DARK MATTER AND ASTROPARTICLE PHYSICS

PART I

INTRO TO DM

OUTLINE

- Lightning review of cosmology
- What we do and don’t know about dark matter
- Candidates for dark matter (theory vs anomaly driven)
- An oscillating scalar field as DM
- Thermal relics

OUTLINE

- The “neutralino” (whatever that is)
- The canonical WIMP: (2 ±1/2) Dirac fermion
  - (aka the “Higgsino” or 4th gen neutrino)
- Signals of thermal dark matter
  - direct detection
  - indirect detection
  - colliders

OUTLINE

- Anomalies in direct detection
  - DAMA
  - CoGeNT
  - CRESST
- Scenarios: light WIMPs, spin-dependent, inelastic WIMPs, other exotica

OUTLINE

- Anomalies in indirect detection
  - INTEGRAL
  - PAMELA/Fermi (electrons)
  - WMAP/Fermi (photons)
- Scenarios: MeV DM, “eXciting” DM, decaying DM
- Dark forces and signals

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a cheat sheet for the early universe

The universe is expanding

Characterized by time H^{-1}

"Hubble time" = time for universe to ~double in size

Later universe is cooler

$$\boxed{t = T^{-1}}$$

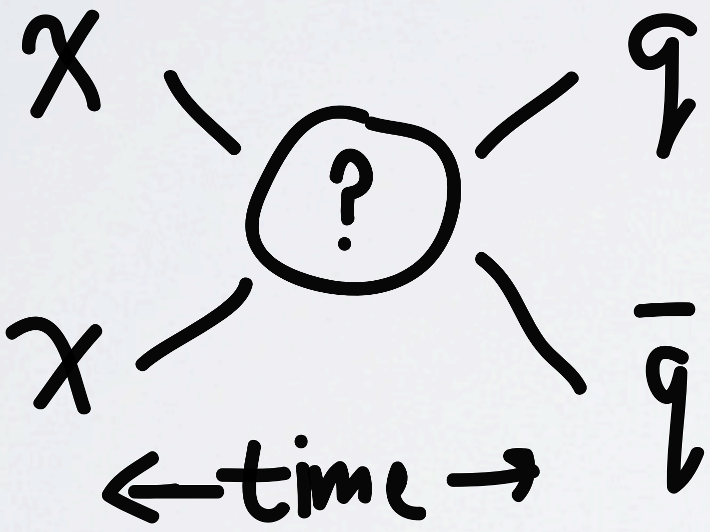
a cheat sheet for the early universe

Rate is governed by

$$\Gamma = \underset{\substack{\uparrow \\ \text{number} \\ \text{density} \\ \text{of} \\ \chi}}{n_\chi} \; \underset{\substack{\nwarrow \\ \text{cross} \\ \text{section} \\ \text{for} \\ \text{process}}}{\sigma} \, v \leftarrow \text{relative velocity}$$

We are interested in equilibrium processes

e.g.



Want to compare

$$\underset{\substack{\uparrow \\ \text{rate of} \\ \text{annihilation}}}{\Gamma} = n\sigma v \quad \text{vs} \quad \underset{\substack{\uparrow \\ \text{rate for} \\ \text{universe} \\ \text{to} \\ \text{double}}}{H}$$

a cheat sheet for the early universe

Key formulae

$H^2 \sim \frac{\rho}{M_{pl}^2}$ ← energy density

$n_{Rel} \sim T^3$

$n_{NR} \sim (m_x T)^{3/2} e^{-m_x/T}$

exponen

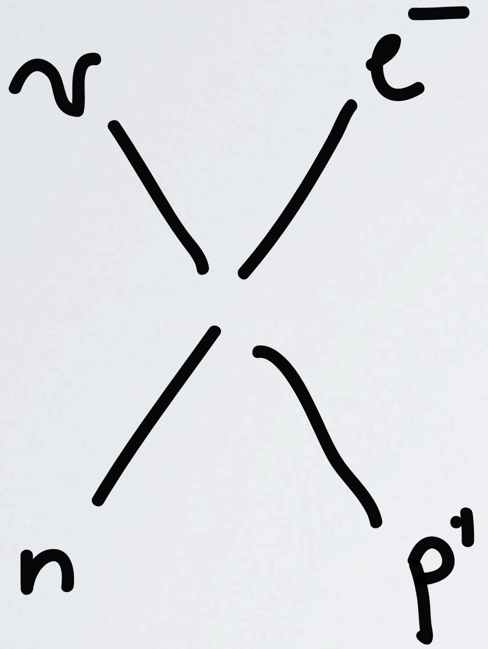
$$H^2 \sim \frac{\rho}{M_{pl}^2}$$

$$n_{Rel} \sim T^3$$

$$n_{NR} \sim (mT)^{3/2} exp(-m/T)$$

a cheat sheet for the early universe

E.g. neutron ⟺ proton conversion

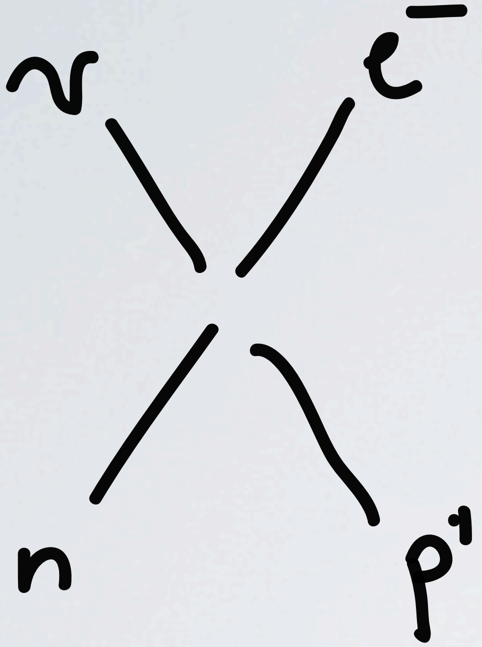


$$\mathcal{M} \propto G_F$$

$$\Rightarrow \sigma \propto G_F^2$$

$$\underset{\underset{T^3}{\uparrow}}{n}\;\underset{\underset{\propto G_F^2}{\uparrow}}{\sigma}\;\underset{\underset{c}{\uparrow}}{v} \propto G_F^2 T^3 \times \underset{\underset{\text{dimensions of cross section}}{\uparrow}}{T^2}$$

E.g. neutron $\Leftrightarrow$ proton conversion



$$M \propto G_F$$

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$$\underset{\underset{T^3}{\nearrow}}{n}\ \underset{\underset{\propto G_F^2}{\uparrow}}{\sigma}\ \underset{\underset{c}{\nwarrow}}{v} \propto G_F^2 T^3 \times \underset{\underset{\text{dimensions of cross secti}}{\uparrow}}{T^2}$$

When does

$$G_F^2 T^5 = \frac{T^2}{M_{pl}} \ ?$$

$$\Rightarrow T = \left(\frac{1}{M_{pl} G_F^2}\right)^{1/3}$$

$$\simeq 0.9 \text{ MeV}$$

“freezeout”

a cheat sheet for the early universe

- The universe is pretty much an equilibrium place (your charming selves excluded)
- Determining deviations from equilibrium are interesting and are useful to us
- We find this by calculating **freezeout**, when a scattering or annihilation rate is equal to the Hubble rate

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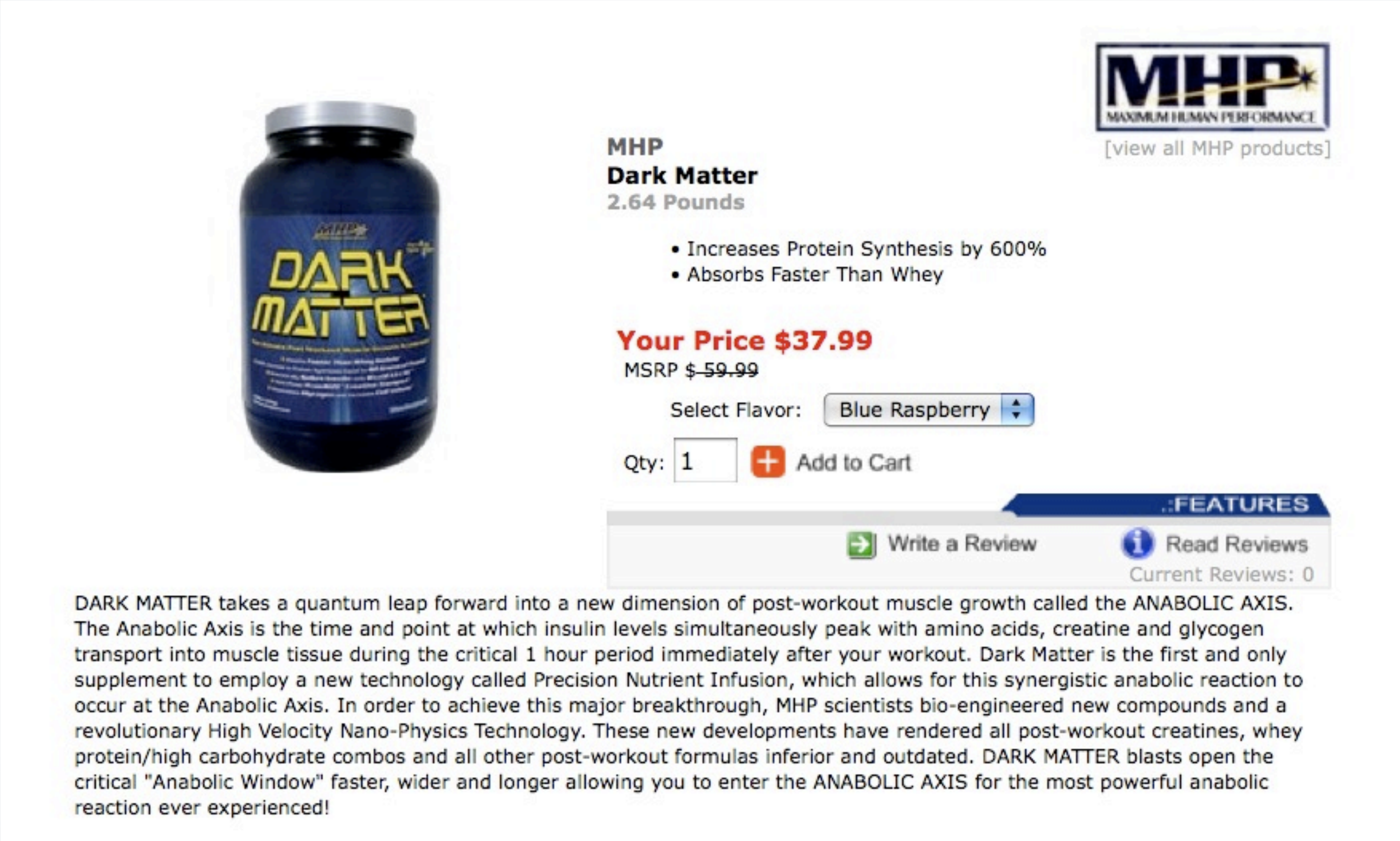
What we do and don’t know about DM



MHP
Dark Matter
2.64 Pounds

- Increases Protein Synthesis by 600%
- Absorbs Faster Than Whey

Your Price $37.99
MSRP $ ~~59.99~~

Select Flavor: Blue Raspberry

Qty: 1

Current Reviews: 0

DARK MATTER takes a quantum leap forward into a new dimension of post-workout muscle growth called the ANABOLIC AXIS. The Anabolic Axis is the time and point at which insulin levels simultaneously peak with amino acids, creatine and glycogen transport into muscle tissue during the critical 1 hour period immediately after your workout. Dark Matter is the first and only supplement to employ a new technology called Precision Nutrient Infusion, which allows for this synergistic anabolic reaction to occur at the Anabolic Axis. In order to achieve this major breakthrough, MHP scientists bio-engineered new compounds and a revolutionary High Velocity Nano-Physics Technology. These new developments have rendered all post-workout creatines, whey protein/high carbohydrate combos and all other post-workout formulas inferior and outdated. DARK MATTER blasts open the critical "Anabolic Window" faster, wider and longer allowing you to enter the ANABOLIC AXIS for the most powerful anabolic reaction ever experienced!

What we do and don't know about DM

The two key things to remember about dark matter:

- **No one knows anything about dark matter**
- **We already know a great deal about dark matter**

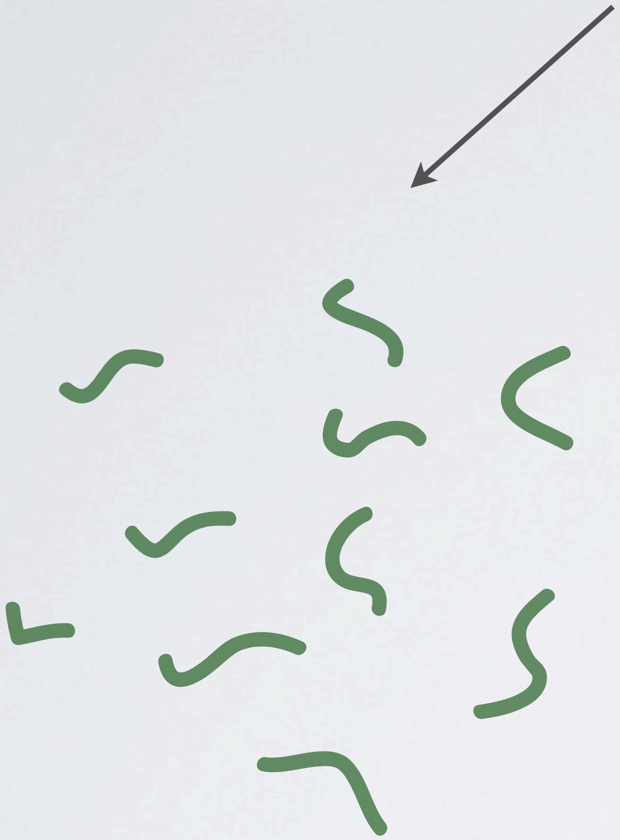
If you can remember these two things you shouldn't go too wrong

our historical attitudes towards dark matter

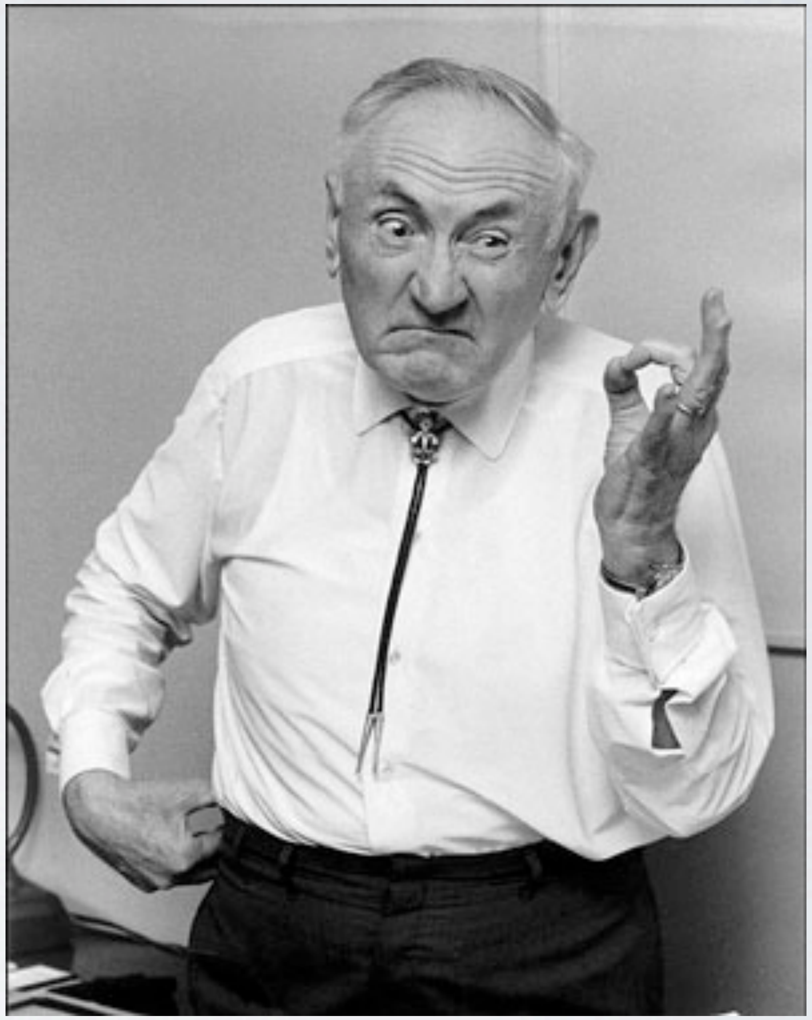
Favored candidate	**Properties**
(pre 1930's) none	nothing
(70's-80's) gas/brown dwarfs	ordinary matter
(~80's-90's) neutrinos	weak interactions, light, "hot"
(~90's+) neutralinos	heavy, cold, **really** weakly interacting
?	?

our ideas of what DM is or could be evolve, and our ideas of what is unnatural today could be natural tomorrow

Evidence for DM



galaxies
in bound
cluster



Evidence for DM

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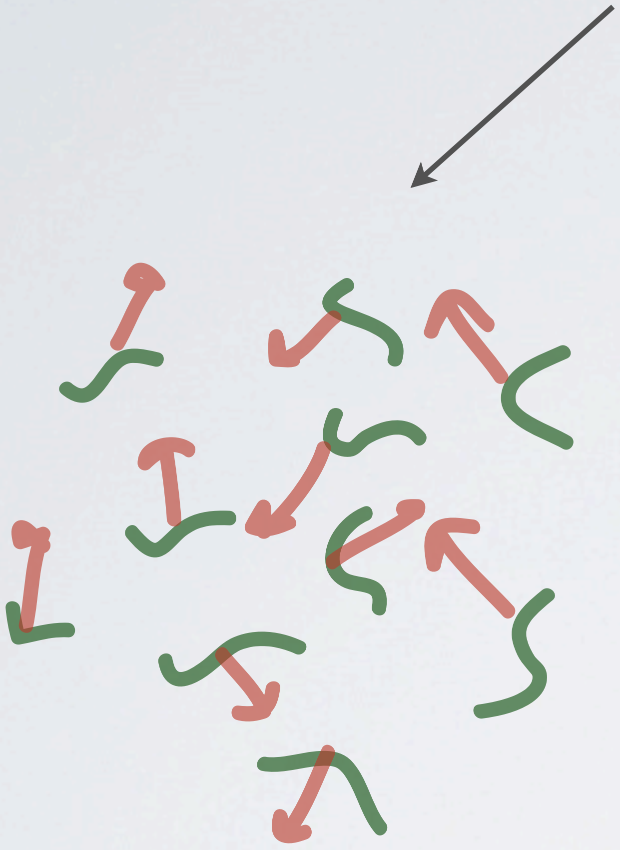
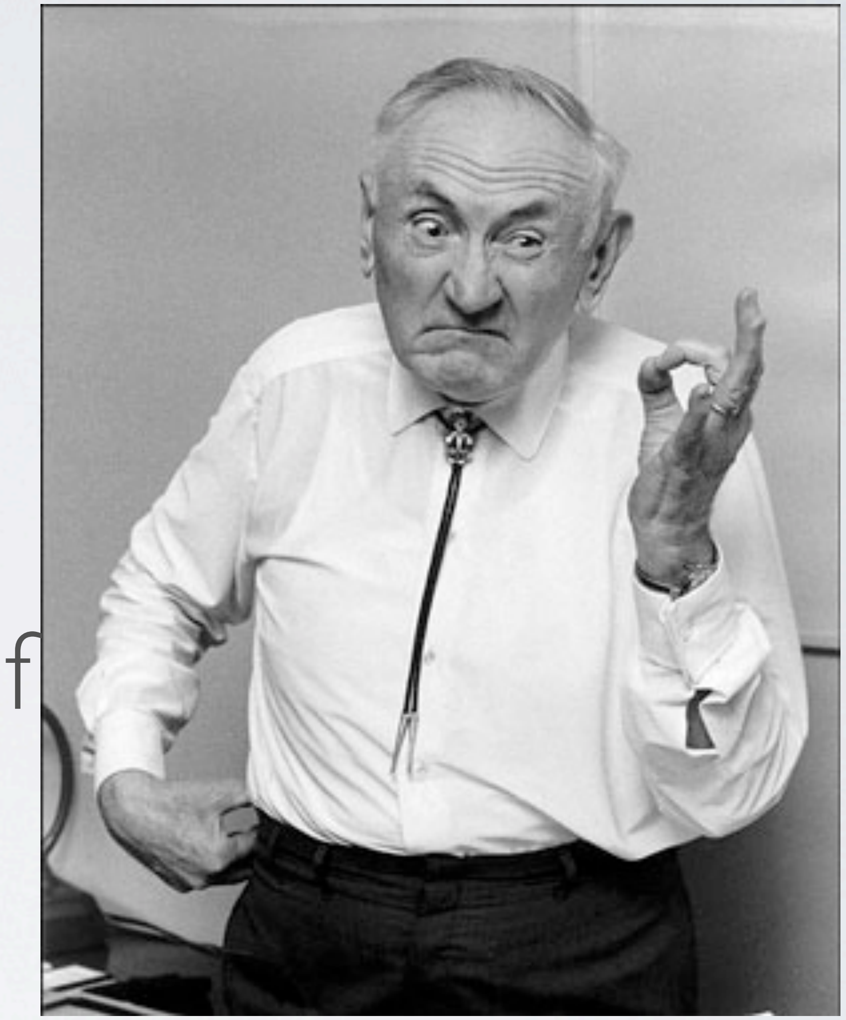


velocities
allow a
determination of
potential



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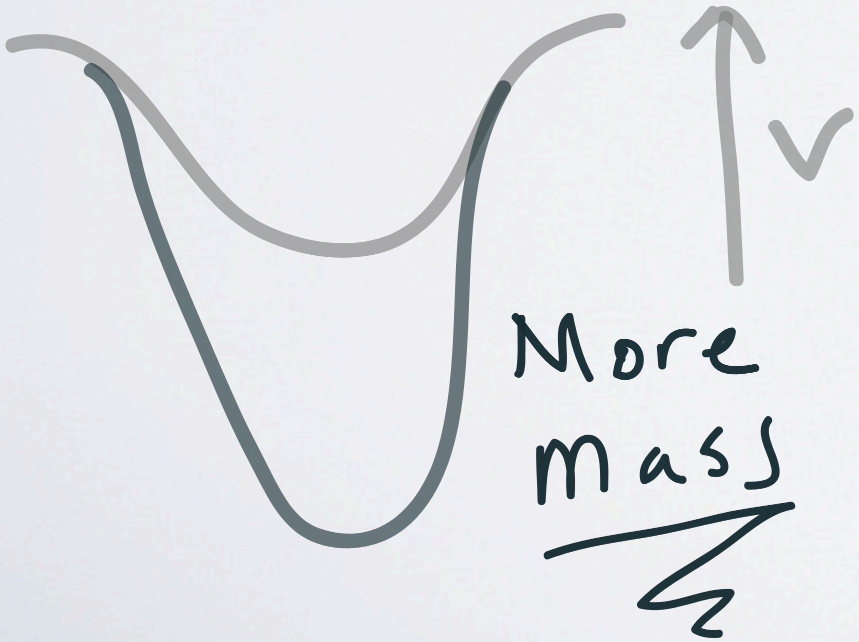
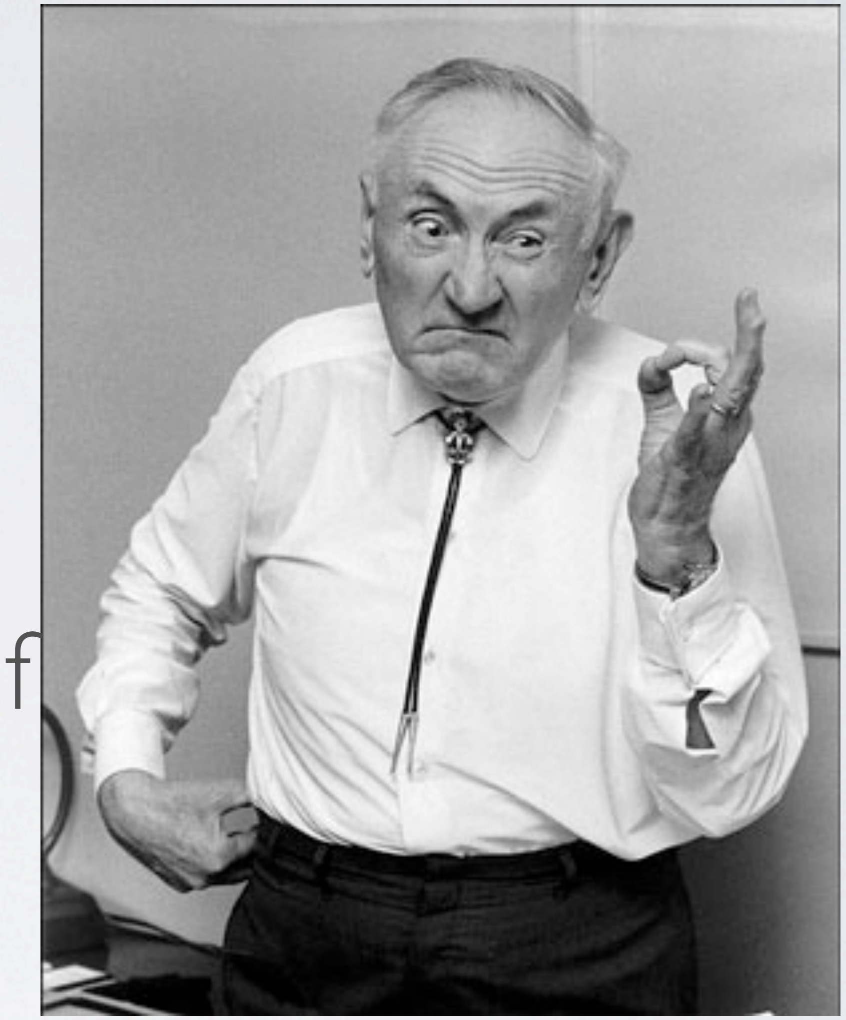
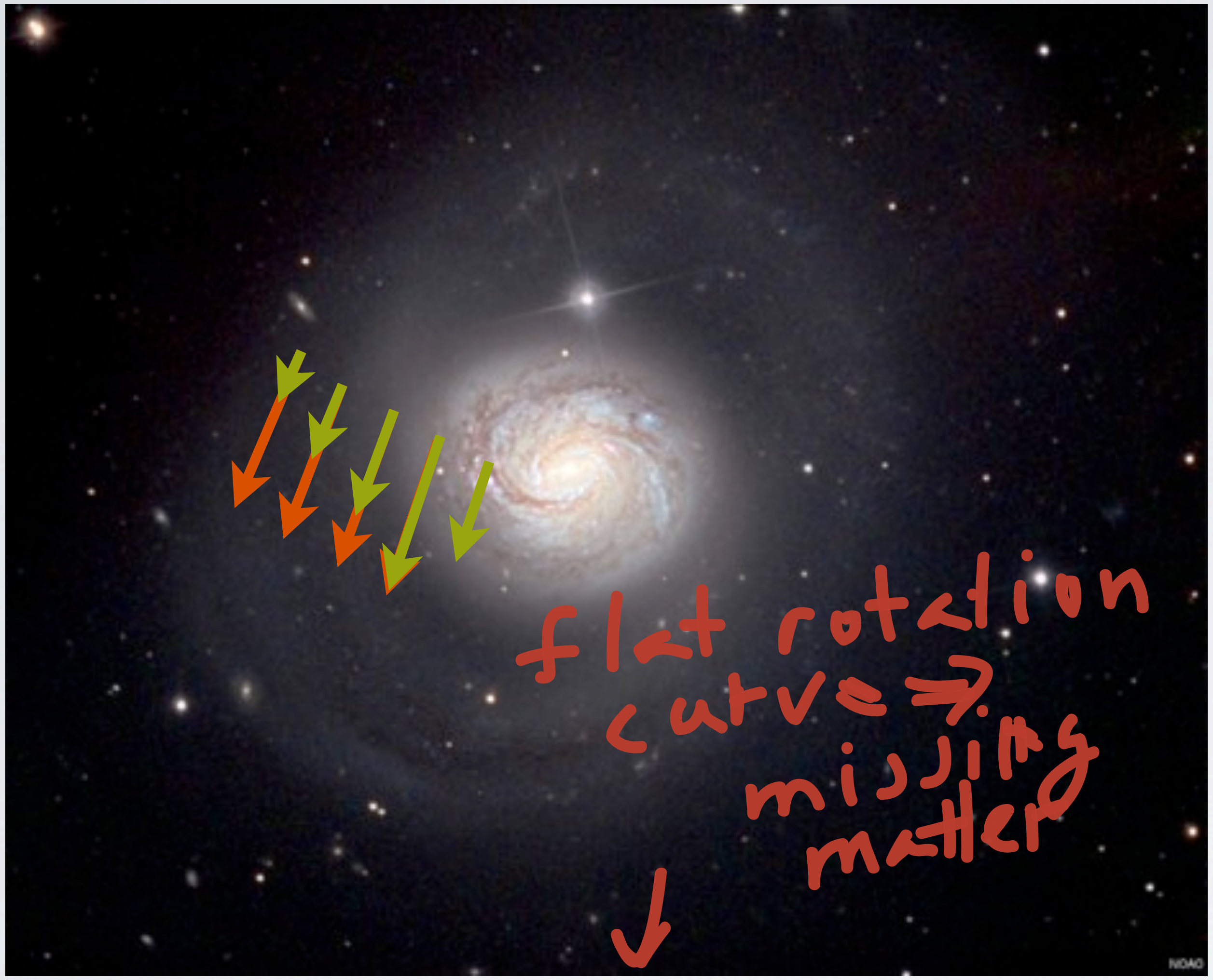
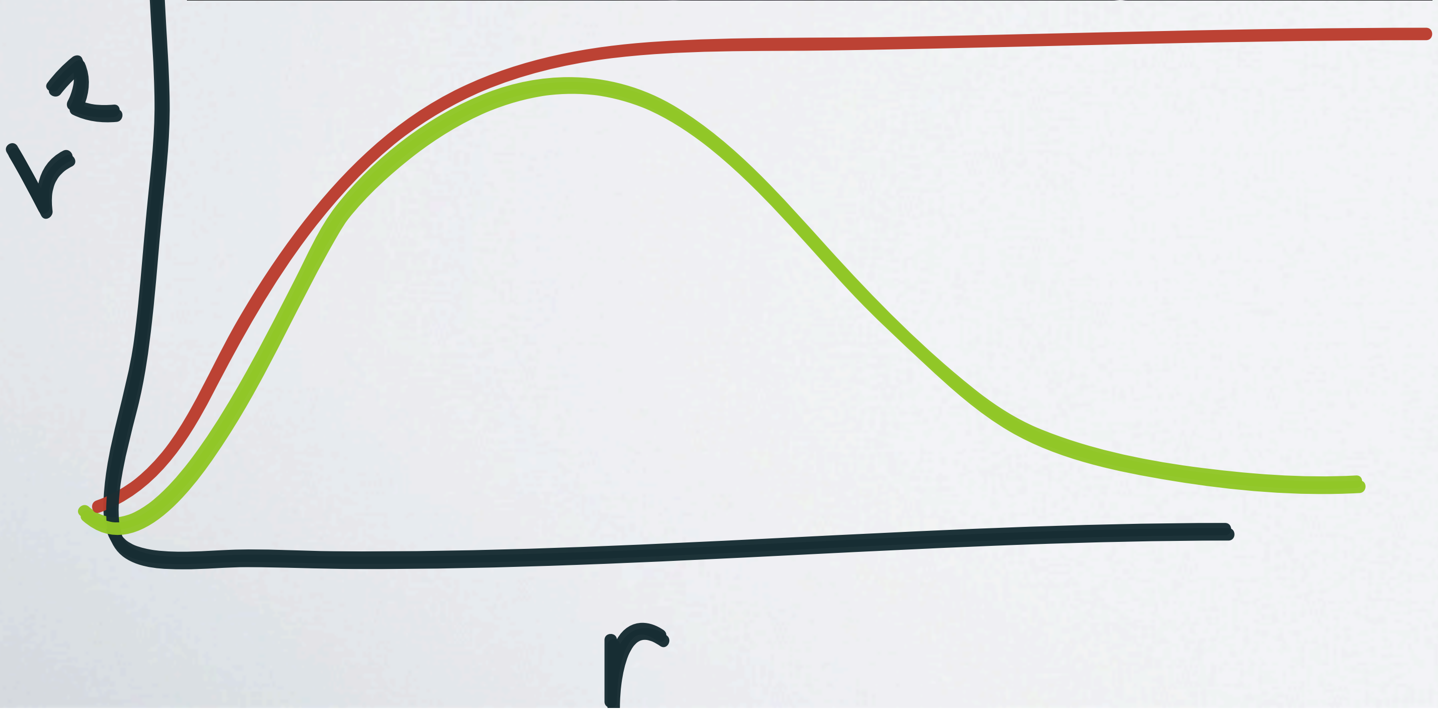




Evidence for DM

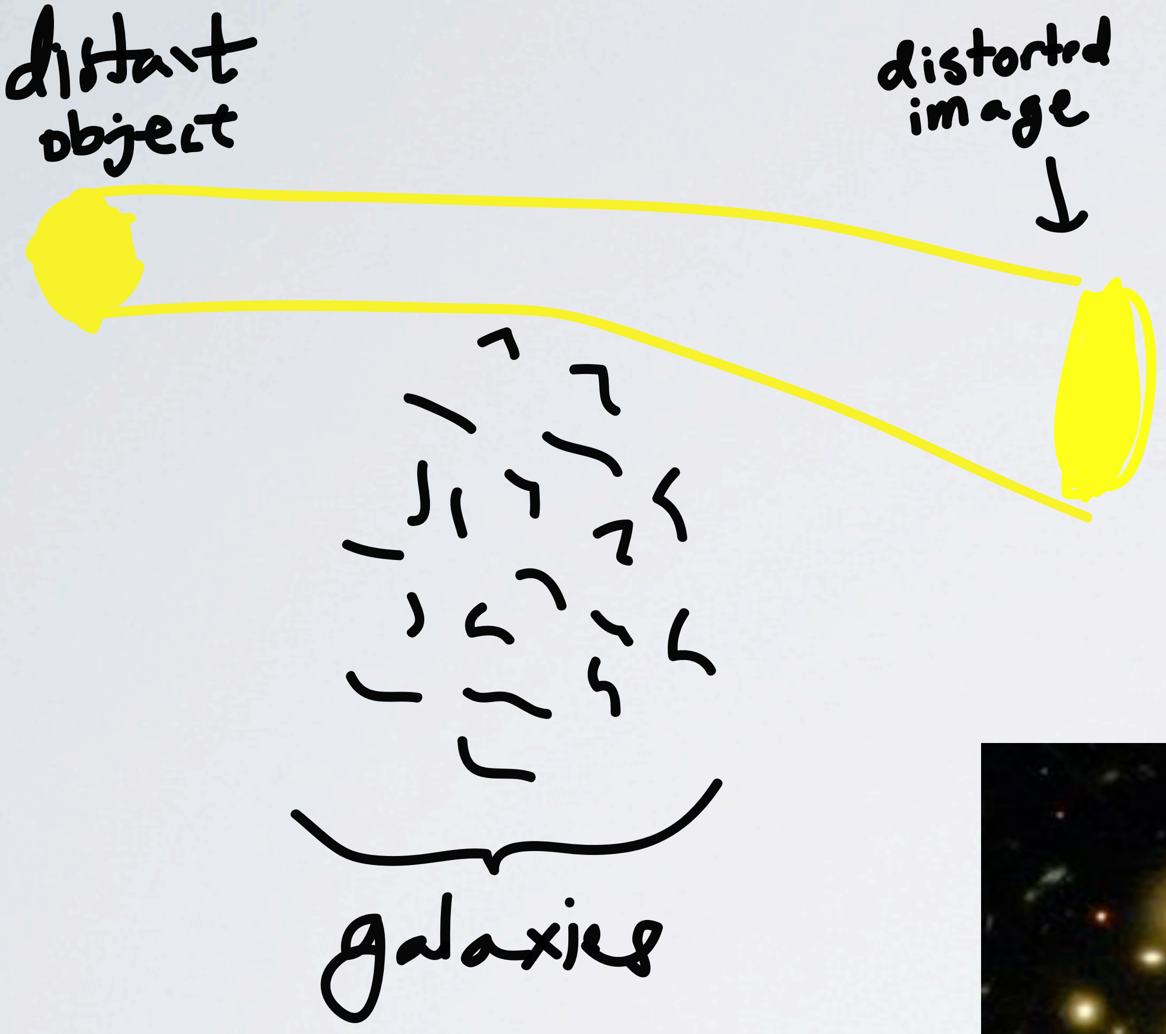


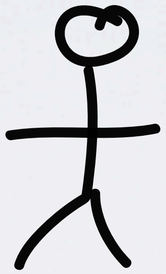
flat rotation curve ⇒ missing matter ↓



$$\frac{v^2}{r} = \frac{GM(r)}{r^2} \Rightarrow v^2 = \frac{GM(r)}{r}$$

Evidence for DM





Lensing

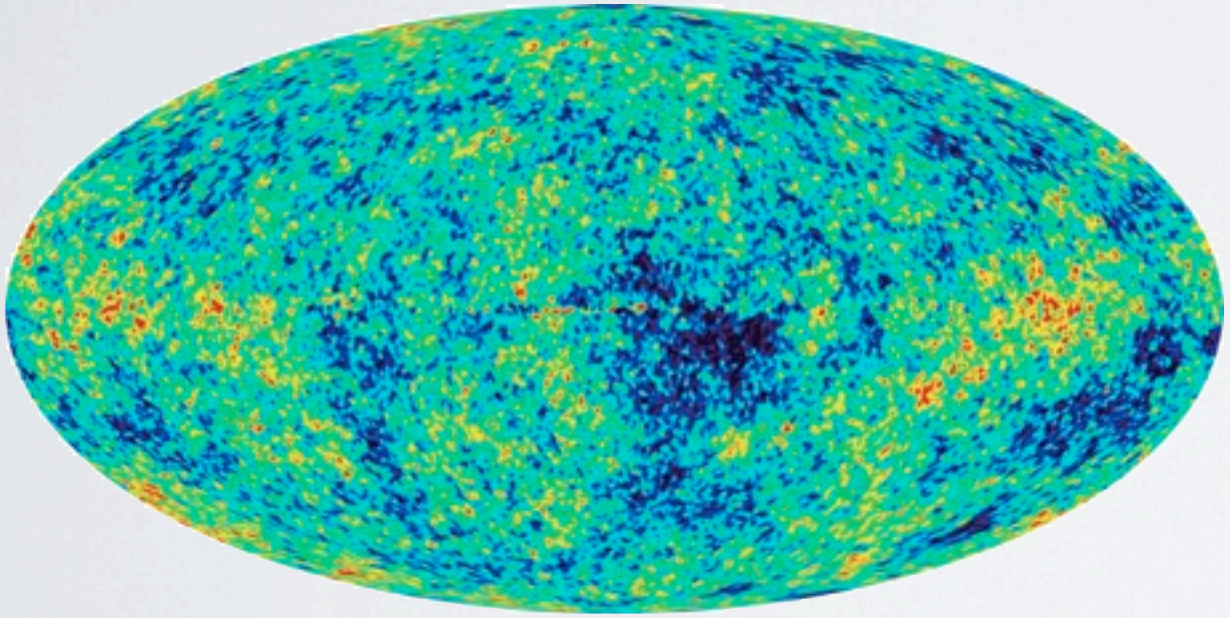
Evidence for DM

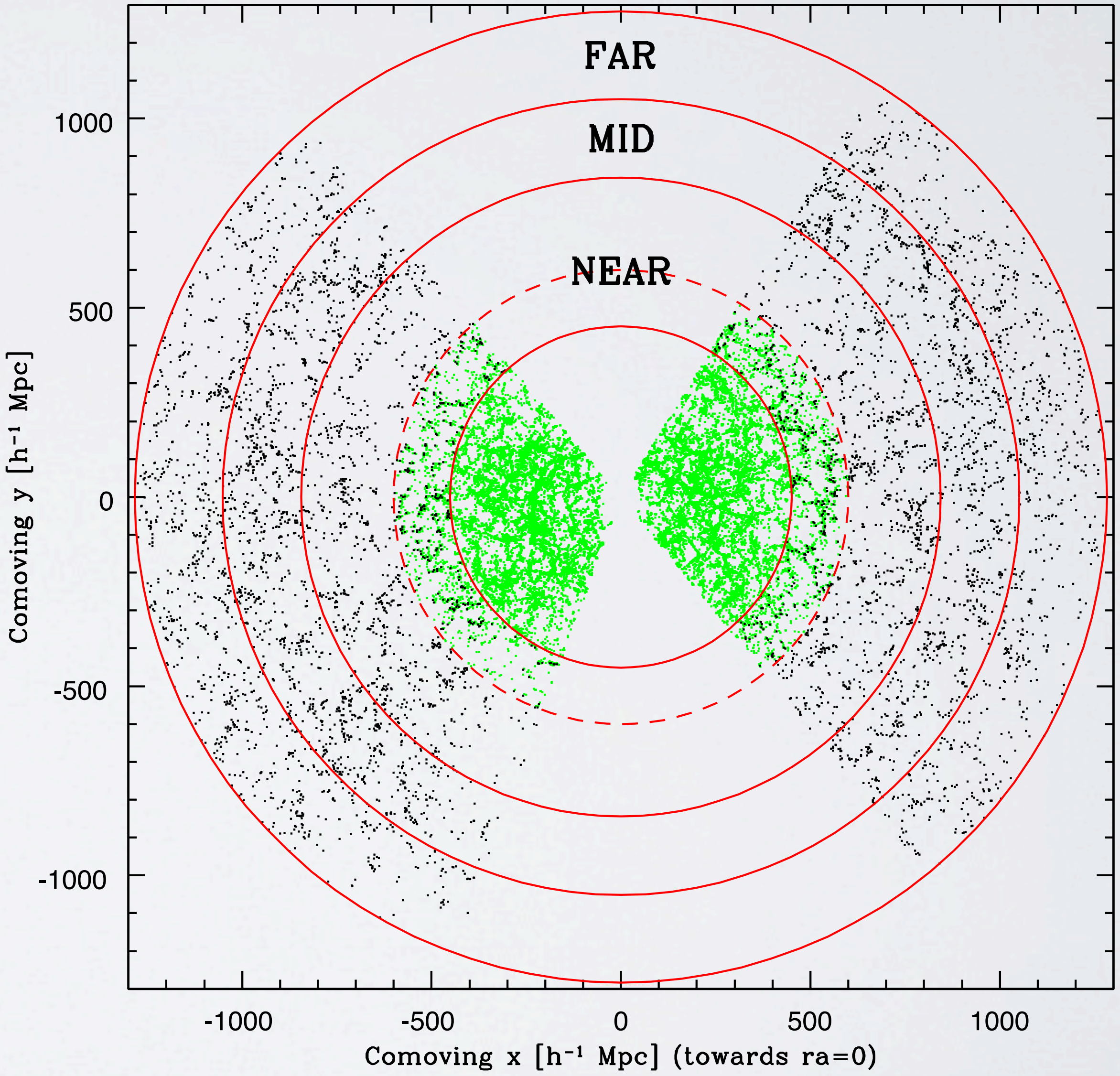
Dark matter visible through lensing

Ordinary matter visible in X-rays

Evidence for DM

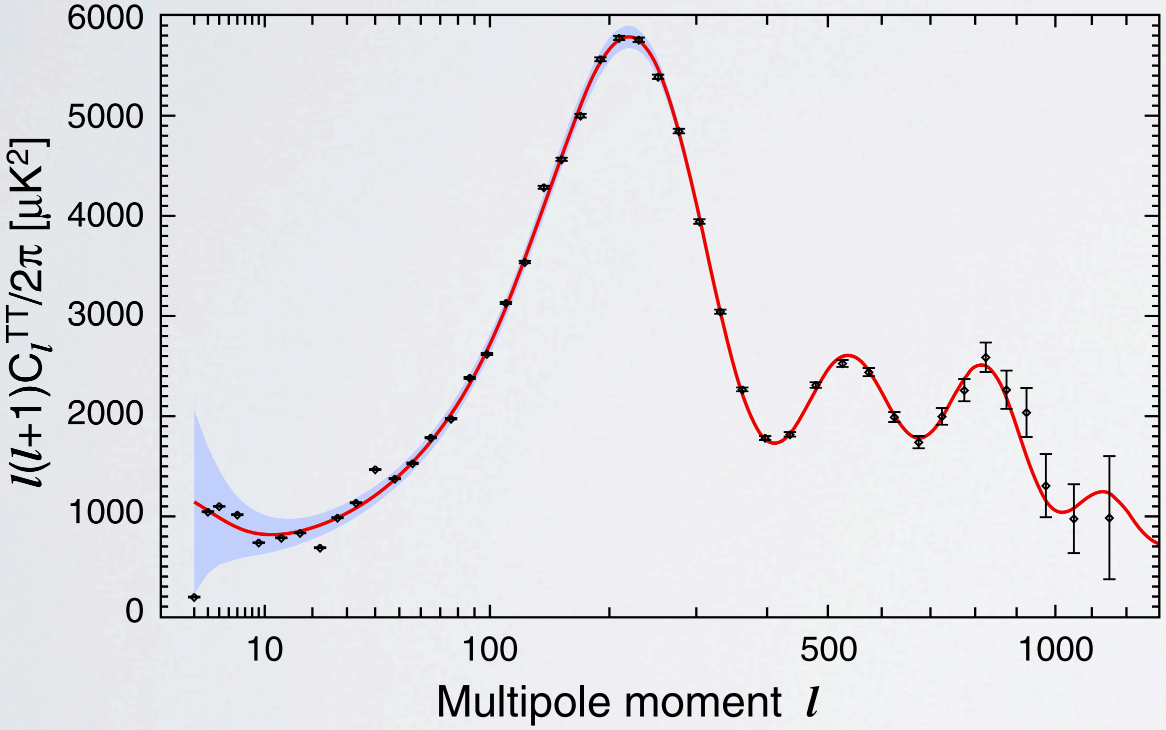
- Power spectra / CMB

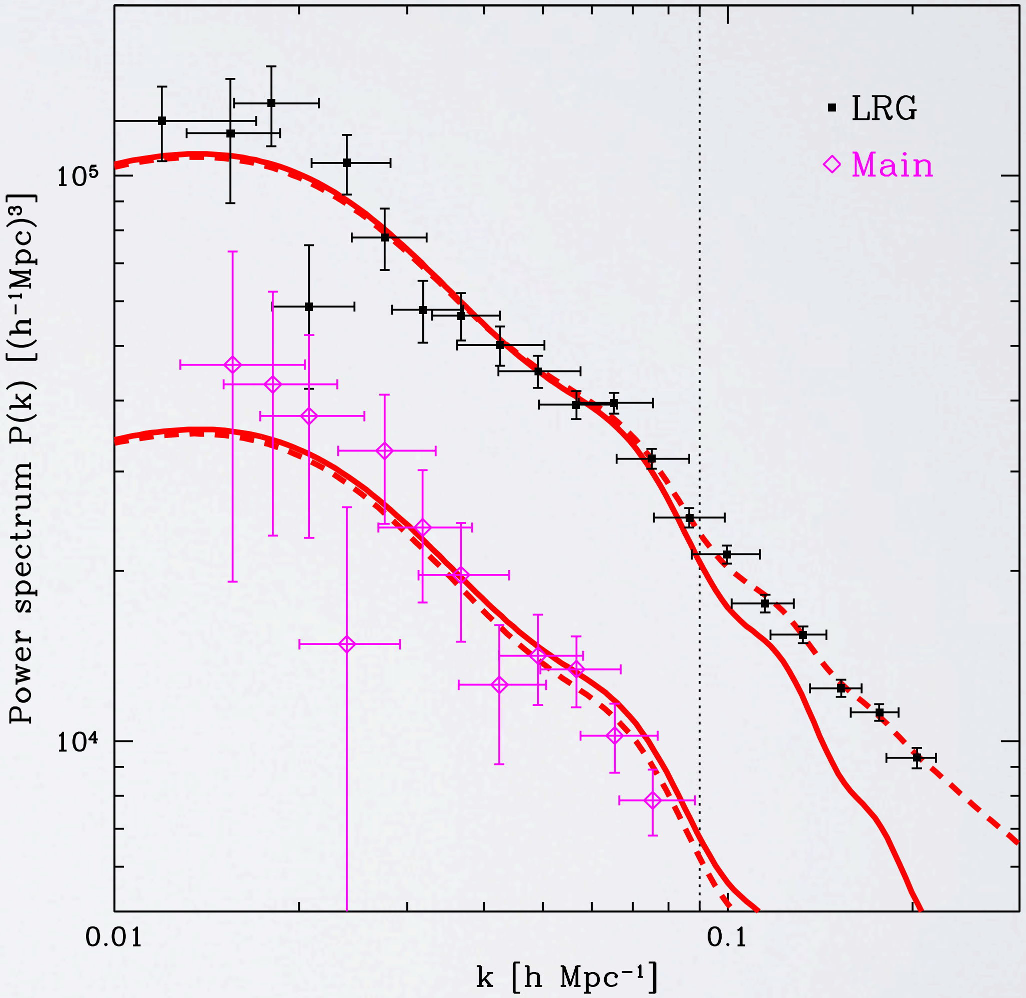




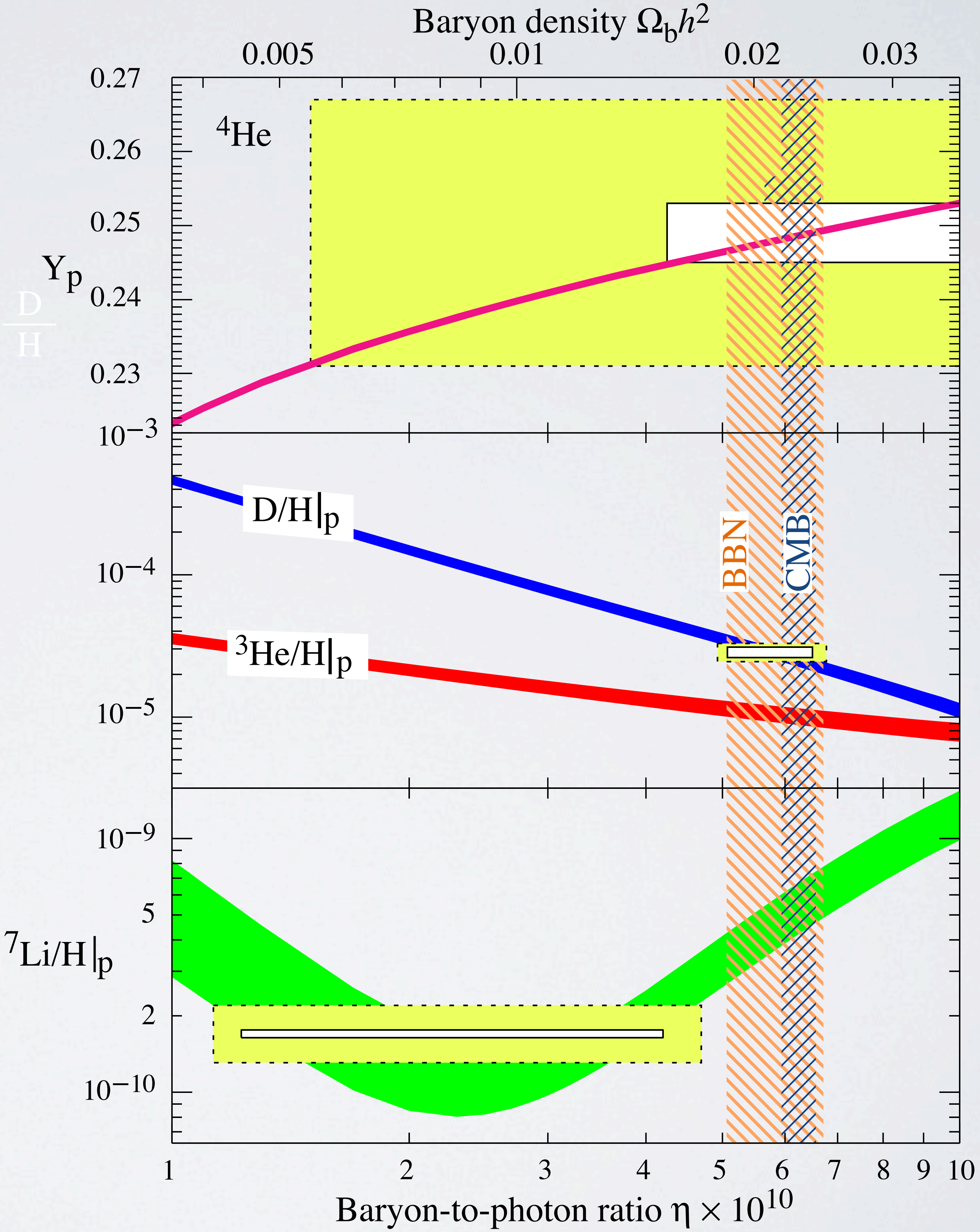
Evidence for DM

- Power spectra/ CMB





Evidence for DM



Higher amounts of baryons in the early universe determine the primordial light element abundances

What do we know about dark matter?

(mostly negative, i.e., what it is *not*)

0) Massive

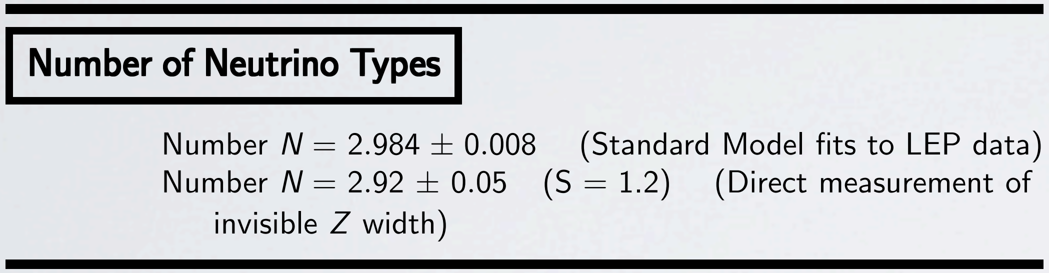
$$\rho_\chi = m_\chi n_\chi \propto a^{-3} = a^{-3(w+1)}$$

“equation of state” or “pressure”

dark matter diluting with volume = “pressureless fluid”

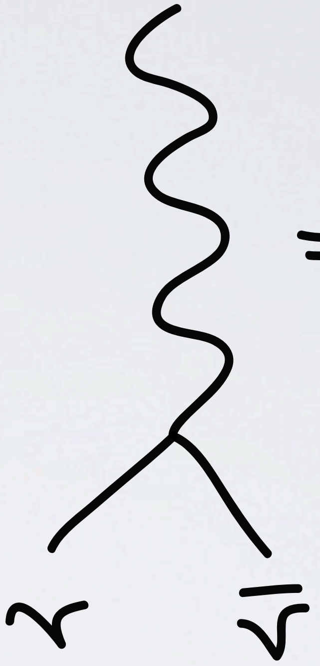
What do we know about dark matter?

0) Neutral

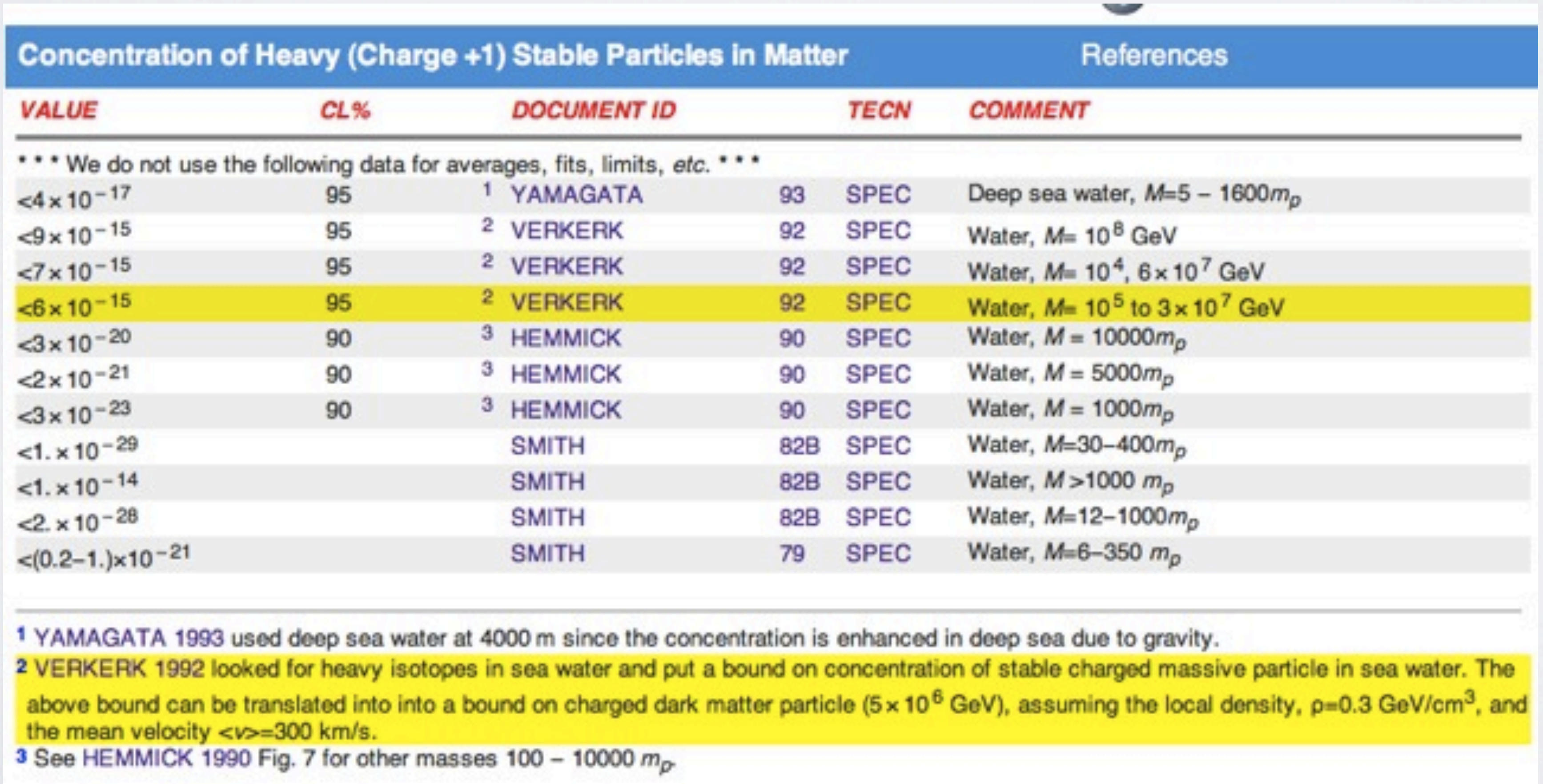


Number of Neutrino Types

Number $N = 2.984 \pm 0.008$ (Standard Model fits to LEP data)
Number $N = 2.92 \pm 0.05$ (S = 1.2) (Direct measurement of invisible Z width)



$\Rightarrow \Gamma_Z$



Concentration of Heavy (Charge +1) Stable Particles in Matter References

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, *etc.* • • •				
$<4\times10^{-17}$	95	[1] YAMAGATA 93	SPEC	Deep sea water, M=5 – 1600m_p
$<9\times10^{-15}$	95	[2] VERKERK 92	SPEC	Water, M= 10^8 GeV
$<7\times10^{-15}$	95	[2] VERKERK 92	SPEC	Water, M= 10^4, 6×10^7 GeV
$<6\times10^{-15}$	95	[2] VERKERK 92	SPEC	Water, M= 10^5 to 3×10^7 GeV
$<3\times10^{-20}$	90	[3] HEMMICK 90	SPEC	Water, $M = 10000m_p$
$<2\times10^{-21}$	90	[3] HEMMICK 90	SPEC	Water, $M = 5000m_p$
$<3\times10^{-23}$	90	[3] HEMMICK 90	SPEC	Water, $M = 1000m_p$
$<1.\times10^{-29}$		SMITH 82B	SPEC	Water, M=30–400m_p
$<1.\times10^{-14}$		SMITH 82B	SPEC	Water, M >1000 m_p
$<2.\times10^{-28}$		SMITH 82B	SPEC	Water, M=12–1000m_p
$<(0.2–1.)\times10^{-21}$		SMITH 79	SPEC	Water, M=6–350 m_p

---

[1] YAMAGATA 1993 used deep sea water at 4000 m since the concentration is enhanced in deep sea due to gravity.

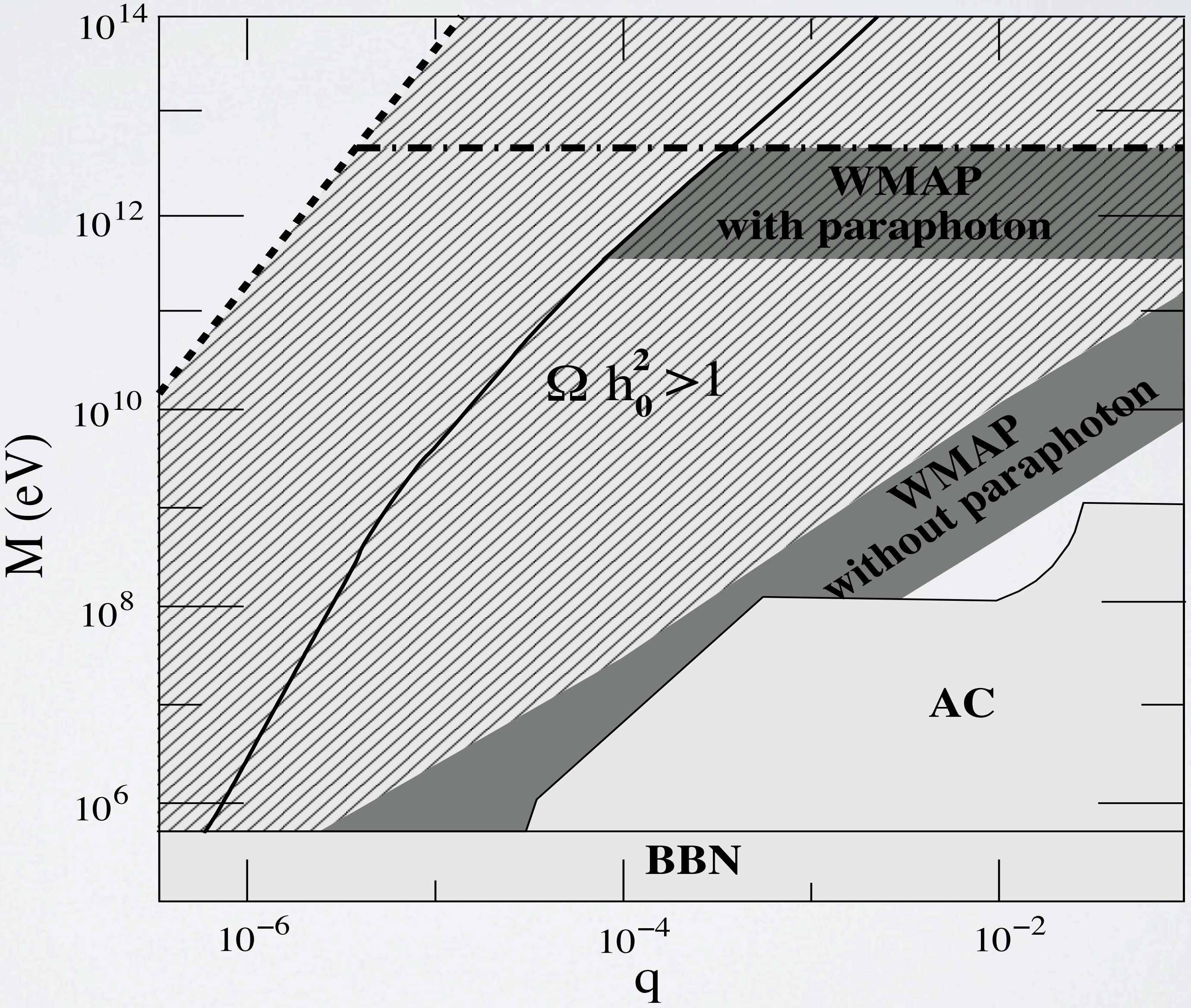
[2] VERKERK 1992 looked for heavy isotopes in sea water and put a bound on concentration of stable charged massive particle in sea water. The above bound can be translated into into a bound on charged dark matter particle (5×10^6 GeV), assuming the local density, ρ=0.3 GeV/cm^3, and the mean velocity $<v>$=300 km/s.

[3] See HEMMICK 1990 Fig. 7 for other masses 100 – 10000 m_p.

What do we know about dark matter?

Dubovksy, Gorbunov, Rubtsov, hep-ph/0311189

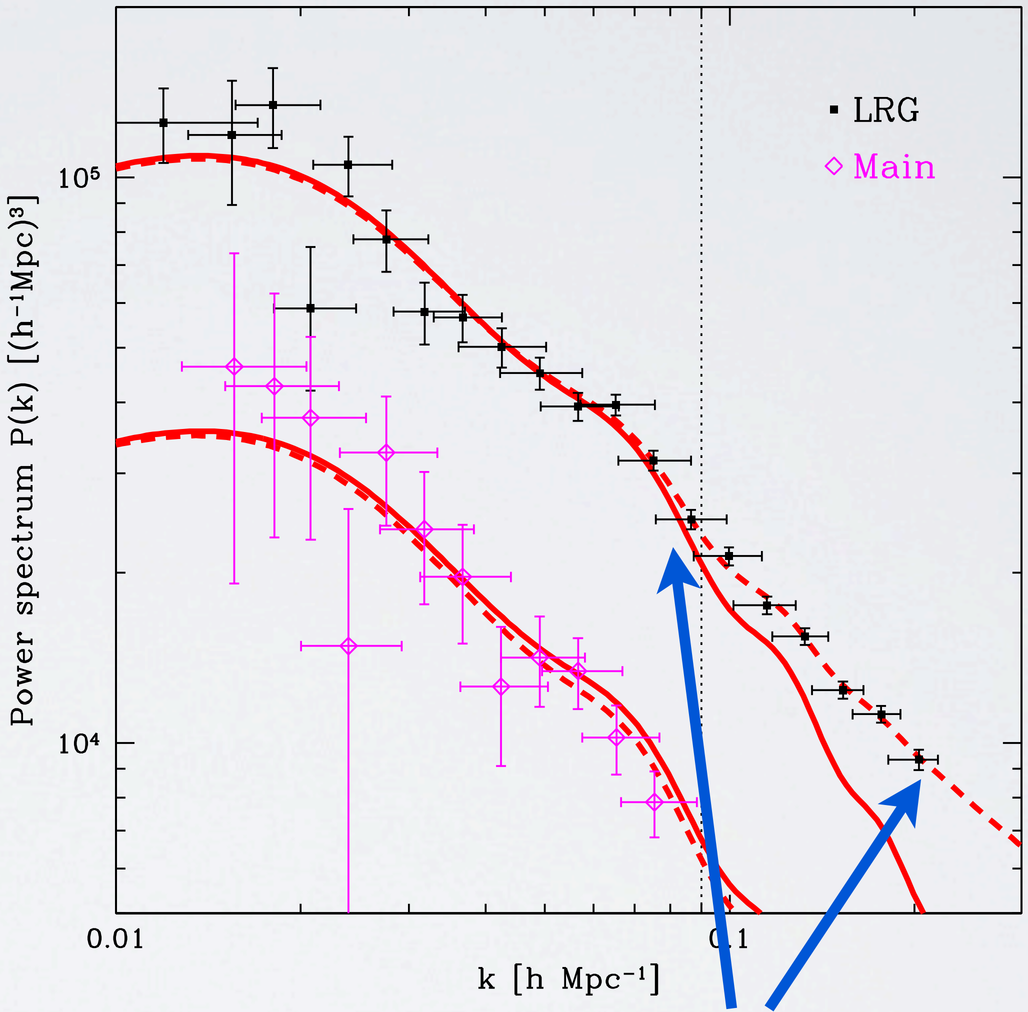
millicharged?



What do we know about dark matter?

Cold

cold DM builds up structures hierarchically - consistent with observation



hot DM streams out of overdensities depletes small scale structure

What do we know about dark matter?

But what do we really mean by **Cold?**

Usually people mean that **when dark matter was produced, it was moving non-relativistically**

But everything massive slows down and becomes cold (eventually - even 2/3 neutrinos are currently cold)

Experimentally, DM should have been cold at ~ keV temperatures

What do we know about dark matter?

Non-interacting

Hard scattering

$$n\sigma v\tau = 1 \Rightarrow \frac{\sigma}{10^{-24}\mathrm{cm}^2} \lesssim \frac{TeV}{M_\chi}$$

massless gauge forces

$$\alpha \lesssim 10^{-3}$$

(Ackerman et al, 0810.5126)

Corrections to 1/r^2
F_dark/F_grav < 0.2

(Kesden+Kamionkowski, 0608095

But some interactions might be good!
Spergel+Steinhardt, '00

What do we know about dark matter?

Stable

Pretty easily achieved with symmetries (real, approximate, gauged, or global)

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Models of Dark Matter (theory drive)

Name	What is it?	Motivation	Alive?
axion	Promote theta parameter to dynamical variable. Dynamics drive to zero. $\theta G_{\mu\nu}\tilde{G}^{\mu\nu} \Rightarrow (\theta + a/f)G_{\mu\nu}\tilde{G}^{\mu\nu}$	Strong CP problem	Yes
neutralino	Fermionic partner of Z, photon, and Higgses $\tilde{B} + \tilde{W}_3 + \tilde{H}_u + \tilde{H}_d$	Hierarchy problem	Yes
sneutrino	superpartner of neutrino	Hierarchy problem	No*
sterile neutrino	keV mass, mixed weakly with neutrino	Minimality	Yes (borderline)
LTOP	Lightest T-Odd Particle	Hierarchy problem	As much as little Higgs theories
KKDM	$B^{(1)}$, $\nu^{(1)}$ - lightest KK excitation of SM states	Weak scale	Yes (has already been observed by ATIC)

Models of Dark Matter (theory drive)

Name	What is it?	Motivation	Alive?
axino	Superpartner of axion	Strong CP problem+HP	Yes
gravitino	superpartner of gravitino, aka superWIMP	Hierarchy problem+hatred of DM detection	Yes
inert doublet	(2, ±1/2) representation	weak scale	If tweaked
topological DM	DM formed from topological elements of new field theory	Field theories	Yes (not theoretically constrained)
BHs	Black holes formed through sudden process in early universe	Black holes	MACHO limits, evaporation
?	?	?	?

Models of Dark Matter (anomaly drive)

Name	What is it?	Motivation	Alive?
light WIMP	A light WIMP	Strong CP problem+HP	?
inelastic WIMP	A WIMP that scatters off nuclei into excited state DM->DM*	DAMA	Dipole couplings or DM streams
resonant DM	WIMP that binds with nucleus in scattering	DAMA	?
mirror DM	Complex DM system mirroring our own, effectively millicharged	DAMA/CoGeNT	Complicated
eXciting DM	TeV DM that scatters off itself into excited states and annihilates into sub-GeV dark forces	INTEGRAL, PAMELA/FERMI	Tense
MeV DM	Dark matter at the MeV scale	INTEGRAL	?

Models of Dark Matter

- In general, the LNSWP is a DM candidate
- Many frameworks (e.g., WIMPless, dark force models) contain many candidates

Forming DM

Thermal
i.e., dark matter was
at one time in thermal
equilibrium

Non-Thermal

- phase transition
- decay of other particles
- incomplete $n\sigma v$

Canonical WIMP example #1

The oscillating scalar field

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$ (Klein-Gordon in expanding universe)

$$\phi \rightarrow \phi_0 e^{wt}$$

$$\Rightarrow w^2 + 3wH + m^2 = 0$$

$$\Rightarrow w = \frac{-3H \pm \sqrt{9H^2 - 4m^2}}{2}$$

(assume H is constant)

if $m \gg H$

$$w = -\frac{3H}{2} \pm im$$

$$\Rightarrow \phi = \phi_0 \underset{\uparrow \text{decay}}{e^{-\frac{3Ht}{2}}} \underset{\nwarrow \text{oscillation}}{e^{\pm imt}}$$

Canonical WIMP example #1

$$\rho = \dot{\phi}^2 + m^2\phi^2 \propto \langle \phi_0^2 \rangle m^2 e^{-3Ht}$$

$$a = \underset{\substack{\uparrow \\ \text{constant} \\ H}}{e^{Ht}} a_0 \Rightarrow \rho \propto \rho_0 a^{-3}$$

$\Rightarrow$ depletes like volume

$\Rightarrow$ $w=0$

$\Rightarrow$ pressureless DM

Canonical WIMP example #1

Case $m << H$

$w = -3H, \ \frac{-2m^2}{3H} \leftarrow \sim$ constant for $t \sim \frac{H}{m^2} >> H^{-1}$

↑

decays in 1 Hubble time

Canonical WIMP example #1

Note: the natural size for $\phi_0 \sim M_{pl}$

$$\langle \phi_0^2 \rangle m^2 = M_{pl}^2 m^2 = \rho$$

$$\Rightarrow H^2 = \frac{\rho}{M_{pl}^2} = m^2$$

BUT transition only happens when $H = m$

$\Rightarrow$ this field is dominating the energy density of the universe!

$\Rightarrow$ BAD DM candidate

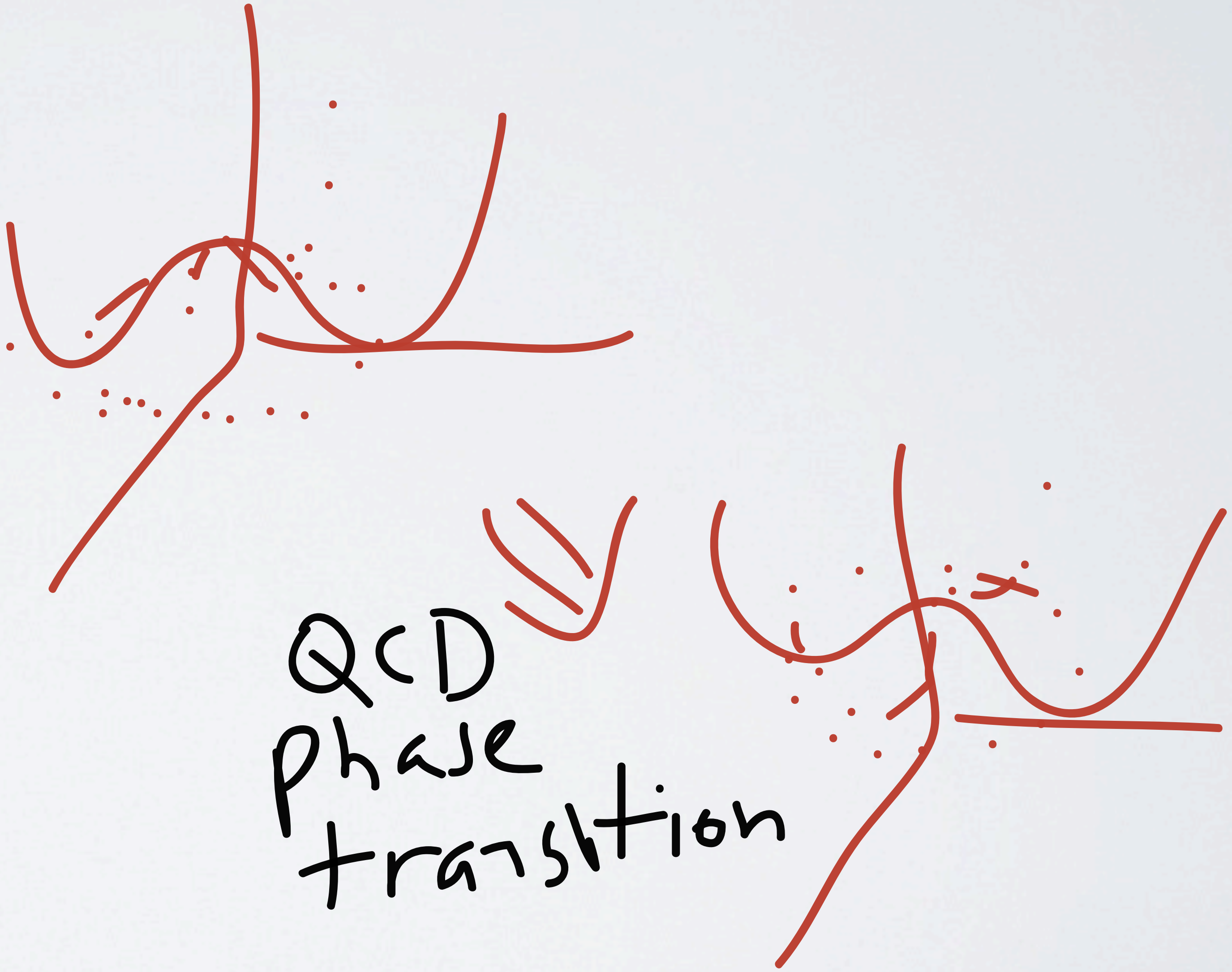
The axion

- Loosely speaking the ***axion*** is this type of model

$$\mathcal{L} = (\theta + a/f)G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\Rightarrow V \approx m_\pi^2 f_\pi^2 (1 - \cos(\theta + \frac{a}{f_a}))$$

$$m_a \sim 6 \times 10^{-6} eV \times \frac{10^{12}\mathrm{GeV}}{f_a}$$



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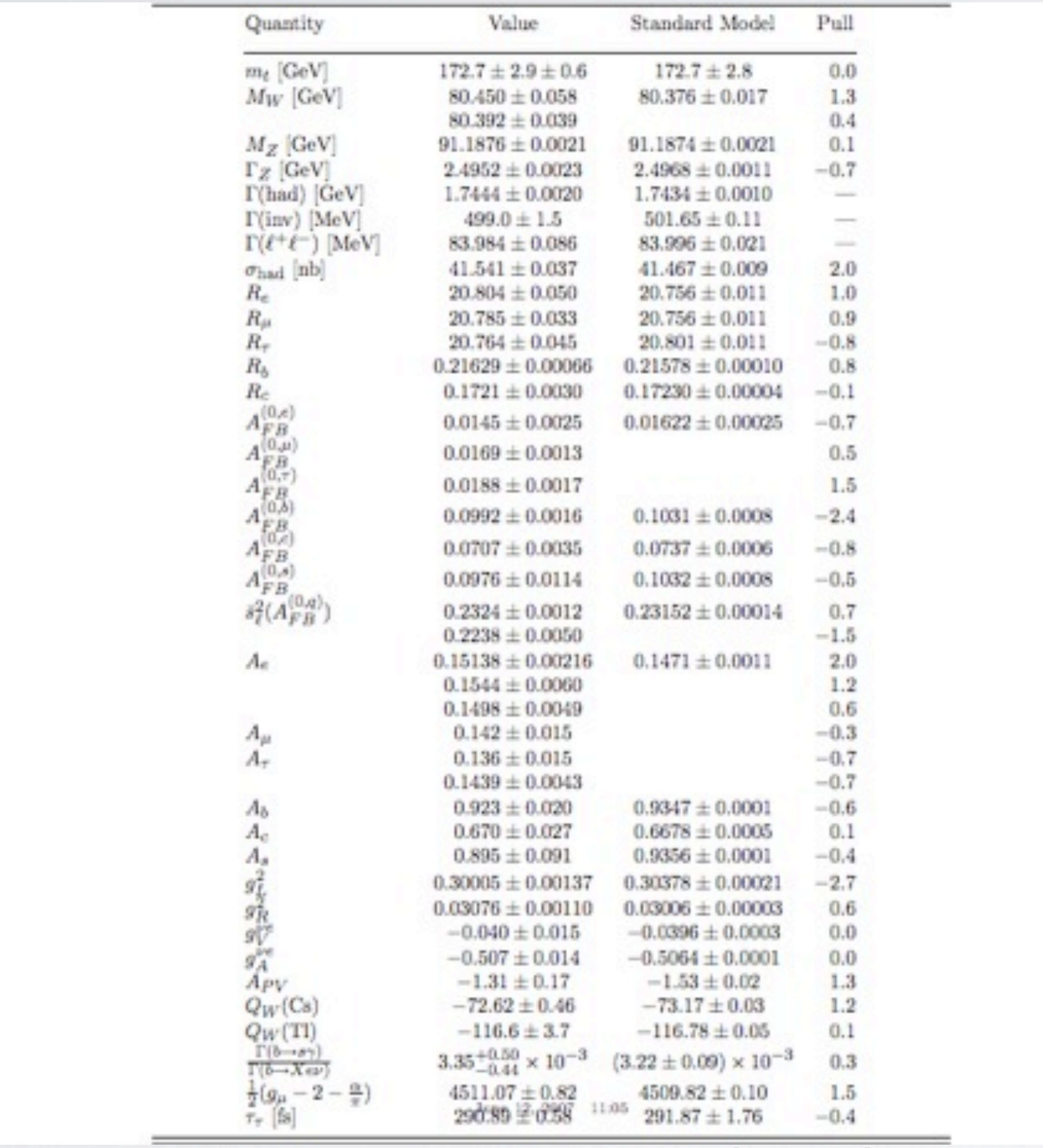
The weak scale...

- Just because we haven’t detected new particles doesn’t mean we don’t know much about physics beyond the standard model

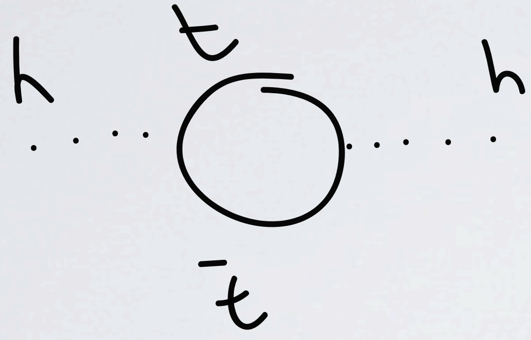


Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	−0.7
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	−0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	−0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	−0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	−2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	−0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	−0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		−1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		−0.3
A_τ	0.136 ± 0.015		−0.7
	0.1439 ± 0.0043		−0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	−0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	−0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	−2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\mathrm{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\mathrm{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	−0.4

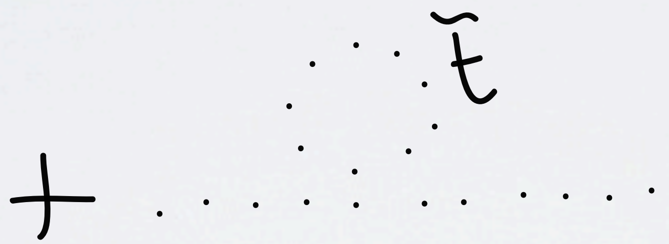
	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766	
m_Z [GeV]	91.1875 ± 0.0021	91.1874	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ_{had}^0 [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21585	
R_c	0.1721 ± 0.0030	0.1722	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.392 ± 0.029	80.371	
Γ_W [GeV]	2.147 ± 0.060	2.091	
m_t [GeV]	171.4 ± 2.1	171.7	

In general, new physics at the weak scale should have shown up in these precision studies

The hierarchy problem



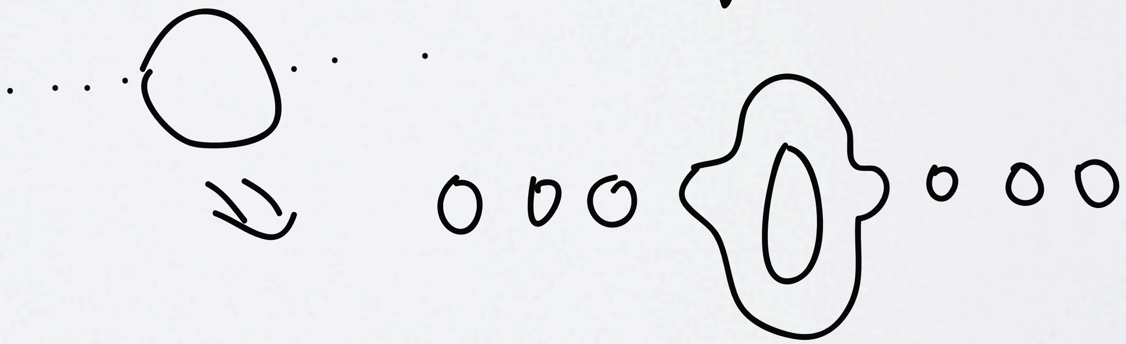
$$\delta m_h^2 = \frac{3\lambda_t^2}{16\pi^2}\Lambda^2$$



susy

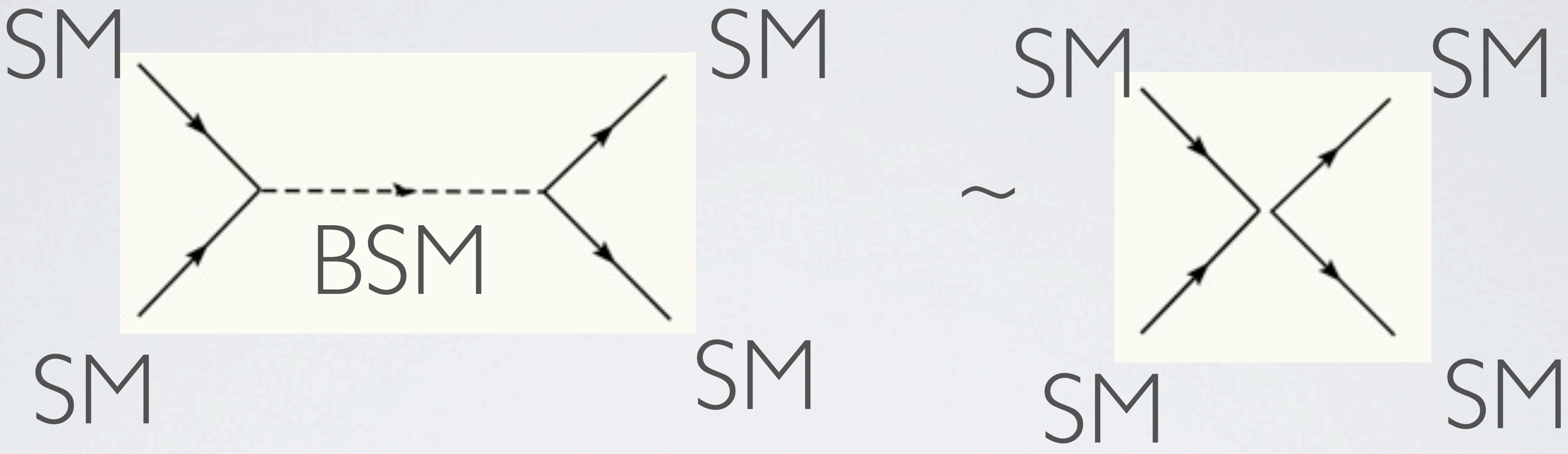
or

compositeness



T-Parity (Cheng and Low)

- The problem arises from



Need to forbid these diagrams somehow

Vertex comes from Lagrangian term

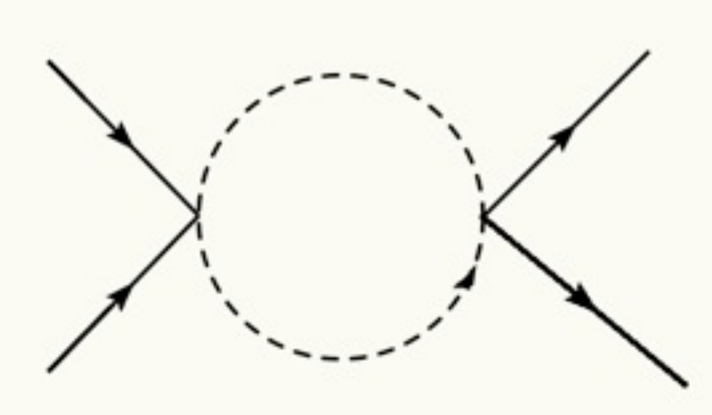
$$\mathcal{L} \supset SM_1 SM_2 BSM$$

I.e., problem is presence of single BSM field

If only even numbers of BSM fields were allowed, this term is forbidden!

T-parity

Then process occurs via loop



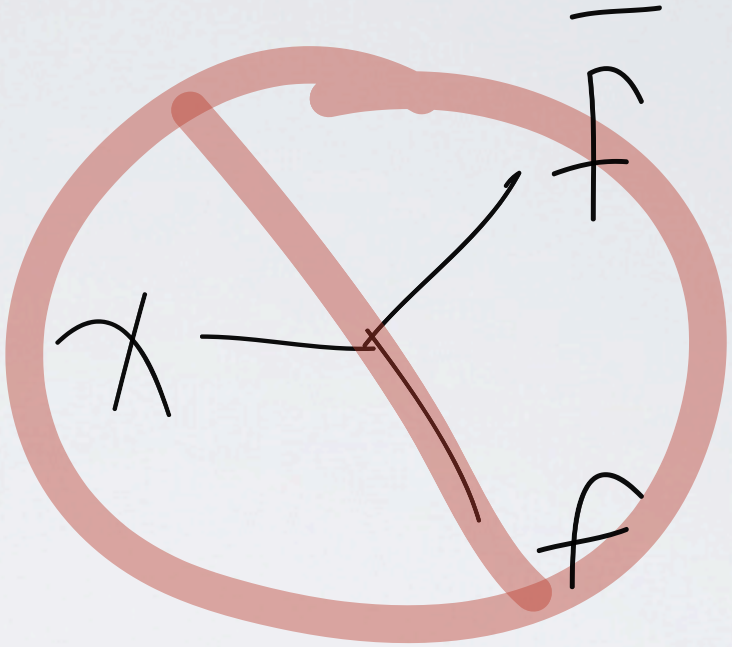
loops smaller by ~ $1/16\pi^2$
enough to solve problem

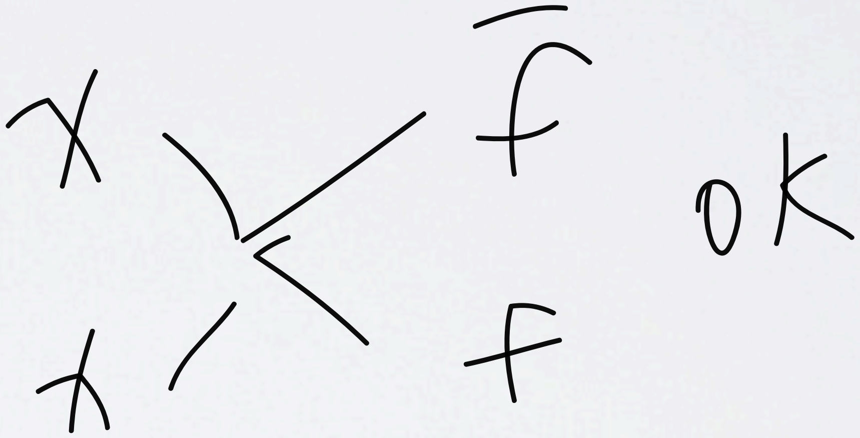
Parity

$\chi \bar{f} f \Rightarrow \cancel{-\chi \bar{f} f}$

$\chi^2 \bar{f} f \Rightarrow \chi^2 \bar{f} f$

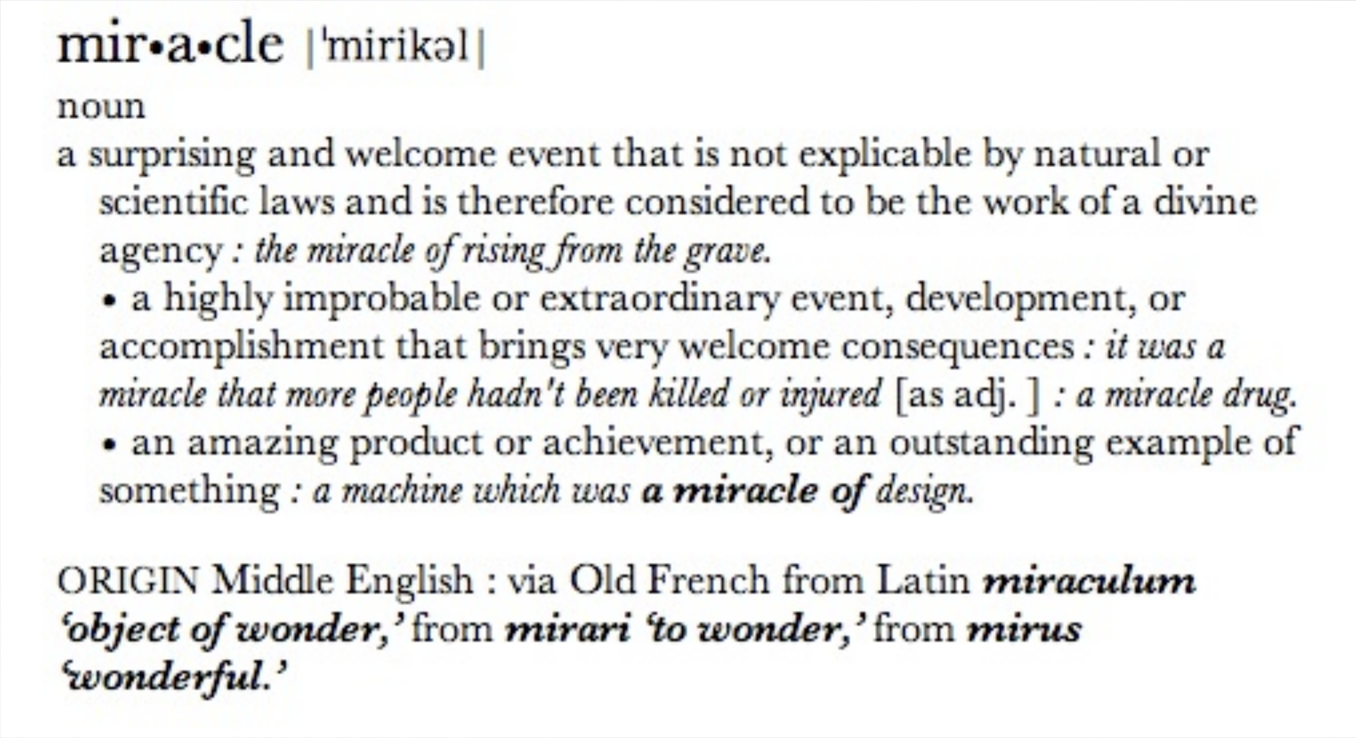
OK





Introduce parity at weak scale => stable DM candidates

The WIMP “~~miracle~~”



mir•a•cle |ˈmirikəl|

noun

a surprising and welcome event that is not explicable by natural or scientific laws and is therefore considered to be the work of a divine agency : *the miracle of rising from the grave.*

- a highly improbable or extraordinary event, development, or accomplishment that brings very welcome consequences : *it was a miracle that more people hadn't been killed or injured* [as adj.] : *a miracle drug.*
- an amazing product or achievement, or an outstanding example of something : *a machine which was* ***a miracle of*** *design.*

ORIGIN Middle English : via Old French from Latin ***miraculum*** ***‘object of wonder,’*** from ***mirari*** ***‘to wonder,’*** from ***mirus*** ***‘wonderful.’***

assume thermal equilibrium