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 ↔ boson link
• invented to explain conceptual puzzles of Standard Model
• other theoretical motivation and attraction (aside from DM!)

Basic SUSY hypothesis:

<table>
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<tr>
<th>every particle has “super-partner” w/ opposite statistics</th>
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<td>• e.g., $s = \frac{1}{2}$ electron $\rightarrow$ $s = 0$ scalar electron = <em>selectron</em> $\tilde{e}$</td>
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<td>• $s = 1$ photon $\rightarrow$ fermionic $s = \frac{1}{2}$ <em>photonio</em> $\tilde{\gamma}$</td>
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• 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 \( Q_{\text{EM}}(\tilde{e}) = -1; Q_{\text{EM}}(\tilde{\nu}) = 0 \)

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?*
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 $\sim$ 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 $F_{\text{WIMP}} = n v_0$
$\Rightarrow$ Look for $\text{WIMP-nucleus elastic scattering}$ – challenging!

Search using sensitive detectors: cryogenic, underground
interaction: $\text{WIMP collision} \rightarrow \text{nuclear recoil}$
measure: effects of recoiling ($E_{\text{kin}} \sim 1 - 100\text{keV}$) nucleus
$Q: \text{for example}$?
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 \( \Delta T \) rise

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

- **scintillation, ionization**: charged recoil nucleus excites medium
  relax via \( \gamma, e \) 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 → Galactic dark halo full of them but Galactic halo density \( \gg \) cosmic mean → annihilation rate \( q \propto \langle \sigma v \rangle \rho_{\text{wimp}}^2 \) can be large → 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**
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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 $\gamma$ signature
but: two-photon annihilation $\psi \bar{\psi} \rightarrow \gamma \gamma$ must be suppressed
else $\chi$ 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 $\bar{d} = [\bar{n} \bar{p}]$
$
\Rightarrow$ can look for these in cosmic rays!
but “foreground”: “normal” antimatter
from cosmic ray propagation
e.g., $p_{cr} + p_{ism} \rightarrow ppp\bar{p}$

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 Ionization Calorimeter (2009)
balloon sees excess in total $e^+ + e^-$ flux at $E \gtrsim 100$ GeV
www: ATIC electron flux
ATIC + PAMELA → *excess of high-energy positrons!*
→ 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