Astro 596/496 NPA
Lecture 24
March 27, 2019

Announcements:

- **Problem Set 4 due Friday** Updated version posted!
  fixed numerical typo in eq (1)
  clarified Q 5(a) parameters and assumptions
- Office Hours after class today
- Physics Colloquium today, 4pm Loomis: Prof. Joaquin Vieira
  "Observing the History of the Universe with the South Pole Telescope"

Last time: began particle dark matter
Q: why do we need to invent new particles for dark matter?
we consider a symmetric relic ψ
created in pairs in early Universe: $n_\psi = n_{\bar{\psi}}$
can and does annihilate to Standard Model X: $\psi\bar{\psi} \to X\bar{X}$
Q: why are there any left at all?

Freezeout of Annihilations

we have already seen: *freezout* epoch (temperature $T_{\rm f}$) set by *reaction rate balance with expansion rate:*

$$\Gamma(T_{\rm f}) = H(T_{\rm f}) \tag{1}$$

annihilation rate per DM particle

$$\Gamma_{\rm ann} = n_\psi \langle \sigma_{\rm ann} v \rangle \tag{2}$$

▷ *before freezeout:* DM in equilibrium $n_\psi = n_{\psi,\rm eq}(T)$
▷ *after freezeout:* DM set by $n_{\psi,\rm eq}(T_{\rm f})$

freezout condition $H = n_{\psi,\rm eq}\langle \sigma_{\rm ann} v\rangle$
controlled by *annihilation cross section* via $\langle \sigma_{\rm ann} v\rangle$

consider DM non-relativistic at freezeout ("cold relic")
Q: what is $n_{\psi,\rm eq}(T)$*?*

Cold Relics: WIMPs

cold relic: non-relativistic at freezeout
so with no chemical potential (number not conserved)

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

Freezeout:
$\Gamma_{\mathrm{ann}} = H$ at $T = T_{\mathrm{f}}$
$\Rightarrow n_{\mathrm{eq}}\langle\sigma v\rangle_{\mathrm{ann}} \sim \sqrt{G}T^2$

Q: 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: $n=0$)

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

  Planck Mass

set $\Gamma_{\mathsf{ann}}(T_{\mathsf{f}}) = H(T_{\mathsf{f}})$, and solve for T_{f}

Find: $x_{\mathsf{f}} = m/T_{\mathsf{f}} \sim \ln(m M_{\mathsf{Pl}} \sigma_1) \Rightarrow T_{\mathsf{f}} = m/x_{\mathsf{f}}$

So at freezeout

$$n_{\mathsf{f}} \sim \frac{x_{\mathsf{f}}^{3/2}}{m M_{\mathsf{Pl}} \sigma_1} T_{\mathsf{f}}^3 \tag{4}$$

$\longrightarrow$ present relic number density

$$n_{\psi,0} = n_{\psi,\mathrm{f}} \left(\frac{a_\mathrm{f}}{a_0} \right)^3 = n_{\psi,\mathrm{f}} \left(\frac{T_0}{T_\mathrm{f}} \right)^3 \sim \frac{x_\mathrm{f}^{3/2}}{m M_\mathrm{Pl} \sigma_1} T_0^3 \qquad (5)$$

present relic mass density

$$\rho_{\psi,0} = m n_{\psi,0} \simeq \frac{x_\mathrm{f}^{3/2} n_{\gamma,0}}{M_\mathrm{Pl} \sigma_1} \qquad (6)$$

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?

Cold Relics: Present Abundance

⋆ $\rho_{\psi,0}$ indep of m_ψ

⋆ $\rho_{\psi,0} \propto 1/\sigma_1$: 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

$$\sigma_1 = \frac{x_{\rm f}^{3/2} n_{\gamma,0}}{\Omega_\psi M_{\rm p} \rho_{\rm crit}} \tag{7}$$

$$\sim 10^{-37}\ {\rm cm}^2 \left(\frac{x_{\rm f}}{10}\right)^{3/2} \tag{8}$$

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?

The Physics of WIMPs: Models

Many theories of particle physics beyon the Standard Model predict new physics at ~ 1 TeV

longtime favorite: **Supersymmetry**
(“SUSY”; see Director’s Cut Extras)
predicts partners for every known (Standard Model) particle with opposite statistics (boson $\leftrightarrow$ fermion)

SUSY starting to be challenged by non-detections at LHC
some other particle theories also predict TeV scale particles
some don’t

∞

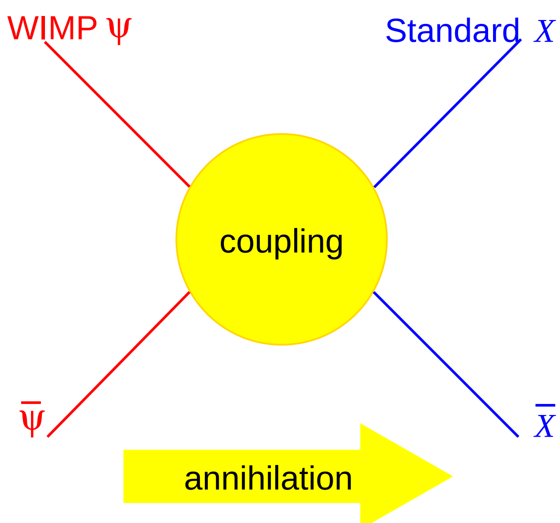
Q: what can we say for sure about WIMPs and their interactions?

The Physics of WIMPs: Model-Independent Properties

We do not know what WIMPs are (though models exist!)

but regardless, by definition they must annihilate
and produce Standard Model particles

this implies a WIMP-Standard Model **interaction**

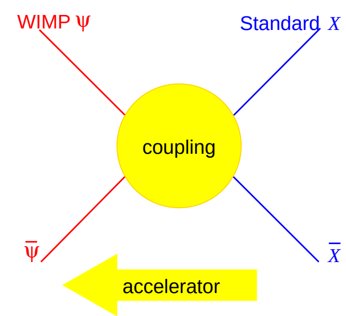


so: *some coupling exists between WIMPs and SM*

WIMP Searches: Accelerators

WIMP cross section implies $\sim$ TeV energy scale

if WIMPs exists in nature
can produce them with with accelerators
that attain this energy:
CERN Large Hadron Collider
`www: CERN, LHC`

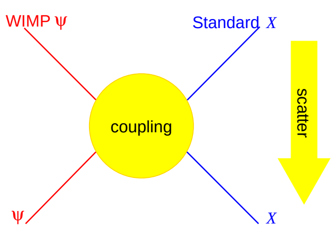


$$X\bar{X} \longrightarrow \psi\bar{\psi}$$

Note: dark matter particle could be missed at LHC and still exist
e.g., if mass too high for LHC energy
but: if dark matter is a WIMP, other ways to find out
Q: namely?

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 $v_0^2 \sim GM_{\text{halo}}/R_{\text{halo}} \sim (400 \text{ km/s})^2$
$\Rightarrow$ WIMP flux $F_{\text{WIMP}} = nv_0$
$\Rightarrow$ Look for *WIMP-nucleus elastic scattering* – challenging!



$\psi X \rightarrow \psi X$

Search using sensitive detectors: cryogenic, underground
interaction: *WIMP collision $\rightarrow$ nuclear recoil*
measure: effects of recoiling ($E_{\text{kin}} \sim 1 - 100$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

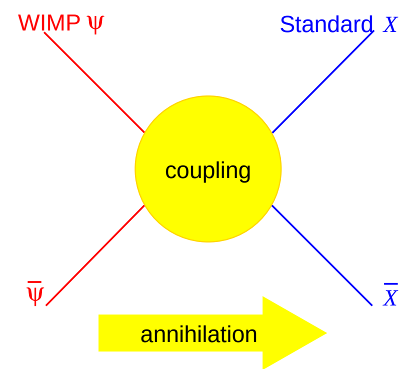
▷ *momentum transfer*: detector lattice (phonons) excited

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

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 $q \propto \langle \sigma v \rangle \rho^2_{\rm wimp}$ can be large
$\rightarrow$ annihilation products potentially observable

$$\psi\bar{\psi} \rightarrow X\bar{X}$$

Local annihilations

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

Galactic center annihilations

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

Indirect Detection: Local Annihilation Signatures

if $\psi\bar{\psi}\to\gamma\gamma$ *only*: line emission $E_\gamma \sim m_\psi$
$\Rightarrow$ local contribution to diffuse γ signature
but: two-photon annihilation $\psi\bar{\psi}\to\gamma\gamma$ must be *suppressed*
else ψ has direct EM coupling $\to$ electric charge $\to$ DM not dark!
but *can and often do* make **gamma-rays** via $\psi\bar{\psi}\to\pi\to\gamma$, e.g.

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

Hints of Dark Matter? Indirect Detection

One direct detection group
has claimed *detection* for ~ 14 years!
DAMA experiment, Gran Sasso Italy

they see strong signal with clear *annual modulation*
as expected due to Earth's motion around Sun
changing relative flux through WIMP cloud
`www: modulation plot`

But:
- no other groups see this signal
- includeing those with exactly the same detectors (NaI)

Hints of Dark Matter? Gamma Rays

Fermi-LAT data towards Galactic Center shows anomaly above expectations for conventional (cosmic-ray) processes!
`www: Galactic Center excess`

But:
- signal strength and spatial pattern model-dependent
- could be explained by additional conventional souces
  e.g., millisecond pulsars
- and no signal from dark-matter-dominated dwarf galaxies

Hints of Dark Matter? Cosmic Rays

PAMELA Payload for Anitmatter Exploration and Light-nuclei Astrophysics (2009)
satellite sees unexplained e^+ enrichment at $E \gtrsim 10$ GeV
`www: PAMELA positron fraction` $e^+/(e^+ + e^-)$

confirmed by **AMS02** experiment on Space Station

But:

- nearby pulsars can produce e^+ signal at observed level
- as can a nearby supernova ~ 2 Myr ago (!)

WIMP Search Summary: Dark Matter at the Crossroads

WIMPs are well-motivated non-baryonic dark matter candidates
- naturally arise in beyond the Standard Model particle theories
- viable parameter space still exists and needs to be explored
- some hints do exist in multiple experiments

But:
- no WIMP evidence in LHC or other accelerators
- existing hints are inconclusive, could have alternate explanations

This is leading to a re-thinking of particle dark matter
- broader class of models
- non-WIMP candidates
- drive new experiments of all types (direct, indirect, accelerator)

Stay tuned!

Director's Cut Extras

WIMP Candidates: Supersymmetry

No Standard Model particle is a WIMP
but Particle physics offers candidates

e.g., **Supersymmetry** (SUSY):
postulates new symmetry: fundamental fermion $\leftrightarrow$ boson link

- invented to explain conceptual puzzles of Standard Model
- other theoretical motivation and attraction (aside from DM!)

Basic SUSY hypothesis:

every particle has "super-partner" w/ opposite statistics

- e.g., $s = \frac{1}{2}$ electron $\rightarrow$ $s = 0$ scalar electron = *selectron* $\tilde{e}$
- $s = 1$ photon $\rightarrow$ fermionic $s = \frac{1}{2}$ *photino* $\tilde{\gamma}$
- *half* of all supersymmetric particles already discovered! ;>

bold idea, but perhaps like antimatter:
symmetry $\rightarrow$ doubling of particle inventory

The Nature of Superpartners

Superpartner fundamental interactions:

⋆ interactions *same* as ordinary (Standard Model) partner:
i.e., usual strong, EM, weak, gravity
and e.g., $\tilde{e}$ feels only EM, weak, gravity

⋆ couplings (charges) also *same* as SM partners
e.g., electric charge $Q_{\mathrm{EM}}(\tilde{e}) = -1$; $Q_{\mathrm{EM}}(\tilde{\nu}) = 0$

SUSY *fermionic* partners (e.g., photino) are "Majorana"
i.e., particle = antiparticle $\tilde{\chi} = \overline{\tilde{\chi}}$

lowest mass spartner stable (conserved quantum # "R-parity")
⇒ there is a *"lightest supersymmetric particle"* = **LSP**
identity depends on SUSY model details, but often LSP=$\tilde{\gamma}$

SUSY partner masses/annihilation: Weak scale $\sim few$ TeV

Q: implications for early universe?

Supersymmetric Cosmology

put SUSY in context of Early Universe:

at high T: normal and partner particles abundant
and in equal numbers

as T drops:

- normal (Standard Model) particles $\rightarrow n, p, e, \nu$ remain
- spartners: decay $\rightarrow$ LSP
  but no LSP $\rightarrow$ Standard Model particles (R conservation)
  can annihilate $\chi\tilde{\chi} \rightarrow$ SM, but annihilations freezeout at $\sim$ TeV

$\rightarrow$ remains today as dark matter!

Q: how to test this in the laboratory? which lab?