Introduction to Dark Matter

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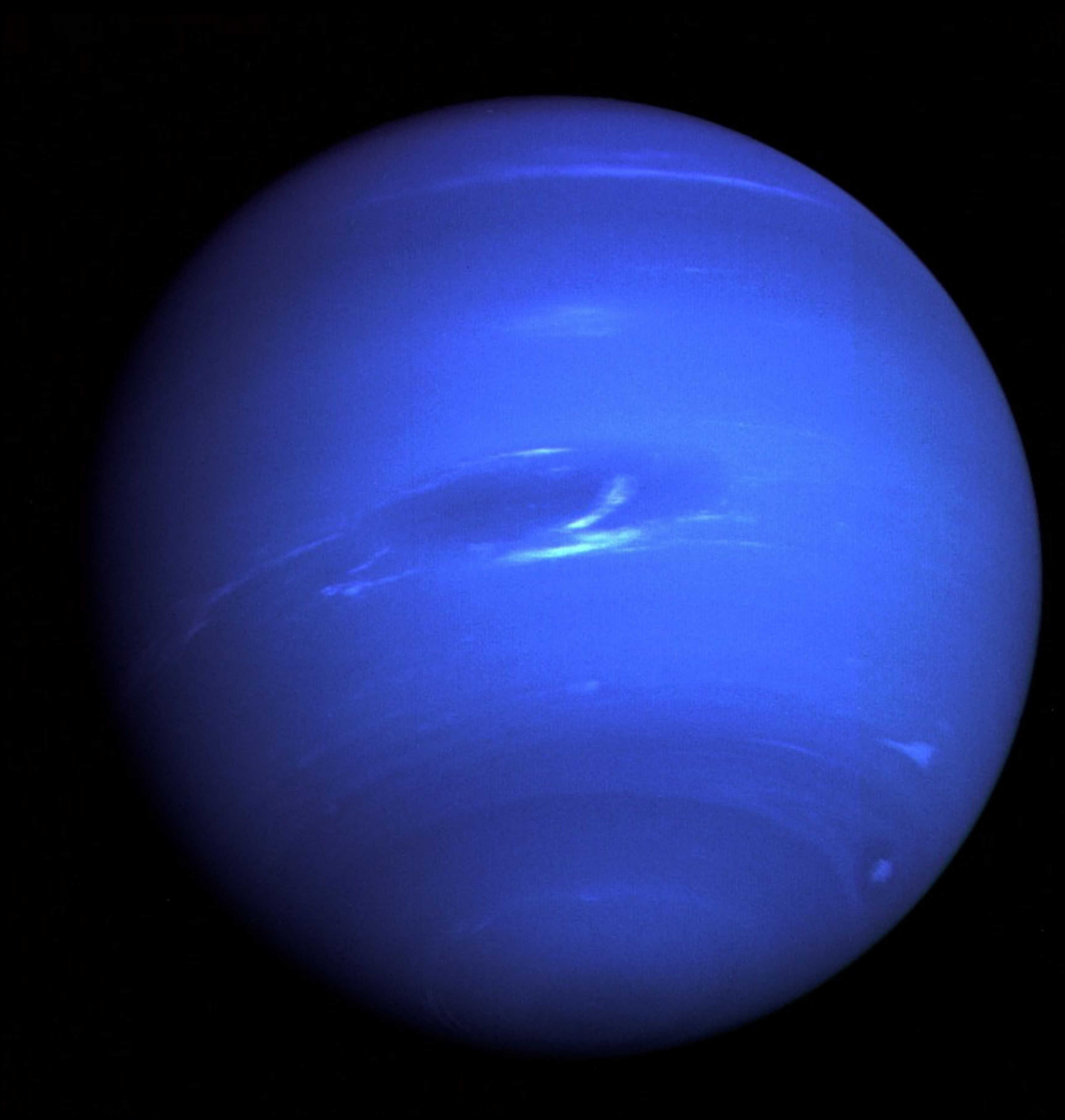
Dark matter overview

1. Why is this a problem?
2. Detour: self-defence against Lagrangians
3. Some leading dark matter candidates
4. Looking for dark matter (Part 1)

1. Why is this a problem?

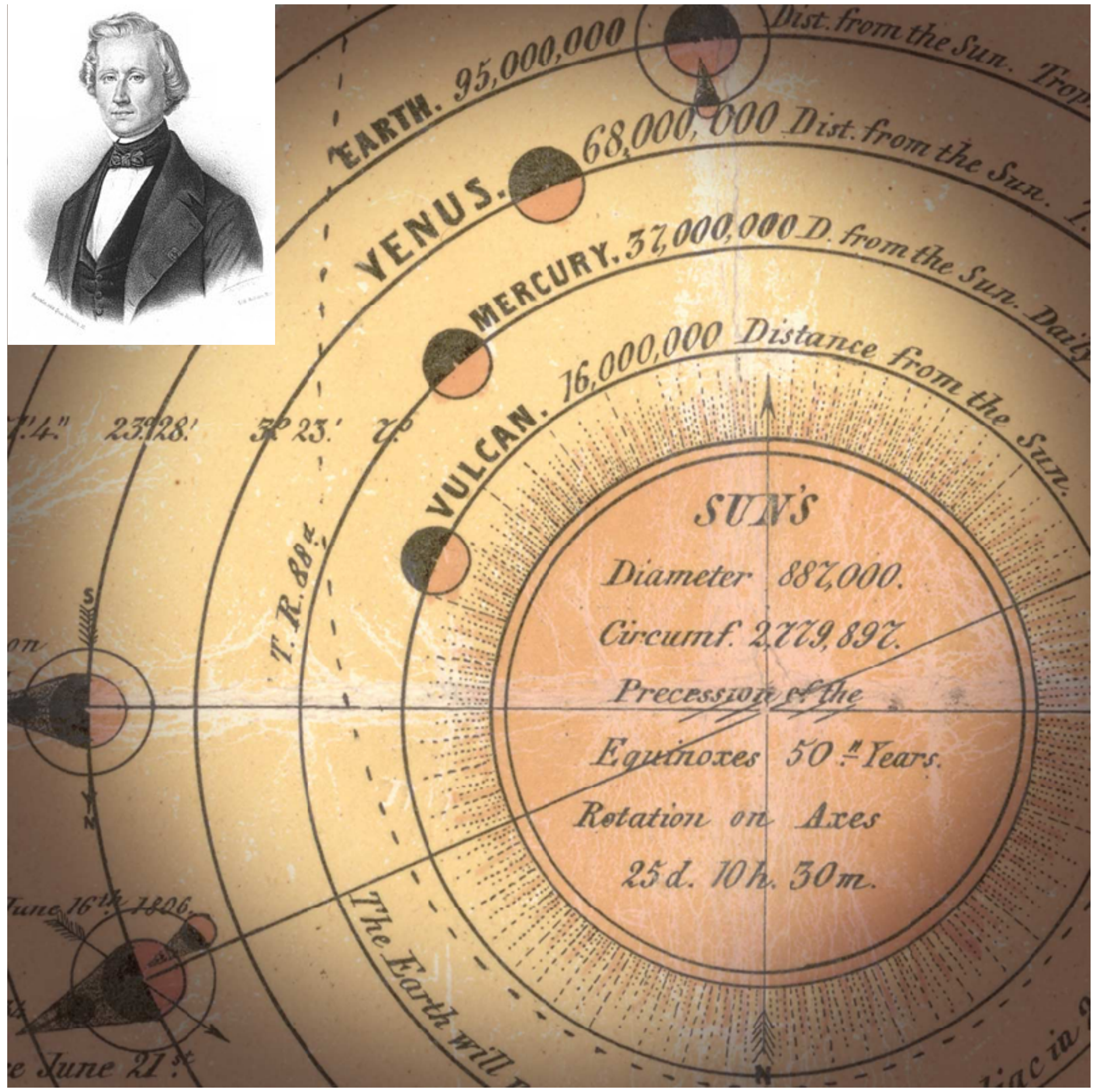
A photograph of dark matter

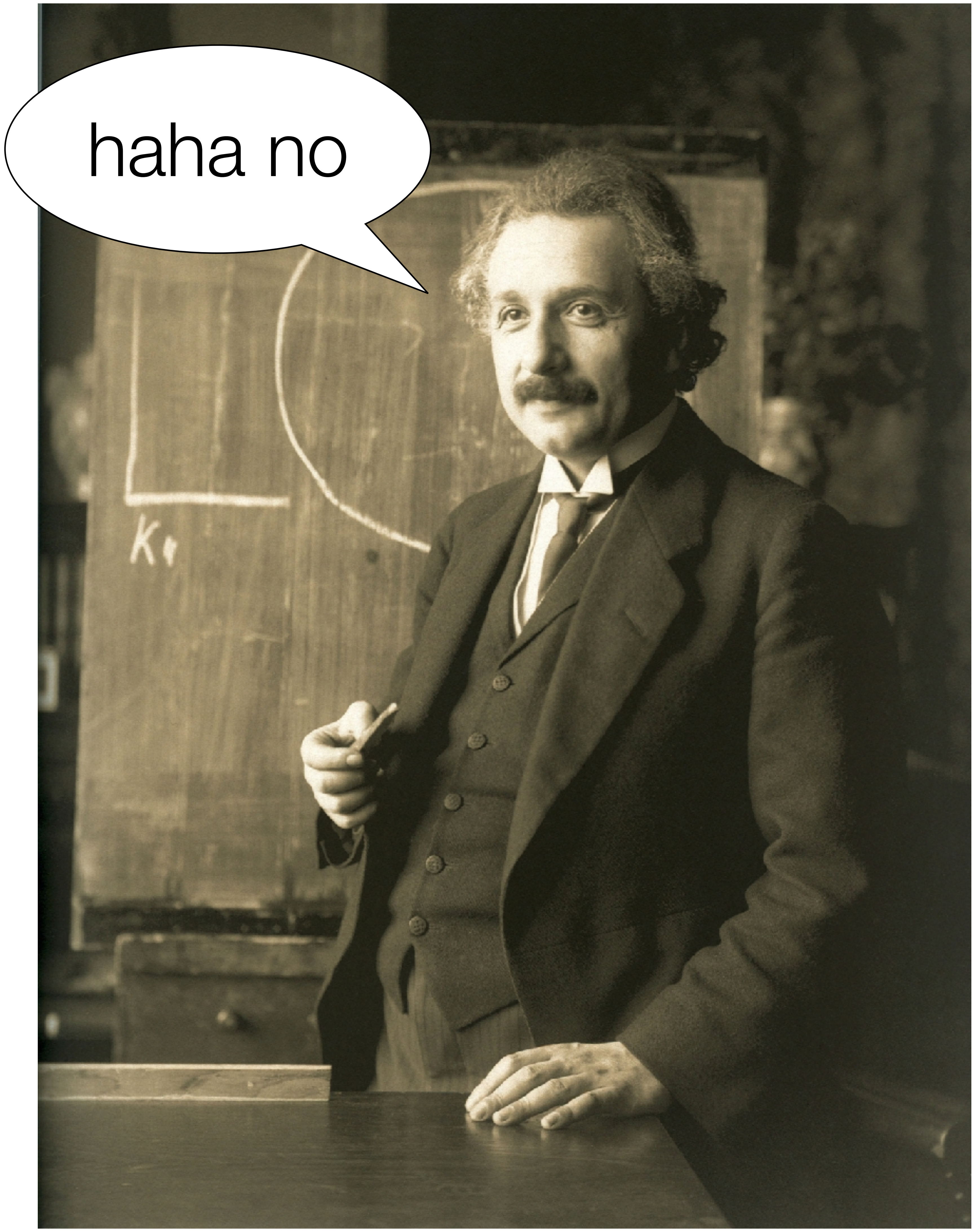


1846: Urbain le Verrier notices something odd with Uranus' orbit: postulates the existence of a new planet.

His calculations are so precise that Johann Galle finds Neptune within 1 degree of le Verrier's prediction.

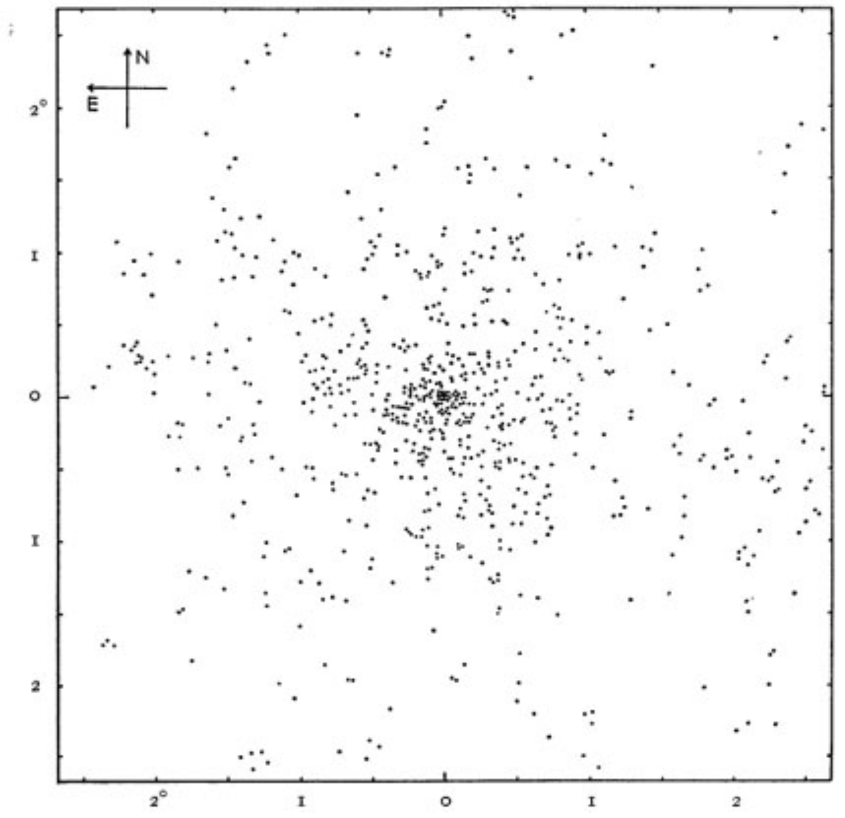
Same success story: Vulcan





Missing matter on larger scales

Zwicky and the Coma cluster (1932)



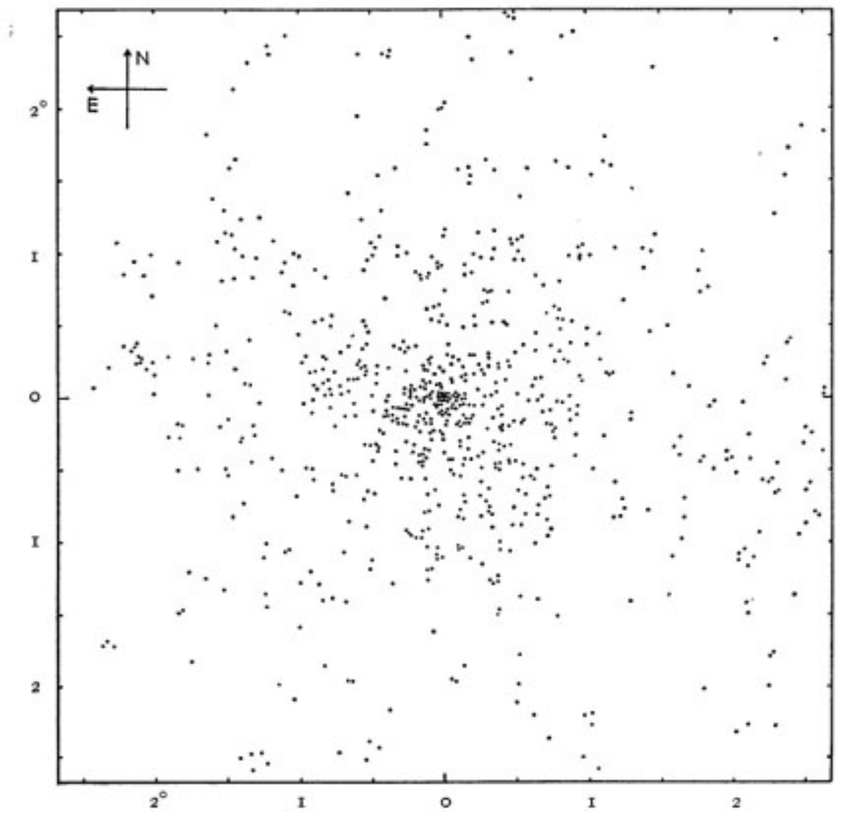
Russ Carroll, Robert Gendler, and Bob Frank

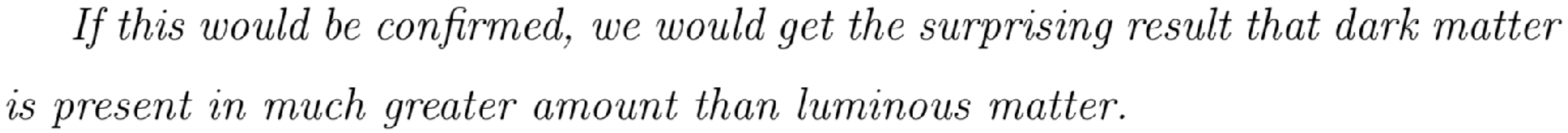
Missing matter on larger scales

Zwicky and the Coma cluster (1932)

Zwicky measures the orbital velocities of galaxies in the Coma cluster.

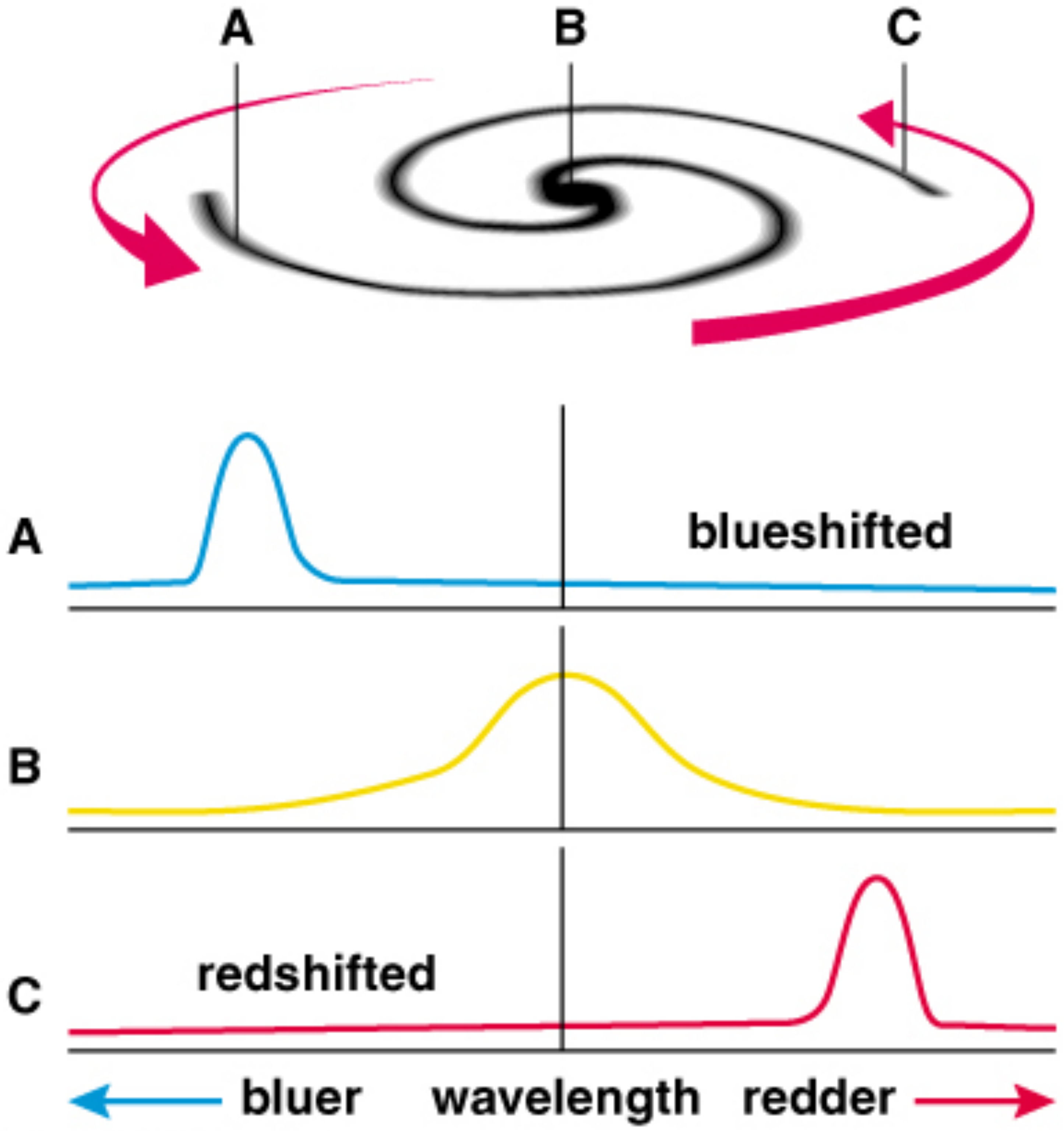
He calculates how much mass is needed to explain the orbital speeds, and finds that this is **500 times more** than can be observed from the luminosity of galaxies.





If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.

The rotation curves of galaxies



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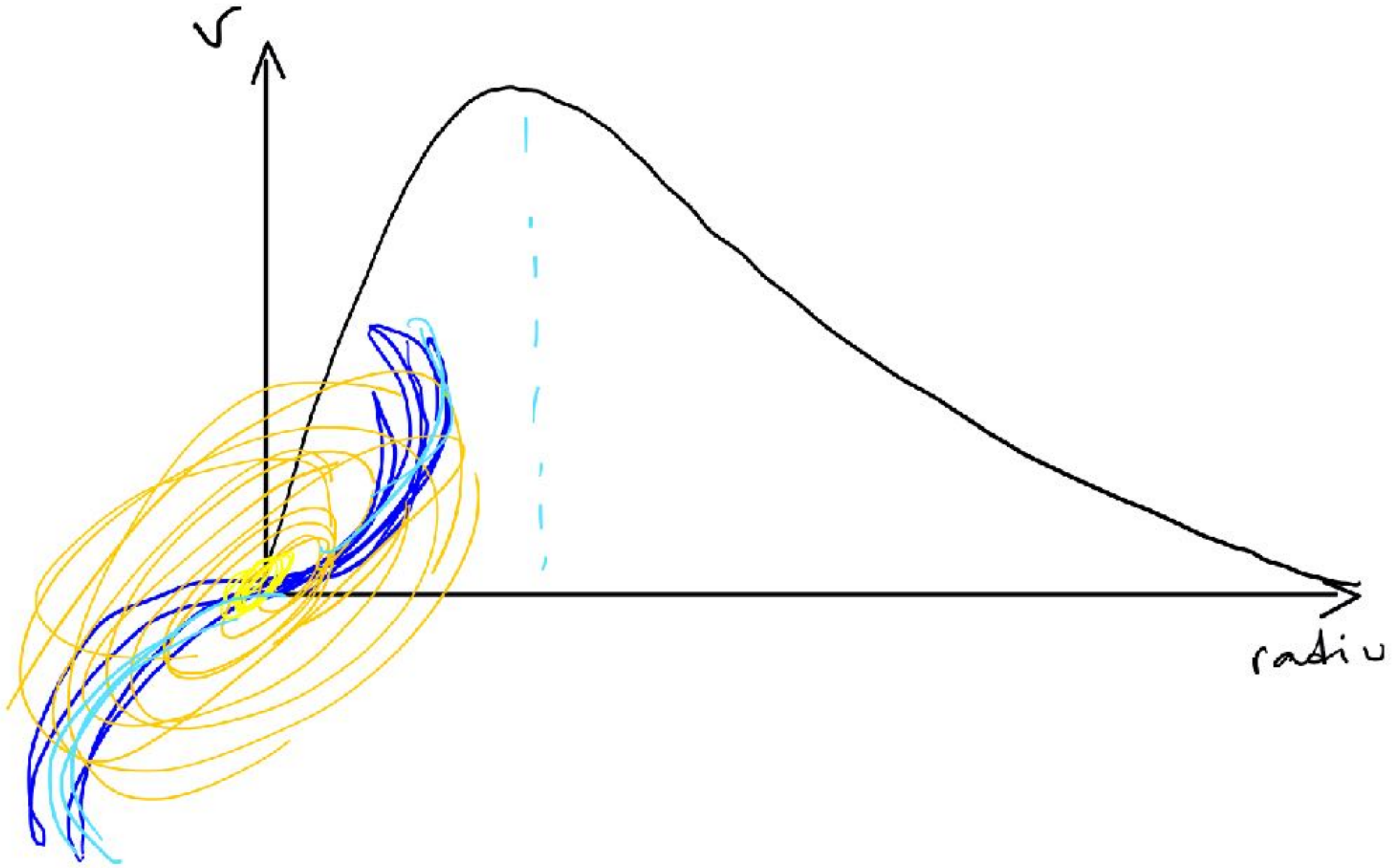
As we look outside the visible parts of galaxies, the rotation rates should be keplerian, since the small amount of matter is seeing only the galaxy within its orbit

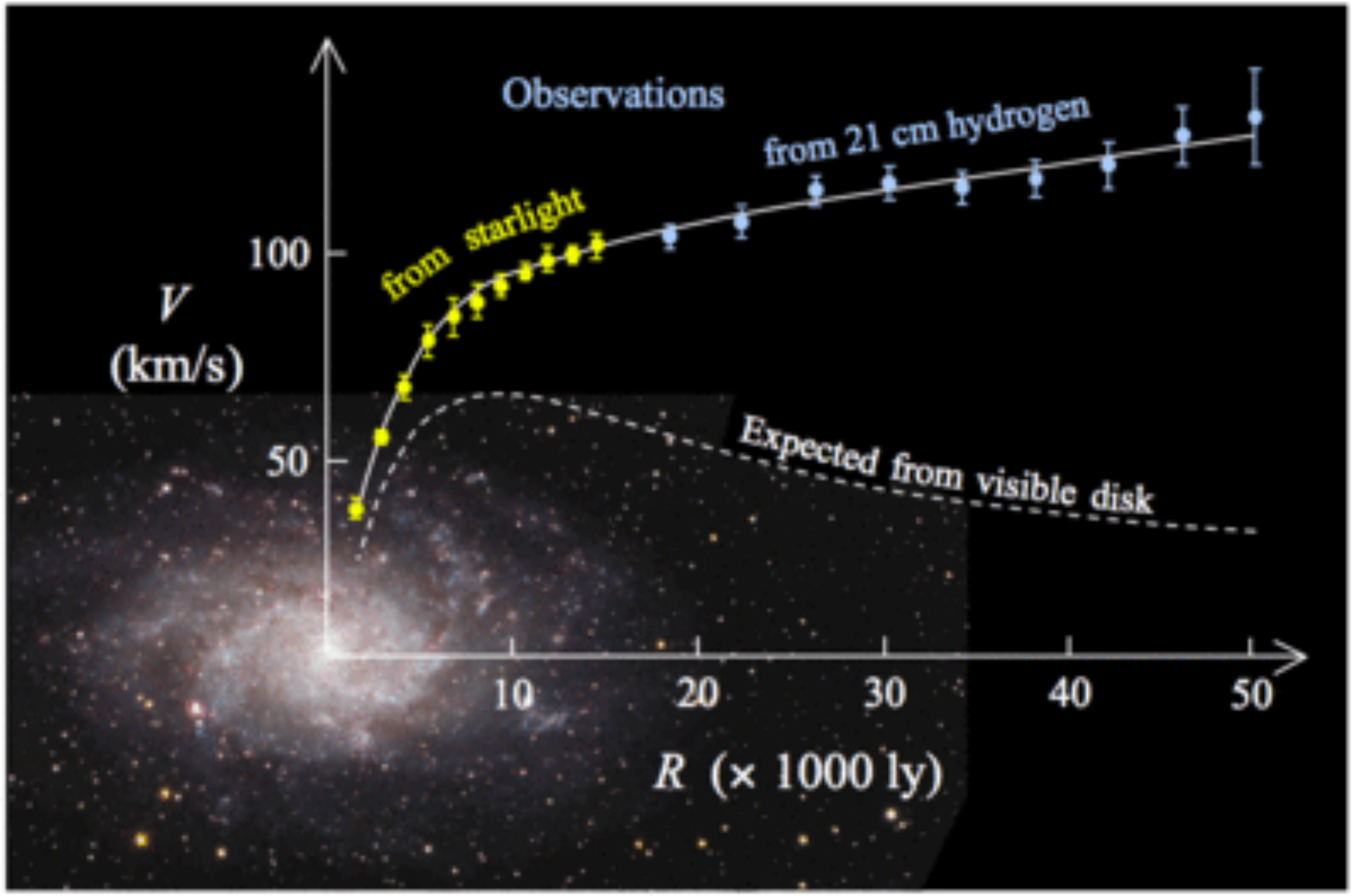


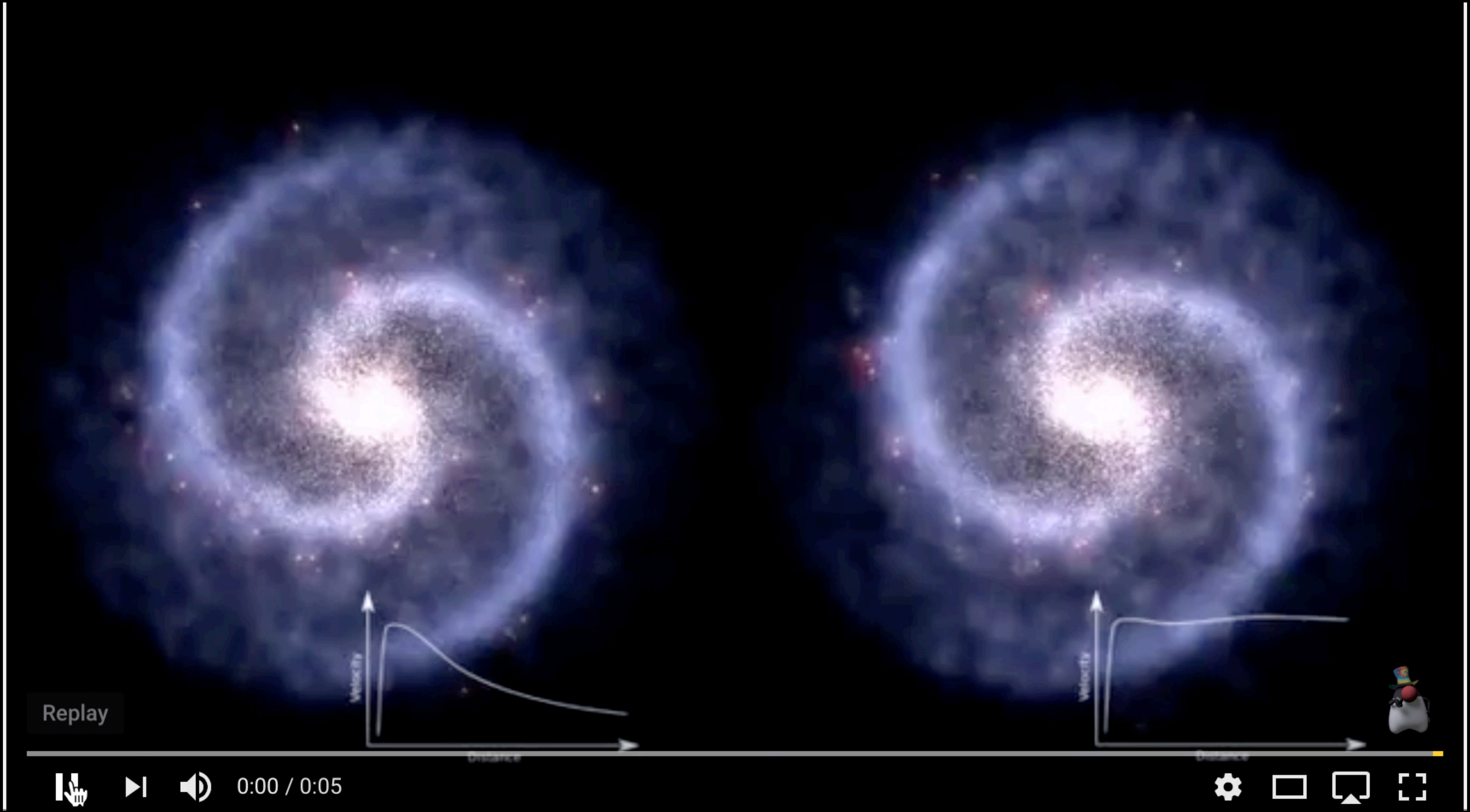
The rotation curves of galaxies

Vera Rubin (1980)

Kent Ford's flux tube spectrograph (National Air & Space Museum

The rotation curves of galaxies

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Velocity
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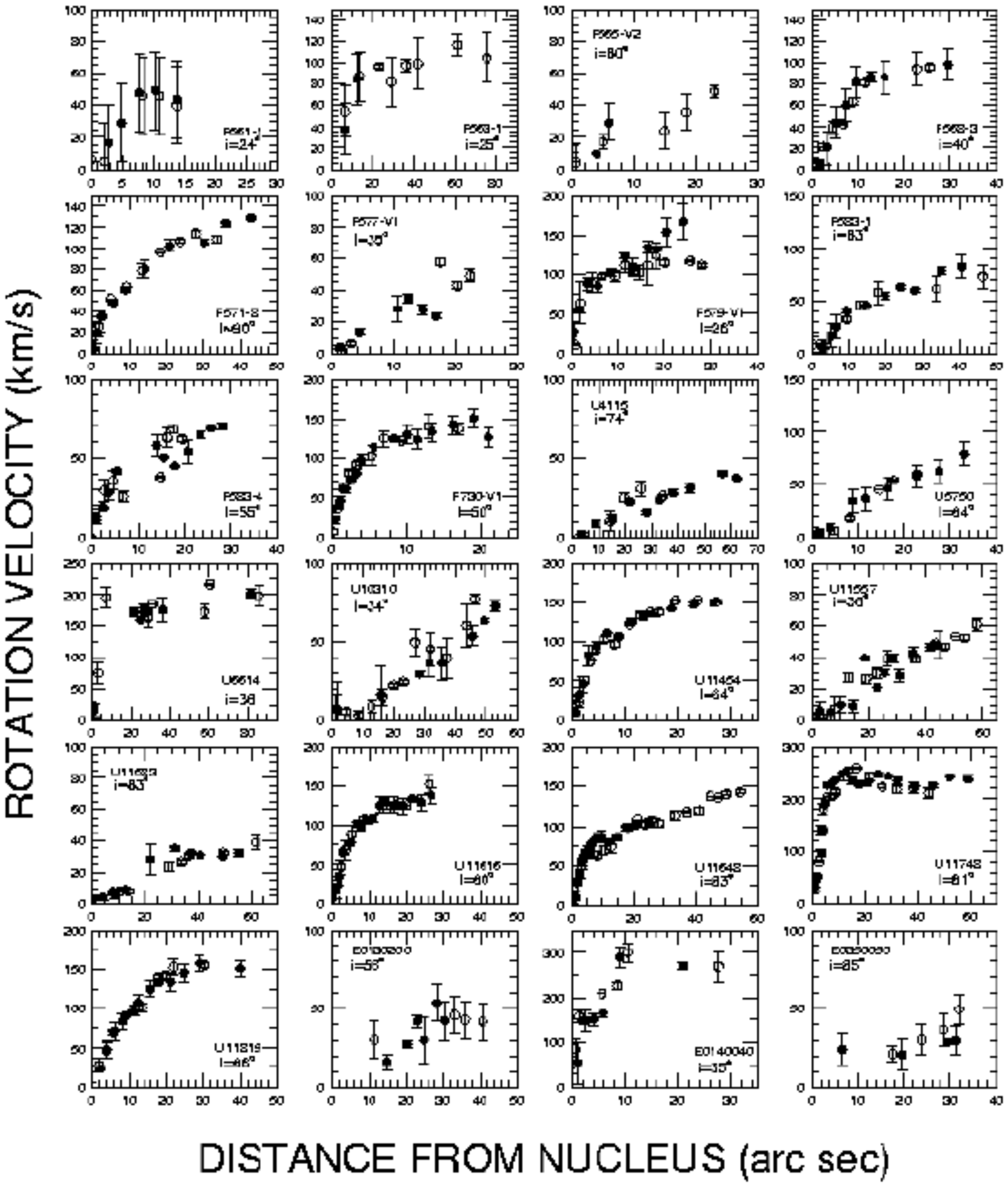
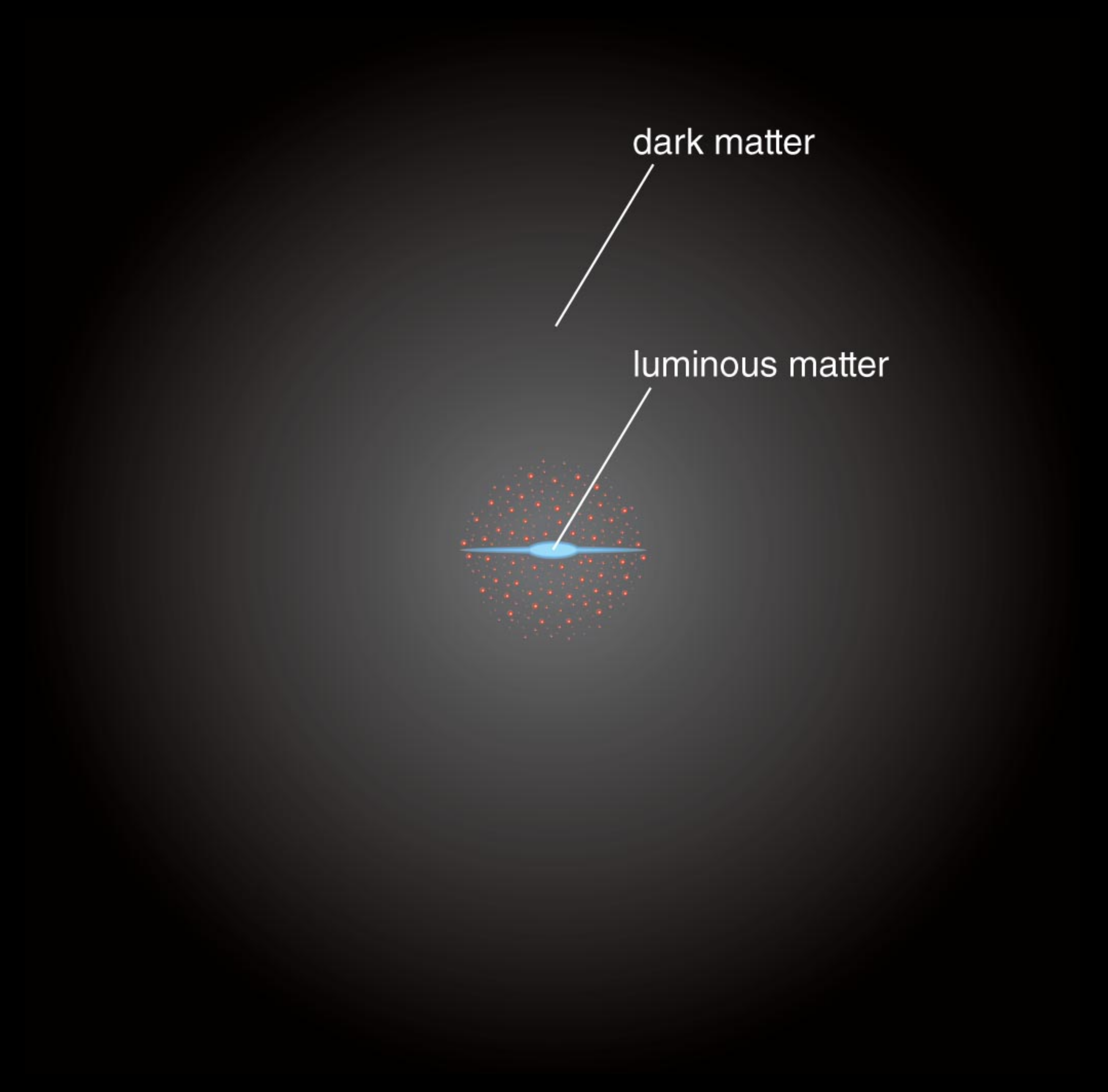


Rotation curves flattened in every galaxy that Vera Rubin looked at.

To explain this there must be some heavy, diffuse contribution to the mass of the galaxies: **dark matter**


dark matter
luminous matter

The local dark matter density

Particle physicist units $\rho_\chi \simeq 0.4\,\mathrm{GeV\,cm^{-3}}$

Astronomer units $\rho_\chi \simeq 0.01\,\mathrm{M_\odot\,pc^{-3}}$

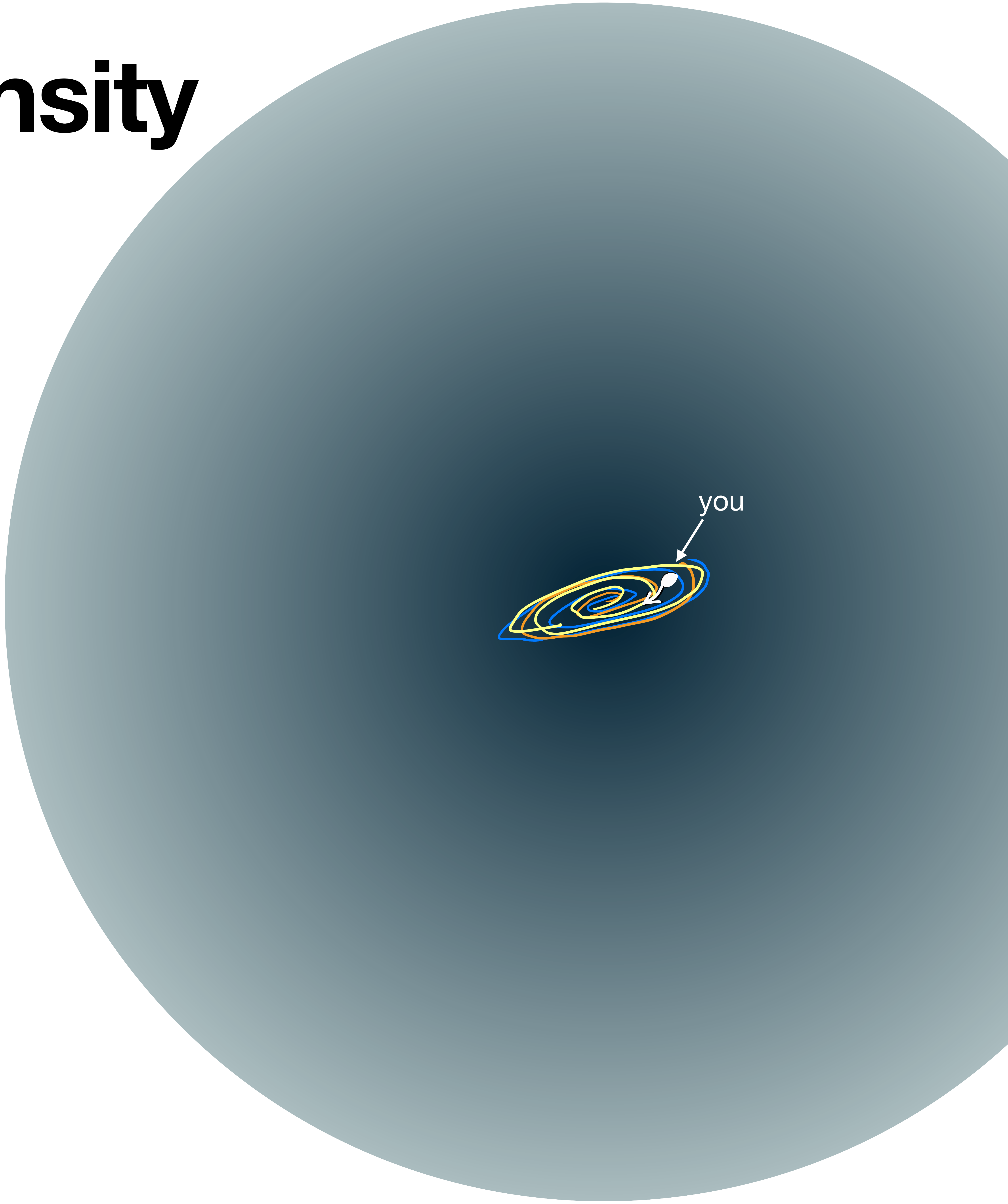
British units $\rho_\chi \simeq 1\,\mathrm{DMPPP}$

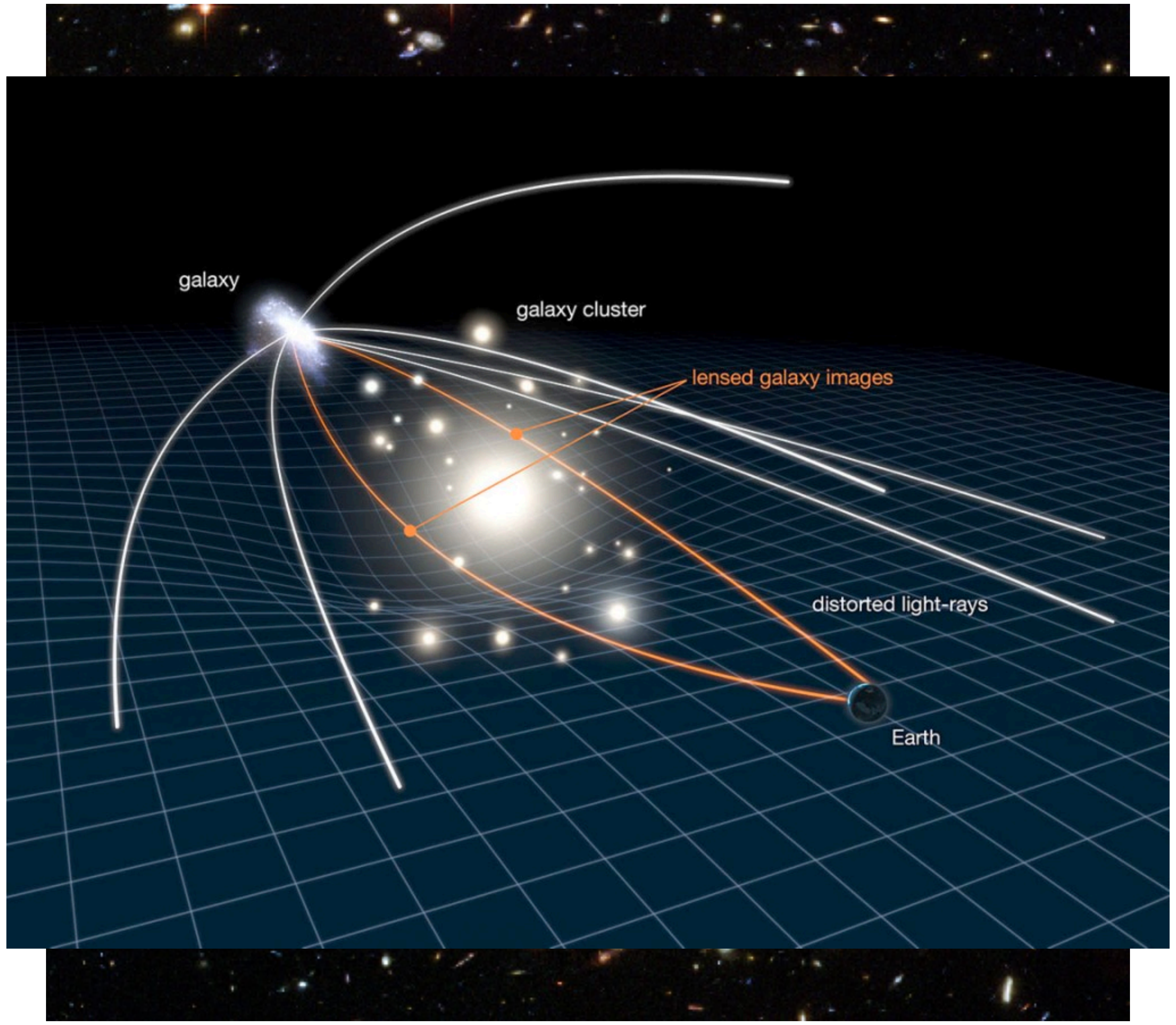
Roughly Maxwellian velocity distribution

$$f(v) \propto v^2 e^{-v^2/v_0^2}$$

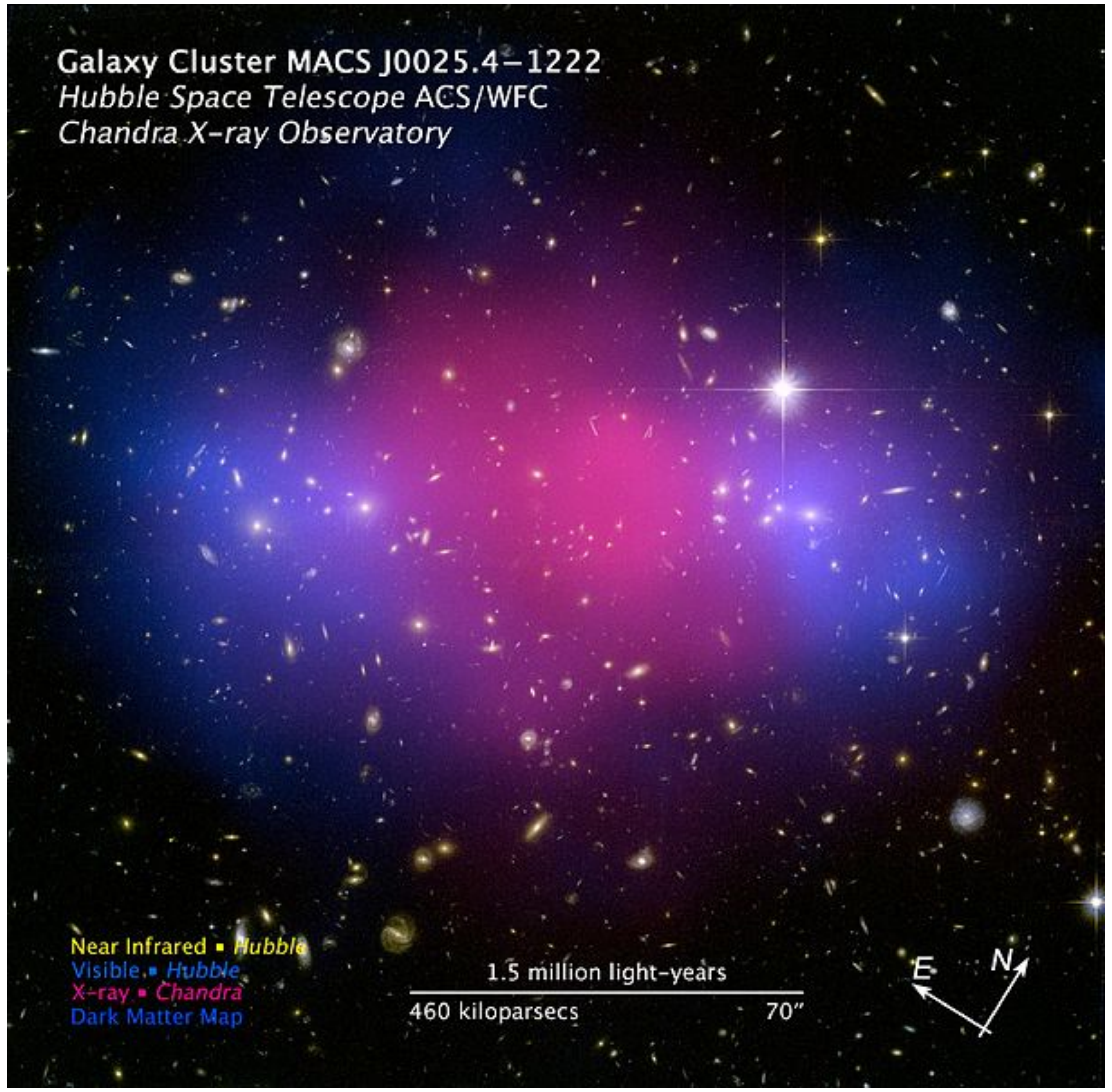
$$v_0 = 270\,\mathrm{km/s}$$

Not corotating with the galactic disk (220 km/s here)





Gravitational lensing: more bending of light than can be explained by the galaxies we can see

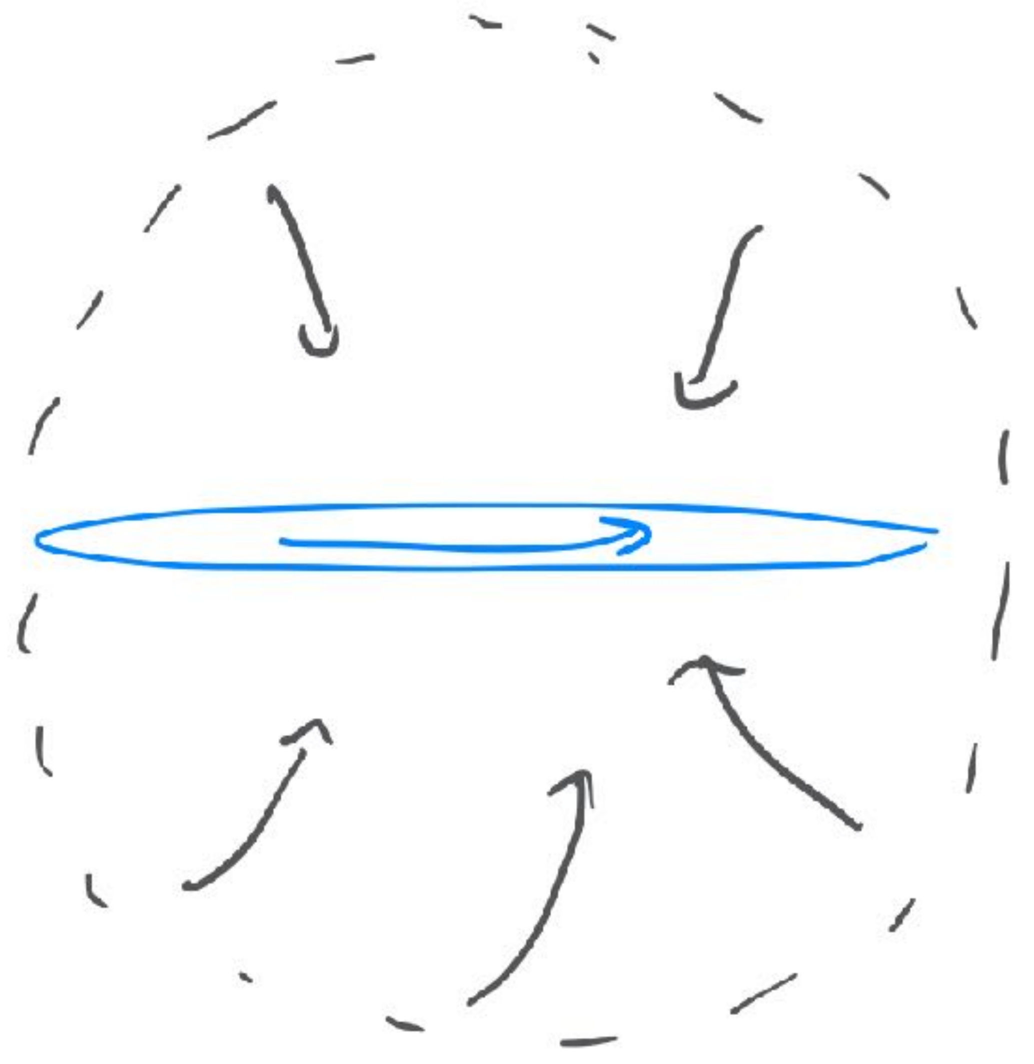


Collision of clusters: pink: x-ray image of gas; blue: mass inferred from gravitational lensing. There seems to be a heavy collisionless component of matter holding clusters together.

Dark matter and structure formation

Simulations of galaxy formation show that it **doesn’t work** unless we add a large amount of **dark matter** to help structure collapse.

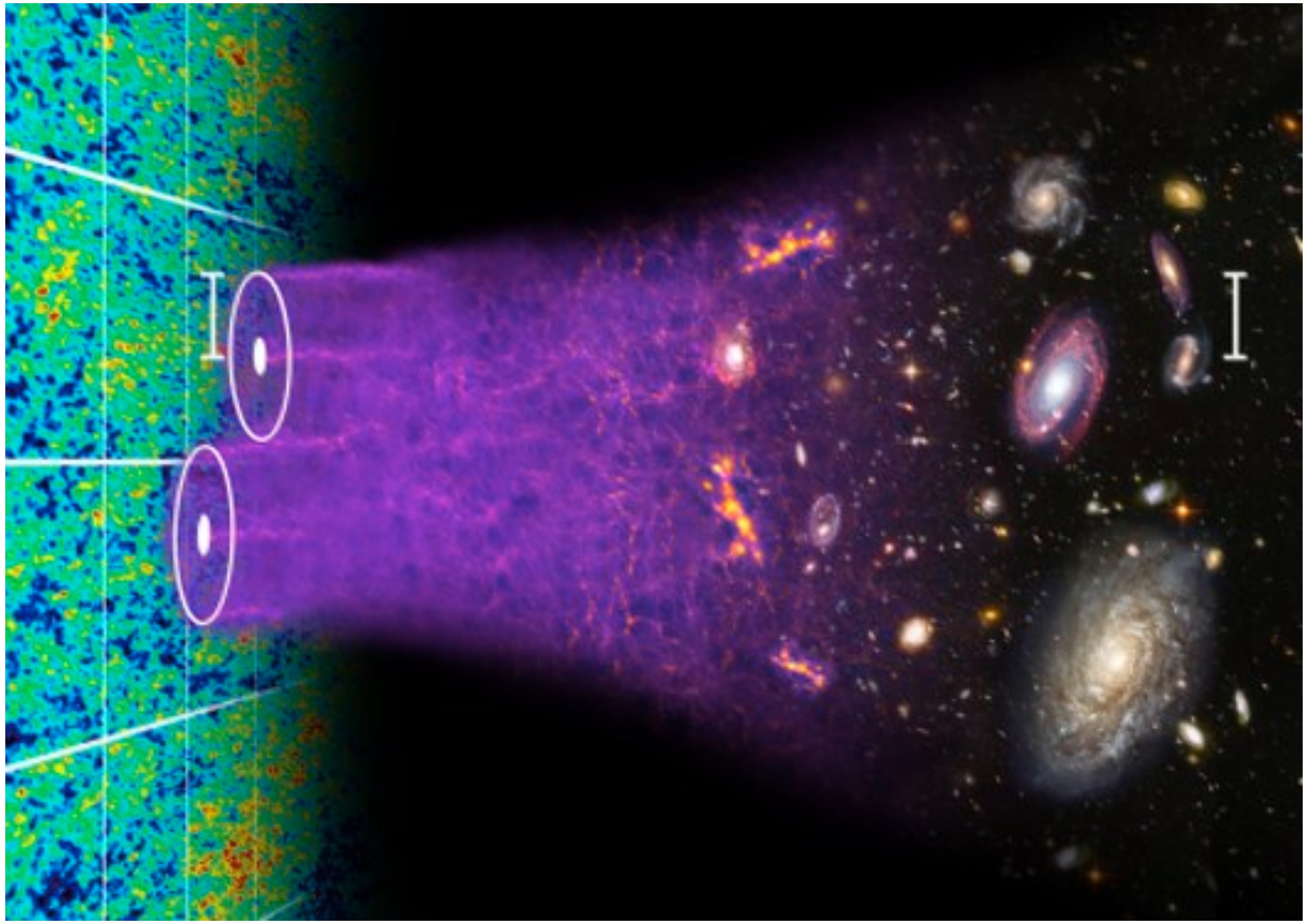
Given the known amount of stars and gas in the Milky Way, it would have taken **40 billion** years to collapse to its current size, under its own gravity



The problem is even worse on the scale of galaxy clusters

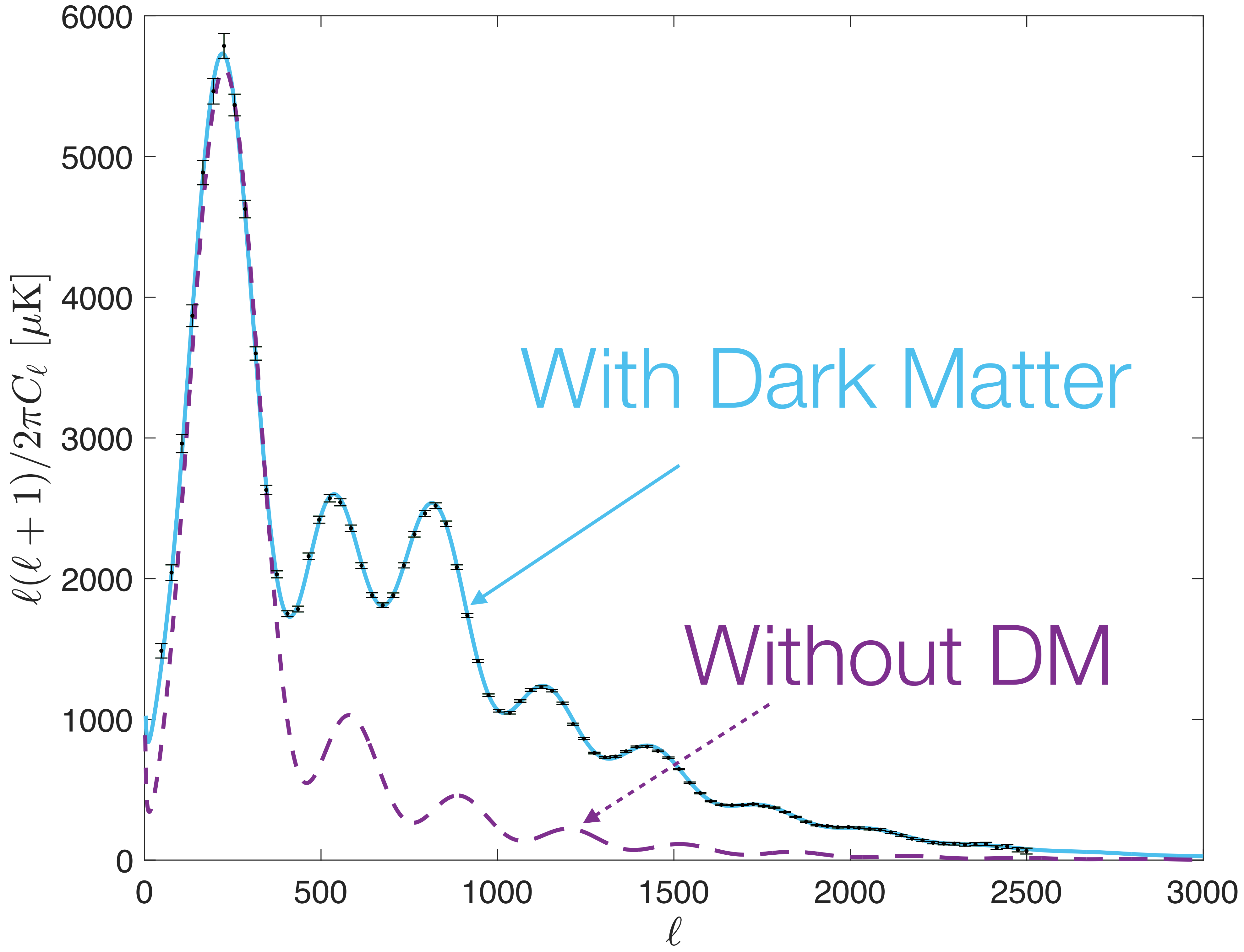
The cosmic microwave background

- The CMB is an imprint of the universe when it was ~300,000 years old (redshift z = 1000).
- It is a near-perfect blackbody, but with tiny fluctuations $\dfrac{\delta\rho}{\rho} \sim 10^{-5}$
- These fluctuations later grew to become the galaxies that we see today (well, not the ones we see. Those are somewhere else now)
- The behaviour of these fluctiations as a function of scale tells us what physics was acting at what scales.

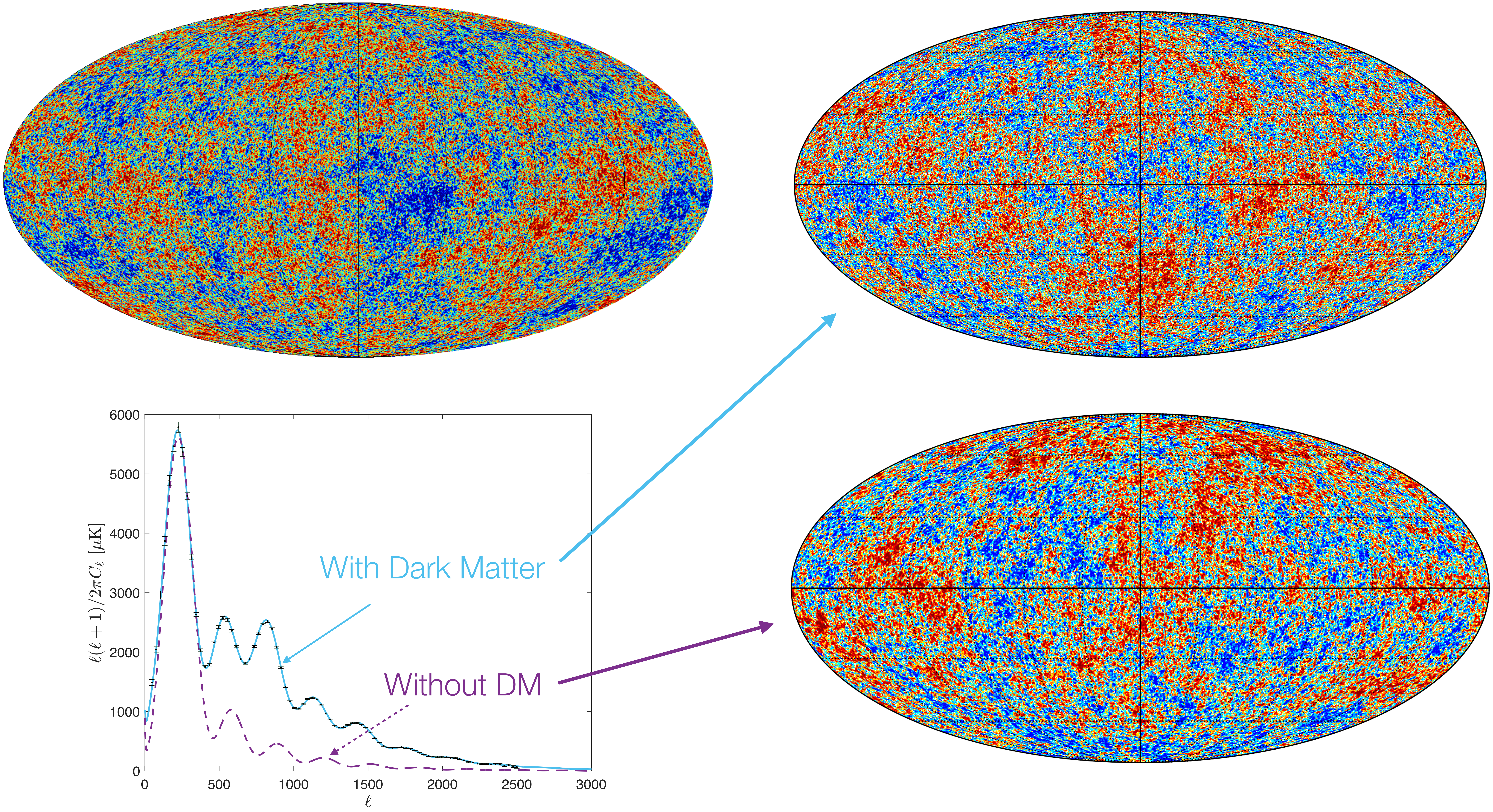


The Cosmic microwave background

Early Universe fluctuations on small scales



If all the matter in the universe is **baryonic** (i.e. normal matter) it exerts pressure preventing small scale fluctuations from growing. This would lead to **damping** of the CMB on small scales, inconsistent with data.



With Dark Matter

Without DM

What properties dark matter must have

- **Cold:** Its kinetic energy must be low enough (i.e. its temperature) so that it doesn’t “fly out” of galaxies. This is the reason **neutrinos** don’t work.

- **Dark:** More accurately: **transparent**. Can’t be seen, so does not interact with light (i.e., it’s neutral).

- **Matter**: It behaves, and clusters like matter, rather than like light.

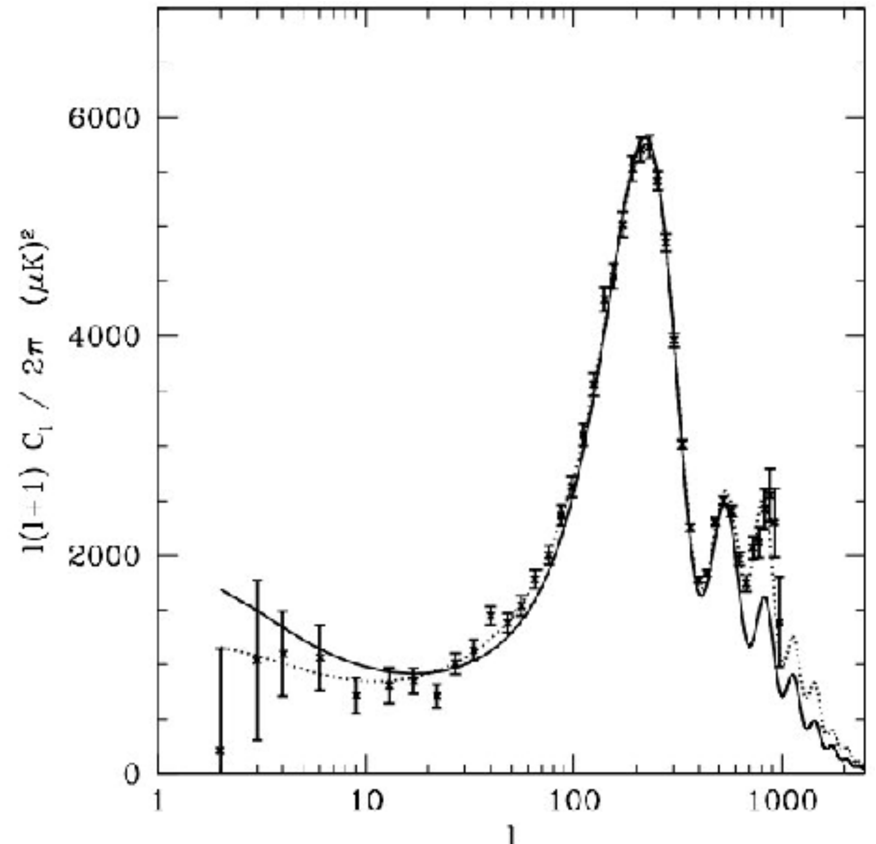
Current measurements suggest that **85% of the matter in the Universe** is in the form of **cold dark matter**

What is dark matter?

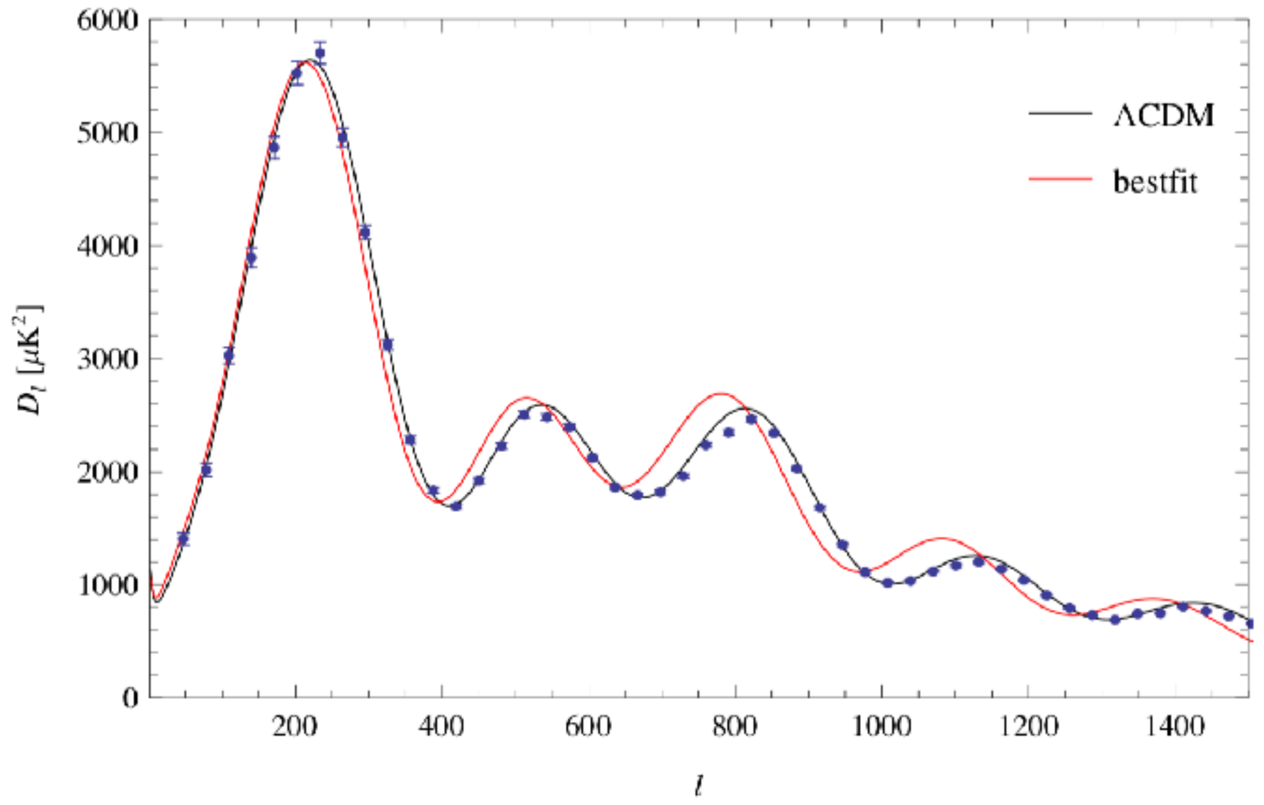
Vulcan? (i.e. we got gravity wrong?)

Theories of **modified gravity** can account for galactic rotation curves and cluster dynamics, but are not able to reproduce:
-Colliding galaxy clusters
-CMB
-Structure formation on all scales

MOND (Modified Newtonian Dynamics)

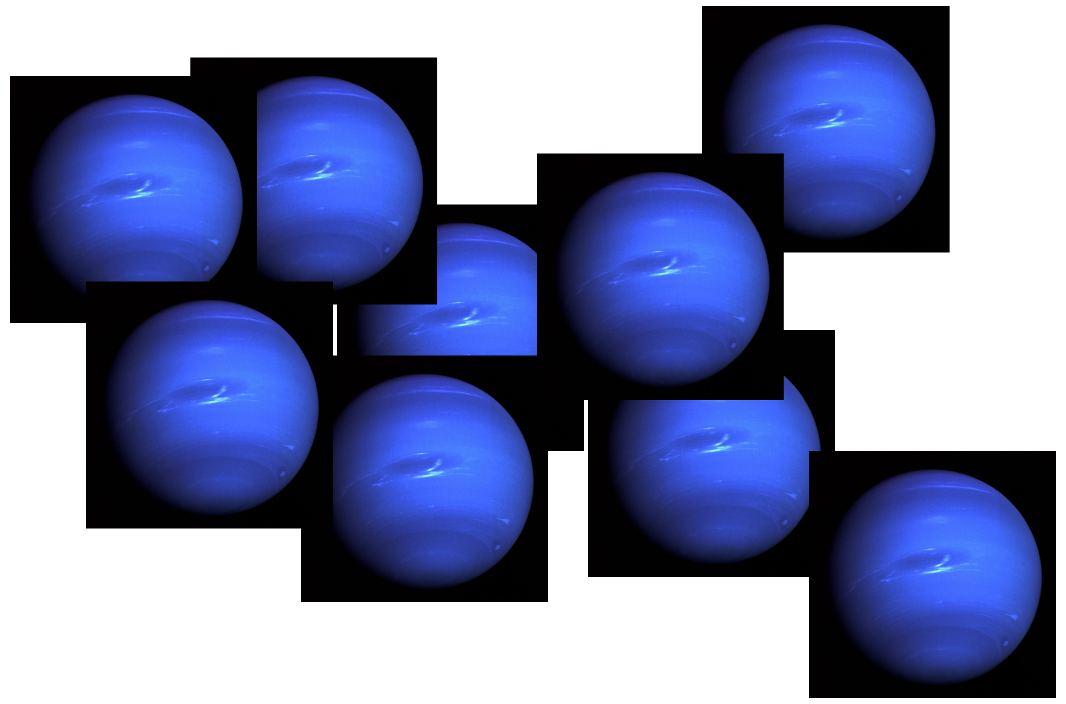


TeVeS gravity



What is dark matter?

Neptunes? (i.e. regular macroscopic objects that don't glow like stars?)



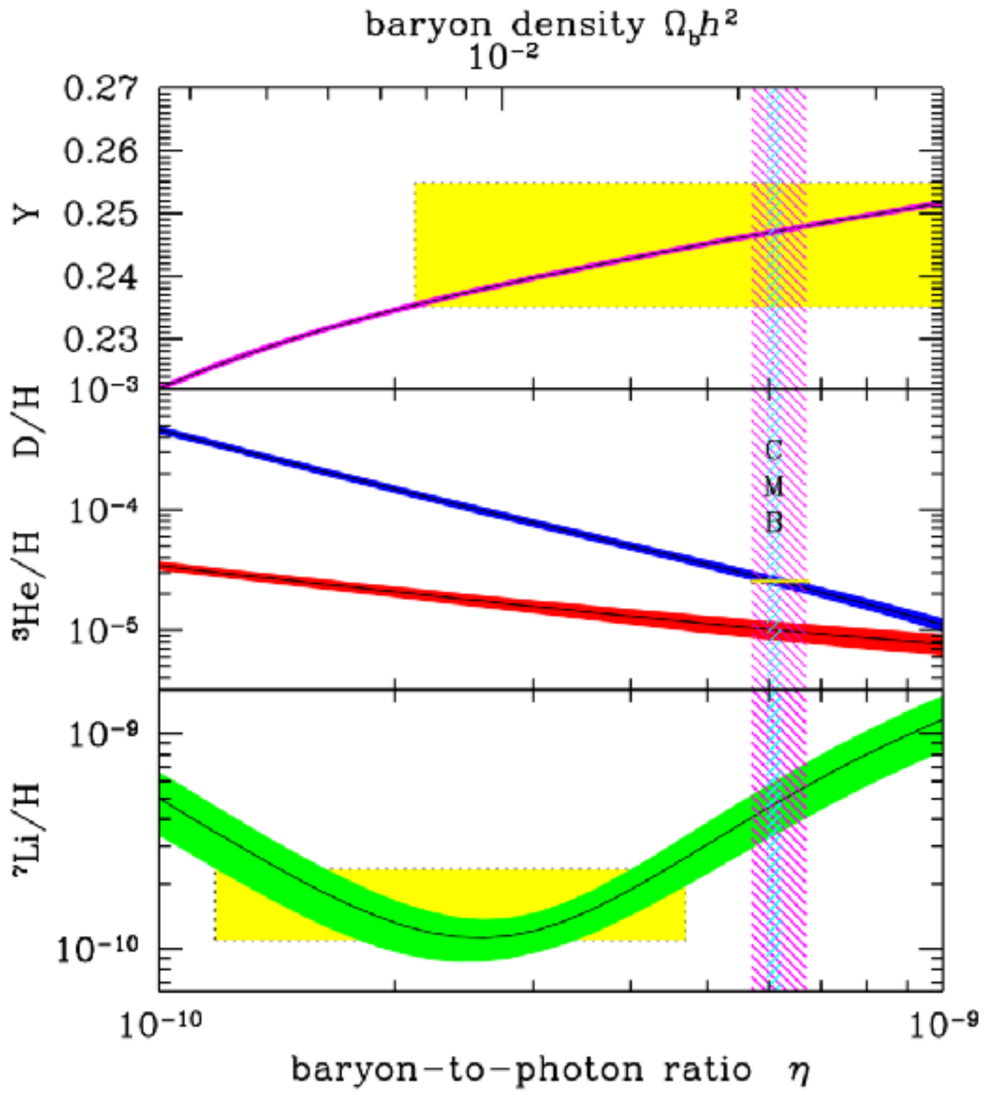
MACHOS: Massive Compact Halo Objects

-brown dwarfs

-rocks

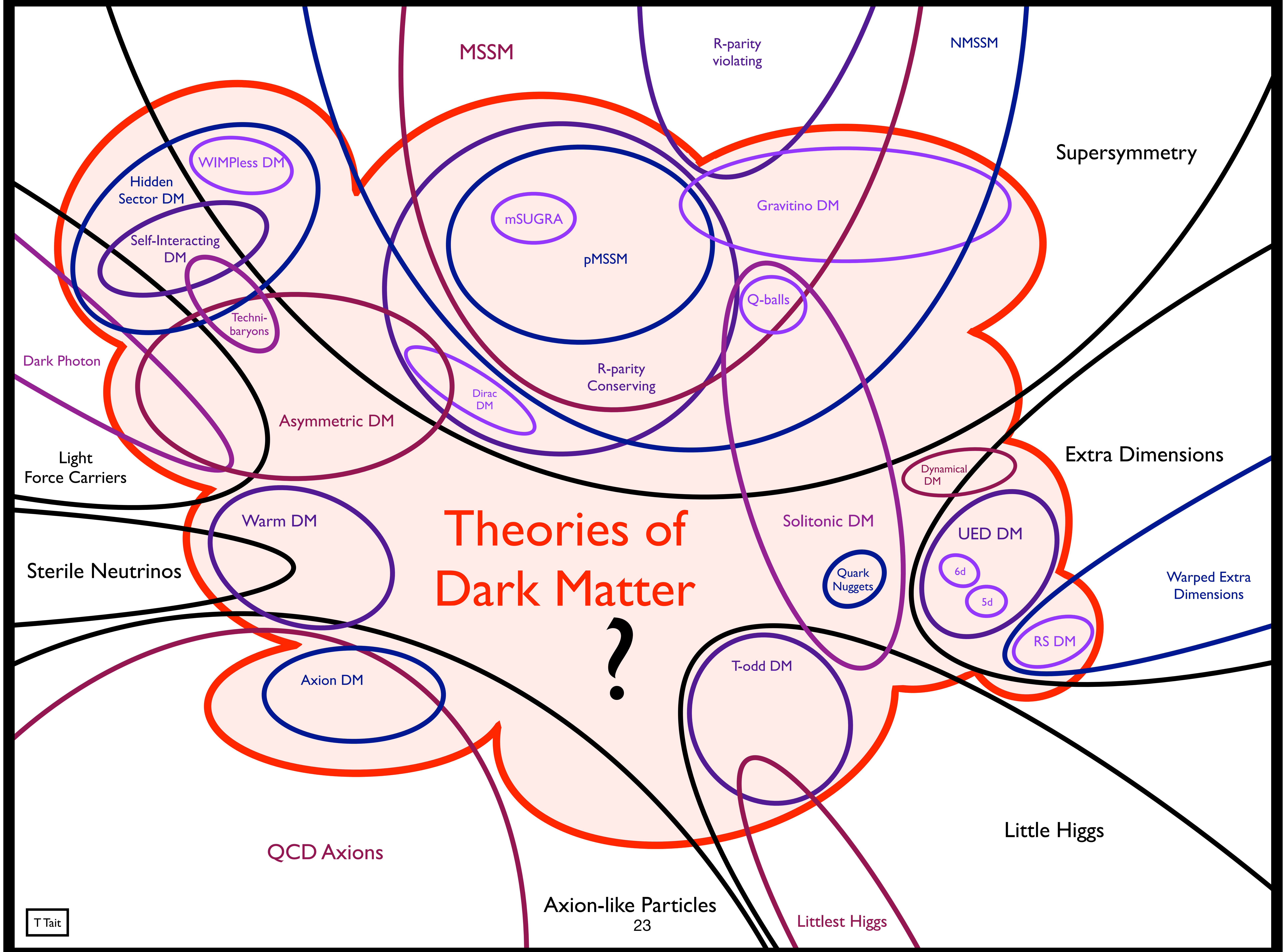
-planets

-jam 



This doesn't work. In the hot early universe these would have been atomized! We know from **nucleosynthesis** the amount of regular (baryonic) matter. Assuming the dark matter contributed to this gets it wrong by a factor of 5!

Theories of Dark Matter ?



MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Techni-baryons

mSUGRA

pMSSM

Gravitino DM

Q-balls

R-parity Conserving

Dirac DM

Dark Photon

Asymmetric DM

Light Force Carriers

Extra Dimensions

Dynamical DM

Warm DM

Solitonic DM

UED DM

Quark Nuggets

6d

5d

Warped Extra Dimensions

Sterile Neutrinos

RS DM

T-odd DM

Axion DM

Little Higgs

QCD Axions

Axion-like Particles

Littlest Higgs

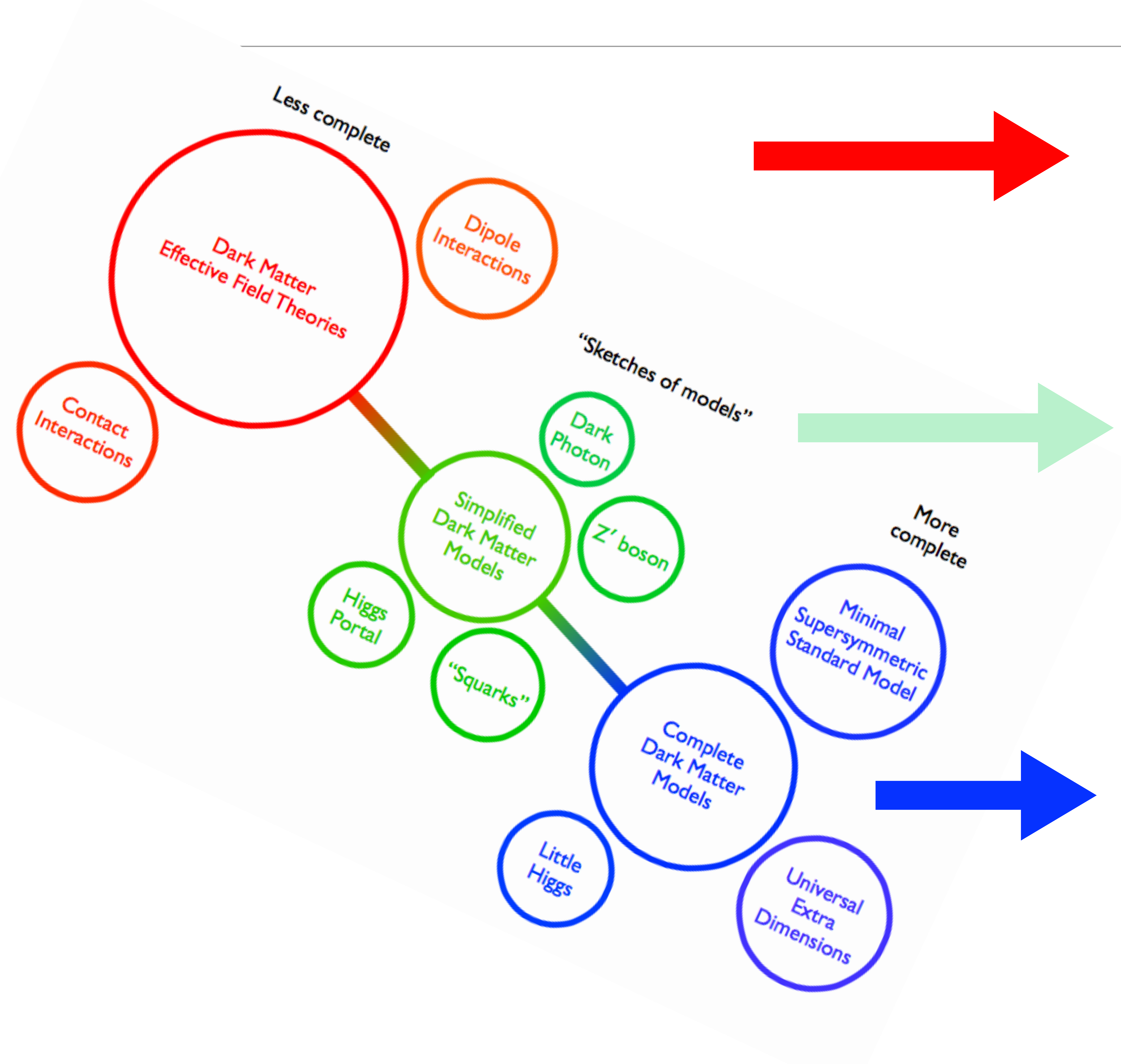
T Tait

A Map of The Charted and Uncharted Territories of Dark Matter and its Theories

A. C. Vincent

Caveats

Models



These break down if the scale you are probing reaches the effective coupling scale

Need to be careful with gauge invariance, anomaly cancellation. Adding new particles often imposes new couplings for SM particles, or new particles altogether. Patrick Tunney has some nice papers about this

Observables are model-specific:

$$\mathrm{Prob}\left(\begin{array}{c}\text{your model}\\ \text{is true}\end{array}\right) \ll 1$$

2. Detour: Self defence against Lagrangians

Self-Defense against Lagrangians

In classical physics $L = T - V$

$$T \downarrow \tfrac{1}{2}\dot{x}^2$$

$\frac{d}{dt}$ not

↓

boost → time dilation

↳ frame dependent

$$L = \int d^3x \, \mathcal{L}$$

↳ boost invariant

$\mathcal{L}$ contains the energy budget

- kinetic
- mass
- interactions

} potential energy

$(c = \hbar = k_B = 1)$

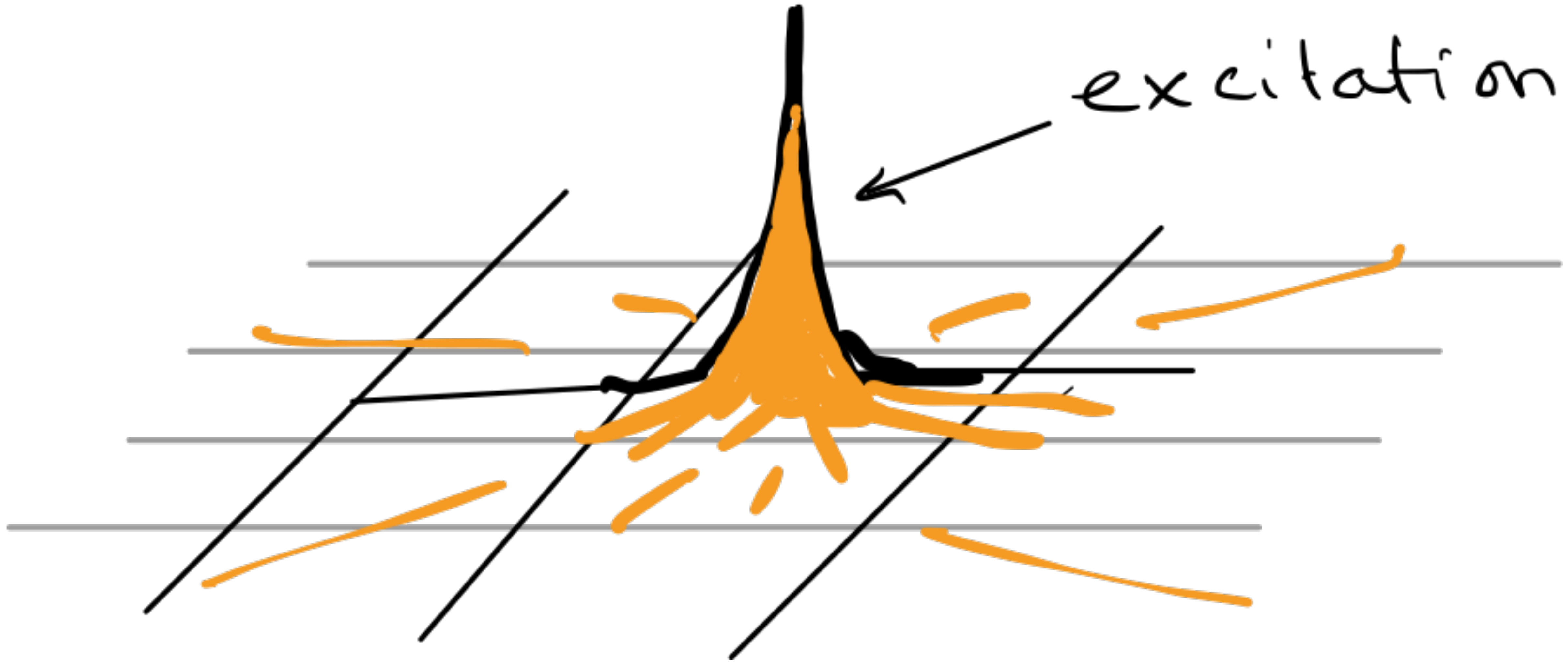
I Ingredients

Particles are represented as fields

$\phi(\vec{x},t)$: generic boson (spin 0)

$\psi(\vec{x},t)$: generic fermion

$A^{\mu}(\vec{x},t)$: little μ means it's a spin-1 boson (vector)



excitation of the field at some $t, \vec{x}$: there is a particle

Standard model particles

Spin

$\frac{1}{2}$ $\quad \underbrace{e^\pm, \mu^\pm, \tau^\pm}_{\ell^\pm}, \nu_\ell, \quad q \begin{Bmatrix} u & s & t \\ d & c & b \end{Bmatrix} \quad \bar{\nu}_\ell \quad \bar{q}$ } boring fermions $f, \bar{f}$

1 $\quad A^\mu, W^\mu_\pm, Z^\mu, g^\mu$ } force carriers

0 $\quad h$ higgs

Exciting new particles

$\frac{1}{2}$ $\quad \chi, \bar{\chi}$ (sometimes $x, \bar{x}$) cool new fermion!

1 $\quad A', Z'$ cool new vector

0 $\quad \phi$ new scalar (can be real or complex)

II Kinetic and mass energy

∂^μ, $\partial_\mu = \frac{\partial}{\partial x^\mu}$: like $\frac{\partial}{\partial t}$, but all coordinates $\mu = t, x, y, z$

γ^μ, γ_μ : this is a Dirac matrix, it lets fermions talk to spacetime

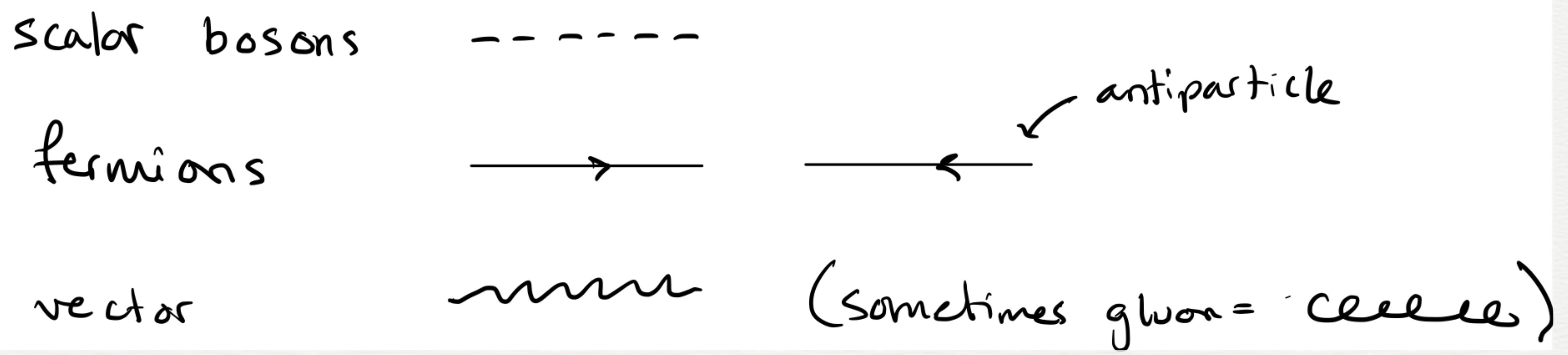
If it has ∂'s, it's probably a kinetic term

$$\partial_\mu \phi \partial^\mu \phi, \quad \bar{\Psi} \not{\partial} \Psi, \quad F^{\mu\nu} F_{\mu\nu}, \text{ where } F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

if it has an m and 2 powers of the same field, it's the particle's mass

$$\frac{1}{2}\mu\phi^2, \quad m\bar{\Psi}\Psi \quad \frac{1}{2} m A^\mu A_\mu$$

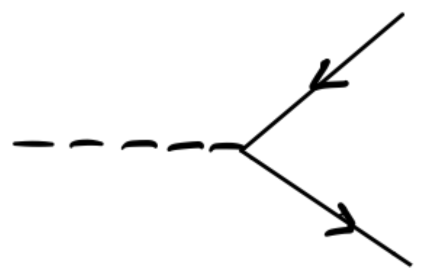
Together, they give us the propagator



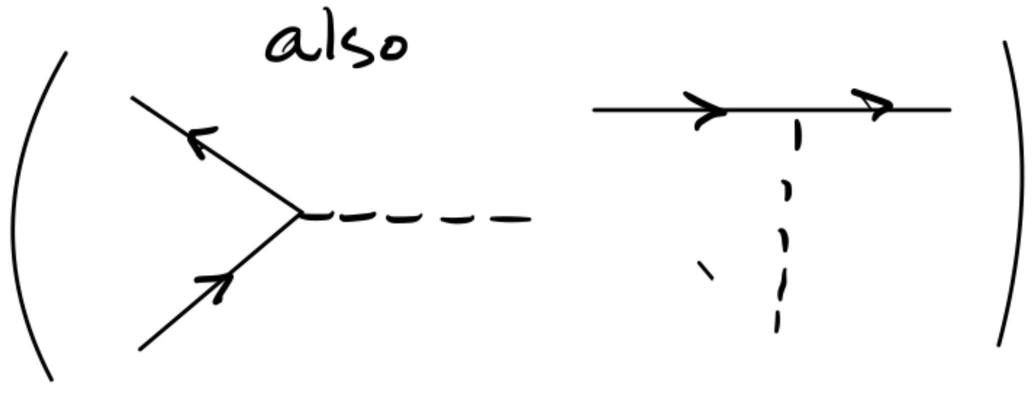
III Interactions

If a term mixes fields, it is parametrizing interactions.

$g\phi\bar\Psi\Psi$ ⇒



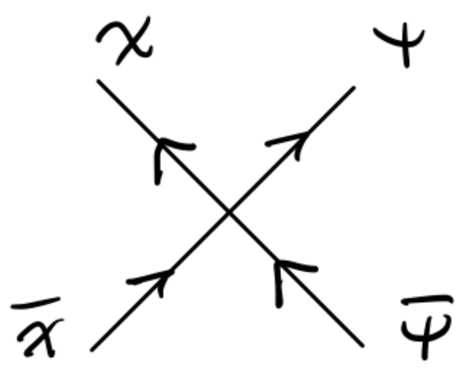
also



strength of interaction

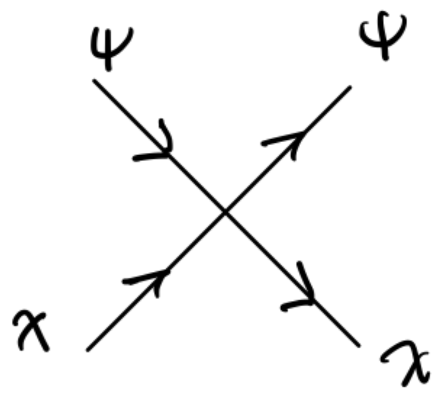
note $\chi \rightarrow$ are continuous as are $\Psi \rightarrow$

$g\bar\Psi\Psi\bar\chi\chi$ ⇒



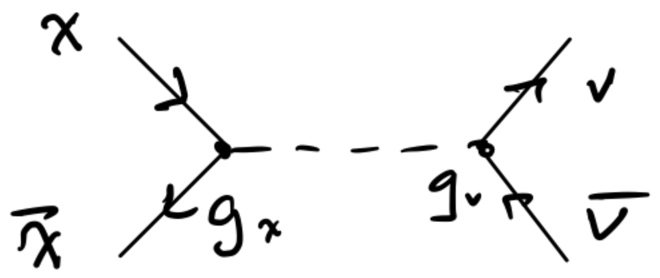
annihilation

and

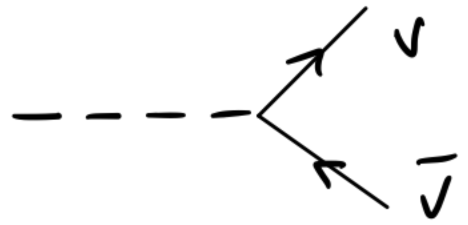


scattering

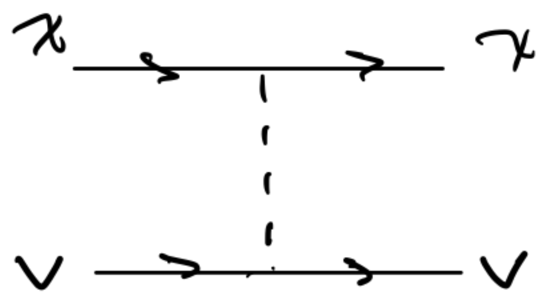
Can assemble to get e.g.



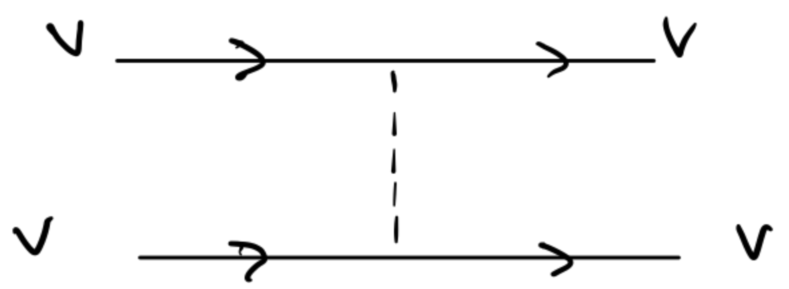
dark matter annihilation to neutrinos



scalar decay to ν



dark matter scattering with neutrinos



neutrino self-interaction (watch out!)

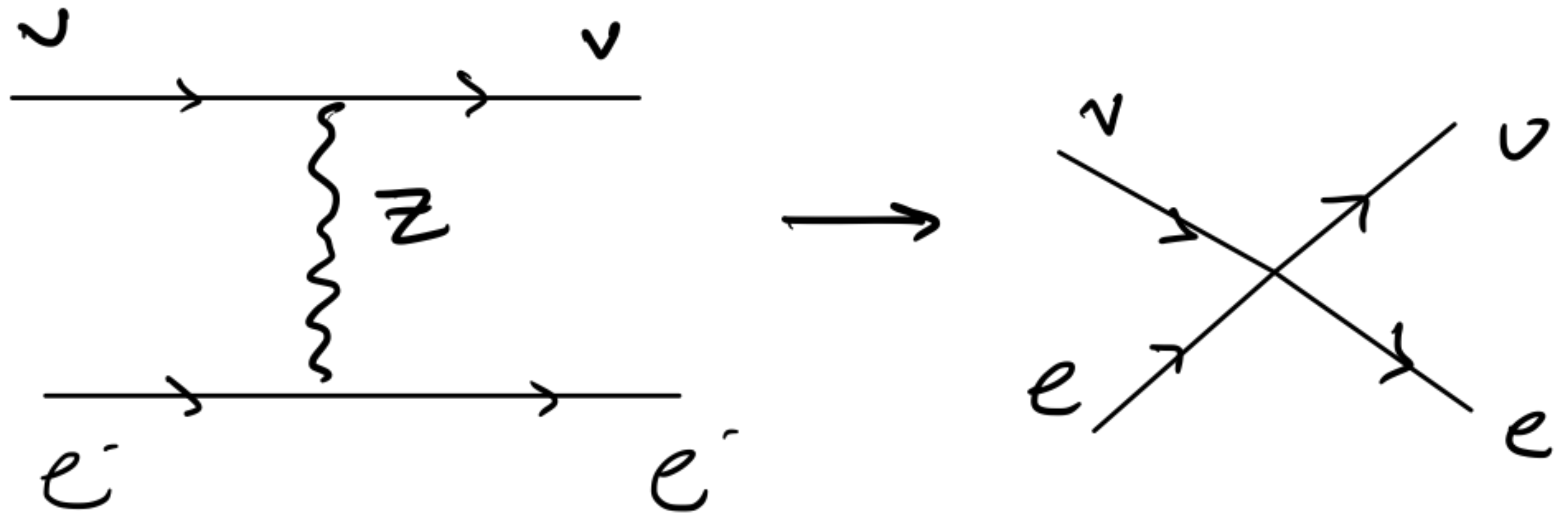
$$\mathcal{L} = \mathcal{L}_{SM} + \underbrace{\frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \bar\chi\not\partial\chi}_{\text{kinetic}} \underbrace{-\frac{1}{2}m^2\phi^2 - m\bar\chi\chi}_{\text{masses}} \underbrace{-g_\nu\phi\bar\nu\nu - g_\chi\phi\bar\chi\chi}_{\text{new interactions}}$$

Standard model exists

$\mathcal{L}$ must be Lorentz-invariant, Hermitian, $[\mathcal{L}] = E^4$

Notes

- If $m_\phi \gg$ energies you can probe, we can "shrink" these interactions to a point



$$\mathcal{L} \supset G_F \bar{\nu}\nu\bar{e}e$$

↓ "effective coupling"

This is an **effective theory** and is valid for $E \ll m_Z$

It is not UV-complete = valid to arbitrarily high energies. That's fine, nothing is.

- DM doesn't need to be a fermion. Could be a scalar or vector. Same rules apply

If a theorist asks

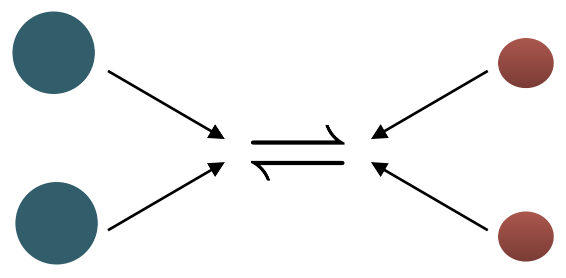
- Q: Why are your fields out of order?
  - A: Those terms are Hermitian, it’s fine
- Q: Your theory isn’t renormalizable
  - A: It’s an effective theory, it’s fine
- Q: Why are your derivatives out of order?
  - A: I integrated by parts, it’s fine.
- Q: Are you talking about chirality or helicity?
  - A: We’re not relativistic here, those concepts aren’t well-defined
- Q: Are those spinors Weyl, Dirac, or Majorana?
  - A: (Run away screaming)

3. Some leading dark matter candidates

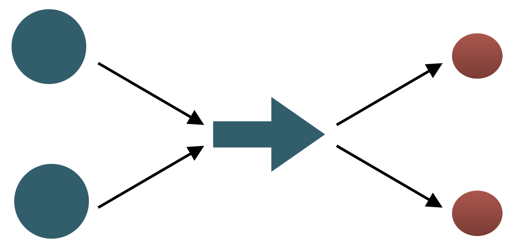
The WIMP

Weakly Interacting Massive Particle

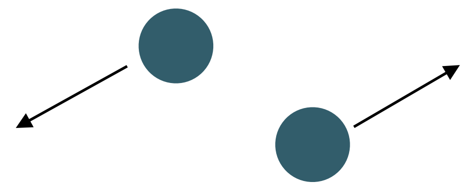
1) At very high temperatures, particles are created and destroyed in the plasma, maintaining **equilibrium** as long as $k_B T \gtrsim M$

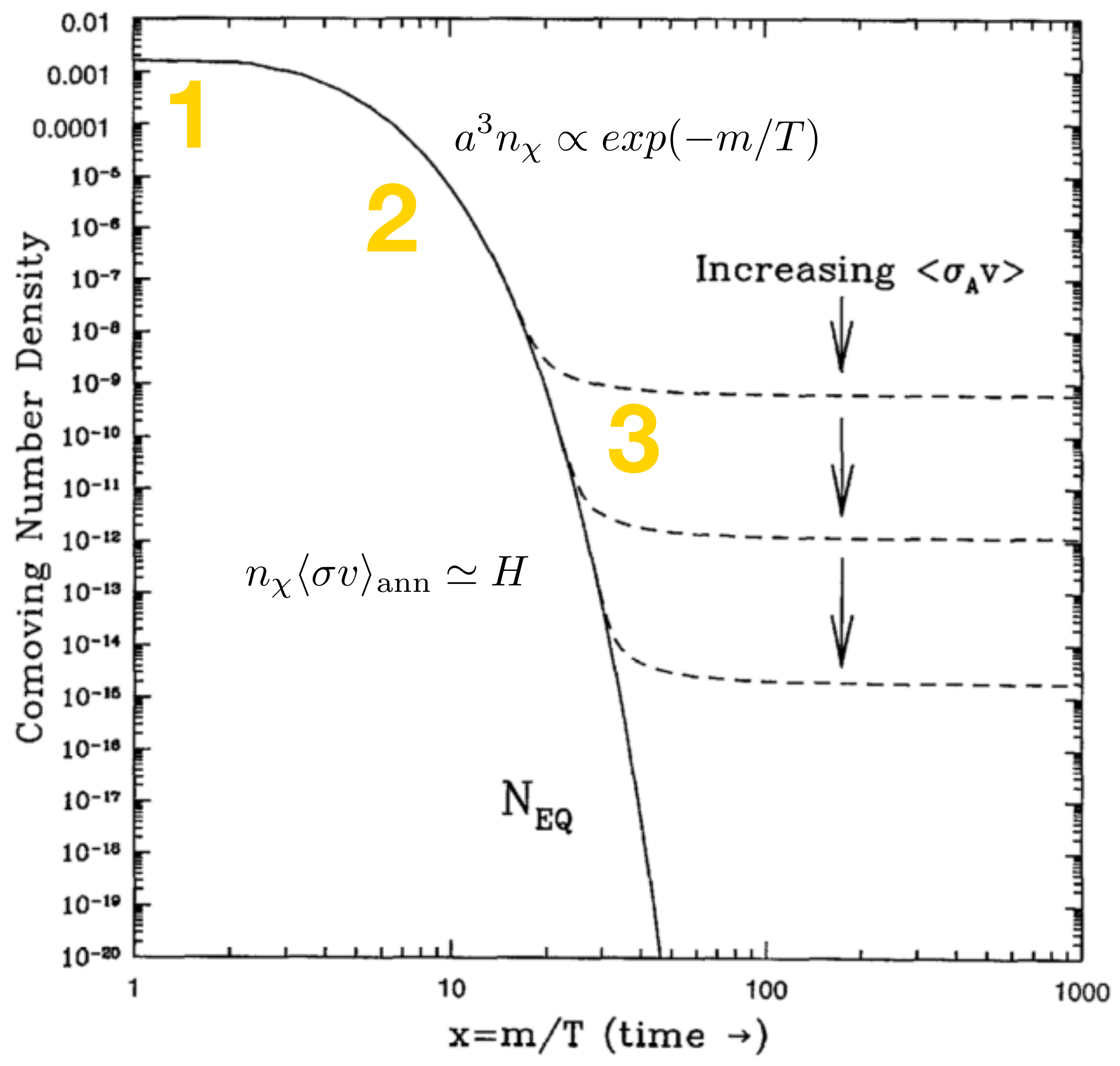


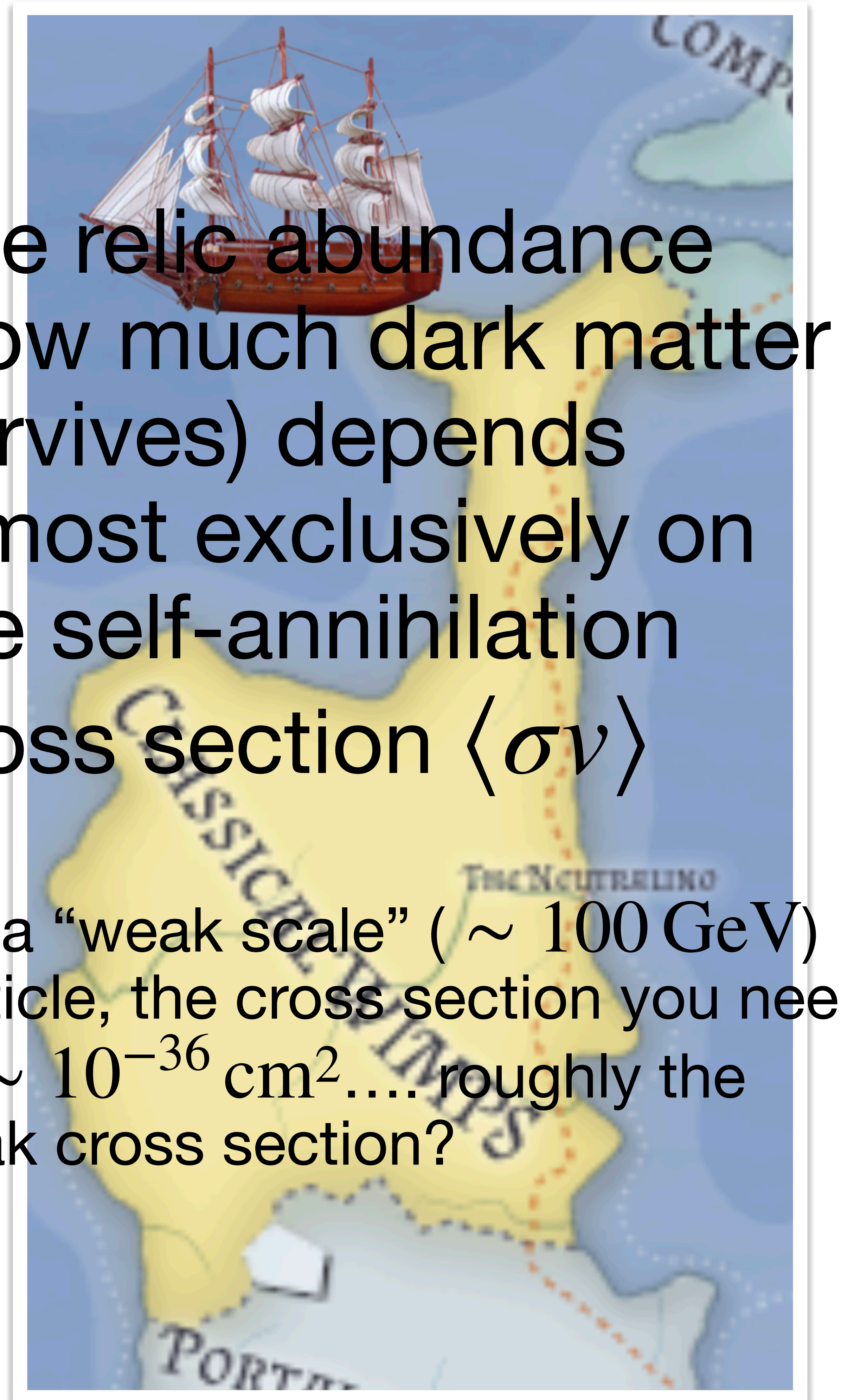
2) Falling temperature: heavy particles become Boltzmann suppressed (harder to make them, not enough energy)



3) **Freeze-out** occurs when Hubble expansion stops annihilation







The relic abundance (how much dark matter survives) depends almost exclusively on the self-annihilation cross section $\langle \sigma v \rangle$

For a "weak scale" ($\sim 100\,\mathrm{GeV}$) particle, the cross section you need is $\sim 10^{-36}\,\mathrm{cm}^2$.... roughly the weak cross section?

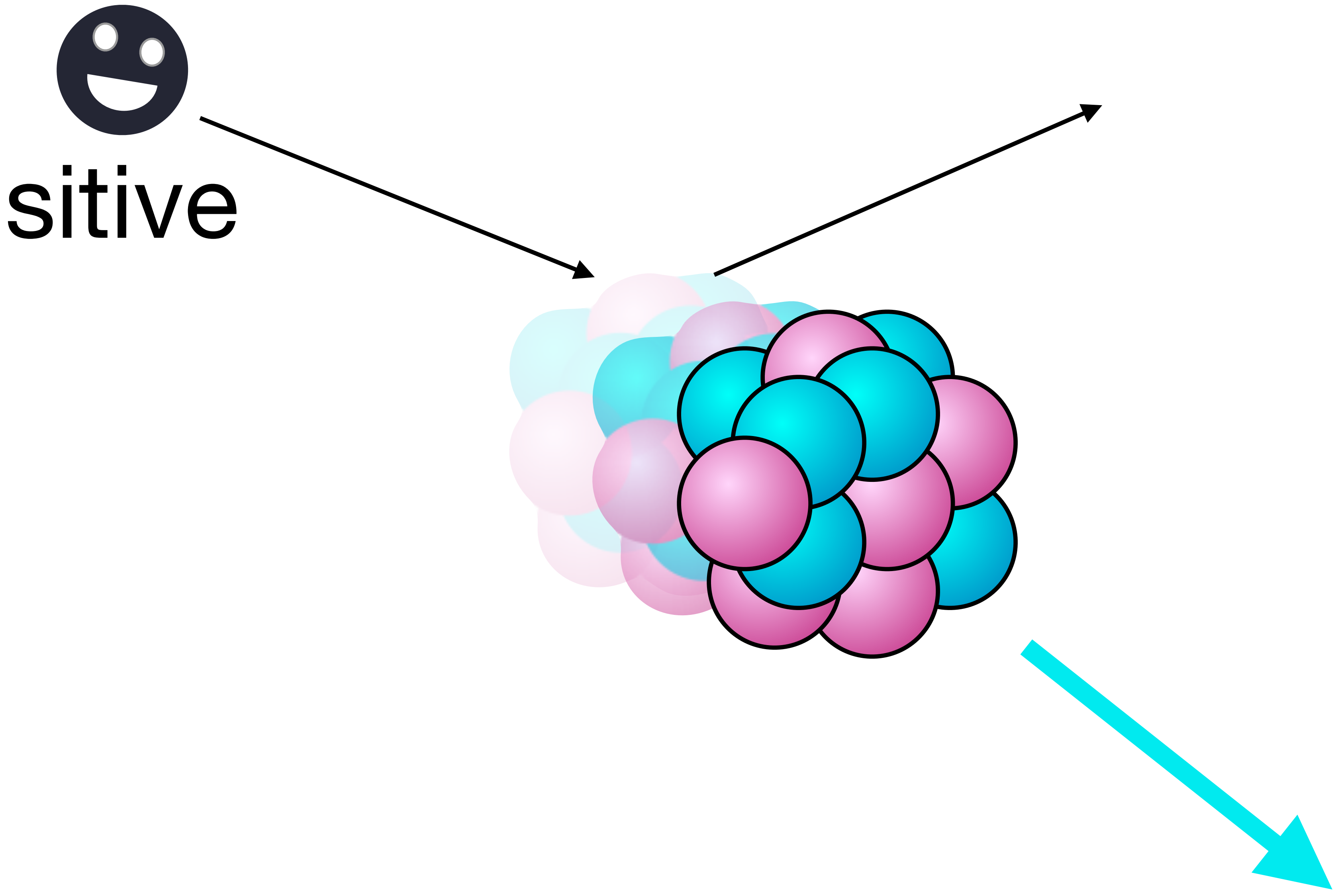
it's the WIMP miracle!

The WIMP

Weakly Interacting Massive Particle

Generically $\mathscr{L} \supset \bar{\chi}\chi\bar{f}f$
(doesn't need to be a fermion)

- Mass ~ 1-1000 GeV (but you can go even further)
- "weak-scale" cross sections
- Many theories of supersymmetry predict a WIMP-like particle.
- Can look for dark matter annihilating into energetic stuff, or bonking into nuclei in sensitive experiments (what many of you are doing)



The axion

photon field strength

$$\underset{\text{axion field}}{a}\, \tilde{F}^{\mu\nu} F_{\mu\nu} \propto a \vec{E} \cdot \vec{B}$$

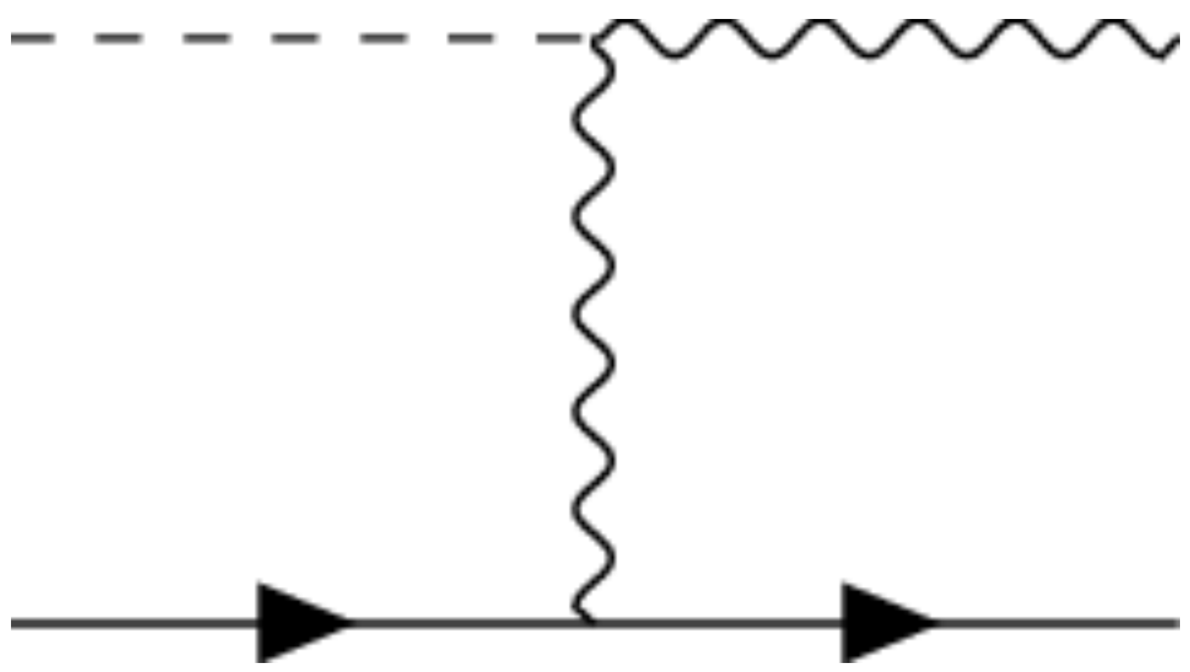
- The strong CP problem: The neutron electric dipole moment seems to be zero, and there’s no good reason for that.

- Peccei & Quinn introduced a solution, which happens to also predict a new scalar particle (if this seems suspicious, this is how the Higgs was predicted)

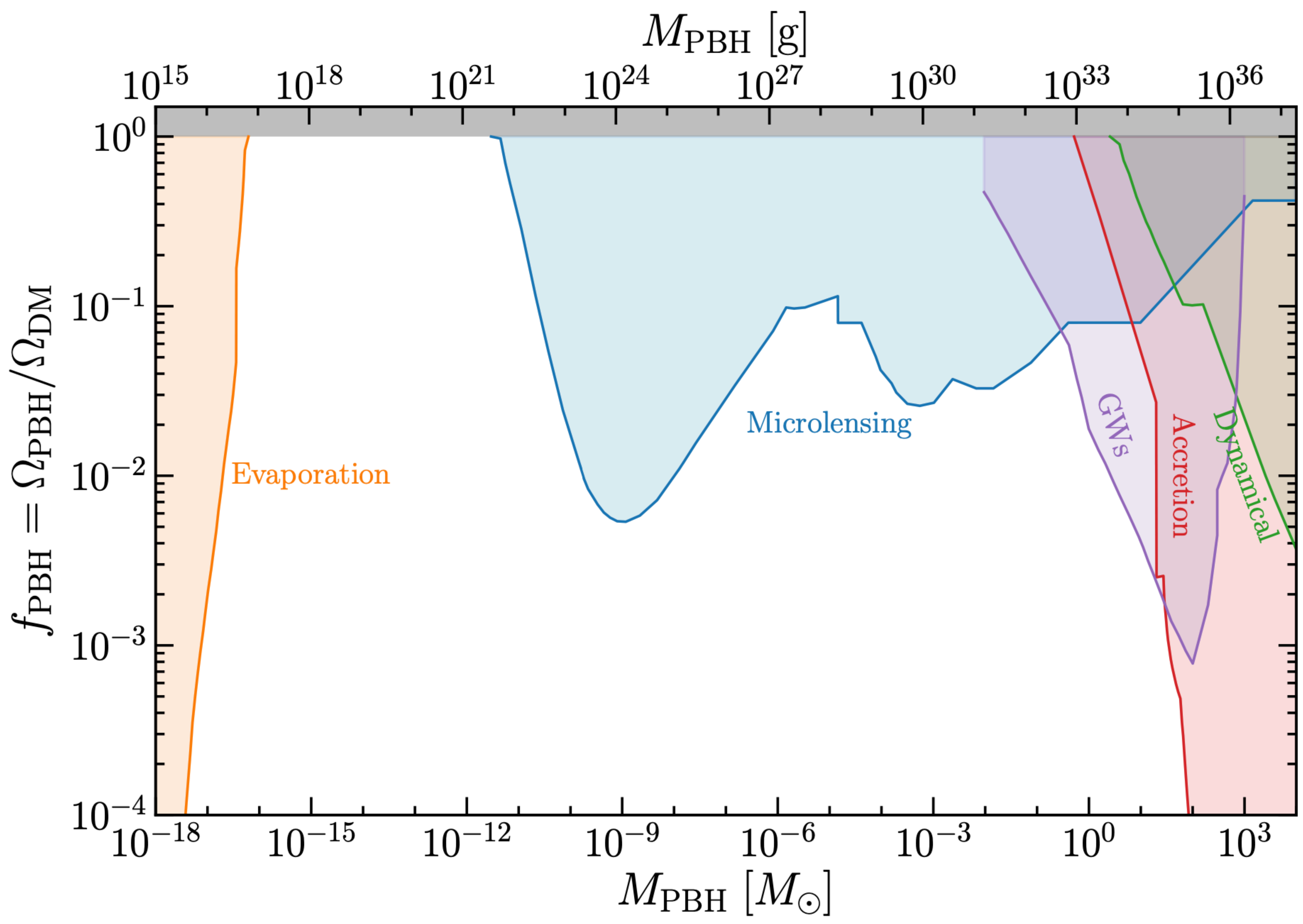
- For this to be dark matter, it must be light ($m \sim 10^{-6}$ eV)

- The same mechanism could pop up independent of the strong CP problem, giving **axion-like particles** (ALPs). The could be ultralight and weird, behaving like waves on galactic scales.

- Axions can ‘convert’ into a photon in the presence of a magnetic field. “Light-shining-through-walls” experiments are a classic way to look for them.



Primordial black holes



Green & Kavanagh

If some mechanism existed in the early universe to produce black holes, they would behave just like dark matter.

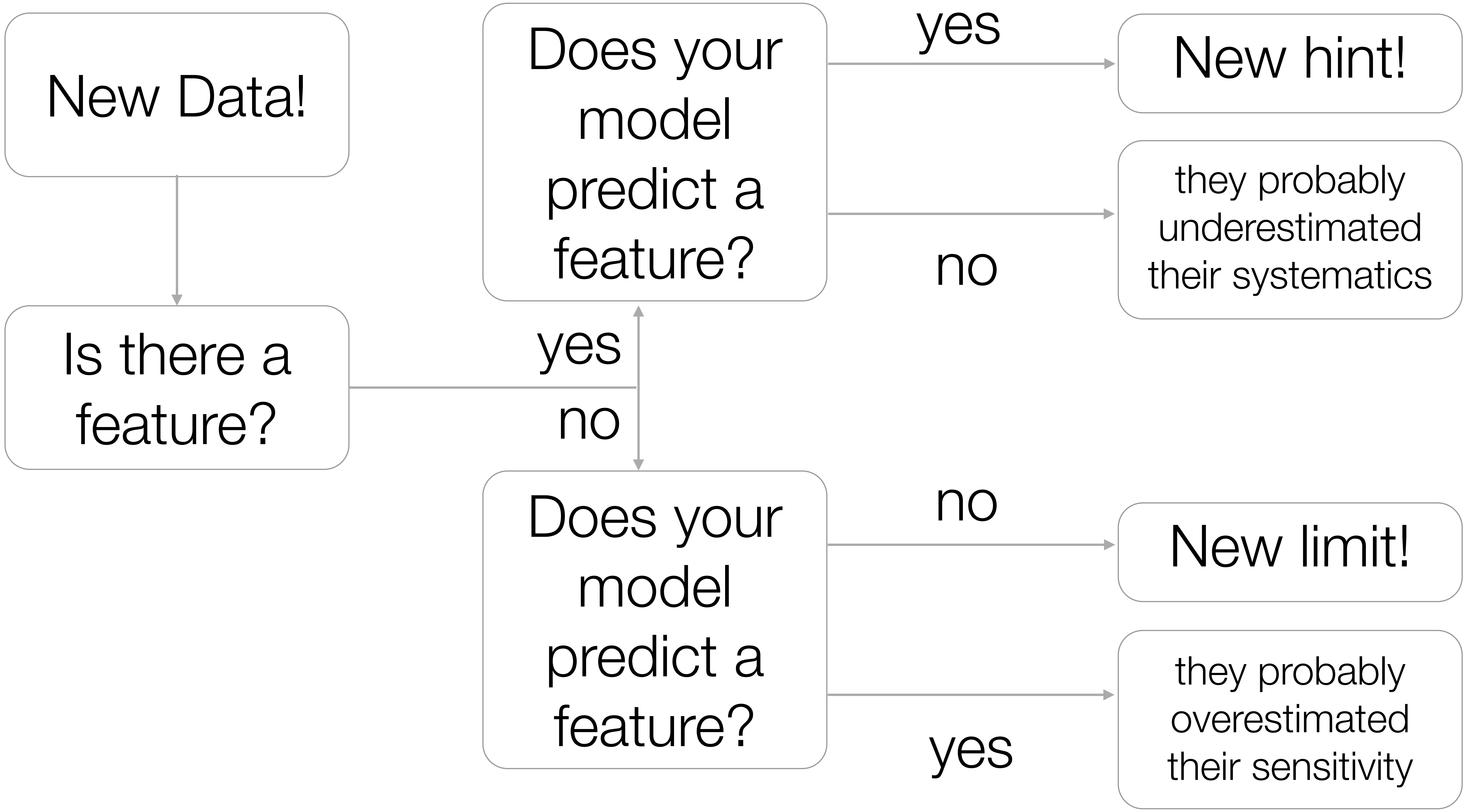
They could have survived until today.

High mass: limits from microlensing & dynamics

Low mass: limits from Hawking evaporation

3. Looking for dark matter (part 1)

DM phenomenologist's guide to new data



New Data!

Is there a feature?

yes

no

Does your model predict a feature?

yes

New hint!

no

they probably underestimated their systematics

Does your model predict a feature?

no

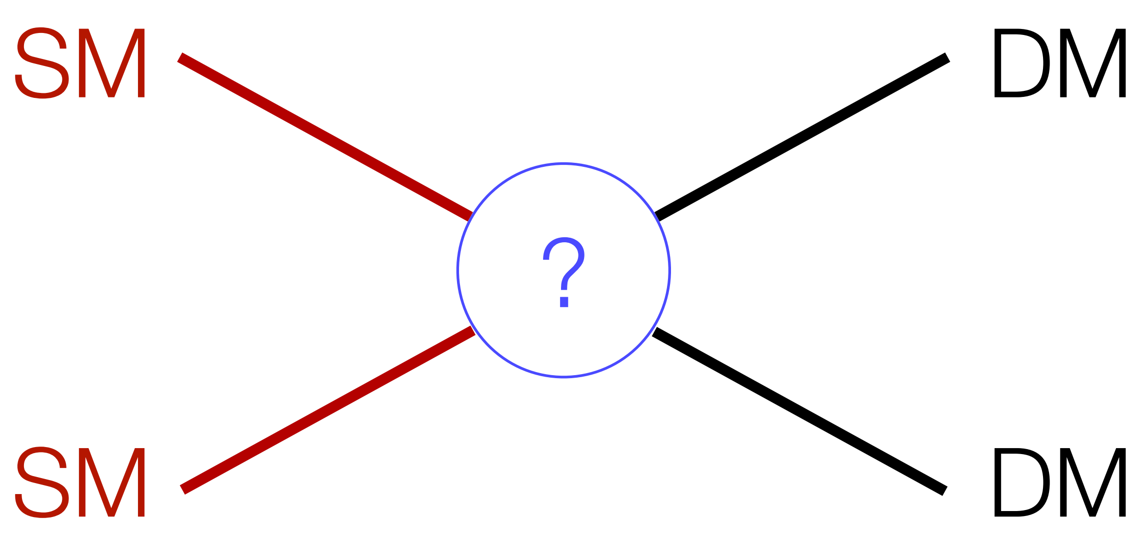
New limit!

yes

they probably overestimated their sensitivity

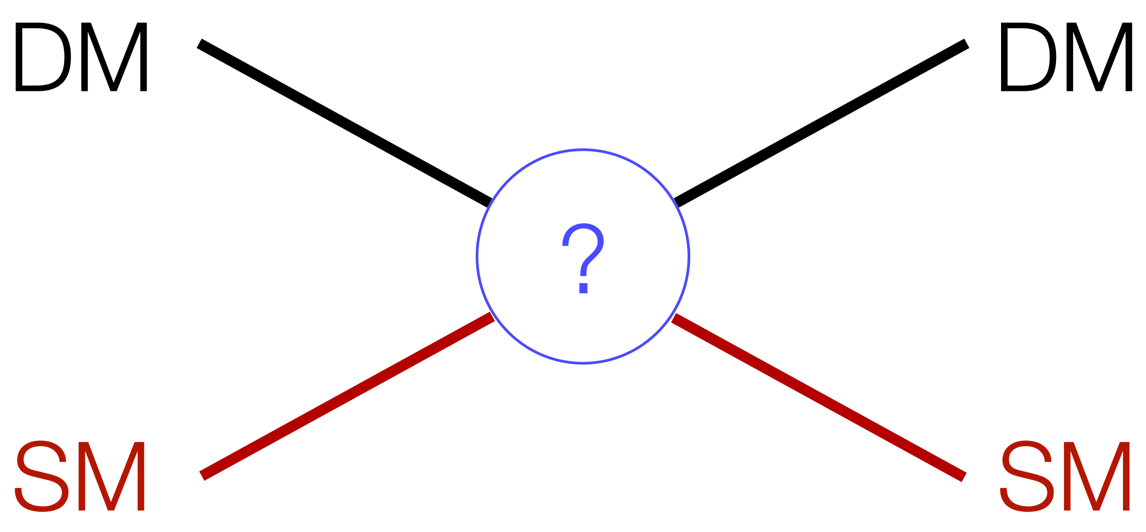
Laboratory searches for particle dark matter

make it



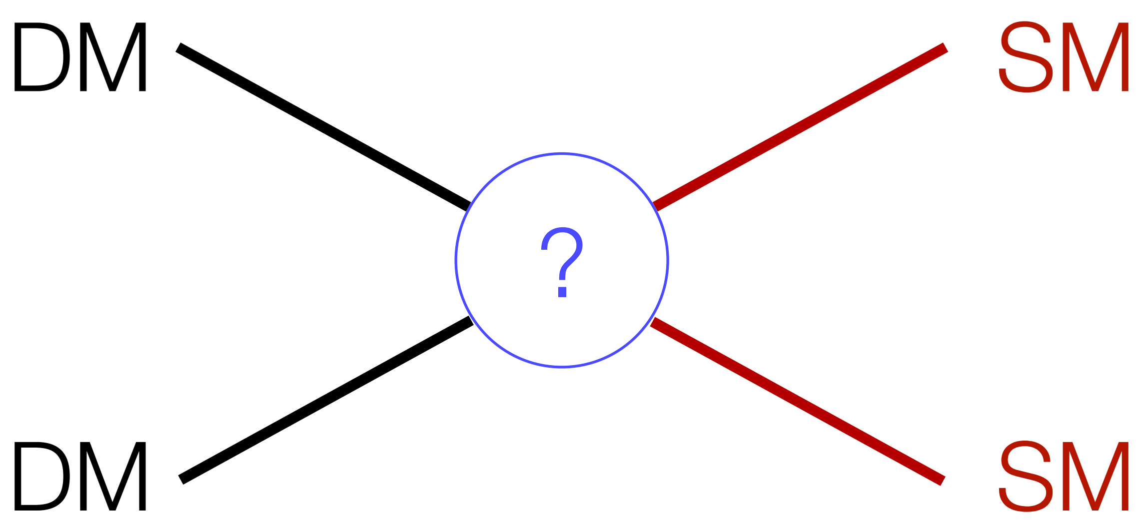
collider searches

shake it



direct detection

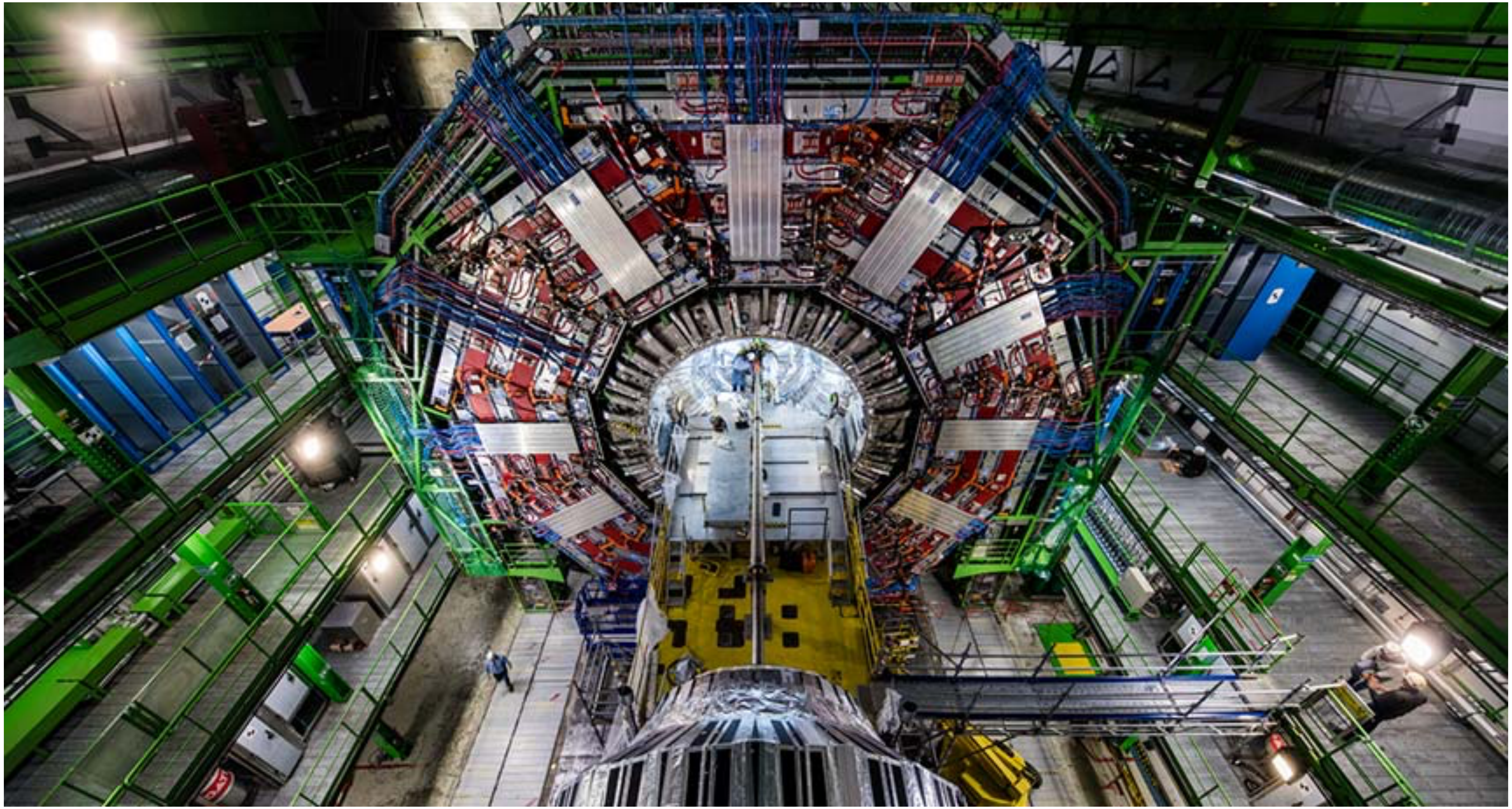
break it

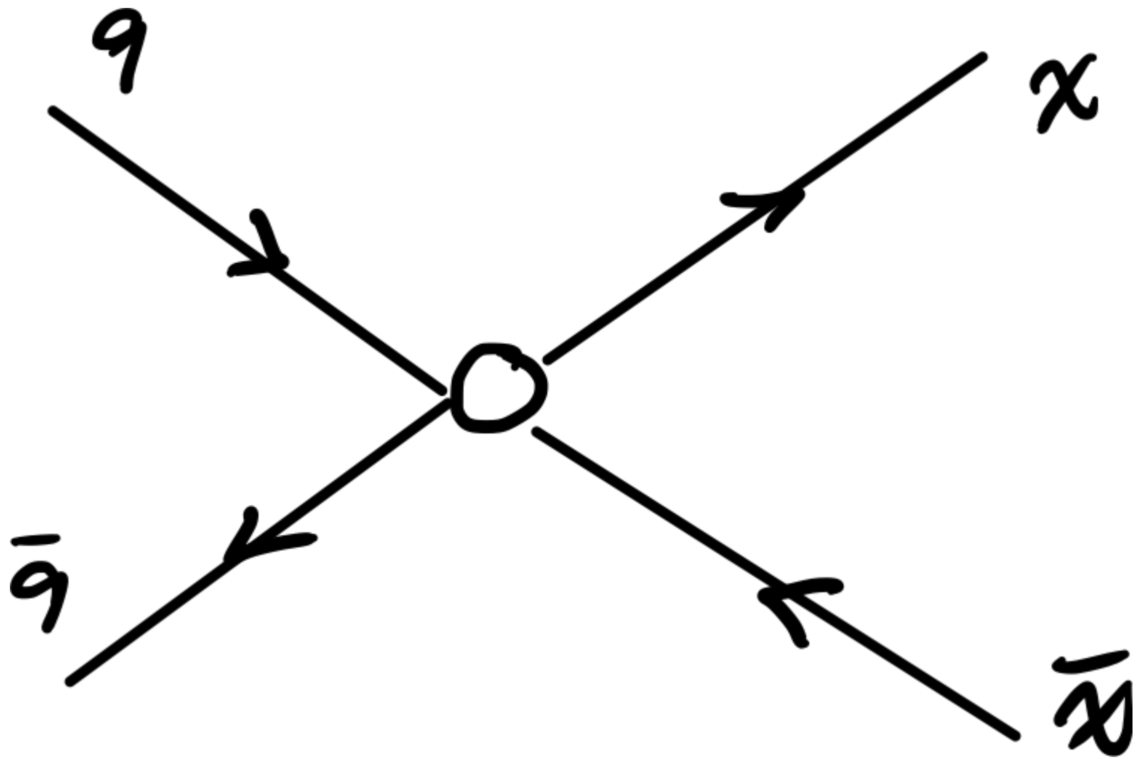


indirect detection

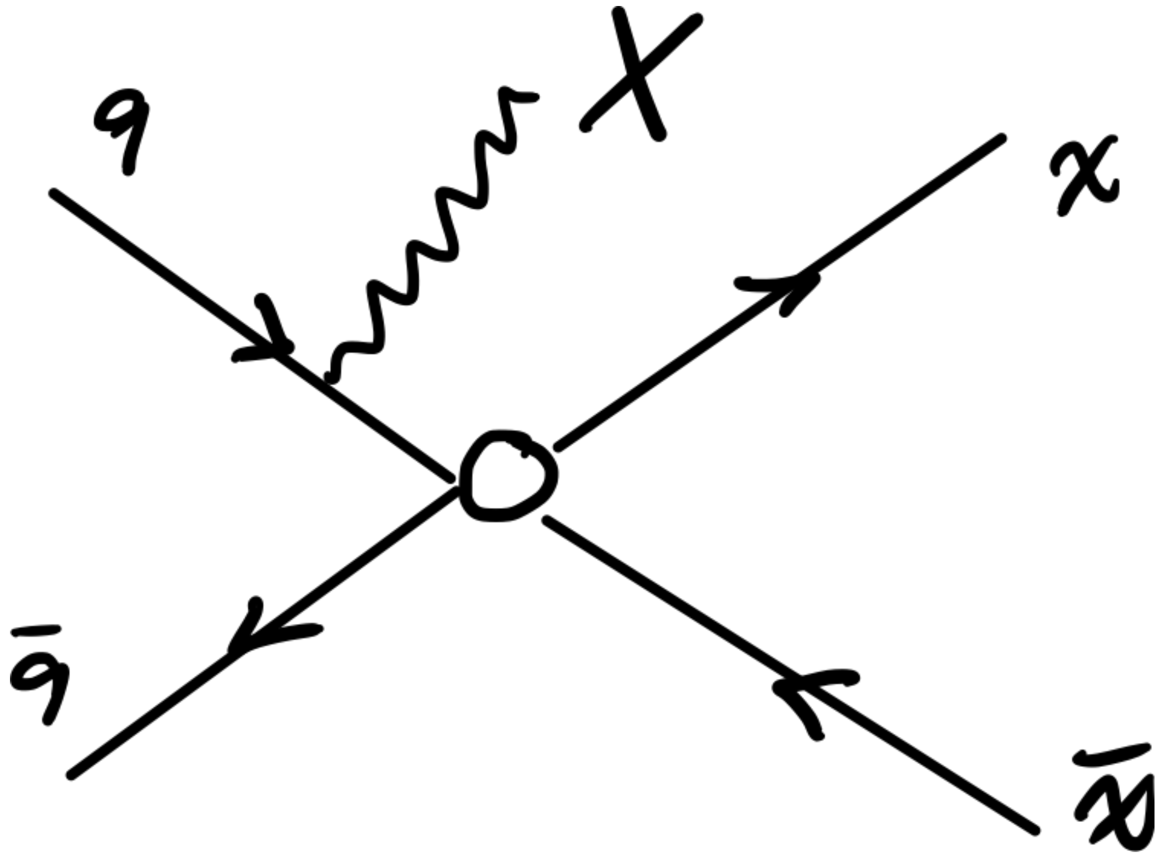
the next 2 talks

By colliding particles with $E_{cm} > m_{DM}$, can produce dark matter particles as long as they are strongly coupled enough to the SM particles being collided.





can’t be seen



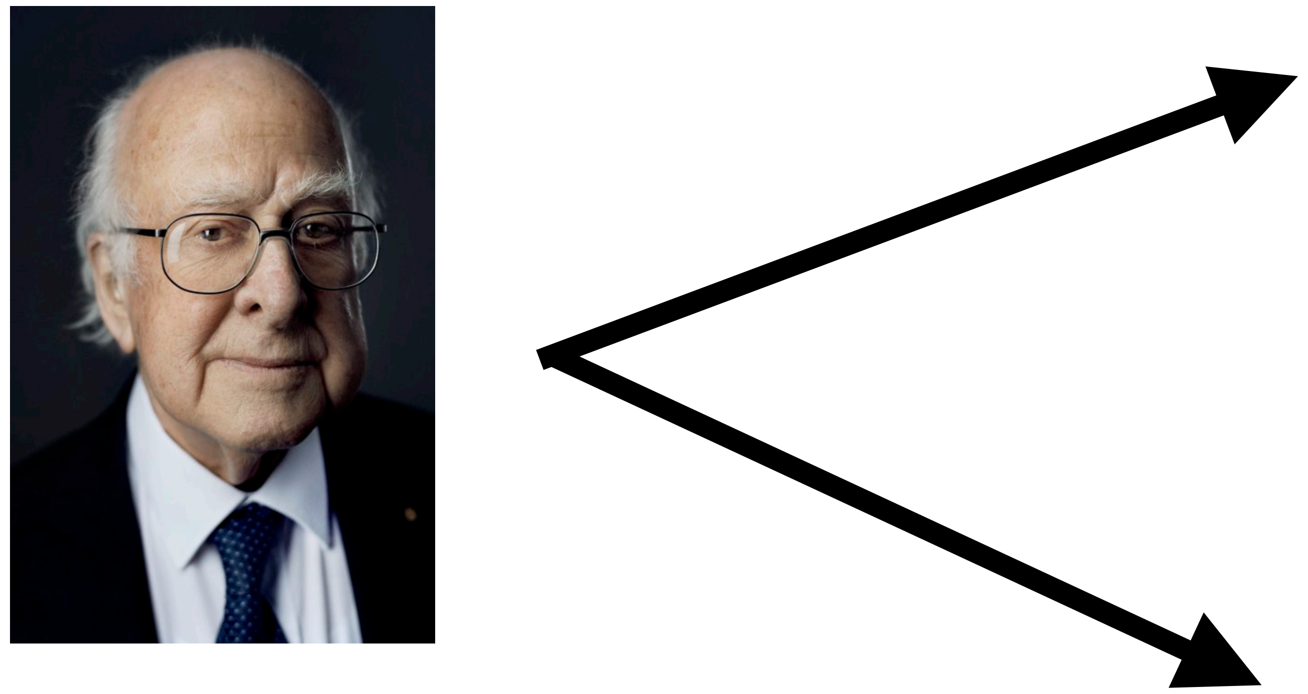
Look for missing momentum.

X is some standard model particle that may or may not form a jet.

“Mono-X” — the r DM

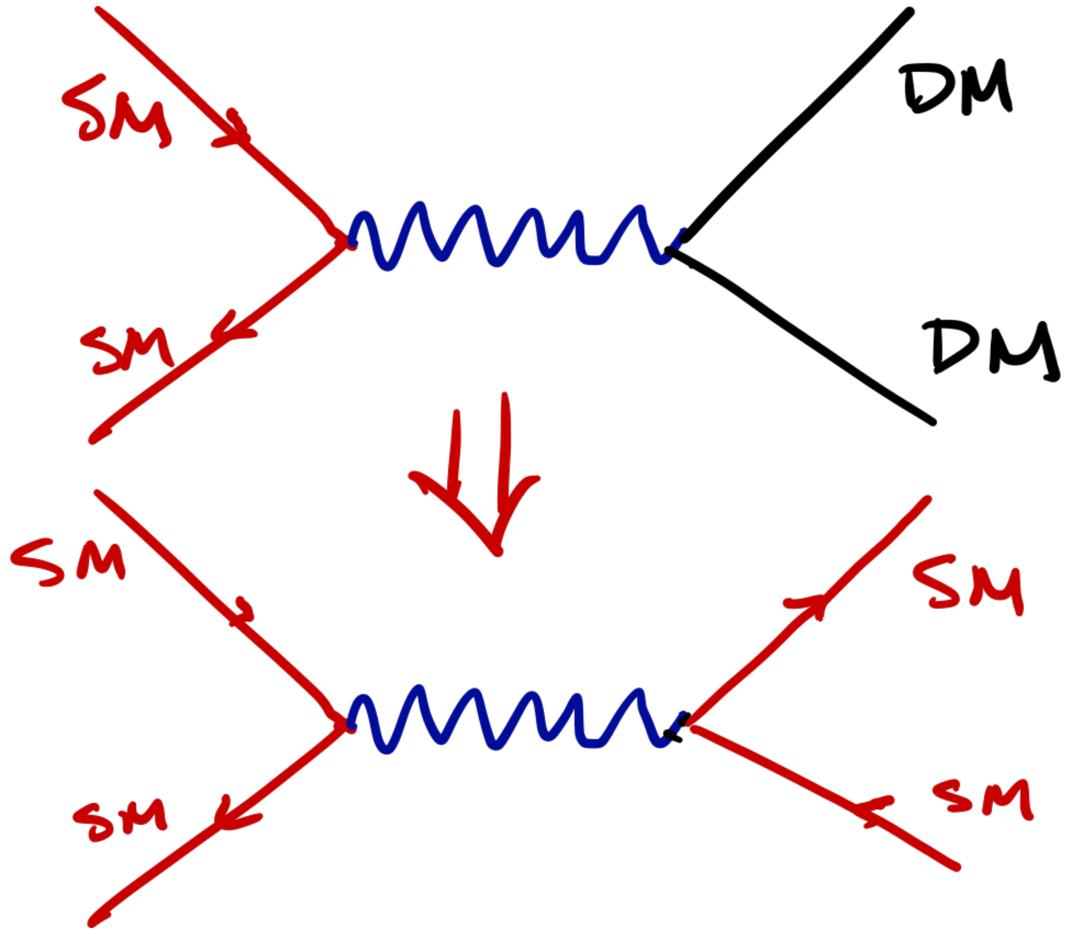
Other signals to look for

Invisible Higgs decays



Mediator production

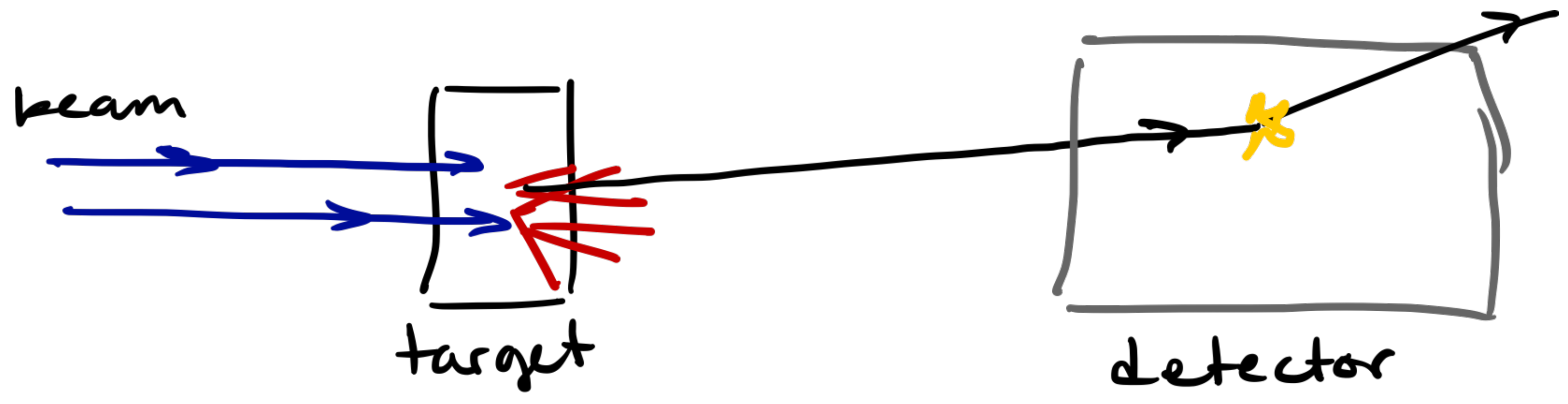
If production is s-channel
and exchanged momentum
is above mediator mass scale:



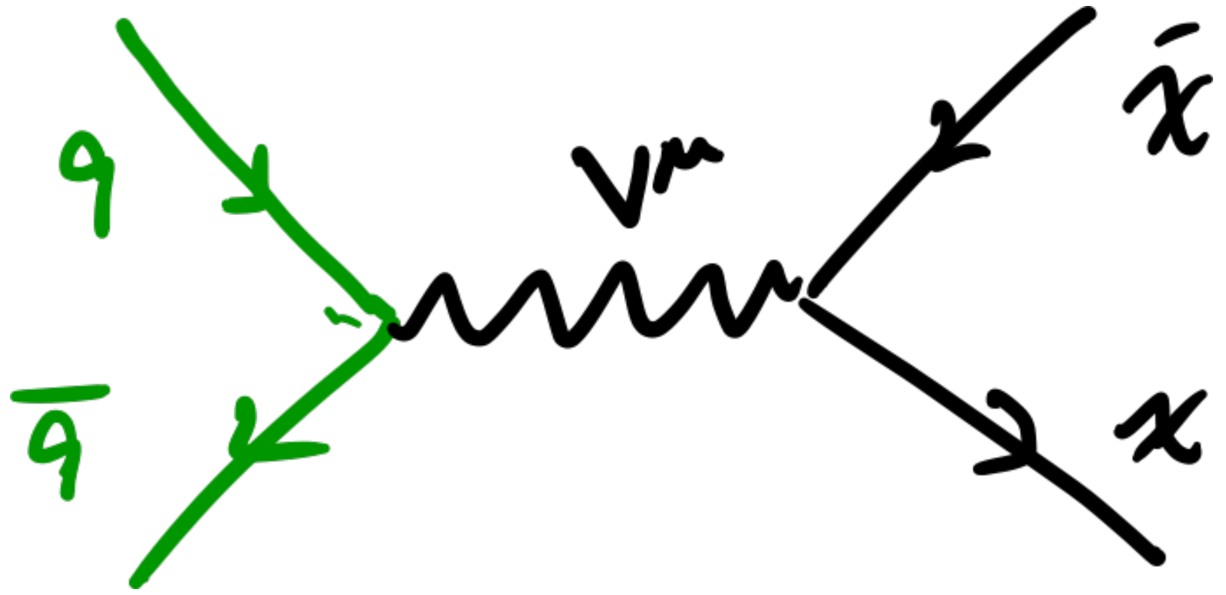
resonant dijet production

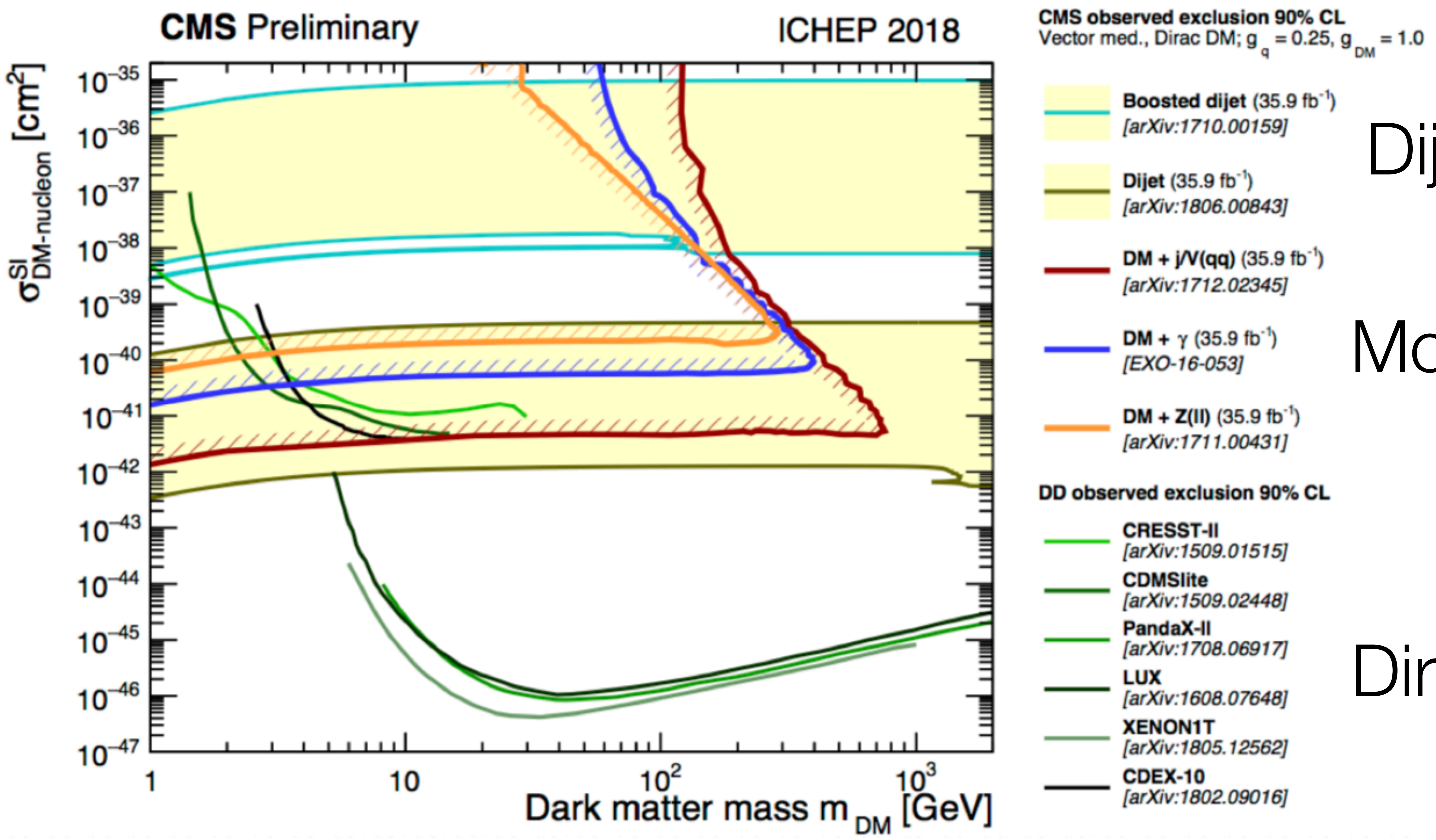
See also searches
for long-lived particles

Light DM at fixed target



Comparison to Direct detection: model-dependent





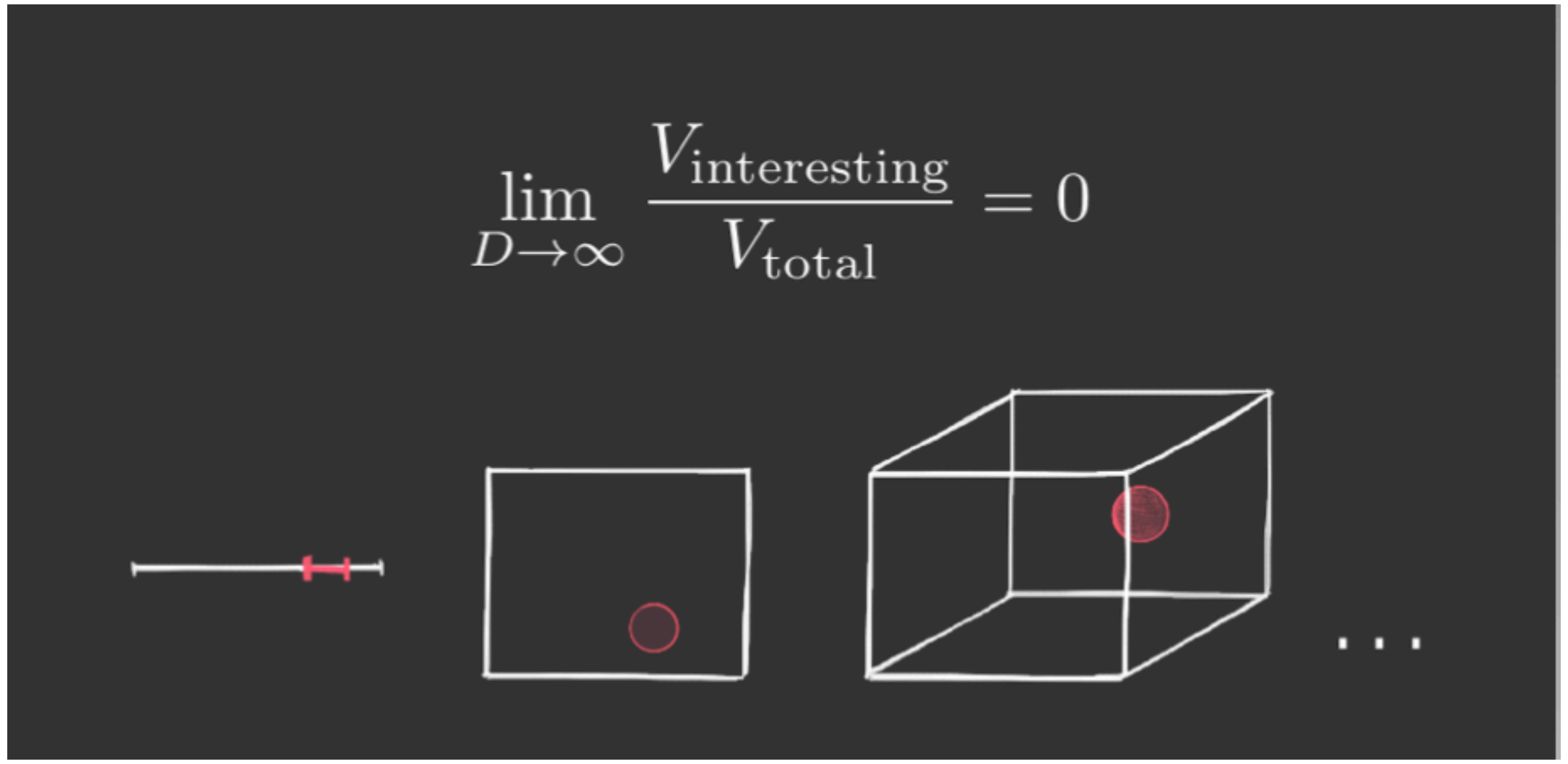
Dijets

Mono-X

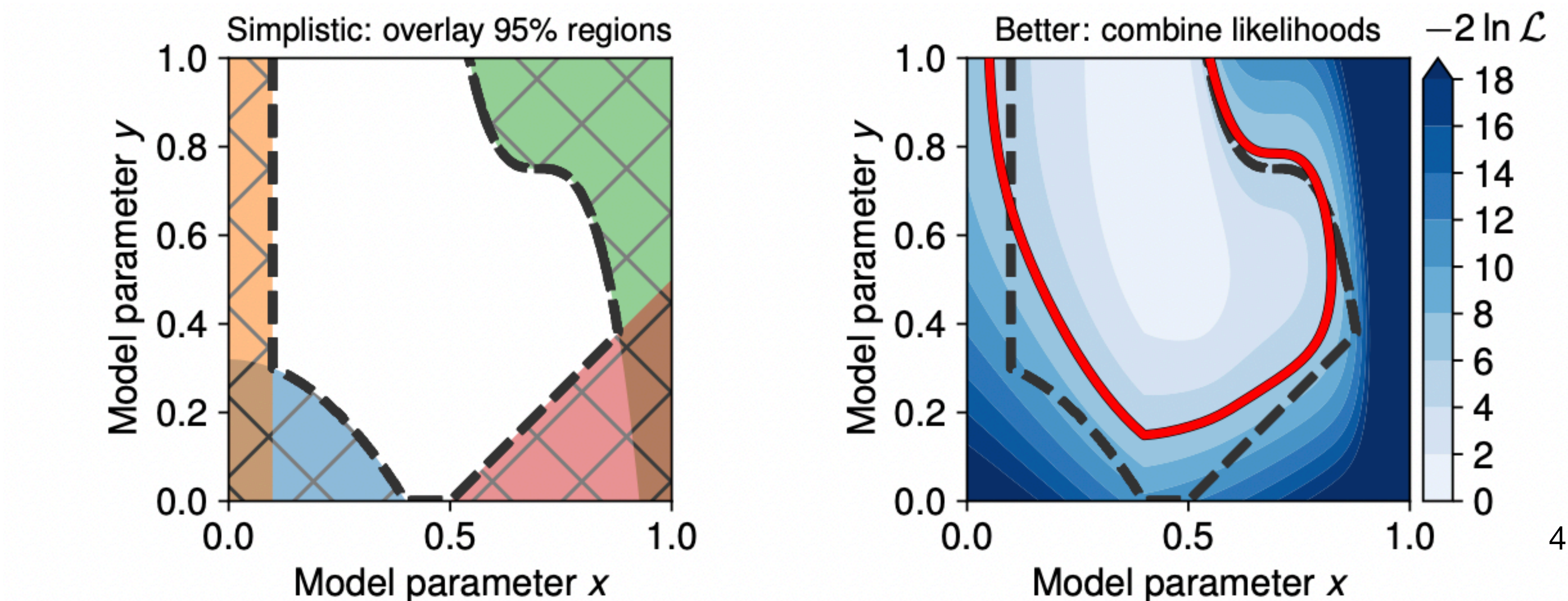
Direct Det.

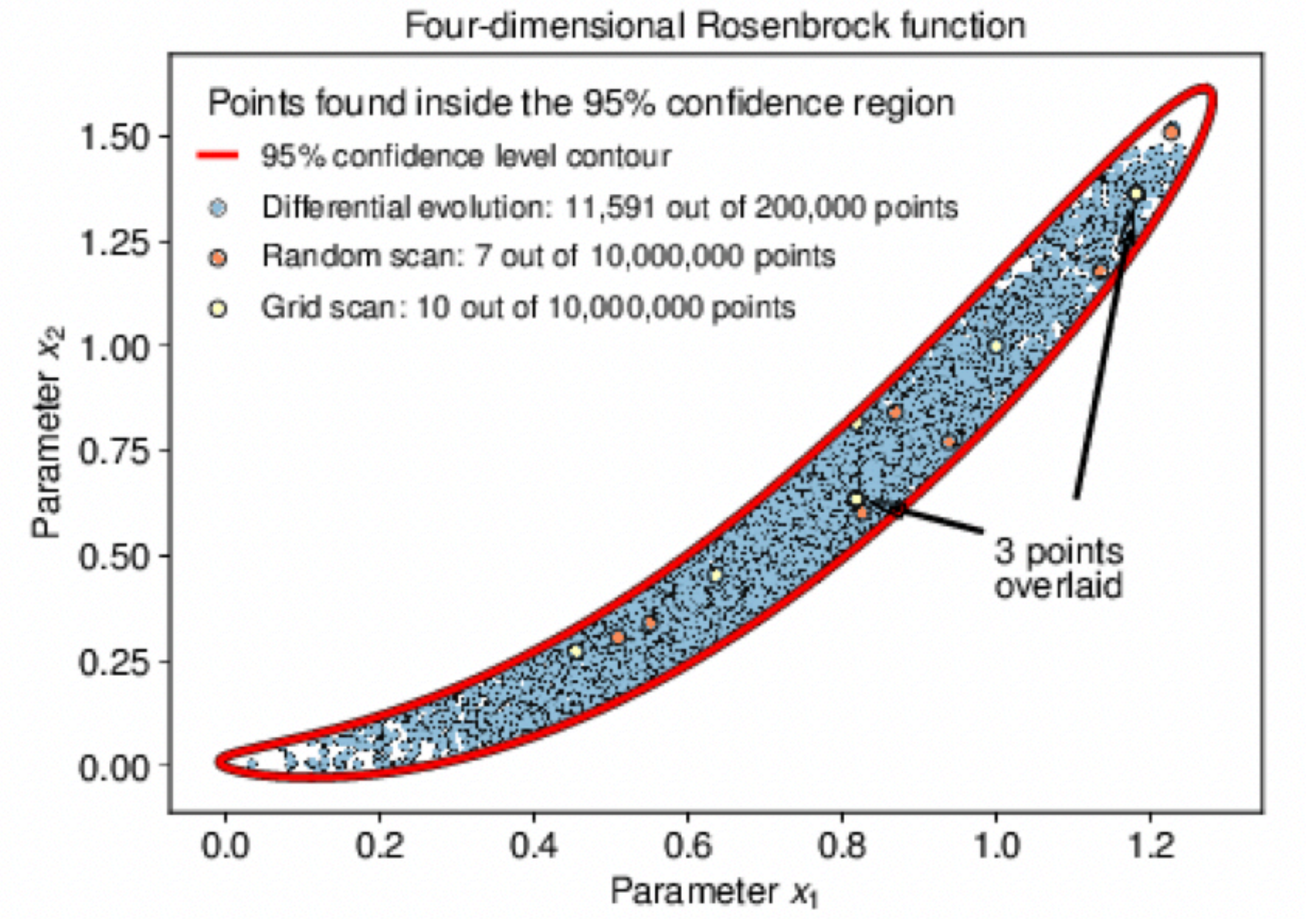
Global searches

- Constraints from many different sectors
- Experiments should be compared **self-consistently**
- Models have **many free parameters**: the space of models is a **high-dimension problem**



$$\lim_{D\to\infty}\frac{V_{\text{interesting}}}{V_{\text{total}}}=0$$





Global searches

1. Write down a model: Lagrangian $\mathscr{L}(\theta_i)$ where θ_i are the parameters, $i = 1,2,...N$
2. Pick a point in parameter space
3. Calculate all the physics observables, and evaluate the likelihood based on the data: $L(\theta_i) = P(d\,|\,\theta_i)$

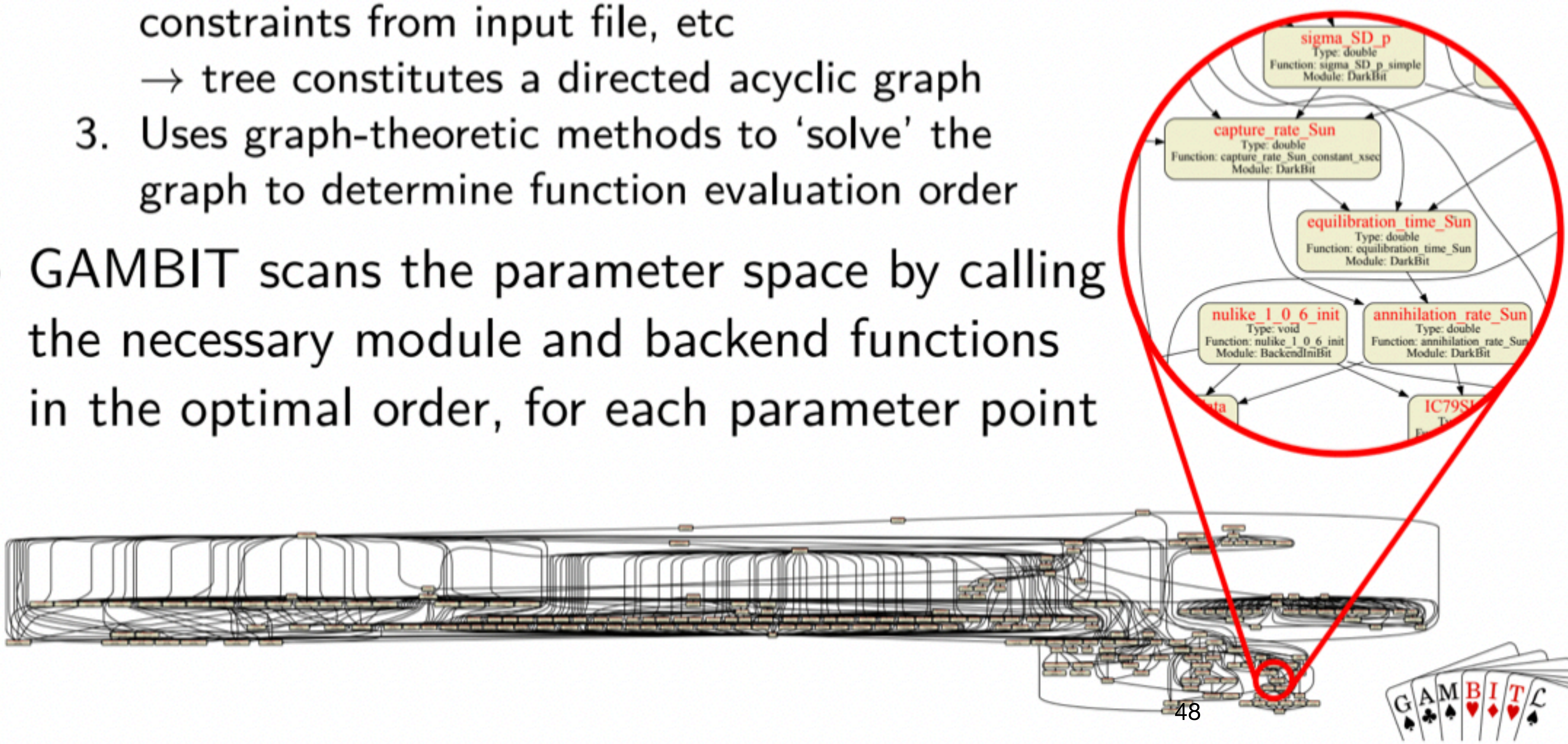
   this is hard
4. Jump to another point.

   this requires you to be clever
5. Repeat.

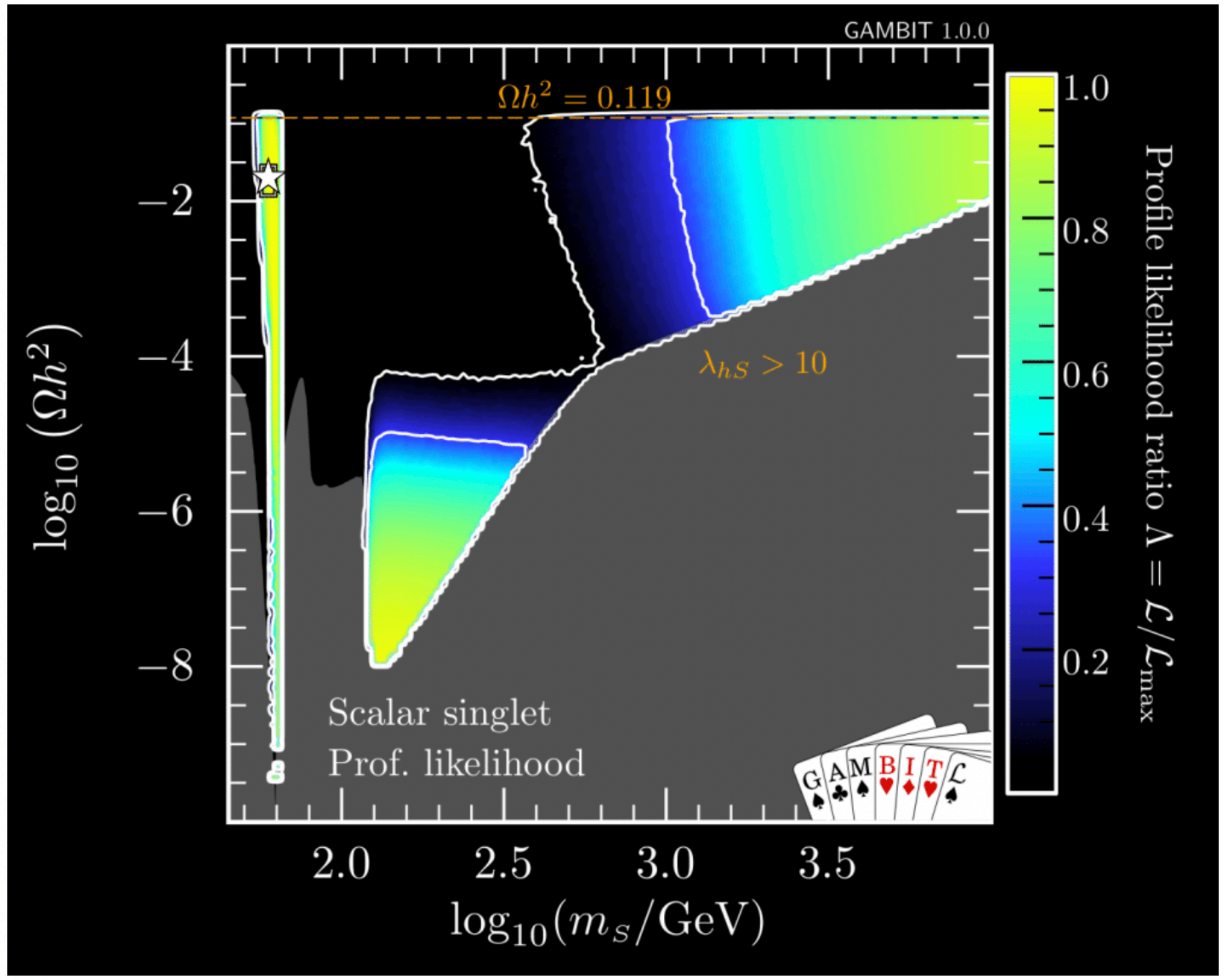
   this is time-consuming

Global searches: GAMBIT

- User chooses a model to scan, which observables to include, and the scanning method
- GAMBIT constructs a **dependency tree**
  1. Identifies which functions and inputs are needed to compute the requested observables
  2. Obeys **rules** at each step: allowed models, allowed backends, constraints from input file, etc
     → tree constitutes a directed acyclic graph
  3. Uses graph-theoretic methods to 'solve' the graph to determine function evaluation order
- GAMBIT scans the parameter space by calling the necessary module and backend functions in the optimal order, for each parameter point



output example:
non-trivial combination of constraints

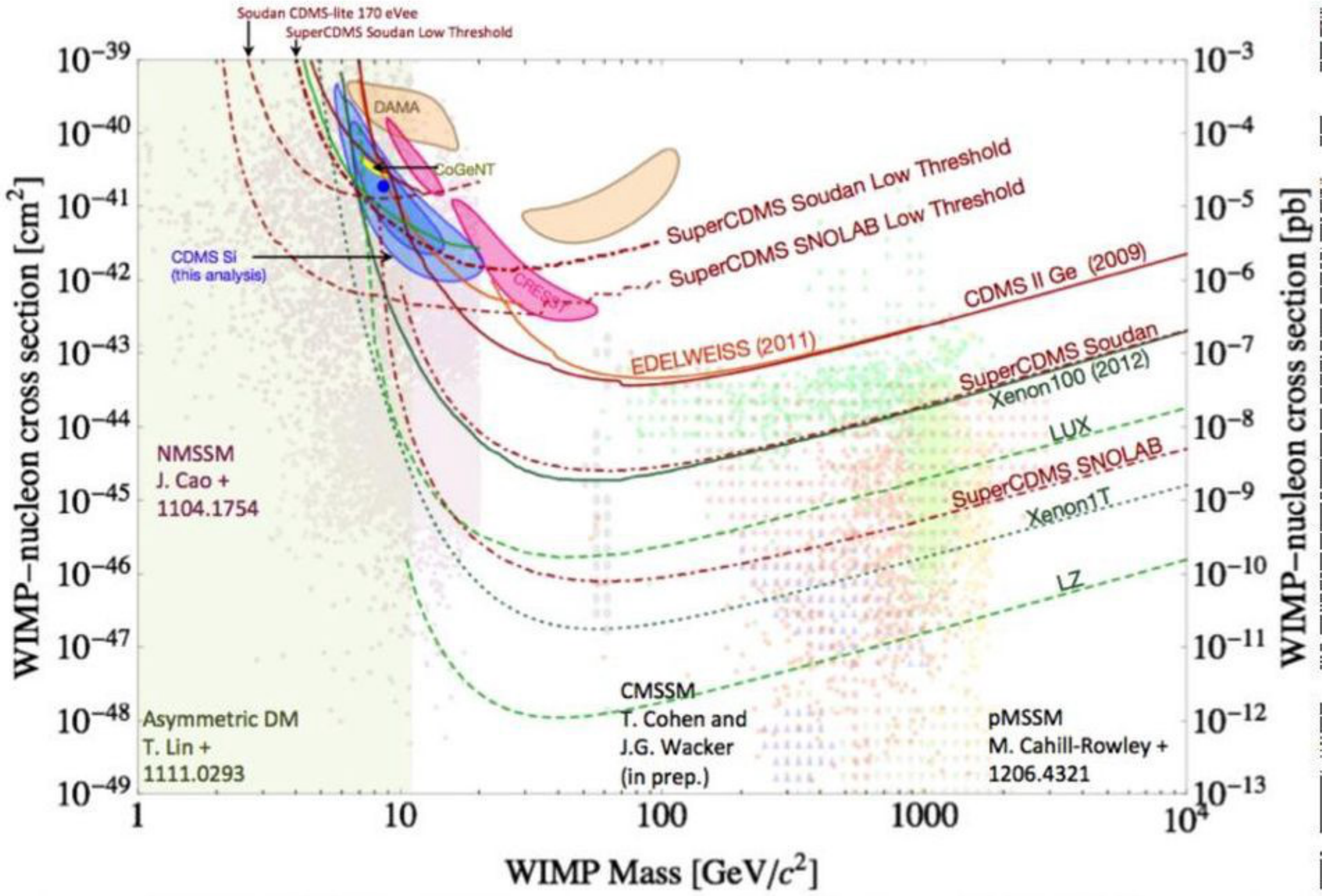


$$\mathcal{L} = \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hS} S^2 |H|^2 + \frac{1}{4}\lambda_S S^4 + \frac{1}{2}\partial_\mu S \partial^\mu S.$$

Summary

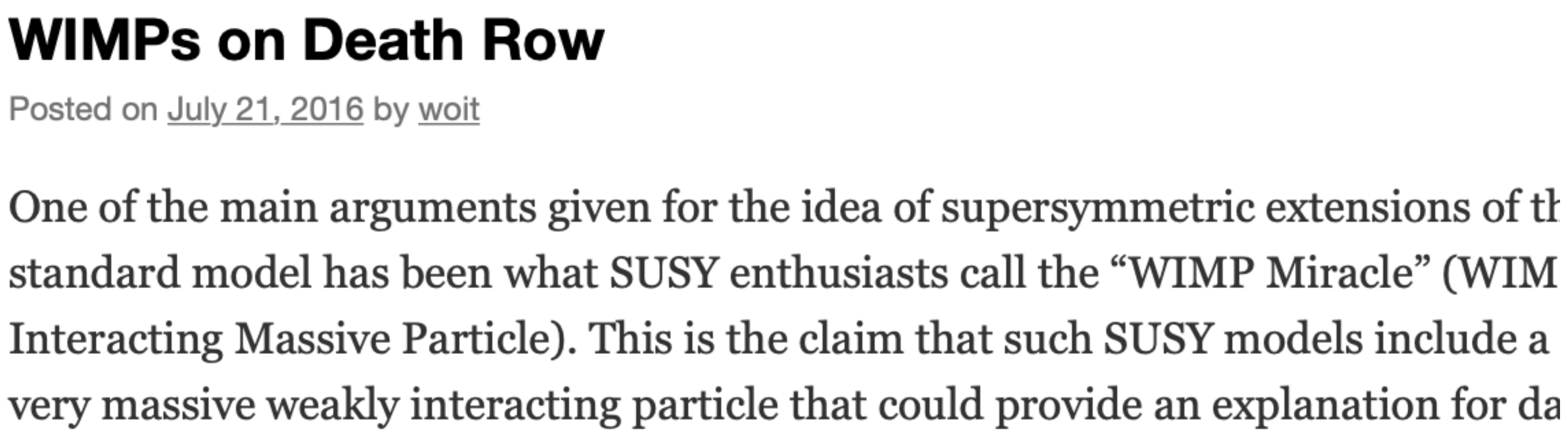
- Dark matter is there, go find it

Bye



The 'WIMP Miracle' Hope For Dark Matter Is Dead

Ethan Siegel Senior Contributor
Starts With A Bang Contributor Group ⓘ
Science
The Universe is out there, waiting for you to discover it.

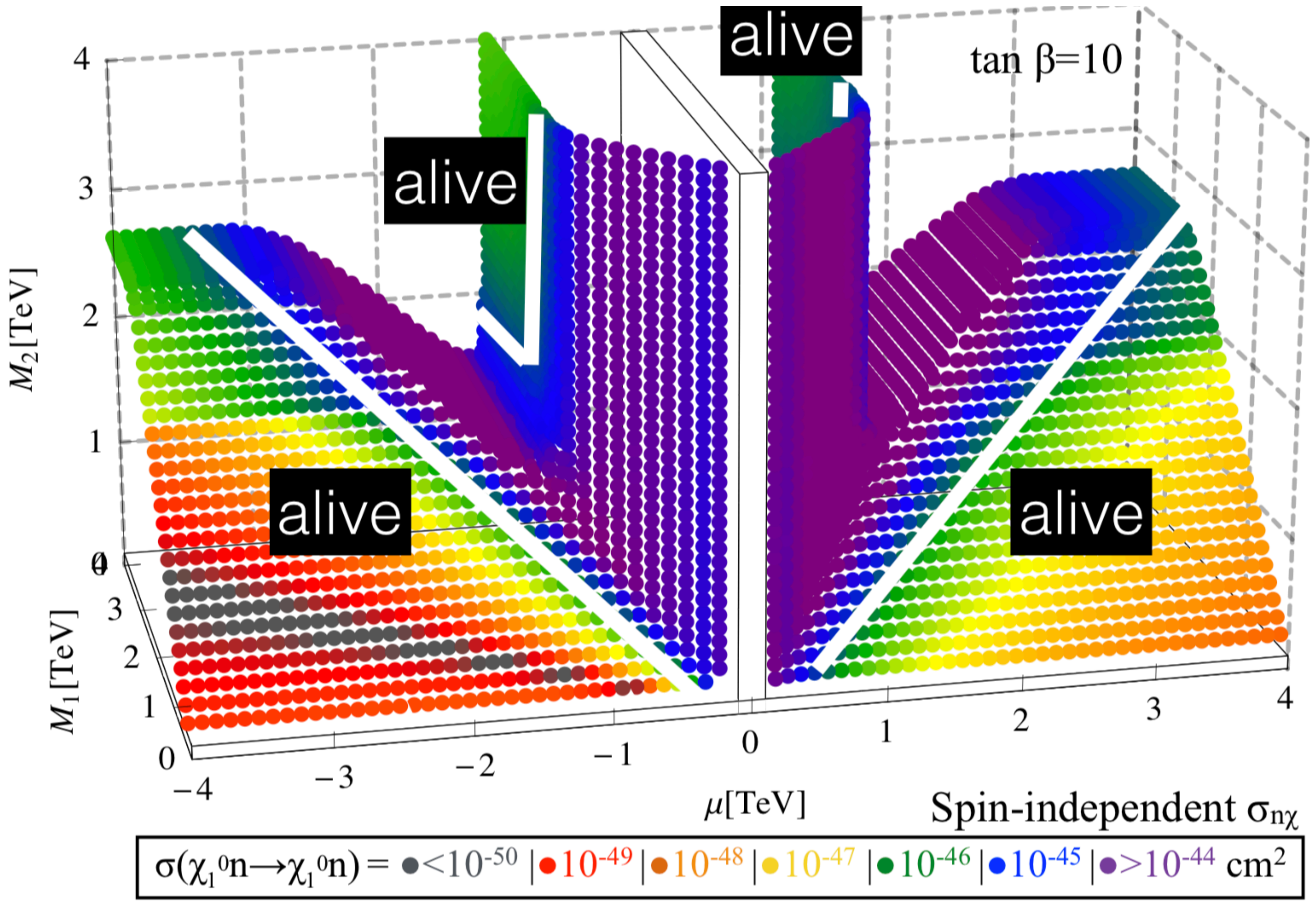


WIMPs on Death Row

Posted on July 21, 2016 by woit

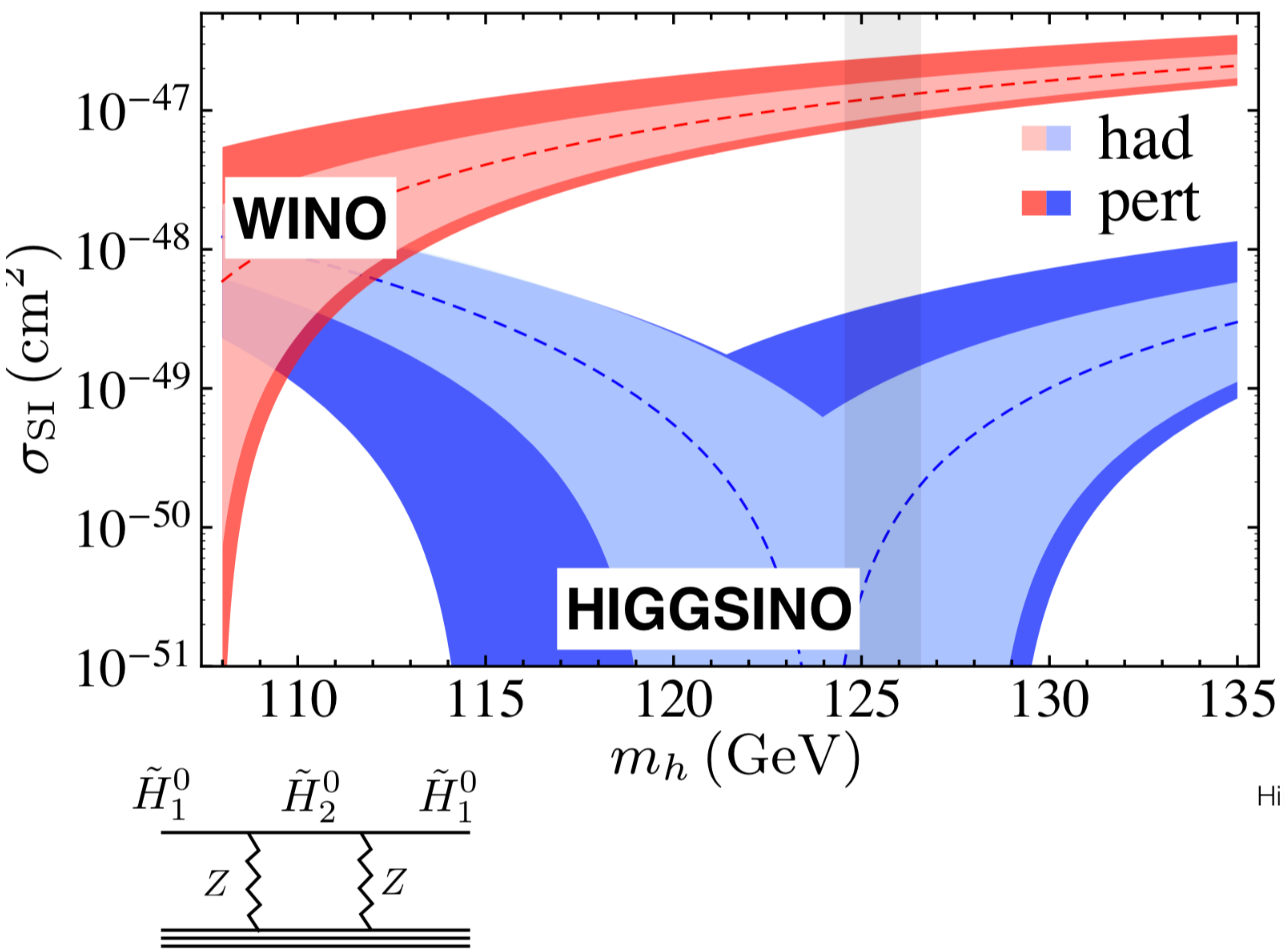
One of the main arguments given for the idea of supersymmetric extensions of t
standard model has been what SUSY enthusiasts call the “WIMP Miracle” (WIM
Interacting Massive Particle). This is the claim that such SUSY models include a
very massive weakly interacting particle that could provide an explanation for da

Neutralino (arguably the OG WIMP)
Not close to dead



Joe Bramante

WINO & Higgsino DM
should not have been found yet



Hill, Solon 1309.4092