Astro 596/496 NPA
Lecture 22
Oct. 14, 2009

Announcements:

- Preflight 4 due noon Friday

Last time: the WIMP Miracle

Q: what's a WIMP? what's miraculous?

if a symmetric stable species ever created
(annihilates but not decays)
then annihilations will freeze, and
inevitably have nonzero relic density today.

to make $\Omega_{\text{WIMP}} = \Omega_{\text{NBDM}}$ today
needed *annihilation cross section* is at Weak scale!
corresponding energy: if $\sigma \sim \alpha/E^2$
then $\sigma \sim 10^{-36}\ \text{cm}^2 = 10\ \text{pb} \rightarrow E \sim 1\ \text{TeV}$

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 $s = \frac{1}{2}$ *photonio* $\tilde{\gamma}$
- *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")
$\Rightarrow$ 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?

WIMP Searches: Accelerators

if Supersymmetry exists in nature
spartners likely to be found in $\sim few$ yrs
at CERN Large Hadron Collider (or maybe even Fermilab)
`www: CERN, LHC`
`www: FNAL, CDF`
SUSY discovery would revolutionize particle physics
and all but guarantee dark matter = cold relics

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

Note: even if discover supersymmetry,
  maybe not directly see the LSP
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!

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 $\longrightarrow$ Galactic dark halo full of them
but Galactic halo density $\gg$ cosmic mean
$\longrightarrow$ annihilation rate $q \propto \langle \sigma v \rangle \rho^2_{\mathrm{wimp}}$ can be large
$\longrightarrow$ annihilation products potentially observable

Local annihilations

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

Galactic center annihilations

Q: how see if $\psi\bar{\psi} \rightarrow \gamma\gamma$ only?
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Indirect Detection: Local Annihilation Signatures

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

if $\psi\bar{\psi} \rightarrow q\bar{q}$: 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., $p_{\text{cr}} + p_{\text{ism}} \rightarrow ppp\bar{p}$

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

Positron Excess: Hints of Dark Matter?

Hot off the presses:
Cosmic-ray experiments sensitive to e^+ (and e^-)

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

ATIC Advanced Thin Ionizaton Calorimeter (2009)
balloon sees excess in total $e^+ + e^-$ flux at $E \gtrsim 100$ GeV
`www: ATIC electron flux`
ATIC + PAMELA $\rightarrow$ *excess of high-energy positrons!*
$\rightarrow$ can fit with dark matter models (but not minimal SUSY!)

But:

- nearby pulsars can produce e^+ signal at observed level
- *Fermi* gamma-ray observatory (2009) also sensitive to $e^+ + e^-$ and *does not* see ATIC excess