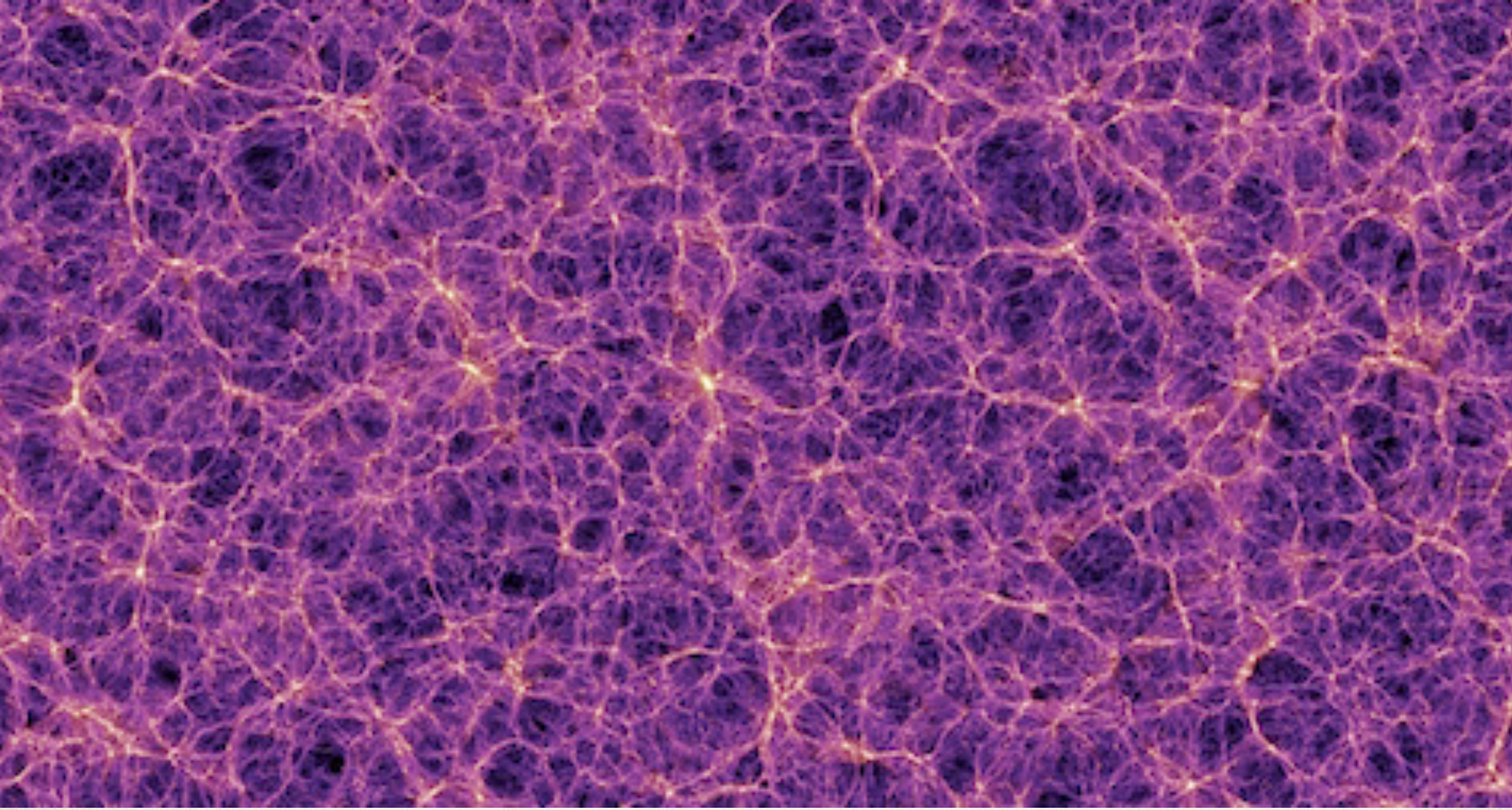
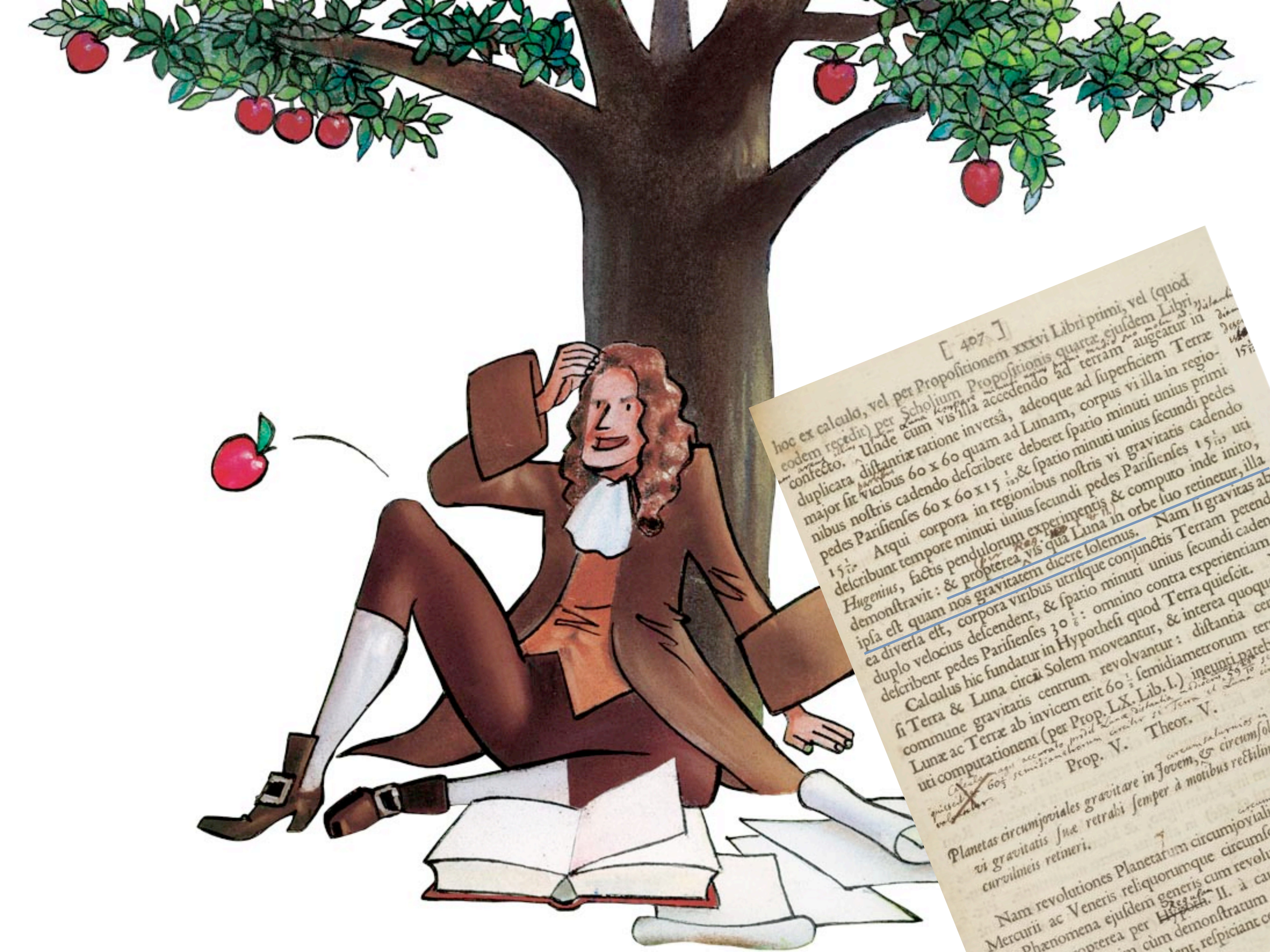


Shining Light on Dark Matter

Tim Linden - CCAPP Postdoctoral Fellow

May 19, 2018



[407]

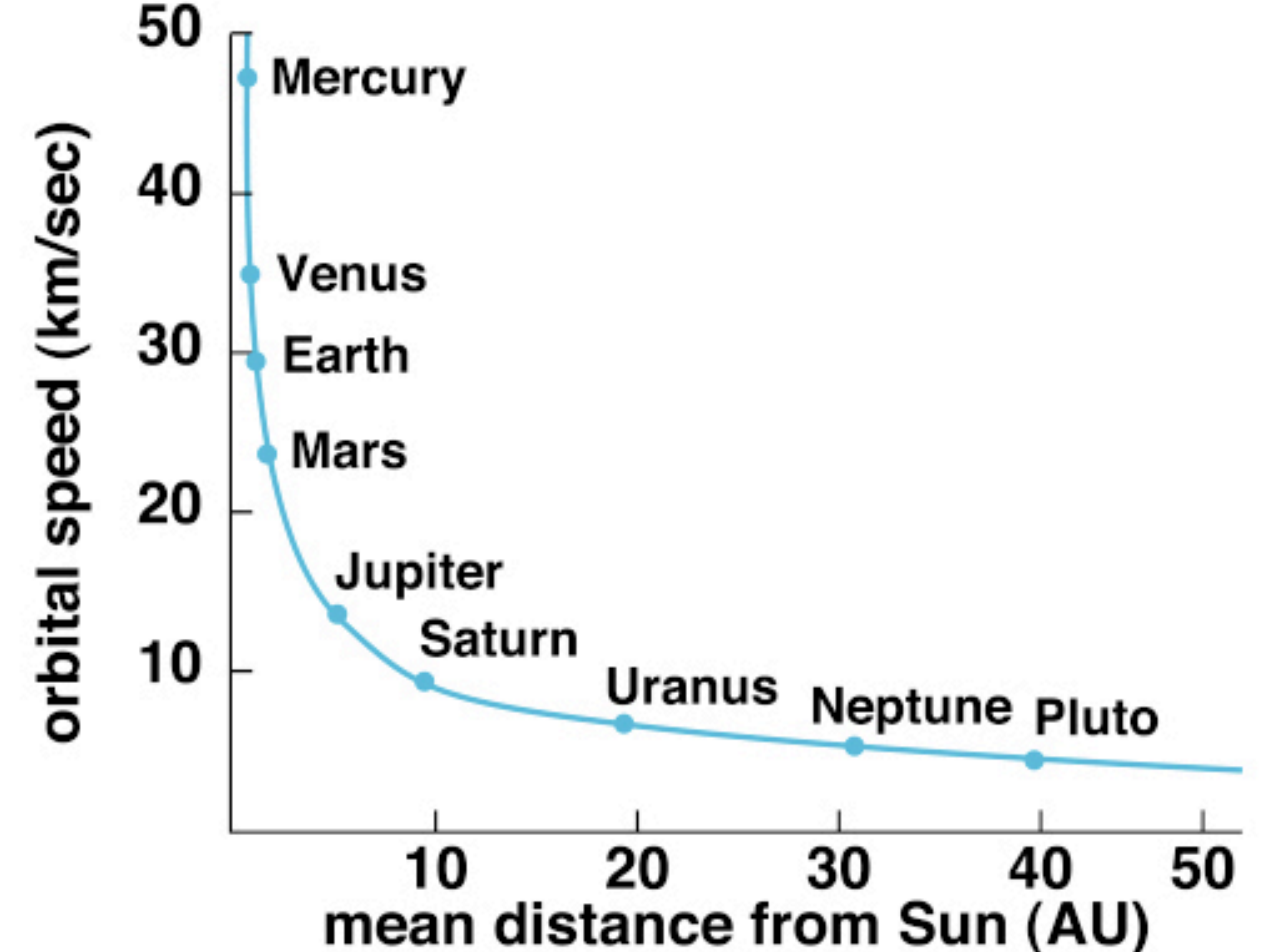
hoc ex calculo, vel per Propositionem xxxvi Libri primi, vel (quod eodem recedit) per Scholium Propositionis quartæ ejusdem Libri, confecto. Unde cum vis illa accedendo ad terram augeatur in duplicata distantiæ ratione inversâ, adeoque ad superficiem Terræ major sit vicibus 60 x 60 quam ad Lunam, corpus vi illa in regionibus nostris cadendo describere deberet spatio minuti unius primi pedes Parisienses 60 x 60 x $15\frac{1}{12}$, & spatio minuti unius secundi pedes $15\frac{1}{12}$. Atqui corpora in regionibus nostris vi gravitatis cadendo describunt tempore minuti unius secundi pedes Parisienses $15\frac{1}{12}$, uti *Hugenius*, factis pendulorum experimentis & computo inde inito, demonstravit: & propterea vis qua Luna in orbe suo retinetur, illa ipsa est quam nos gravitatem dicere solemus. Nam si gravitas ab ea diversa est, corpora viribus utrisque conjunctis Terram petend duplo velocius descendent, & spatio minuti unius secundi caden describent pedes Parisienses $30\frac{1}{6}$: omnino contra experientiam.

Calculus hic fundatur in Hypothesi quod Terra quiescit. si Terra & Luna circum Solem moveantur, & interea quoque commune gravitatis centrum revolvantur: distantia cen Lunæ ac Terræ ab invicem erit $60\frac{1}{2}$ semidiametrorum te uti computationem (per Prop. LX. Lib. I.) ineunti patebit.

Prop. V. Theor. V.

Planetas circumjoviales gravitare in Jovem, & circumsol vi gravitatis suæ retrahi semper à motibus rectilin curvilineis retineri.

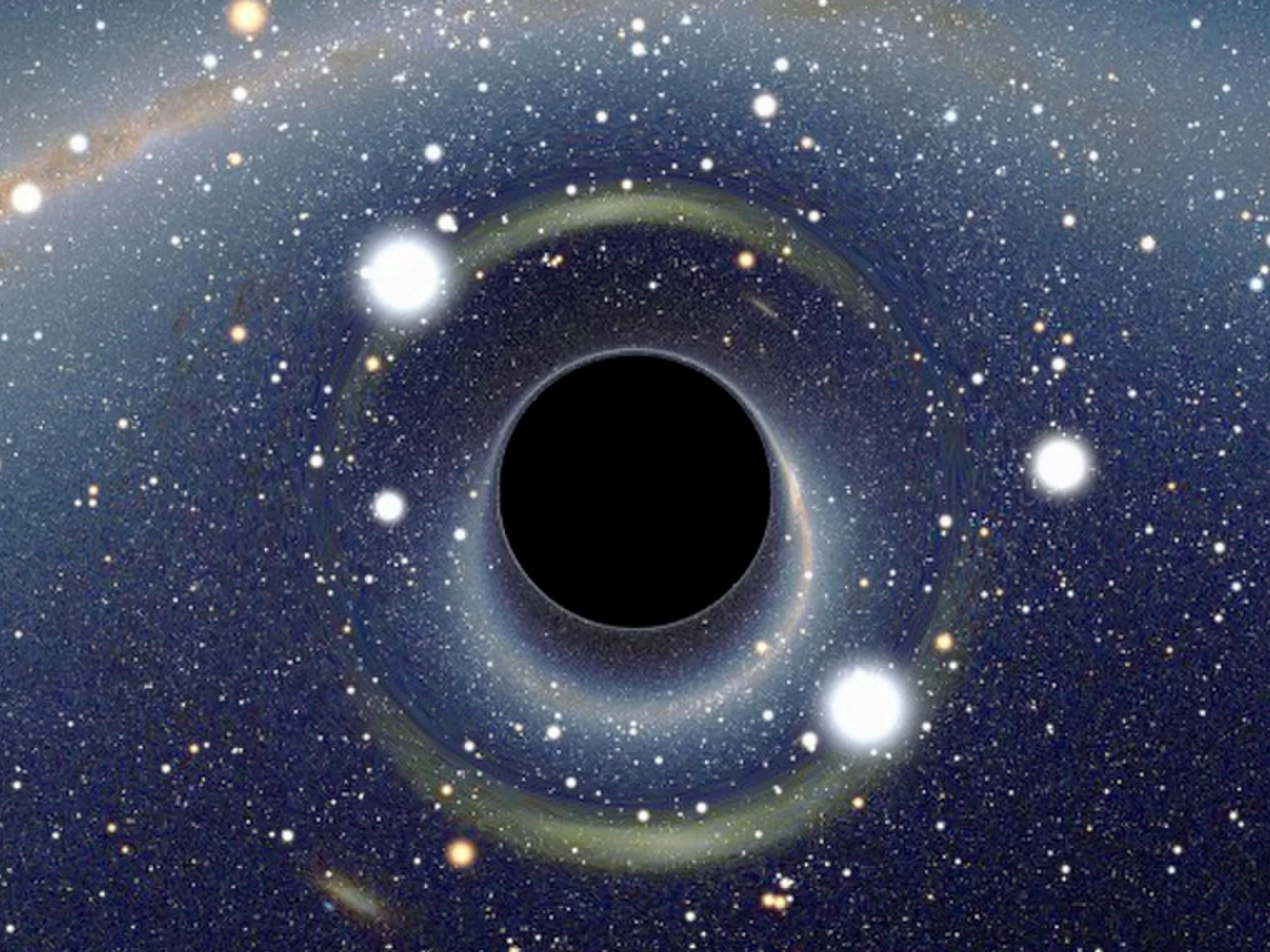
Nam revolutiones Planetarum circumjoviali Mercurii ac Veneris reliquorumque circumsol Phænomena ejusdem generis cum revolu propterea per Hypoth. II. à ca

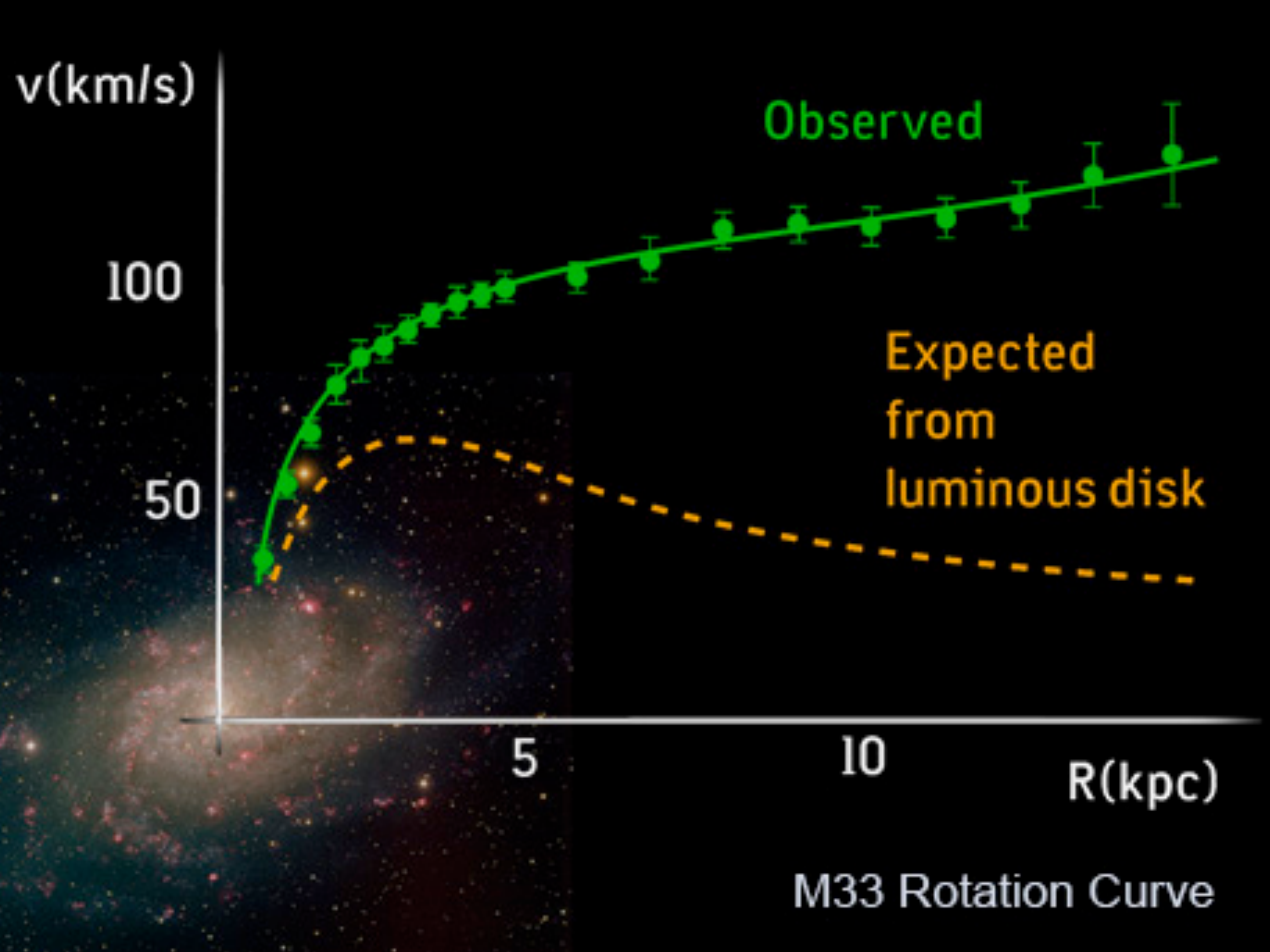


orbital speed (km/sec)
50
40
30
20
10
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
10
20
30
40
50
mean distance from Sun (AU)

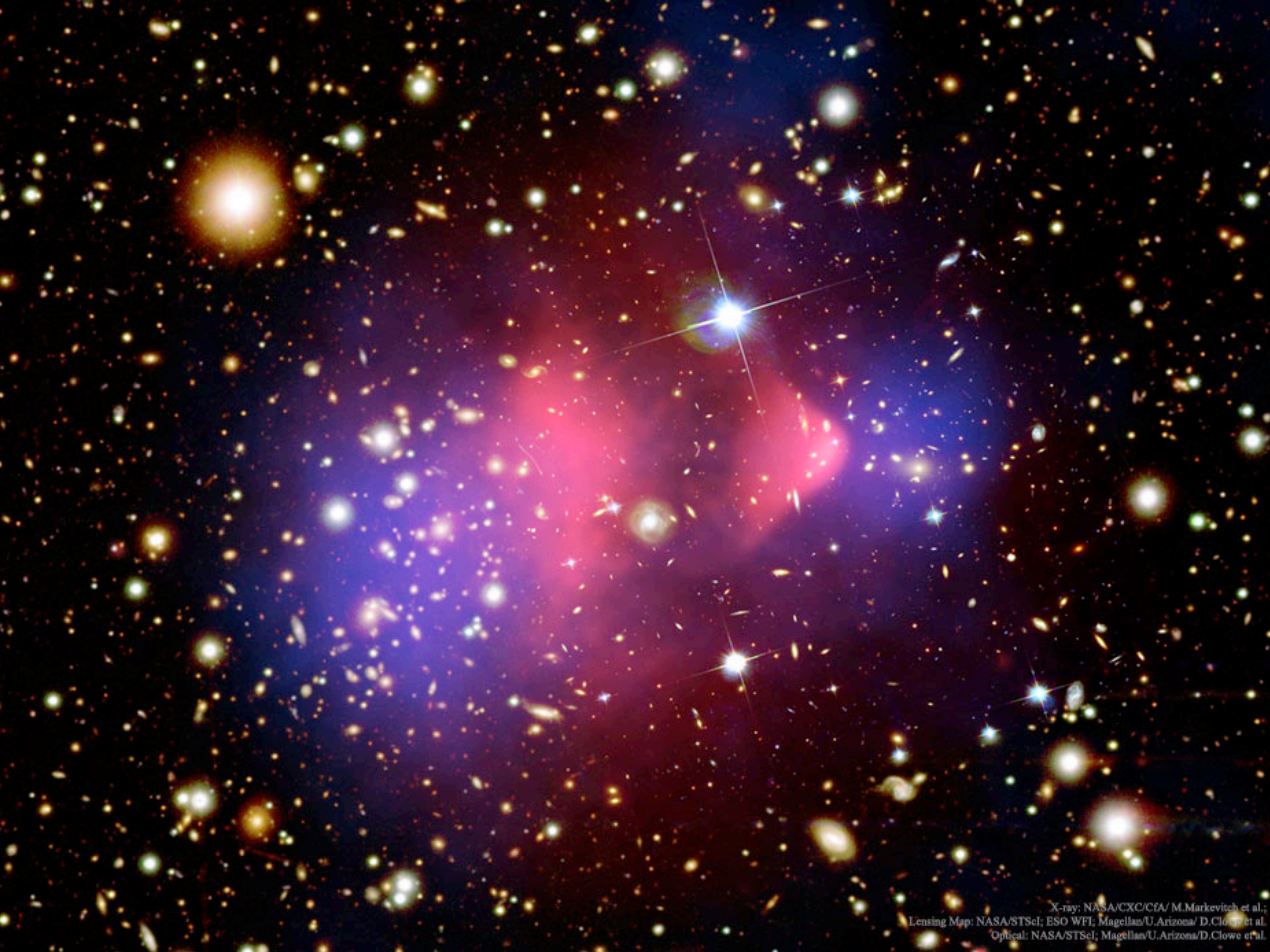
How does this work on bigger scales?


we are here



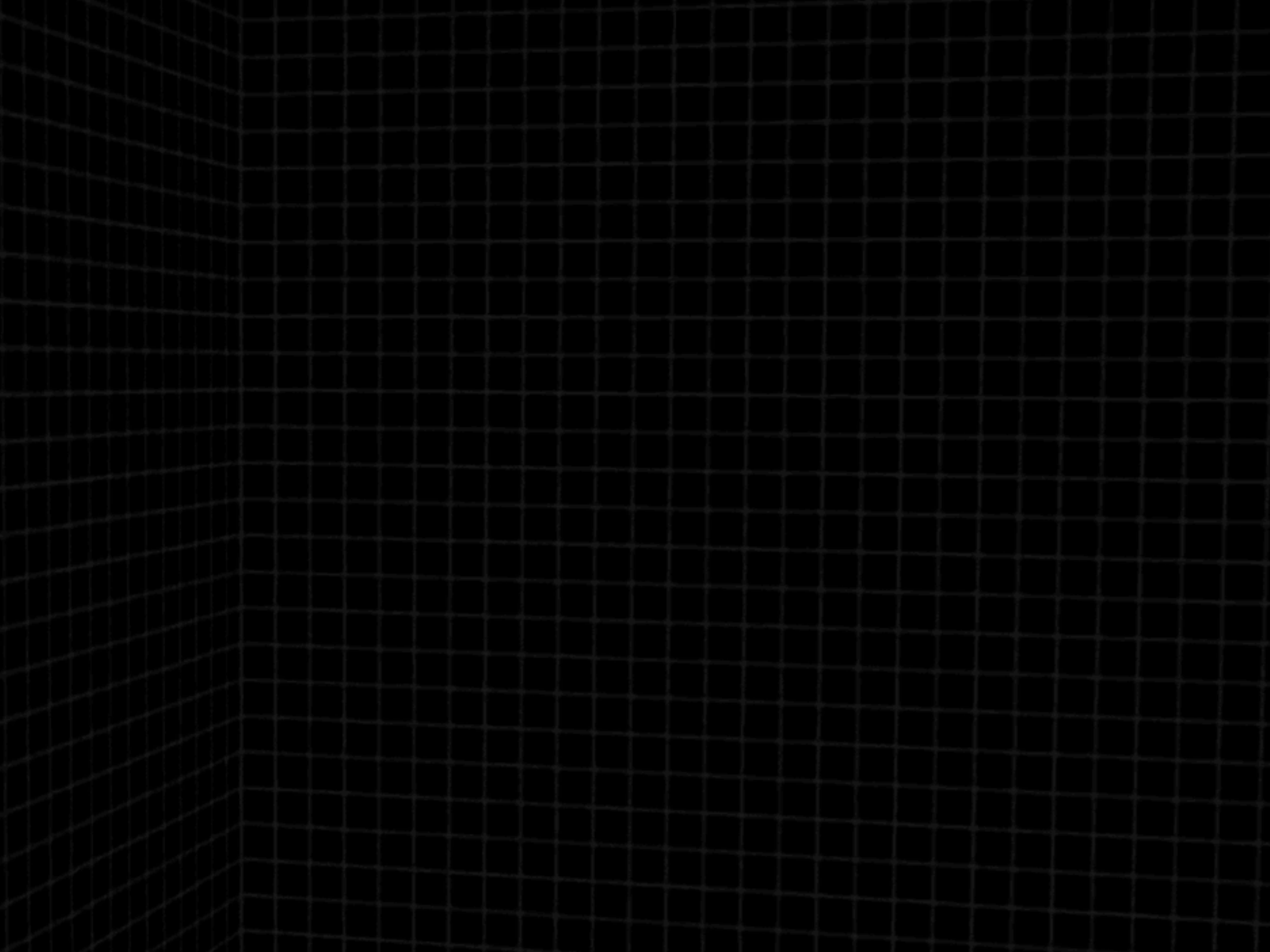

v(km/s)
100
50
Observed
Expected
from
luminous disk
5
10
R(kpc)
M33 Rotation Curve

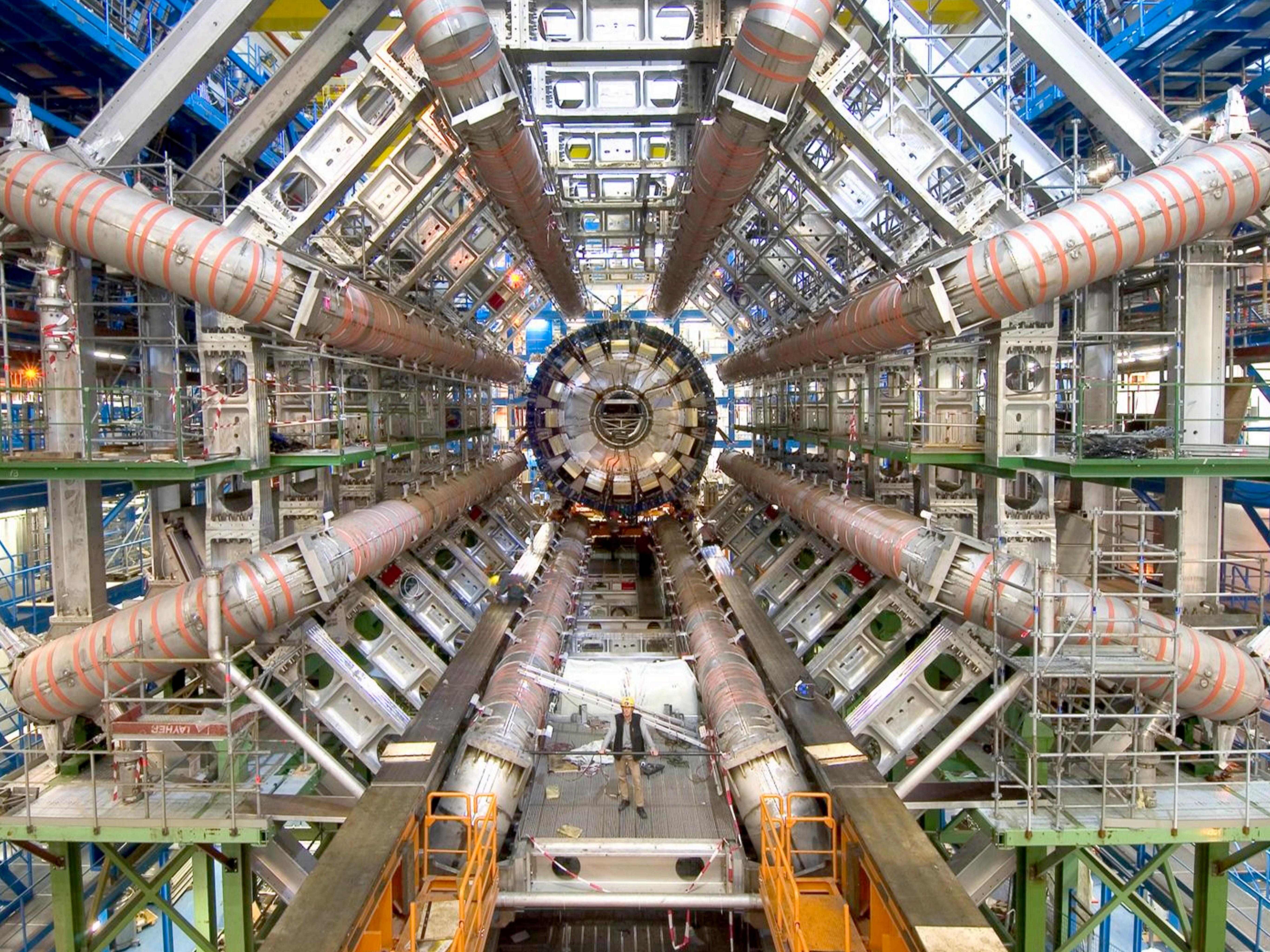

THERE'S
SOMETHING OUT
THERE


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.

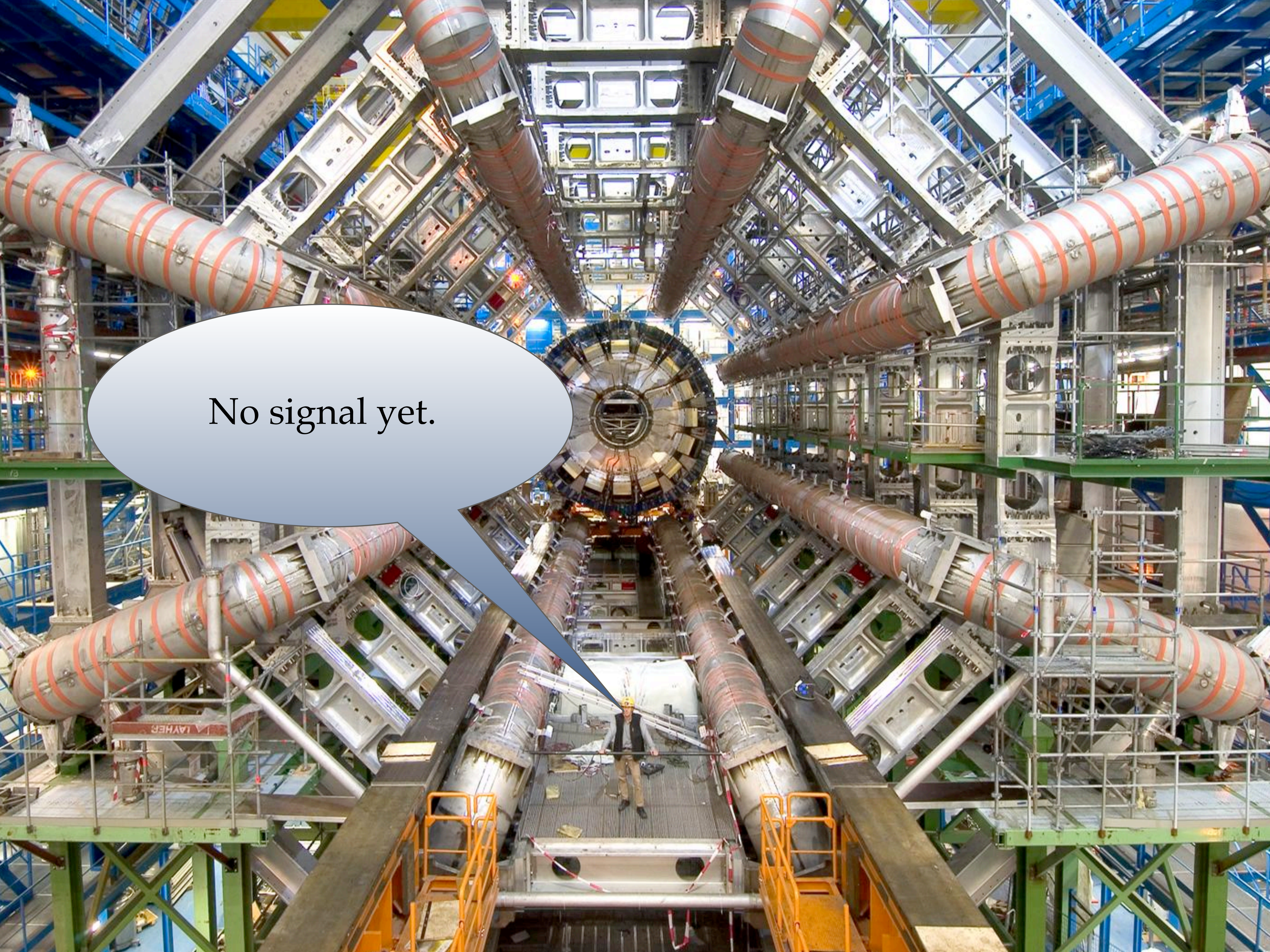
What Do We Know About Dark Matter?

- **Dark -** Doesn’t produce (or absorb) light.
- **Matter -** Has a lot of mass (overall, at least)
- **Cold** - Moving slowly, can accumulate in galaxies.
- **Collisionless -** Dark Matter particles can pass right through each other.



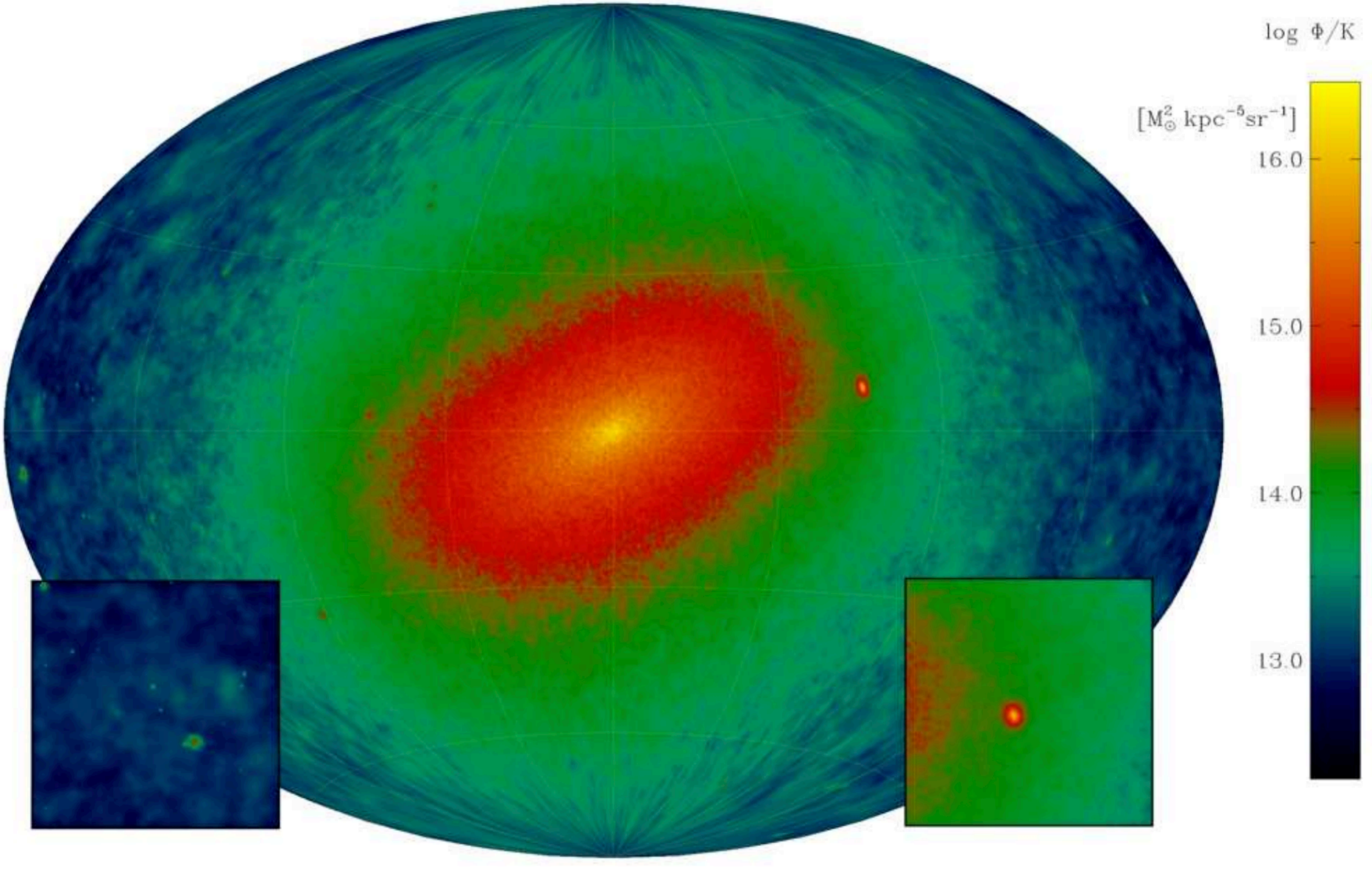



Xe
XENON
Matter Project
enlightening the

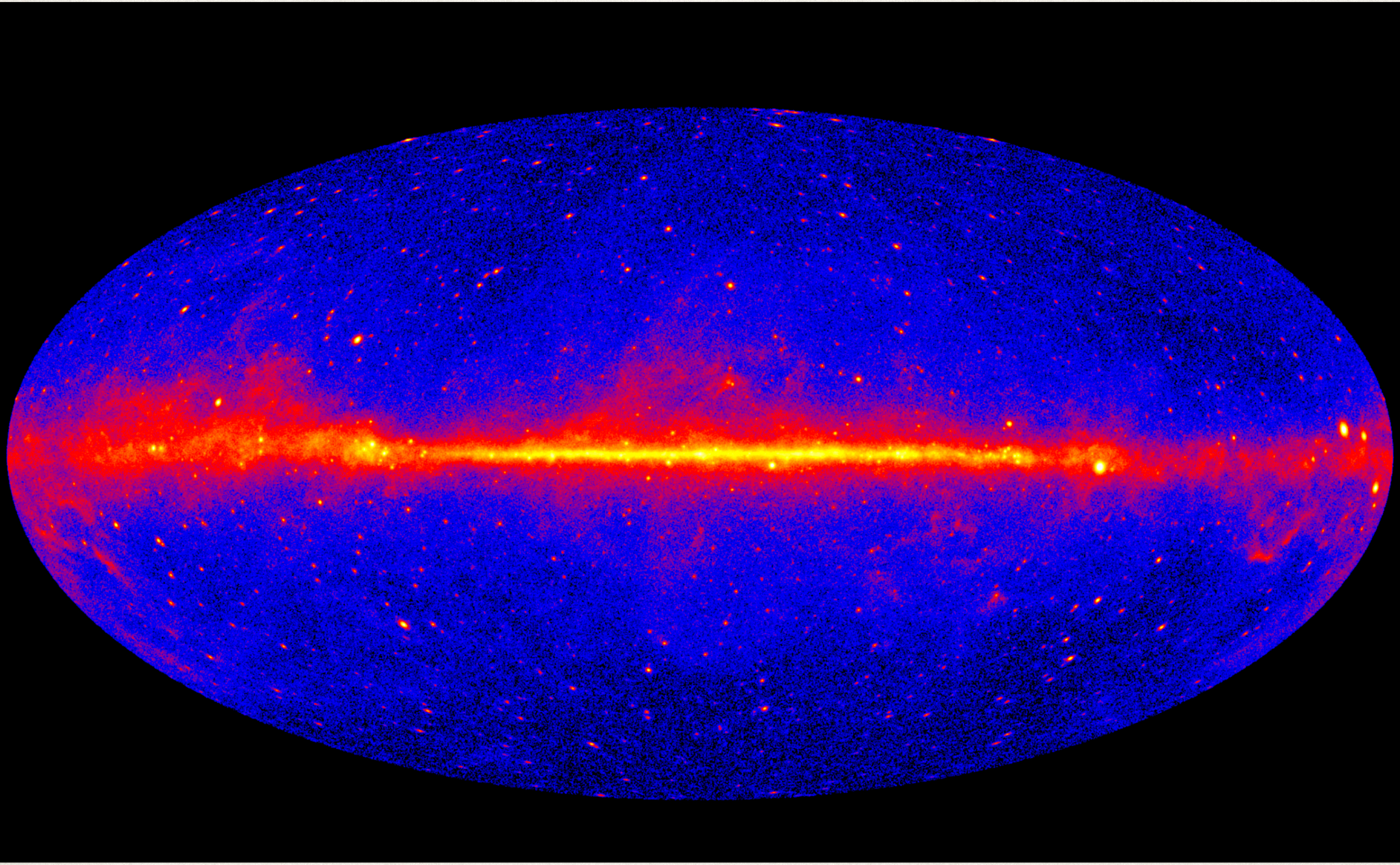

No signal yet.


Xe
XENON
No events at all.

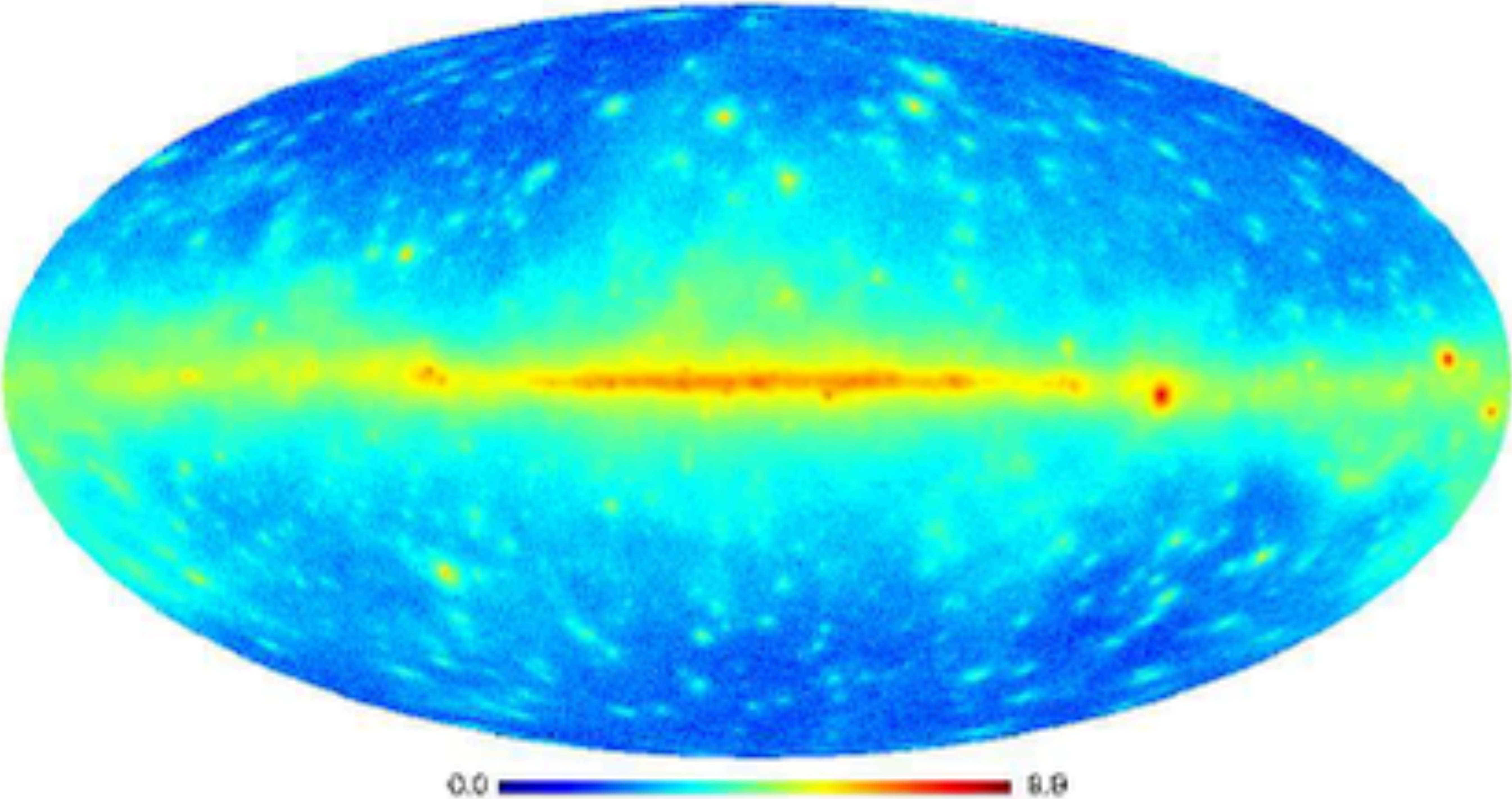

Yes!
Wait, no…
Yes! — err maybe not…
Maybe??

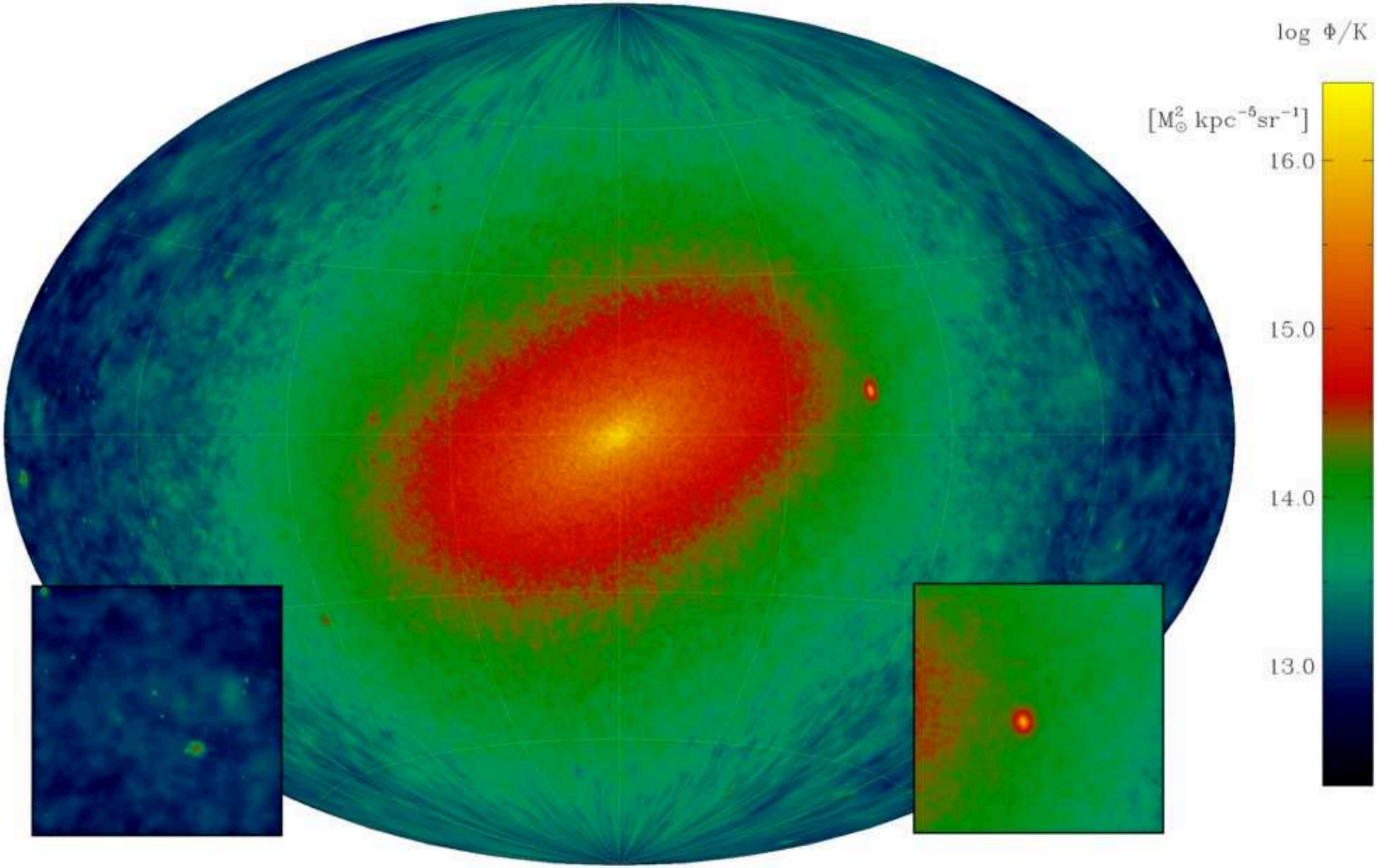


log Φ/K
[M$_\odot^2$ kpc^{-5}sr^{-1}]
16.0
15.0
14.0
13.0



Simulated Fermi data




log Φ/K
[$M_\odot^2$ kpc^{-5}sr^{-1}]
16.0
15.0
14.0
13.0

FERMILAB-PUB-09-494-A

Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope

Lisa Goodenough[1] and Dan Hooper[2,3]

[1] Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003
[2] Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510
[3] Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637

We study the gamma rays observed by the Fermi Gamma Ray Space Telescope from the direction of the Galactic Center and find that their angular distribution and energy spectrum are well described by a dark matter annihilation scenario. In particular, we find a good fit to the data for dark matter particles with a 25-30 GeV mass, an annihilation cross section of $\sim 9 \times 10^{-26}$ cm^3/s, and that are distributed with a cusped halo profile, $\rho(r) \propto r^{-1.1}$, within the inner kiloparsec of the Galaxy. We cannot, however, exclude the possibility that these photons originate from an astrophysical source or sources with a similar morphology and spectral shape to those predicted in an annihilating dark matter scenario.

Searches for dark matter annihilation products are among the most exciting missions of the Fermi Gamma Ray Space Telescope (FGST). In particular, the FGST collaboration hopes to observe and identify gamma rays from dark matter annihilations occuring cosmologically [1], as well as within the Galactic Halo [2], dwarf galaxies [3], microhalos [4], and the inner region of the Milky Way [5].

Due to the very high densities of dark matter predicted to be present in the central region of our galaxy, the inner Milky Way is expected to be the single brightest source of dark matter annihilation radiation in the sky. This region is astrophysically rich and complex, however, making the task of separating dark matter annihilation products from backgrounds potentially challenging. In particular, the Galactic Center contains a $2.6 \times 10^6 \, M_\odot$ black hole coincident with the radio source Sgr A* [6],

from the direction of the Galactic Center that is observed, $\rho(r)$ describes the dark matter density profile, and the integral is performed over the line-of-sight. dN_γ/dE_γ is the spectrum of prompt gamma rays generated per annihilation, which depends on the dominant annihilation channel(s). Note that Eq. 1 provides us with predictions for both the distribution of photons as a function of energy, and as a function of the angle observed. It is this powerful comb
identify and s
from astrophy

With a perf
dark matter e
described in E
point spread
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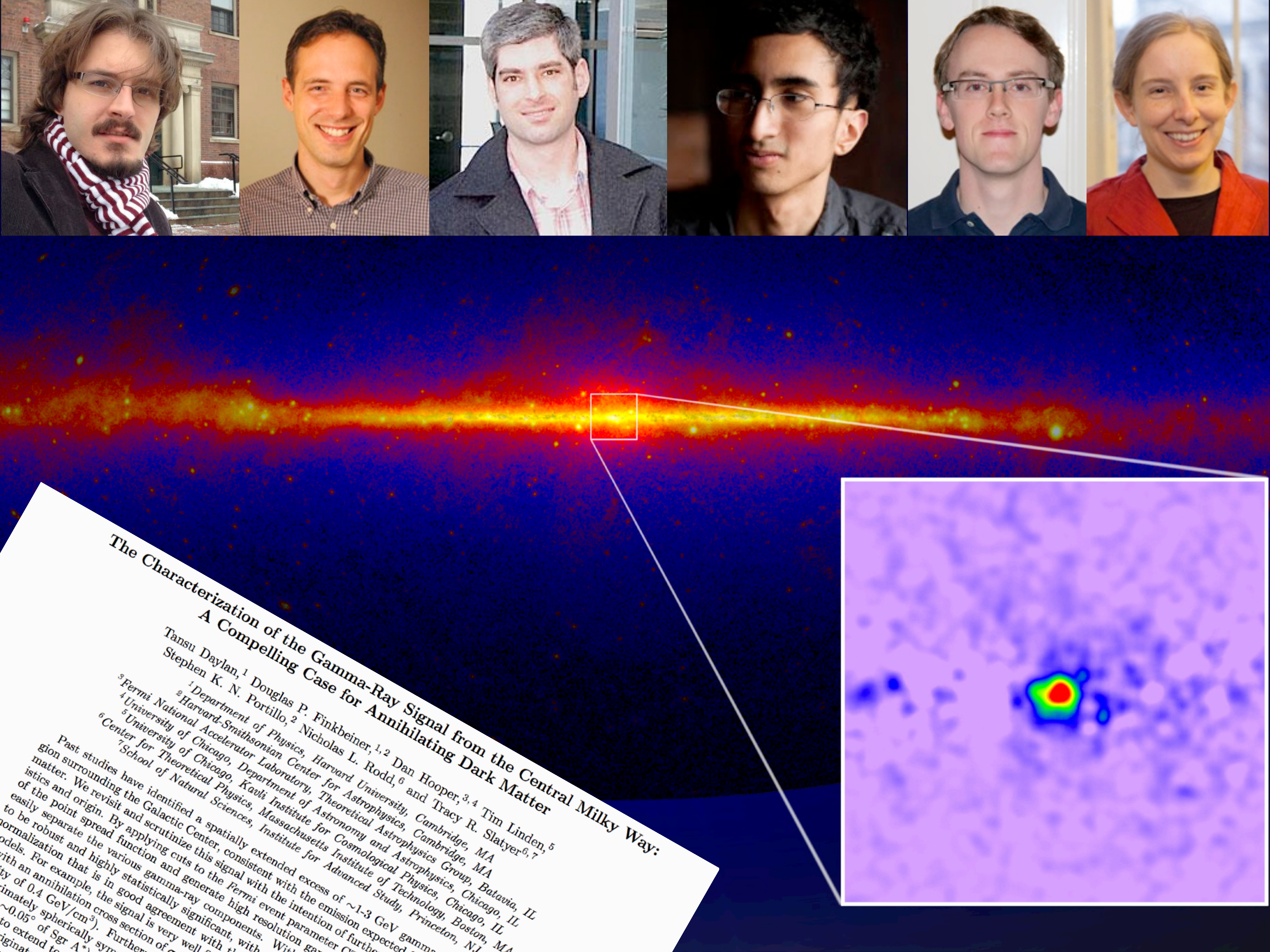
modeled the p


The Characterization of the Gamma-Ray Signal from the Central Milky Way:
A Compelling Case for Annihilating Dark Matter
Tansu Daylan,1 Douglas P. Finkbeiner,1,2 Dan Hooper,3,4 Tim Linden,5
Stephen K. N. Portillo,2 Nicholas L. Rodd,6 and Tracy R. Slatyer6,7
1Department of Physics, Harvard University, Cambridge, MA
2Harvard-Smithsonian Center for Astrophysics, Cambridge, MA
3Fermi National Accelerator Laboratory, Theoretical Astrophysics Group, Batavia, IL
4University of Chicago, Department of Astronomy and Astrophysics, Chicago, IL
5University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL
6Center for Theoretical Physics, Massachusetts Institute of Technology, Boston, MA
7School of Natural Sciences, Institute for Advanced Study, Princeton, NJ
Past studies have identified a spatially extended excess of ~1-3 GeV
gion surrounding the Galactic Center, consistent with the emission expected
matter. We revisit and scrutinize this signal with the intention of
istics and origin. By applying cuts to the Fermi event parameter
of the point spread function and generate high resolution
easily separate the various gamma-ray components.

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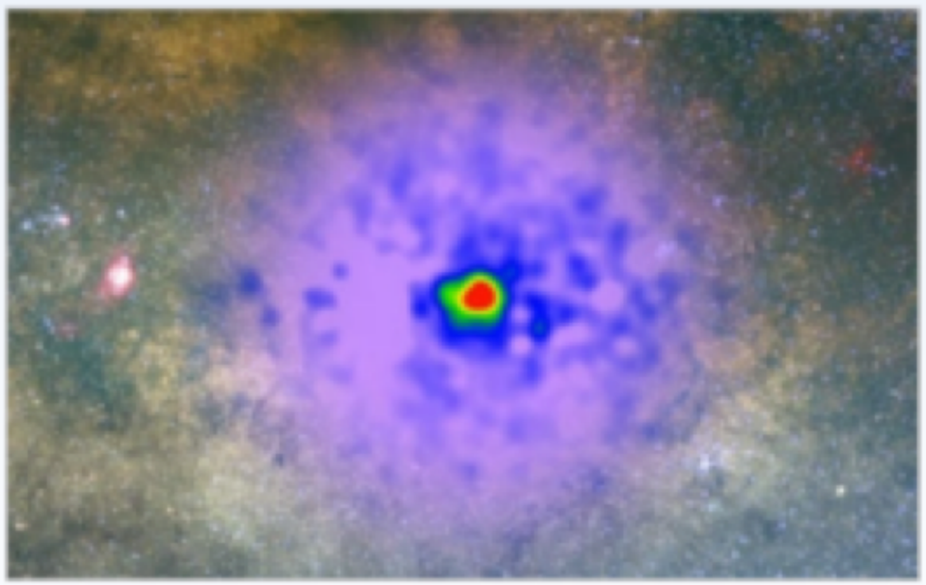
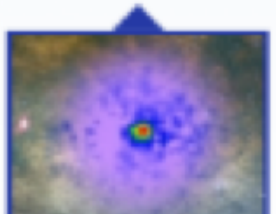
Fermi Data Tantalize With New Clues To Dark Matter



A new study of gamma-ray light from the center of our galaxy makes the strongest case to date that some of this emission may arise from dark matter, an unknown substance making up most of the material universe. Scientists have developed new maps showing that the galactic center produces more high-energy gamma rays than can be explained by known sources and that this excess emission is consistent with some forms of dark matter.


Fermi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Monday, April 7: NES Video Robotics at NASA, 1 p.m. E

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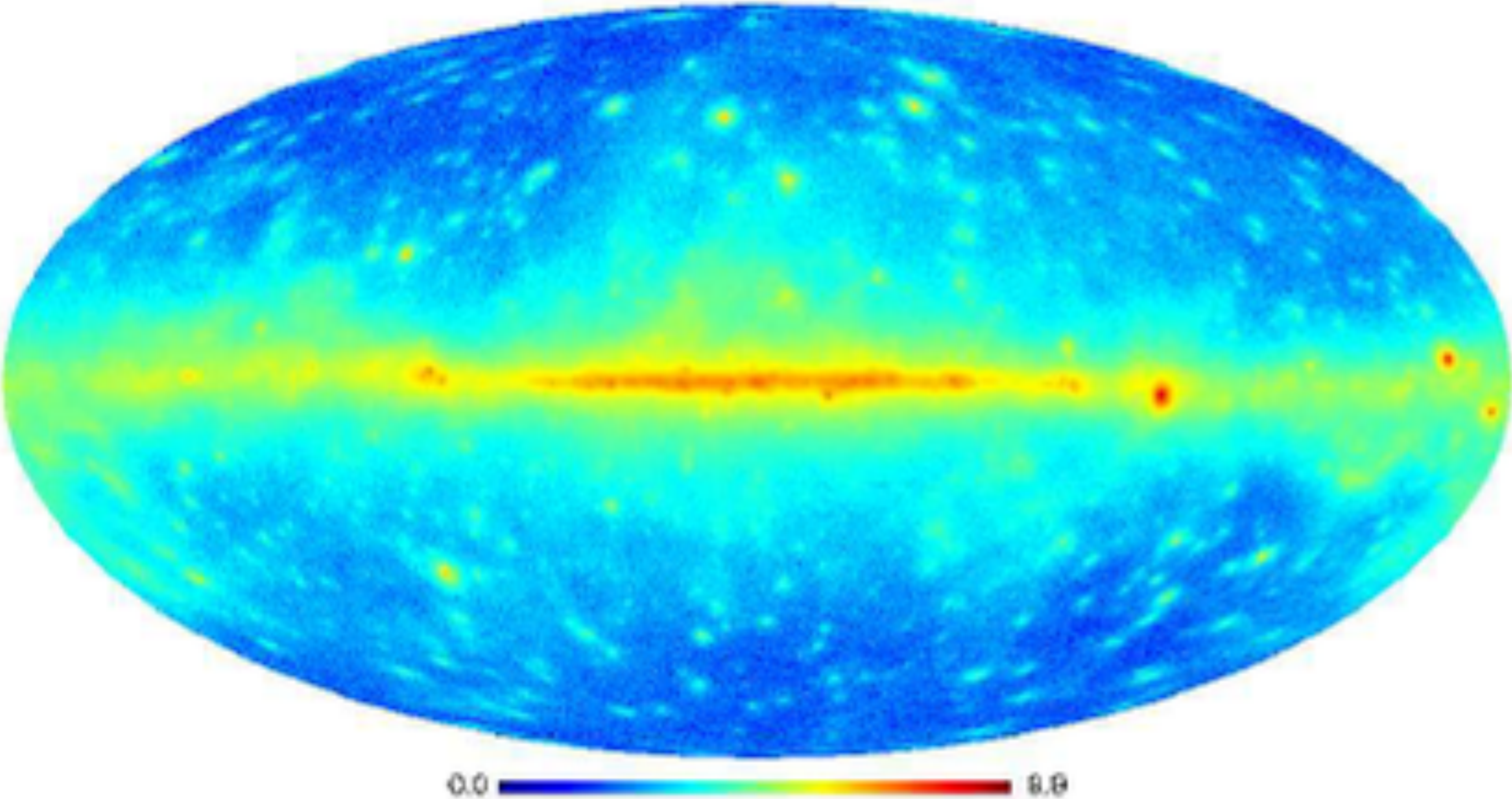
OCO-2 to bring sharp new focus o

Simulated Fermi data



Prepared for submission to JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

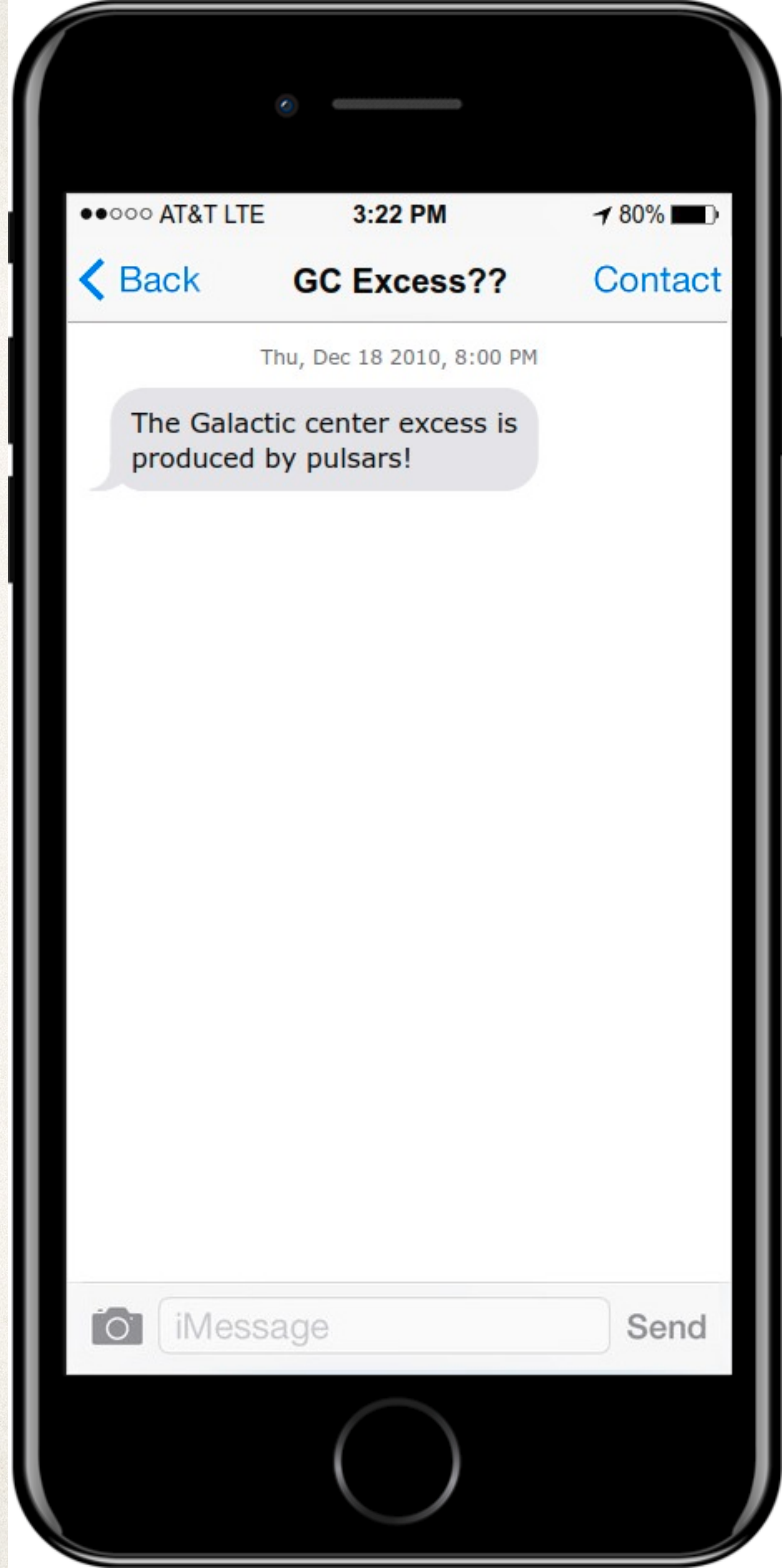
Kevork N. Abazajian

Maryland Center for Fundamental Physics & Joint Space-Science Institute, Department of Physics, University of Maryland, College Park, Maryland 20742 USA

E-mail: kev@umd.edu

Abstract. I show that the spectrum and morphology of a recent Fermi-LAT observation of the Galaxy center are consistent with a millisecond pulsar population in the nuclear Central stellar cluster of the Milky Way. The Galaxy Center gamma-ray spectrum is consistent with the spectrum of four of eight globular clusters that have been detected in the gamma-ray. A dark matter annihilation interpretation cannot be ruled out, though no unique features exist that would require this conclusion.

Keywords: millisecond pulsars, gamma ray experiments, dark matter theory



arXiv:1011.4275v3 [astro-ph.HE] 28 Feb 2011

Prepared for submission to JCAP

UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

astro-ph.HE] 3 May 2013

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

Dan Hooper[1,2], Ilias Cholis[1], Tim Linden[3], Jennifer Siegal-Gaskins[4], and Tracy Slatyer[5]

[1]*Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510*

[2]*Department of Astronomy and Astrophysics, University of Chicago, 5640 S Ellis Ave., Chicago, IL 606*

[3]*Department of Physics, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95064*

[4]*Einstein Fellow, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125 and*

[5]*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540*

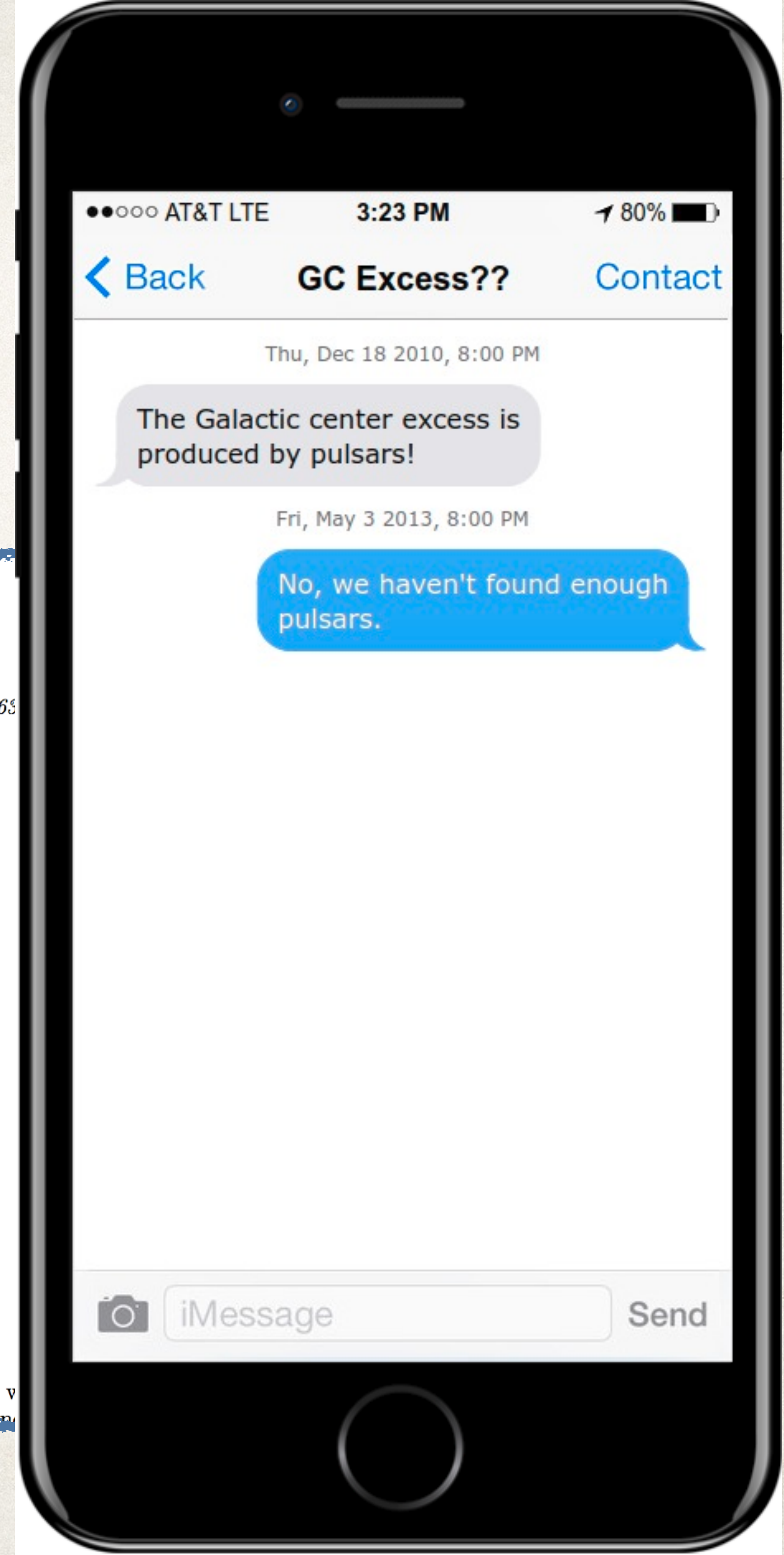
(Dated: April 16, 2018)

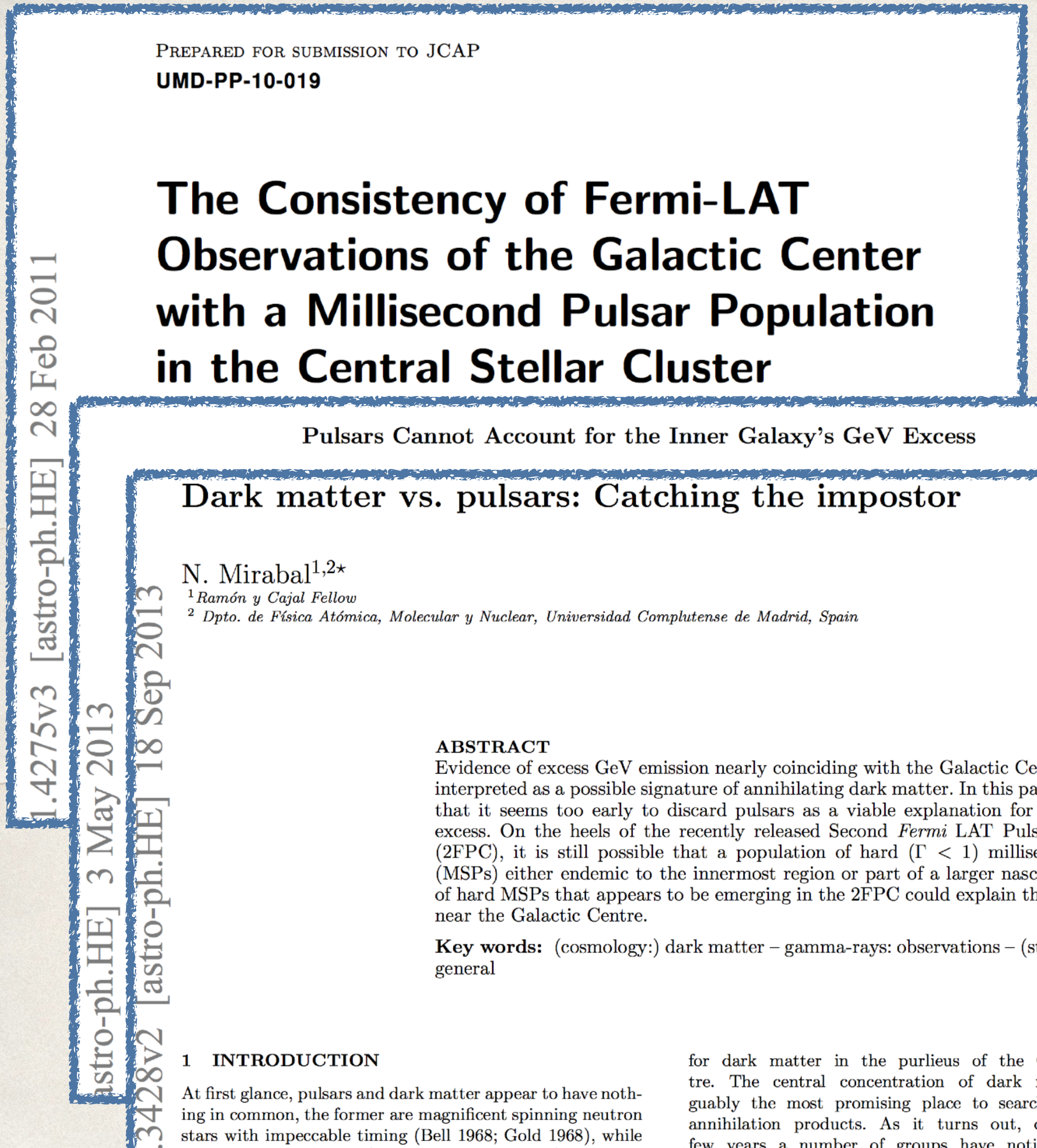
Using data from the Fermi Gamma-Ray Space Telescope, a spatially extended component of gamma rays has been identified from the direction of the Galactic Center, peaking at energies of ~2-3 GeV. More recently, it has been shown that this signal is not confined to the innermost hundreds of parsecs of the Galaxy, but instead extends to at least ~3 kpc from the Galactic Center. While the spectrum, intensity, and angular distribution of this signal is in good agreement with predictions from annihilating dark matter, it has also been suggested that a population of unresolved millisecond pulsars could be responsible for this excess GeV emission from the Inner Galaxy. In this paper, we consider this later possibility in detail. Comparing the observed spectral shape of the Inner Galaxy's GeV excess to the spectrum measured from 37 millisecond pulsars by Fermi, we find that these sources exhibit a spectral shape that is much too soft at sub-GeV energies to accommodate this signal. We also construct population models to describe the spatial distribution and luminosity function of the Milky Way's millisecond pulsars. After taking into account constraints from the observed distribution of Fermi sources (including both sources known to be millisecond pulsars, and unidentified sources which could be pulsars), we find that millisecond pulsars can account for no more than ~10% of the Inner Galaxy's GeV excess. Each of these arguments strongly disfavor millisecond pulsars as the source of this signal.

PACS numbers: 97.60.Gb, 95.55.Ka, 95.35.+d; FERMILAB-PUB-13-129-A

I. INTRODUCTION

trophysical sources or backgrounds. Second w





Prepared for submission to JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

1.4275v3 [astro-ph.HE] 28 Feb 2011

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

astro-ph.HE] 3 May 2013

Dark matter vs. pulsars: Catching the impostor

3428v2 [astro-ph.HE] 18 Sep 2013

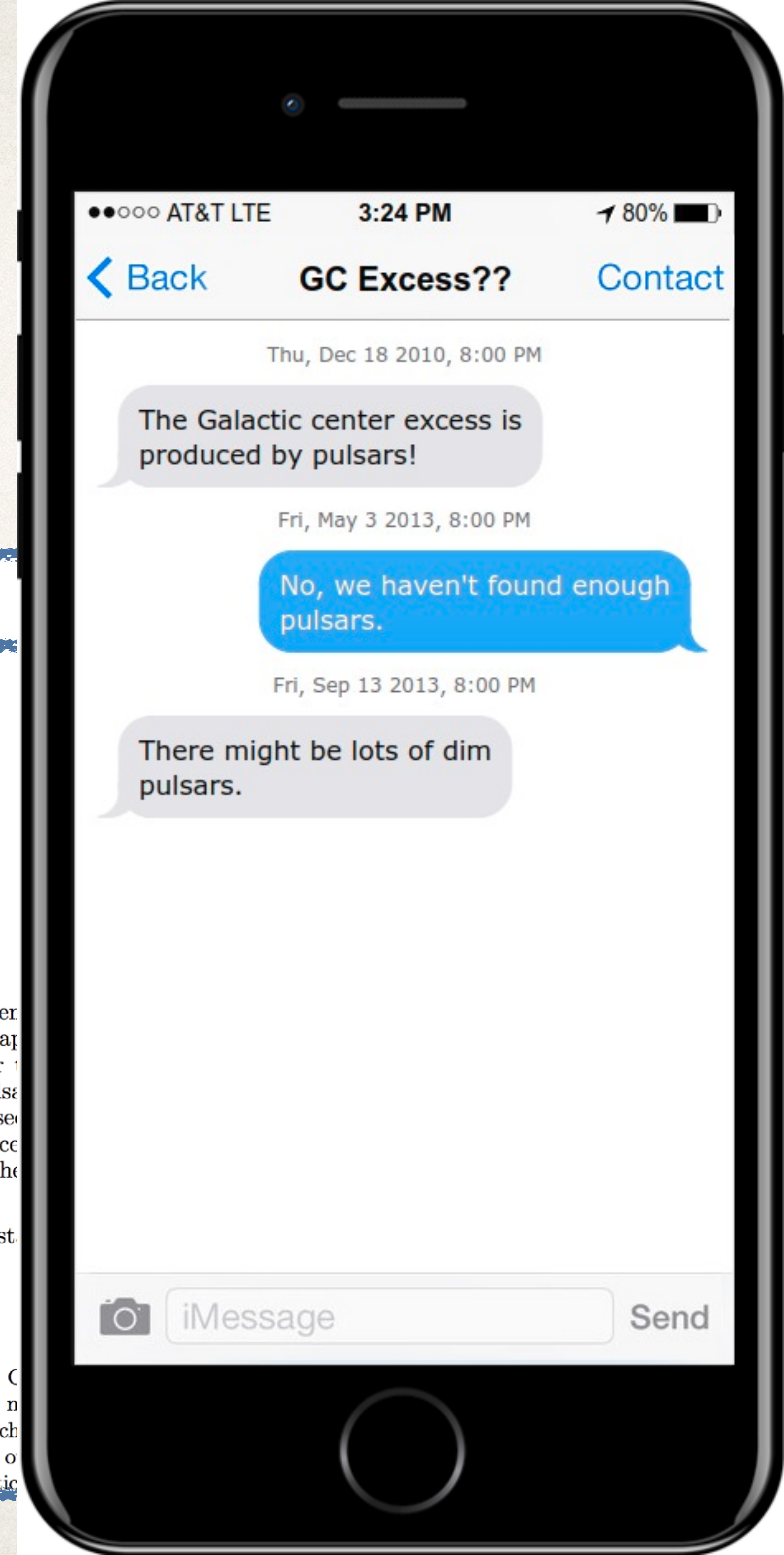
N. Mirabal[1,2⋆]
[1] *Ramón y Cajal Fellow*
[2] *Dpto. de Física Atómica, Molecular y Nuclear, Universidad Complutense de Madrid, Spain*

ABSTRACT
Evidence of excess GeV emission nearly coinciding with the Galactic Cen
interpreted as a possible signature of annihilating dark matter. In this pa
that it seems too early to discard pulsars as a viable explanation for
excess. On the heels of the recently released Second *Fermi* LAT Puls
(2FPC), it is still possible that a population of hard ($\Gamma < 1$) millise
(MSPs) either endemic to the innermost region or part of a larger nasc
of hard MSPs that appears to be emerging in the 2FPC could explain th
near the Galactic Centre.

Key words: (cosmology:) dark matter – gamma-rays: observations – (st
general

1 INTRODUCTION

At first glance, pulsars and dark matter appear to have nothing in common, the former are magnificent spinning neutron stars with impeccable timing (Bell 1968; Gold 1968), while for dark matter in the purlieus of the C tre. The central concentration of dark n guably the most promising place to search annihilation products. As it turns out, o few years a number of groups have notic



PREPARED FOR SUBMISSION TO JCAP
UMD-PP-10-019

The Consistency of Fermi-LAT Observations of the Galactic Center with a Millisecond Pulsar Population in the Central Stellar Cluster

Pulsars Cannot Account for the Inner Galaxy's GeV Excess

Dark matter vs. pulsars: Catching the impostor

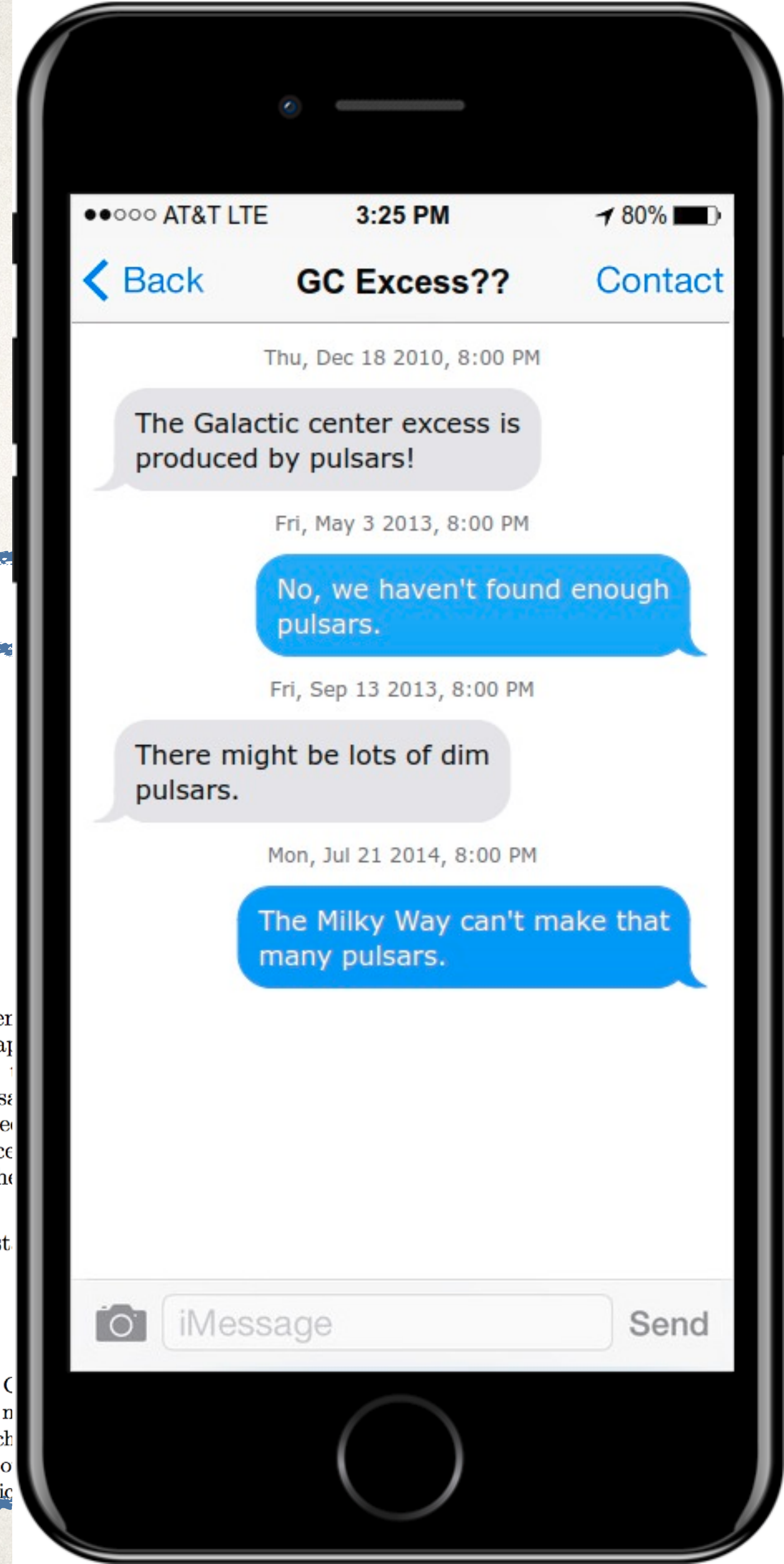
Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

Ilias Cholis[a] Dan Hooper[a,b] Tim Linden[b]

[a]Fermi National Accelerator Laboratory, Center for Particle Astrophysics, Batavia, IL
[b]University of Chicago, Kavli Institute for Cosmological Physics, Chicago, IL

E-mail: cholis@fnal.gov, dhooper@fnal.gov, trlinden@uchicago.edu

Abstract. Millisecond pulsars have been discussed as a possible source of the gamma-ray excess observed from the region surrounding the Galactic Center. With this in mind, we use the observed population of bright low-mass X-ray binaries to estimate the number of millisecond pulsars in the Inner Galaxy. This calculation suggests that only ∼1-5% of the excess is produced by millisecond pulsars. We also use the luminosity function derived from local measurements of millisecond pulsars, along with the number of point sources resolved by Fermi, to calculate an upper limit for the diffuse emission from such a population. While this limit is compatible with the millisecond pulsar population implied by the number of low-mass X-ray binaries, it strongly excludes the possibility that most of the excess originates from such objects.



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Challenges in Explaining the Galactic Center Gamma-Ray Excess with Millisecond Pulsars

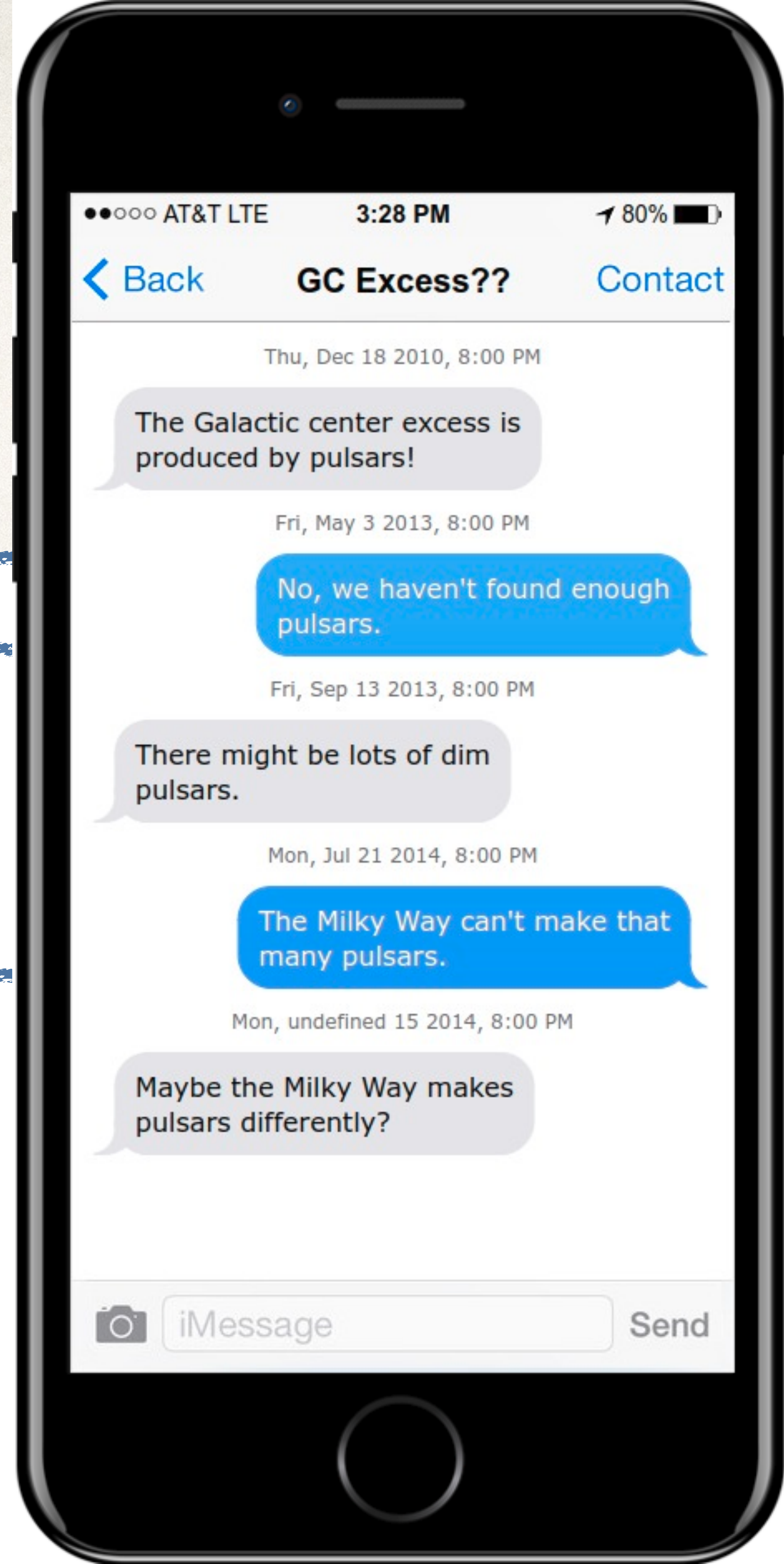
Millisecond pulsars and the Galactic Center gamma-ray excess: the importance of luminosity function and secondary emission

Jovana Petrović[a,b], Pasquale D. Serpico[c], Gabrijela Zaharijas[d,e,f]

[a] *Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski trg 16 , 11000 Beograd, Serbia*

[b] *Department of Physics, Faculty of Sciences, University of Novi Sad, Trg Dositeja Obradovića 4, 21000 Novi Sad, Serbia*

[c] *Laboratoire de Physique Théorique d' Annecy-le-Vieux (LAPTh), Univ. de Savoie,*



Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Samuel K. Lee,[1,2] Mariangela Lisanti,[3] Benjamin R. Safdi,[4] Tracy R. Slatyer,[4] and Wei Xue[4]
[1] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544*
[2] *Broad Institute, Cambridge, MA 02142*
[3] *Department of Physics, Princeton University, Princeton, NJ 08544*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139*
(Dated: February 4, 2016)

We present a new method to characterize unresolved point sources (PSs), generalizing traditional template fits to account for non-Poissonian photon statistics. We apply this method to *Fermi* Large Area Telescope gamma-ray data to characterize PS populations at high latitudes and in the Inner Galaxy. We find that PSs (resolved and unresolved) account for ~50% of the total extragalactic gamma-ray background in the energy range ~1.9 to 11.9 GeV. Within 10° of the Galactic Center with $|b| \geq 2°$, we find that ~5–10% of the flux can be accounted for by a population of unresolved PSs, distributed consistently with the observed ~GeV gamma-ray excess in this region. The excess is fully absorbed by such a population, in preference to dark-matter annihilation. The inferred source population is dominated by near-threshold sources, which may be detectable in future searches.

Dark-matter (DM) annihilation in the Galactic halo can contribute to the flux of high-energy gamma rays detected by experiments such as the *Fermi* Large Area

excess. The choice of this energy range keeps the signal-to-background ratio in the region of interest (ROI) high, maintains a sufficiently large number of photons over the

Strong Support for the Millisecond Pulsar Origin of the Galactic Center GeV Excess

Richard Bartels,[1,*] Suraj Krishnamurthy,[1,†] and Christoph Weniger[1,‡]
[1] *GRAPPA Institute, University of Amsterdam, Science Park 904, 1090 GL Amsterdam, Netherlands*
(Dated: 4 February 2016)

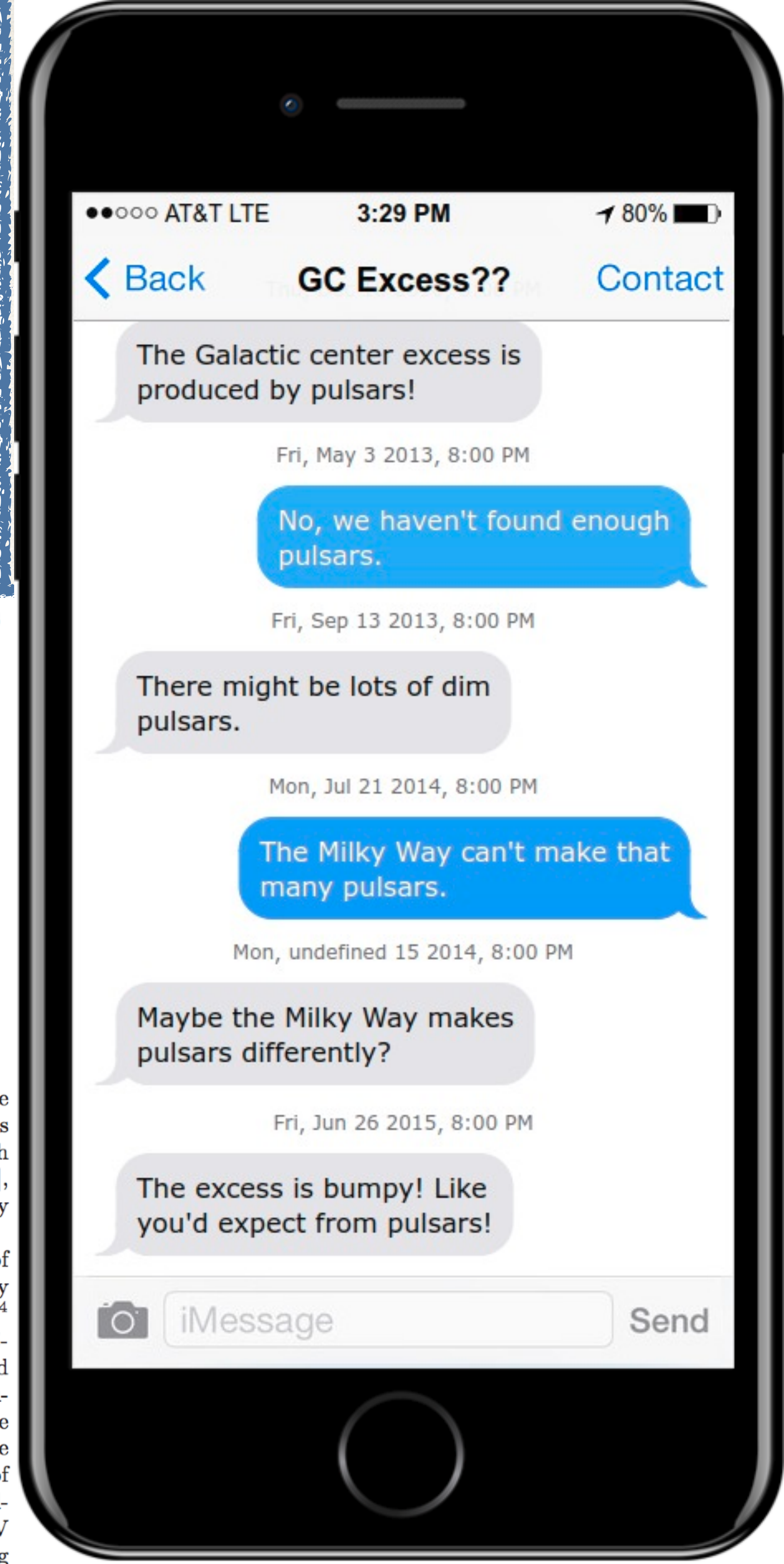
Using γ-ray data from the *Fermi* Large Area Telescope, various groups have identified a clear excess emission in the Inner Galaxy, at energies around a few GeV. This excess resembles remarkably well a signal from dark-matter annihilation. One of the most compelling astrophysical interpretations is that the excess is caused by the combined effect of a previously undetected population of dim γ-ray sources. Because of their spectral similarity, the best candidates are millisecond pulsars. Here, we search for this hypothetical source population, using a novel approach based on wavelet decomposition of the γ-ray sky and the statistics of Gaussian random fields. Using almost seven years of *Fermi*-LAT data, we detect a clustering of photons as predicted for the hypothetical population of millisecond pulsar, with a statistical significance of 10.0σ. For plausible values of the luminosity function, this population explains 100% of the observed excess emission. We argue that other extragalactic or Galactic sources, a mismodeling of Galactic diffuse emission, or the thick-disk population of pulsars are unlikely to account for this observation.

Introduction. Since its launch in 2008, the *Fermi* Large Area Telescope (LAT) has revolutionized our understanding of the γ-ray sky. Among the major successes are the detection of more than 3000 γ-ray sources [1], the discovery of the *Fermi* bubbles [2], some of the most stringent limits on dark-matter annihilation [3] and, most recently, the detection of cross-correlations between the extragalactic γ-ray background and various galaxy catalogs [4].

One of the most interesting γ-ray signatures identified in the *Fermi*-LAT data by various groups [5–16], is an excess emission in the Inner Galaxy at energies around a few GeV. This excess attracted great attention because it has properties typical for a dark-matter annihilation signal. This Galactic center excess (GCE) is detected both within the inner 10 arcmin of the Galactic Center (GC) [7, 9, 10] and up to Galactic latitudes of more than 10° [13, 15, 17, 18]. It features a remarkably uniform

ther possible support for the MSP hypothesis might come from *Chandra* observations of low-mass x-ray binaries (which are progenitor systems of MSPs) in M31, which show a centrally peaked profile in the inner 2 kpc [27, 28], as well as the recent observation of extended hard X-ray emission from the Galactic Center by *NuSTAR* [29].

It was claimed that an interpretation of 100% of the GCE emission in terms of MSPs would be already ruled out: a sizeable fraction of the required 10^3–10^4 MSPs should have been already detected by the *Fermi*-LAT [30, 31], but no (isolated) MSP has been identified so far in the bulge region. This conclusion depends crucially, however, on the adopted γ-ray luminosity of the brightest MSPs in the bulge population, on the effective source sensitivity of *Fermi*-LAT, and on the treatment of unassociated sources in the Inner Galaxy [25, 32]. A realistic sensitivity study for MSPs in the context of the GeV excess, taking into account all these effects, was lacking



Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

Samuel K. Lee,[1,2] Mariangela Lisanti,[3] Benjamin R. Safdi,[4] Tracy R. Slatyer,[4] and Wei Xue[4]
[1]*Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544*
[2]*Broad Institute, Cambridge, MA 02142*

506.05124v3 [astro-ph.HE] 3 Feb 2016

DISRUPTED GLOBULAR CLUSTERS CAN EXPLAIN THE GALACTIC CENTER GAMMA RAY EXCESS

Timothy D. Brandt[1,3] and Bence Kocsis[1,2]
Draft version September 1, 2015

05616v2 [astro-ph.HE] 31 Aug 2015

ABSTRACT

The *Fermi* satellite has recently detected gamma ray emission from the central regions of our Galaxy. This may be evidence for dark matter particles, a major component of the standard cosmological model, annihilating to produce high-energy photons. We show that the observed signal may instead be generated by millisecond pulsars that formed in dense star clusters in the Galactic halo. Most of these clusters were ultimately disrupted by evaporation and gravitational tides, contributing to a spherical bulge of stars and stellar remnants. The gamma ray amplitude, angular distribution, and spectral signatures of this source may be predicted without free parameters, and are in remarkable agreement with the observations. These gamma rays are from fossil remains of dispersed clusters, telling the history of the Galactic bulge.

Subject headings:

1. INTRODUCTION

While there are strong indications for the existence of cold dark matter from its gravitational effects (e.g. Planck Collaboration et al. 2014), there has not yet been any conclusive direct or indirect detection of the corresponding dark matter particles. One promising avenue to look for these particles is through annihilation in which two dark matter particles (a particle and its antiparticle) convert into high energy photons that we can observe. The dark matter annihilation signal is expected to be strongest where the density of dark matter is highest, i.e., in the centers of galaxies.

Detailed analyses of the *Fermi* satellite's map of the gamma-ray sky have revealed an excess around the Galactic center peaking at energies of ∼2 GeV (e.g. Hooper & Goodenough 2011; Gordon & Macías 2013; Daylan et al. 2014). This excess appears to be roughly

the central few pc around Sgr A* itself, extending fro soft X-rays to ∼100 TeV gamma rays (Baganoff et a 2001; Aharonian et al. 2004; Bélanger et al. 200 Perez et al. 2015). The origin of this emission is su ject to debate; see van Eldik (2015) for a review. The r gion near the event horizon of Sgr A* is likely responsib for bright outbursts in soft X-rays (Baganoff et al. 2001 but this scenario struggles to explain the steady emissi at much higher energies. Alternative explanations for t GeV and TeV flux include the supernova remnant Sgr East (Crocker et al. 2005), though this is strongly di favored based on its observed offset from the very hig energy emission centered on Sgr A* (Acero et al. 2010 Secondary emission from particles accelerated by Sgr A is another candidate, either in a steady state or fro a past burst of accretion (e.g. Atoyan & Dermer 200 Aharonian & Neronov 2005; Chernyakova et al. 2011

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Introduction. Since its launch in 2008, the *Fermi* Large Area Telescope (LAT) has revolutionized our understanding of the γ-ray sky. Among the major successes are the detection of more than 3000 γ-ray sources [1], the discovery of the *Fermi* bubbles [2], some of the most stringent limits on dark-matter annihilation [3] and, most recently, the detection of cross-correlations between the extragalactic γ-ray background and various galaxy catalogs [4].

One of the most interesting γ-ray signatures identified in the *Fermi*-LAT data by various groups [5–16], is an excess emission in the Inner Galaxy at energies around a few GeV. This excess attracted great attention because it has properties typical for a dark-matter annihilation signal. This Galactic center excess (GCE) is detected both within the inner 10 arcmin of the Galactic Center (GC) [7, 9, 10] and up to Galactic latitudes of more than 10° [13, 15, 17, 18]. It features a remarkably uniform

ther possible support for the MSP hypothesis might come from *Chandra* observations of low-mass x-ray binaries (which are progenitor systems of MSPs) in M31, which show a centrally peaked profile in the inner 2 kpc [27, 28], as well as the recent observation of extended hard X-ray emission from the Galactic Center by *NuSTAR* [29].

It was claimed that an interpretation of 100% of the GCE emission in terms of MSPs would be already ruled out: a sizeable fraction of the required 10^3–10^4 MSPs should have been already detected by the *Fermi*-LAT [30, 31], but no (isolated) MSP has been identified so far in the bulge region. This conclusion depends crucially, however, on the adopted γ-ray luminosity of the brightest MSPs in the bulge population, on the effective source sensitivity of *Fermi*-LAT, and on the treatment of unassociated sources in the Inner Galaxy [25, 32]. A realistic sensitivity study for MSPs in the context of the GeV excess, taking into account all these effects, was lacking

Evidence for Unresolved Gamma-Ray Point Sources in the Inner Galaxy

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DISRUPTED GLOBULAR CLUSTERS CAN EXPLAIN THE GALACTIC CENTER GAMMA RAY EXCESS

Timothy D. Brandt[1,3] and Bence Kocsis[1,2]
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Low Mass X-Ray Binaries in the Inner Galaxy: Implications for Millisecond Pulsars and the GeV Excess

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Abstract. If millisecond pulsars (MSPs) are responsible for the excess gamma-ray emission observed from the region surrounding the Galactic Center, the same region should also contain a large population of low-mass X-ray binaries (LMXBs). In this study, we compile and utilize a sizable catalog of LMXBs observed in the the Milky Way's globular cluster system and in the Inner Galaxy, as well as the gamma-ray emission observed from globular clusters, to estimate the flux of gamma rays predicted from MSPs in the Inner Galaxy. From this comparison, we conclude that only up to ∼4-23% of the observed gamma-ray excess is likely to originate from MSPs. This result is consistent with, and more robust than, previous estimates which utilized smaller samples of both globular clusters and LMXBs. If MSPs had been responsible for the entirety of the observed excess, INTEGRAL should have detected $\sim 10^3$ LMXBs from within a 10° radius around the Galactic Center, whereas only 42 LMXBs (and 46 additional LMXB candidates) have been observed.

both within the inner 10 arcmin of the Galactic Center (GC) [7, 9, 10] and up to Galactic latitudes of more than 10° [13, 15, 17, 18]. It features a remarkably uniform

unassociated sources in the Inner Galaxy [25, 32]. A realistic sensitivity study for MSPs in the context of the GeV excess, taking into account all these effects, was lacking

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ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we search for members of an unresolved population of γ-ray pulsars located in the inner Galaxy that are predicted by the interpretation of the GC excess as being due to a population of such sources. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40° \times 40°$ region of the Galaxy, derive a list of approximately 400 sources, and apply pulsar selection criteria to extract pulsar candidates among our source list. We performed the entire data analysis chain with two different interstellar emission models (IEMs), and found a total of 135 pulsar candidates, of which 66 were selected with both IEMs.

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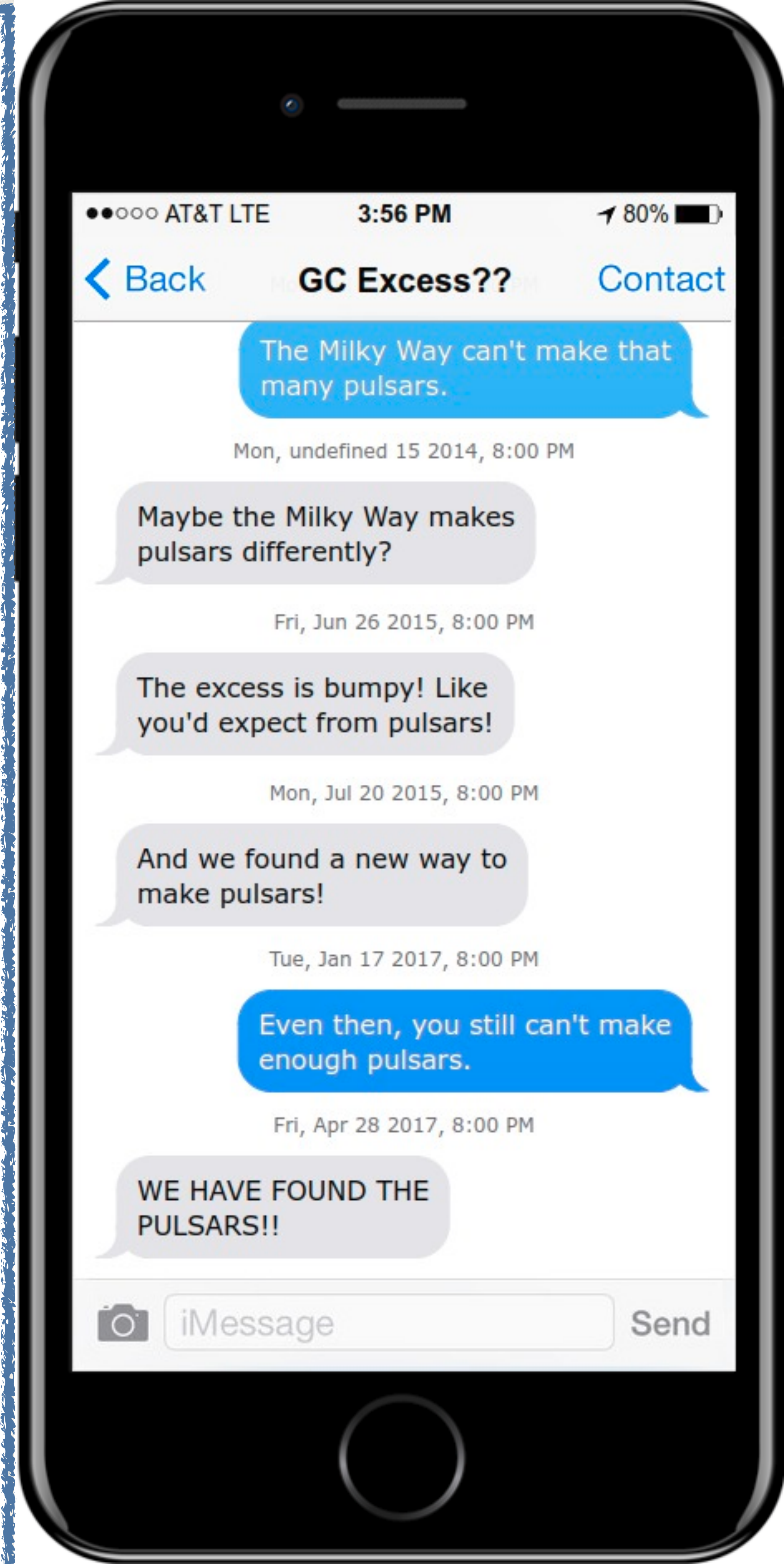

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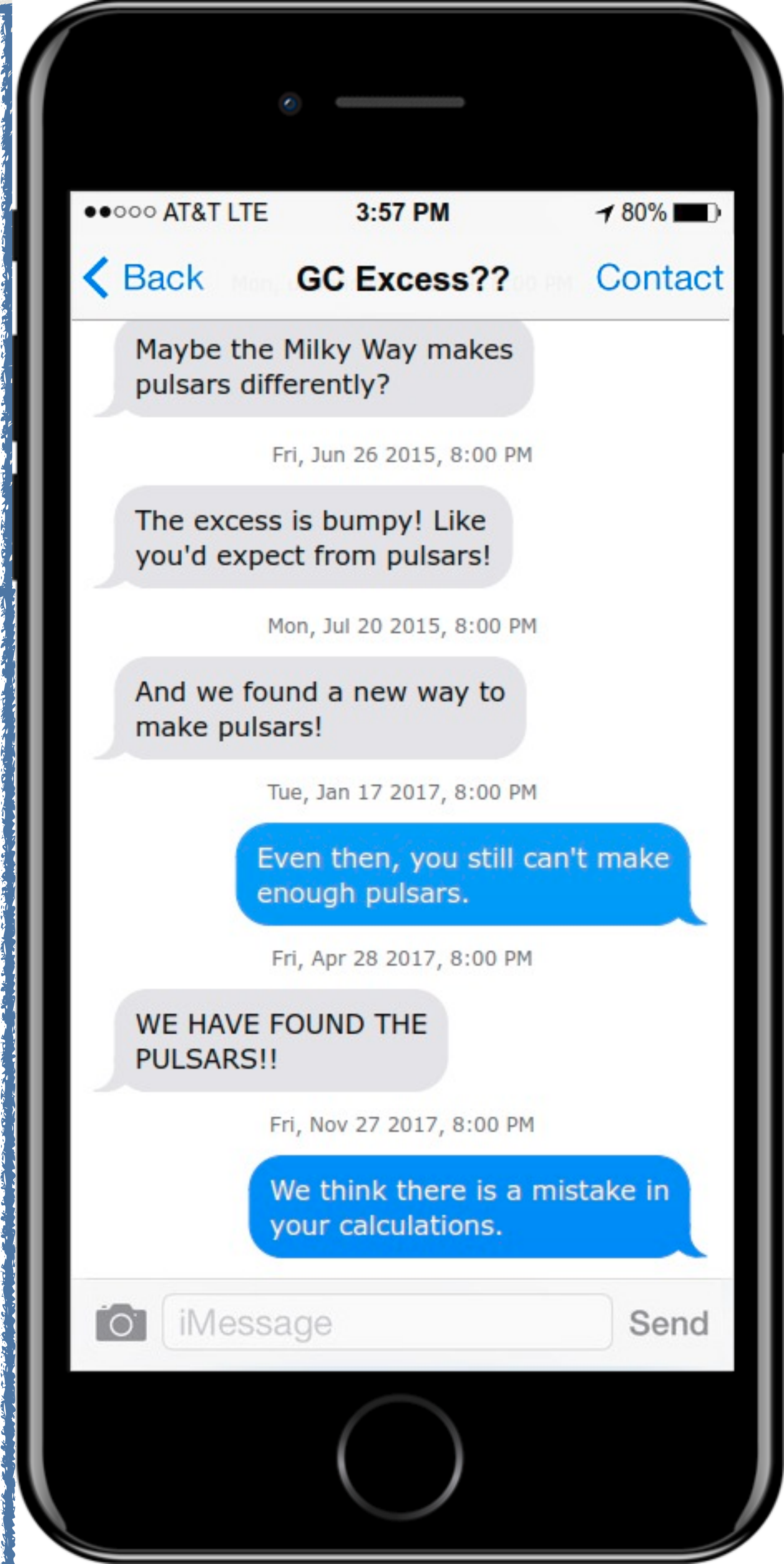
ABSTRACT

The *Fermi*-LAT Collaboration recently presented a new catalog of gamma-ray sources located within the $40° \times 40°$ region around the Galactic Center (Ajello et al. 2017) – the Second Fermi Inner Galaxy (2FIG) catalog. Utilizing this catalog, they analyzed models for the spatial distribution and luminosity function of sources with a pulsar-like gamma-ray spectrum. Ajello et al. (2017) v1 also claimed to detect, in addition to a disk-like population of pulsar-like sources, an approximately 7σ preference for an additional centrally concentrated population of pulsar-like sources, which they referred to as a "Galactic Bulge" population. Such a population would be of great interest, as it would support a pulsar interpretation of the gamma-ray excess that has long been observed in this region. In an effort to further explore the implications of this new source catalog, we attempted to reproduce the results presented by the *Fermi*-LAT Collaboration, but failed to do so. Mimicking as closely as possible the analysis techniques undertaken in Ajello et al. (2017), we instead find that our likelihood analysis favors a very different spatial distribution and luminosity function for these sources. Most notably, our results do not exhibit a strong preference for a "Galactic Bulge" population of pulsars. Furthermore, we find that masking the regions immediately surrounding each of the 2FIG pulsar candidates does *not* significantly impact the spectrum or intensity of the Galactic Center gamma-ray excess. Although these results refute the claim of strong evidence for a centrally concentrated pulsar population presented in Ajello et al. (2017), they neither rule out nor provide support for the possibility that the Galactic Center excess is generated by a population of low-luminosity and currently largely unobserved pulsars. In a spirit of maximal openness and transparency, we have made our analysis code available at https://github.com/bsafdi/GCE-2FIG.

1. A COMPARISON WITH AJELLO *ET AL.*

The *Fermi*-LAT Collaboration recently presented the Second Fermi Inner Galaxy (2FIG) source catalog (Ajello et al. 2017).[1] This catalog consists of 374 sources that have been detected with a test statistic (TS) of 25 or greater, located within the $40° \times 40°$ region surrounding the Galactic Center. Among this list, there are 104 sources (86 of which are not contained in the 3FGL catalog (Acero et al. 2015)) that exhibit best-fit spectral parameters that are characterized as pulsar-like by Ajello et al. (2017).[2] More specifically, Ajello et al. (2017) classifies a source as a pulsar candidate if its spectrum prefers a power-law with an exponential cutoff over that of a simple power-law at a level of TS > 9 and is best-fit by a spectral index $\Gamma < 2$ and a cutoff energy $E_{\rm cut} < 10$ GeV.

By combining the Galactic coordinates and fluxes of these sources with an efficiency function that describes the probability of detecting a given source at a particular sky location and flux, one can test various models for the underlying spatial distribution and luminosity function of the pulsar-like source population. For the disk-like component of pulsars, Ajello et al. (2017) adopt the standard Lorimer distribution (Lorimer



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The *Fermi*-LAT Collaboration recently presented a new catalog of gamma-ray sources located within the $40° \times 40°$ region around the Galactic Center (Ajello et al. 2017) – the Second Fermi Inner Galaxy (2FIG) catalog. Utilizing this catalog, they analyzed models for the spatial distribution and luminosity function of sources with a pulsar-like gamma-ray spectrum. Ajello et al. (2017) v1 also claimed to detect, in addition to a disk-like population of pulsar-like sources, an approximately 7σ preference for an additional centrally concentrated

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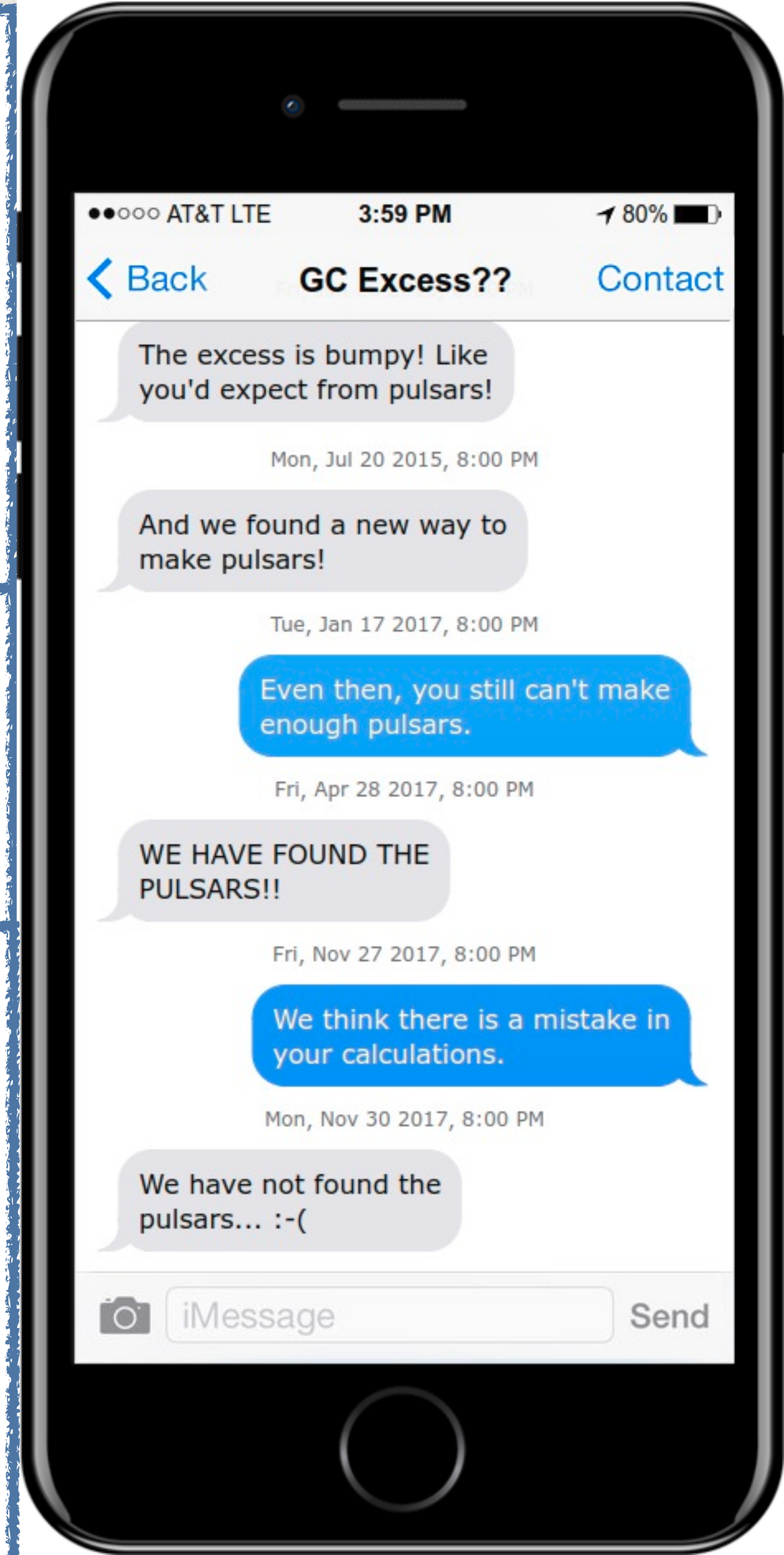
M. Ajello[1], L. Baldini[2], J. Ballet[3], G. Barbiellini[4,5], D. Bastieri[6,7], R. Bellazzini[8], E. Bissaldi[9,10], R. D. Blandford[11], E. D. Bloom[11], E. Bottacini[11], J. Bregeon[12], P. Bruel[13], R. Buehler[14], R. A. Cameron[11], R. Caputo[15], M. Caragiulo[9,10], P. A. Caraveo[16], E. Cavazzuti[17], C. Cecchi[18,19], E. Charles[11,20,*], A. Chekhtman[21], G. Chiaro[7], S. Ciprini[22,18], D. Costantin[7], F. Costanza[10], F. D'Ammando[23,24], F. de Palma[10,25], R. Desiante[26,27], S. W. Digel[11], N. Di Lalla[2], M. Di Mauro[11,28,*], L. Di Venere[9,10], C. Favuzzi[9,10], E. C. Ferrara[29], A. Franckowiak[14], Y. Fukazawa[30], S. Funk[31], P. Fusco[9,10], F. Gargano[10], D. Gasparrini[22,18], N. Giglietto[9,10], F. Giordano[9,10], M. Giroletti[23], D. Green[32,29], L. Guillemot[33,34], S. Guiriec[29,35], A. K. Harding[29], D. Horan[13], G. Jóhannesson[36,37], M. Kuss[8], G. La Mura[7], S. Larsson[38,39], L. Latronico[26], J. Li[40], F. Longo[4,5], F. Loparco[9,10], M. N. Lovellette[41], P. Lubrano[18], S. Maldera[26], D. Malyshev[31], L. Marcotulli[1], P. Martin[42], M. N. Mazziotta[10], M. Meyer[43,39], P. F. Michelson[11], N. Mirabal[29,35], T. Mizuno[44], M. E. Monzani[11], A. Morselli[45], I. V. Moskalenko[11], E. Nuss[12], N. Omodei[11], M. Orienti[23], E. Orlando[11], M. Palatiello[4,5], V. S. Paliya[1], D. Paneque[46], J. S. Perkins[29], M. Persic[4,47], M. Pesce-Rollins[8], F. Piron[12], G. Principe[31], S. Rainò[9,10], R. Rando[6,7], M. Razzano[8,48], A. Reimer[49,11], O. Reimer[49,11], P. M. Saz Parkinson[50,51,52], C. Sgrò[8], E. J. Siskind[53], D. A. Smith[54], F. Spada[8], G. Spandre[8], P. Spinelli[9,10], H. Tajima[55,11], J. B. Thayer[11], D. J. Thompson[29], L. Tibaldo[56], D. F. Torres[40,57], E. Troja[29,32], G. Vianello[11], K. Wood[58], M. Wood[11,59,*], G. Zaharijas[60,61]

Draft version October 31, 2017

ABSTRACT

An excess of γ-ray emission from the Galactic Center (GC) region with respect to predictions based on a variety of interstellar emission models and γ-ray source catalogs has been found by many groups using data from the *Fermi* Large Area Telescope (LAT). Several interpretations of this excess have been invoked. In this paper we search for members of an unresolved population of γ-ray pulsars located in the inner Galaxy that are predicted by the interpretation of the GC excess as being due to a population of such sources. We use cataloged LAT sources to derive criteria that efficiently select pulsars with very small contamination from blazars. We search for point sources in the inner $40° \times 40°$ region of the Galaxy, derive a list of approximately 400 sources,



THE FERMI-LAT GEV EXCESS TRACES STELLAR MASS IN THE GALACTIC BULGE

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(Received November 15, 2017; Revised; Accepted)

ABSTRACT

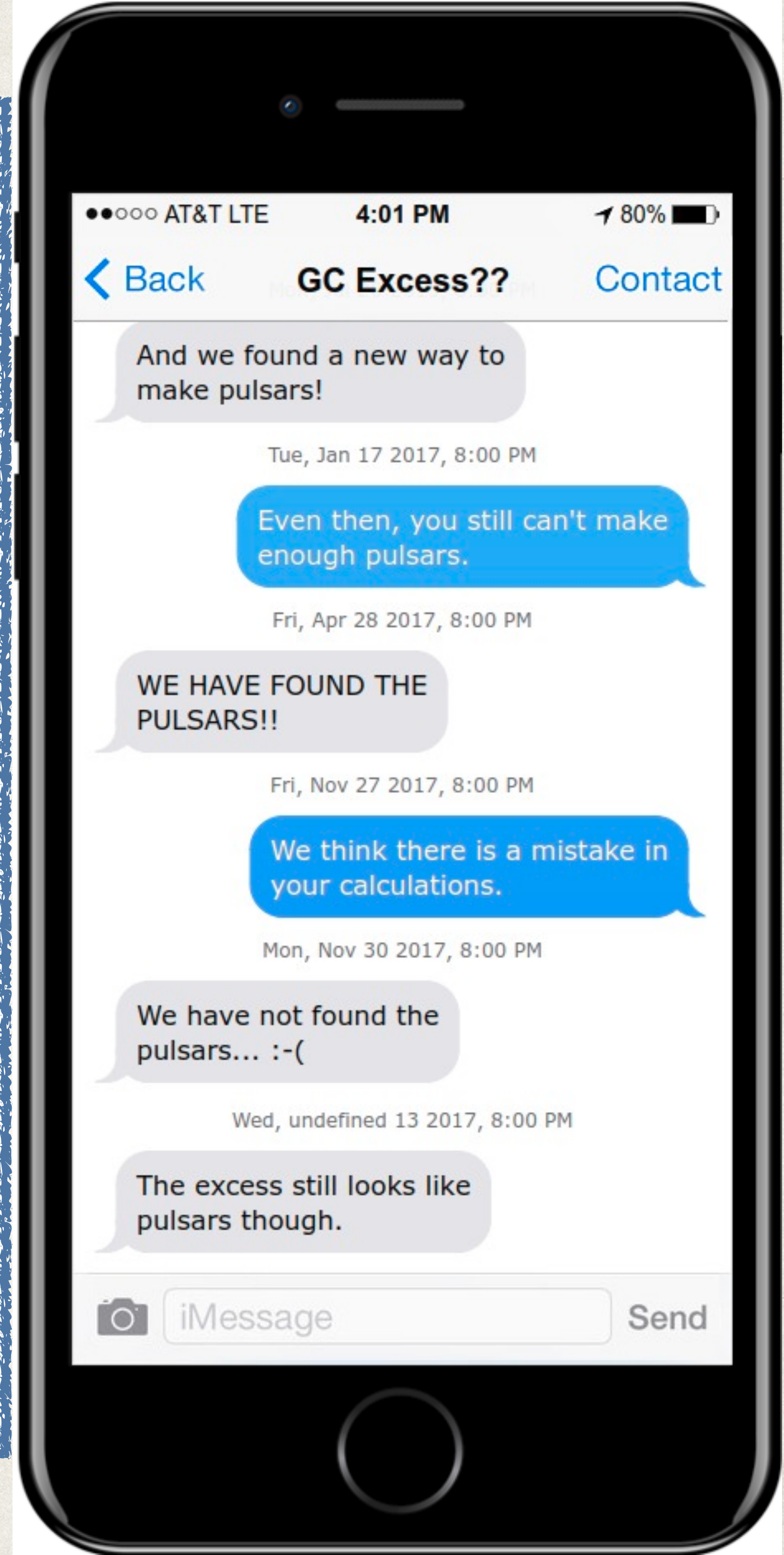
An anomalous emission component at energies of a few GeV and located towards the inner Galaxy is present in the *Fermi*-LAT data. It is known as the *Fermi*-LAT GeV excess. Using almost 8 years of data we reanalyze the characteristics of this excess with SkyFACT, a novel tool that combines image reconstruction with template fitting techniques. We find that an emission profile that traces stellar mass in the boxy and nuclear bulge provides the best description of the excess emission, providing strong circumstantial evidence that the excess is due to a stellar source population in the Galactic bulge. We find a luminosity to stellar mass ratio of $(2.1 \pm 0.2) \times 10^{27}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}$ for the boxy bulge, and of $(1.4 \pm 0.6) \times 10^{27}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}$ for the nuclear bulge. Stellar mass related templates are preferred over conventional DM profiles with high statistical significance.

1. INTRODUCTION

An anomalous emission component, often referred to as the Galactic center GeV excess (GCE), has been identified in the *Fermi*-LAT data by many groups (e.g. Goodenough & Hooper 2009; Vitale & Morselli 2009; Hooper & Linden 2011; Abazajian & Kaplinghat 2012; Macias & Gordon 2014; Daylan et al. 2016; Zhou et al. 2015; Calore et al. 2015b; Huang et al. 2016; de Boer et al. 2016; Ajello et al. 2016). Its spectrum peaks at energies of a few GeV and it appears to be uniform over the emission region. The morphology is usually described as almost spherically symmetric around the Galactic center, with a radial extent of $\sim 10°$. Intriguingly, a signal from dark matter (DM) annihilation into b-quark pairs and a DM mass $\sim 50\,\mathrm{GeV}$ has been shown to be consistent with the GCE (Goodenough & Hooper 2009; Abazajian & Kaplinghat 2012; Macias & Gordon 2014; Daylan et al. 2016; Calore et al. 2015a), provided the centrally peaked DM distribution in the Galactic bulge follows a radial power-law profile with index $\gamma \sim 1.2$. However, the exact details of the morphology and spectrum remain sub-

et al. 2010; Su et al. 2010; Ackermann et al. 2014), the low-latitude behavior of which is not well-characterized (Ackermann et al. 2017a; Linden et al. 2016).

Besides DM, more 'conventional' astrophysical explanations do exist, with various degrees of plausibility. These are either related to a large number of hitherto unresolved point sources in the Galactic bulge, just at and below the detection threshold of *Fermi*-LAT, or to diffuse photons coming from a central population of cosmic rays. Nowadays, a population of unresolved millisecond pulsars (MSPs), whose γ-ray spectrum was shown to match that of the GCE (Abazajian 2011; Abazajian et al. 2014; Calore et al. 2015b), represents the most promising astrophysical interpretation to the GCE (Abazajian 2011; Gordon & Macias 2013; Petrović et al. 2015; Yuan & Zhang 2014). Corroborative evidence for this interpretation was recently found in analyses of the γ-ray data using wavelet fluctuations, and non-Poissonian template fits (Bartels et al. 2016; Lee et al. 2016). Spectral classification of low-significance γ-ray sources and analyses of their distribution remain however inconclusive about the



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ABSTRACT

An anomalous emission component at energies of a few GeV and located towards the inner Galaxy is present in the *Fermi*-LAT data. It is known as the *Fermi*-LAT GeV excess. Using almost 8 years of data we reanalyze the characteristics of this excess with SkyFACT, a novel tool that combines image reconstruction with template fitting techniques. We find that an emission profile that traces stellar mass in the boxy and nuclear bulge provides the best description of the excess emission, providing strong circumstantial evidence that the excess is due to a stellar source population in the Galactic

Analyzing the Gamma-ray Sky with Wavelets

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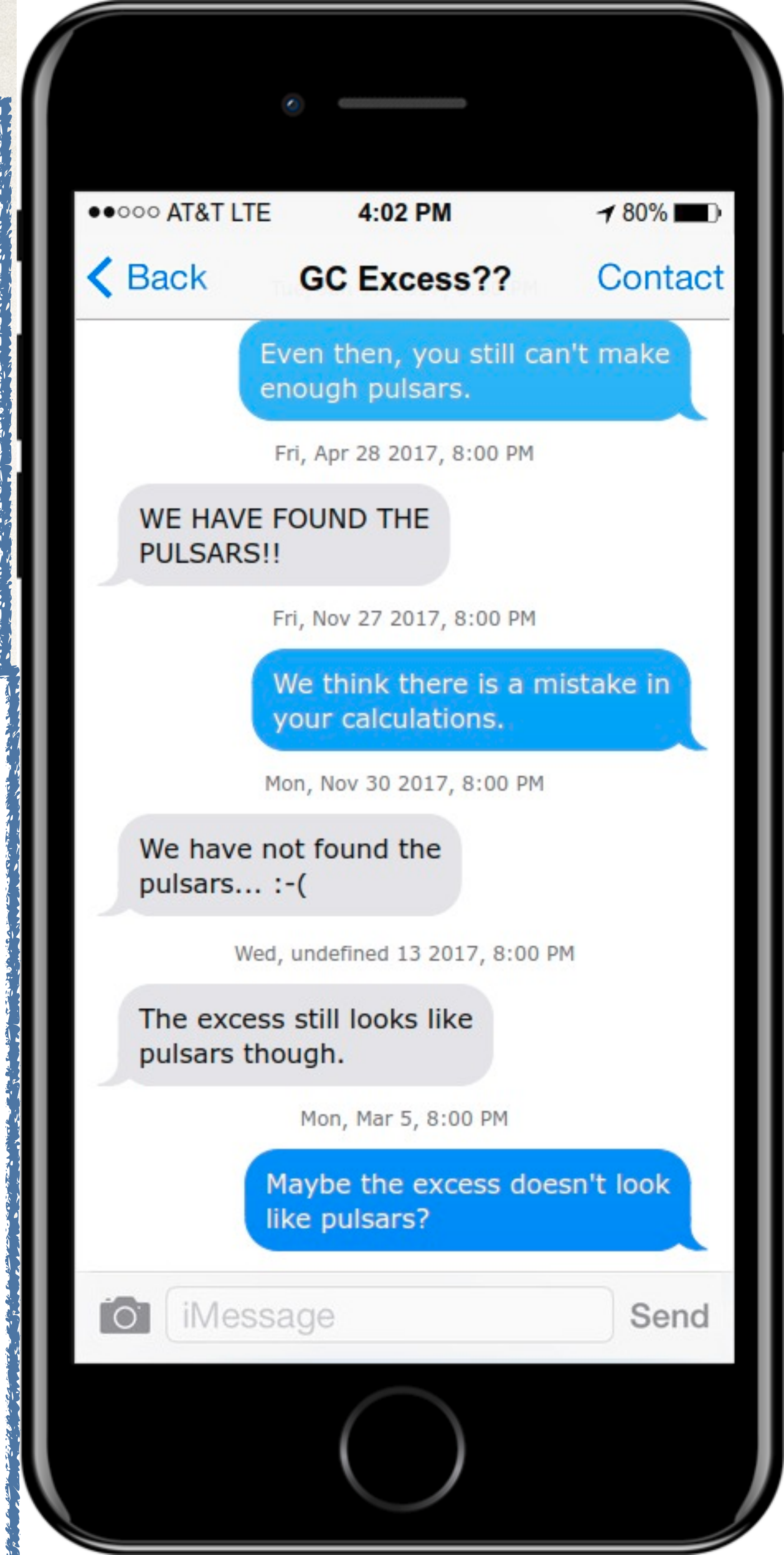
[2] *Theoretical Physics Department, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[3] *Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
(Dated: March 7, 2018)

We analyze the gamma-ray sky at energies of 0.5 to 50 GeV using the undecimated wavelet transform on the sphere. Focusing on the inner $60^\circ \times 60^\circ$ of the sky, we identify and characterize four separate residuals beyond the expected Milky Way diffuse emission. We detect the *Fermi* Bubbles, finding compelling evidence that they are diffuse in nature and contain very little small-scale structure. We detect the "cocoon" inside the Southern Bubble, and we also identify its northern counterpart above 2 GeV. The Northern Cocoon lies along the same axis but is $\sim 30\%$ dimmer than the southern one. We characterize the Galactic center excess, which we find extends up to 20° in $|b|$. At latitudes $|b| \leq 5^\circ$ we find evidence for power in small angular scales that could be the result of point-source contributions, but for $|b| \geq 5^\circ$ the Galactic center excess is dominantly diffuse in its nature. Our findings show that either the Galactic center excess and *Fermi* Bubbles connect smoothly or that the Bubbles brighten significantly below 15° in latitude. We find that the Galactic center excess appears off-center by a few degrees towards negative ℓ. Additionally, we find and characterize two emissions along the Galactic disk centered at $\ell \simeq +25^\circ$ and -20°. These emissions are significantly more elongated along the Galactic disk than the Galactic center excess.

I. INTRODUCTION

Electromagnetic radiation has allowed us a gateway to the mysteries of the Universe since time immemorial. Over the ages, we have become sensitive to radiation of increasingly higher energy. The highest energy photons are classified as gamma rays. Gamma-ray astronomy started in 1961 with 22 events observed by *Explorer 11* [1]. This was followed by *OSO-3*, which observed 621 photons and provided the first proof of emission from our own Milky Way [2]. Observations ensued with the *SAS-2*

cosmic rays (CRs) propagating in the Galaxy and interacting with the interstellar medium (ISM). The mechanism of diffuse emission is conventionally broken down into three classes, depending on the type of CR and the type of target it impinges upon. The dominant contribution to diffuse emission is from inelastic collisions of CR *nuclei* with ISM gas; these collisions produce neutral particles, predominantly π^0 and η mesons, whose decay products include photons. This emission is conventionally referred to as π^0-emission [14, 15]. CR *electrons* can also interact with the ISM gas [16]. The resulting photons



If it is dark matter, it is this type of dark matter!

Chan (1607.02246)
Jia (1607.00737)
Barrau et al. (1606.08031)
Huang et al. (1605.09018)
Cui et al. (1605.08138)
Krauss et al. (1605.05327)
Kumar et al. (1605.00611)
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Chen & Nomura (1501.07413)
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Biswas et al. (1501.02666)
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Frank & Mondal (1408.2223)
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Tang (1407.5492)
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Park & Tang (1404.5257)
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Finkbeiner & Weiner (1402.6671)
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Alves et al. (1312.5281)
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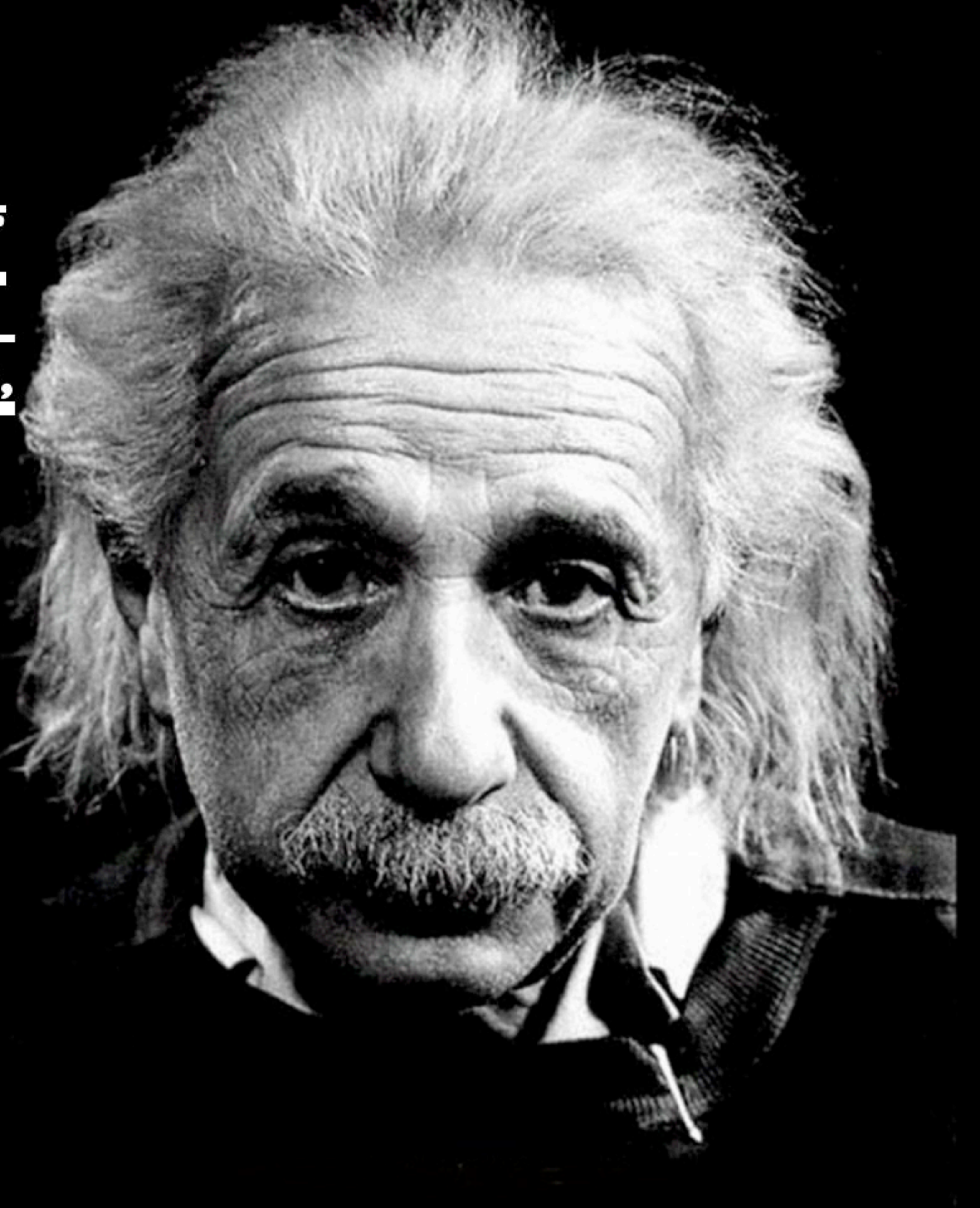
Marshall et al. (1102.0492)
Abada et al. (1101.0365)
Tytgat (1012.0576)
Logan (1010.4214)
Barger et al. (1008.1796)
Raklev et al. (0911.1986)

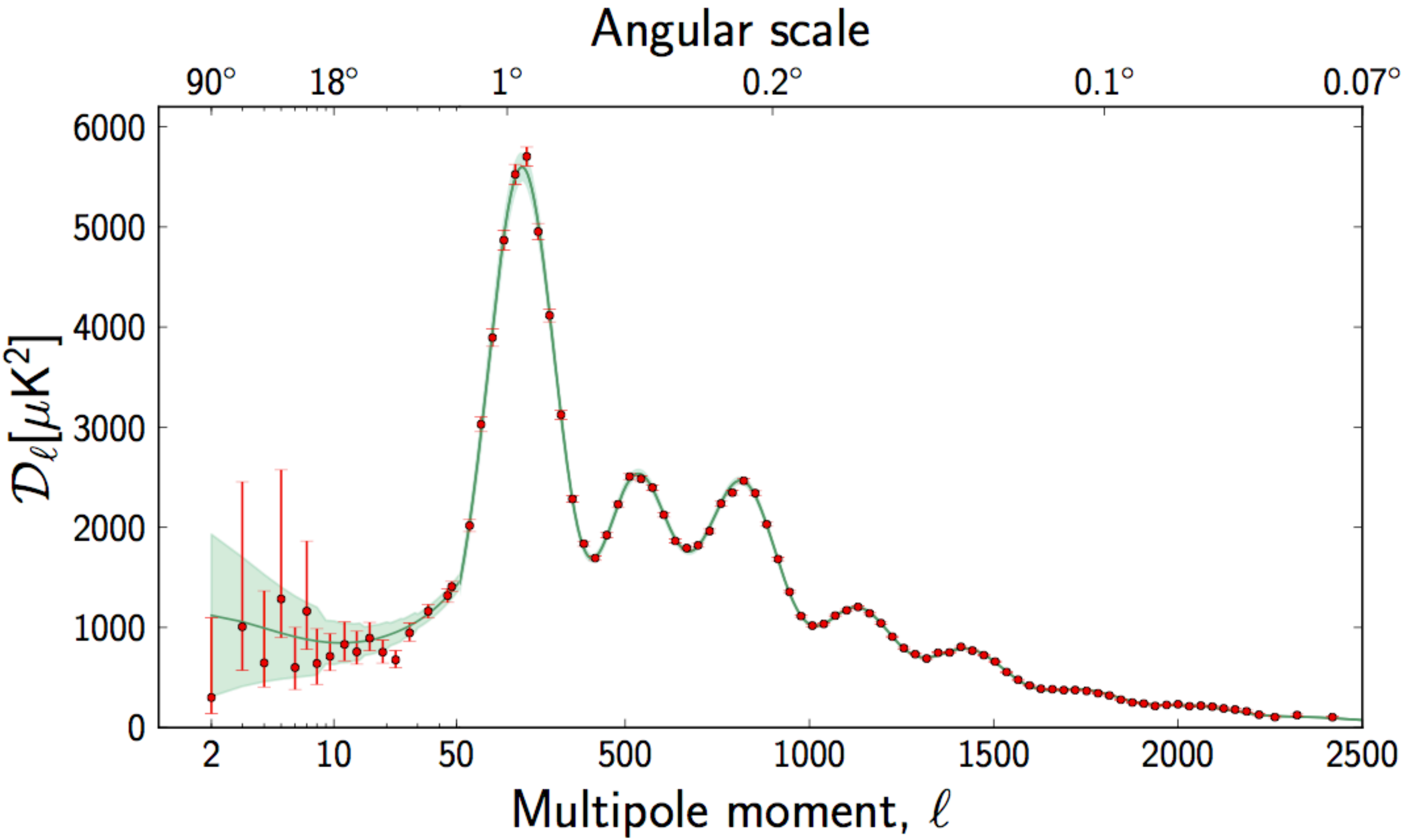
IF WE KNEW WHAT IT WAS WE WERE DOING, IT WOULDN'T BE CALLED RESEARCH.

-ALBERT EINSTEIN



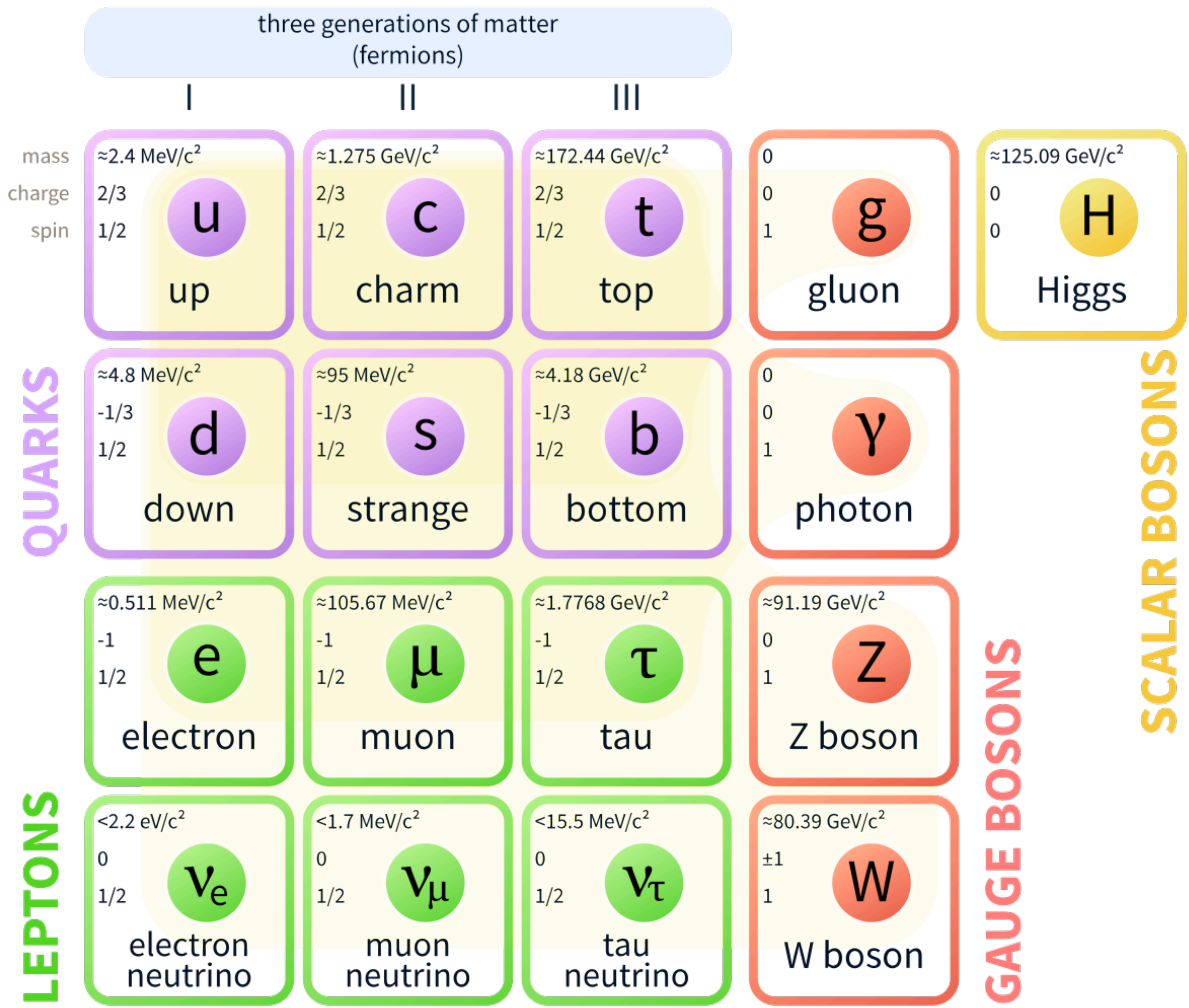
Conclusions

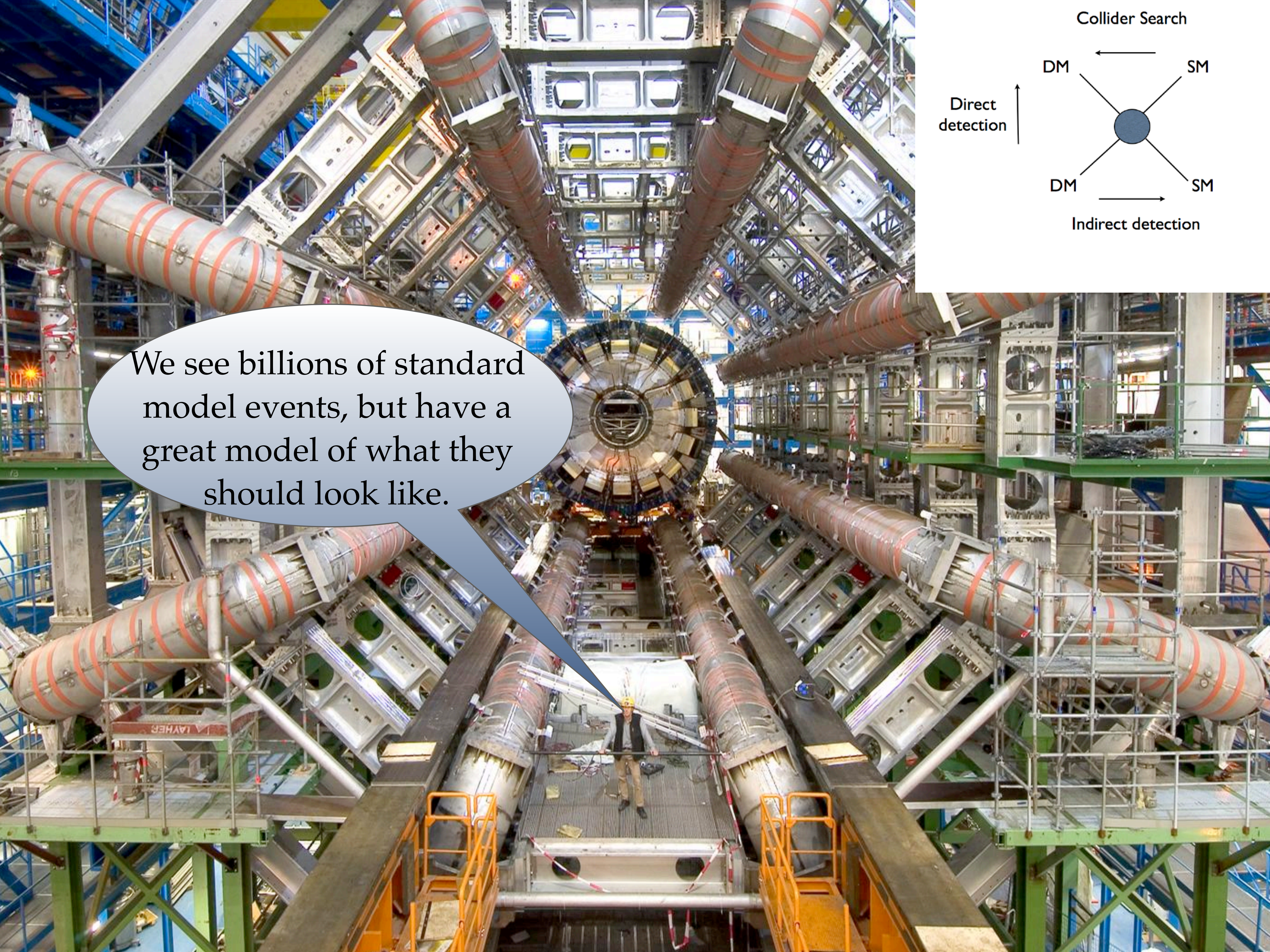
- Most of the mass in the universe is invisible - and appears to be made of a matter that doesn't interact with light.
  - The evidence for dark matter is extremely strong.
- The amount of dark matter is best explained if it is a particle that interacts with normal matter in the early universe.
- We know how to look for this dark matter, but haven't found it yet.



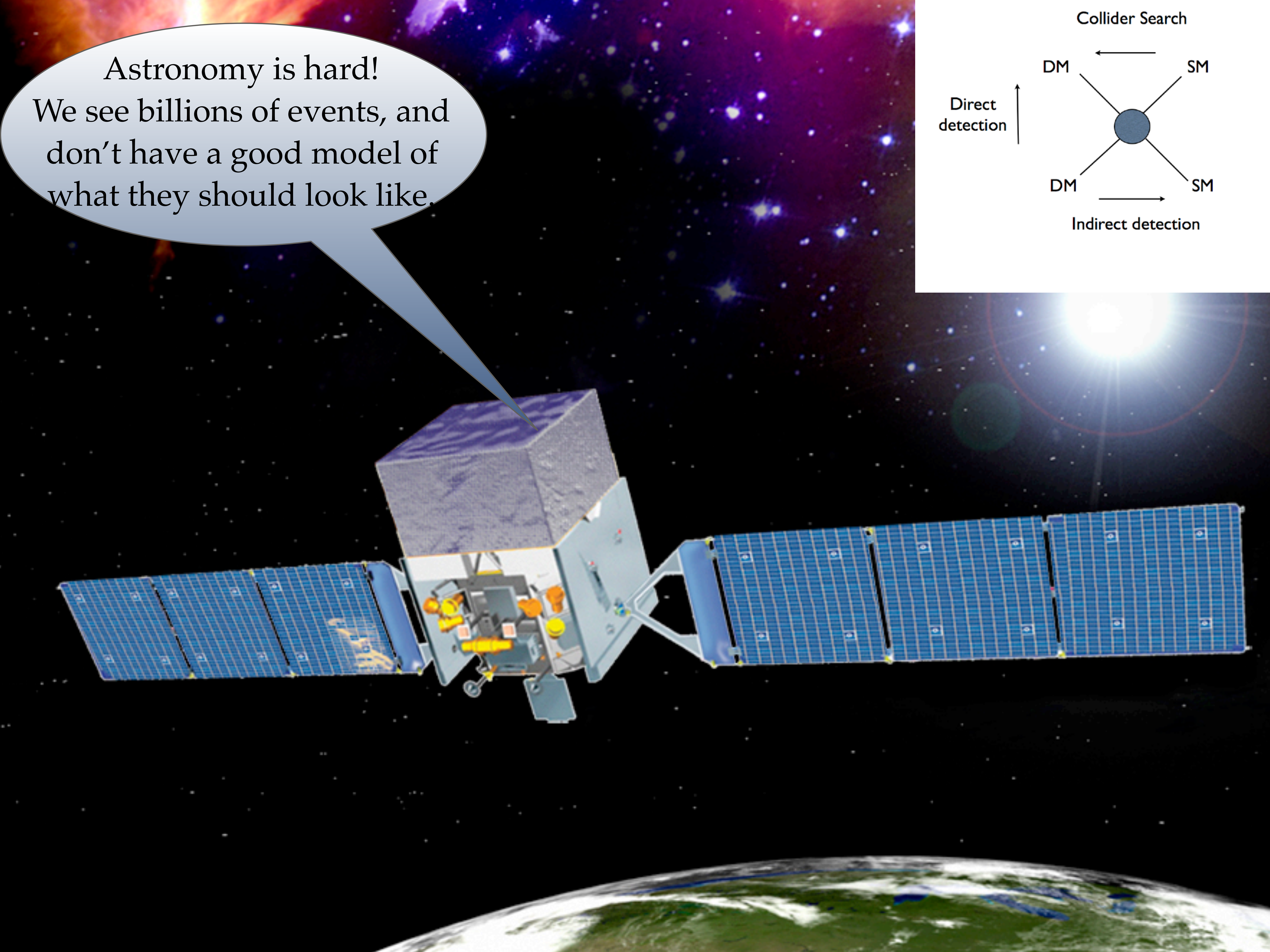
Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Standard Model of Elementary Particles

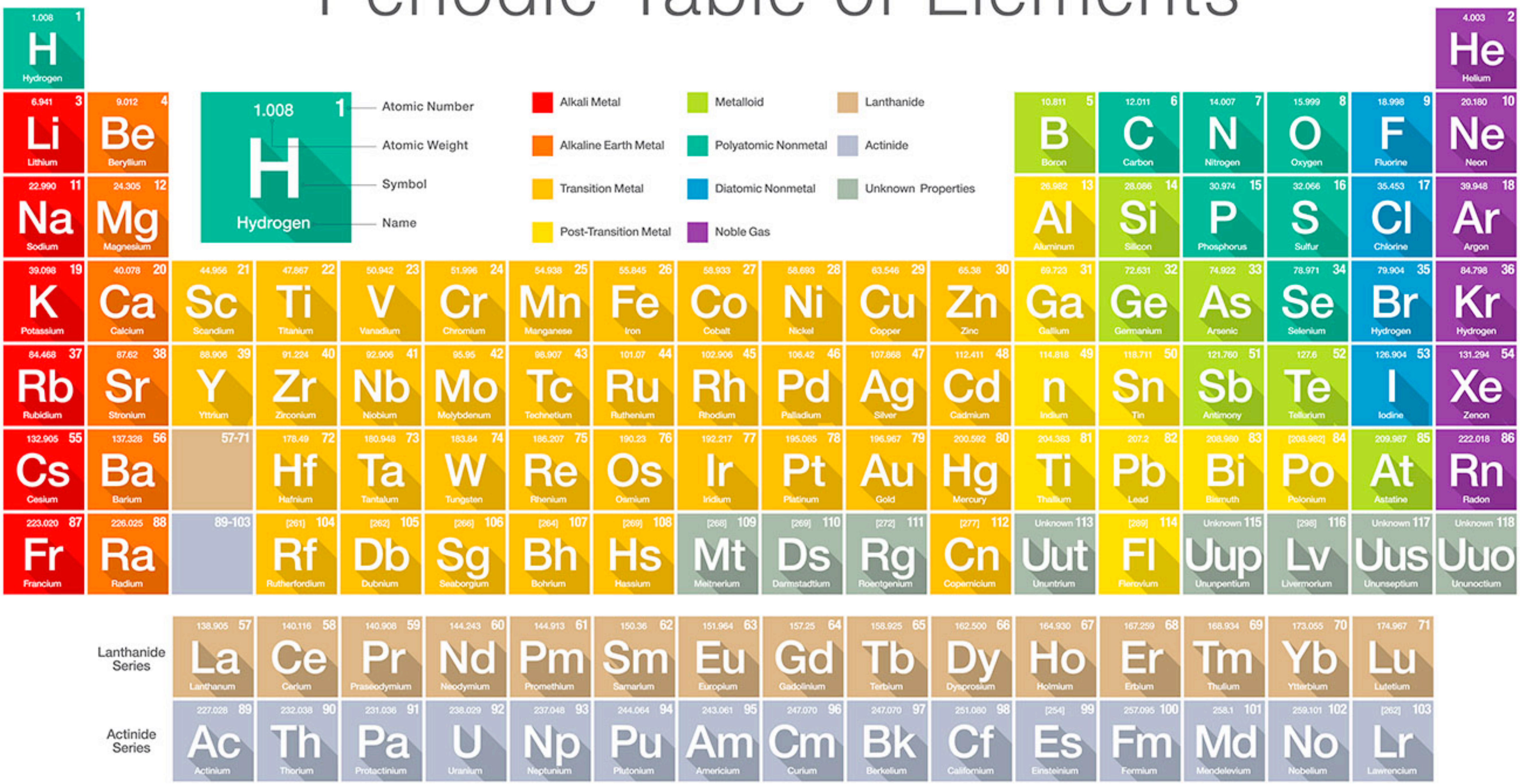


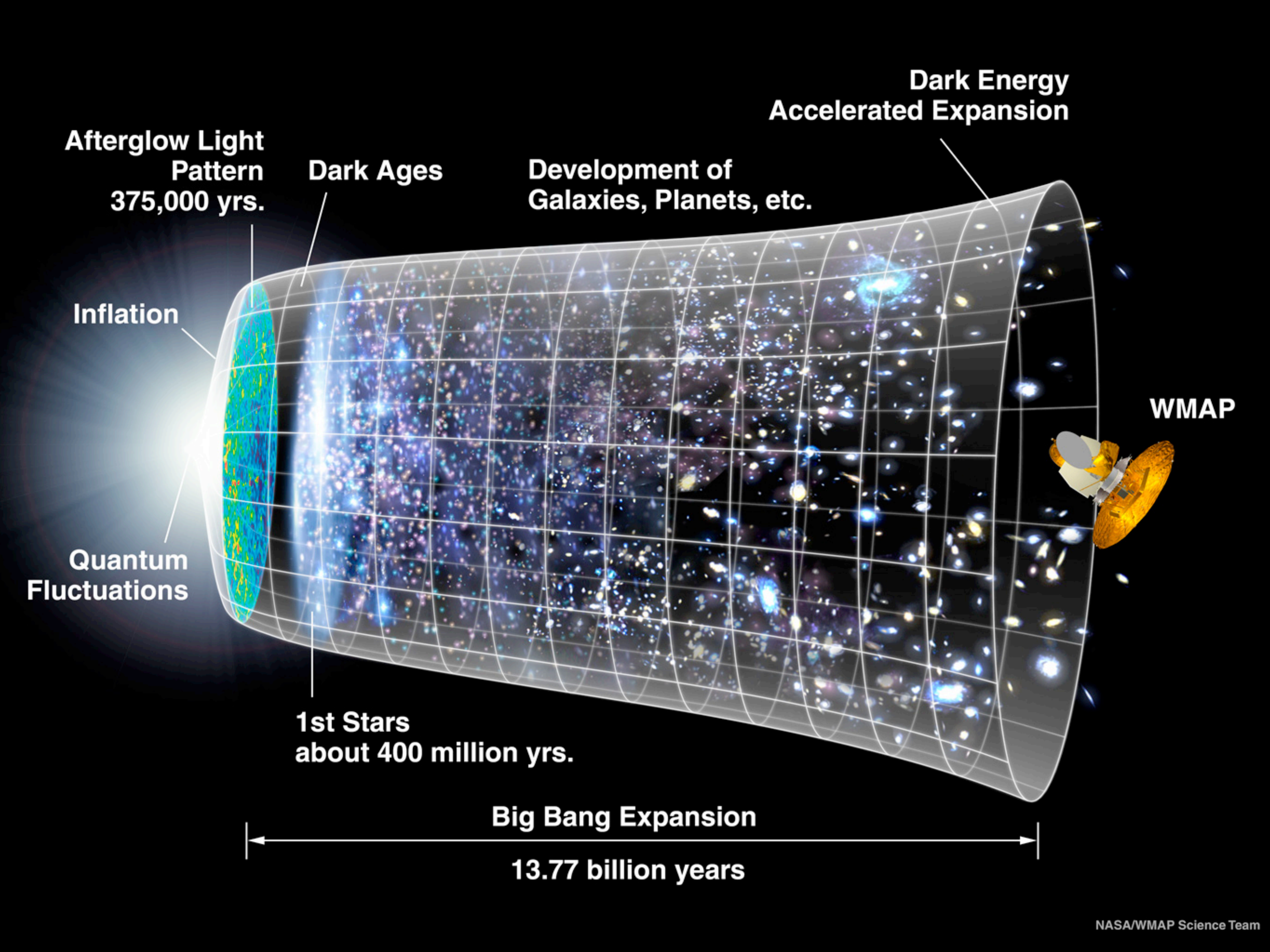

We see billions of standard model events, but have a great model of what they should look like.
Collider Search
DM
SM
Direct detection
DM
SM
Indirect detection

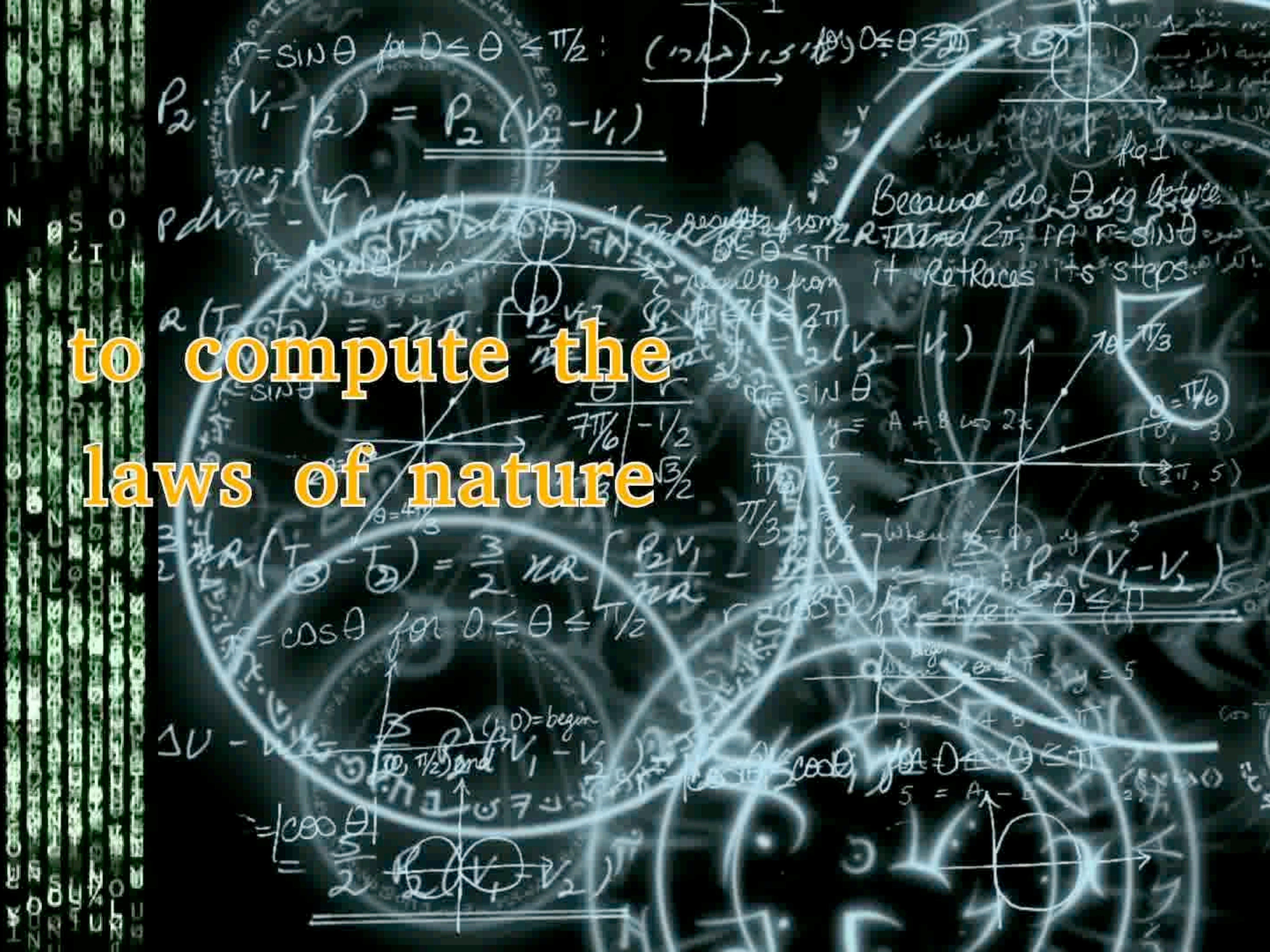

Xe
XENON
Matter Project
We see thousands of background events, but have great methods to remove them.
Collider Search
DM
SM
Direct detection
DM
SM
Indirect detection

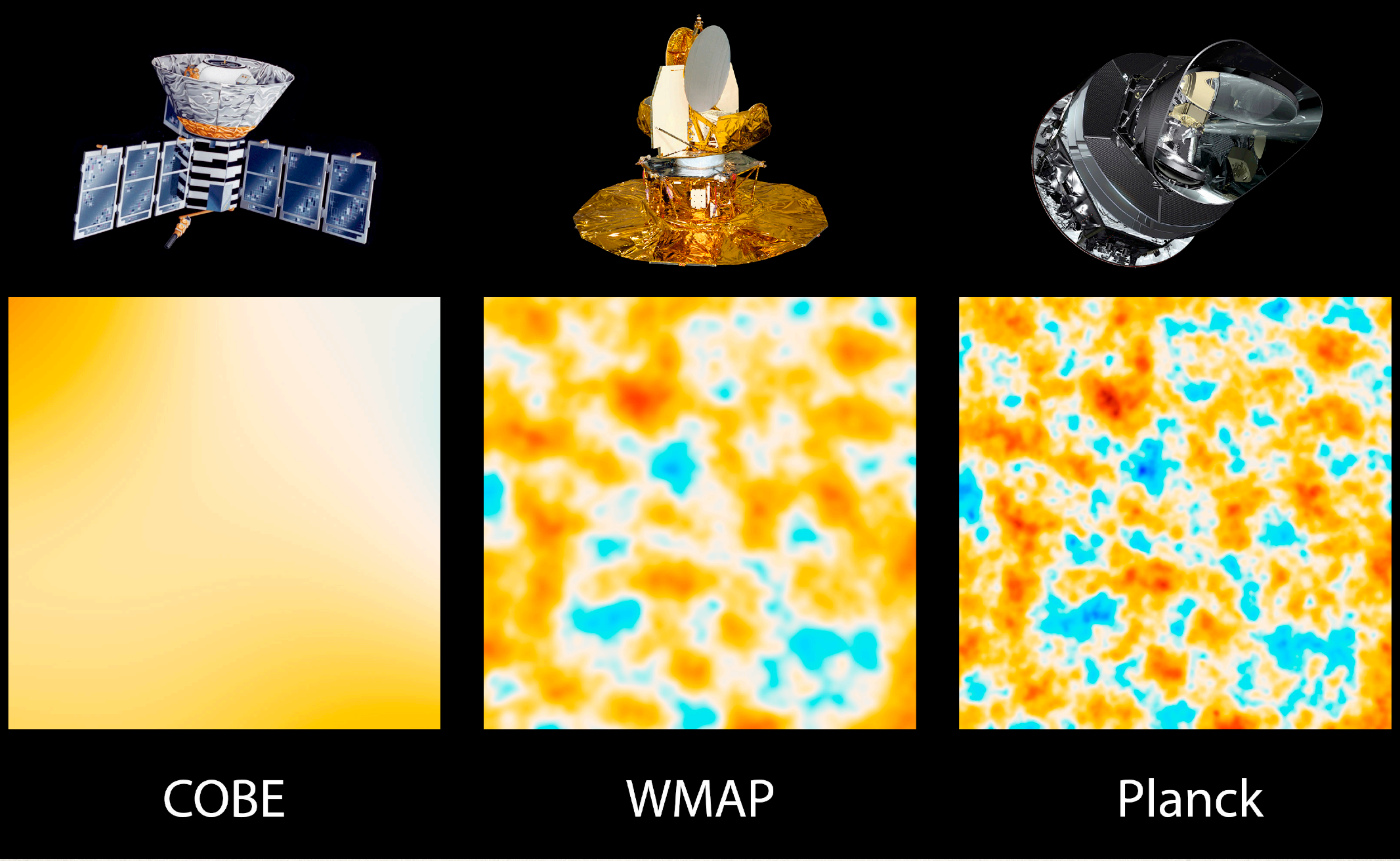

Astronomy is hard!
We see billions of events, and don’t have a good model of what they should look like.
Collider Search
DM
SM
Direct detection
DM
SM
Indirect detection

Periodic Table of Elements




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team


to compute the
laws of nature



Talk to your kids — about building better instruments.


z = 48.4
T = 0.05 Gyr
500 kpc