Astro 507

Lecture 28

April 6, 2020

Announcements:

- **Problem Set 5 due Friday**
  can post questions in Homework Discussion
- Office Hours: by email, by appointment, or
  Instructor–after class Wednesday
  TA: noon-1pm Thurday (email)

Last time: BBN theory vs observation

- D/H very precise, ^{4}He agrees
  measures cosmic baryons: $\eta \to n_{\rm B} \to \rho_{\rm B}$
  requires 2 kinds of dark matter *Q: how? what?*
- ^{7}Li/H strongly disagrees with D/H: "lithium problem"

Subcritical Baryons and Two Kinds of Dark Matter

$$0.024 \leq \Omega_B \leq 0.049$$

$\Omega_{\rm B} \ll 1$

baryons do not close the universe!

$\Omega_{\rm B} \ll \Omega_{\rm Matter} \simeq 0.3$

most of cosmic matter is not made of baryons!

"non-baryonic dark matter"

huge implications for particle physics–more on this to come

Measure known baryons which are directly observable optically
i.e., in *luminous* form (stars, gas): $\rho_{\rm lum} = (M/L)_\star \mathcal{L}_{\rm vis}$

$\Omega_{\rm lum} \simeq 0.0024 h^{-1} \sim 0.004 \ll \Omega_{\rm B}$

$\Rightarrow$ most *baryons* dark! **"baryonic dark matter"**

Q: Where are they?

Where are the dark baryons?

• **compact objects** (white dwarfs, neutron stars, black holes)
search for *MACHOs*: MAssive COmpact Halo Objects
via gravitational microlensing
`www: lensing diagram, MACHO event`
see lensing events towards LMC!
but are they MACHOs or LMC stars? ...probably the latter

• **warm/hot intergalactic medium** (WHIM)
structure formation $\rightarrow$ infall $\rightarrow$ shock heat to $T \sim 10^5 - 10^7$ K
note: in galaxy clusters, most baryons in
hot "intracluster" gas, not galaxies!
`www: X-ray cluster`
but X-rays from WHIM gas harder to see...
recent evidence of diffuse "X-ray forest"
`www: Chandra spectra`

BBN and the CMB: Battle of the Baryons

Until recently:
BBN was the premier means for measuring $\eta \propto \Omega_B$
$\rightarrow$ the best cosmic "baryometer"

Now: CMB independently measures η

battle of the baryons
compare independent measures of η
test of cosmology!

If agreement: big bang working very well!
$z \sim 10^{10}$ theory & light elements
quantitatively consistent with $z \sim 10^3$ theory & CMB

If disagreement: a pressing problem!

BBN in Light of the CMB

Planck 2018: Final Data Release

$\Omega_{\rm baryon,CMB} h^2 = 0.022298 \pm 0.000214$

$\Rightarrow \eta_{\rm CMB} = (6.104 \pm 0.058) \times 10^{-10}$

- 1% precision!
- independent of BBN!

BBN vs CMB: Testing Cosmology

pillar vs pillar!

`www: Schramm plot:` $\eta_{\rm BBN}$ `vs` $\eta_{\rm CMB}$

Concordance!

in more detail:

1. use $\eta_{\rm CMB}$ as input to (Std) BBN theory,
2. compute light elements
3. compare with observations

`www: abundance likelihoods (BDF, Olive, Yeh, & Young 2020)`

- D agreement perfect! ^{4}He agreement excellent
- ^{7}Li tension clearer – hot research topic
  "lithium problem" could point to new physics!

What's up with ^{7}Li?

- observational systematics (e.g., stellar parameters)? Quite possible.
  (Melendez & Ramirez 2004; FOV05)

- astrophysical systematics (e.g., depletion)? but what about ^{6}Li? and Li dispersion small ($\lesssim 0.2$ dex)...

- BBN calculation systematics: nuke reaction rates? But well-measured, and can use solar neutrinos to test dominant source: $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ (CFO04)

- new physics? if so, nature kind–didn't notice till now
  otherwise, would not have believed hot big bang...

Particle Dark Matter

BBN and Particle Dark Matter

BBN motivates dark matter theory & searches two ways:

Quantitative. $\Omega_B \ll \Omega_{\rm m}$: must have non-baryonic dark matter
...and lots of it!

Qualitative. BBN success at $t \sim 1$ s $\rightarrow$ early U as physics lab

"The universe is the poor man's particle accelerator"
– Ya. Zel'dovich

Big implications for–and motivations from–particle physics

Q: what can we say about DM properties generally?

Q: what can we say if DM is in particle form?
lifetime, mass, interactions, quantum #s?

Q: what known particles are candidates for non-baryonic DM?

Q: does particle theory offer dark matter candidates?

Elementary Particle Physics and Dark Matter

Dark matter
dark: no/feeble EM, strong interactions
matter: behaves as nonrelativistic material $\rightarrow \rho \propto a^{-3}$, $P \ll \rho c^2$
naturally leads to hypothesis of DM as
Weakly Interacting Massive Particles: WIMPs

If DM is swarms of WIMPs, what are their properties?

lifetime: must exist today $t_0 \sim 14$ Gyr
$\rightarrow$ stable or very long-lived

mass: don't know!
only know mass dens $\rho_{\mathrm{m},0}$ today on cosmic, galactic scales
but without also knowing # dens $n_{\mathrm{m},0}$, can't get $m = \rho/n$
$\rightarrow$ in fact, with specific model, from m get n_0

Could the Dark Matter be Neutrinos?

interactions/quantum #s:
BBN: dark matter not baryonic

Standard Model of particle physics *does* provide
a candidate for non-baryonic DM
stable + massive: neutrinos; can show (PS5):

$$\Omega_\nu h^2 = \frac{\sum_{\rm species} m_\nu}{92 \text{ eV}} \tag{1}$$

...but can show (β decay, ν oscillations, CMB, LSS)
$\sum_{\rm species} m_\nu \lesssim 1$ eV, and so

$$\Omega_\nu \sim 0.01 < \Omega_B \ll \Omega_{\rm m} \tag{2}$$

we see: νs *are* non-baryonic DM
but *negligible contribution to density*
most dark matter is not neutrinos!

Dark Matter: Who Ordered That?

Dark matter isn't neutruinos. What else could it be?

no other known particle candidates are viable!
i.e., DM absent from **Standard Model of Particle Physics**
that accounts for all known particles an interactions

non-baryonic DM demands physics beyond the Standard Model

particle candidates available "off the shelf"
in models of physics Beyond the Standard Model
i.e., particle physics models designed to explain
origin of standard model features

examples:
lightest supersymmetric particle, axion, strangelets...

Dark Matter: Cold Relics

Director's Cut below gives details. Basic idea simple:

consider a stable particle χ and $\bar{\chi}$

- in Early U: thermally created (and annihilated) as $\chi\bar{\chi}$ pairs so always $n_\chi = n_{\bar{\chi}}$
- freezes out when cold=non-relativisitic: $m_\chi \gg T_{\rm freeze} \gg T_0$
- candidate for dark matter today

Q: if χ always in equilibrium, what is n_χ today?
Q: but can have $n_{\chi,0} = n_{\bar{\chi},0} > 0$ today: how?
Q: what determines n_χ today?
Q: what is required for χ to be the dark matter?

Dark Matter: The WIMP Miracle

for $\chi\bar{\chi}$ created and annihilated in pairs

- *equilibrium abundance* today ($T_0 \ll m$) is exponentially tiny
  in equilbrium, χ annihilation never stops!

- but in expanding U: annihilations freeze out!
  χ particles too dilute to find each other!

Freezout condition: $\Gamma_{\text{ann}} = n_\chi \sigma_{\text{ann}} v = H$

⋆ smaller σ_{ann} $\rightarrow$ earlier freeze $\rightarrow$ fewer annihilations
smaller cross section $\rightarrow$ higher relic abundance
the weak prevail!

⋆ today want $m_\chi n_{\chi,0} = \rho_{\text{DM},0}$
implies σ_{ann} is at Weak scale: $T_{\text{freeze}} \sim 1$ TeV $\sim E_{\text{LHC}}$
the WIMP miracle

But: intenstive WIMP searches have found nothing (so far)
See Director's Cut for status and outlook: **new ideas needed!**

Director's Cut Extras

Particle Dark Matter: Thermal Relics

Kolb & Turner, Ch. 5; Dodelson Ch. 3.4

Consider stable particle species χ (& antiparticle $\bar{\chi}$)

- nonrelativistic today: $m_\chi \gg T_0 \sim 3 \times 10^{-4}$ meV
- thermally produced in the early universe

What determines its abundance today?

Q: if χ is still in thermal (chemical) eq?

Q: and so?

Relic Particles

for non-relativistic species:
if *still in (chemical) equilibrium*: number density

$$n_\chi = g_\chi \left(\frac{m_\chi T}{2\pi \hbar^2} \right)^{3/2} e^{-(m_\chi - \mu_\chi)/T} \qquad (3)$$

chem potential: $\mu \neq 0$ iff conserved particle number

if χ number *not conserved*–i.e., equal numbers of χ and $\bar{\chi}$
then $\mu_\chi = 0$, and so $n_\chi \sim e^{-m_\chi/T} \to 0$
$\Rightarrow$ no relic particles remain – terrible dark matter candidate!

Lessons: relic dark matter particles should

- *either* have *particle/antiparticle asymmetry*
  this is thought to be origin of baryons
- *or* must have dropped *out of equilibrium*
  Q: how might this happen?

Freezeout and **Relic Abundance** of a Symmetric Species

a *symmetric* species χ has a cosmic abundance
with *equal* numbers of particle and antiparticle
...or particle = antiparticle

thus $n_\chi = n_{\bar{\chi}}$ exactly: no "net χ number"
$\Rightarrow$ complete annihilation would leave no remaining particles

but: annihilation requires particle interactions!
these must compete successfully with expansion & cooling

in cosmic setting, essentially *guaranteed*
that at some point **annihilations freeze out**:
$\Gamma(\chi\bar{\chi} \to \text{stuff}) < H$
$\Rightarrow$ nonzero relic χ abundance, mass density also *guaranteed*!
Q: so does this guarantee that χ is the dark matter?

Annihilation Freezeout

Sketch of calculation appears here; more details in extras

Annihilation rate per χ (and $\bar{\chi}$) particle is

$$\Gamma_{\rm ann}(T) \simeq n_{\chi,{\rm eq}}(T) \ \langle \sigma_{\rm ann} v \rangle \sim (m_\chi T)^{3/2} e^{-m_\chi/T} \ \langle \sigma_{\rm ann} v \rangle \qquad (4)$$

where σ is the annihilation cross section,
and $\langle \sigma_{\rm ann} v \rangle$ is a thermal average

Freezeout temperature $T_{\rm f}$ set by

$$H(T_{\rm f}) \sim \frac{T_{\rm f}^2}{M_{\rm pl}} = \Gamma_{\rm ann}(T_{\rm f}) \sim (m_\chi T_{\rm f})^{3/2} e^{-m_\chi/T_{\rm f}} \ \langle \sigma_{\rm ann} v \rangle \qquad (5)$$

dominated by exponential: $T_{\rm f} \sim m_\chi$
so freezeout χ density is

$$n_{\chi,{\rm f}} \simeq \frac{H(T_{\rm f} = m_\chi)}{\langle \sigma_{\rm ann} v \rangle} \sim \frac{m_\chi^2}{M_{\rm pl} \, \langle \sigma_{\rm ann} v \rangle} \qquad (6)$$

Relic Abundance and Density

relic χ abundance at freezeout $T_{\rm f} \sim m_\chi$:

$$n_{\chi,\rm f} \simeq \frac{H(T_{\rm f} = m_\chi)}{\langle \sigma_{\rm ann} v \rangle} \sim \frac{m_\chi^2}{M_{\rm pl} \langle \sigma_{\rm ann} v \rangle} \tag{7}$$

But we want χ abundance and mass density *today*
note that after freeze, χ conserved!
$\rightarrow n_\chi = n_{\chi,\rm f}(a_{\rm f}/a)^3 \propto T^3 \propto n_\gamma$
$\rightarrow Y_\chi \equiv n_\chi / n_\gamma$ DM/photon ratio *constant*, set at freeze:

$$Y_\chi = \frac{n_{\chi,\rm f}}{n_{\gamma,\rm f}} \sim \frac{m_\chi^2/M_{\rm pl} \langle \sigma_{\rm ann} v \rangle}{m_\chi^3} \sim \frac{1}{M_{\rm pl} m_\chi \langle \sigma_{\rm ann} v \rangle} \tag{8}$$

So present number and mass densities are

$$n_{\chi,0} = Y_\chi n_{\gamma_0} \tag{9}$$

$$\rho_{\chi,0} = m_\chi n_{\chi,0} \sim \frac{1}{M_{\rm pl} \langle \sigma_{\rm ann} v \rangle} \tag{10}$$

What have we shown?

if a symmetric stable species ever created

(annihilates but not decays)

then annihilations will freeze, and

inevitably have nonzero relic density today, namely

$$\rho_{\chi,0} = m_\chi n_{\chi,0} \sim \frac{1}{M_{\rm pl} \langle \sigma_{\rm ann} v \rangle} \tag{11}$$

This calculation is of the highest interest to particle physicists

Q: why?

We have calculated a relic density

Q: Notable aspects about what it does, doesn't depend on?

Q: To what should it be compared?

Cold Relics: Present Abundance

★ $\rho_{\psi,0}$ indep of m_ψ

★ $\rho_{\psi,0} \propto 1/\sigma$: the weak prevail!
Q: what sort of cross section is relevant here?

★ To get "interesting" present density:
$\Omega_\psi \sim 1 \rightarrow \rho_\psi \sim \rho_{\rm crit}$ *demands* a *specific* cross section

$$\sigma_{\rm ann} \sim \frac{n_{\gamma,0}}{\Omega_\psi M_{\rm p} \rho_{\rm crit}} \quad (12)$$

$$\sim 10^{-38}\ {\rm cm}^2 \quad (13)$$

scale of the Weak interaction! $[\sigma_{\rm weak}(E \sim {\rm GeV}) \sim 10^{-38}\ {\rm cm}^2]$

The WIMP Miracle

Dark Matter candidate:
if DM is a cold symmetric relic
needed *annihilation cross section* is at Weak scale!
corresponding energy: if $\sigma \sim \alpha/E^2$
then $\sigma \sim 10^{-36}\ \mathrm{cm}^2 = 10\ \mathrm{pb} \rightarrow E \sim 1\ \mathrm{TeV}$

deeper reason for DM as
Weakly Interacting Massive Particle: **WIMP**

that weak-scale annihilations $\rightarrow \Omega_\chi \sim \Omega_{\mathrm{nbdm}}$: **"WIMP Miracle"**

How to find them?
What if we do? What if we don't?

Director's Cut Extras

Freezeout and Relic Abundanceof a Symmetric Species

for *conserved* species ψ (chem. pot. $\mu_\psi \neq 0$)
constant comoving number: $d(na^3) = 0$

$\Rightarrow \dot{n}_\psi + 3\frac{\dot{a}}{a} n_\psi = 0$

for *non-conserved* species: $d(n_\psi a^3) = q a^3 \, dt \neq 0$, where
q = *source/sink* rate = creation/destruction rate per unit vol

$\Rightarrow \boxed{\dot{n}_\psi + 3\frac{\dot{a}}{a} n_\psi = q}$

assume annihilation $\psi\bar{\psi}\to X\bar{X}$ product X thermal,
with chem. pot. $\mu_X \ll T \;\Rightarrow\; n_X = n_{\bar{X}}$

$$
\begin{aligned}
q = q_{\rm net} &= q_{\rm prod} - q_{\rm ann} && (14)\\
&= \langle \sigma v \rangle_{\rm prod}\, n_X n_{\bar{X}} - \langle \sigma_{\rm ann} v \rangle_{\rm ann}\, n_\psi n_{\bar{\psi}} && (15)\\
&= \langle \sigma v \rangle_{\rm prod}\, n_X^2 - \langle \sigma v \rangle_{\rm ann}\, n_\psi^2 && (16)
\end{aligned}
$$

in equilib, *Q: what condition holds for q?*

chem equilib: $q = 0 \Rightarrow \boxed{q_{\text{prod}} = q_{\text{ann}}}$
so in general

$$\dot{n}_\psi + 3Hn_\psi = q = -\langle\sigma v\rangle_{\text{ann}}\left[n_\psi^2 - (n_\psi^{\text{eq}})^2\right] \tag{17}$$

and a similar expression for $\bar\psi$

Change variables:
(1) use comoving coords:
photon density $n_\gamma \propto T^3 \propto a^{-3}$,
so put $Y = n_\psi/n_\gamma$ to remove volume dilution
then $\dot{n_\psi} + 3\dot{a}/a\, n_\psi = n_\gamma \dot{Y}$
(2) put $x = m_\psi/T \propto a$
since $t \propto 1/T^2 \propto x^2$,
$dY/dt = dY/dx\ \dot{x} = H\ x\ dY/dx$

Then:

$$Hx\frac{dY}{dx} \;=\; -n_\gamma \langle\sigma v\rangle_{\text{ann}}\left(Y^2 - Y_{\text{eq}}^2\right) \tag{18}$$

(19)

finally

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_A}{H}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \tag{20}$$

where $\Gamma_A = n_\psi^{\rm eq} \langle \sigma v \rangle_{\rm ann}$: annihil. rate

So: change in comoving ψ controlled by
(1) annihil. effectiveness Γ/H
(2) deviation from equil

when $\Gamma/H \gg 1$
Q: what if $Y < Y_{\rm eq}$? $Y > Y_{\rm eq}$?

when $\Gamma/H < 1$
Q: how does Y change?

Q: how you you expect Y to evolve?

when $\Gamma/H \gg 1$, Y driven to $Y_{\rm eq}$
when $\Gamma/H < 1$, Y change is small $\rightarrow$ freezeout!

relic abundance at $T \rightarrow 0$ or $x \rightarrow \infty$ is
$Y_\infty \simeq Y_{\rm eq}(x_f)$: value at freezeout

Step back:
How can a symmetric species have
$n_\psi = n_{\bar{\psi}} \neq 0$ at $T \ll m$?

physically: expansion is key

if $H = 0$, $Y_\infty = Y_{\rm eq}(\infty) = 0$:

$\rightarrow$ all ψ find $\bar{\psi}$ partner, annihilate

but $H \neq 0$: when U dilute enough,

ψ never finds $\bar{\psi}$: i.e., $\Gamma \ll H$

nonzero relic abundance

hot relics: $x_f \ll 1$ ($T_f \gg m$)

cold relics: $x_f \gg 1$

Note: hot/cold *relics* refers to freezeout conditions

But: hot/cold *dark matter* refers to structure formation criteria

(namely, m vs temp $T_{\rm eq}$ at matter-rad equality)

Cold Relics: WIMPs

cold relic: non-relativistic at freezeout

so $x_f = m/T_f \gg 1 \to T_f \ll m$

$\Rightarrow n_{\rm eq} \sim e^{-m/T} (mT)^{3/2}$

$\Rightarrow Y_{\rm eq} \sim e^{-x} x^{3/2}$

Freezeout:

$\Gamma_{\rm ann} = H$ at $T = T_f$

$\Rightarrow n_{\rm eq} \langle \sigma v \rangle_{\rm ann} \sim \sqrt{G} T^2$

what needed to find value of T_f?

To solve:

- need annihilation cross section

  for many models, $\langle \sigma v \rangle \propto v^n$ (S-wave: $n = 0$)

  $\Rightarrow \langle \sigma_{\rm ann} v \rangle (x) = \sigma_1 c x^{n/2}$, where $\sigma_1 = \sigma(E = m)$
- convenient rewrite $1/\sqrt{G} = M_{\rm Pl} \simeq 10^{19}$ GeV

  (Planck Mass)

set $\Gamma_{\rm ann}(T_f) = H(T_f)$, and solve for T_f

Find: $x_f \sim \ln(m M_{\rm Pl} \sigma_1) \Rightarrow T_f = m/x_f$

So

$$Y_\infty \simeq Y_{\rm eq}(x_f) \quad (21)$$

$$\sim \frac{x_f^{3/2}}{m M_{\rm Pl} \sigma_1} \quad (22)$$

→ present relic number density

$$n_{\psi,0} = Y_\infty n_{\gamma,0} = 400\ Y_\infty\ \mathrm{cm}^{-3} \tag{23}$$

present relic mass density

$$\rho_{\psi,0} = m n_{\psi,0} \simeq \frac{x_f^{3/2} n_{\gamma,0}}{M_{\mathrm{Pl}} \sigma_1} \tag{24}$$

What have we shown?

if a symmetric stable species ever created

(annihilates but not decays)

then annihilations will freeze, and

inevitably have nonzero relic density today.

This calculation is of the highest interest to particle physicists

Q: why?

We have calculated a relic density

Q: To what should this be compared?

WIMP Searches: Accelerators

if WIMPs exist in nature
...and especially if they are supersymmetric particles
likely to be found in $\sim few$ yrs
at CERN Large Hadron Collider `www: CERN, LHC`
SUSY/WIMP discovery would revolutionize particle physics
and all but guarantee dark matter = cold relics

Q: what would the signature be at a collider?
What are challenges to digging it out?

Even if nature is not supersymmetric
many particle theories predict new physics at ~ 1 TeV

WIMP Searches: Direct Detection

if WIMPs are DM $\rightarrow$ dark halo full of them

local density $\rho = mn \sim 0.3$ GeV cm^{-3}

virial velocities $v_0^2 \sim GM_{\rm halo}/R_{\rm halo} \sim (400 \text{ km/s})^2$

$\Rightarrow$ WIMP flux $F_{\rm WIMP} = nv_0$

$\Rightarrow$ Look for tblue*WIMP-nucleus elastic scattering* – challenging!

Search using sensitive detectors: cryogenic, underground

interaction: *WIMP collision → nuclear recoil*

measure: effects of recoiling ($E_{\rm kin} \sim 1 - 100$keV) nucleus

Q: for example?

WIMP-nucleus recoil signatures

▷ *energy injection*: recoil heats detector
crystal specific heat $C = dE/dT \sim T^3$
$\Delta T = \Delta E/C \propto T^{-3}$
if supercold, can detect ΔT rise

▷ *momentum transfer*: detector lattice (phonons) excited

▷ *scintillation, ionization*: charged recoil nucleus excites medium
relax via γ, e, phonon emission $\rightarrow$ detect these

Hints at WIMPS?

several direct detection experiments see...*anomalies*

- DAMA ($\geq$ 1998): 250 kg NaI, Gran Sasso, Italy
  annual modulation seen ! very high significance

Q: why is $P = 1$ yr modulation interesting?

- CRESST (2011): $CaWO_4$ crystals, 730 kg days, Gran Sasso
  excess of events in signal region

- CoGENT (2011, 2013): 100 g Ge, Soudan, Minnesota
  annual modulation announced

- CDMS Si (2013): silicon, low-background, 124 kg days, Soudan
  excess of events in signal region

what if anomalies are dark matter?

`www:` `plots of` $\sigma_{\chi N \to \chi N}$ `vs` m_χ

- recoils are low-energy $\to$ suggest "light" dark matter
  $m_\chi \sim 10 m_{\text{nucleon}} \sim 10$ GeV: weak nuclear recoil

- curse: low-energy recoils more difficult to dig from noise

- note: not all anomalies are consistent with each other

But: *many other experiments see nothing*, especially

- LUX: 370 kg liquid Xe, Sanford Laboratory, South Dakota
- SuperCDMS: SNOLab, Canada

at face value, LUX rules out other signals
though alternatives remain (DM-nucleon spin dependence, DM bound states)

clearly: situation messy and confused!

that's still not all...
Q: astrophysical means infer WIMP existence and properties?

WIMP Searches: Indirect Detection

if WIMPs are DM $\rightarrow$ Galactic dark halo full of them
but Galactic halo density $\gg$ cosmic mean
$\rightarrow$ annihilation rate $q \propto \langle \sigma_{\text{ann}} v \rangle \, \rho^2_{\text{wimp}}$ can be large
$\rightarrow$ annihilation products potentially observable

Local annihilations

Q: how see if $\chi\bar{\chi} \rightarrow \gamma\gamma$ *only?*
Q: how see if $\chi\bar{\chi} \rightarrow$ *other Standard Model particles?*
e.g., $\chi\bar{\chi} \rightarrow e^+ e^-$ *or* $q\bar{q}$*?*

Galactic center annihilations

Q: how see if $\chi\bar{\chi} \rightarrow \gamma\gamma$ *only?*
Q: how see if $\chi\bar{\chi} \rightarrow$ *other Standard Model particles?*
e.g., $\chi\bar{\chi} \rightarrow e^+ e^-$ *or* $q\bar{q}$*?*

Indirect Detection: Local Annihilation Signatures

if $\chi\bar{\chi}\to\gamma\gamma$ only: line emission $E_\gamma \sim m_\chi$
$\Rightarrow$ local contribution to diffuse γ signature
but: two-photon annihilation $\chi\bar{\chi}\to\gamma\gamma$ must be *suppressed*
else χ has direct EM coupling $\to$ electric charge $\to$ DM not dark!
but *can and often do* have things like $\chi\bar{\chi}\to\pi' s\to\gamma' s$

if $\chi\bar{\chi}\to q\bar{q}$: hadronize, sometimes to nucleons $N\bar{N}$
source of $\bar{n}, \bar{p}$, and $\bar{d} = \boxed{\bar{n}\bar{p}}$
$\Rightarrow$ can look for these in *cosmic rays!*
but *"foreground"*: "normal" antimatter
from cosmic ray propagation
e.g., $p_{\rm cr} + p_{\rm ism}\to ppp\bar{p}$

if $\chi\bar{\chi}\to e^+e^-$: local source of *high-energy* e^+

Indirect Detection: Galactic Center Annihilation

Galactic center is $\rho_{\rm DM}$ peak $\rightarrow$ annihilation goldmine!?!

Direct Photon Production

⋆ $\chi\bar{\chi} \rightarrow \gamma\gamma$ line: $E_\gamma = m_\chi$, and

⋆ $\chi\bar{\chi} \rightarrow q\bar{q} \rightarrow \pi^0 \rightarrow \gamma\gamma$ continuum $E_\gamma < m_\chi$

Galactic center seen in TeV range

`www: HESS`

but point source too localized(?), energy spectrum a power-law

Galactic center in GeV range

`www: Fermi sky`

astrophysical foregrounds large:

- cosmic-ray interactions with ISM
- in Galactic plane $p_{\rm cr} + p_{\rm ism} \to \pi^0 \to \gamma\gamma$

Daylan+ (2014): strongest claims of non-astrophysical signal
centered on Galactic center, axisymmetric geometry
energy spectrum $\to \chi\chi \to b\bar{b}$, $m_\chi \sim 30$ GeV

Dark Matter: Where Do We stand?

Obviously, no clear detections thus far

Current status:
accelerator and astrophysical constraints are:
competitive: both place strong constraints
on particle models for WIMPS
complementary: different methods strong in different parts
of parameter space

Upgrades coming soon on all fronts
$\rightarrow$ the race is on!
$\rightarrow$ an answer will emerge in the non-distant future!

If confirmed WIMP detection:

- DM found
- need particle physics beyond Standard Model

★ payoff big! but why asymmetrical?
modified gravity?
hidden in braneworld?