2eV
keV
GeV
100TeV
10s $M_\odot$
Bosonic DM
WIMP
WIMP
Neighborhood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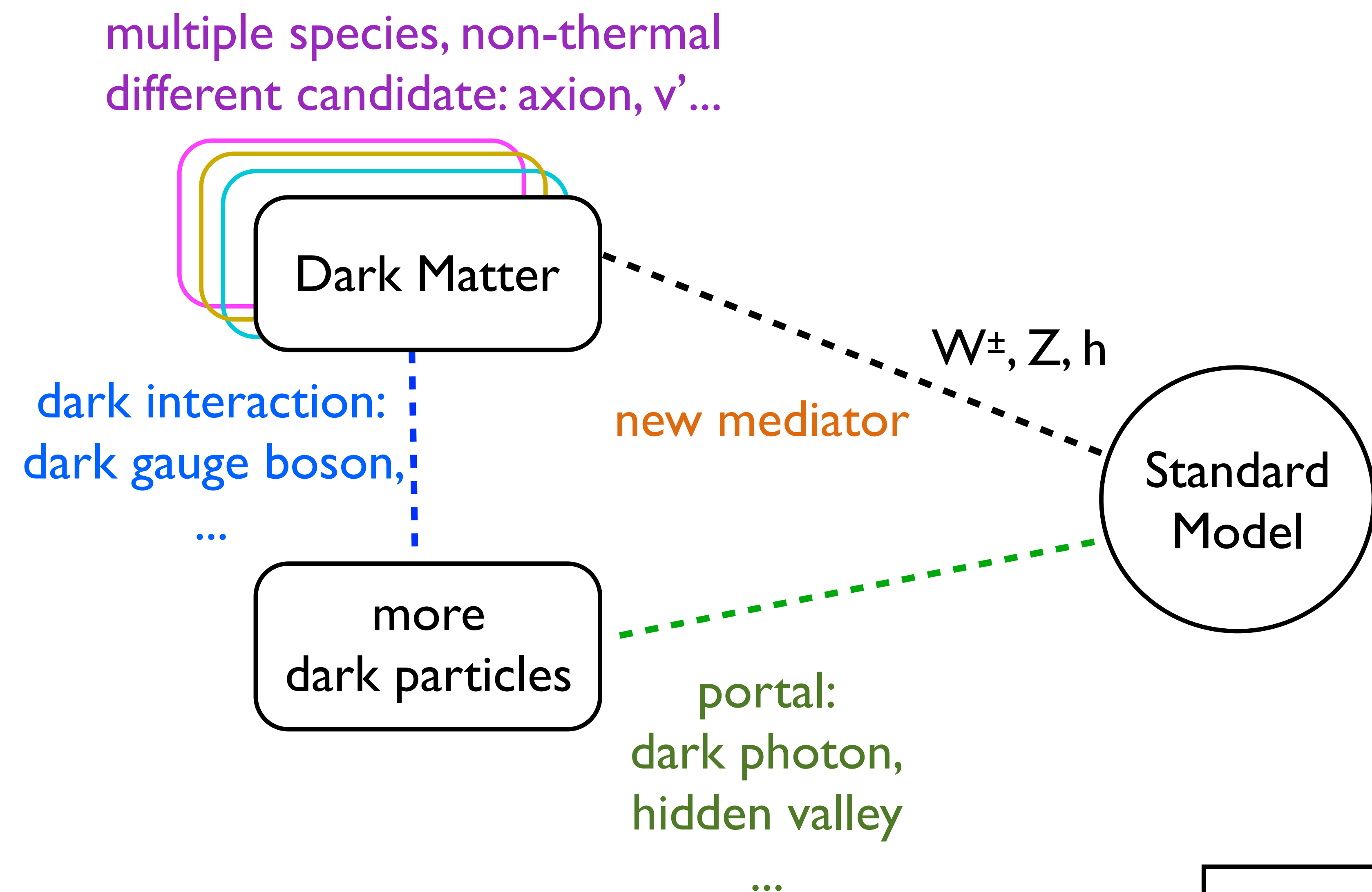
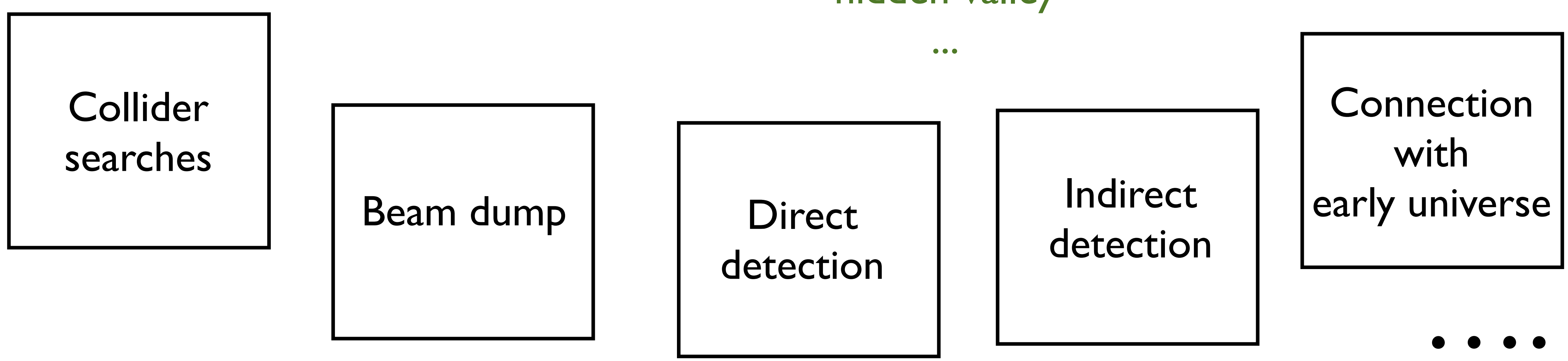
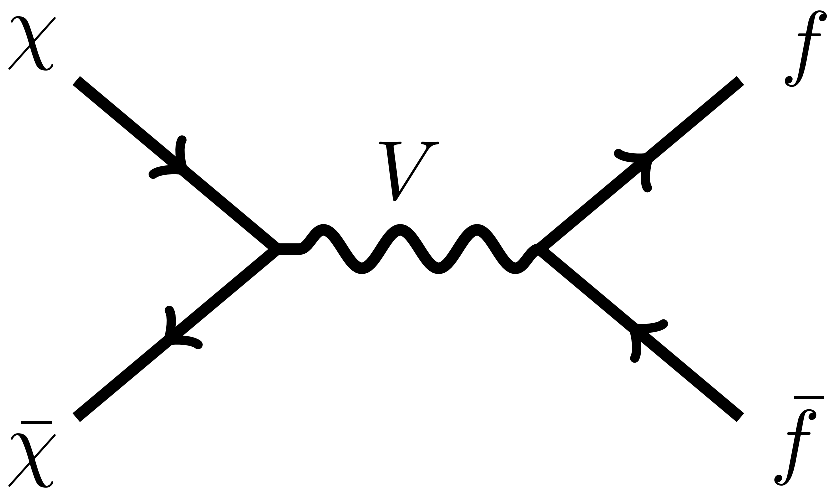
Beyond the simple WIMPs





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

Extend the WIMP story to lower masses



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

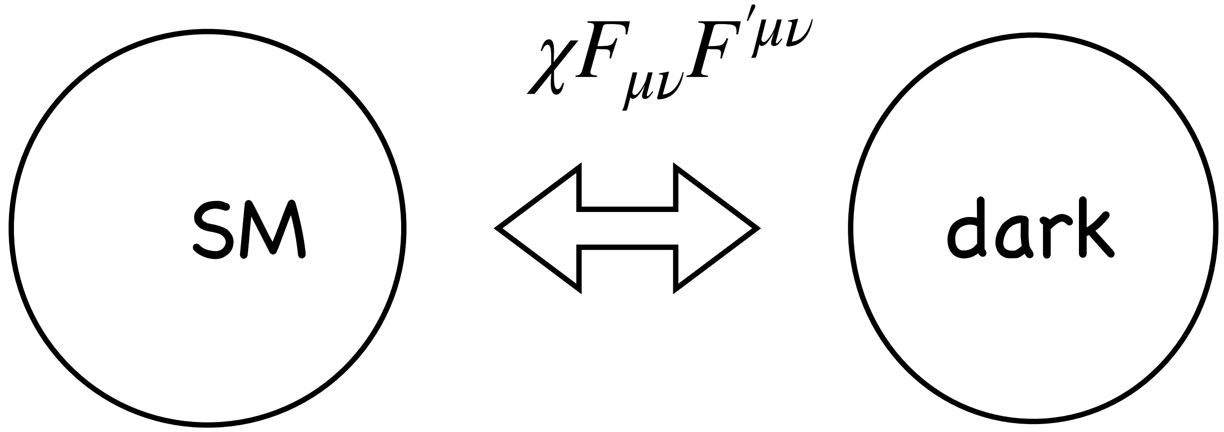
g: coupling

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

We can consider lighter mediators, m_V < GeV

Dark photon

$\chi F_{\mu\nu} F'^{\mu\nu}$



photon: $|\gamma\rangle$ photon': $|\gamma'\rangle$

dark photon: a quantum superposition of γ and γ'

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

Mediates an interaction with strength $\propto \chi$

Roles of dark photon

As mediator for thermal freeze out. (Discussed earlier)

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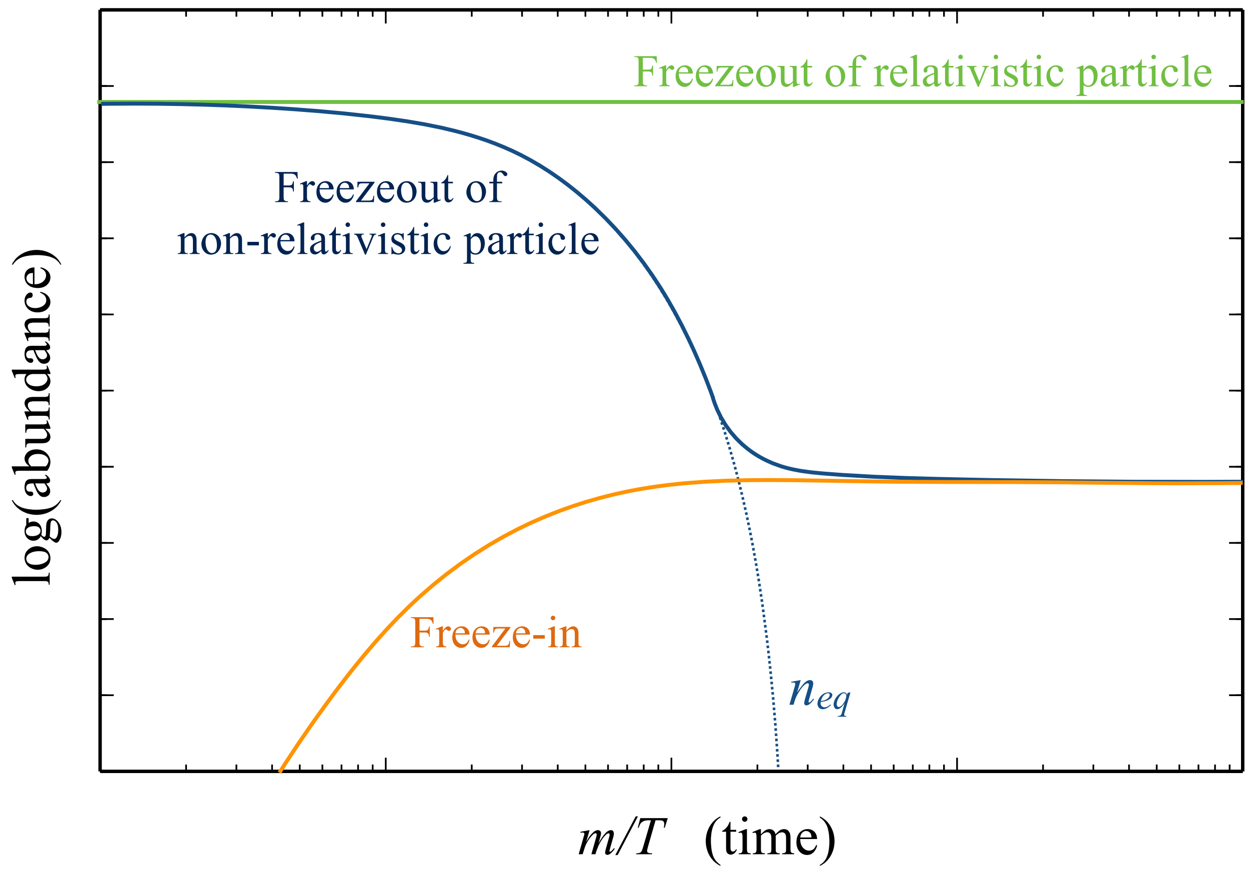
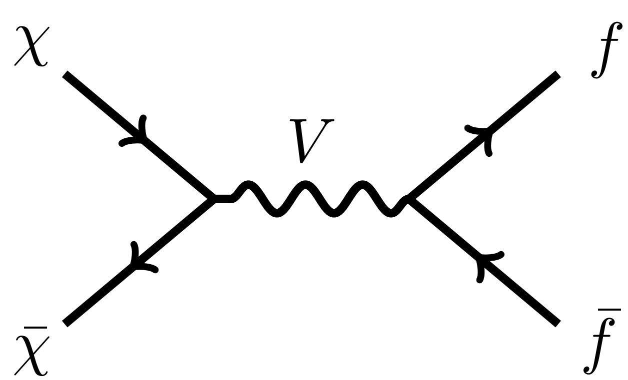
Freeze-in



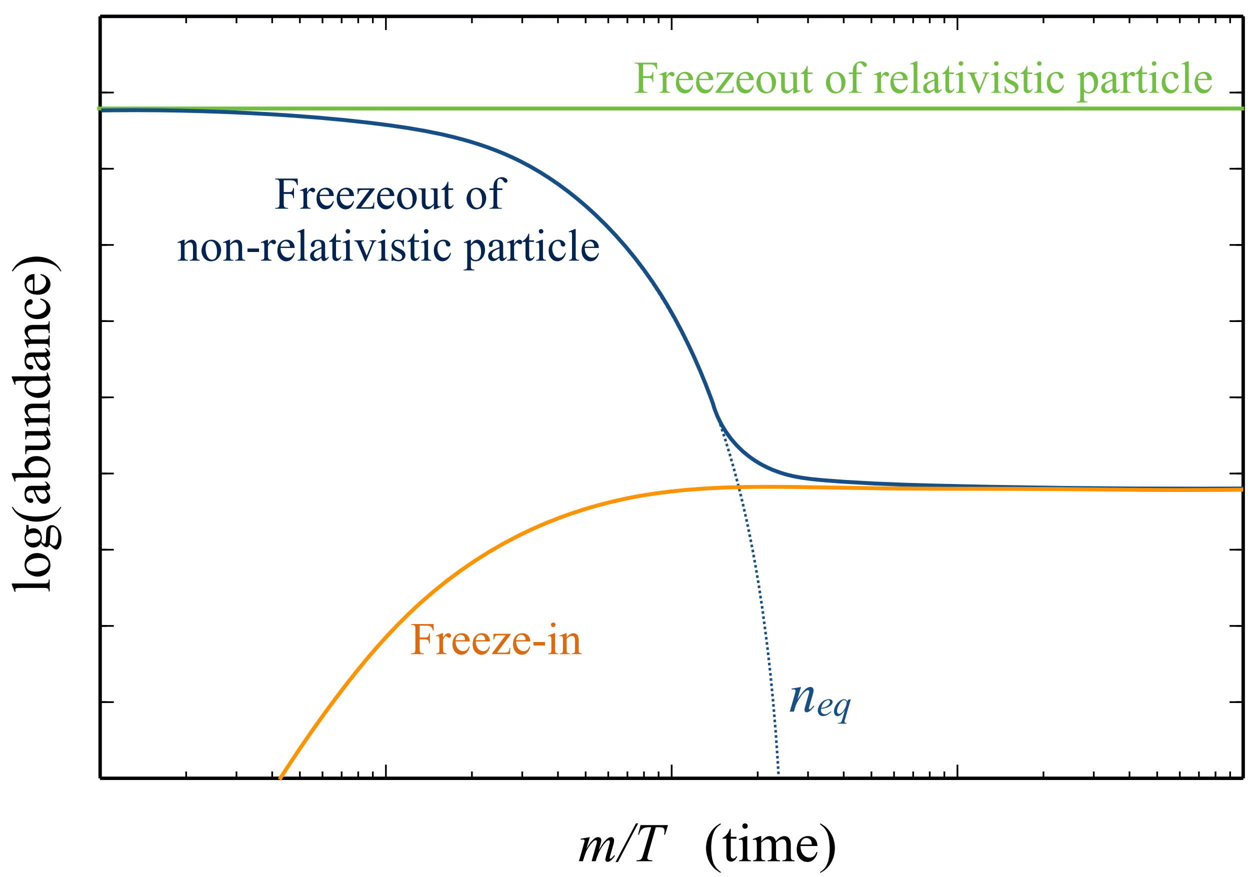


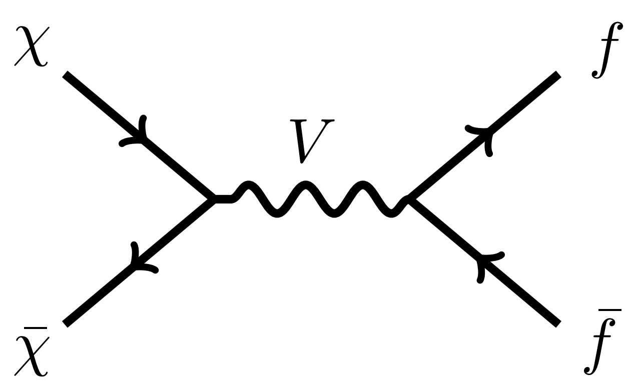
Weak coupling, dark matter not in thermal eq.
It approaches the correct relic abundance.

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.

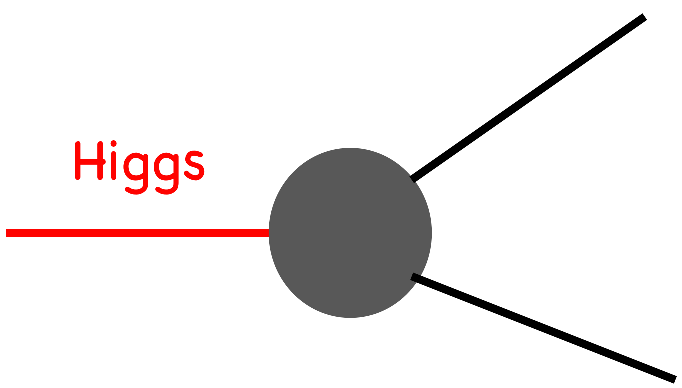
Examples

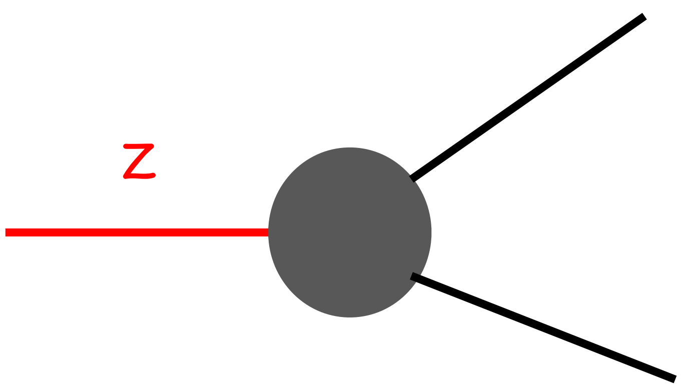
Thermal freeze out: $m_{\rm DM} = 10$ MeV, $m_V = 30$ MeV, $\chi \simeq 10^{-4}$

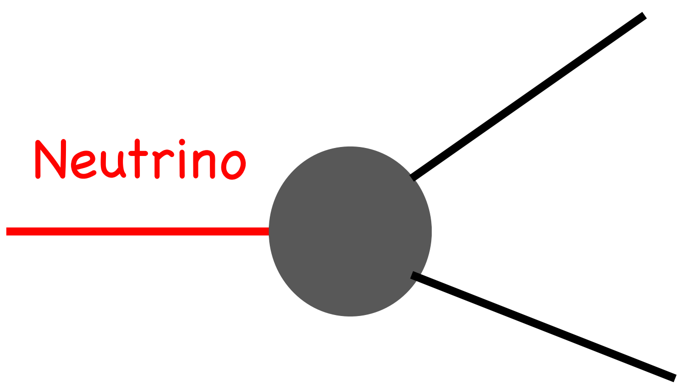
Freeze in: $m_{\rm DM} = 1$ MeV, $m_V = 10^{-12}$ eV, $\chi \simeq 10^{-6}$

Windows into dark sector: portals

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

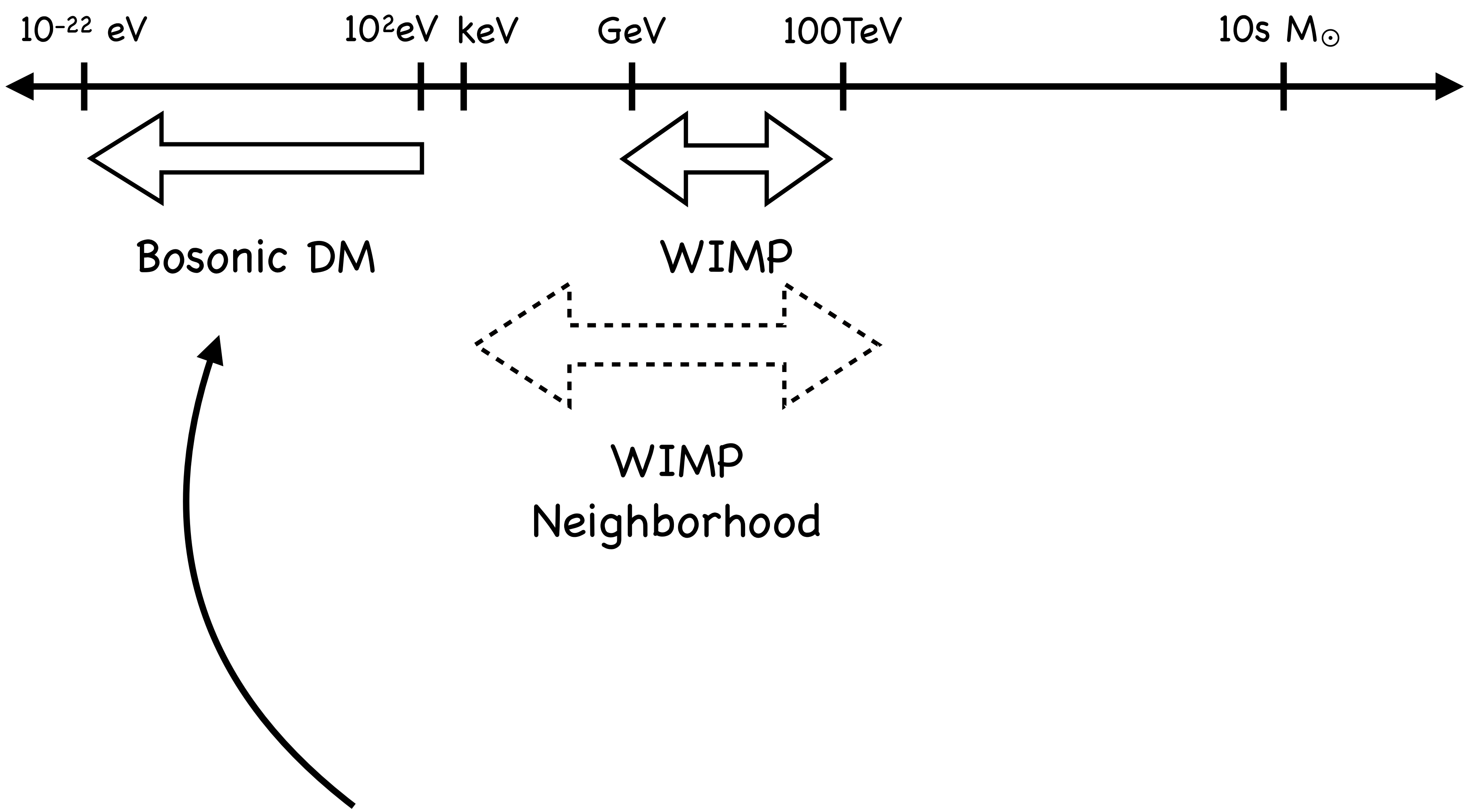






Higgs/Z factories, such as CEPC
Neutrino facilities, fixed target experiments...

Theories of dark matter



Axion, dark photon

Not single particle-like.

Dark matter = classical wave

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

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

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

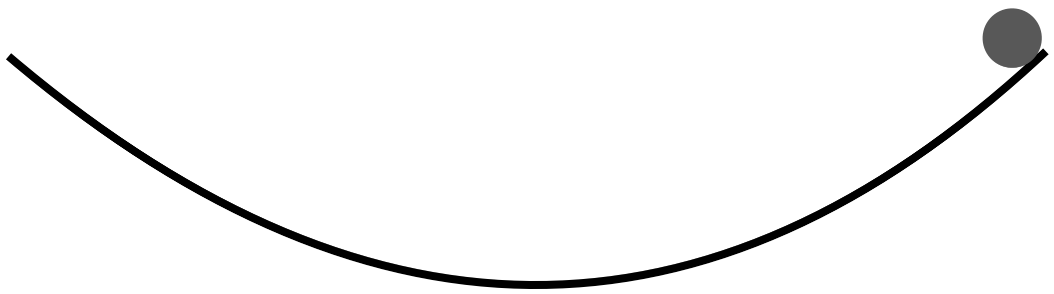
Classical field in two limits

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

Hubble expansion more important

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

mass more important



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

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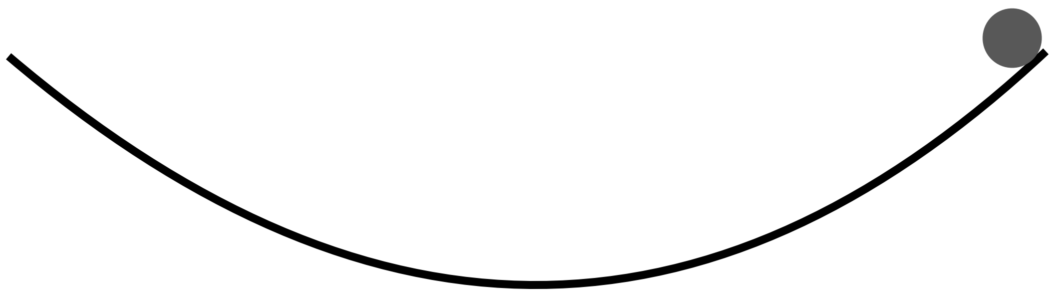

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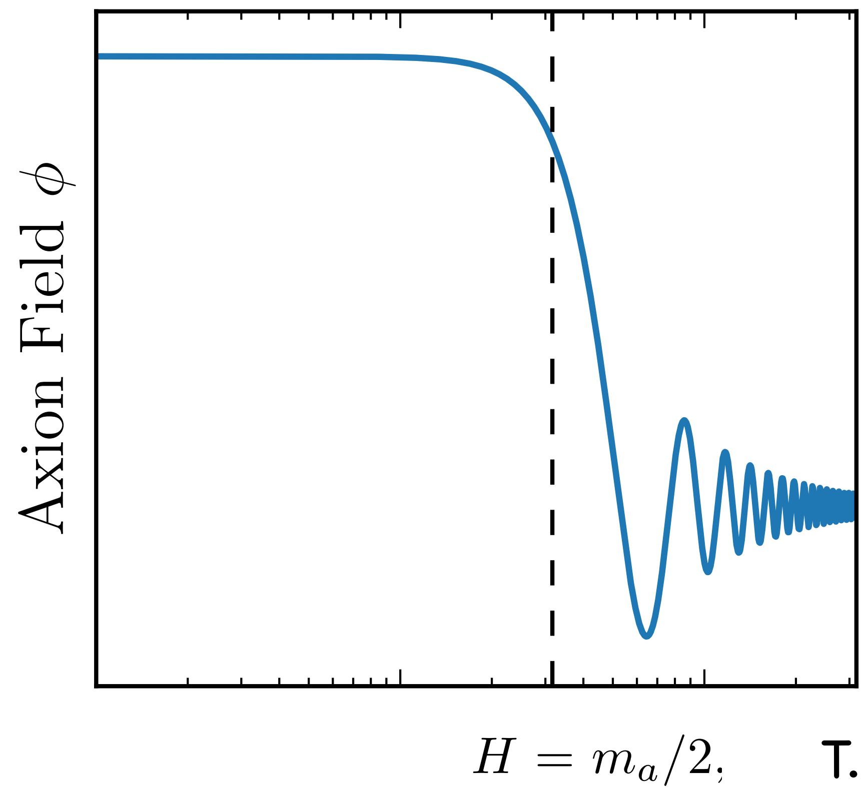

T. Lin 2018 TASI lecture

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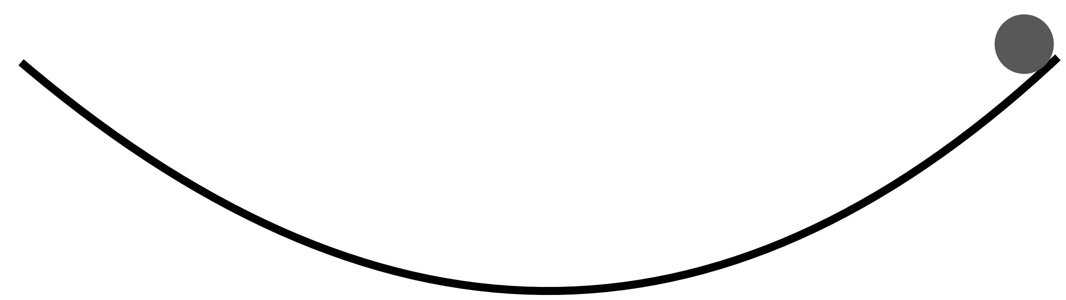


$$\phi(t) \propto \frac{1}{a^{3/2}(t)} \sin(m_\phi t + \phi_0)$$

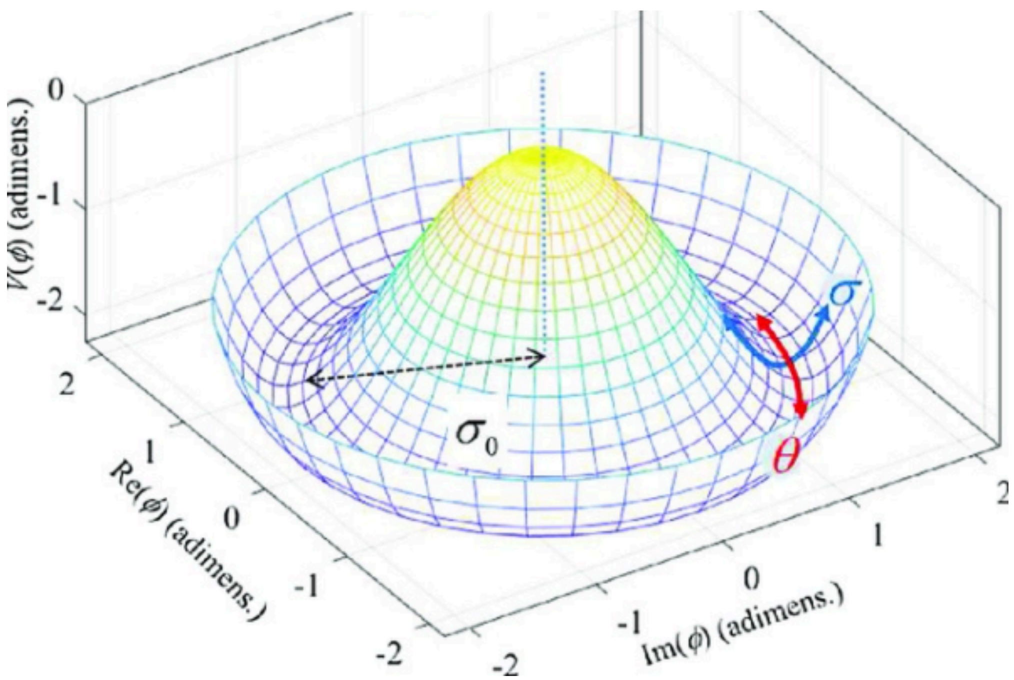
$$\rho \propto m_\phi^2 \phi^2(t) \propto \frac{1}{a^3(t)}$$

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.

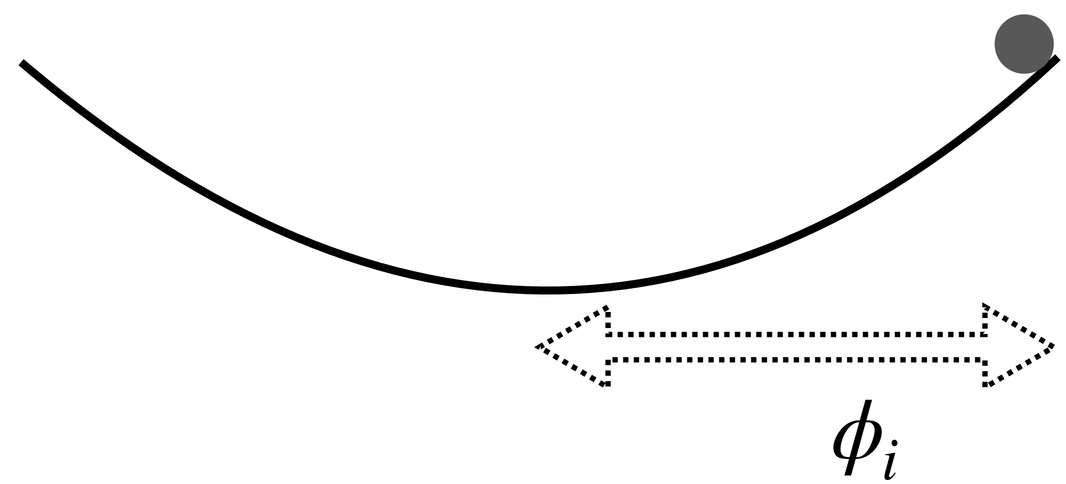
Production: misalignment

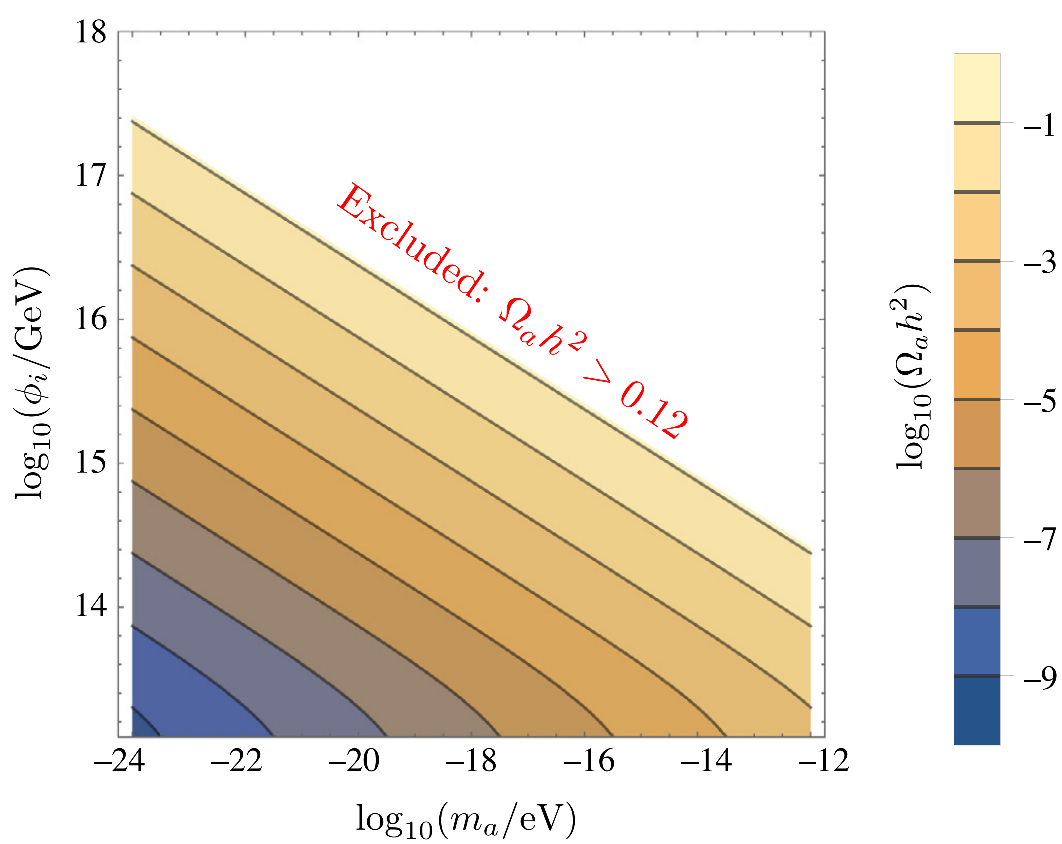
$H > m_\phi$

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.

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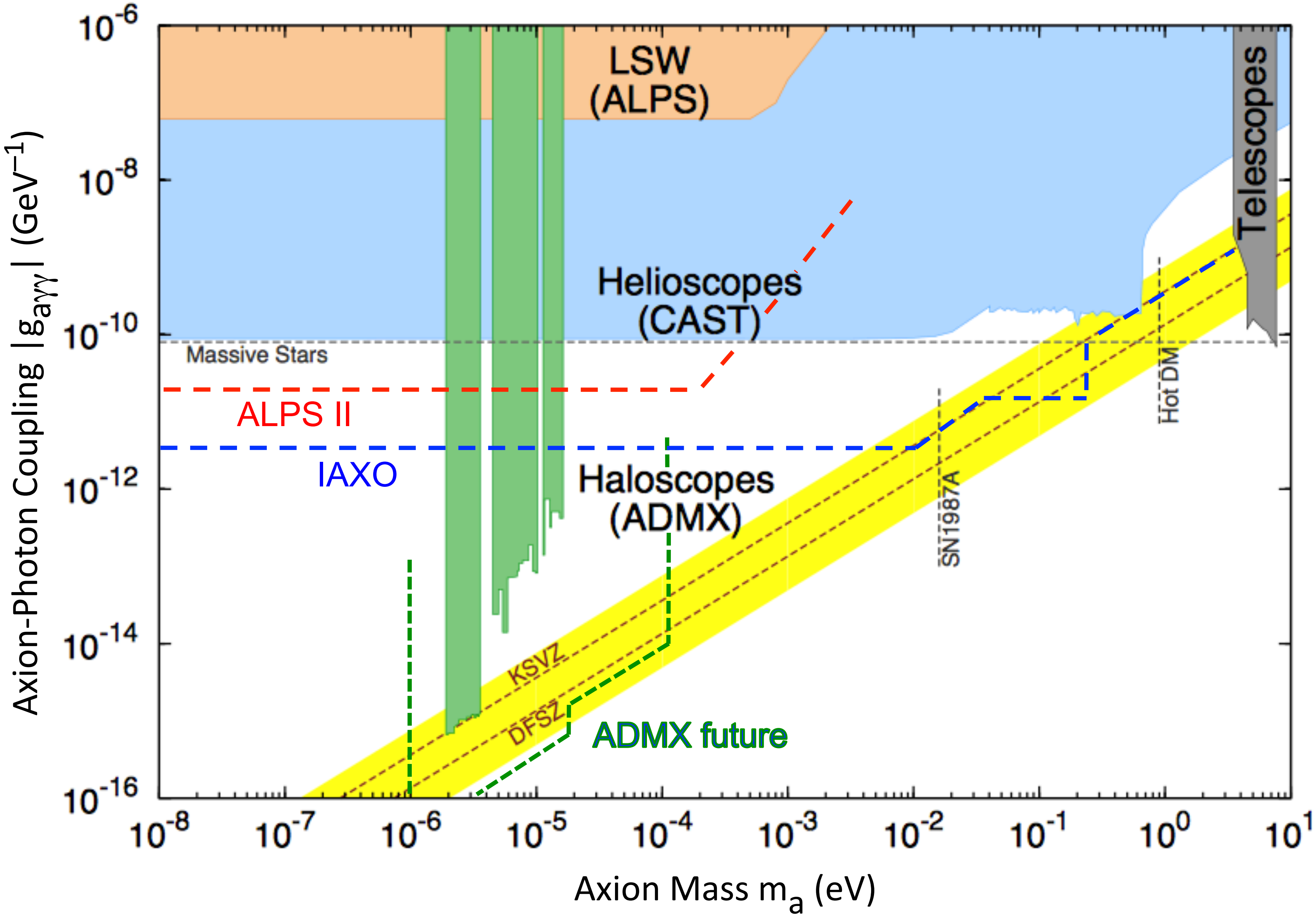
Axion like particles: ALPs

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

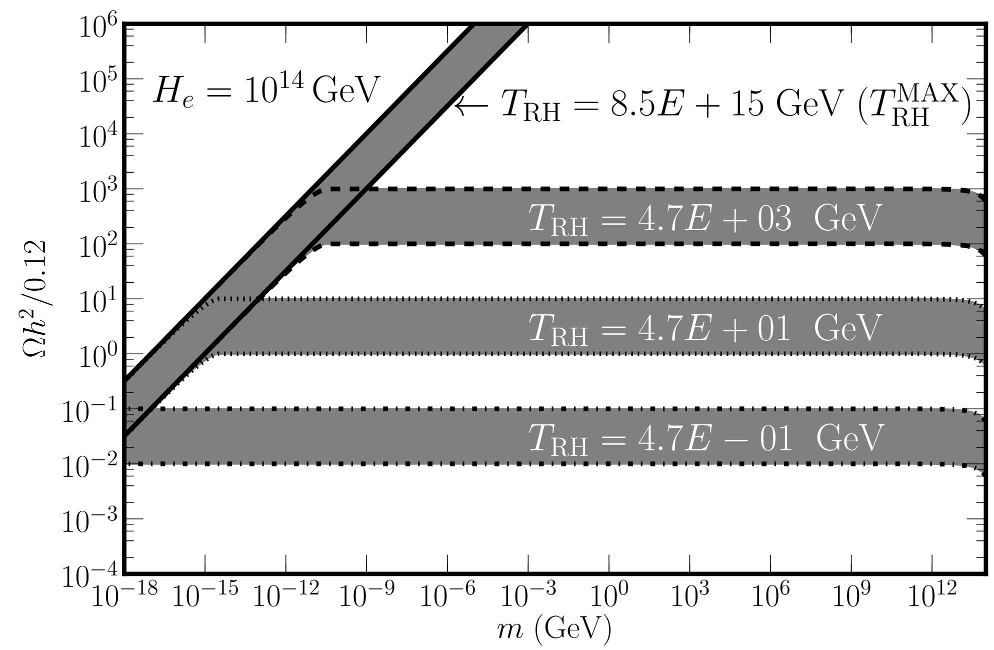
$$g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Dark photon dark matter

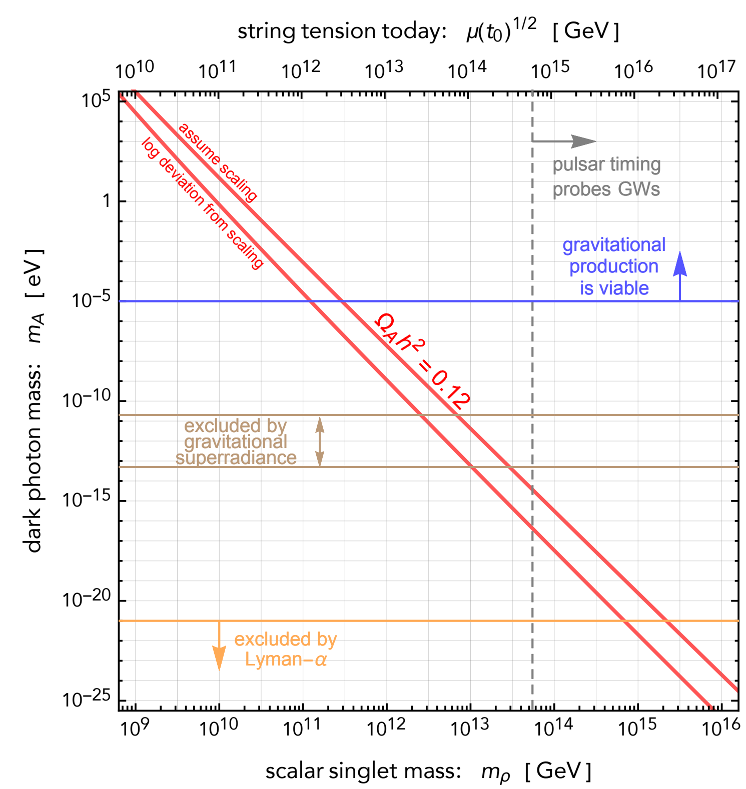
Multiple production mechanisms:

Produced gravitationally during inflation and reheating



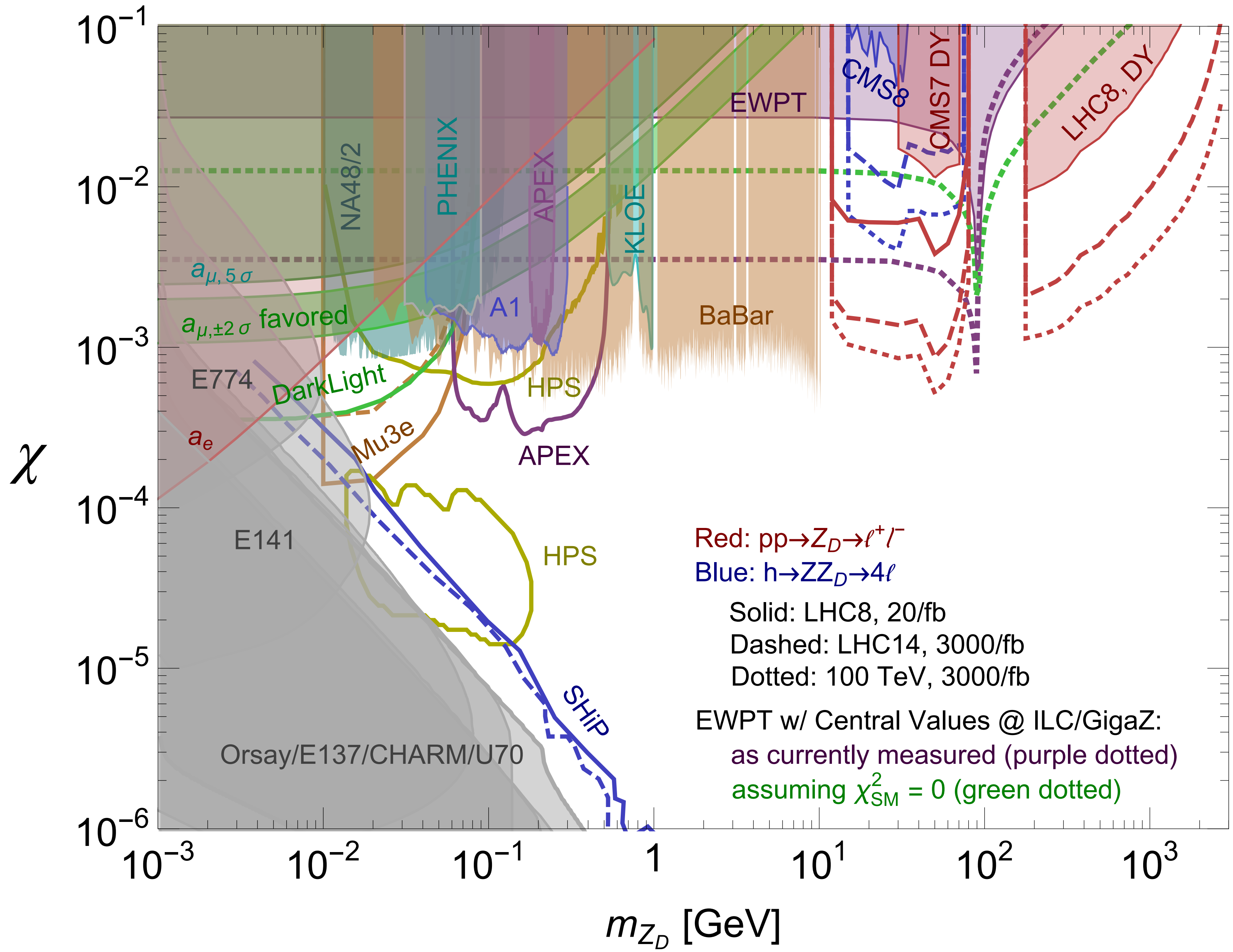
Similar to Hawking radiation, but applied to expanding universe.

From topological defects (such as cosmic strings) radiation



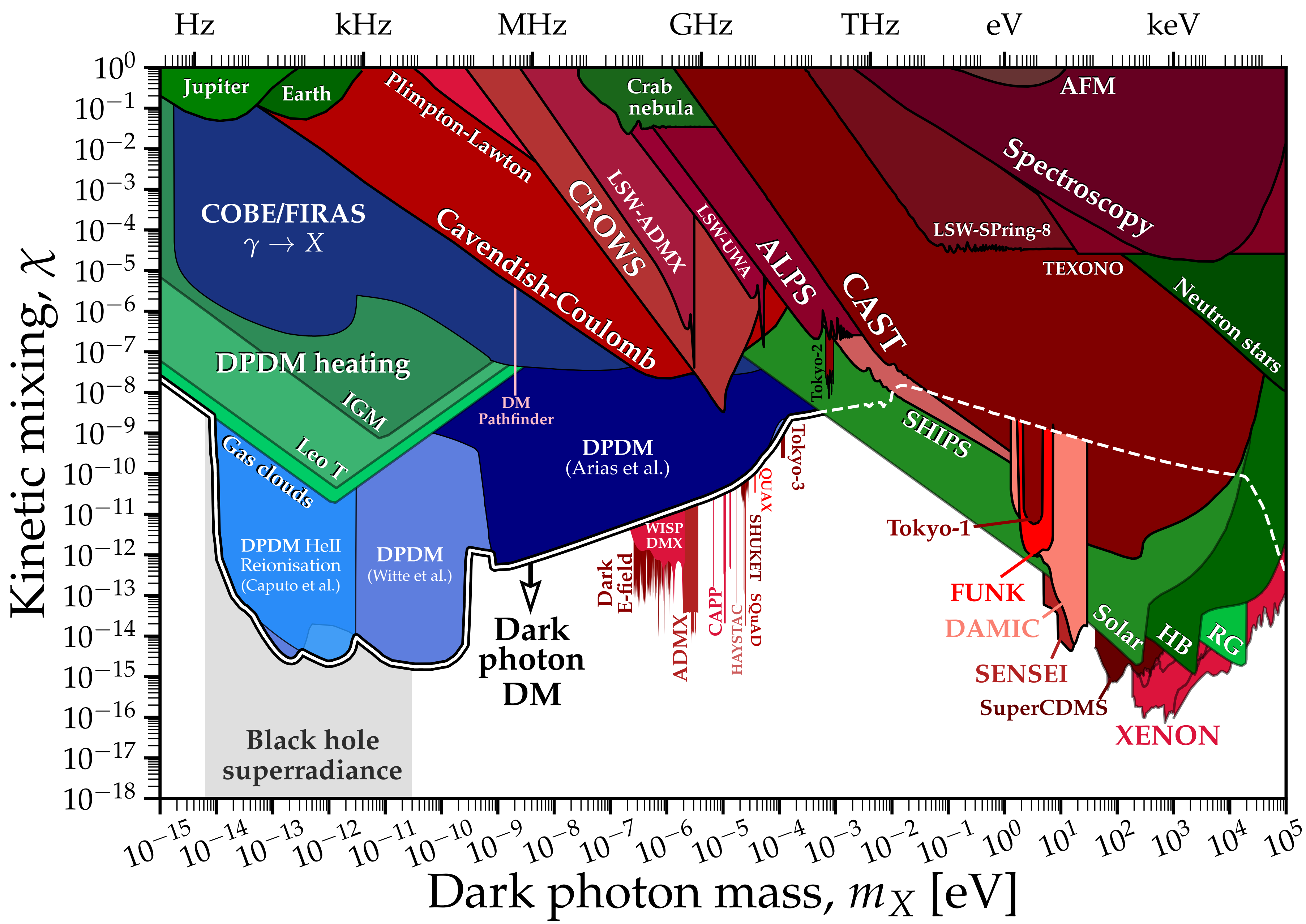
+ from misalignment, coupling to axions, ...

Dark photon searches



Heavier dark photon: Colliders, fixed target experiments

Dark photon searches



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

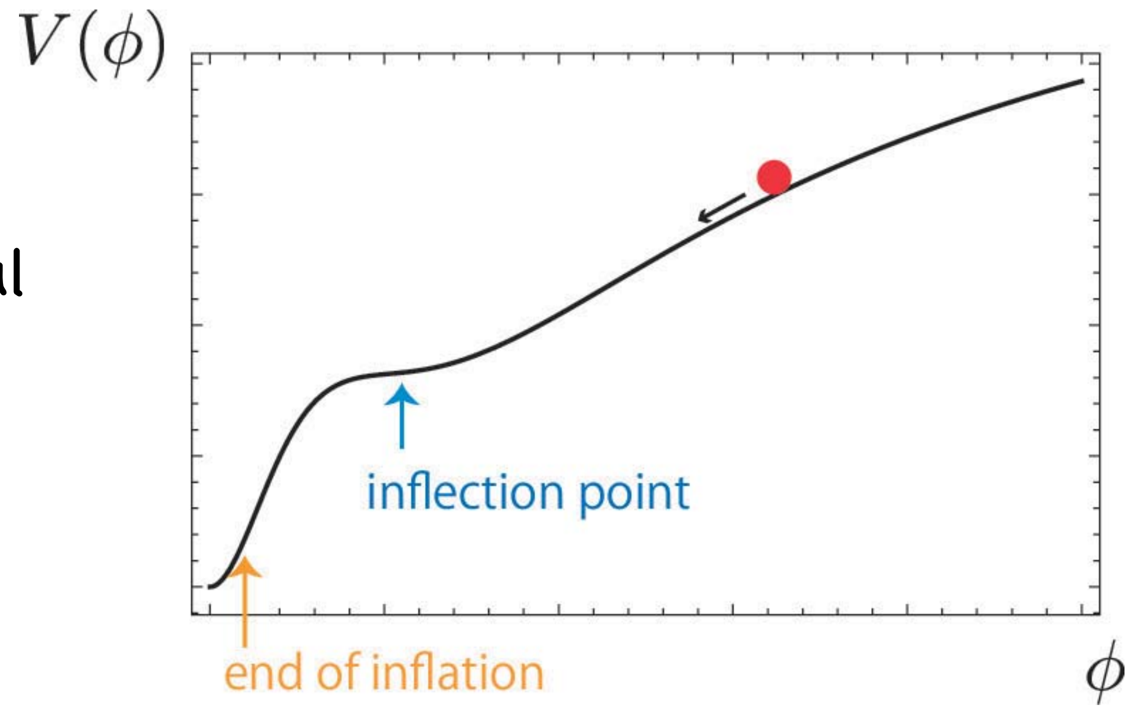
Many new ideas still emerging: e.g. H. An, F. P. Huang, J. Liu, W. Due, 2010.15836

Are axion/dark photon good theories?

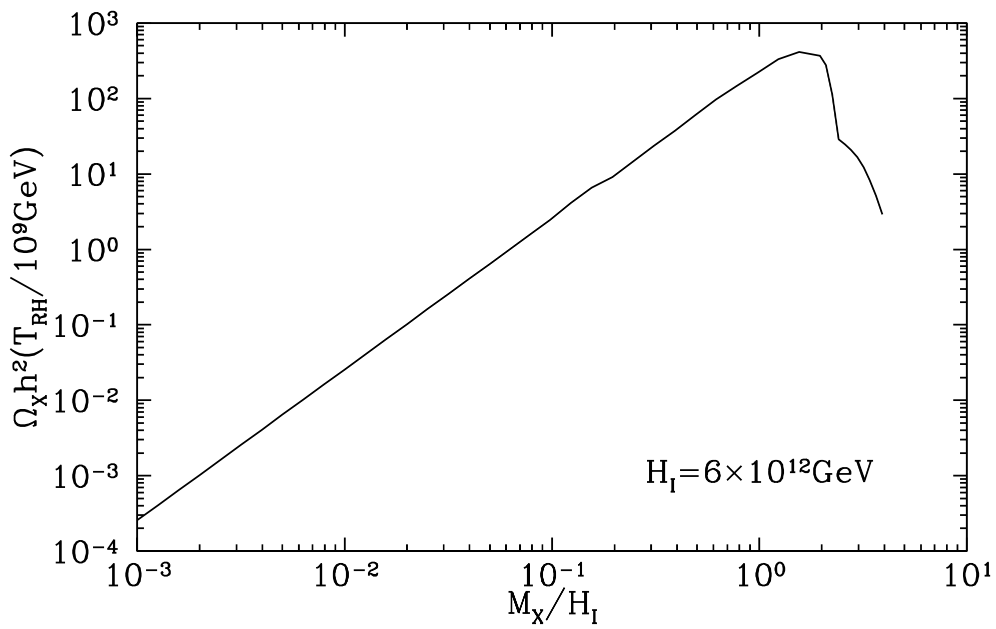
- Quite reasonable:
  - Based on well known physics (such as Goldstone boson and symmetry breaking).
  - QCD axion can solve strong CP problem.
- Testable:
  - Simple coupling to the Standard Model. Large possible region of coupling strength.
  - Many new development for new techniques.

Pretty good theories. Good guide for experiments.

Other stories

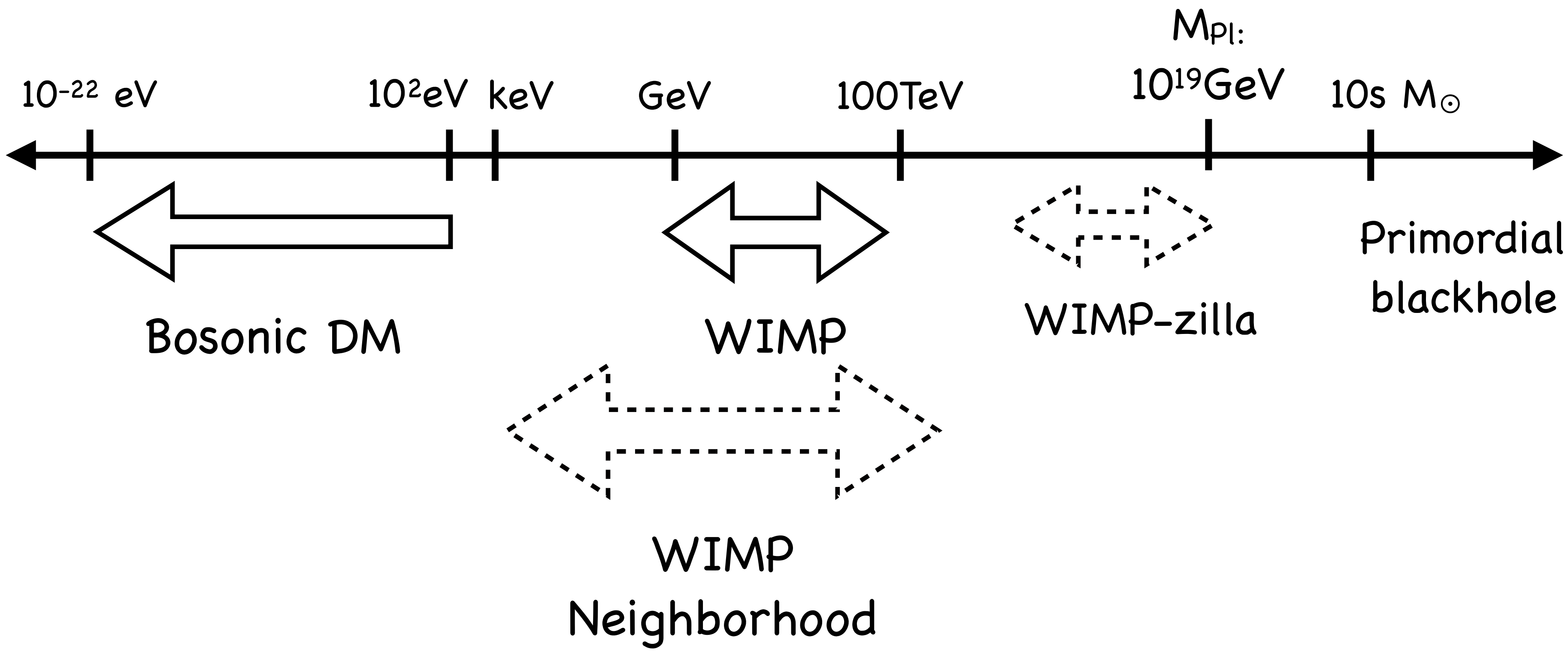


A special feature on the inflaton potential gives large fluctuations
⇒ primordial blackhole production



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

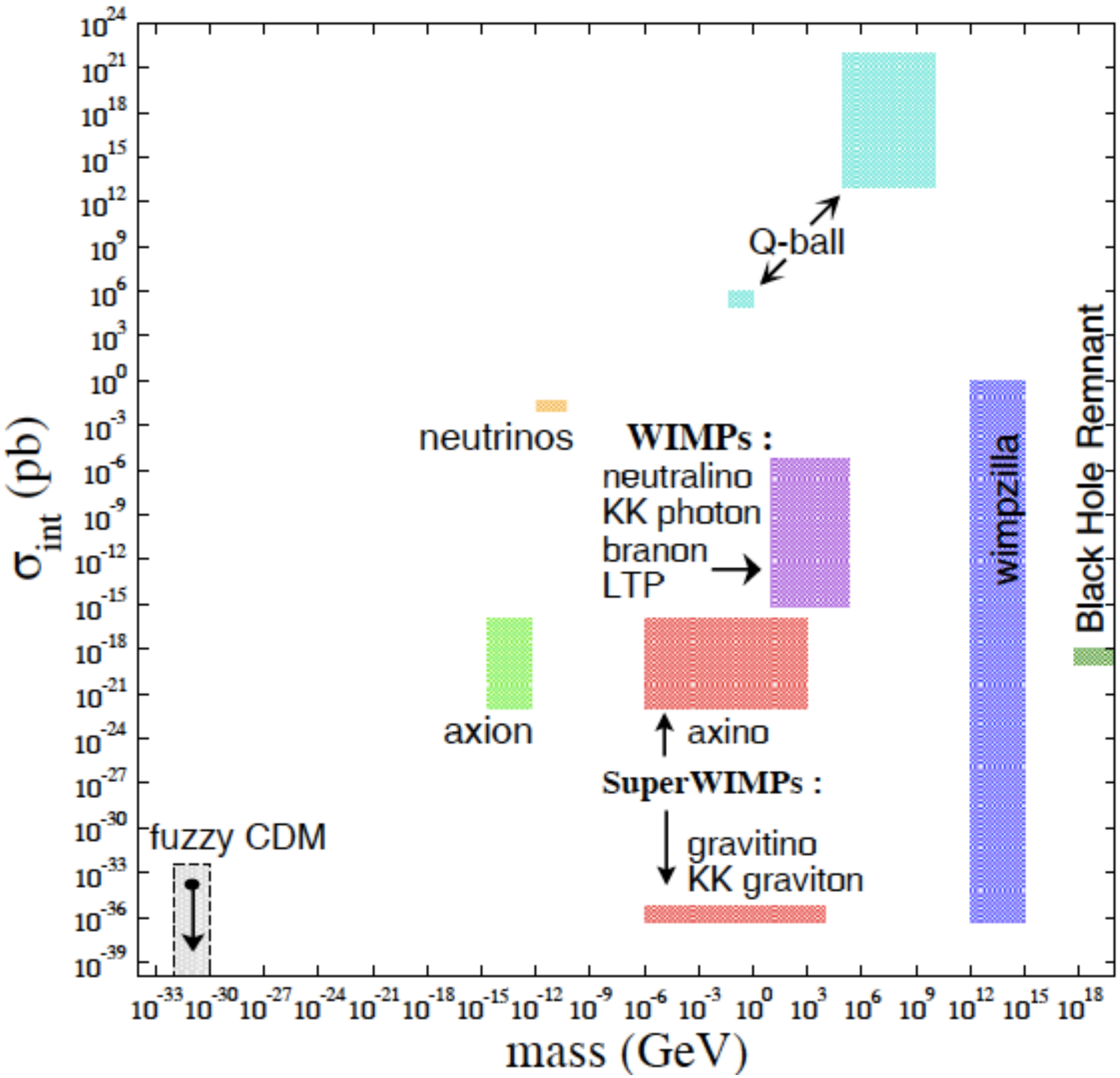
The gaps in our stories



- Still, many orders of magnitudes empty.

The gaps

J. Feng



– Even more if we also take into account coupling strength

Conclusion

- Understanding dark matter is one of the most pressing questions in physics.
- It is a very difficult task.
  - Vast range of possibilities, yet we know extremely little.
- After decades of effort, we have several good theories: WIMP + dark sector, axion,...
- Much more is needed to cast a wide net! Huge amount of work left to be done!

extra

Limits from annihilation