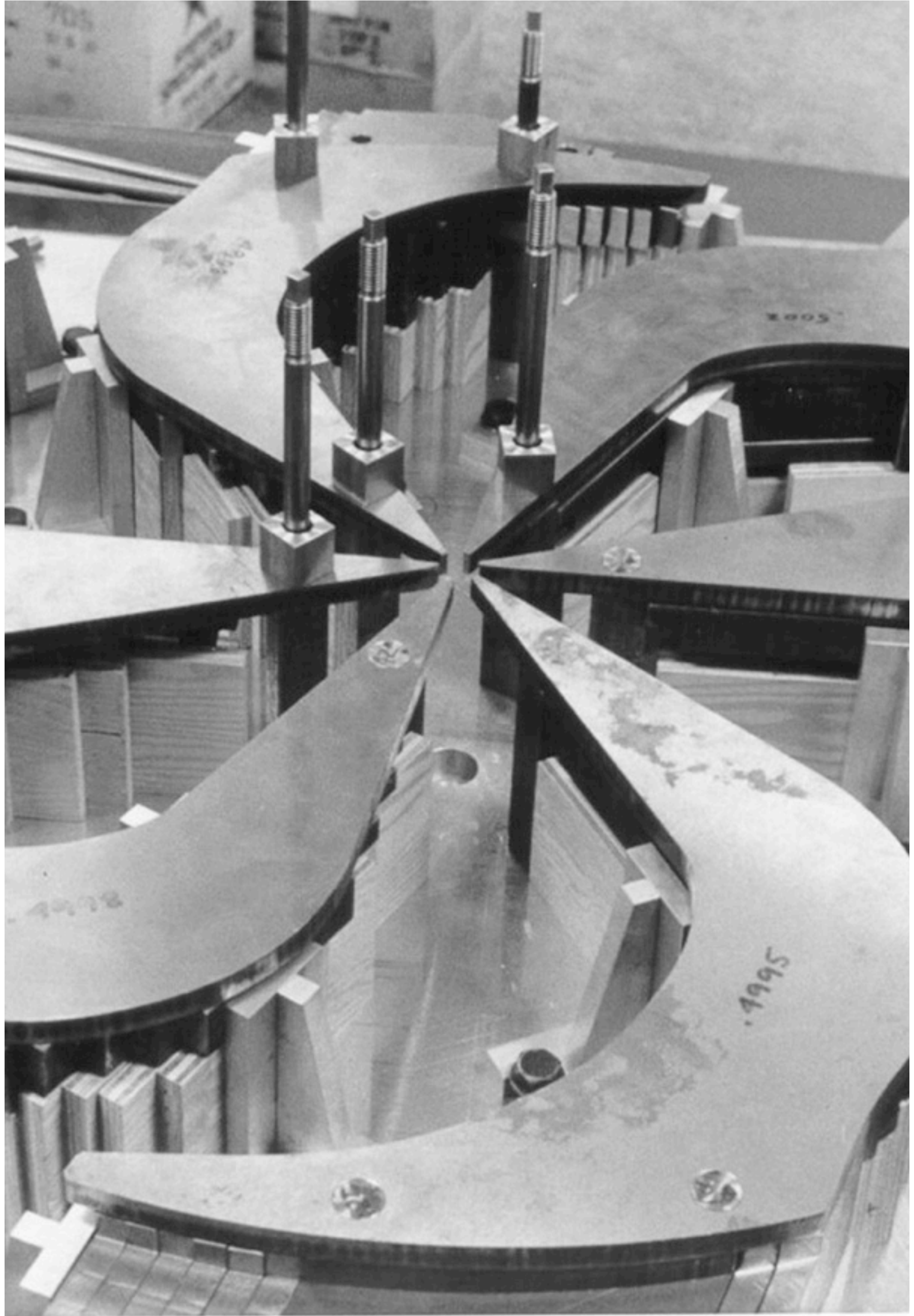
TRIUMF

What is Dark Matter?

David Morrissey
TRIUMF

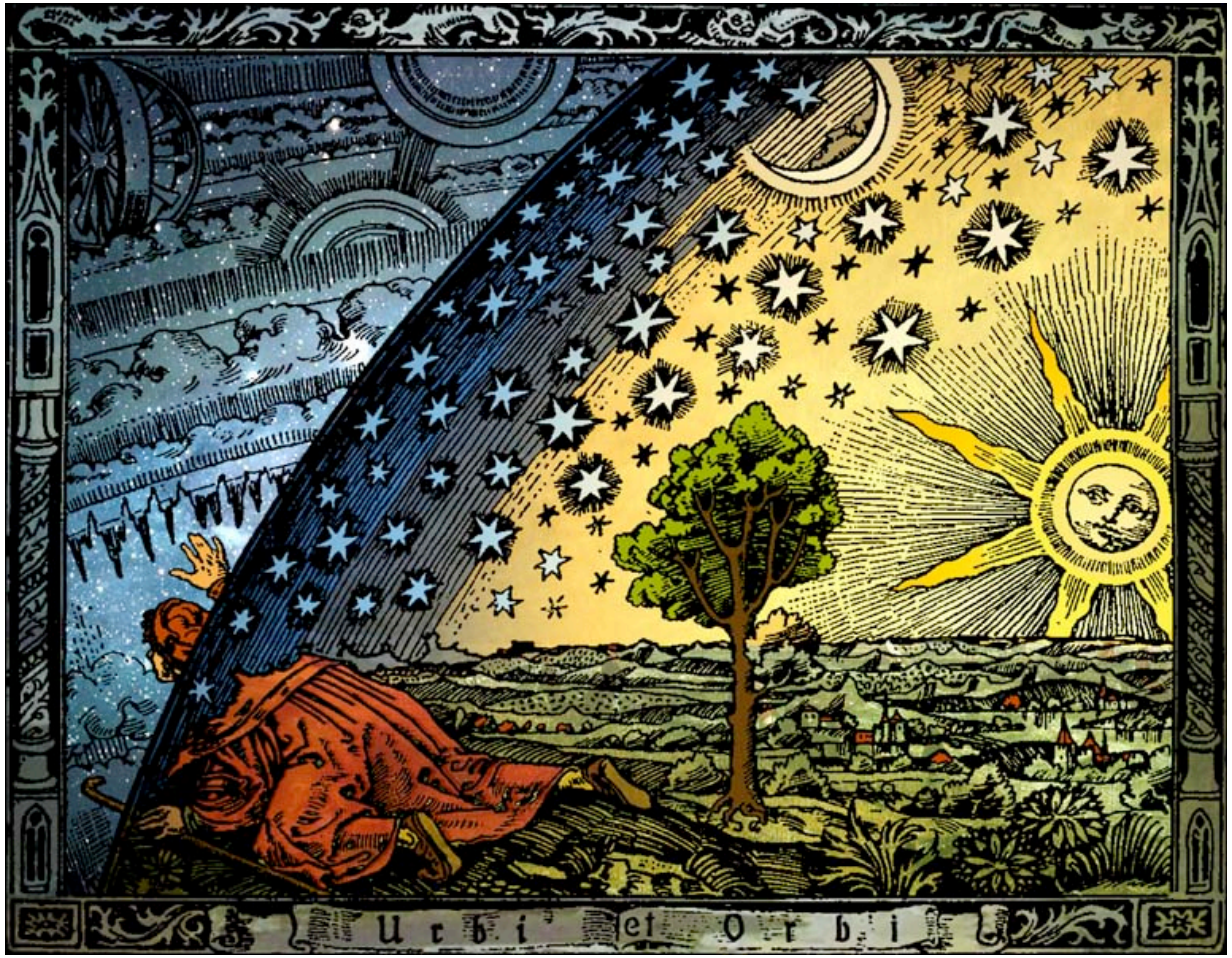
SNOLAB User Meeting

August 12-13, 2021



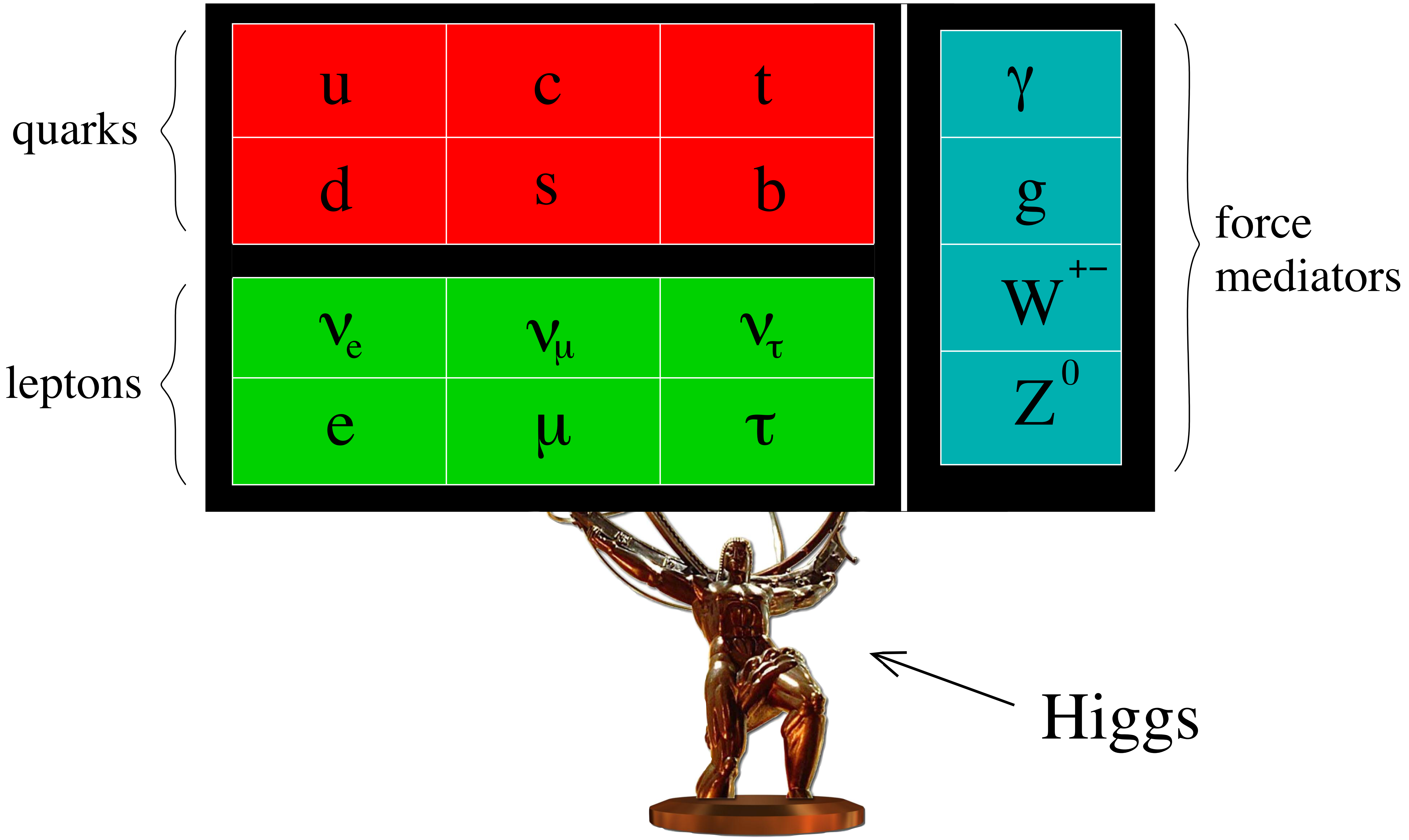
Discovery, accelerated

Our Goal

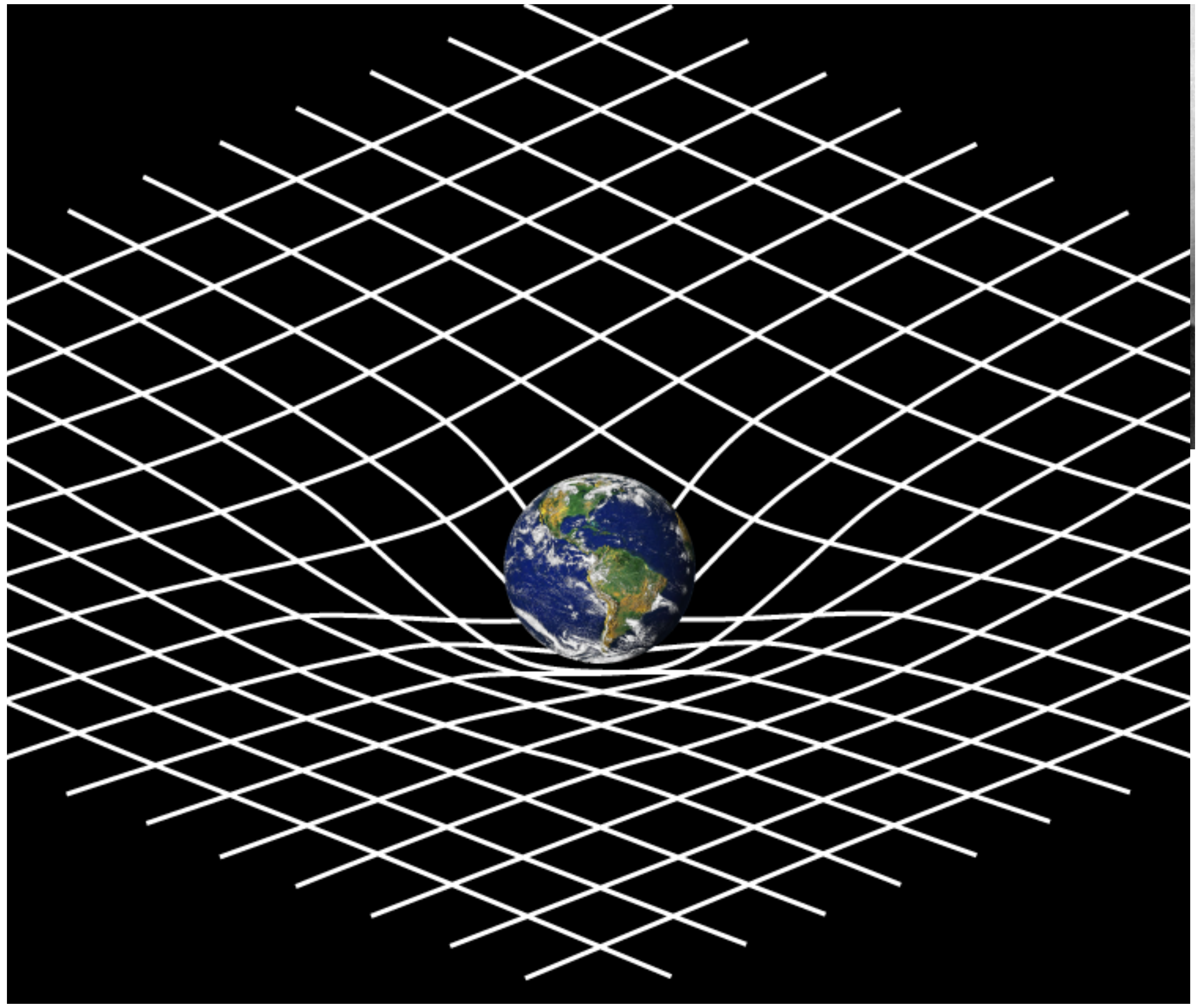


[Flammarion Engraving 1888]

Building Blocks



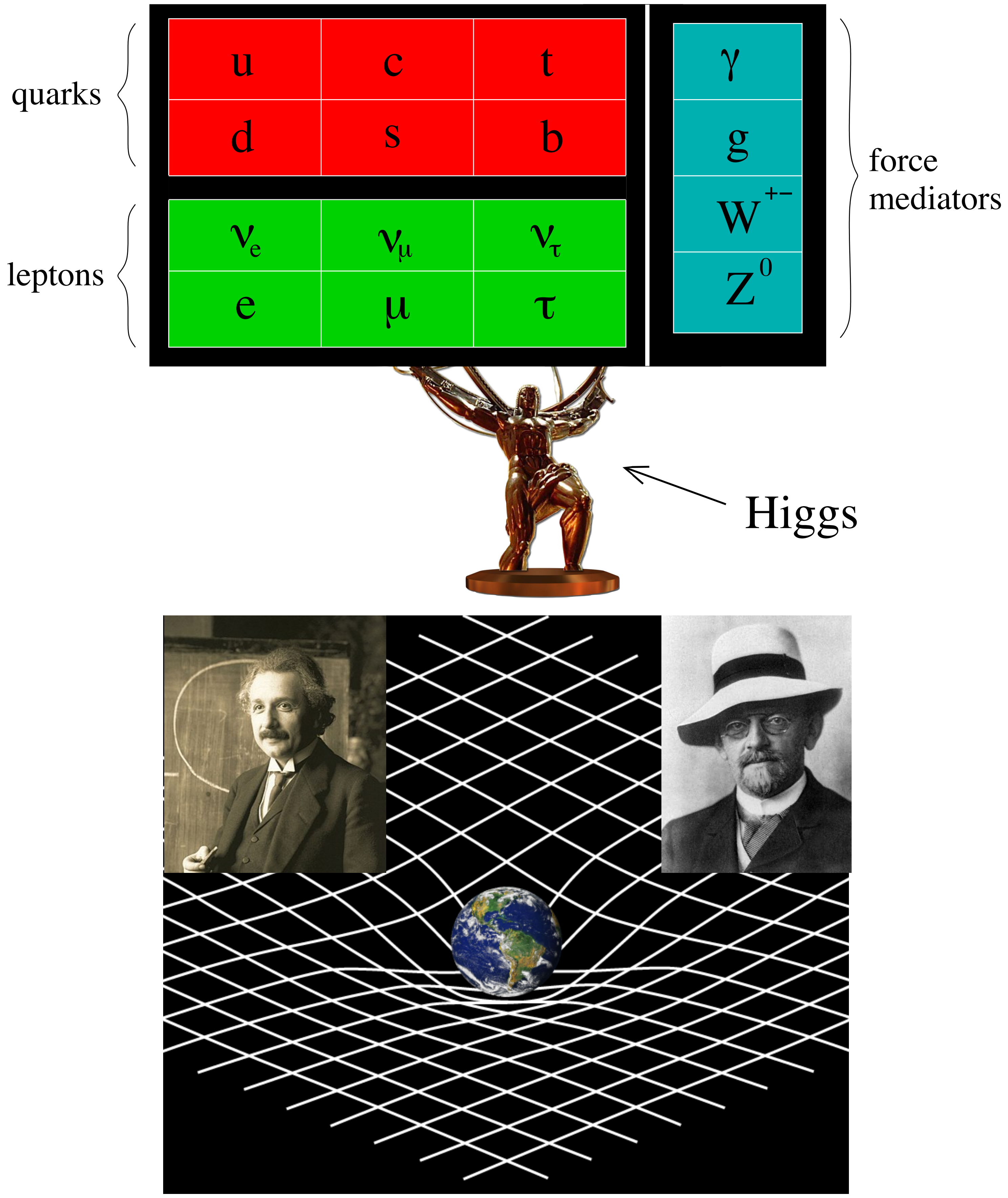
Elementary Particles
=
Standard Model (SM)



Gravity
=
General Relativity (GR)

Extrapolating the SM+GR

Does this …



… explain that?

Extrapolating the SM+GR

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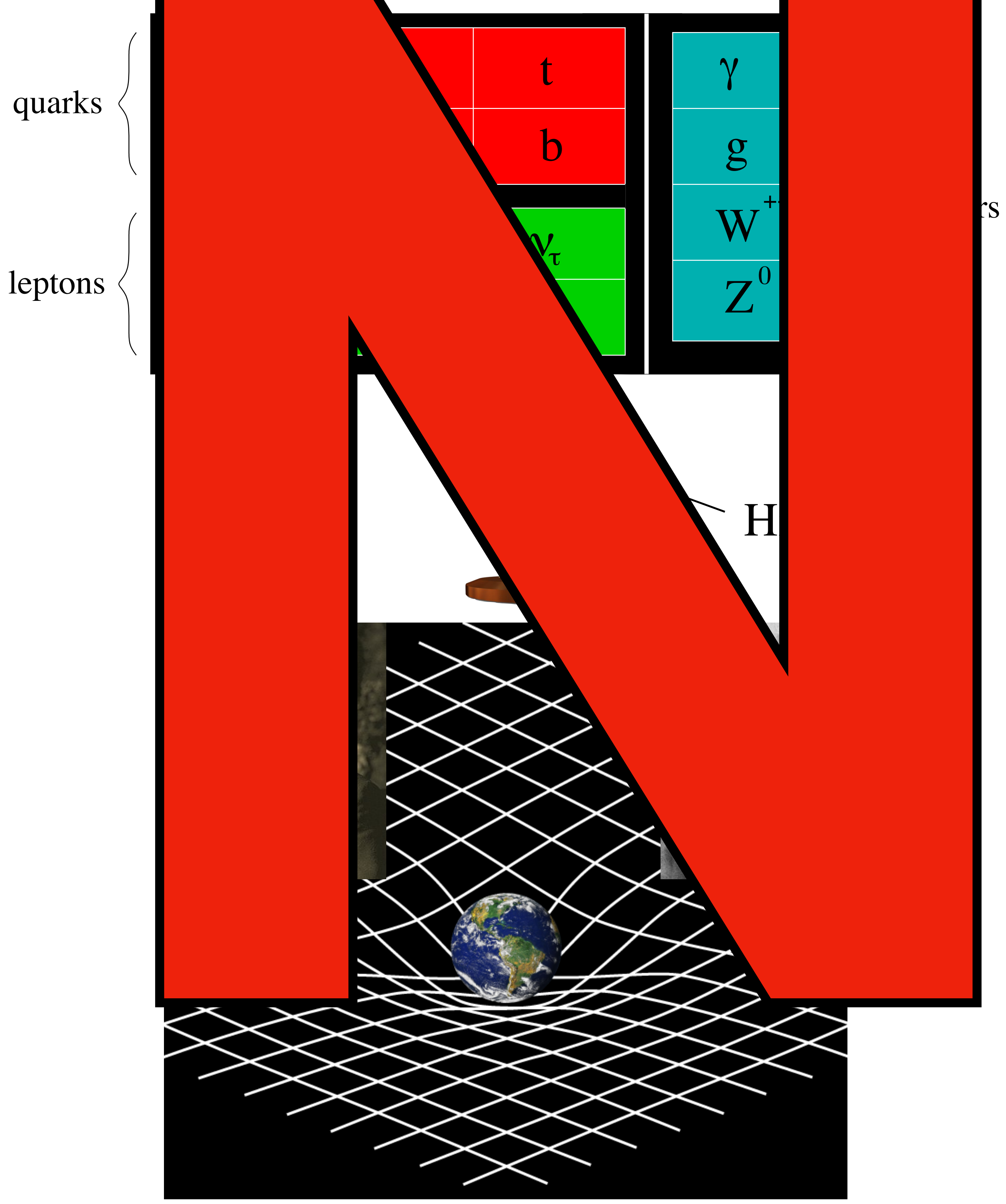
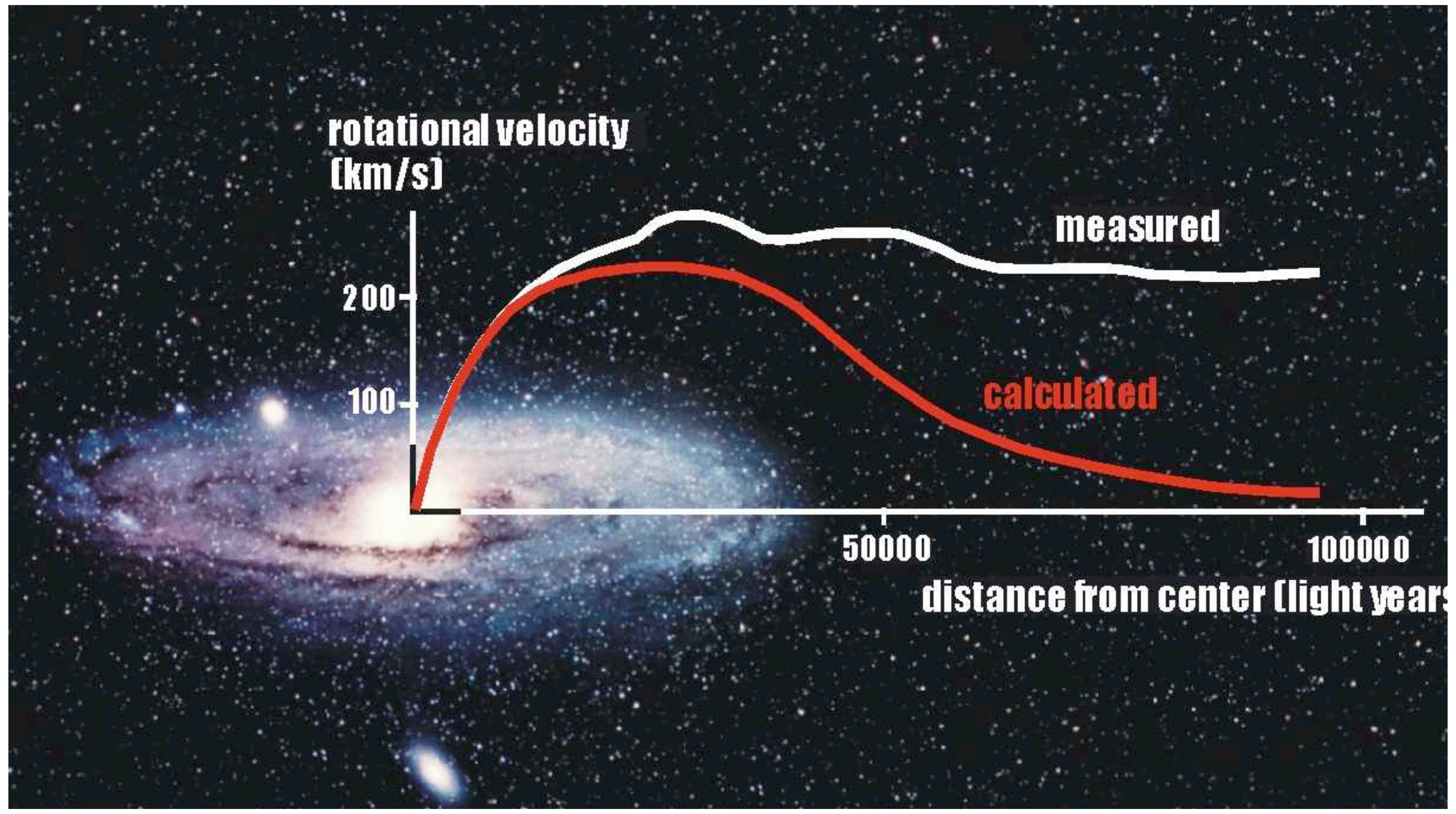
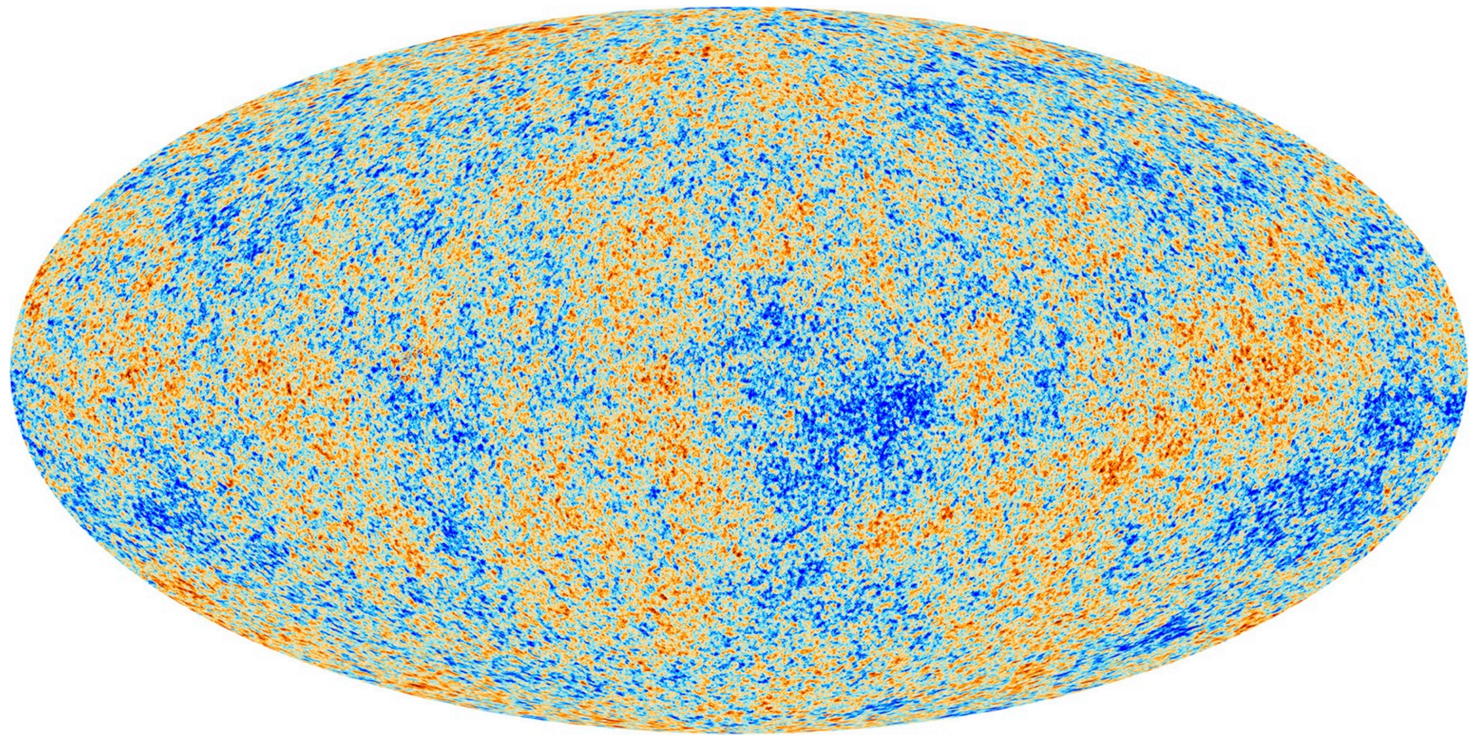


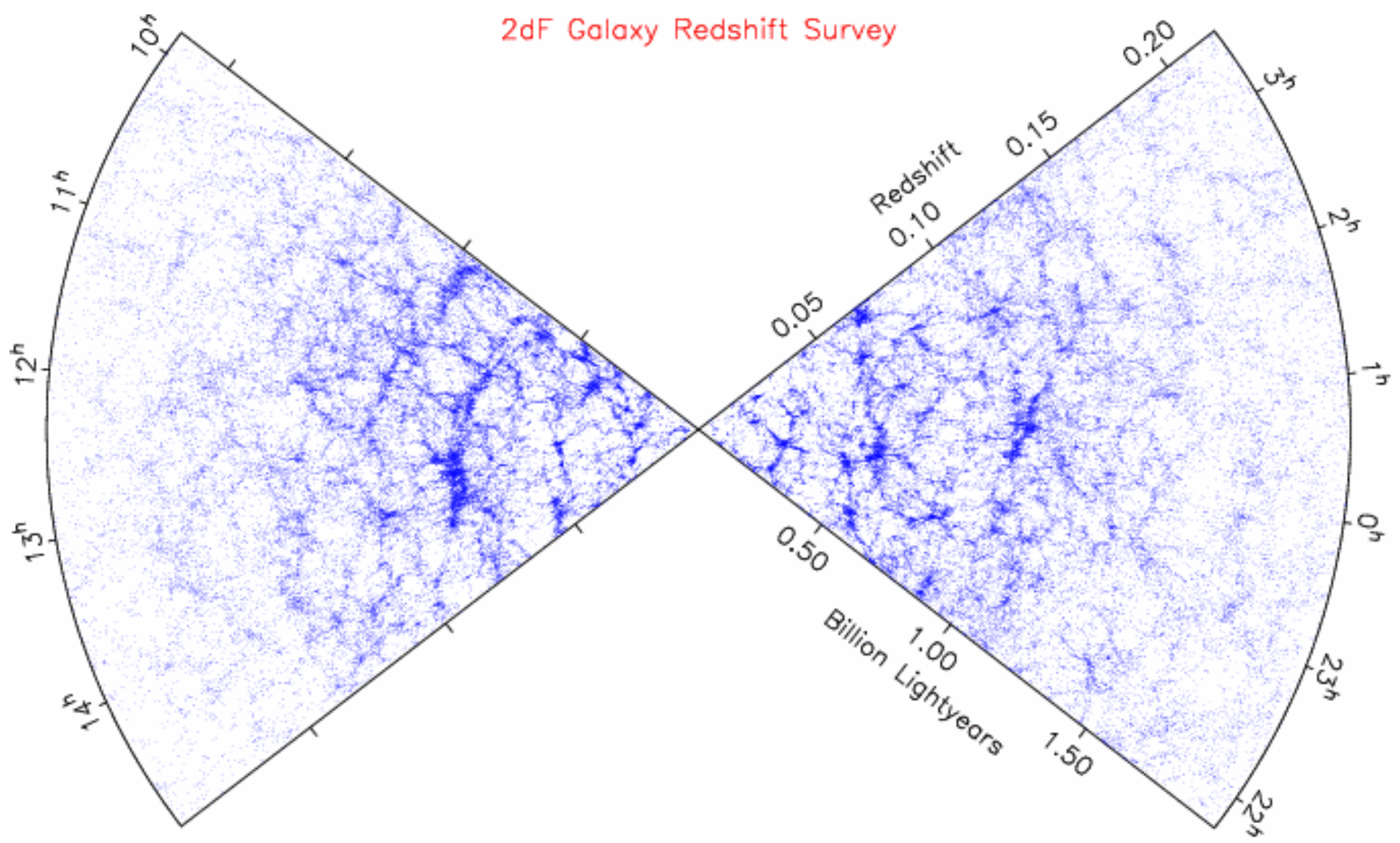
NO!

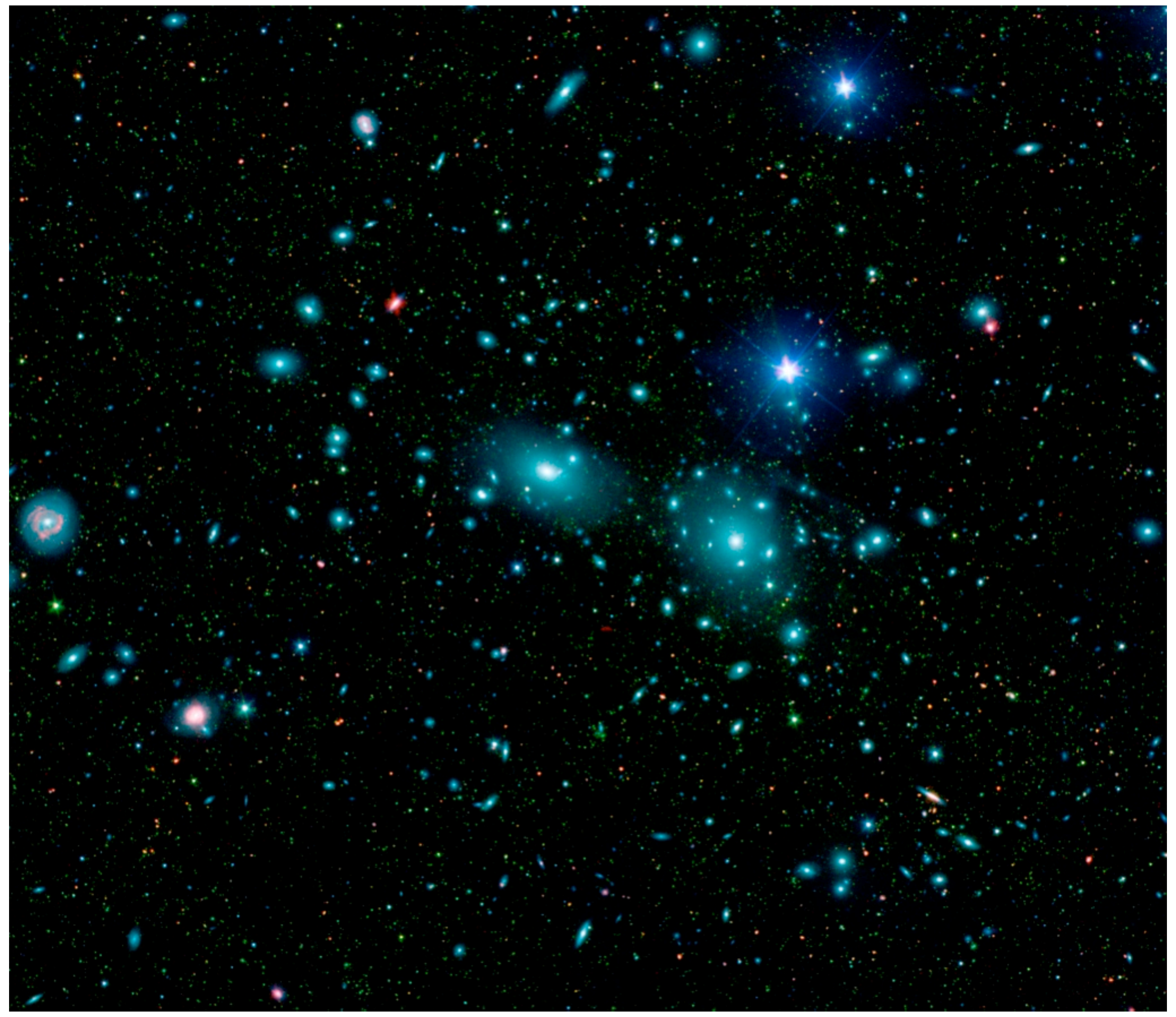
… explain that?

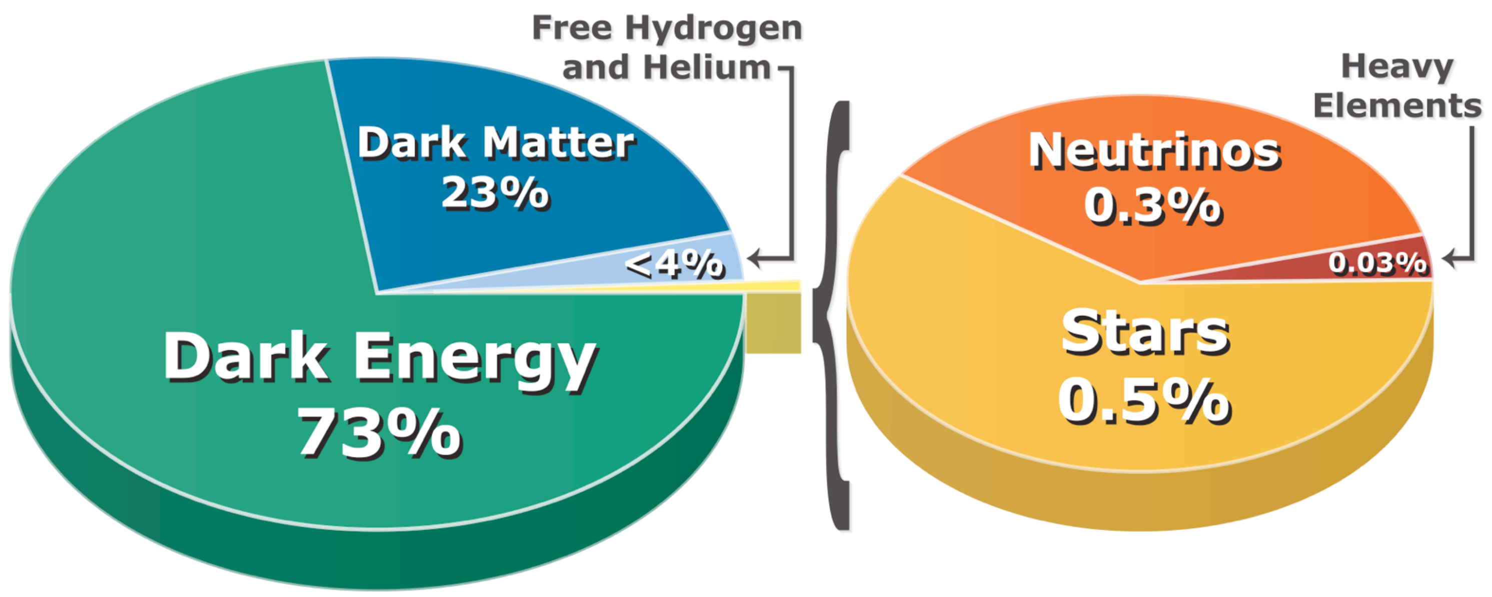
Evidence for Dark Matter











Evidence for Dark Matter

- **Data:** motions of visible matter suggest lots of matter that we can't see.

- **Theory #1**: there is more matter out there than we can see: **Dark Matter**
- **Theory #2**: GR breaks down at large distances: **Modified Gravity**

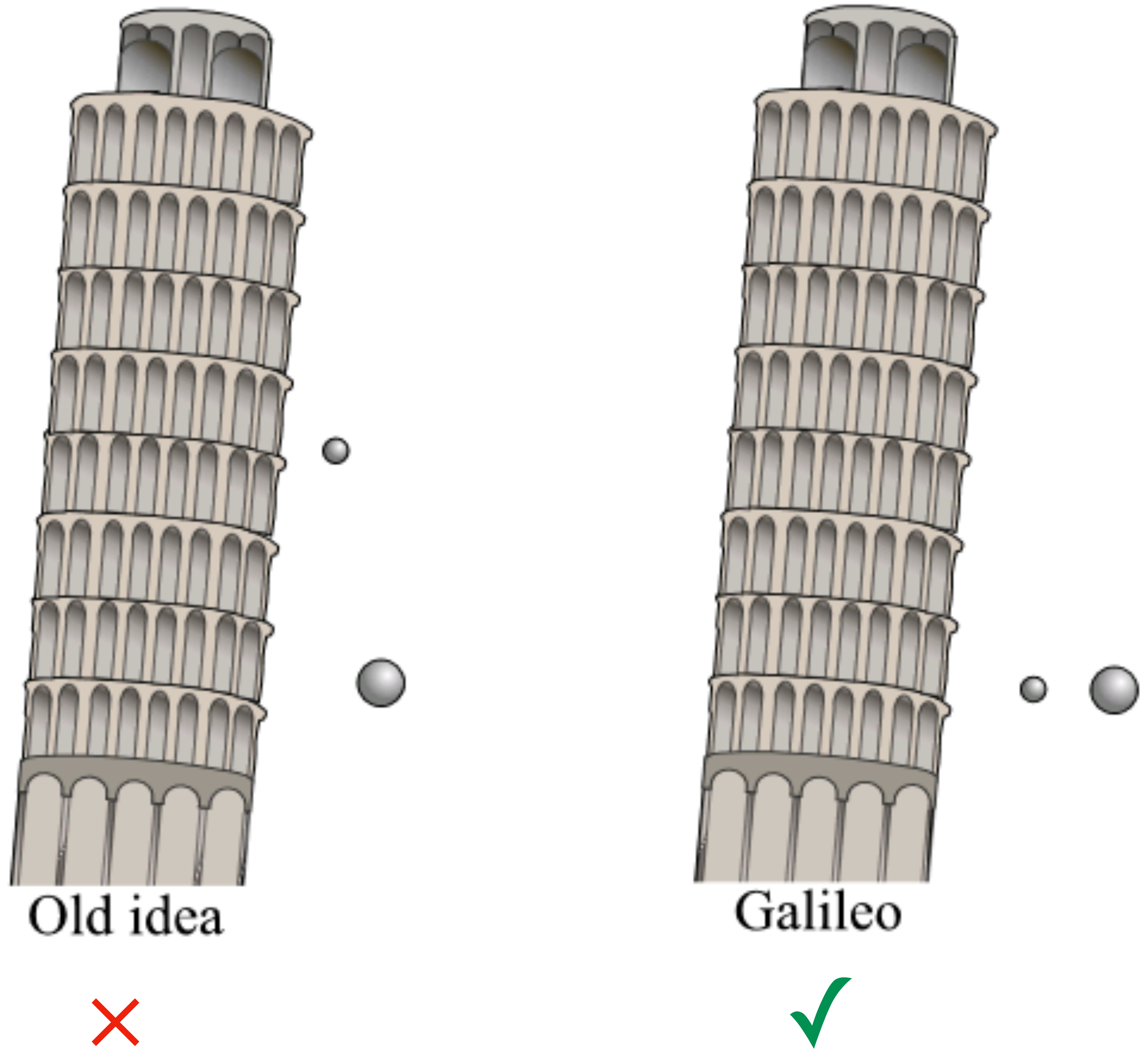
- The dark matter explanation seems to work much better!
  But no known particle or matter has the right properties to be dark matter.

- **What is dark matter?**

What is Dark Matter?

- **We don’t know!**

- Evidence for DM comes from its gravitational influence on regular matter. Gravity is universal, so our current data doesn’t tell us what DM is.



What is Dark Matter?

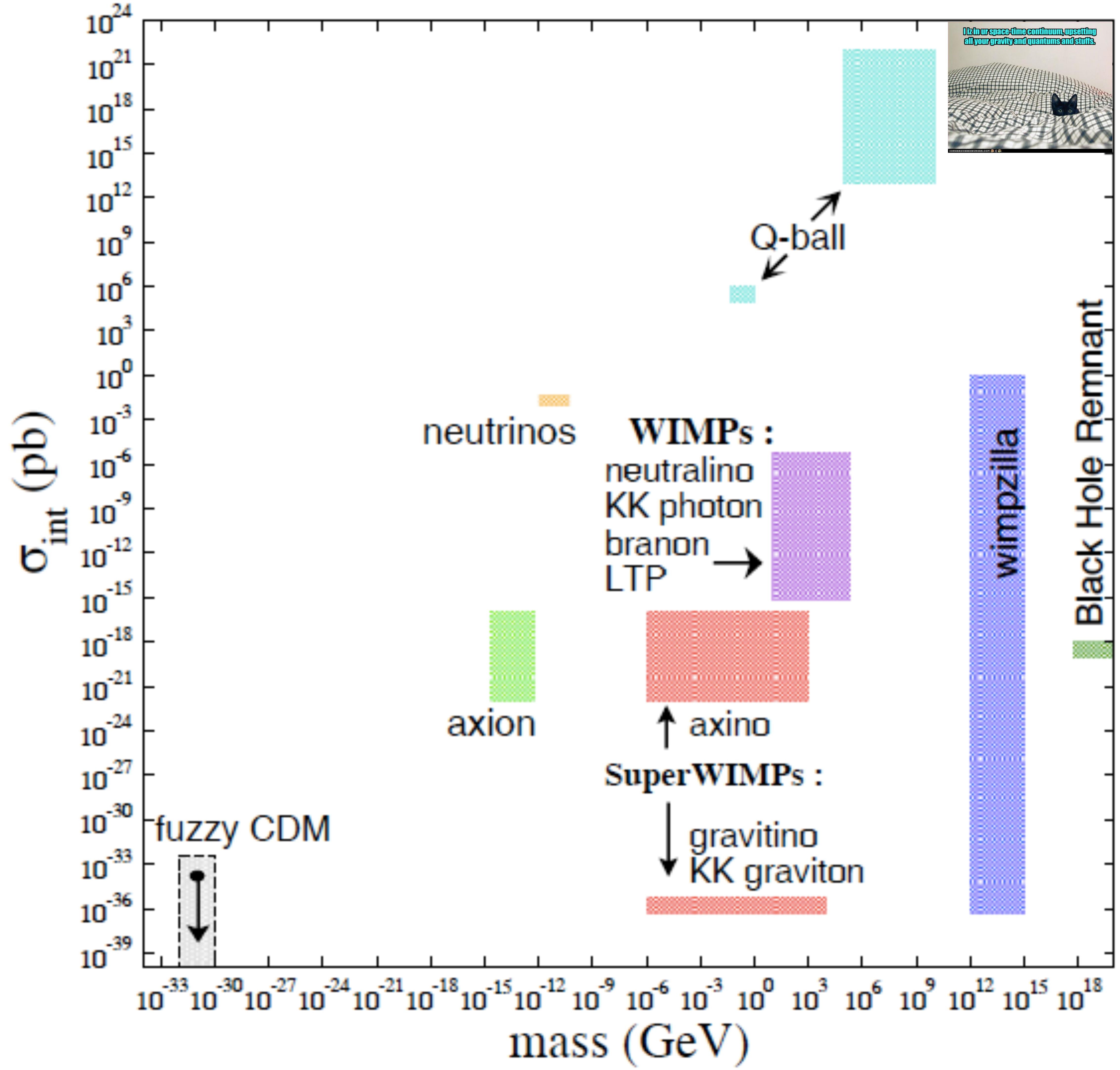
- **We don’t know!**

- But dark matter must:
  - not interact too strongly with ordinary matter (“dark”)
  - be non-relativistic today and in the early Universe (“matter”)
  - obtain the observed cosmological density (determined from CMB+)
  - not interact too strongly with itself (for gravitational clumping)

- Detecting DM through non-gravitational interactions is (probably) needed!
  Where and how do we start looking for it?

What is Dark Matter?

- **We don't know!**
- Some DM theories:



[E.K. Park, HEPAP DMSAG, 2007]

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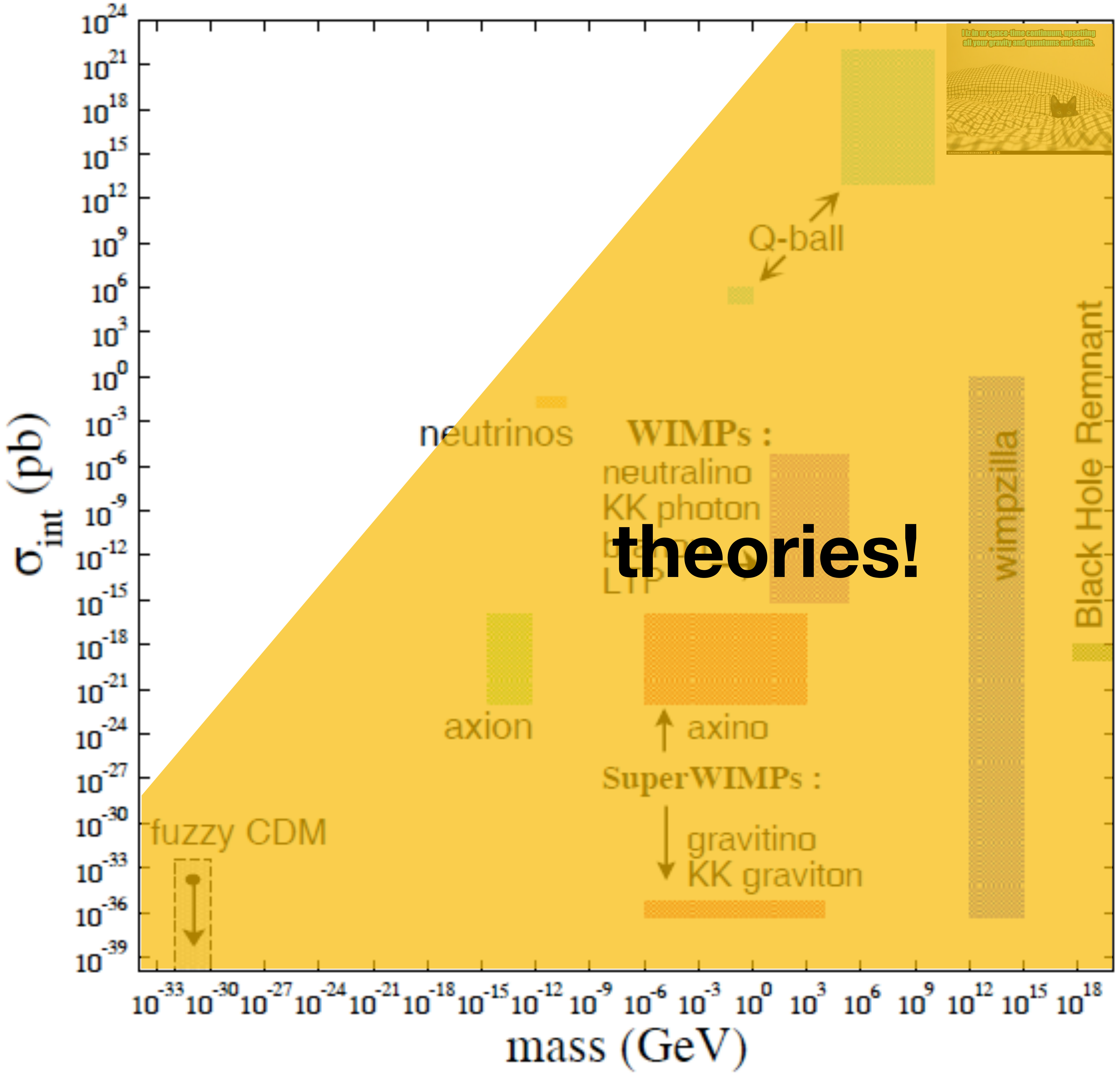

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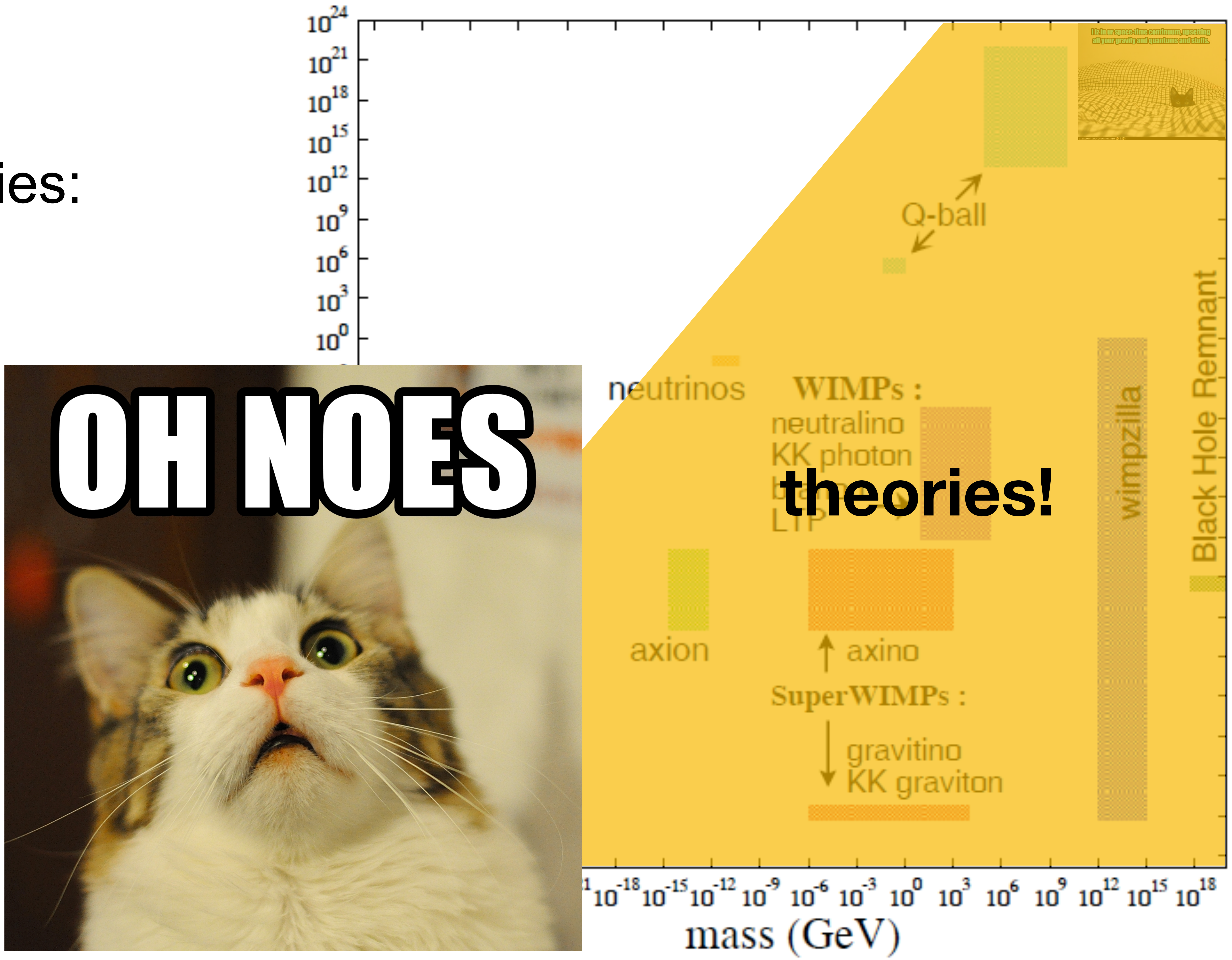


[E.K. Park, HEPAP DMSAG, 2007]

What is Dark Matter?

- In most theories, DM corresponds to a new particle or field.
- Since there are so many theories, let's organize by production mechanisms in the early universe.*
- A useful classification:
  - **Thermal DM:** produced by thermal SM reactions in the hot early Universe
  - **Non-Thermal DM:** produced in other ways not related to the SM plasma

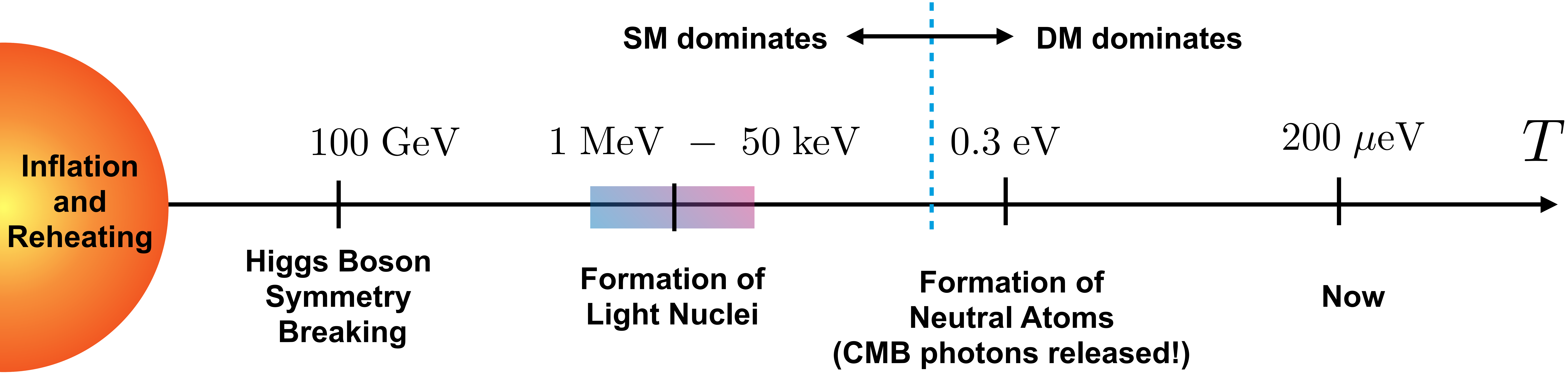
* Note: I can't cover everything!

Thermal Dark Matter

Thermal Dark Matter

- Early Universe = hot soup of relativistic particles $(T \gtrsim \text{MeV})$

  As it expanded, it cooled off and some things happened:



- **"Thermal DM"** $\Rightarrow$ was once in thermodynamic equilibrium with the SM

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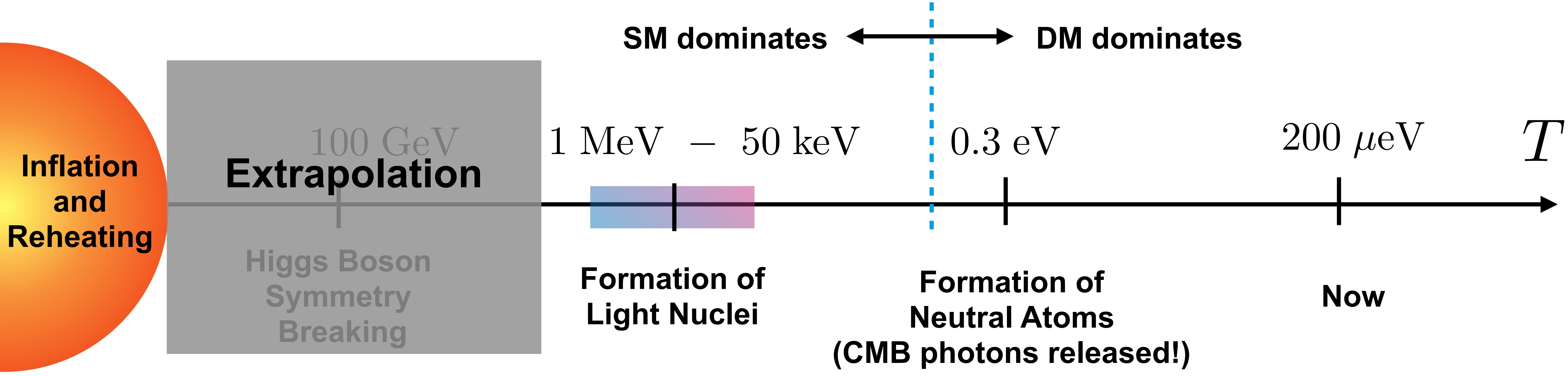


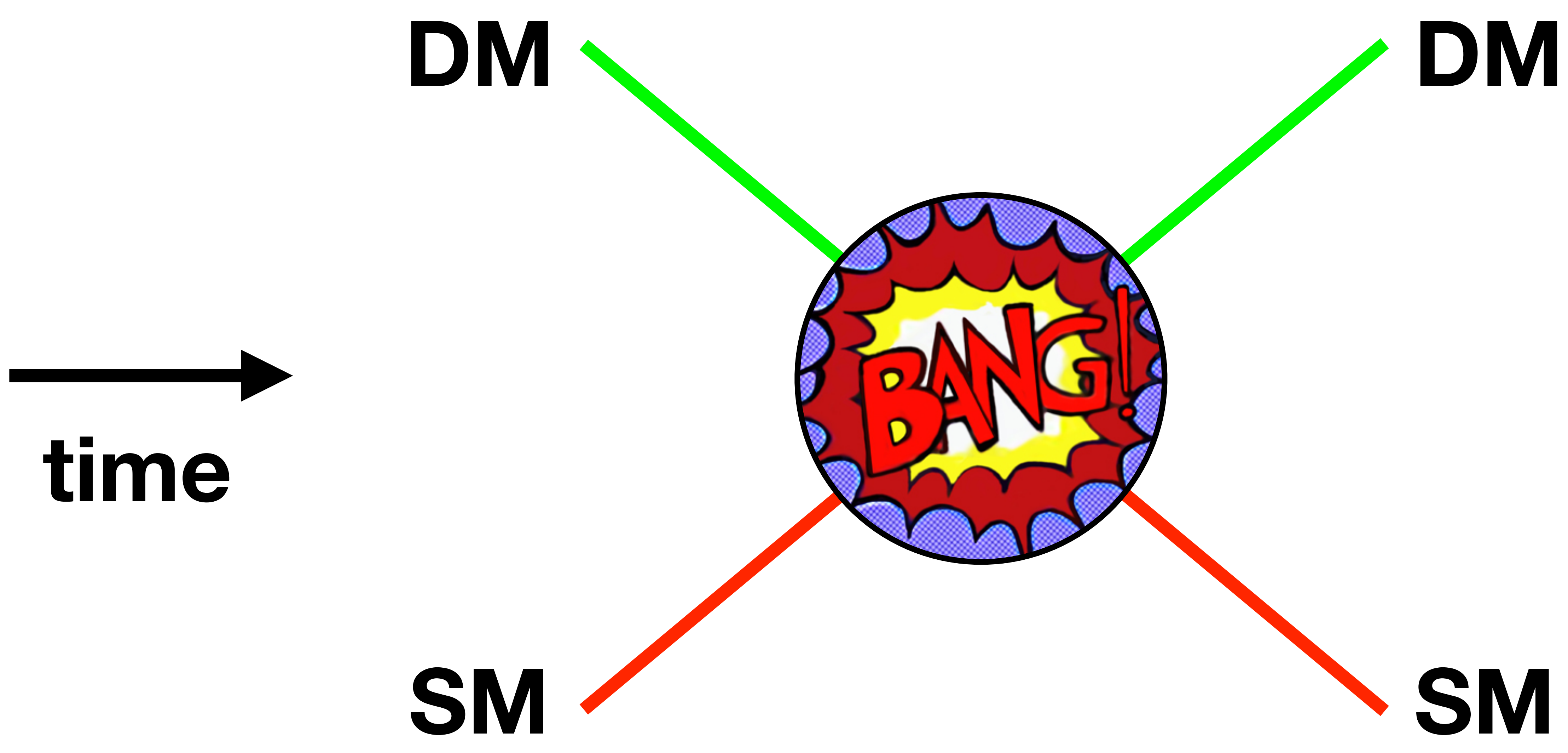
- **"Thermal DM"** ⇒ was once in thermodynamic equilibrium with the SM

Why Thermal Dark Matter?

- Thermal DM is created by collisions of SM particles.
- Thermal DM can develop the correct relic abundance during the subsequent expansion and cooling of the universe through **freeze out**.
- Thermal DM candidates arise in many theories that extend the SM.
- Thermal DM requires non-gravity interactions between DM and the SM.
  $\Rightarrow$ **an excellent target for dark matter searches in the laboratory!**

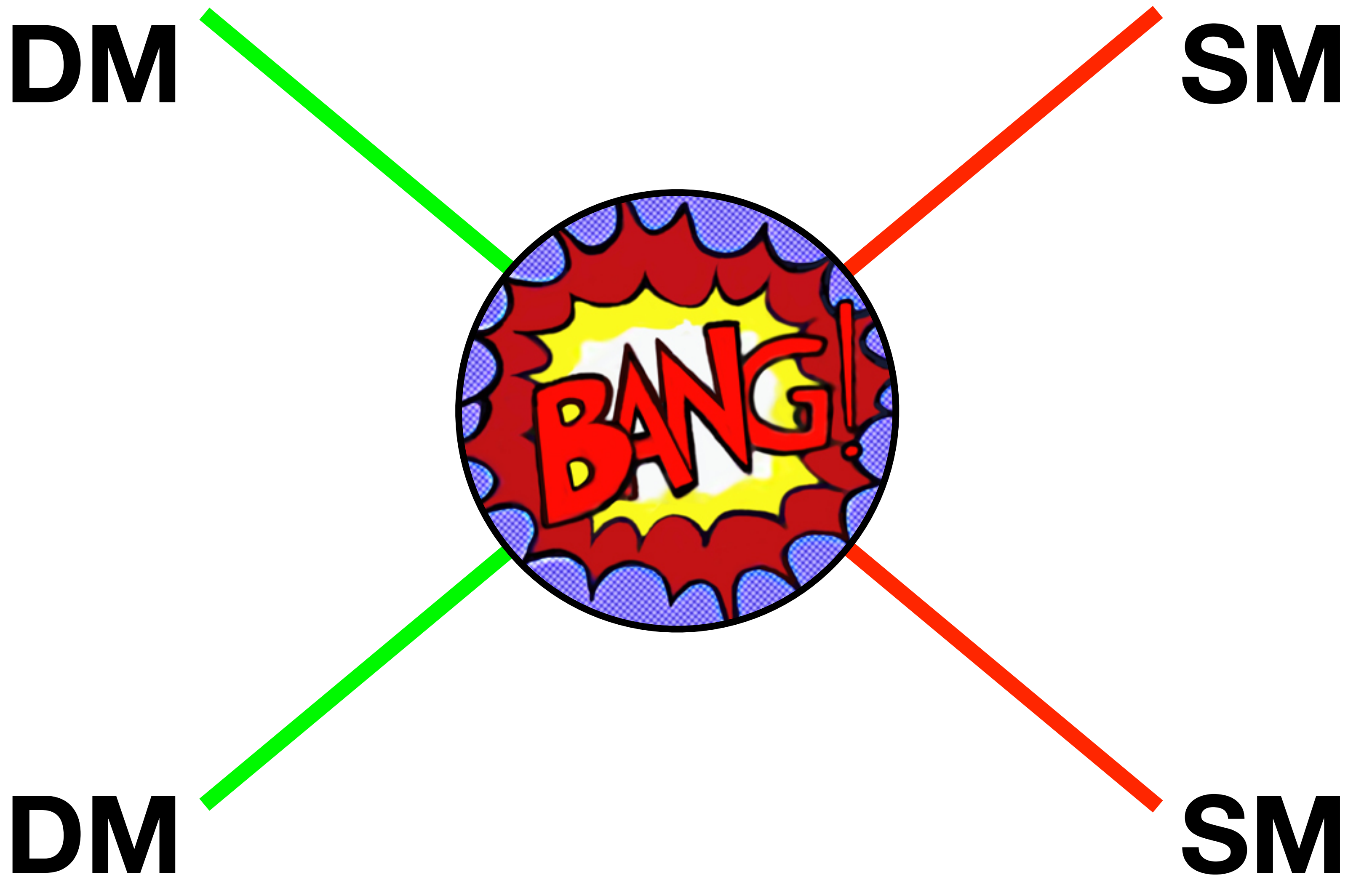
Thermal Dark Matter: Equilibration

- Thermal DM ⇔ was once in thermodynamic equilibrium with the SM
- Equilibrium needs **non-gravitational** interactions between DM and the SM:



$$\mathrm{DM} + \mathrm{SM} \leftrightarrow \mathrm{DM} + \mathrm{SM}$$

kinetic equilibrium



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chemical equilibrium

Thermal Dark Matter: Equilibration

- Thermal DM ⇔ was once in thermodynamic equilibrium with the SM
- **Kinetic equilibrium:** DM and SM have the same temperature *T*.
- **Chemical equilibrium:** number density of DM species of mass m is

$$n_{\rm DM}^{eq} \sim \int \frac{d^3p}{(2\pi)^3} \frac{1}{e^{E/T} \mp 1}\,, \quad \left(E = \sqrt{m^2 + p^2},\ \hbar = c = k_B = 1\right)$$

↓ **Bose-Einstein or Fermi-Dirac**

↓ **Relativistic Energy**

Thermal Dark Matter: Equilibration

- "Thermal" ⇒ DM that was once in thermodynamic equilibrium with the SM
- **Kinetic equilibrium:** DM and SM have the same temperature *T*.
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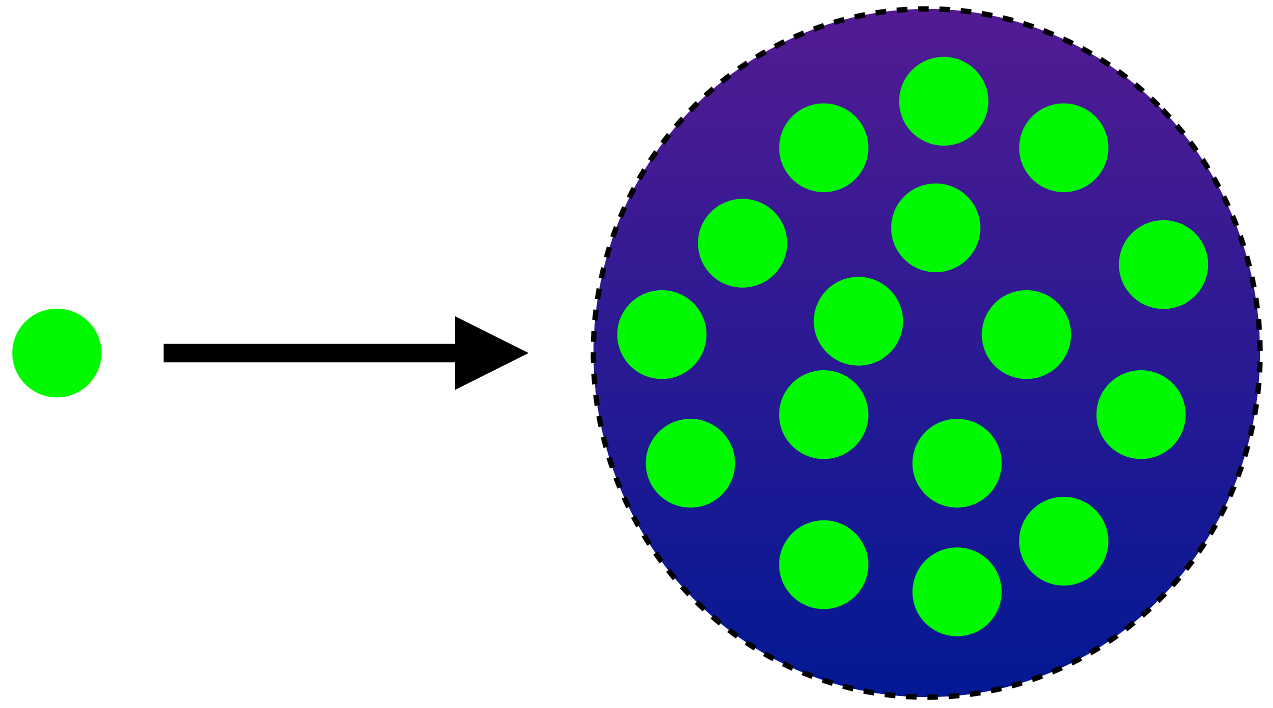
$$\sim \begin{cases} T^3 & ; \quad m \ll T \\ (mT)^{3/2} e^{-m/T} & ; \quad m \gg T \end{cases}$$

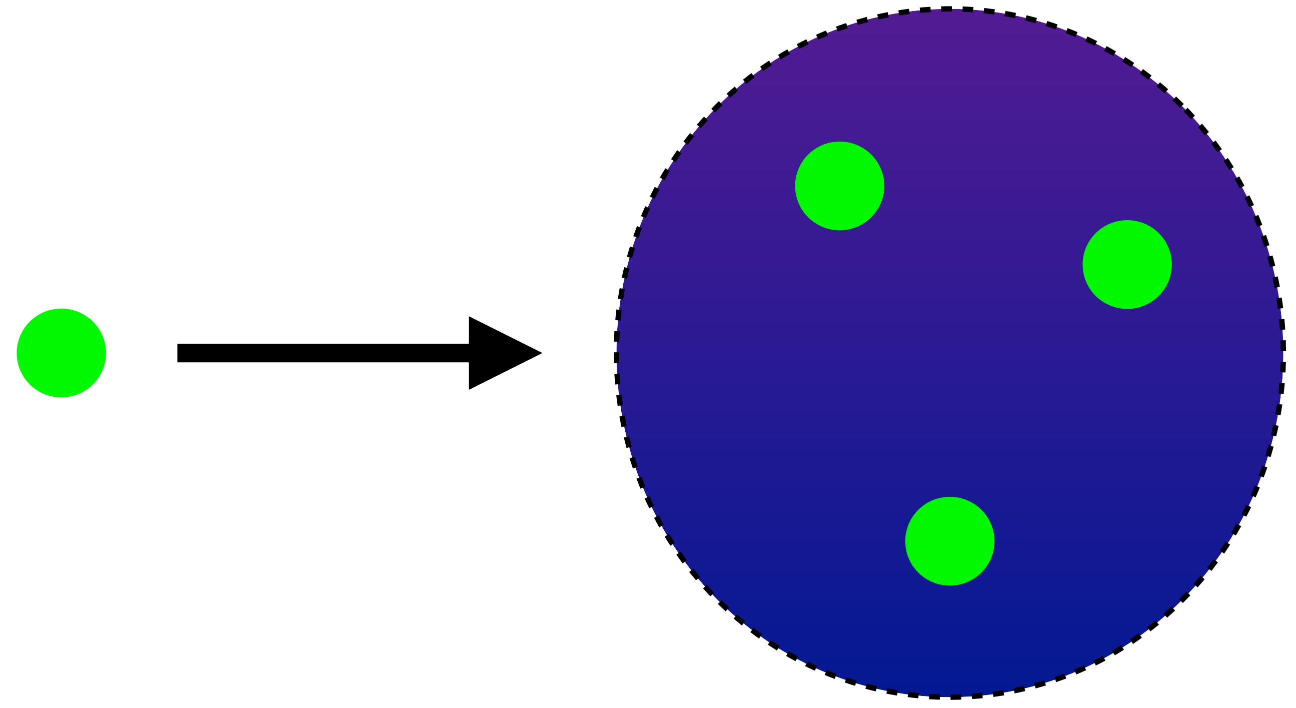
Thermal Dark Matter: Freeze Out

- Chemical equilibrium of DM is lost as the Universe cools.
- Reaction rate for DM annihilation **DM + DM → SM + SM** :

$$R_{ann} = \langle \sigma_{ann} v \rangle \, n_{\mathrm{DM}} \sim$$ **(scattering probability) x (target density)**



$$T \gg m \Rightarrow n_{\mathrm{DM}}/T^3 \sim 1$$

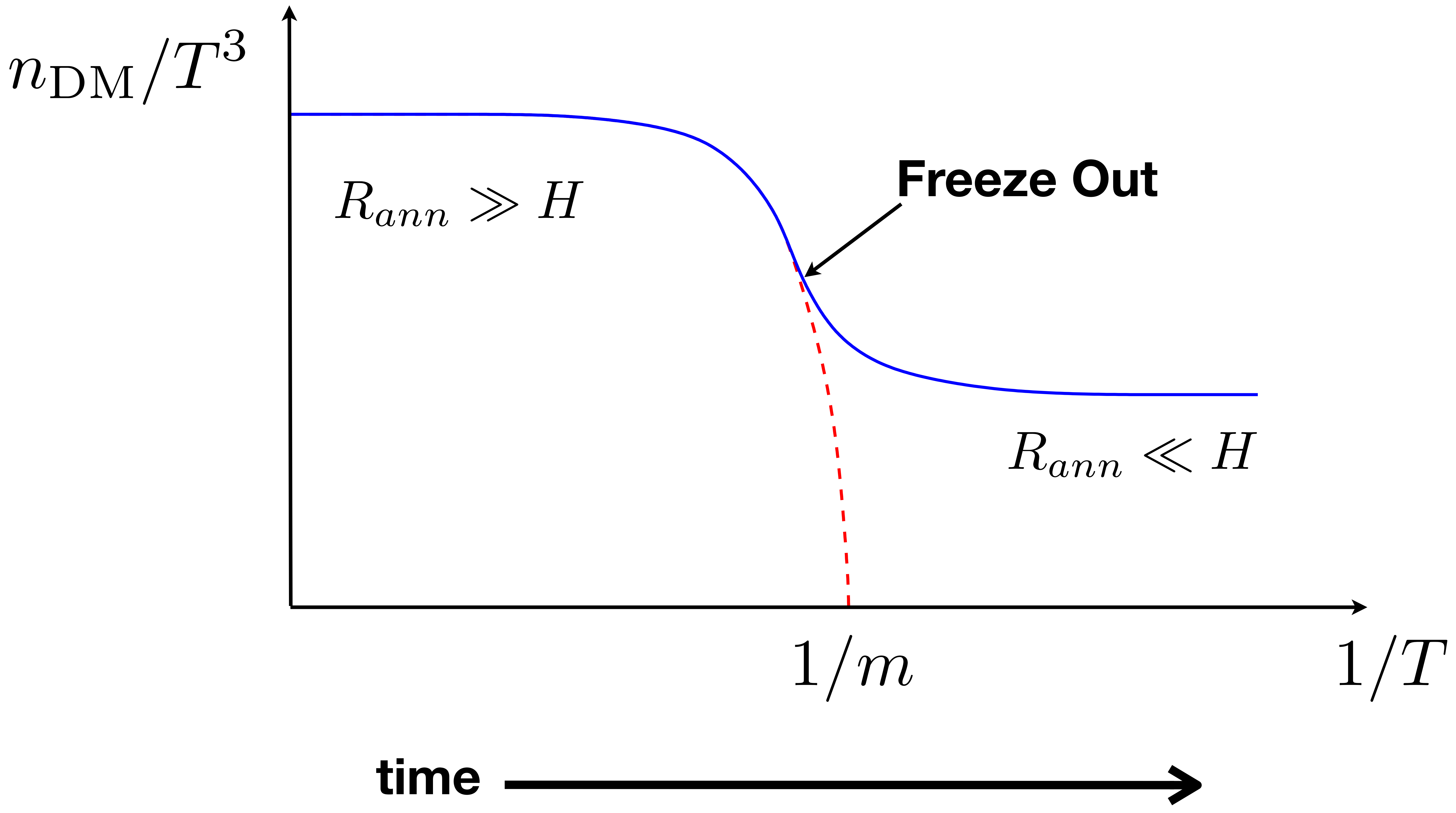


$$T \ll m \Rightarrow n_{\mathrm{DM}}/T^3 \sim e^{-m/T}$$

- Equilibrium requires $R_{ann} > H \simeq 1/\tau_{universe}$

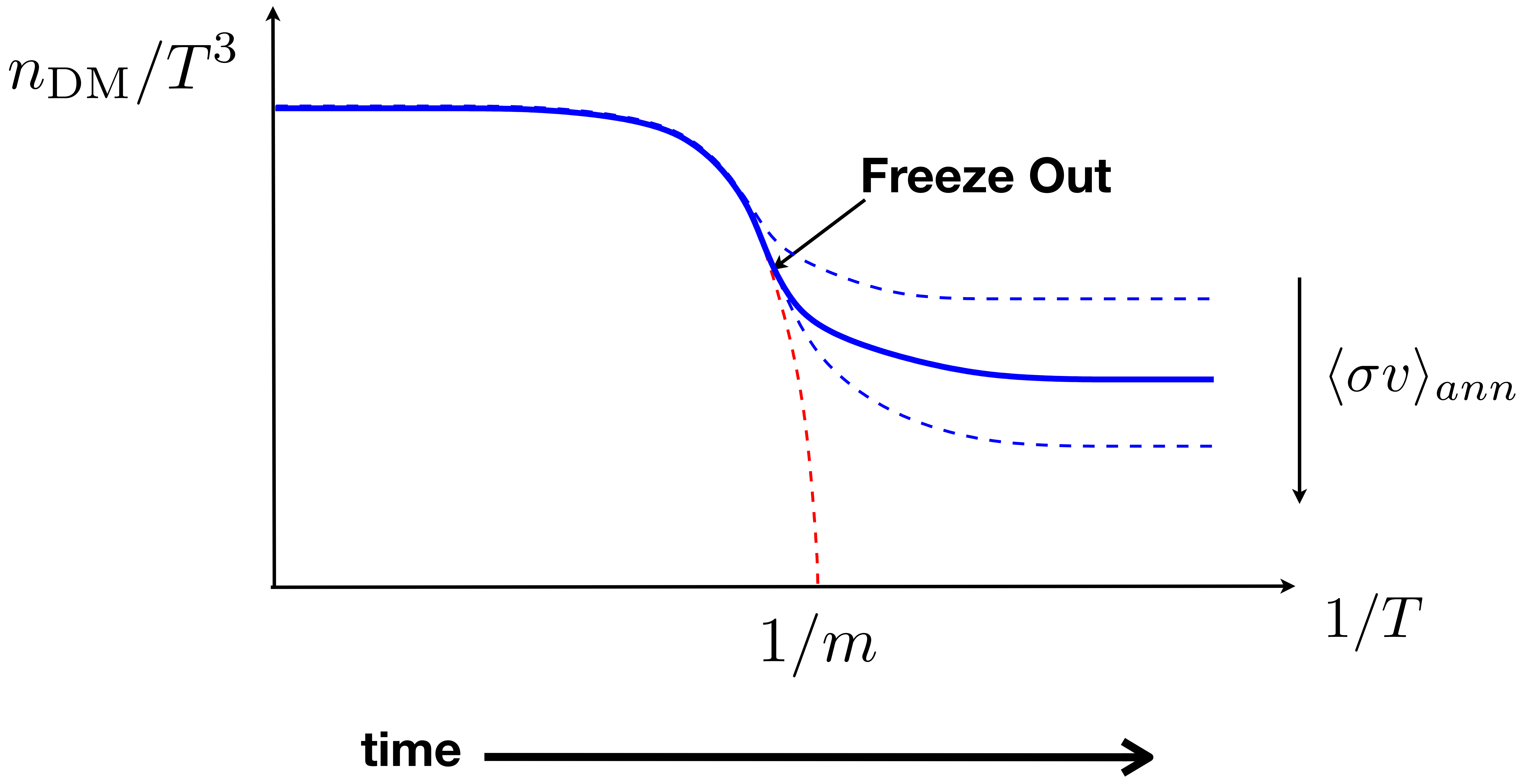
Thermal Dark Matter: Freeze Out

- For moderate DM-SM interaction strength:



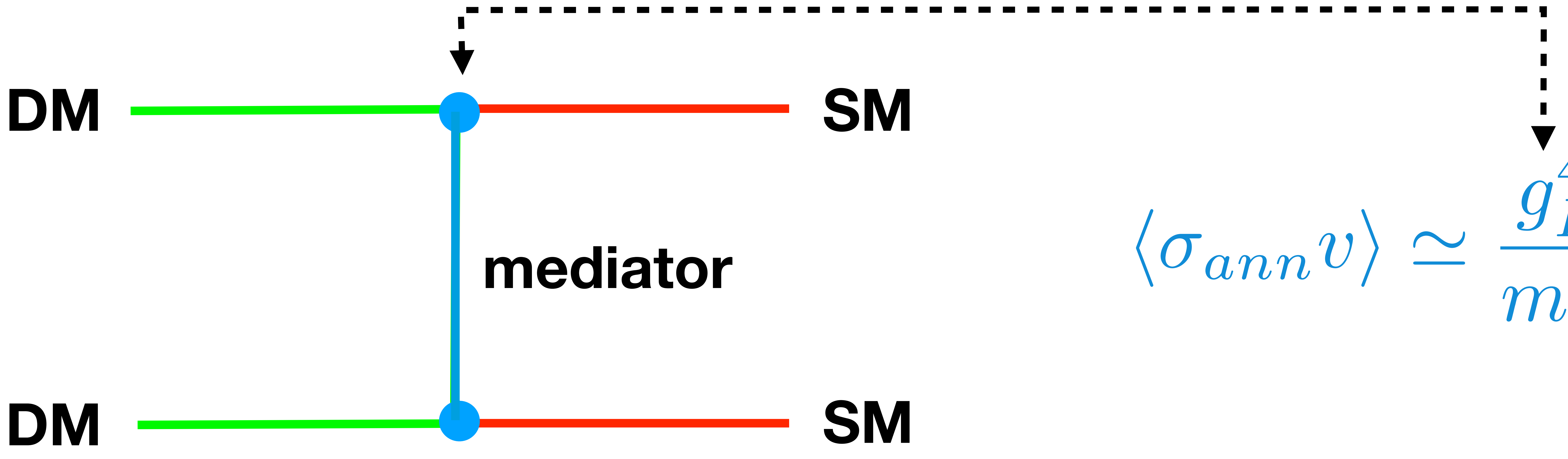
Thermal Dark Matter: Freeze Out

- Dark Matter “relic density from freeze out: $\frac{n_{\rm DM}}{n_{obs}} \simeq \frac{3 \times 10^{-26} {\rm cm}^3/s}{\langle \sigma_{ann} v \rangle}$



Thermal Dark Matter: Freeze Out

- Thermal DM can produce the observed abundance by **Freeze Out**!
- Requirement: $\langle \sigma_{ann} v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3 / s$
- This is determined by particle physics.
  e.g.



$$\langle \sigma_{ann} v \rangle \simeq \frac{g_{DM}^4}{m_{DM}^2}$$

Thermal Dark Matter: WIMPs

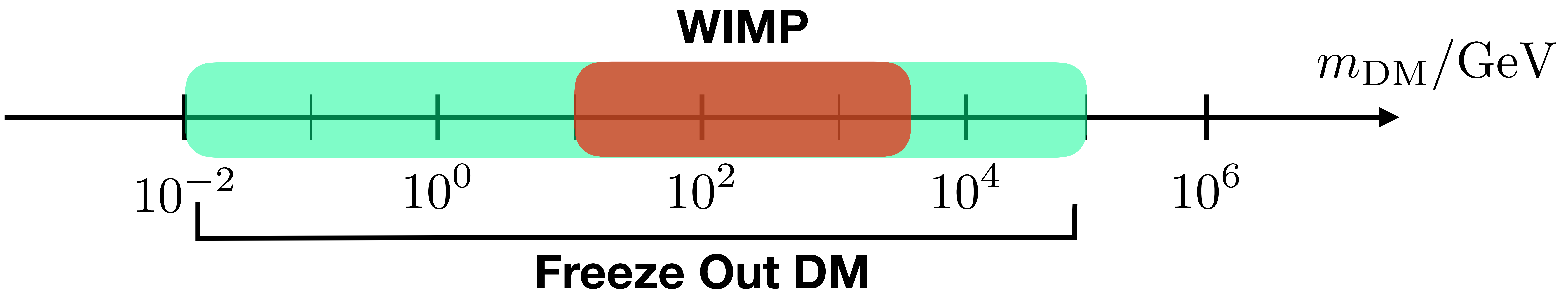
- Special case: **WIMP** = **W**eakly **I**nteracting **M**assive **P**article
  - weak interactions between DM and SM predict $g_{\mathrm{DM}} \sim 0.3$
  - correct freeze out density then follows for $m_{\mathrm{DM}} \sim 100 - 3000\,\mathrm{GeV}$
- New particles in this mass range are motivated by Higgs quantum stability!

⇒ "WIMP Miracle"

- **Some WIMP candidates:**
  - lightest superpartner in supersymmetry (LSP)
  - lightest odd particle in any theory with a new DM parity (LKP, LTP,…)
  - heavier friends of the SM neutrinos

Freeze Out Beyond WIMPS

- Freeze Out works over a wide mass range: $10\,\mathrm{MeV} \lesssim \mathrm{m_{DM}} \lesssim 100\,\mathrm{TeV}$



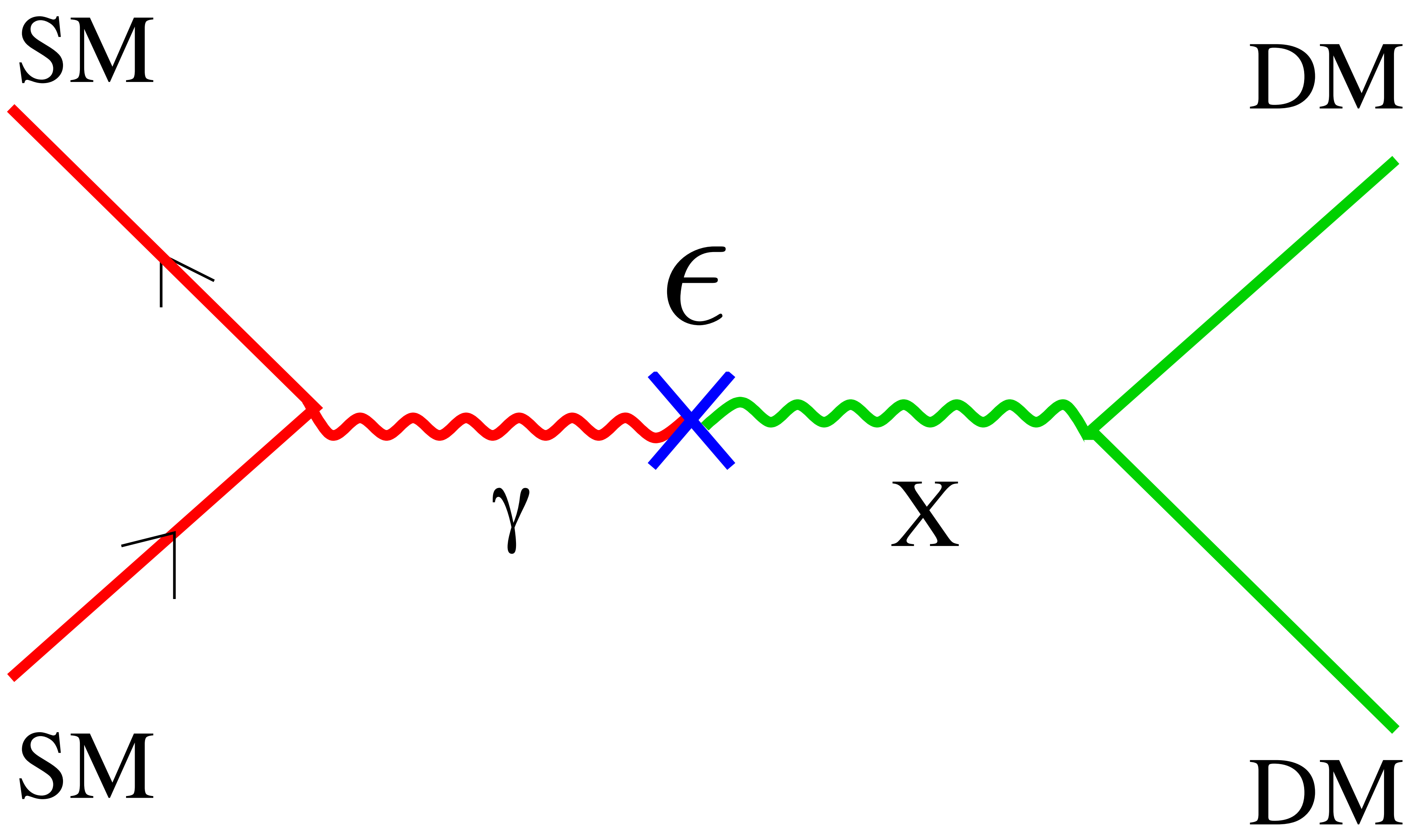
- New forces connecting DM to the SM are needed to get the right freeze out density for masses outside the WIMP range of $m_{\mathrm{DM}} \sim 100 - 3000\,\mathrm{GeV}$.

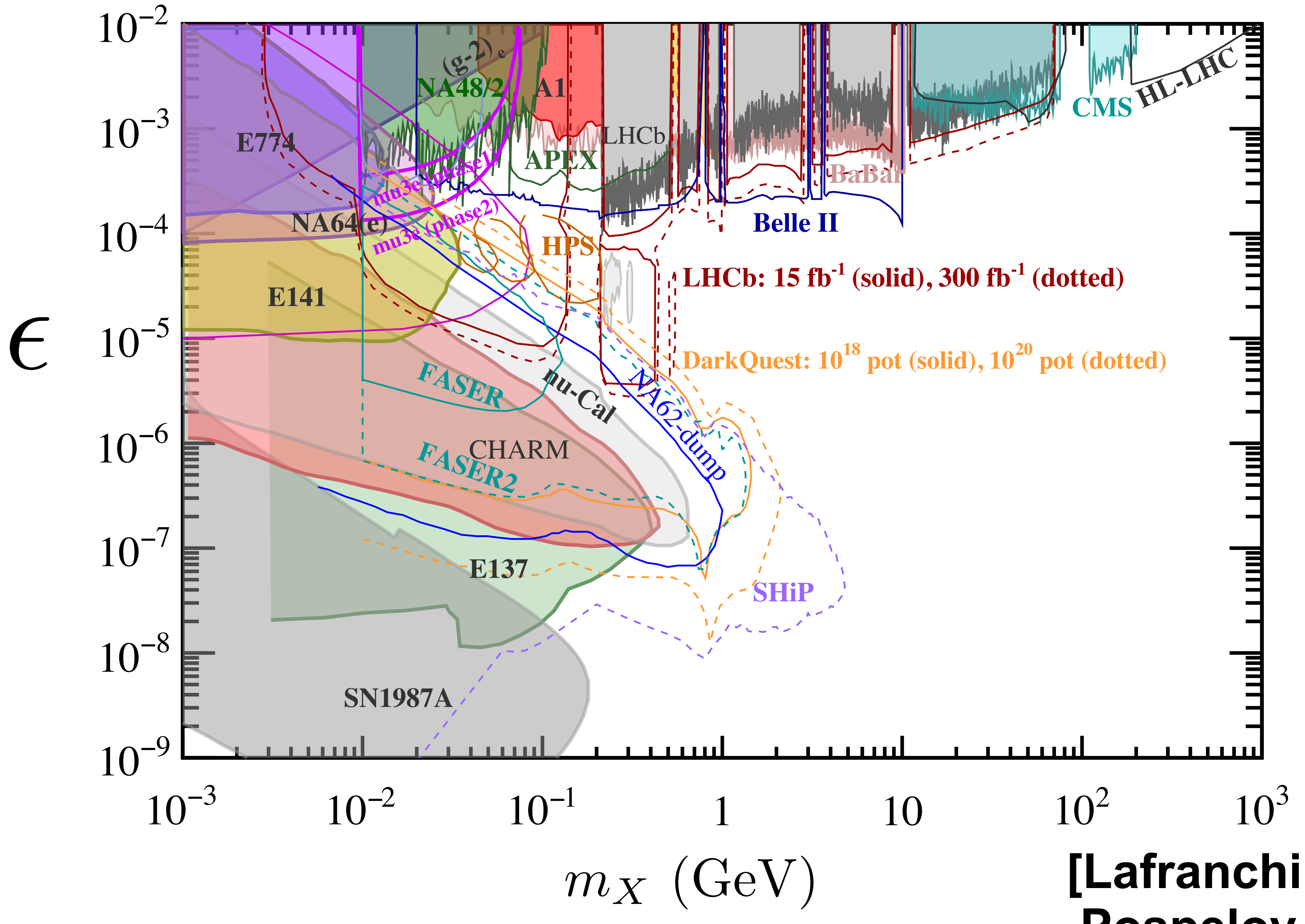
- **Idea:** dark matter might be part of a larger **dark sector**!

Beyond WIMPS: Dark Sectors

- **Idea:** (thermal) dark matter might be part of a larger **dark sector**!

e.g. Dark Matter coupled to a (massive) Dark Photon





[Lafranchi, Pospelov, Schuster 2020]

Beyond Thermal Freeze Out

- **Asymmetric DM:** more DM than anti-DM, nearly all anti-DM annihilates (Analogous to the density of regular matter, but why an asymmetry?)
- **Super-WIMP DM:** a thermal particle freezes out and then decays to DM
- **Self-Heating (Cannibal) DM:** relic density from $3 \to 2$ self-annihilation
- **Freeze-In DM:** DM is never thermalized but created by SM collisions
- …
- All these mechanisms rely on DM interactions with matter beyond gravity!

Dark Matter Detection (Thermal)

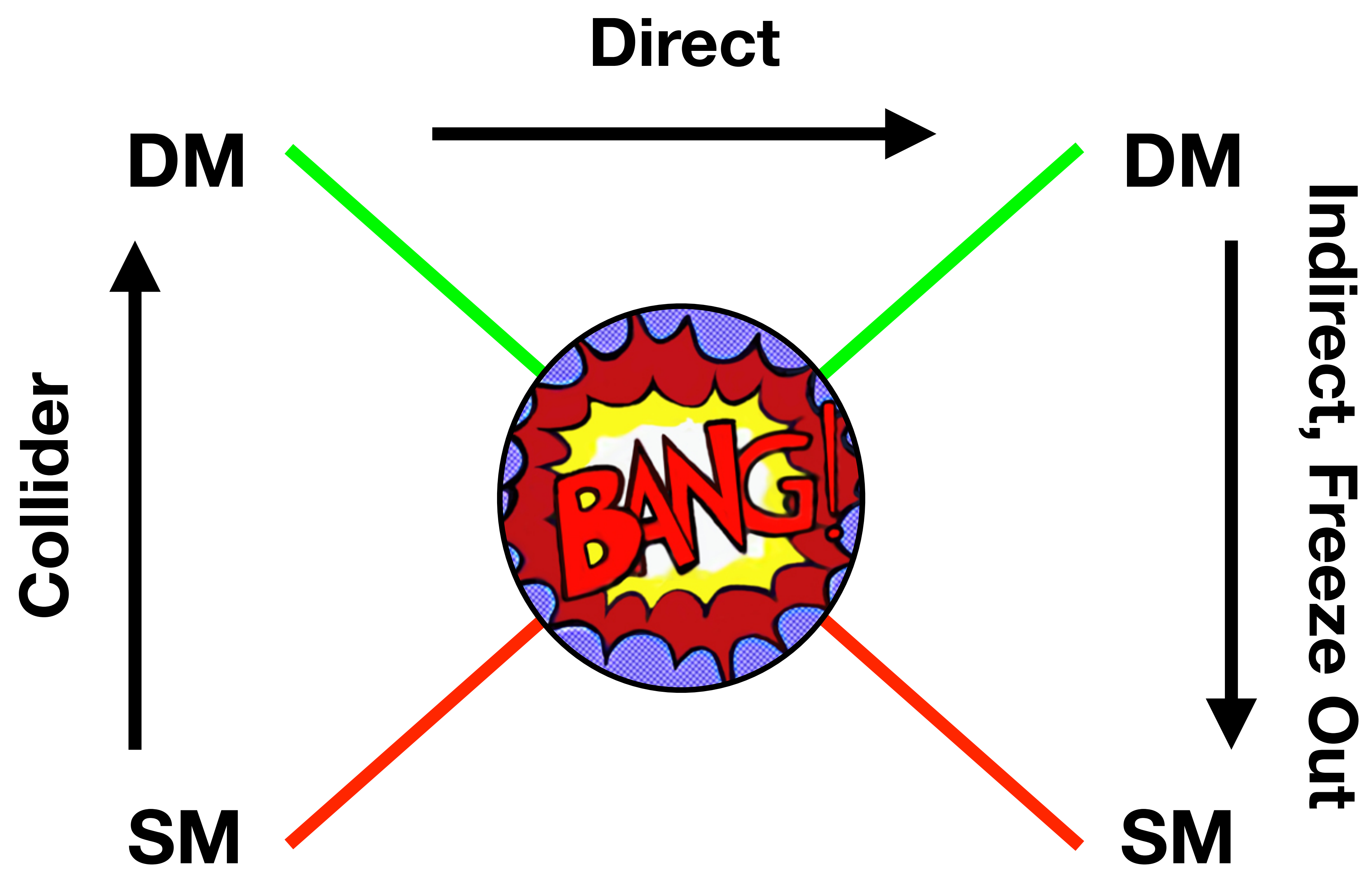
- We want non-gravitational evidence for dark matter!
  This is expected for thermal dark matter.

- Three main approaches:

  1. **Direct Detection**
     → scattering of local DM in detectors

  2. **Indirect Detection**
     → cosmic rays and more from DM

  3. **Colliders**
     → create DM in energetic collisions



"shake it, break it, make it"

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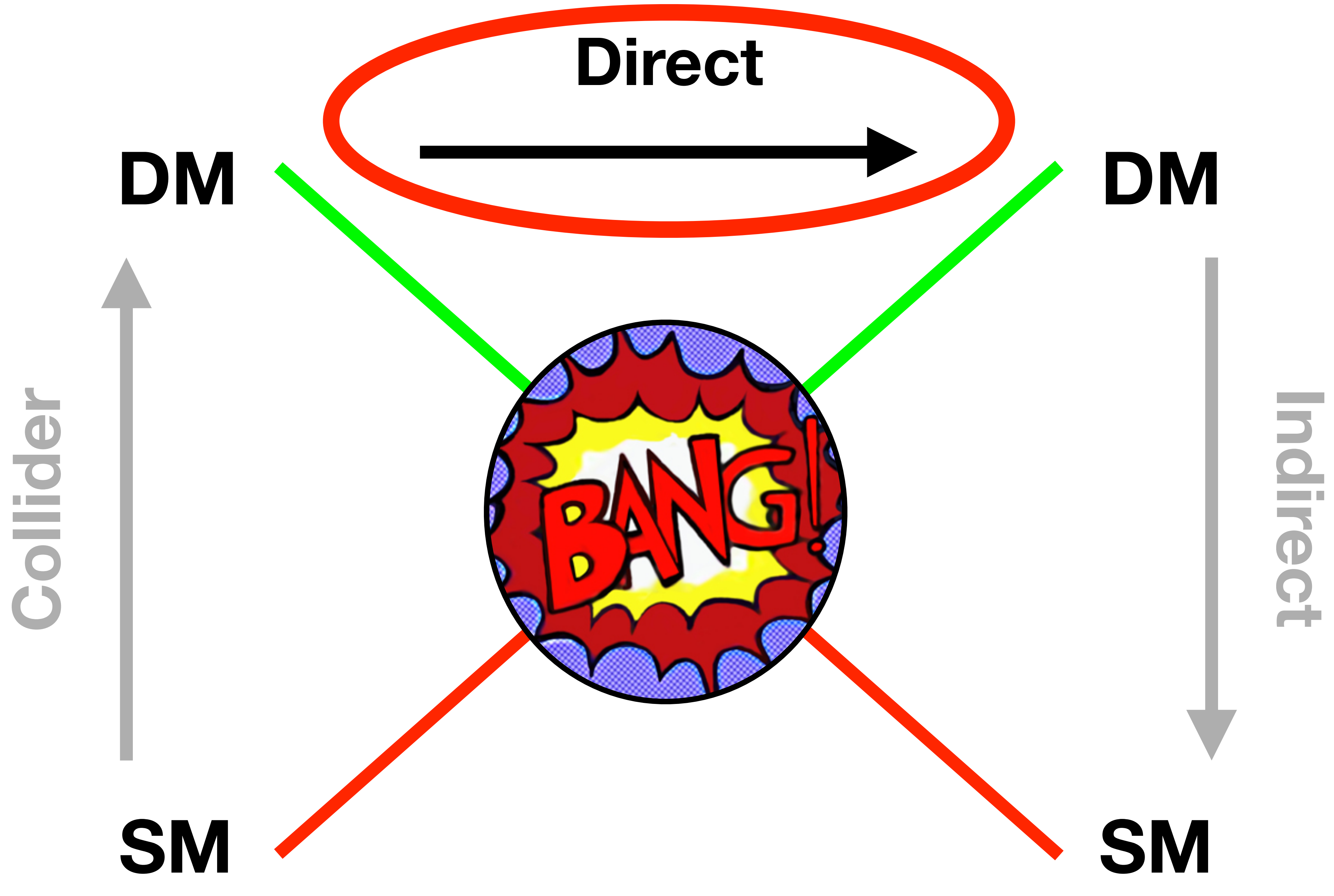

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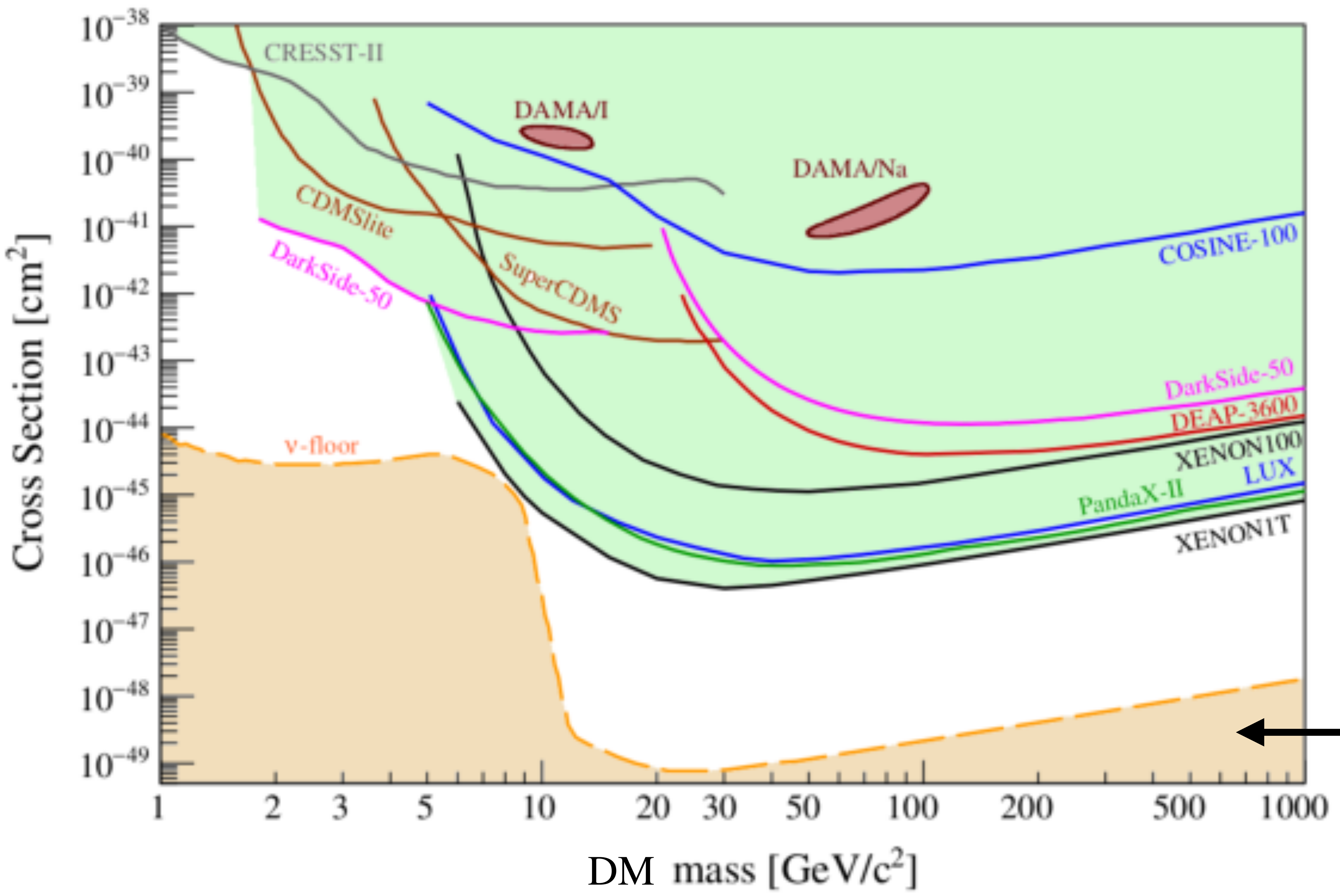
Dark Matter Direct Detection (Thermal)

- Searches for **DM-nuclear** scattering have not seen anything yet.
- For **spin-independent** elastic scattering on nuclei:



neutrino background

[Schumann, 1903.03026]

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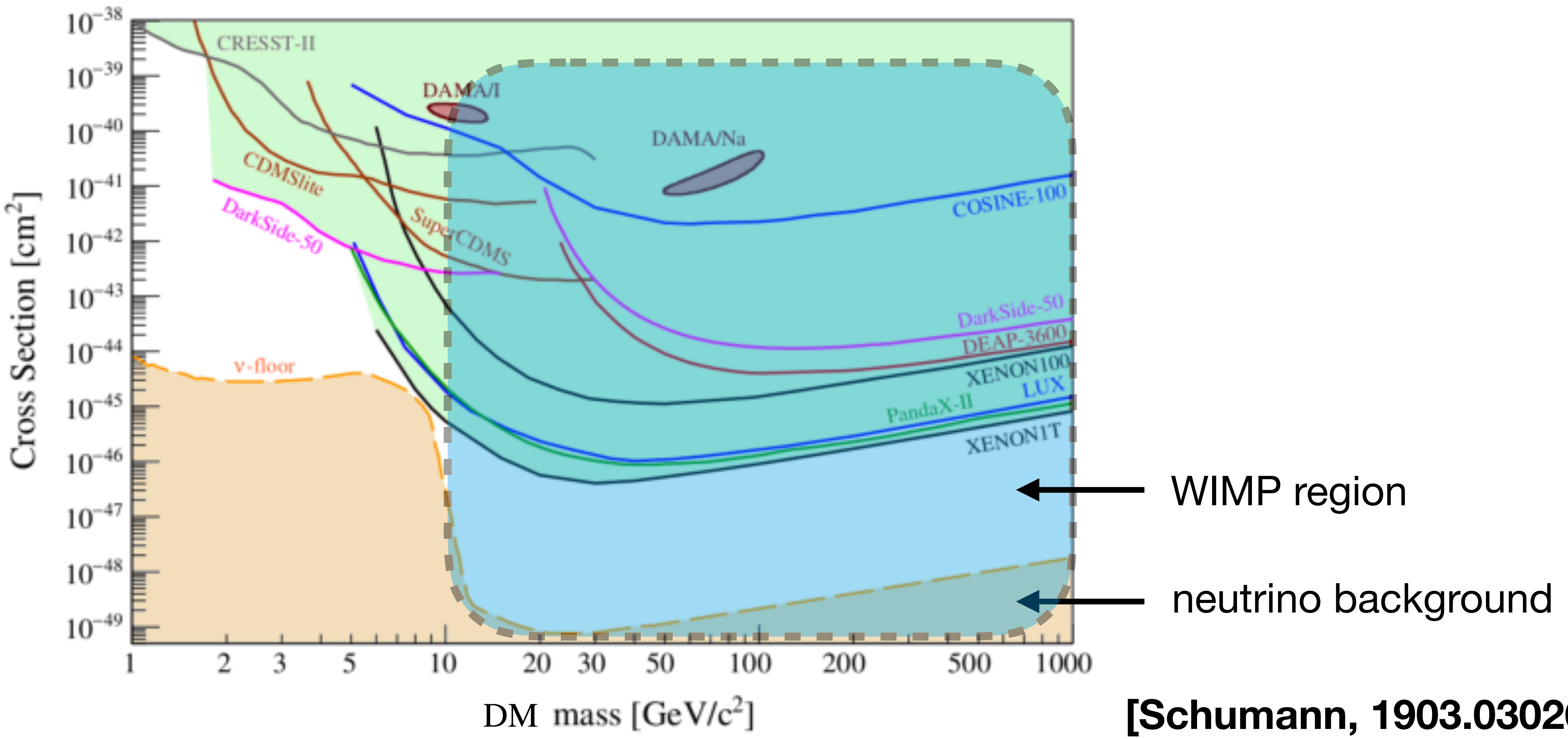

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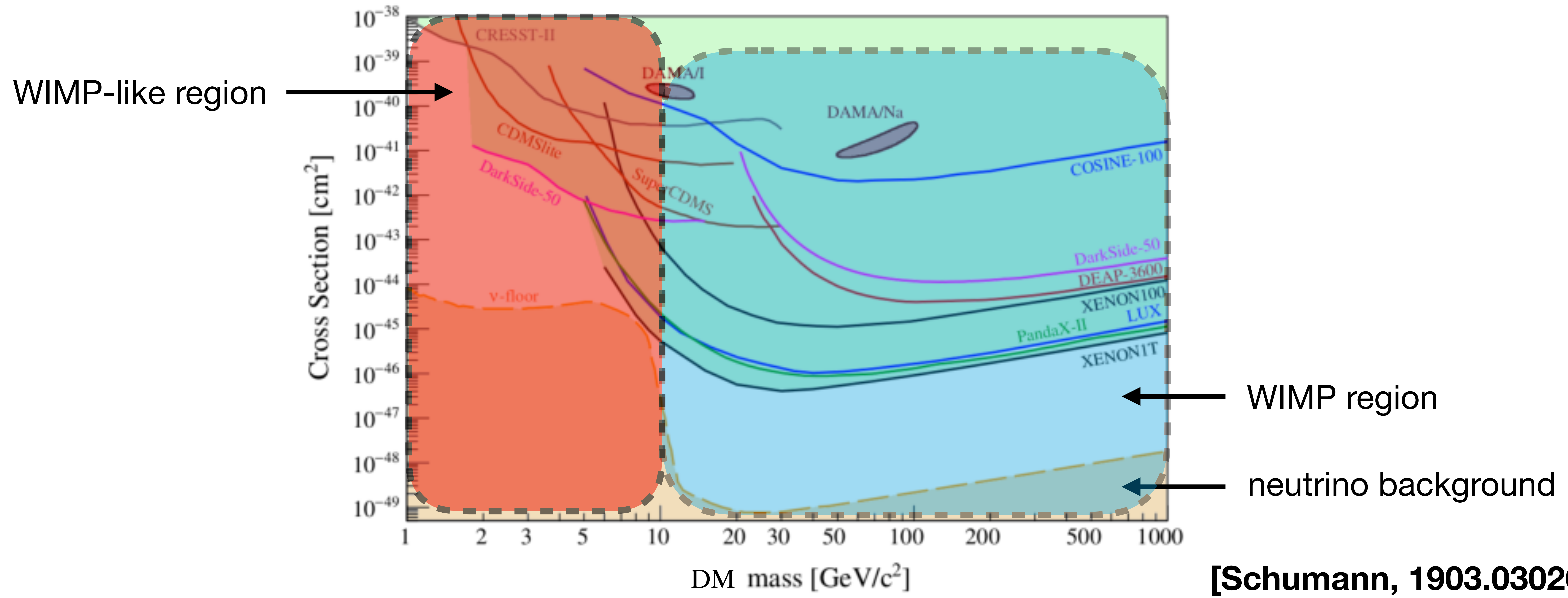
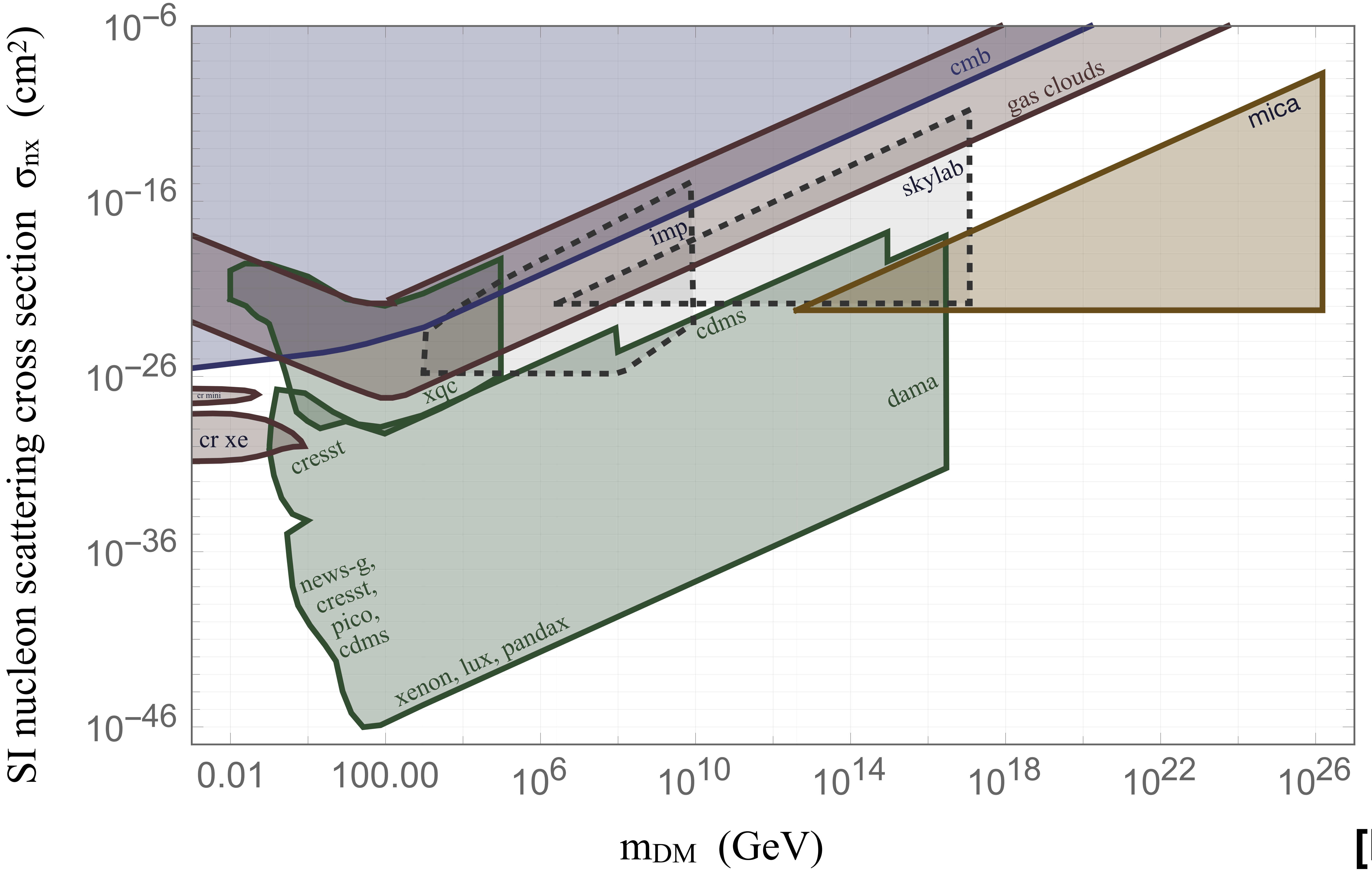


[Schumann, 1903.03026]

Direct Detection Beyond Thermal

- Previous SI bounds zoomed out and compared with other limits:



[Bhoonah *et al.* 2018]

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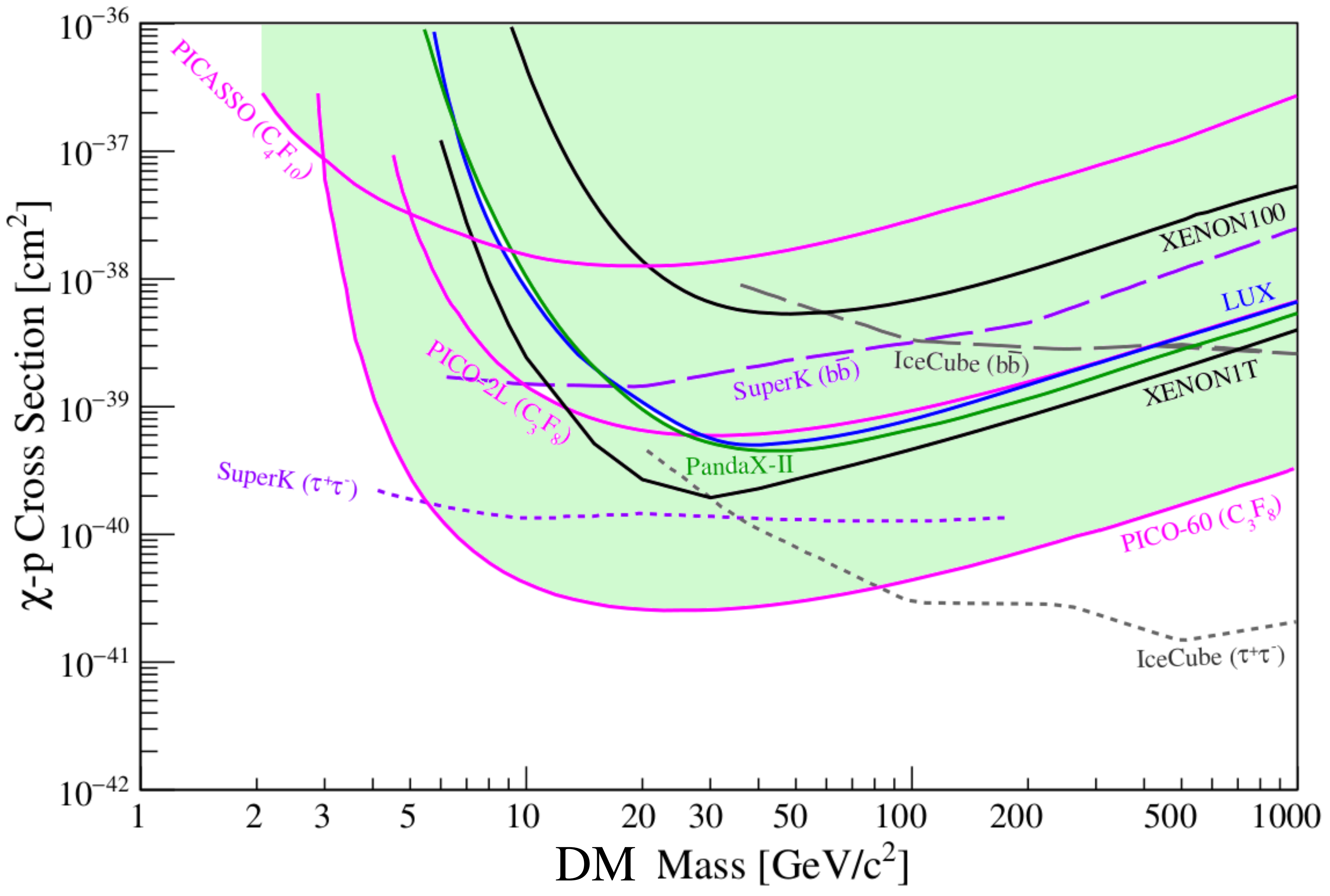

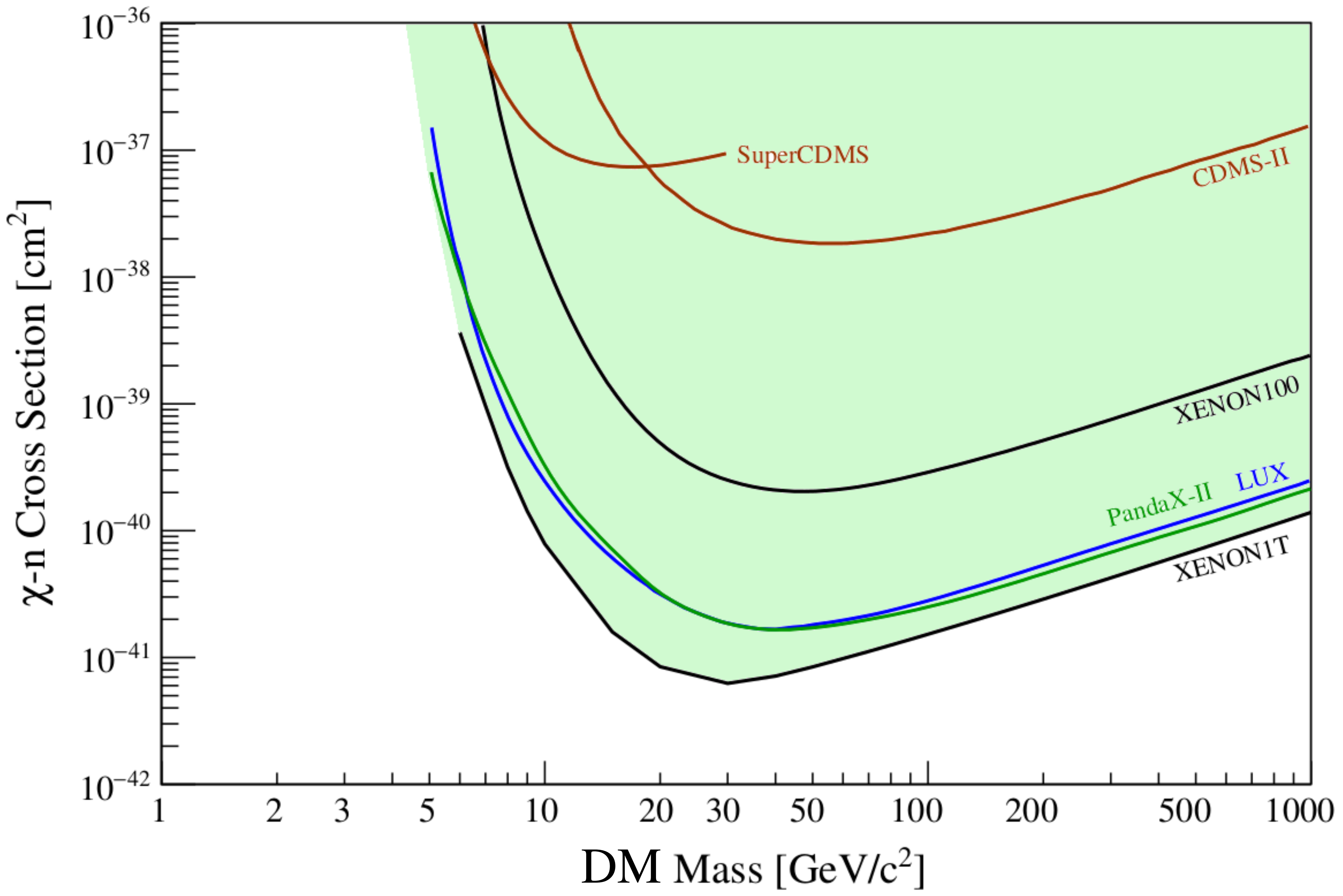

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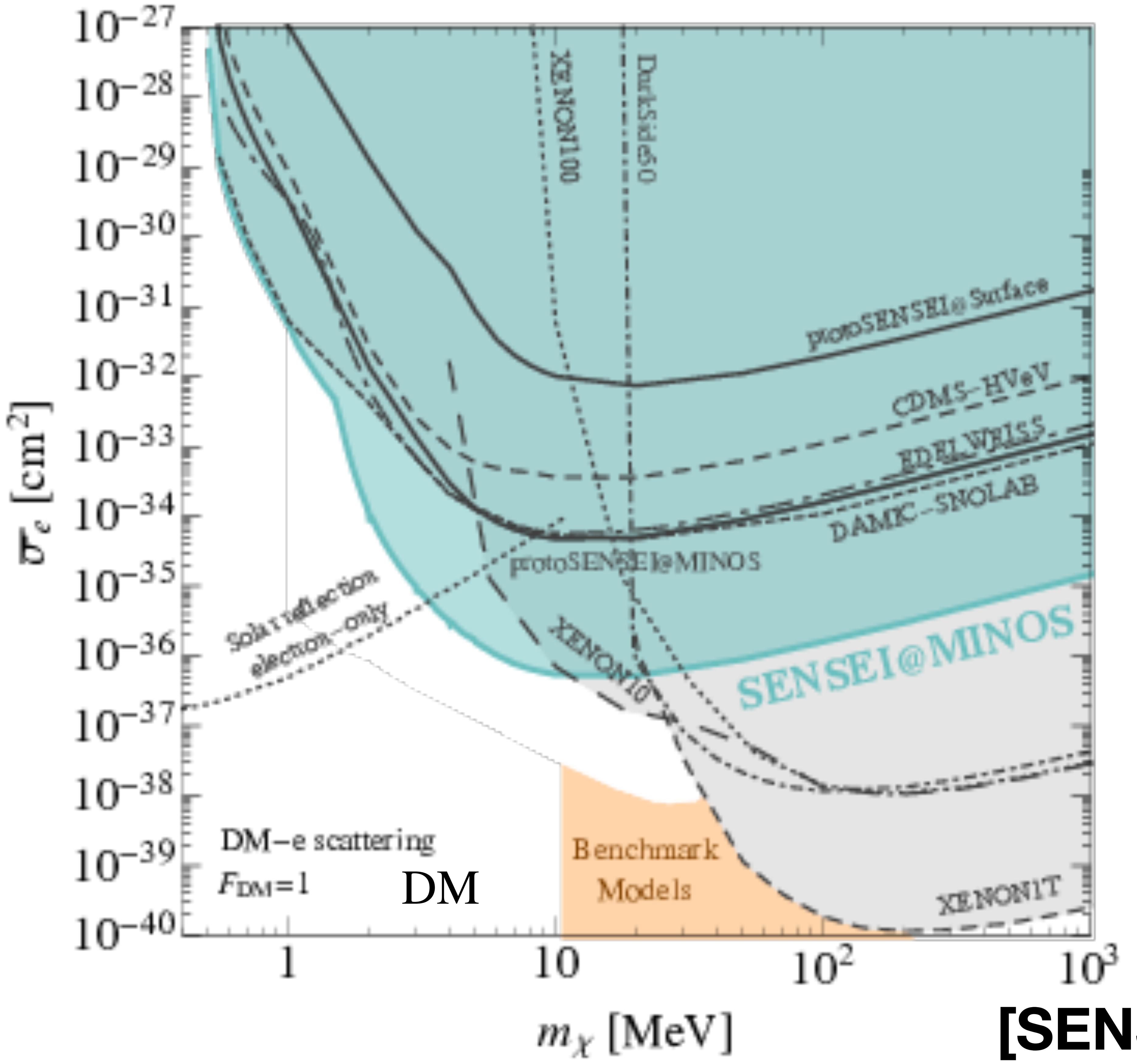
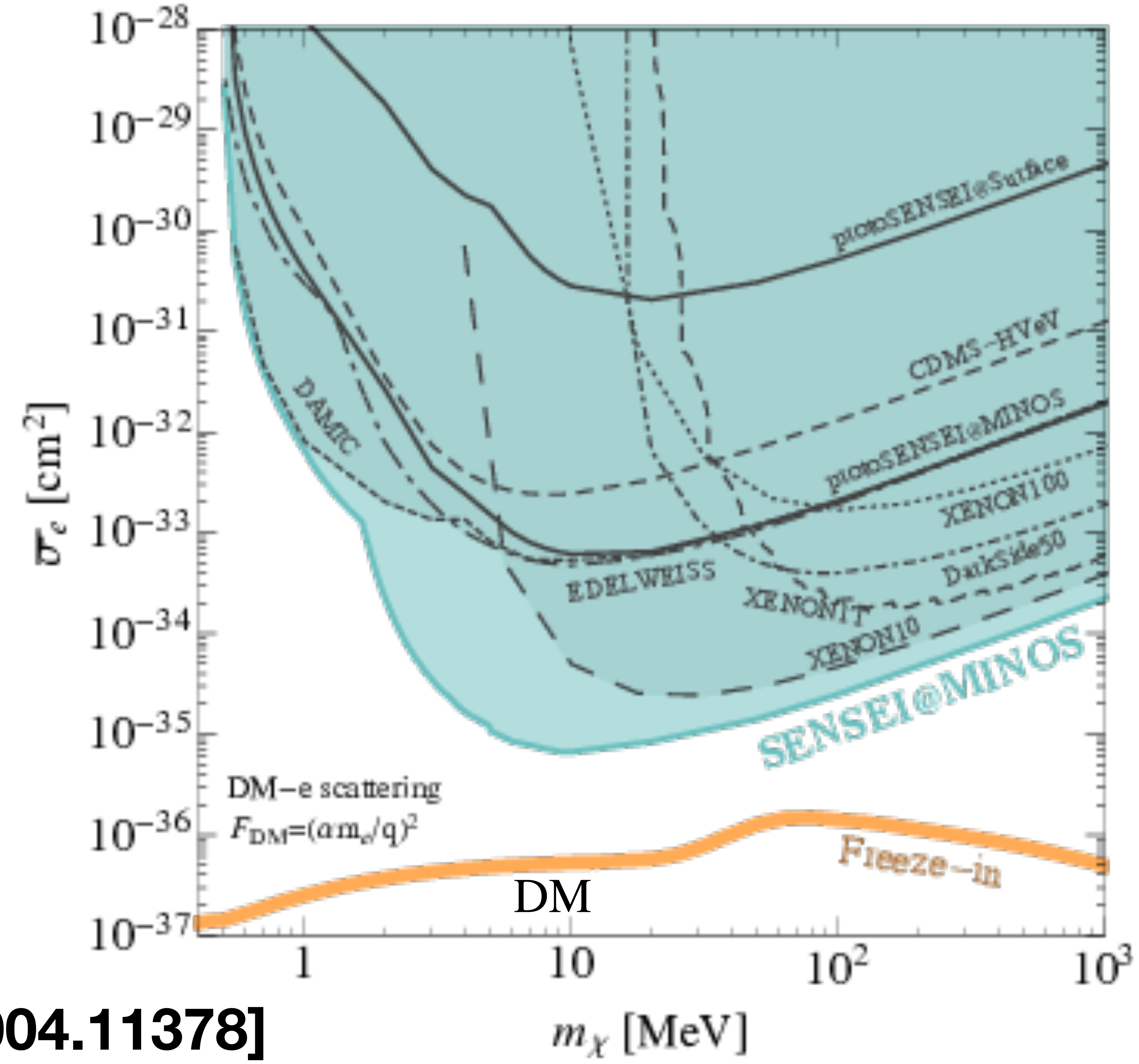
- These are sensitive to lower masses due to kinematics.





[SENSEI, 2004.11378]

Non-Thermal Dark Matter

Non-Thermal Dark Matter

- DM does not have to be thermal - no guarantees!
- Non-thermal usually implies tiny interactions between DM and SM.
- ***e.g.* heavy particle produced with “just so” abundance in inflation**
  → not a very compelling production story
- ***e.g.* primordial black holes (PBHs)**
  → hard to create enough of them, only allowed for $M_{\rm BH} \in [10^{-16}, 10^{-10}]\, M_\odot$
- ***e.g.* axions (QCD axion, axion-like particles = ALPs)**
  → well-motivated and **potentially detectable**

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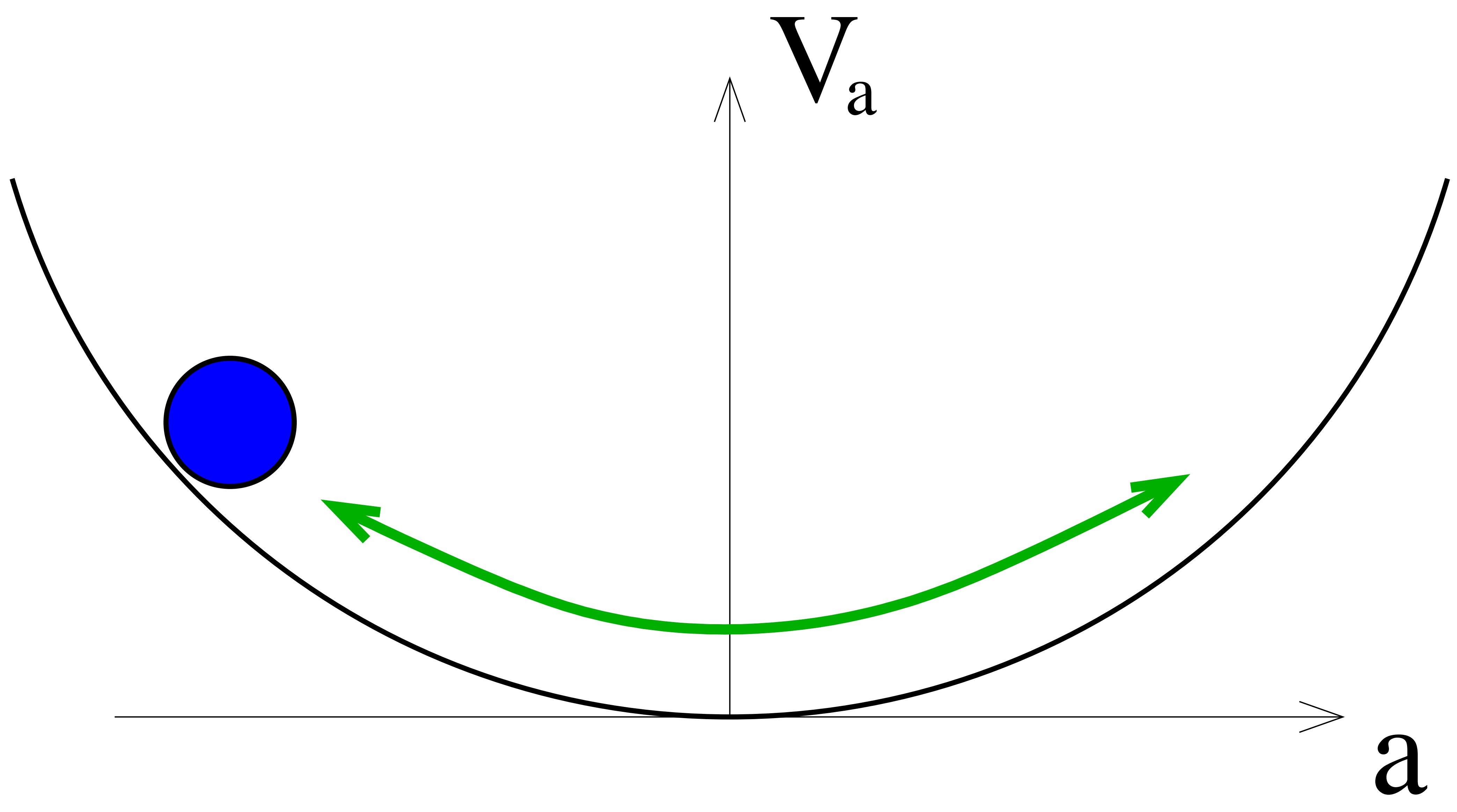
Axion-(Like) Dark Matter

- Axion = pseudoscalar boson associated with approximate symmetry breaking
- Can be DM if they couple very feebly to the SM and are non-thermal!



Axion DM Formation

- axion field is displaced from its minimum a fixed by Hubble expansion
- field starts to oscillate coherently as the expansion slows down $H \lesssim m_a$
- oscillation energy gravitates like matter and acts as DM

⇒ axions are “wave like” dark matter

QCD Axions

- QCD (= strong force) has a problem with too much CP violation.
- Can be solved with a light axion field a that couples to the gluon.

$$\mathcal{L} \supset \frac{\alpha_s}{8\pi} \frac{a}{f_a} G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}$$

- Axion mass and potential come from QCD confinement.

$$m_a \sim \frac{m_\pi f_\pi}{f_a} \sim 1\,\mathrm{eV} \left(\frac{10^7\,\mathrm{GeV}}{f_a} \right)$$

- Realistic axion theories also predict photon and fermion couplings.

$$\mathcal{L} \supset \frac{\alpha}{8\pi} \frac{a}{f_a} C_{a\gamma\gamma}\, F_{\mu\nu} \widetilde{F}^{\mu\nu} + \frac{C_f}{f_a} (\partial_\mu a)\, \bar{f} \gamma^\mu \gamma^5 f$$

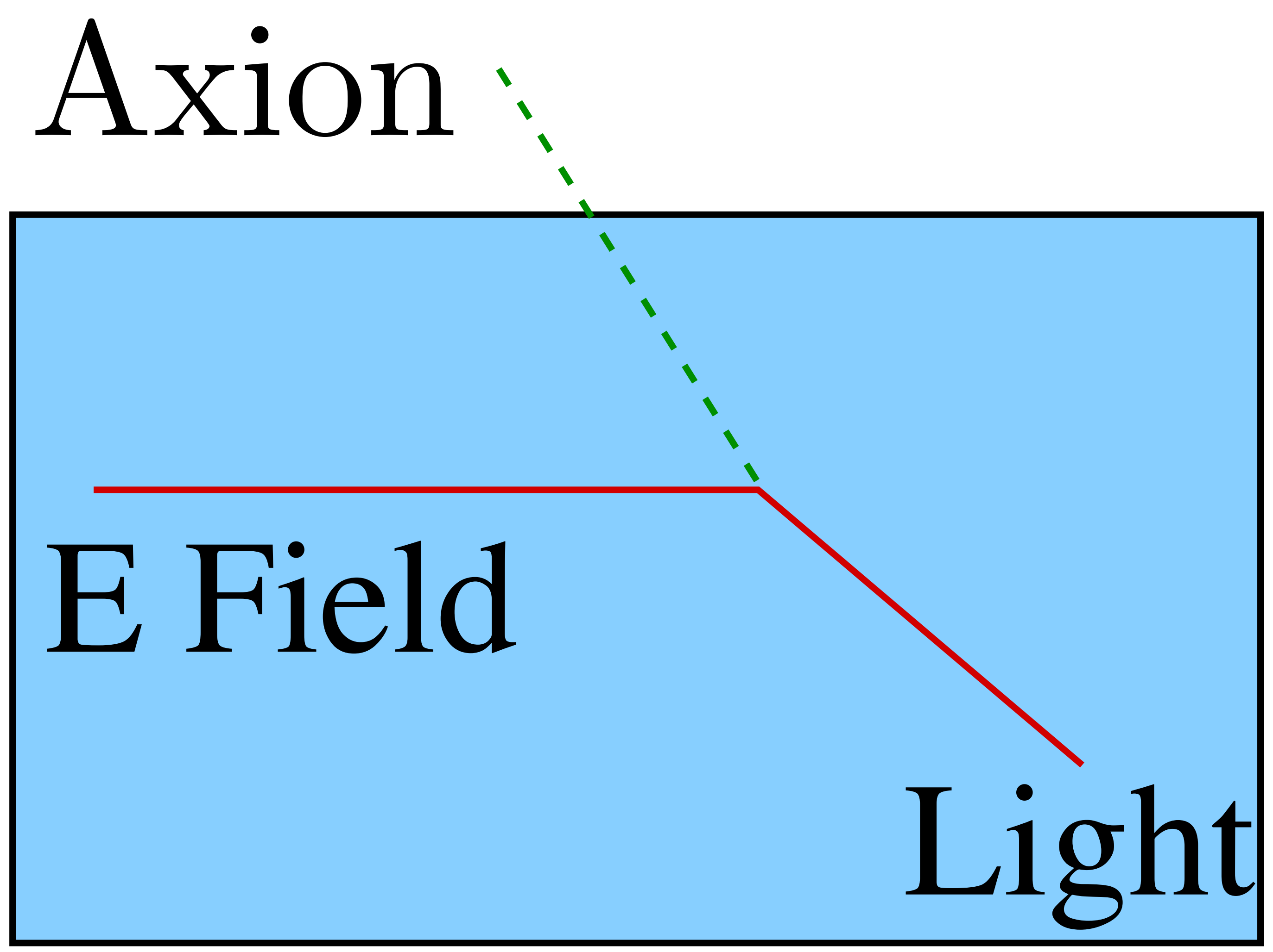
QCD Axion Direct Detection

- Direct detection of axions is very different from WIMP(-like) DM.

- Use the photon coupling!

$$\frac{\alpha}{8\pi}\frac{a}{f_a}C_{a\gamma\gamma}\,F_{\mu\nu}\widetilde{F}^{\mu\nu} \;=\; \frac{\alpha}{8\pi}\frac{a}{f_a}C_{a\gamma\gamma}\,\vec{E}\cdot\vec{B}$$

- Search for axions via conversion within resonant cavities:



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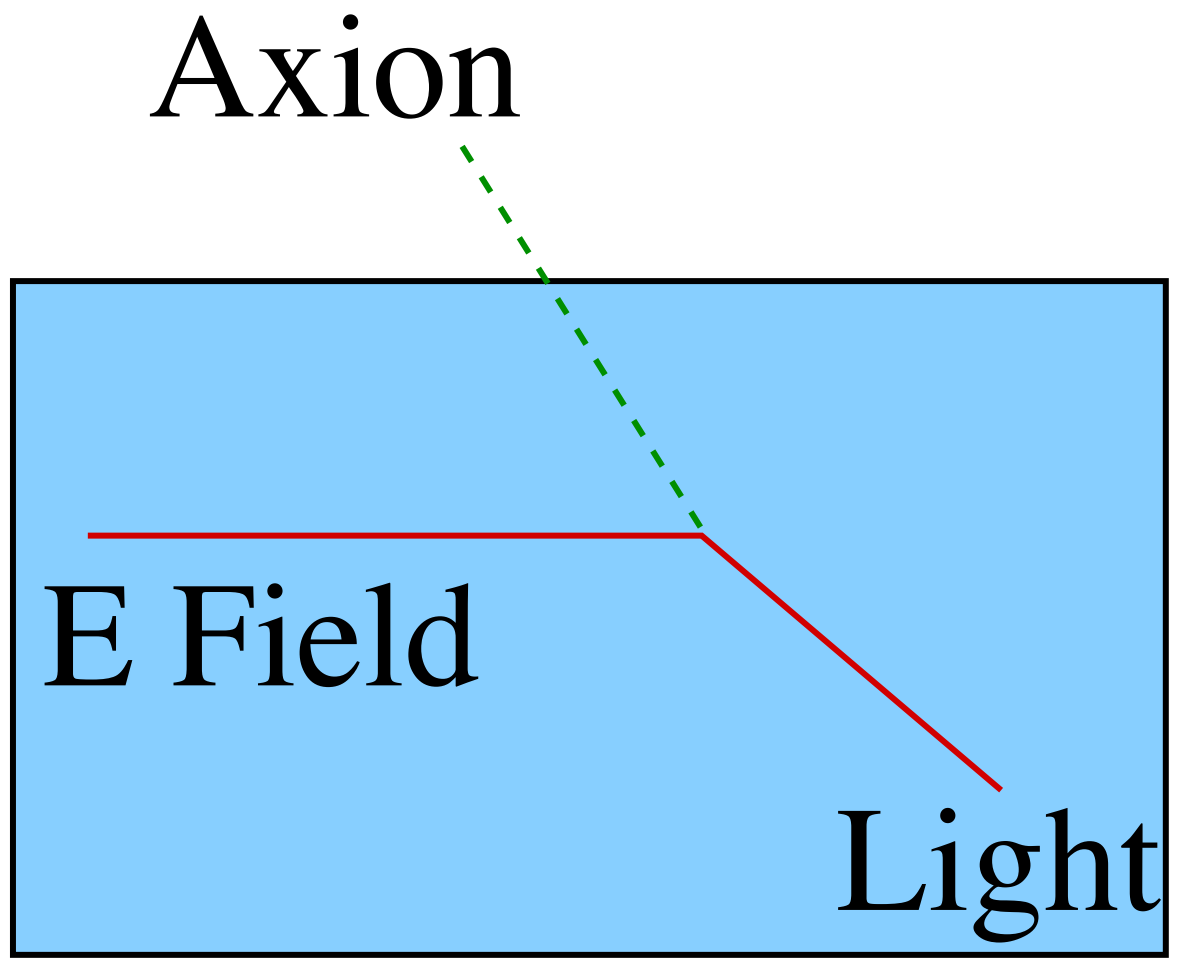

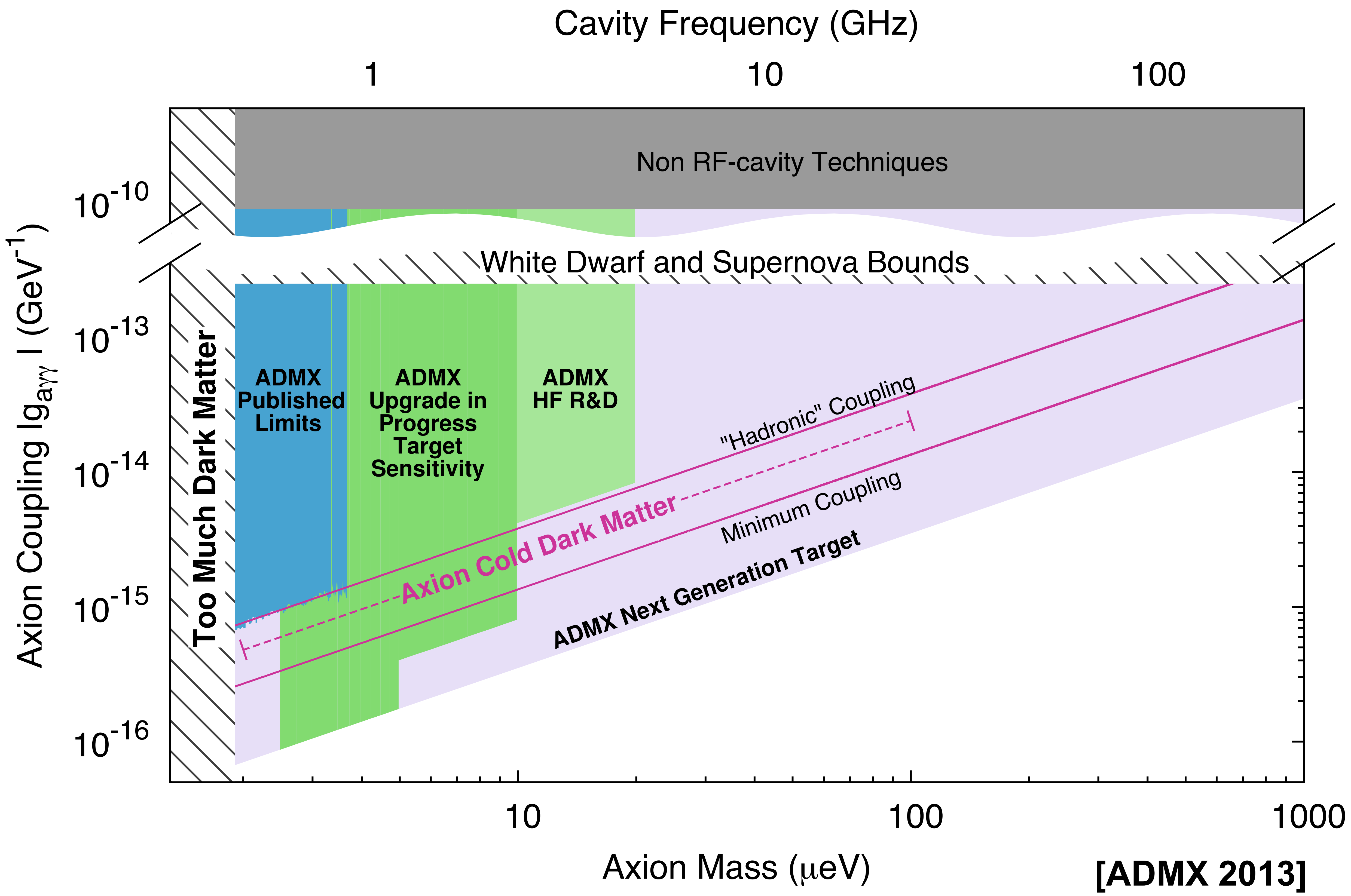

[ADMX 2013]

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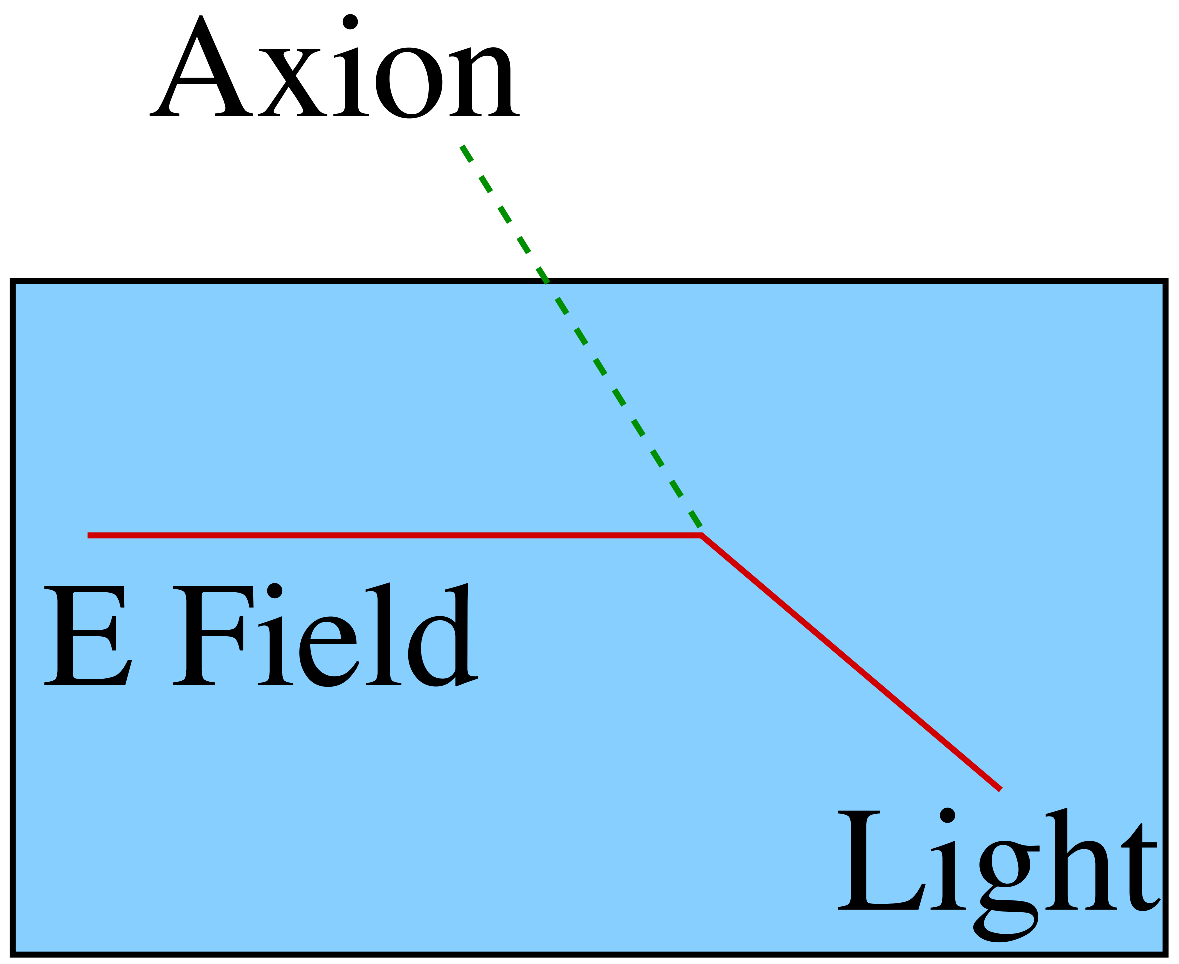
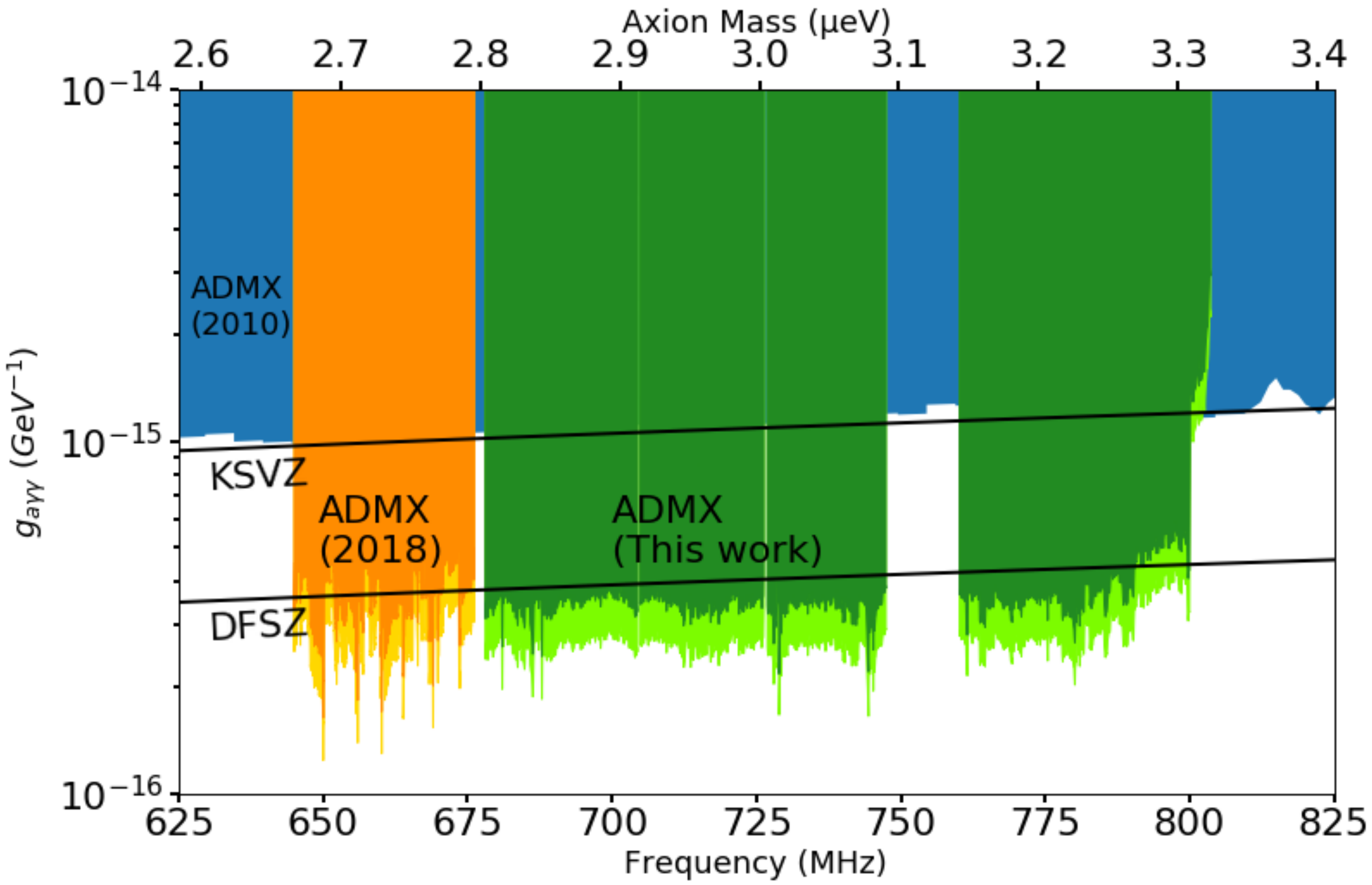
$$\mathcal{L} \supset \frac{\alpha}{8\pi}\frac{a}{f_a} C_{a\gamma\gamma}\, \vec{E}\cdot\vec{B}$$





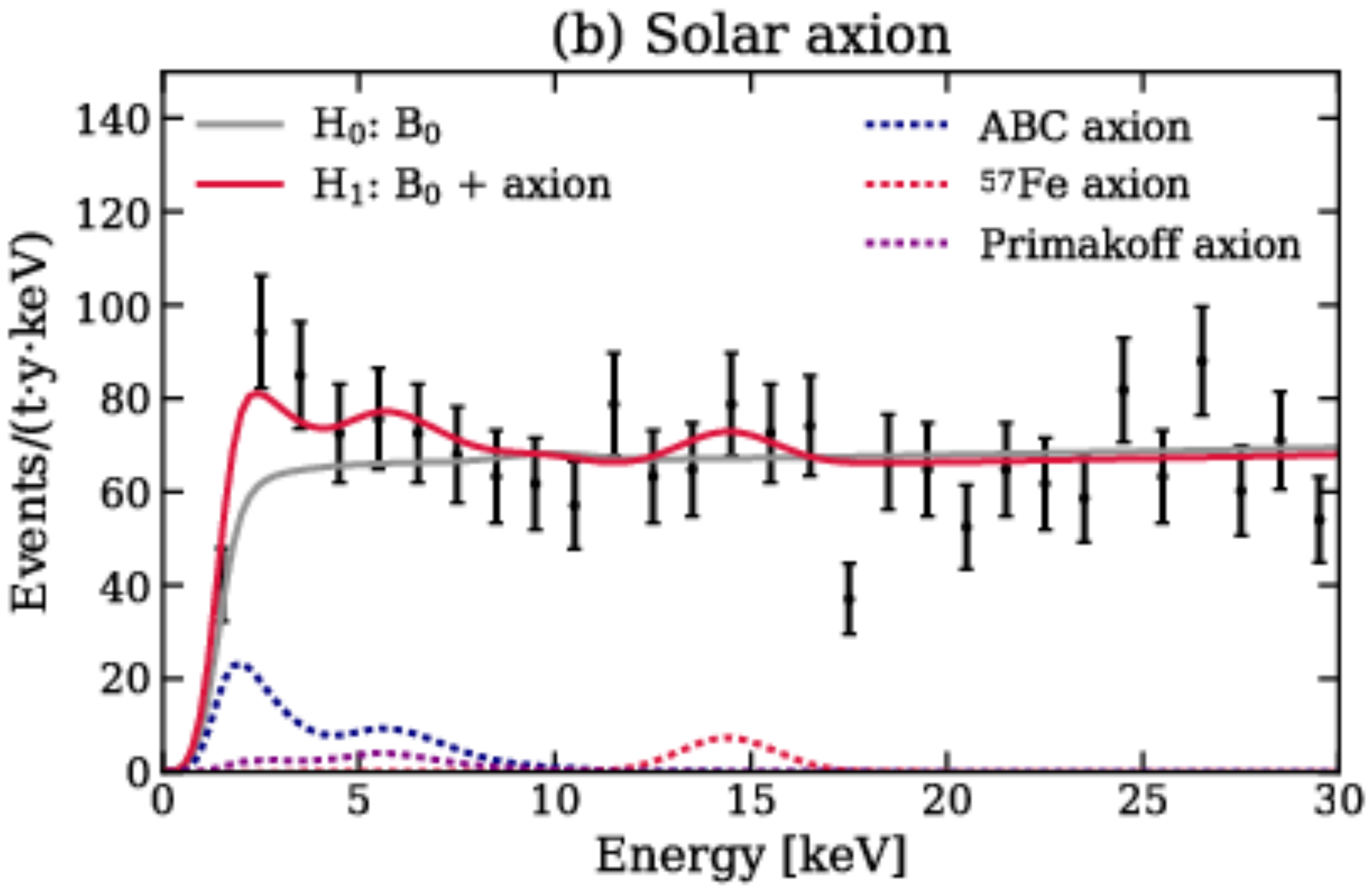
[ADMX 2019]

(QCD) Axion Direct Detection

- Direct searches for WIMP-like DM can also be sensitive to axions!

- Axions can be created in the Sun with $E \sim \mathrm{keV}$ and escape to us. WIMP-like DM searches are sensitive to recoils in this energy range.

- XENON1T even sees an excess in electron recoils with an axion-consistent shape.



[XENON, 2006.09721]

What is Dark Matter

- **We don’t know!**
- Thermal dark matter motivates searches in direct detection, indirect detection, and colliders.
- Non-thermal dark matter may also be detectable in the lab.
- A diverse range of probes are needed to test the many possibilities.
- Discovering Dark Matter would teach us about particle physics as well as the evolution of the very early Universe!

Thank you
Merci

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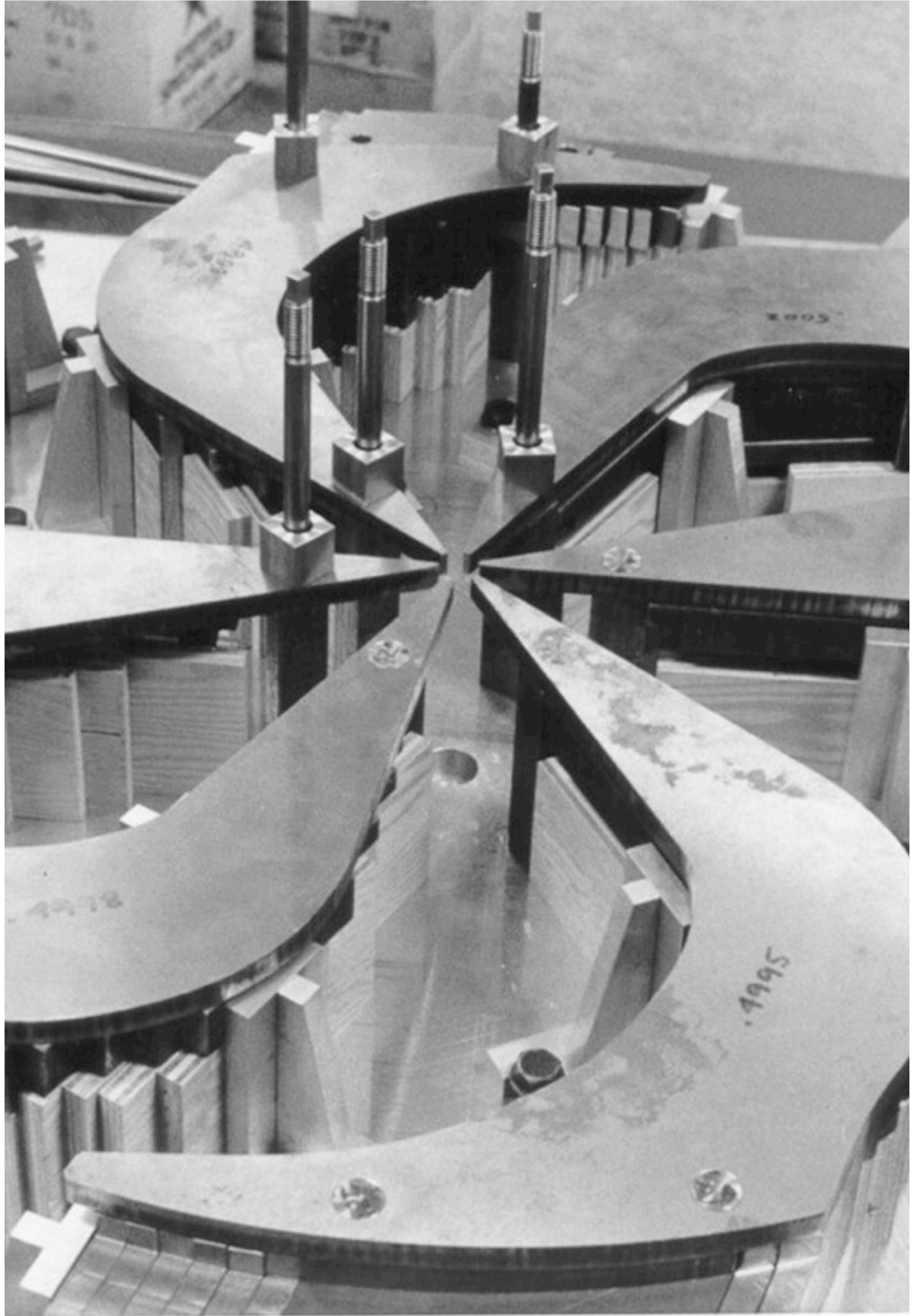
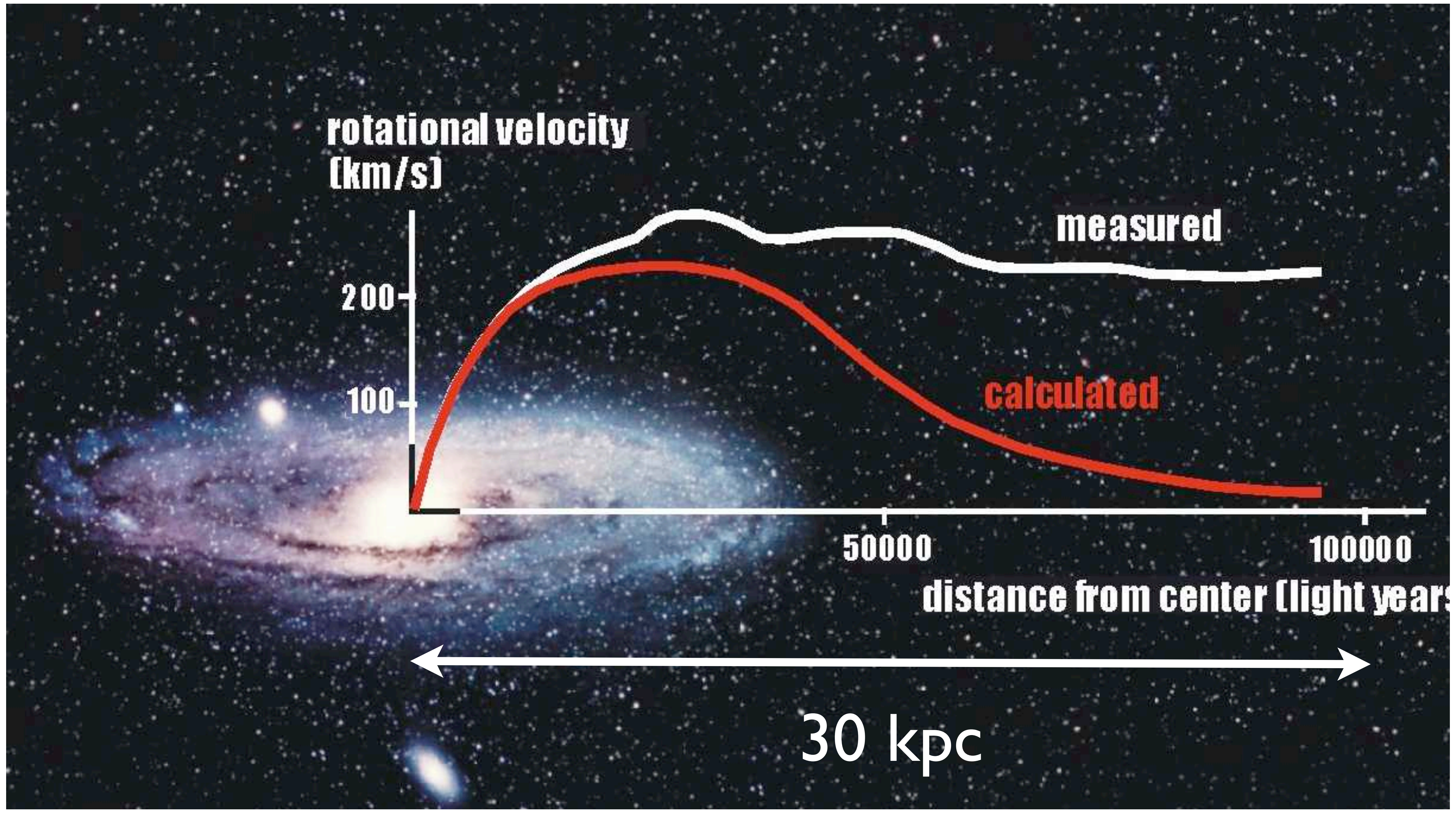


Discovery, accelerated

Extra Slides

DM Evidence #1: Galaxy Rotation

- Many galaxies look like rotating pancakes of stars. Compare rotation velocity to visible matter enclosed:



- More matter is needed! (Vera Rubin 1970)

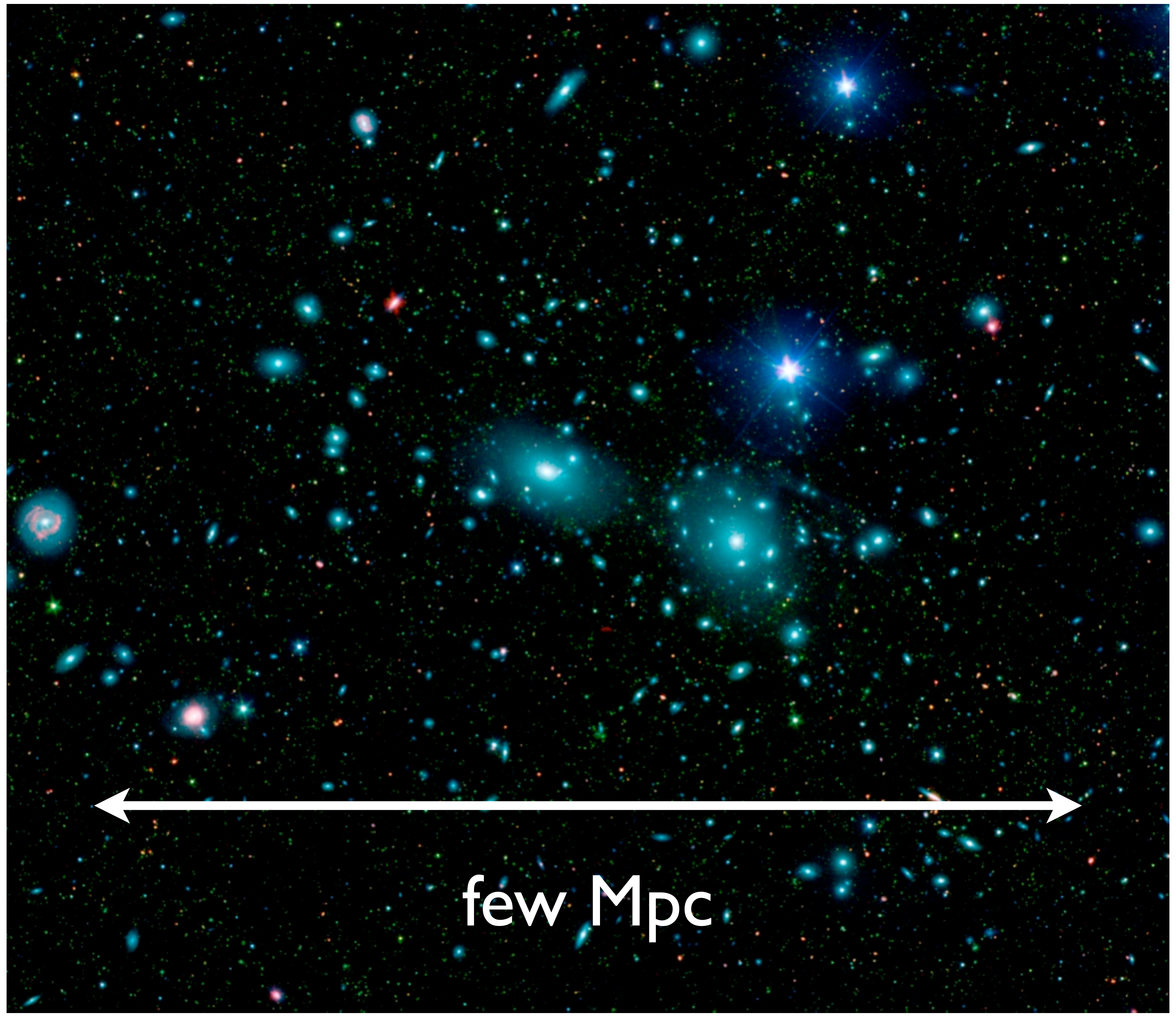
DM Evidence #2: Galaxy Clusters

- Galaxies are often found within self-gravitating galaxy clusters.
- Virial Theorem:

$$\langle E_{kin} \rangle \sim \langle |V| \rangle$$

$$\downarrow$$

$$\langle v_{gal}^2 \rangle \sim \frac{G M_{tot}}{\langle R \rangle}$$

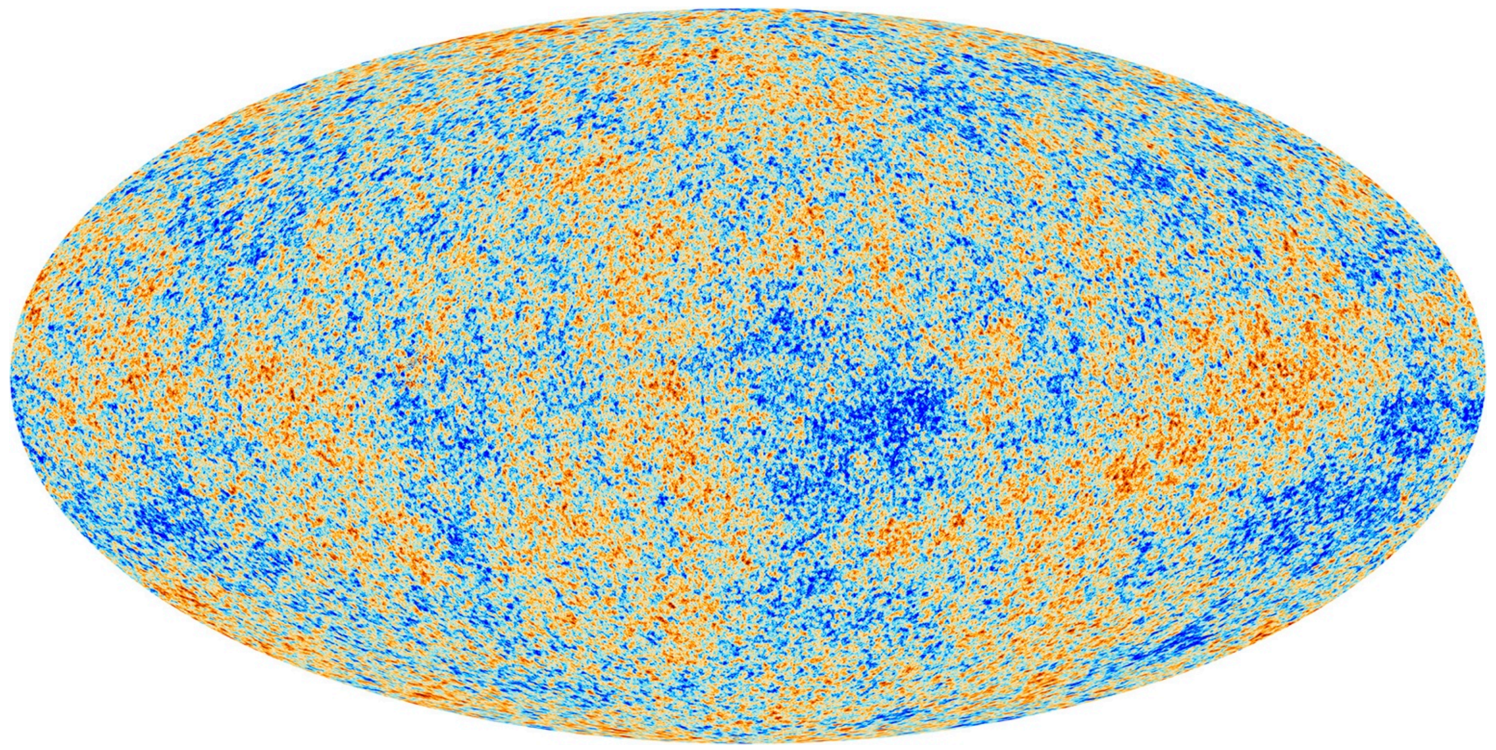


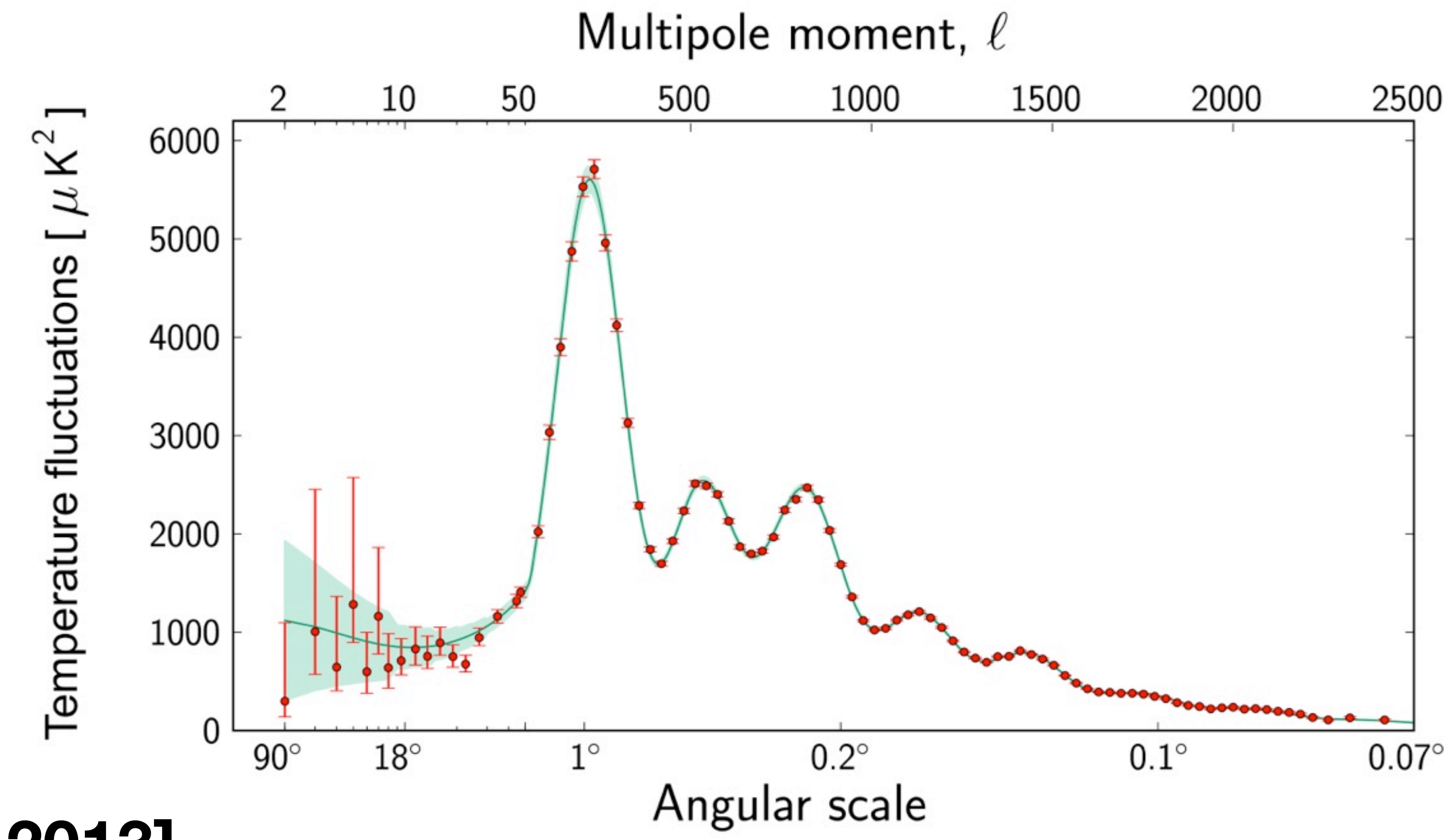
- More mass is needed to explain the observed velocities! (Fritz Zwicky 1933)

DM Evidence #3: CMB

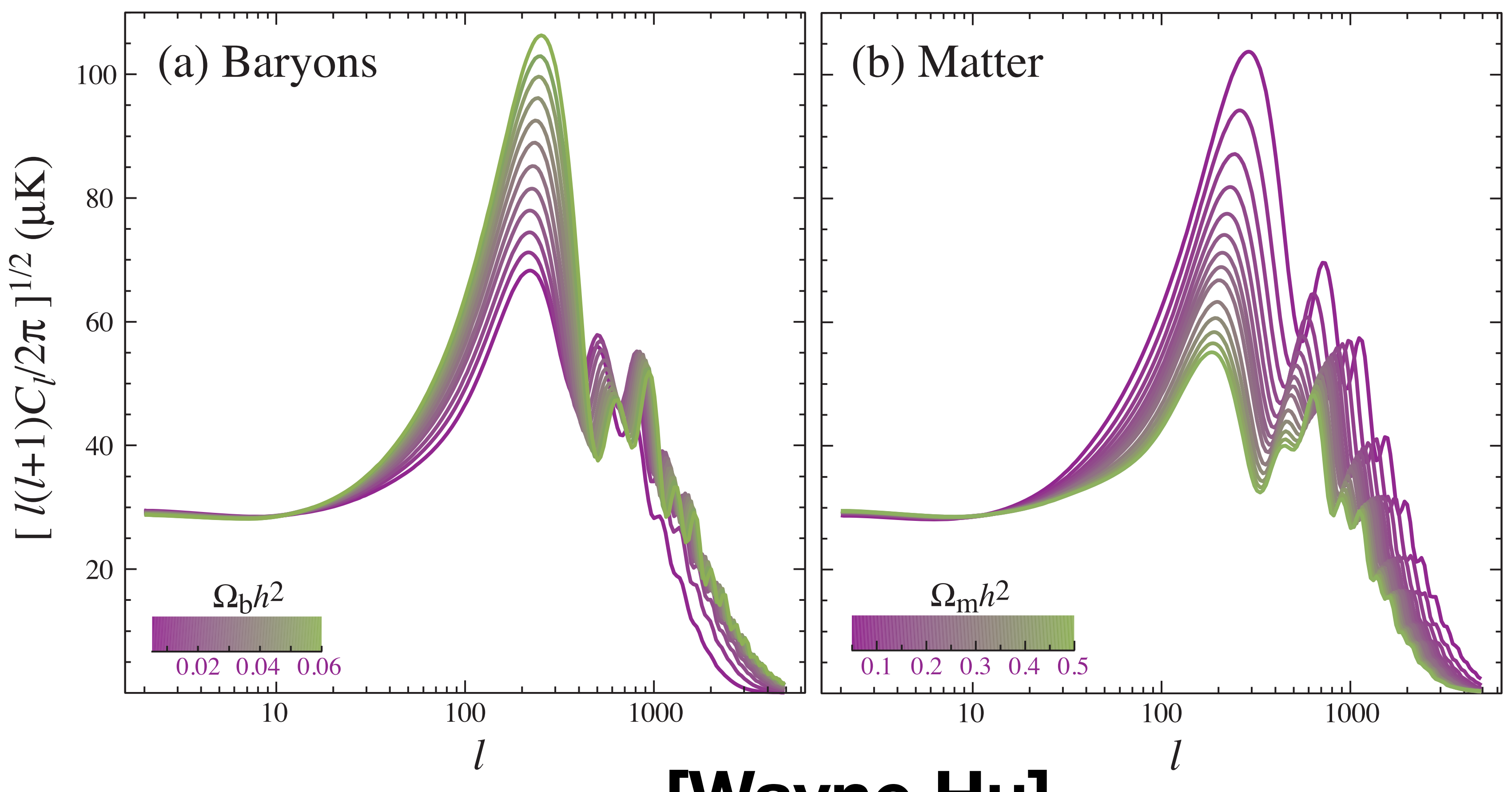
- CMB = Cosmic Microwave Background = 2.725 K photons left from Big Bang

- Temperature fluctuations in the CMB depend on energy content of Universe.





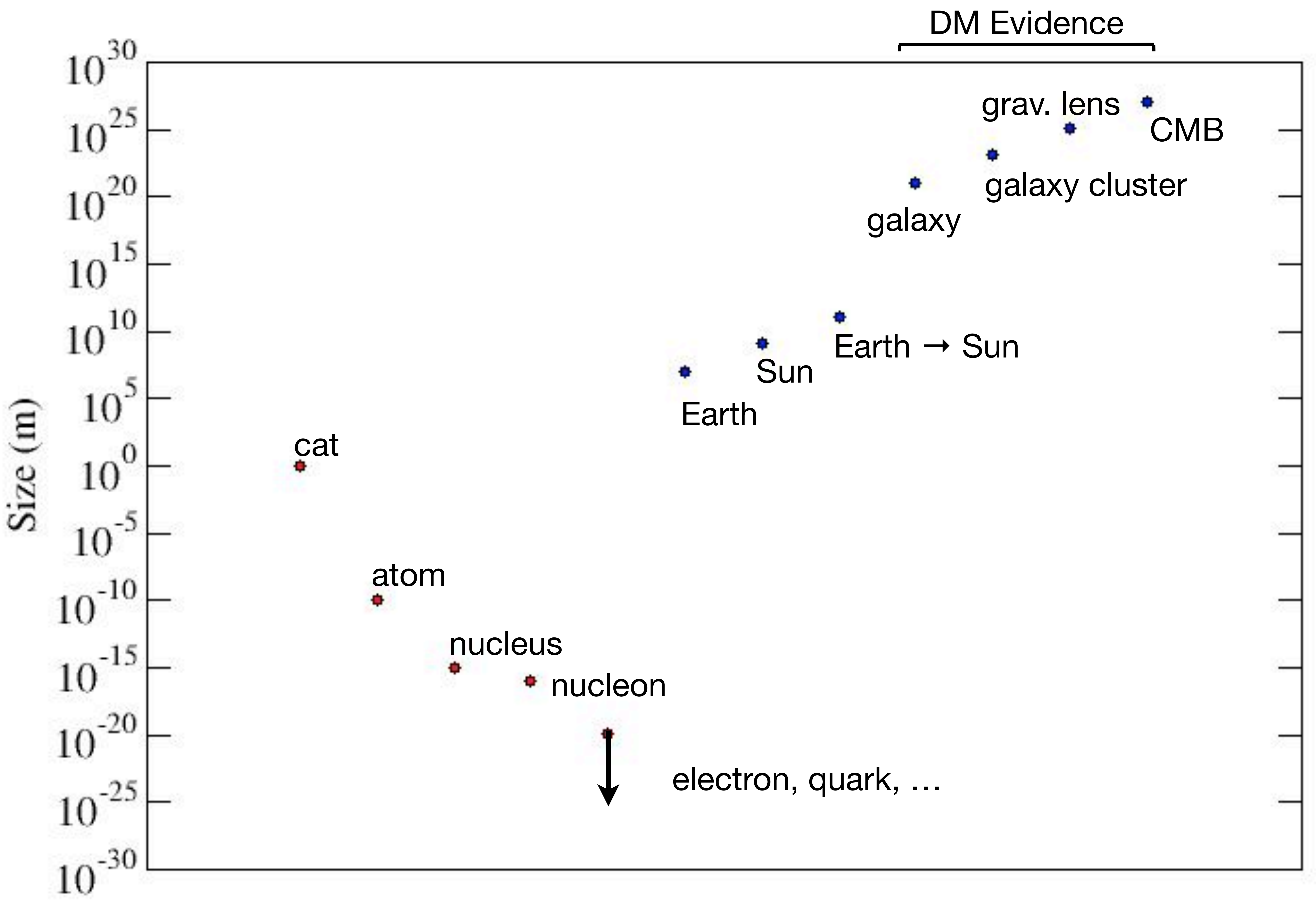
[Planck 2013]



[Wayne Hu]

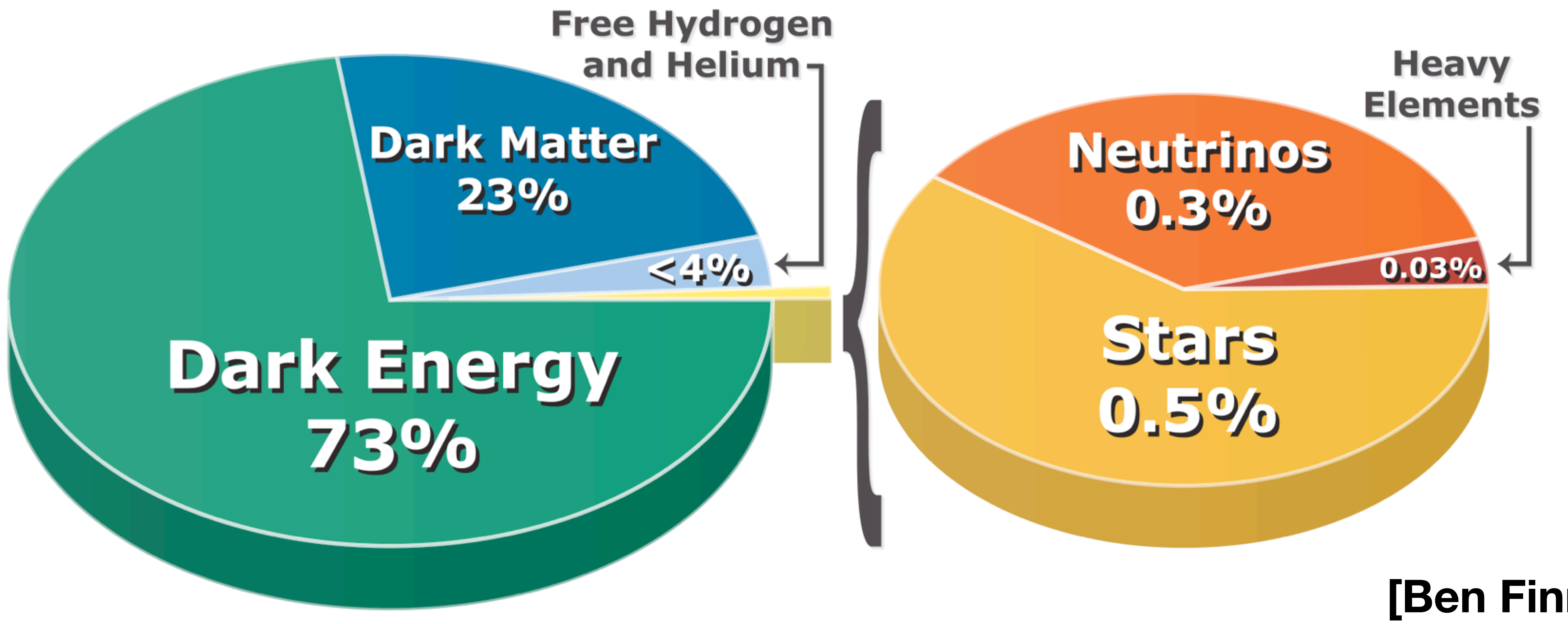
- Data fits to 30% of energy in matter, but only 5% in regular matter (baryons)!

Evidence for Dark Matter



Energy Content of the Universe

- Energy content of the Universe now:

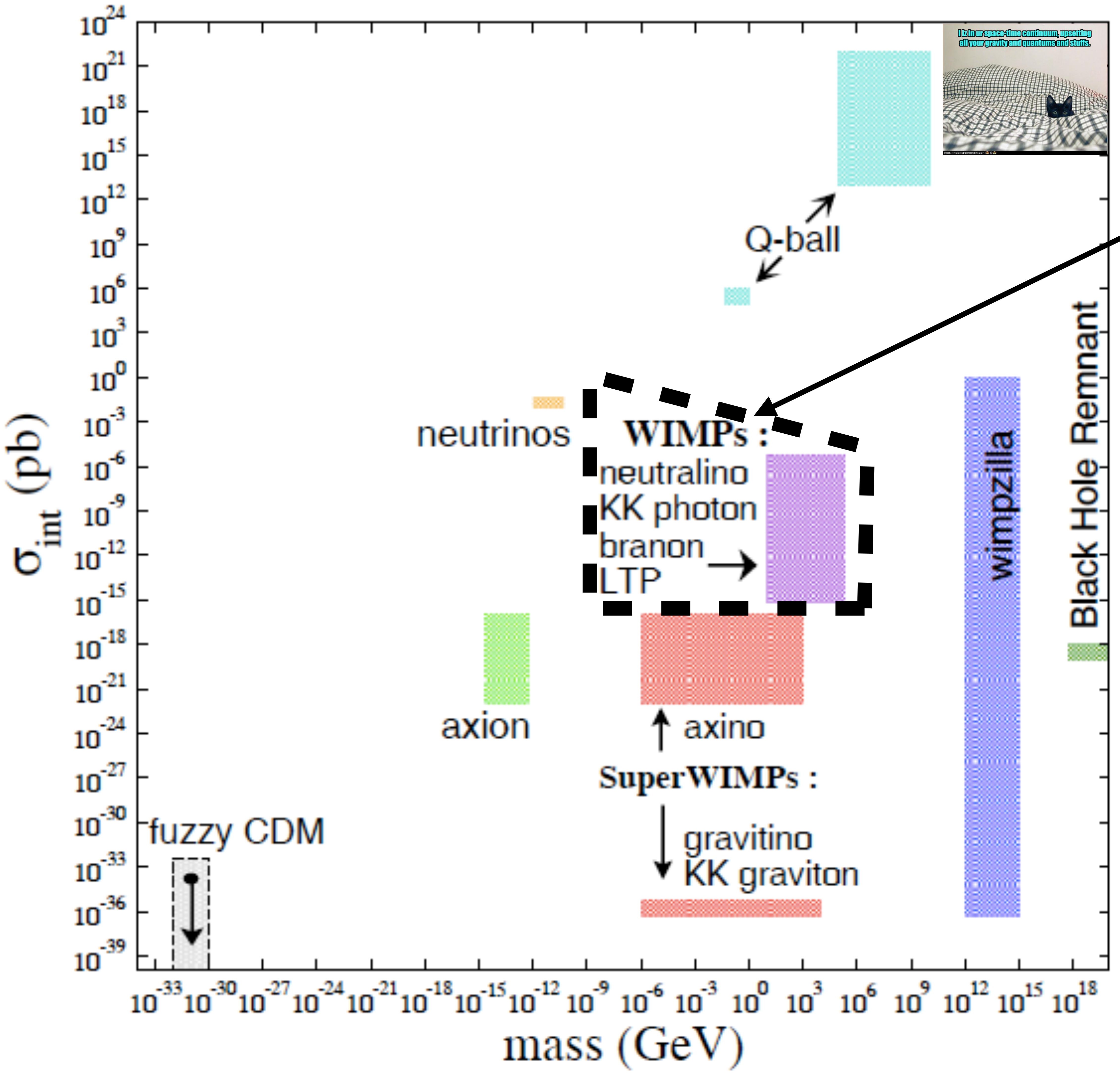


[Ben Finney 2012]

- Only 5% of matter seems to come from stuff in the Standard Model!
- Missing matter = “Dark Matter”

What is Dark Matter?

- **We don't know!**
- Some DM theories:
- Thermal DM is a good place to start!
- But keep in mind **Non-Thermal** too!

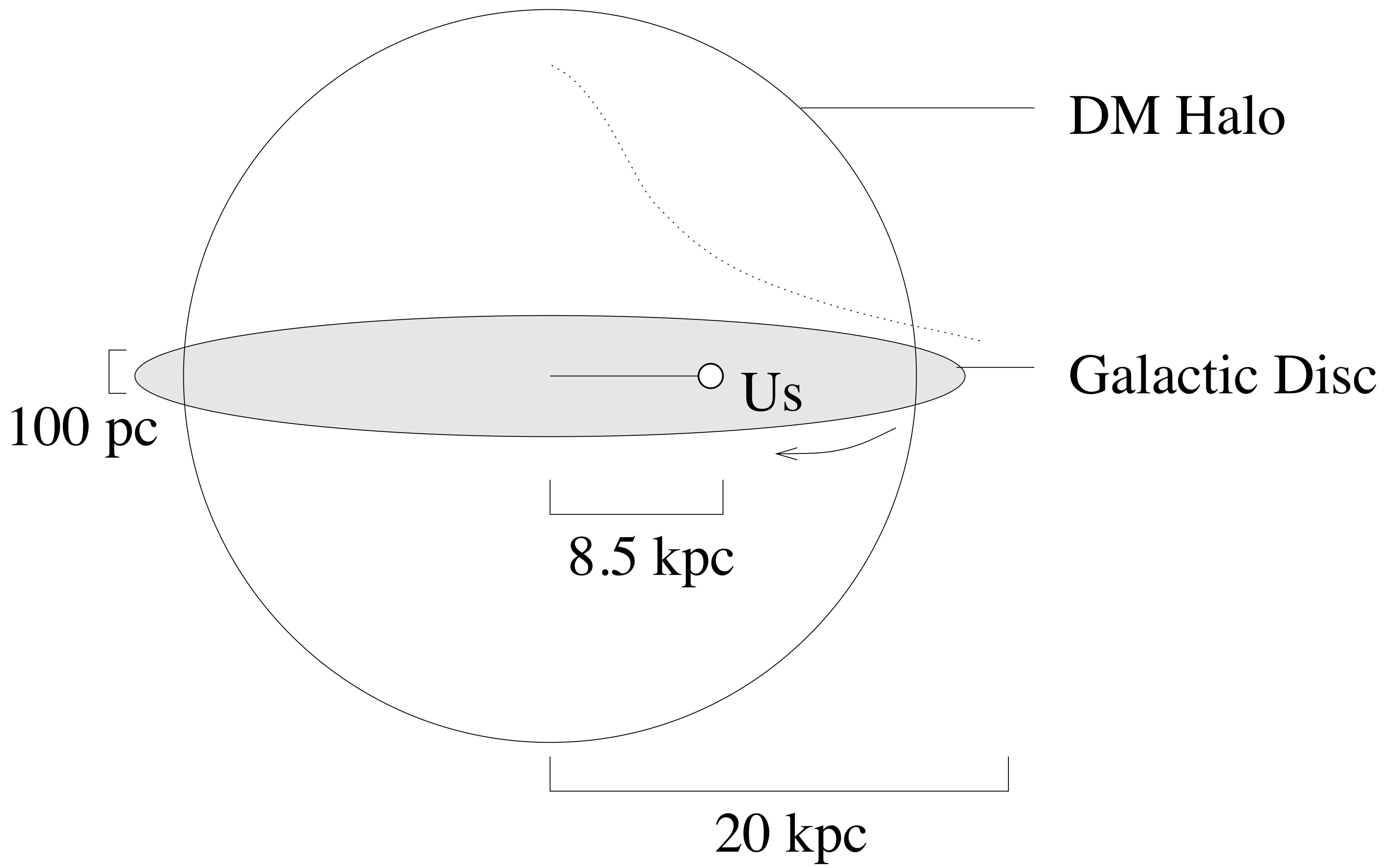


Thermal DM

[E.K. Park, HEPAP DMSAG, 2007]

Dark Matter Near Us

- If DM exists, we should be surrounded by it.

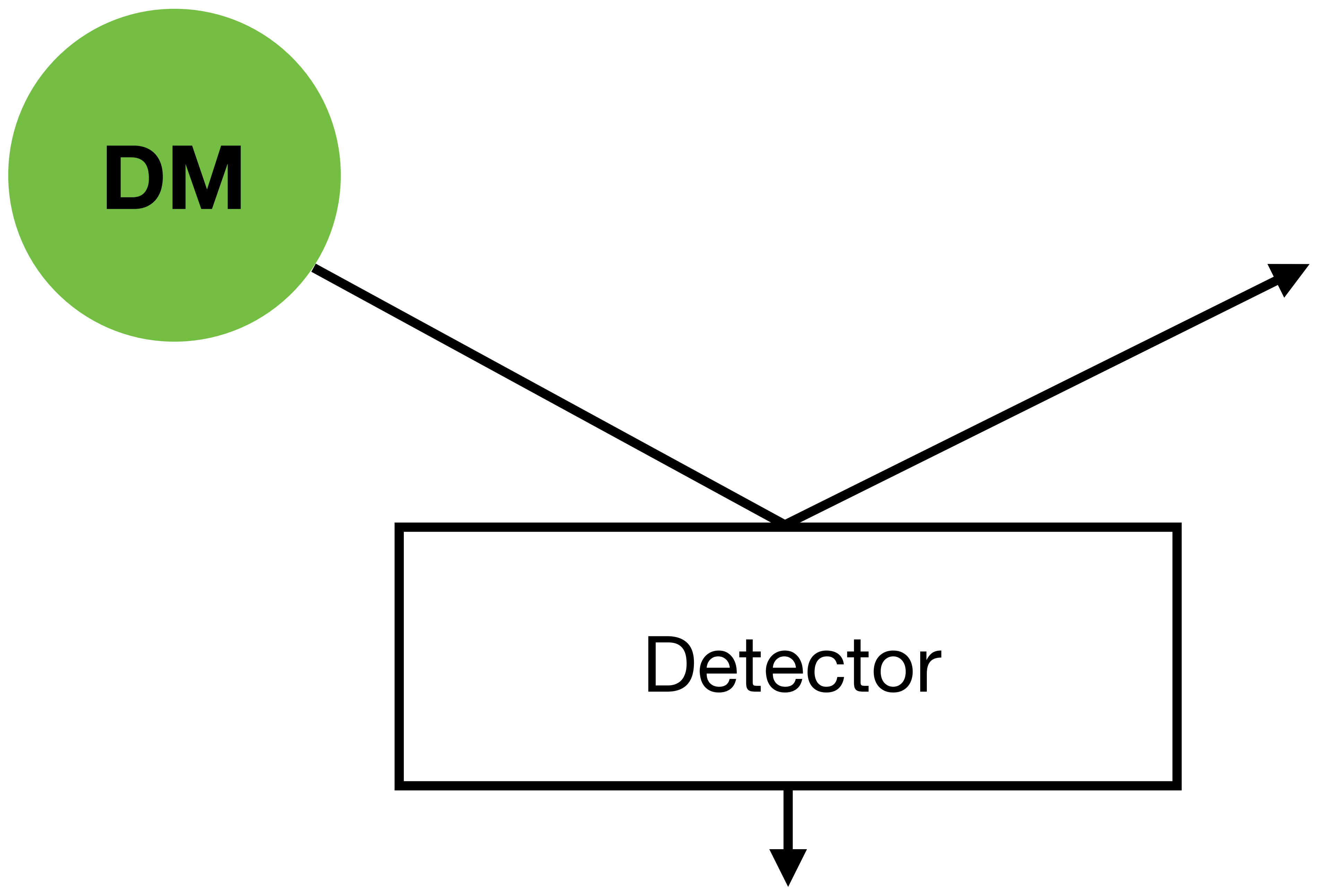


- In our local region:

$$\rho_{\rm DM} \simeq 0.3\,{\rm GeV/cm^{-3}}$$
$$\langle v_{\rm DM}\rangle \simeq 300\,{\rm km/s} \simeq 10^{-3}\,{\rm c}$$

Dark Matter Detection in the Lab

- If DM is all around us and interacts with the SM, it might be detectable!
- Direct Detection: (elastic) scattering in a detector.

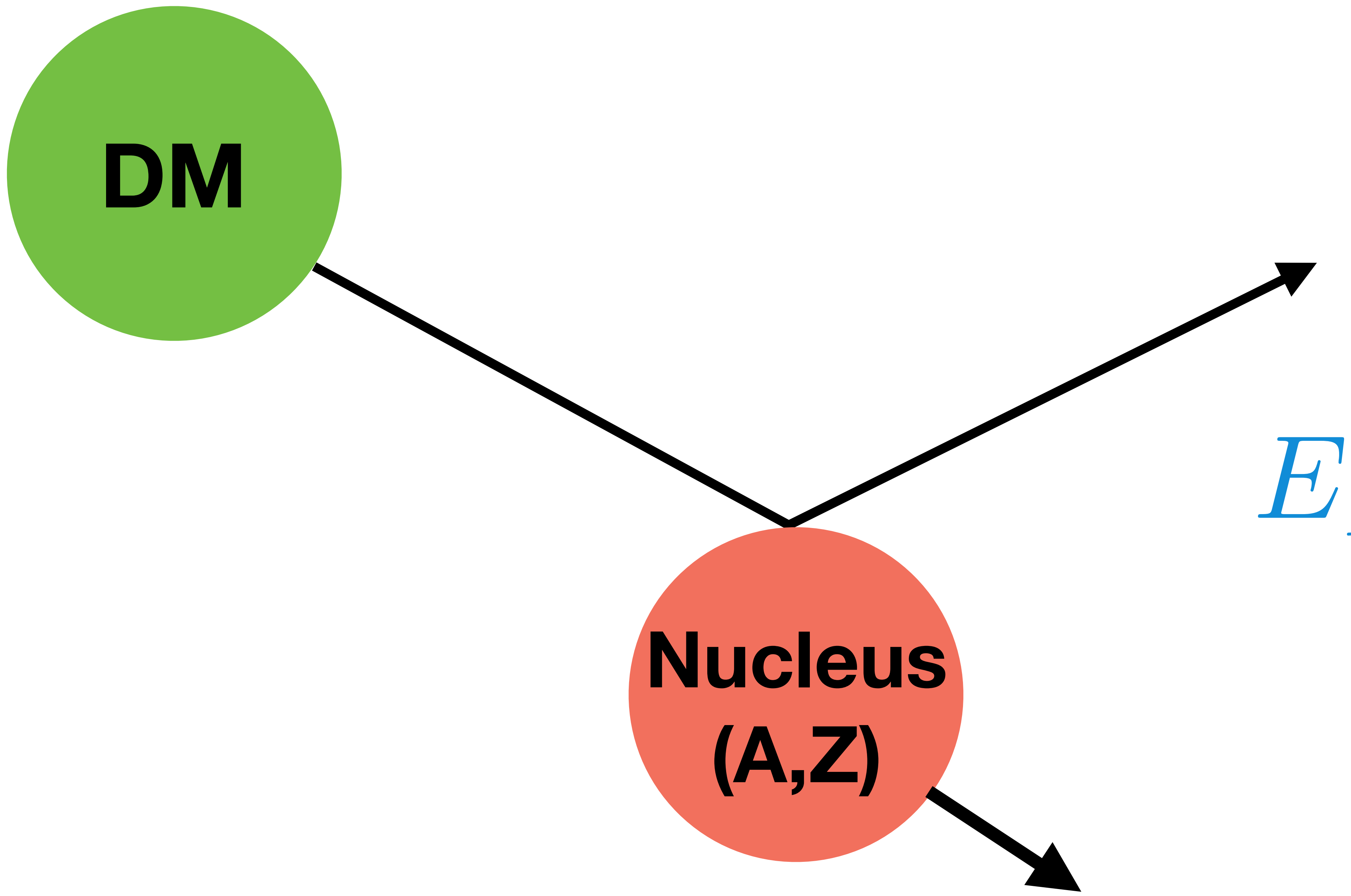


$$T = E_{\rm DM} - E'_{\rm DM}$$
$$\vec{q} = \vec{p}_{\rm DM} - \vec{p}'_{\rm DM}$$

Response: $S(T, \vec{q})$

Dark Matter Detection in the Lab

- If DM is all around us and interacts with the SM, it might be detectable!
- The most common detection strategy is to look for **nuclear recoils**.

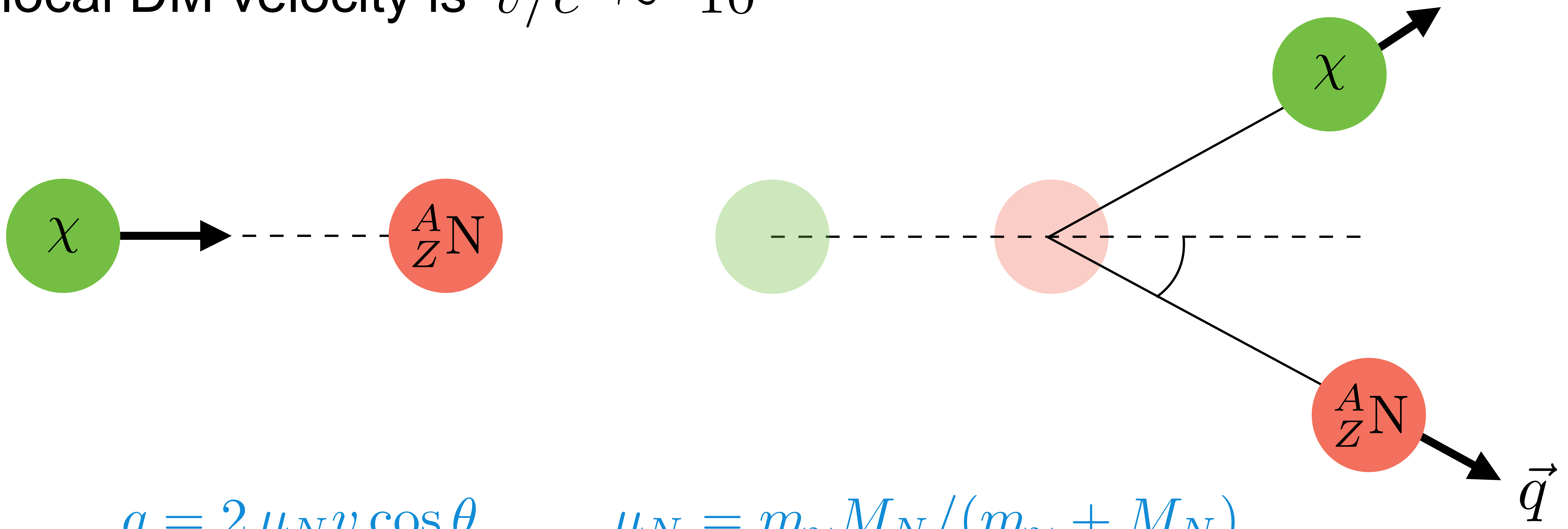


$$E_R = E_{\rm DM} - E'_{\rm DM}$$
$$\vec{q} = \vec{p}_{\rm DM} - \vec{p}\,'_{\rm DM}$$

scintillation, heat, ionization, …

DM-Nucleus Kinematics

- Typical local DM velocity is $v/c \sim 10^{-3}$



$$q = 2\,\mu_N v \cos\theta\ , \qquad \mu_N = m_\chi M_N/(m_\chi + M_N)$$

$$E_R = \frac{q^2}{2M_N} \lesssim (200\,\mathrm{keV}) \left(\frac{M_N}{100\,\mathrm{GeV}}\right)\left(\frac{\mu_N}{100\,\mathrm{GeV}}\right)$$

DM $= \chi$

DM-Nucleus Interactions

- DM-quark interaction → DM-nucleon interaction → DM-nucleus interaction

- In many theories, get DM-nucleon potential of:

$$V_{n\chi}(\vec{x}) = \begin{cases} f_n\,\delta^{(3)}(\vec{x}) & ; \quad \textbf{spin-independent (SI)} \\ a_n\,\delta^{(3)}(\vec{x})\,(\vec{S}_\chi \cdot \vec{S}_n) & ; \quad \textbf{spin-dependent (SD)} \end{cases}$$

- For SI scattering, the nuclear cross section on nucleus ${}^{A}_{Z}N$ has the form

$$\frac{d\sigma_N}{dE_R} = \frac{A^2}{v^2}\left(\frac{\mu_N}{\mu_n}\right)^2 \sigma_n\,|F_N(E_R)|^2$$

DM-nucleon effective cross section (σ_n)

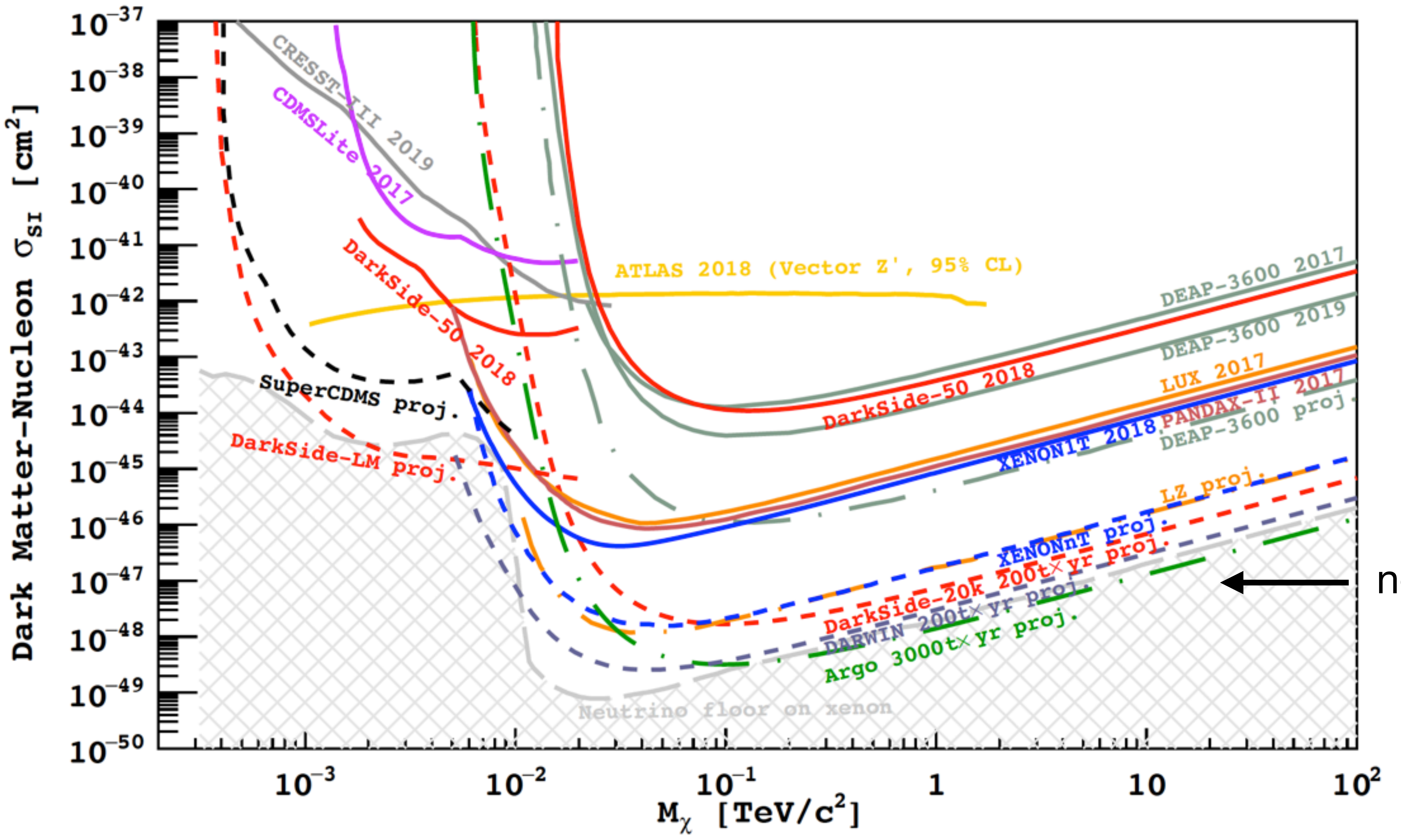
Nuclear Response ($|F_N(E_R)|^2$)

Dark Matter Direct Detection (SI)

- Near future searches for WIMP ($m_\chi \gtrsim 10\,\mathrm{GeV}$) spin-independent DM:
  - XENONnT: 8.3 tonnes of liquid **Xe** at Gran Sasso (LNGS)
  - LZ: 7 tonnes of liquid **Xe** at Sanford (SURF)
  - PandaX-4T: 4 tonnes of liquid **Xe** at Jinping (CJPL)
  - DarkSide20k: 20 tonnes of liquid **Ar** at Gran Sasso (LNGS)
- And beyond:
  - DARWIN: 40 tonnes of liquid **Xe** at (?)
  - ARGO: 300 tonnes of liquid **Ar** at SNOLAB (?)
  - SuperCDMS, SBC, NEWS-G, SENSEI, … at lower masses ($m_\chi \lesssim 10\,\mathrm{GeV}$)

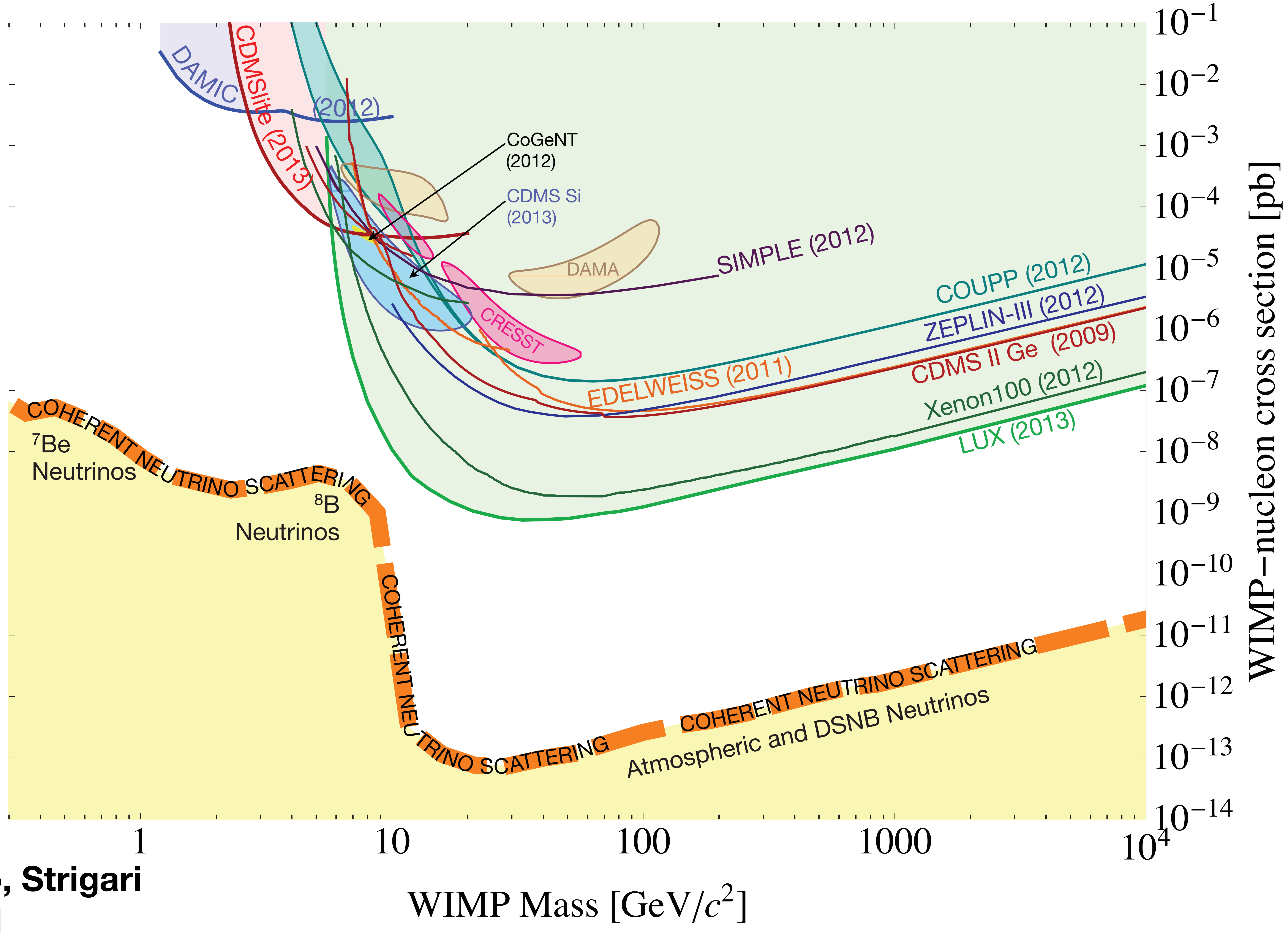
Dark Matter Direct Detection

- Future projections (Spin-Independent):



neutrino background

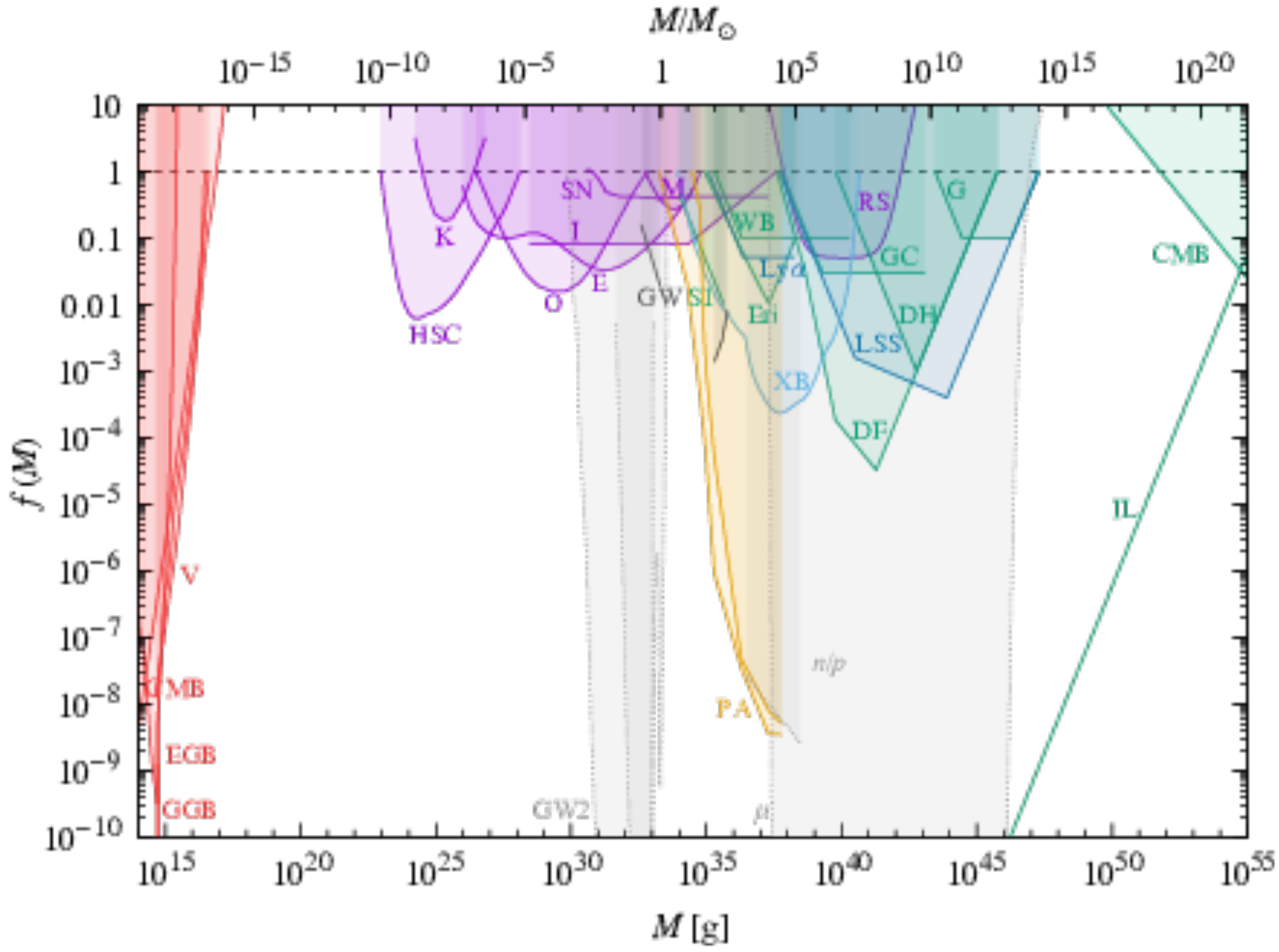
The Neutrino Floor



[Billard, Figueroa-Feliciano, Strigari hep-ph/1307.5458]

Primordial Black Holes as DM

- How are they formed?
- What is allowed?
- $f = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$



A Question: the Invisible Moon

- Suppose we couldn't "see" the moon with electromagnetic radiation.
  e.g. thick, permanent cloud layer, …
- How would we deduce its existence? What could we learn about its structure?

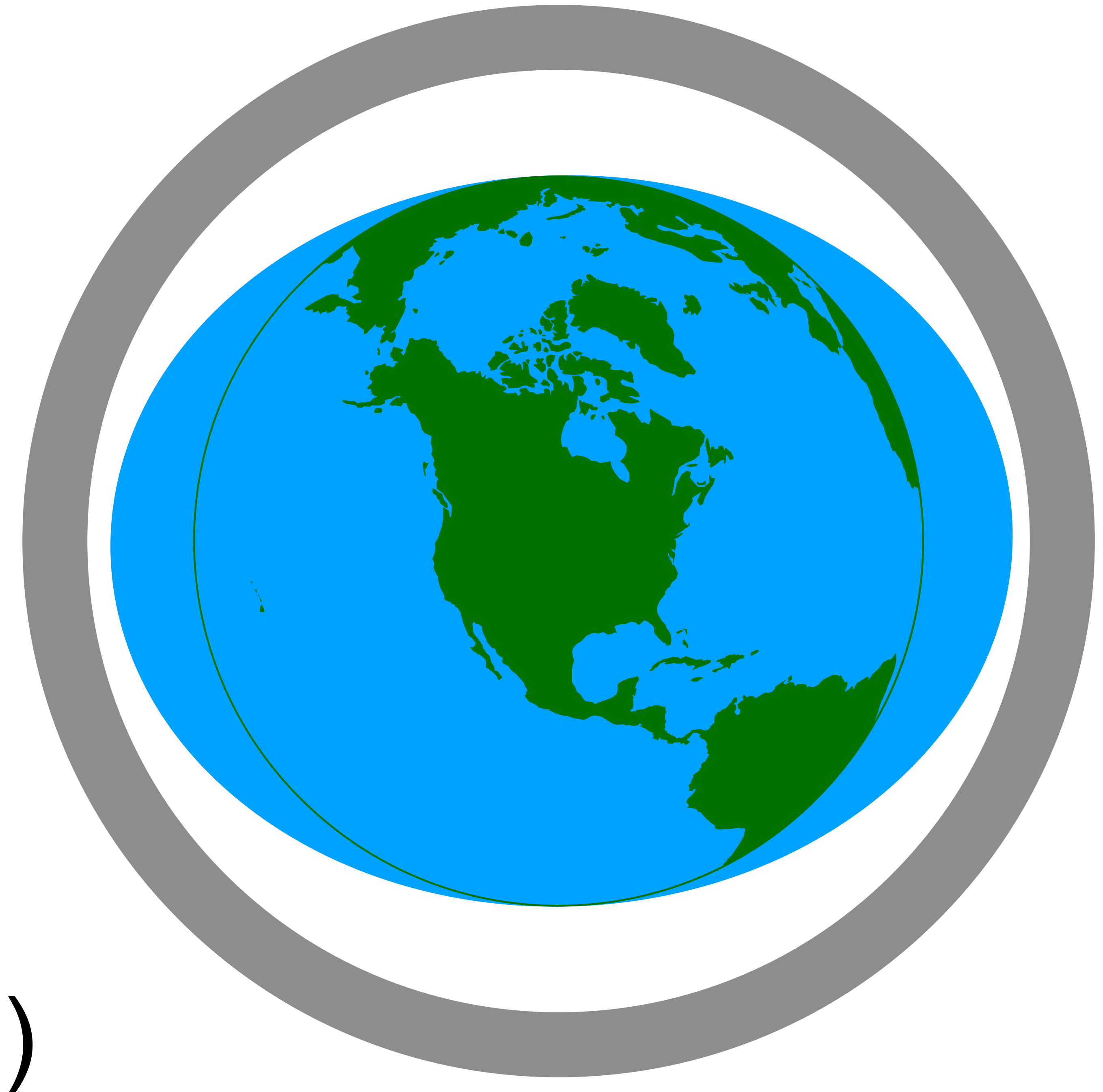
A Question: the Invisible Moon

- Suppose we couldn't "see" the moon with electromagnetic radiation.
  e.g. thick, permanent cloud layer, …
- How would we deduce its existence? What could we learn about its structure?
- Assumptions:
  - we can observe the sun
  - we understand Newtonian gravity (or General Relativity)

A Question: the Invisible Moon

- From the observation of tides, theoretical astronomers propose the existence of a “Moon” orbiting the Earth with a 28 day period.

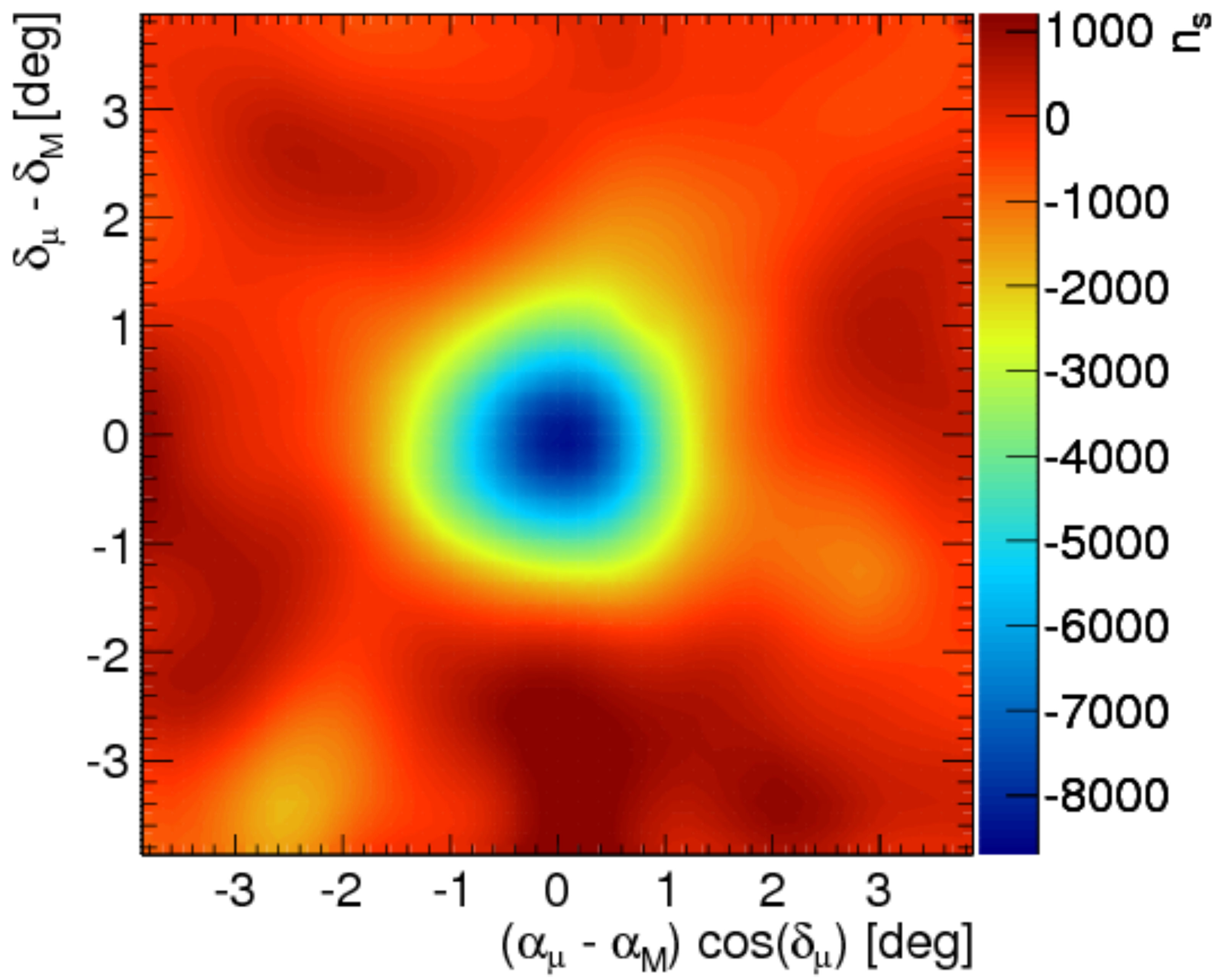
- How much more could we say?
    - mass?
    - distance?
    - size?
    - microphysics?
      (*e.g.* 50μm black hole? cheese?)



- Are there other observations we could use?

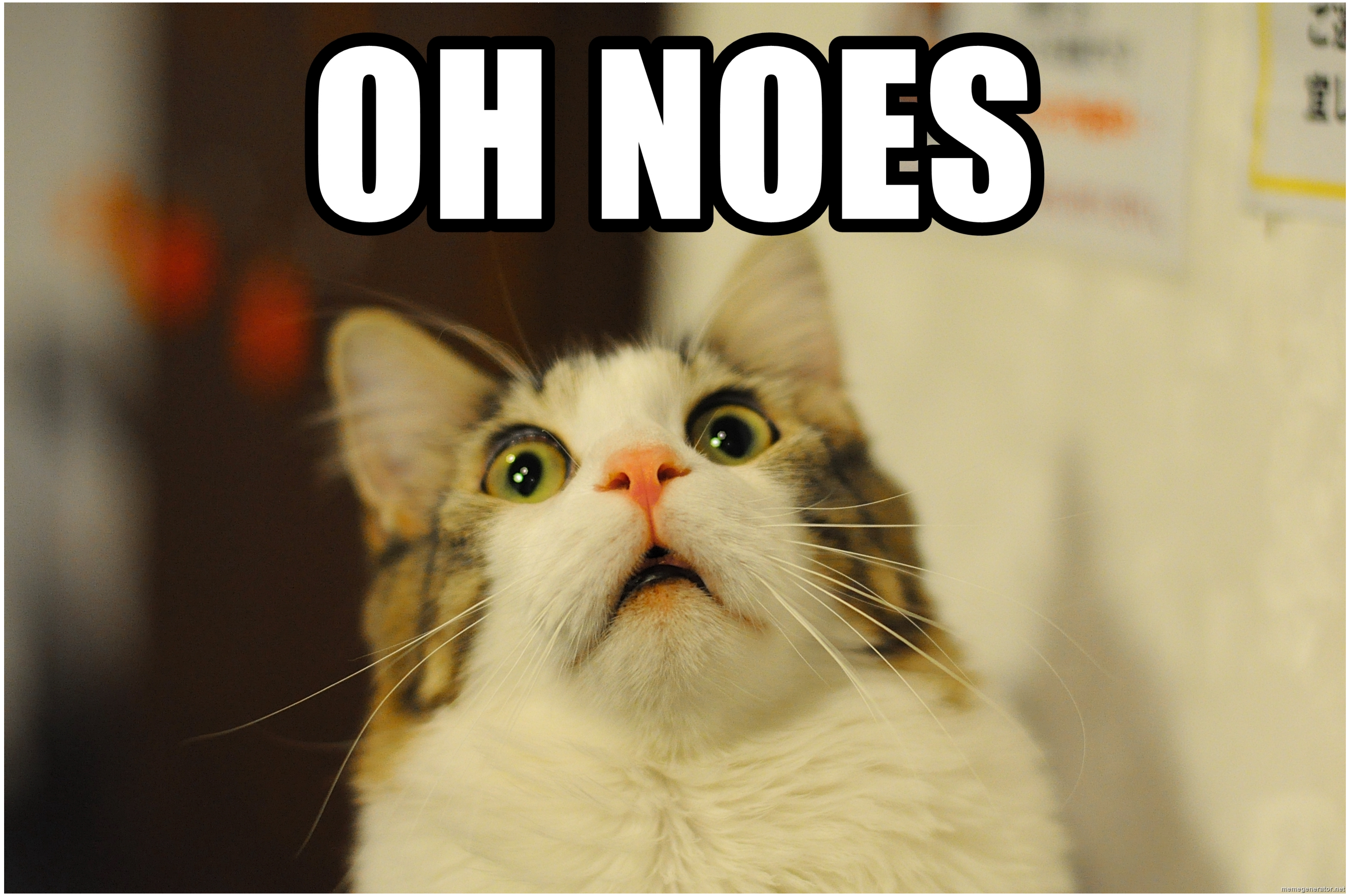
Addendum: the Invisible Moon

- The IceCube neutrino telescope imaged the moon in neutrinos!
- They mostly observe atmospheric neutrinos produced by cosmic rays hitting the atmosphere.
- The moon can block some of these cosmic rays creating a “neutrino shadow”.



[IceCube 2013]

Gratuitous Cat Pictures



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