

Stephani cosmology - can describe inhomogeneous universes
Simple models seem to have trouble fitting all observations

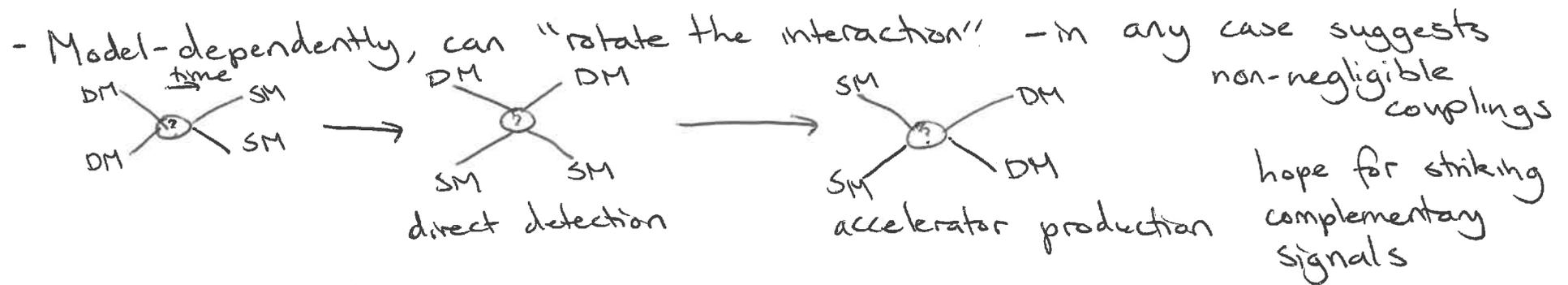
Green & Wald gr-qc/1407.8084 - looks at backreaction of small-scale inhomogeneities on large-scale metric, concludes it's small

Goals for today:

- ~~Work on~~ Thermal DM
 - Work out some implications of thermal scenario
 - Discuss mass limits on thermal DM
 - Discuss possible link to supersymmetry
 - Axions
 - Discuss motivation from strong CP problem
 - Calculate (estimate of) cosmological evolution
 - Work out viable DM parameter space
 - Non-minimal dark sectors (if time permits)
 - Simple dark photon models
 - Phenomenology
 - Self-interactions
-

Thermal dark matter implications

- Gives a simple mechanism to generate observed DM abundance
- Predicts the DM annihilation rate $\langle\sigma v\rangle$
 - If $\langle\sigma v\rangle$ is the same today as in the early universe, predicts rate at which SM particles should currently be produced by DM ("indirect detection")



- Valid across a wide range of masses - how wide?
- Coincidence (?) w/ weak-scale mass/coupling suggests possible link to electroweak physics, hierarchy problem

Effects of $\langle\sigma v\rangle$ in late universe: at freezeout, $O(1)$ fraction of DM annihilates per

Hubble time ($n\langle\sigma v\rangle \sim H$). At later times, what is this fraction $n\langle\sigma v\rangle H^{-1}$?

(assume $\langle\sigma v\rangle$ constant for now)

$$n \propto a^{-3}, \quad H^{-1} \propto a^2 \text{ (radiation domination) or } a^{3/2} \text{ (matter domination)}$$

Power liberated by annihilating DM per Hubble time per baryon $\tilde{\rho} \approx n\langle\sigma v\rangle H^{-1} \cdot m_\chi \left(\frac{n}{n_b}\right) = n\langle\sigma v\rangle H^{-1} \cdot m_\chi \frac{\Omega_\chi}{\Omega_b}$

That is, during rad. dom., power injected per baryon per Hubble time scales in same way as temperature/baryon KE $\propto \begin{cases} a^{-1} & \text{rad dom} \\ a^{-3/2} & \text{matter dom} \end{cases}$

Thus from thermal DM annihilation we expect a steady trickle of heating (& maybe also ionization, etc) throughout universe's history - injected power scaling in same way as overall temperature (per baryon per Hubble time)

Actual ~~energy injected~~ ^{energy injected} per baryon per Hubble - $5 \text{ GeV} \times \left(\frac{af}{a}\right) \approx 5 \text{ GeV} \left(\frac{T}{T_f}\right)$ If $T_f \ll 5 \text{ GeV}$, annihilation can heat baryons

Arguments of this type exclude thermal DM annihilating to visible SM particles (not neutrinos) for $m_\chi \leq 10 \text{ GeV}$ (other annihilation searches extend bound up to $\sim 20 \text{ GeV}$, Leane et al '18) unless annihilation is suppressed at ~~late~~ ^{late} times (e.g. DM asymmetry, $\langle \sigma v \rangle \propto v^2$, etc) by factor $\gg 1$

Other variations: coannihilation (multiple new particles involved), annihilation into new "dark sector" particles, 3+-body annihilation, freeze-in - equilibrium never reached, DM-SM interactions produce DM rather than depleting it

Valid range of masses for thermal DM:

Standard picture: in the early universe, ^($z > 1000$) cosmos ~~was~~ contained a photon-baryon plasma + dark matter + neutrinos - at around $z \sim 1000$ ~~photons~~ ions formed into atoms, photons decoupled from visible matter (cosmic microwave background radiation emitted at this point). Early universe was close to homogeneous, but contained small density perturbations - over time these overdensities grew under gravity, collapsing into vialized structures.

"Cold" (non-relativistic) DM - small clumps form first, accrete into larger structures
 "Hot" (relativistic) DM - free-streaming early erases small structures, large structures form first, then fragment
 "Warm" DM - like cold DM, but less structure at smallest scales

Observations are inconsistent w/ more than $\sim 1\%$ of DM being hot (see e.g. Archidiacono et al '13)
If 100% of DM is warm, can put limits on how warm by looking at small-scale structure (e.g. Viel et al 1702.01764) - for thermal DM, requires $m_\chi \gtrsim 5 \text{ keV}$,
(recall thermal DM shares a temperature with the SM until it decouples, at $T \lesssim m_\chi$)

Such light DM would also act like radiation for $T_{\text{universe}} \gtrsim 5 \text{ keV}$ - contributes to ρ_{rad} during radiation domination, and hence changes H (expansion rate). Modifies formation of nuclei, which occurs at $T \sim 1 \text{ MeV}$.

Consequently it is hard to reconcile $< \text{MeV}$ thermal DM with observations (see Berlin & Blinov '17 for an example of how to make it work).

Bottom line: works fine in MeV-100 TeV range (although must suppress late-time annihilation to visible particles for $m_\chi \lesssim 20 \text{ GeV}$), possible to engineer for keV-MeV DM, hard below 1 keV.

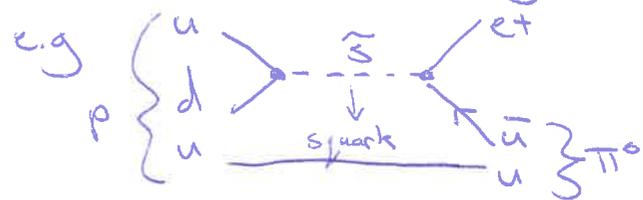
Links to top-down physics: supersymmetry?

Intro to SUSY (for more detail, see Martin hep-ph/9709356)

Basic idea: new fundamental symmetry \Rightarrow every particle has a superpartner

- Same quantum numbers except for spin - bosons have fermionic superpartners & vice versa
- Helps w/ hierarchy problem - contributions to Higgs mass from superpartners have opposite sign & cancel (up to SUSY-breaking effects)
- In unbroken SUSY, superpartners have same mass as original particles, closely related interactions. SUSY must be broken as we haven't found SPs yet
- If we break it "softly", masses are split but interactions still fixed by SUSY - many quantities can be calculated just from masses of SPs

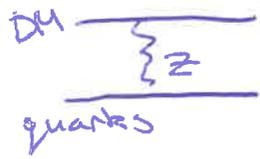
- In particular, naively this implies interactions that make protons decay!



experimental limit: lifetime $> 10^{33}$ yr

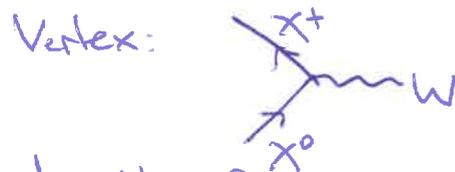
- To prevent this, impose R-parity - all SPs have $R=-1$, all ordinary particles $R=+1$, product of R-parities must be conserved in interactions
 \Rightarrow SPs only couple to ordinary particles in pairs
- But then lightest SP (w/ $R=-1$) must be absolutely stable - cannot decay to other SPs (too heavy), or to 100% SM particles ($R=+1$).
- If this LSP is neutral, good DM candidate.

- Many regions of SUSY parameter space excluded by colliders / direct searches
- In general, if SUSY DM interacts w/ visible matter by exchanging Z or Higgs, should (mostly) have already seen direct-detection signal



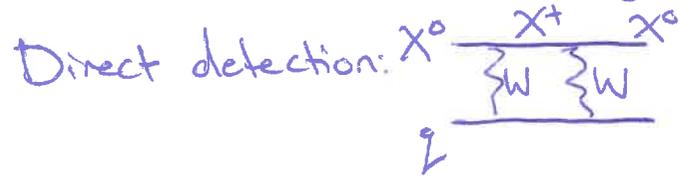
Example of what future experiments will test: "wino" DM

Superpartners of W bosons: χ^\pm, χ^0



DM candidate
slightly heavier, charged

Has correct relic density for $m_\chi \sim 3 \text{ TeV}$



- cross section

$\sigma \approx 2 \times 10^{-47} \text{ cm}^2$ - right at neutrino floor!

