Ratcheting Up The Search For Dark Matter

Sam McDermott
URA Thesis Award Talk
5/10/15

Based on work in collaboration with:
Asher Berlin, Ilias Cholis, Rouven Essig, Paddy Fox, Dan Hooper, Eric Kuflik, Tomer Volansky, Hai-Bo Yu, and Kathryn Zurek

Fermilab

Motivation

- Standard Model is finally complete
- Where to look for new physics?
- Dark matter:
  - Where should we look for dark matter?
  - Dark matter phenomenology can guide searches
  - Narrower searches ⇔ better odds of discovery

Outline

I. Why do we think there is “dark” matter?

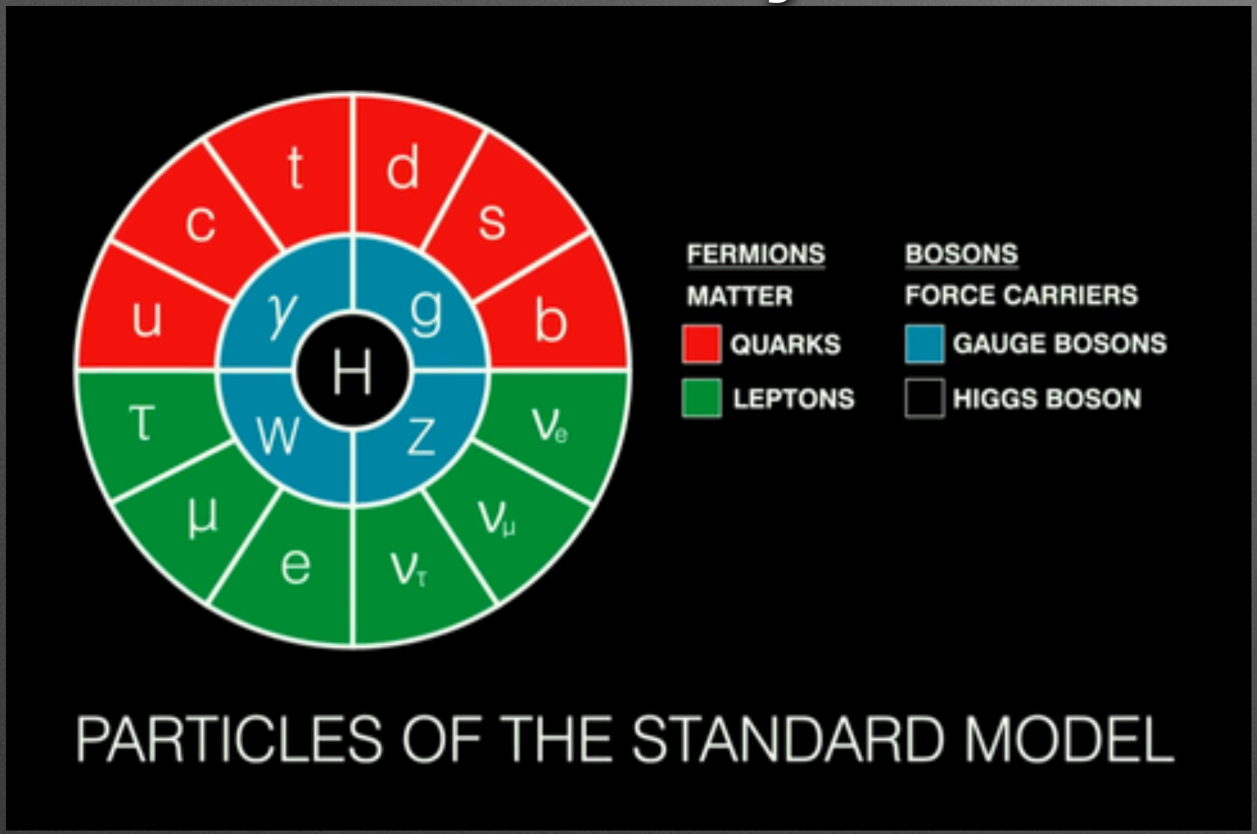
II. Neutron star constraints

III. Current and future directions

I. Why Do We Think There is “Dark” Matter?

The Standard Model

Particle Physics



⇔

Astrophysics

High energies

(colliders)

Large scales

(cosmology)

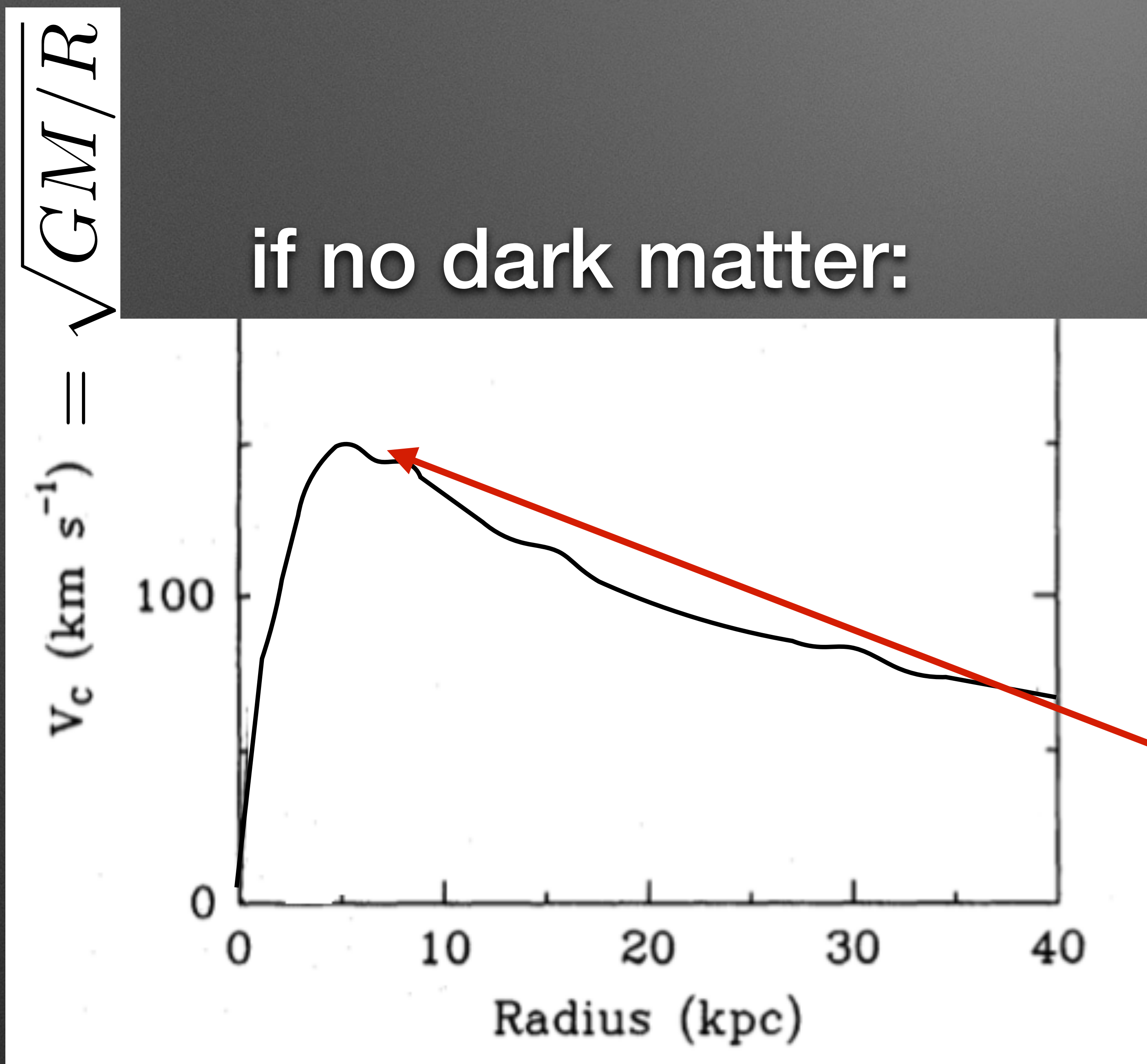
If the Universe was only the Standard Model…

- Large scales would just be gas, stars, etc.
- Galactic ***dynamics*** and ***structure*** = how much and what kind of light do galaxies give off?

Concrete predictions for how largest scale structures should behave

Prediction: Rotation Curve

if no dark matter:



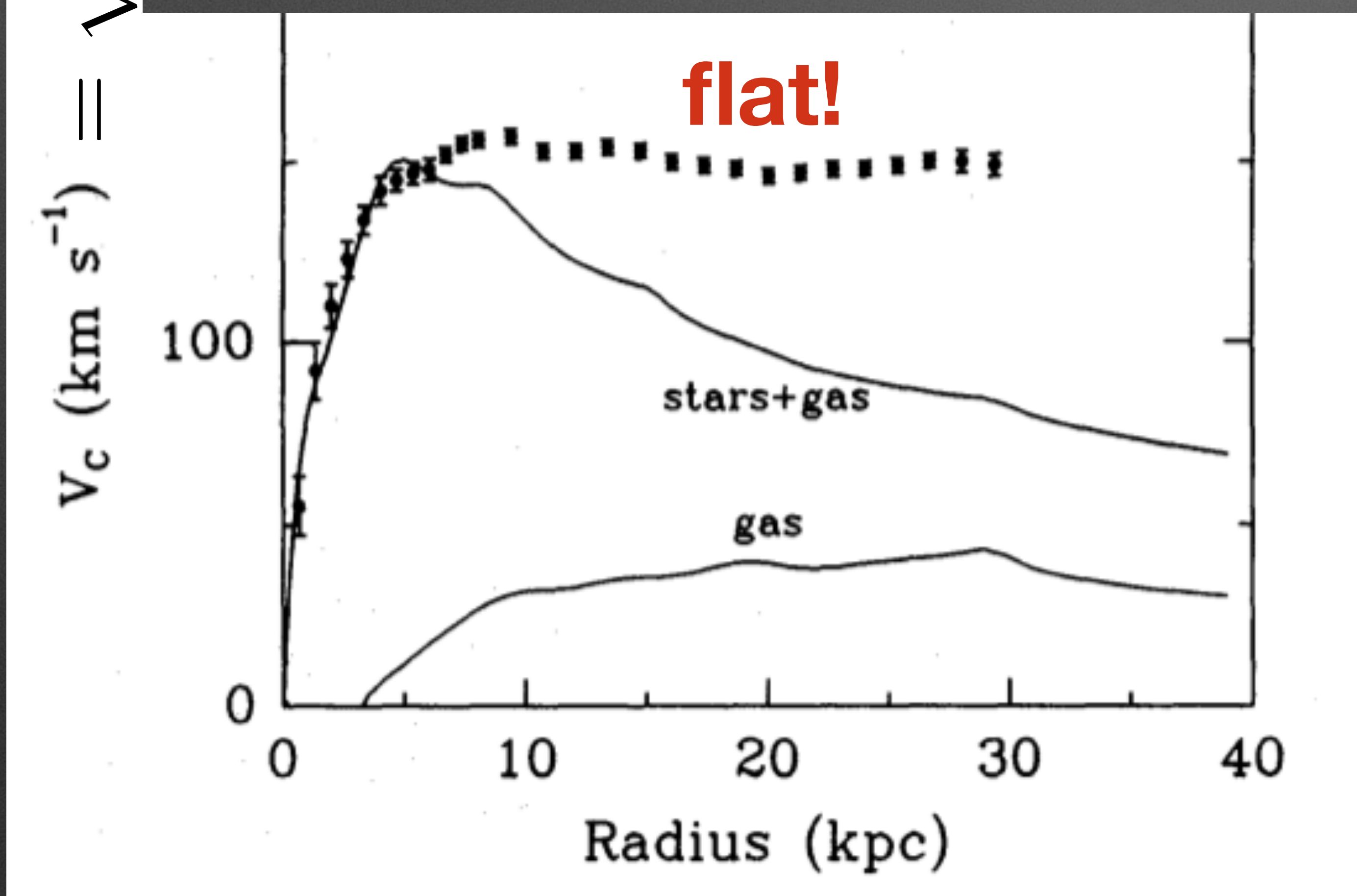
rotational velocity is a good proxy for gravitational potential

most stars (= most SM mass) are at the center of the cluster

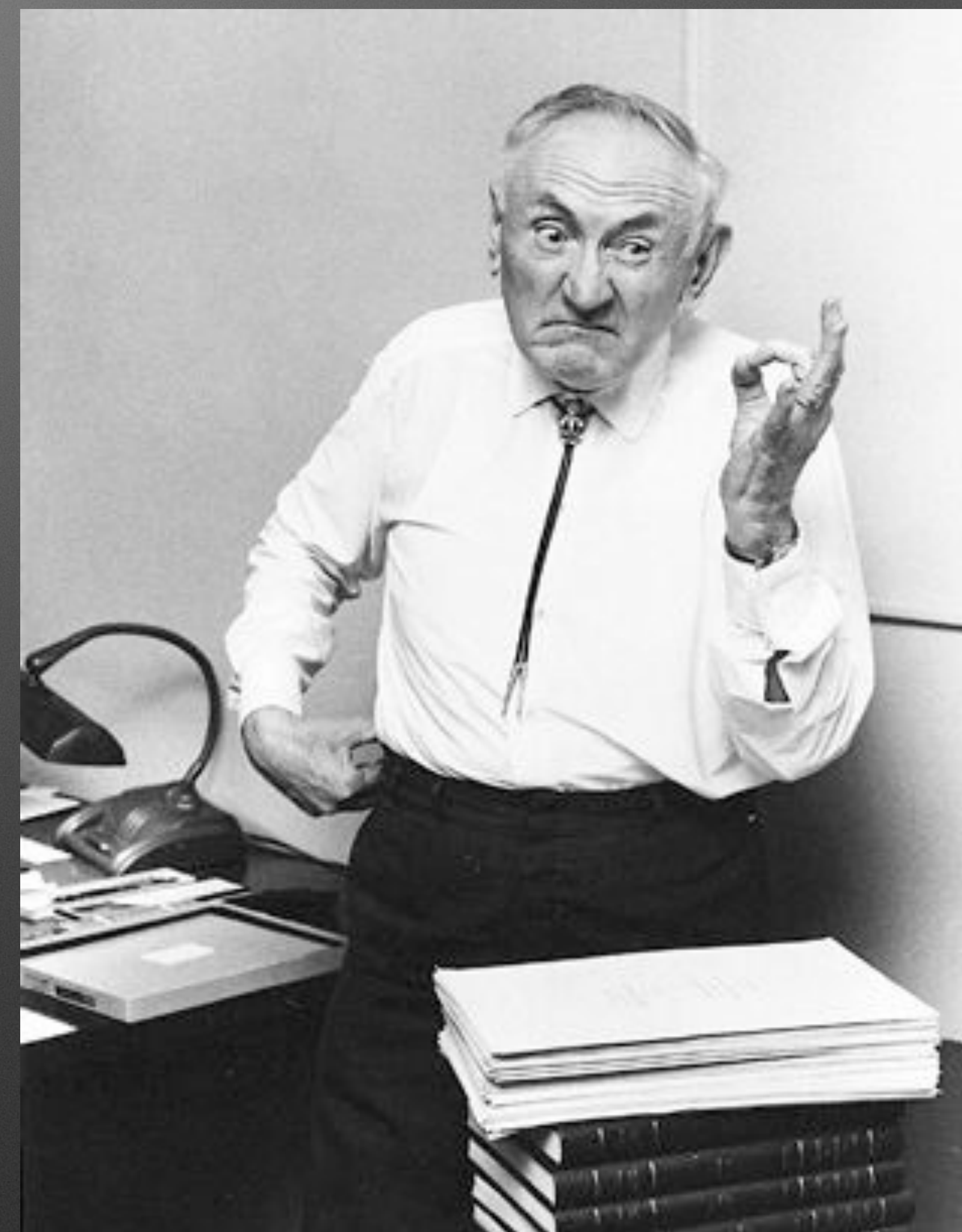
characteristic turn over point

Prediction: Rotation Curve

Zwicky (1933):
"missing mass" needed
to explain rotation curves



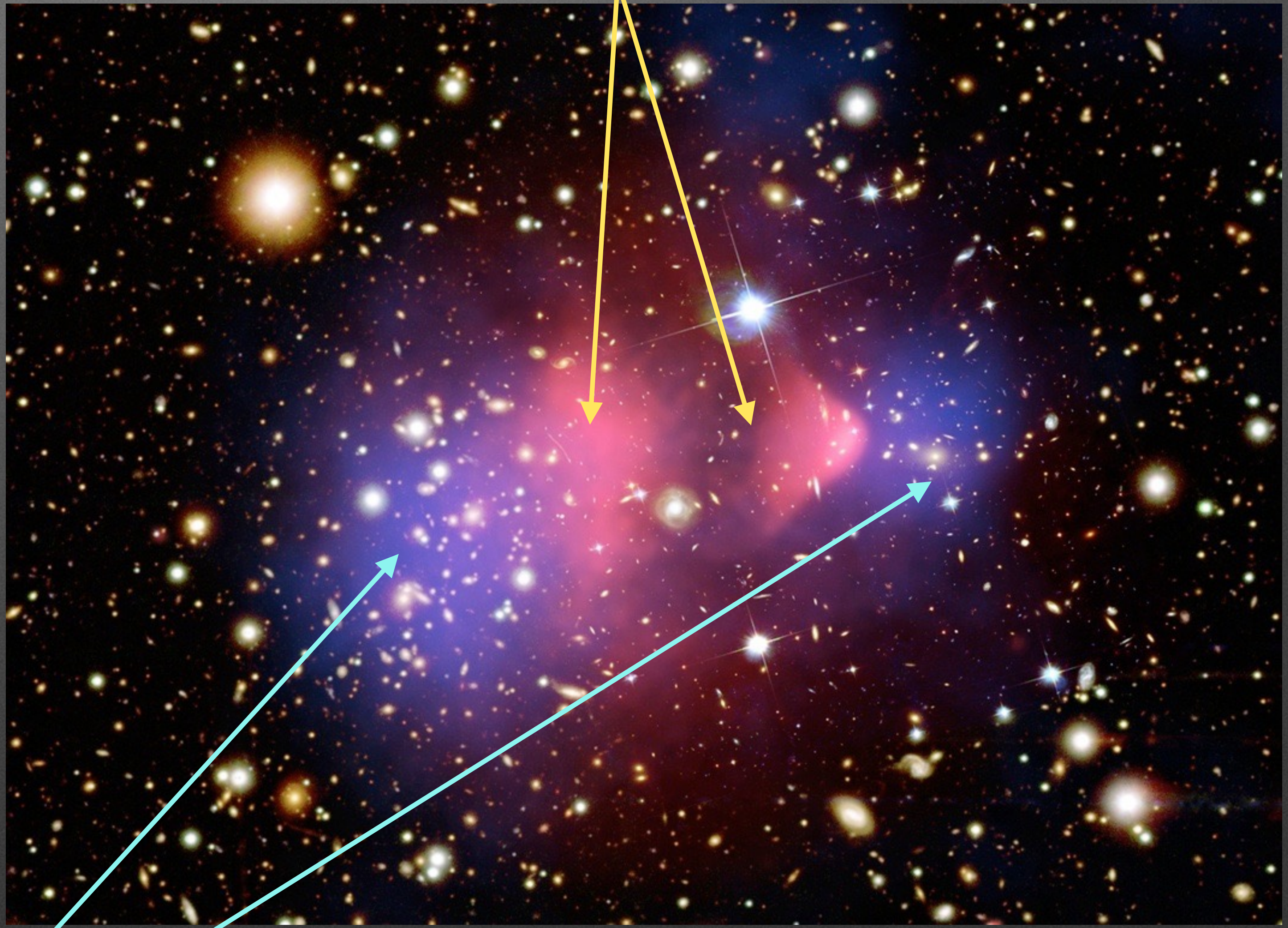
NGC3198 (Begeman 1989)



more evidence….

Bullet Cluster

most of the visible mass



The majority of the mass *does not* follow gas

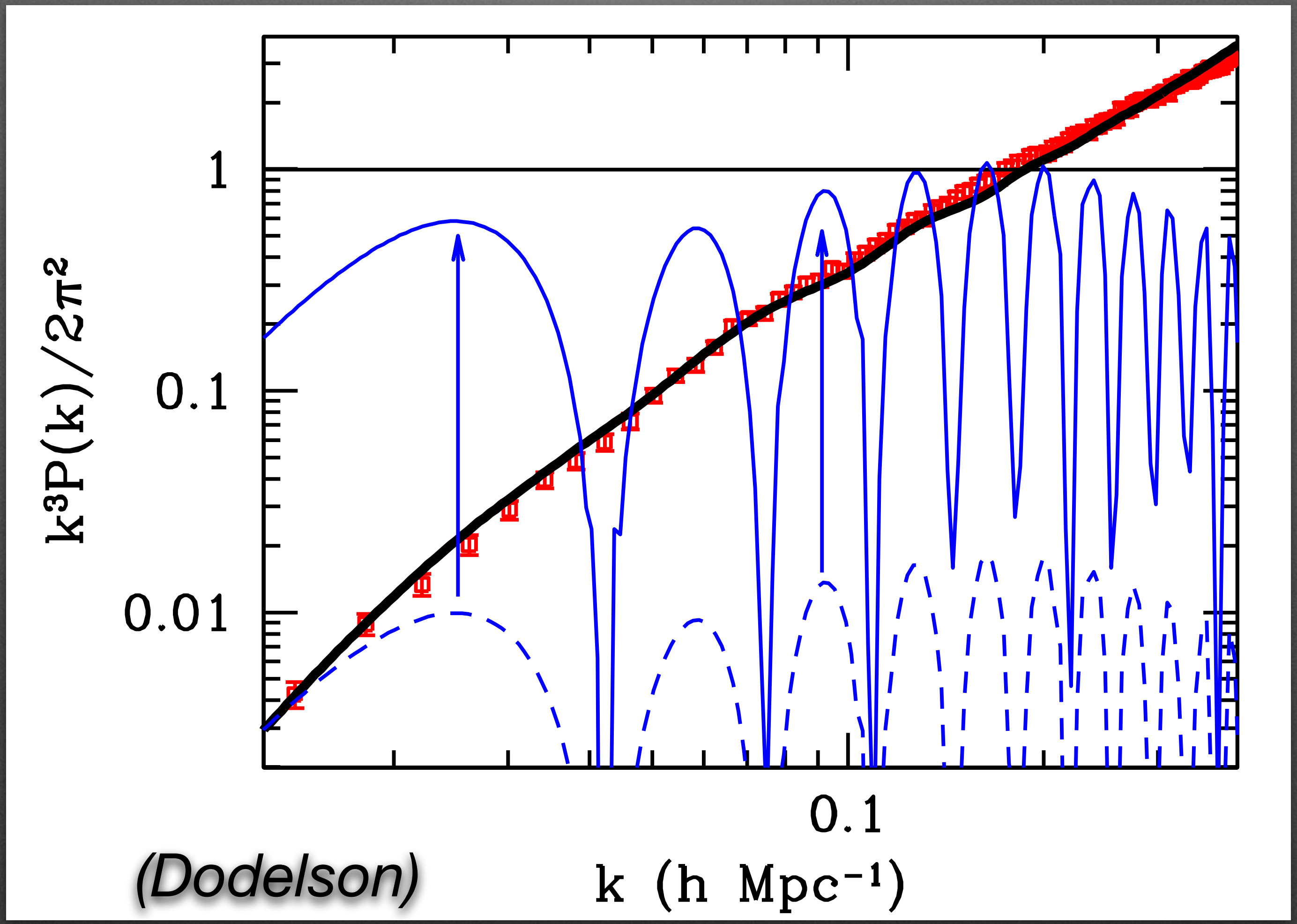
⇔

Dark matter particles rarely interact with one another

most of the mass

X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

Matter Power Spectrum

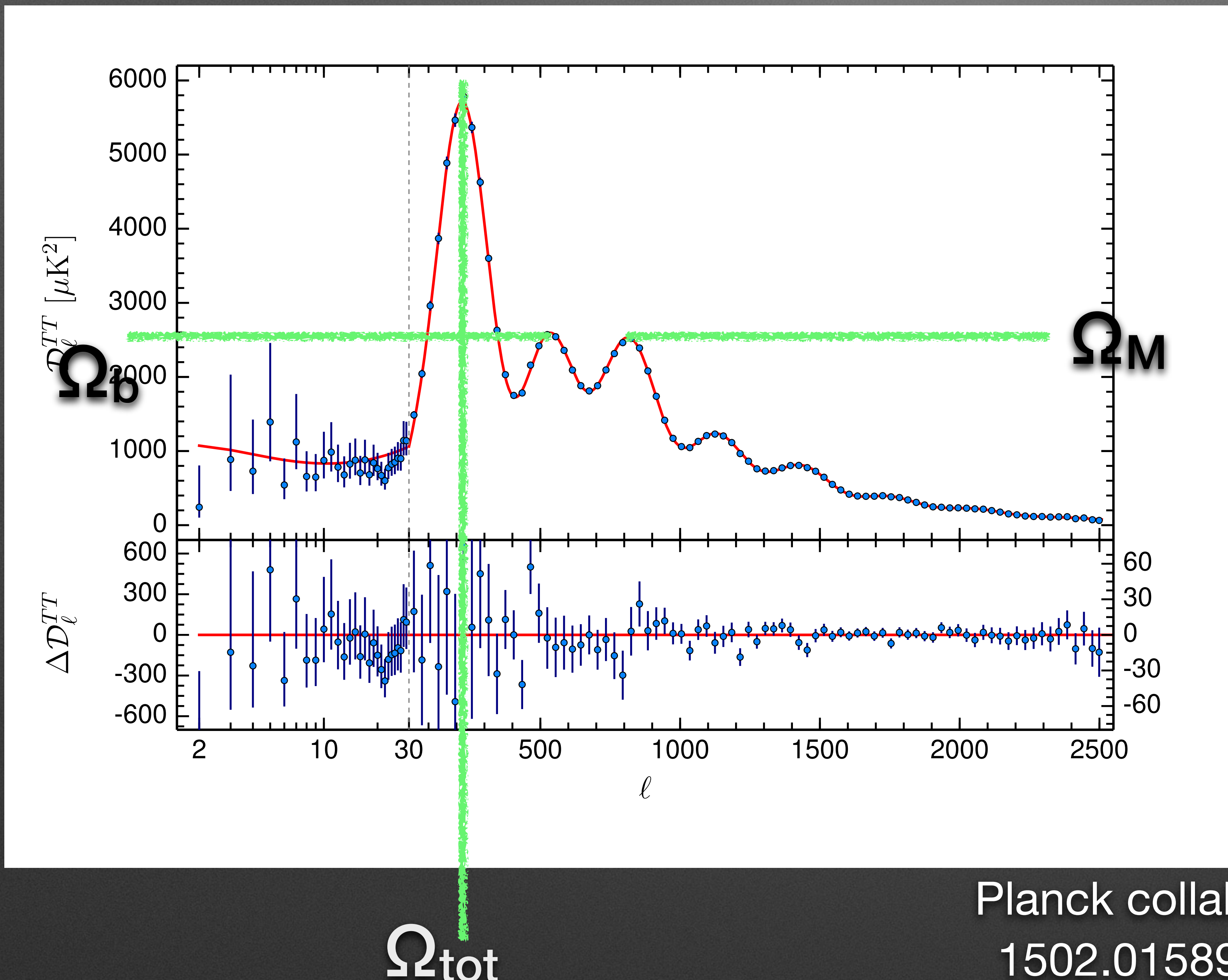


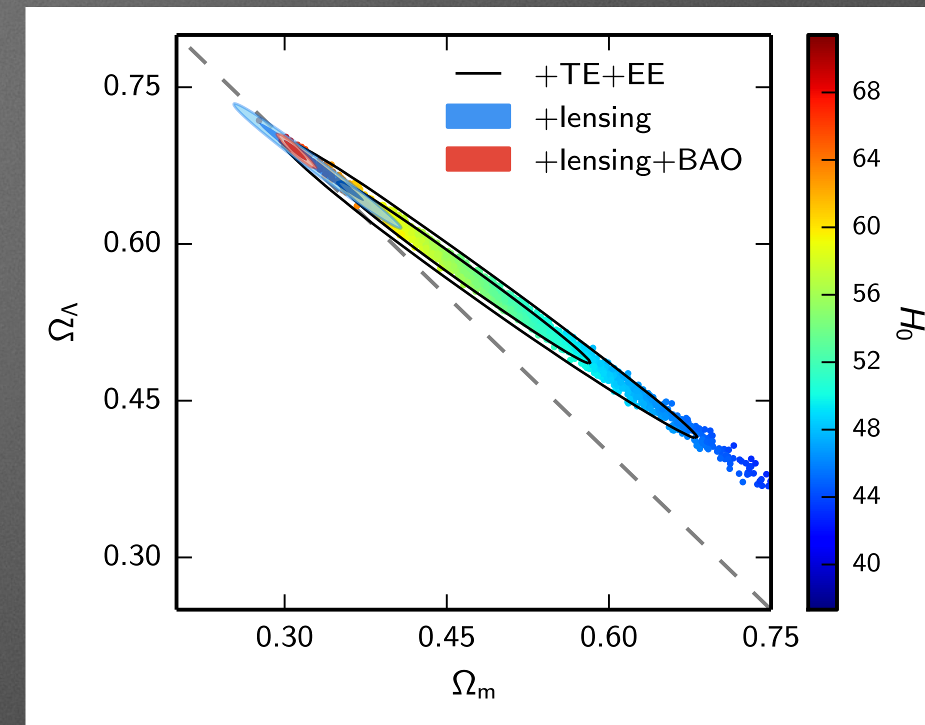
Power spectrum largely featureless

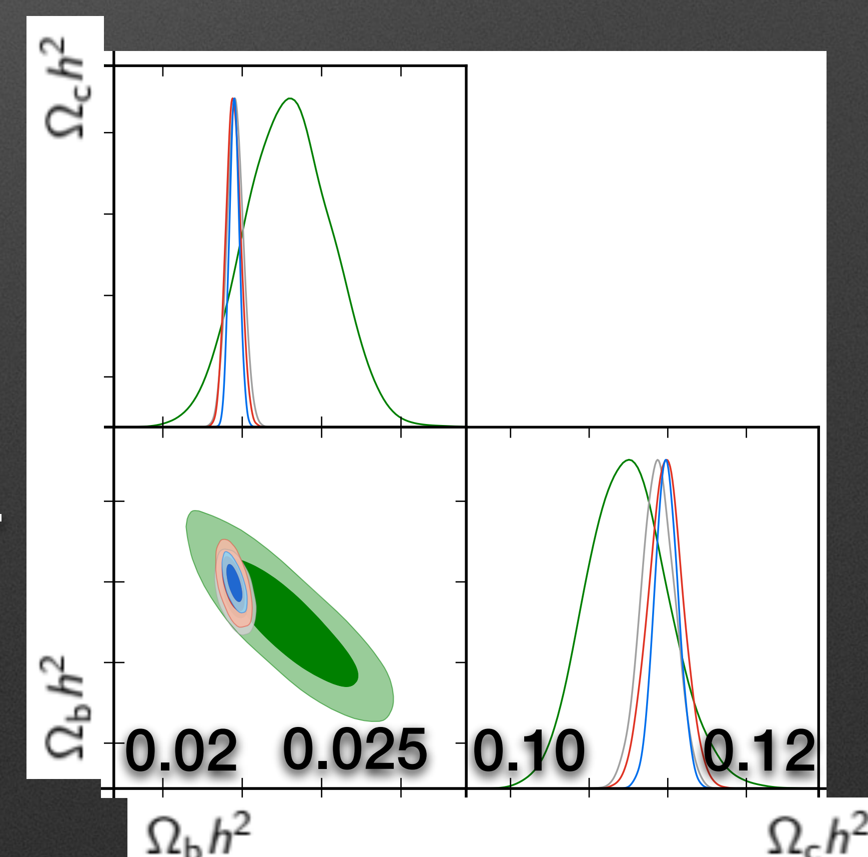
⇔

Structure formation does not rely on a light mediator

Peaks in the CMB

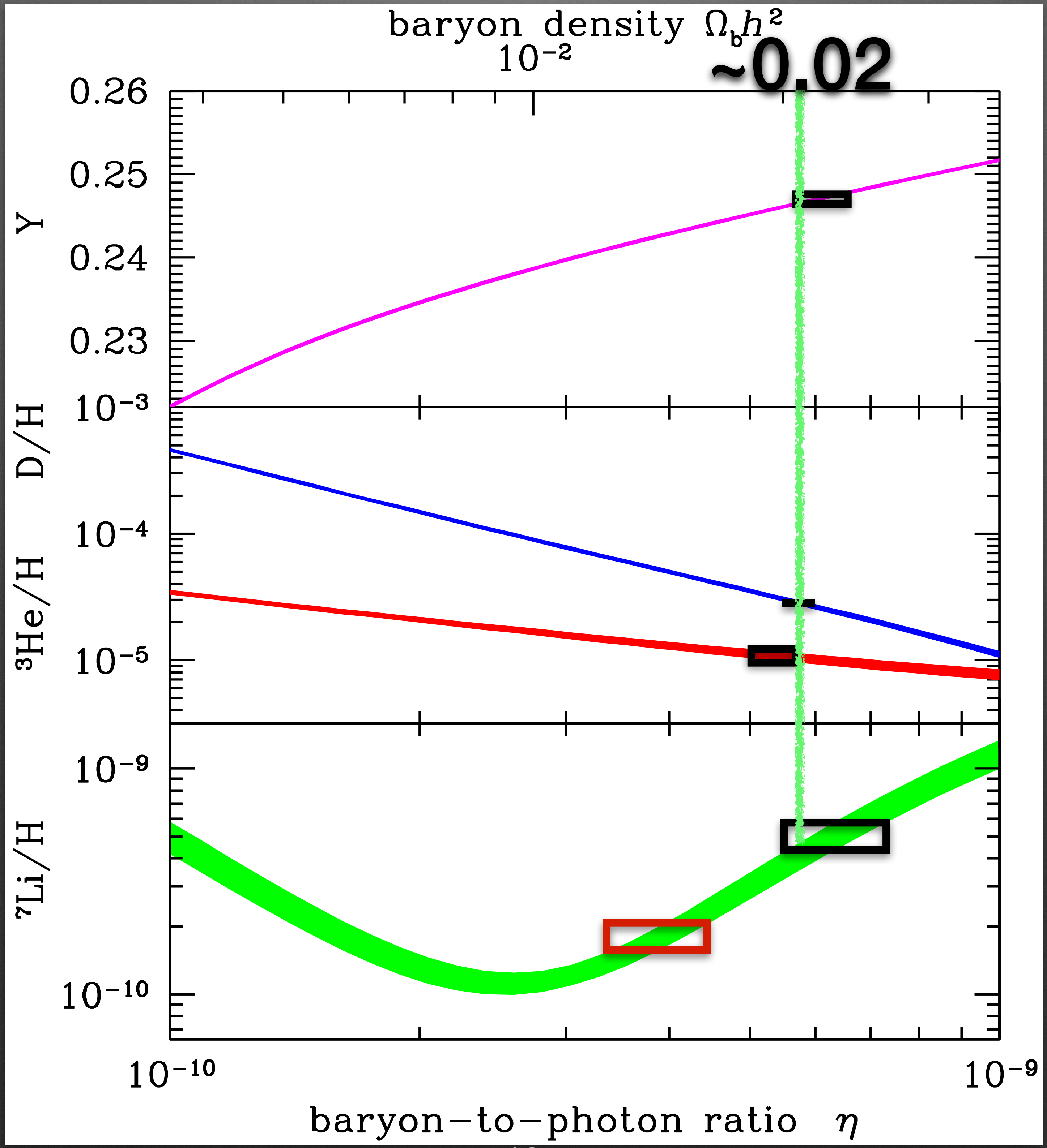






Planck collab.
1502.01589

Element Abundances



Cyburt et al
1505.01076

Dark Matter Properties

Massive particle:

- present over many cosmological epochs
- forms gravitational potentials for galaxies and galaxy clusters
- interacts more weakly than Standard Model

Dark Matter Properties

Massive particle:

- present over many cosmological epochs
- forms gravitational potentials for galaxies and galaxy clusters
- interacts more weakly than Standard Model

This is certainly something, but we'd like to know a lot more!

Dark Matter Properties

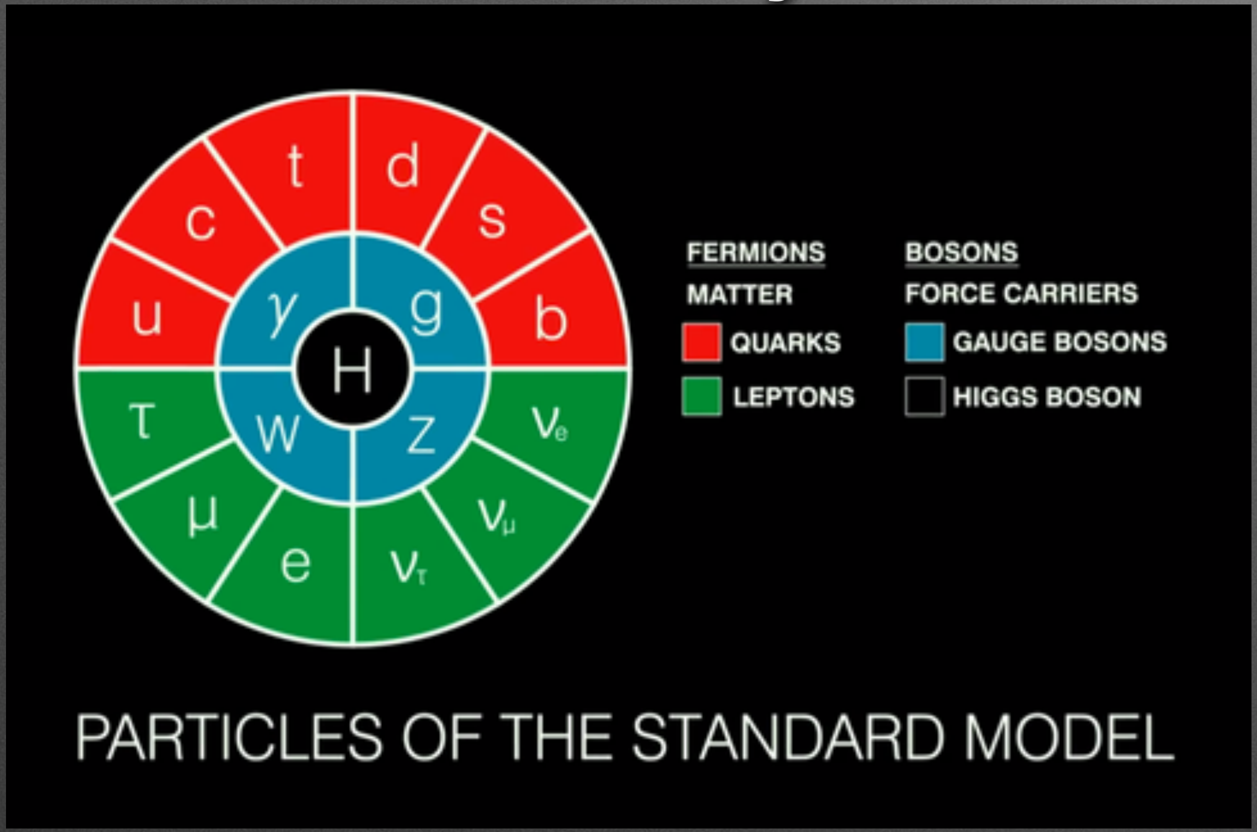
Massive particle:

- present over many cosmological epochs
- forms gravitational potentials for galaxies and galaxy clusters
- interacts more weakly than Standard Model

This is certainly something, but we'd like to know a lot more!

...mass?
...interaction channels?
...interaction cross sections?
...does it have any friends?
...how was it produced?
...where is it on the largest scales?

Particle Physics



⇔

Astrophysics

⇖ ⇗

?

Dark Matter

II. Neutron Star Constraints on Scalar Asymmetric Dark Matter

Restricting DM parameter space by considering extreme environments

from 1103.5472
with Kathryn Zurek and Hai-Bo Yu

Asymmetric Dark Matter

Baryons are asymmetric. What if Dark Matter is asymmetric, too? ***Nussinov (1985); Kaplan, Luty, Zurek (2009)...***

A: If DM / SM asymmetries are related:

$$\frac{n_{\rm DM}}{n_{\rm SM}} \sim 1 \Rightarrow \frac{\Omega_{\rm DM}}{\Omega_{\rm SM}} \sim \frac{m_{\rm DM}}{m_{\rm SM}}$$

B: Collections of ADM particles will not self-annihilate

Accumulation of ADM

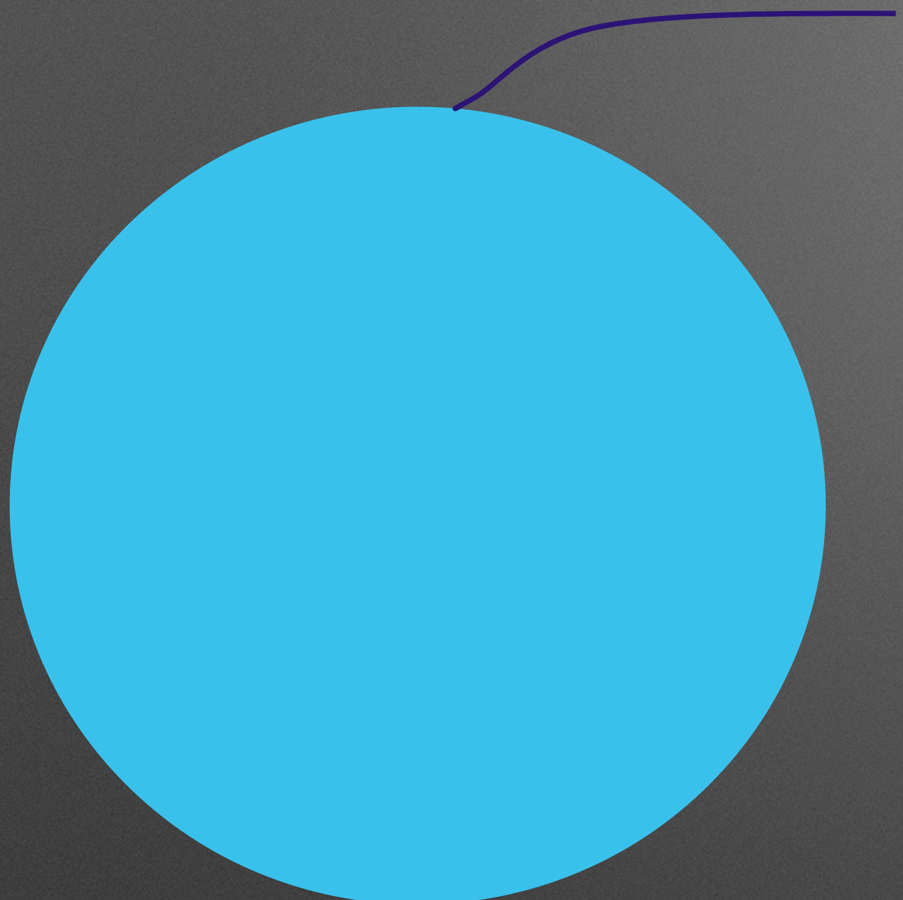
Over time, dense environments will accumulate many ADM particles:

$M_\odot$	Mass	$1.4 M_\odot$
$10^3 \mathrm{kg/m^3}$	density	$10^{18} \mathrm{kg/m^3}$
$\sim 2 \times 10^{-3}\ c$	v_{esc}	$\sim .6\ c$

Easy to pass through

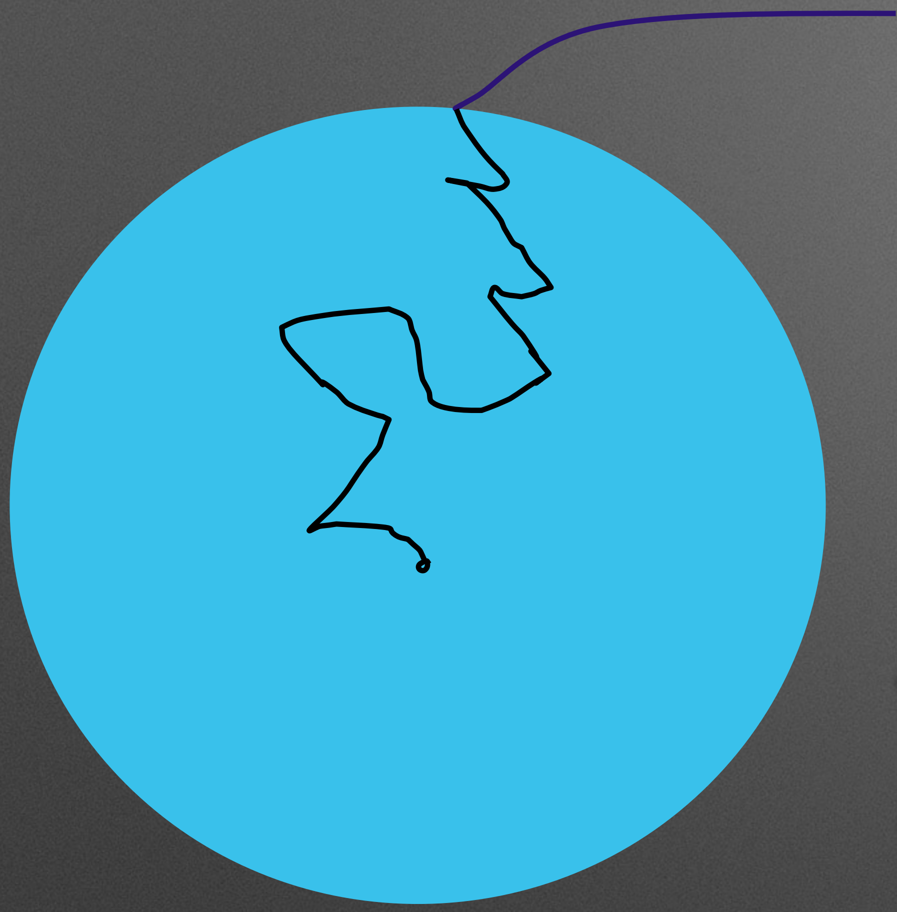
scatters more, harder to escape

ADM in the Neutron Star
I : Capture



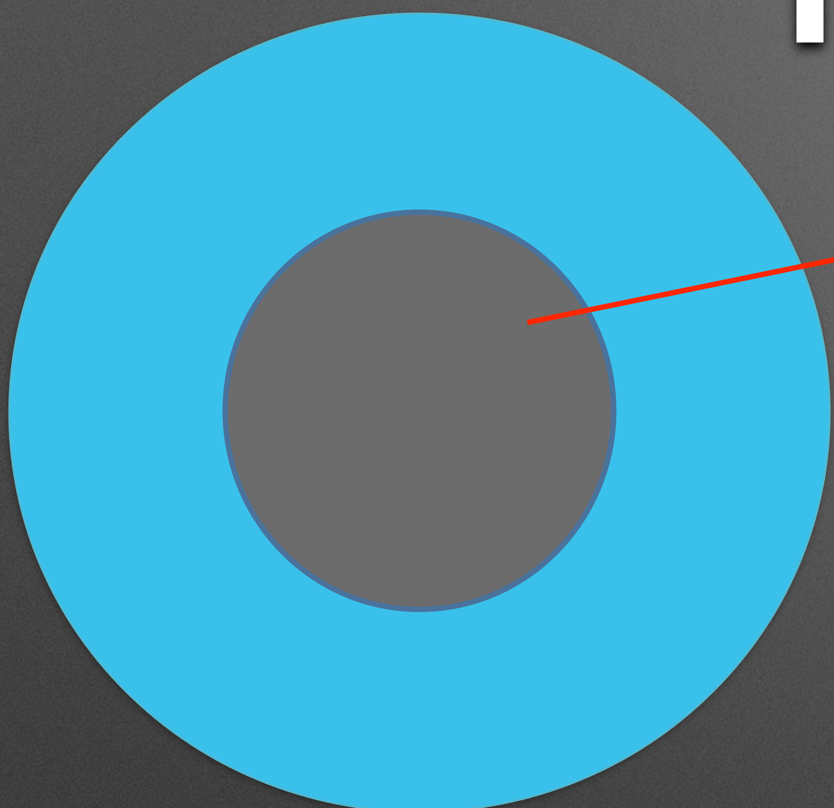
The differential capture rate per unit volume sets the total number of particles

ADM in the Neutron Star
II : Thermalization



The ADM particle will scatter many times with SM particles, eventually attaining thermal equilibrium

ADM in the Neutron Star III : Self-Gravitation



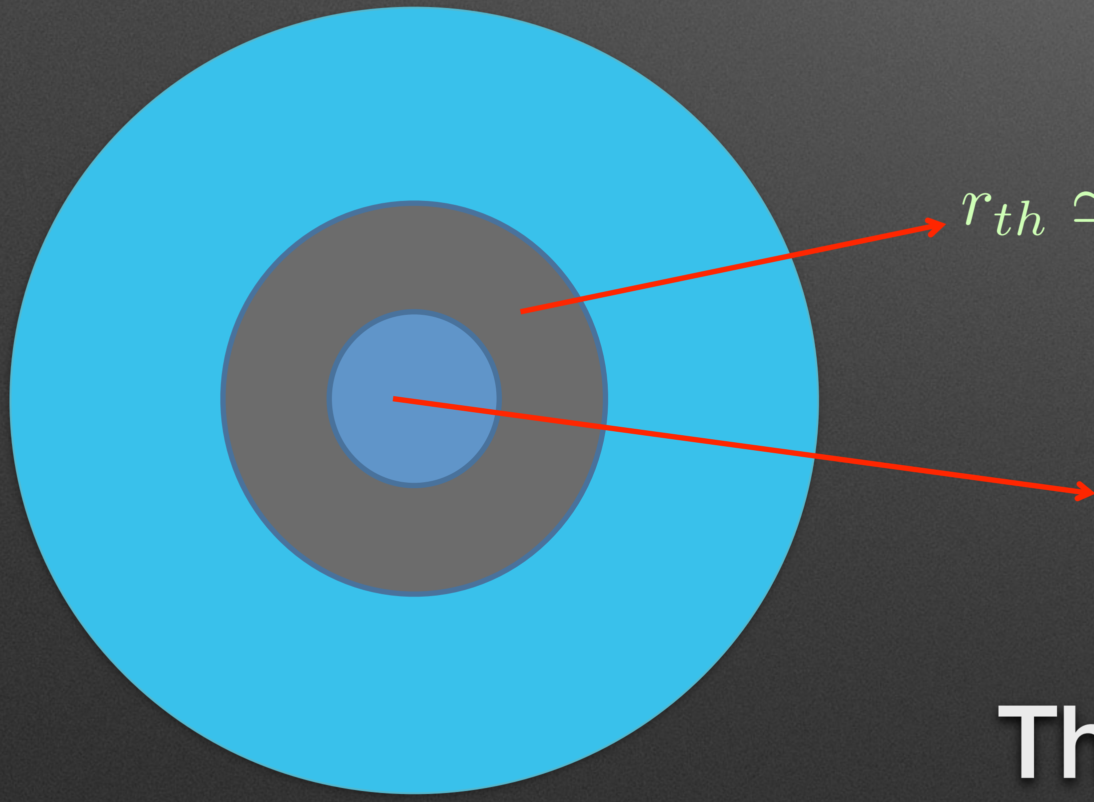
$$\frac{3N_X m_X}{4\pi r_{th}^3} \gtrsim \rho_B$$

Self-gravity sets in when the density of ADM particles within the thermal radius exceeds the baryon density

Too many particles will lead to gravitational collapse!

ADM in the Neutron Star IIIb : Condensation

Under the right conditions, a Bose-Einstein condensate (BEC) can form



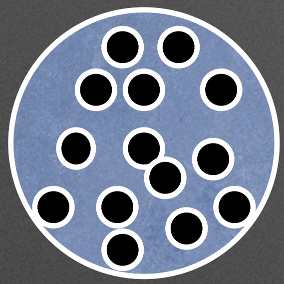
$$r_{th} \simeq 24 \text{ cm} \left(\frac{T}{10^5 \ K} \cdot \frac{100 \text{ GeV}}{m_X} \right)^{1/2}$$

$$r_{BEC} \simeq 1.5 \times 10^{-5} \text{ cm} \left(\frac{100 \text{ GeV}}{m_X} \right)^{1/2}$$

The BEC is much denser than the thermal state!

The Chandrasekhar Limit

Gravity vs. Fermi pressure



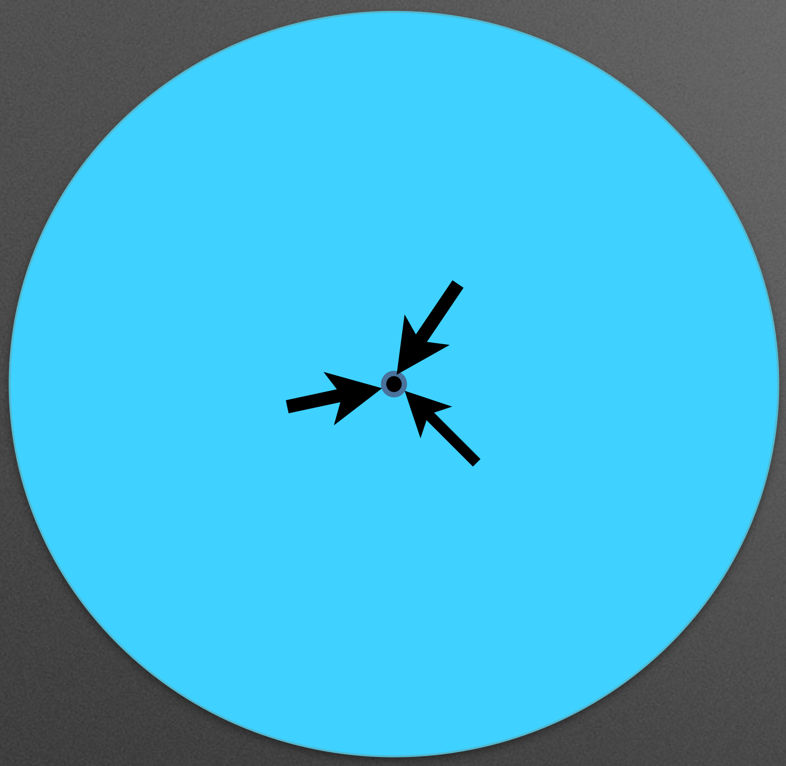
Fermions: $$E \sim -\frac{GNm^2}{R} + \frac{N^{1/3}}{R}$$

$$N_{Cha}^{fermion} \sim \left(\frac{M_{pl}}{m}\right)^3 \simeq 1.8 \times 10^{51} \left(\frac{100\ \text{GeV}}{m}\right)^3$$

Bosons: $$E \sim -\frac{GNm^2}{R} + \frac{1}{R}$$

$$N_{Cha}^{boson} \sim \left(\frac{M_{pl}}{m}\right)^2 \simeq 1.5 \times 10^{34} \left(\frac{100\ \text{GeV}}{m}\right)^2$$

Gravitational Collapse



If the self-gravitating mass exceeds the Chandrasekhar limit, ADM collapses!

BEC black hole (stronger for low mass ADM):

$$t_{\mathrm{BEC}} < t_{\mathrm{self}} < t_{\mathrm{Cha}}$$

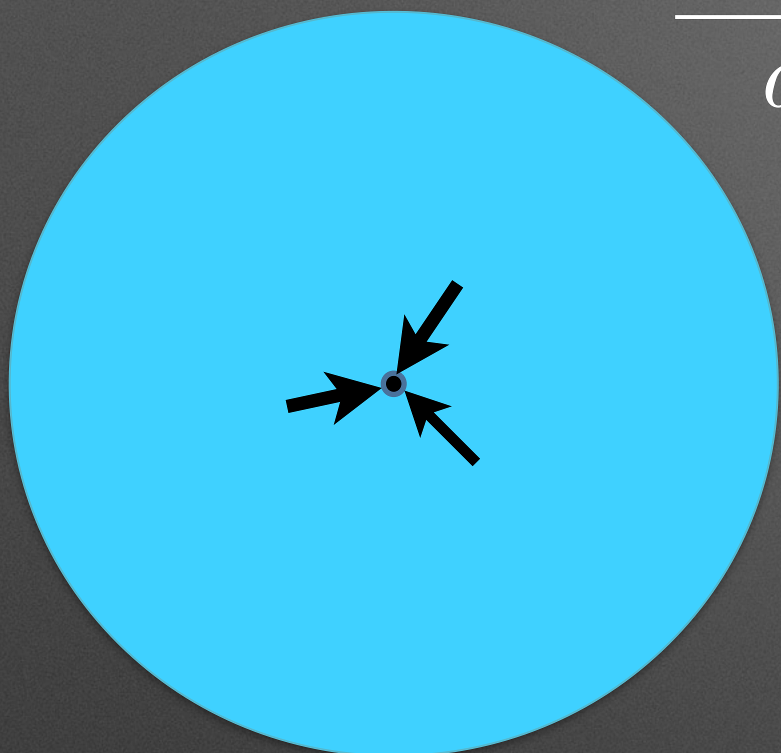
$$t_{\mathrm{self}} < t_{\mathrm{BEC}} < t_{\mathrm{Cha}}$$

conventional black hole (stronger for high mass ADM):

$$t_{\mathrm{Cha}} < t_{\mathrm{self}} < t_{\mathrm{BEC}}$$

Collapse happens for a wide range of masses!

Black Hole Mass Accretion



$$\frac{dM_{\rm BH}}{dt} = 4\pi\lambda_s \left(\frac{GM_{\rm BH}}{c_s^2}\right)^2 \rho_{\rm B} c_s + \left(\frac{dM_{\rm BH}}{dt}\right)_{\rm DM} - \frac{1}{15360\pi G^2 M_{\rm BH}^2}$$

Eating baryons

Eating ADM

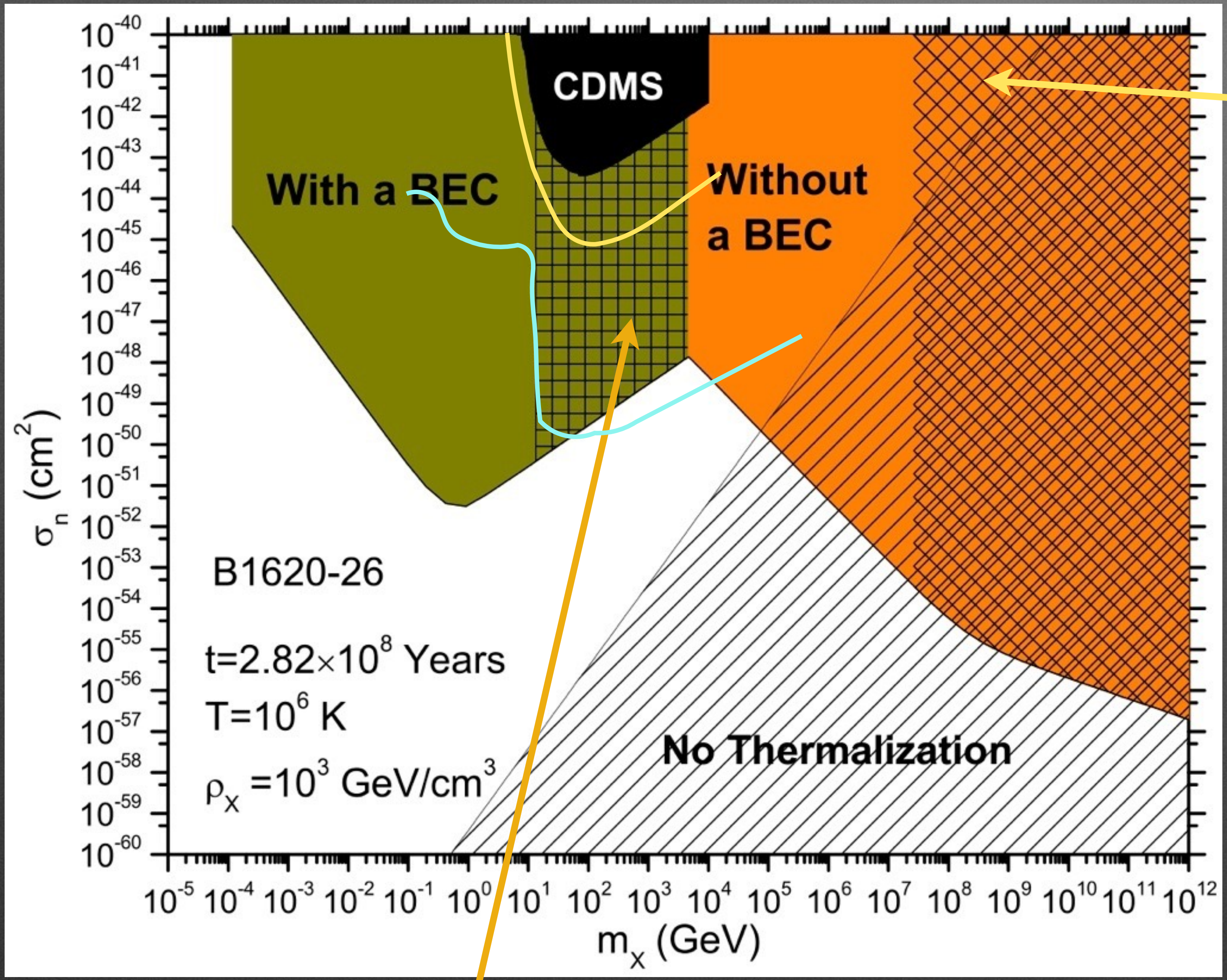
Hawking Evaporation

RHS must be positive for BH to survive. The critical initial mass is:

$$M_{BH}^{crit} \simeq 1.2 \times 10^{37}\ \mathrm{GeV}$$

$$m_X \lesssim 2.6 \times 10^6\ \mathrm{GeV}(\mathrm{T}/10^5\mathrm{K})$$

Constraints from M4

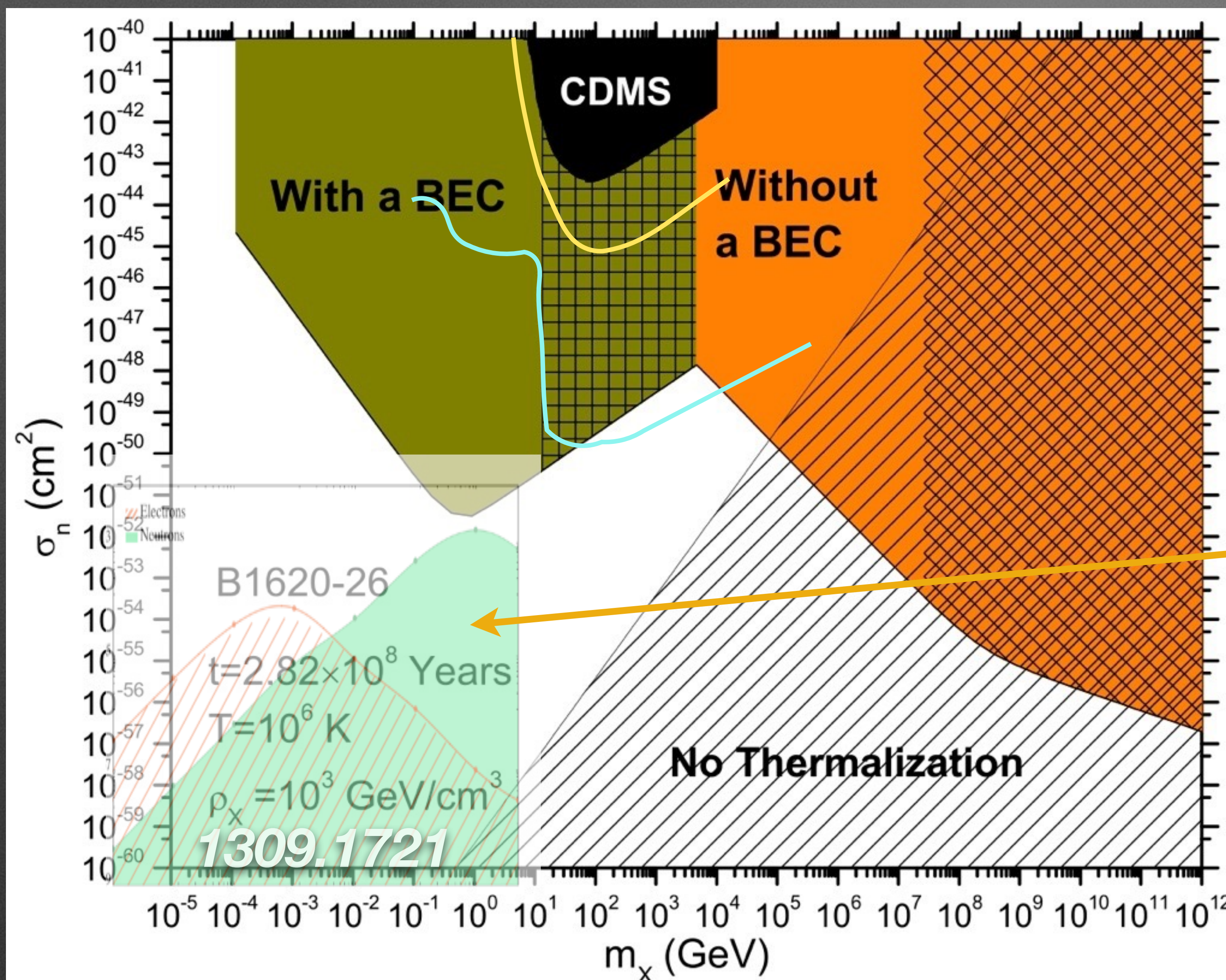


initial black hole mass below critical value

Hawking radiation may be important

Very strong constraints, but slightly uncertain local values

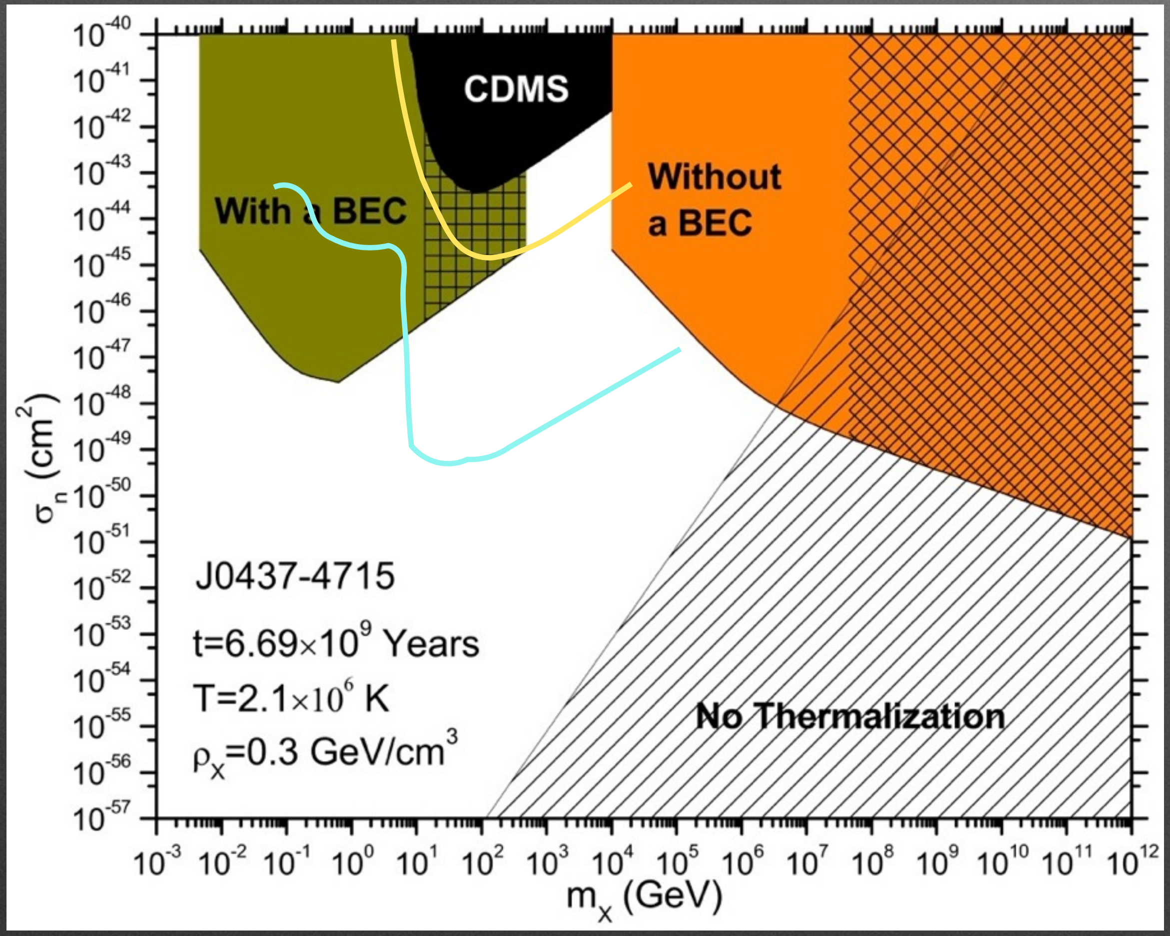
Constraints from M4

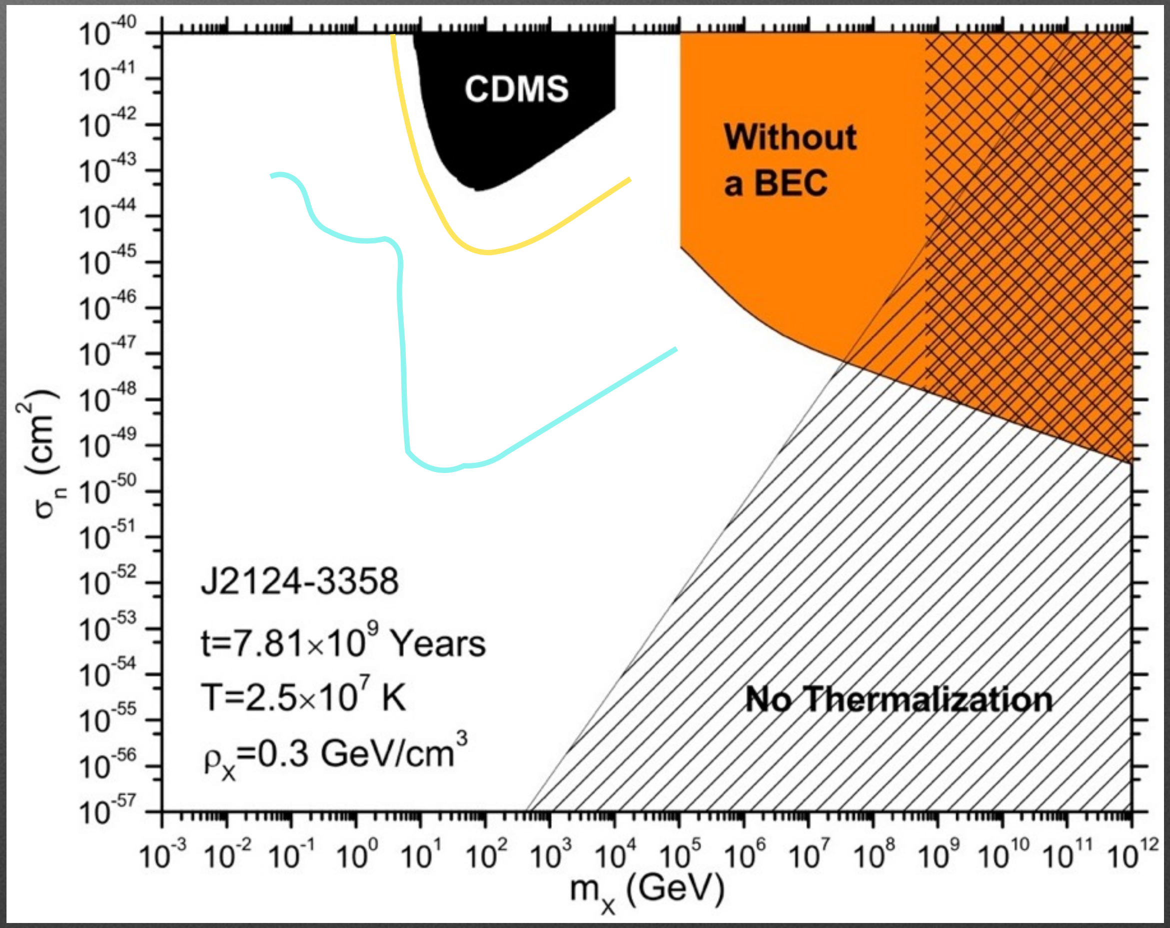


Related (prior) work: Kouvaris + Tinyakov: *1012.2039*; Goldman + Nussinov, 1989

Additional related work: Bertoni, Nelson, Reddy: *1309.1721*; Kouvaris + Tinyakov: *1104.0382*, *1111.4364*, *1312.3764*; Bramante, Kumar et al: *1301.0026*, *1310.3509*; Bell, Melatos, Petraki: *1301.6811*; Goldman, Mohapatra, Nussinov, et al: *1305.6908*; Bramante, *1505.07464*

Constraints from nearby pulsars





Constraints somewhat weaker, but more reliable

Conclusions

- Dark matter is not identical to the Standard Model — but it still might be quite interesting

- Strong bounds if dark matter has no Fermi pressure and doesn't annihilate — constrains asymmetric dark matter theories

Looking Forward…

- Lots of exciting prospects
  - new searches
  - new model building
- Will we find dark matter soon?

Thank you!

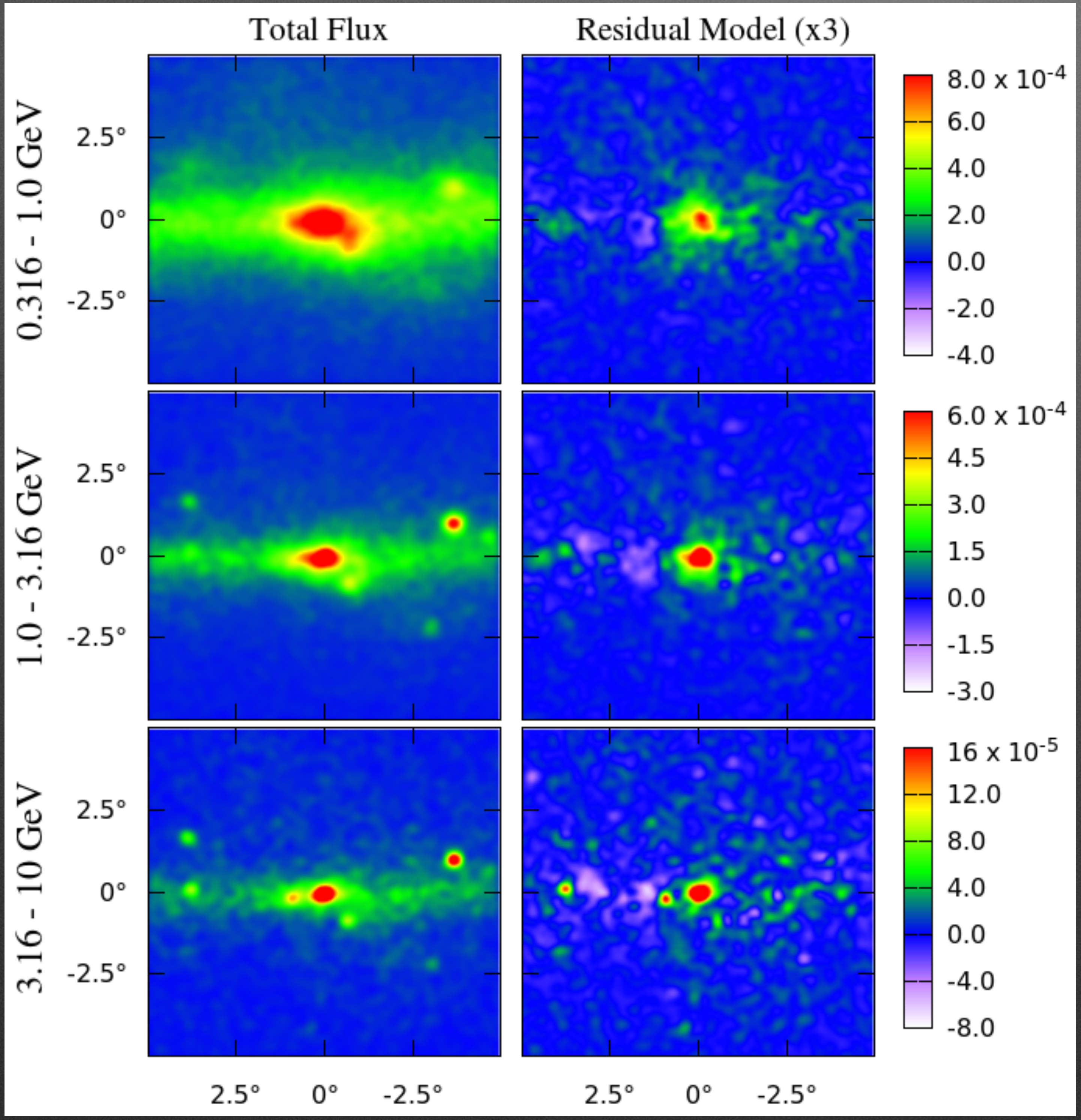
Thanks to everyone, especially:

my advisors, Kathryn Zurek and Dan Hooper;
my collaborators on these and other projects;
Fermilab and URA

Bonus: Current and future directions

Simplified Dark Matter Models for the Galactic Center Gamma-Ray Excess
from 1404.0022,
with Asher Berlin and Dan Hooper
and
Image Processing in the Galactic Center
upcoming work with Paddy Fox and Ilias Cholis

Extra Gamma Rays



excess with normalization ~ 30% of raw!

could this be from dark matter?

Current Technique

Test *assumption of dark matter annihilation*:

- statistical discrimination (χ^2 test) between fits with and without dark matter template
- fits with template do better

Current Technique

Test *assumption of dark matter annihilation*:

- statistical discrimination (χ^2 test) between fits with and without dark matter template
- fits with template do better

…but what if there is a *totally different shape* on the sky that was not adequately tested?

Current Technique

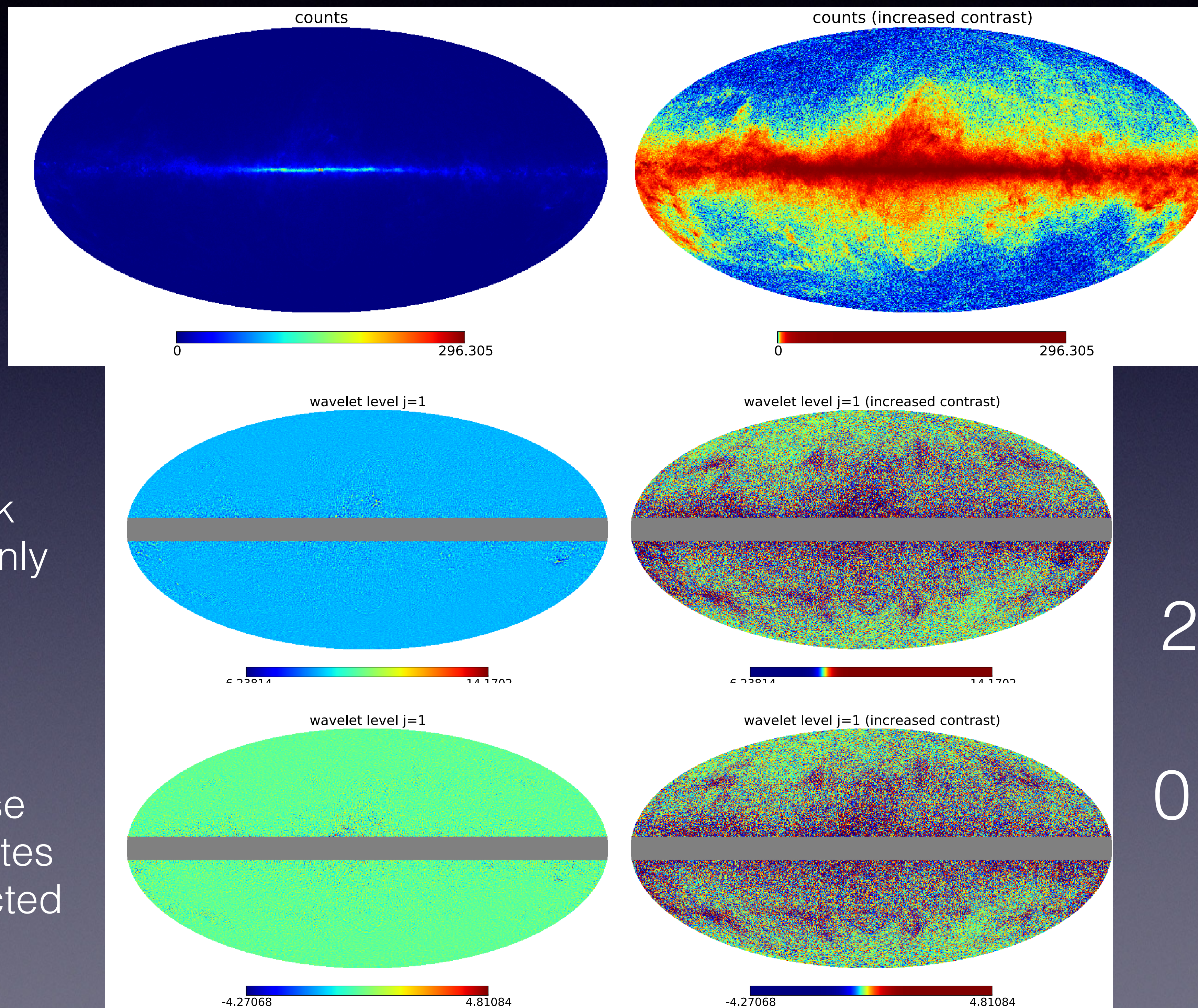
Test *assumption of dark matter annihilation*:

- … ween … late
- …

It would be nice to find evidence without making this assumption!

…but what if there is a *totally different shape* on the sky that was not adequately tested?

Example (mock data)



ℓ_{max}=512

mock data only

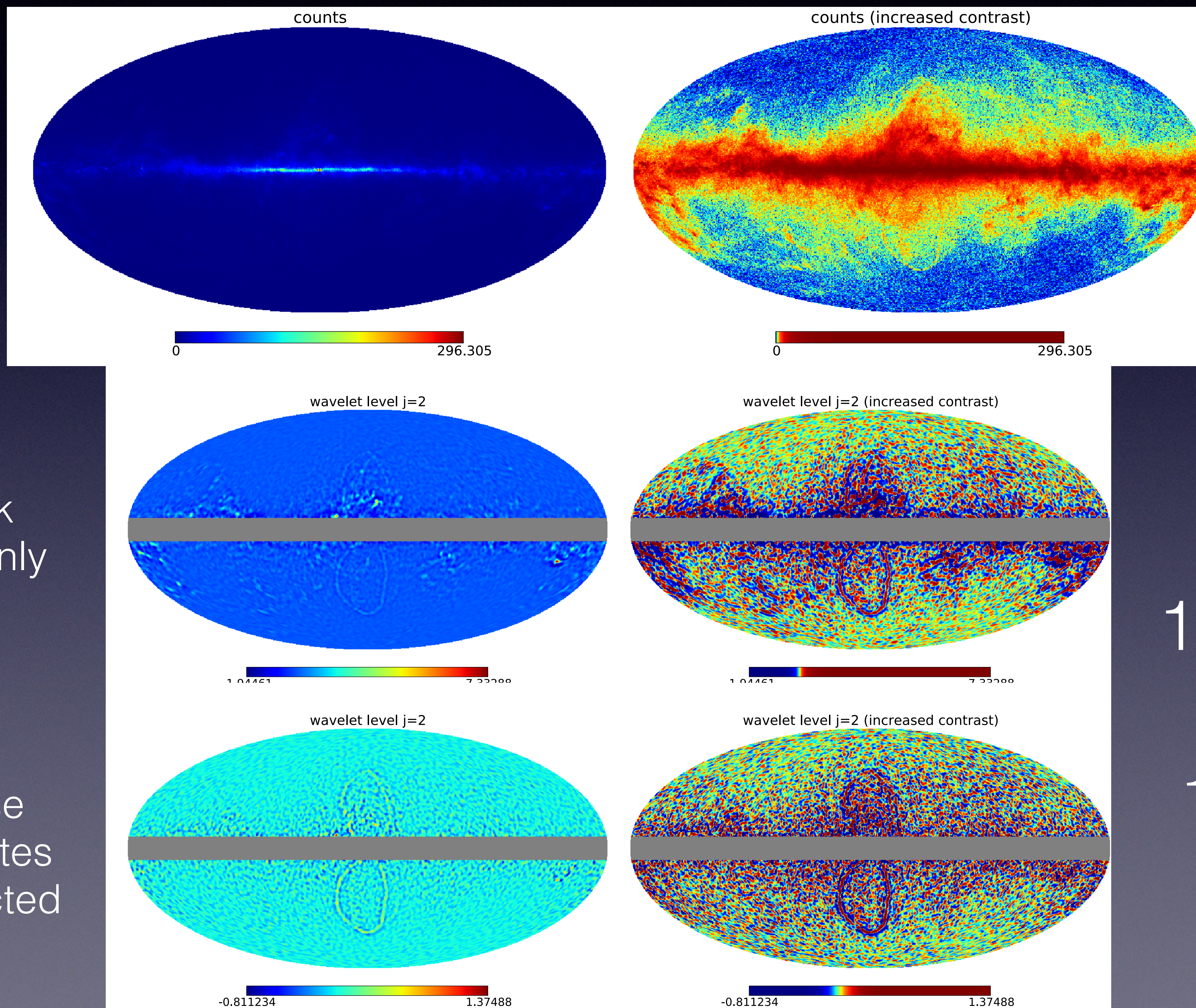
diffuse templates subtracted

$256<\ell<512$

$\Downarrow$

$0.7^\circ<\theta<1.4^\circ$

Example (mock data)



$\ell_{max}=512$

mock data only

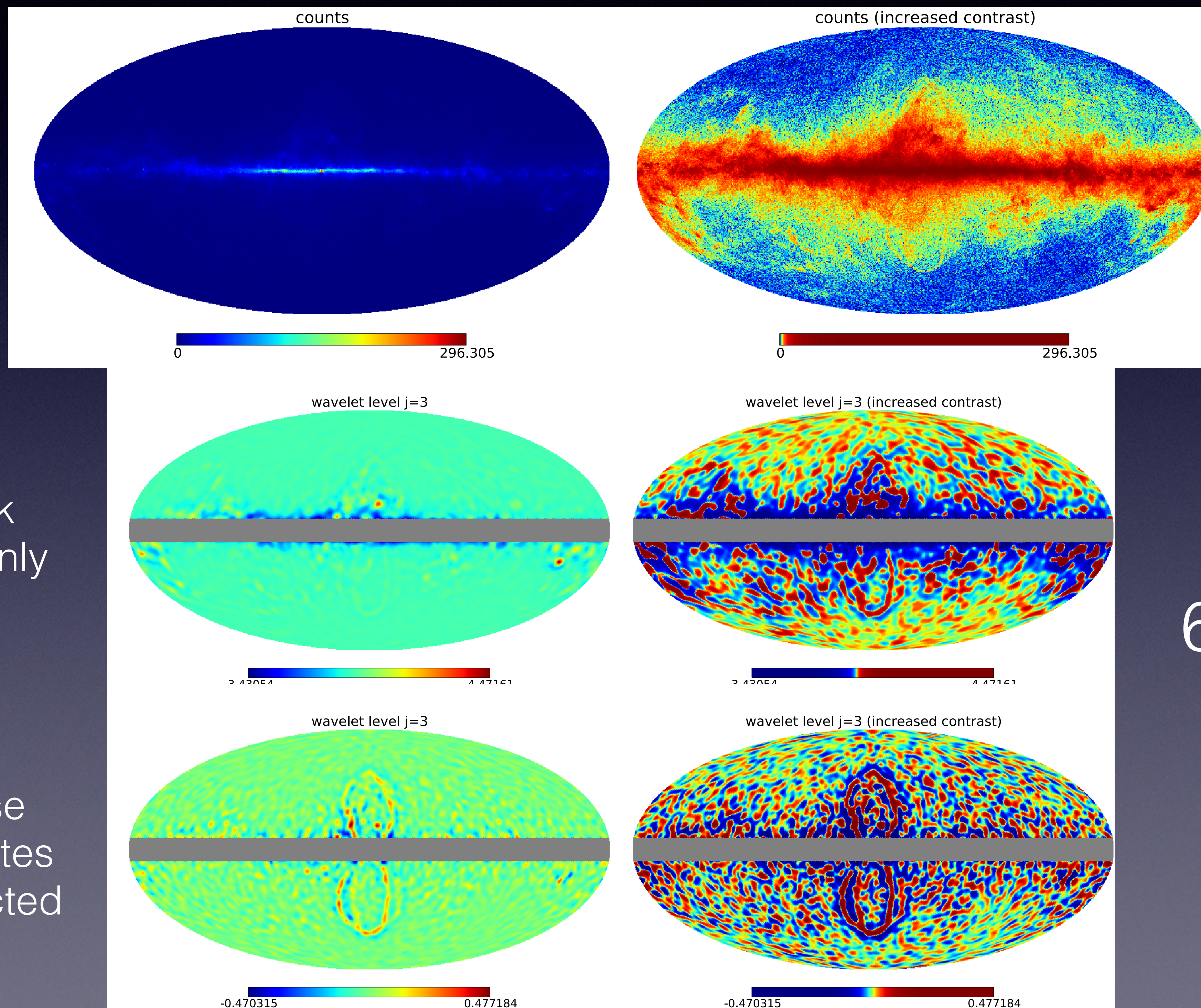
diffuse templates subtracted

$128<\ell<256$

$\Downarrow$

$1.4^\circ<\theta<3^\circ$

Example (mock data)



$\ell_{max}=512$

mock
data only

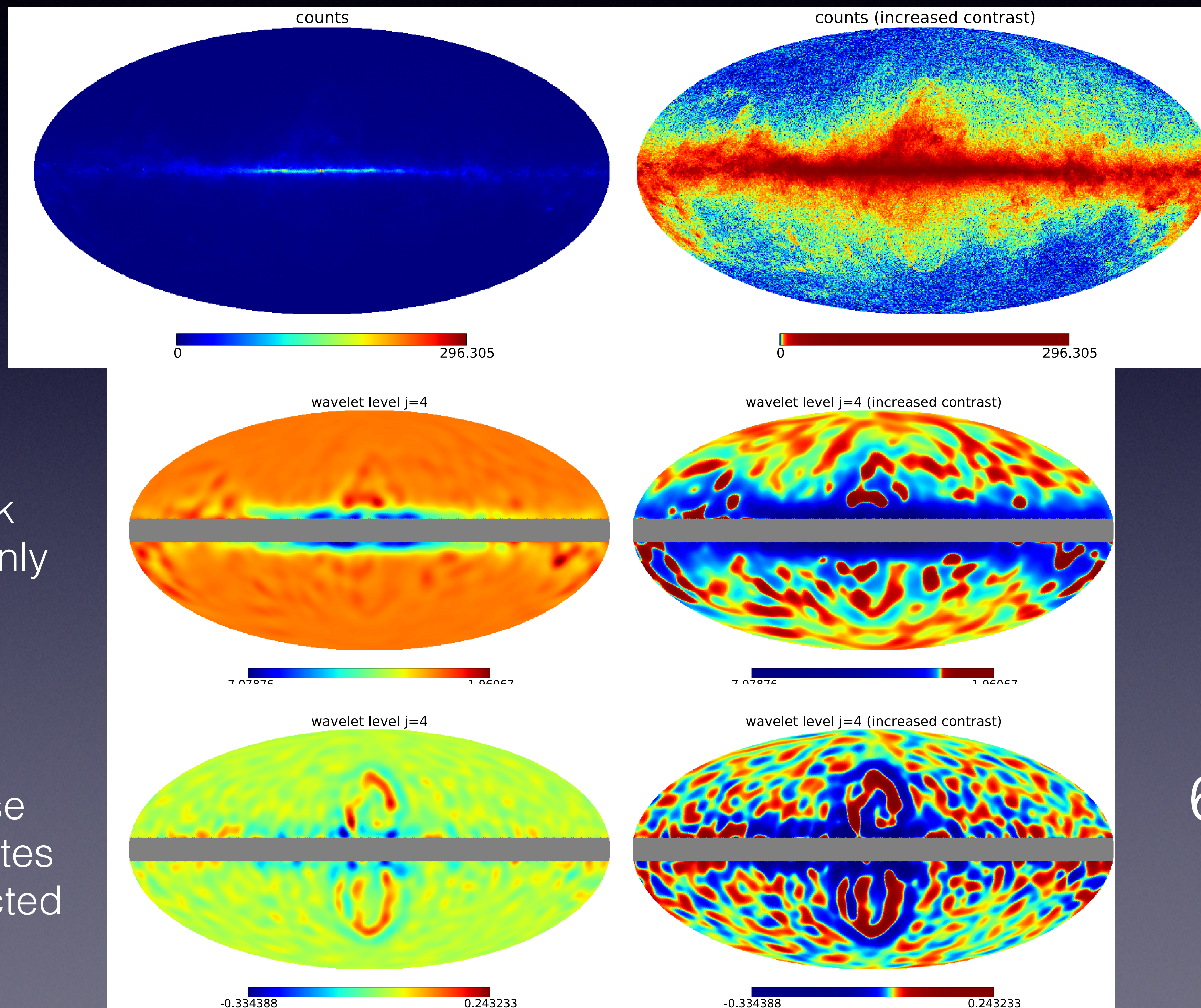
diffuse
templates
subtracted

$64<\ell<128$

$\Downarrow$

$3^{\circ}<\theta<6^{\circ}$

Example (mock data)



$\ell_{max}=512$

mock data only

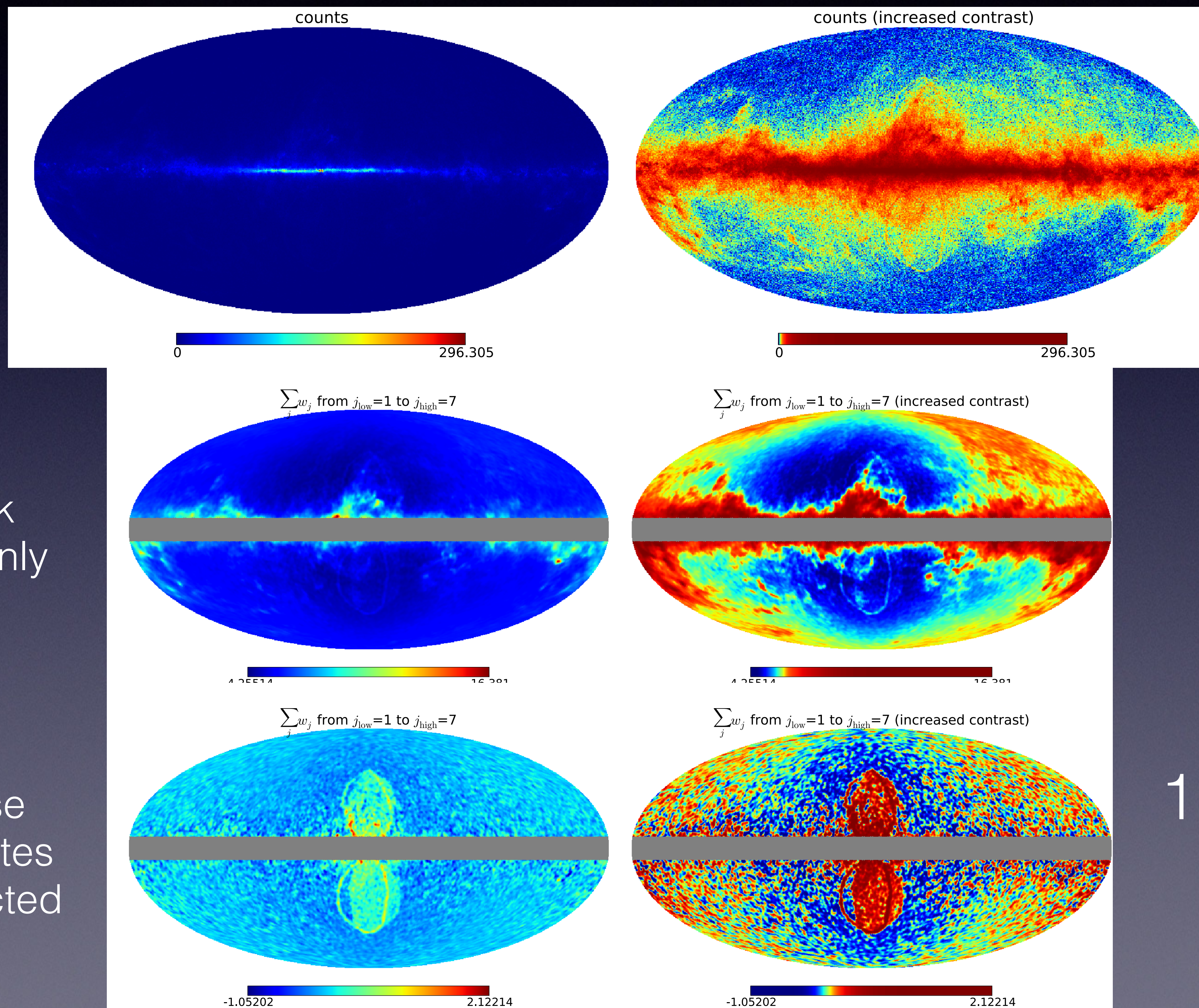
diffuse templates subtracted

$32<\ell<64$

$\Downarrow$

$6^\circ<\theta<10^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only

diffuse
templates
subtracted

$4<\ell<256$

$\Downarrow$

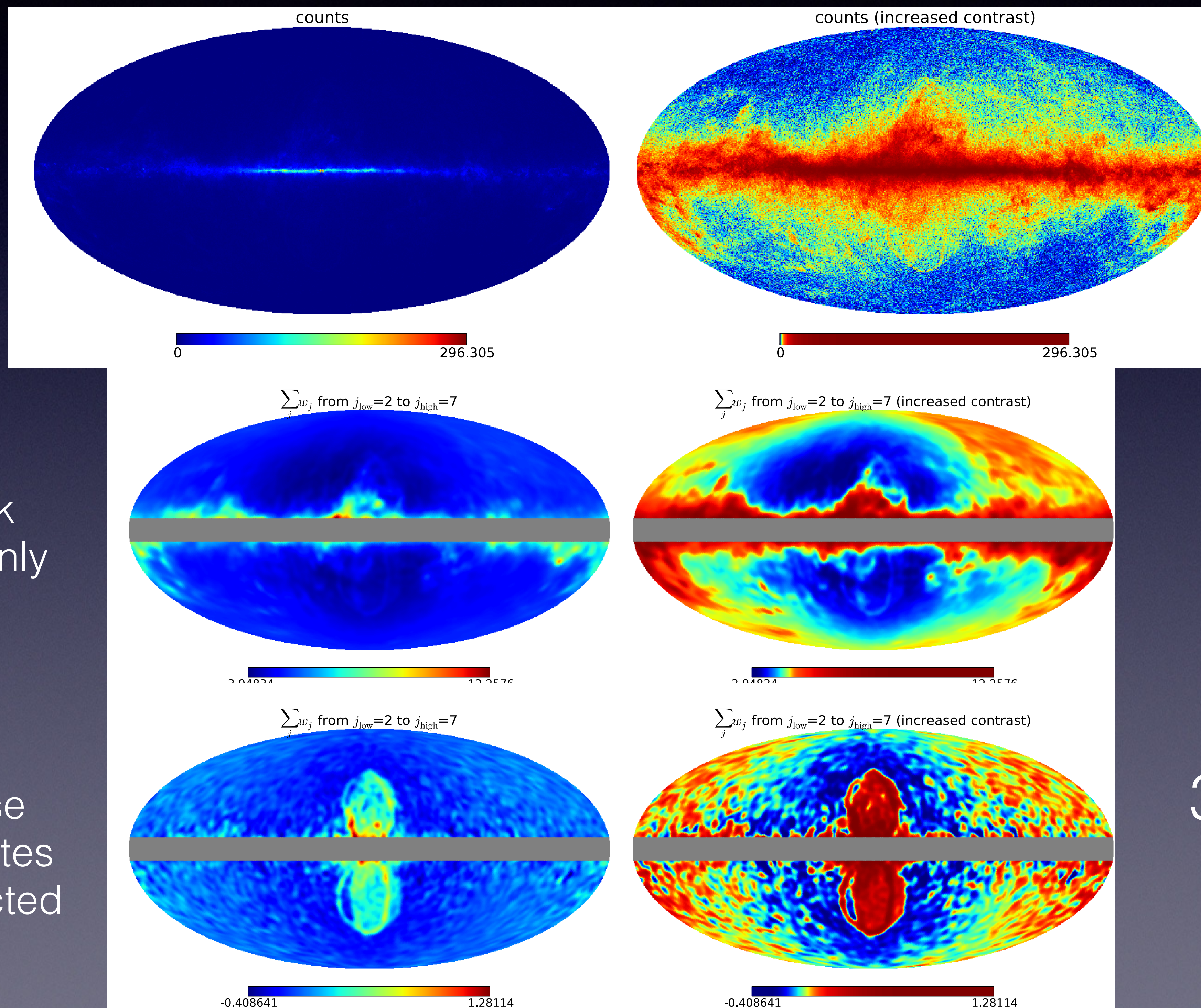
$1.4^\circ<\theta<90^\circ$

Example (mock data)

ℓ_{max}=512

mock
data only

diffuse
templates
subtracted

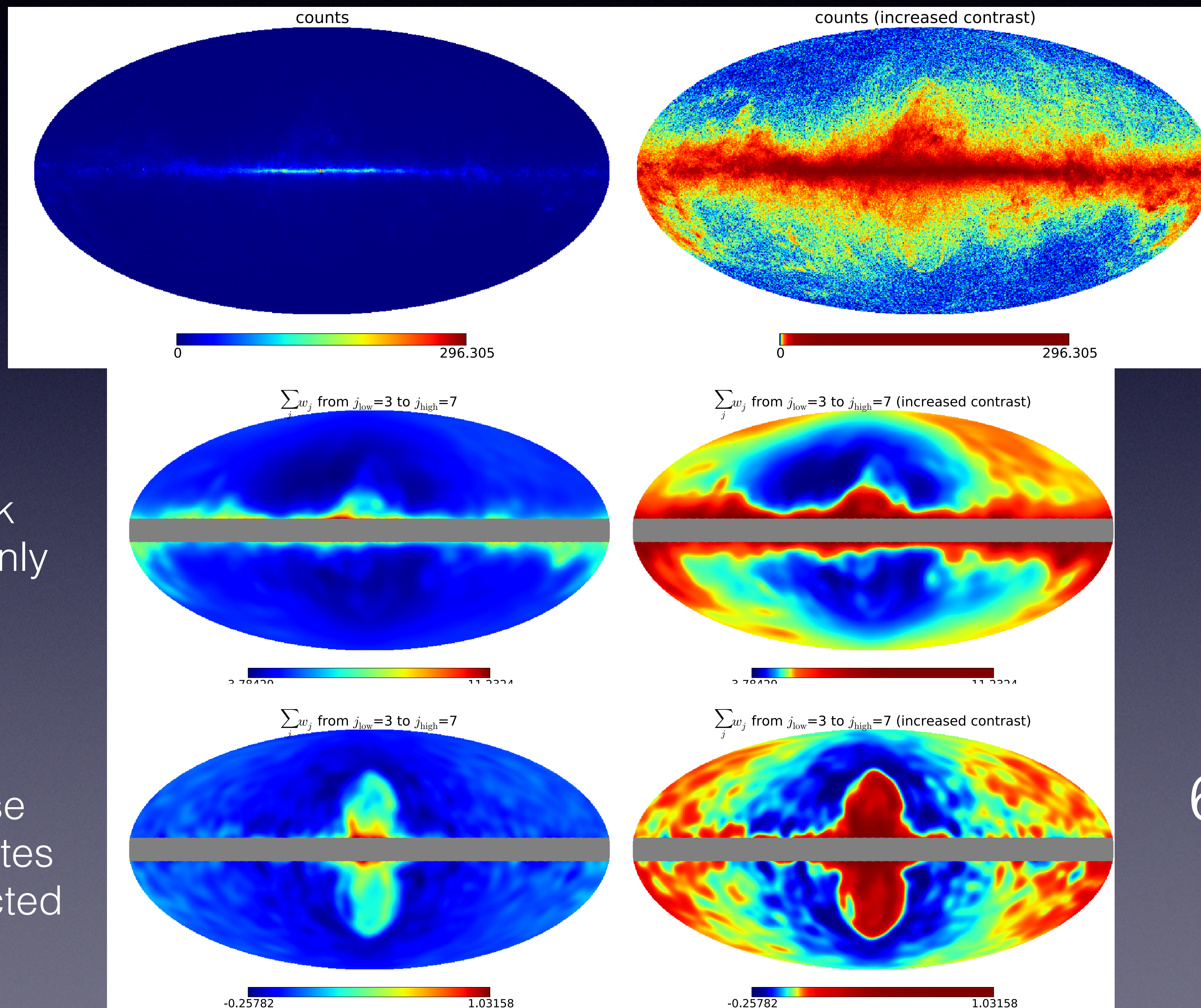


$4<\ell<128$

$\Downarrow$

$3^\circ<\theta<90^\circ$

Example (mock data)



$\ell_{\rm max}$=512

mock data only

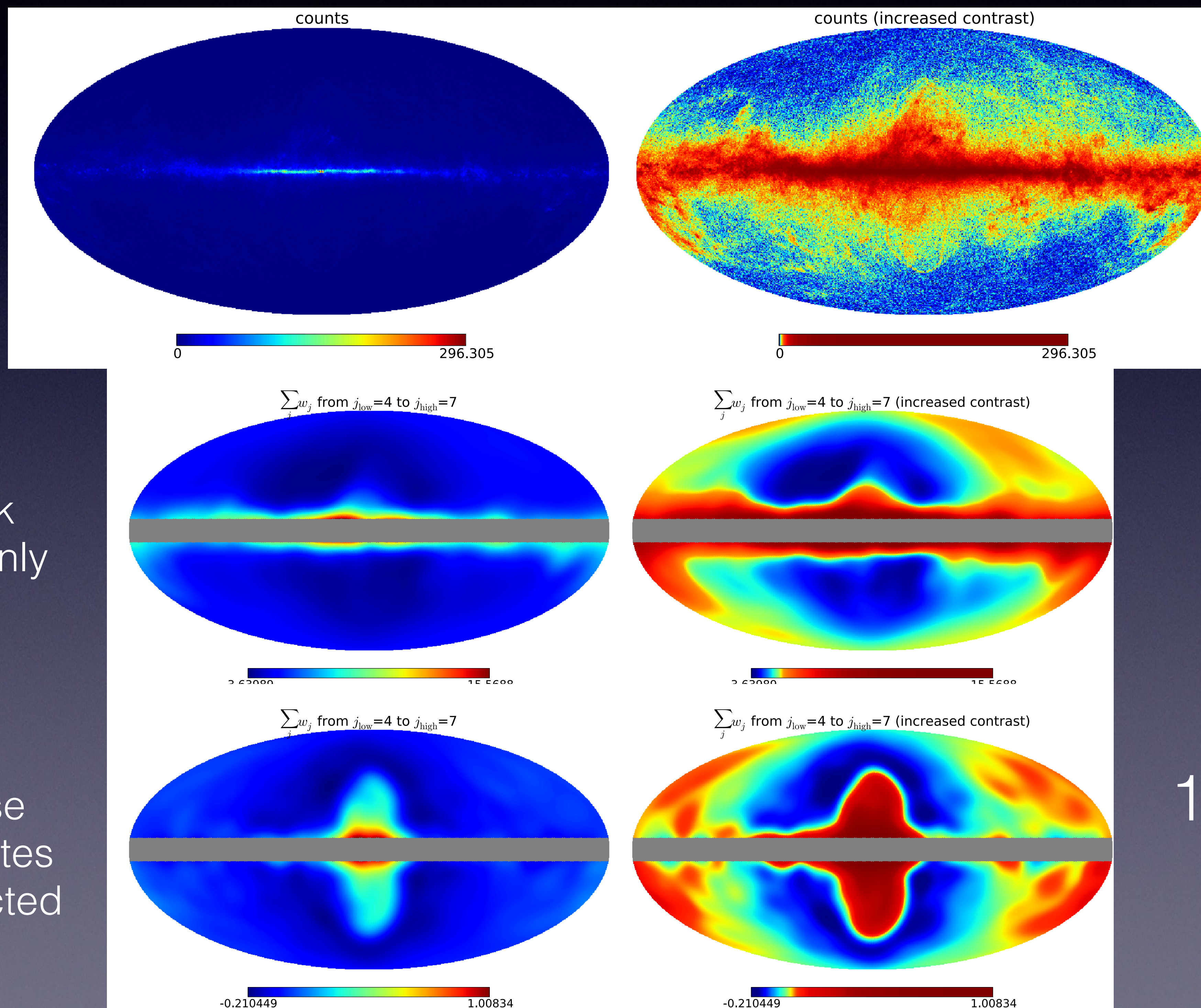
diffuse templates subtracted

$4<\ell<64$

$\Downarrow$

$6^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock data only

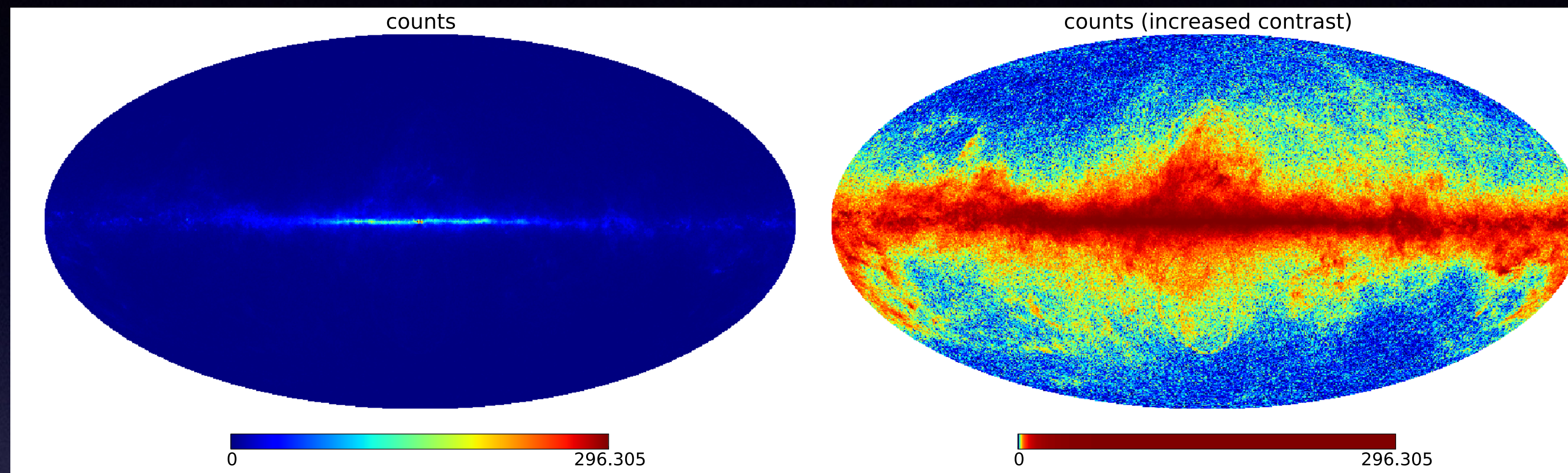
diffuse templates subtracted

$4<\ell<32$

$\Downarrow$

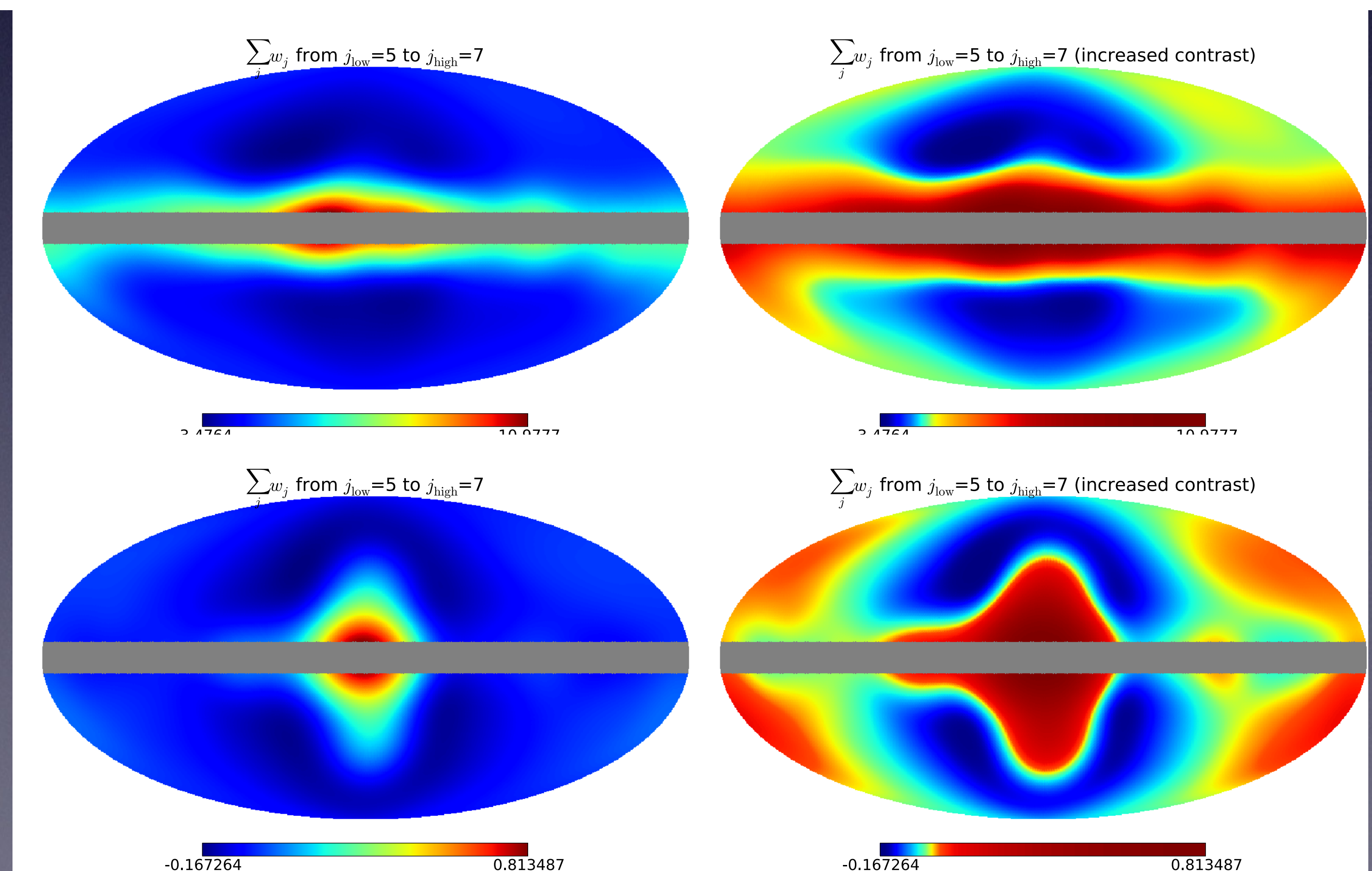
$10^\circ<\theta<90^\circ$

Example (mock data)



ℓ_{max}=512

mock
data only



diffuse
templates
subtracted

$4<\ell<16$

$\Downarrow$

$22^\circ<\theta<90^\circ$

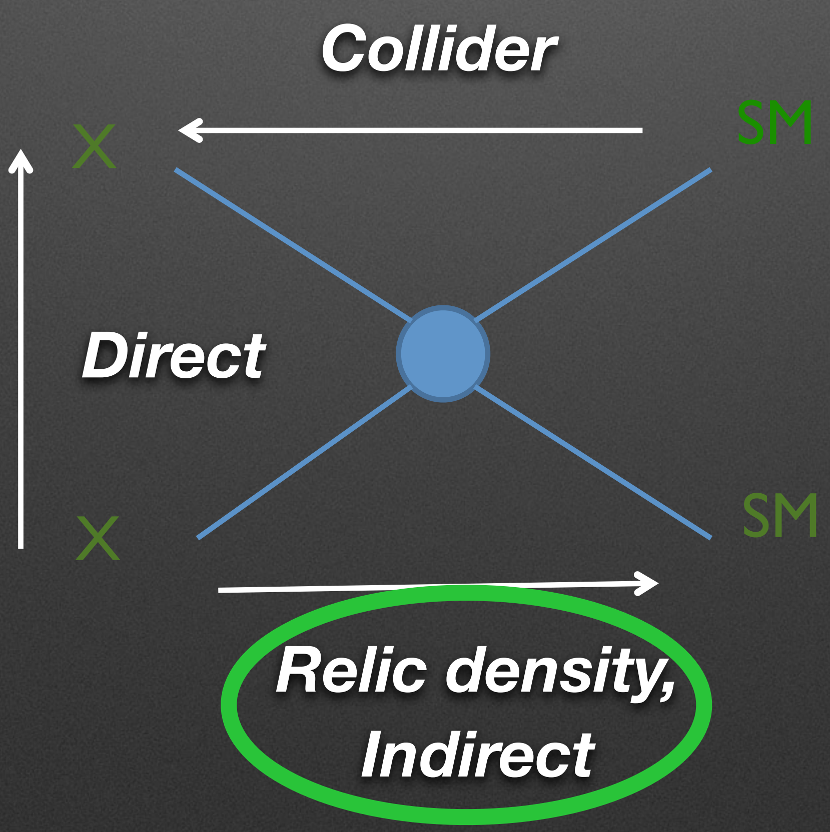
Can wavelets discriminate between alternative explanations?

Should be able to effectively test between smooth and non-smooth theories:

- burst scenarios disfavored if removing edgy stuff removes the whole excess
- again, can't distinguish between different smooth explanations

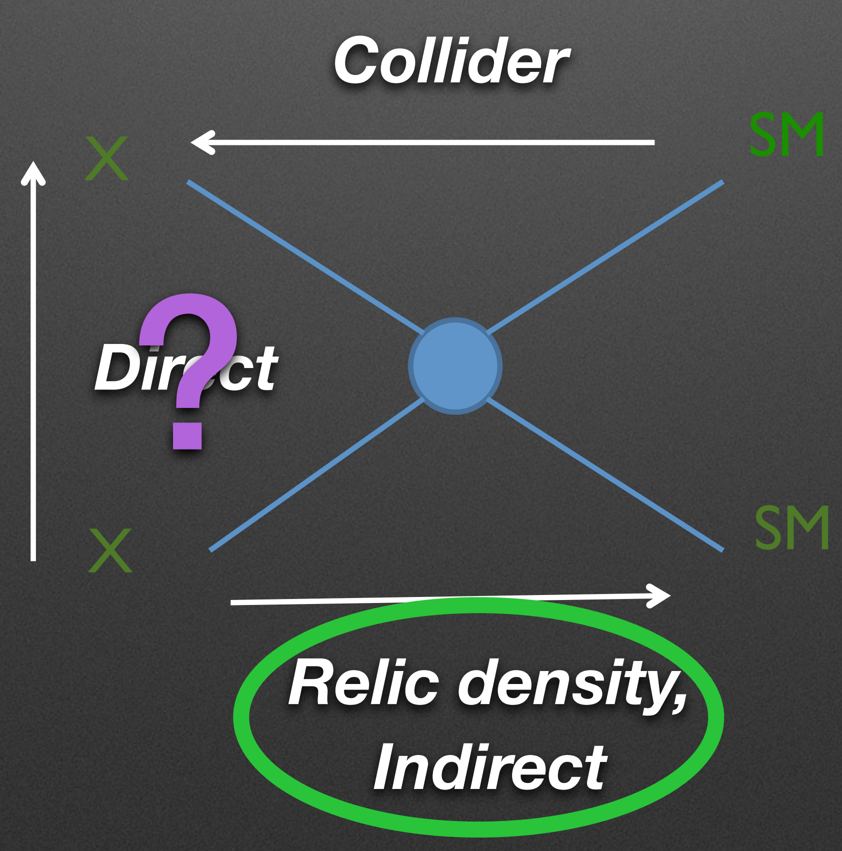
Prospects

...suppose this *is* dark matter:
should we expect to see its effects in any other channel?



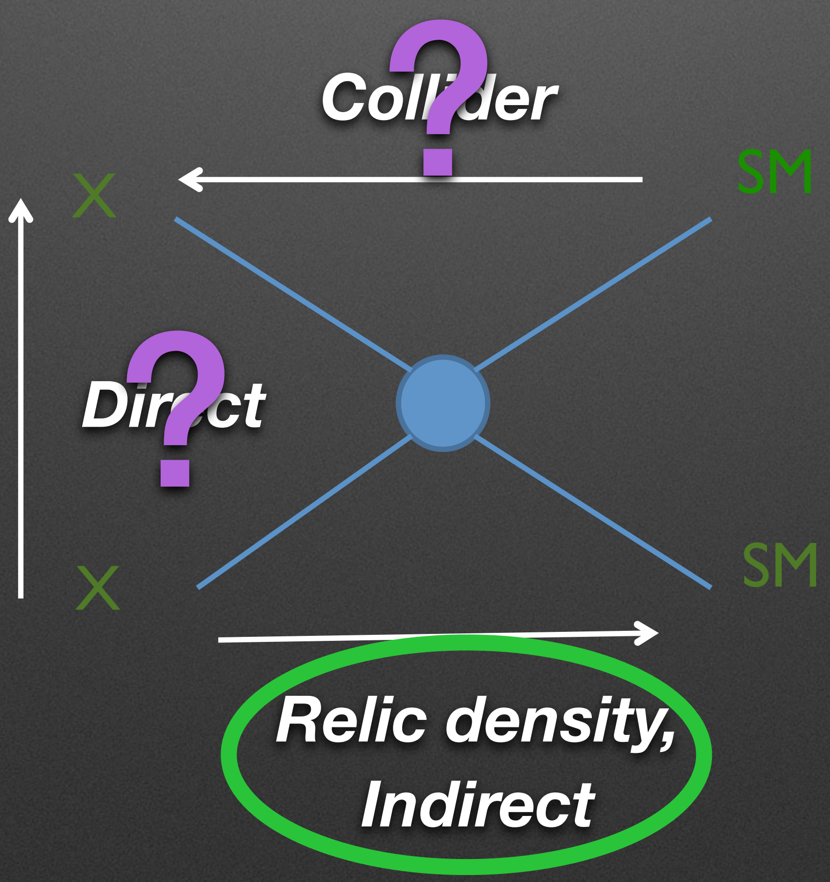
Prospects

...suppose this *is* dark matter:
should we expect to see its effects in any other channel?

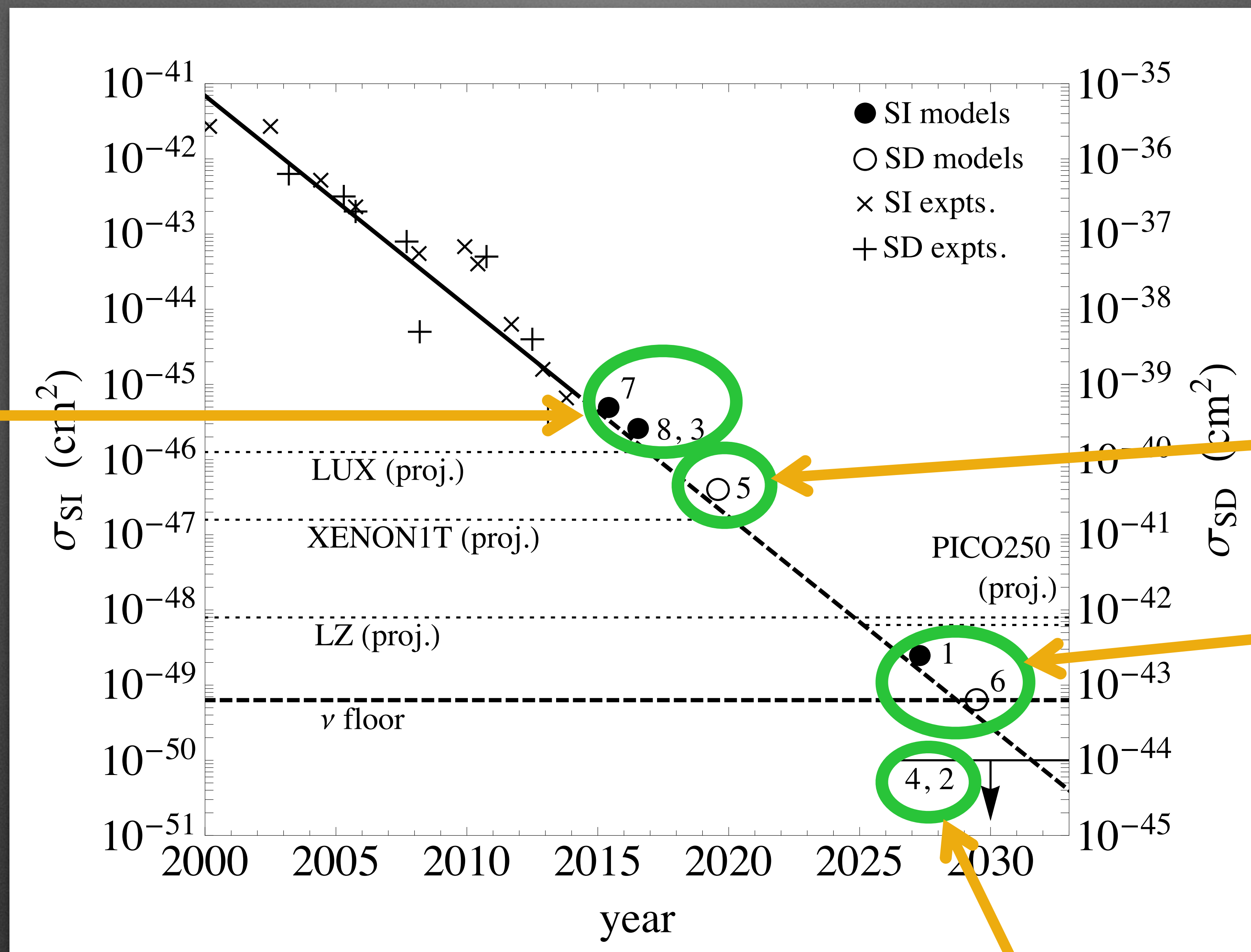


Prospects

…suppose this *is* dark matter:
should we expect to see its effects in any other channel?



Possibly…



σ_{SI}, loop suppressed (flavor…)

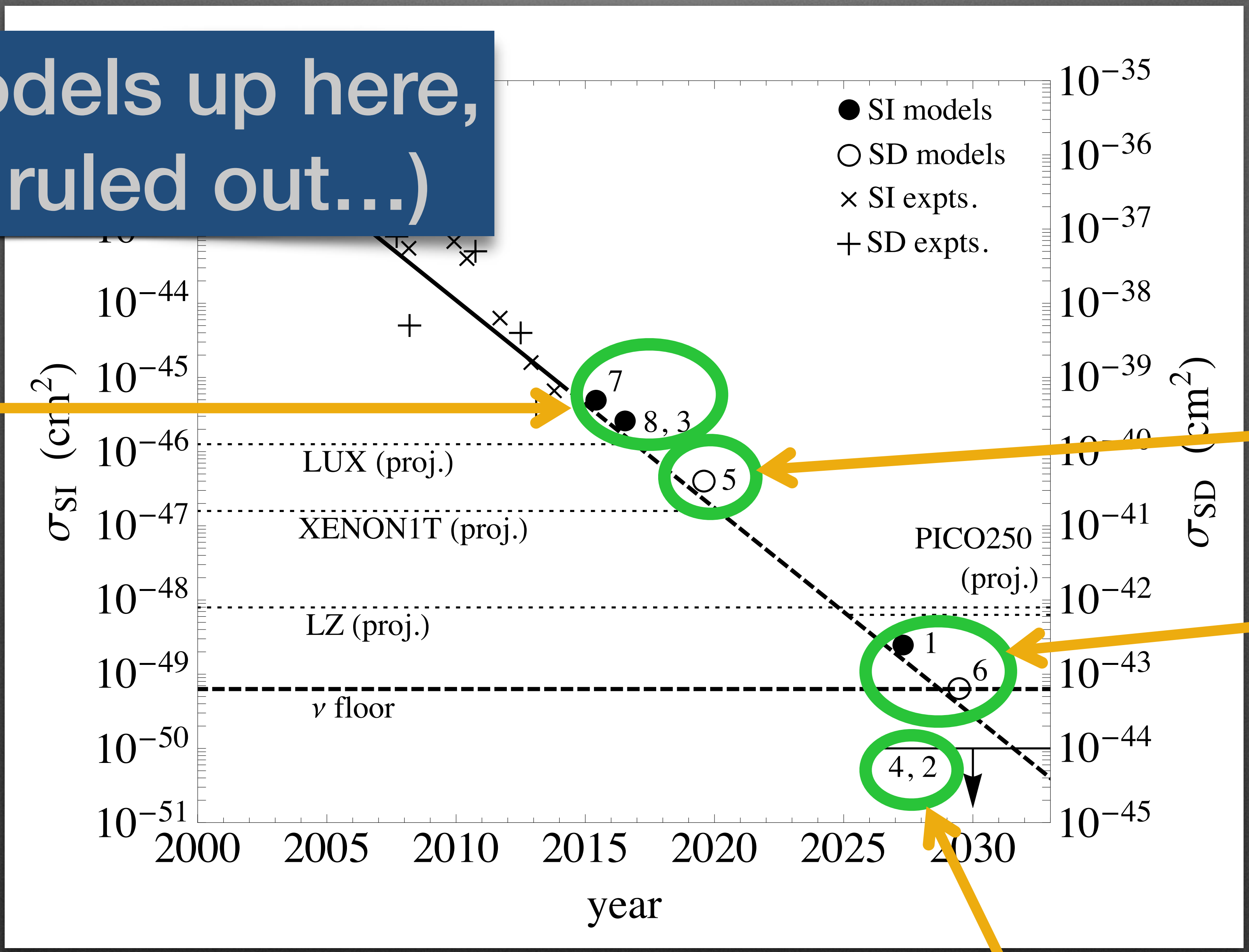
σ_{SD}

σ_{SI}, momentum suppressed

σ_{SD}, momentum suppressed

Possibly...

(note: models up here, already ruled out...)



σ_{SI}, loop suppressed (flavor...)

σ_{SD}

σ_{SI}, momentum suppressed

σ_{SD}, momentum suppressed