PHY418 PARTICLE ASTROPHYSICS

Introduction: What is particle astrophysics?

What is particle astrophysics?

- Particle astrophysics is the use of particle physics techniques (experimental or theoretical) to address astrophysical questions.
- Topics included:
  - early-universe cosmology
    - inflation (and alternatives), baryogenesis, dark energy
  - ***cosmic rays***
  - ***γ-ray astronomy***
  - ***high-energy neutrino astronomy***
  - low-energy neutrino astronomy
  - dark matter (*see PHY326/426*)
- I will focus on high-energy particle astrophysics

These form a coherent field with a lot of common factors—"high-energy particle astrophysics"

PHY418 Syllabus

- Introduction
  - brief outline of those topics I am not going to cover in detail
- High-energy particle astrophysics: the observations
  - cosmic rays
  - radio emission
  - high-energy photon emission (X-rays and γ-rays)
  - neutrinos
- Acceleration mechanisms
  - Fermi second-order
  - diffusive shock acceleration
  - magnetic reconnection
- Sources
  - case studies of the principal source types

PHY418 Resources

- There isn’t an ideal course text—so I have basically written one
  - too long to photocopy for you but you can download the pdf from the website (or from the MOLE reading list)
  - **www.hep.shef.ac.uk/cartwright/phy418**
  - this also contains copies of slides
- The nearest thing to a “proper” course text is Malcolm Longair, *High Energy Astrophysics* 3rd edition, CUP
  - several copies in IC
  - different organisation and emphasis compared to course
  - rather more detail in the mathematics
  - it is in SI units—note that a lot of texts at this level are in cgs

PHY418 Assessment

- End-of-semester exam (85%)
  - One compulsory question (30 marks)
  - Any two from four optional questions (20 marks each)
  - *A practice exam will be provided since this is a new module*
- Also short class tests (15%)
  - designed to test your ability to apply the taught material to problems
  - similar to exam questions (but without bookwork)
  - 3 (two during *Observations*, and one after *Acceleration Mechanisms*)
  - open notes format

INTRODUCTION TO PARTICLE ASTROPHYSICS

Early-universe cosmology

Early-universe cosmology

- In the early universe, energies are extremely high
  - appropriate physics is *very* high-energy particle physics
    - GUTs, string theory??
  - consequences in early universe
    - inflation (breakdown of GUT?)
    - baryogenesis (matter-antimatter asymmetry)
  - consequences in later universe
    - dark energy (vacuum energy? scalar field?)
    - dark matter (lightest supersymmetric particle? axion?)
- Particle physics of early universe is very difficult to test
  - energies are much too high for feasible accelerators

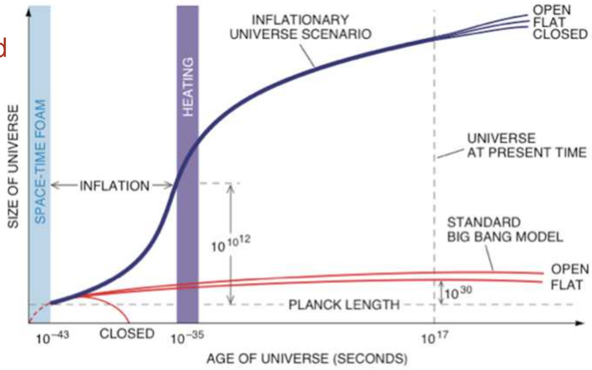
notes section 1.2.1

Inflation

- Observational evidence shows that the universe is
  - geometrically flat ($k = 0$ in Robertson-Walker metric)
  - extremely uniform at early times ($\Delta T/T \sim 10^{-5}$ in CMB)
  - not *precisely* uniform (with nearly scale invariant fluctuations)
- These properties are unexpected in the classical Big Bang model
  - no reason in GR why overall geometry should be flat
    - and if it is not flat originally it evolves rapidly in the direction of increased curvature
  - no expectation that the CMB temperature should be uniform
    - horizon distance expands faster than universe, so causally connected regions at ~400000 years correspond to only ~2° on sky now
  - if initial conditions force it to be uniform, no explanation for the fact that it is not *quite* uniform

Inflation

- Observational features can be accounted for by **inflation**
  - period of very fast (~exponential) expansion in very early universe
  - expansion $\dot{a} \propto e^{Ht}$ or $\dot{a} \propto a^{n}$, $n > 1$, will force geometry towards flatness and ensure that visible universe is causally connected
  - quantum fluctuations provide the anisotropies
    - with the right spectrum



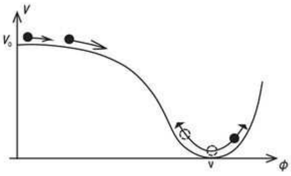
Inflation and the inflaton

- Exponential expansion requires equation of state $P = -\mathcal{E}$ (vacuum energy)
  - this can be approximated by a **scalar field** (the ***inflaton***) ϕ:

$$\mathcal{E}_{\phi} = \frac{1}{2\hbar c^{3}}\dot{\phi}^{2} + V(\phi);$$

$$P_{\phi} = \frac{1}{2\hbar c^{3}}\dot{\phi}^{2} - V(\phi);$$

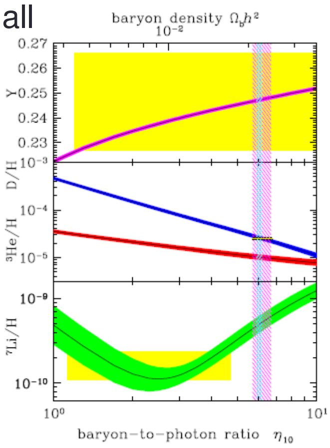
    - if the kinetic term is small this is *almost* a vacuum energy
  - this is very similar to the Higgs field (but expected mass of inflaton ≫ Higgs mass)
    - most extensions to Standard Model (e.g. supersymmetry) predict more Higgs fields
  - various models of inflationary cosmology exist
    - testable using CMB polarisation, cf. BICEP2



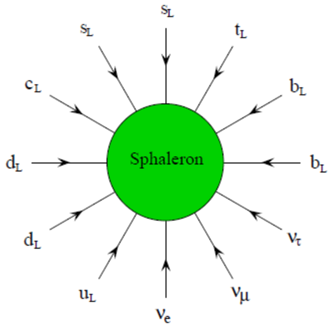
notes section 1.2.2

Baryogenesis

- The universe contains matter, but not antimatter
    - evidence: no annihilation signatures
- The amount of (baryonic) matter is small
    - ratio of baryons to photons ~6×10^{-10}
- At some point in the very early universe, non-zero baryon number must be generated
- Sakharov conditions:
    - B must be violated
    - reactions must take place out of thermodynamic equilibrium
    - C and CP must be violated



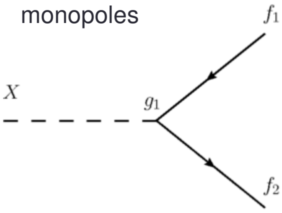
Baryogenesis

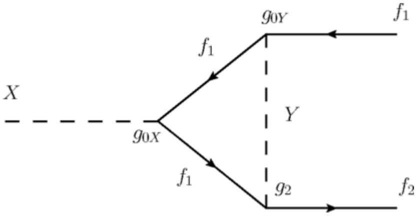


- *B* violation occurs in Standard Model
    - via transitions called ***sphalerons*** which conserve *B* – *L* but violate *B* and *L* separately (by 3 units)
    - these are quantum tunnelling transitions which are suppressed to non-existence in the present universe but would have occurred easily at sufficiently high energies
- Out-of-equilibrium conditions are natural
    - in a rapidly expanding and cooling early universe
- *C* and *CP* violation are observed in weak interactions
    - level of *CP* violation insufficient for observed asymmetry
    - *CP* violation may also occur in neutrino sector

Baryogenesis models

- *GUT baryogenesis*
  - takes place via heavy gauge bosons X and Y
    - problem—may allow production of heavy GUT relics such as magnetic monopoles

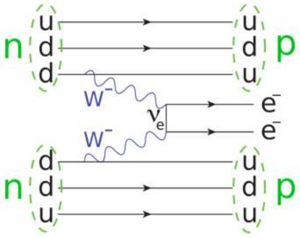




- *Electroweak baryogenesis*
  - takes place at electroweak phase transition (~100 GeV)
    - problem: requires first-order phase transition to satisfy out-of-equilibrium condition, and this requires a light Higgs (<75 GeV/c^2, cf. 126 GeV/c^2)

Leptogenesis models

- Generate non-zero *lepton* number, convert to *B* via sphaleron transitions
  - lepton number violation is testable at low energies via double β decay
    - occurs if neutrinos are *Majorana particles* (neutrino and antineutrino are the same particle with different "handedness")



  - expected in "seesaw models" which use massive right-handed neutrino to explain why (left-handed) neutrino mass so small compared to other fermions
  - possible link to axion dark matter
    - lightest of the "heavy" neutrino states could be linked to axion symmetry-breaking scale ***f*** (see later)

INTRODUCTION TO PARTICLE ASTROPHYSICS

Dark Energy and Dark Matter

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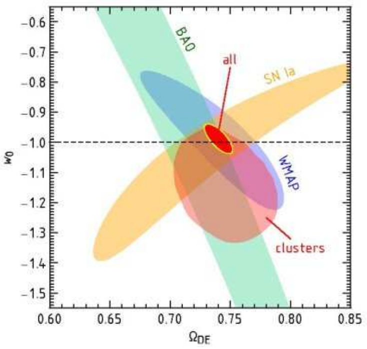
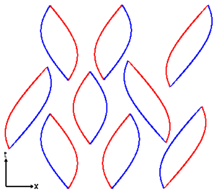
notes section 1.3

Dark energy

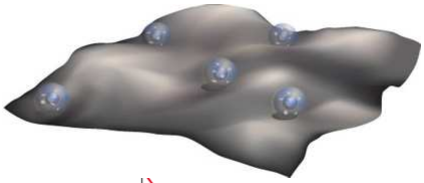


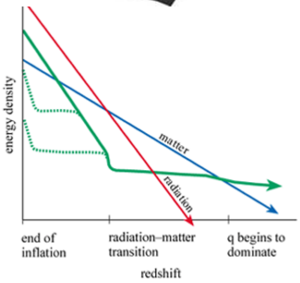
- There is a great deal of observational evidence from astrophysics and cosmology that the expansion of the universe is currently accelerating
  - requires a component with equation of state $P = w\mathcal{E}$ where $w < -1/3$ ($w = -1$ is a vacuum energy or cosmological constant, Λ)
- Vacuum energy is "natural" because of spontaneous pair creation (uncertainty principle)
  - but "natural" value of Λ is ~10^{120} times too large!



Models of dark energy

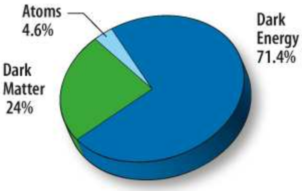
- Vacuum energy plus weak anthropic principle
  - if Λ had its “natural” value, we would not exist, therefore Λ must be “unnaturally” small
    - works best in multiverse models such as chaotic inflation (there are then many other universes with “natural” Λ and no life)
- Scalar field (as in inflation)
  - in this case the effective value of Λ will evolve over time
    - in some “tracker” models it is constrained to stay close to the density of radiation or matter
- Modified gravity
  - especially in models with extra dimensions



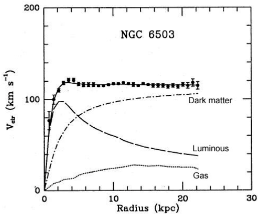


Dark matter

notes section 1.6



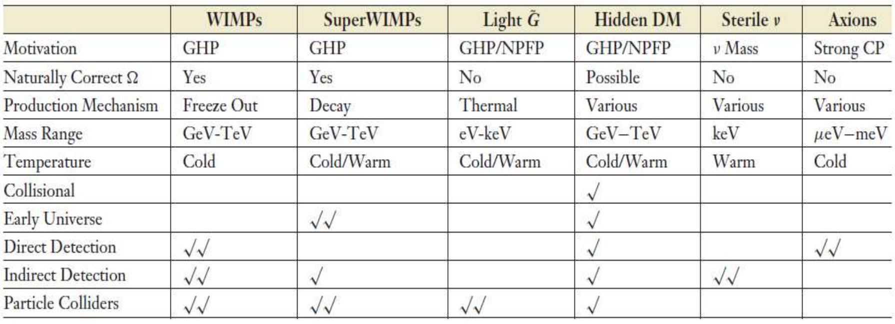
- Much observational evidence that most matter in the universe is (a) non-luminous and (b) non-baryonic
  - non-luminous:
    - rotation curves of galaxies
    - gravitational potential of galaxy clusters
    - weak lensing maps
  - non-baryonic
    - comparison of light-isotope abundances with gravitational mass
    - comparison of X-ray luminosity of clusters with gravitational potential
    - power spectrum of CMB anisotropies



Dark matter properties

- From observations, dark matter must
  - not absorb or emit light (and hence, not interact electromagnetically)
    - because it is not seen, in emission or absorption, at any wavelength, and from CMB power spectrum which implies it does not interact with photons
  - not be hadronic (i.e. strongly interacting)
    - from discrepancy between light-element abundances and gravitational mass measurements
  - be non-relativistic at $z \sim 3000$
    - so that it can be bound in galaxy-sized potential wells when structures form
  - be stable or very nearly so
    - because mass measurements in local universe agree with CMB
- No Standard Model particle satisfies this list
  - neutrinos are closest, but are relativistic at $z \sim 3000$ ("hot")

Dark matter candidates



	WIMPs	SuperWIMPs	Light $\tilde{G}$	Hidden DM	Sterile ν	Axions
Motivation	GHP	GHP	GHP/NPFP	GHP/NPFP	ν Mass	Strong CP
Naturally Correct Ω	Yes	Yes	No	Possible	No	No
Production Mechanism	Freeze Out	Decay	Thermal	Various	Various	Various
Mass Range	GeV-TeV	GeV-TeV	eV-keV	GeV–TeV	keV	μeV–meV
Temperature	Cold	Cold/Warm	Cold/Warm	Cold/Warm	Warm	Cold
Collisional				√		
Early Universe		√√		√		
Direct Detection	√√			√		√√
Indirect Detection	√√	√		√	√√	
Particle Colliders	√√	√√	√√	√		

GHP = Gauge Hierarchy Problem; NPFP = New Physics Flavour Problem
√ = possible signal; √√ = expected signal

Jonathan Feng, *ARAA* **48** (2010) 495 (highly recommended)

WIMPs

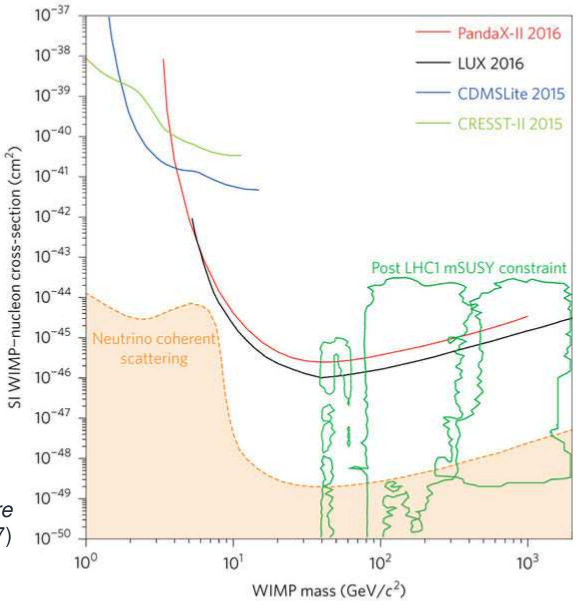
- Weakly Interacting Massive Particles
  - predicted by various extensions of the Standard Model, the most popular and widely studied being **supersymmetry** (SUSY)
  - in most variants of SUSY the lightest supersymmetric particle is absolutely stable
    - it is a “neutralino”, $\tilde{\chi}_1^0$ (a mix of the SUSY partners of the h, H, γ and Z)
- These can be detected by identifying the recoil of an atomic nucleus struck by the WIMP
  - SUSY neutralinos can also be detected indirectly by identifying their annihilation products from regions of high WIMP density, e.g. the centre of the Sun
  - it is also possible that WIMPs could be produced at the LHC and identified as missing energy/momentum (they would not interact in the detectors)

WIMP limits

There are some claimed signals at low WIMP masses (not shown), but they are inconsistent with each other and with limits from other experiments.

Their interpretation is still unclear.

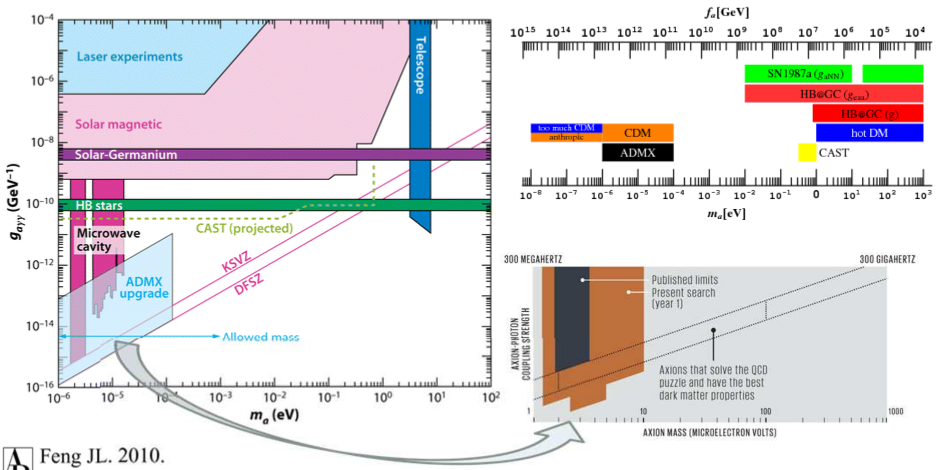
Liu, Chen and Ji, *Nature Physics* **13**, 212–216 (2017)



Axions

- The axion is a hypothetical particle arising from attempts to understand why the strong interaction conserves *CP*
  - in the Standard Model there is no reason why it should do so
- Axions are expected to be extremely light (μeV−meV), but are “cold” because they are not produced thermally
  - they arise from a phase transition in the *very* early universe
- Unlike WIMPs, axions do couple—*extremely* weakly—to photons and can be detected by the Primakoff effect
  - resonant conversion of axion to photon in highly tuned magnetic field
  - this coupling is the basis of the ADMX experiment (ask Ed Daw…)

Axion limits



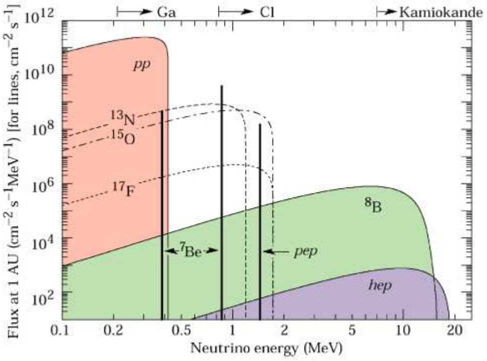
Feng JL. 2010.
Annu. Rev. Astron. Astrophys. 48:495–545

INTRODUCTION TO PARTICLE ASTROPHYSICS

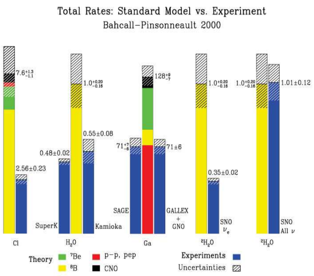
Low energy neutrino astrophysics

Solar neutrinos

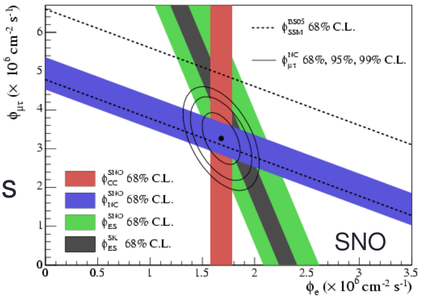
- Hydrogen fusion *must* involve neutrino emission:
  $4\ {}^1H \rightarrow {}^4He + 2e^+ + 2\nu_e$
  - two protons get converted to two neutrons—must emit $2e^+$ to conserve charge, then require $2\nu_e$ for lepton number
  - must be electron neutrinos as insufficient energy to produce μ^+ or τ^+
- Many routes to the final result
  - Q-values, and hence neutrino energies, vary



Solar neutrinos

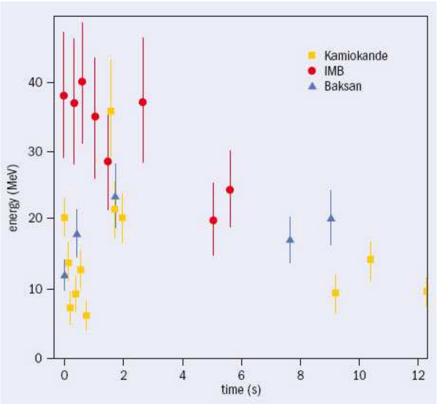


- Detection techniques
  - inverse β decay, e.g. ^{37}Cl + ν_e → ^{37}Ar + e⁻
    - low energy threshold, especially on ^{71}Ga, but no directional or energy information
  - electron elastic scattering, ν + e⁻ → ν + e⁻
    - sensitive to all neutrino types, but mostly ν_e
  - capture on deuterium
    CC: ν_e + d → p + p + e⁻
    NC: ν + d → p + n + ν
    - sensitive to all neutrino types
- Deuterium measurement established that solar neutrinos change flavour before detection (*neutrino oscillation*)



Supernova neutrinos

- 99% of the energy of a core-collapse supernova comes out as neutrinos
  - neutronisation pulse, p + e⁻ → n + ν_e
  - thermal pair production
- Verified when neutrinos detected from SN 1987A
  - only 24, but enough to confirm energy scale
- Potential for a great deal of interesting physics in the event of a Galactic CCSN
  - thousands of neutrinos would be detected



Summary

You should read sections 1.2, 1.3, 1.5.2, 1.5.3 and 1.6 of the notes

You should know about

- *inflation*
- *baryogenesis*
- *dark energy*
- *dark matter*
- *solar neutrinos*
- *supernova neutrinos*

- Particle astrophysics covers a very wide range of topics
  - early-universe cosmology
  - dark energy
  - dark matter
  - low-energy neutrino astrophysics
  - high-energy astrophysics
    - cosmic rays
    - radio emission from high-energy particles
    - high-energy photons
    - high-energy neutrinos
- This section has summarised the first four of these
  - rest of course will focus on last topic

Next: cosmic rays

- history
- detection techniques
- observed properties

Notes section 2.2