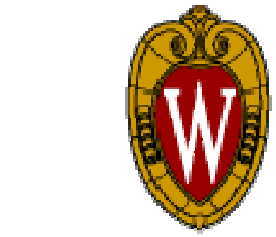
A Perspective on the Future of Dark Matter Cosmology

Daniel J. H. Chung



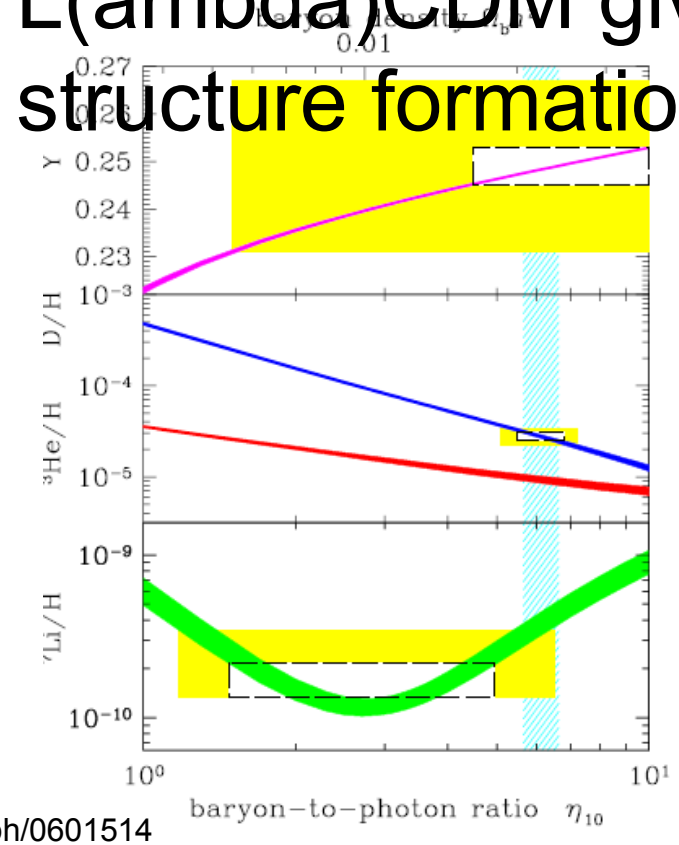
Outline of Presentation

- DM properties consistent w/ cosmological observations
- Utility of discovering non-gravitational properties of DM
- Future directions in DM cosmology

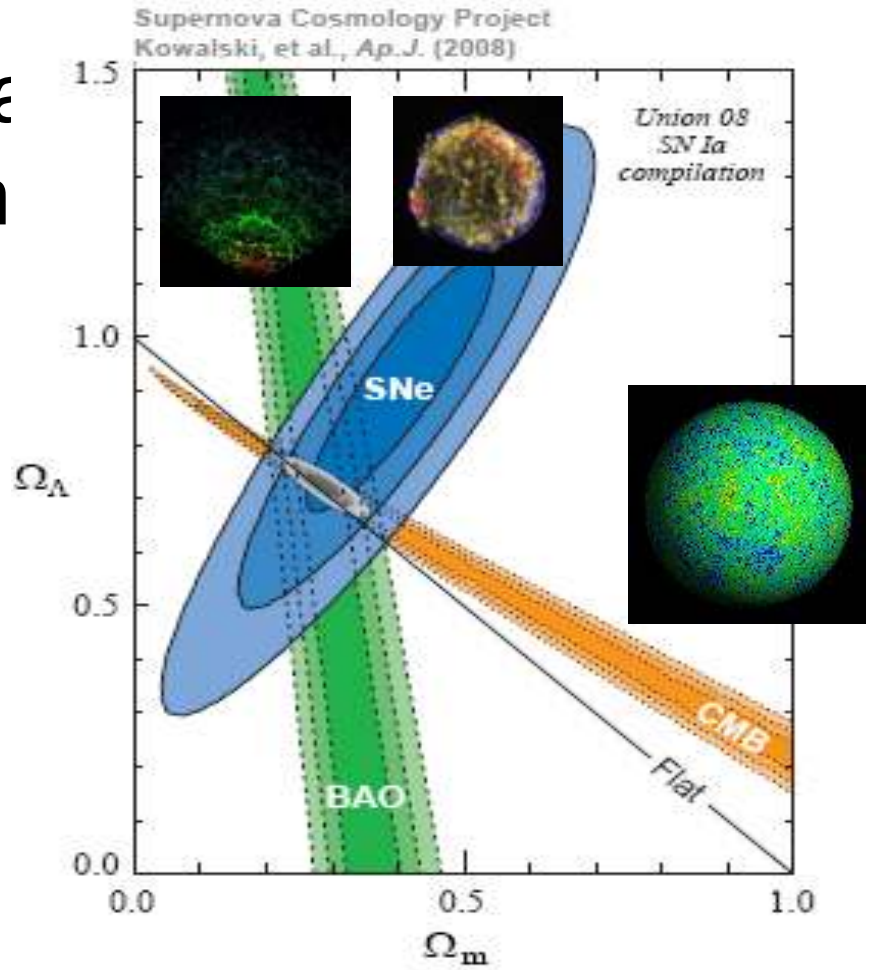
Emerging Picture in Cosmology Relevant for DM

- BBN + Lensing by dim obj → DM is not ordinary baryons
- L(ambda)CDM gives a structure formation on

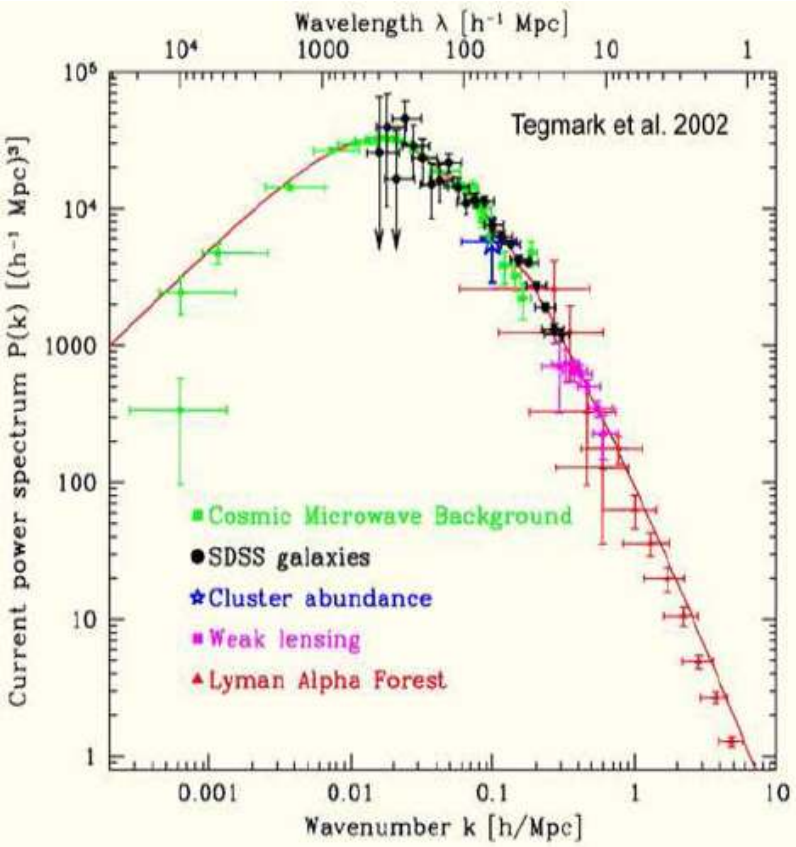
D → He → Li



astro-ph/0601514



Assumed Key Properties of CDM in LCDM



"very successful"

BC dependent property:

- $P(t_{\rm eq}) \approx 0$ ☆(e.g. cold; attractor)
- Primordial density fluctuation on superhorizon described by a nearly Gaussian and scale invariant probability functional ☆
- superhorizon: $\frac{\delta n_\gamma}{n_\gamma} \approx \frac{\delta n_X}{n_X} \approx \frac{\delta n_b}{n_b}$
- $\frac{\rho}{\rho_c}|_{t_0} \approx \Omega_b + \Omega_X + \Omega_\Lambda$ comparable ☆

BC independent property:

- Nearly stable (symmetry) ☆
- Minimally coupled to gravity
- Non-gravitational interaction negligible during structure formation (e.g. dark)

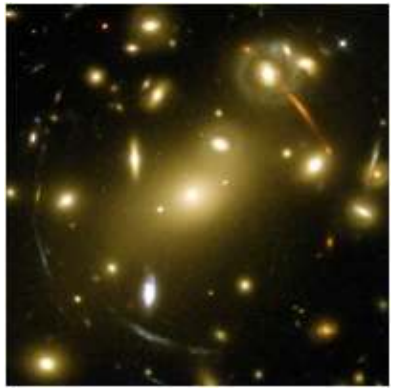
Key physics in linear regime:

$$\frac{\delta\rho_X}{\rho_X} \propto ag\left(a, \frac{\Omega_\Lambda}{\Omega_b + \Omega_X}\right)$$

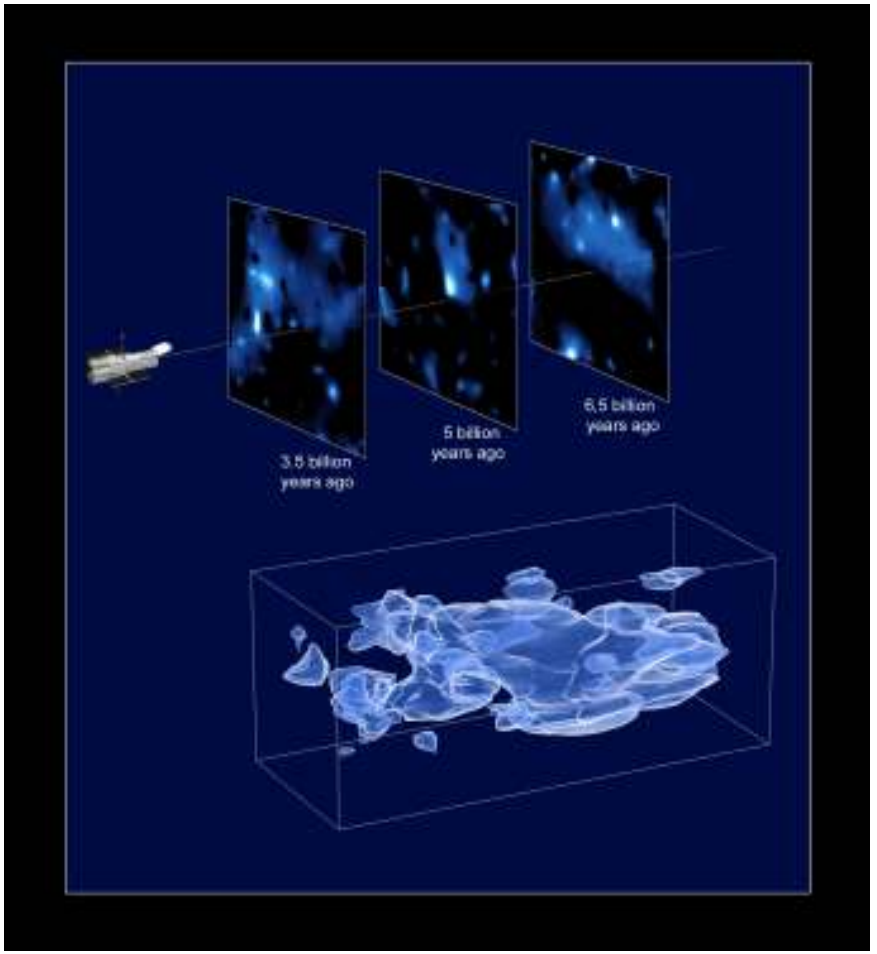
Lensing Probes Cosmological Scale DM Through Gravity

HST
Cosmic Evolution Survey (07):

1E 0657-56 (04)
Lensing Map: NASA/STScI;



Abell 2218 (98)
W. Couch, R. Ellis



NASA, ESA and R. Massey

Emerging picture is approximately self-consistent

Want More than Mostly Gravitational Evidence

[Beyond nongravitational evidence: BBN → DM not ordinary baryons]

Why?

- Connect with fundamental laws of nature
- Predictions for particle astrophysics
- New landmark in cosmology

e.g. BBN: lab probe of nuclear reactions meet cosmology

outcome: 1) ordinary baryons cannot be DM

2) energy density at T=10 MeV "known"
in terms of lab measured particles

e.g. sterile neutrino: $\Delta N_\nu < 2$

lepton asymm: $(n_{\nu_e} - n_{\bar{\nu}_e})/s < 2.5 \times 10^{-3}$

How to Go Beyond Gravitational Evidence

What will it take to convince us we "detected" standard WIMP cosmological dark matter?

A (subjectively) weighted combination of the following:

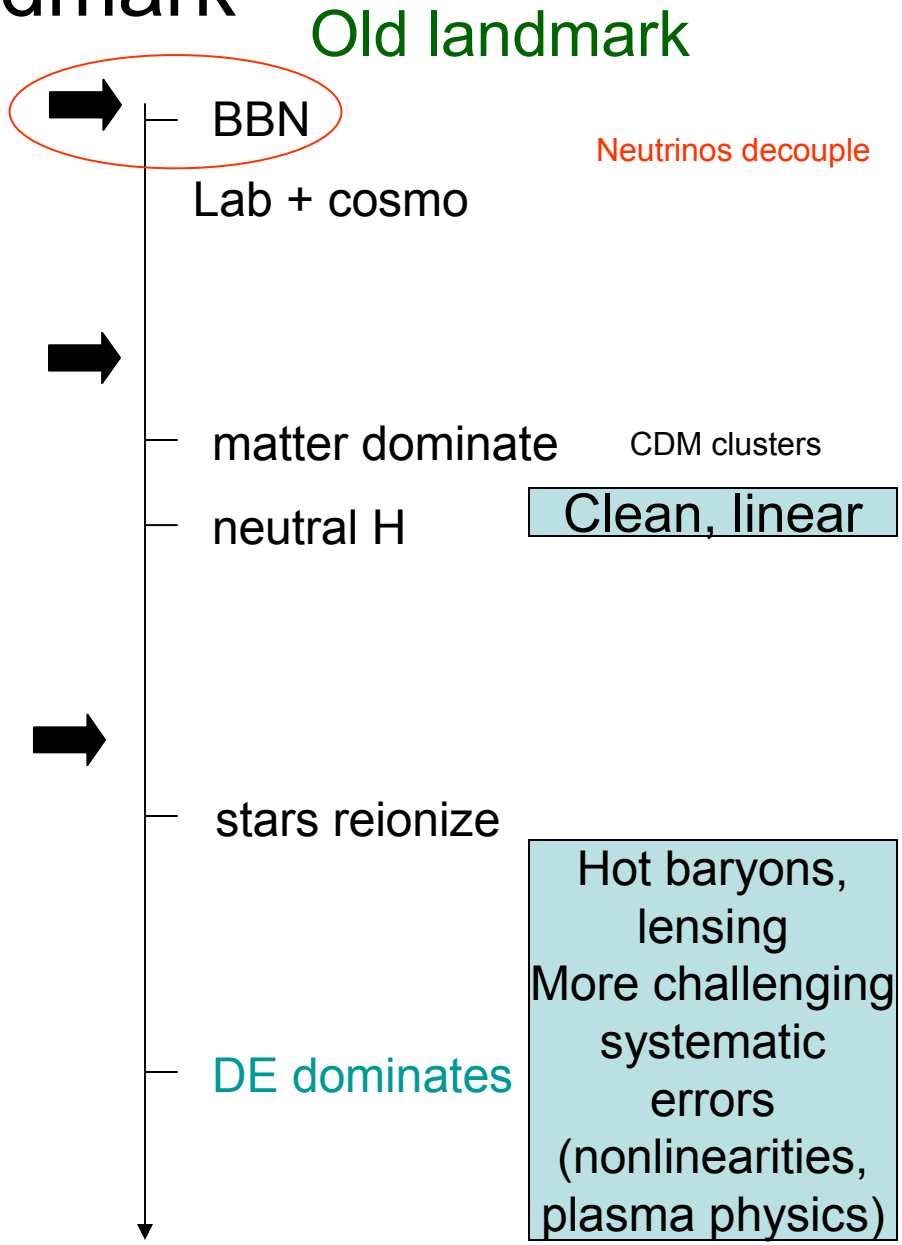
- Collider "discovery" of candidate(s): mass, spin, interaction couplings
  e.g. neutralino and attendant couplings in collider energy range
- Direct and indirect detection → candidate is astrophysical
  e.g. R-parity approx conserved, low energy extrapolation consistent
- Cosmologically consistent: structure formation agrees
  e.g. globally consistent thermal relic abundance,
  simulated halo properties, N-point functions

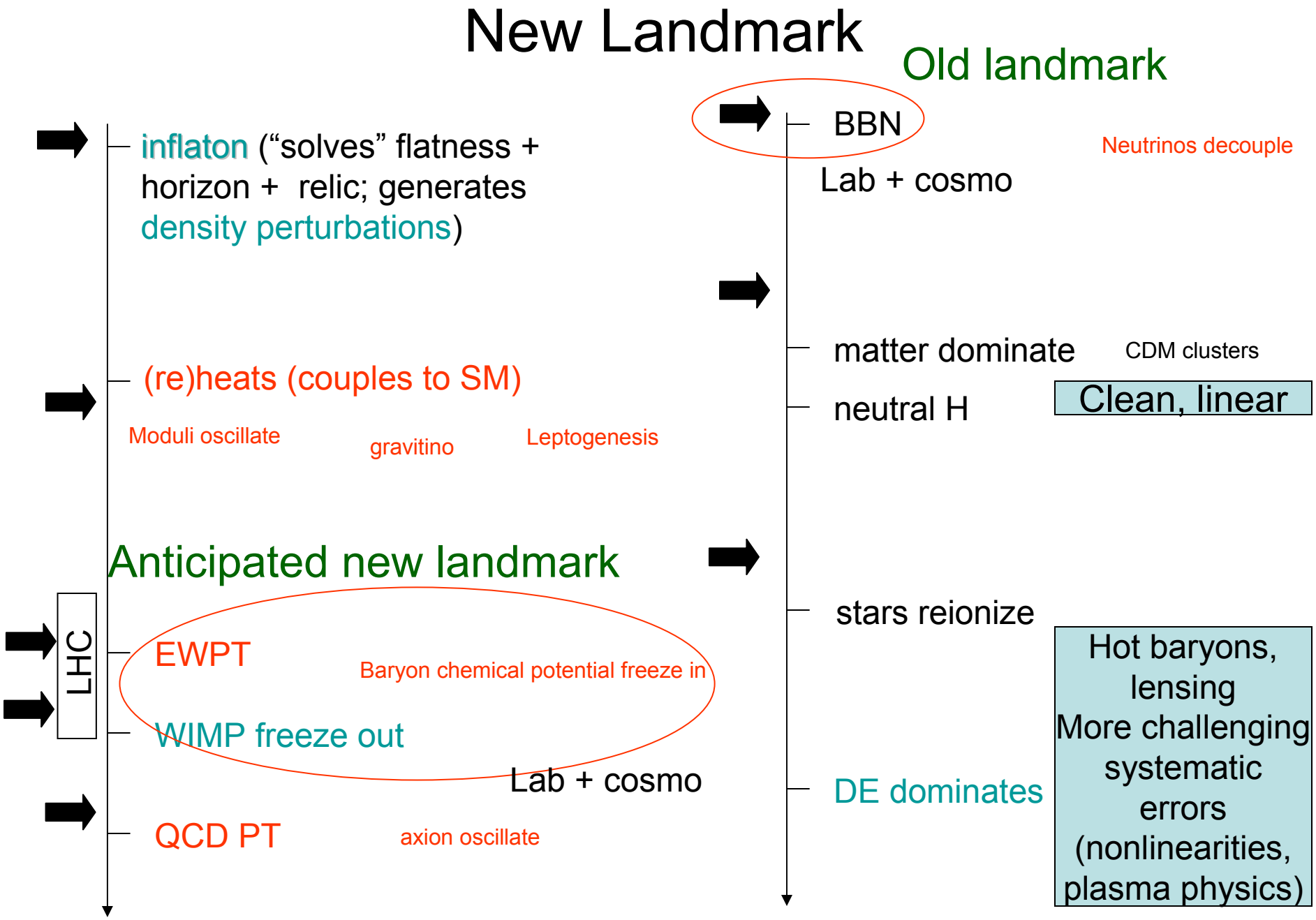
workshop

Opportune time (2010-2020):

new energy + new precision + obs. cosmology frontier

Old Landmark




New Landmark
Old landmark
inflaton ("solves" flatness + horizon + relic; generates density perturbations)
BBN
Neutrinos decouple
Lab + cosmo
matter dominate
CDM clusters
(re)heats (couples to SM)
neutral H
Clean, linear
Moduli oscillate
gravitino
Leptogenesis
Anticipated new landmark
LHC
stars reionize
EWPT
Baryon chemical potential freeze in
Hot baryons, lensing
More challenging systematic errors (nonlinearities, plasma physics)
WIMP freeze out
Lab + cosmo
DE dominates
QCD PT
axion oscillate

New Landmark → DM as a probe of exotics

Non-gravitational properties can probe surprises in cosmology:

Suppose exotics exist: $H_F^2 \propto \rho_{\text{lab measurable}} + \rho_{\text{exotic}}$

e.g. $\Omega_\chi h^2 \propto \left(\frac{T_{\text{today}}}{m_\chi x_F}\right)^3 \left(\frac{m_\chi H_F}{\langle \sigma_A v \rangle}\right)$

Sensitivity similar to BBN

lab

One parameter dependent axion-like exotic field

DE
$w'(a) \neq 0$

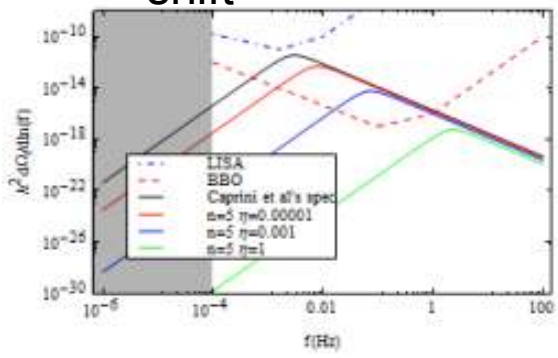
DM
fix discrepancy

LHC

need direct det.

Inflation
no B-mode

GW
peak and amplitude shift



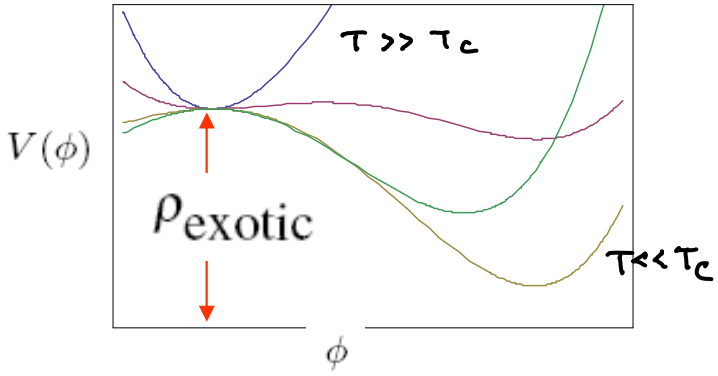
[1003.2462]

EW Bgenesis
out of equilib

Pamela/
HEAT excess
boost factor
[0704.3285]

LHC

Even CC Can Be Probed



Freeze out change:

$$\frac{\Delta n_X(t_0)}{n_X^{(U)}(t_0)} = 1 + \left[\frac{1}{2}\left(\delta + \frac{(1+3\delta)}{n-3}\left(1 - \frac{\Delta\rho_{\text{exotic}}}{\rho_{\text{exotic}}}\right)\right) - \frac{3}{2}\frac{1}{\ln A}\right]\varepsilon_1 + \frac{2}{3}\frac{a_f}{a_{PT}}\varepsilon_2 + \frac{1}{6}\frac{m_N}{T_f}\varepsilon_3 + \frac{a_f}{a_{PT}}\varepsilon_4 - \varepsilon_5$$

$$\varepsilon_1 \equiv \frac{30}{\pi^2}\frac{\rho_{\text{exotic}}}{g_E(T_f)T_f^4} = \text{fractional energy of the exotic during freeze out}$$

DM can be used to test the tuning of the cosmological constant!
[in progress w/ Long, Tulin, Wang]

Promising Theoretical Cosmology Efforts for DM in the Near Future

- Non-gravitational Property Efforts (NG)

  Relevant for establishing new cosmological rigidity

- Gravitational Property Efforts (G)

  Where most of the new cosmological data will be

Cold or Warm?

[G,NG]

- Hints of LCDM not matching observations (also 0908.3897)

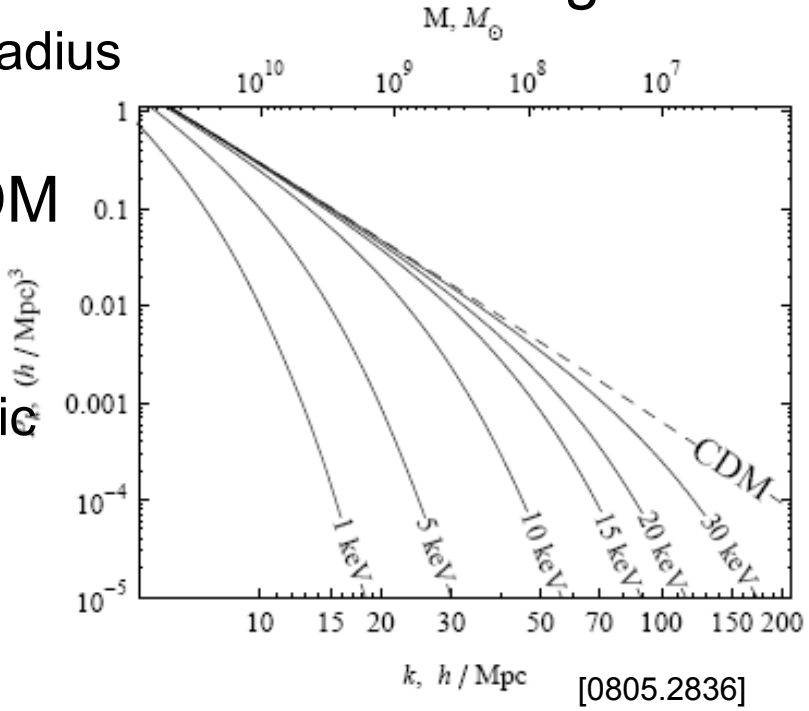
e.g. simulations on small scales give too much clustering:

  - cuspy halo density as a function of radius
  - overabundance of satellite galaxies

- Old, well known solution: warm DM
  - Typically non-thermal DM scenario
  - Gravitino: well-motivated candidate
  - Similar to thermal case if thermal relic decays just after freeze out

  Implication → light (e.g. keVish) DM

- As data improves,discriminate
  - Some recent efforts:
    - dSph galaxies: 0805.2836
    - LSB galaxies: 0912.3518
    - Late decaying DM producing gamma: 1004.1008



[0805.2836]

May rule out cold axions as DM?!
Rigorous techniques still lacking

DM phase space distribution

[G,NG]

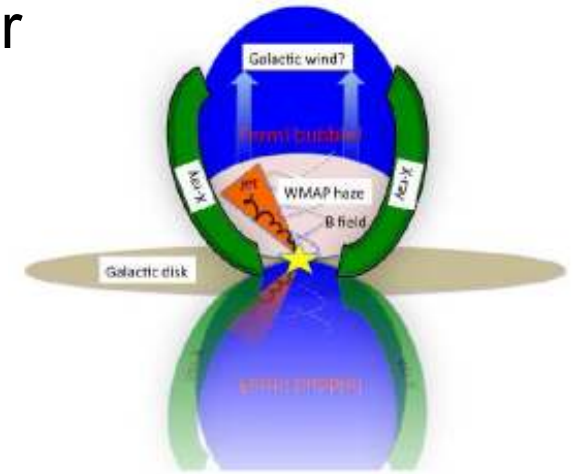
- Direct detection requires understanding the phase space distribution of DM in our galaxy and solar system

  0804.2896, 0812.1048, 0907.0018, 0910.4272

- Indirect detection requires understanding the phase space distribution of DM in the source

- Probes of our galaxy using tools such as Fermi-LAT reveal surprises that will help us better estimate the phase space history

- Progress requires advancements in both observations and modeling sources, densities, propagation, …



1005.5480

Planck (analysis release 2012)

[G]

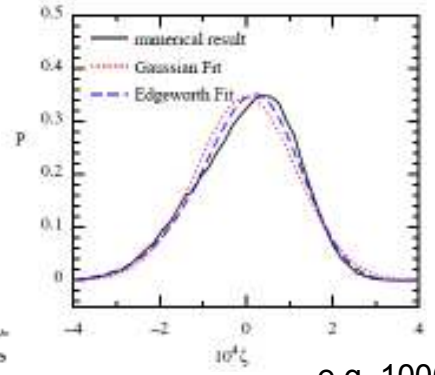
- Possible detection of non-Gaussianity

  2 sigma hint from WMAP3 0712.1148 0803.0547

  hint from structure formation 0806.1046

  Can rule out all single field slow roll

$$\langle \zeta^n \rangle = \int \zeta^n P(\zeta) d\zeta$$



e.g. 1006.4615

- Implications for DM: scale dependent bias (DM trace B); clustered object distribution changes (e.g. more voids), etc.

  [0710.4560; 0809.0506; 0909.3224; 1006.1950]

- About a factor of 3 improvement in $\frac{P_T}{P_R}$ down to 0.1.

If tensors, 1) $1 - n_T = \frac{1}{8}\frac{P_T}{P_R}$

2) Evidence for quantized massless spin 2.

3) Improve constraints/discovery of isocurvature.

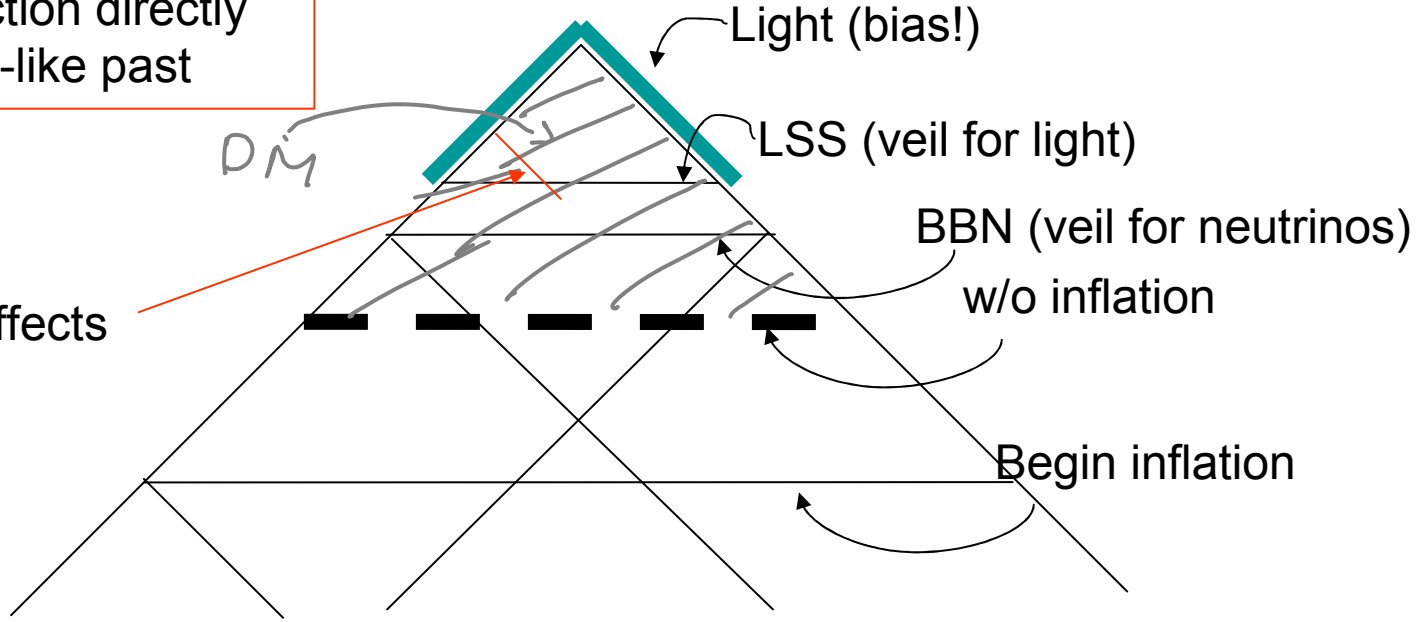
4) Rules out appreciable quintessence kinetic energy during WIMP freeze out 0704.3285

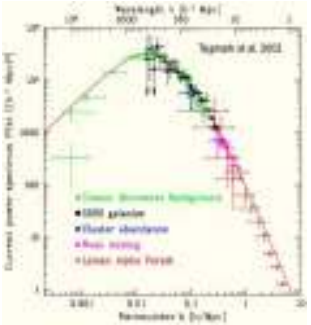
can be DM

Parts of Past Causal Domain Directly Observed

[G]

DM direct detection directly probes the time-like past





Full equivalence class consistent with observations?

e.g. 1007.0204, 0909.4954, 0712.0370

e.g. Nonperturbatively different from FRW universe?

Gravity Waves (and other techniques)?

[G]

- Advanced LIGO (2014) will measure gravity waves:

  Gravity wave astronomy will begin

- LISA hopefully will then follow

- Implications for DM has not been explored much

  (e.g. Lensing?, new standard candles for geometry measurement affecting DM dependent fits?, …)

  astro-ph/0701629

- Other astronomy techniques such as 3D tomography of hydrogen in the universe planned (21 cm measurement).

A Rich DM Sector?

[NG]

- SM sector has a rich set of quasi-stable particles

- DM sector may as well

  example: hidden sectors motivated in SUSY models

- May include long range forces

astro-ph/0412586, astro-ph/0506663, 0810.5126, 0901.1611

Aside: Light field hard to disentangle from modified gravity

EWPT Effects on DM

[G,NG] [0808.3994, 0909.1317]

inflaton ("solves" flatness + horizon + relic; generates density perturbations)

(re)heats (couples to SM)

Moduli oscillate gravitino Leptogenesis

Anticipated new landmark

LHC

EWPT Baryon chemical potential freeze in

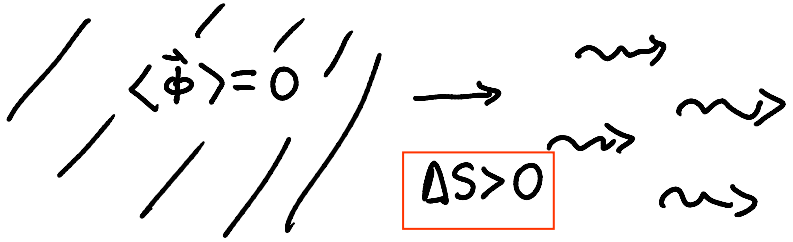
WIMP freeze out

Lab + cosmo

QCD PT axion oscillate

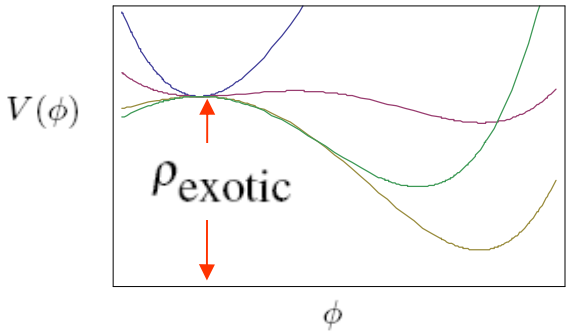
- PT affects masses, cross sections, and entropy

$$m_0^2 \to m_0^2 + c|\langle\vec{\phi}\rangle|^2 + \ldots$$



- DM as a probe of PT

$$\Omega_\chi h^2 \propto \left(\frac{T_{\rm today}}{m_\chi x_F}\right)^3 \left(\frac{m_\chi H_F}{\langle\sigma_A v\rangle}\right)$$



The Hope

- LHC shows early signs of DM candidate
- Interaction strength consistent w/ thermal relic
- Consistent DM candidate seen in direct detection experiments

- With some hints, may be much easier to discern the nature of DM.

Conclusions

- LCDM has a small set of firm ingredients thus far, just about gravitational nature
- Non-gravitational nature of DM is important to establish a rigid new landmark in cosmology
- Future directions:
  - Cold or warm?
  - Phase space distribution for direct and indirect measurements.
  - Planck: non-Gaussianities, isocurvature, tensor perturbations
  - Nonperturbatively different from FRW universe?
  - How to use gravity wave astronomy for DM?
  - DM sector as complicated as the observable chemistry sector; modified gravity
  - Interplay of electroweak phase transition and DM
  - Of course, need not mention a healthy dose of ambulance chasing
- Signs from LHC will help a great deal for narrowing in on DM properties