~~B~~SM in the Sky

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- Historical perspective

~1600 Galileo: LAB (pendulum, ...), SKY (Jupiter satellites, Venus phases, ...)
→ Newton's gravity

~1850 Maxwell, ...: LAB

⋮

~1950 Anderson: SKY (positron 1932, muon 1936 with Neddermeyer)

~1950-2012 Particle "revolution": LAB τ, J/ψ, ... (1970's), W Z (80's), ... h (2012)

⋮

2019: Established theory: SM (LAB), GR (SKY) → Standard Cosmo Model

Need of BSM (~ SKY)

- BSM

- ν oscillations   1960's ... deficit of ν_e from the Sun   Homestake mine (US)
  1990's ... deficit of ν_μ " " Atmosphere   SuperKamiokande

- baryon asymmetry   Earth: OK
  other planets: VISITED
  Sun: Solar winds
  Outer Solar System: no antimatter, otherwise signals from annihilations w/ solar winds
  Our galaxy: assume no antimatter, predict $\bar{p}/p$ & e^+/e^- ratios in CRs ⟹ consistent with observations
  ⋮
  Cosmology

- Dark Matter

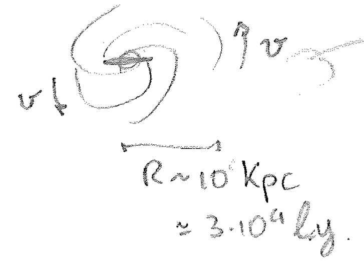
BSM in the Sky

Dislaimer: from now on, main focus = Dark Matter
[but conection with other problems will be mentioned]

Outline A. Properties from evidences B. Candidates C. Tests

A. DM properties from DM evidences

A.1. Galactic (& smaller) Scales, ↦ 1) Rotation curves



measure velocities of gases (neutral Hydrogen via 21cm line)

Expectation: $G_N \frac{M(r) m}{r^2} = m \frac{v_c^2}{r} \Rightarrow v_c(r) = \sqrt{\frac{G M(r)}{r}}$

Assume circular motion for simplicity

$\Rightarrow$ for $r > R$, $v_c(r) = \sqrt{\frac{G M(R)}{r}} \sim r^{-1/2}$

Observation $\Rightarrow$ $M(r) \propto r$ for $r > R$
$= 4\pi \int_0^r r^2 dr\, \rho(r)$

$\Rightarrow \boxed{\rho_{DM}(r) \propto \frac{1}{r^2} \text{ @ } r > R}$ ✩

NB $\rho \propto \frac{1}{r^2}$ = distribution of self-grav. isothermal gas. Proof: see Felix's notes

MOND = Mod. Newton Dynamics. (1983, Milgrom)

$F = ma \xrightarrow{a \ll a_0} F = m\frac{a^2}{a_0} \Rightarrow \frac{GM}{r^2} = m\frac{(v^2/r)^2}{a_0} \Rightarrow v \propto \underline{cte}$

Problems @ cluster scales

No known working theory to explain cosmo evidence for DM

✩ $\boxed{\begin{array}{l} \text{also } R_{DM} \sim 10\, R_{baryons} \\ M_{DM} \sim 10\, M_b \;\; .. \end{array}}$

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A.1.2 Milky Way

$$\boxed{\rho^{obs}_{DM}(r = R_{sun}) \simeq 0.4\, \frac{GeV}{cm^3}} \;☆$$

From $\longrightarrow$ $\begin{cases}\text{Rotational curve measurements} \\ \text{all proposed baryon modelings}\end{cases}$ see e.g. Pato+ 1504.06324

$\longrightarrow$ vertical oscillation of stars around gal. disk see e.g. Buch+ 1808.05603 GAIA data

$$\boxed{\begin{matrix}\langle v_{DM}\rangle (r = R_{sun}) \\ \wr\wr \\ 10^{-3}\, c \simeq 300\, Km/s\end{matrix}} \simeq \left(G_N \frac{M(r<R)}{R}\right)^{1/2} \simeq \left(\frac{1}{M_{Pl}^2} \frac{10^{11} M_\odot}{\underbrace{10\, Kpc}_{3\cdot 10^{17} Km}}\right)^{1/2} = \left(\frac{10^{68}\, GeV \cdot 2\cdot 10^{-19}\, GeV}{10^{38}\, GeV^2\; 3\cdot 10^{19}}\right)^{1/2} \simeq 10^{-3}$$

(Conversion

$GeV \simeq 1.8 \cdot 10^{-24}\, gr$

$N_A \simeq 6 \cdot 10^{23} \Rightarrow 1 gr \simeq 6\cdot 10^{23}\, GeV \Rightarrow M_\odot \simeq 2 \cdot 10^{30}\, Kg \simeq 10^{57}\, GeV$

$UA \simeq 1.5 \cdot 10^{8}\, Km, \quad pc = \frac{UA}{arcsec} = \frac{UA}{\frac{\pi}{180}/3600} \simeq 2 \cdot 10^{5}\, UA \simeq 3 \cdot 10^{13}\, Km$

$pc \simeq 3\, l.y.$

$\hbar \simeq 200\, MeV \cdot fm \Rightarrow Km \simeq \hbar (2\cdot 10^{-19}\, GeV)^{-1}$

$GeV \simeq \hbar (2 \cdot 10^{-14}\, cm)^{-1}$)

$$\Phi_{DM} = \frac{\rho_{DM}\, v}{m_{DM}} \simeq \left(\frac{TeV}{m_{DM}}\right) \frac{4\cdot 10^{-4}}{cm^3} \cdot 3\cdot 10^{7} \frac{cm}{s} \simeq \left(\frac{TeV}{m_{DM}}\right) \frac{10^4}{cm^2 \cdot s}$$

We are hit by 10^8 Higgsinos/sec! σ_{DM-us} is too low to give effects

More seriously, this is relevant for experiments of "Direct Detection"

[but still, see "Death by Dark Matter" 1907.06674]

A.1.3 DM on smaller scales

Solar System

$$M_{DM}(r<R_\odot) = 4\pi \int_0^{R_\odot} s^2 ds\, \rho_{DM} \simeq 10^{40}\,\text{cm}^3\ \frac{0.4\,\text{GeV}}{\text{cm}^3} \simeq 10^{16}\,\text{gr}$$

$$\ll M_{\text{asteroids}}$$

Pitjev Pitjeva 1306.5534 $M_{DM}(r<R_\odot) \lesssim 1.7 \cdot 10^{21}\,\text{gr}$

No evidence for DM here. ρ_{DM}^{sun} is just average over larger scales!

Dwarf Spheroidal Galaxies

- Low-lumi galaxies w/little gas & few (10 to 10^3's) stars
- $D_{ds} \sim 20-200$ Kpc (so linked to MW or Andromeda
- $M_{dw} \gtrsim 10^7 M_\odot$, $R_{dw} \approx 1$ Kpc ($\Rightarrow v \simeq 3 \cdot 10^{-5}$)

Smallest objects observed that are supported by gravity of DM

$\Downarrow$

Can learn a lot on DM from them!

☆ $M_{DM} \lesssim 10^5 - 10^6 M_\odot$ from existence of dSph's

☆ $m_{DM} \gtrsim 10^{-22}\,\text{eV}$ if scalar particle

indeed $\lambda_{DB} = \dfrac{h}{mv} \simeq 2\,\text{Kpc} \left(\dfrac{10^{-22}\,\text{eV}}{m}\right)\left(\dfrac{3\cdot 10^{-5}}{v}\right)$

So if m_{DM} would be smaller then it would not be possible to localize DM on scales smaller than a few Kpcs, contrary to observations

(see Hui+ 1610.08297 for details + refs)

Note:

DM occupation number $\dfrac{N_{DM}}{\text{cell}} \simeq \dfrac{\rho_{DM}}{m_{DM}} \left(\dfrac{1}{mv}\right)^3 \gtrsim 1$ for $m_{DM} \lesssim \text{eV}$

$\Rightarrow$ Particle DM behaves classically, i.e. a fluid for " " !

A.1.3 DM on subgalactic scales ... cont'd

☆ $m_{DM} > 0.5$ KeV if fermion particle

indeed Pauli exclusion principle $\Rightarrow$ phase space distr. $f_{DM}(\vec{x}, \vec{p}) \leq h^{-3}$

$$M_{halo} = m_{DM} \int f_{DM}(\vec{x}, \vec{p})\, d^3x\, d^3p \;\leq\; m_{DM} R^3 (m_{DM} v)^3 h^{-3}$$

$$= m_{DM}^4 R^3 \left(\frac{G M(R)}{R}\right)^{3/2} h^{-3}$$

$$\Rightarrow \quad m_{DM} > \left(G^3 M(R) R^3 h^{-6}\right)^{1/8} \simeq 0.5 \text{ KeV for dSph's}$$

[see e.g. Felix Kahlhoefer lectures, or Domcke Urbano 1409.3167]

Partial recap of lessons from galactic & smaller scales

☆ $\left(\rho_{DM}(r) \propto \frac{1}{r^2} \text{ @ } r > R \rightarrow \text{see next sheets}\right)$

☆ $\rho_{DM}(R_{sun}) \simeq 0.4 \frac{GeV}{cm^3}$

☆ $\langle v_{DM} \rangle^{gal} \simeq 10^{-3} c$, $\langle v_{DM} \rangle^{dSph} \simeq 10^{-5} c$

Properties of DM constituent:

☆ $10^5 M_\odot > m_{DM} > \begin{cases} 10^{-22} \text{ eV} & \text{if scalar} \\ 0.5 \text{ KeV} & \text{if fermion} \end{cases}$

CAVEAT: multi-component DM

A.1.4 DM density profile in galaxies

"N-body simulations"

- $N \gg 1$ DM "particles" of mass $\sim 10^5 - 10^6 M_\odot$ in a box
- give initial displacement. $\frac{\delta\rho}{\rho} \simeq 10^{-5}$ (see later for justification)
- put gravity with a cut-off @ $r < r_{cut} \simeq$ 100's pc in today's simulations

$\Rightarrow$ evolve

Outcomes: 1. structures form bottom-up: first small ones, then big

2. Universal density profile ρ_{DM}, fitted well by "NFW" distribution

$$\rho_{NFW}(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

3. Typical values to fit MW observations: $\begin{cases} r_s \approx 20\,\text{kpc} \\ \rho \approx 0.2\,\text{GeV/cm}^3 \end{cases}$

3. lots of DM substructures, — not in these lectures

After ~2010: Baryons added in the picture (Warning: take this just as a "Notice to skippers")

Remember: "Particle" $\gtrsim 10^5 M_\odot$ $\Rightarrow$ not enough resolution to model single stars, supernovae, etc

$\Rightarrow$ need collective "hydrodynamic" treatment! of "baryonic feedback"

e.g. SN explosions send baryons outside denser regions
baryons drag DM via gravity

Many free parameters, fitted to some criteria (diff people use diff ones!)

e.g. $\boxed{\text{"Abundance Matching"} \approx \text{impose observed } M_*/M_{DM}}$

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A.1.4 DM density profile in galaxies

Before baryons included: all galaxies have same ρ_{DM}

After " " : ρ_{DM} depends on galaxy properties! e.g. $\frac{M_*}{M_{DM}}$ & size

Example: $\left.\frac{M_*}{M_{DM}}\right|_{MW} \simeq 10^{-2}$ ⟶ ($\sim$all) simulations find NFW $\rho(r \ll r_s) \simeq r^{-1}$, a "cusp"

$\left.\frac{M_*}{M_{DM}}\right|_{dSph} \simeq 10^{-3}$ ⟶ i) some simulations find cusps [e.g. Sawala, Frenk+ 1511.01098]

⟶ ii) others find cores [eg Di Cintio+ 1306.0898]

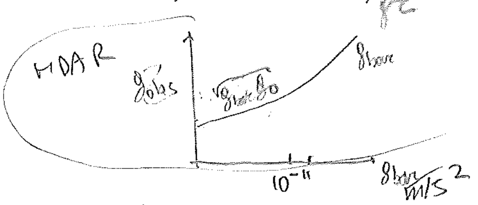
Observations: [MW & larger galaxies: difficult to say anything @ $r \lesssim$ few kpc's because there are way more baryons than DM there
dSphs have cores!

If i) correct ⟶ could DM self-interactions be responsible for cores in dSphs?
[Spergel Steinhardt astro-ph/9909386
before baryons included in sim]

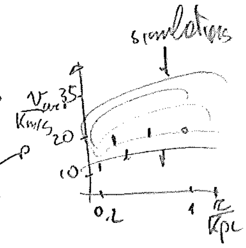
Idea: O(1) scatter per DM particle
⇓
DM goes away of denser regions (like Gal. center)

Scattering rate = $\frac{\sigma}{m} v \rho_{DM} \simeq \frac{0.1}{\text{Gyr}} \left(\frac{\rho_{DM}}{0.1\, M_\odot/\text{pc}^3}\right)\left(\frac{v}{50\,\text{km/s}}\right)\left(\frac{\sigma/m}{\text{cm}^2/\text{gr}}\right)$

$\sigma/m \simeq \text{cm}^2/\text{gr}$ could solve "core vs cusps" "problem" !!



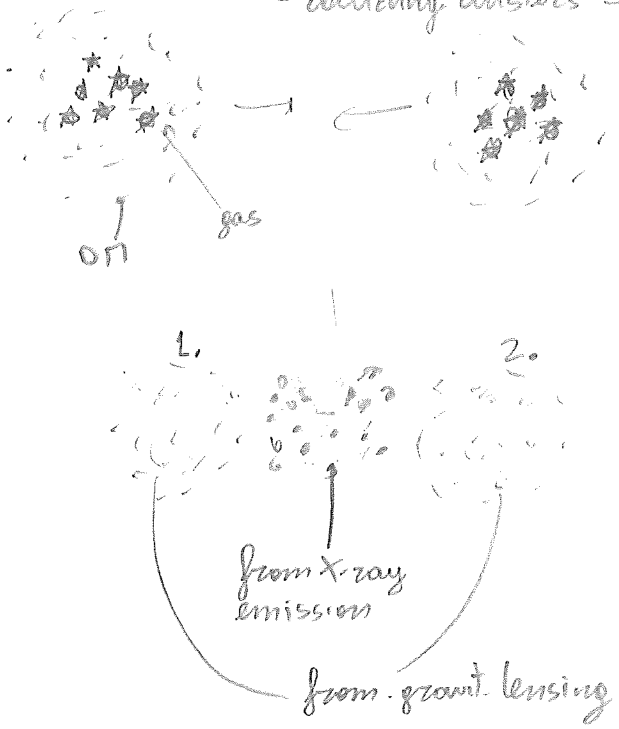
& others... ("too big to fail"
"diversity" ⟶ Oman+ 1504.01437
...)



[See Tulin-Yu 1705.02358 for a review]

A.2 Galaxy cluster scales

Evidence from - virial theorem
- grav. lensing
- colliding clusters → focus here



→ This is what people observed.
1st & most famous collision
= "bullet cluster"
astro-ph/0608407

☆ DM collides less than ordinary matter!

σ = DM self-interaction

Prob that one DM particle in 1. scatters with DM particle in 2., per unit time:

$$\frac{dP}{dt} = \sigma\, \Phi_{DM,2} = \sigma \frac{\rho_2}{m_{DM}} v_{cluster}$$

$$\frac{dP}{dx} = \frac{1}{v}\frac{dP}{dt} = \sigma \frac{\rho_2}{m_{DM}}$$

$$\text{Total scatt. prob} = \int_0^{L_B} \frac{dP}{dx}dx = \frac{\sigma}{m_{DM}} \underbrace{\int \rho_2\, dx}_{\simeq\, 0.3\ \mathrm{gr/cm^3}\ \text{(see paper)}} \simeq \frac{\sigma}{m_{DM}}\, 0.3\ \frac{\mathrm{gr}}{\mathrm{cm}^3}$$

$$\text{Prob} \lesssim 0.3 \implies \boxed{\frac{\sigma}{m_{DM}} \lesssim 1\ \frac{\mathrm{gr}}{\mathrm{cm}^3} \simeq 1.7\ \frac{\mathrm{barn}}{\mathrm{GeV}}}$$

barn = 100 fm^2

For comparison: $\sigma_{n-n} \simeq 10\,\mathrm{barn}$

Note
Most baryonic mat. in cluster is in ionized H & He
long. distance EM non-negligible w.r.t. σ_{nn}!

[For more on DM self-interactions, see Tulin Yu 1705.02358]

A.3 Cosmological scales

A.3.1 Flash intro to cosmology (See Daniel Baumann Cambridge lectures)

General Relativity applied to entire Universe:

Content of Universe $\Rightarrow \begin{cases} \text{its geometry} \\ \text{its evolution} \end{cases}$

"FRW metric"

Metric: Isotropy + Homogeneity $\Rightarrow$ $ds^2 = dt^2 - a^2(t)(dx^2 + dy^2 + dz^2)$

(Isotropy: ok from obs; Homogeneity: not from obs)

$$= dt^2 - a^2(t)\left[\frac{dr^2}{1-Kr^2} + r^2 d\Omega^2\right]$$

$K=0$ case flat

a = "scale factor" describes expansion/contraction of space

a_0 = " " today = 1 by convention

"Comoving" volume = volume $\propto a^3$, that expands as the universe

$\frac{\dot{a}}{a} \equiv H$ = Hubble parameter

$a = \frac{1}{1+z}$, z redshift

Dynamics: Isotropy + Homogeneity $\Rightarrow$ Stress energy tensor of perfect fluid

$$T^\mu{}_\nu = \begin{pmatrix} \rho & & & \\ & -p & & \\ & & -p & \\ & & & -p \end{pmatrix}.$$

Einst. Equation $G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$

$G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu}$ $\supset$ derivatives of $g_{\mu\nu}$, $\cancel{so}$ $\dot{a}$, $\ddot{a}$ etc

$$\boxed{H^2 = \frac{8\pi G}{3}\rho = \frac{1}{3}\frac{\rho}{M_{Pl}^2}}$$

"1st Friedmann equation"

$\Downarrow$

Universe expands!

$M_{Pl} = 2.4 \cdot 10^{18}$ GeV = reduced Planck Mass $= M_{Pl}/\sqrt{8\pi}$

$$h = \frac{100\ \mathrm{Km/(sec \cdot Mpc)}}{H_0}$$

$\rho_{crit} \simeq 5 \frac{m_p}{m^3}$ (@2%!) . $\Omega_x \equiv \frac{\rho_x}{\rho_c}$

measured
$\Downarrow$
$\Omega_{tot} = 1$

A.3.1 Flash intro to cosmology - cont'd

Cosmic Inventory We don't deal with dark energy in these lectures

So particles: n = particle number density

$\propto \frac{N}{a^3}$, N = # of particles in a comoving volume

$\frac{dN}{dt} = 0$ for perfect fluid

$\dot{n} a^3 + 3a^2 \dot{a} n \Rightarrow \frac{\dot{n}}{n} = -3\frac{\dot{a}}{a} \Rightarrow \boxed{n(t) \propto a^{-3}}$

Energy densities: $\rho_{matter} = m \cdot n \propto a^{-3}$

$\rho_{rad} = E \cdot n \propto \frac{1}{\lambda} \cdot n \propto a^{-4}$

$\uparrow$ cause waves get stretched by expansion

Temperature

Assume (local) thermal equilibrium, i.e. rate of interactions $\Gamma \gg H$

then one can define T & use " thermodynamics.

$f_{eq}(p) = \frac{1}{e^{E/T} \pm 1}$ (@ chem pot. $\mu = 0$), $E(p) = \sqrt{p^2 + m^2}$

$$n_{eq} = \frac{g}{(2\pi)^3} \int d^3p \, f_{eq} \longrightarrow \begin{cases} m \gg T & g\left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} \\ m \ll T & \approx \frac{g}{\pi^2} T^3 \cdot \zeta(3) \begin{cases} 1 & \text{bosons} \\ \frac{3}{4} & \text{fermions} \end{cases} \end{cases}$$

$$\rho_{eq} = \frac{g}{(2\pi)^3} \int d^3p \, E(p) f_{eq} \longrightarrow \begin{cases} m \, n_{eq}^{matter} \\ \frac{\pi^2}{30} g T^4 \begin{cases} 1 & \text{bosons} \\ \frac{7}{8} & \text{fermions} \end{cases} \end{cases}$$

$$\rho_{SM}^{T \gg m_t} \simeq \frac{\pi^2}{30} T^4 \left[\sum_b g_b + \frac{7}{8} \sum_f g_f \right] = g_* \frac{\pi^2}{30} T^4$$

$g_* = 106.75$

$$\boxed{H \simeq 0.3 \sqrt{g_*} \frac{T^2}{M_{Pl}}}$$

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A.3.1 Flash intro to cosmology - cont'd

From time to T

Need a conserved quantity: total entropy S!

conserved because "there is no outside"

Entropy density $s = \frac{S}{V} = \frac{\rho + P}{T}$

"proof": $dU = TdS - PdV$ (if chem. potential $\mu \simeq 0$)

$dU = Vd\rho + \rho dV$
$dS = Vds + sdV$ $\Rightarrow$ $\frac{dV}{V}(Ts - \rho - P) + (Tds - d\rho) = 0$

dV extensive
ds & $d\rho$ intensive $\Rightarrow$ coefficients must vanish separately $\Rightarrow$ $s = \frac{\rho + P}{T}$

1 s is dominated by radiation, cause ρ_{matter} is exp. suppressed

2. $P_{rad} = \frac{\rho_{rad}}{3}$ $\Rightarrow$ $\boxed{s = g_{*s} \frac{2\pi^2}{45} T^3}$

$g_{*s} = g_*$ when rel. species are in eq. @ same T

if not (like in today's Uni!) $g_{*s} \neq g_*$

$g_* = 3.38$

$g_{*s} = 3.94$

$$0 = \frac{dS}{dt} \propto \frac{d(g_{*s} T^3 a^3)}{dt} \Rightarrow \boxed{T \propto g_{*s}^{-1/3} a^{-1}}$$

BSM in the Sky

A.3.1 Flash intro to cosmology – cont'd

A posteriori consistency check: we assumed $\Gamma \gg H$ to talk about T

$$\Gamma_{SM} = n_{SM} \langle \sigma v \rangle_{SM} \approx 10\, T_{SM}^3 \times \underbrace{\frac{\alpha^2}{T_{SM}^2}}_{\times} \simeq 10\, \alpha^2\, T_{SM}$$

$$H \simeq \frac{\sqrt{\rho/3}}{M_{Pl}} \sim \frac{\sqrt{3 g_*}}{M_{Pl}} T_{SM}^2$$

$$\Gamma > H \quad \text{for} \quad T \lesssim \alpha^2 M_{Pl} \approx 10^{16}\,\text{GeV}!!$$

History of the universe:

As T decreases { particles fall out of equilibrium
{ processes with typical $E \sim T$ happen (PT, BBN, CMB)

T_γ

MeV — highest T probed by observations) → NB (chemical decoupling, i.e. that of number changing interactions)

→ ν's decouple $\Gamma_{\nu\text{-}SM} \sim G_F^2 T^2 \times T^3 \simeq \frac{T^2}{M_{Pl}} \Rightarrow T \approx \text{MeV}$

→ n starts decaying $n \to p + e^- + \bar{\nu}_e$

→ $\approx$ binding energy of D $\Rightarrow$ nucleosynthesis starts! $p + n \to D + \gamma$, $p + D \to {}^3He + \gamma$ ...

BBN: one input $\eta = \frac{n_b}{n_\gamma}$ } → $\boxed{\eta = 6 \cdot 10^{-10}}$

many outputs: abundances of H, D, ${}^{3,4}He$, ${}^7Li$

$$n_\gamma \simeq \frac{2\zeta(3)}{\pi^2} T_0^3 \simeq \boxed{\frac{400}{cm^3}} \Rightarrow \rho_b = m_p\, \eta\, n_\gamma \simeq 2.3 \cdot 10^{-1} \frac{\text{GeV}}{m^3} \simeq 5\% \text{ of } \rho_{crit}$$

γ

eV — CMB = signal from recombination of $p \cdot e^-$ into neutral atoms

these are photons with $T = T_\gamma = T_{uni}$!

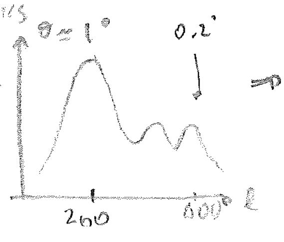
→ Observations $\delta T / T \approx 10^{-5}$ $\boxed{\text{anisotropies}}$ from inflation

→ spherical harmonics

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$C_\ell = \frac{1}{2\ell+1} \sum_m |a_{\ell m}|^2$$

$2.3 \cdot 10^{-4}$ eV
≈ 2.7 K



[Overdensities trap γ that increase P_γ & push baryons away $\Rightarrow$ acoustic oscillations

→ $\Omega_b h^2 \simeq 0.022$
$\Omega_{m} h^2 \simeq 0.12$
$\Omega_{tot} ...$

Comments

- $\Omega_b^{CMB} \simeq \Omega_b^{BBN}$ = non-trivial consistency check

- DM must interact little with baryons to feel less P_γ in wells → this is the meaning of "non-baryonic" in cosmology

- DM must be there before $T \sim eV$, with Ω_{DM}^{CMB}

- fast DM "erase" structures because it free-streams too much

$$\lambda_{fs}^{com} = \int_0^{t_{eq}} \frac{v(t')}{a(t')}\, dt' \sim \ldots 2$$

$\lambda_{fs}^{com} \lesssim$ few kpc (because we observe dSph's) $\Rightarrow m_{DM} \gtrsim keV$ "warm DM"

Add: graph of evolution of $\Omega_{rad,m,\Lambda}(a)$, to make clear that DE wasn't relevant @ BBN & CMB

Summary of properties:

those @ sheet 5/ +

- DM there before CMB
- DM ~ cold
- $\Omega_{DM} \sim 0.25$

B. DM candidates

B.1 "Big" known objects?

(Caveat: DM could be big unknown objects!)

- Cannot be gas, white & brown dwarfs, BH, ... because these objects ∄ @ recombination time!

- Could be Primordial Black Holes!

Formation? see Green 1403.1198

- large ($\frac{\delta\rho}{\rho} \gtrsim 0.3$) overdensities after inflation
- collapse of cosmic defects (e.g. cosmic strings)
- ...

Oss No production mechanism of PBH that does not require BSM

Detection? see Carr+ 1607.06077

- $M_{PBH} \lesssim 10^{17}$ gr ($\simeq 10^{-15} M_\odot$) $\Rightarrow$ they evaporate via Hawking radiation

would give signals @ Fermi, Voyager, !

- larger M_{PBH}: would give signals in grav. lensing!

e.g. Kepler mission, devised to look for exoplanets, actually constrains Ω_{PBH}

- more: not here

Still allowed? yes, in some small mass window!

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B.2 Particle DM: SM

B.2.1 SM neutrinos?

NO for 3 reasons

- $m_\nu <$ eV + fermions $\Rightarrow$ clashes with $\exists$ of dSphs, vs Pauli exclusion
  (see sheet 5/)

- $m_\nu <$ eV + $T_{FO} \sim$ MeV $\Rightarrow$ hot relic $\Rightarrow$ clashes with structures

- $\Omega_\nu h^2 \simeq \dfrac{\sum_j m_\nu}{93\,\mathrm{eV}}$ too small

Now relic ν non-rel
$\Rightarrow n_\nu = \rho_\nu / m$
$\Rightarrow n_\nu \simeq \dfrac{100}{\mathrm{cm}^3} \simeq \dfrac{n_\gamma}{4}$

(Why abundances given as $\Omega_x h^2$?
Because $\rho_{crit} = \dfrac{3 H_0^2}{M_{Pl}^2}$ & $H_0 = h\, H_{ref}$)

Relic abundance of any particle x that freezes out while rel.

$$\Omega_x = \frac{m_x n_{x,0}}{\rho_{crit}} \underbrace{=}_{n_{x0} a_0^3 = n_{xFO} a_{FO}^3} \frac{m_x}{\rho_{crit}} n_{x,FO} \left(\frac{a_{FO}}{a_0}\right)^3 \underbrace{=}_{n_{x,rel} \propto g_s a T = cnst} \frac{m_x}{\rho_{crit}} \frac{g_\nu}{\pi^2} \frac{3}{4} \zeta(3)\, \cancel{T_{xFO}^3} \, \frac{g_{s,0} T_0^3}{g_{s,FO} \cancel{T_{FO}^3}}$$

independent of $T_{x,FO}$! (except for $g_{s,FO}$)

B.2.2 QCD bound state?

di-baryon uuddss. Mass unknown, existence unknown but possible

- $SU(3)_F$ isospin singlet, could be deeply bound (Jaffe NPPS 24B (1991))

- could be DM? Glennys Farrar 1711.10971 & refs therein

- NO, ~~because~~ allowed masses $\lesssim$ $\mathcal{O}$(GeV) give $\Omega_{dibar} < 10^{-12}$

Gross+ 1803.10242
Kolb Turner 1809.06003 (20 yrs after their last paper together)

B.3 Particle DM: thermal relics & WIMPs

B.3.0 Boltzmann Equations

We already used $\Gamma \sim H$ for ν freeze-out, intuitively OK, now a bit more precise

$$\frac{dN}{dt} = \frac{d(a^3 n)}{dt} = a^3 \dot{n} + 3a^2 \dot{a} n = a^3(\dot{n} + 3Hn)$$

less χ if $\langle\sigma v\rangle_{\chi\chi \to \text{whatever}} > 0$.

$$\dot{N}_{\chi,\text{destr}}: N_1 \underset{\uparrow}{2}\, n_2 \frac{\langle\sigma v\rangle}{\underset{\uparrow}{2}} = a^3 n_1 n_2 \langle\sigma v\rangle \Rightarrow \dot{n}_1 + 3Hn_1 = -n_1 n_2 \langle\sigma v\rangle$$

minus 2 per annihilation if 1=2 (ok for self-conj χ for example)

particles 1=2

$\langle\sigma v\rangle_{12\to34}$ number changing

We miss $\dot{N}_{\chi,\text{creation}}$

Trick: if chemical equilibrium, then $n_{1,2} = n_{1,2\,eq}$, $n_{3,4} = n_{3,4\,eq}$

$$\Rightarrow \boxed{\dot{n}_1 + 3Hn_1 = (-n_1 n_2 + (n_1 n_2)_{eq}) \langle\sigma v\rangle}$$

Back to $N_1 = a^3 n_1$:

$$\frac{1}{a^3}\frac{d\,n_1 a^3}{dt} = -\overbrace{n_1 n_2 \langle\sigma v\rangle}^{\Gamma_{ann}} \left(1 - \frac{(n_1 n_2)_{eq}}{n_1 n_2}\right)$$

$$\frac{1}{N_1}\frac{dN_1}{dt} = -\Gamma_{ann}\left[1 - \frac{(N_1 N_2)_{eq}}{N_1 N_2}\right]$$

$$\boxed{\frac{d\log N_1}{d\log a} = \underbrace{-\frac{\Gamma_{ann}}{H}}_{\text{interaction efficiency}}\left[1 - \frac{(N_1 N_2)_{eq}}{N_1 N_2}\right]}$$

Oss: $\dfrac{dN}{dt} = \dfrac{d\,a^3 n}{dt} = \dfrac{d\left(\frac{S}{s}n\right)}{dt} \overset{!}{=} \dfrac{d\left(\frac{n}{s}\right)}{dt} S = S\dfrac{dY}{dt}$

B.3.1 Freeze out of non relativistic relics

- Freeze-out (assume $L=2$)

$$\begin{cases} \Gamma_1 = n_* \langle \sigma v \rangle = g_1 \left(\frac{mT}{2\pi}\right)^{3/2} e^{-m/T} \langle \sigma v \rangle \\ H = 0.3\, g_*^{1/2} \frac{T^2}{M_{Pl}} \end{cases}$$

T_{FO} defined by $\Gamma = H$

$$3 \times (2\pi)^{3/2} \langle \sigma v \rangle M_{Pl} \frac{g_*^{1/2}}{g_1} = (m T_{FO})^{-3/2} e^{+m/T_{FO}} T^2 = m \frac{x_{FO}^{-1/2}}{m} e^{+x_{FO}} \qquad x \equiv \frac{m}{T}$$

$$\Rightarrow \boxed{x_{FO}^{-1/2} e^{x_{FO}} = 3 \cdot (2\pi)^{3/2} \langle \sigma v \rangle m M_{Pl}}$$

$m \in$ GeV – 100 TeV
$\sigma v \in [10^{-28}, \ldots 10^{-24}]\ cm^3/s$ $\Rightarrow$ $\boxed{x_{FO} \simeq 20-30}$ consistent!

- DM abundance

$$\Omega_{DM} = \frac{m\, n_{DM,0}}{\rho_{crit}} = \frac{m}{\rho_c}\left(\frac{T_0}{T_{FO}}\right)^3 \frac{g_0}{g_{FO}} n_{DM,FO} = x_{FO} \frac{g_{0,s}}{g_{FO,s}} \frac{T_0^3}{\rho_c} \frac{n_{DM,FO}}{T_{FO}^2}$$

$n_{FO} \langle \sigma v \rangle = 0.3\, g_{FO}^{1/2}\, T_{FO}^2 / M_{Pl}$

$$= \frac{x_{FO}}{\langle \sigma v \rangle} \times \frac{T_0^3}{\rho_c} \frac{1}{M_{Pl}} \frac{g_{0,s}}{g_{FO,s}} g_{FO,*}^{1/2}$$

$$\boxed{\Omega_{DM} \simeq 0.225 \frac{x_{FO}}{25} \frac{3 \times 10^{-26}\ cm^3/s}{\langle \sigma v \rangle}}$$

See Steigman+ 1204.3622 for more precise numbers

Note 1: $\langle \sigma v \rangle_{FO} \simeq \frac{10^{-2}}{TeV^2}$

Note 2: Ω_{DM} indep of m_{DM}

B.3.2 Mass window for thermal relics

You've seen $M_{DM} < \mathcal{O}(100)\,\mathrm{TeV}$ unless entropy injection happens

Bound is stronger for any non-rel relic χ with $\Omega_\chi < \Omega_{DM}$

cause it needs $\underset{\substack{\S \\ M_{uni}^2}}{\langle\sigma v\rangle} > \underset{\substack{\S \\ \frac{1}{M_{uni,th}^2}}}{\sigma v_{thermal}}$

Lower limit on m of any particle coupled chemically to SM:

$$m \gtrsim 1\text{-}10\ \mathrm{MeV}$$

precise value depends on g_χ degrees of freedom of χ

Limit comes from BBN: η_B from CMB $\Rightarrow$ deuterium abundance

one more relativistic particle in chemical eq. @ Deuterium fusion ($T \lesssim \mathrm{MeV}$)

$$\Downarrow$$
$$g_* > g_{*,SM}$$
$$\Downarrow$$
$$H > H_{SM}$$
$$\Downarrow$$

BBN computations change enough to contradict observations

Summary:

$$\boxed{\text{"Standard" relic} \Rightarrow \mathrm{MeV} \lesssim m \lesssim 100\ \mathrm{TeV}}$$

B.3.3 WIMP $\equiv$ Weakly Interacting Massive Particle

$\langle\sigma v\rangle_{FO} \simeq \frac{3\cdot 10^{-2}}{\mathrm{TeV}^2}$ typical of particle with weak scale coupling & " " mediators

$$\langle\sigma v\rangle|_{Wimp} \approx \frac{\alpha_w^2}{v^2} \approx \langle\sigma v\rangle_{FO}$$

B.3.3 WIMP = Weakly Interacting Massive Particle

We found $\langle \sigma v \rangle_{FO} \simeq \frac{3 \cdot 10^{-2}}{TeV^2}$

This is typical of a particle with weak scale interactions, i.e. WIMPS!

$$\langle \sigma v \rangle_{wimp} \approx \frac{\alpha_w^2}{v^2} \approx \langle \sigma v \rangle_{FO}$$

Disclaimer

In some literature the "W" of WIMPs strictly refers to the Weak interactions of the SM, $SU(2)_w$

In some other literature (in particular recent one) the "W" refers to any interaction of "weak" size.

WIMP "miracle"

Hierarchy Problem of the Fermi scale can be solved by existence of New Physics close to the Fermi Scale, i.e. @ 0.1-1 TeV

Examples: Weak-Scale SUSY, Composite Higgs, ...

See Andi Weiler's lectures for more details.

Point here: NP @ 0.1-1 TeV is independently motivated by 2 outstanding problems of our understanding of Nature.

A remarkable coincidence!

↓

call it miracle if you like...

BSM in the Sky

B.3.4 Example of WIMP candidate: SUSY Neutralino

MSSM = (SM + 2nd Higgs doublet) × 2

Add a global discrete symmetry & call it "R-parity" or "matter parity"

$$Z_2 \begin{cases} \text{particle}: +1 \\ \text{sparticle}: -1 \end{cases}$$

Why? Theory: natural remnant of spontaneously broken $U(1)_R$ symmetry, that is always there in SUSY

Pheno: forbids proton decay

Bonus: Lightest SUSY particle (= LSP) is stable!

⇓

LSP is a good WIMP candidate!

More concretely: "Neutralino LSP"

Neutralinos = fermion partners of W, B, H_1, H_2 bosons

if very mixed among each other ⇒ excluded by experiments

see e.g. Cheung+ 1211.4873

if not very mixed (i.e. "pure") then still viable!

"Higgsino" $\tilde{H}$: $\Omega_{\tilde{H}} = 0.25 \left(\frac{M_{\tilde{H}}}{1.1\,\text{TeV}}\right)^2$

"Wino" $\tilde{W}$: $\Omega_{\tilde{W}} = 0.25 \left(\frac{M_{\tilde{W}}}{3\,\text{TeV}}\right)^2$

WIMP miracle @ play!

B.3.G. SUSY Neutralino Cont'd

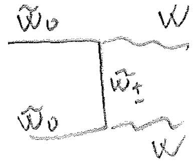
Closer look @ WINO case [see e.g. Cirelli + 0706.4071 for "simple" ref]

- $\widetilde{W} = \begin{pmatrix} \widetilde{w}^+ \\ \widetilde{w}_0 \\ \widetilde{w}_- \end{pmatrix}$ Tree level $M_{\widetilde{w}^\pm} = M_{\widetilde{w}^0}$

  Loop level (

) $\Rightarrow M_{\widetilde{w}^\pm} - M_{\widetilde{w}_0} = 166\,\text{MeV}$

  $\Rightarrow$ good, lightest component is the neutral one !!

0. 

+ u-channel $\Rightarrow \langle\sigma v\rangle_{00^+} \simeq \langle\sigma v\rangle_{00\to WW} = \dfrac{2\pi\alpha_w^2}{M^2}$

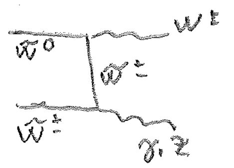
But: plug in value of $\alpha_w \simeq \frac{1}{30}$ & $\langle\sigma v\rangle_{FO}$

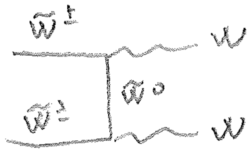
& find $M \lesssim$ TeV $<< 3$ TeV (value I gave you)

why?

1. Coannihilations

@ FO time, $T_{FO} \simeq \dfrac{M_{\widetilde{w}}}{30} >> M_{\widetilde{w}^\pm} - M_{\widetilde{w}^0}$

$\Rightarrow$ also processes like 

, 

are relevant in setting the DM abundance!
(note $\widetilde{w}^\pm \to \widetilde{w}^0 \pi$ later)

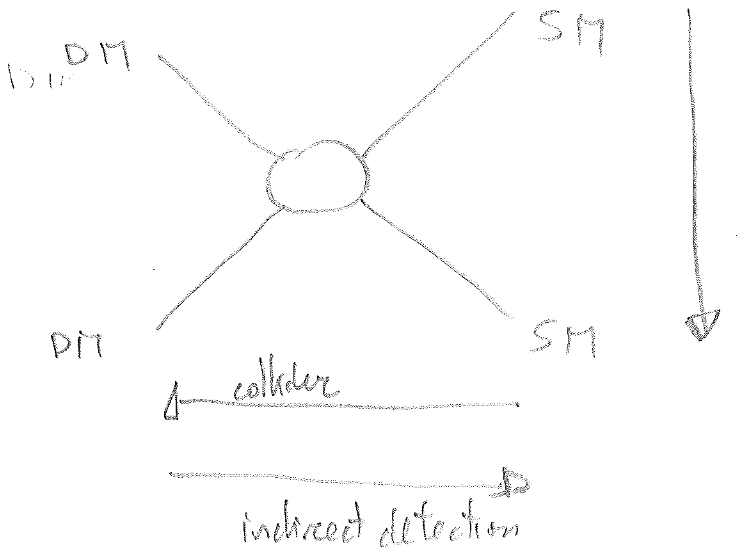
$\Rightarrow \langle\sigma v\rangle_{FO}^{eff} = \langle\sigma v\rangle_{00} + \langle\sigma v\rangle_{+-} + \ldots >> \langle\sigma v\rangle_{00}$

$\Rightarrow \langle\sigma v\rangle_{FO}^{eff}$ again $\propto \dfrac{1}{M_{\widetilde{w}}^2}$ $\Rightarrow$ to match $3\cdot 10^{-26}\,\text{cm}^3/\text{s}$, you need a larger $M_{\widetilde{w}}$ than seen before in 0.

2. Sommerfeld enhancement

See tutorials in afternoon. Other effect that increases $M_{\widetilde{w}}^{FO}$

C. Experimental & observational tests



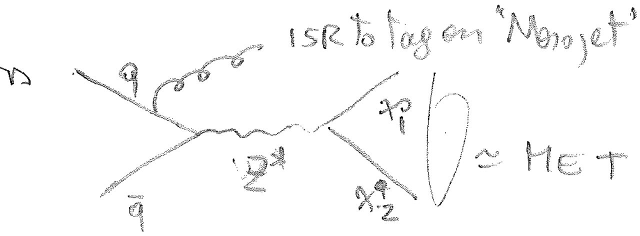
C.1 Collider & DD

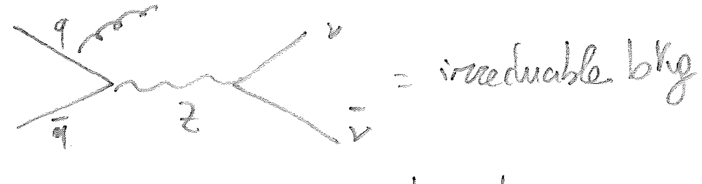
Collider E.g. Higgsino p-p colliders like LHC

other: h or Z invisible decays, Long lived Particles, ...

Look for Missing Transverse Energy ← given by DM but also by any particle w $\tau \gtrsim \mu s$ & " by neutrinos → bkg

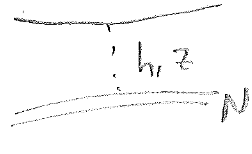
ISR to tag on 'Monojet'





LHC now barely sensitive to $m \simeq 100$ GeV.
FCC-hh will be needed for these WIMPs!

Direct Det



eg nucleons of Xenon ⇒ strong limits!

what killed :($Z^{& h}$-mediated WIMPs, mixed neutralinos, h-...

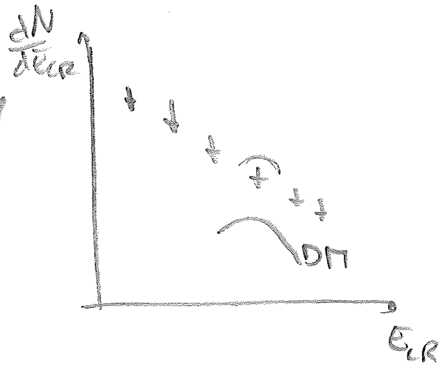
Survivors :) $\tilde{H}, \tilde{W}$, PGB DM (under certain conditions), Secluded DM models (see later), ...

BSM in the Sky

C.2 Indirect Detection

C.2.1 Intro to ID

ID $\stackrel{\text{here}}{=}$ detection of $\begin{cases} \text{CRs } (e^\pm, \bar{p}, \bar{D}, \dots) \\ \gamma \\ \nu \end{cases}$ produced by DM



"Very ID" = $\begin{cases} \text{star evolution \& properties} \\ \text{other CR alterations} \\ \dots \end{cases}$ NOT here

ID vs others:

	Trust	Cosmo history?	Lifetime?
Collider	:D	:/	:(
Direct det	:)	:/	:/
ID	:/	:)	:)
		C.2.2	C.2.3

Selected examples

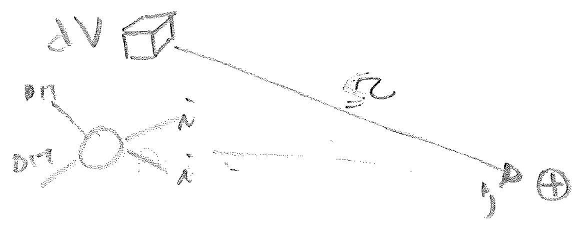
ACTIVE	CHANDRA	Satellite	$\sim 0.04\,m^2$	γ	Xray (0.1–100 keV)	
	Voyager	Satellite	$\sim 10^{-3}\,m^2$	$\gamma, e^+ + e^-$	10–100 MeV	✓
	Fermi	Satellite	$\sim m^2$	$\gamma, e^+ + e^-$	$\lesssim 100$ GeV	✓
	AMS	on ISS	$\sim 0.1\,m^2$	$\bar{p}, p, \dots$	TeV	✓
	Icecube	South Pole	$\sim Km^2$	ν	$\gtrsim 10$ GeV into PeV	✓
	ANTARES	Mediterr	$\sim 0.1\,Km^2$	ν	$\gtrsim 10$–100 GeV into PeV	✓
	HESS	Namibia	$\sim 0.1\,Km^2$	$\gamma, e^+ + e^-$	$\gtrsim 100$ GeV into 100 TeV	✗
NEAR FUTURE	CTA	Canary + Chile	$\gtrsim Km^2$	" "	"	✗
	LHAASO	Tibet	$\gtrsim Km^2$	" "	" & into PeV	✗
	KM3NeT	Mediterr	$\gtrsim Km^2$	ν	" "	✓
	…					

other active Cherenkov γ-telescopes:
VERITAS
MAGIC
HAWC
…

References:
Profumo 1301.0952 TASI '12
Slatyer 1710.05137 " '16
Cirelli+ 1012.4515 "PPPC4DMID"

BSM in the Sky

C.2.2 ID of annihilating DM



spectrum per single annihilation

$$\frac{dN_{CR}}{dE_{CR}\,dA\,dt} = dV\ \underbrace{\frac{n_{DM}^2}{2}}_{\text{this 2 if DM not self-conjugate}} \sum_i \langle\sigma v\rangle_i(E_i)\,\frac{d\bar{N}_{i\to CR}(E_i,E_{CR})}{dE_{CR}}\,\frac{1}{4\pi r^2} \quad \text{from element } dV$$

$$= \frac{r^2 dr\, d\Omega}{8\pi r^2}\,\frac{\rho_{DM}^2}{m_{DM}^2}\sum_i \langle\sigma v\rangle_i\,\frac{d\bar{N}_{i\to CR}}{dE_{CR}}$$

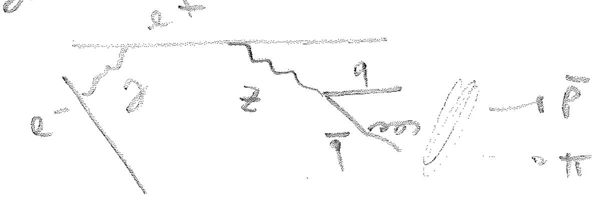
$$= \underbrace{\frac{\sum_i\langle\sigma v\rangle_i}{8\pi m_{DM}^2}}_{\substack{\text{particle}\\ i)}}\ \underbrace{\frac{d\bar{N}_{i\to CR}}{dE_{CR}}}_{\substack{\text{particle}\\ +\\ \text{astro}\\ ii)}}\ \underbrace{\int dr\, d\Omega\, \rho_{DM}^2(r)}_{\substack{\equiv J \text{ factor}\\ \text{astro}\\ iii)}}$$

i) choose your model

Remember $\sum_i \langle\sigma v\rangle_i \simeq 3\cdot 10^{-26}\,\frac{cm^3}{s}$ = "Holy Grail"

ii) Particle: QCD & EW radiation

e.g.



Need tools like
PYTHIA
PPPC

Astro: CR propagation!

charged particles → feel Galactic Mag. field, complicated.
NOT HERE, see reviews & refs therein

ν, γ simple! Go straight & Univ is transparent (for γ only if E_γ ≲ 100 TeV)

Cr 2.2 ID of annihilating DM cont'd

iii) J factor

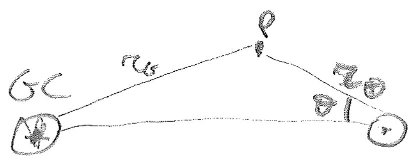
$\propto \rho^2 \Rightarrow$ ID of ann. DM optimal towards overdense regions!

Galactic Center

Dwarf Spheroidal Galaxies

Smaller Substructures

G.C.



$R_s \simeq 8$ Kpc

$$J(\theta) = 2\pi \int_0^{\theta} d\theta' \int_0^{R \gg R_s} dr_\oplus \; \rho^2_{DM}(r_G[r_\oplus, \theta])$$

$$r_G[r_\oplus, \theta] = \sqrt{R_s^2 + r_\oplus^2 - 2 r_\oplus R_s \cos\theta}$$

$$\frac{J}{[\text{GeV}^2/\text{cm}^5]} \simeq \begin{cases} 10^{22\text{-}24} & \text{GC w/ } \theta \lesssim 10^\circ \\ 10^{19\text{-}20} & \text{most promising dSphs (Draco, Ursa Minor)} \\ \text{substructures} & \end{cases}$$

compute it for NFW profile
" " " " with core

(Draco, Ursa Minor) → computation needs closer data input, see eg Hayashi+

substructures
Usually modelled as "boost" of DM ID signal, most relevant for → local ($\bar{e}^+$, $\bar{p}$, $\bar{p}$)
→ galaxy clusters

On GC & core $\quad \rho_{NFW,c} = \rho_s \dfrac{r r_s}{r + r_0}\left(1 + \dfrac{r}{r_s}\right)^{-2}$ → Study variation of $J(\theta, r_{co})$

On dSphs typ. distances 30 - 200 kpc.
$\mathcal{O}(10^3)$ stars !! - $\mathcal{O}(10)$ stars
But, simulations predict $\mathcal{O}$(few) dSph w/ $J \gtrsim 10^{20}$

tell stories of
- MAGIC & Segue I
- Triangulum II

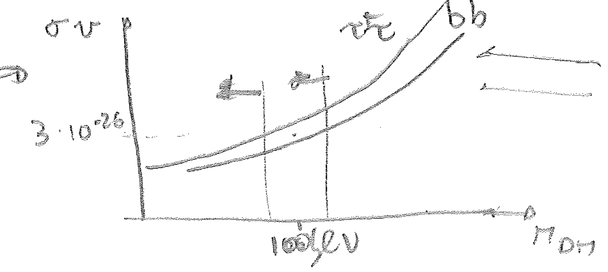
	Signal	Robustness of DM interpretation	Backgrounds
GC	:)	:|	:(
dSphs	:(	:)	:)

→ can be compensated by "stacking" many, see Fermi next sheet

C.2.2 ID of annihilating DM cont'd

Example of searches in γ-rays w/ **Fermi 1503.02641**

dSph stacked $\Longrightarrow$



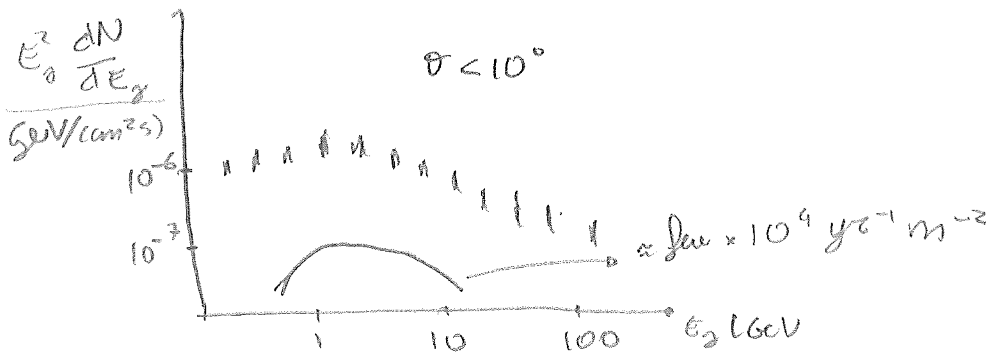
different DM annihilation channels

DM DM $\to b\bar{b}$, $\tau^+\tau^-$, ...

Probing thermal relic paradigm!?! :)

GC excess

aka "Hooperon"



$$\text{DM: } \frac{E^2 dN}{dA\,dt\,dE} = \frac{\text{few} \times 10^9}{\text{yr m}^2} \underbrace{\left(\frac{E^2 dN_\gamma}{dE}\right)}_{\sim\text{same shape observed by Fermi!}} \left(\frac{30\,\text{GeV}}{m_{DM}}\right)^2 \frac{J}{10^{23}\,\text{GeV}^2/\text{cm}^5} \frac{\langle\sigma v\rangle}{3\cdot 10^{-26}\,\frac{\text{cm}^3}{\text{s}}}$$

Signal ~ 1 o.o.m. less than data, not simple to extract

$\Longrightarrow$ see **Fermi 1704.03910**

Still, of course particle physicists got excited!

Status:
- could come from population of "millisecond pulsars" in GC that is ~ unresolved
- maybe statistical pref. for it, maybe not.

see e.g. the recent **Leane Slatyer** 1904.08430 & refs therein

BSM in the sky

6.2.3 ID of decaying DM

[see e.g. Ibarra+ 1307.6434 for more details]

DM in galaxies ~ today $\Rightarrow \tau_{DM} \gg \tau_{uni} \simeq 10^{10}\,yr \simeq 3\cdot 10^{17}\,sec$

e.g. by some global symmetry G (like proton & $U(1)_{Baryon}$)

If G global then accidental & broken @ some higher scale, like in the SM

tenable point of view, no need to call explicit breaking of G from gravity

Example $\mathcal{L} \supset \frac{O_6}{\Lambda^2}$, $O_6 = (\bar\psi_{DM} f_1)(\bar f_2 f_3) \Rightarrow \Gamma_{\psi\to 123} \simeq 10^{27}\,sec \left(\frac{\Lambda}{10^{16}\,GeV}\right)^4 \left(\frac{300\,GeV}{m_{DM}}\right)^5$

NB Same parametrics of p decay!

Testable? Yes! ☺

$$E_p \frac{dN_p}{dE\,dt} = r^2 dr\, d\Omega\; n_{DM}\, \Gamma_i \cdot E_p \frac{dN_{i\to p}}{dE_p} \cdot \frac{A_{det}}{4\pi r^2}$$

$$= \frac{\Gamma_i}{m_{DM}} E_p \frac{dN_{i\to p}}{dE_p} \cdot \int_0^L dr\, \rho_{DM}(r)$$

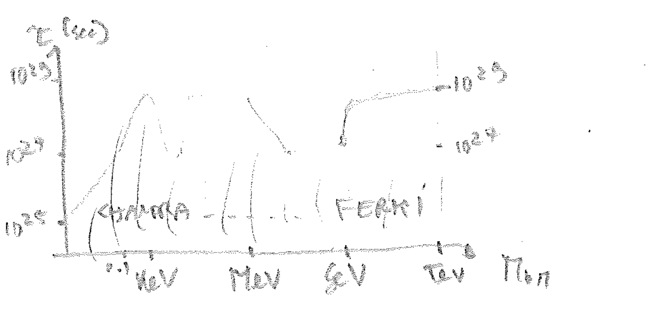
$$\simeq \frac{10^3}{yr}\left[\frac{10^{27}\,sec}{\tau}\;\frac{300\,GeV}{m_{DM}}\;\frac{A}{m^2}\;\frac{\rho}{0.4\,\frac{GeV}{cm^3}}\;\frac{L}{Kpc}\right] \frac{E_p dN}{dE_p}$$

All parameters relevant for AMS02!

> Ex: Which O_5 can make a scalar DM decay?
> What masses are interesting for ID, if $\Lambda = 10^{16}\,GeV$?
> & if $\Lambda = 10^{11}\,GeV$?

Example

Summary of constraints on DM decaying in γ-lines:



This & more summaries in

Mambrini + 1508.06635

C.2.4 Back to ID from annihilation: variations on standard FO

- Velocity dependences

$$\langle \sigma v \rangle = \begin{cases} a & \text{"s-wave"} \\ b/v & \text{long-range interactions (Sommerfeld)} \\ c v^2 & \text{"p-wave"} \end{cases}$$

$v_{FO} \simeq .3$

$v_{MW} \simeq 10^{-3}$

$v_{dSph} \simeq 10^{-5}$

$\Longrightarrow \begin{cases} \text{p-wave gives less signals than s-wave} \\ \text{long-range " more " " "} \end{cases}$

FO fixes $\langle \sigma v \rangle \big|_{v = v_{FO}}$

More on Sommerfeld in tutorial. Exercise: Sommerfeld from gravity

- "3 exceptions" (Griest Seckel PRD43(1991)) - here 2

i) coannihilations $\quad \sigma_{DM\,DM} v$ too small (would overclose)

but $\sigma_{DM\,X} v$ large enough to give Ω_{DM}

& then X decays

$\boxed{\text{realised in SUSY e.g. Wino of previous sheets}}$

ii) resonances $\quad \sigma \propto \dfrac{1}{(s - M_{res}^2)^2 + M^2\Gamma^2} \propto \dfrac{1}{\left[\dfrac{4 m_{DM}^2 (1 + v^2)}{M_{res}^2} - 1\right]^2 + \dfrac{\Gamma^2}{M_{res}^2}}$

if $\dfrac{v_{FO}^2 m_{DM}^2}{M_{res}^2} \gg \dfrac{\Gamma}{M}$ $\begin{cases} \text{if res @ FO} \Longrightarrow \langle \sigma v \rangle_{today} < \langle \sigma v \rangle_{FO} \text{, less signals than standard} \\ \text{if res in MW or dSph} \Longrightarrow \text{" > " , more " "} \end{cases}$