Dark matter theory

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IPPP, Durham

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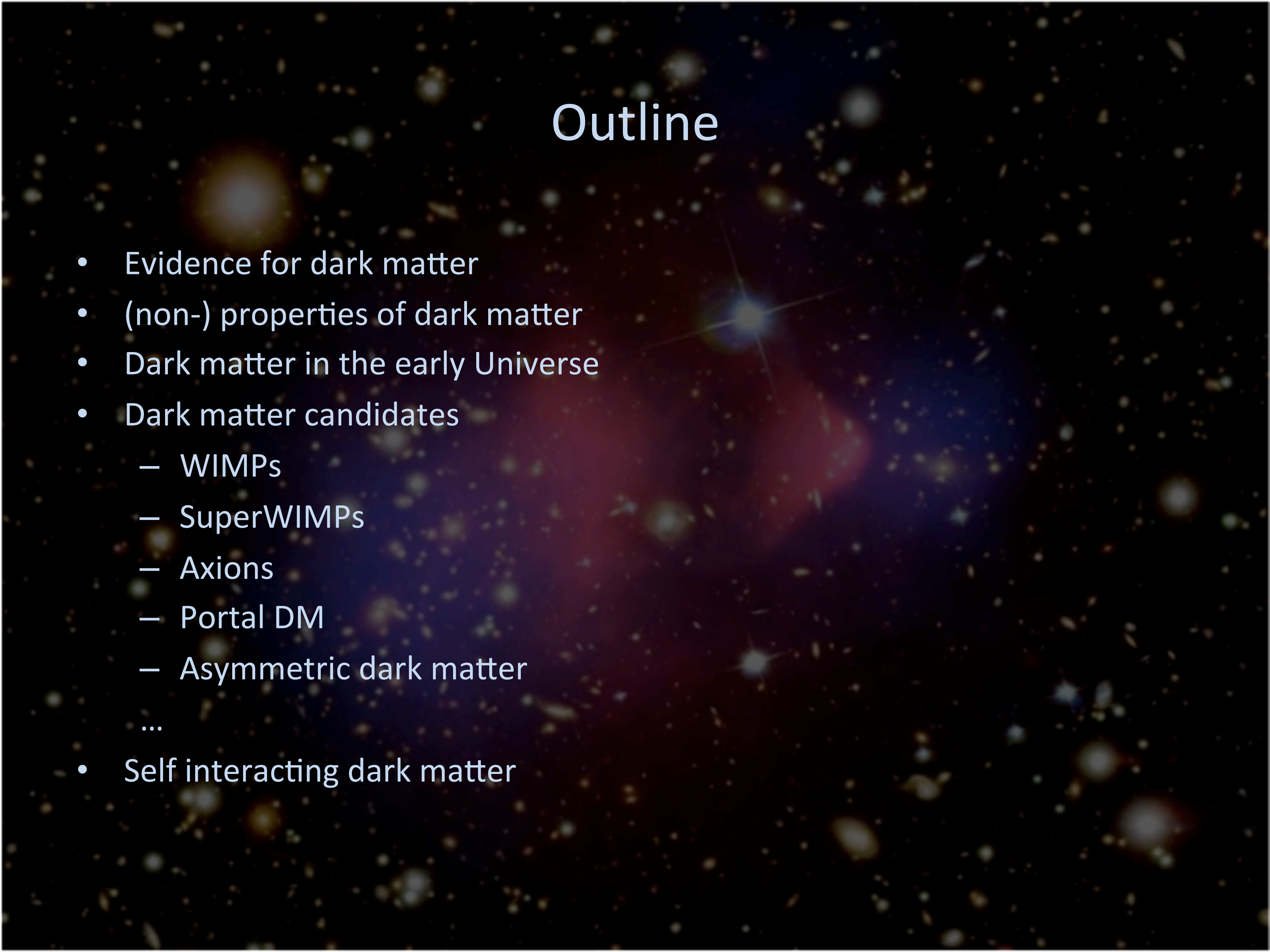
Material used from Feng, Kahlhoefer, Raffelt, Ringwald, Sarkar…



Outline

- Evidence for dark matter
- (non-) properties of dark matter
- Dark matter in the early Universe
- Dark matter candidates
  - WIMPs
  - SuperWIMPs
  - Axions
  - Portal DM
  - Asymmetric dark matter
  - …
- Self interacting dark matter

Evidence for dark matter

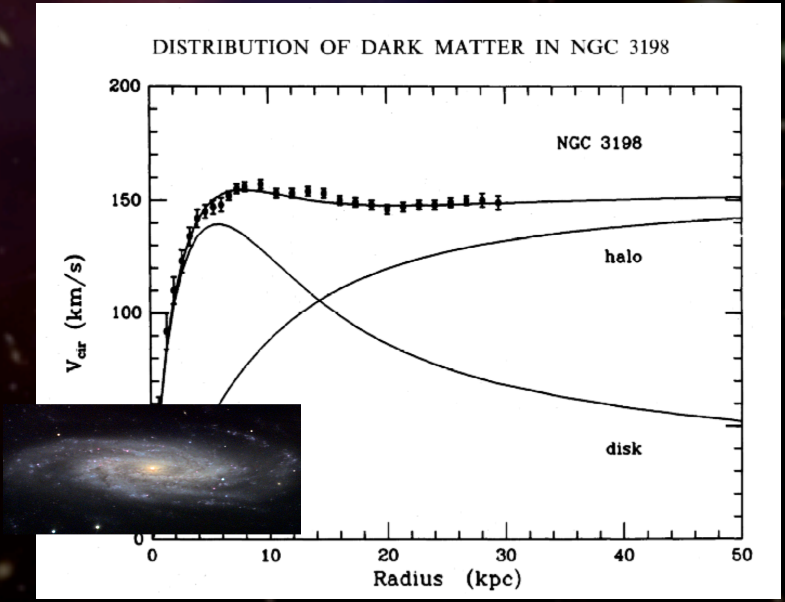
- Galactic scales: Rotation curves of Galaxies

Using Newtonian Gravity $v(r) = \sqrt{\frac{GM(r)}{r}}$ **with** $M(r) = 4\pi \int \rho(r) r^2 dr$

Would expect the rotational velocity to scale like $r^{-1/2}$ beyond the visible disc

Inferred velocity from 21cm line of neutral Hydrogen well beyond the visible disc

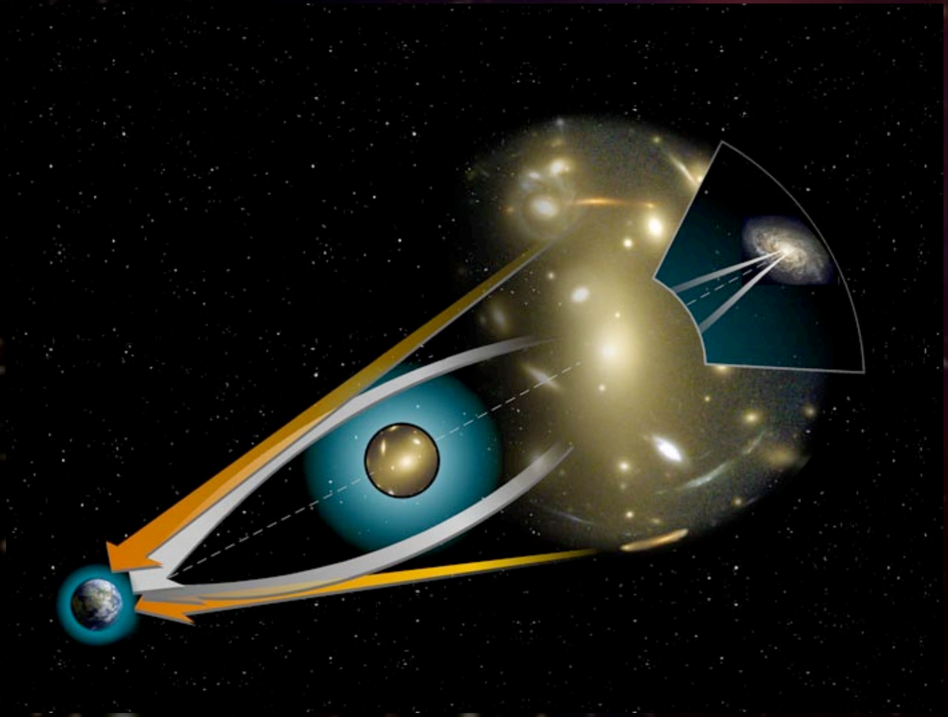
$$v(r) \sim \text{const} \Rightarrow \rho(r) \propto r^{-2}$$



We live in an extended halo of DM!

Evidence for dark matter

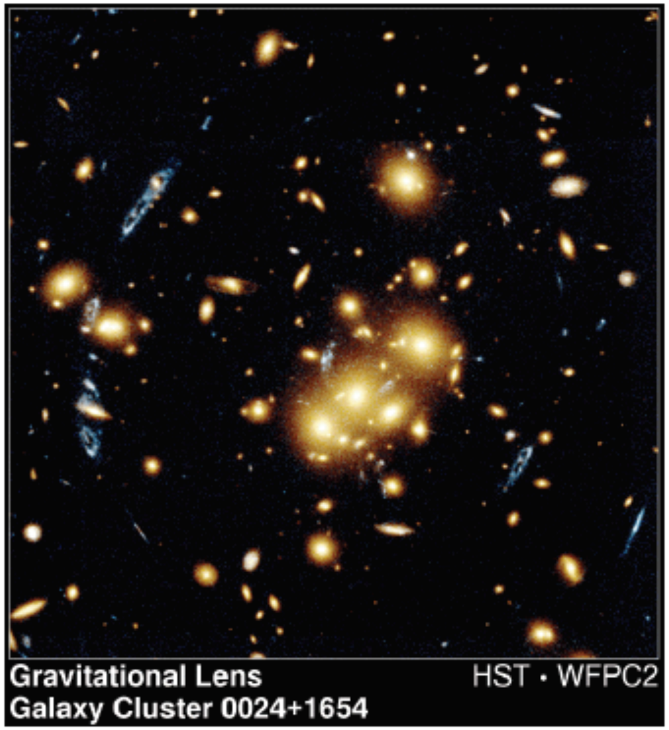
- Cluster scales: Gravitational lensing

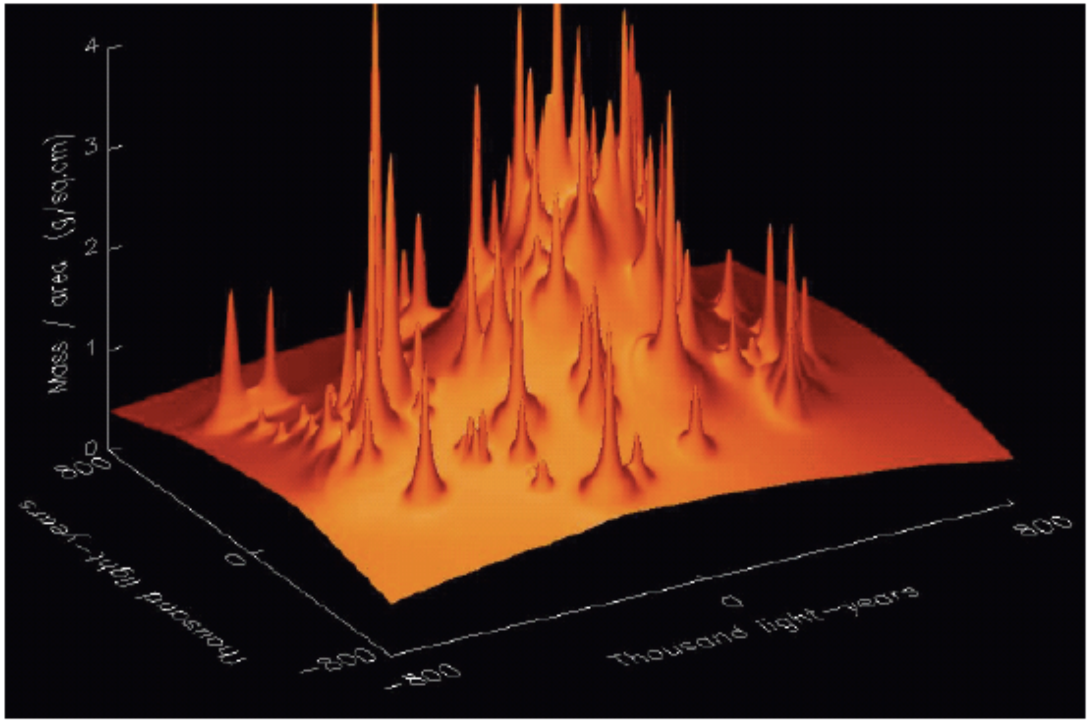


- Strong lensing (visible distortions, arcs, multiple images)
- Weak lensing
- Microlensing

Evidence for dark matter

Can infer the mass distribution

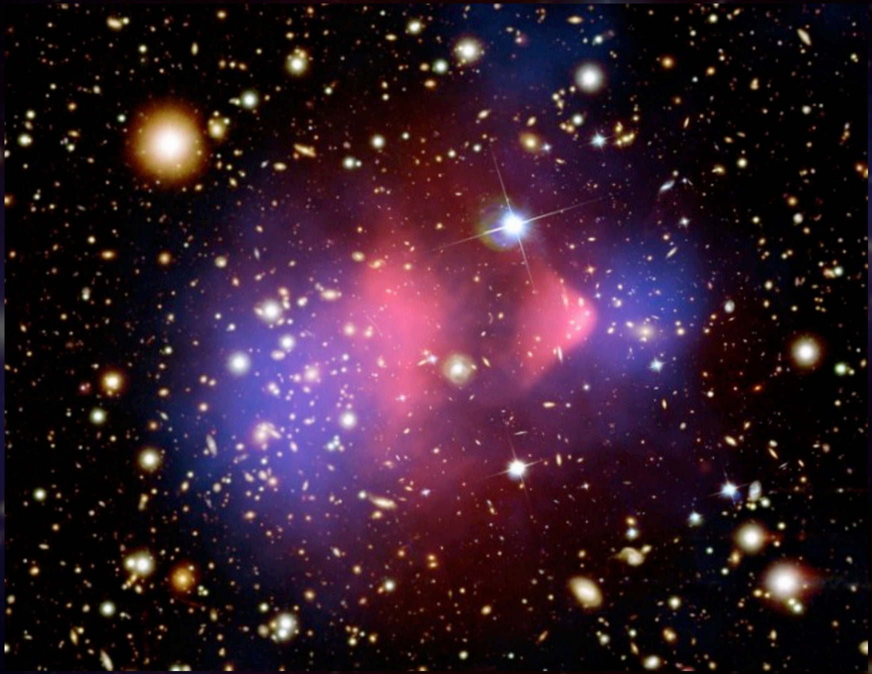




This reveals that the gravitational mass is dominated by an extended smooth distribution of dark matter

Evidence for dark matter

Merging Galaxy Cluster (Bullet Cluster)



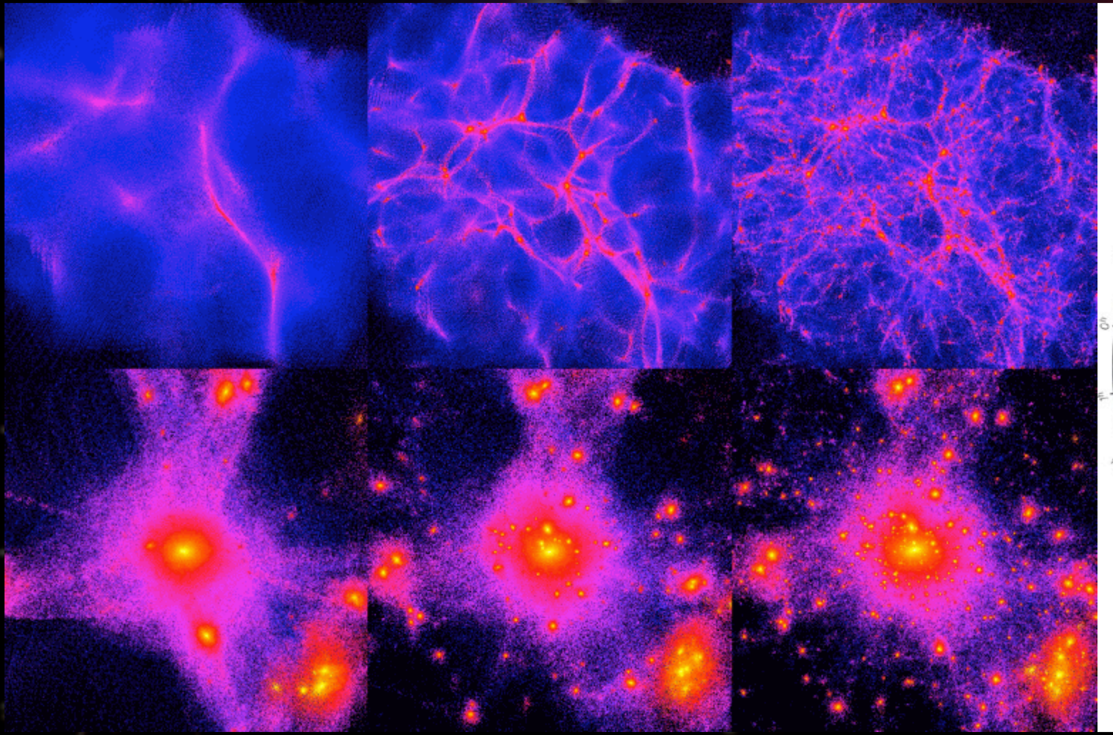
Separation between the collisional gas and the mass reconstructed from weak lensing

Evidence for dark matter

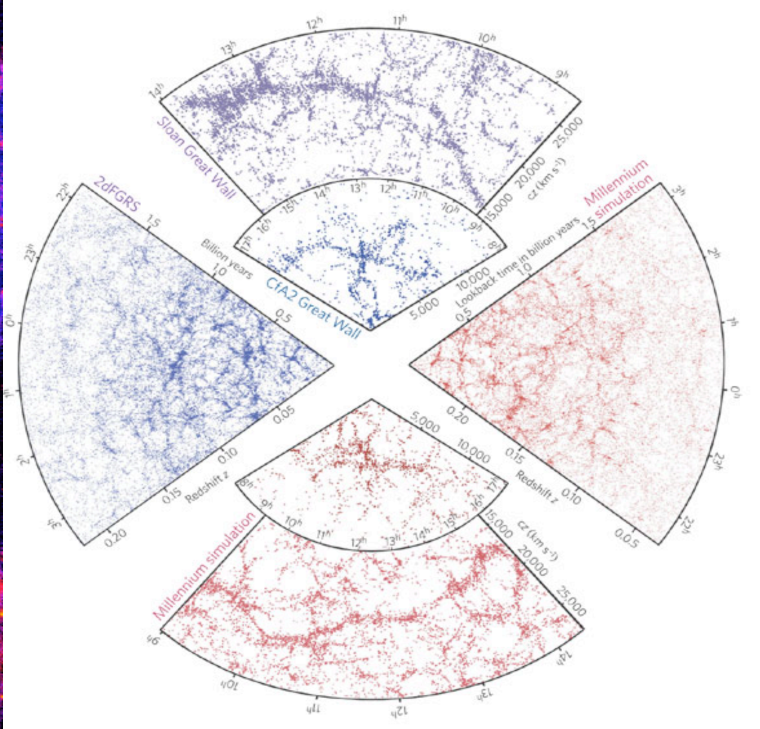
cf. lecture Peter Coles

- Cosmological scales: Large scale structure (N body simulations) and CMB
- Small initial density perturbations grow under gravity
- Input: collisionless hot/warm/cold DM (different free streaming)

cf. lecture by Carlton Baugh



hot warm cold



Evidence for dark matter

Compelling evidence for dark matter on all astrophysical scales:

- Galactic scales: Rotation curves of Galaxies
- Cluster scales: Gravitational lensing
- Cosmological scales: Large scale structure (N body simulations) & CMB

What is it ???

What do we know about its properties?

What dark matter is NOT - MACHOs

- MACHOs (massive compact halo objects – e.g. brown dwarf or black hole)

- Microlensing (apparent temporal change in luminosity)

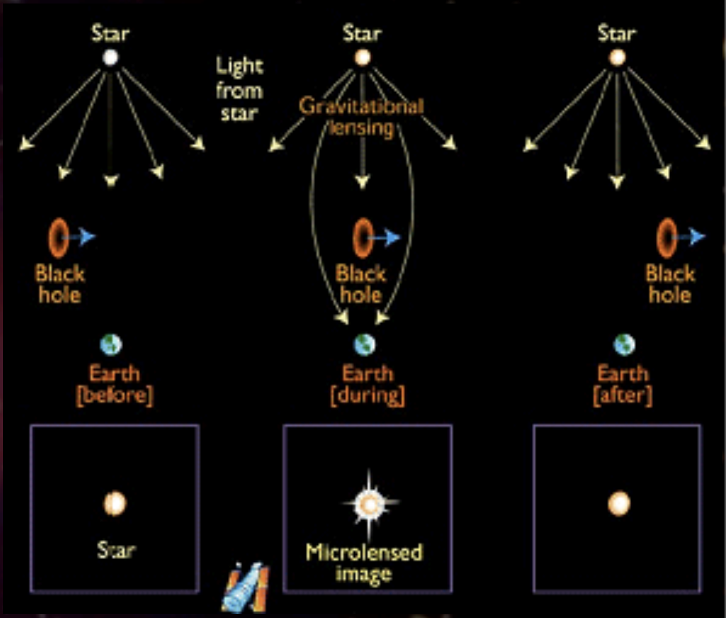
- EROS-2 monitored more than 10^7 stars over 6.7 years in the Magellanic clouds for microlensing events caused by such objects

- MACHOs ruled out as primary component of dark matter in the range

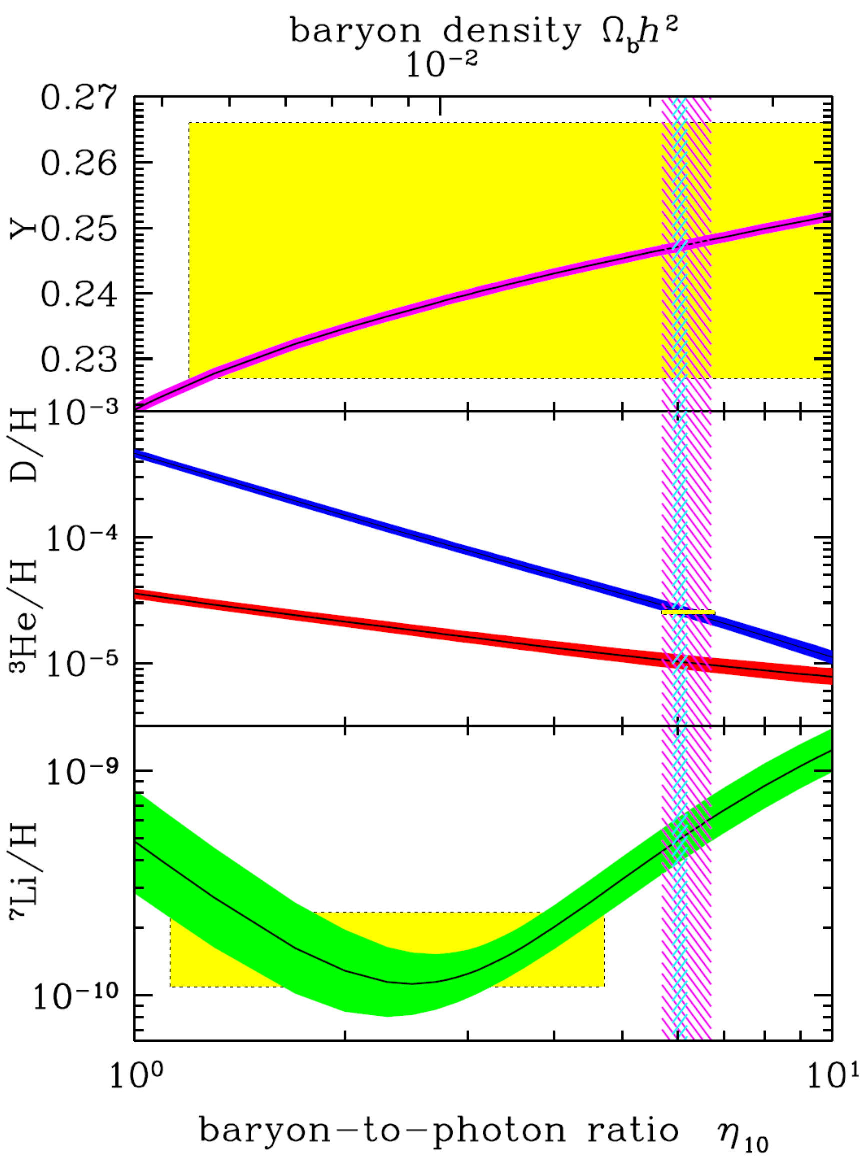
$$0.6 \times 10^{-7} M_\odot < M < 15 M_\odot$$

- and with Kepler now down to 2 x 10^{-9} (1307.5798)

~ Moon size



What dark matter is NOT - baryons



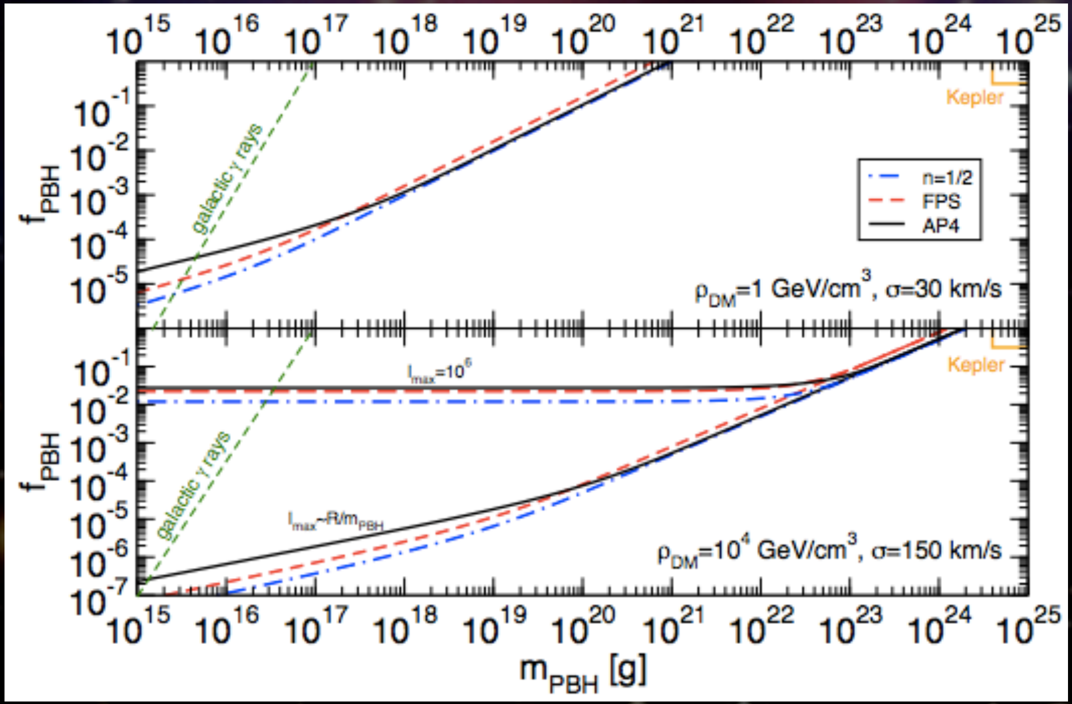
Fields, Molaro, Sarkar, PDG (2013)

- At T ~ 1 MeV, around the binding energy of nuclei, the universe cooled enough for light elements to start forming
- The abundance of each light species is a function of a single parameter, η, the baryon-to-photon ratio
- BBN and CMB determinations are consistent (except possibly for Li) for a single choice of η and constrain the density in baryons: $\Omega_B h^2 \sim 0.02$
- Cannot make up the required Ω_M

Primordial black holes?

- Primordial black holes could have formed in the very early universe
- Too light black holes will have Hawking evaporated and slightly heavier ones should give a sizable signal in gamma rays, leading to $M_{bh} > 10^{17}$ g
- Remember: MACHO constraints give $M_{bh} < 10^{24}$ g

- Currently ongoing discussion about the remaining mass window (and constraints coming from PBH capture and destruction of neutron stars)



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Maggelanic Cloud

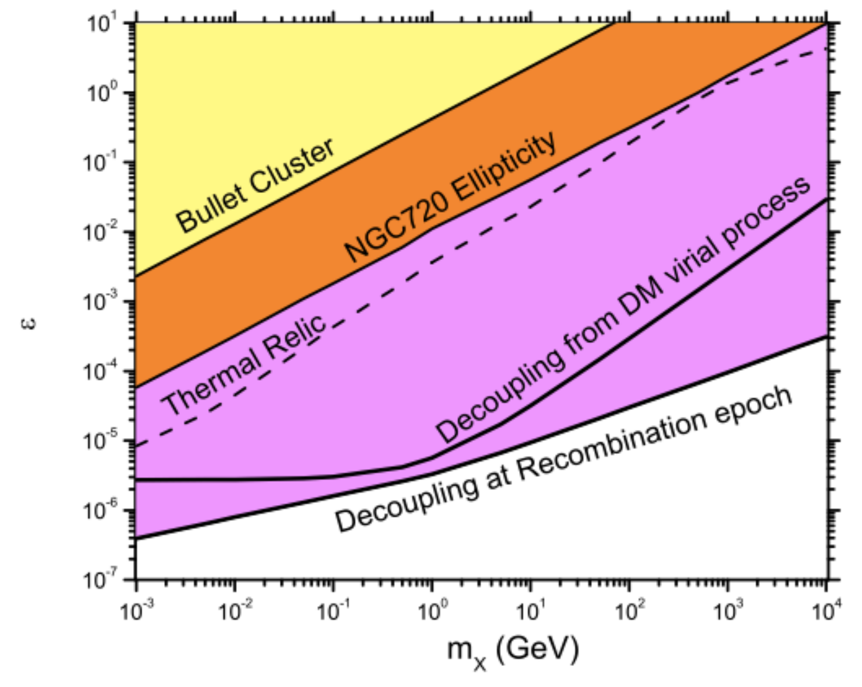
Milky Way

What dark matter is NOT – CHAMPs ?

- Could dark matter have electric charge?
- … less trivial than you might think …
- Many constraints don’t apply if dark matter is expelled from the Galactic disc by supernovae and kept out by magnetic fields.

But there are cosmological constraints: Coulomb scattering can change structure formation, leading to the following plot

Also different coupling to photon possible …
(e.g. magnetic moment)



1011.2907

What dark matter is NOT – SIMPs ?

- Could dark matter have colour charge?
- Strong constraints from anomalous heavy isotopes - should not bind to other isotopes…
- But again less trivial than you might think…

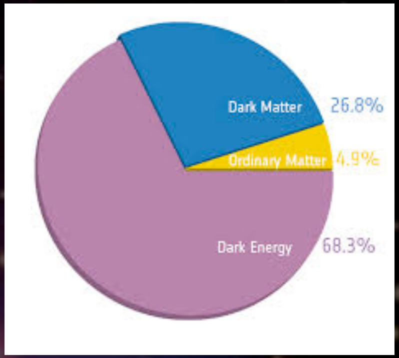
- There might be an ‘H dibaryon’ (uuddss) (G Farrar)
- It would be a ~1.5 GeV spin-0, flavor-singlet, scalar carrying baryon-number of 2
- The H is largely inert with respect to nuclear interaction and thus does not affect primordial nucleosynthesis

- Need lattice calculations… (always the problem in strong dynamics: Stuff cannot be excluded because its not calculable and you can employ wishful thinking…)

Summary - What do we know?

- How much: $\Omega \approx 0.26$ (CMB+…)

- Dark:
  - Likely electrically neutral
  - Likely colour neutral
- Cold: nonrelativistic during structure formation
- Sufficiently long-lived
- Non-baryonic (from BBN)



Summary - What do we know?

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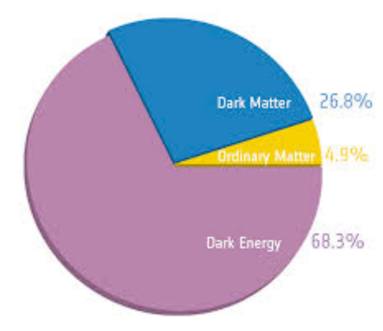

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Candidate within the Standard Model of particle physics?

- Neutrinos
  - Correspond to hot DM
  - Cannot account for the observed dark matter density

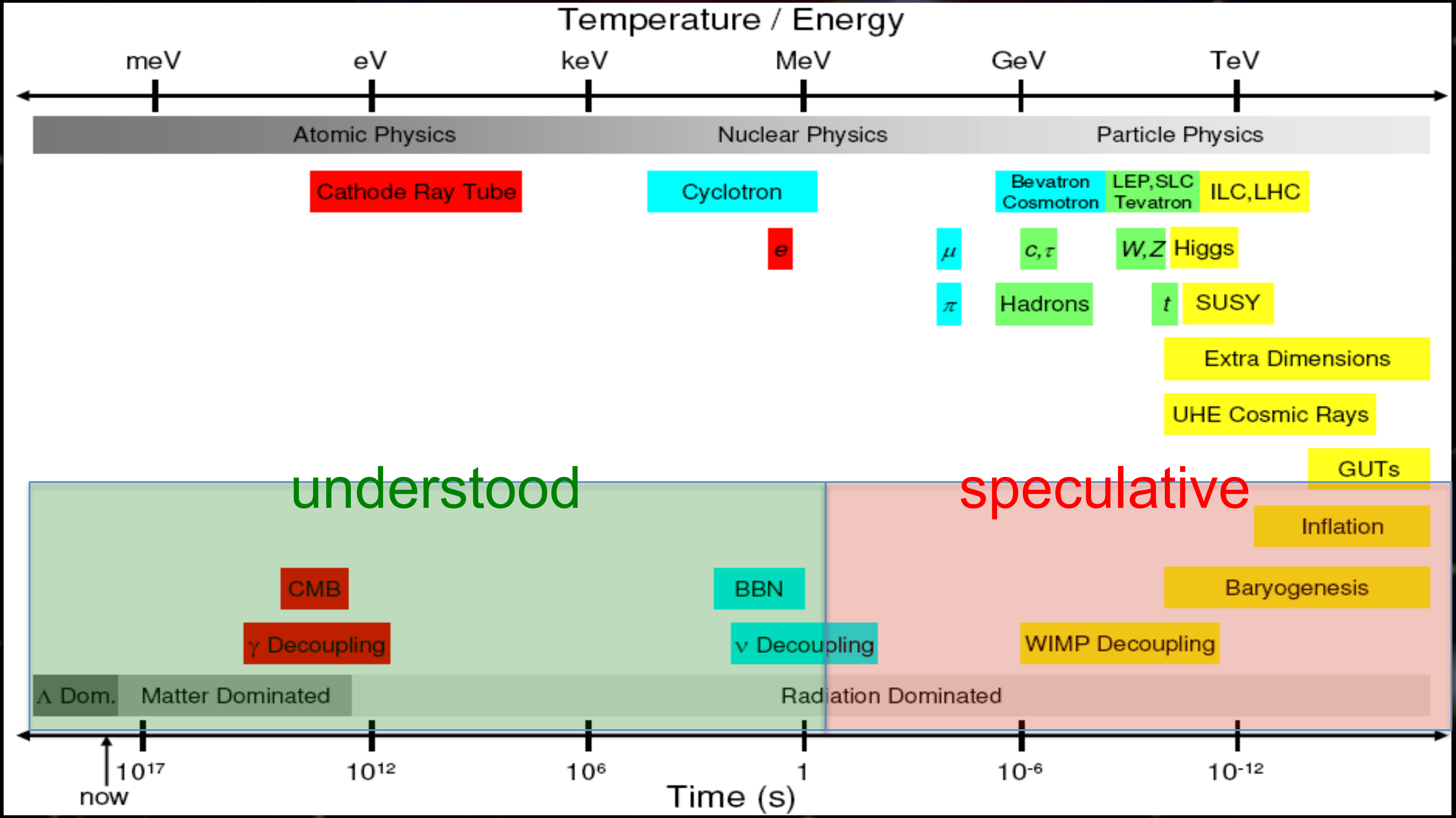
$$\sum \Omega_\nu h^2 \simeq m_{\nu_i}/93\mathrm{eV}$$

Physics beyond the Standard Model ?!

Many candidates (theorists are inventive)

Early universe cosmology

- Universe empty after inflation – need to produce DM somehow
  - Non-thermal production (e.g. via inflaton decay)
  - Thermal production



Freeze out

$$n_{\rm eq} \simeq g \left(\frac{mT}{2\pi}\right)^{3/2} e^{-\frac{m}{T}}$$ **Non relativistic** m>>T

Internal d.o.f.

$$n_{\rm eq} \simeq gT^3$$ **Relativistic** T>>m

(1) Assume a new heavy particle *X* is initially in thermal equilibrium:

$$XX \leftrightarrow qq$$

(2) Universe cools:

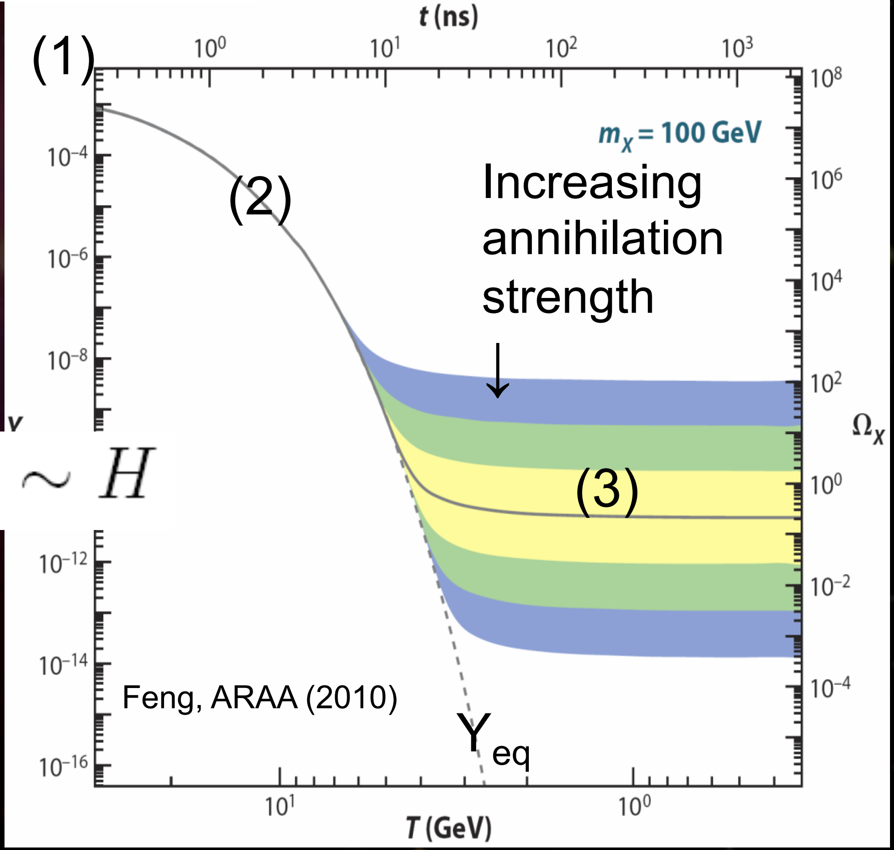
$$XX \underset{\not\leftarrow}{\rightarrow} qq$$

$$n_{\rm eq}\langle\sigma v\rangle \sim H$$

(3) Universe expands:

$$XX \underset{\not\leftarrow}{\not\rightarrow} qq$$

The abundance is determined by the annihilation cross section!



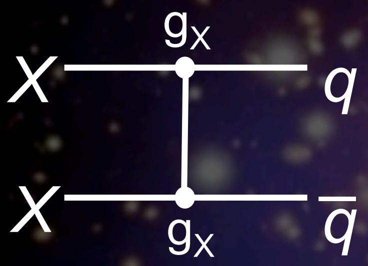
Feng, ARAA (2010)

The WIMP miracle

- What is the required annihilation cross section?

$$\langle \sigma v \rangle \simeq 3 \times 10^{-26} \frac{\mathrm{cm}^3}{\mathrm{s}}$$

- The relation between Ω_X and annihilation strength is nice and simple:



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

Needed relation between g and m:

$$g^2 \sim \frac{m}{10\ \mathrm{TeV}}$$

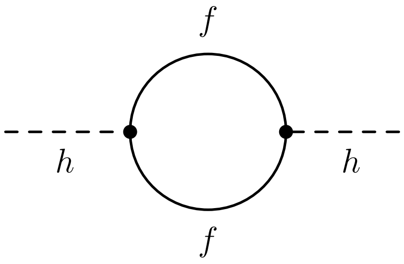
For weak couplings g~0.1-1, masses should be in the 100 GeV to TeV region !!!
This is where we expect new physics for many other reasons too!

Also: Unitarity implies an upper bound on the mass, about 50 TeV.

Why WIMPs?

Found the Higgs!
Hierarchy problem in the Standard Model

Expect new physics to come to the rescue at about TeV



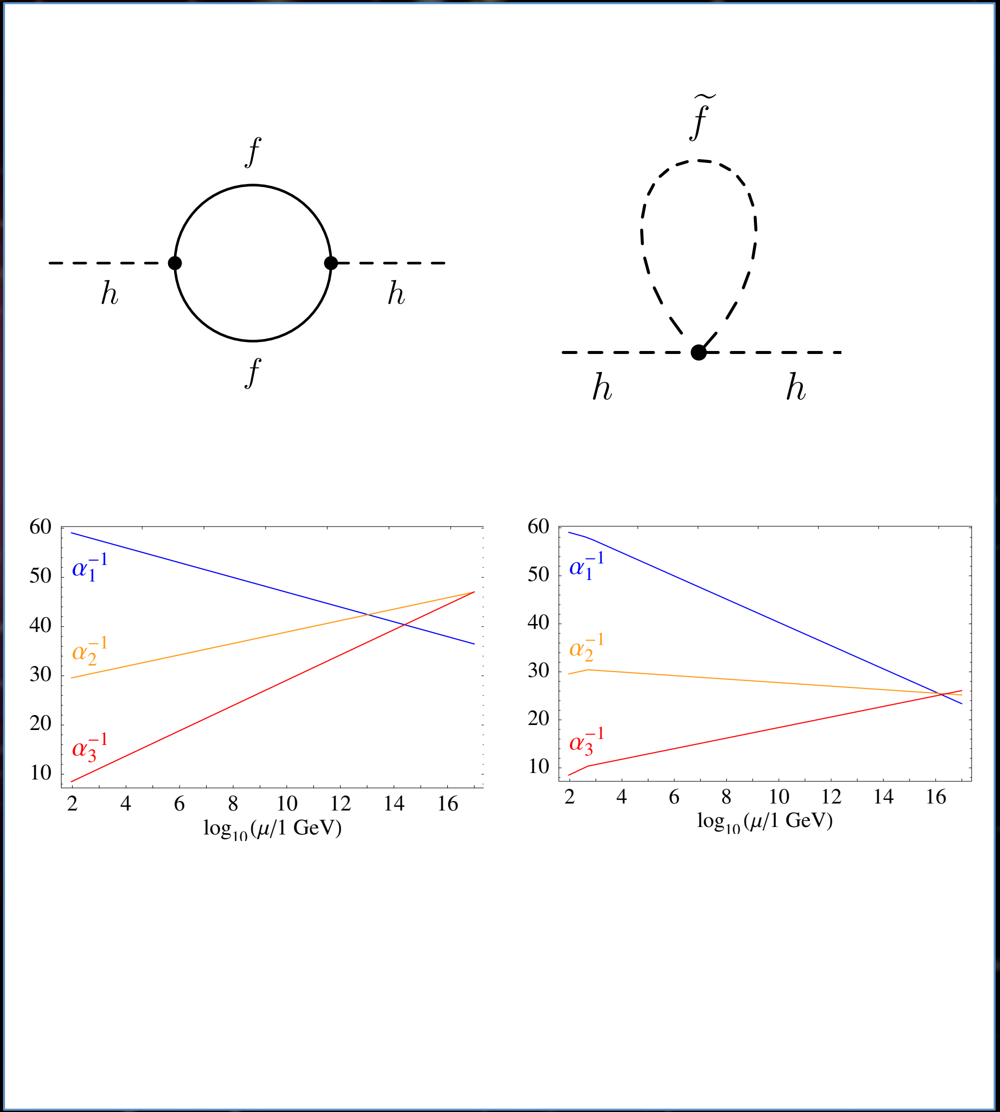
Why WIMPs?

Found the Higgs!
Hierarchy problem in the Standard Model

Expect new physics to come to the rescue at about TeV

Still prime candidate: SUSY

- Ameliorates the hierarchy problem
- Gauge coupling unification
- Expect Higgs mass of about m_W
- Potentially provides a DM candidate



The prototypical WIMP: neutralinos in supersymmetry

Spin	U(1)	SU(2)	Up-type	Down-type		
2						G graviton
3/2						
1	B	W^0				
1/2					ν	
0				H_d		

The prototypical WIMP: neutralinos in supersymmetry

Spin	U(1) M_1	SU(2) M_2	Up-type μ	Down-type μ	$m_{\tilde{\nu}}$	$m_{3/2}$
2						G graviton
3/2						$\tilde{G}$ gravitino
1	B	W^0				
1/2	$\tilde{B}$ Bino	$\tilde{W}^0$ Wino	$\tilde{H}_u$ Higgsino	$\tilde{H}_d$ Higgsino	ν	
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

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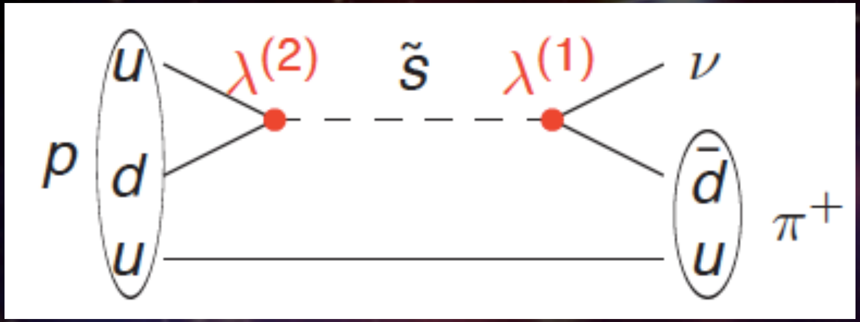
0			H_u	H_d	$\tilde{\nu}$ sneutrino	

Neutralinos: $\{\chi \equiv \chi_1, \chi_2, \chi_3, \chi_4\}$

Is the LSP stable?

- With only SUSY and gauge invariance as symmetries of the theory: additional terms: proton decay

$$\lambda^{(1)}_{ijk} L_i Q_j D^c_k + \lambda^{(2)}_{ijk} U^c_i D^c_j D^c_k$$



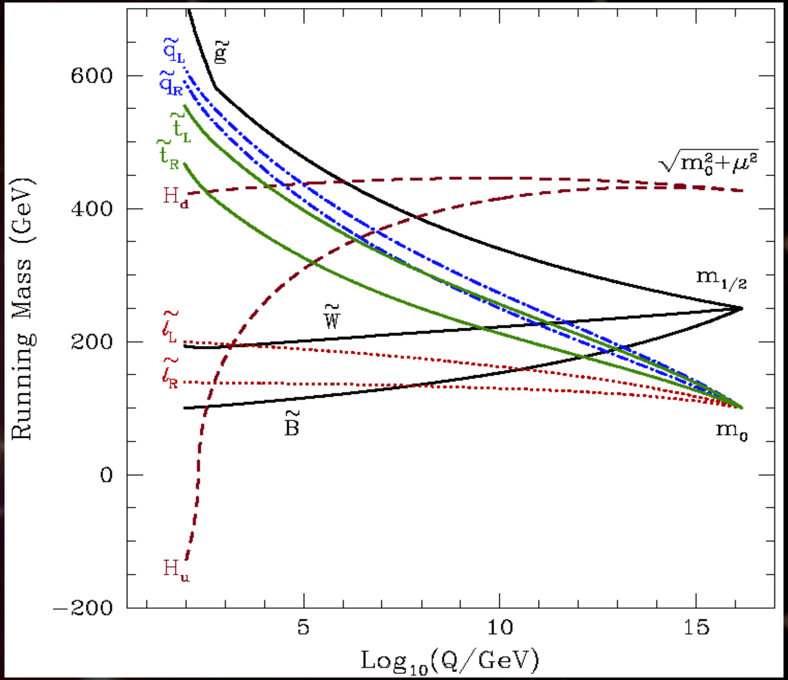
- Need additional symmetry to be viable!
- Standard assumption: R-parity conservation:
- SM particles have $R_p = 1$, SUSY particles have $R_p = -1$
  - Require $\Pi\ R_p = 1$ at all vertices

- Consequence: the lightest SUSY particle (LSP) is stable!

(Good enough for us now, although not sufficient to make the proton stable!)

What is the LightestSusyParticle?

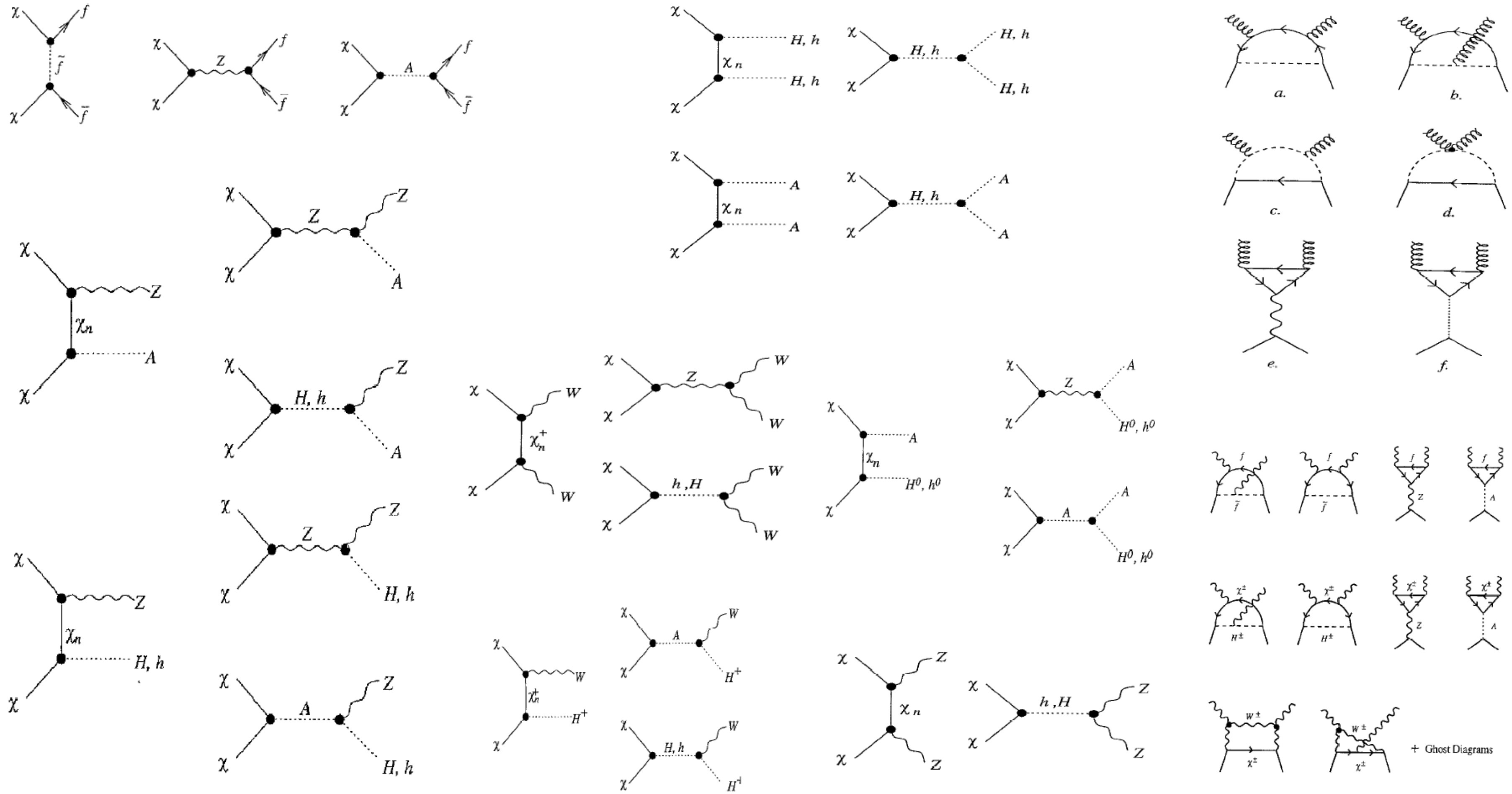
- SUSY is broken in nature
- High-scale → weak scale through RGEs
- Often universal gaugino masses assumed at high scale, at low scale M3:M2:M1 ~ 6:2:1
- “typical” CMSSM LSPs: bino χ , $\tilde{\tau}_R$
- Crucially depends on assumption of SUSY breaking terms! Other patterns possible (and even consistent with GUTs)
- What is the relic abundance?



Olive (2003)

Neutralino annihilation

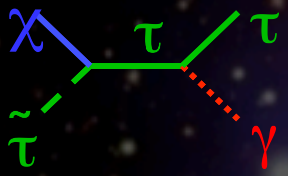
Don’t forget to use micrOMEGAs / DarkSUSY …



Jungman, Kamionkowski, Griest (1995)

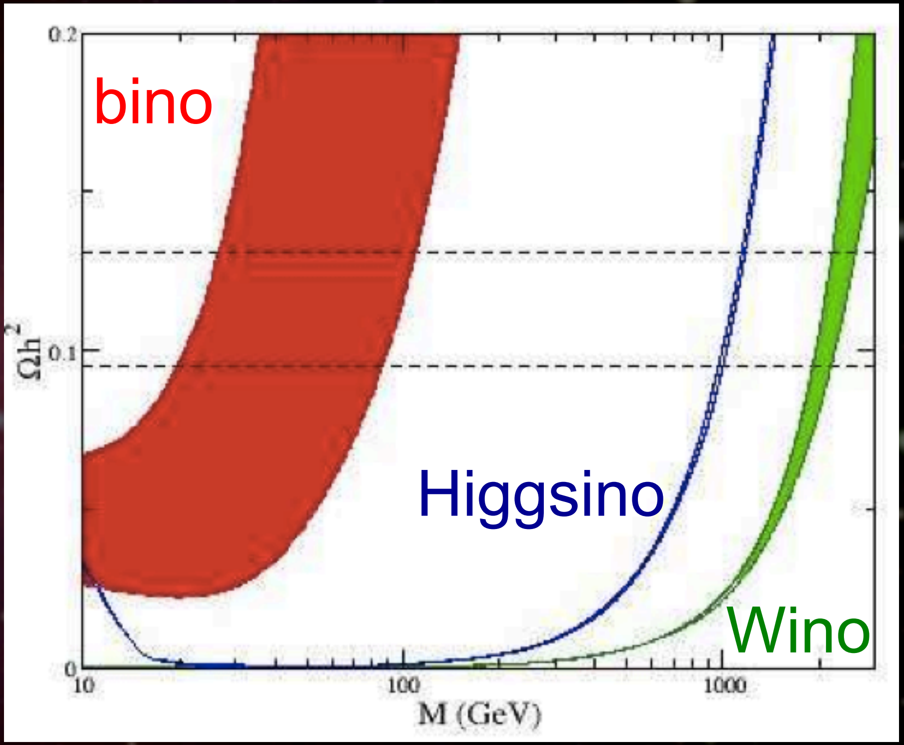
Neutralino relic abundance?

- Relic abundance of binos with m_B>100 GeV typically too large
- Need to go to special places (coannihilation, A-funnel)



Stau and χ almost degenerate

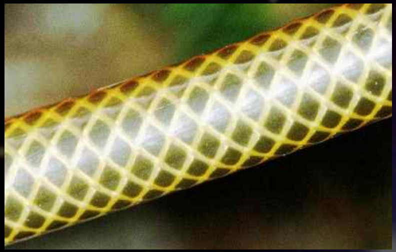
- 1 TeV Higgsino would be fine
- Also mixings…
- But of course have to take into account m_h ~125 GeV, collider constraints…



hep-ph/0601041

Other WIMPs - KK dark matter

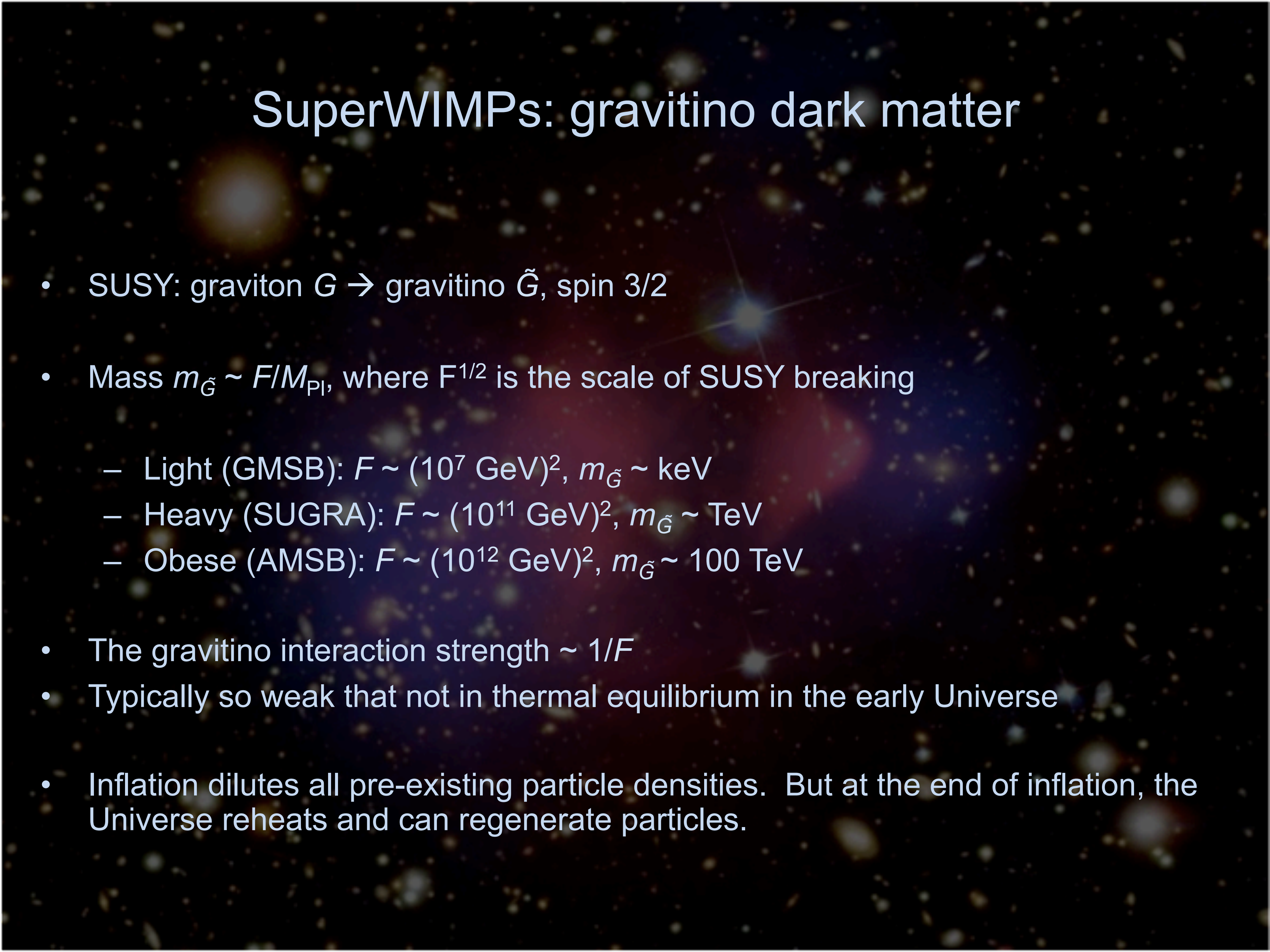
- Consider 1 extra spatial dimensions curled up in a small circle



- Compactification on circle too simple (to do with chiral fermions)
- Need extra parity → S^1/Z_2 orbifold
- LKP (lightest KK particle) is stable – dark matter!

- Particles moving in extra dimensions appear as a set of copies of normal particles.

SuperWIMPs: gravitino dark matter



- SUSY: graviton G → gravitino $\tilde{G}$, spin 3/2
- Mass $m_{\tilde{G}} \sim F/M_{\rm Pl}$, where $F^{1/2}$ is the scale of SUSY breaking
  - Light (GMSB): $F \sim (10^7 \text{ GeV})^2$, $m_{\tilde{G}} \sim$ keV
  - Heavy (SUGRA): $F \sim (10^{11} \text{ GeV})^2$, $m_{\tilde{G}} \sim$ TeV
  - Obese (AMSB): $F \sim (10^{12} \text{ GeV})^2$, $m_{\tilde{G}} \sim$ 100 TeV
- The gravitino interaction strength ~ $1/F$
- Typically so weak that not in thermal equilibrium in the early Universe
- Inflation dilutes all pre-existing particle densities. But at the end of inflation, the Universe reheats and can regenerate particles.

Gravitino relic abundance

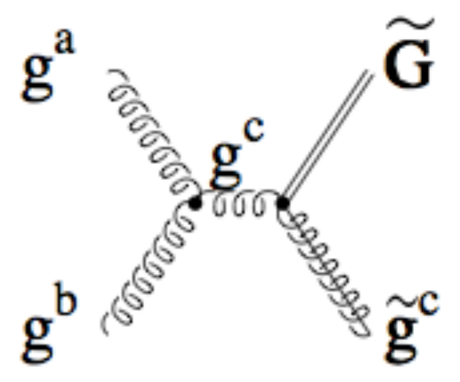
- Thermal bath of MSSM particles X: occasionally they interact to produce a gravitino: X X → X $\tilde{G}$

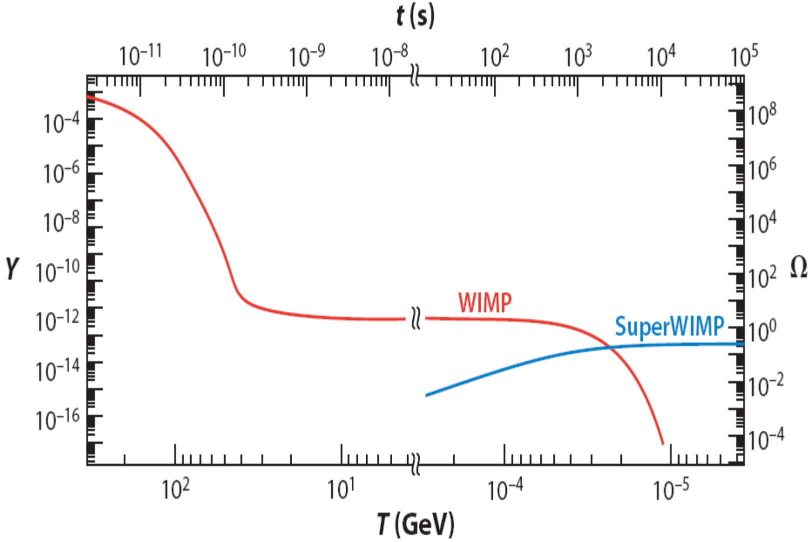
- Relic density depends linearly on the reheat temperature T_R

- Gravitino as thermal relic for $T_R \sim 10^9$ GeV (-> leptogenesis)

- Also non-thermal contribution from decay
- NLSP lifetime $\sim 10^4$ s, depending on masses
- Dangerous for BBN (but done cleverly might solve ‘Li problem’)

- No chance for direct or indirect detection





LHC searches

- NLSP long lived → metastable particles, may be charged (often stau)
- Signature of new physics is “stable”, charged, massive particles, not misssing E_T
- If stable on timescales of s to months, could in principle collect these particles and study their decays.
- What could be learned?

$$\Gamma_{\tilde{\tau}}(\tilde{\tau} \rightarrow \tau + \tilde{G}) = \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\mathrm{P}}^2}\left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2}\right)^4$$

- Can reconstruct all masses:
- Allows for determination of Newton’s constant in a particle physics experiment!

(as well as the SUSY breaking scale)

Axions - the strong CP problem

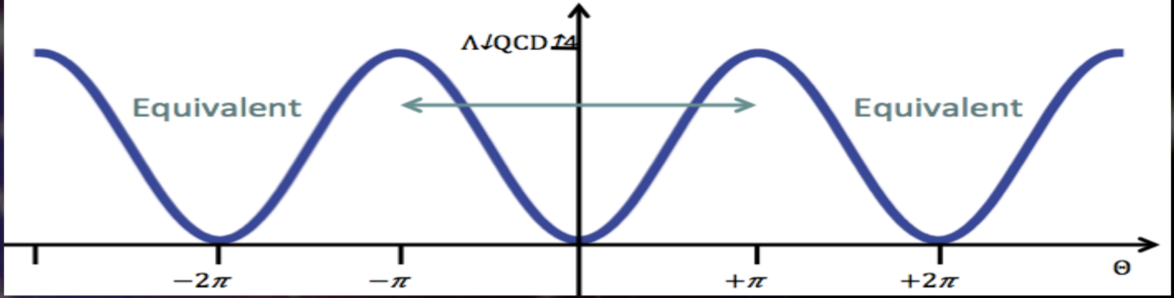
The gauge invariant QCD Lagrangian allows for a CP violating term

$$\frac{\alpha_s}{8\pi}\,\theta\, G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

neutron EDM: $|\bar{\theta}| \lesssim 10^{-9}$

A priori would expect the parameter θ of order unity (angular variable [0,2π]

QCD vacuum energy



Problem: θ not dynamical – can't go to state of minimal energy

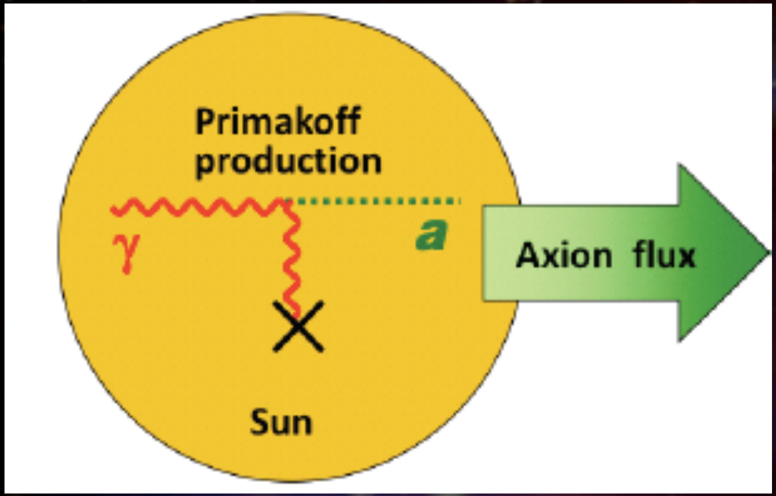
The axion solution: Make θ dynamical

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a\,\partial^\mu a - \frac{\alpha_s}{8\pi}\left(\bar{\theta} + \frac{a}{f_a}\right) G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} C_{a\gamma}\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

Axions

The axion mass as well as all couplings to SM fields are suppressed by the scale f_a

Strong astrophysical constraints (to avoid energy loss in stars)



The coupling to photons also implies that the axion does decay…

$$f_a \gtrsim 10^9 \ \text{GeV}$$

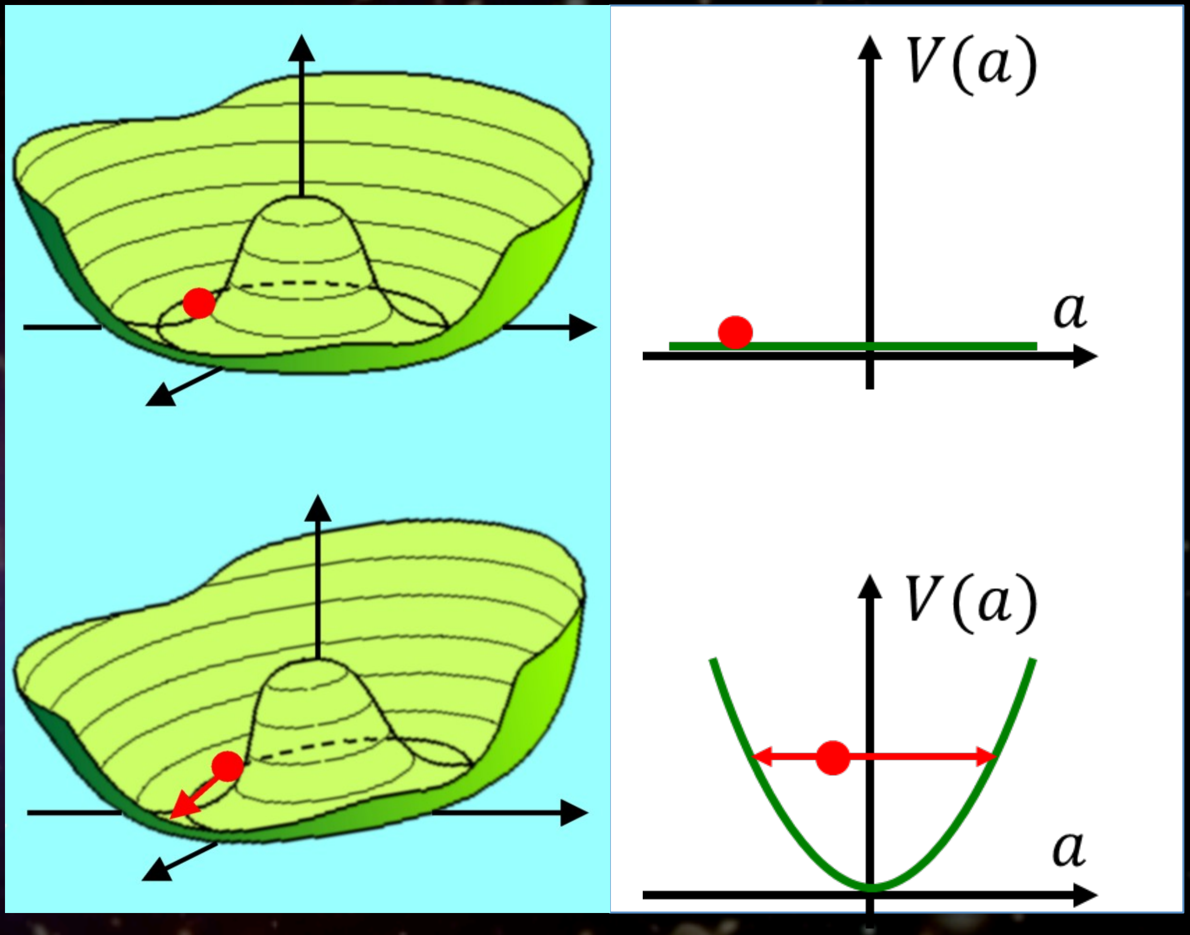
$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 6\,\text{meV} \times \left(\frac{10^9\,\text{GeV}}{f_a}\right)$$

Implies very small mass

Corresponds to hot dark matter?

Axion Dark Matter

- In early universe, the axion mass is zero, so axion field frozen at random initial value (also damped oscillator).
- Later, field feels pull of mass towards zero and oscillates around it



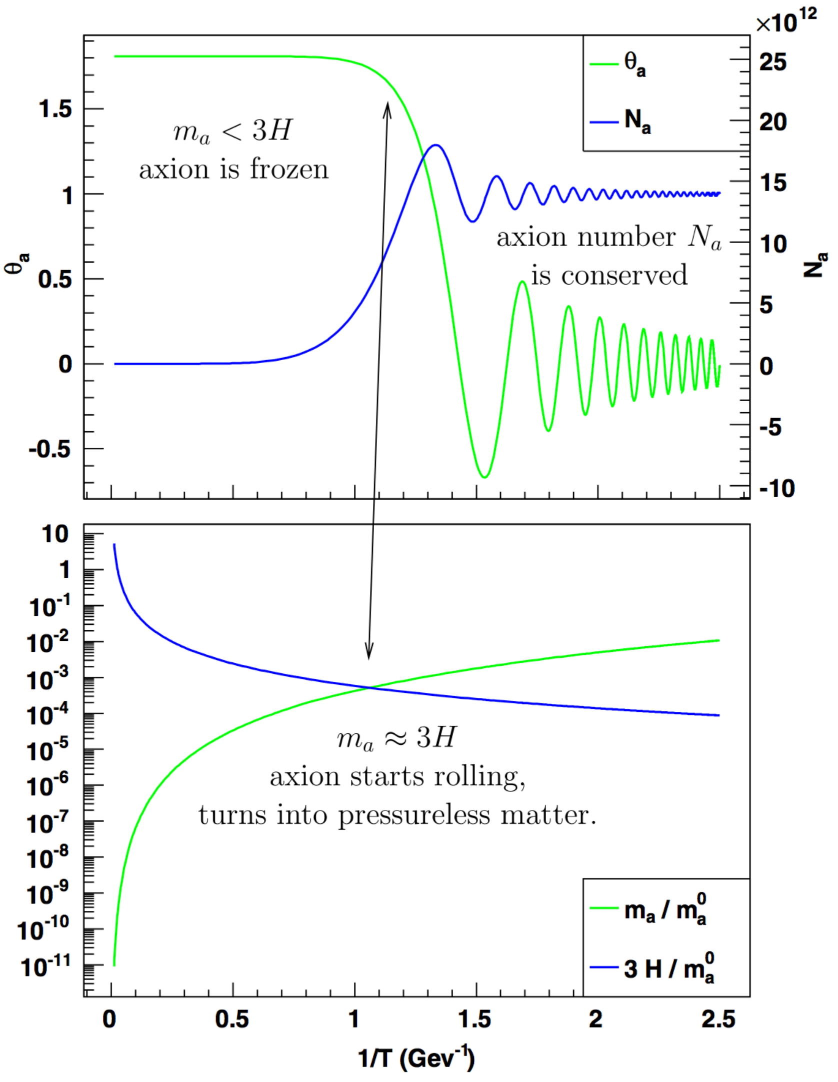
Axion Dark Matter

- In early universe, axion frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = cold dark matter (CDM)

[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83]

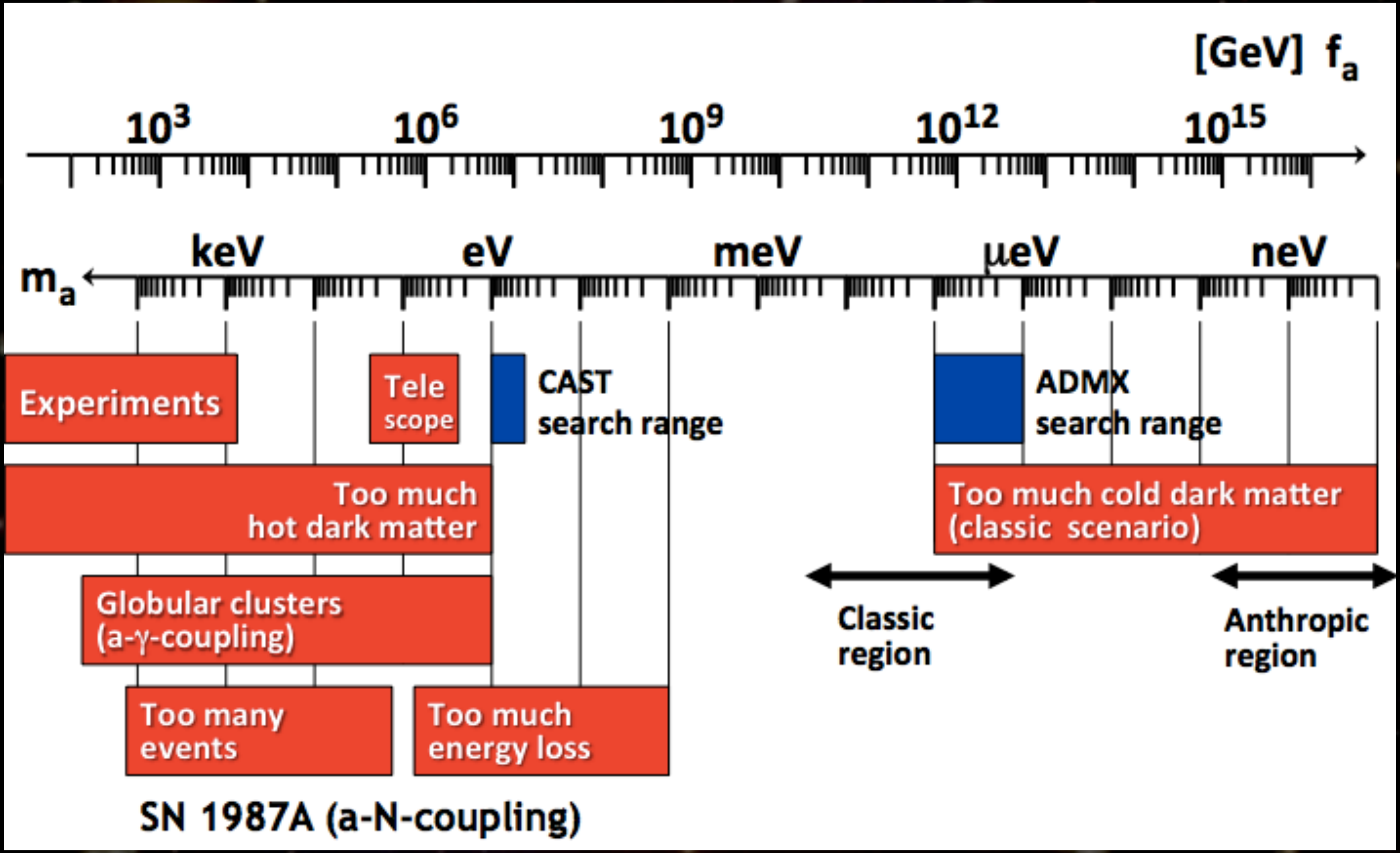
$$\Omega_a h^2 \approx 0.71 \times \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \left(\frac{\Theta_a}{\pi}\right)^2$$

- Axion can be dominant part of CDM if decay constant $f_a \gtrsim 10^{11}$ GeV
- Axion with GUT scale decay constant would overclose universe unless initial misalignment angle very small



[Wantz,Shellard 09]

Axion Dark Matter

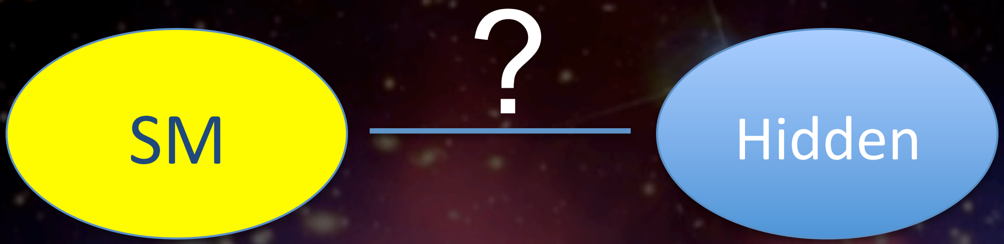


Also other axion like particles (not QCD axion) – more freedom…

Or supersymmetric versions with an axino…

Hidden sectors – portal dark matter

There might be a dark sector with no SM gauge interaction at all (E_8 x E_8)



How would interactions look? Use effective theory as ordering principle…
Every operator should be a product of a visible and hidden ‘gauge singlet’.

$$\mathcal{L} = \mathcal{O}_4 + \frac{1}{M}\mathcal{O}_5 + \frac{1}{M^2}\mathcal{O}_6 + \ldots$$

Operators are grouped by their mass dimension, with [scalar] = 1, [fermion] = 3/2, [$F_{\mu\nu}$] = 2 and higher dimensional operators suppressed.

Dimension 4 operators are renormalisable and can be fundamental
If mediators are light, higher terms are also relevant…

Example: The Higgs portal

For scalar dark matter there is the unique operator

$H^+H\ \varphi^+\ \varphi$

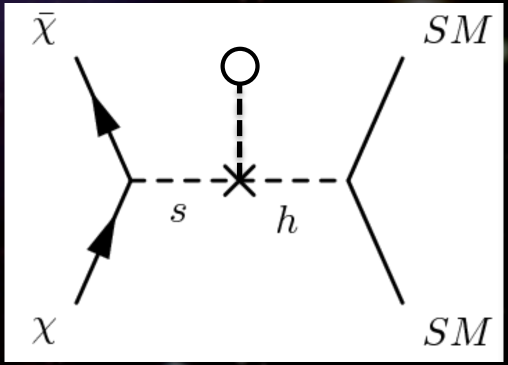
When EW symmetry is broken, $H \rightarrow v + h$, this leads to vertex $h\ \varphi^+\ \varphi$. Higgs mediates the interaction between SM fermions and dark matter!

Would also work for fermionic dark matter (no direct coupling - via mixing with a 'dark higgs')

$H^+H\ \ \varphi\ \ +\ \ \varphi\ X\ X$

Implies invisible Higgs decays (if kinematically allowed) – current limit around 30%

A leading motivation for precision Higgs studies and future colliders, such as ILC.

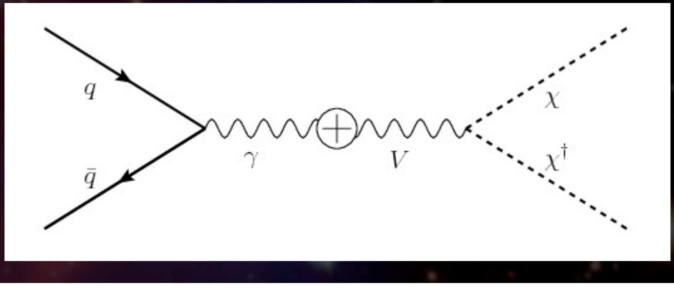


A dark photon (or Z’)

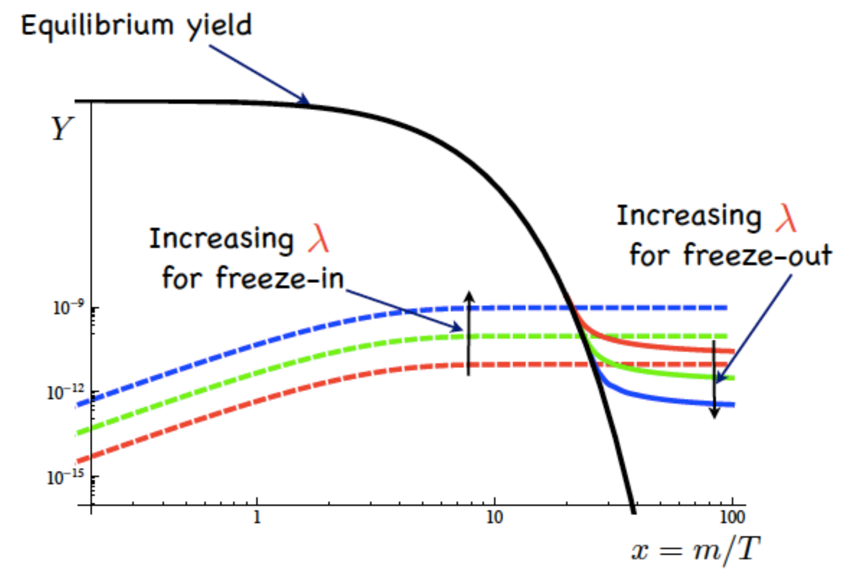
- Another possibility is the kinetic mixing term

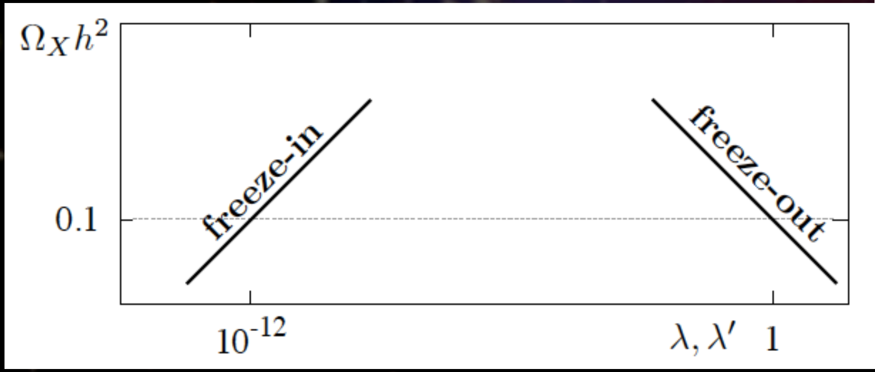
$$\varepsilon \; B_{\mu\nu} \, V^{\mu\nu}$$

- leads to mixing between the SM photon and a hidden vector A’ or Z’. Diagonalizing the mass matrix, one finds that the SM particles have a hidden “milli-charge” ε
- Natural portal to the dark sector
(with dark matter charged under the dark U(1))



Even with tiny couplings (mixings)
can still have a thermal relic abundance
via ‘freeze in’ (similar to the gravitino)

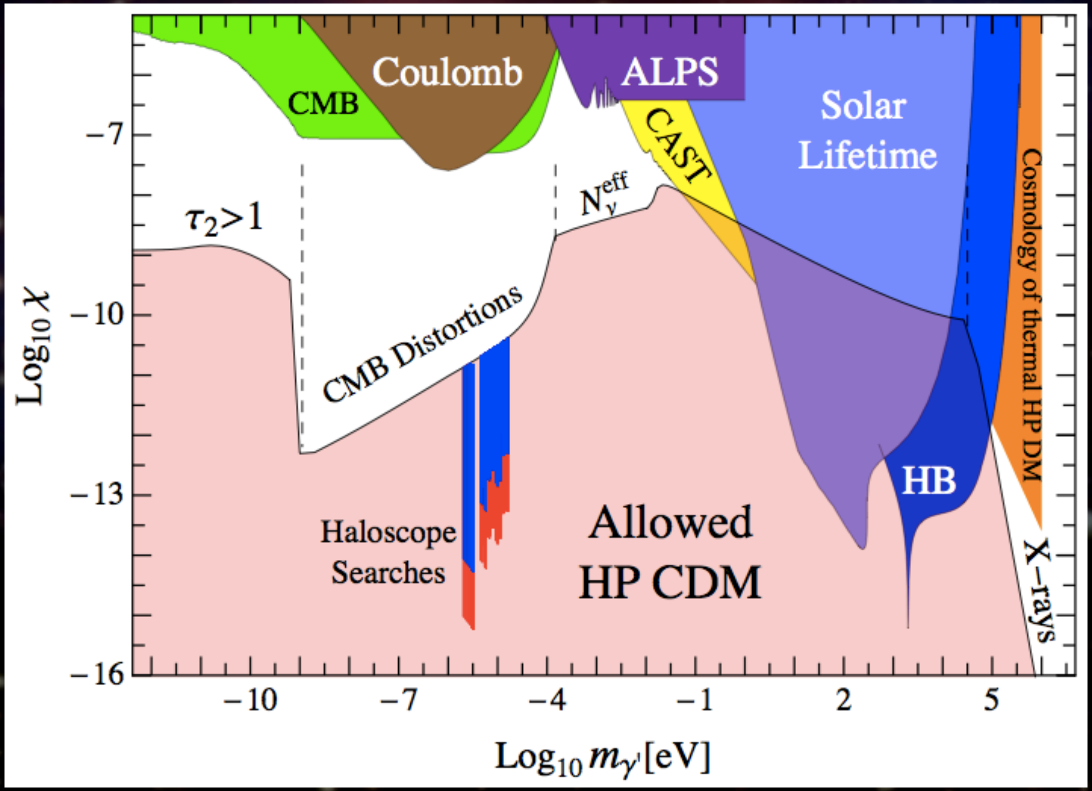




A dark photon (or Z')

- If the dark photon is very light, m_A~ eV, it could even be the dark matter itself (with a long lifetime)

- It can be produced non-thermally, similar to axions



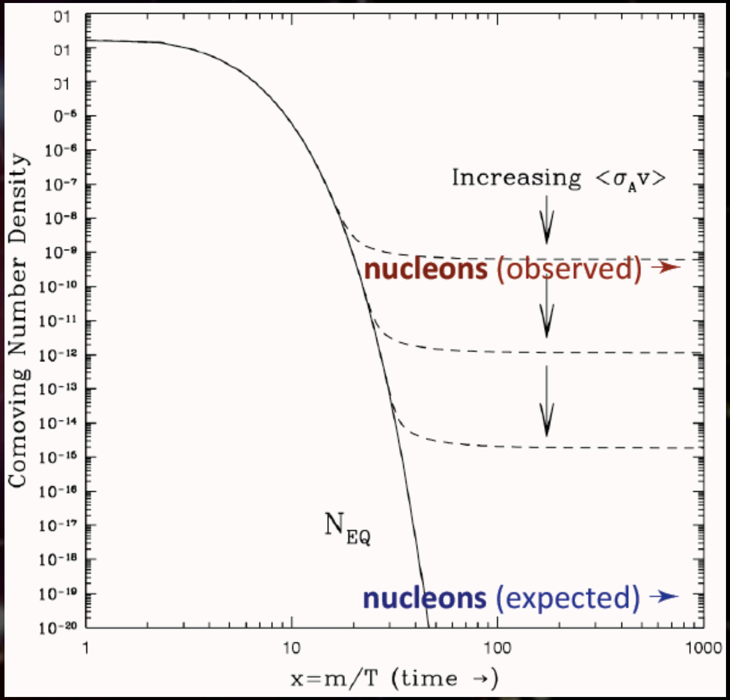
Asymmetric dark matter

Why is the dark matter abundance so similar to that of baryons?
Do they have the same origin?

Apply our freeze out calculation to baryons:

Large baryon cross section:
Freeze out occurs at T~m/45, leading to

$Y_B = Y_B = 10^{-19}$

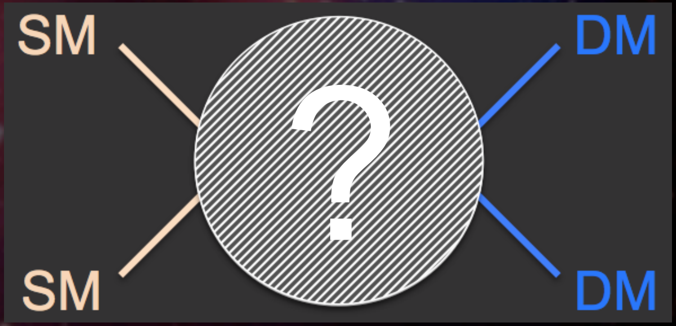


However, there are 10^9 times more baryons and no antibaryons, so we must invoke an initial asymmetry

$$\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-9}$$

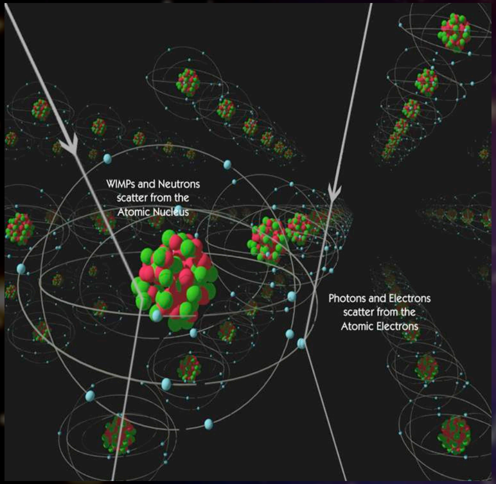
This requires baryogenesis, and there are ideas that the dark matter abundance could have the same origin (several candidates again)

Dark matter – how to test it?

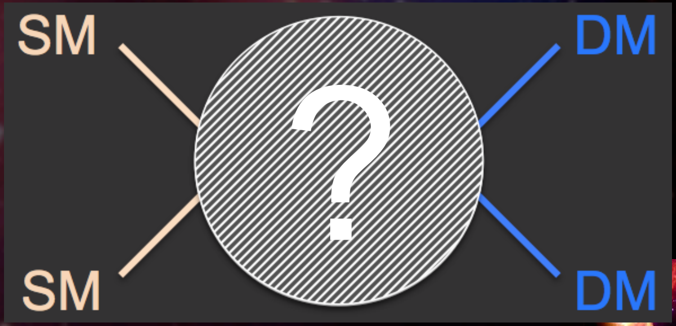


Dark matter – how to test it?

Collider searches

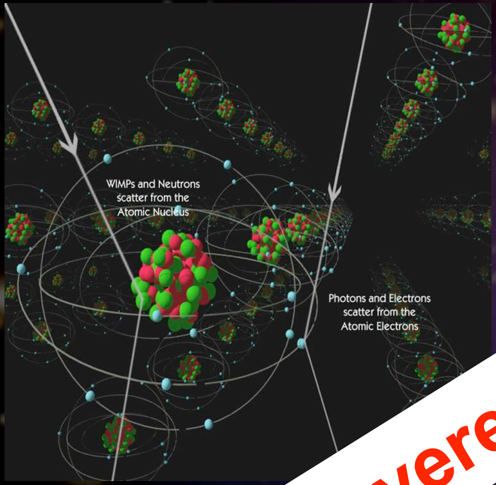


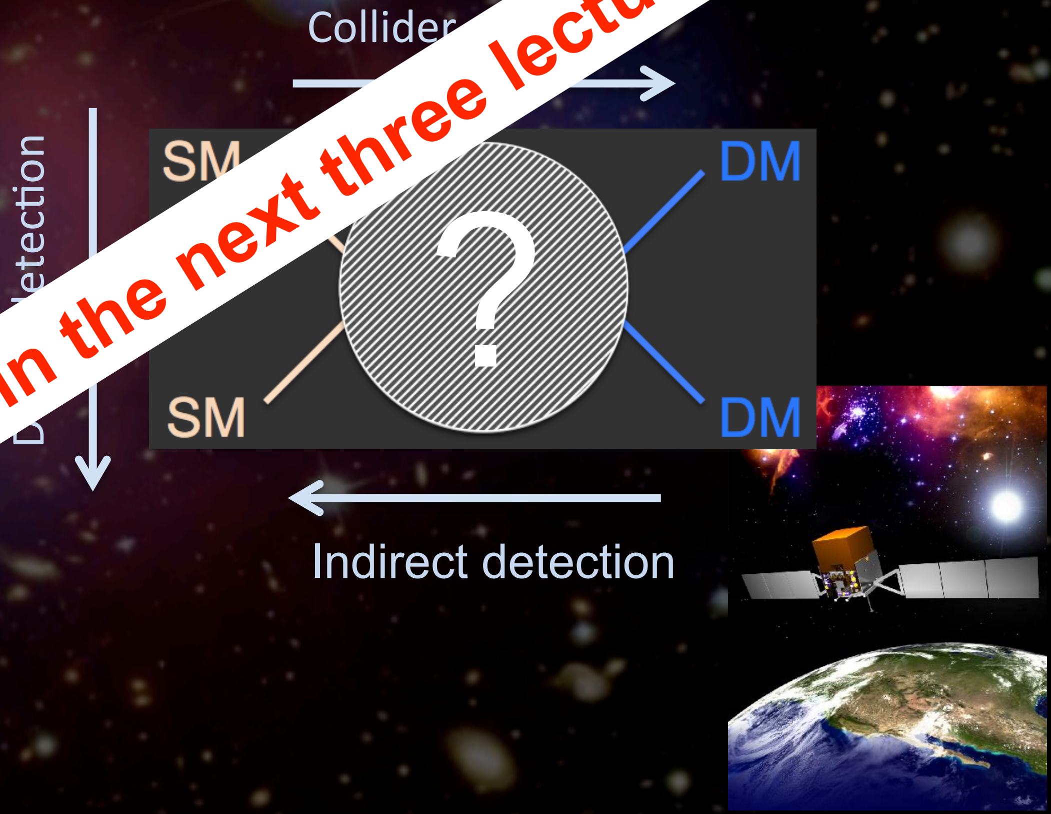
Direct detection



Indirect detection

Dark matter – how to test it?





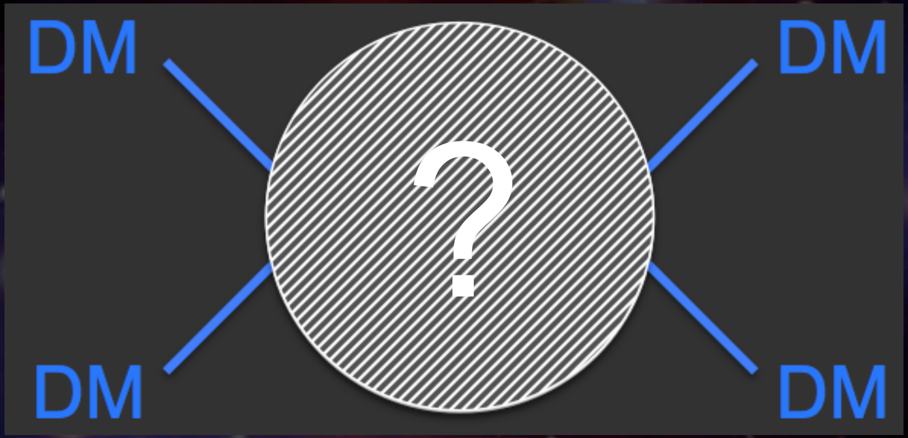
Collider

D etection

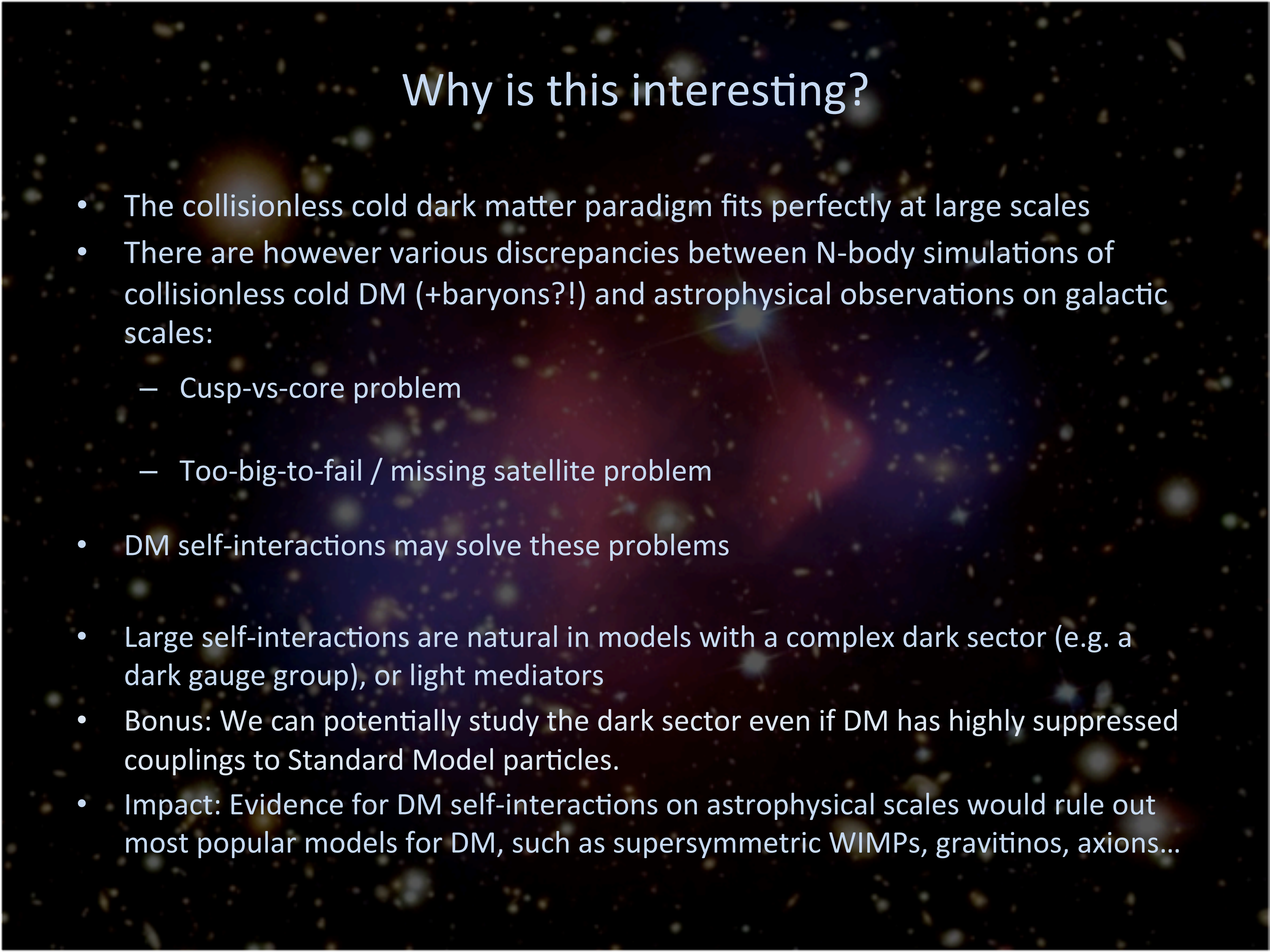
Indirect detection

Will be covered in the next three lectures

Self-Interactions?



Why is this interesting?



Why is this interesting?

- The collisionless cold dark matter paradigm fits perfectly at large scales
- There are however various discrepancies between N-body simulations of collisionless cold DM (+baryons?!) and astrophysical observations on galactic scales:
  - Cusp-vs-core problem
  - Too-big-to-fail / missing satellite problem
- DM self-interactions may solve these problems
- Large self-interactions are natural in models with a complex dark sector (e.g. a dark gauge group), or light mediators
- Bonus: We can potentially study the dark sector even if DM has highly suppressed couplings to Standard Model particles.
- Impact: Evidence for DM self-interactions on astrophysical scales would rule out most popular models for DM, such as supersymmetric WIMPs, gravitinos, axions…

How large a cross section?

- To be observable on astrophysical scales, self-interaction cross sections have to be large, typically

$$\sigma / m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \sim 2\ \mathrm{barns}/\mathrm{GeV}$$

- The typical cross section of a WIMP is 15 orders of magnitude smaller!
- Various astrophysical observations give constraints on the DM self-interaction cross section, e.g.
  - Subhalo evaporation rate
  - Halo ellipticity

Gnedin, Ostriker: astro-ph/0010436

Miralda-Escude (2002)

- Recent numerical simulations suggest $\sigma / m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g}$ may still be viable.

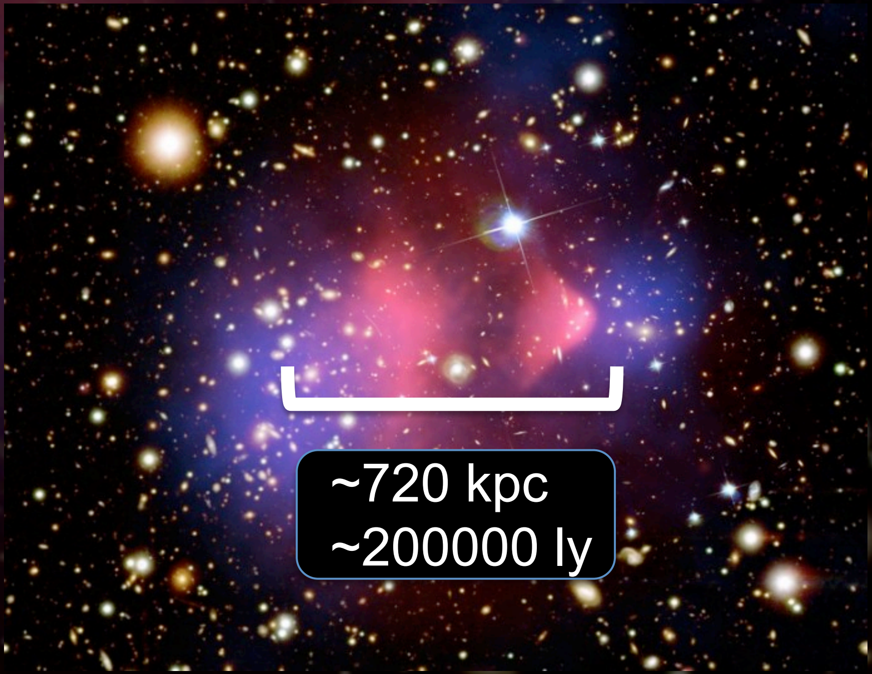
Galaxy clusters

- Huge gravitationally bound objects with around 1000 Galaxies, Gas and DM
- Particularly interesting:

  Galaxy cluster collisions, e.g. Bullet Cluster

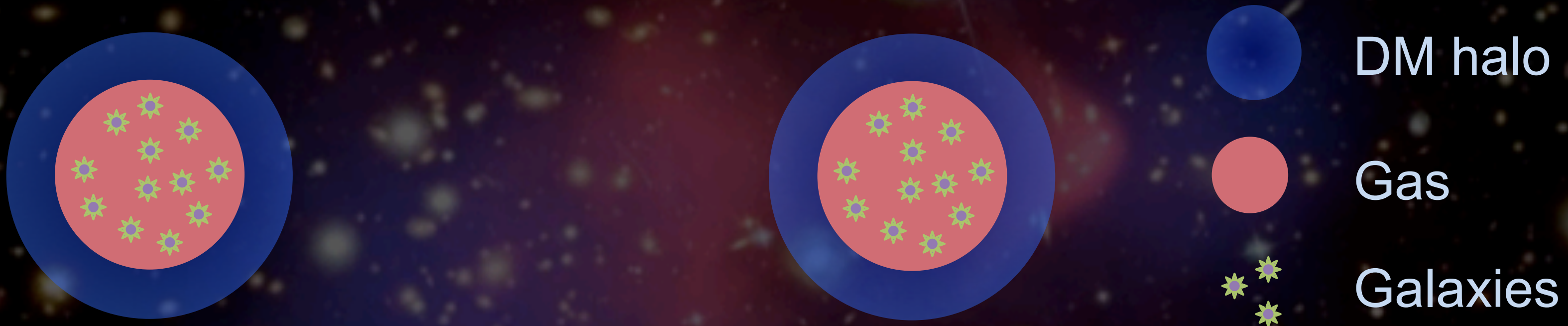
Merger velocity ~ 4000 km/s

Time since collision ~ 10^8 years



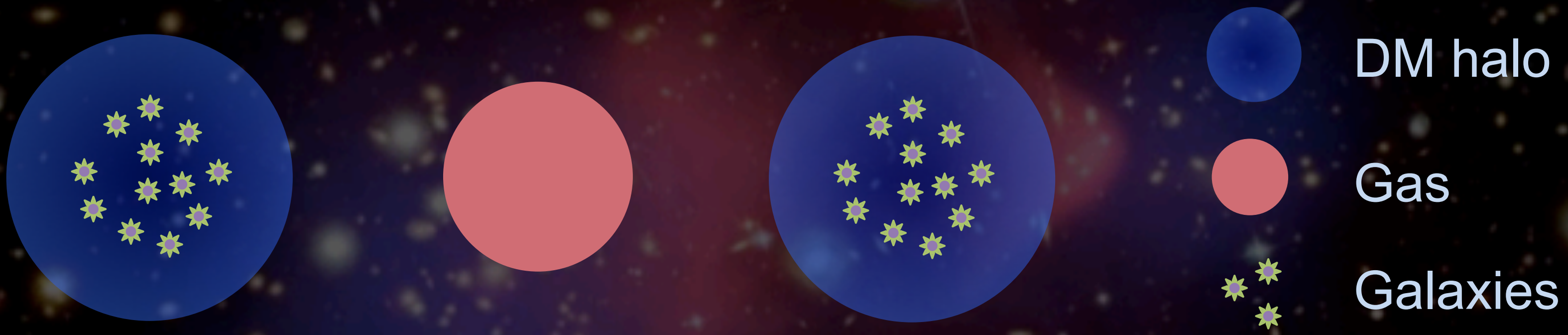
Colliding clusters

- In the absence of DM self-interactions, we expect the following picture

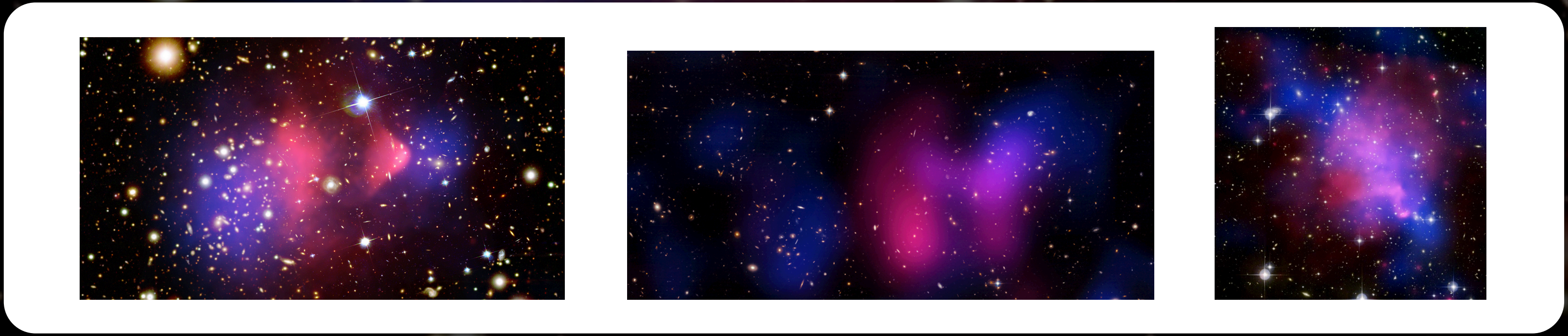


Colliding clusters

- In the absence of DM self-interactions, we expect the following picture

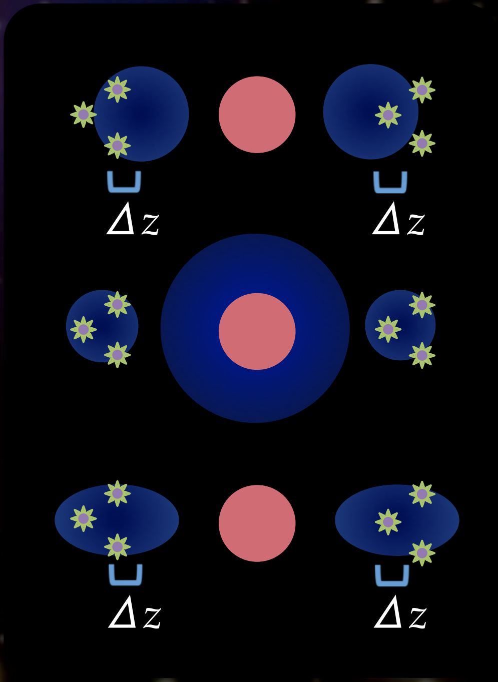


in agreement with observations:



Colliding clusters

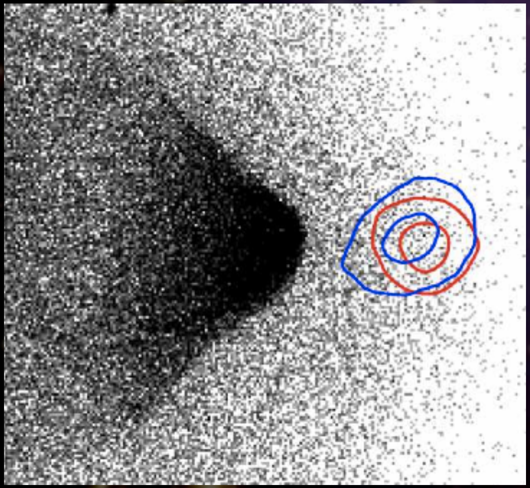
- We see that DM behaves differently from the collisional gas.
- However, before concluding that DM is actually collisionless, we need to understand how self-interactions would modify the picture:
  - Does the DM halo slow down?
    - Observables: Velocity, offset
  - Does the DM halo evaporate?
    - Observables: M/L ratio, dark core
  - Is the DM halo deformed?
    - Observables: Ellipticity, offset



Data?

- The predicted separations from numerical simulations (10 – 30 kpc) are slightly below current bounds for the Bullet Cluster

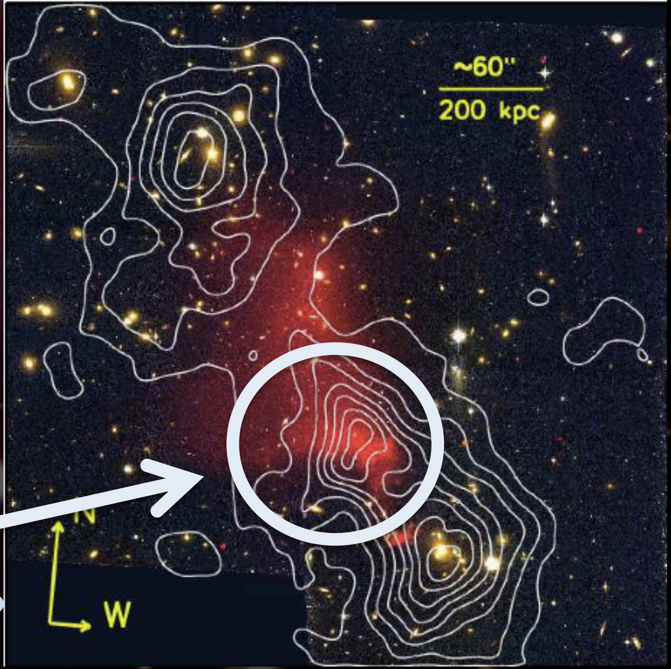
- ($\Delta z = 25 \pm 28$ kpc).



Randall et al.: 0704.0261

- Dark substructure in Abell 520?

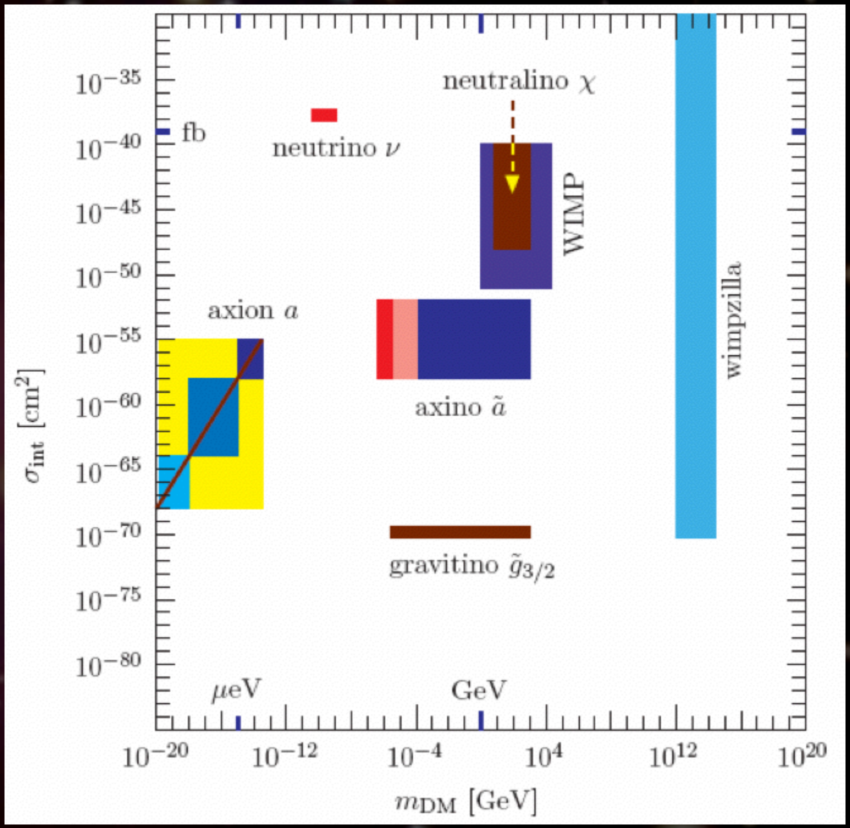
What is this ?



Jee, Hoekstra, Mahdavi, Babul, 1401.3356

Summary

- Dark matter exists – much more than you can say about most other BSM physics
- It is almost certainly BSM – MANY candidates with VERY different properties – strong connections to particle physics
- Three 'classic' detection possibilities – upcoming lectures
- To search for self interactions via astrophysical observations might be an interesting additional route



Primordial black holes

Thanks for your attention!