Title: Wandering in the Dark

Date: Sep 22, 2011 10:20 AM

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Abstract: TBA

Wandering in the Dark

Kris Sigurdson
University of British Columbia

Unravelling Dark Matter
September 22, 2011

There are at least 2 kinds of Dark Matter

Kris Sigurdson

University of British Columbia

Unravelling Dark Matter

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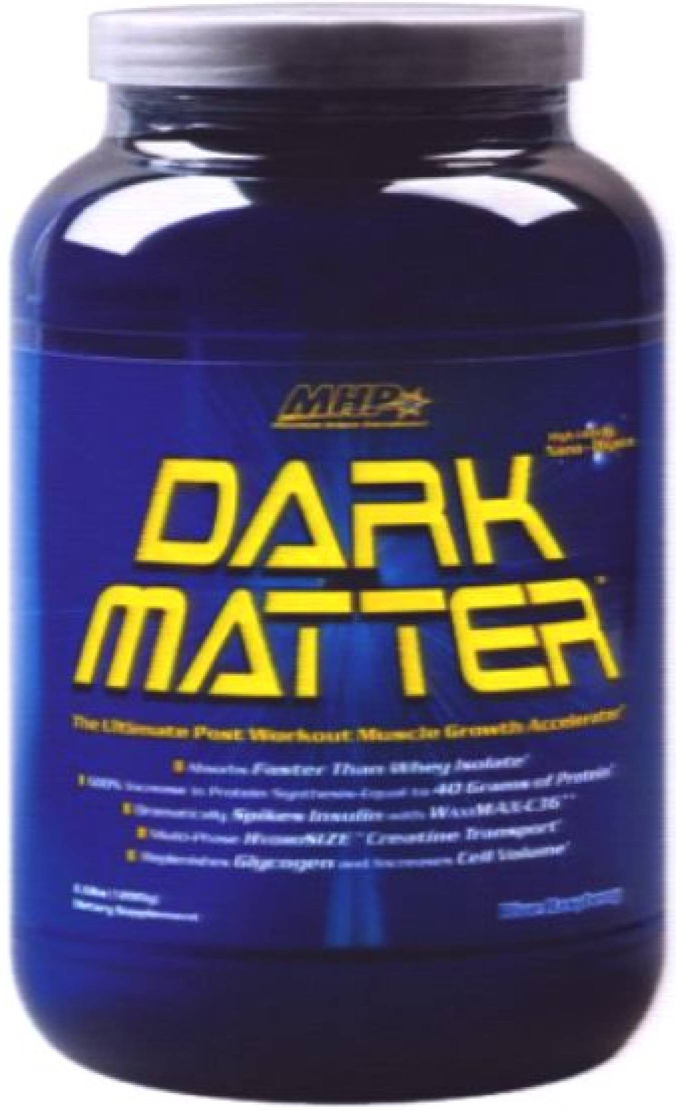

MHP
DARK
MATTER


BREWMASTER'S RESERVE
DARK
MATTER

Plan

- My Dark Philosophy
- Upcoming/Recent Dark Matter Projects

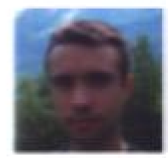
Dark Matter Projects

- Dark Atom Cosmology (with Francis Cyr-Racine)

Graduating Soon!

- Hidden CDM / WDM/ HDM (with Subinoy Das)

- Hylogenesis (with Hooman Davoudaisl, Sean Tulin, and David Morrissey)
  Induced Nucleon Decay



- Particle DM and Strong Lensing (with Lexi Moustakas & OMEGA crew)

- DM Perturbations Before Reheating (with Adrienne Erickcek)

- More, but talk to me later...

The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

—*Feb. 12, 2002, **Department of Defense** news briefing*

by Donald Rumsfeld

آنکس که بداند و بداند که بداند

اسب خرد از گنبد گردون بجهاند

آنکس که بداند و نداند که بداند

بیدار کنیدش که بسی خفته نماند

آنکس که نداند و بداند که نداند

لنگان خرک خویش به منزل برساند

آنکس که نداند و نداند که نداند

در جهل مرکب ابدالدهر بماند

-Ibn Yamin Faryumadi
1286 – 1368
Persian-Tajik Poet

One who knows and knows that he knows...
This is a man of knowledge; get to know him!

One who knows, but doesn't know that he knows...
This is a man who's unaware, so bring it to his attention.

One who doesn't know, but knows that he doesn't know...
This is an illiterate man; teach him!

One who doesn't know and doesn't know that he doesn't know...
This is an ignorant man; and will be ignorant forever!

آنکس که بداند و بداند که بداند
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-Ibn Yamin Faryumadi
1286 – 1368
Persian-Tajik Poet

One who knows and knows that he knows...
His horse of wisdom will reach the skies.

One who knows, but doesn't know that he knows...
This is a man who's unaware, so bring it to his attention.

One who doesn't know, but knows that he doesn't know...
His limping mule will eventually get him home.

One who doesn't know and doesn't know that he doesn't know...
This is an ignorant man; and will be ignorant forever!

My Dark Philosophy

We know, and know that we know...
We are masters of dark matter physics; Look it up in the textbook!

We know, but don't know that we know...
We are unaware of dark matter physics, we need more imagination to see it.

We don't know, but know that we don't know...
We are illiterate in dark matter physics, but know the places to look and learn!

We don't know and don't know that we don't know...
We are ignorant of dark matter physics, and will be ignorant until our imagination saves us!

My Dark Philosophy

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1) Expand our imagination to ensure we are not ignorant or unaware!

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2) Let's make sure we are only illiterate!

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My Dark Philosophy

4) Dark Matter Unraveled!

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We are masters of dark matter physics; Look it up in the textbook!

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3) Look/Learn.

2) Let's make sure we are only illiterate!

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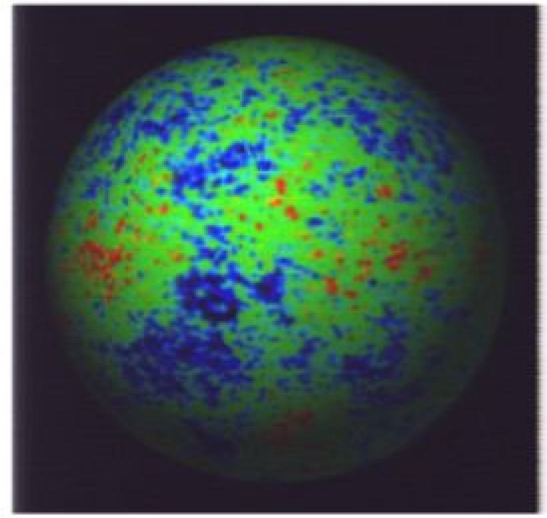
1) Expand our imagination to ensure we are not ignorant or unaware!

Dark Matter: The Known Knowns

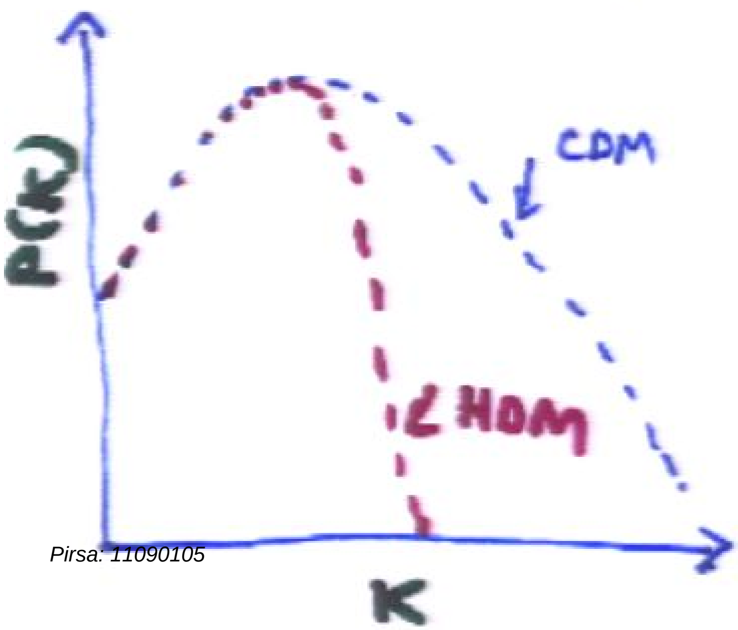
Abundance:

$$\Omega_d h^2 \simeq 0.11$$

"Small" Interaction Atoms

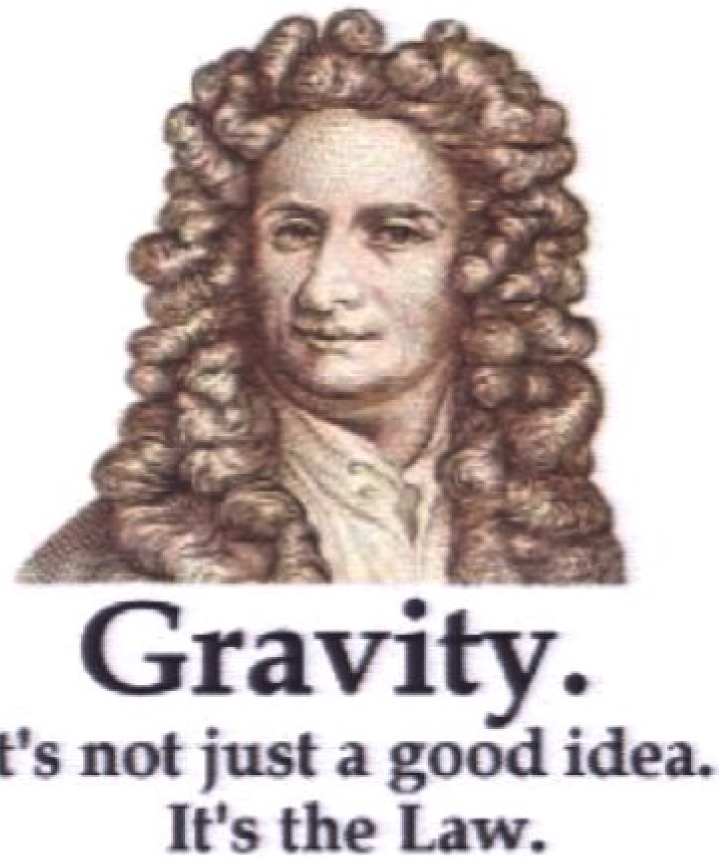


Not *Too Much* Free Streaming:



"Small" Self-Interaction:

Dark Matter: The Known Knowns

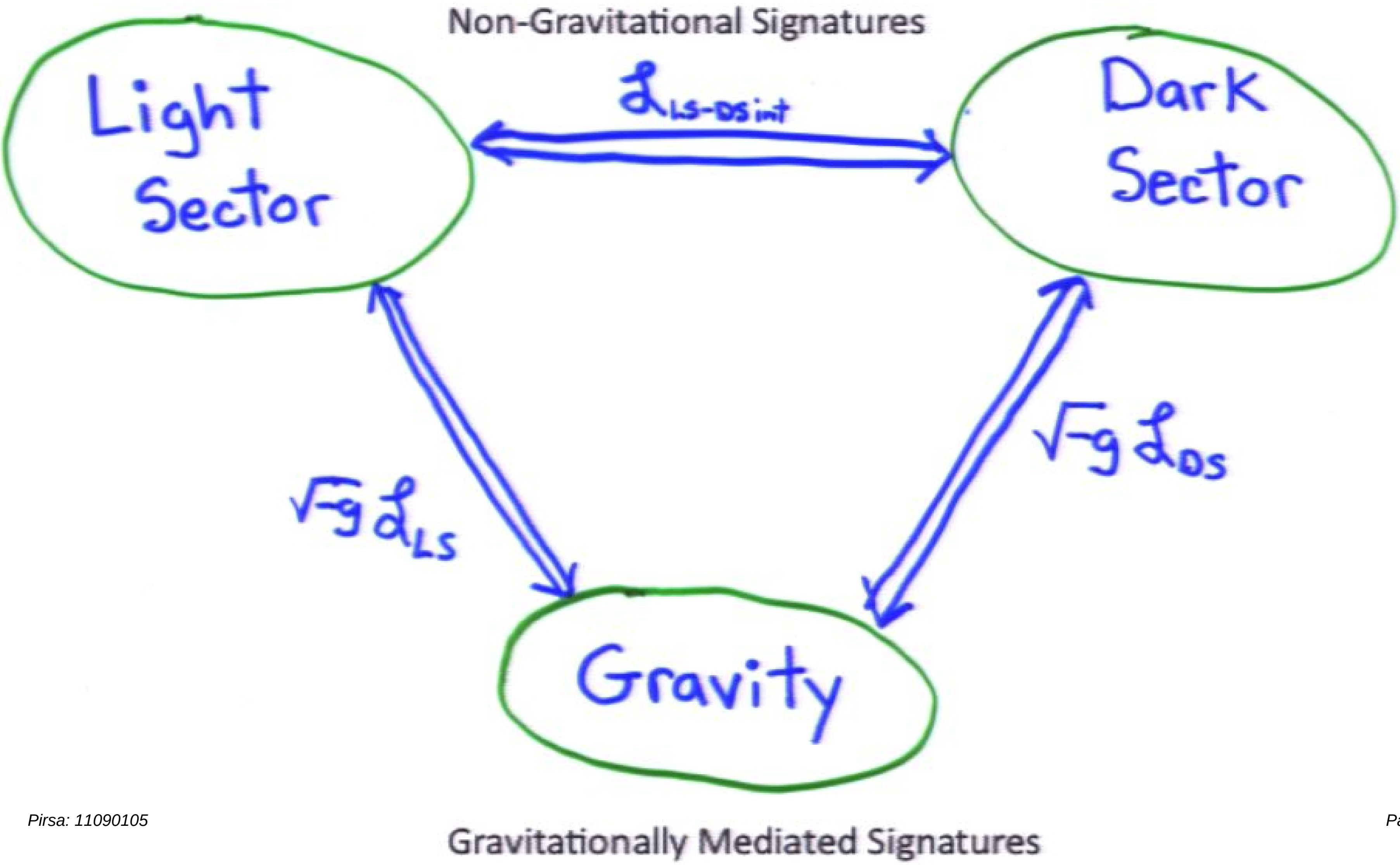


"All the action is in the Action"

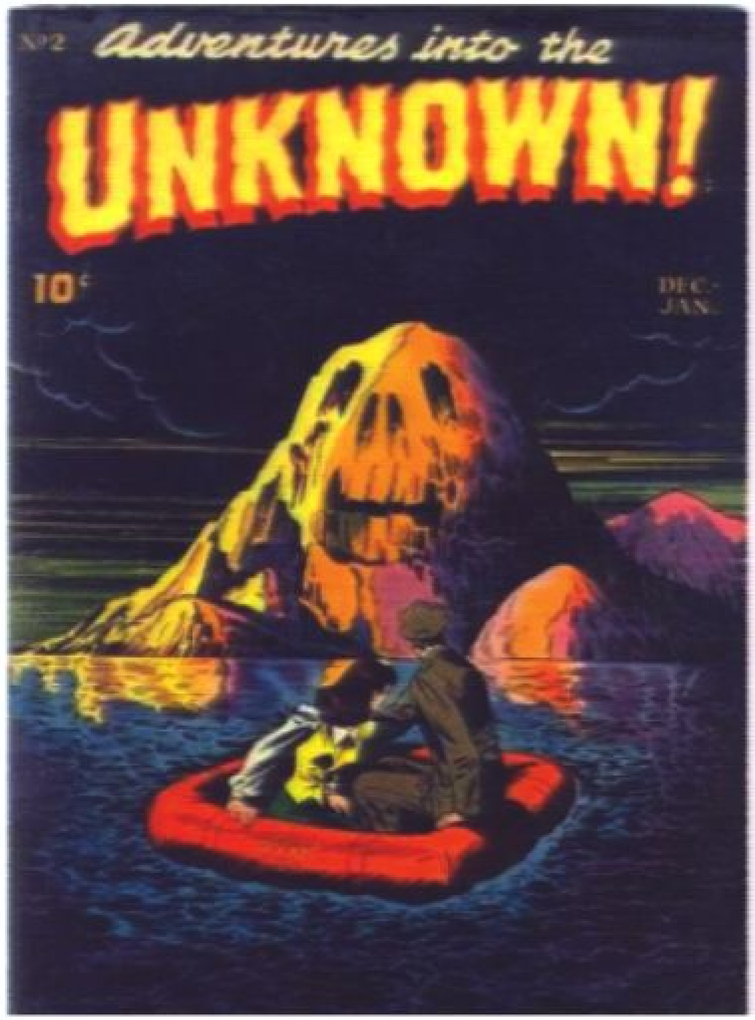
$$S = \int d^4x \sqrt{-g}\left(\frac{1}{16\pi G_N} R + \mathcal{L}_{LS} + \mathcal{L}_{DS} + \mathcal{L}^{int}_{LS-DS}\right)$$

$$\sqrt{-g} \sim 1 + 6\,\Phi_{Newton}$$

Paths to the Dark Side



Dark Matter Physics



Dark Matter: The Known Unknowns

How many components?

Weird Gravity?

How much Self-Interaction?

Substructure Distribution?

Any Complex "Dastrophysics?"

How much Hidden-Interaction?

What are the DM-SM interactions?

MORE: What are we missing??

Dark Matter: The Unknown Unknowns

What are we missing??

Ways to Detect Dark Matter

- Direct: Elastic Scattering of Dark Matter from Nucleons
- Indirect: Annihilation of Dark Matter into Photons/Neutrinos

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- Direct: Elastic Scattering of Dark Matter from Nucleons
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- Direct: Destruction of Nucleons By Dark Matter
- Indirect: Gravitational Scattering of Photons off Dark Matter Structures

Ways to Detect Dark Matter

- Direct: Elastic Scattering of Dark Matter from Nucleons
- Indirect: Annihilation of Dark Matter into Photons/Neutrinos
- Direct: Destruction of Nucleons By Dark Matter Induced Nucleon Decay: Talk by David Morrissey on Saturday
- Indirect: Gravitational Scattering of Photons off Dark Matter Structures

Strong Lensing: Talk by Lexi Morrissey Today

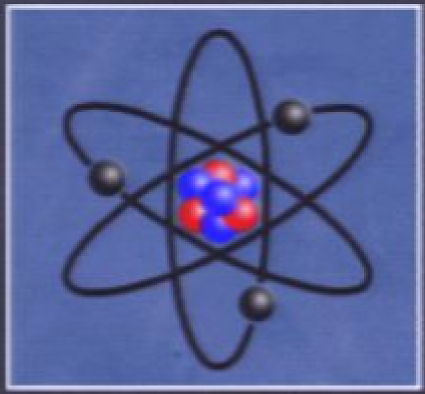
Dark Atom Cosmology

Francis-Yan Cyr-Racine

Atomic Dark Matter

in collaboration with Francis-Yan Cyr-Racine

- ✓ Postulate a new U(1) gauge force in the Dark Sector.
- ✓ Postulate Dark Matter to be an "atomic" bound state.
- ✓ Dark "proton", Dark "electron", Dark "photon".
- ✓ Obeys the "no-long-range-force" condition (Dark Sector is neutral).
- ✓ Respects the constraint on the number of relativistic degrees of freedom during BBN.



Model described by 4 parameters:

$$\alpha_D, B_D, m_D, T_D$$

D. Kaplan et al., JCAP 05 (2010) 021
D. Kaplan et al. ArXiv: 1105.2073

Atomic Dark Matter: New Phenomenology in the Dark Sector

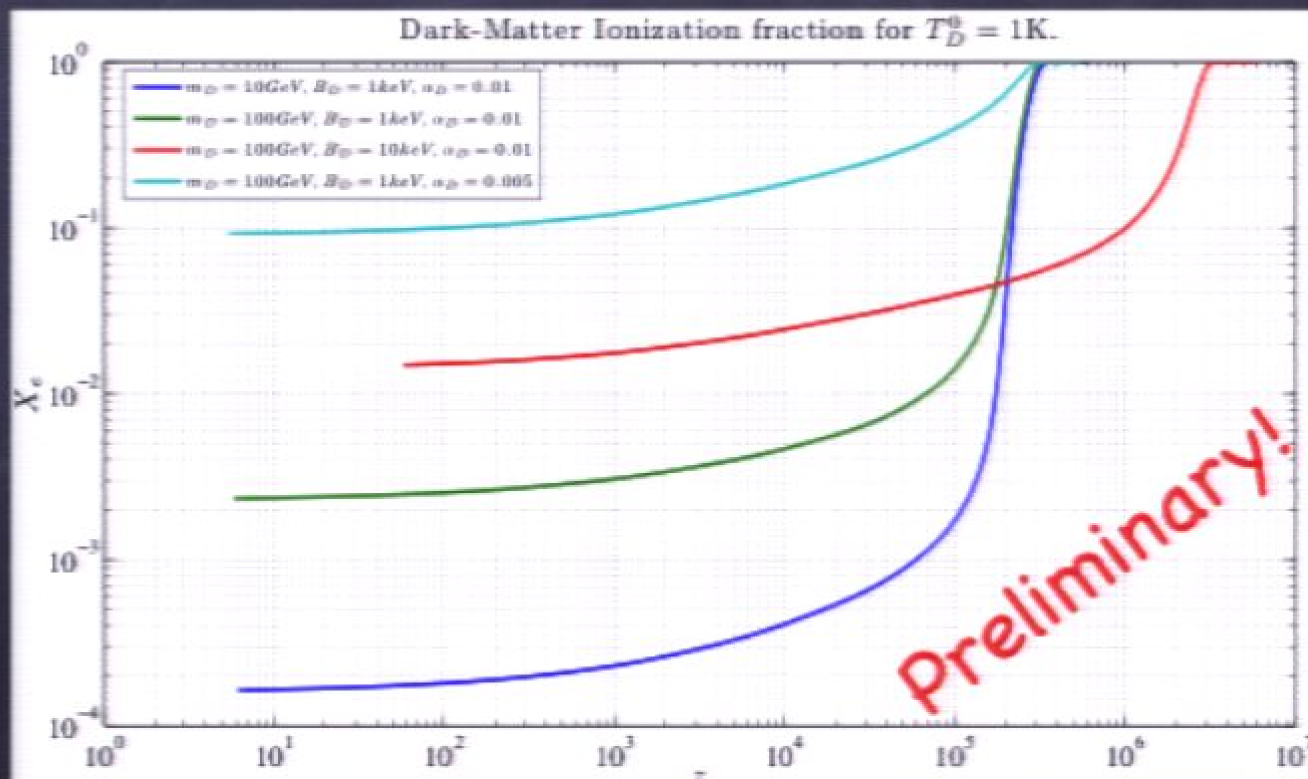
✓ In the very early Universe, dark matter and dark radiation are tightly coupled in a hot plasma.

➡ Dark matter Acoustic Oscillations (DAO)

✓ When the "dark-photon" temperature satisfies

$$T_D \ll B_D$$

the "dark proton" and "dark electron" can recombine to form mostly neutral, collision-less dark matter.



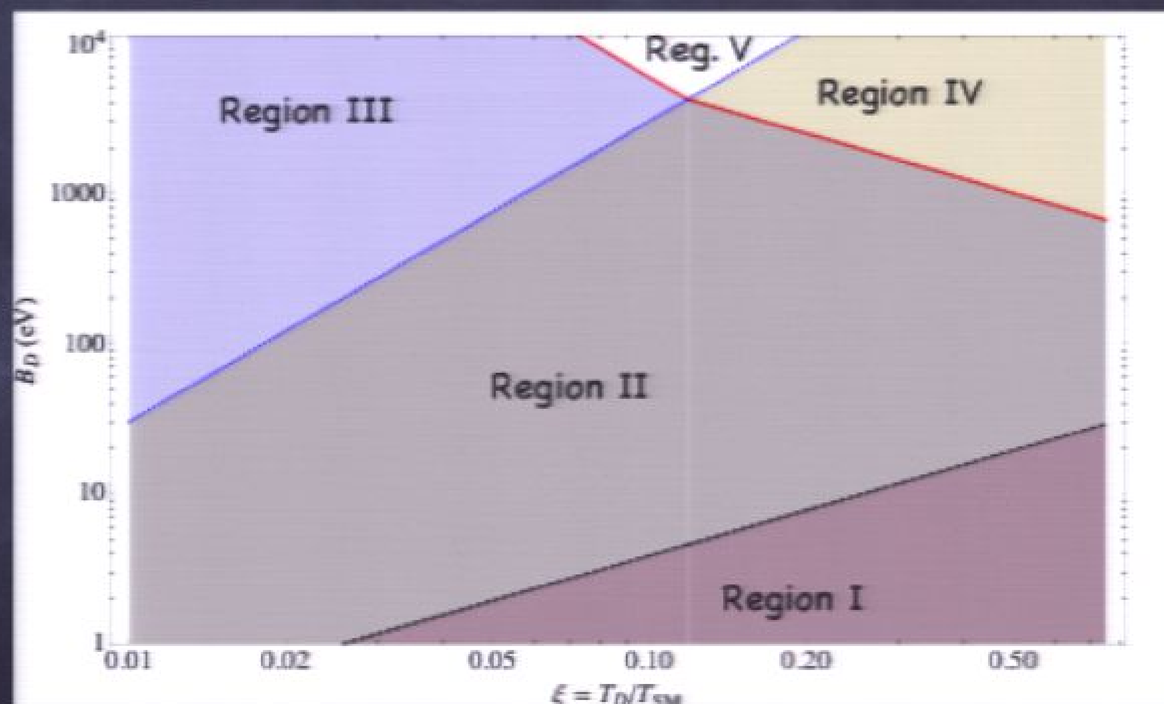
Atomic Dark Matter: Mapping Out the Thermal History

Preliminary!

tomic DM has very rich parameter space:

- ₹egion I: Standard case, similarly to egular hydrogen.
- ₹egion II: Dark photons decouple efore onset of dark recombination, M recombines.
- ₹egion III: Compton heating nefficient before onset of dark ecombination, DM recombines (new hysics likely important).
- ₹egion IV: Compton heating efficient, o dark recombination.
- ₹egion V: Pure adiabatic cooling, no ark recombination, left with dilute lasma.

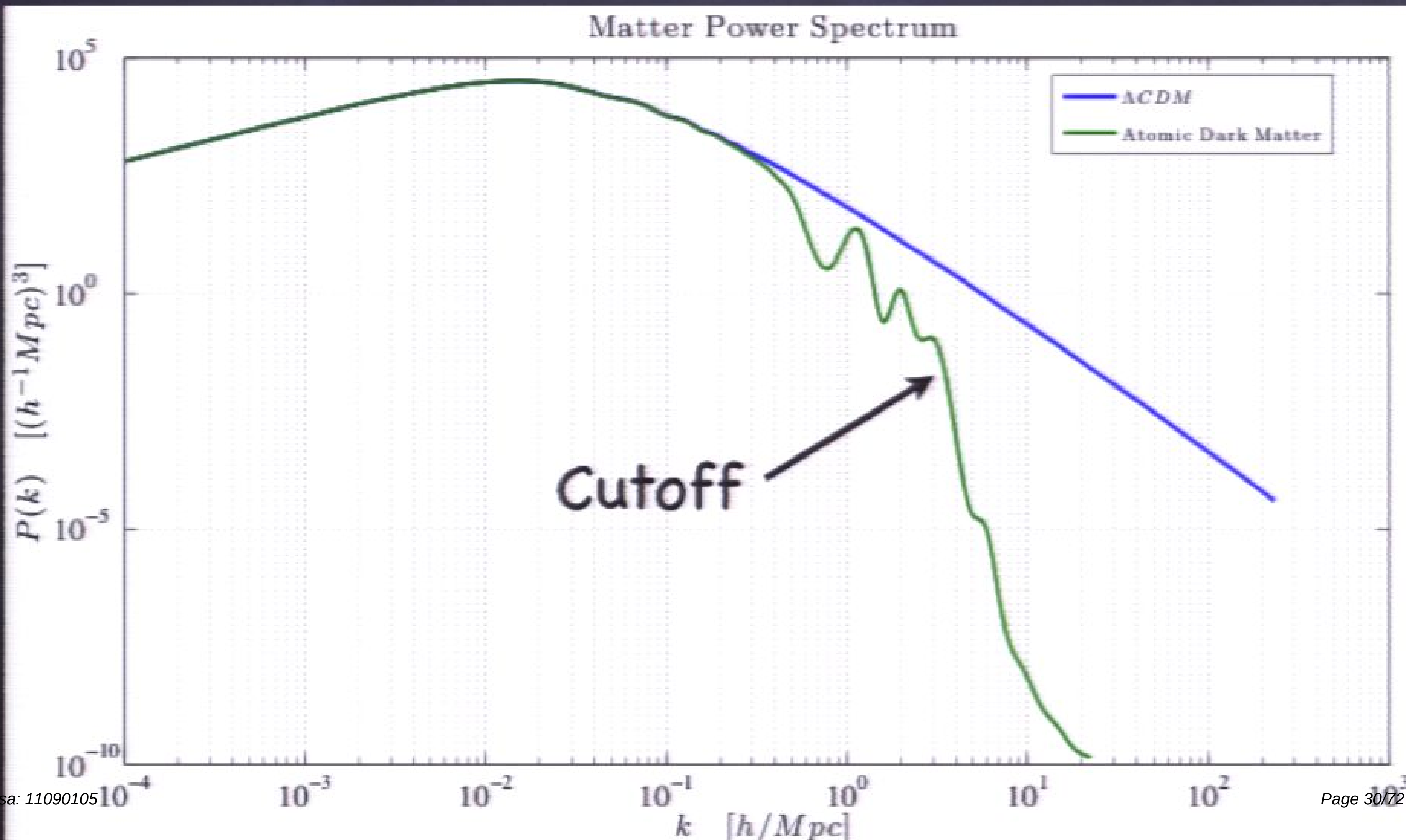
Example of Phase Diagram:



$\alpha_D = 3 \times 10^{-3}, m_D = 10\,\mathrm{GeV}$

Atomic Dark Matter: Matter Power Spectrum

Key observables: Damping of power on small scales and DAO.



Atomic Dark Matter: Challenges

- Solving Reliably the Perturbation Equations:
  - Setting self-consistent initial conditions.
  - Coping with breaking of tight-coupling approximation.
  - Accounting for all energy-exchange mechanism between dark radiation and DM.
- Incorporating Direct Detection Constraints.

Hidden CDM / WDM/ HDM

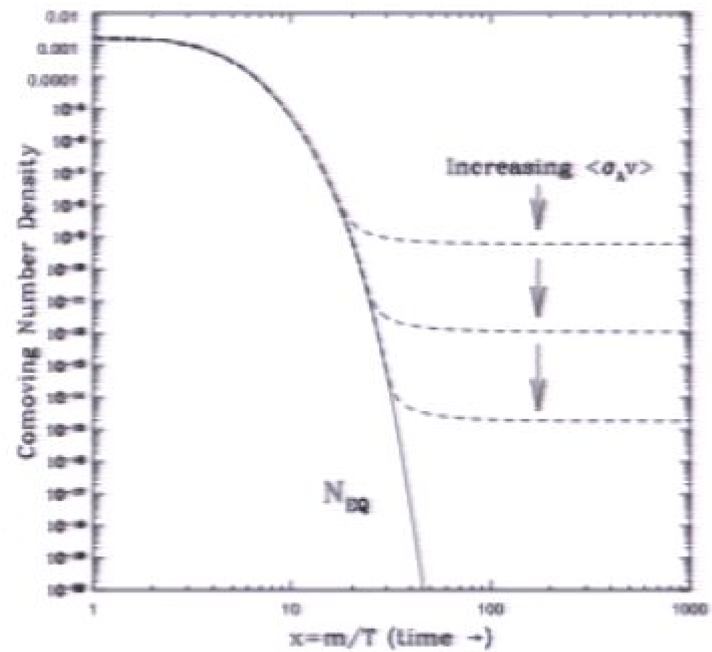
Cosmological Limits on Hidden Sector Dark Matter, Subinoy Das and KS arXiv:1012.4458

Hidden Hot Dark Matter as Cold Dark Matter, KS arXiv:0912.2346

WIMPs

Abundance: ☑

$$\Omega_\chi h^2 \sim 0.1 \left(\frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}}{\langle \sigma v \rangle} \right)$$



Not *Too Much* Free Streaming ☑

Parameter to fiddle with to fit the data.

"Small" Self-Interaction ☑

Standard Model ν's

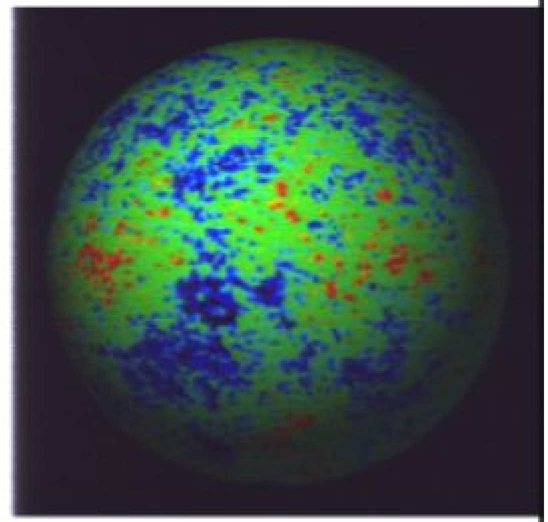
"Freeze-Out" when

$$\Gamma_{weak} \simeq G_F^2 T_{dec}^5 = H \simeq 1.66\sqrt{g_*}\frac{T_{dec}^2}{M_{pl}}$$

$$T_{dec} \simeq 1\,\mathrm{MeV} \gg m_\nu \sim \mathrm{eV}$$

$$n_\nu \propto \frac{3\zeta(3)}{4\pi^2} T_\nu^3$$

Hot Dark Matter Not Dark Matter



To get: $\Omega_d h^2 \simeq 0.11$

For a single Dirac fermion require that decouples before the QCD phase transition :

$$\text{mass} \simeq 50 \text{ eV}$$

Standard Model ν's need a LOWER mass.

Hot Dark Matter
Not Dark Matter

Dynamical Role of Light Neutral Leptons in Cosmology

Scott Tremaine
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125, and Institute of Astronomy, Cambridge, England

and

James E. Gunn
W. K. Kellogg Radiation Laboratory, Hale Observatories, California Institute of Technology, Pasadena, California 91125, and Carnegie Institution of Washington, Washington, D. C. 20005
(Received 31 May 1978)

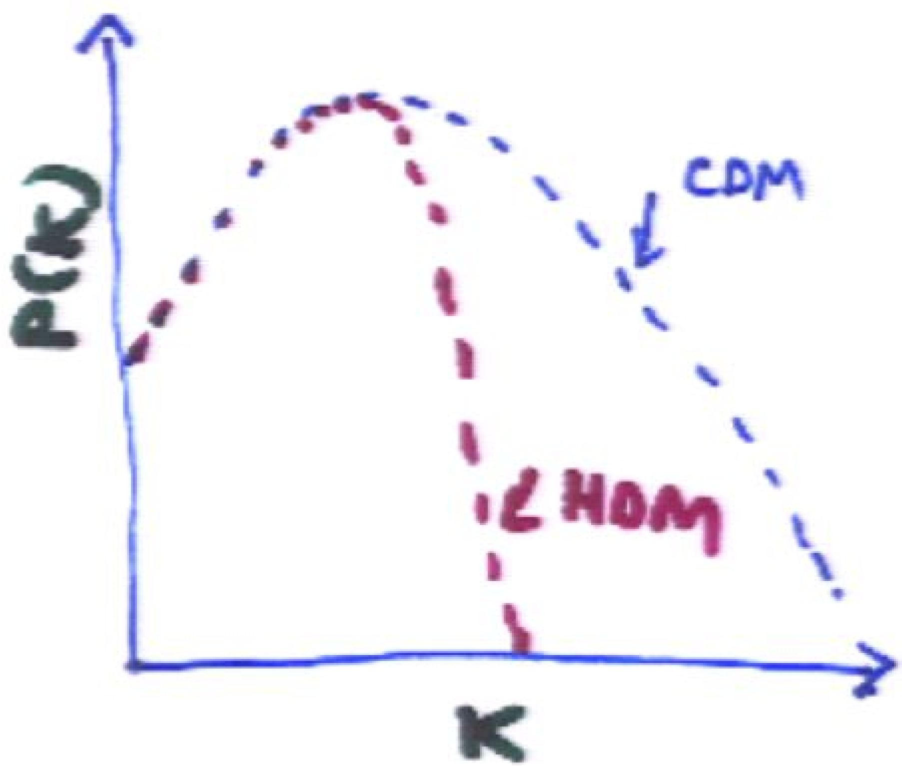
Tremaine-Gunn, Phys. Rev. Lett. 42, 407 (1979)

Coarse grained PSD must be less than the maximum of the fine-grained PSD g/h^3

$$m_\nu{}^4 > \frac{9h^3}{4(2\pi)^{5/2} g_\nu G \sigma r_c{}^2} \quad m_\nu > (101\ \mathrm{eV})\left(\frac{100\ \mathrm{km\ s^{-1}}}{\sigma}\right)^{1/4}\left(\frac{1\ \mathrm{kpc}}{r_c}\right)^{1/4} g_\nu{}^{-1/4}$$

100eV-scale Fermions Can Not Act as Dark Matter

Hot Dark Matter
Not Dark Matter



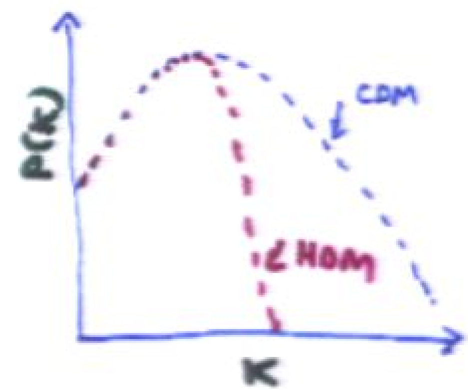
HDM Free-stream too much

Hot Dark Matter
Not Dark Matter

Abundance: ☒

Not *Too Much* Free Streaming ☒

"Small" Self-Interaction ☑

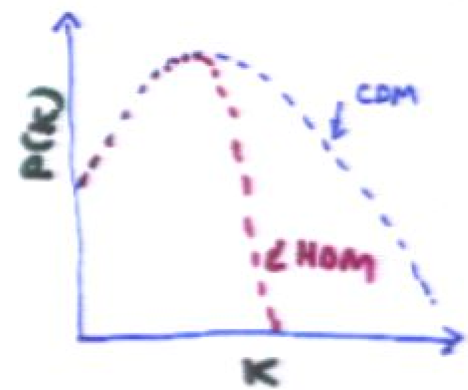


Hot Dark Matter
Not Dark Matter

Abundance: ☒

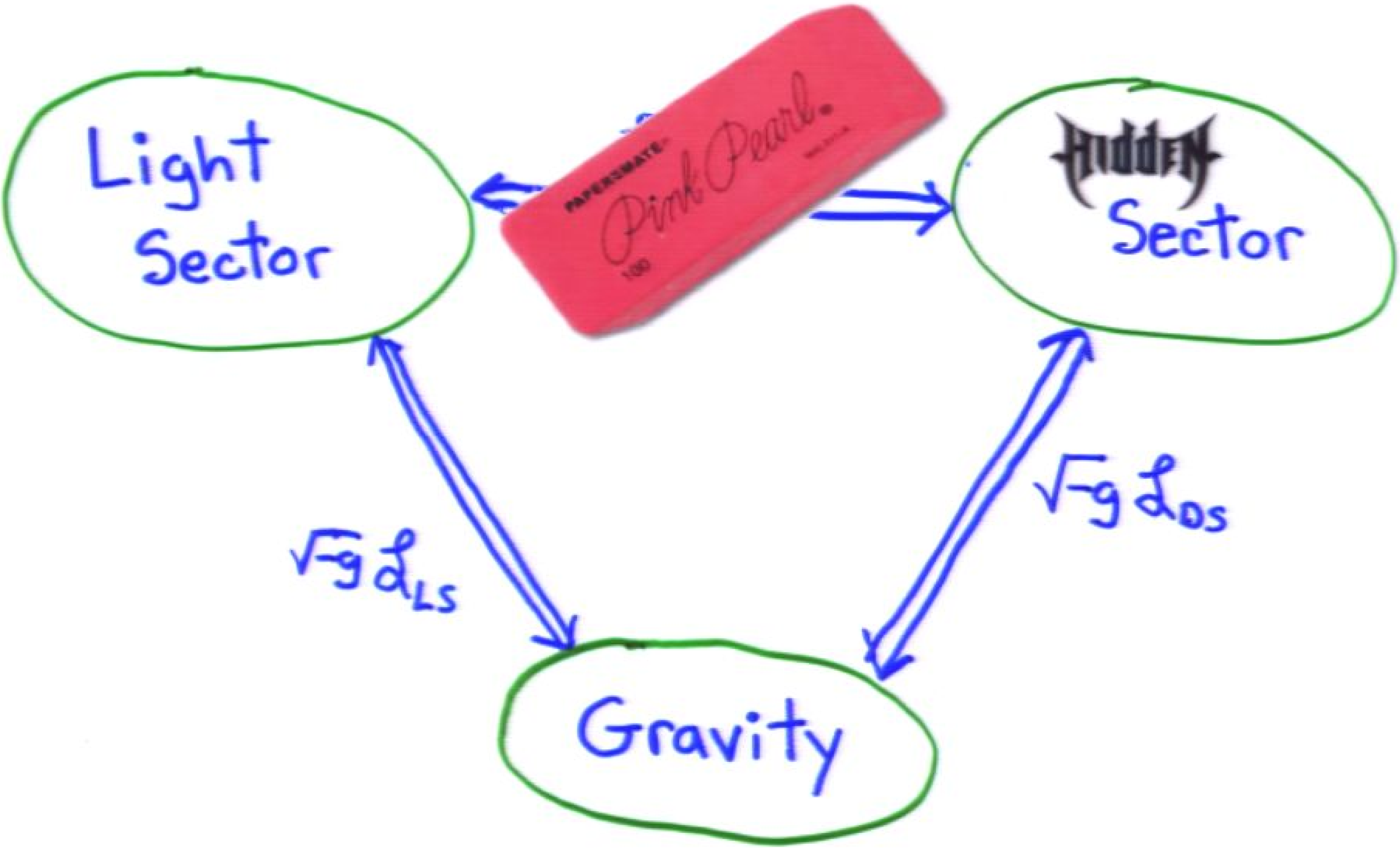
Not *Too Much* Free Streaming ☒

"Small" Self-Interaction ☑



Not enough freedom to fit data.
Can we fix this?

Paths to the HIDDEN Side



The Hidden Sector

"All the physics you ever wanted to see but (maybe) never can see… "

Disclaimer: Not A Comprehensive List!

Hidden WIMPs: J. Feng and J. Kumar: Phys. Rev. Lett. 101, 231301 (2008)
J. Feng, H. Tu, and H. Yu: JCAP 0810, 043 (2008)

Hidden "Charged" Particles: L. Ackerman, M. Buckly, S. Carroll, and M. Kamionkowski: Phys. Rev. D 79, 023519 (2009)

Hidden/Dark Atoms: D. Kaplan, G. Krnjaic, K. Rehermann, C. Wells
arXiv: 0909.0753
F. Cyr-Racine, KS (2011)
arXiv: SOON.

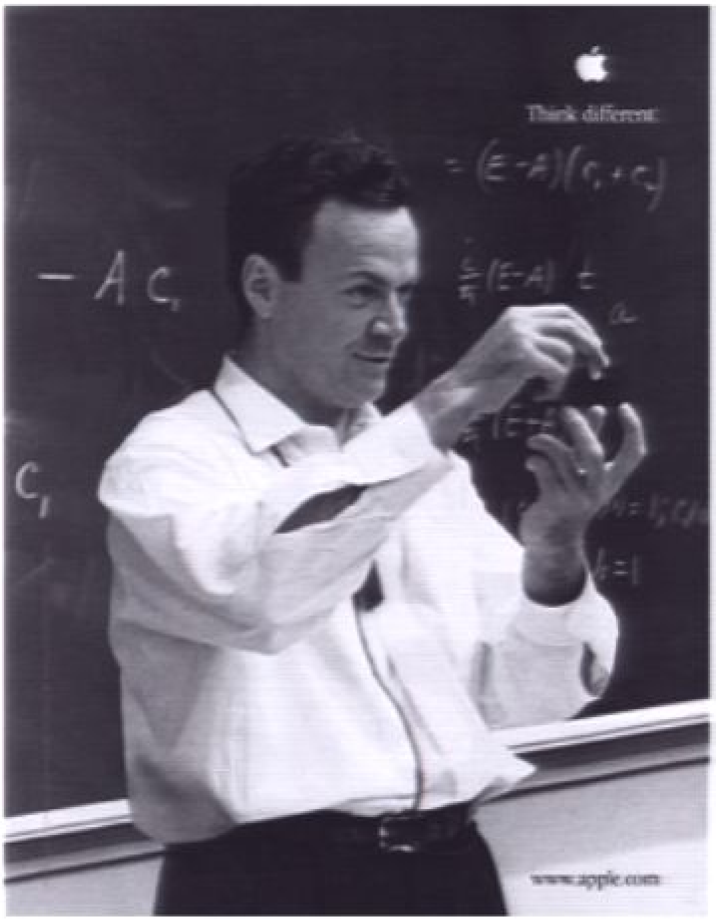
Hidden Light Particles

This Work

Hidden "Etc.. Etc.."

Many More Possibilities

The Hidden Sector



Feynman

"There is Plenty of Room at the Bottom"

... to fit things at small scales.

The Hidden Sector

Fourier Transform of
Feynman

"There is Plenty of Room in the Cold"

... to fit particles at small momentum.

The Hidden Sector

The Fix:

Parameter to fiddle with to fit the data.

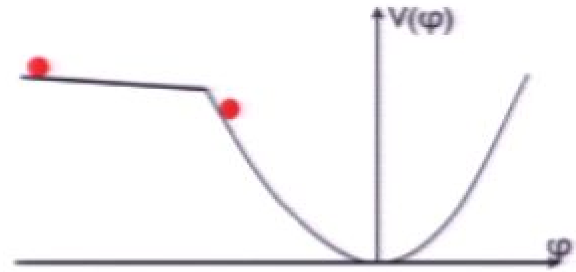
If they are decoupled...

$$T_{\mathrm{H}} \neq T_{\mathrm{SM}}$$

Can fit many of degrees of freedom in the hidden plasma.

The Hidden Sector

How? $$T_{\rm H} \neq T_{\rm SM}$$



1) Different reheating efficiencies lead to different temperatures (never efficiently coupled).
2) Many degrees of freedom in SM-sector prior to hidden sector decoupling.

The Hidden Sector

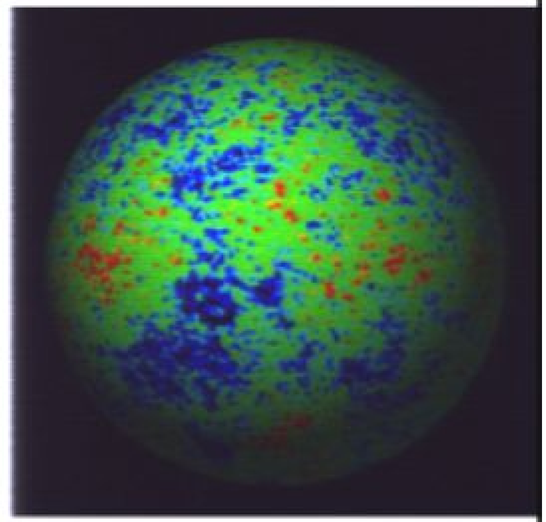
For a fermion χ with $T_\chi \gg m_\chi$

$$n_\chi = d_\chi \frac{3\zeta(3)}{4\pi^2} T_\chi^3 = d_\chi \frac{3\zeta(3)}{4\pi^2} \frac{g^s(T)}{g_f^s} \xi^3 T^3$$

Small (compared to say n_ν) if $\xi \equiv T_\chi / T$ is small.

Parameter to fiddle with to fit the data.

Hidden Hot Dark Matter as Cold Dark Matter



To get: $\Omega_d h^2 \simeq 0.11$

Need:

$$m_\chi = 40\left(\frac{\Omega_d h^2}{0.11}\right)\left(\frac{4}{d_\chi}\right)\left(\frac{g_f^s}{g_0^s}\frac{3.91}{83}\right)\left(\frac{0.1}{\xi_f}\right)^3 \text{ keV}$$

If χ freezes out when

Hidden Hot Dark Matter as Cold Dark Matter

Requirements:

Relativistic Freeze Out 

but.. Non-Relativistic Today

Abundance: ☑

$$\Omega_d h^2 \simeq 0.11$$

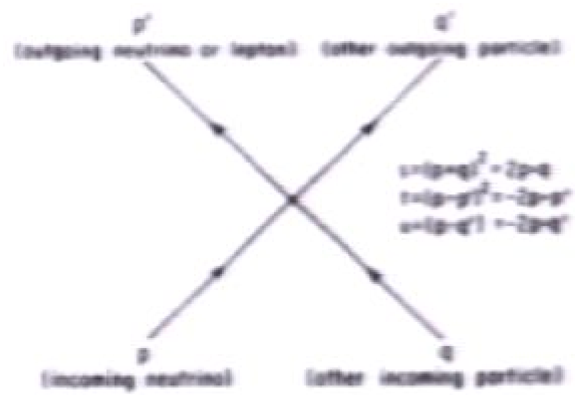
Not *Too Much* Free Streaming ☑

$$\lambda_{FS} \sim 0.4\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_\chi}\right)^{4/3}$$

"Small" Self-Interaction ☑

Hidden Hot Dark Matter as Cold Dark Matter

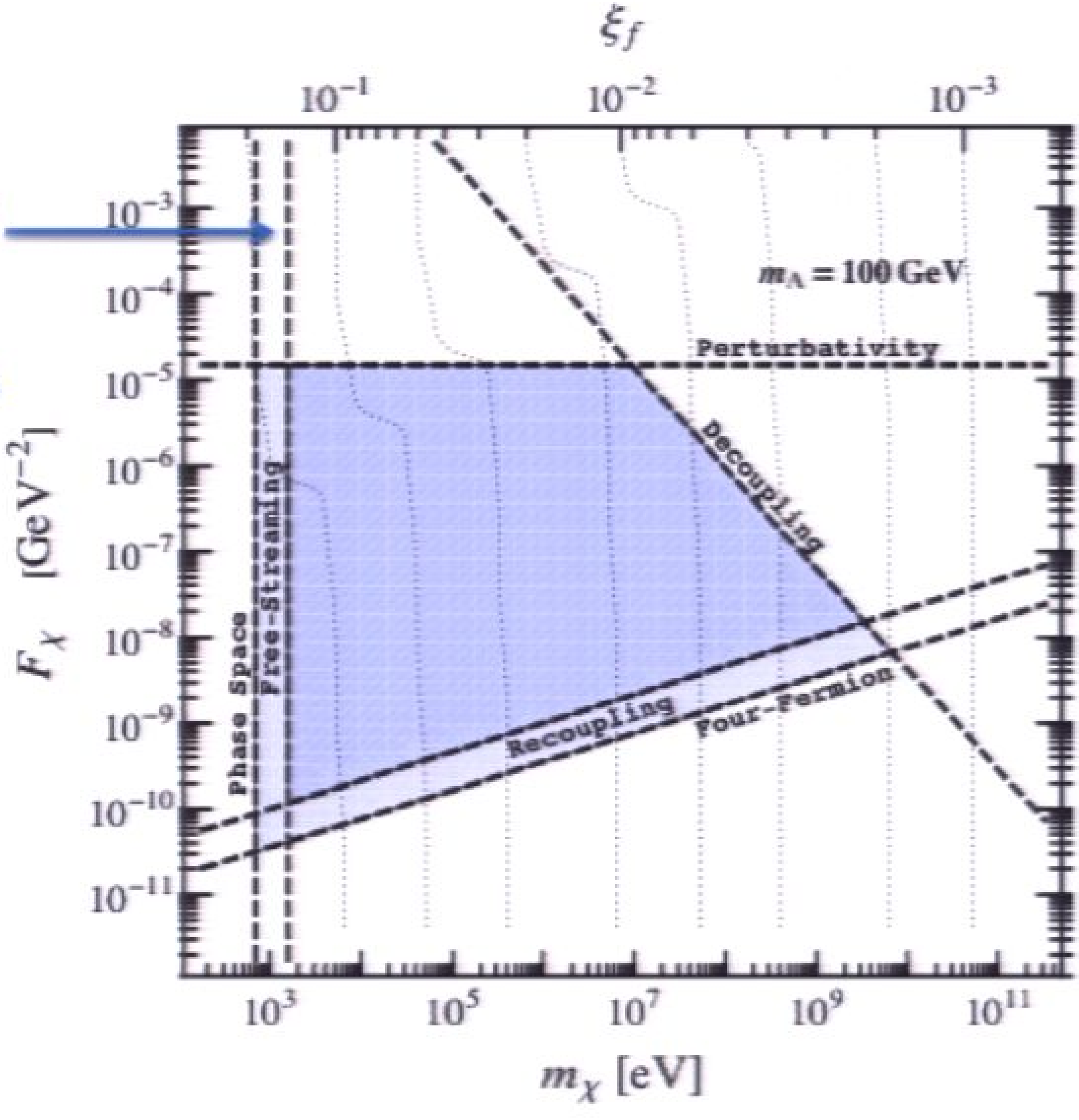
Prototypical HDM: SM neutrinos with G_F strength 4–fermion interactions



Candidate HHDM: Think... light fermion with G_Λ strength 4–fermion interactions.

4-Fermion HHDM Parameters

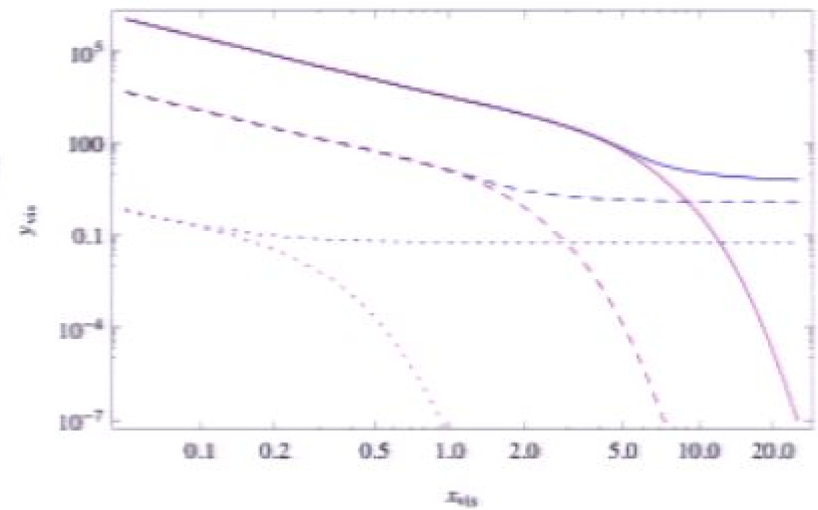
Constraints from LSS and Local DM Distributions



Hidden Dark Matter as Cold/Warm Dark Matter

Non-Relativistic / Semi-Relativistic / Relativistic Freeze Out

but.. Non-Relativistic Today



Abundance: ☑

$$\Omega_d h^2 \simeq 0.11$$

Not *Too Much* Free Streaming ☑

$$\lambda_{FS} \sim 0.4\,\mathrm{Mpc}\left(\frac{\mathrm{keV}}{m_\chi}\right)^{4/3}$$

"Small" Self-Interaction ☑

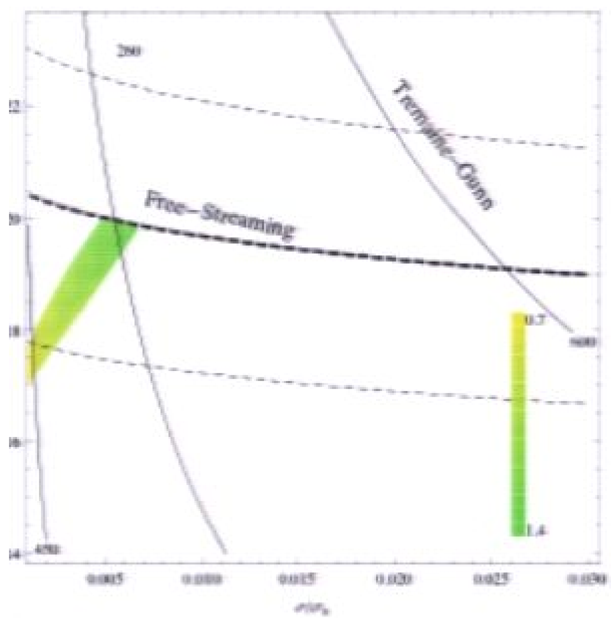
$$\frac{dY}{dx} = -\frac{1}{x^2}\frac{s(m_\chi)}{H(m_\chi)}\langle\sigma v\rangle\left[Y^2 - Y_0(x)^2\right]$$

$$Y_0(x;\xi) \equiv \xi\frac{45}{4\pi^4}\frac{d_\chi}{g^s(x)}x^2 K_2(x/\xi)$$

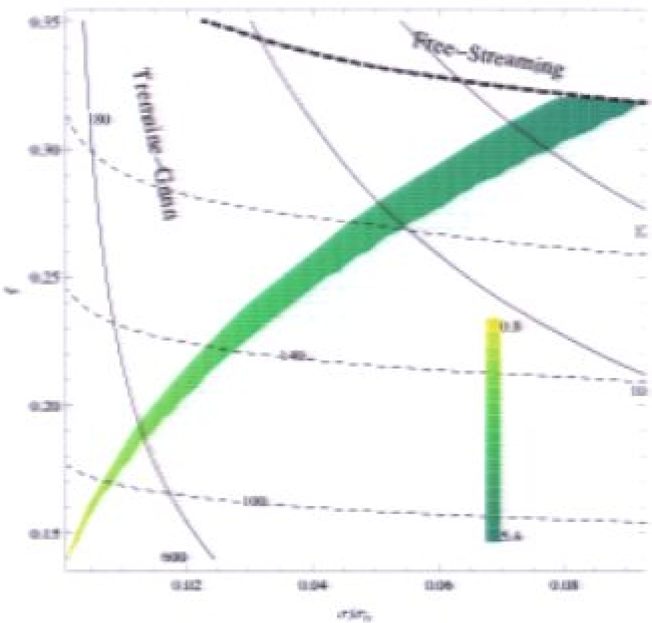
$$\Omega_\chi = m_\chi s_0\frac{Y(x_\infty,\xi)}{\rho_c}$$

Hidden Dark Matter as Cold/Warm Dark Matter

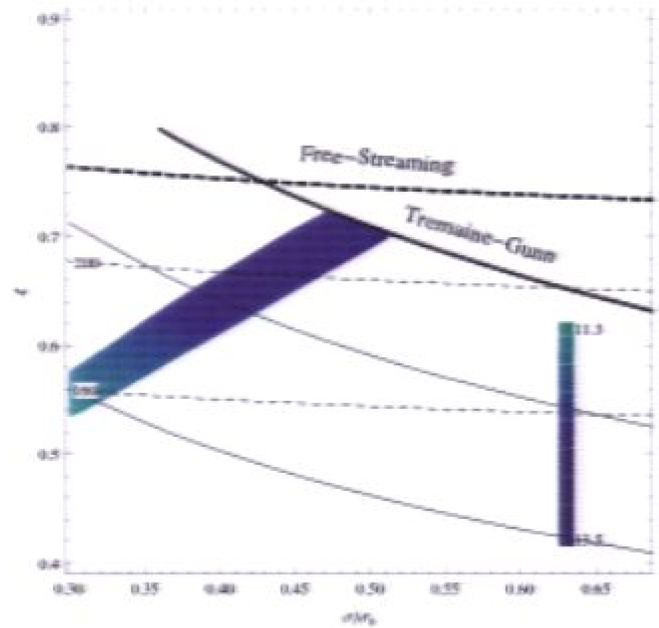
Non-Relativistic / Semi-Relativistic / Relativistic Freeze Out



1.5 keV



3 keV



10 keV

No Parameter Space below 1.4 keV

Even if no interactions with SM – Gravitational Limit!

Hylogenesis / Induced Nucleon Decay

Talk on Saturday!!

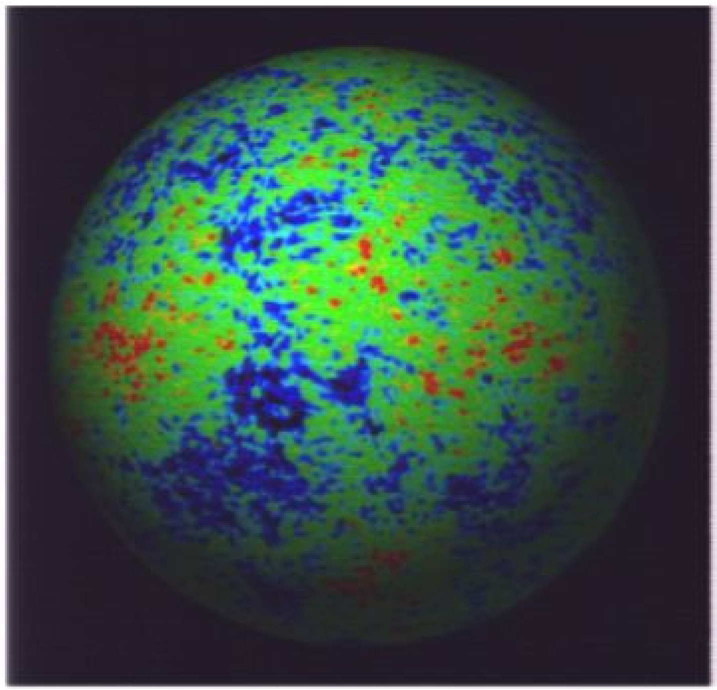
Hylogenesis[1]

[1] From Greek, *hyle* "primordial matter" + *genesis* "origin."

Hooman Davadousl, David E. Morrisey, KS, Sean Tulin

PRL 105 (2010) 211304
arXiv:1008.2399.

The Problem of Five



$$\Omega_d/\Omega_b \quad = \; 4.97 \; \pm \; 0.28$$

Why not 50000 or 1/623 ?

The Problem of Five

$$\rho_d \simeq 5\rho_b$$

$$m_d n_d \simeq 5 m_b n_b$$

For a typical WIMP: $$m_d \sim 100\,\mathrm{GeV}$$

$$m_b \sim 1\,\mathrm{GeV}$$

$$n_d \sim n_b/20$$

Why are the densities of dark matter and baryons so similar if they arise from unrelated physical phenomena?

Hmm...

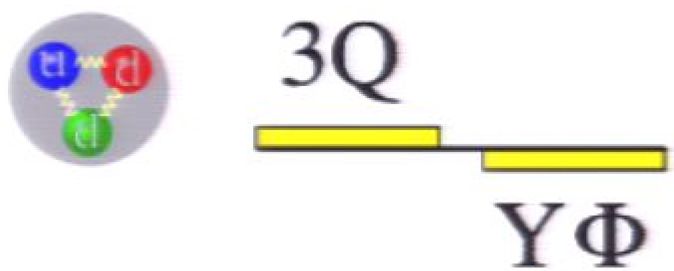

PARKER BROTHERS
THE
CLUE
Special
Dark Matter
Edition!
ROTHERS' CLASSIC DETECTIVE GAME
AGES
8+

Unified Origin for Baryons and Dark Matter

A potential solution to "The Problem of Five"

"Connector" Particle

$\underbrace{XU^cD^cD^c}_{\text{Neutron B=1}} \quad \bar{X}_a \underbrace{Y^c\Phi^*}_{\text{Dark Matter B=-1}} \quad + \quad \text{h.c.}$

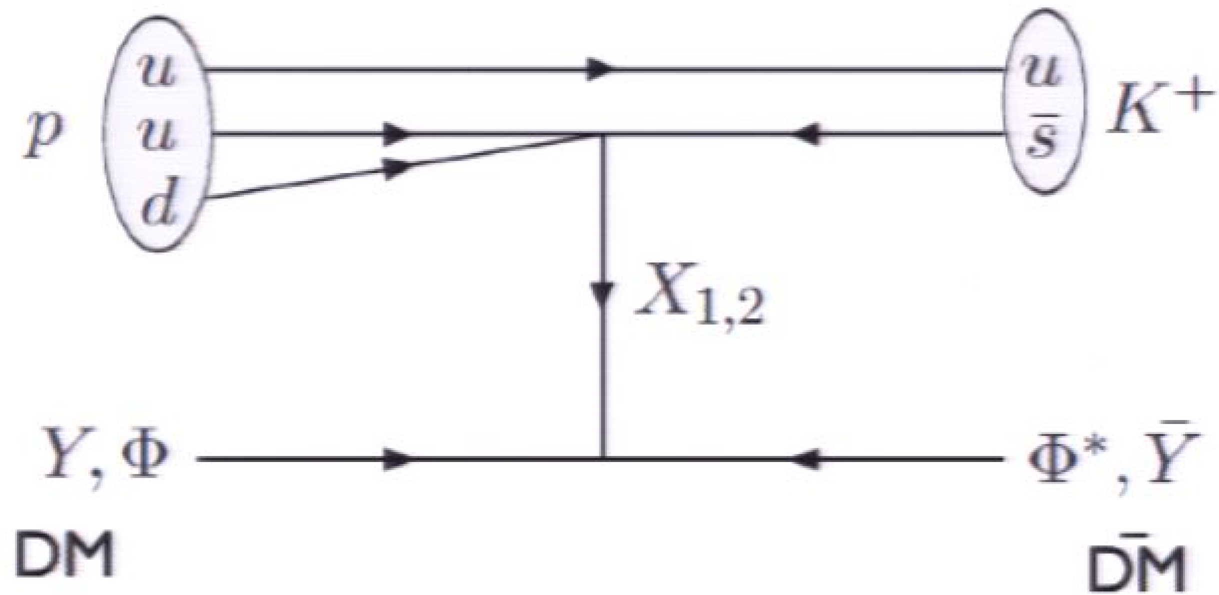


$$n_B = n_Y = n_\Phi$$

$$\Omega_d/\Omega_b = (m_Y + m_\Phi)/m_p$$

Unified Origin for Baryons and Dark Matter

- DM carries antibaryon number. Can annihilate nucleons.



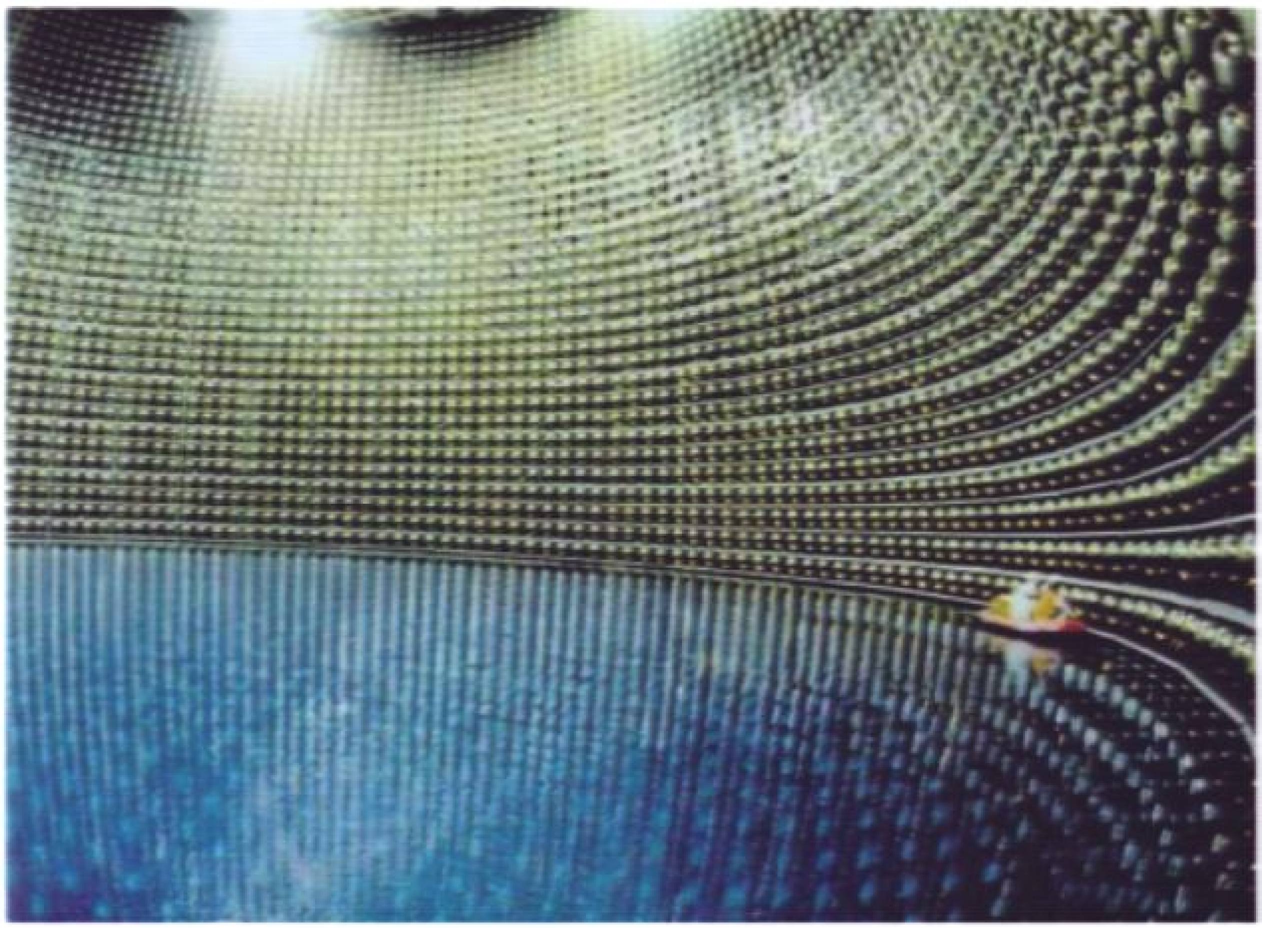
Several different meson final states possible $\quad p \longrightarrow K^+, \pi+, \ldots \quad n \longrightarrow K^0, \pi^0, \eta, \ldots$

(We only considered lightest pseudo-Goldstone bosons.)

Can have both up-scattering and down-scattering.

Unified Origin for Baryons and Dark Matter

Induced Nucleon Decay at SuperK?



Hylogenesis / Induced Nucleon Decay

Talk on Saturday!!

Hylogenesis[1]

[1] From Greek, *hyle* "primordial matter" + *genesis* "origin."

Hooman Davadousl, David E. Morrisey, KS, Sean Tulin

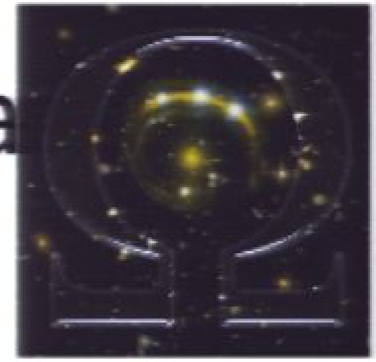
PRL 105 (2010) 211304

arXiv:1008.2399.

Particle Dark Matter and Strong Lensing

NOT! an official logo.

OMEGA Explorer Science Tea



Leonidas Moustakas, PI

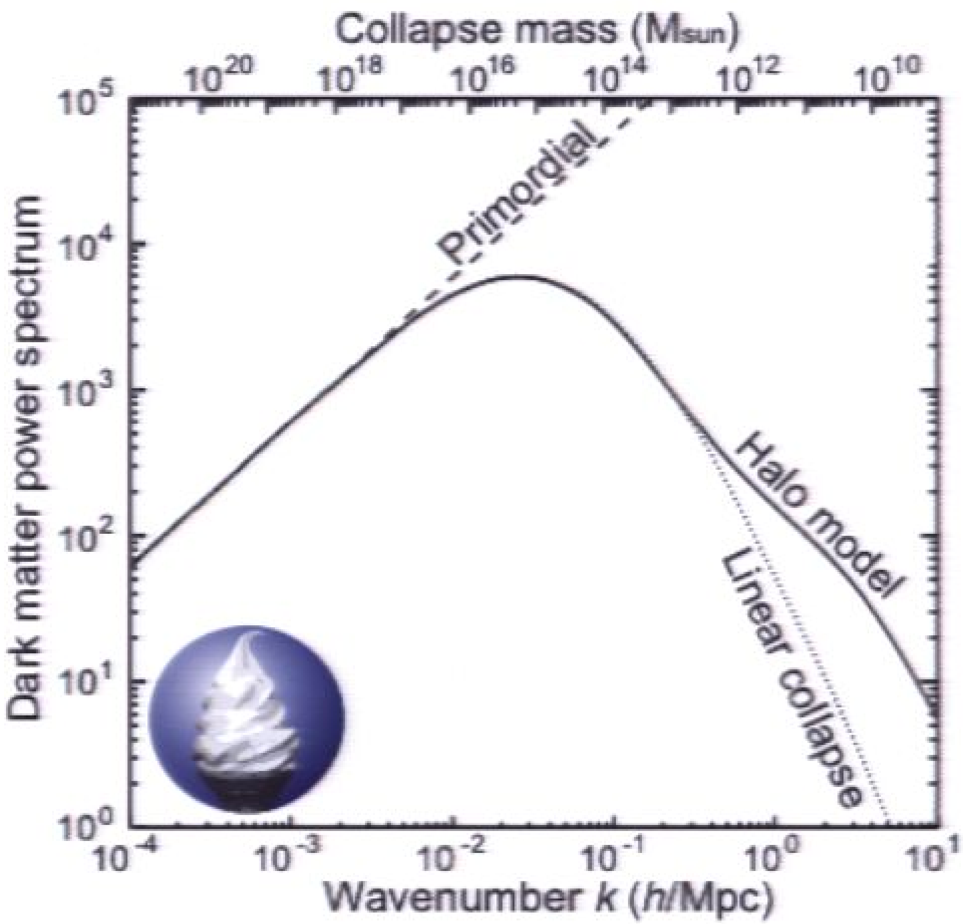
Adam Amara
Misty Bentz
Adam Bolton
James Bullock
Remi Cabanac
Ed Cheng
Dan Coe
Art Congdon
Francis-Yan Cyr-Racine
Ben Dobke
Greg Dobler
Peter Eisenhardt
Richard Ellis

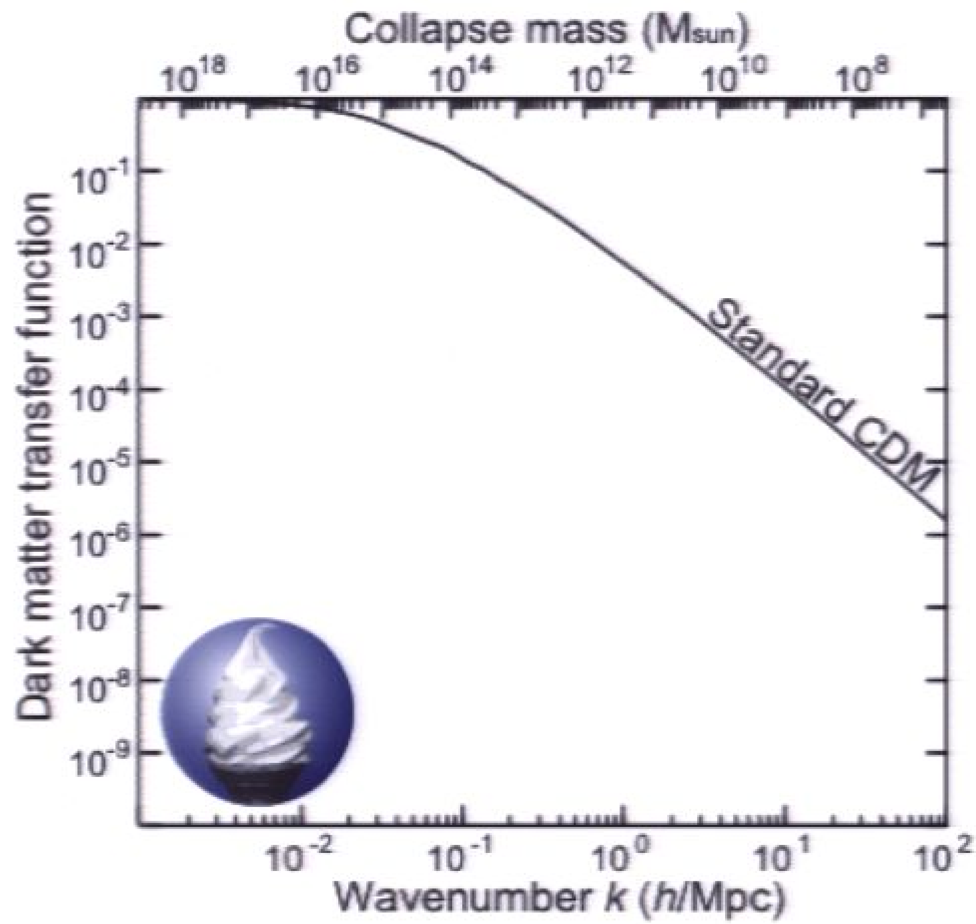
Ross Fadely
Chris Fassnacht
Sarah Gallagher
Raphael Gavazzi
Tim Goodsall
Varoujan Gorjian
Manoj Kaplinghat
Chuck Keeton
Jean-paul Kneib
Mike Kuhlen
Charles Lawrence
Phil Marshall
Richard Massey

Ben Metcalf
Priya Natarajan
Patrick Ogle
Masamune Oguri
Annika Peter
Brad Peterson
Jason Rhodes
KS
Daniel Stern
Kyle Stewart
Harry Teplitz
Tommaso Treu
Joachim Wambsganss

+Andrew Benson; Chris Kochanek

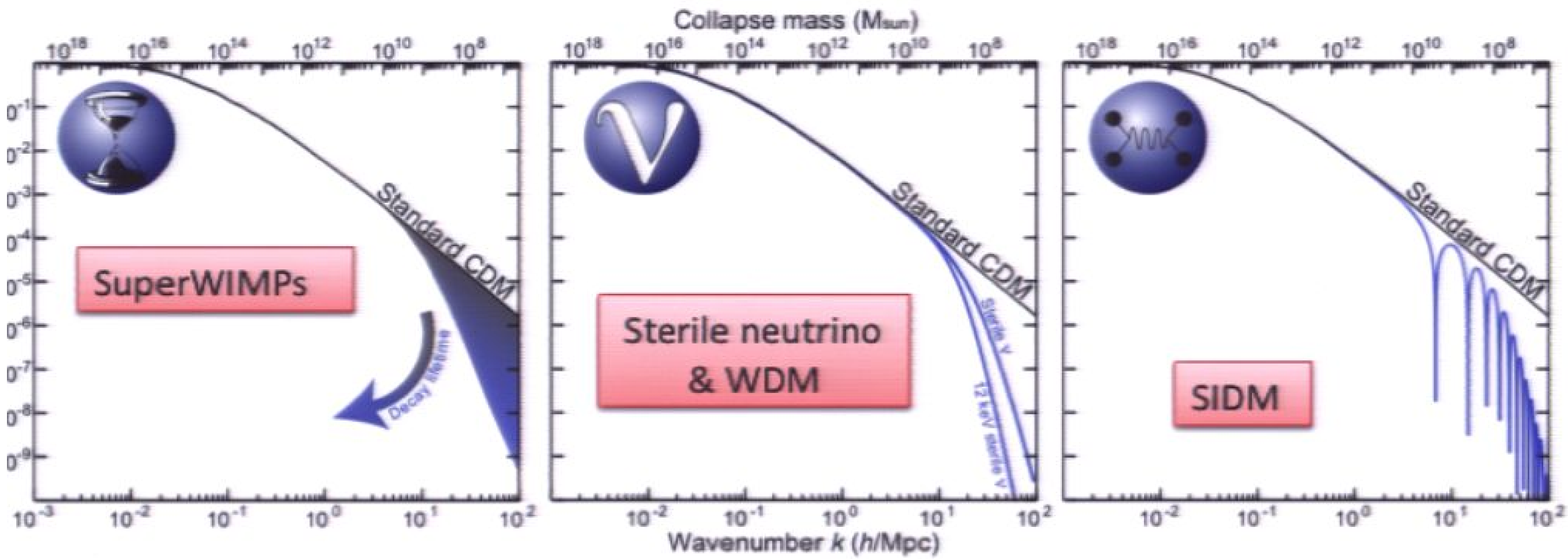
LCDM power spectrum and T(k)





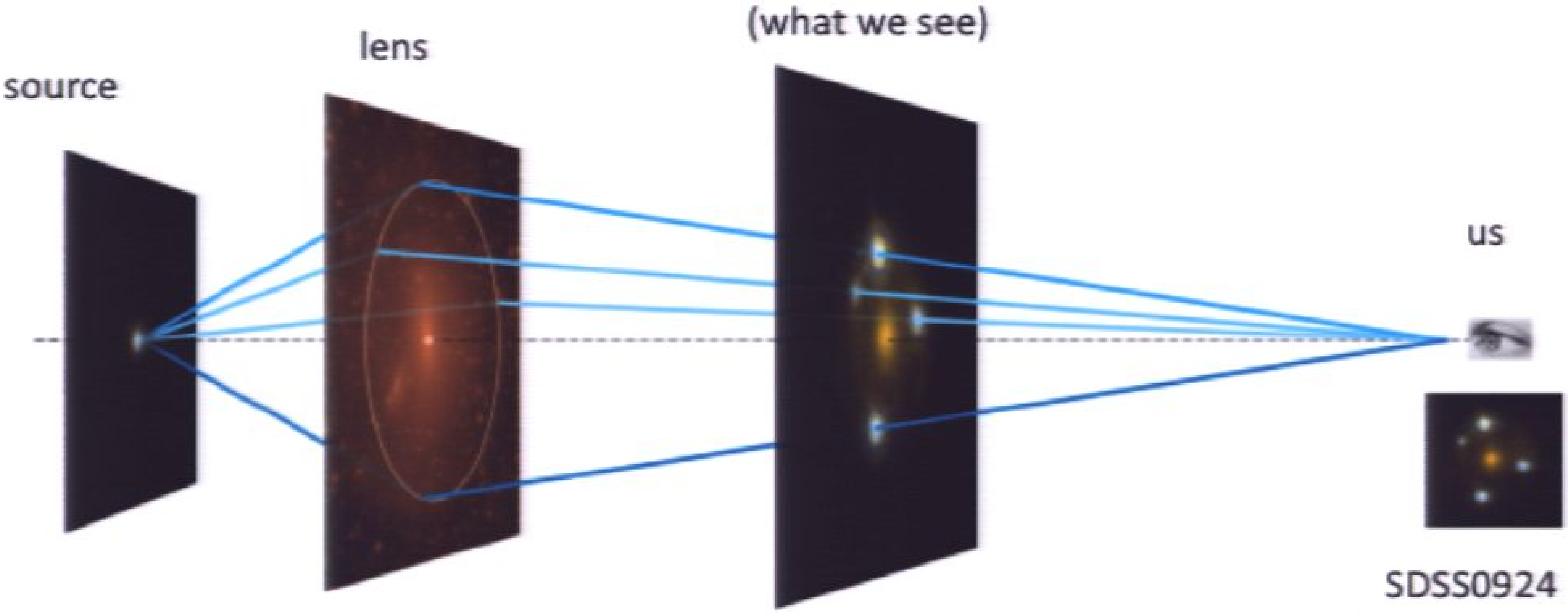
Beyond LCDM transfer functions

Collapse Mass (Msun)



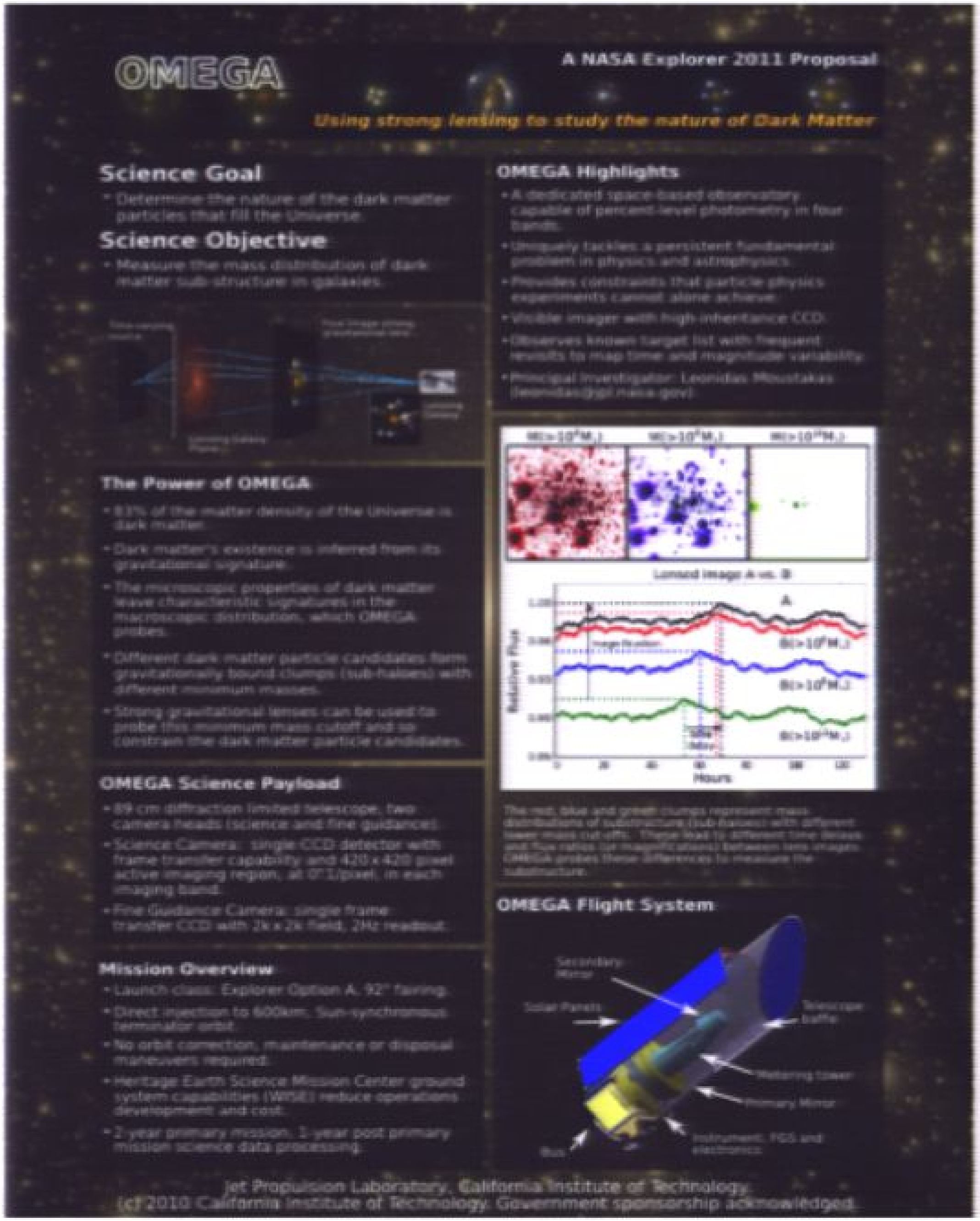
Wavenumber k (h/Mpc)

Strong gravitational lensing



A simple geometric relation between the angular diameter distances between source, lens, and us determine the critical surface mass density for strong gravitational lensing.

Leonidas Moustakas (JPL/Caltech)



Leonidas Moustakas (JPL/Caltech)

Particle Dark Matter and Strong Lensing

NOT! an official logo.

Dark Matter Perturbations Before Reheating

arXiv: 1106.0536 --- Accepted by PRD

Dark Matter Perturbations Before Reheating

How do dark matter perturbations evolve before and through reheating??

Dark Matter Perturbations Before Reheating

Answer: Be here in 100 mins!

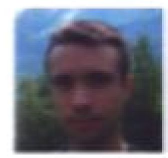
Dark Matter Projects

- Dark Atom Cosmology (with Francis Cyr-Racine)

Graduating Soon!

- Hidden CDM / WDM/ HDM (with Subinoy Das)

- Hylogenesis (with Hooman Davoudaisl, Sean Tulin, and David Morrissey)
  Induced Nucleon Decay



- Particle DM and Strong Lensing (with Lexi Moustakas & OMEGA crew)

- DM Perturbations Before Reheating (with Adrienne Erickcek)

- More, but talk to me later...