Frontiers in Astrophysics

Particle Astrophysics:

Dark Matter 1: Overview, distributions, production

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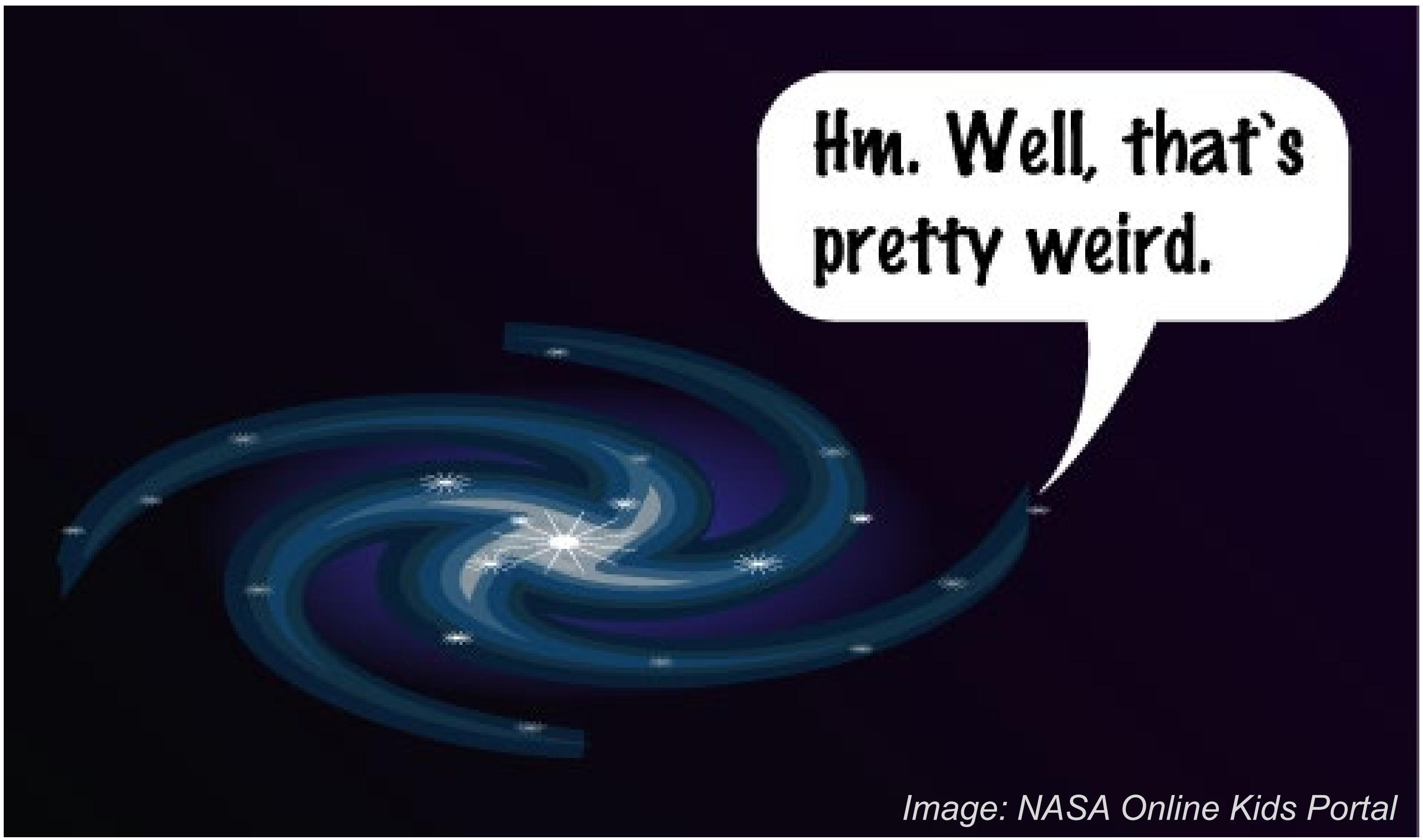
Credit to Pat Scott for many of the slides

Overview

- Background + some models for Dark Matter
- Models for density/velocity distributions
- Gravitational probes and observables
- Production: thermal production, WIMP miracle

Part 1: Overview + models



How we know dark matter exists

(Clowe et al., *ApJL* 2006)

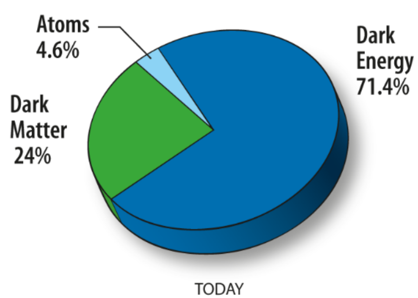
The only way to consistently explain:

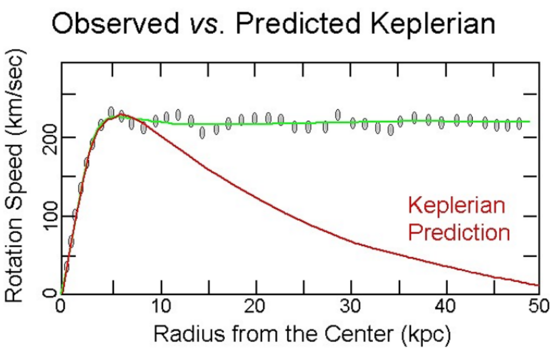
1. rotation curves + vel. dispersions
2. gravitational lensing
3. cosmological data
   - Large-scale structure (2dF/Chandra/SDSS-BAO) says $\Omega_{\text{matter}} \approx 0.27$
   - BBN says that $\Omega_{\text{baryonic}} \approx 0.04$
   - $\implies \Omega_{\text{non-baryonic}} \approx 5 \times \Omega_{\text{baryons}}$
   - CMB and SN1a agree; also indicate that $\Omega_{\text{total}} \approx 1$
   - $\implies$ universe is 26% dark matter, 5% baryonic (visible) matter, 69% something else

What we know about dark matter

Must be:

- massive (gravitationally-interacting)
- unable to interact via the electromagnetic force (dark)
- non-baryonic
- “cold(ish)” (in order to allow structure formation)
- stable on cosmological timescales
- produced with the right relic abundance in the early Universe.





img: [WMAP 2018]

What we know about dark matter

Bad options:

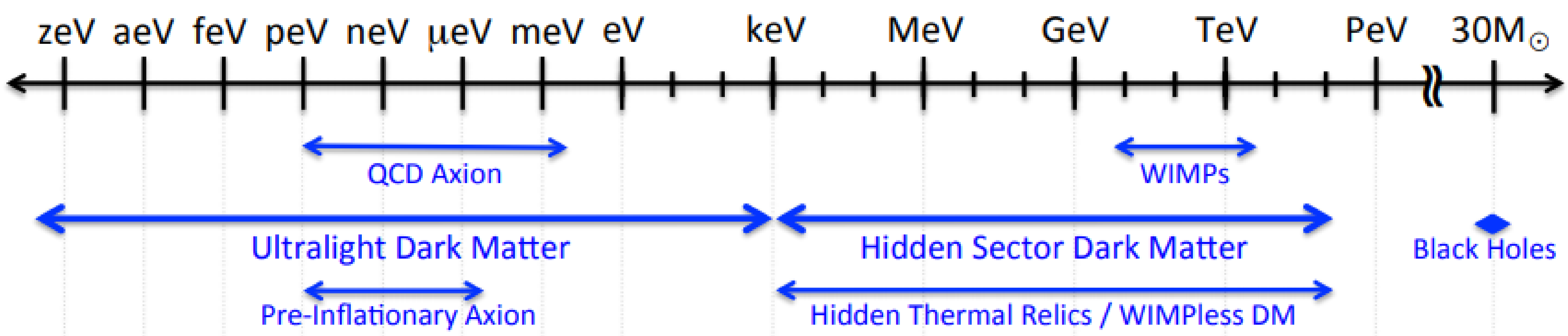
- primordial black holes (strong experimental constraints, dubious theoretical motivation)
- MAssive Compact Halo Objects (MACHOs; baryonic)
- standard model neutrinos (too warm; insufficient relic density)

Good options:

- Weakly Interacting Massive Particles (WIMPs)
- axions or axion-like particles
- sterile neutrinos
- gravitinos, axinos

What we don't know about dark matter

- Essentially everything else… mass, coupling, interactions
- Possible mass range: spans 90(!) orders-of-magnitude



img: [US Cosmic Visions report, arXiv:1707.04591]

- Though many are tightly constrained by observations

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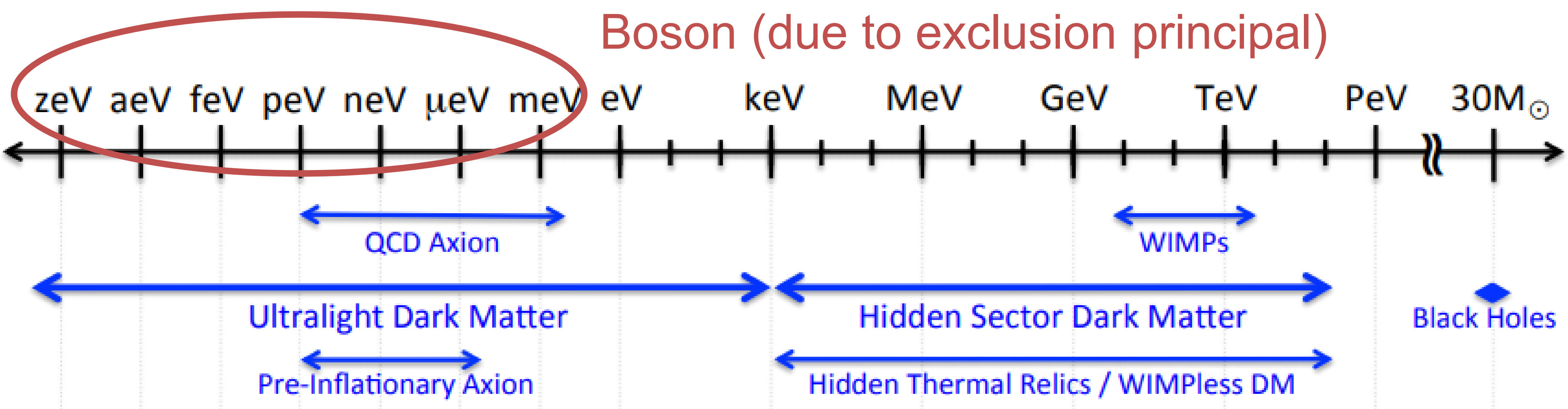


img: [US Cosmic Visions report, arXiv:1707.04591]

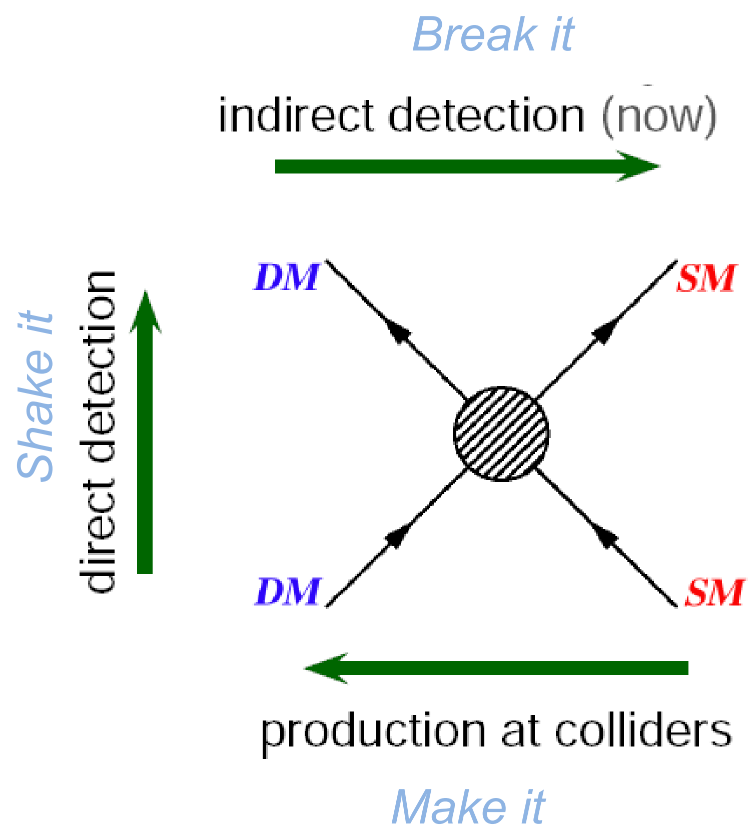
- Though many are tightly constrained by observations

WIMPs

- ✓ Dark because no electromagnetic interactions
- ✓ Cold because very massive ($\sim$10 GeV to $\sim$10 TeV)
- ✓ Non-baryonic and stable – no problems with BBN or CMB
- Weak interaction means scattering with nuclei
  $\Longrightarrow$ detection channel
- Many WIMPs are Majorana particles (own antiparticles)
  $\Longrightarrow$ self-annihilation $\Longrightarrow$ detection channel
- ✓ Weak-scale annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude $\Longrightarrow$ WIMP Miracle

Detection Strategies

- Direct detection – nuclear collisions and recoils
- Indirect detection – annihilations producing SM particles
- Impacts on stars – the Sun and “dark stars”
- Direct production – missing E_T or otherwise – LHC, future colliders

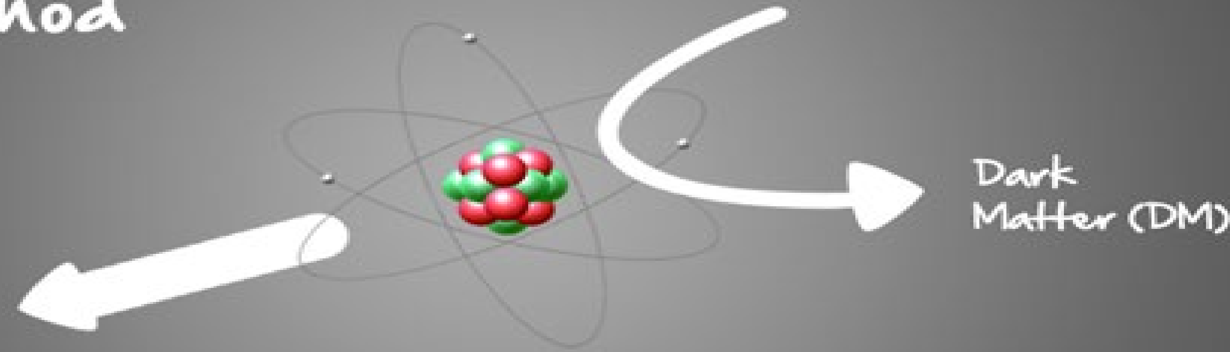


img: [https://www.mpi-hd.mpg.de]

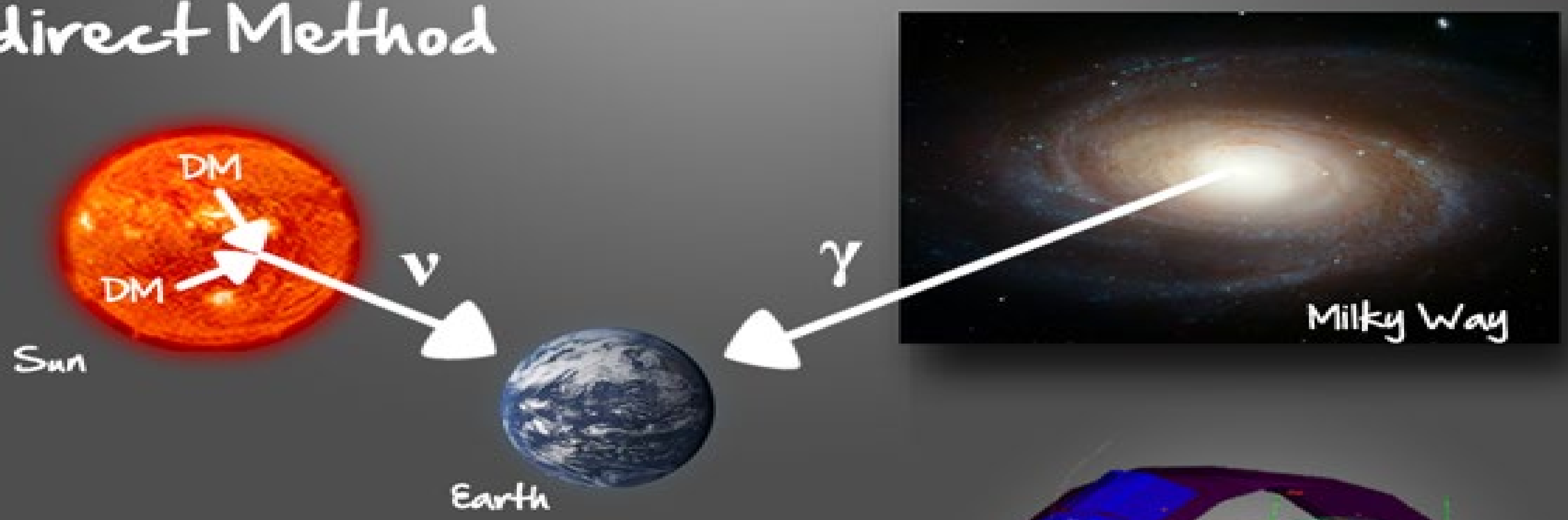
- More next lecture

Dark Matter search strategies

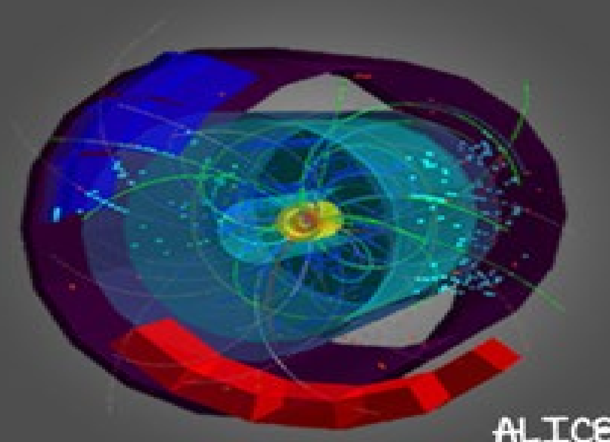
Direct Method



Indirect Method

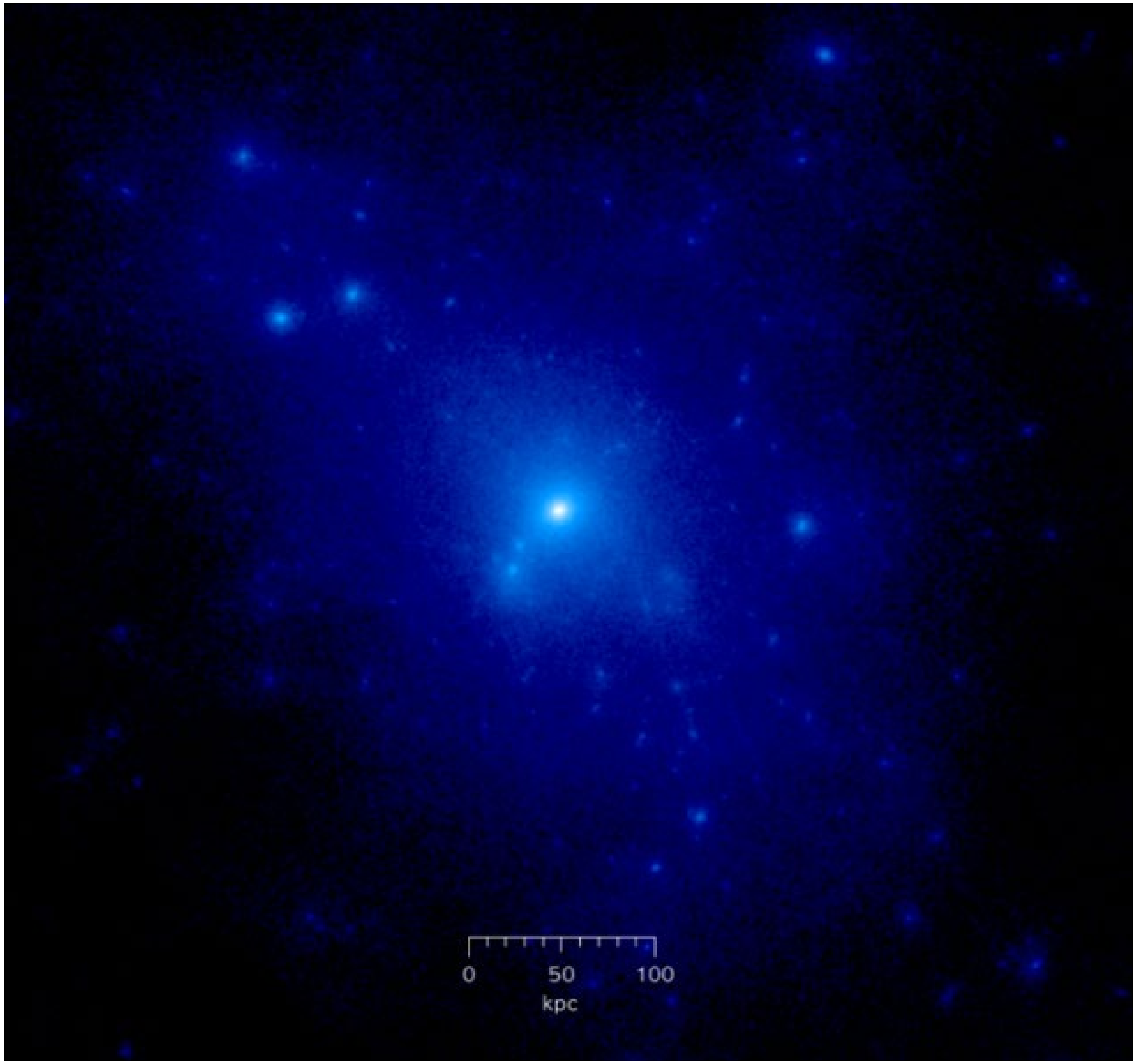


Production at the Large Hadron Collider



img: HAP / A. Chantelauze

Part 2: Distributions, gravitational probes



- Gravitationally bound
- Frictionless
- Galactic DM halos

Simulated dark matter halo from a cosmological N-body simulation [wiki]

Dark matter density profiles

- Gravitationally bound
- Frictionless
- Galactic DM halos

N-body simulations of dark matter halo formation suggest universal (all-scale) Navarro-Frenk-White profile

$$\rho(r) = \frac{\delta_c \rho_c}{r/r_s\,(1 + r/r_s)^2},$$

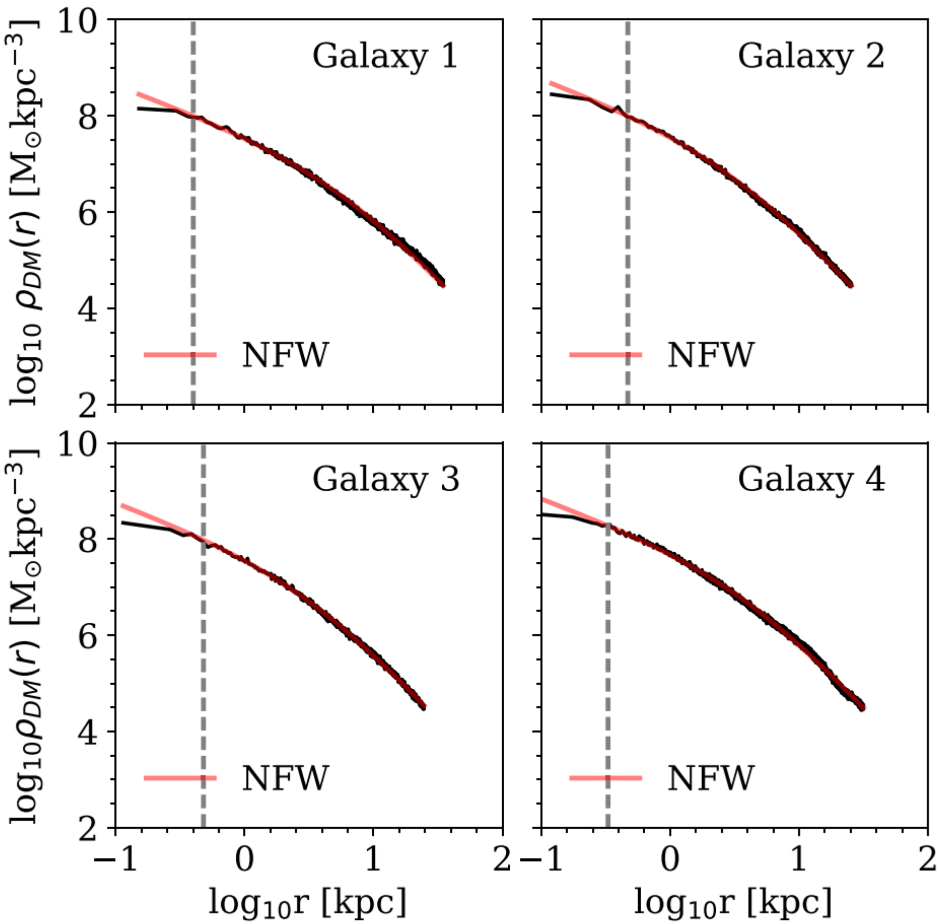
or Einasto profile

$$\rho(r) = \rho_s \exp\left\{-2n\left[\left(\frac{r}{r_s}\right)^{\frac{1}{n}} - 1\right]\right\}$$

- May be steepened in innermost region by adiabatic contraction
- . . . or, may be softened in innermost region by baryonic effects
- Data seem to suggest some sort of core in Milky-Way type galaxies $\Longrightarrow$ baryonic effects favoured
- ***but*** inner parts of halos not well constrained by data

Dark matter density profiles: Cusp-Core Problem

- Discrepancy between simulations/observations for low-mass galaxies



- Simulations imply “cusp”: higher density at low r
- Data imply “core”: flattening of profile at low r

Dark matter density profiles: Cusp-Core Problem

Solutions:

- Misunderstood baryonic effects (not captured in sims)
  - Indications that baryonic “feedback” effects can flatten out inner distribution
  - seems most favoured solution

- Beyond “standard” ΛCDM
  - Warm dark matter, DM with self-interactions
  - Ultralight or “fuzzy” dark matter

Dark matter velocity distribution

- Gravitationally bound
- Frictionless
- Galactic DM halos

Maxwell-Boltzmann distribution:

$$f(v) = \frac{4}{\sqrt{\pi}} \left(\frac{3}{2}\right)^{3/2} \frac{\rho_\chi}{m_\chi} \frac{v^2}{\bar{v}^3} \exp\left(-\frac{3v^2}{2\bar{v}^2}\right)$$

- DM halo is isothermal to a first approximation
- $\Longrightarrow$ DM kinetic energies follow Boltzmann partitioning with single temperature T
- $\equiv$ DM velocities follow Maxwell-Boltzmann distribution with mean $\bar{v}(T)$

Dark matter velocity distribution

Standard Halo Model

$$\tilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{esc}}\left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{esc}, \\ 0, & \text{otherwise.} \end{cases}$$

Here

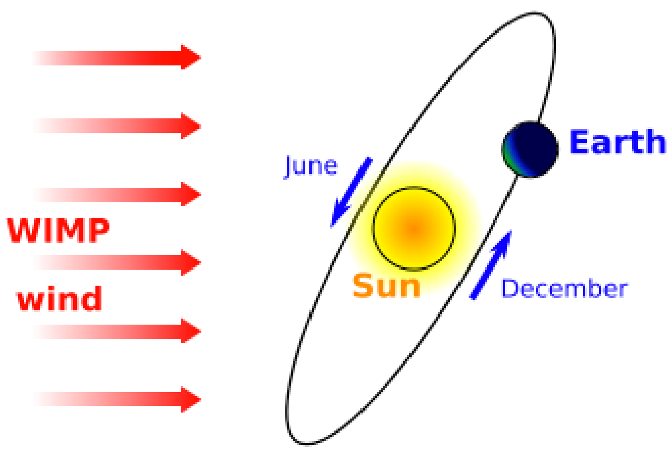
$$N_{esc} = \mathrm{erf}(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}, \qquad v_{esc} \approx 550\ km/s$$

with $z \equiv v_{esc}/v_0$, is a normalization factor and

$$v_0 = \sqrt{2/3}\,\sigma_v \qquad \approx 235\ km/s$$

- Typically, sharp cut-off smoothed out

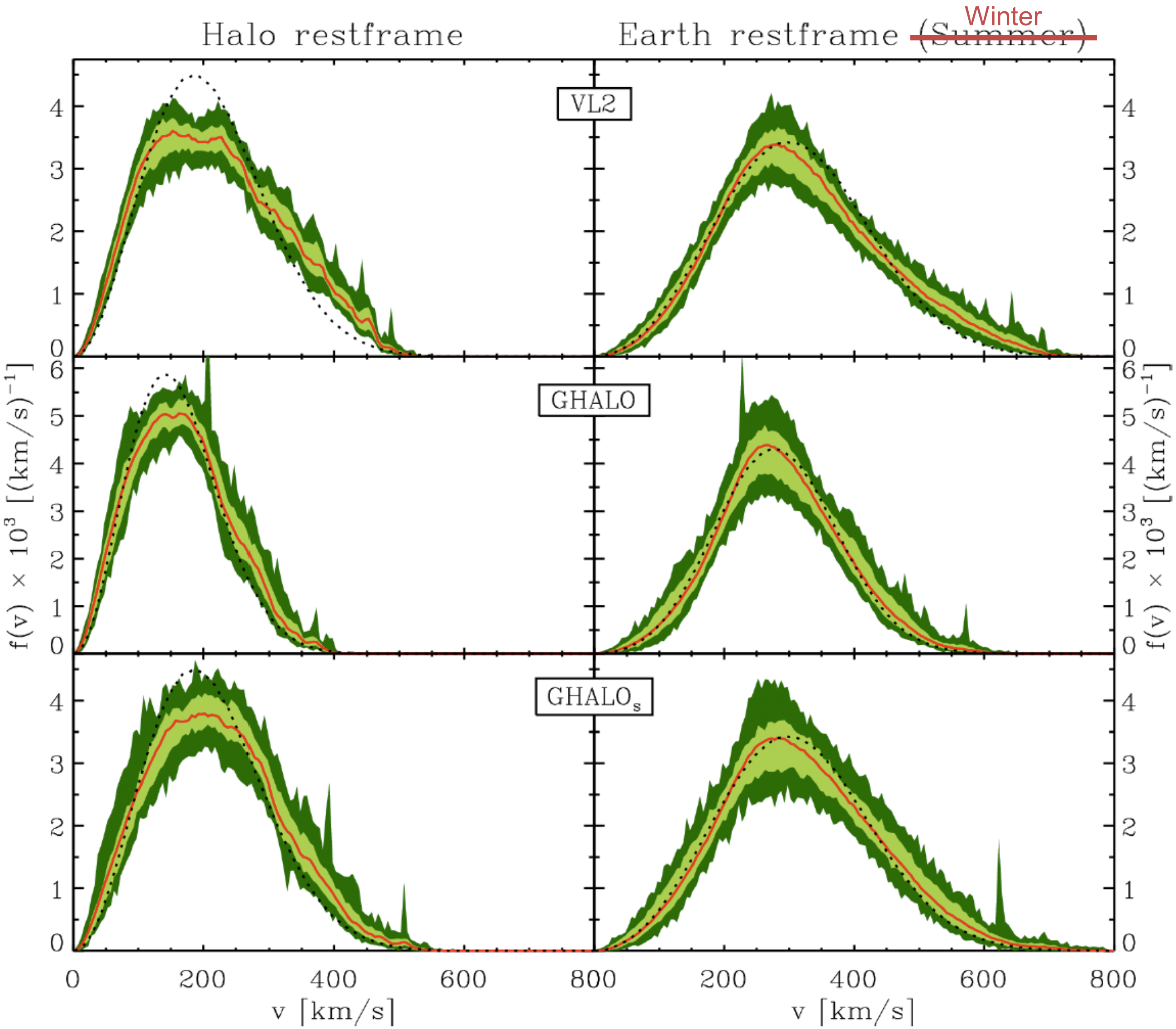
In Galactic frame: "boost" to earth frame



- Annual/daily modulations:
- More next lecture

[1] K. Freese, M. Lisanti, and C. Savage, Rev. Mod. Phys. **85**, 1561 (2013).

Dark matter velocity distribution

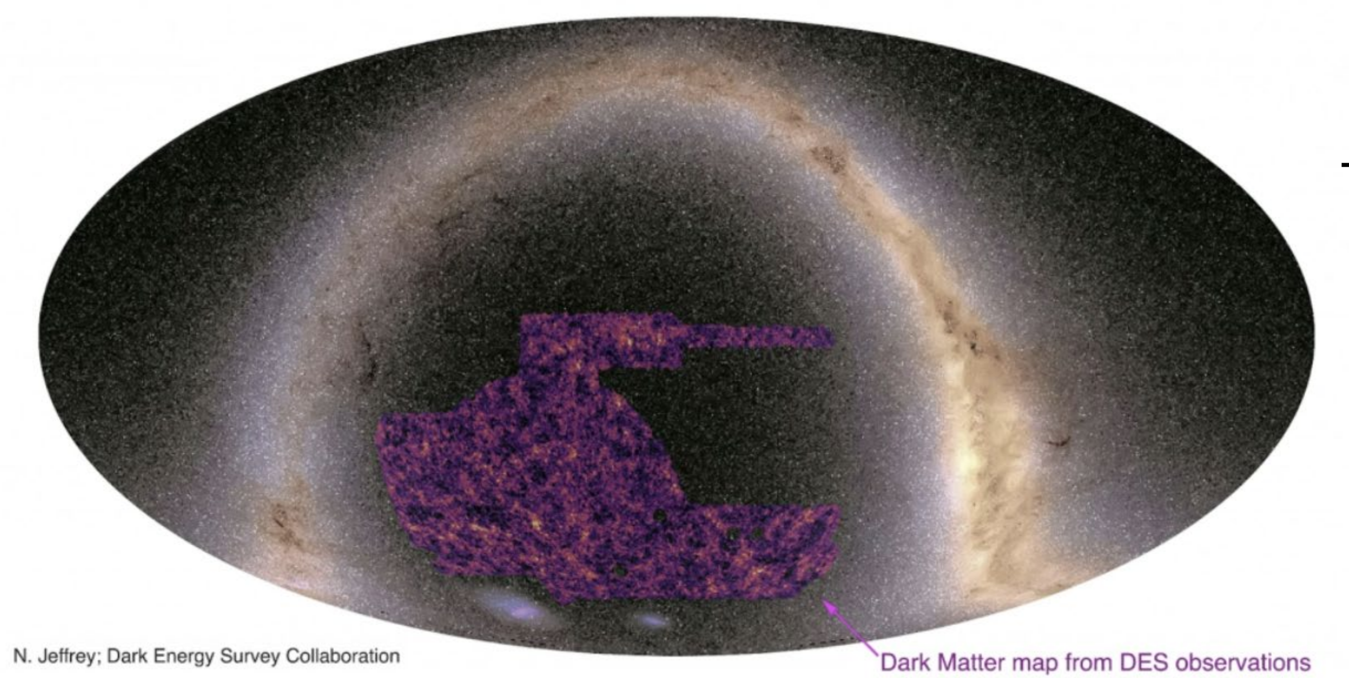


Kuhlen et al *JCAP* 2010

- DM halo is isothermal to a first approximation
- $\implies$ DM kinetic energies follow Boltzmann partitioning with single temperature T
- $\equiv$ DM velocities follow Maxwell-Boltzmann distribution with mean $\bar{v}(T)$
- . . . as usual, real life is more complicated (but only a little). . .

Gravitational Lensing

- Dark Matter mass: bends light => lensing
- Information on amount, and distribution of DM across galaxies



The extent of the DES dark matter map of the sky so far, after the latest findings. The bright spots represent the highest concentrations of dark matter, while darker areas indicate low densities.

DARK ENERGY SURVEY

Tamara (+UQ) involved

Impacts of particle physics

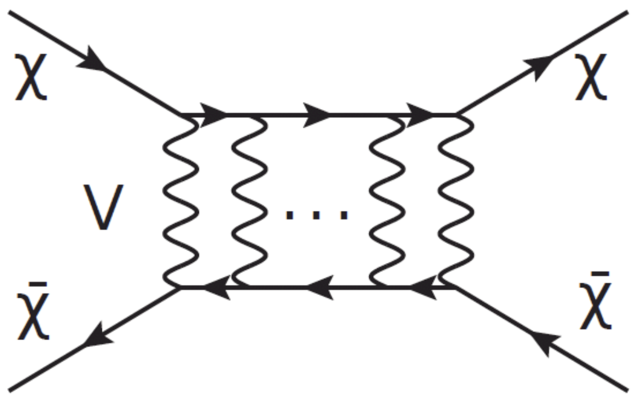
Dark matter may have a small self-interaction

→ No longer entirely dissipationless
→ washes out highest densities → galaxy cores

Rocha, Peter, Bullock et al *MNRAS* 2012

Impacts of particle physics

- Dark matter may have more complicated interactions where v and ρ both matter
- E.g. models with light vector mediators that connect DM and standard model particles
- $\rightarrow$ 'Sommerfeld' enhancement



- $\rightarrow$ enhanced DM-DM scattering for certain DM-DM relative velocities
- $\rightarrow$ wash out structure where DM moves at a certain speed $\rightarrow$ (e.g. cores of dwarf galaxies, maybe fixing cusp vs core issue)

van den Aarssen, Bringmann, Pfrommer, *PRL* 2012

Part 3: Production of DM

img: [Sandbox Studio, Chicago with Corinne Mucha, Symmetry Magazine]

Thermal and non-thermal production

Thermal Production

Everything is in perfect thermal equilibrium in early Universe

$\Longrightarrow$
- Particle populations are all in equilibrium (cf Saha, Boltzmann Eqs) $\rightarrow$ set by T
- Velocities are all in kinetic equilibrium (cf Maxwell dist) $\rightarrow$ set by T

$\Longrightarrow$ As stuff falls out of equilibrium, populations and velocities must be evolved explicitly

$\Longrightarrow$ Always present at some level, not always dominant in $\Omega_{\rm DM}$

Non-thermal Production

Any other process that dominates the DM relic density

- Some other heavy BSM particle X decays $\rightarrow$ DM
- Decays/evaporations of topological defects like cosmic strings
- Evaporation of primordial black holes
- Not always present

Thermal production

Particle populations can be obtained by solving the Boltzmann Equation

$$\mathbf{L}f = \mathbf{C}f \qquad (3)$$

for the particle phase space f, given a collision operator $\mathbf{C}$ (basically just the rate of creation $-$ destruction of particles) and the Louiville operator $\mathbf{L}$

$$\mathbf{L} = E\frac{\partial}{\partial t} - H|\mathbf{p}|^2\frac{\partial}{\partial E}. \qquad (4)$$

Integrating over all particle momenta (see Kolb & Turner Chap 5 for details), this becomes

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \langle \sigma v \rangle ({n_{\chi,\mathrm{eq}}}^2 - {n_\chi}^2) \qquad (5)$$

- **Solve eq: determine abundance at late times**

Thermal production

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \langle \sigma v \rangle ({n_{\chi,\mathrm{eq}}}^2 - {n_\chi}^2)$$

Write in terms of dimensionless variables: s' = entropy density; S = entropy per co-moving volume

$$Y \equiv n/s' \qquad S \equiv a^3 s' \qquad x \equiv m/T$$

$$\frac{\mathrm{d}Y(x)}{\mathrm{d}x} = \sqrt{\frac{\pi}{45}} \frac{m M_{\mathrm{Pl}}}{x^2} \sqrt{g_*(x)} \langle \sigma_{\mathrm{eff}} v \rangle (x) \left[Y_{\mathrm{eq}}^2(x) - Y^2(x) \right]$$

$M_{\mathrm{Pl}} = G^{-1/2} \approx 1.2 \times 10^{19}\,\mathrm{GeV}$

g* = Effective energetic/entropic degrees of freedom

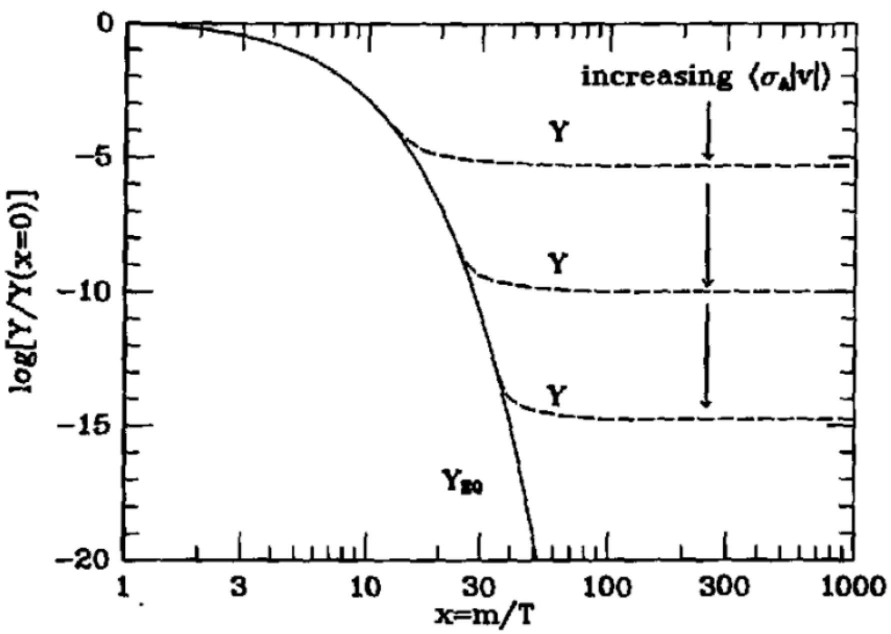
$$Y_{\mathrm{eq}}(x) = \frac{45}{4\pi^4} \frac{x^2}{h_{\mathrm{eff}}(x)} \sum_i g_i \left(\frac{m_i}{m_1} \right)^2 K_2 \left(x \frac{m_i}{m_1} \right) \qquad Y_0 \approx 3.63 \times 10^{-9}\, \Omega h^2 \left(\frac{\mathrm{GeV}}{m} \right)$$

$$g_i = 2J_i + 1$$

Thermal production

$$\frac{\mathrm{d}Y(x)}{\mathrm{d}x} = \sqrt{\frac{\pi}{45}} \frac{m M_{\mathrm{Pl}}}{x^2} \sqrt{g_*(x)} \langle \sigma_{\mathrm{eff}} v \rangle (x) \left[Y_{\mathrm{eq}}^2(x) - Y^2(x) \right]$$

Solving it numerically in terms of dimensionless variables $Y \equiv n/s$ and $x \equiv m_\chi / T$, we see the classic 'freeze-out' WIMP miracle:



- Larger $\langle \sigma v \rangle$ can withstand more expansion before "freezing out"
- Tricky to solve. What happens at low x (early times?)

$$Y_0 \approx 3.63 \times 10^{-9}\, \Omega h^2 \left(\frac{\mathrm{GeV}}{m} \right)$$

x>1 => T<m => Freeze out cold

- See this in action in your project 3

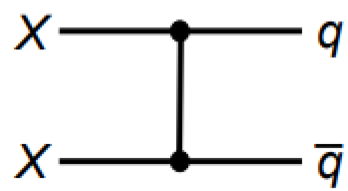
img: [Kolb + Turner]

WIMP Miracle

Assuming WIMP is initially in thermal equilibrium:

Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



$G_F \approx 1.1\ 10^5\ \text{GeV}^{-2} \rightarrow$ a new mass scale in nature

$m_{weak} \sim 100$ GeV

$m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

$$< \sigma v > \sim 3 * 10^{-26}\ cm^3/s$$

Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

- **However, null results from direct detection appear to rule out all simplest "literal" WIMP models (more next week)**

Units Example: (Useful for Proj. 3)

$$\frac{\hbar c}{1\,\mathrm{fm}} \approx 197.326\,\mathrm{MeV}$$
$$\mathrm{fm}^{-1} \approx 197.326\,\mathrm{MeV}$$
$$\mathrm{GeV} \approx 5.07 \times 10^{13}\,\mathrm{cm}^{-1}$$

$$\frac{\sigma v}{\mathrm{GeV}^{-2}} = \frac{\sigma(v/c)}{\mathrm{GeV}^{-2}} = \#$$
$$= \frac{\sigma(v/c)}{\mathrm{GeV}^{-2}} \times \frac{c}{3 \times 10^{10}\mathrm{cm/s}} \times \frac{\mathrm{GeV}^{-2}}{3.9 \times 10^{-28}\mathrm{cm}^2}$$
$$= \frac{\sigma v}{\mathrm{cm}^3\mathrm{s}^{-1}} \times \frac{1}{1.17 \times 10^{-17}}$$

$$\sigma v = 1.17 \times 10^{-17} \left[\frac{\sigma v}{\mathrm{GeV}^{-2}}\right] \mathrm{cm}^3\mathrm{s}^{-1}$$

Dimensionless number

Summary

- Dark matter is very obviously out there
- A number of good theories for its identity exist
- Dark matter has only been observed via gravity so far
- Its identity *does* impact its expected distribution – and therefore its gravitational signatures
- Dark matter production in the early Universe places strong constraints on properties – and therefore its identity

Bonus: Axions

Bonus: Axions

Strong *CP* Problem

- Observed lack of *CP*-violation in QCD ($\theta < 10^{-10}$)
- Resolution: Pseudoscalar particle "Axion" [1]

- Low-mass (<< eV), high number: Axion condensate (classical axion field)
- May be cold dark matter [2]
- Nice candidate: solve two problems
- Named Axion (Wilczek) because it "cleaned up" problem

[1] Peccei, Quinn, Phys. Rev. Lett. **38**, 1440 (1977); Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[2] Preskill, Wise, Wilczek, Phys. Lett. B **120**, 127 (1983); Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); Dine, Fischler, Phys. Lett. B **120**, 137 (1983).

Bonus: Axions

Anomalous effective couplings to SM particles:

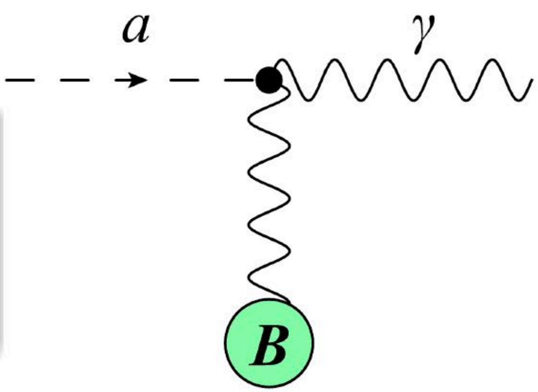
$$\overbrace{\frac{a}{f_a} F^{\mu\nu}\tilde{F}_{\mu\nu}}^{Photon} \quad \overbrace{\frac{a}{f_a} G^{\mu\nu}\tilde{G}_{\mu\nu}}^{Gluon} \quad \overbrace{\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma_5\psi}^{Fermion}$$

$$a(t) = a_0 \cos(m_a t) \qquad \frac{1}{f_a} \approx 2 \times 10^{-20}\ \mathrm{eV}^{-1} \left(\frac{m_a}{10^{-4}\ \mathrm{eV}}\right)$$

Classical Region: $m_a \sim 10^{-6} - 10^{-4}$ eV (∼MHz – GHz)
Anthropic Region: $m_a \sim 10^{-10} - 10^{-8}$ eV (∼kHz – MHz)

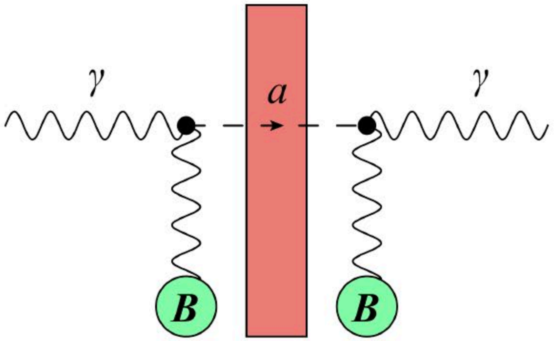
- Saturates DM density: $\Rightarrow a_0/f_a \sim 4 \times 10^{-19}$ (QCD axion)
- (In general, DM ALP, f_a free parameter, $a_0 \sim 1/m_a$)

Bonus: Axions
Axion-photon conversions



Axion–photon conversion

- e.g. ADMX, CAST, IAXO, ...
- $P_{a\to\gamma} \sim (1/f_a)^2$ *Quadratic*



Light shining through a wall

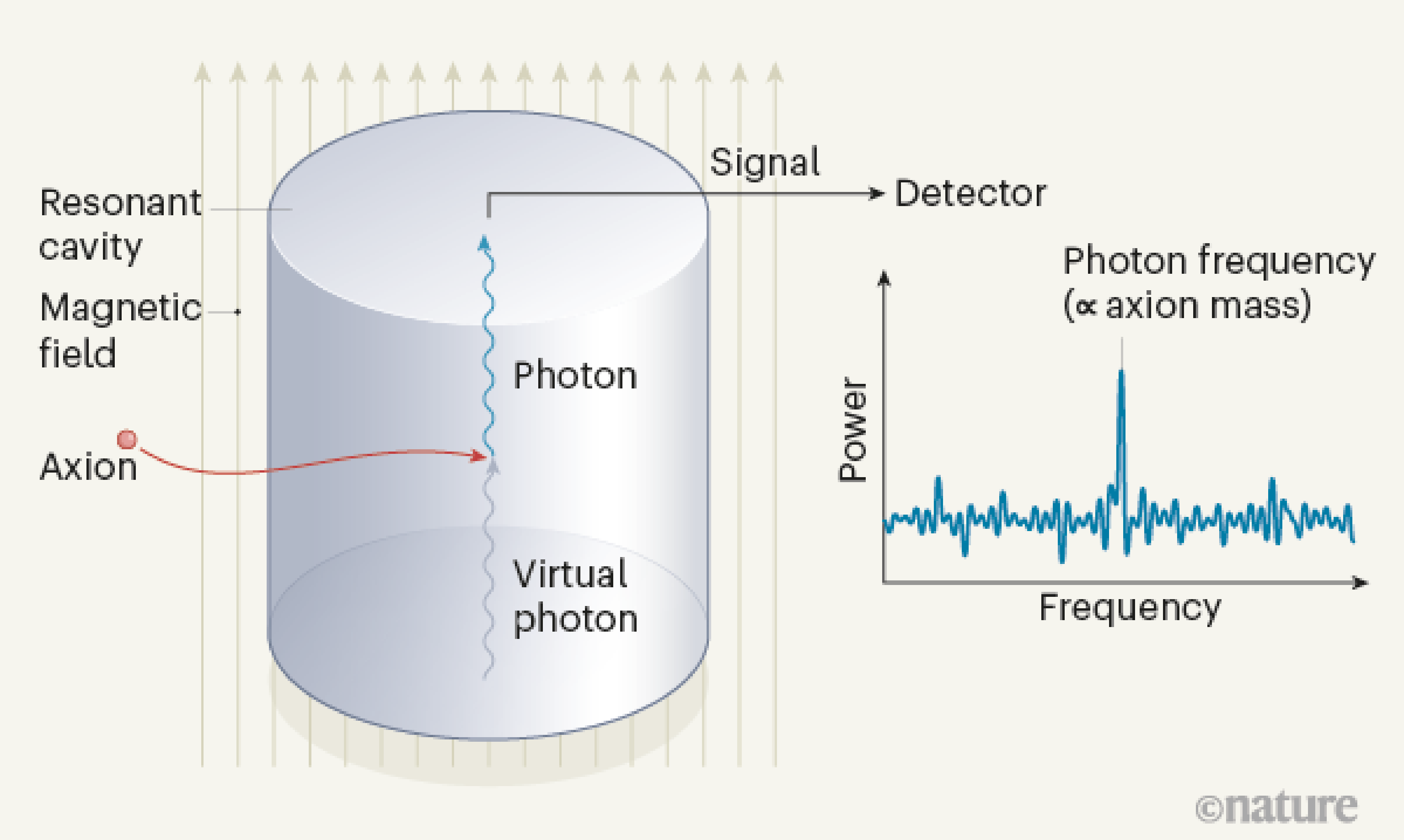
- e.g. ALPS, BMV, CROWS, ...
- $P_{\gamma\to a\to\gamma} \sim (1/f_a)^4$ *Quartic*

- Good for $\sim \ f_a < 10^{13}$ GeV

▶ Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

▶ e.g. : depts.washington.edu/admx/, cast.web.cern.ch/CAST/, alps.desy.de/

Bonus: Axions
Axion-photon conversions



Igor G. Irastorza, Nature **590**, 226 (2021)