DARK MATTER IN THE COMING DECADE: COMPLEMENTARY PATHS TO DISCOVERY AND BEYOND

MANOJ KAPLINGHAT

UC IRVINE

COSMIC FRONTIER

CONVENERS: JONATHAN FENG AND STEVE RITZ

CF1-4 ARE DIRECTLY RELEVANT FOR DARK MATTER.

- ☐ CF1: WIMP DARK MATTER DIRECT DETECTION (PRISCILLA CUSHMAN, CRISTIAN GALBIATI, DAN MCKINSEY, HAMISH ROBERTSON, TIM TAIT)
- ☐ CF2: WIMP DARK MATTER INDIRECT DETECTION (JIM BUCKLEY, DOUG COWEN, STEFANO PROFUMO)
- ☐ CF3: NON-WIMP DARK MATTER (ALEX KUSENKO, LESLIE ROSENBERG)
- ☐ CF4: DARK MATTER COMPLEMENTARITY (DAN HOOPER, MANOJ KAPLINGHAT, KONSTANTIN MATCHEV)
- ☐ CF5: DARK ENERGY AND CMB (SARAH CHURCH, SCOTT DODELSON, KLAUS HONSCHEID)
- ☐ CF6: COSMIC PARTICLES AND FUNDAMENTAL PHYSICS (JIM BEATTY, ANN NELSON, ANGELA OLINTO, GUS SINNIS)

SHORT VERSION OF COMPLEMENTARITY DOCUMENT HTTP://ARXIV.ORG/ABS/1305.1605

COSMIC FRONTIER HAD ITS MAIN PRE-SNOWMASS MEETING AT SLAC MARCH 6-8.

HTTP://WWW-CONF.SLAC.STANFORD.EDU/COSMIC-FRONTIER/2013/.

SHORTER DOCUMENT AS A RESULT OF WORK LEADING UP TO THIS MEETING.

THE LONGER DOCUMENT (TO BE READY BY THE END OF THE SNOWMASS MEETING) WILL FLESH OUT THE DETAILS AND ADD MORE EXAMPLES OF COMPLEMENTARITY.

SHORT VERSION OF COMPLEMENTARITY DOCUMENT HTTP://ARXIV.ORG/ABS/1305.1605

- ☐ COMPLEMENTARITY BETWEEN AND WITHIN THE FOUR PILLARS OF DARK MATTER DETECTION
  - ☐ DIRECT DETECTION EXPERIMENTS THAT LOOK FOR DARK MATTER INTERACTING IN THE LAB
  - ☐ INDIRECT DETECTION EXPERIMENTS THAT CONNECT LAB SIGNALS TO DARK MATTER IN OUR OWN AND OTHER GALAXIES
  - ☐ COLLIDER EXPERIMENTS THAT ELUCIDATE THE PARTICLE PROPERTIES OF DARK MATTER
  - ☐ ASTROPHYSICAL PROBES SENSITIVE TO NON-GRAVITATIONAL INTERACTIONS OF DARK MATTER

- [ ] NEXT: EVIDENCE FOR DARK MATTER.

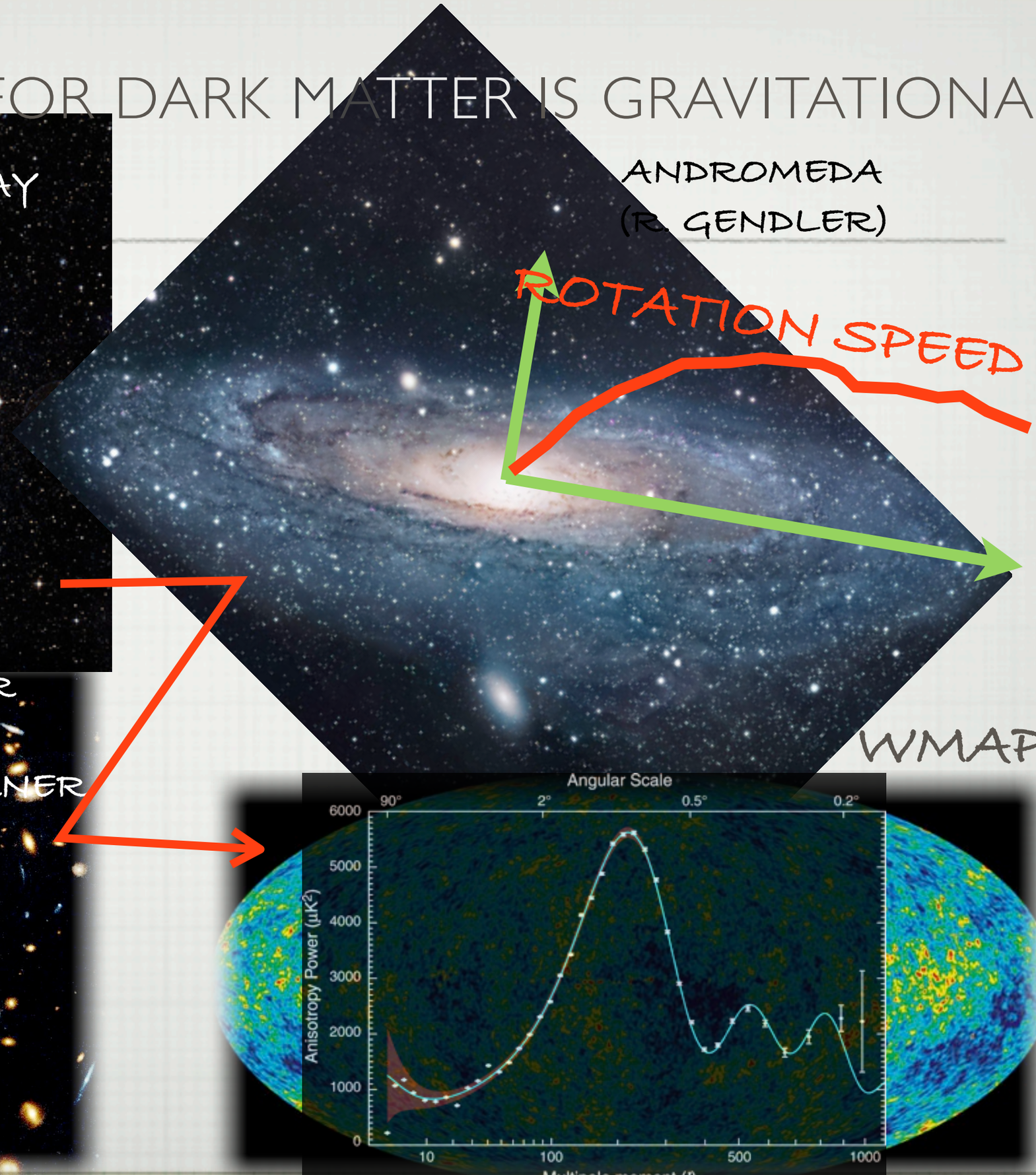
- [ ] HOW MAY ASTROPHYSICS SAY SOMETHING ABOUT THE PARTICLE NATURE OF DARK MATTER? WE WILL PICK ONE PARTICULAR EXAMPLE.

  - [ ] CAUTION!

    - [ ] (1) I AM GOING TO START FAR AFIELD AND THEN GET CLOSER TO THE ENERGY FRONTIER TOPICS.

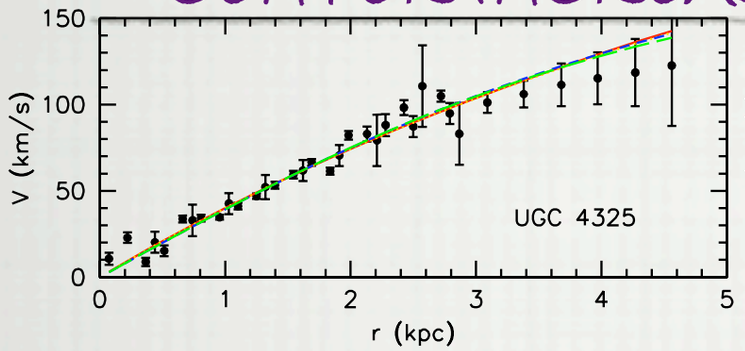
    - [ ] (2) I AM GOING TO FOCUS ON SOMETHING THAT INTERESTS ME CURRENTLY BUT THAT IS OK BECAUSE IT SERVES AS A WELL-MOTIVATED EXAMPLE AND THE POINT IS NOT TO BE EXHAUSTIVE

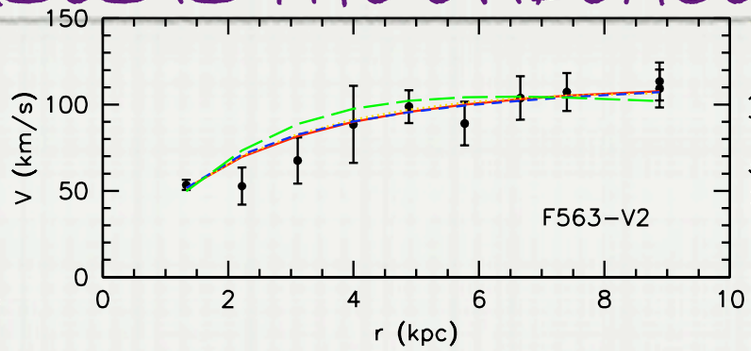
ALL EVIDENCE FOR DARK MATTER IS GRAVITATIONAL

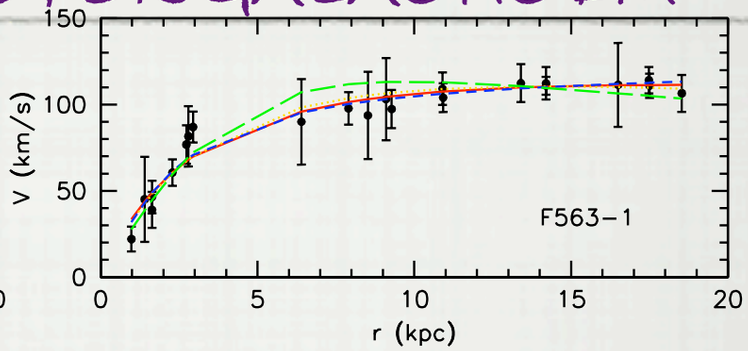


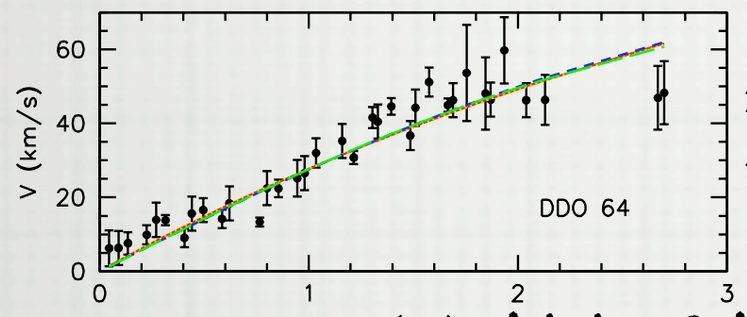
ROTATION SPEED AND DARK MATTER IN GALAXIES

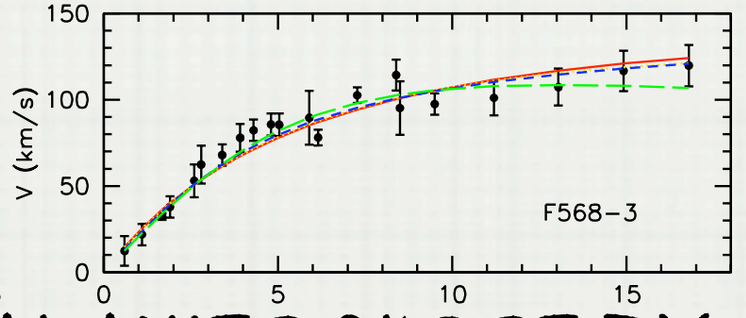
THE PLATEAU IN SPEED AS THE DISTANCE FROM THE CENTER INCREASES IS THE EVIDENCE FOR GALACTIC DM

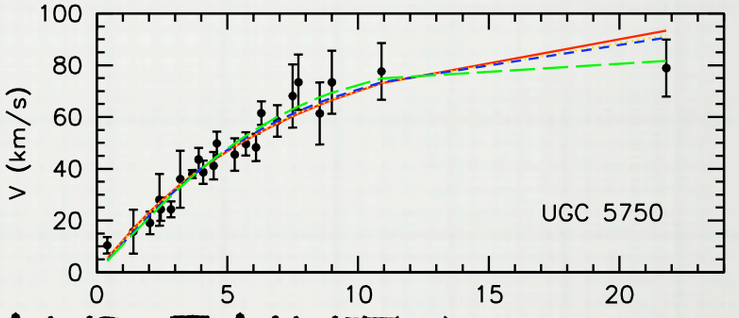




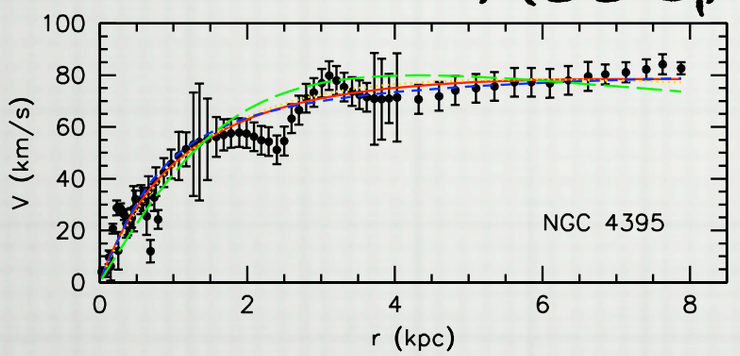


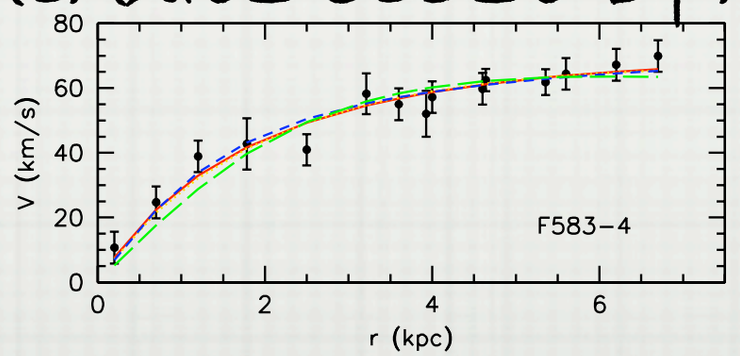


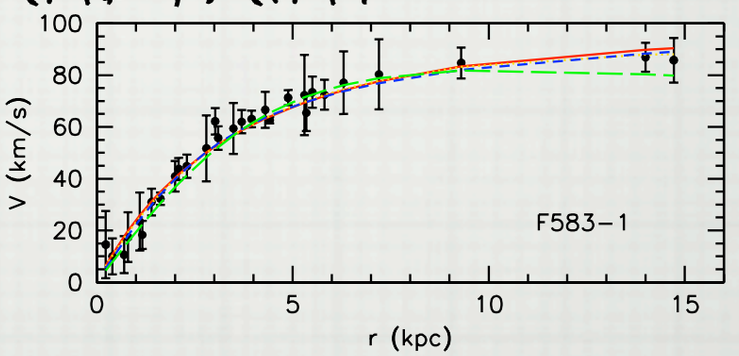




ALL GALAXIES CLOSE-BY AND FAINT







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ROTATION SPEED AND DARK MATTER IN GALAXIES

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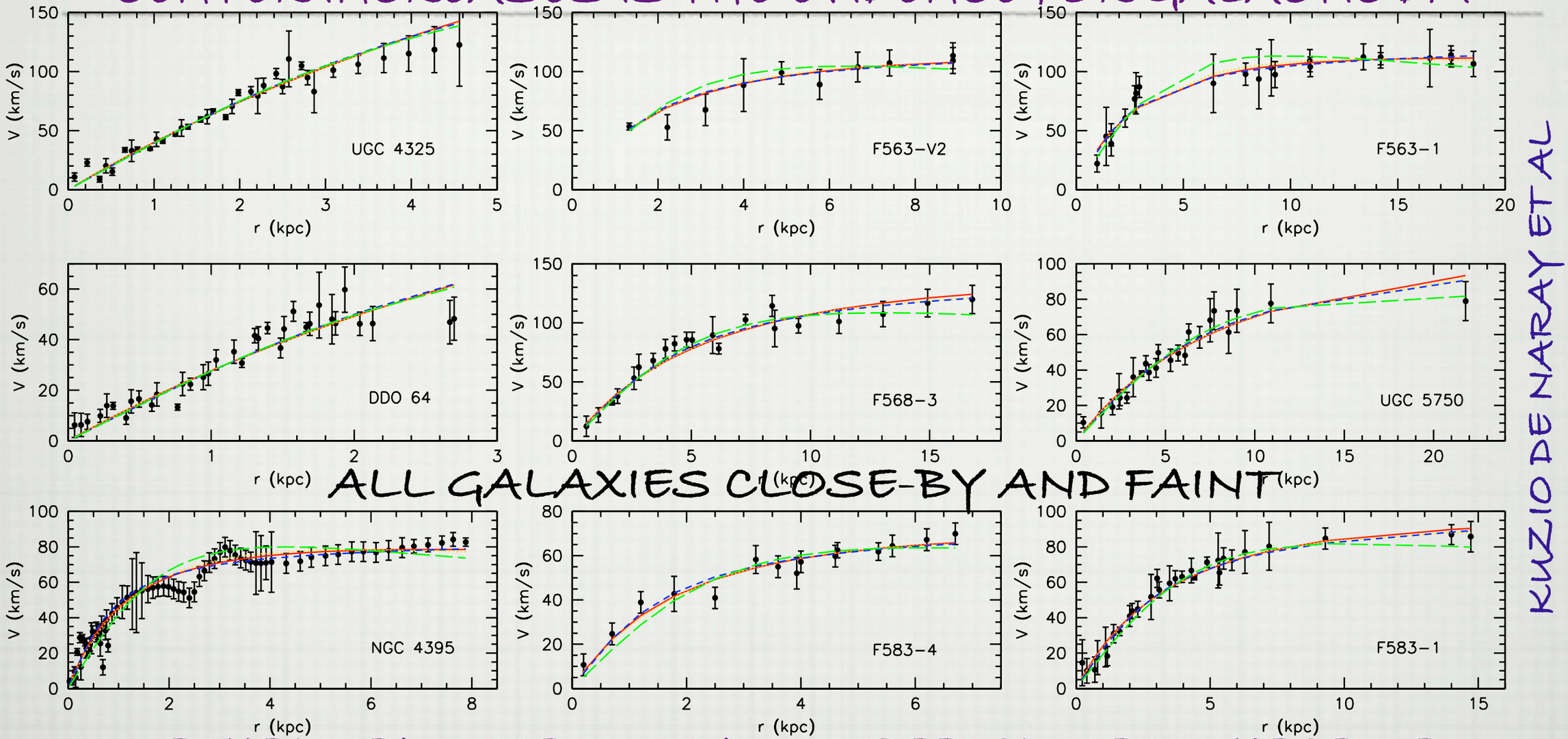

ALL GALAXIES CLOSE-BY AND FAINT

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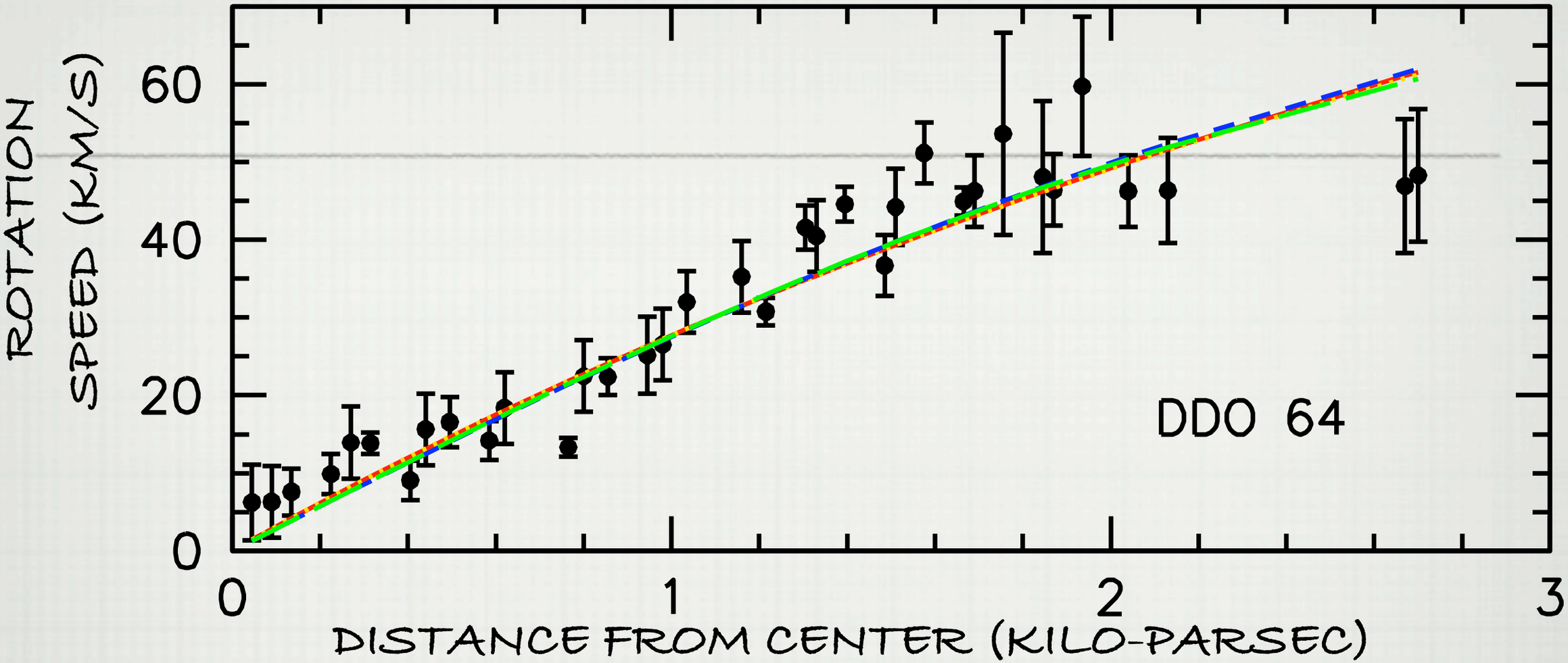
NOTE THE LINEAR RISE IN ROTATION SPEED CLOSE TO THE CENTER. THIS COULD BE A HINT THAT THE DOMINANT COMPONENT OF DARK MATTER IS NOT A WIMP. BUT WE STILL NEED TO SORT OUT HOW STAR FORMATION AFFECTS PREDICTIONS FOR DARK MATTER DENSITIES.

ROTATION SPEED AND DARK MATTER IN GALAXIES



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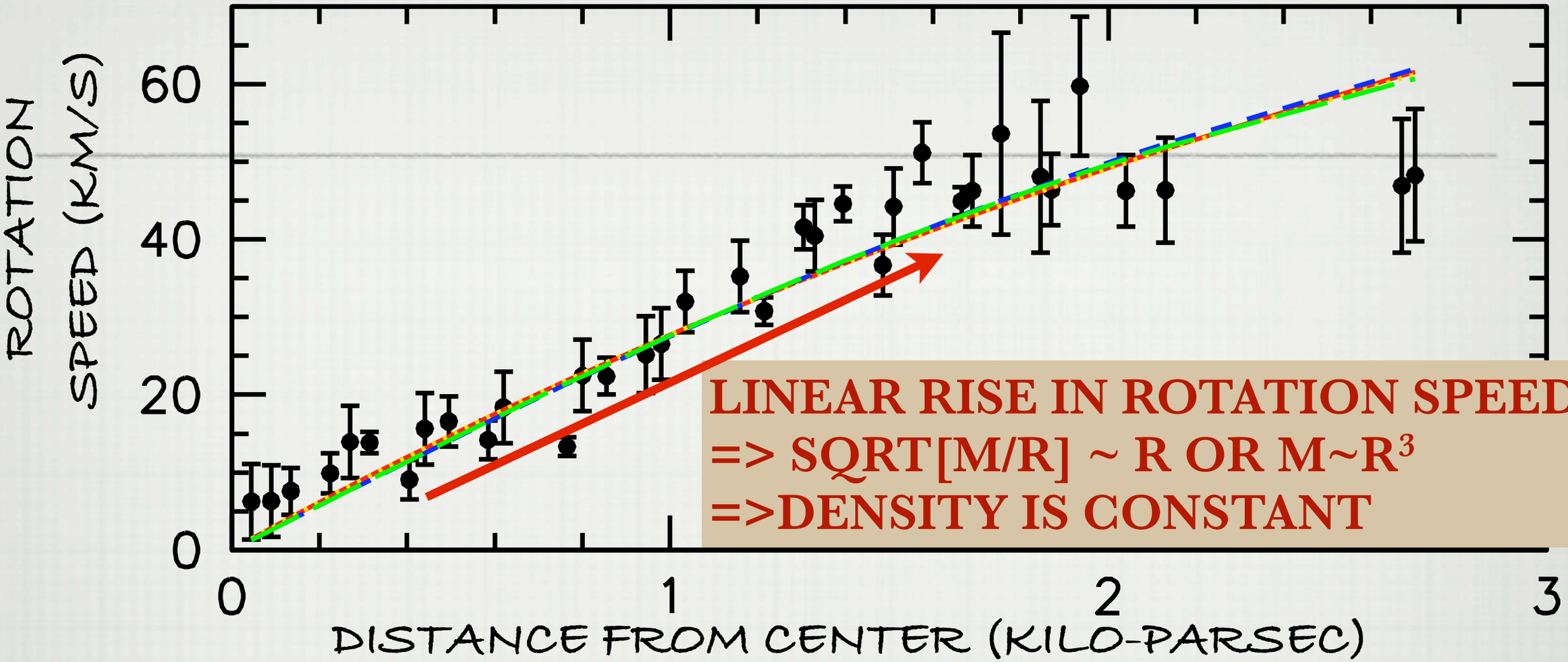
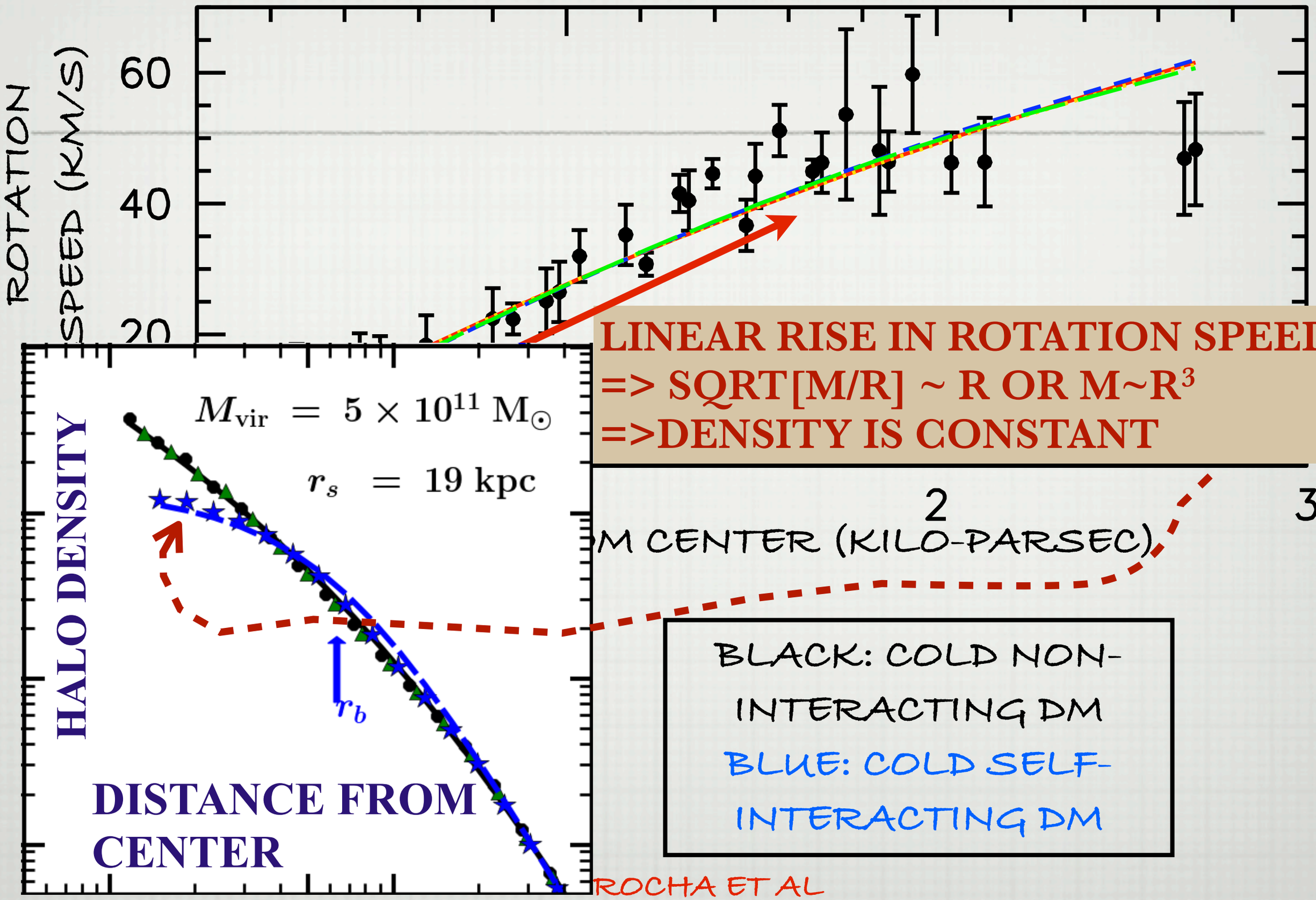


LINEAR RISE IN ROTATION SPEED
=> SQRT[M/R] ~ R OR $M \sim R^3$
=>DENSITY IS CONSTANT

ROTATION SPEED AND DARK MATTER IN GALAXIES



LINEAR RISE IN ROTATION SPEED
=> SQRT[M/R] ~ R OR M~R^3
=>DENSITY IS CONSTANT

BLACK: COLD NON-INTERACTING DM

BLUE: COLD SELF-INTERACTING DM

ROCHA ET AL

The LOCAL GROUP

EVEN CLOSER TO HOME

Figure 18.17 These are the galaxies of the Local Group, arranged to represent their actual physical relationships to the Milky Way http://universe.colorado.edu/fig/18-17.html

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EVEN CLOSER TO HOME

SATELLITES ALSO SEEM TO BE UNDER-DENSE COMPARED TO COLD NON-INTERACTING DARK MATTER EXPECTATIONS.

IMAGE COPYRIGHT 2005 CETIN BAL

LARGER SCALES: DARK MATTER IN CLUSTERS OF GALAXIES

BLUE: MATTER FROM "WEAK" GRAVITATIONAL LENSING

RED: GAS IN X-RAYS

Composite Credit: 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.;

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BULLET CLUSTER

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BLUE: MATTER FROM "WEAK" GRAVITATIONAL LENSING
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- Visceral evidence for dark matter.
- DM self-interactions strength $\sigma/m < \sim 1$ barn/GeV.
- If cross section close to this value, then the "small-scale problems" with cold (WIMP) dark matter can be solved.

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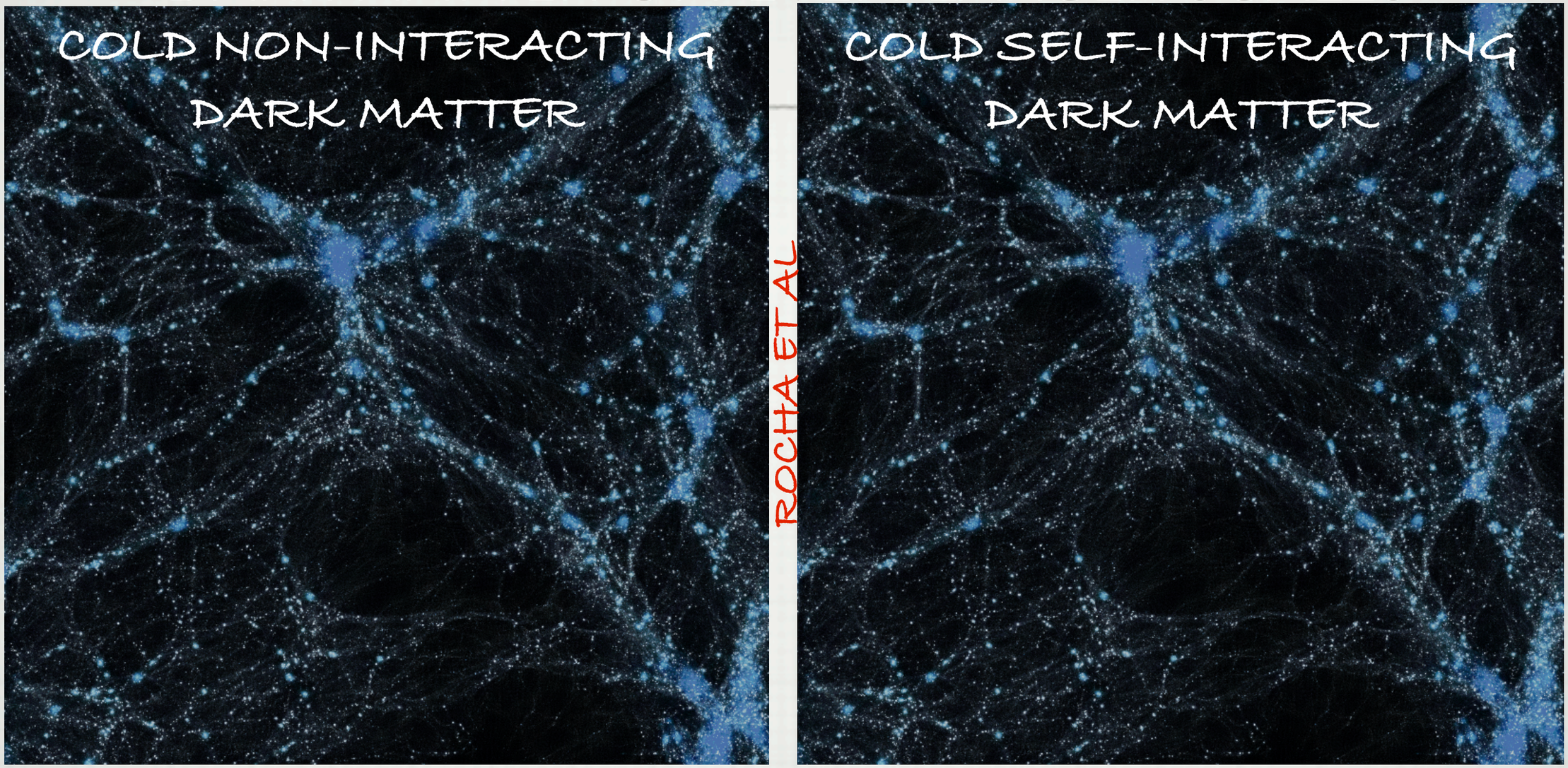
ABOUT 10 MORE MERGING CLUSTERS HAVE BEEN FOUND!

DARK MATTER ON EVEN LARGER SCALES



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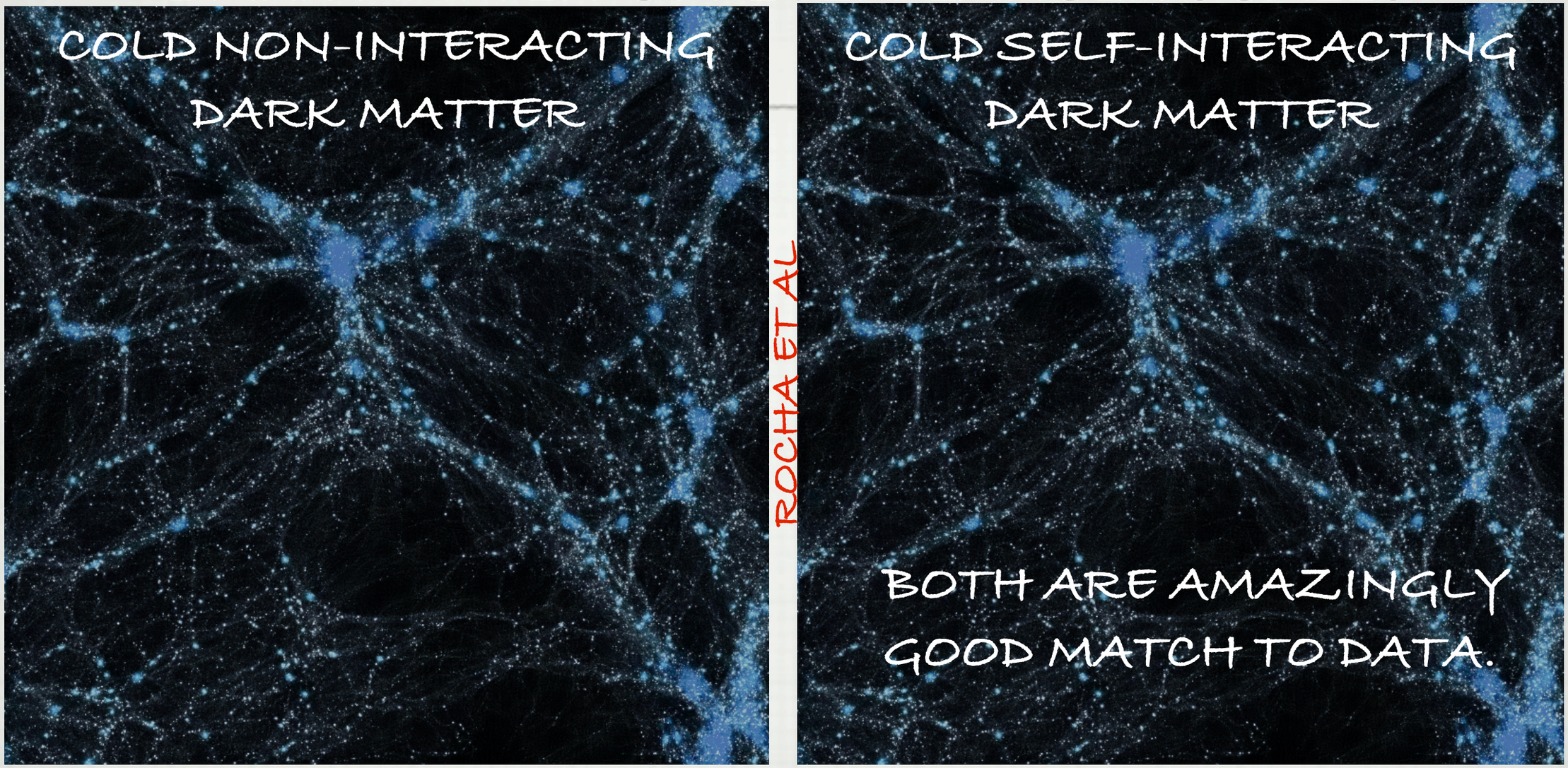


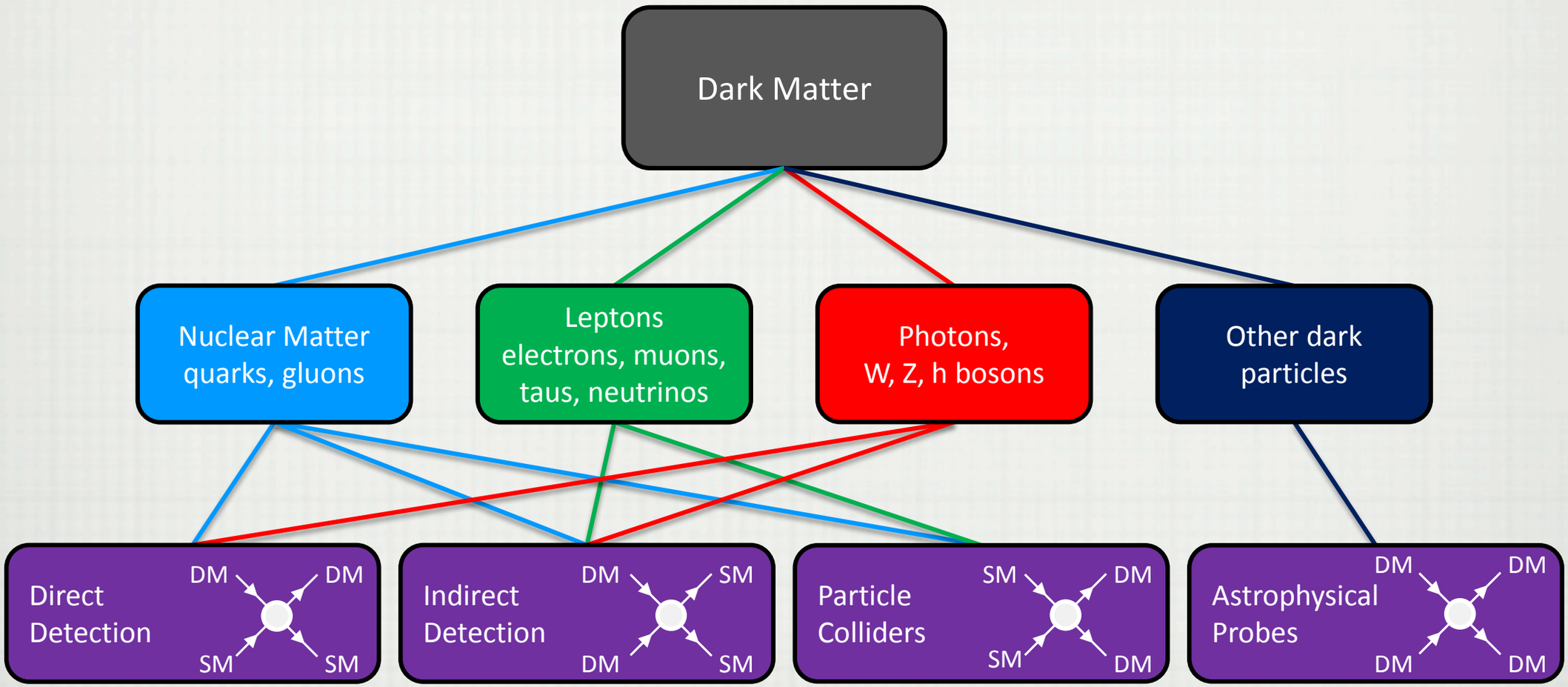
DARK MATTER ON EVEN LARGER SCALES

(A) MOTIVATION TO THINK ABOUT NON-WIMP CANDIDATES AND

(B) EXAMPLE OF HOW ASTROPHYSICS COULD GUIDE MODEL BUILDING

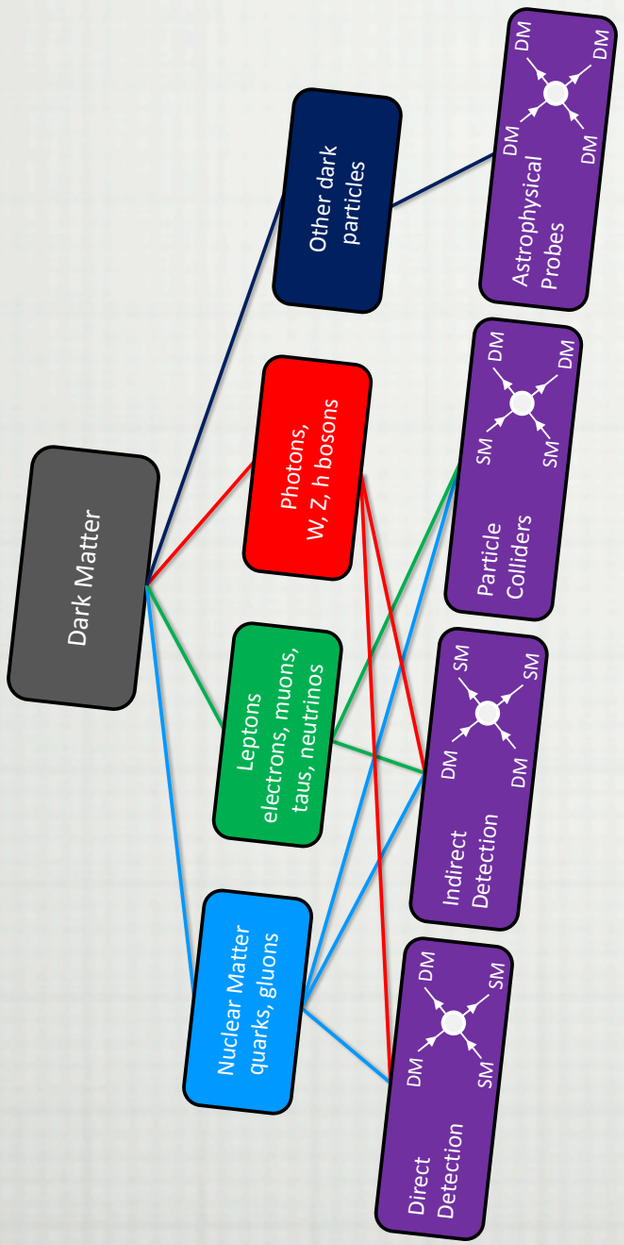
- [ ] NEXT: SEARCHING FOR THE NON-GRAVITATIONAL INTERACTIONS OF DARK MATTER
  - [ ] DUE TO LACK OF TIME, WILL FOCUS ON WIMPS HERE

SPREADING THE NET WIDE



THE CONNECTIONS SHOWN ARE REPRESENTATIVE AND NOT EXHAUSTIVE

HOW DO YOU SEARCH FOR DARK MATTER?



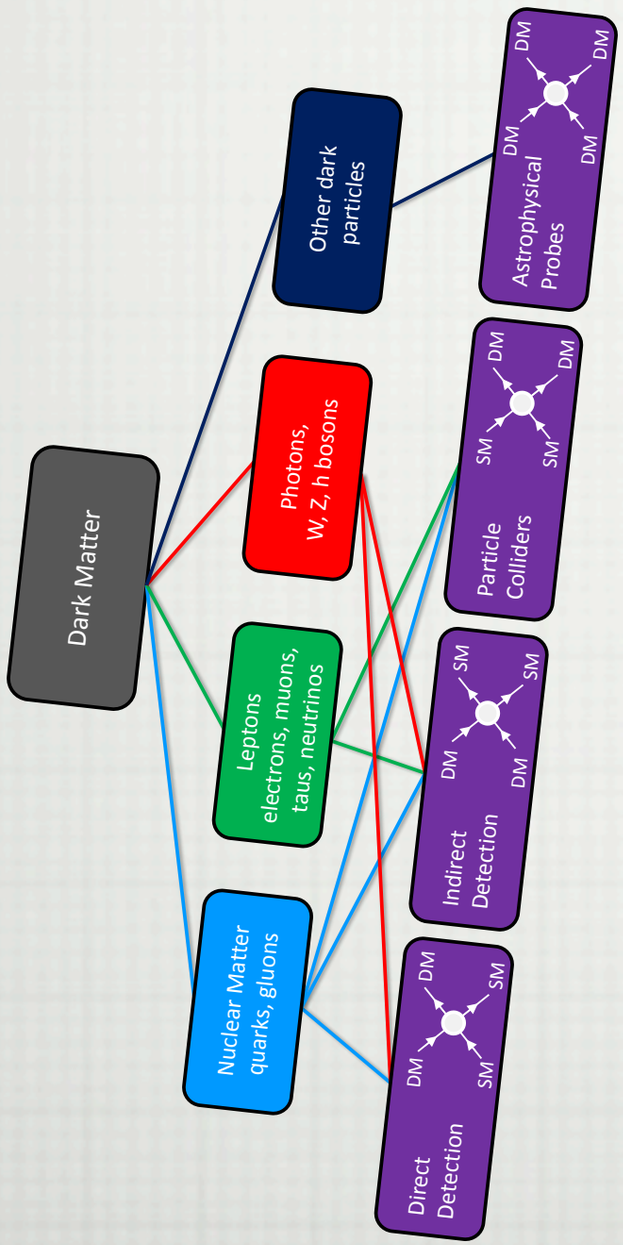
DEPENDS ON WHAT <u>YOU</u> THINK DARK MATTER IS. SEEMS LIKE A TRIVIAL STATEMENT BUT IT INTRODUCES A GREAT DEAL OF SUBJECTIVITY.

IT IS USEFUL TO KEEP REMINDING OURSELVES THAT <u>ALL</u> EVIDENCE FOR THE "DARK SECTOR" STEMS FROM GRAVITATIONAL INTERACTIONS.

IS THE DARK SECTOR AS SIMPLE AS ONE WIMP + COSMOLOGICAL CONSTANT?

NEED TO SPREAD THE NET AS WIDE AS POSSIBLE TO AVOID "LOOKING UNDER THE LAMPPOST."

IS DARK MATTER MADE UP OF ONE OR MORE PARTICLES?

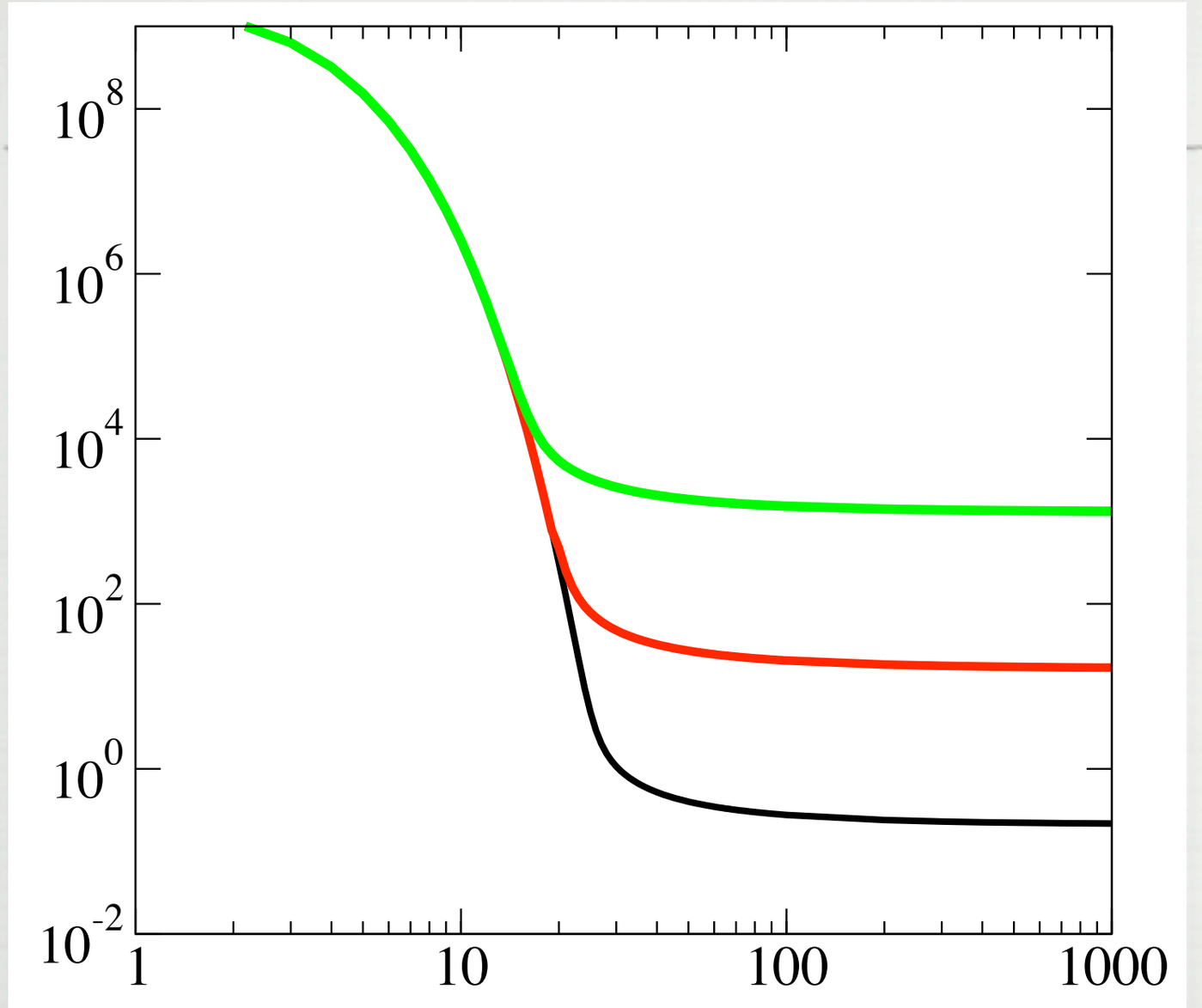


DIFFERENT SEARCHES COULD BE SENSITIVE TO DIFFERENT PARTICLES.

ALL SEARCHES DON'T ALL HAVE TO POINT TO THE SAME REGION OF SOME PARAMETER SPACE.

THEIR ABUNDANCES SHOULD ADD UP TO THE WMAP/PLANCK MEASURED VALUE.

THE ABUNDANCE OF DM VIA EARLY UNIVERSE FREEZE-OUT



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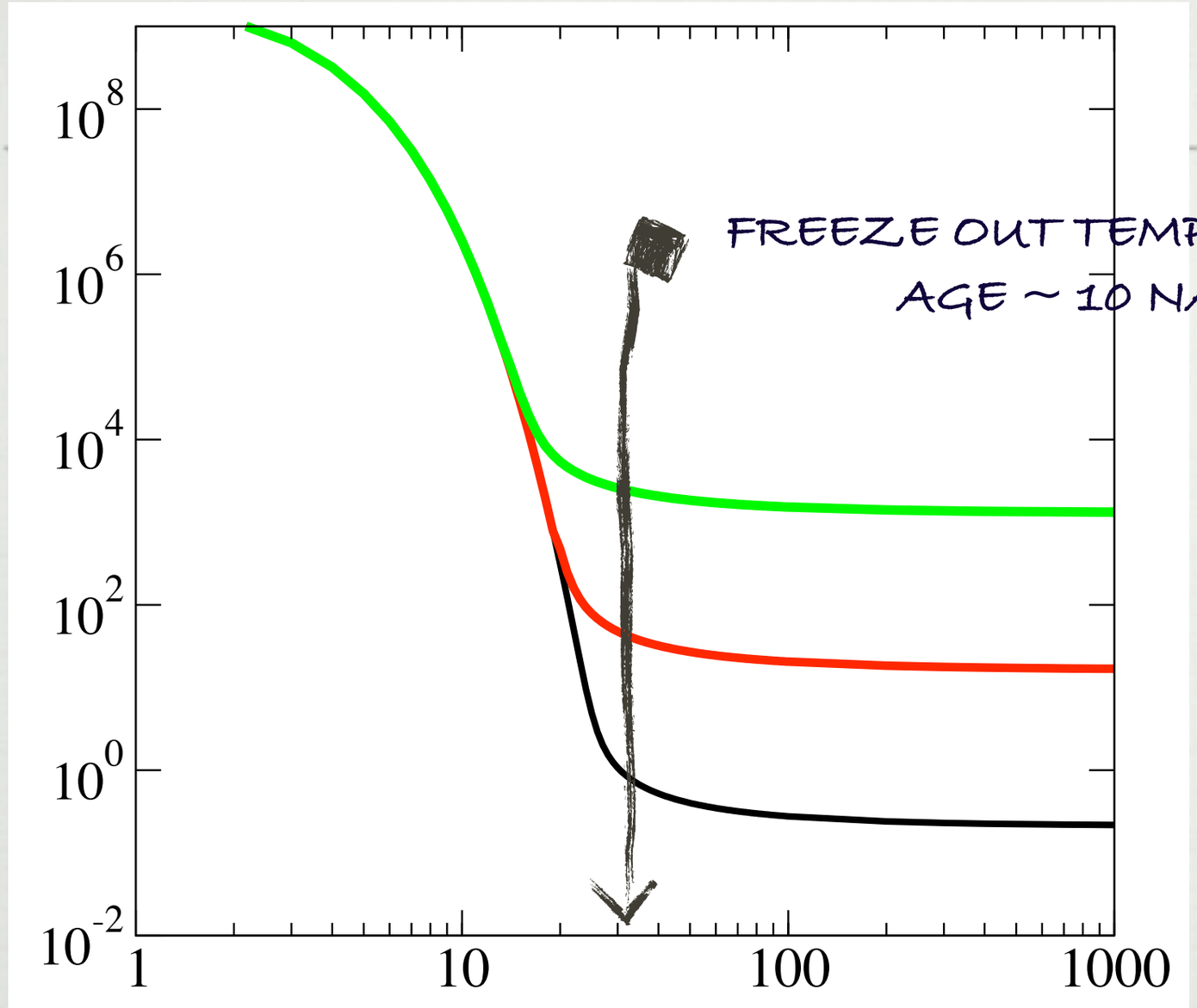

FREEZE OUT TEMPERATURE ~ 10 GEV

AGE ~ 10 NANO-SECOND

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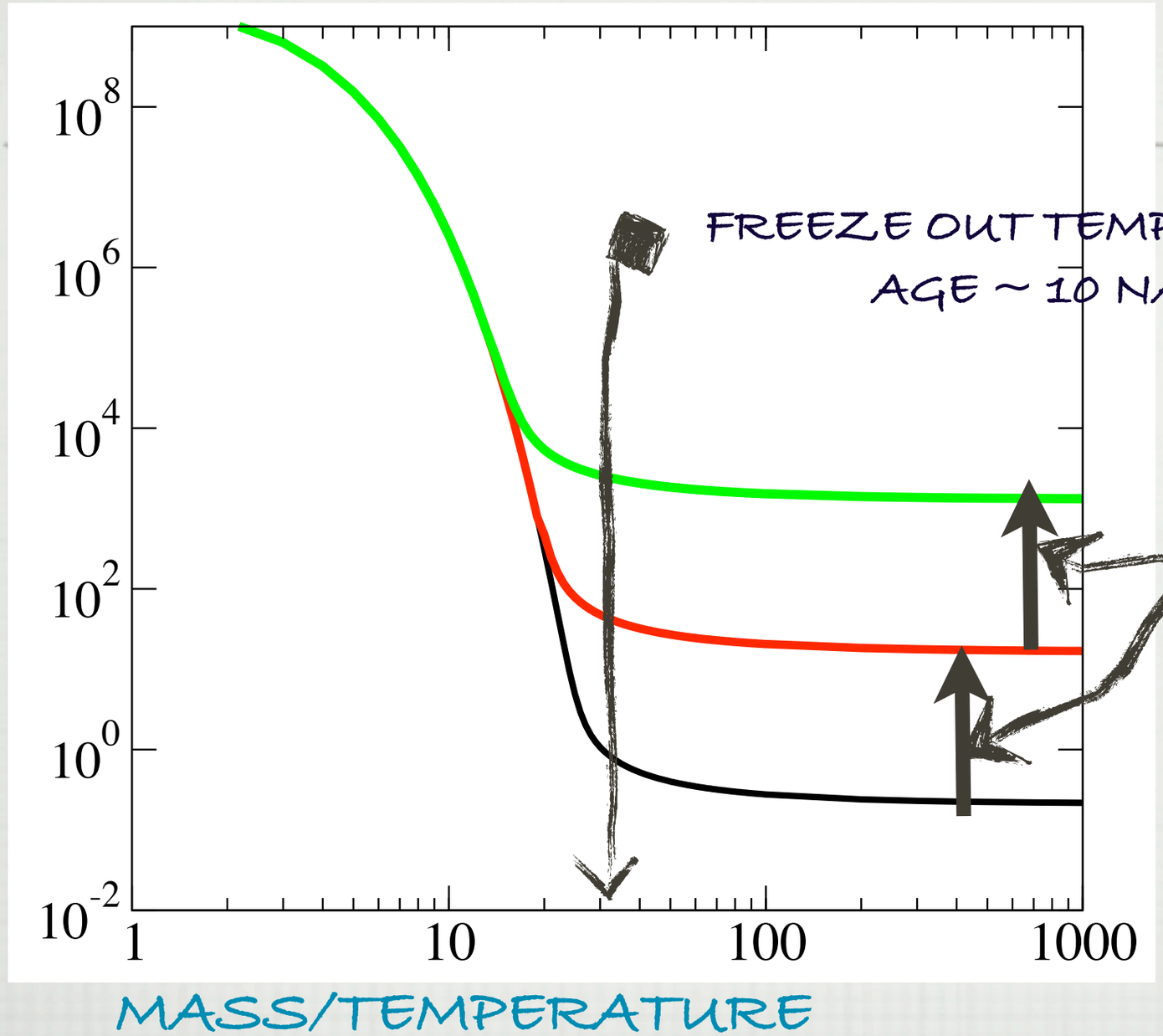

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ANNIHILATION MORE RAPID

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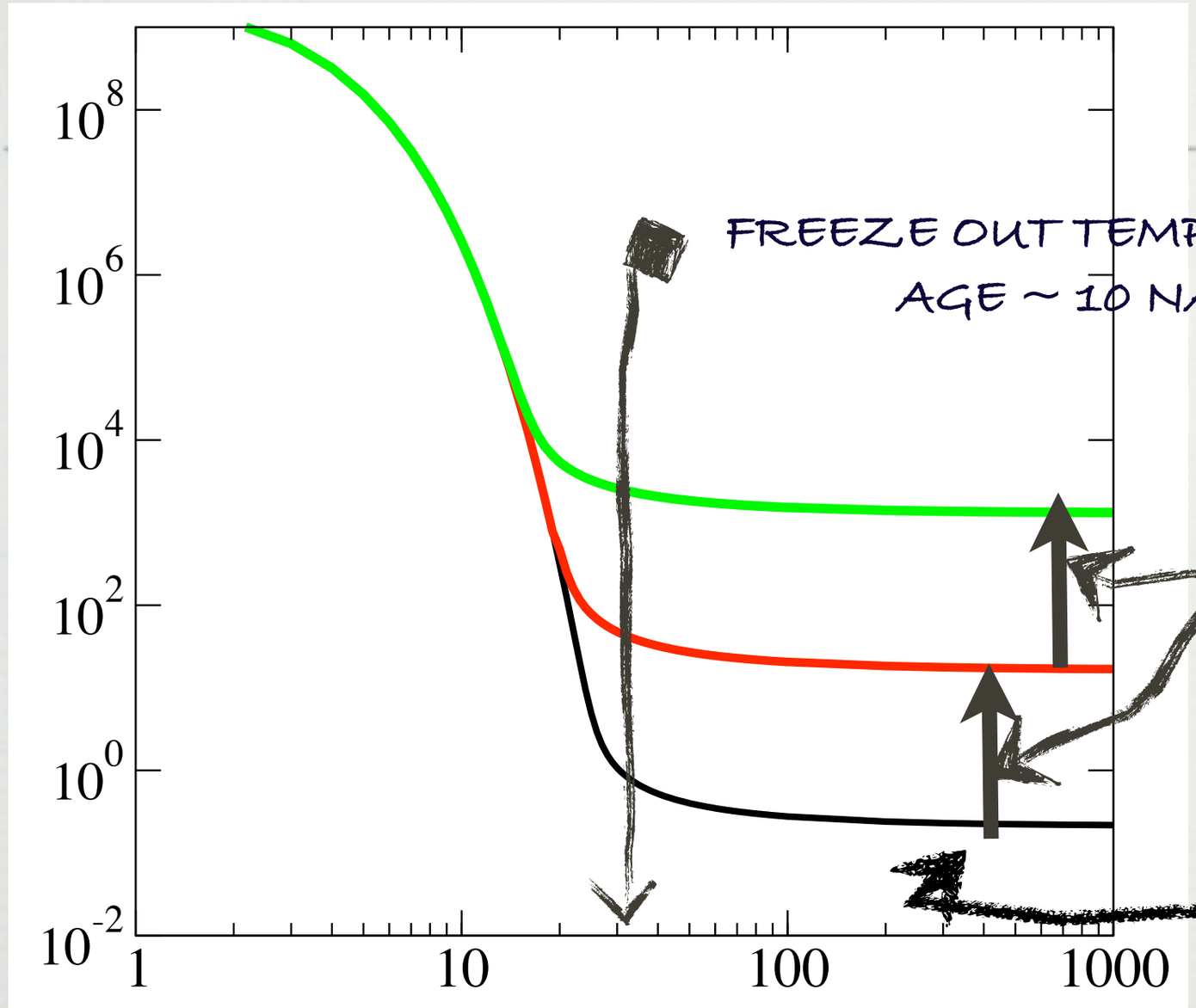

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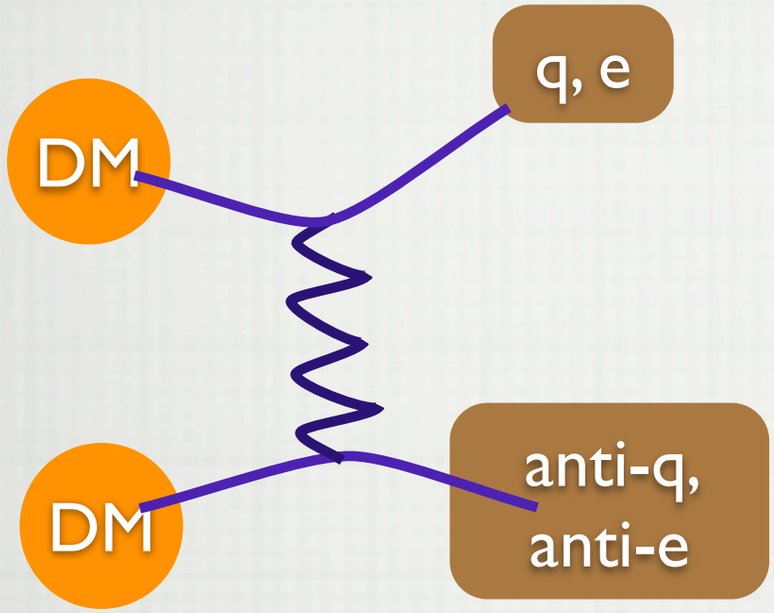
ANNIHILATION MORE RAPID

$$\langle \sigma_{\rm ann} v \rangle = \pi \left(\frac{\alpha}{0.025} \right)^2 \left(\frac{\rm TeV}{m_X} \right)^2 2.3 \times 10^{-26} \frac{\rm cm^3}{s}$$

CORRELATION BETWEEN ABUNDANCE AND INDIRECT SEARCHES



INDIRECT SEARCHES RELY ON THE SAME ANNIHILATION THAT TOOK PLACE IN THE EARLY UNIVERSE TO SET THE WIMP ABUNDANCE

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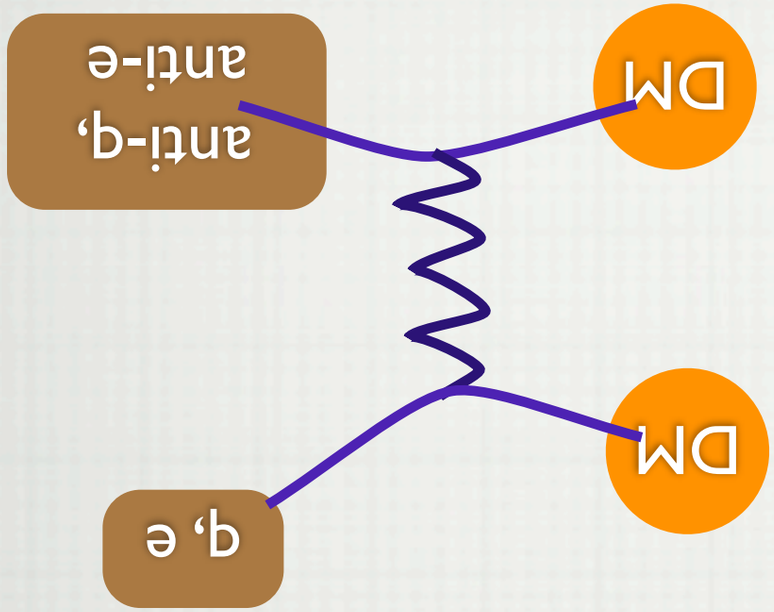

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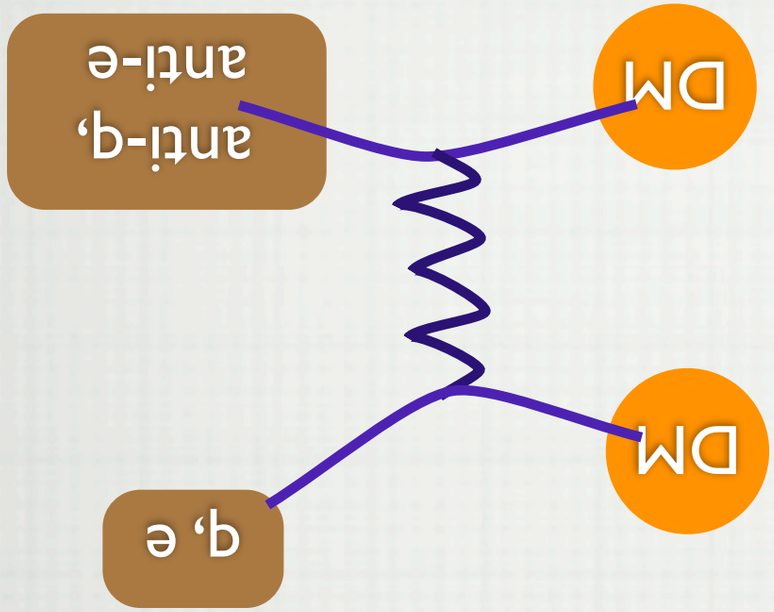

- S-WAVE OR P-WAVE PIECE OF ANNIHILATION CROSS SECTION COULD DOMINATE IN THE EARLY UNIVERSE

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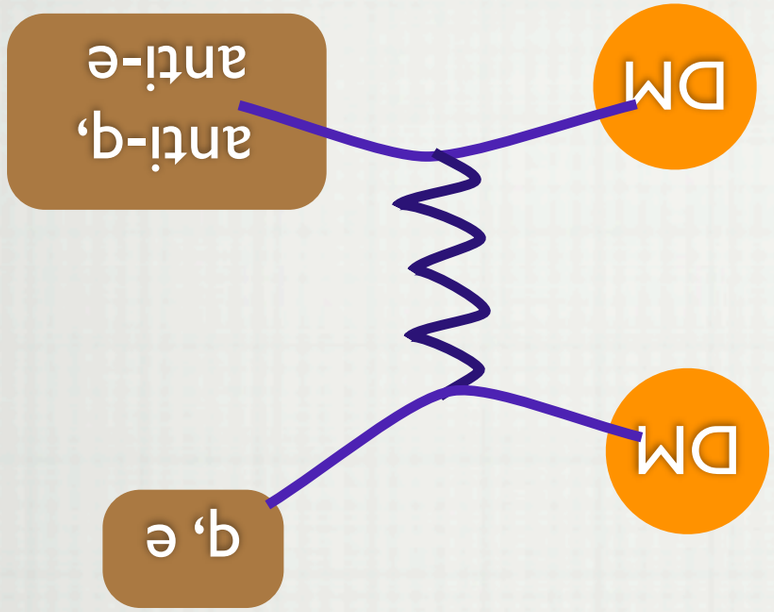

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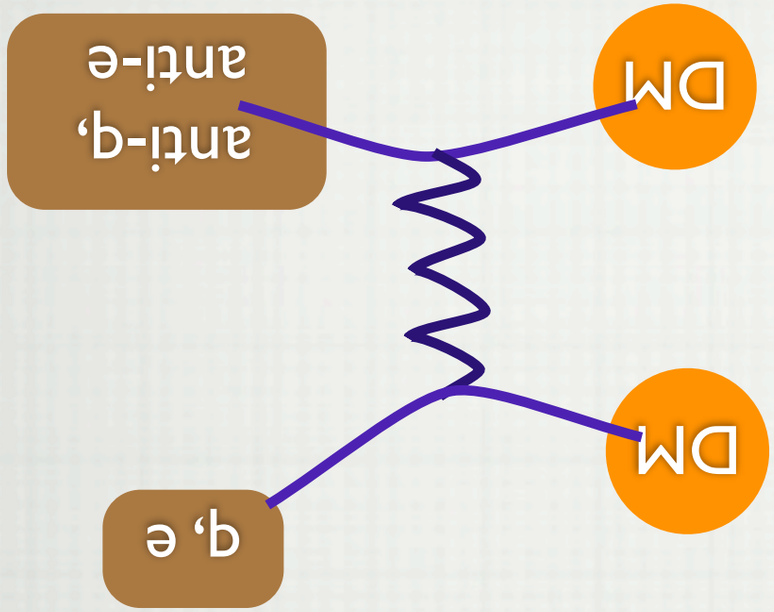
- P-WAVE CROSS SECTION PROPORTIONAL TO V^2. IN THE EARLY UNIVERSE $V^2 \sim 0.2$. EXAMPLE: DM COUPLING TO QUARKS THROUGH AXIAL VECTOR CURRENT

CORRELATION BETWEEN ABUNDANCE AND INDIRECT SEARCHES



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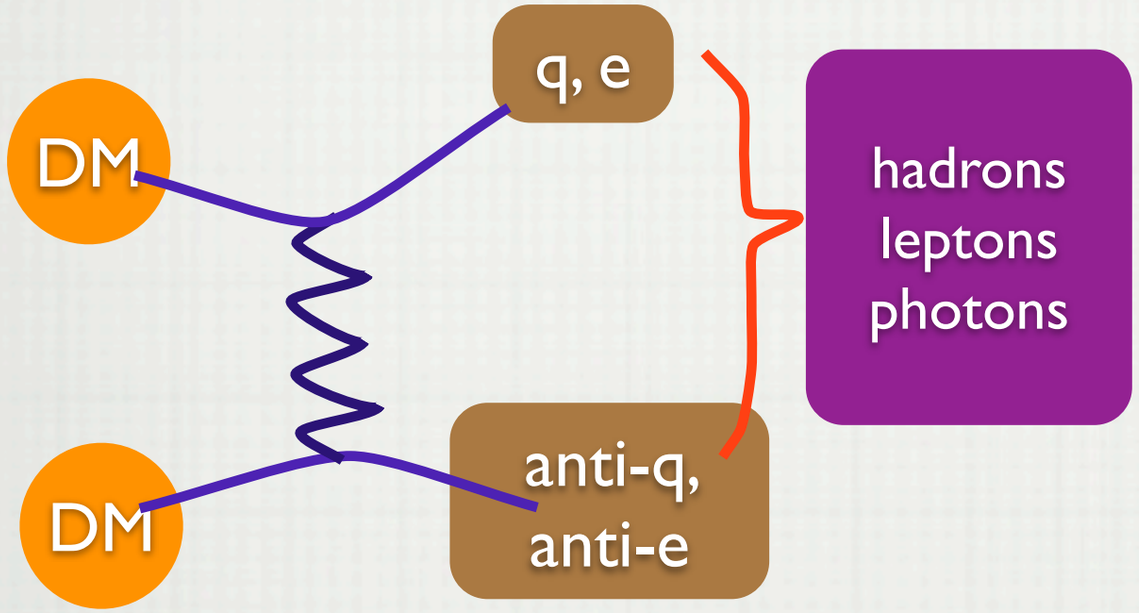
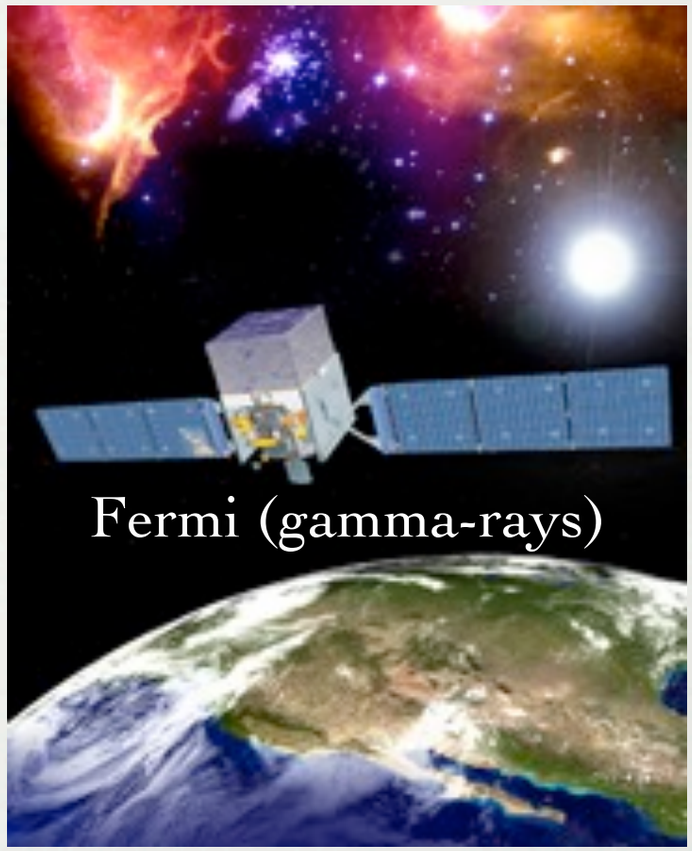
- S-WAVE IS THE ONLY PIECE RELEVANT FOR INDIRECT SEARCHES SINCE $V^2 \sim 10^{-6}$ LOCALLY

- [ ] NEXT: INDIRECT SEARCHES
  - [ ] SEARCHES FOR PRODUCTS OF DARK MATTER ANNIHILATION OR DECAY

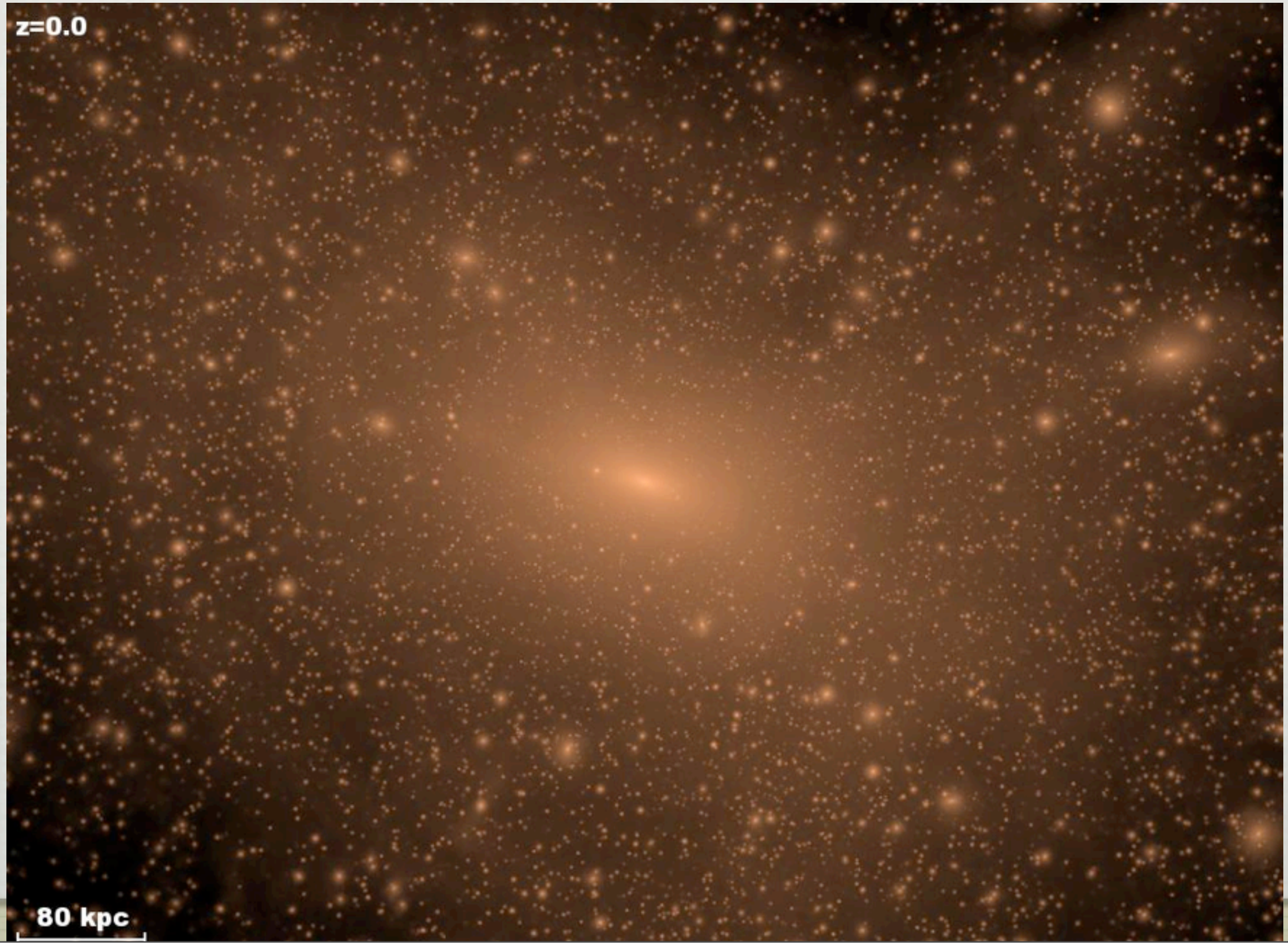
INDIRECT SEARCH EXAMPLES





AMS-02 shown circled in red, also PAMELA in space (antimatter)

SOURCES FOR GAMMA-RAY SEARCHES



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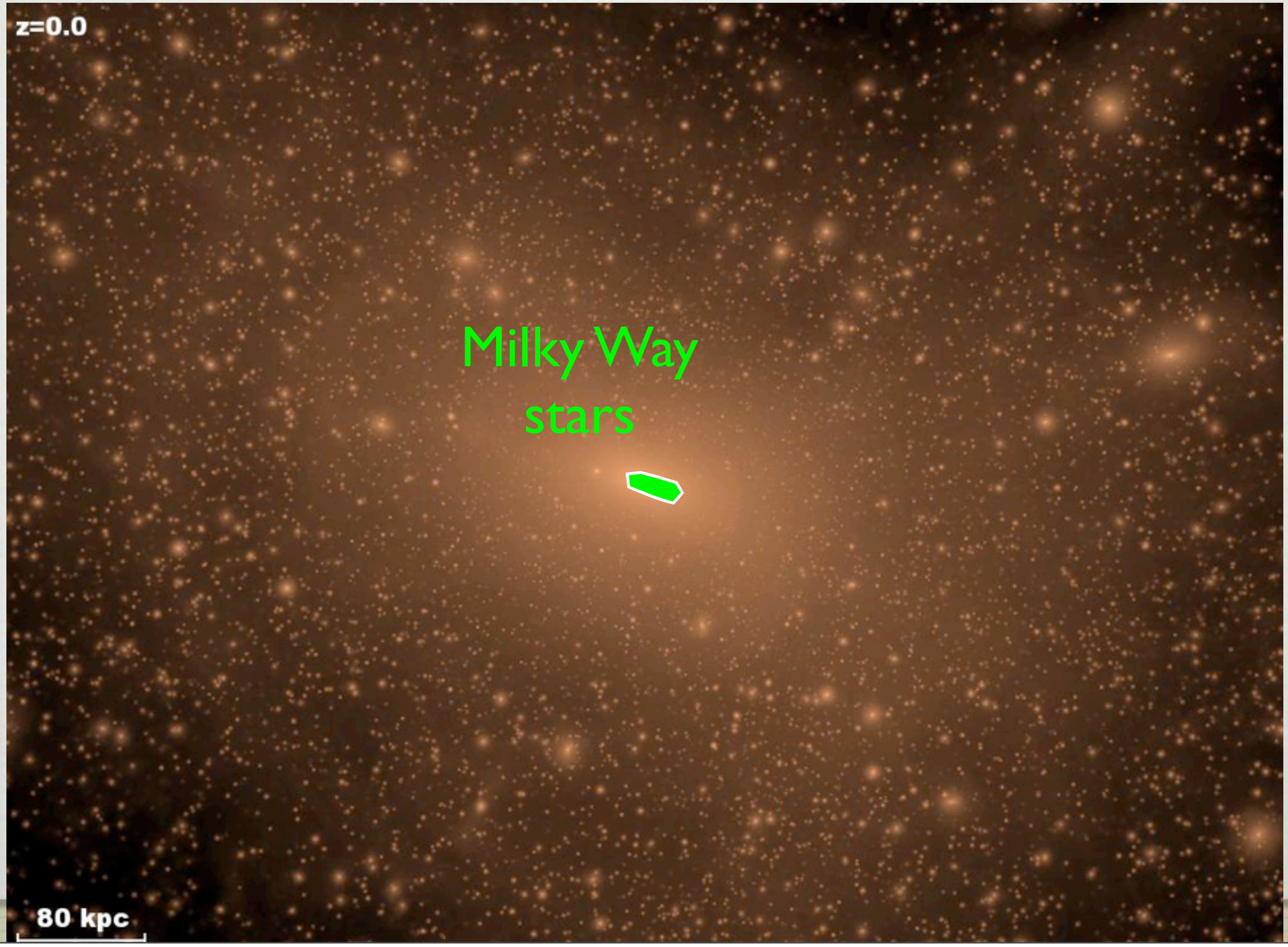

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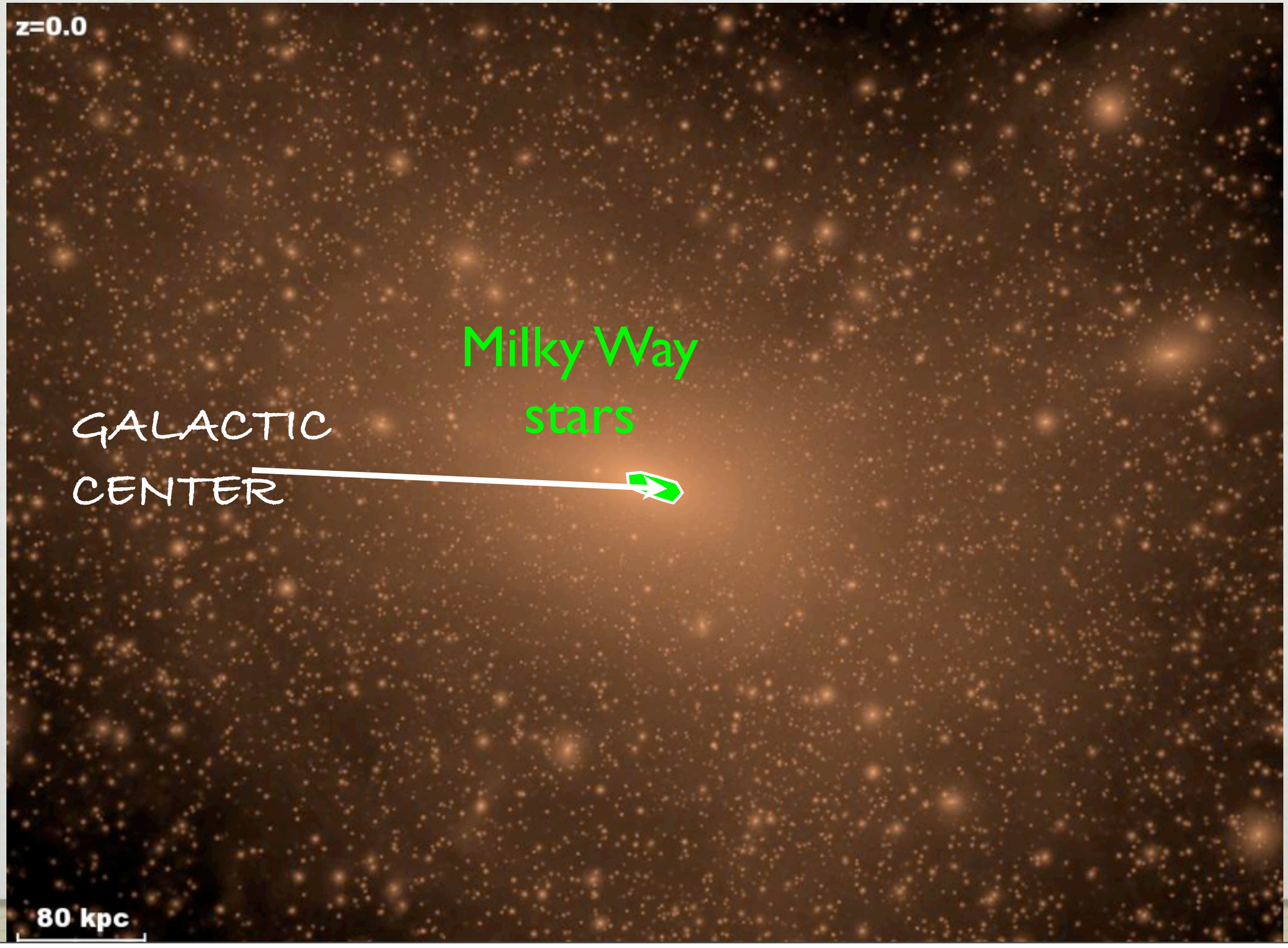

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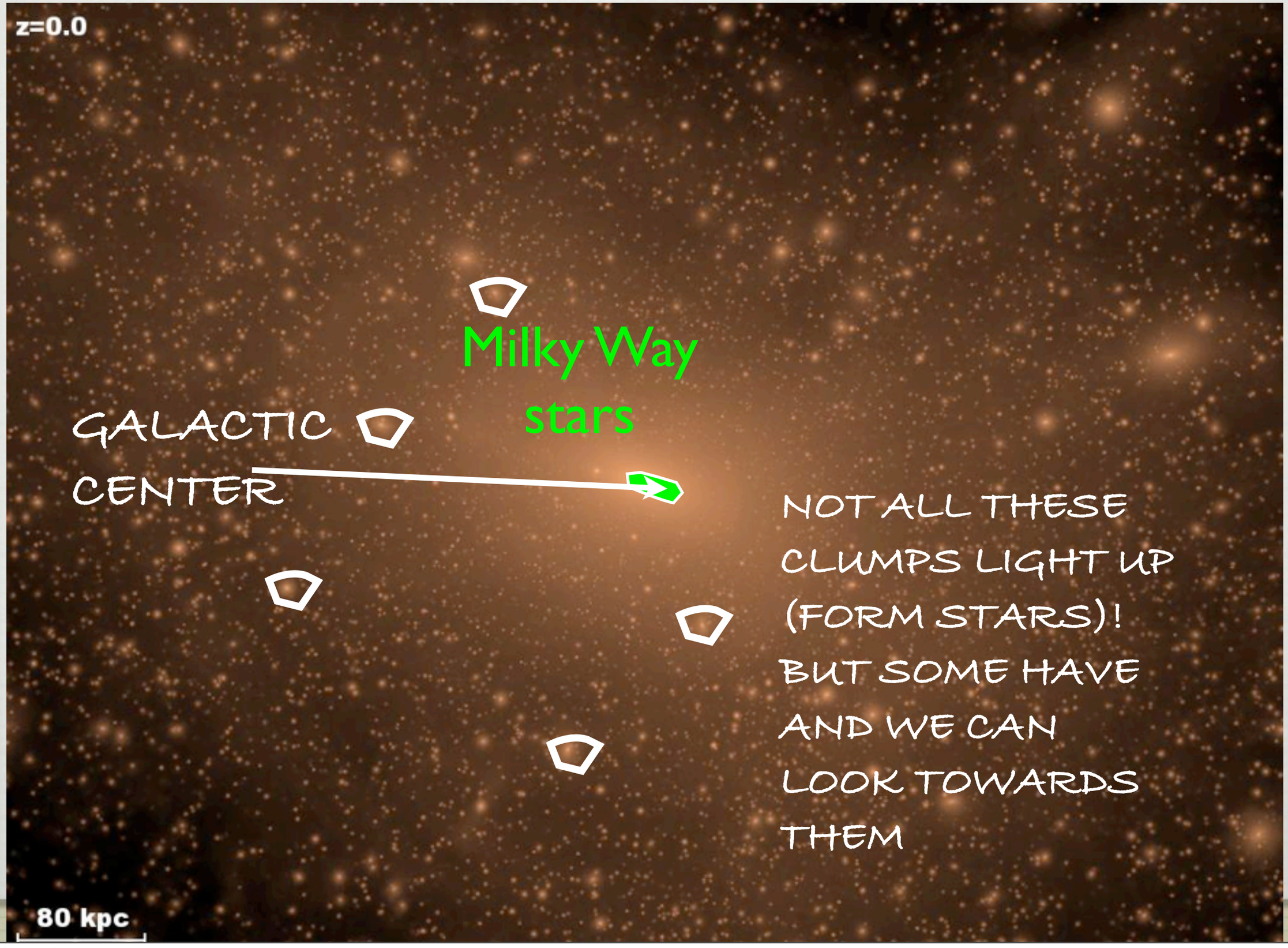

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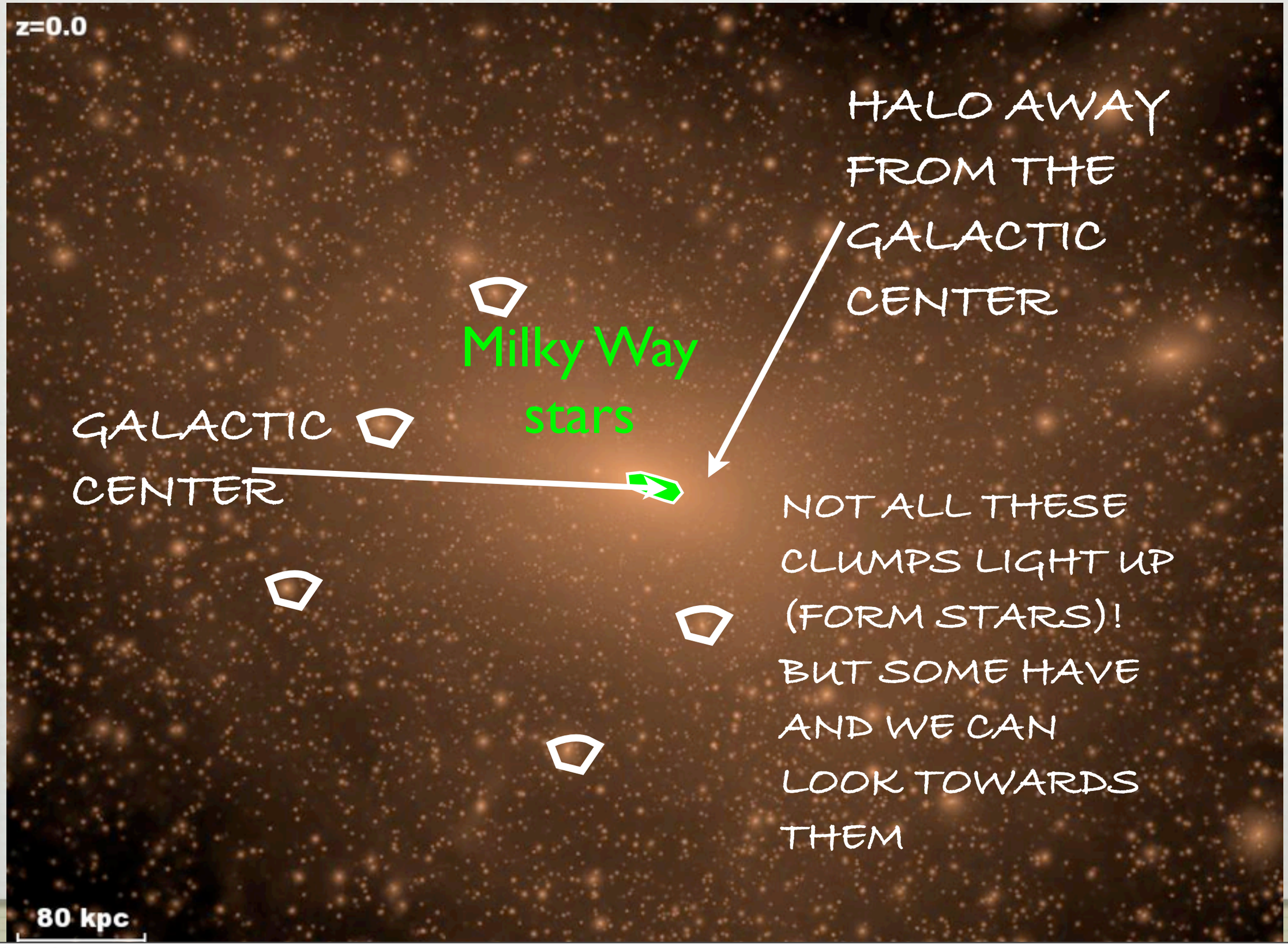
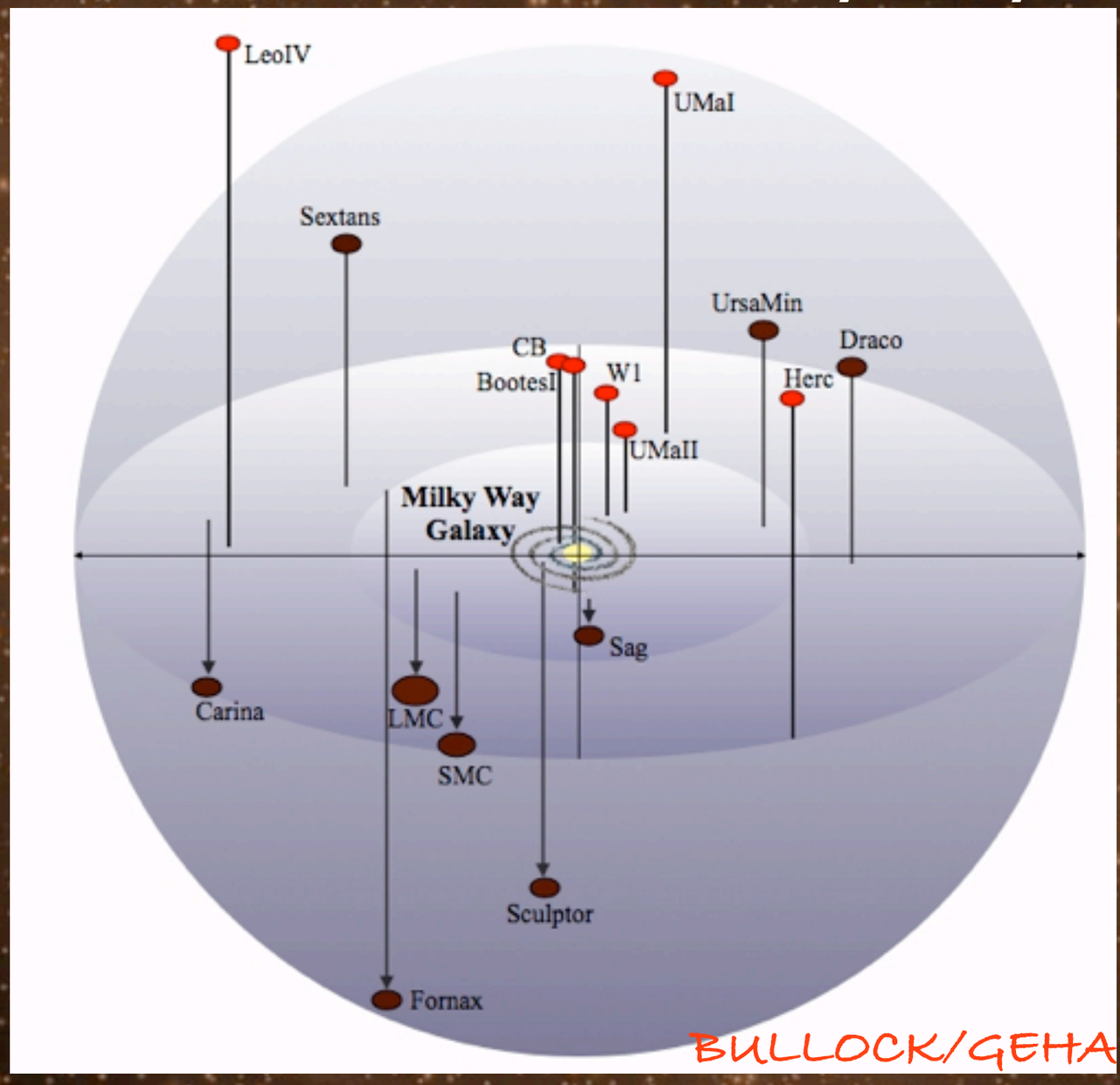


SOURCES FOR GAMMA-RAY SEARCHES

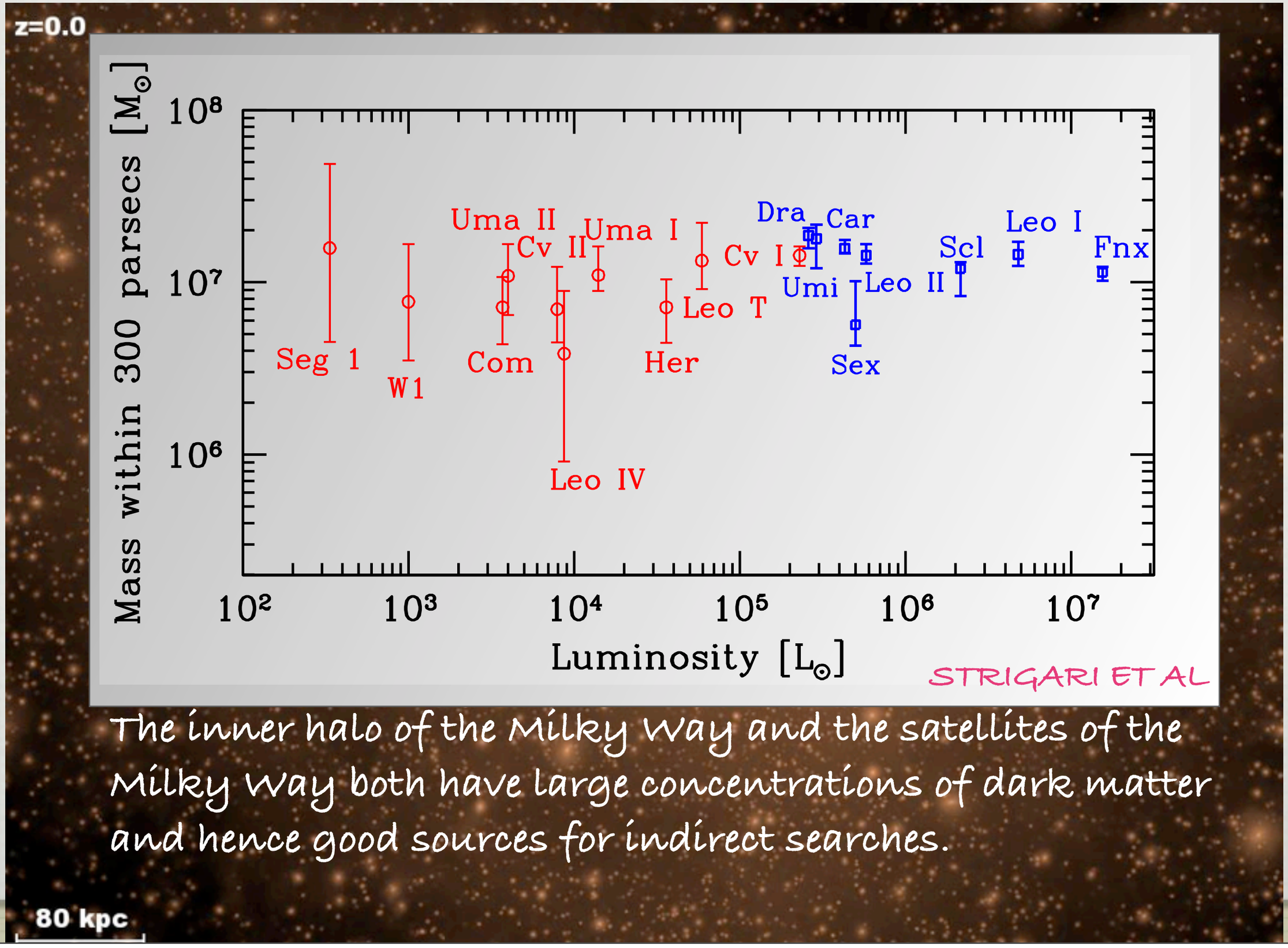
z=0.0

Satellites of the Milky Way

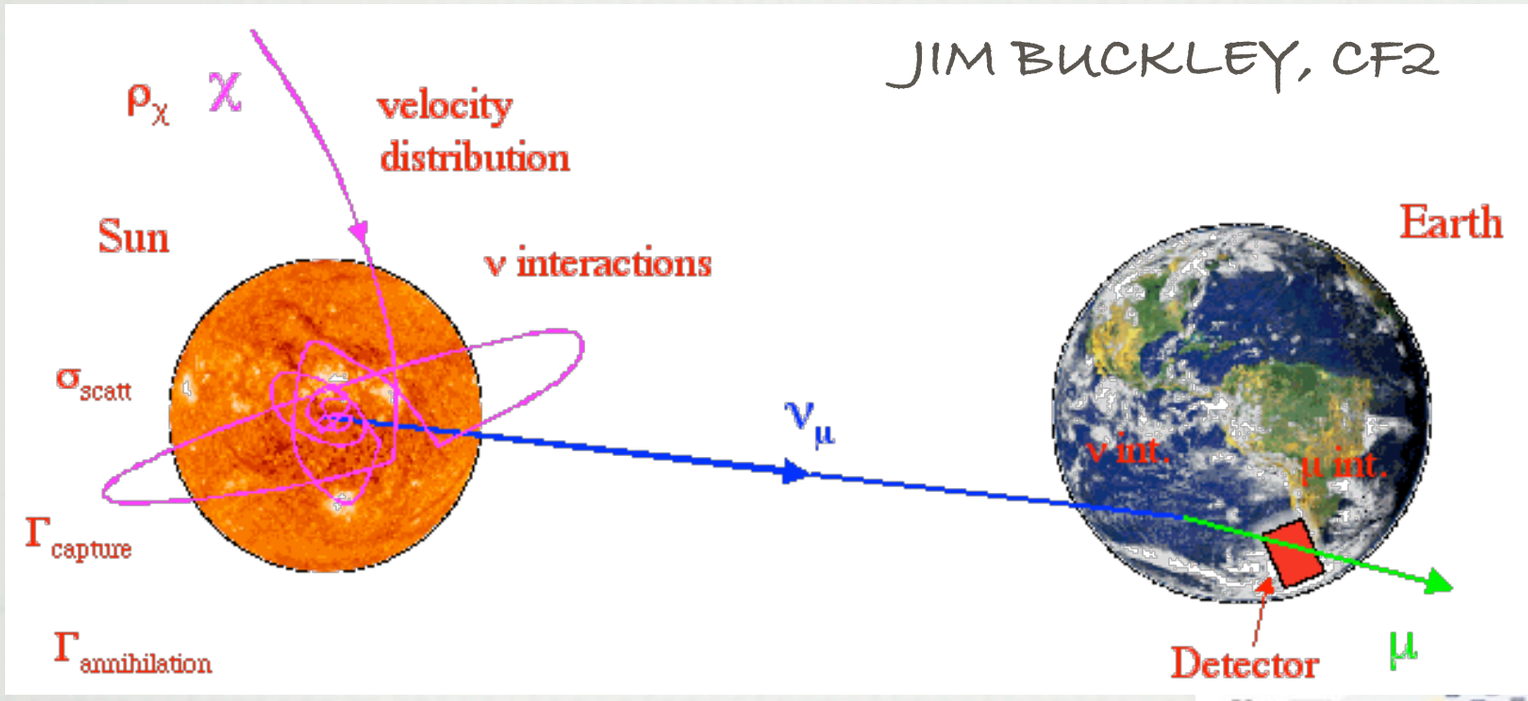


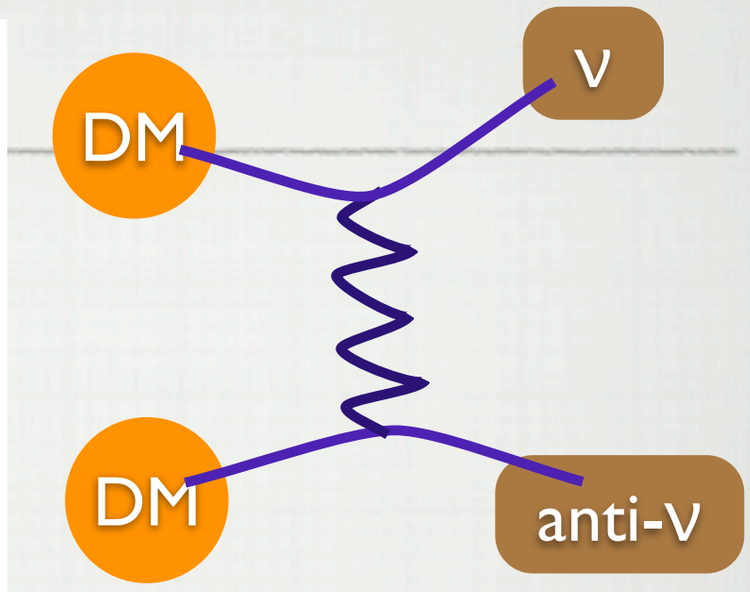
80 kpc

SOURCES FOR GAMMA-RAY SEARCHES

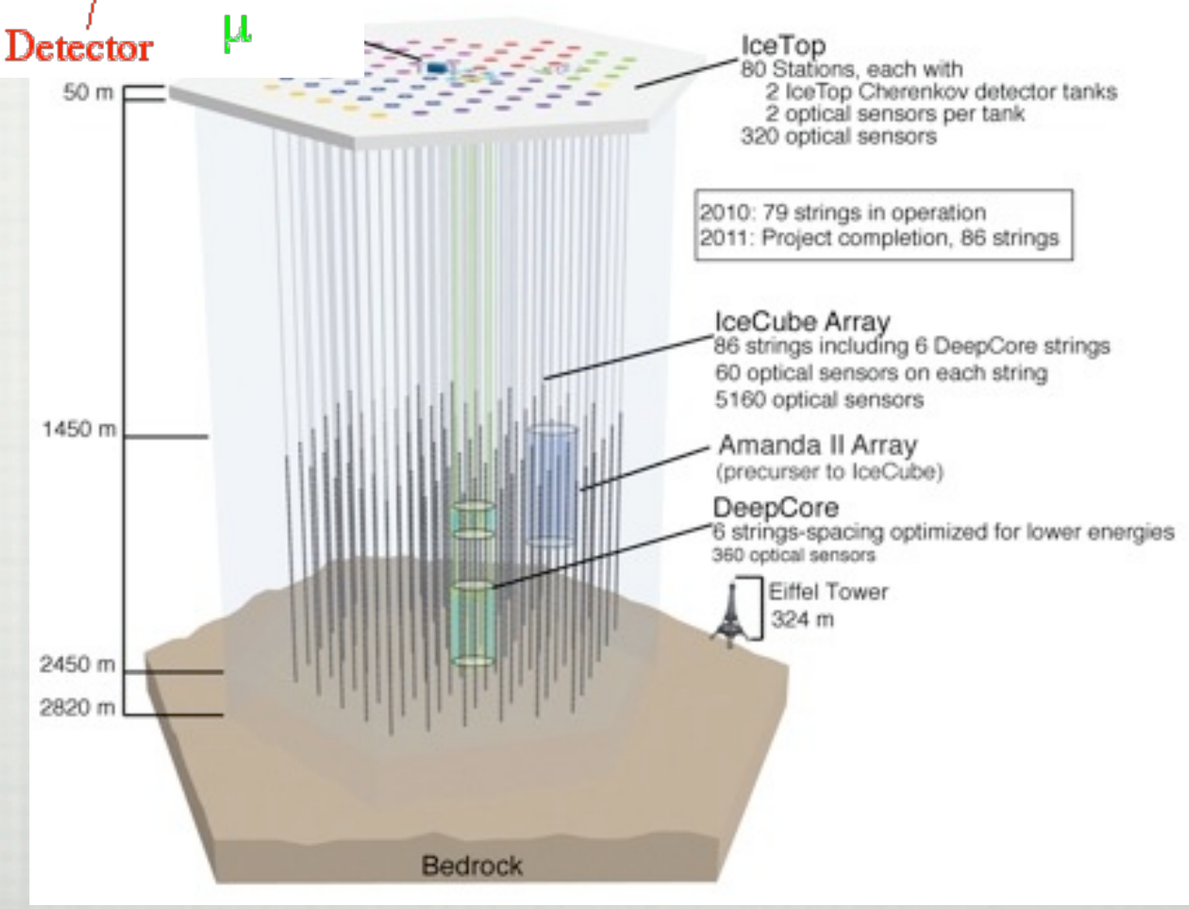


SUN AS THE SOURCE FOR NEUTRINO SEARCHES

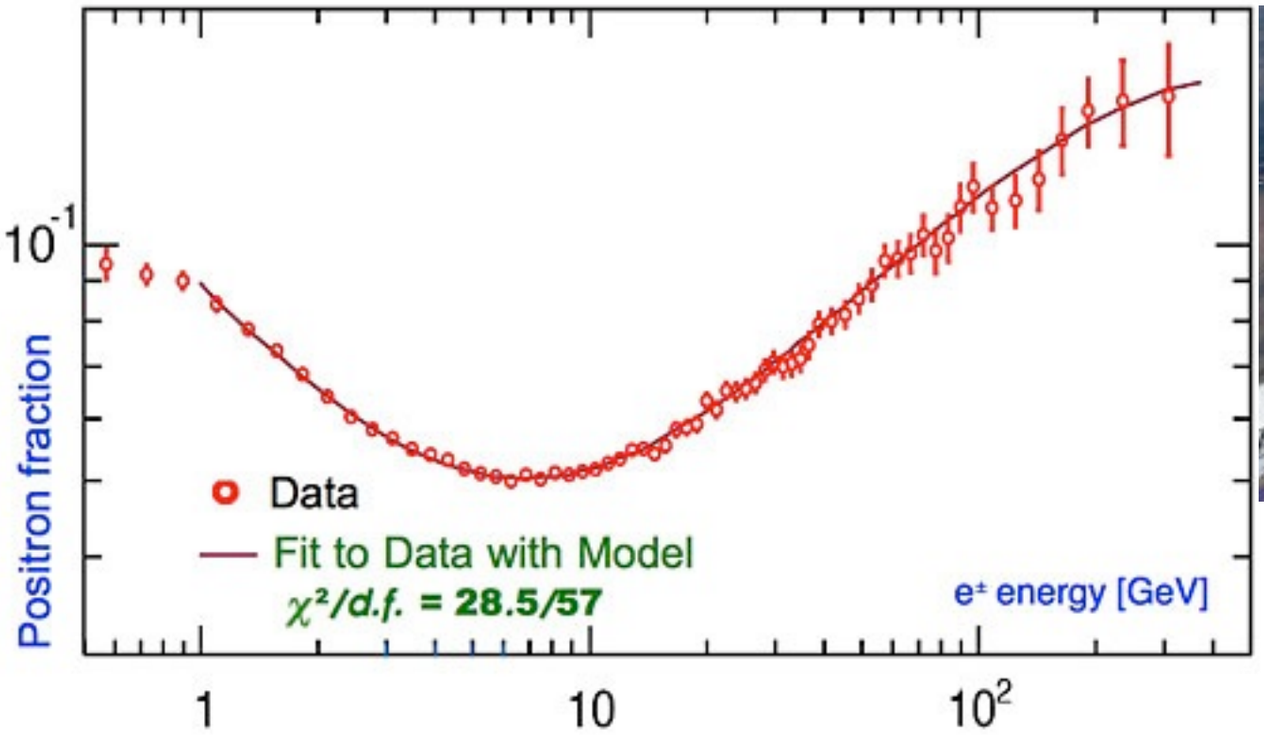




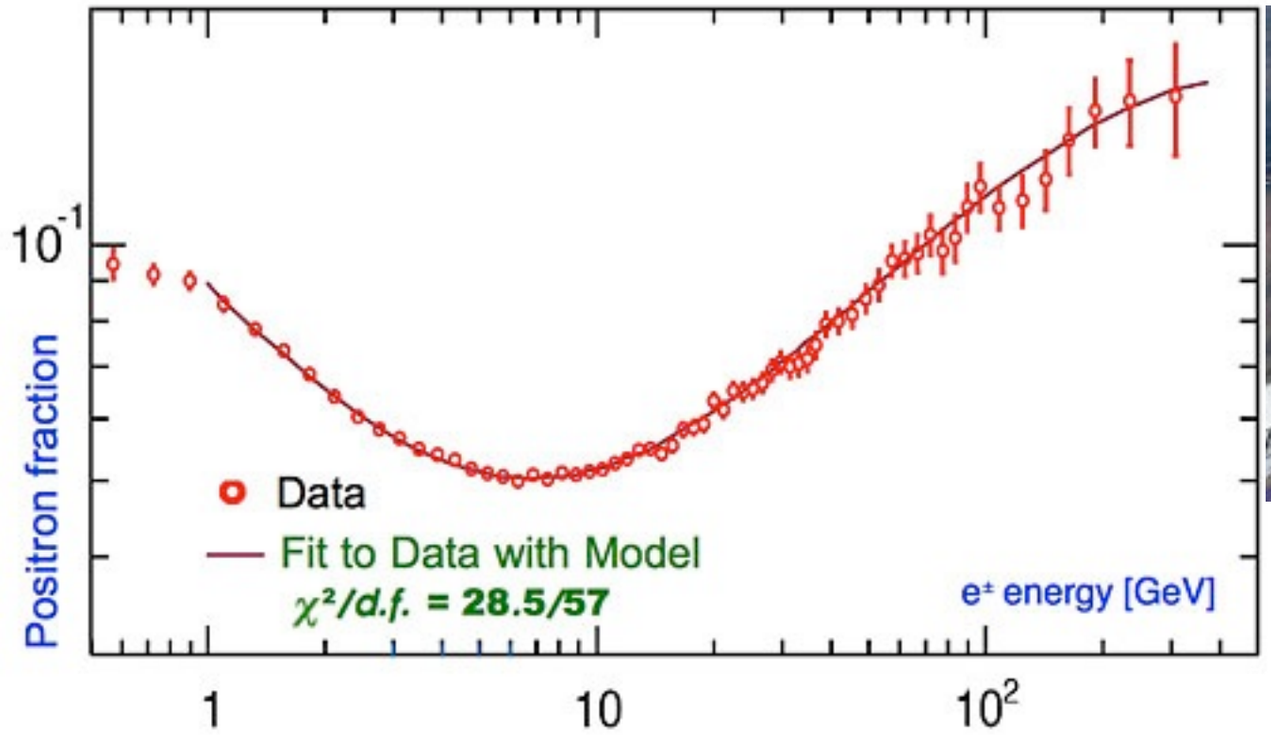
IN EQUILIBRIUM, ANNIHILATION RATE IS RELATED TO CAPTURE RATE AND HENCE TO THE SCATTERING OF DM OFF BARYONS

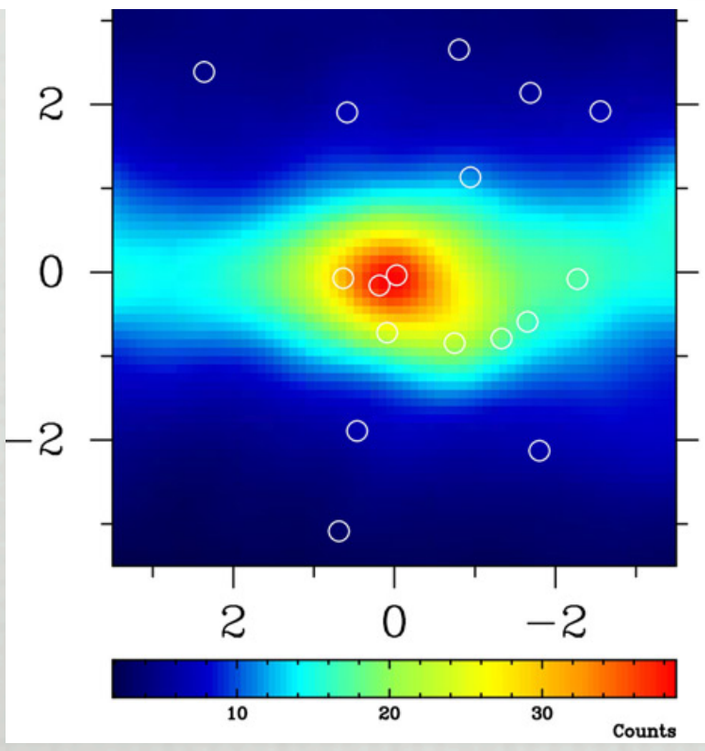


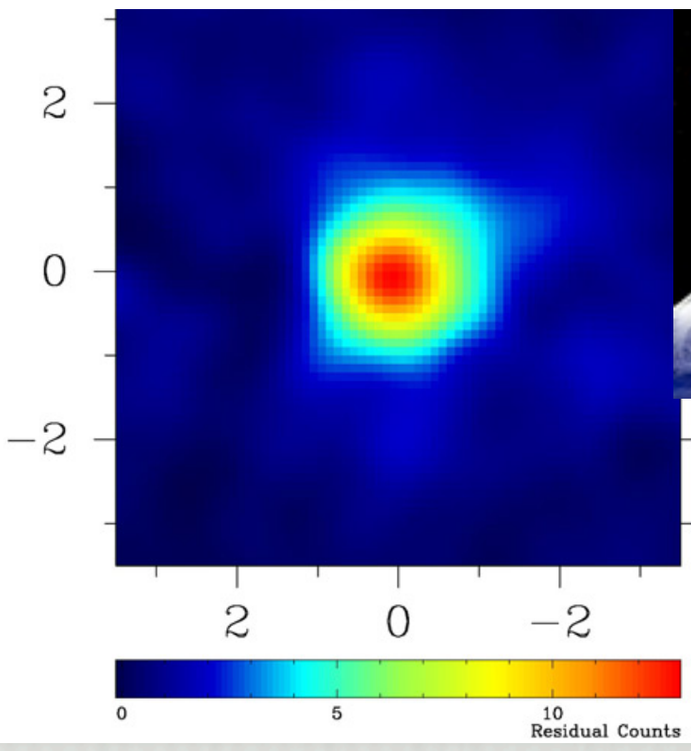
INDIRECT SEARCHES: EXAMPLE DM-LIKE SIGNALS



INDIRECT SEARCHES: EXAMPLE DM-LIKE SIGNALS



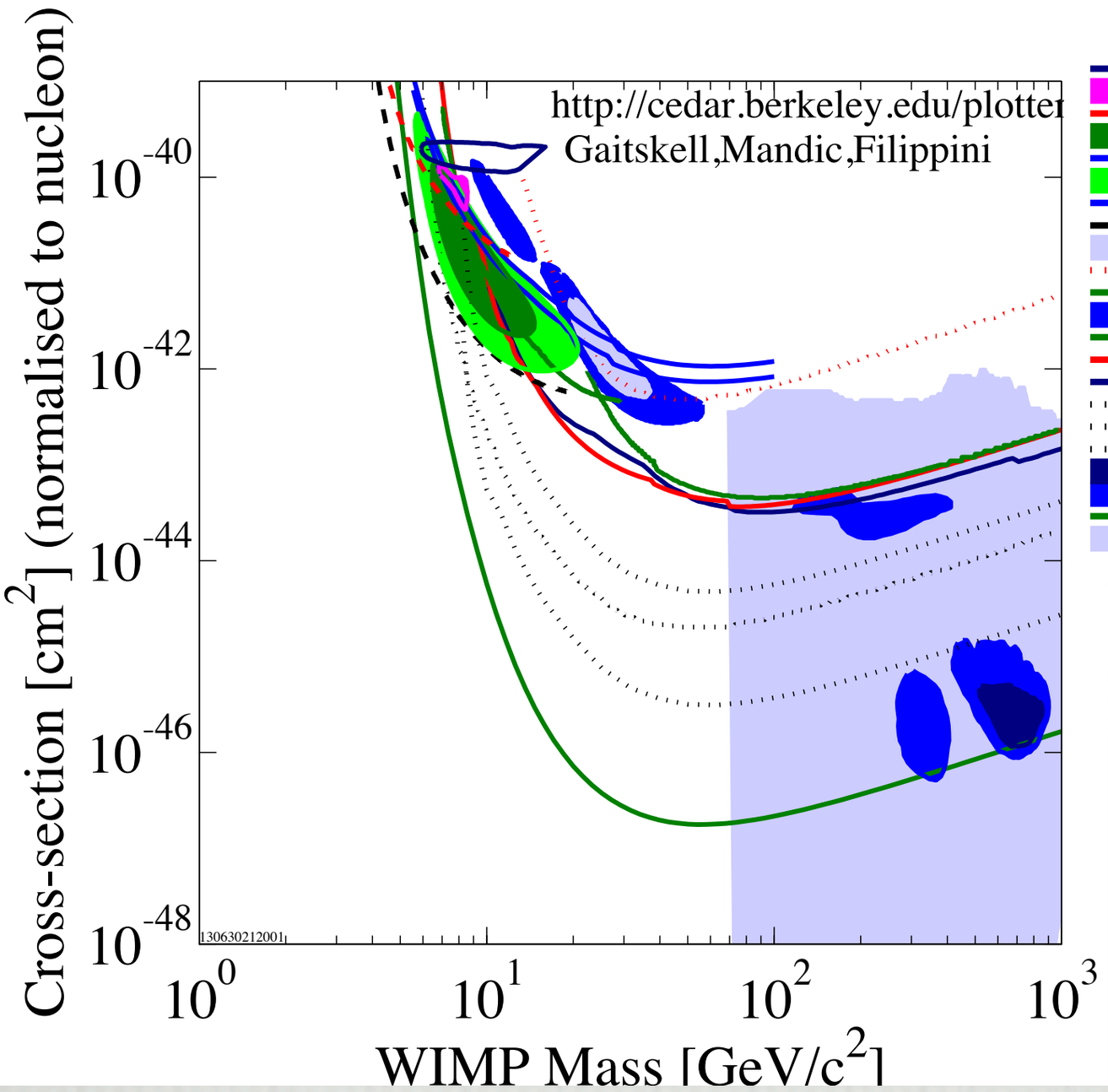


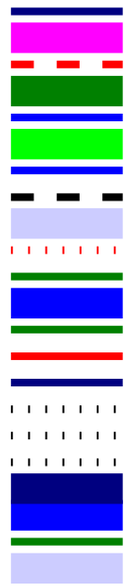


Hooper, Goodenough
Hooper, Linden
Abazajian, Kaplinghat

- [ ] NEXT: DIRECT SEARCHES FOR WIMPS
  - [ ] AXIONS NOT COVERED IN THIS TALK
- [ ] COMPLEMENTARITY OF DIRECT, INDIRECT AND COLLIDER SEARCHES

DIRECT SEARCHES: EXCLUSIONS AND DM-LIKE SIGNALS

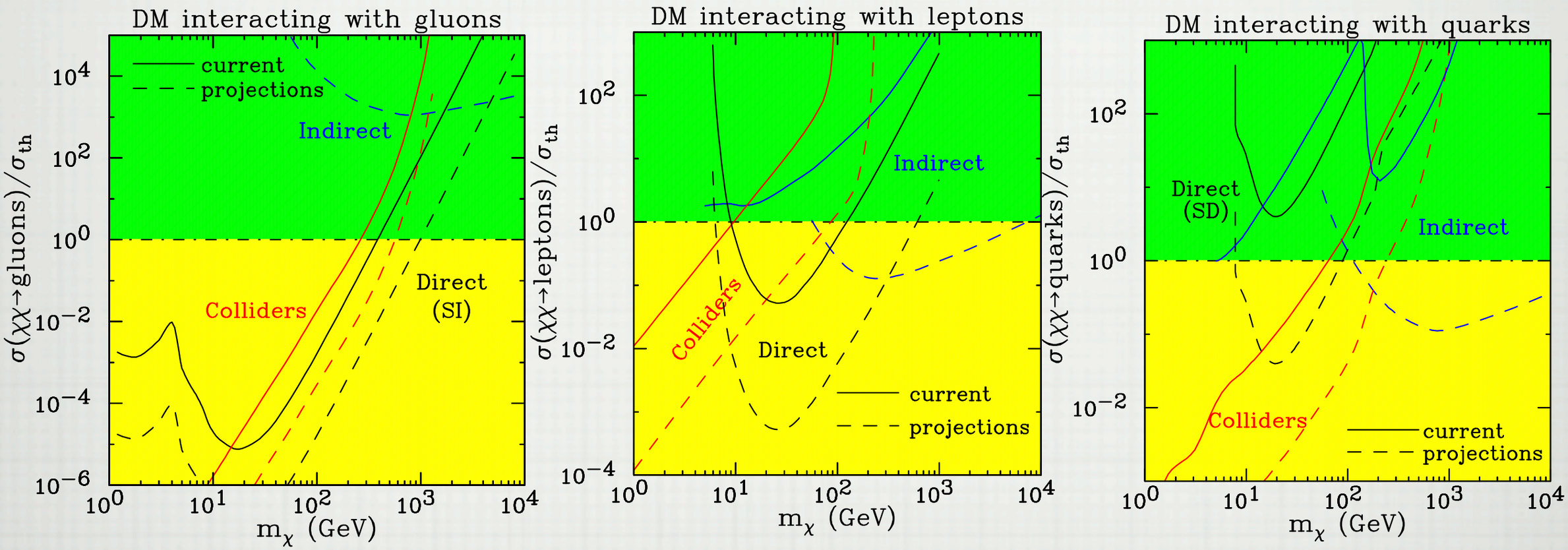




DATA listed top to bottom on plot
DAMA region, 90% C.L., Hooper PRD 2010
CoGeNT Annual Modulation Search, PRL 107 (2011), Reg
CDMS II (Soudan) Low Threshold Result, Spin Independer
CDMS-II (Soudan Silicon SI Result, R125-128, contour, 68
CDMS-II (Soudan Silicon SI Result, R125-128 upper limit)
CDMS-II (Soudan Silicon SI Result, R125-128, contour 90
CDMS-II (Soudan Silicon SI Result, R123-128 combined u
Xenon10, S2 only (2011)
CRESST-II 1-Sigma Allowed Region, 730kg-days data
CRESST-II upper limit (2009) on coherent WIMP-nucleon
Edelweiss II Low Threshold Result (5 Sept 2012)
CRESST-II 2-sigma Allowed Region part 1, 730kg-days da
Edelweiss II Final result (March 25 2011)
CDMS: Soudan 2004-2009 Ge
CDMS-Edelweiss Combined Limit
SuperCDMS - 15 kg at Soudan
XENON 100 Results from 225 live days of data presented a
SuperCDMS - 100 kg at SNOLAB
BayesFITS (Fowlie et al.), 2012, 68% C.L.
BayesFITS (Fowlie et al.), 2012, 95% C.L.
XENON 1T Projected (2017)
Phenomenological MSSM (Arbey et. al.), 2013, 99.5% C.L
130630212001

LARGE REGIONS STILL TO BE TESTED AFTER FIRST LHC RESULTS

QUANTITATIVE COMPLEMENTARITY: EFT APPROACH



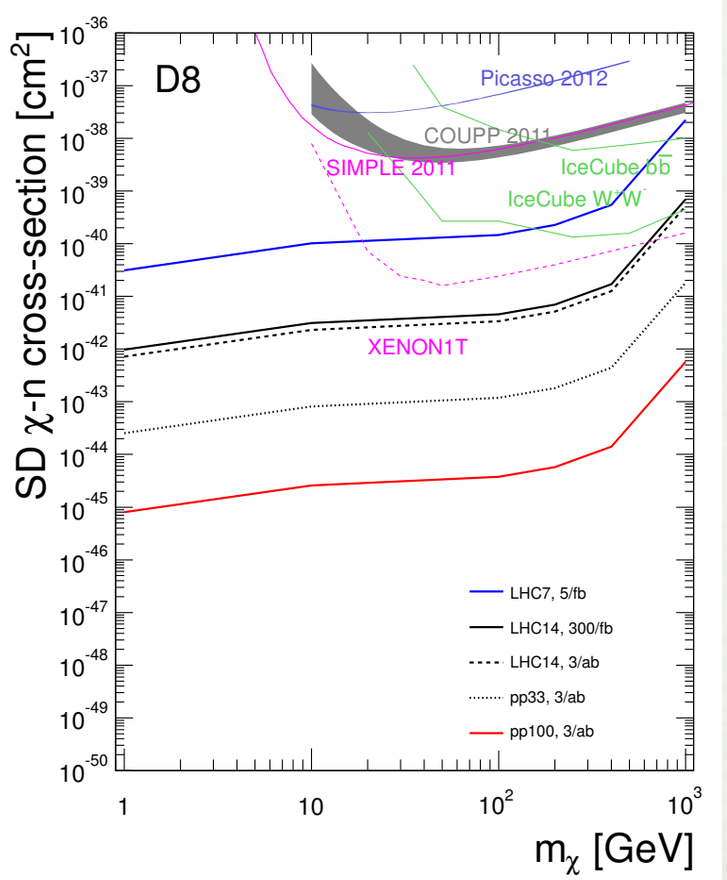
$$\frac{\alpha_S}{M_g^3}\,\bar{\chi}\chi G^{a\mu\nu}G^a_{\mu\nu}$$

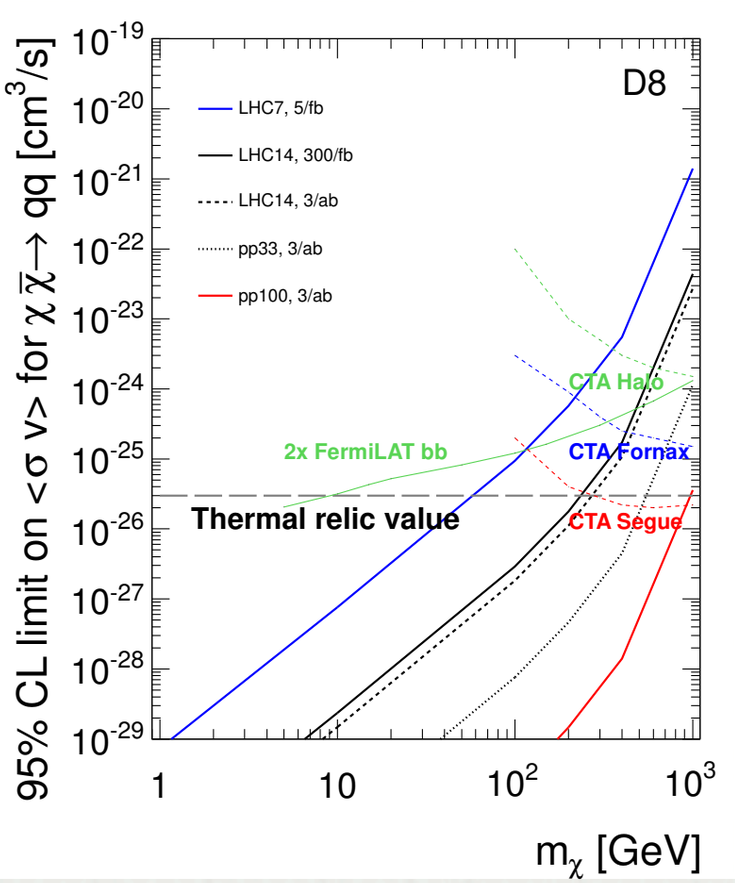
$$\frac{1}{M_\ell^2}\,\bar{\chi}\gamma^\mu\chi\sum_\ell\bar{\ell}\gamma_\mu\ell$$

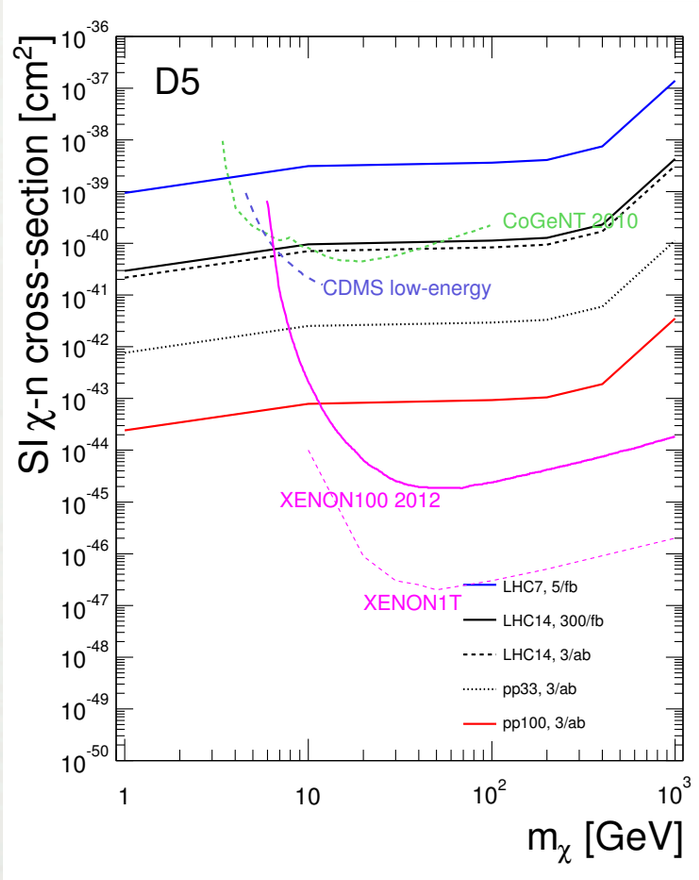
$$\frac{1}{M_q^2}\,\bar{\chi}\gamma^\mu\gamma_5\chi\sum_q\bar{q}\gamma_\mu\gamma_5 q$$

TYPICALLY COLLIDERS ARE ABLE TO GO LOWER IN MASS. COMPLEMENTARITY IS EVIDENT.

QUANTITATIVE COMPLEMENTARITY: EFT APPROACH







$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q$$

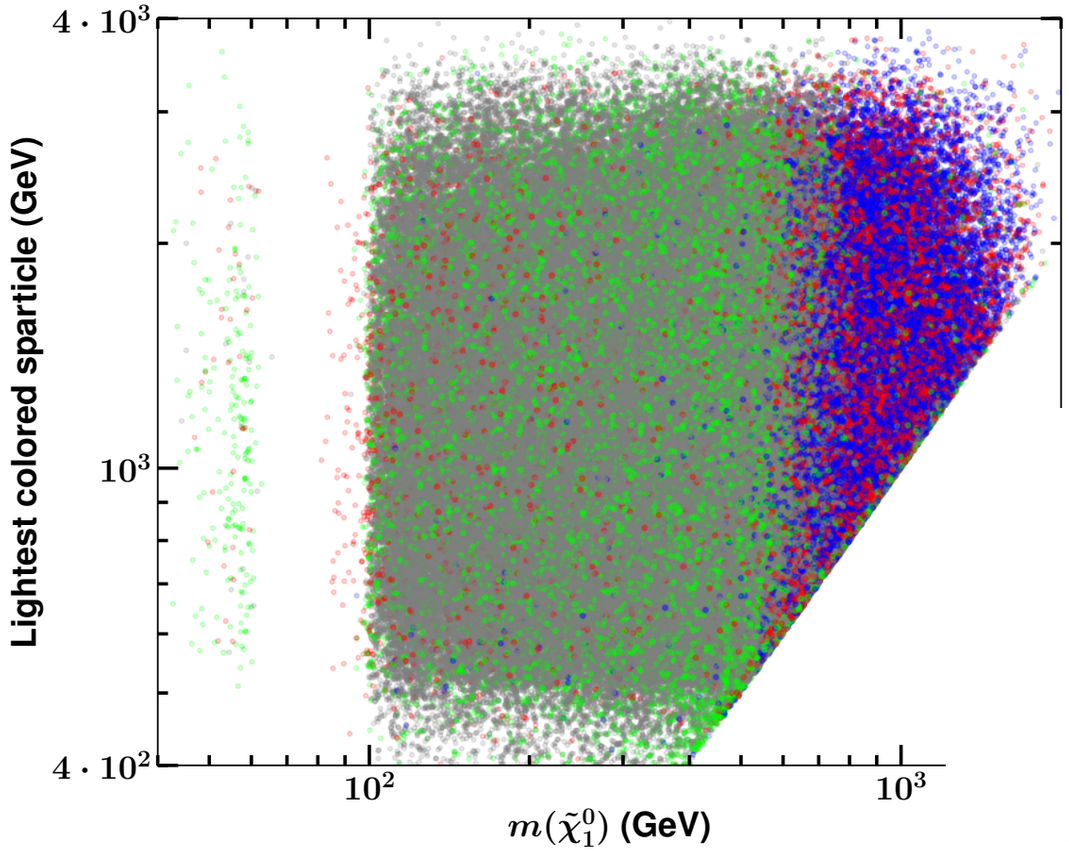
$$\frac{1}{M_q^2}\ \bar{\chi}\gamma^\mu\gamma_5\chi\sum_q \bar{q}\gamma_\mu\gamma_5 q$$

$$\frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

SNOWMASS WHITEPAPER BY ZHOU, BERGE, WANG, WHITESON, TAIT, TO BE POSTED

QUANTITATIVE COMPLEMENTARITY: PMSSM

PMSSM BENCHMARKS HTTP://ARXIV.ORG/ABS/1305.6921

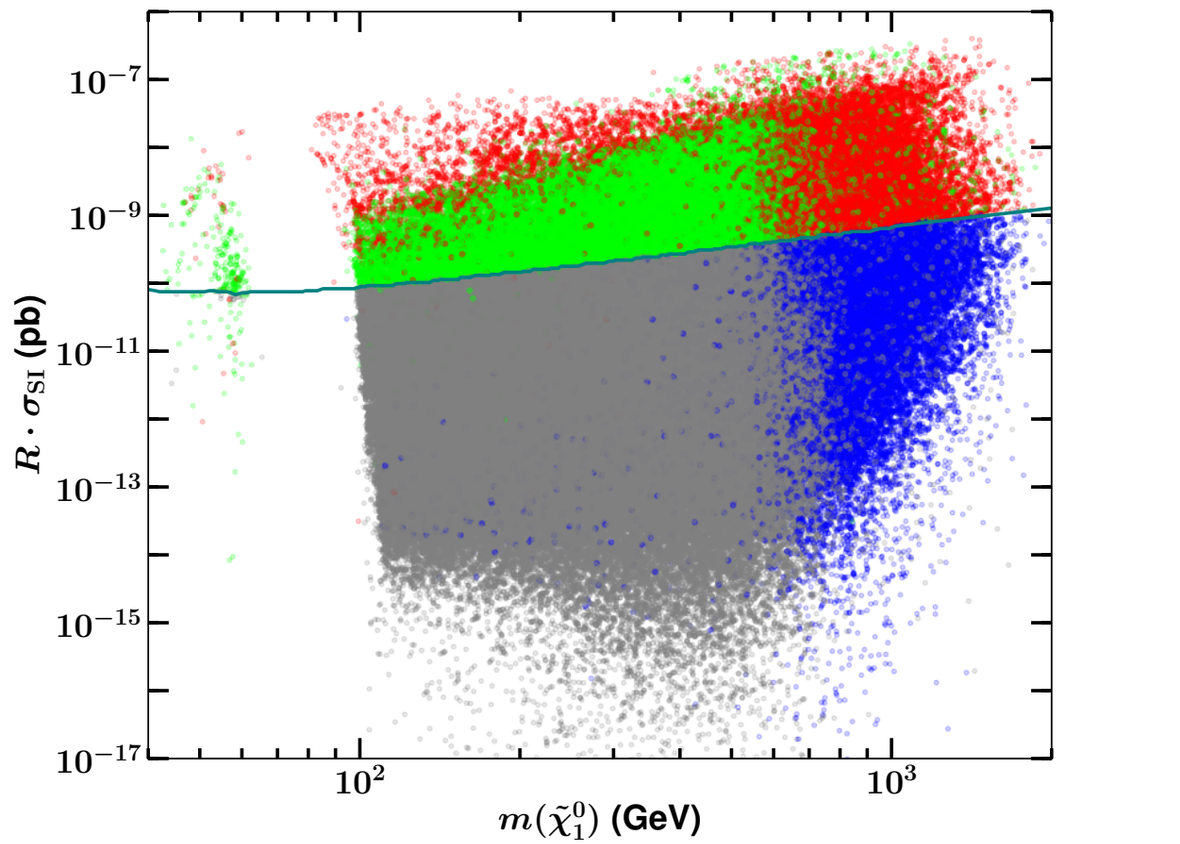


GREEN: DIRECTLY ACCESSIBLE

BLUE: INDIRECTLY ACCESSIBLE

RED: DIRECTLY AND INDIRECTLY ACCESSIBLE

GRAY: ACCESSIBLE ONLY TO UPGRADED LHC



A POST-DISCOVERY SCENARIO HIGHLIGHTING COMPLEMENTARITY

- ☐ DIRECT SEARCHES AND LHC FIND A 60 GEV NEUTRALINO.
- ☐ FURTHER LHC+ILC STUDIES REVEAL IT ONLY CONTRIBUTES ABOUT HALF OF THE RELIC DENSITY
- ☐ IN TIME, AXION DETECTORS MAKE A DISCOVERY CONSISTENT WITH AXIONS BEING THE OTHER HALF OF DARK MATTER
- ☐ COSMOLOGICAL SIMULATIONS AND OBSERVATIONS PROGRESS SUFFICIENTLY THAT THEY ASCERTAIN DARK MATTER IS COLD AND NON-INTERACTING
- ☐ THIS WOULD EXTEND OUR UNDERSTANDING OF THE UNIVERSE BACK TO NANO-SECONDS.

SUMMARY: COMPLEMENTARITY IS ESSENTIAL TO UNDERSTANDING DARK MATTER FULLY