Dark Matter: Phenomenology and Dark Stars

Katherine Freese

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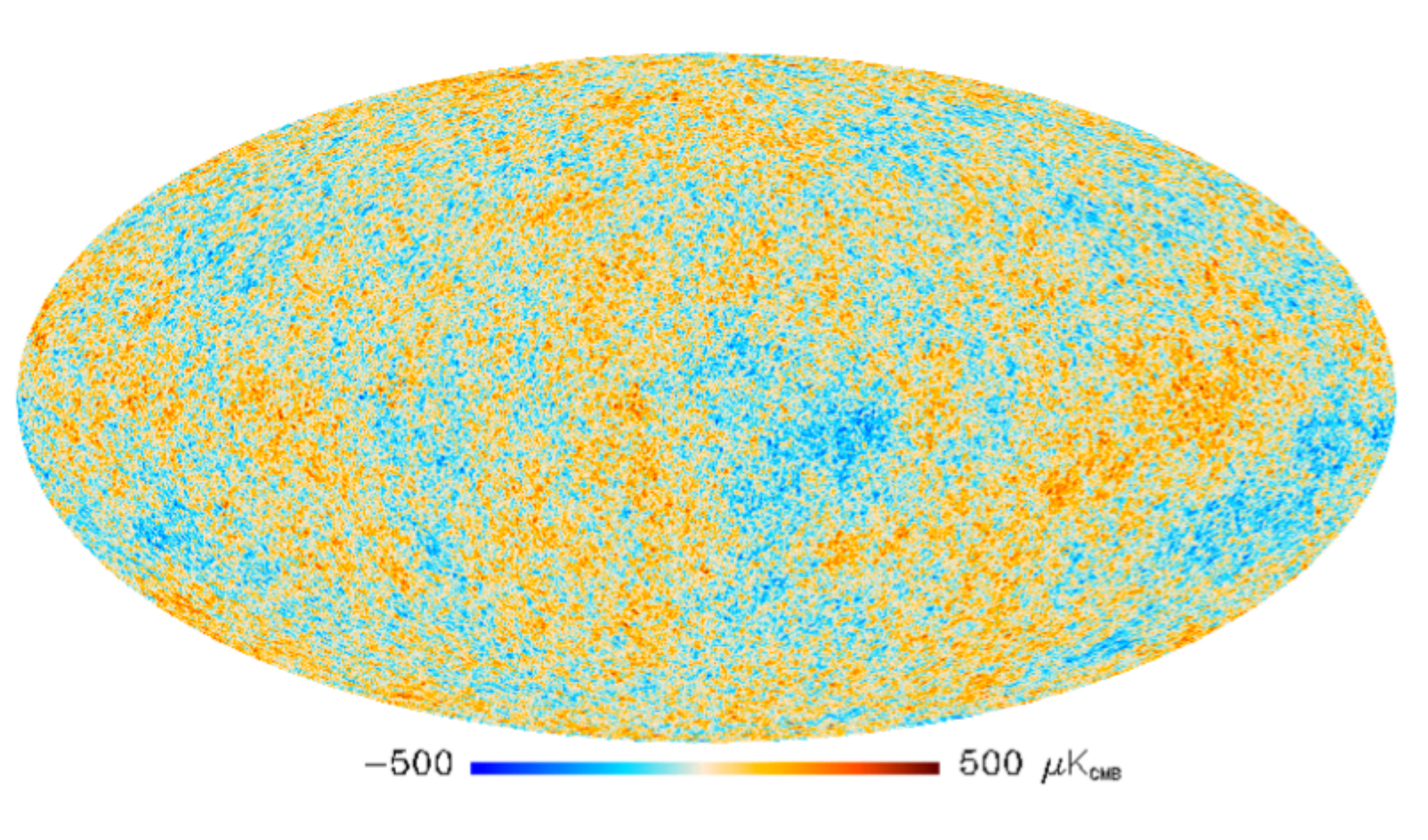
- Guest Professor, Stockholm University

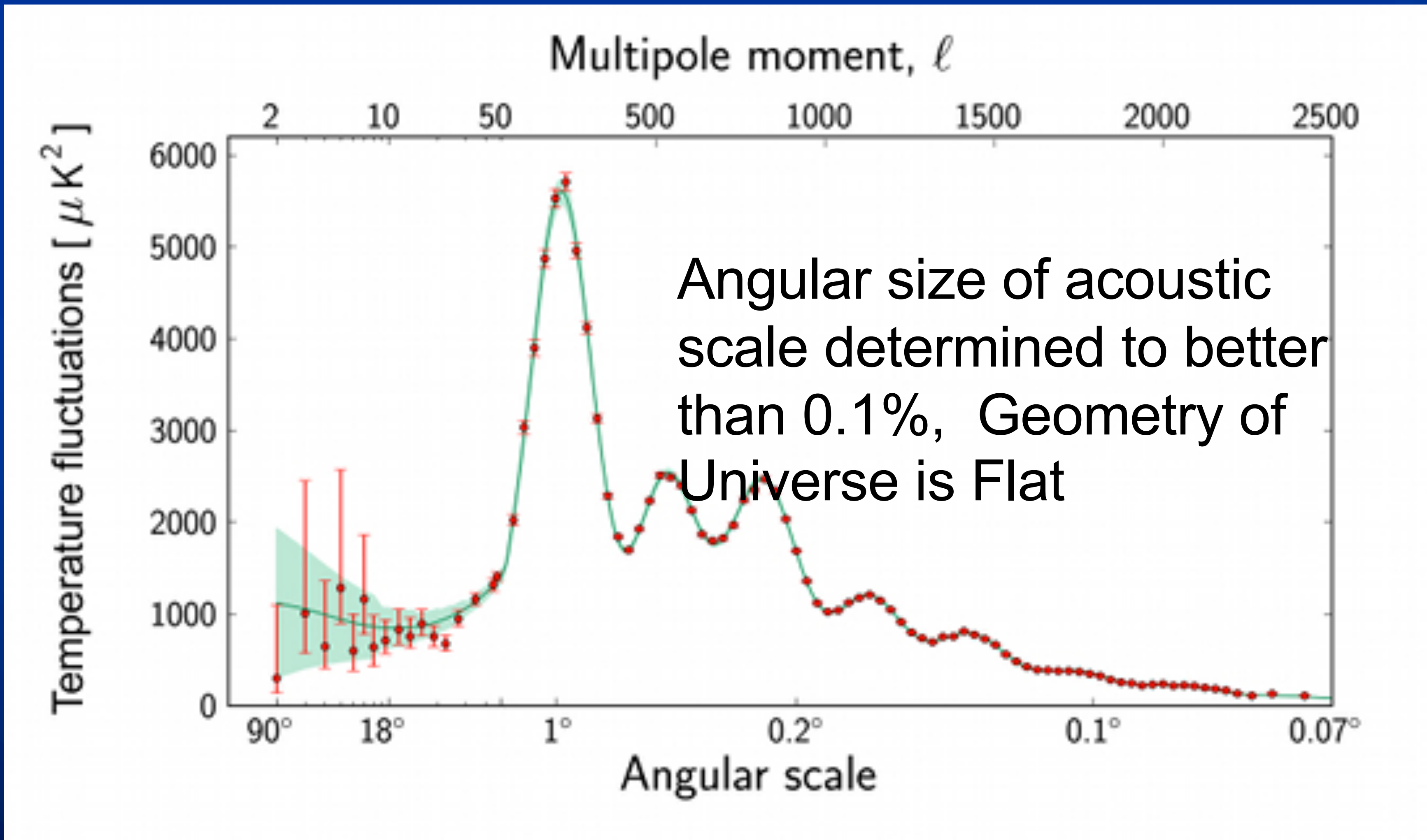
- Director Emerita, Nordita (Nordic Institute for Theoretical Physics, in Stockholm)

The Universe according to ESA's Planck Space Telescope



Planck Satellite

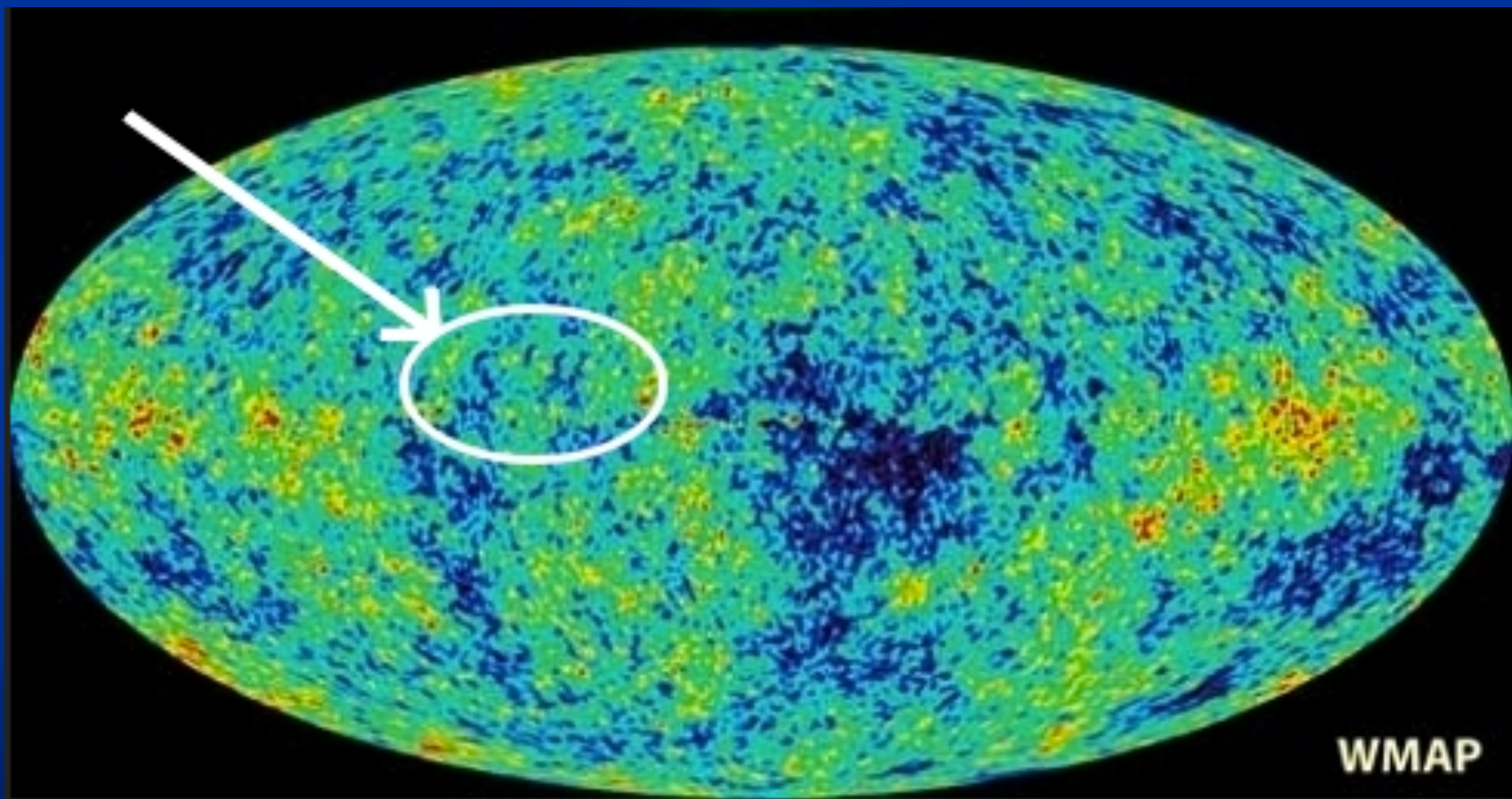
(7 acoustic peaks)



Implies energy density of the Universe is

$$\rho = \rho_c = 10^{-29}\ \text{gm/cm}^3$$

SH initials in WMAP satellite data

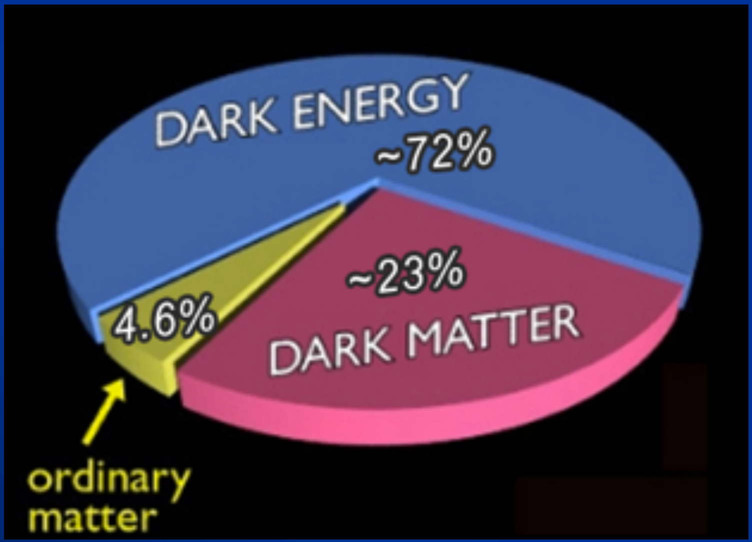


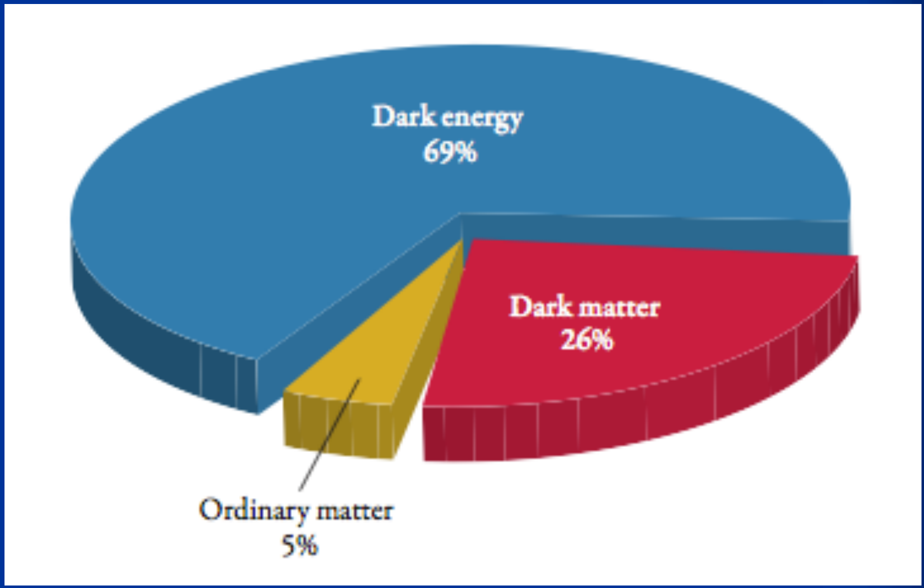
Cosmological Parameters from Planck

Parameter	*Planck* (CMB+lensing) Best fit	*Planck* (CMB+lensing) 68 % limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025
Ω_Λ	0.6964	0.693 ± 0.019	0.6914	0.692 ± 0.010
σ_8	0.8285	0.823 ± 0.018	0.8288	0.826 ± 0.012
z_{re}	11.45	$10.8^{+3.1}_{-2.5}$	11.52	11.3 ± 1.1
H_0	68.14	67.9 ± 1.5	67.77	67.80 ± 0.77
Age/Gyr	13.784	13.796 ± 0.058	13.7965	13.798 ± 0.037
$100\theta_*$	1.04164	1.04156 ± 0.00066	1.04163	1.04162 ± 0.00056
r_{drag}	147.74	147.70 ± 0.63	147.611	147.68 ± 0.45
$r_{drag}/D_V(0.57)$	0.07207	0.0719 ± 0.0011		

More Dark Matter (thanks to Planck)

- WMAP: 4.7% baryons, 23% DM, 72% dark energy
- PLANCK: 4.9% baryons, 26% DM, 69% dark energy





Less than 5% ordinary matter.
What is the dark matter? What is the dark energy?

Outline: Thoughts on what DM is (and isn't) and how to find it

- 1) Neutrino mass: we are close to knowing it. Cosmology is very powerful.
- 2) WIMP searches: what is going on with DAMA?
- 3) Dark Stars: the first stars could have been powered by Dark Matter rather than by fusion. Powered by WIMPs or SIDM or …
- 4) New ways to test nature of DM: GAIA satellite and stellar streams as a test of Cold Dark Matter

What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- --
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Asymmetric Dark Matter
- Light Dark Matter
- Self Interacting Dark Matter
- Primordial black holes
- Q-balls
- WIMPzillas

1) Neutrinos as Dark Matter? No

- Nearly relativistic, move large distances, destroy clumps of mass smaller than clusters
- Too light,

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.5\mathrm{eV}}$$

- 50 eV neutrinos would "close" the Universe.
- BUT
- The sum of the neutrino masses adds to roughly 0.1 eV
- Neutrinos contribute ½% of the mass of the Universe.

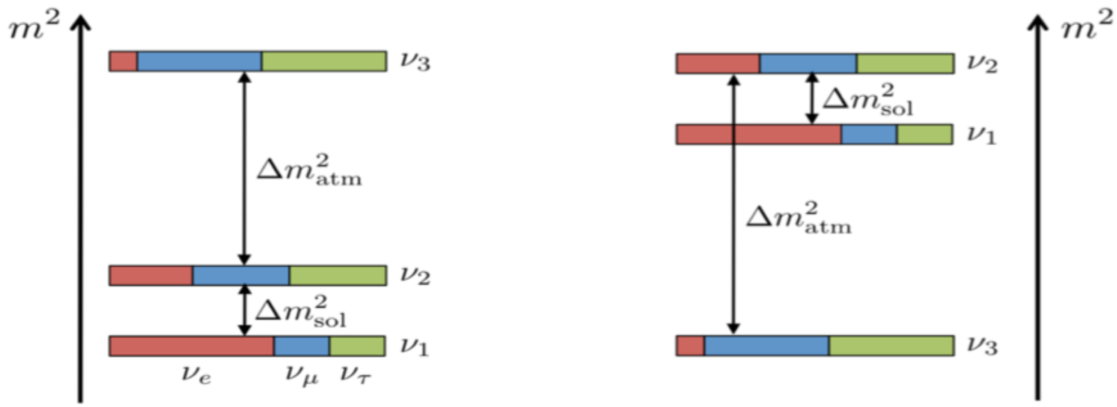
NEUTRINO MASS

We know from the observation of neutrino oscillations that neutrinos have mass (Nobel prize 2015 to Kajita & McDonald!)
However, oscillations measure mass ***differences*** (with few % accuracy):

$$\Delta m^2_{21} = 7.6 \times 10^{-5}\ \mathrm{eV}^2 \qquad |\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \mathrm{eV}^2\ \text{(NH)}$$
$$2.4 \times 10^{-3}\ \mathrm{eV}^2\ \text{(IH)}$$

We do not know yet the mass pattern (hierarchy) nor the absolute mass scale

normal hierarchy (NH) vs. inverted hierarchy (IH)



$\Sigma m_\nu > 0.06$ eV $\qquad \Sigma m_\nu > 0.10$ eV

Oscillations put a ***lower limit*** on the mass scale

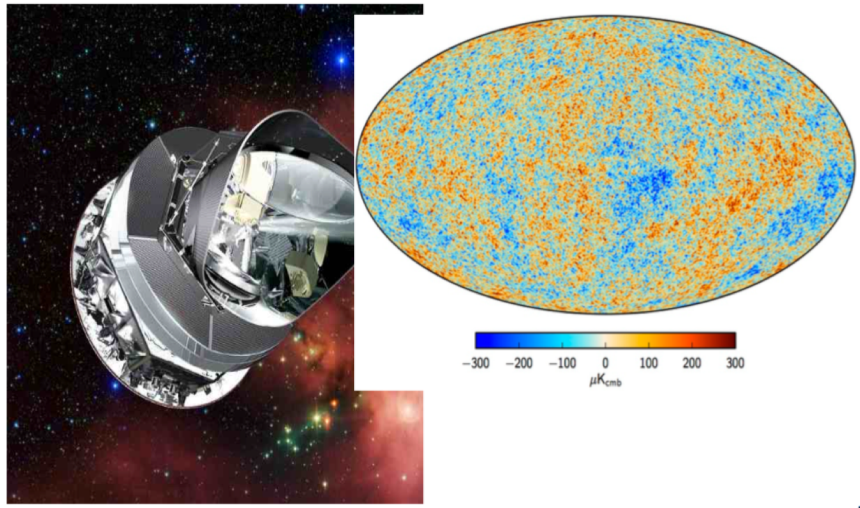
(depending on the hierarchy)

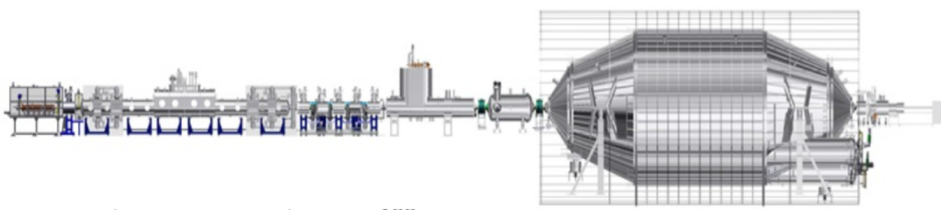
Figure credit: Juno Collaboration

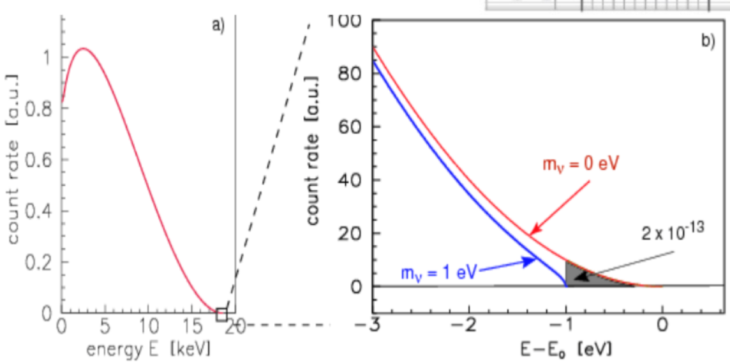
The tiny neutrino masses are a puzzle for the Standard Model of particle physics

The absolute scale of neutrino masses can be measured in different ways

Cosmological observations (CMB, LSS)

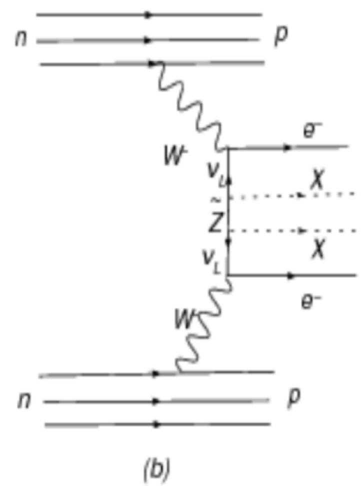






Kinematic measuremets (Tritium β decay)

Neutrinoless double β decay



The absolute mass scale can be measured through:

- tritium beta decay

$$m_\beta \equiv \left[\sum |U_{ei}|^2 m_i^2\right]^{1/2} < 1.1 \text{ eV @ 90\%CL} \quad \text{(KATRIN)}$$

- neutrinoless double beta decay

$$m_{\beta\beta} \equiv \left|\sum U_{ei}^2 m_i\right| \quad < 0.06 - 0.16 \text{ eV @ 90\%CL}$$

(Kamland-Zen)

- cosmological observations

$$\sum m_\nu \equiv \sum_i m_i \quad < 0.12 - 0.24 \text{ eV @ 95\%CL}$$

(Planck+…)

PHYSICAL REVIEW LETTERS

Editors' Suggestion

Improved Limit on Neutrinoless Double-Beta Decay in ^{130}Te with CUORE

D. Q. Adams *et al.* (CUORE Collaboration)

Phys. Rev. Lett. **124**, 122501 – Published 26 March 2020

ABSTRACT

We report new results from the search for neutrinoless double-beta decay in ^{130}Te with the CUORE detector. This search benefits from a fourfold increase in exposure, lower trigger thresholds, and analysis improvements relative to our previous results. We observe a background of $(1.38 \pm 0.07) \times 10^{-2}$ counts $/(\mathrm{keV\ kg\ yr})$ in the $0\nu\beta\beta$ decay region of interest and, with a total exposure of 372.5 kgyr, we attain a median exclusion sensitivity of 1.7×10^{25} yr. We find no evidence for $0\nu\beta\beta$ decay and set a 90% credibility interval Bayesian lower limit of 3.2×10^{25} yr on the ^{130}Te half-life for this process. In the hypothesis that $0\nu\beta\beta$ decay is mediated by light Majorana neutrinos, this results in an upper limit on the effective Majorana mass of 75–350 meV, depending on the nuclear matrix elements used.

PRIMORDIAL NUCLEOSYNTHESIS: A CRITICAL COMPARISON OF THEORY AND OBSERVATION

J. YANG,[1,2] M. S. TURNER,[2,3] G. STEIGMAN,[4] D. N. SCHRAMM,[2,3] AND K. A. OLIVE[3]

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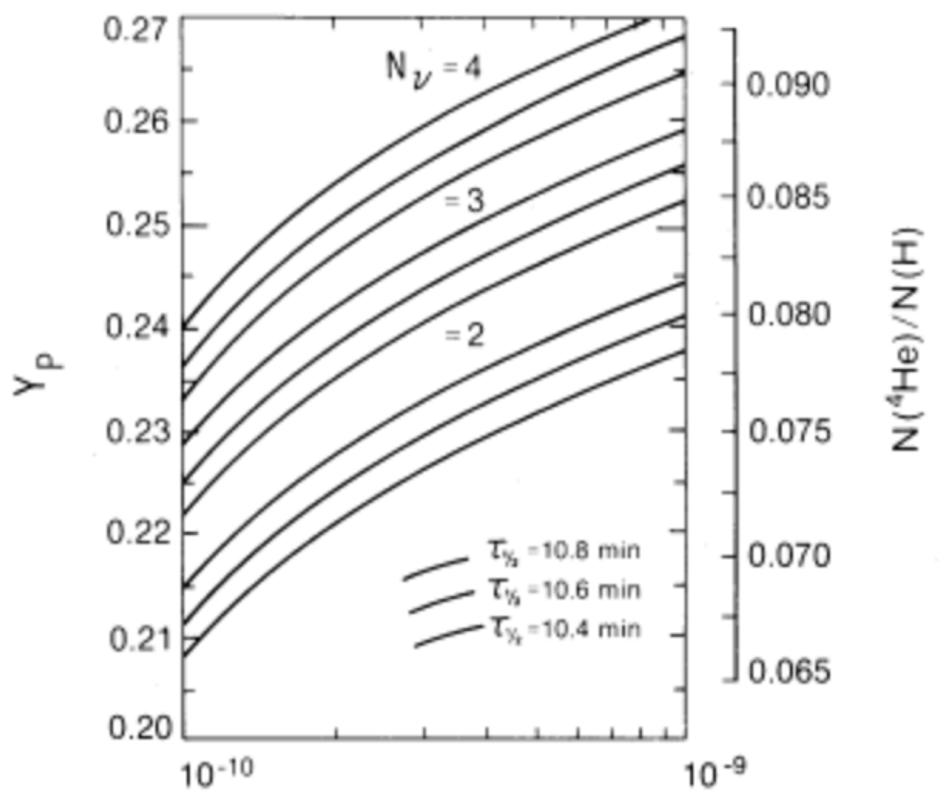


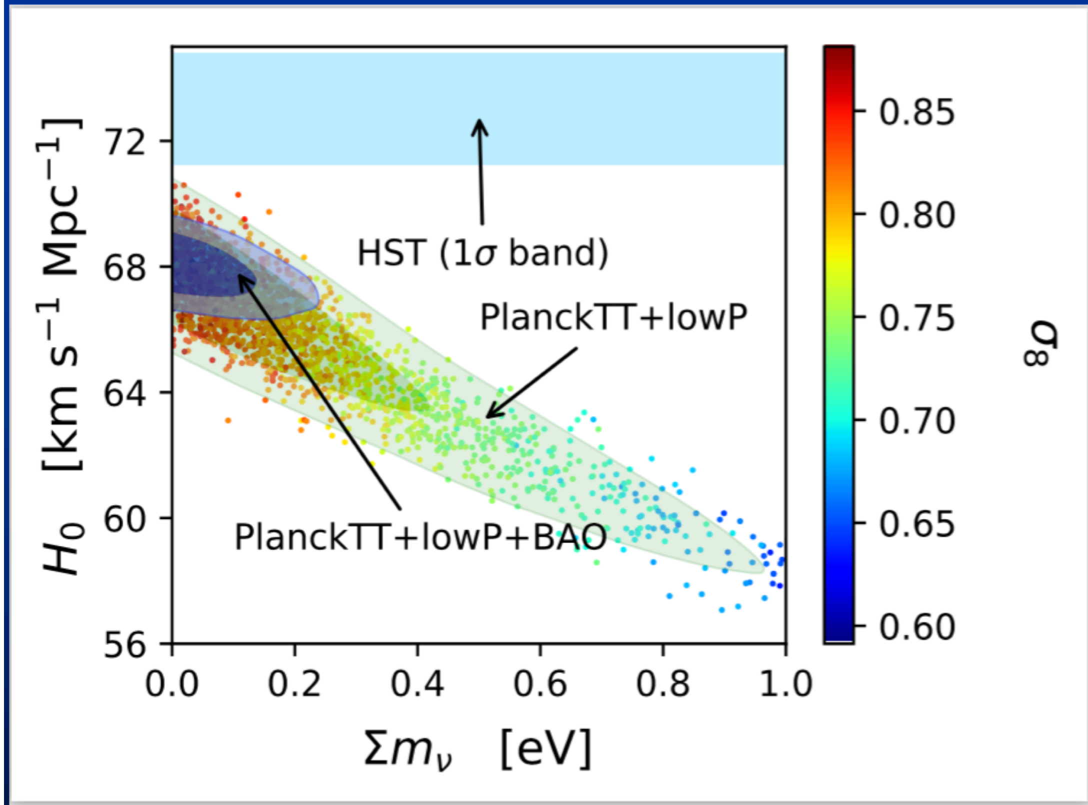
Neff=2.99+/-0.33

Current Bounds on Number of Neutrino Species:

In CMB lowers Silk damping tail i.e. at l>200.
Planck 2018+BAO gives
Neff=2.99+/-0.33 at 95% CL.
If there are only 3 active neutrinos, the expected value is Neff=3.046

Therefore, models with Delta Neff=1 are ruled out at almost 3sigma level.
A fourth active neutrino species Is ruled out (but sterile is OK)

Cosmological data (CMB plus large scale structure) bound neutrino mass



$$\sum m_\nu < 0.15 \text{ eV}$$

at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXIv:1701.0872

Planck Satellite: < 0.12 eV

Assumes standard Lambda CDM
If w>-1, stronger bounds

From oscillations: >0.06 eV

Giusarma, KF etal arXiv:1405:04320
Neutrino Properties in Particle Data Group's Review of Particle Properties

LARGE SCALE STRUCTURES

Full shape of the matter power spectrum:
Power at small scales is affected by the presence of neutrinos (due to free streaming)
issues: non-linearities, scale-dependent bias

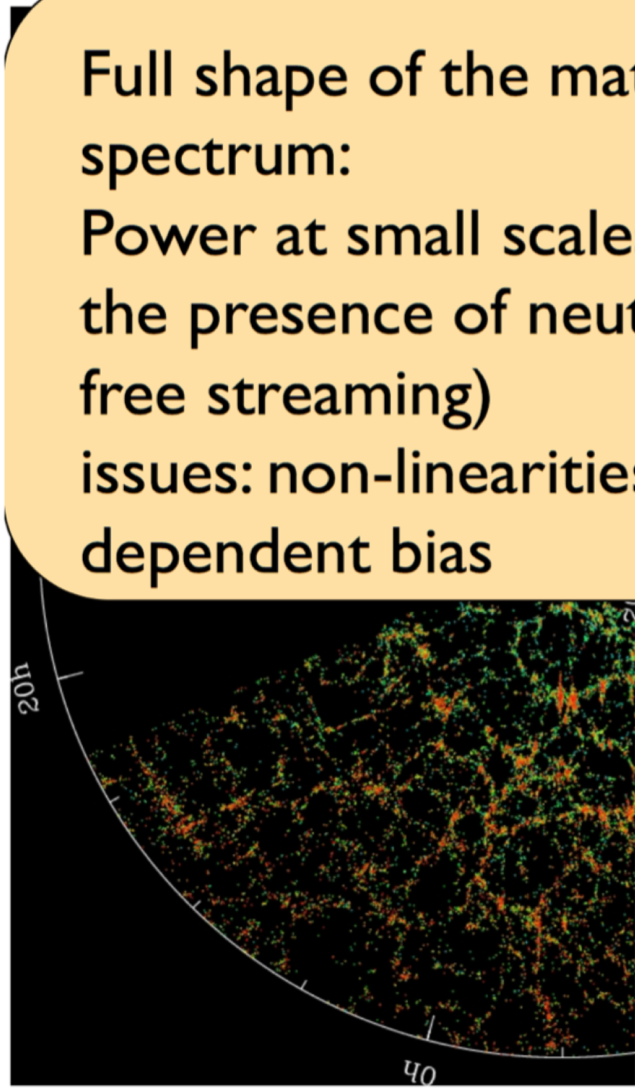
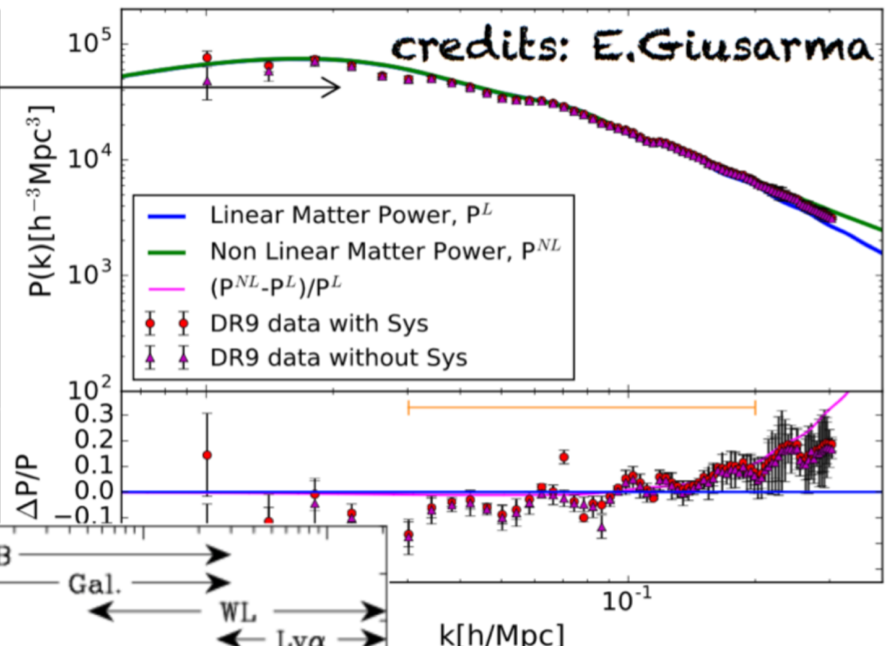
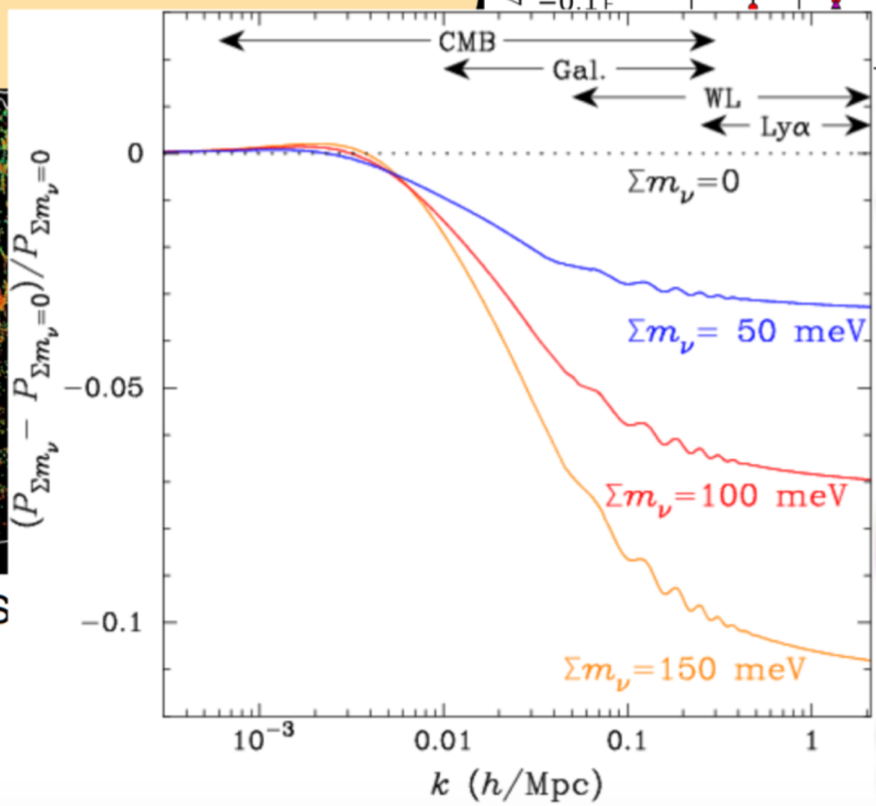
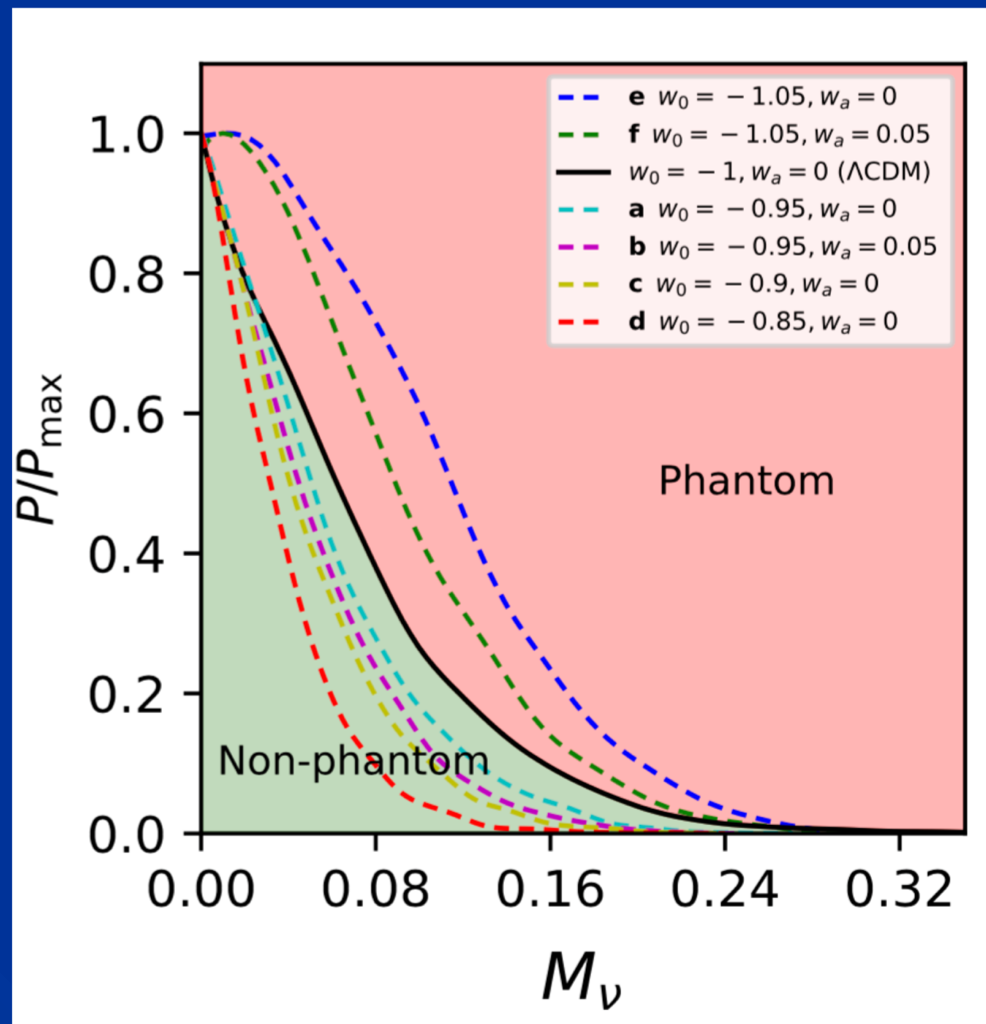


Image Credit: M. Blanton and the S





Neutrino Mass bounds are tighter for arbitrary dark energy with w>-1 (nonphantom) than for Lambda CDM



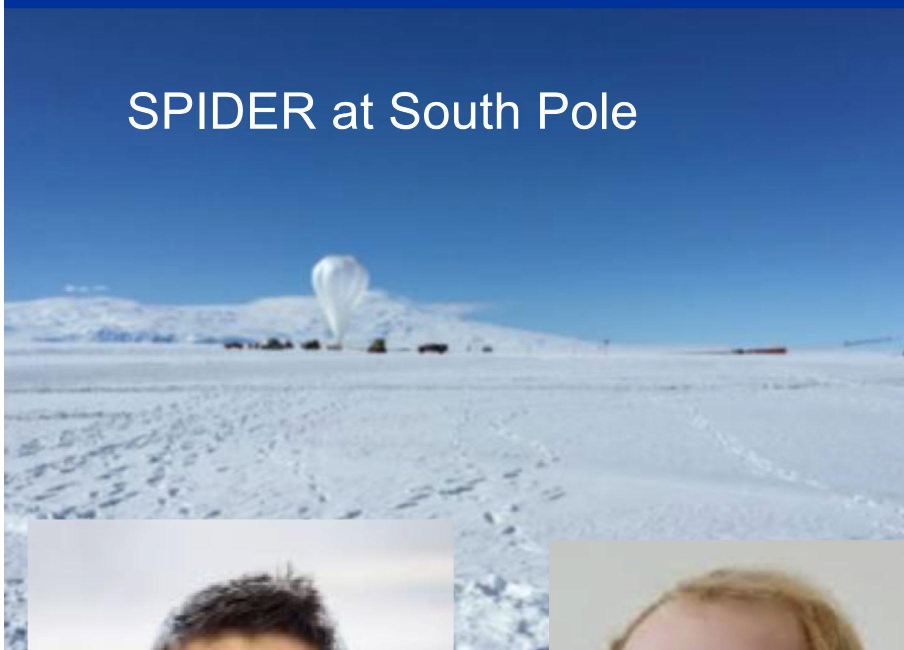
MARTINA GERBINO

SUNNY VAGNOZZI

Vagnozzi, Gerbino, KF, etal http://lanl.arxiv.org/pdf/1801.08553

Upcoming Cosmic Microwave Background Experiments

My group has joined these two experiments



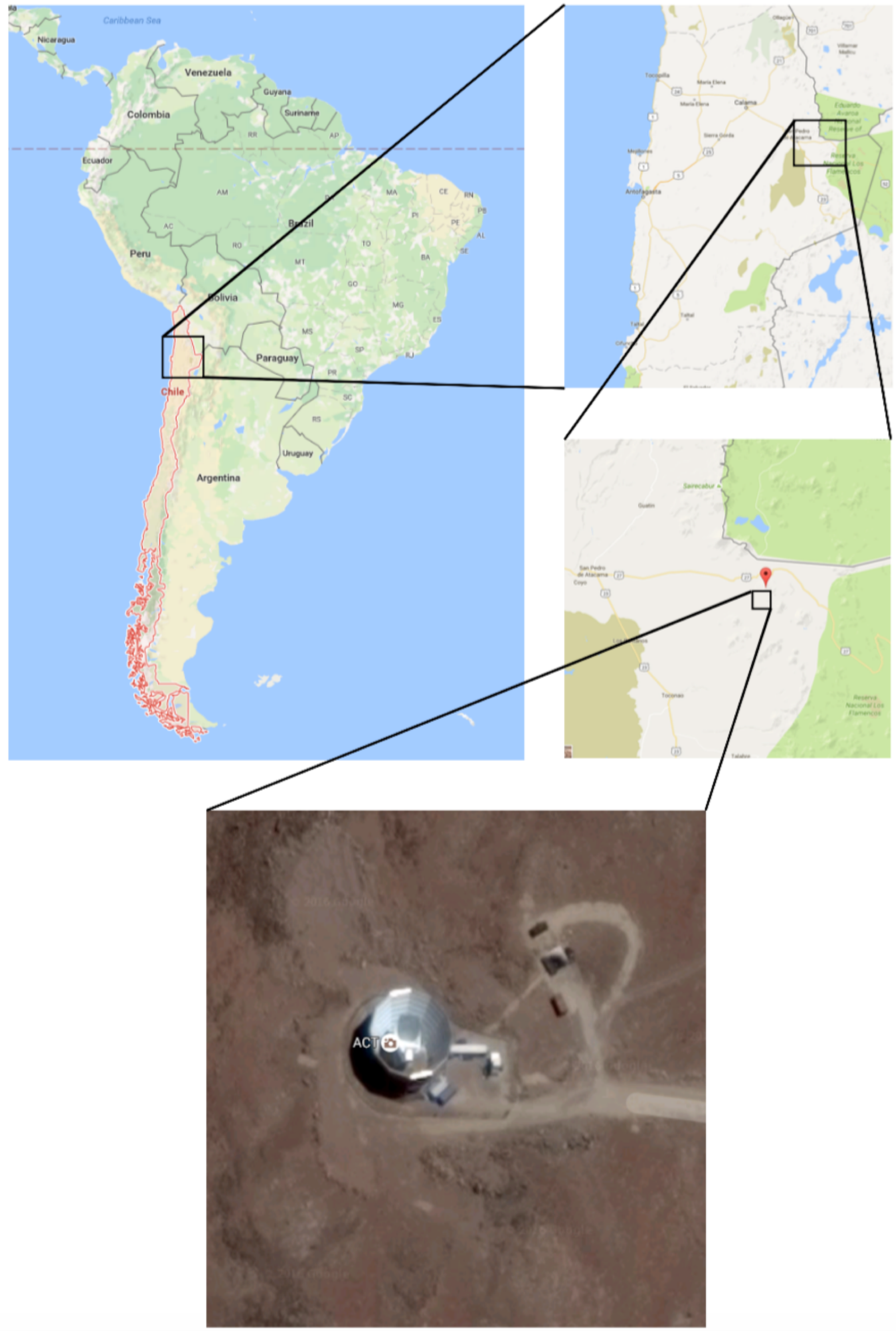
Jon Gudmundsson

Adri Duivenvoorden

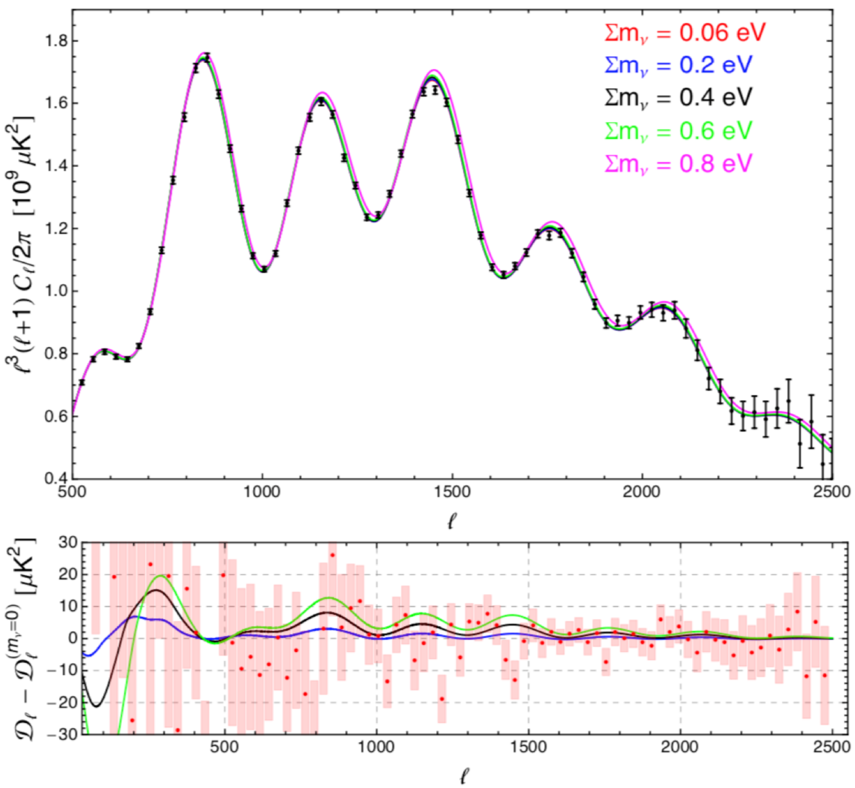
Simons Observatory

- The Simons Observatory will be located in the high Atacama Desert in Northern Chile at 5,200 meters (17,000 ft) above sea level.

- The large existing structure is the Atacama Cosmology Telescope (ACT) and the smaller ones are PolarBear/Simons Array



Main effect of neutrino mass on CMB: decreases the effect of lensing due to photons damping small scale structure



CMB angular power spectrum and neutrino masses

Background effects can be mostly reabsorbed by varying other parameters

Perturbations: free streaming, damping of small-scale perturbations
Net effect is to ***decrease lensing***

- proportional to the neutrino energy density
- the effect is larger for larger masses

Simons Observatory Science Goals

Table 9
Summary of SO key science goals[a]

	Parameter	SO-Baseline[b] (no syst)	**SO-Baseline**[c]	SO-Goal[d]	Current[e]	Method
Primordial perturbations	r	0.0024	**0.003**	0.002	0.03	BB + ext delens
	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt
		1	**2**	1		kSZ + LSST-LSS
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO
		0.035	**0.04**	0.03		tSZ-N $\times$ LSST-WL
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS
		1.2%	**2%**	1%		tSZ-N $\times$ LSST-WL
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)

[a] All of our SO forecasts assume that SO is combined with *Planck* data.

Neutrino Mass close to being measured (for the 3 active neutrinos)

- From oscillation experiments:

- $\sum m_\nu$ > 0.06 eV (Normal Hierarchy)
- > 0.1 eV (Inverted Hierarchy)

- From cosmology (CMB + Large Scale Structure +BAO)

$\sum m_\nu$ < 0.15 eV at 95% C.L.

Vagnozzi, Gerbino, KF etal
arXiv:1701.0872

Planck Satellite: < 0.12 eV

Pablo Fernandez de Salas

Steffen Hagstotz

arXiv.org > astro-ph > arXiv:2003.02289

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 4 Mar 2020]

Bounds on light sterile neutrino mass and mixing from cosmology and laboratory searches

For m_nu < keV

Steffen Hagstotz, Pablo F. de Salas, Stefano Gariazzo, Martina Gerbino, Massimiliano Lattanzi, Sunny Vagnozzi, Katherine Freese, Sergio Pastor

We provide a consistent framework to set limits on properties of light sterile neutrinos coupled to all three active neutrinos using a combination of the latest cosmological data and terrestrial measurements from oscillations, β-decay and neutrinoless double-β decay ($0\nu\beta\beta$) experiments. We directly constrain the full $3+1$ active-sterile mixing matrix elements $|U_{\alpha 4}|^2$, with $\alpha \in (e, \mu, \tau)$, and the mass-squared splitting $\Delta m^2_{41} \equiv m^2_4 - m^2_1$. We find that results for a $3+1$ case differ from previously studied $1+1$ scenarios where the sterile is only coupled to one of the neutrinos, which is largely explained by parameter space volume effects. Limits on the mass splitting and the mixing matrix elements are currently dominated by the cosmological data sets. The exact results are slightly prior dependent, but we reliably find all matrix elements to be constrained below $|U_{\alpha 4}|^2 \lesssim 10^{-3}$.
Short-baseline neutrino oscillation hints in favor of eV-scale sterile neutrinos are in serious tension with these bounds, irrespective of prior assumptions. We also translate the bounds from the cosmological analysis into constraints on the parameters probed by laboratory searches, such as m_β or $m_{\beta\beta}$, the effective mass parameters probed by β-decay and $0\nu\beta\beta$ searches, respectively. When allowing for mixing with a light sterile neutrino, cosmology leads to upper bounds of $m_\beta < 0.09$ eV and $m_{\beta\beta} < 0.07$ eV at 95\% C.L, more stringent than the limits from current laboratory experiments.

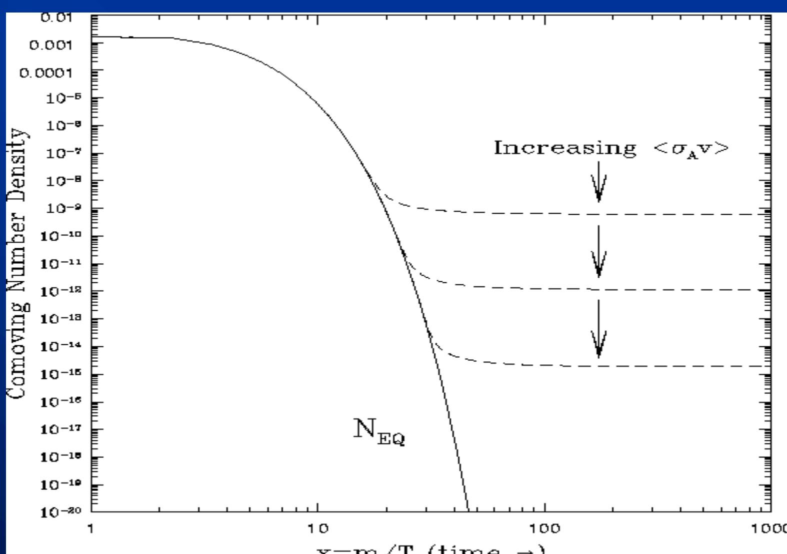
2) What is the Dark Matter? Candidates:

- Cold Dark Matter candidates w/ strong theoretical motivation:
- WIMPs (SUSY or extra dimensions)
- Axions (exist automatically in solution to strong CP problem)
- ---
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Asymmetric Dark Matter
- Light Dark Matter
- Self Interacting Dark Matter
- Primordial black holes
- Q-balls
- WIMPzillas

Florian Kuhnel
Primordial
Black Holes

Dark Matter: Good news: cosmologists don't need to "invent" new particle

- Weakly Interacting Massive Particles (WIMPS). e.g.,neutralinos



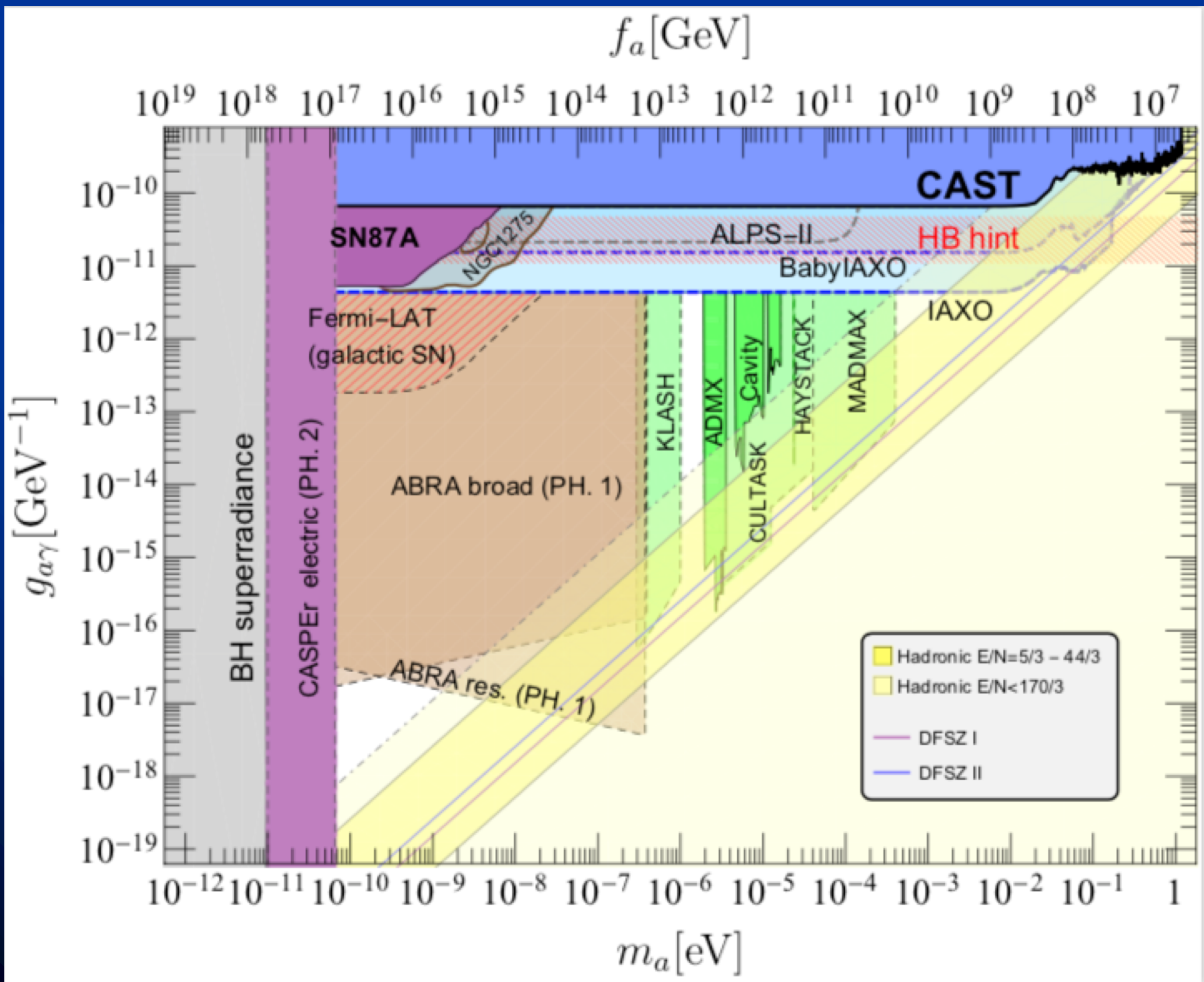
- Axions

  $m_a \sim 10^{-(3\text{-}6)}$ eV

arise in Peccei-Quinn solution to strong-CP problem

(Weinberg; Wilczek; Dine, Fischler, Srednicki; Zhitnitskii)

Bounds on Axions and ALPs



From review by Luca Visinelli 2003.01100

Why WIMPS? Among the best motivated candidates: First, the relic abundance

Weakly Interacting Massive Particles Many are their own antipartners. Annihilation rate in the early universe determines the density today.

$$\Omega_\chi h^2 = \frac{3\times 10^{-27}\ cm^3/\text{sec}}{<\sigma v>_{ann}}$$

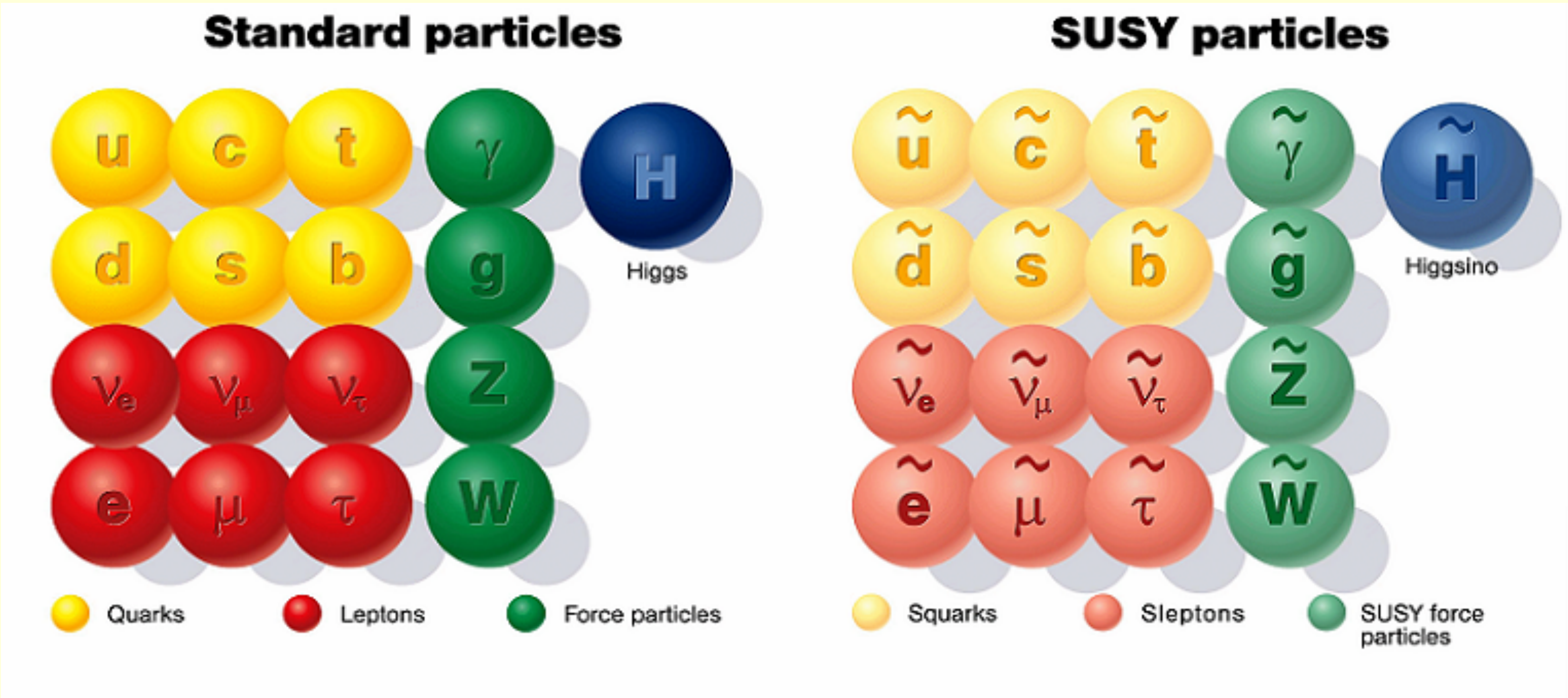
n.b. thermal WIMPs

This is the mass fraction of WIMPs today, and gives the right answer if the dark matter is weakly interacting

WIMP mass: GeV – 10 TeV

Second motivation for WIMPS: in particle theories, eg supersymmetry

- Every particle we know has a partner

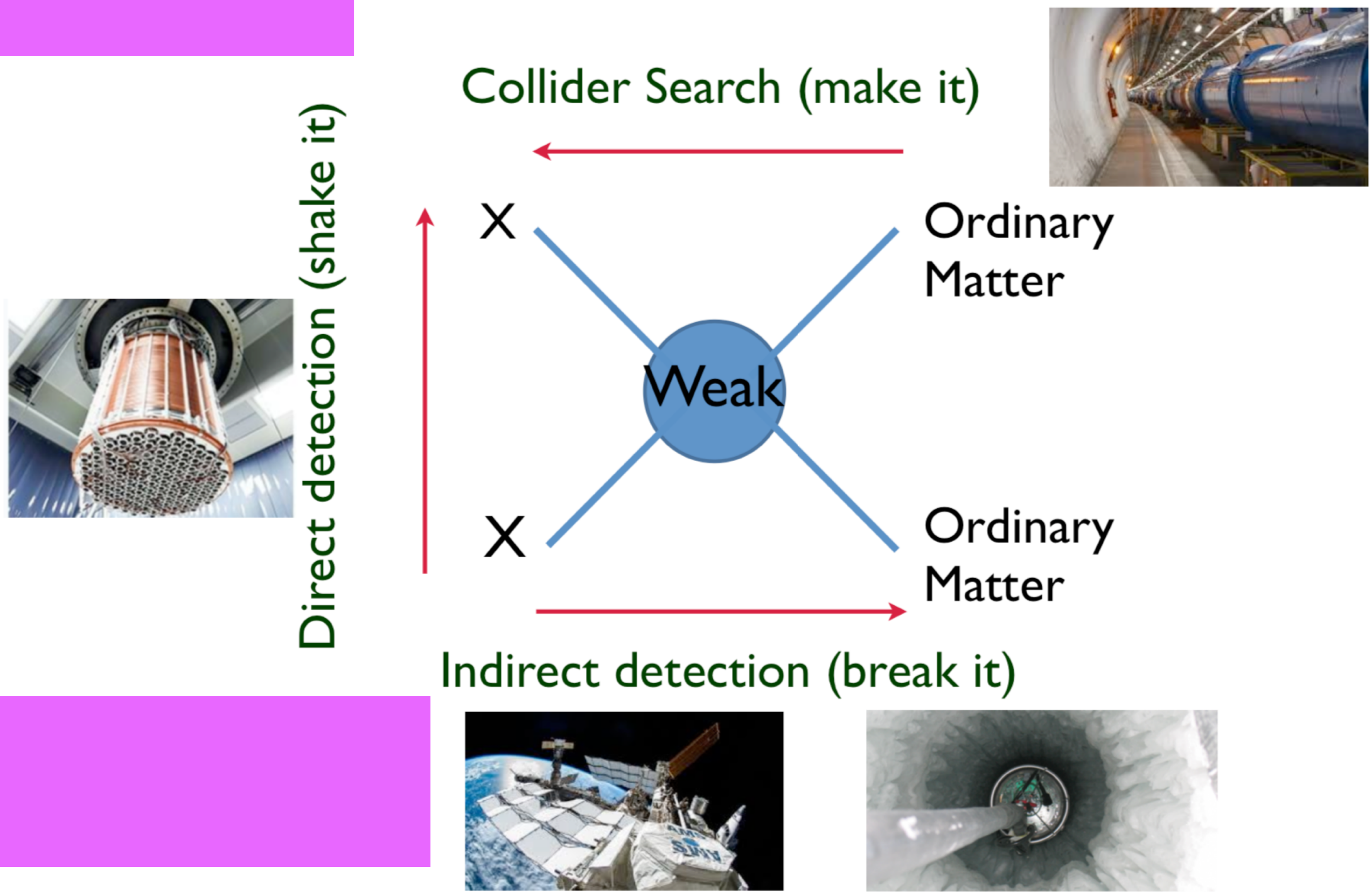


- The lightest supersymmetric particle may be the dark matter.

Another type of WIMP from Universal Extra Dimensions

- All standard model fields propagate in a higher dimensional bulk that is compactified on a space TeV^-1
- Higher Dimensional momentum conservation in bulk translates in 4D to KK number (w/ b.c. to KK parity)
- Lightest KK particle (LKP) does not decay and is dark matter candidate

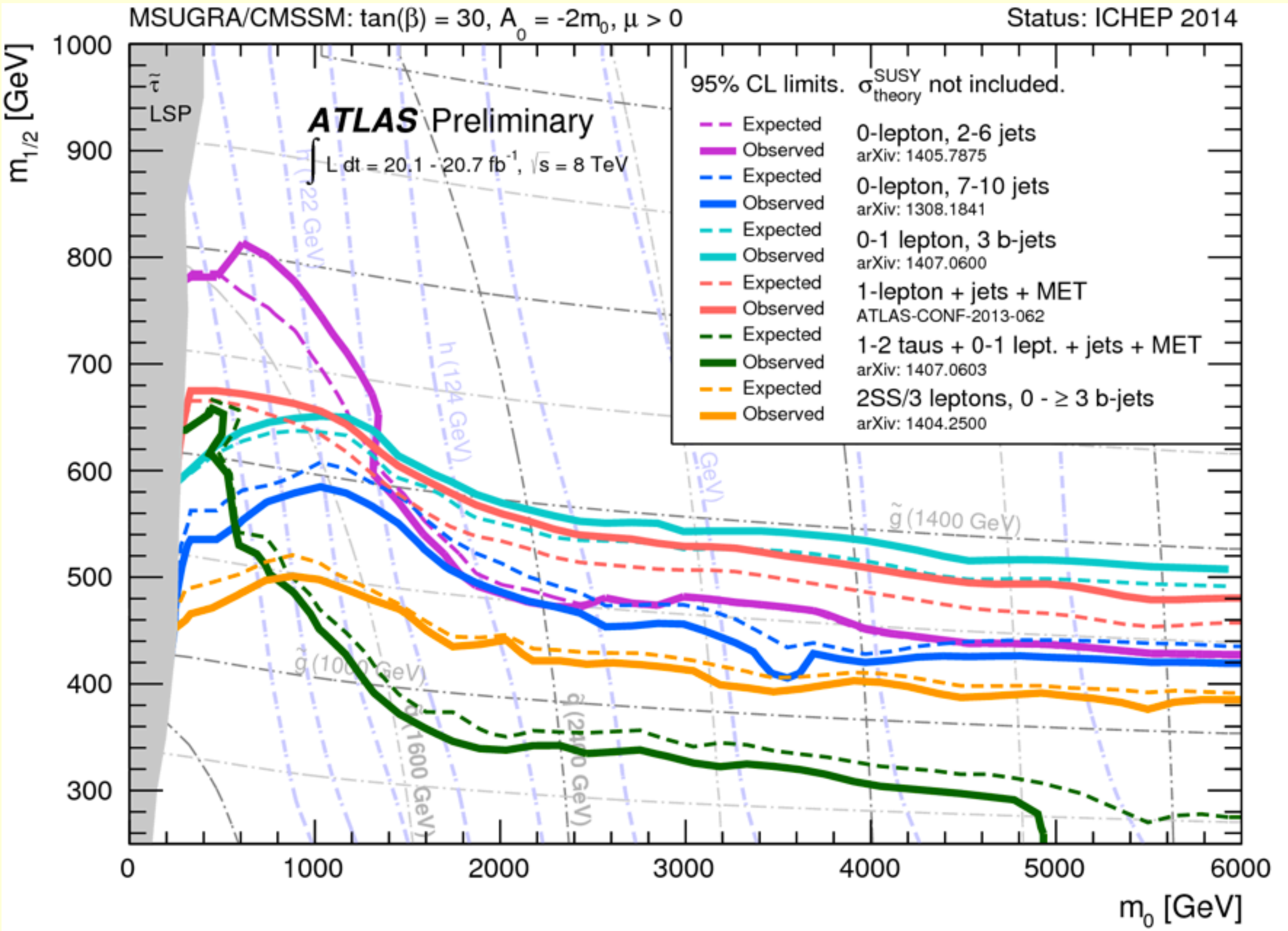
THREE PRONGED APPROACH TO WIMP DETECTION



FIRST WAY TO SEARCH FOR WIMPS

Ring that is 17 miles around.
Two proton beams traveling underground in opposite directions. Collide at four intersection points where there are detectors.

ATLAS bounds on CMSSM

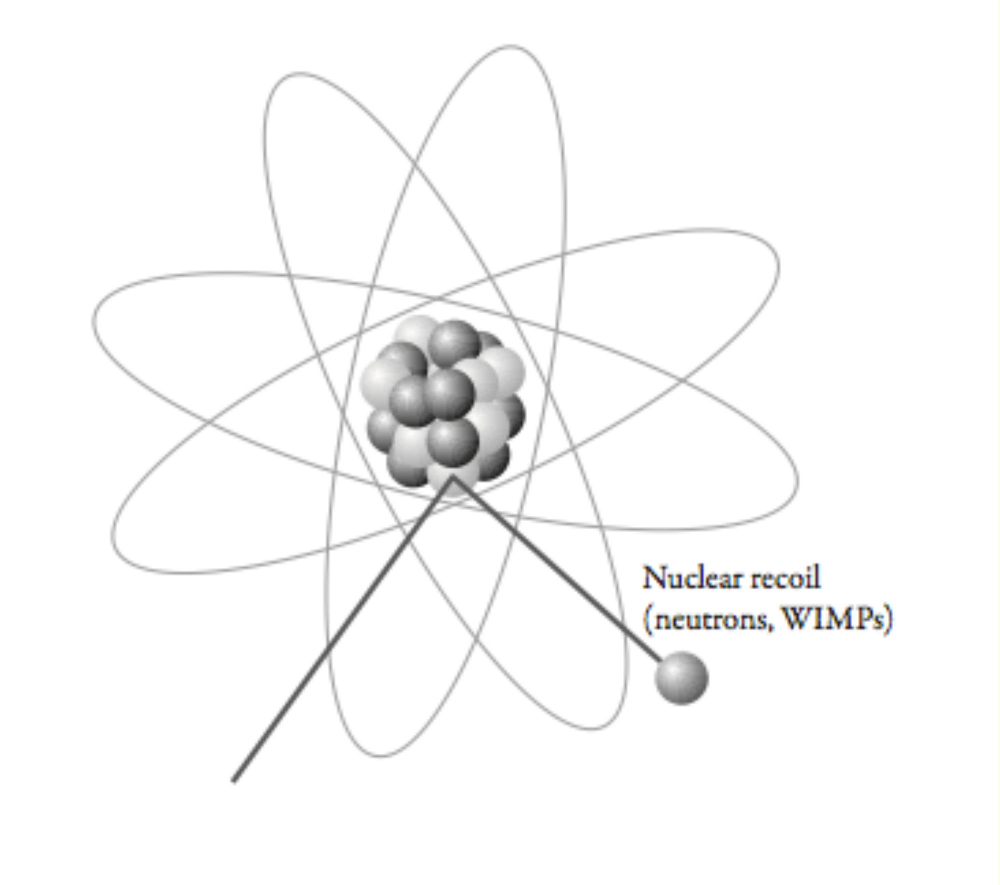


Comments on Dark Matter at LHC

- If the LHC sees nothing, can SUSY survive? Yes.
- It may be at high scale,
- It may be less simple than all scalars and all fermions at one scale, e.g. NUHM (Pearl Sandick)
- In any case, to prove it's dark matter (rather than barely living long enough to escape CERN detector), must do astrophysical searches

DIRECT DETECTION OF WIMP DARK MATTER

A WIMP in the Galaxy travels through our detectors. It hits a nucleus, and deposits a tiny amount of energy. The nucleus recoils, and we detect this energy deposit.



Expected Rate: less than one count/kg/day!

Drukier, Freese, & Spergel (1986)

We studied the WIMPs in the Galaxy and the particle physics of the interactions to compute expected count rates, and we proposed annual modulation to identify a WIMP signal

Event rate

(number of events)/(kg of detector)/(keV of recoil energy)

$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times nv\, f(v,t)\, d^3v$$

$$= \frac{\rho\sigma_0 F^2(q)}{2m\mu^2} \int_{v>\sqrt{ME/2\mu^2}} \frac{f(v,t)}{v}\, d^3v$$

Spin-independent $\sigma_0 = \frac{A^2\mu^2}{\mu_p^2}\sigma_p$

Spin-dependent $\sigma_0 = \frac{4\mu^2}{\pi} \left| \langle S_p \rangle G_p + \langle S_n \rangle G_n \right|^2$

Canonical DM distribution in halo

use a Maxwellian distribution, characterized by an rms velocity dispersion σ_v, to describe the WIMP speeds, and we will allow for the distribution to be truncated at some escape velocity $v_{\rm esc}$,

$$\tilde{f}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}} \left(\frac{3}{2\pi\sigma_v^2}\right)^{3/2} e^{-3\mathbf{v}^2/2\sigma_v^2}, & \text{for } |\mathbf{v}| < v_{\rm esc} \\ 0, & \text{otherwise.} \end{cases}$$

Here

$$N_{\rm esc} = \mathrm{erf}(z) - 2z\exp(-z^2)/\pi^{1/2},$$

with $z \equiv v_{\rm esc}/\overline{v}_0$, is a normalization factor. The most probable speed,

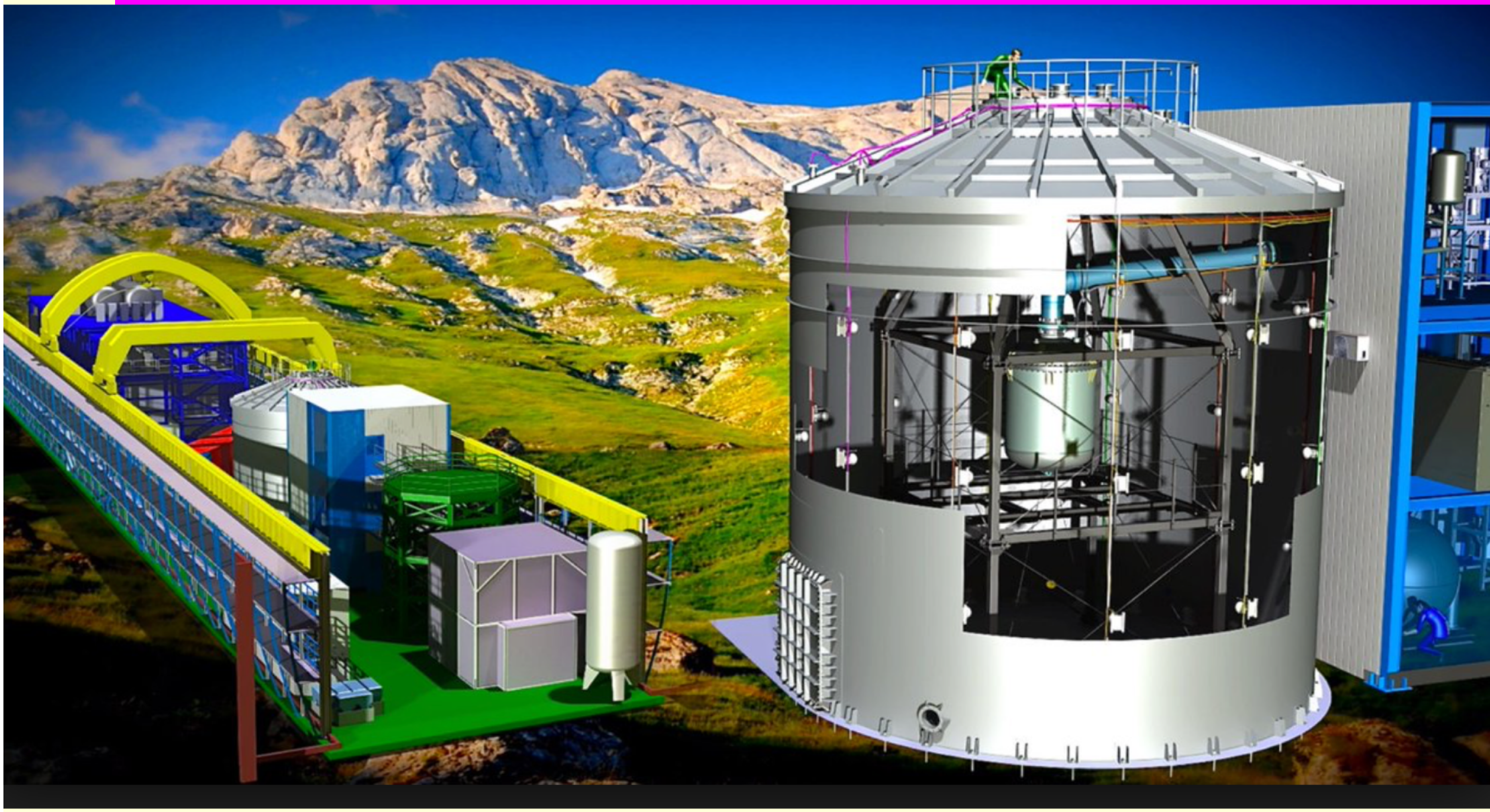
$$\overline{v}_0 = \sqrt{2/3}\,\sigma_v,$$

Typical particle speed is about 270 km/sec.

$$dR/dE \propto e^{-E/E_0}$$

$E_0 = 2\mu^2 v_c^2/M$ so

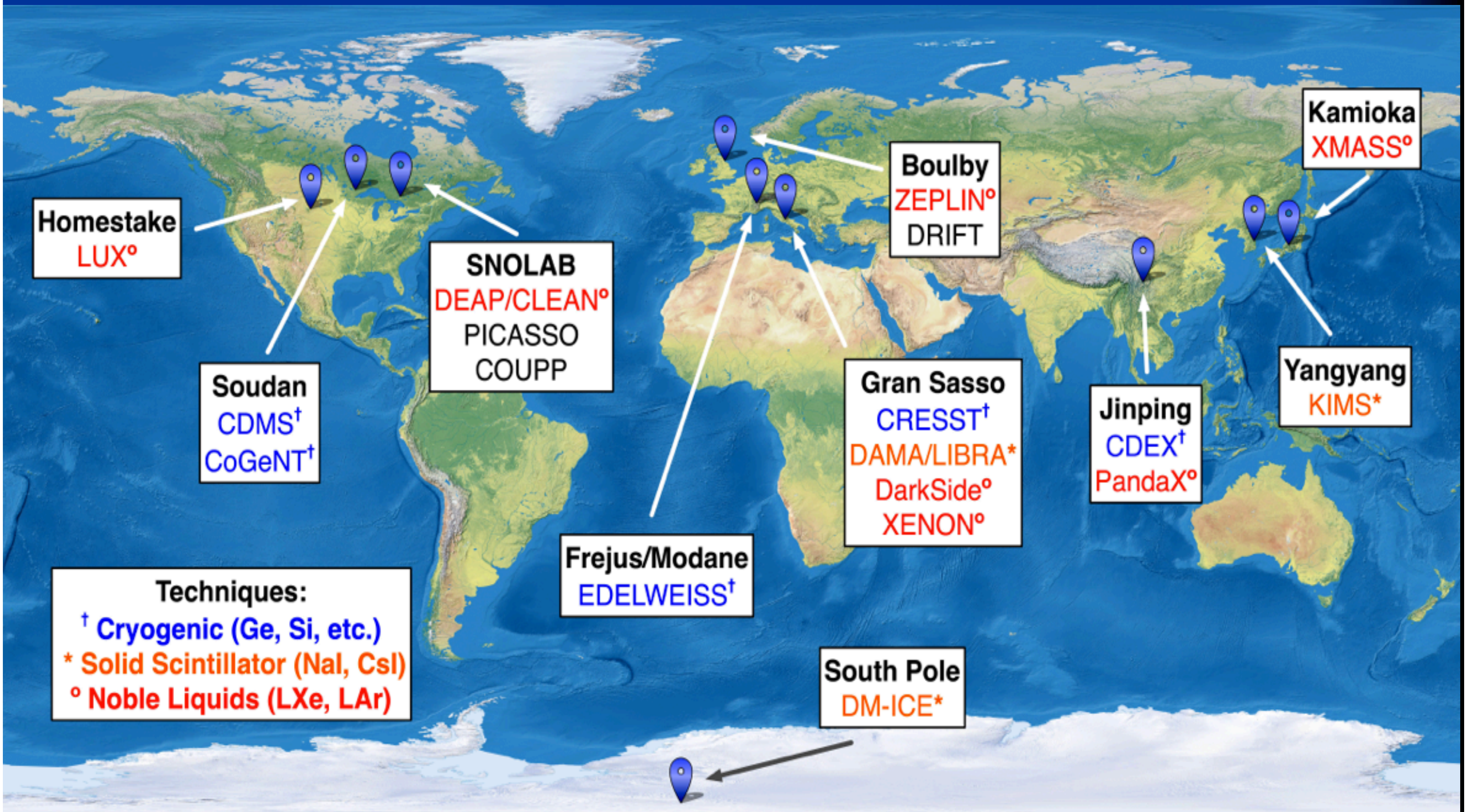
WIMP detectors must be in underground laboratories



Need to shield from Cosmic Rays

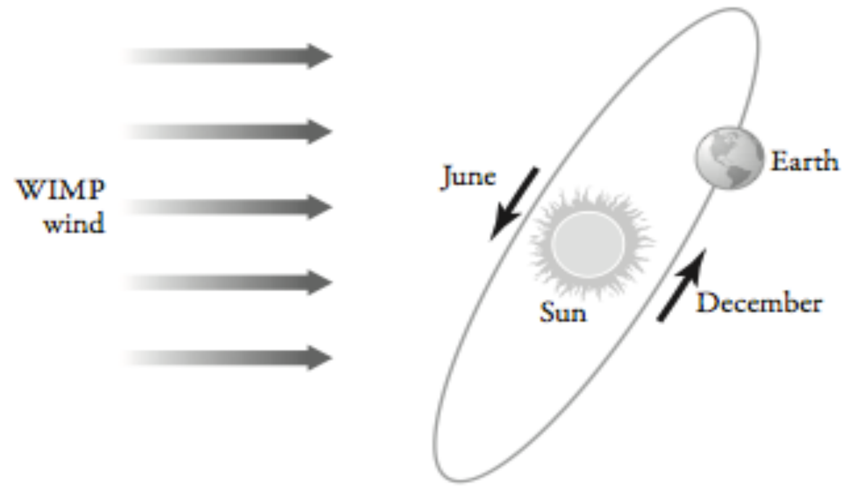
XENON experiment in Gran Sasso Tunnel

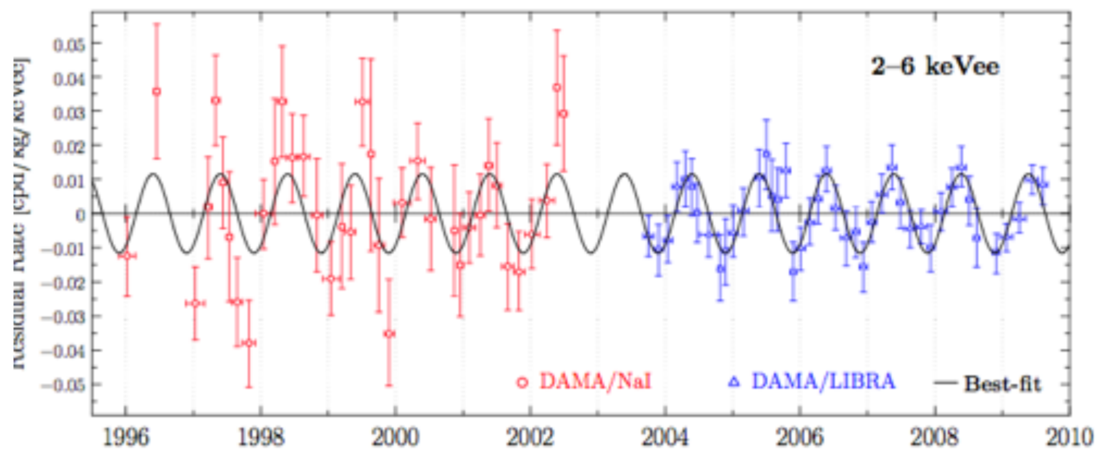
UNDERGROUND DARK MATTER LABORATORIES WORLDWIDE



DAMA annual modulation

Drukier, Freese, and Spergel (1986);
Freese, Frieman, and Gould (1988)





NaI crystals in Gran Sasso Tunnel under the Apennine Mountains near Rome.

Data do show modulation at 12 sigma! Peak in June, minimum in December (as predicted). Are these WIMPs??

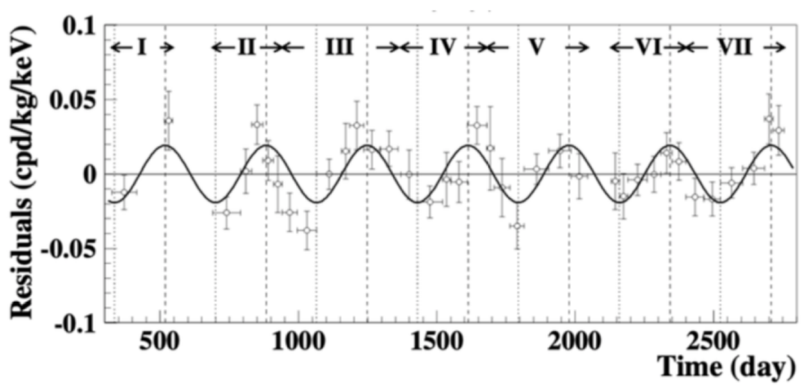


Figure 24: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/NaI in the (2–6) keV energy interval as a function of the time (exposure of 0.29 ton $\times$ yr) . The superimposed curve is the cosinusoidal functional forms $A \cos \omega(t - t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (June 2^{nd}).

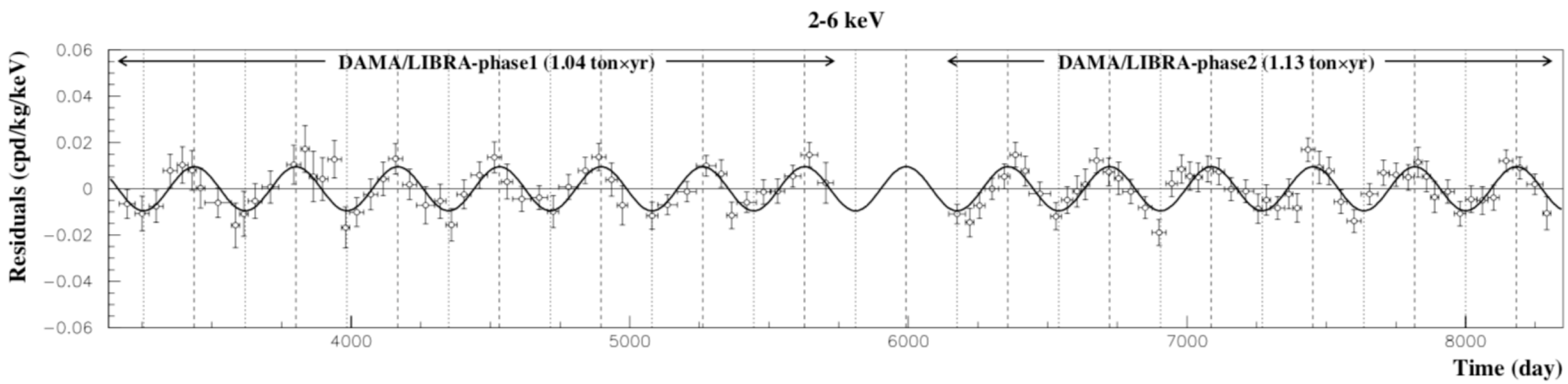


Figure 25: Experimental residual rate of the *single–hit* scintillation events measured by DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2 in the (2–6) keV energy intervals as a function of the time. The superimposed curve is the cosinusoidal functional forms $A \cos \omega(t - t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, a phase $t_0 = 152.5$ day (June 2^{nd}) and modulation amplitude, A, equal to the central value obtained by best fit on the data points of DAMA/LIBRA–phase1 and DAMA/LIBRA–phase2. For details see caption of Fig. 23.

Two Issues with DAMA

- 1. The experimenters won’t release their data to the public

"If you can bear to hear the truth you've spoken twisted by knaves to make a trap for fools, you'll be a Man my son!"

(quote from Rudyard Kipling on the DAMA webpage)

- 2. Comparison to other experiments:

null results from XENON, CDMS, LUX.

But comparison is difficult because

experiments are made of different

detector materials!

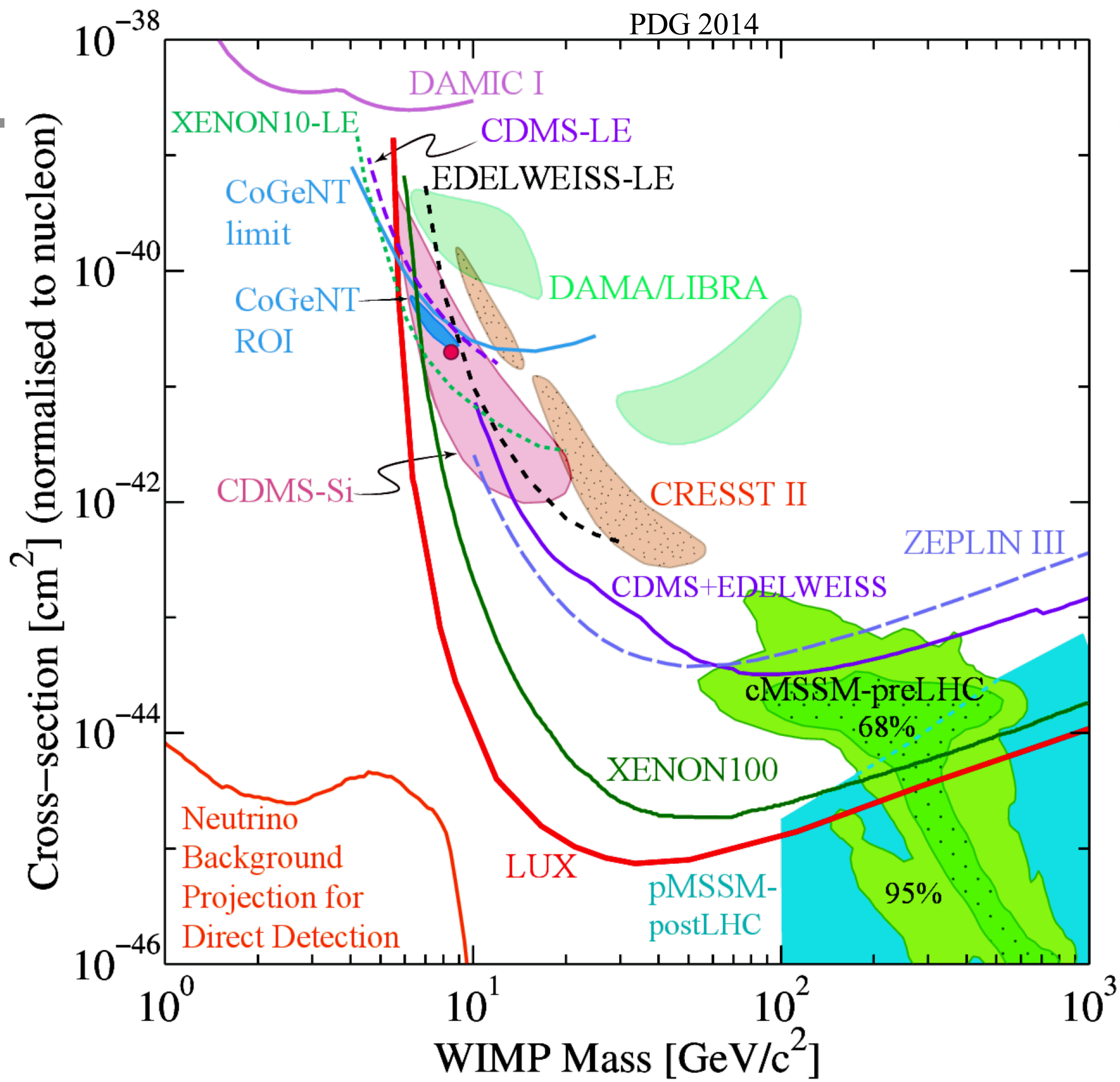
“I’ m a Spaniard caught between two Italian women”

Rita Bernabei, DAMA

Juan Collar, COGENT PICO

Elena Aprile, XENON

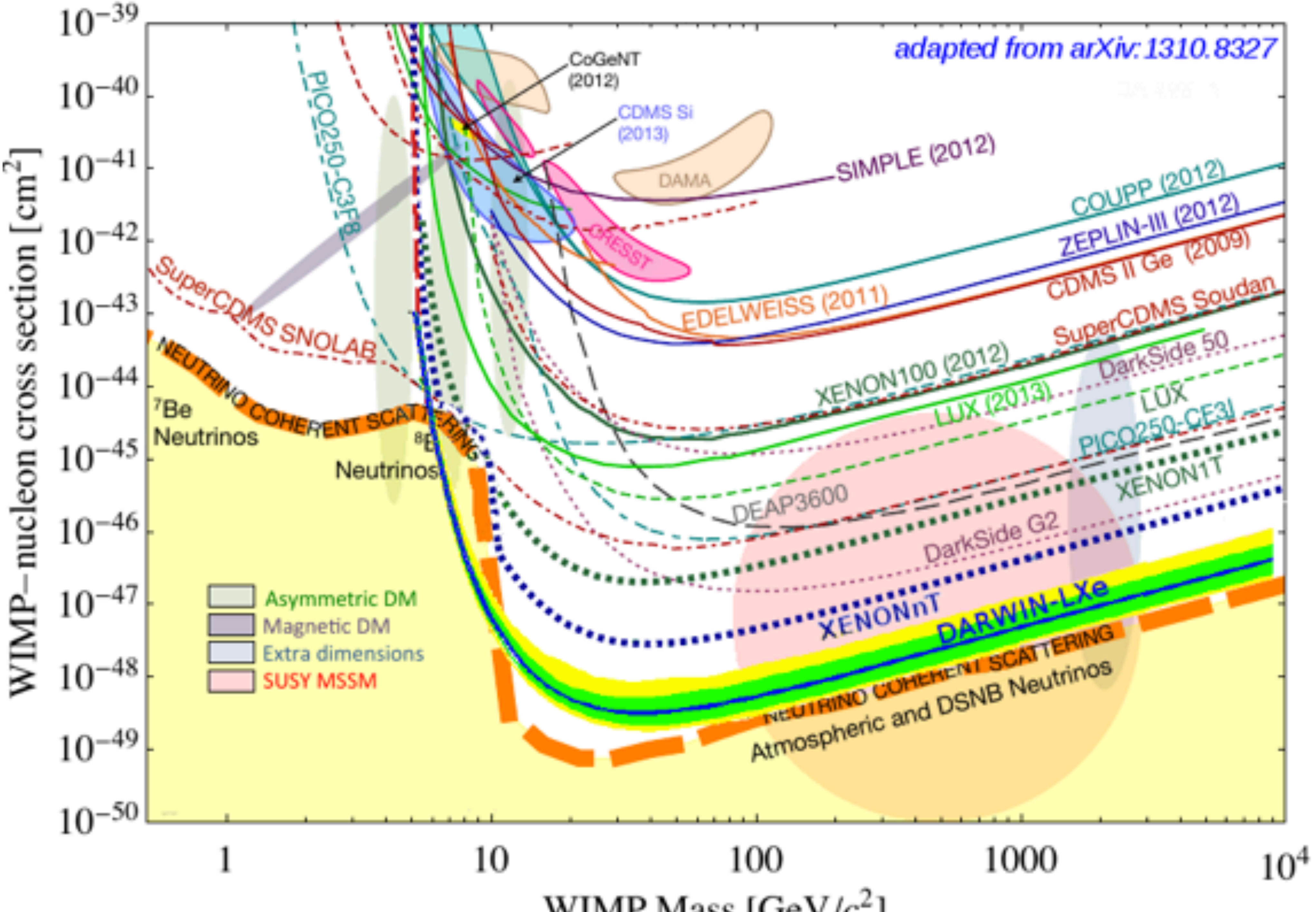
Bounds on Spin Independent WIMPs



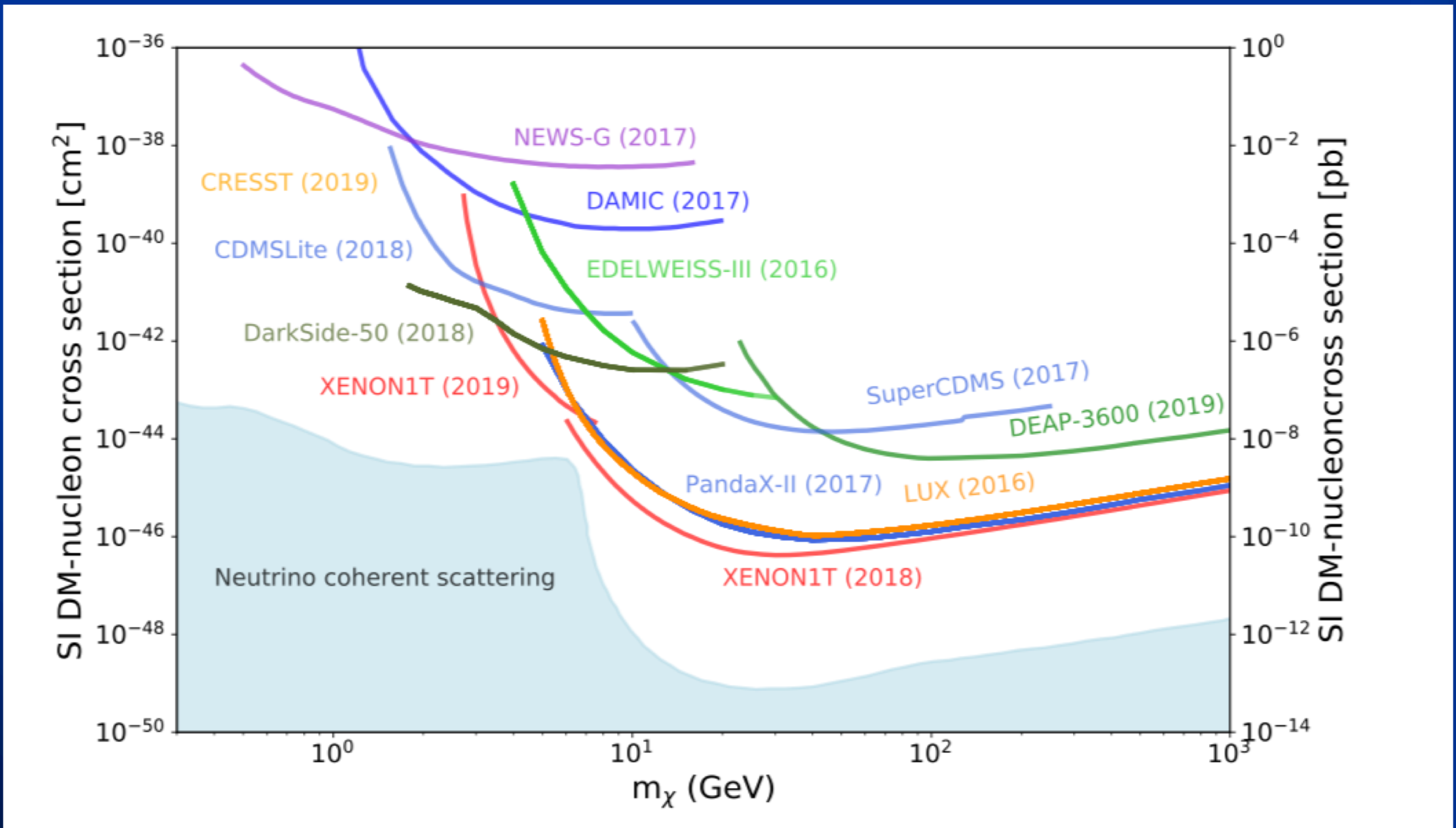
BUT:

--- it's hard to compare results from different detector materials

--- can we trust results near threshold?

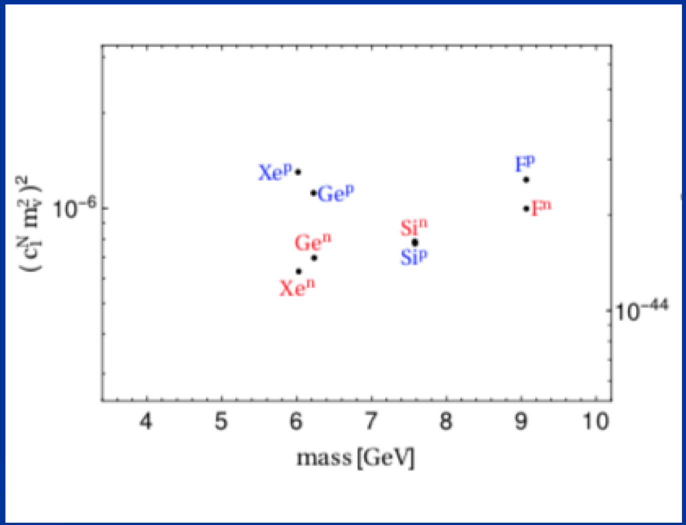

adapted from arXiv:1310.8327
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
10⁻³⁹
10⁻⁴⁰
10⁻⁴¹
10⁻⁴²
10⁻⁴³
10⁻⁴⁴
10⁻⁴⁵
10⁻⁴⁶
10⁻⁴⁷
10⁻⁴⁸
10⁻⁴⁹
10⁻⁵⁰
1
10
100
1000
10⁴
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
SuperCDMS Soudan
SuperCDMS SNOLAB
PICO250-C3F8
XENON100 (2012)
DarkSide 50
LUX (2013)
LUX
PICO250-CF3I
XENON1T
DEAP3600
DarkSide G2
XENONnT
DARWIN-LXe
NEUTRINO COHERENT SCATTERING
⁷Be Neutrinos
⁸B Neutrinos
Atmospheric and DSNB Neutrinos
Asymmetric DM
Magnetic DM
Extra dimensions
SUSY MSSM

From PDG 2019



How to get below neutrino floor

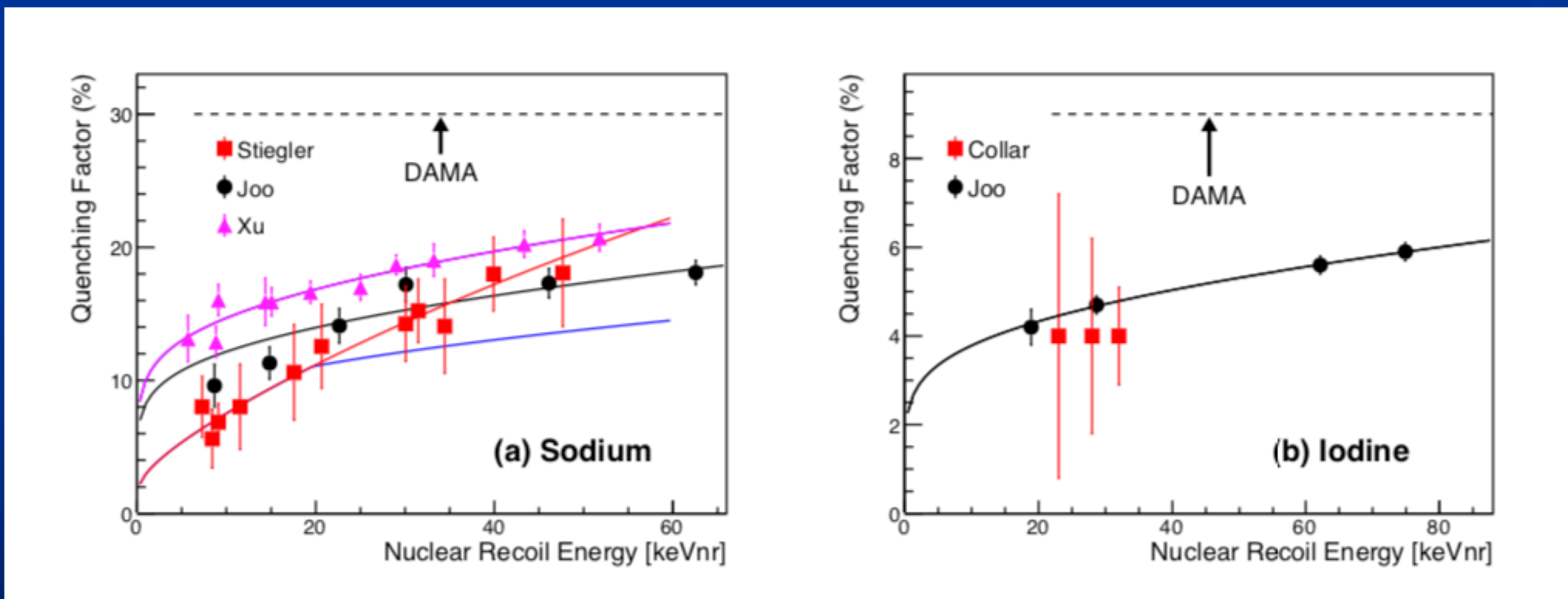
- 1) Know neutrino backgrounds well so you can subtract them off
- 2) Directional Detection
- 2) Different energy spectra for WIMPs v.s neutrinos
- Except B8 neutrinos can have same spectra as 6 GeV WIMPs
- https://arxiv.org/pdf/1602.05300.pdf
- E.g. for SI WIMPs:



To test DAMA within next 5 years

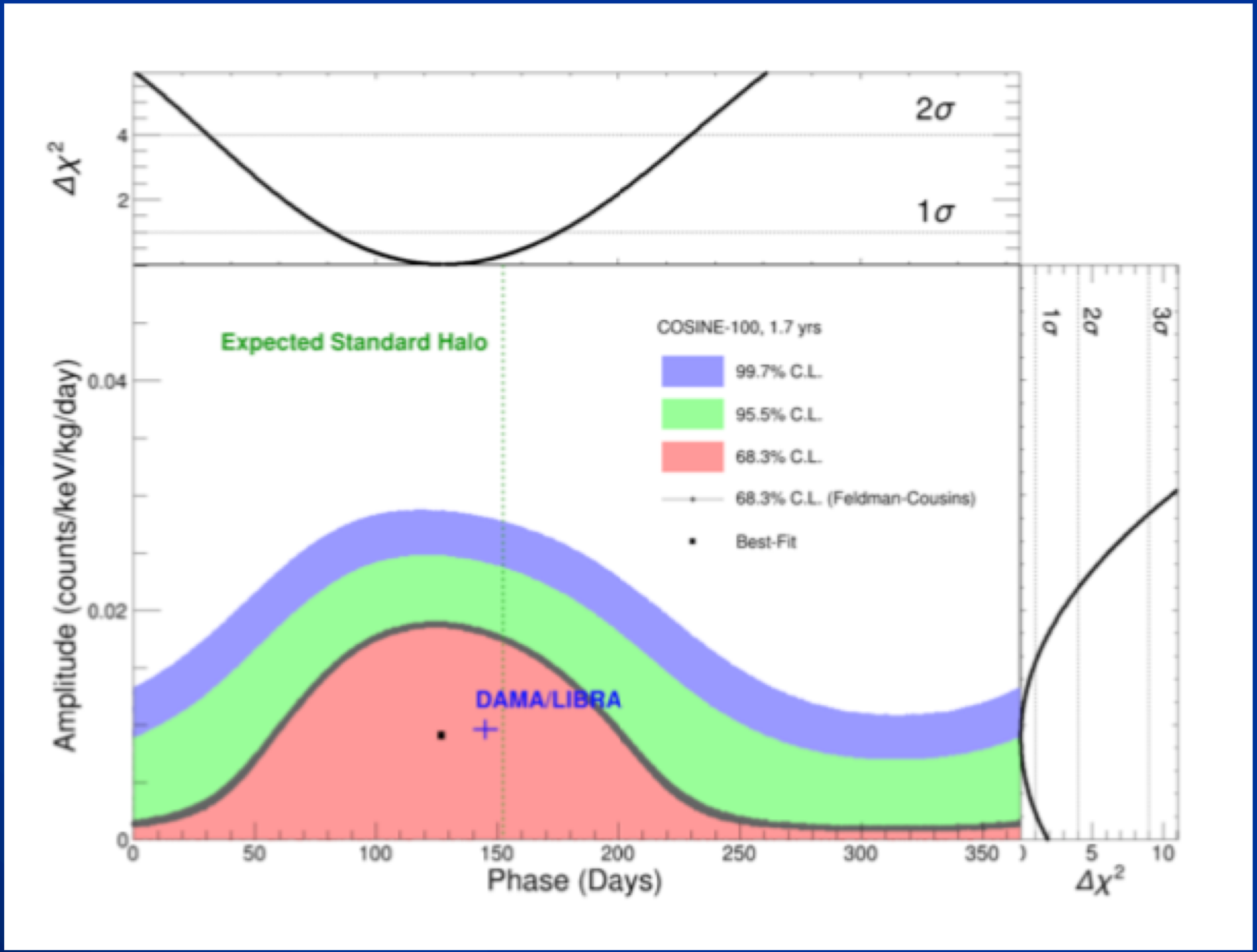
- The annual modulation in the data is still there after 13 years and still unexplained.
- New DAMA data down to 1keV still see modulation (DAMA all by itself is not compatible with SI scattering) Baum, Freese,Kelso 2018
- Other groups are using NaI crystals:
- COSINE-100 has 1.7 years of data release, will have an answer within 3-5 years
- SABRE (Princeton) with Australia
- ANAIS

DAMA quenching factor: is it really so much better?



convert electron equivalent visible energy produced by recoil nuclei
In scintallation detector to nuclear recoil energy

COSINE-100 1.7 years of data



https://arxiv.org/pdf/1903.10098.pdf

Status of Direct Detection DM searches

- DAMA annual modulation remains unexplained. Cannot be SI. COSINE-100 (Nai) is testing it.
- Difficulty: comparing apples and oranges, since other detectors are made of different materials.
- Theory comes in: Spin independent scattering, Spin dependent, try all possible operators, mediators, dark sector, etc.
- Interesting avenue: nuclear physics. (Fitzpatrick, Haxton, etal)

To go beyond the neutrino floor

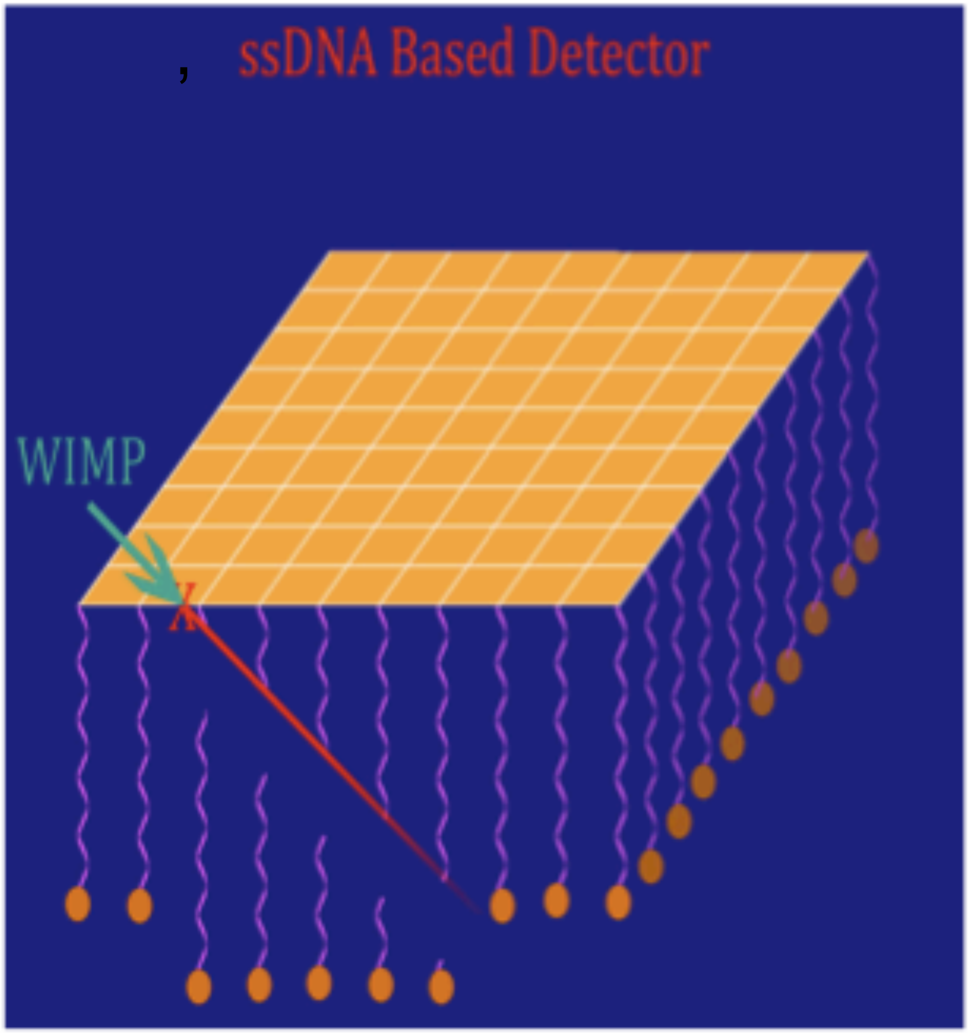
A major Step Forward: Directional Capability

to figure out what direction the WIMP came from

- Nuclei typically get kicked forward by WIMP collision
- Goal: identify the track of the recoiling nucleus i.e. the direction the WIMP came from
- Expect ten times as many into the WIMP wind vs. opposite direction.
- This allows dark matter discovery with much lower statistics (10-100 events).
- This allows for background rejection using annual and diurnal modulation.

DNA/RNA Tracker: directional detector with nanometer resolution

- 1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known



BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

Drukier, KF, Lopez, Spergel, Cantor, Church, Sano

Paleodetectors

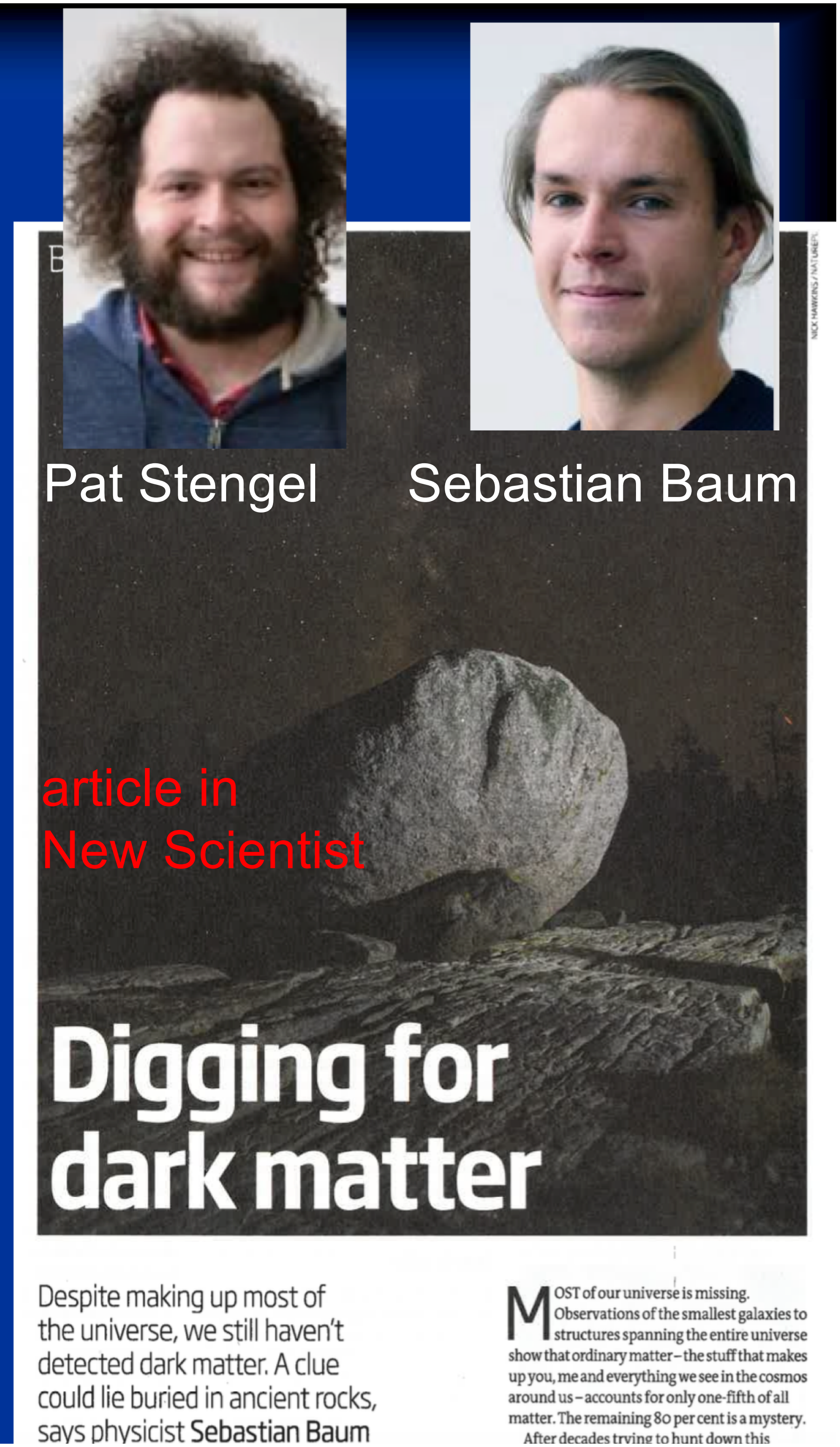
WIMPs leave tracks in ancient minerals from 10km below the surface of the Earth.

Collecting tracks for 500 Myr.

Backgrounds: Ur-238 decay and fission

Take advantage of nanotools: can identify nanometer tracks in 3D

Baum, Drukier, Freese, Gorski, Stengel arXiv:1806.05991



Digging for dark matter

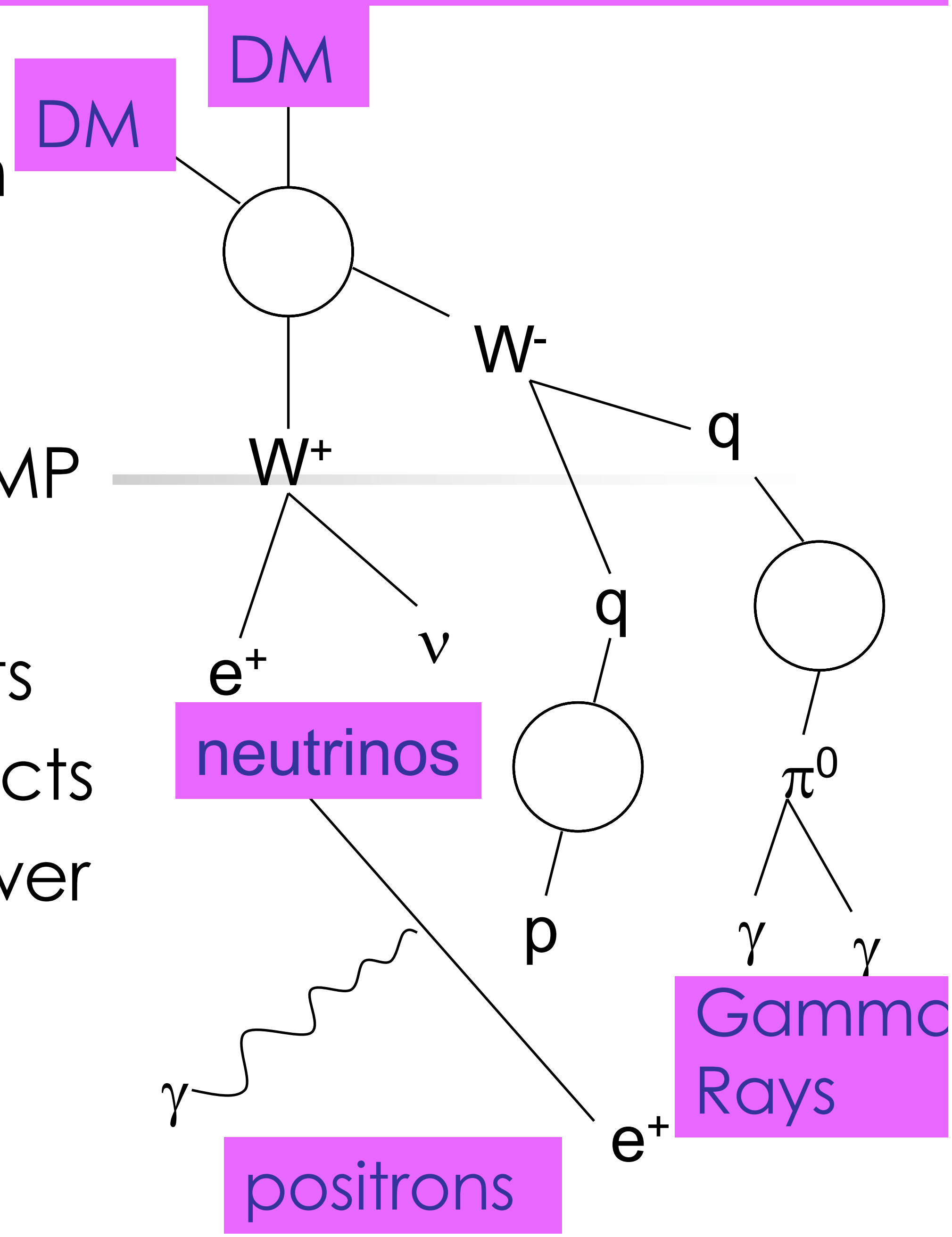
Despite making up most of the universe, we still haven't detected dark matter. A clue could lie buried in ancient rocks, says physicist Sebastian Baum

MOST of our universe is missing. Observations of the smallest galaxies to structures spanning the entire universe show that ordinary matter – the stuff that makes up you, me and everything we see in the cosmos around us – accounts for only one-fifth of all matter. The remaining 80 per cent is a mystery. After decades trying to hunt down this

Third Way to Search for WIMPs: Indirect Detection of WIMP Annihilation

Many WIMPs are their own antiparticles, annihilate among themselves:

- 1) Early Universe gives WIMP miracle
- 2) Indirect Detection expts look for annihilation products
- 3) Same process can power Stars (dark stars)

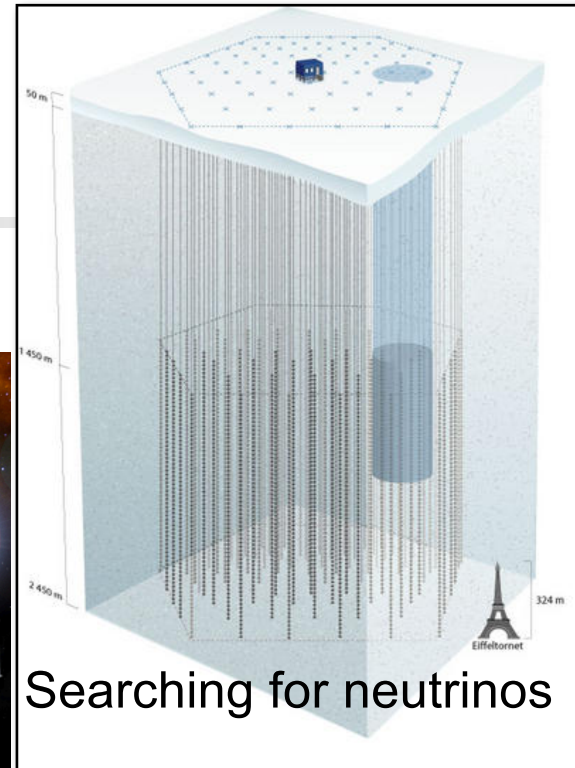


Indirect Detection: looking for DM annihilation signals

AMS aboard the International Space Station

Found
excess e+

IceCube
At the South Pole



FERMI

FERMI bounds rule out most channels of dark matter interpretation of AMS positron excess

- Lopez, Savage, Spolyar, Doug Adams (arxiv:1501.01618)
- Almost all channels ruled out,

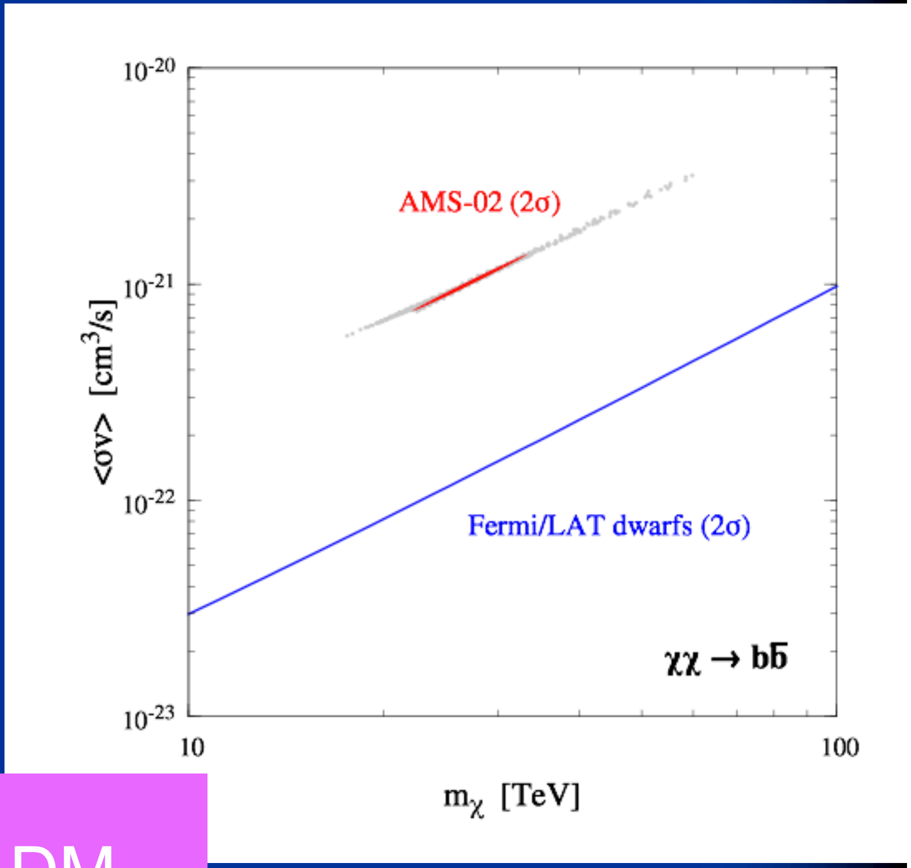
Including all leptophilic channels

(e.g. b bar channel in plot)

What remains

DM annihilation

via mediator to four mus



AMS positron excess is not from DM

Fermi/LAT gamma-ray excess

Goodenough & Hooper (2009)

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2014)

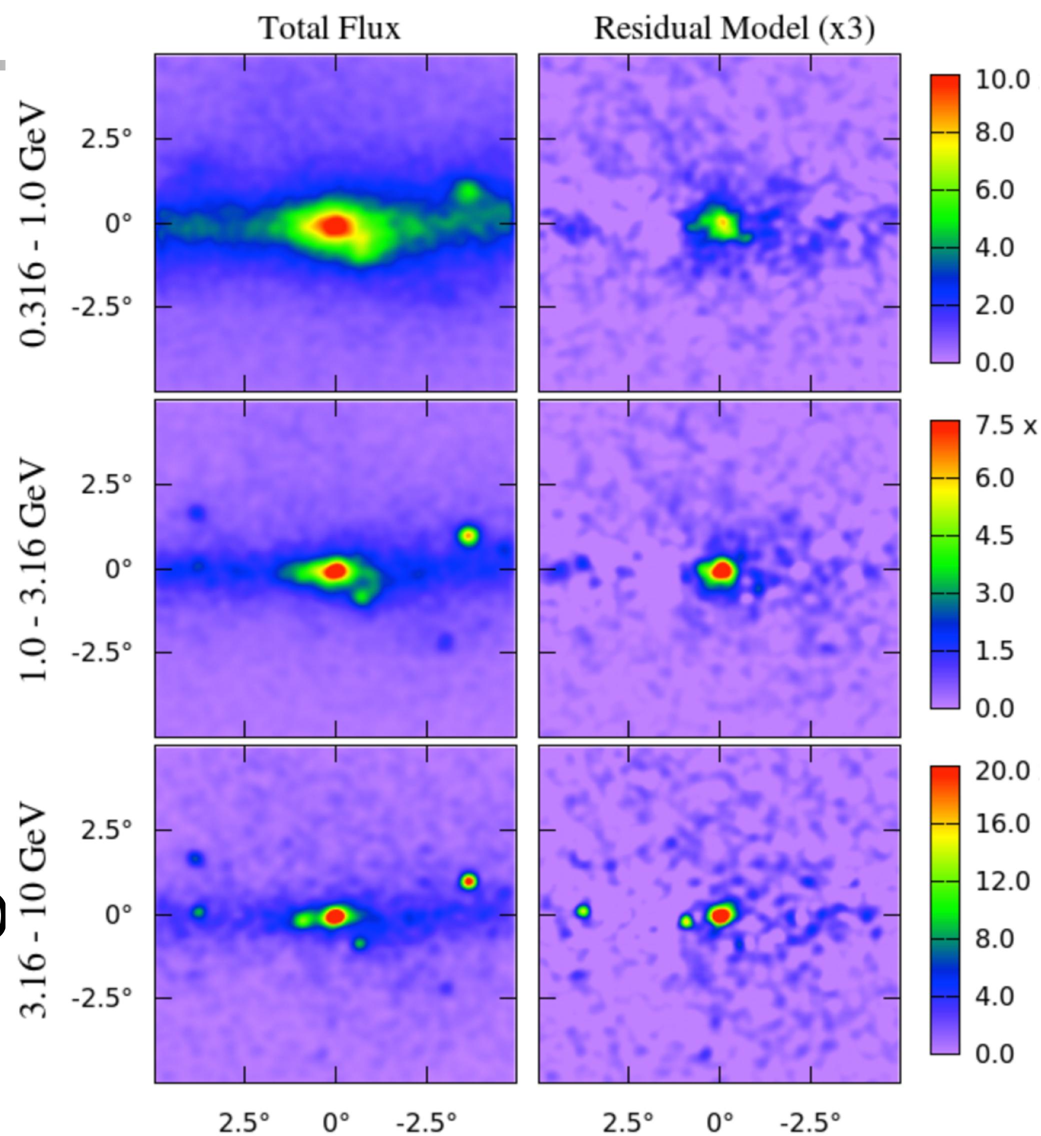
Leane and Slatyer 2002.12371

Buschmann etal 2002.12373

Towards galactic center:

- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with D (30 GeV, χχ → b-bbar)

BUT also consistent with astrophysical point sources. Status unclear.



Possible evidence for WIMP detection :

- Direct Detection:

  DAMA annual modulation

  (but XENON, LUX)
- Indirect Detection:

  FERMI gamma ray excess near galactic center

3) Dark Stars:
Dark Matter annihilation can power the first stars

A new kind of star, and
another way to search for WIMPs


DAVID GRANT presents
A JOHN CARPENTER film
From
ALAN DEAN FOSTER
FIRST
2001: A SPACE ODYSSEY
THEN
THE POSEIDON ADVENTURE
NOW
DARK STAR
A
DS-1
bombed out in space
with a spaced out bomb!
An OPPIDAN ENTERTAINMENTS Release of a JACK H. HARRIS Production Starring DAN O'BANNON and BRIAN NARELLE Produced & directed by JOHN CARPENTER

Collaborators

Doug Spolyar

Paolo Gondolo

Pearl Sandick

Tanja Rindler -Daller

Peter Bodenheimer

Cosmin Ilie

Dark Stars

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion Dark stars are made almost entirely of hydrogen and helium, with dark matter constituting less than 0.1% of the mass of the star).

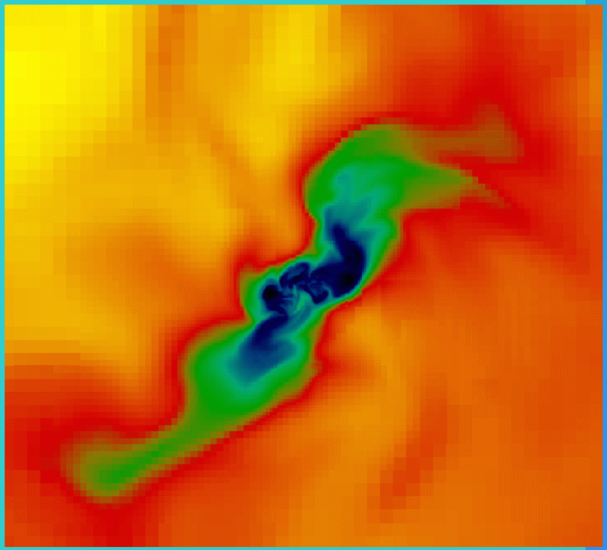
- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. These can be seen in James Webb Space Telescope, sequel to Hubble Space Telescope.
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: is this the origin of supermassive black holes?

Basic Picture

- The first stars form at z=10-20 in $10^6\,M_\odot$ minihaloes, right in the DM rich center.
- As a gas cloud cools and collapses en route to star formation, the cloud pulls in more DM gravitationally.
- DM annihilation products typically include e+/e- and photons. These collide with hydrogen, are trapped inside the cloud, and heat it up.
- At a high enough DM density, the DM heating overwhelms any cooling mechanisms; the cloud can no longer continue to cool and collapse. A Dark Star is born, powered by DM.

First Stars: Standard Picture

- Formation Basics:
  - First luminous objects ever.
  - At $z = 10\text{-}50$
  - Form inside DM haloes of $\sim 10^6\ M_\odot$
  - Baryons initially only 15%
  - Formation is a gentle process



Made only of hydrogen and helium from the Big Bang. No other elements existed yet

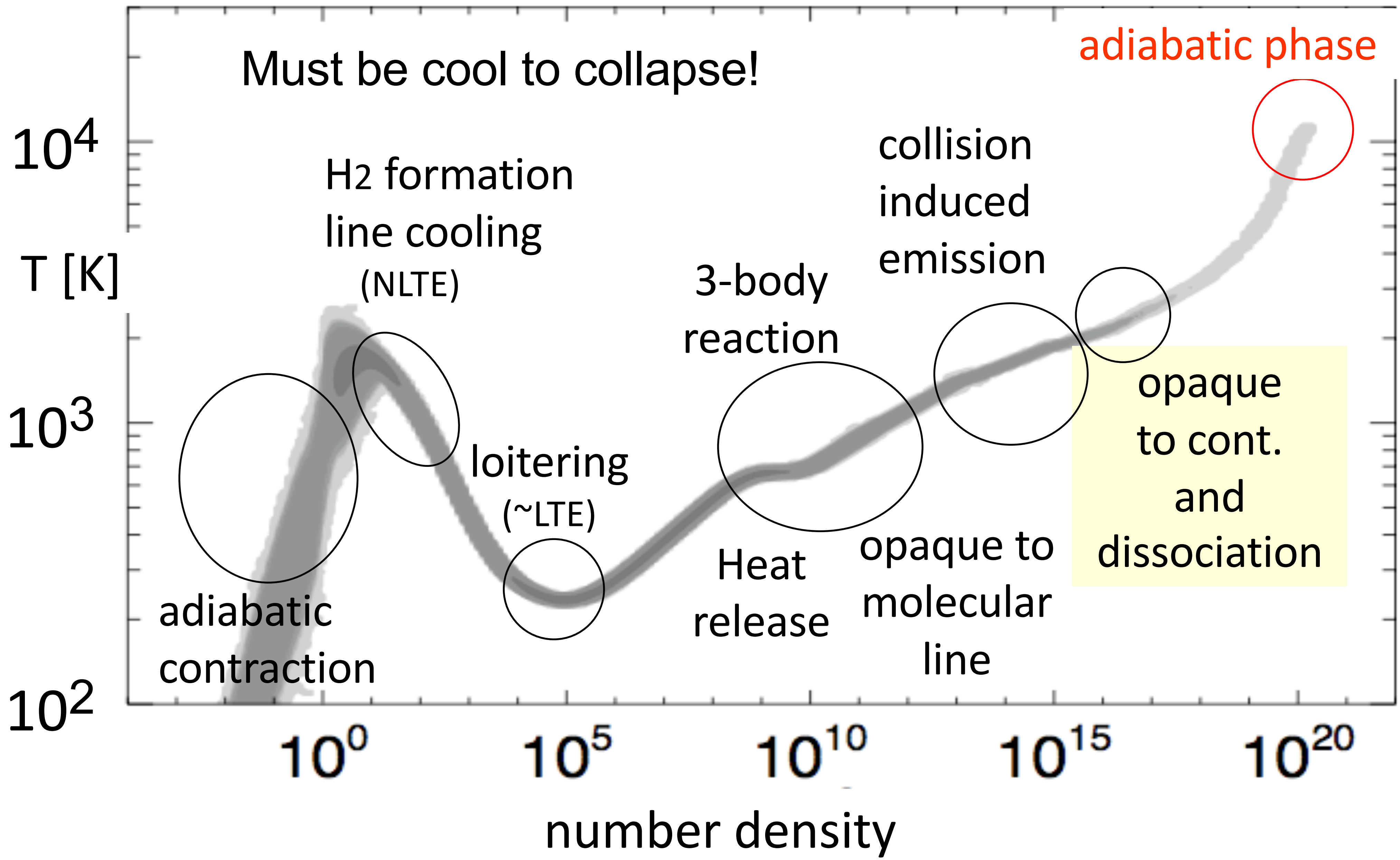
Dominant cooling Mechanism is

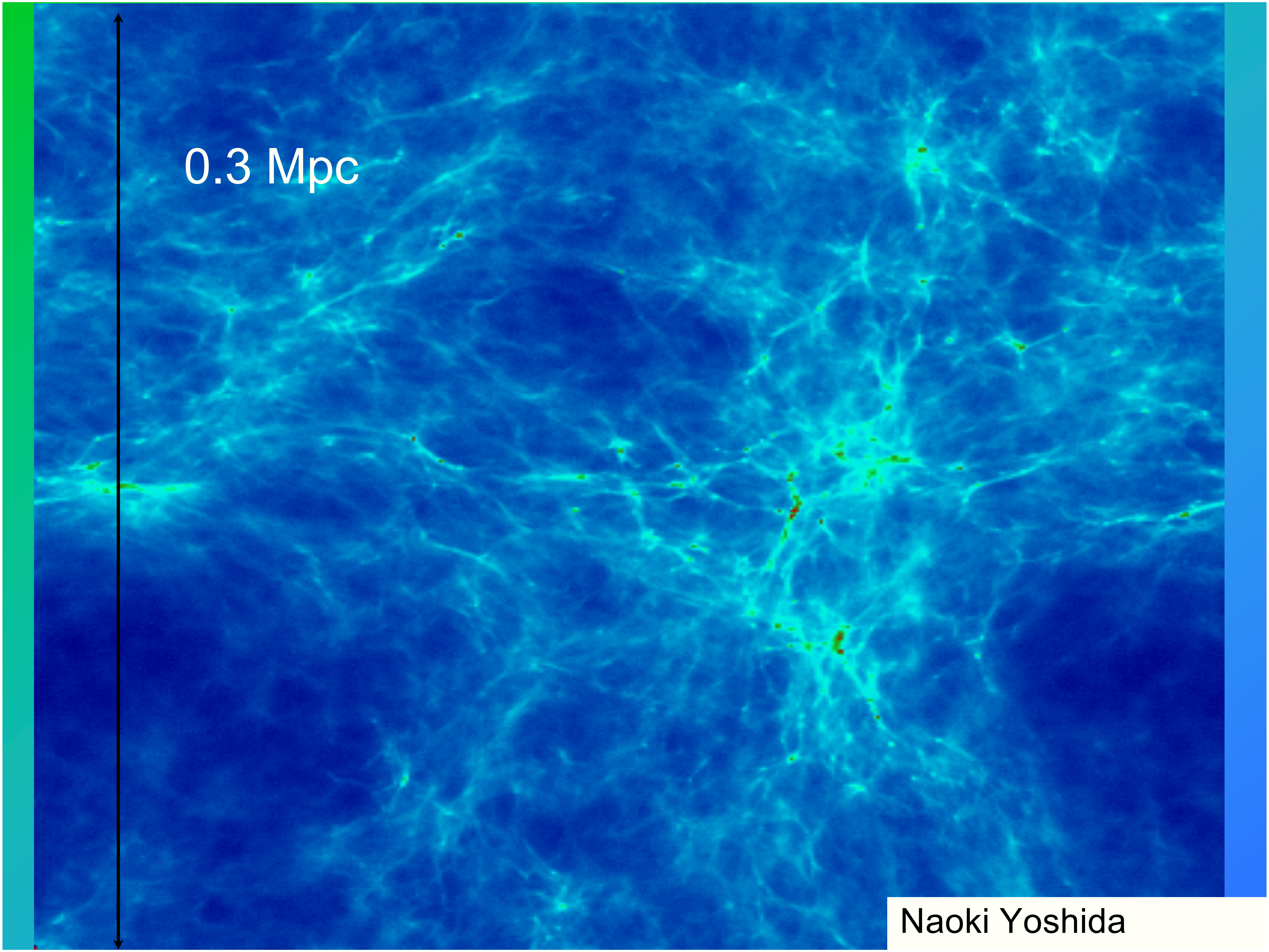
H_2

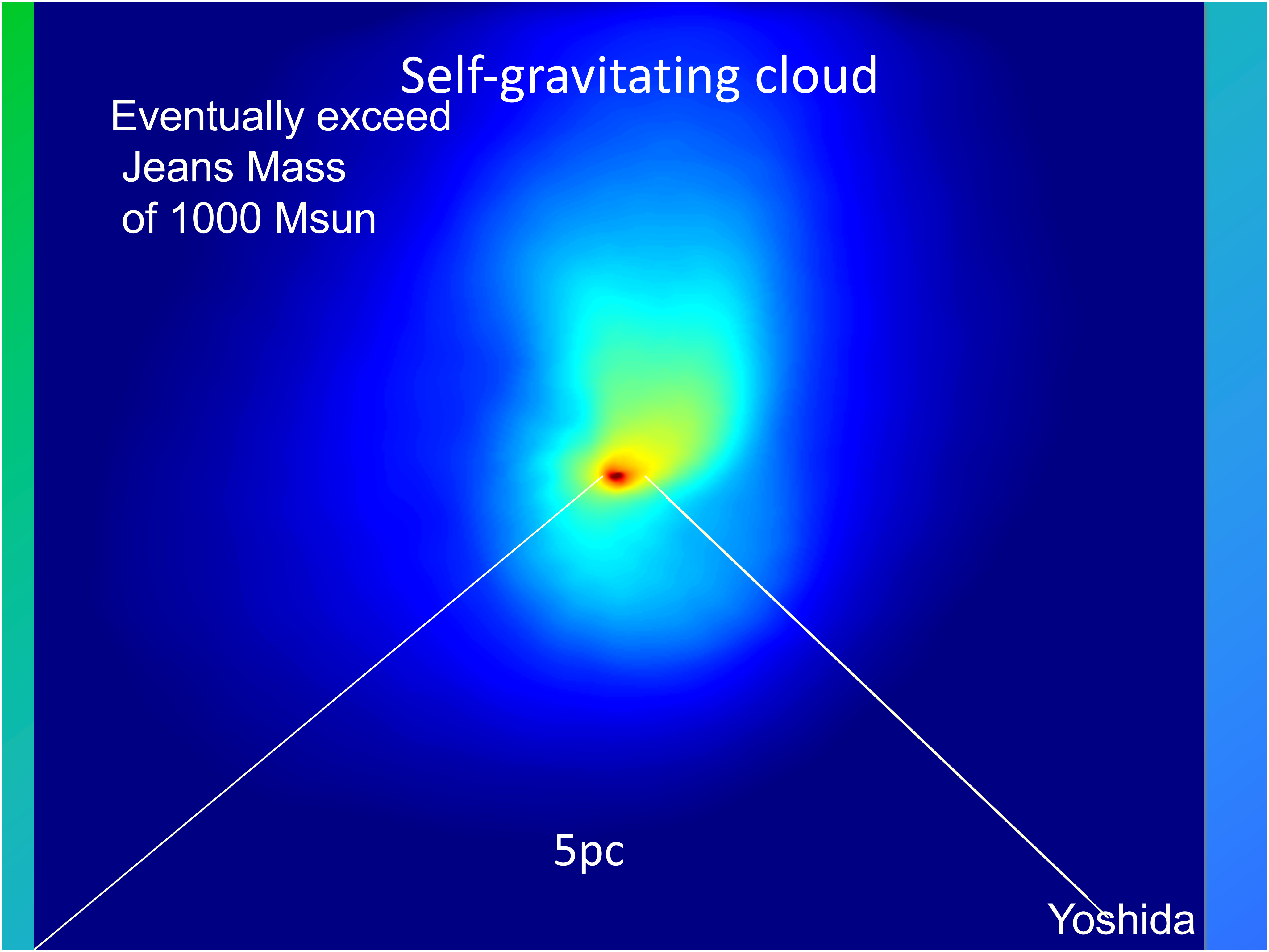
Not a very good coolant

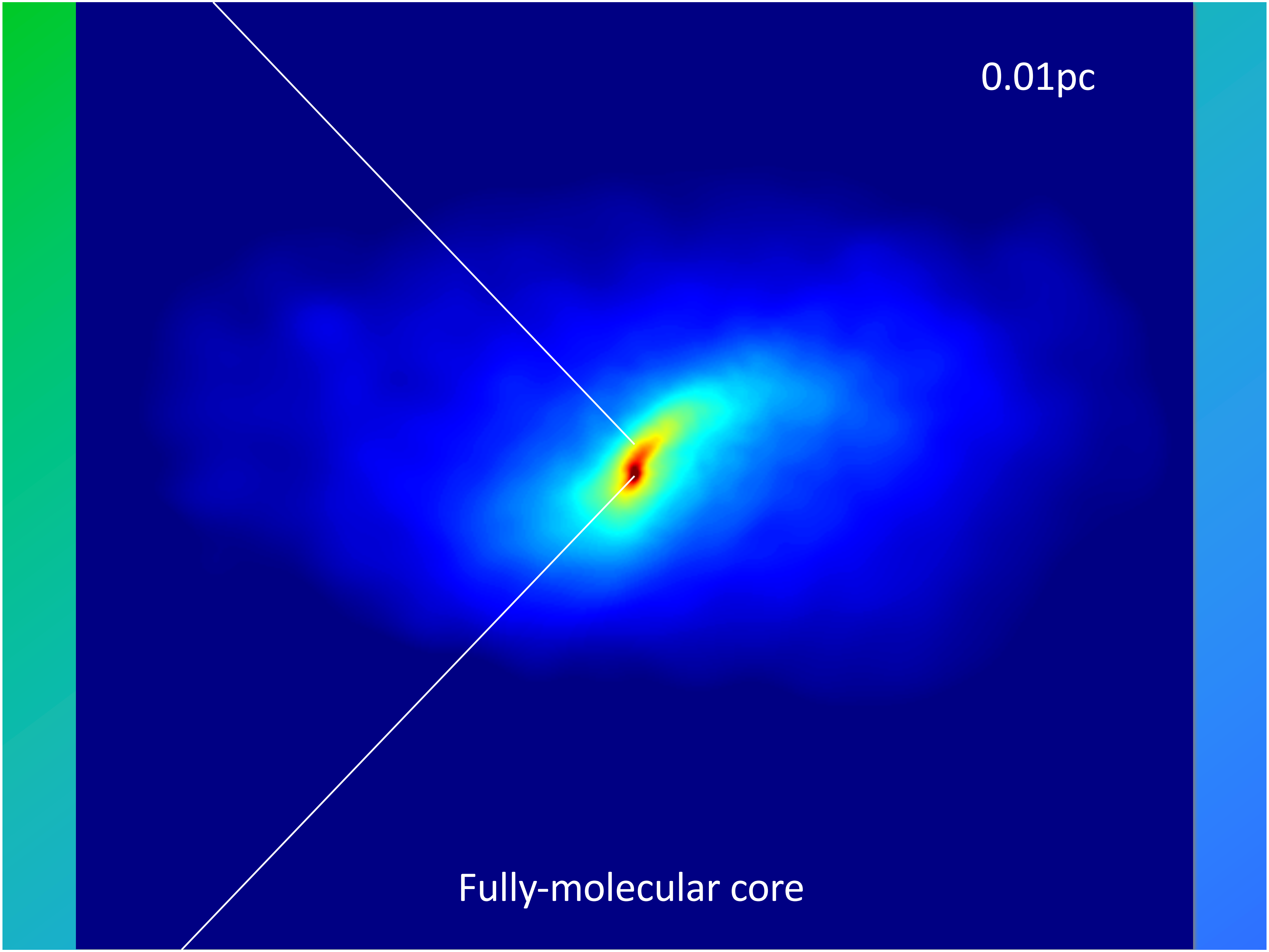
(Hollenbach and McKee '79)

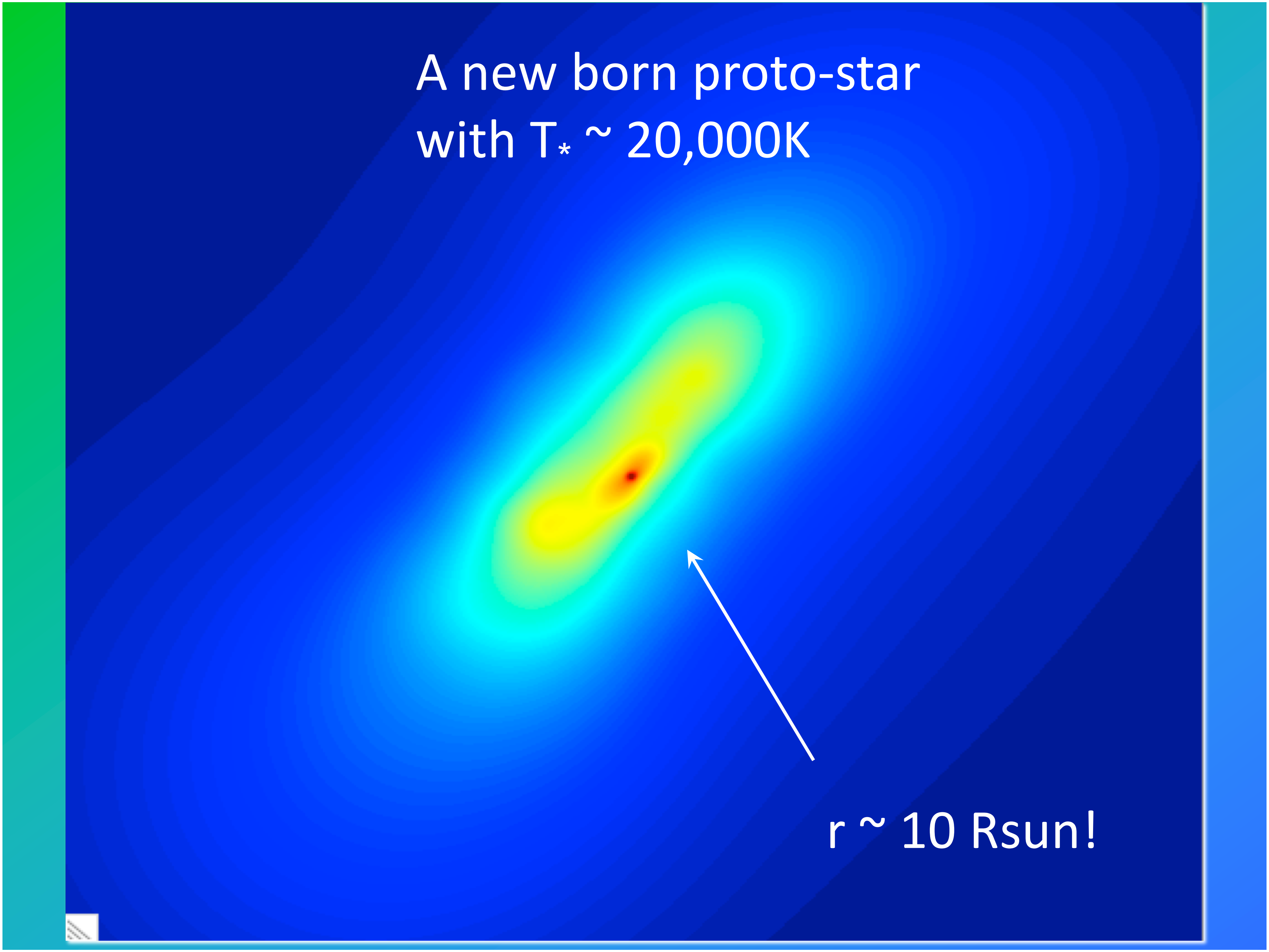
Thermal evolution of a primordial gas




0.3 Mpc
Naoki Yoshida


Self-gravitating cloud
Eventually exceed
Jeans Mass
of 1000 Msun
5pc
Yoshida


0.01pc
Fully-molecular core


A new born proto-star
with T* ~ 20,000K
r ~ 10 Rsun!

Scales

- Halo Baryonic Mass ~ $10^5\ M_\odot$

(Halo Mass $10^6\ M_\odot$)

$\downarrow$

- Jeans Mass ~ $10^3\ M_\odot$

$\downarrow$

- Initial Core Mass ~ $10^{-3}\ M_\odot$

feedback effects
McKee and Tan 2008

$\downarrow$ Accretion

Final stellar Mass??

With DM heating
Much more massive

$100 M_\odot$ Standard Picture

$10^3 - 10^7\ M_\odot$ Dark Star

WIMPs

Mass 1Gev-10TeV (canonical 100GeV)

Annihilation cross section (WIMPS):

$$<\sigma v>_{ann} = 3\times 10^{-26} cm^3/\sec$$

Same annihilation that leads to correct WIMP abundance in today's universe

Same annihilation that gives potentially observable signal in FERMI, PAMELA, AMS

Why DM annihilation in the first stars is more potent than in today's stars: higher DM density

- **THE RIGHT PLACE**:

  one single star forms at the center of a million solar mass DM halo

- **THE RIGHT TIME:**

  the first stars form at high redshift,

  z = 10-50, and density scales as (1+z)^3

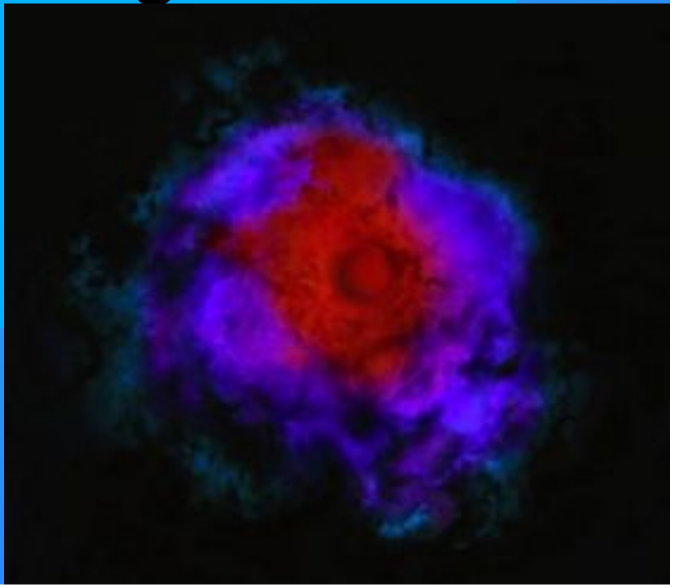
Dark Matter Power vs. Fusion

- DM annihilation is (roughly) 100% efficient in the sense that all of the particle mass is converted to heat energy for the star
- Fusion, on the other hand, is only 1% efficient (only a fraction of the nuclear mass is released as energy)
- Fusion only takes place at the center of the star where the temperature is high enough; vs. DM annihilation takes place throughout the star.

Three Conditions for Dark Stars
(Spolyar, Freese, Gondolo 2007 aka Paper 1)

- I) Sufficiently High Dark Matter Density ?
- 2) Annihilation Products get stuck in star ?
- 3) DM Heating beats H2 Cooling ?

New Phase



Dark Matter Heating

Heating rate:

$$Q_{ann} = n_\chi^2 < \sigma v > \times\ m_\chi$$

$$= \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

$$\Gamma_{DMHeating} = f_Q\ Q_{ann}$$

Previous work noted that at $n \leq 10^4 cm^{-3}$ annihilation products simply escape (Ripamonti,Mapelli,Ferrara 07)

f_Q :

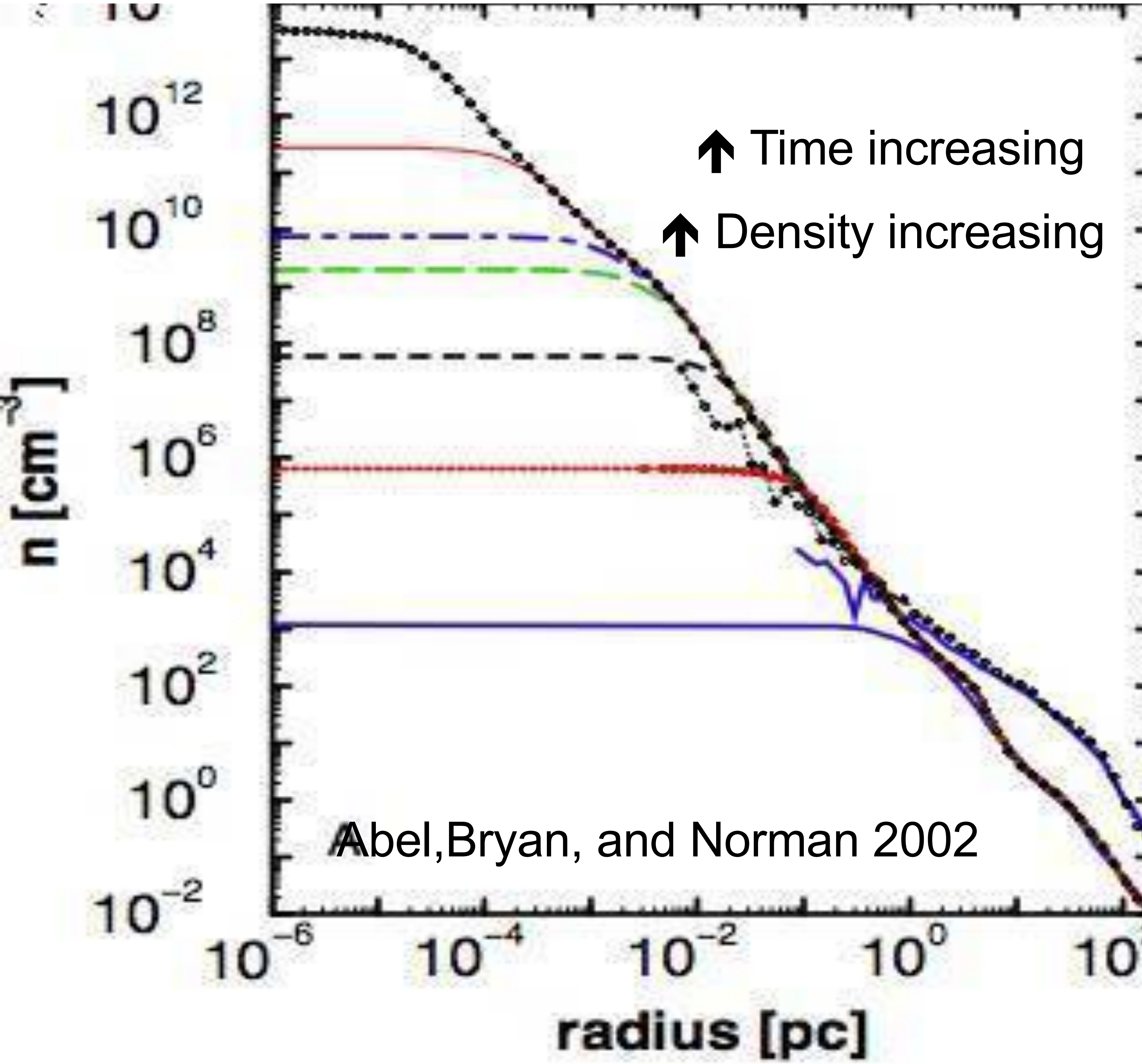
1/3 electrons

1/3 photons

1/3 neutrinos

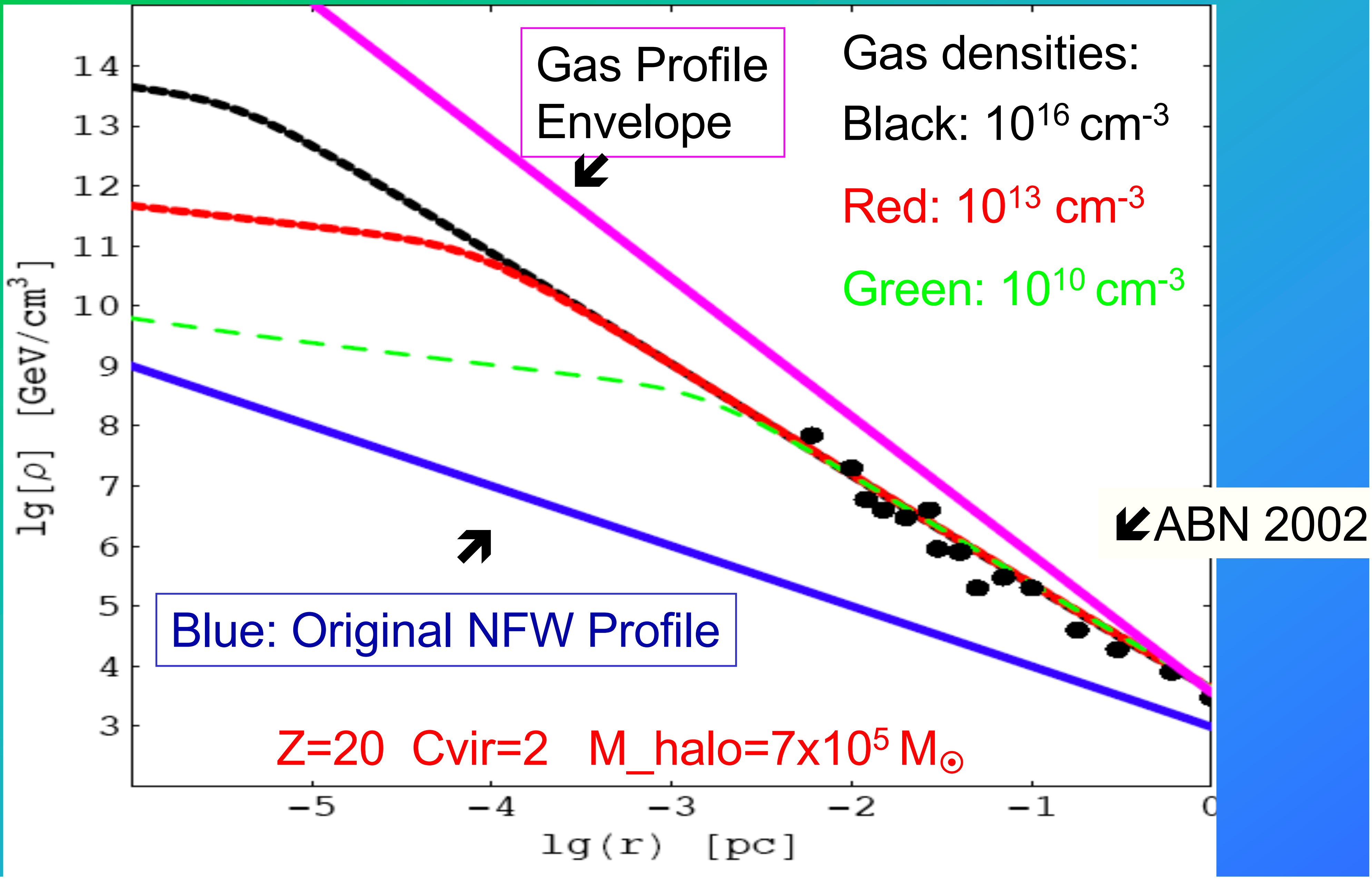
First Condition: Large DM density

- DM annihilation rate scales as DM density squared, and happens wherever DM density is high. The first stars are good candidates: good timing since density scales as $(1+z)^3$ and good location at the center of DM halo
- Start from standard NFW profile in million solar mass DM halo.
- As star forms in the center of the halo, it gravitationally pulls in more DM. Treat via **adiabatic contraction**.
- If the scattering cross section is large, even more gets **captured** (treat this possibility later).



Time increasing
Density increasing
Abel,Bryan, and Norman 2002
n [cm^{-3}]
radius [pc]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-6}
10^{-4}
10^{-2}
10^{0}

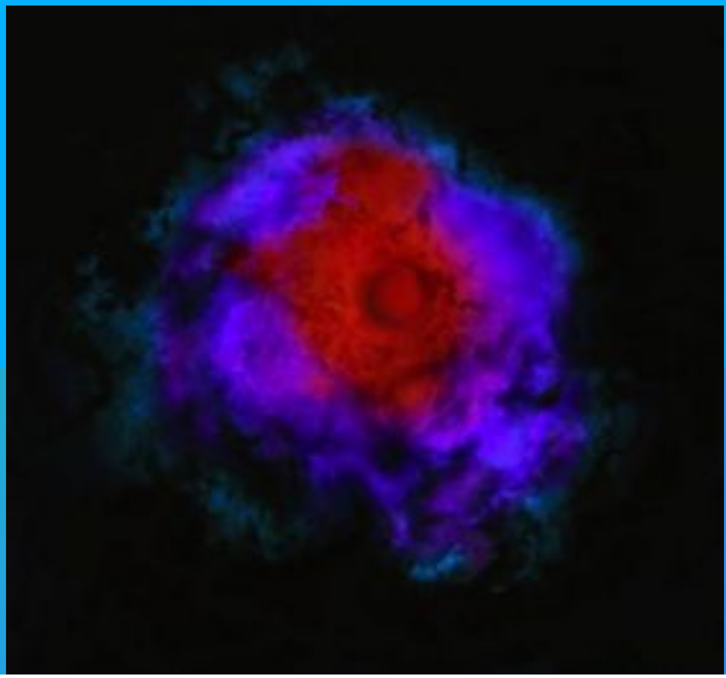
DM profile and Gas



Three Conditions for Dark Stars (Paper 1)

- I) OK! Sufficiently High Dark Matter Density
- 2) Annihilation Products get stuck in star?
- 3) DM Heating beats H2 Cooling?

Leads to New Phase



Dark Matter Heating

Heating rate:

$$Q_{ann} = n_\chi^2 < \sigma v > \times\, m_\chi = \frac{\rho_\chi^2 < \sigma v >}{m_\chi}$$

Fraction of annihilation energy deposited in the gas:

$$\Gamma_{DMHeating} = f_Q\, Q_{ann}$$

Previous work noted that at $n \leq 10^4 cm^{-3}$ annihilation products simply escape (Ripamonti,Mapelli,Ferrara 07)

f_Q:

1/3 electrons

1/3 photons

1/3 neutrinos

Crucial Transition

- At sufficiently high densities, most of the annihilation energy is trapped inside the core and heats it up
- When:

$$m_\chi \approx 1\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{9}/\mathrm{cm}^3$$

$$m_\chi \approx 100\ \mathrm{GeV} \quad \rightarrow \quad n \approx 10^{13}/\mathrm{cm}^3$$

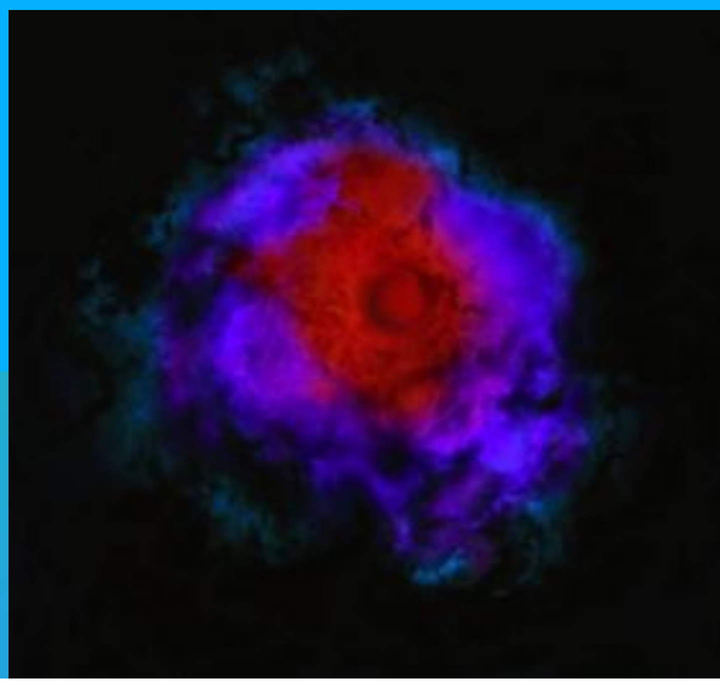
$$m_\chi \approx 10\ \mathrm{TeV} \quad \rightarrow \quad n \approx 10^{15\text{–}16}/\mathrm{cm}^3$$

- The DM heating dominates over all cooling mechanisms, impeding the further collapse of the core

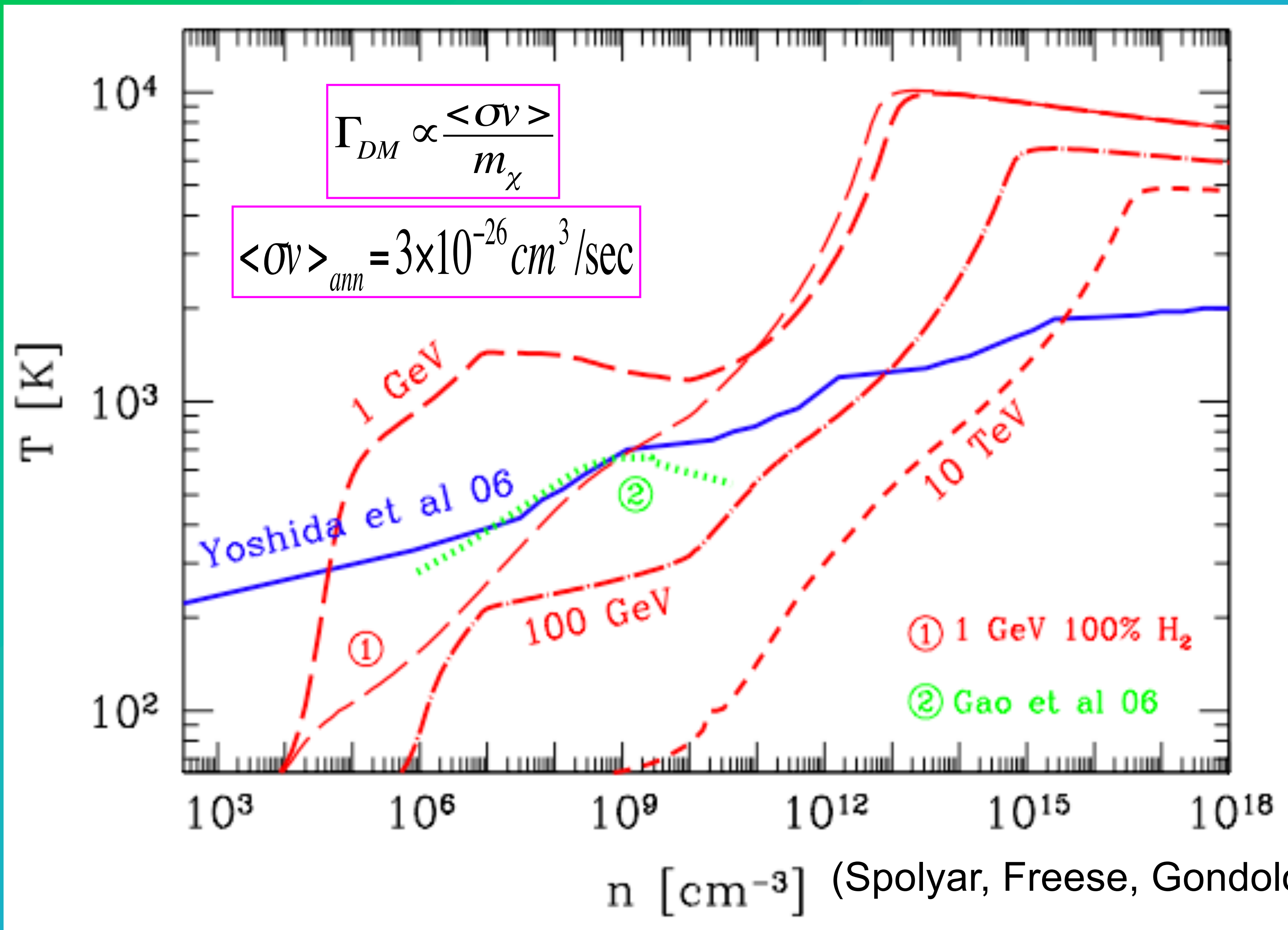
Three Conditions for Dark Stars (Paper 1)

- 1) OK! Sufficiently High Dark Matter Density
- 2) OK! Annihilation Products get stuck in star
- 3) DM Heating beats H_2 Cooling?

New Phase



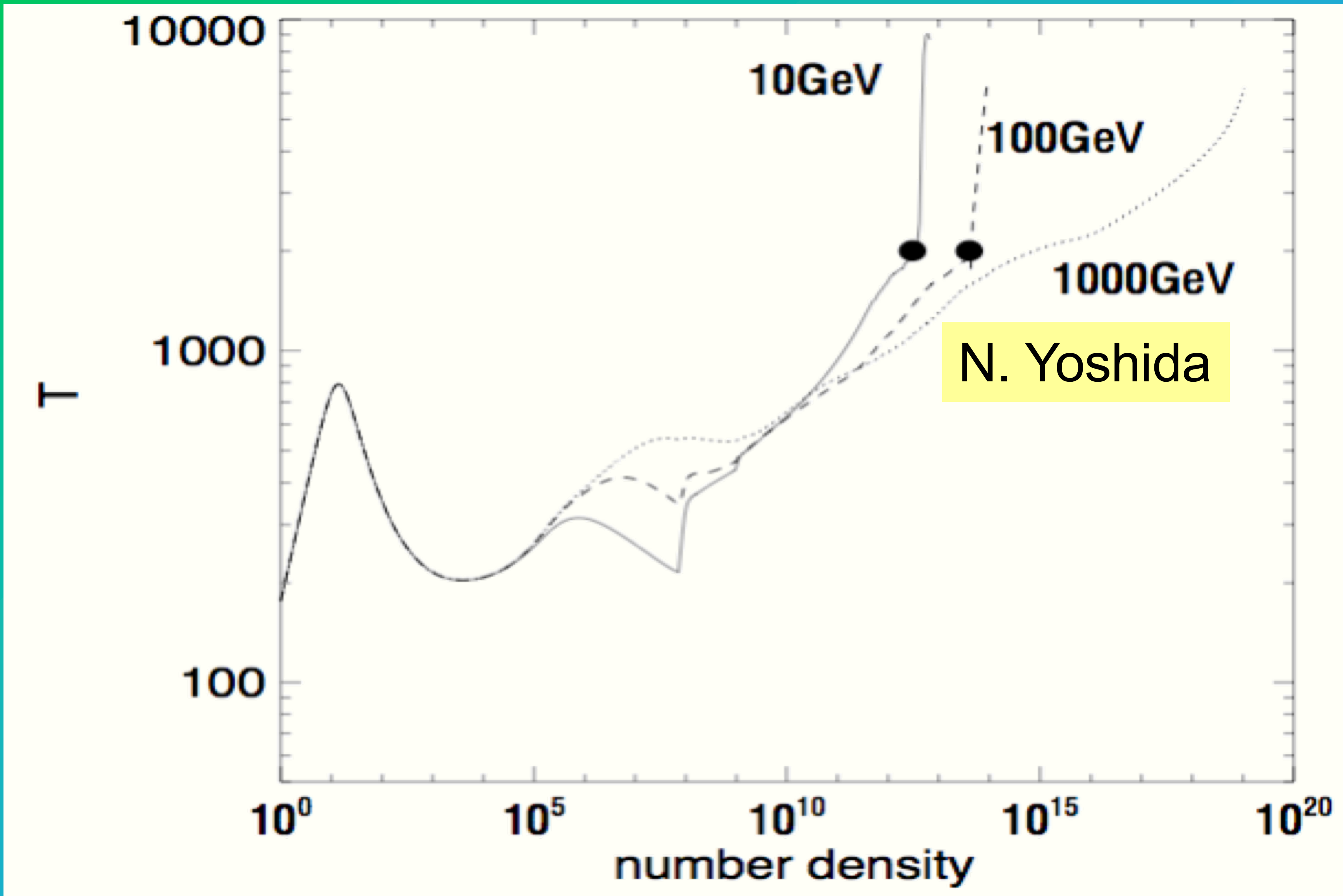
DM Heating dominates over cooling when the red lines cross the blue/green lines (standard evolutionary tracks from simulations). Then heating impedes further collapse.



(Spolyar, Freese, Gondolo April 2007)

New proto-Stellar Phase:

fueled by dark matter



At the moment heating wins:

- "Dark Star" supported by DM annihilation rather than fusion
- They are giant diffuse stars that fill Earth's orbit

$m_\chi \approx 1\ \mathrm{GeV}$ | core radius 960 a.u. | Mass 11 $M_\odot$

$m_\chi \approx 100\ \mathrm{GeV}$ | core radius 17 a.u. | Mass 0.6 $M_\odot$

- THE POWER OF DARKNESS: DM is < 0.1% of the mass of the star but provides the heat source

DS Evolution (w/ Peter Bodenheimer)

- Find hydrostatic equilibrium solutions
- Look for polytropic solution, $p = K\rho^{1+1/n}$

  for low mass n=3/2 convective,

  for high mass n=3 radiative

  (transition at 100-400 $M_\odot$)
- Start with a few solar masses, guess the radius, see if DM luminosity matches luminosity of star (photosphere at roughly 6000K). If not adjust radius until it does. Smaller radius means larger gas density, pulls in more DM via adiabatic contraction, higher DM density and heating. Equilibrium condition:

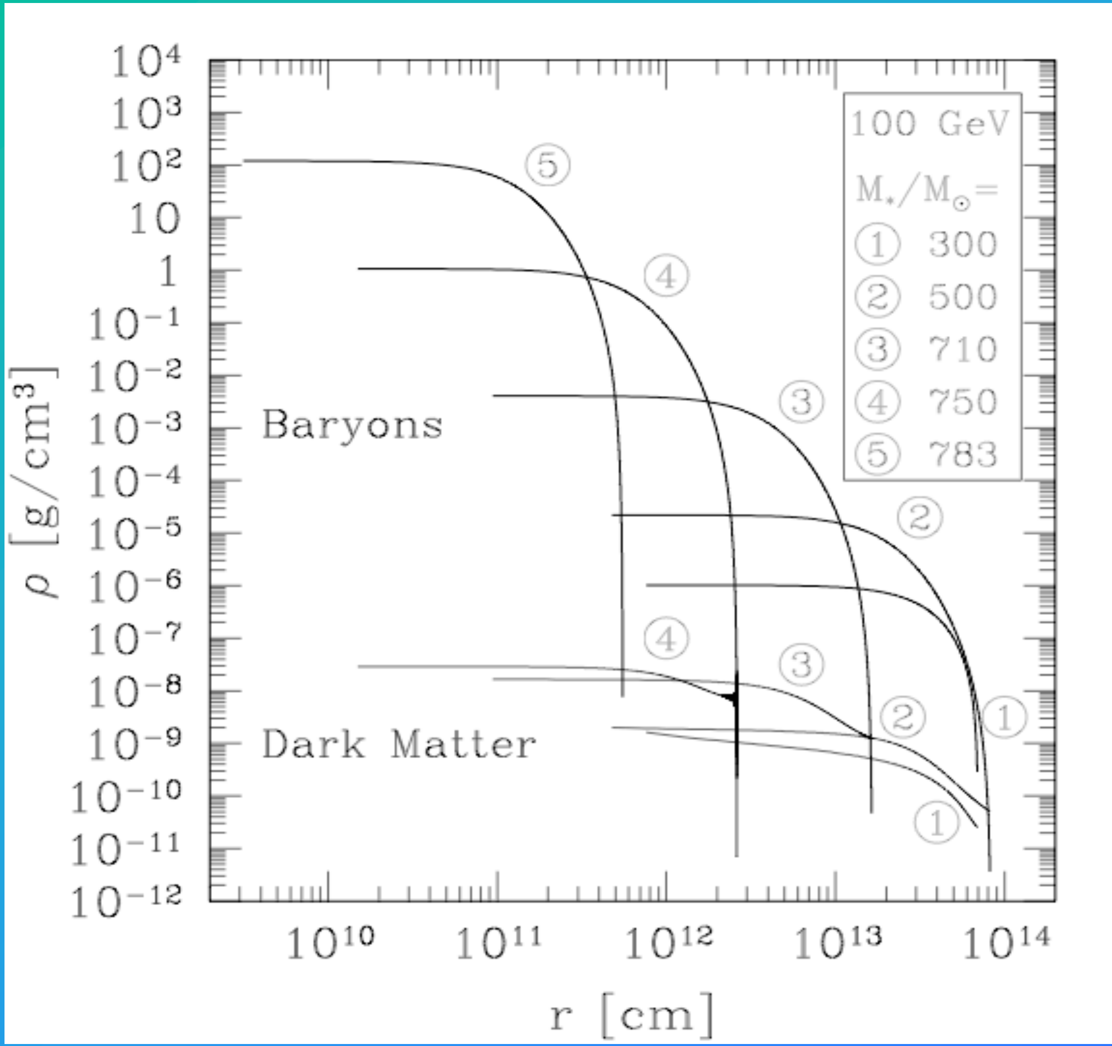
$$L_{DM} = L_*$$

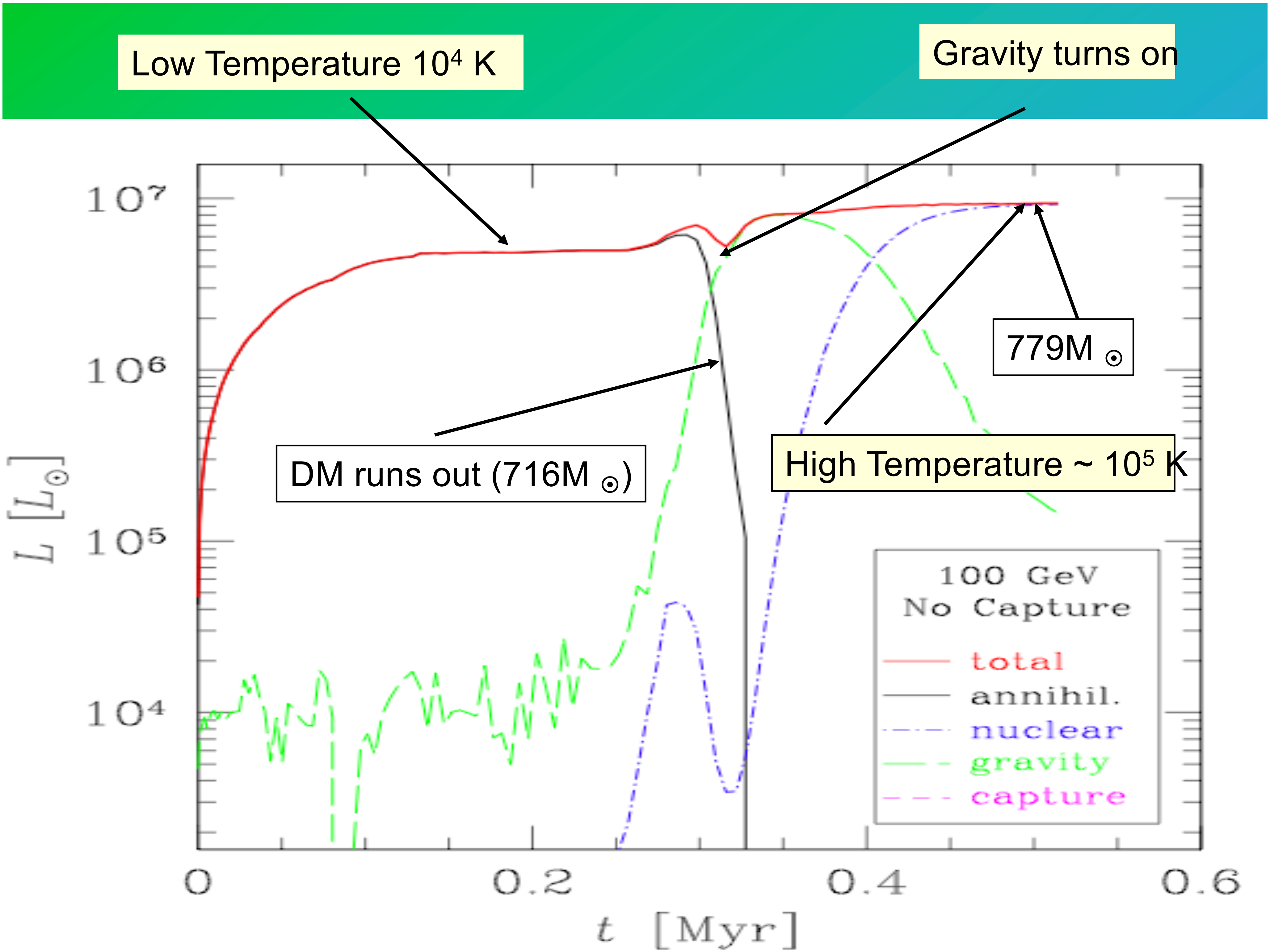
Building up the mass

- Start with a few $M_\odot$ Dark Star, find equilibrium solution
- Accrete mass, one $M_\odot$ at a time, always finding equilibrium solutions
- N.b. as accrete baryons, pull in more DM, which then annihilates
- Continue until no longer in region with DM fuel
- VERY LARGE FIRST STARS. Then, star contracts further, temperature increases, fusion will turn on, eventually make giant black hole

Following DS Evolution

- Gas Accretes onto molecular hydrogen Core, the system eventually forms a star.
- We then solve for stellar Structure by:
  - Self consistently solve for the DM density and Stellar structure
  - (Overly Conservative) DM in spherical halo. We later relax this condition





Low Temperature 10^4 K
Gravity turns on
779M ⊙
DM runs out (716M ⊙)
High Temperature ~ 10^5 K
100 GeV
No Capture
total
annihil.
nuclear
gravity
capture
10^7
10^6
10^5
10^4
L [L⊙]
0
0.2
0.4
0.6
t [Myr]

DS Basic Picture

- We find that DS are:
  - Massive: can grow to ten million $M_{\odot}$
  - Large-a few a.u. (size of Earth's orbit around Sun)
  - Luminous: can be more than 10^7 solar
  - Cool: 10,000 K vs. 100,000 K plus
    - Will not reionize the universe.
  - Long lived: more than 10^6 years, even till today?.
  - With Capture or nonCircular orbits, get even more massive, brighter, and longer lived

How big do Dark Stars get?

- KEY POINT: **As long as the star is Dark Matter powered, it can keep growing** because its surface is cool: surface temp 10,000K (makes no ionizing photons)
- Therefore, baryons can keep falling onto it without feedback.
- Dark stars can grow to supermassive stars, 10^5-10^7 $M_\odot$ and reach 10^9-10^{11} $L_\odot$.
- Visible in James Webb Space Telescope.
- Leads to (as yet unexplained) big black Holes.

- Second mechanism to bring in more dark matter: capture via elastic scattering

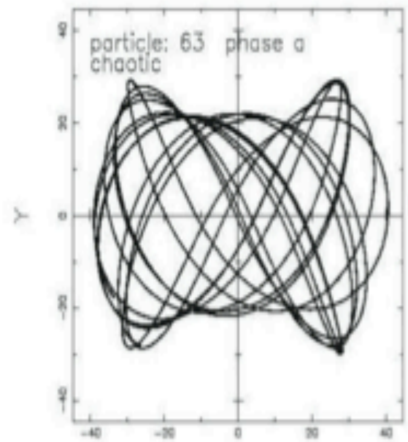
Is there enough DM?

Spherical Halos

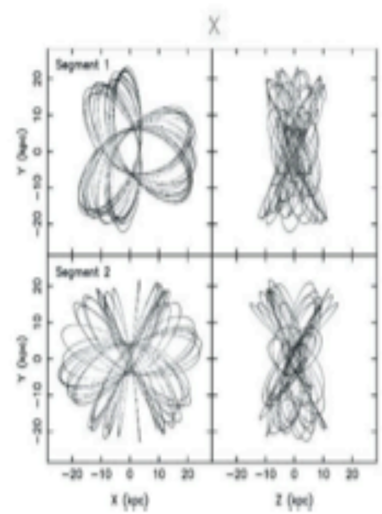
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

Halos are actually Prolate-Triaxial (Bardeen et al. '86).

- Two classes of centrophilic orbits. Box and Chaotic orbits (Schwarzchild '79).
- Traversing arbitrarily close to the center and refilling the loss cone.
- The loss cone could remain full for 10^4 times longer than in the case of a Spherical Halo (Merritt & Poon '04).



Box Orbit

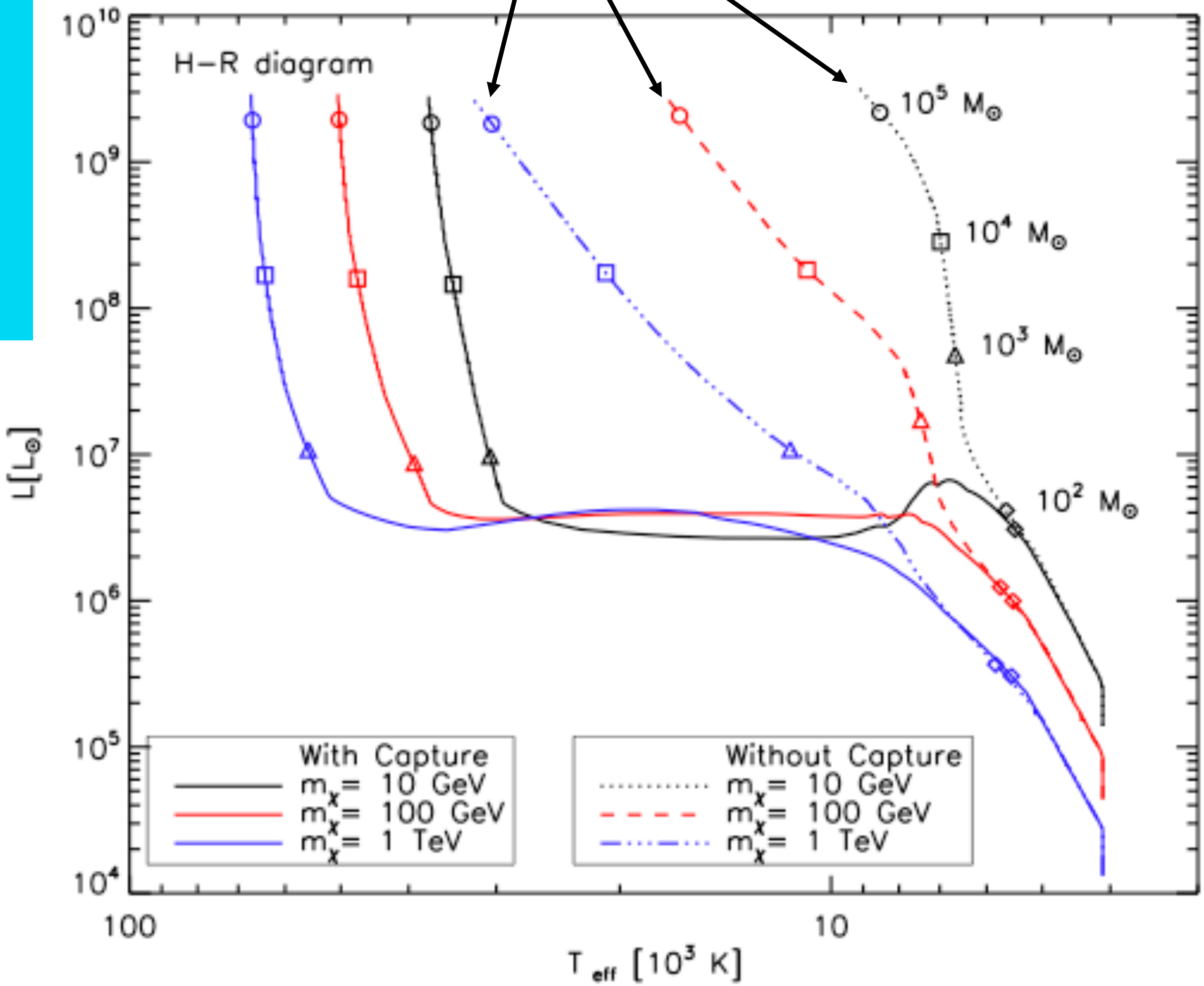


Chaotic Orbit

A particle that comes through the center of the DS can be annihilated. However, that particle was not on an orbit that would pass through the center again anyway. The next particle will come in from a different orbit.

Super Massive DS due to extended adiabatic contraction since reservoir has been replenished due to orbital structure

Assuming all of the baryons can accrete in a $10^6\ M_\odot$ halo



Additional possible source of DM fuel: capture

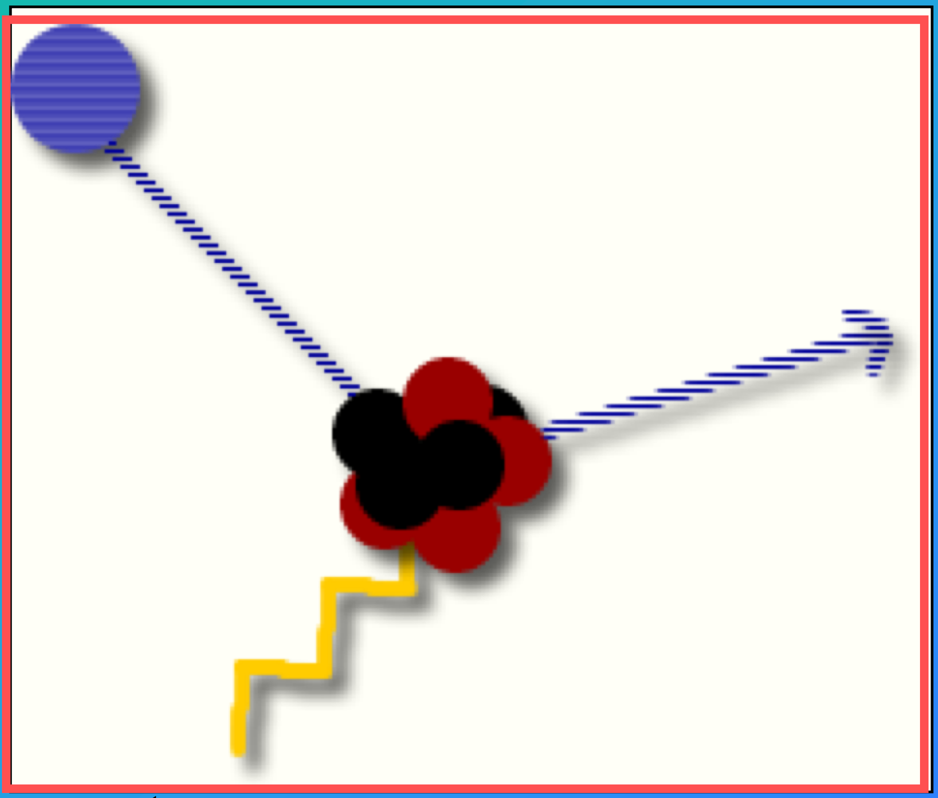
- Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured. (This it the origin of the indirect detection effect in the Earth and Sun).
- Two uncertainties:

  (I) ambient DM density (ii) scattering cross section must be high enough.
- Whereas the annihilation cross section is fixed by the relic density, the scattering cross section is a free parameter, set only by bounds from direct detection experiments.

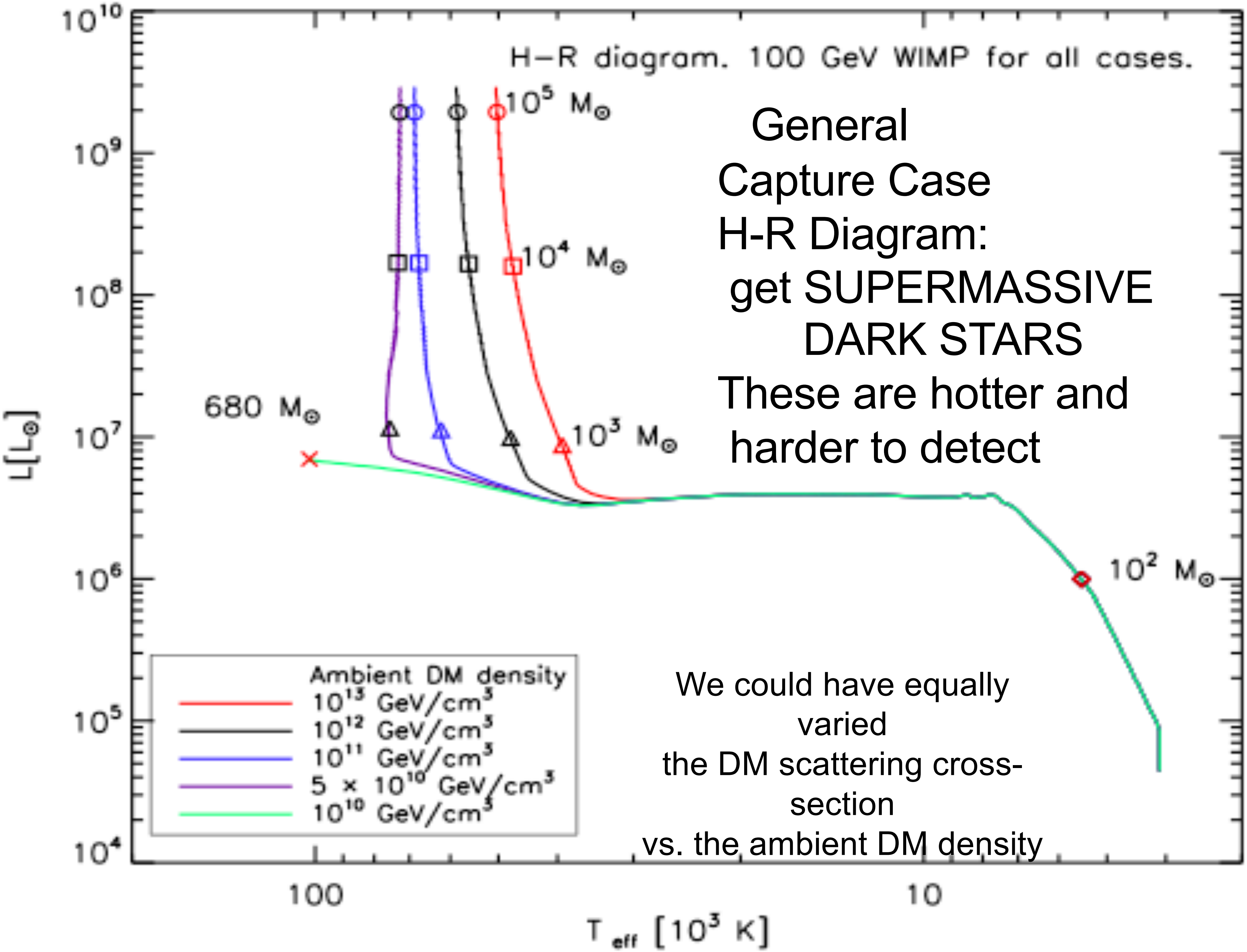
Freese, Aguirre, Spolyar 08; Iocco 08

WIMP scattering off nuclei leads to capture of more DM fuel

Some DM particles bound to the halo pass through the star, scatter off of nuclei in the star, and are captured.



This is the same scattering that direct detection experiments are looking for



General Capture Case H-R Diagram: get SUPERMASSIVE DARK STARS

These are hotter and harder to detect

We could have equally varied the DM scattering cross-section vs. the ambient DM density

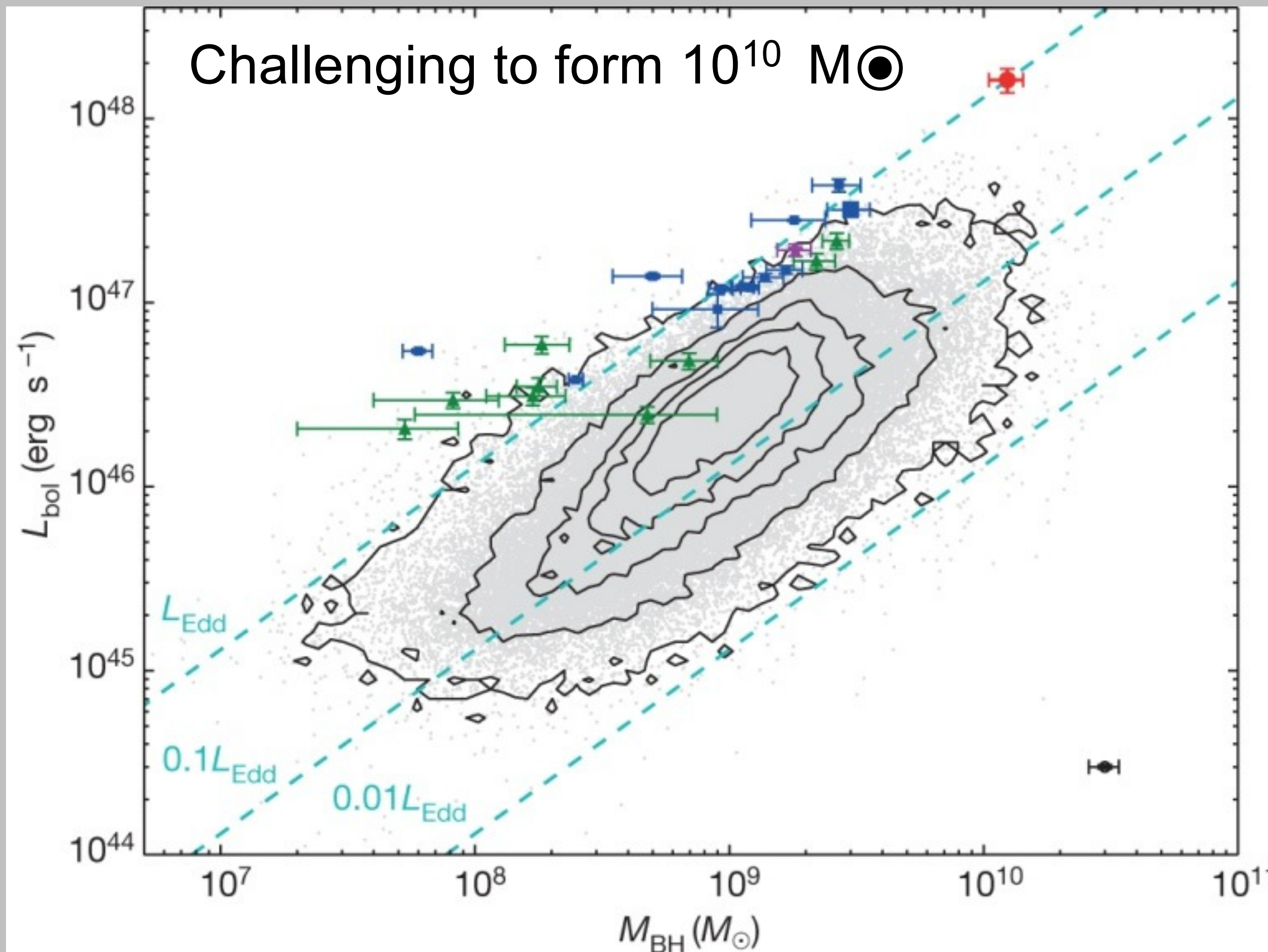
Lifetime of Dark Star

- The DS lives as long as DM orbits continue through the DS or it captures more Dark Matter fuel: millions to billions of years.
- The refueling can only persist as long as the DS resides in a DM rich environment, I.e. near the center of the DM halo. But the halo merges with other objects.
- You never know! They might exist today.
- Once the DM runs out, switches to fusion for the case of lower mass DS, or collapse directly to Black Hole for DS heavier than 150,000 solar masses.

What happens next?
BIG BLACK HOLES

- Center of star reaches $T=10^7$K, fusion sets in.
- A. Heger finds that fusion powered stars heavier than 150,000 solar masses are unstable and collapse to BH
- Less massive Pop III star lives a million years, then becomes a Black Hole
- Helps explain observed black holes:
- (i) in centers of galaxies
- (ii) billion solar mass BH at z=6 (Fan, Jiang)
- (iii) intermediate mass BH

SupperMassive Black holes from Dark Stars
Very Massive progenitor Million Solar Masses
No other way to form supermassive BH this early z=6



X-B Wu *et al.* *Nature* **518**, 512-515 (2015) doi:10.1038/nature14241

nature

An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5

Eduardo Bañados[1,*], Bram P. Venemans[2], Chiara Mazzucchelli[2], Emanuele P. Farina[2], Fabian Walter[2], Feige Wang[3,4], Roberto Decarli[2,5], Daniel Stern[6], Xiaohui Fan[7], Fred Davies[8], Joseph F. Hennawi[8], Rob Simcoe[9], Monica L. Turner[9,10], Hans-Walter Rix[2], Jinyi Yang[3,4], Daniel D. Kelson[1], Gwen Rudie[1], and Jan Martin Winters[11]

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[8]Department of Physics, Broida Hall, University of California, Santa Barbara, CA 93106–9530, USA
[9]MIT-Kavli Center for Astrophysics and Space Research, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
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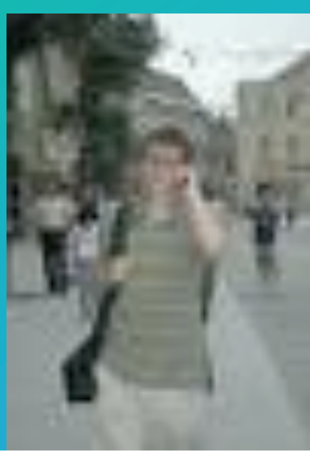
*ebanados@carnegiescience.edu

ABSTRACT

Quasars are the most luminous non-transient objects known, and as such, they enable unparalleled studies of the universe at the earliest cosmic epochs. However, despite extensive efforts from the astronomical community, the quasar ULAS J1120+0641 at $z = 7.09$ (hereafter J1120+0641) has remained as the only one known at $z > 7$ for more than half a decade[1]. Here we report observations of the quasar ULAS J134208.10+092838.61 (hereafter J1342+0928) at a redshift of $z = 7.54$. This quasar has a bolometric luminosity of $4 \times 10^{13} L_\odot$ and a black hole mass of $8 \times 10^8 M_\odot$. The existence of this supermassive black hole when the universe was only 690 Myr old, i.e., just 5% its current age, reinforces early black hole growth models that allow black holes with initial masses $\gtrsim 10^4 M_\odot$[2,3] or episodic hyper-Eddington accretion[4,5]. We see strong evidence of the quasar's Lyα emission line being absorbed by a Gunn-Peterson damping wing from the intergalactic medium, as would be expected if the intergalactic hydrogen surrounding J1342+0928 is significantly neutral. We derive a significant neutral fraction, although the exact value depends on the modeling. However, even in our most conservative analysis we find $\bar{x}_{\rm HI} > 0.33$ ($\bar{x}_{\rm HI} > 0.11$) at 68% (95%) probability, indicating that we are probing well within the reionization epoch.

Observing Dark Stars

- Supermassive Dark Stars may be detected in upcoming James Webb Space Telescope
- One of JWST goals is to find first stars: only if they are dark stars is this goal realizable



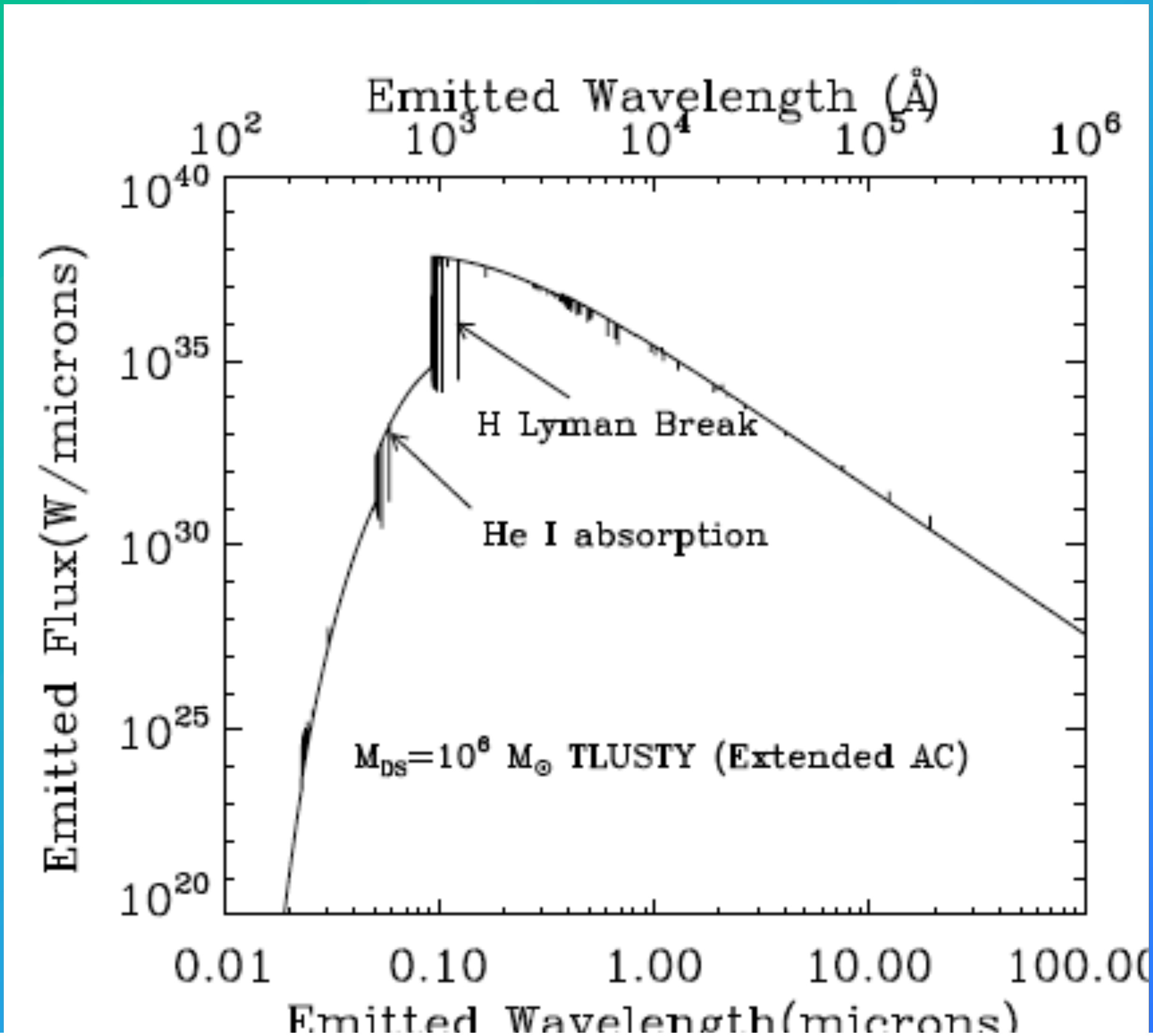
Cosmin Ilie, Paul Shapiro

Pat Scott

DS Spectrum from TLUSTY (stellar atmospheres code)

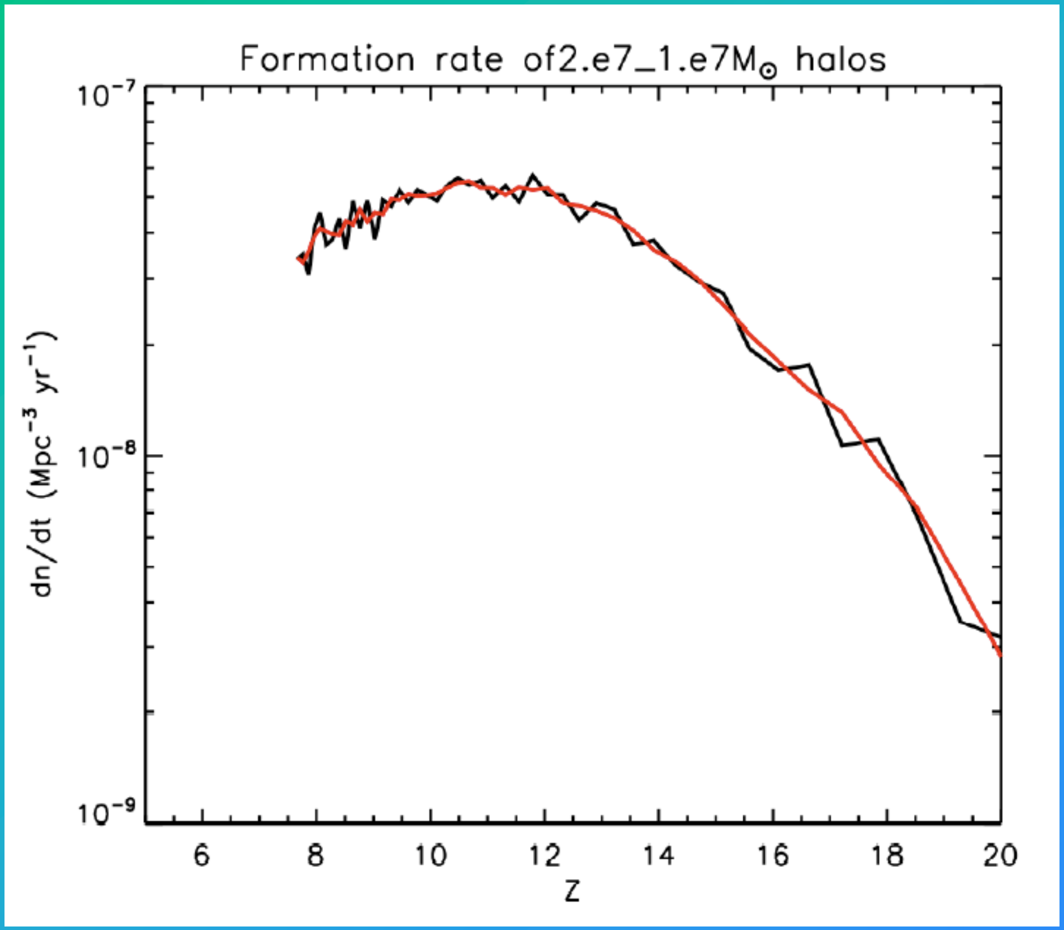
Pat Scott

n.b. DS are made of hydrogen and helium only

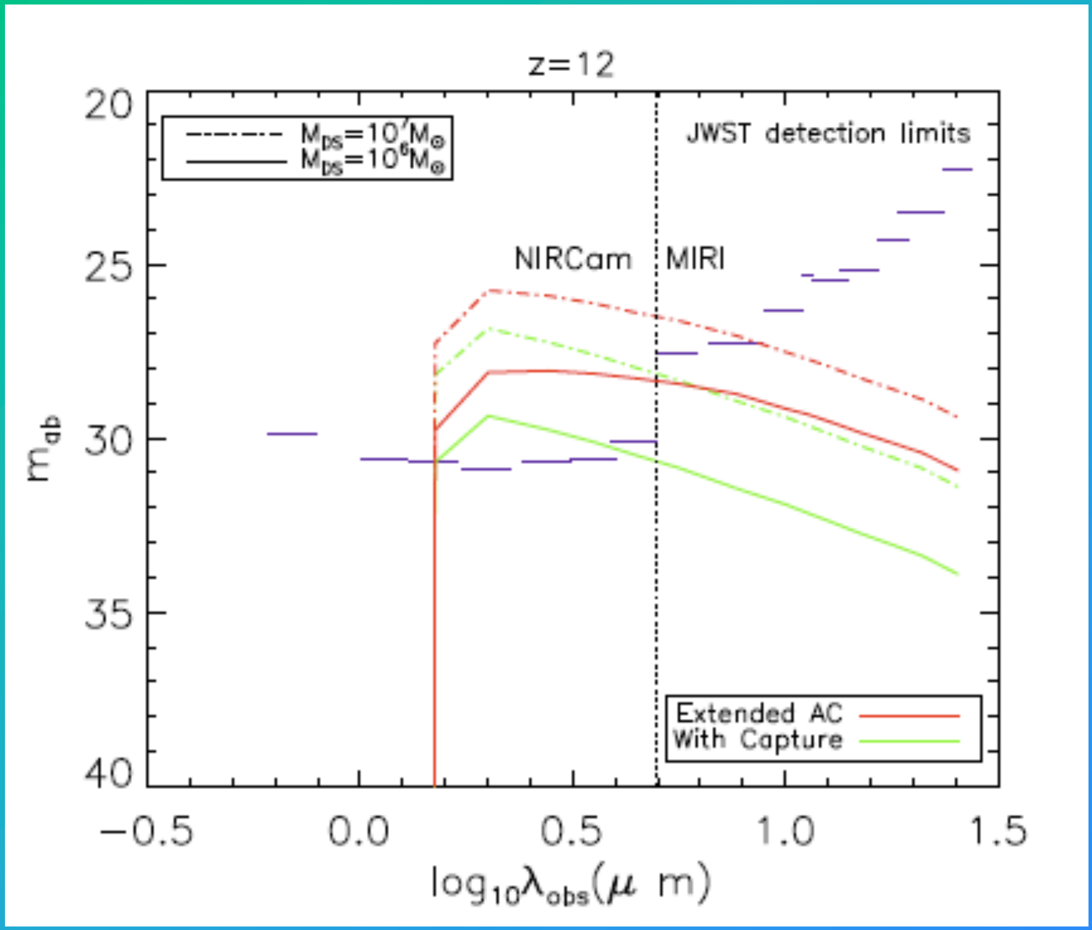


Minihalo formation rate

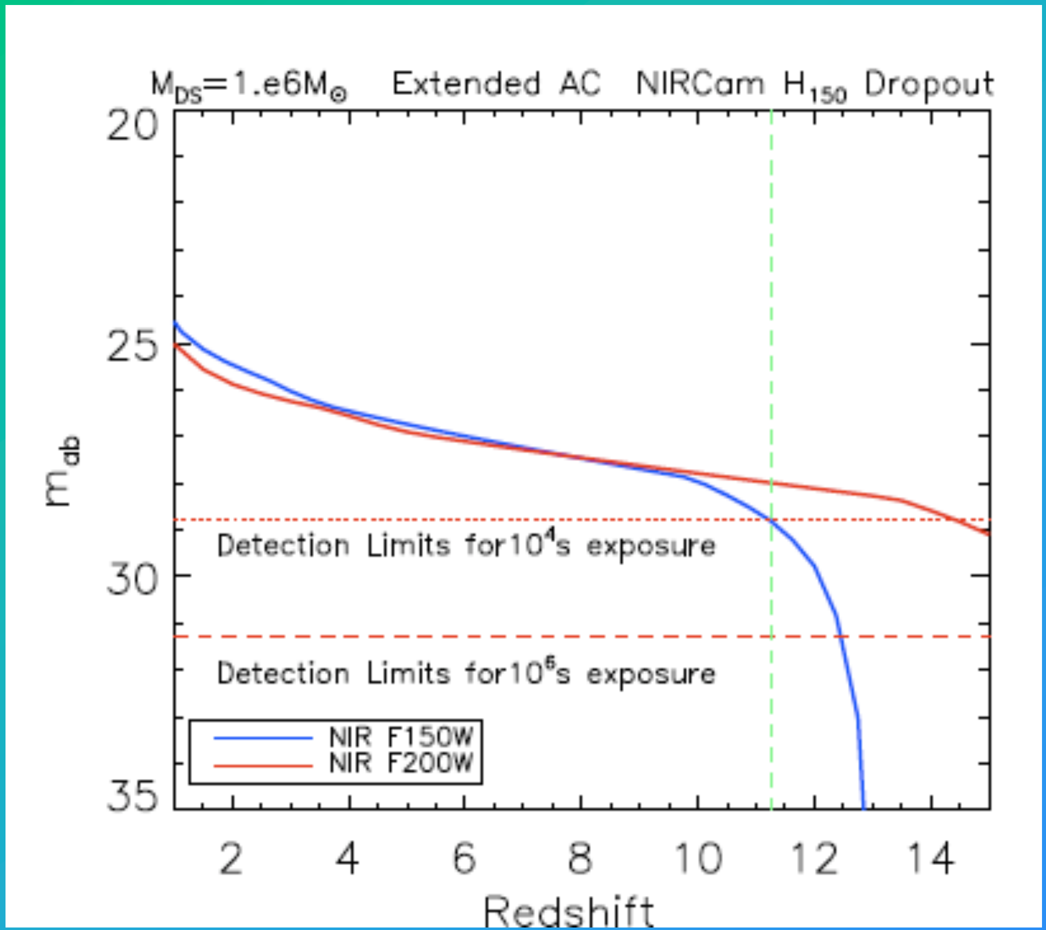
Shapiro, Iliev



Dark Stars in JWST, sequel to HST



Million solar mass SMDS as H-band dropout



(see in 2.0 micron but not 1.5 micron filter, implying it's a z=12 object)

Numbers of SMDS detectable with JWST as H-band dropouts

(see in 2.0 micron but not 1.5 micron filter, implying it's z=12 object)

Upper limits on numbers of SMDS detectable with JWST as H_{150} dropout

$M_{DS}(M_\odot)$	Formation Scenario	Bounds from HST	N_{obs}^{FOV}	N_{obs}^{multi}
10^6	Extended AC	Maximal Bounds	$\lesssim 1$	10
10^6	With Capture	Maximal Bounds	2	32
10^7	Any	Maximal Bounds	$\lesssim 1$	~ 1
10^6	Extended AC	Intermediate	45	709
10^6	With Capture	Intermediate	137	2128
10^7	Any	Intermediate	4	64
10^6	Extended AC	Number of DM halos	28700	444750
10^6	With Capture	Number of DM halos	28700	444750
10^7	Any	Number of DM halos	155	2400

Table 3. Upper limits on the number of SMDS detections as H_{150} dropouts with JWST. In first three rows (labeled "Maximal Bounds") we assume that all the DS live to below z=10 where they would be observable by HST, and we apply the bounds on the numbers of DS f_{SMDS} from HST data in Section 4.2. The middle three rows (labeled "Intermediate") relax those bounds by assuming that only $\sim 10^{-2}$ of the possible DS forming in z=12 haloes make it through the HST observability window. For comparison we also tabulate in the last three rows the total number of potential DM host halos in each case. We also split the number of observations in two categories, N_{obs}^{FOV} and N_{obs}^{multi}. The first assumes a sliver with the area equal to the FOV of the instrument (9.68 arcmin^2), whereas in the second we assume multiple surveys with a total area of 150 arcmin^2 . Note that for the case of the $10^7 M_\odot$ SMDS the predictions are insensitive to the formation mechanism.

Dark stars Pulsations

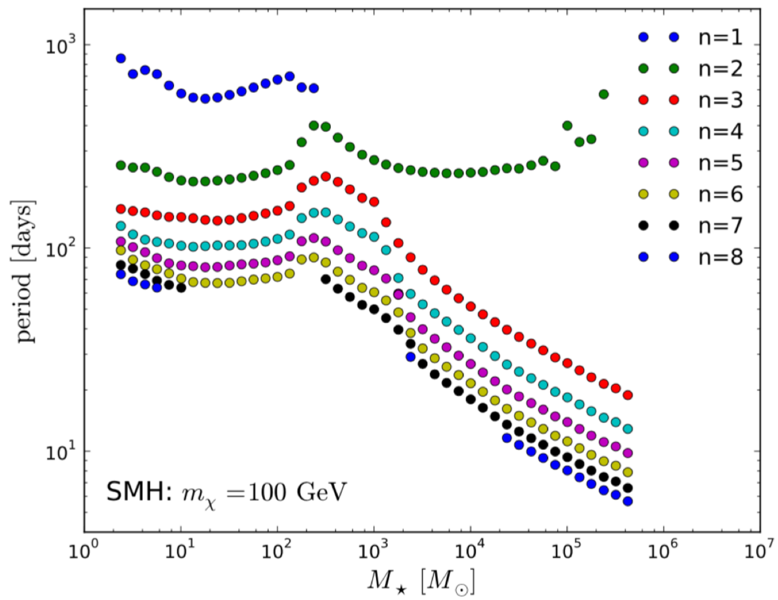


Figure 9. Radial, adiabatic pulsation periods as a function of DS mass for a WIMP mass of 100 GeV and a DS forming in SMH. The periods are given in the restframe of the DS. The curves are for different overtone number, from the fundamental radial oscillation $n = 1$ (upper-most curve) to $n = 8$ (lower-most curve); see also Ref.[16].

Finding pulsations allows differentiation in data from early galaxies
Also, someday will provide standard candles

Final Thoughts: *IMF*

- The IMF of the first fusion powered stars may be determined by the Dark Matter encountered by their Dark Star progenitors: as long as there is DM, the DS keeps growing
- Depends on cosmological merger details of early haloes, million to hundred million solar mass haloes

Dark Stars (conclusion)

- The dark matter can play a crucial role in the first stars
- The first stars in the Universe may be powered by DM heating rather than fusion
- These stars may be very massive (up to 10 million solar masses) and bright (up to ten billion solar luminosities), can be precursors to Supermassive Black Holes, and can be detected by JWST
- WIMPs could first be detected by discovering dark stars

In progress

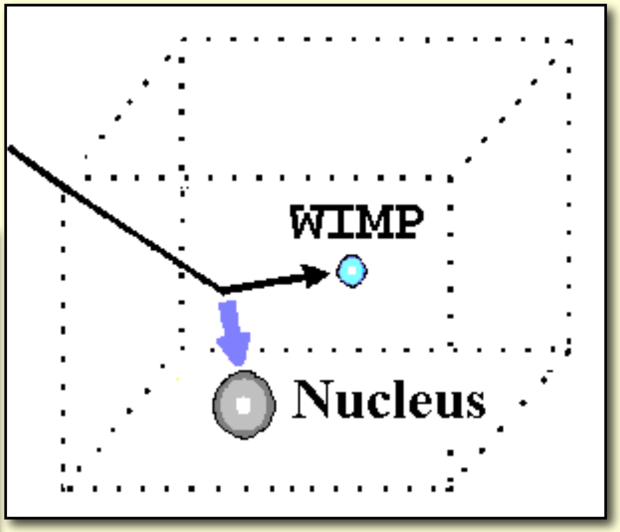
- Dark Stars powered by other types of dark matter
- SIDM (with Haibo Yu, Youija Wu, Luca Visinelli, Sebastian Baum)
- SIDM is in isothermal distribution out to some radius r1 where it matches onto NFW

- Also, DM can help avoid pair instability SN and thereby fill in hole for BHs 50 -150 solar masses (from stellar collapse) (J. Ziegler)

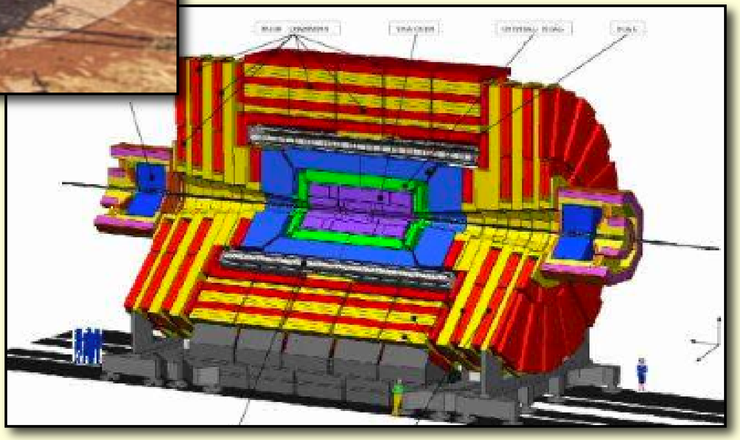
If the dark matter is primordial black holes

- Impact on the first stars:
- They would be adiabatically contracted into the stars and then sink to the center by dynamical friction, creating a larger black hole which may swallow the whole star. End result: 10-1000 solar mass BH, which may serve as seeds for early big BH or for BH in galaxies.
- (Bambi, Spolyar, Dolgov, Freese, Volonteri astro-ph 0812.0585)

WIMP Hunting: Good chance of detection this decade

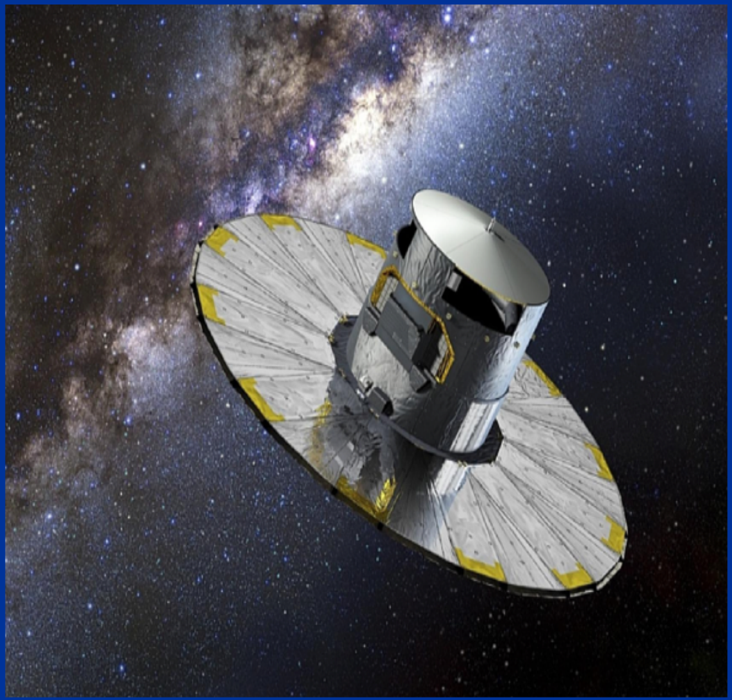


- Direct Detection
- Indirect Detection
- Collider Searches

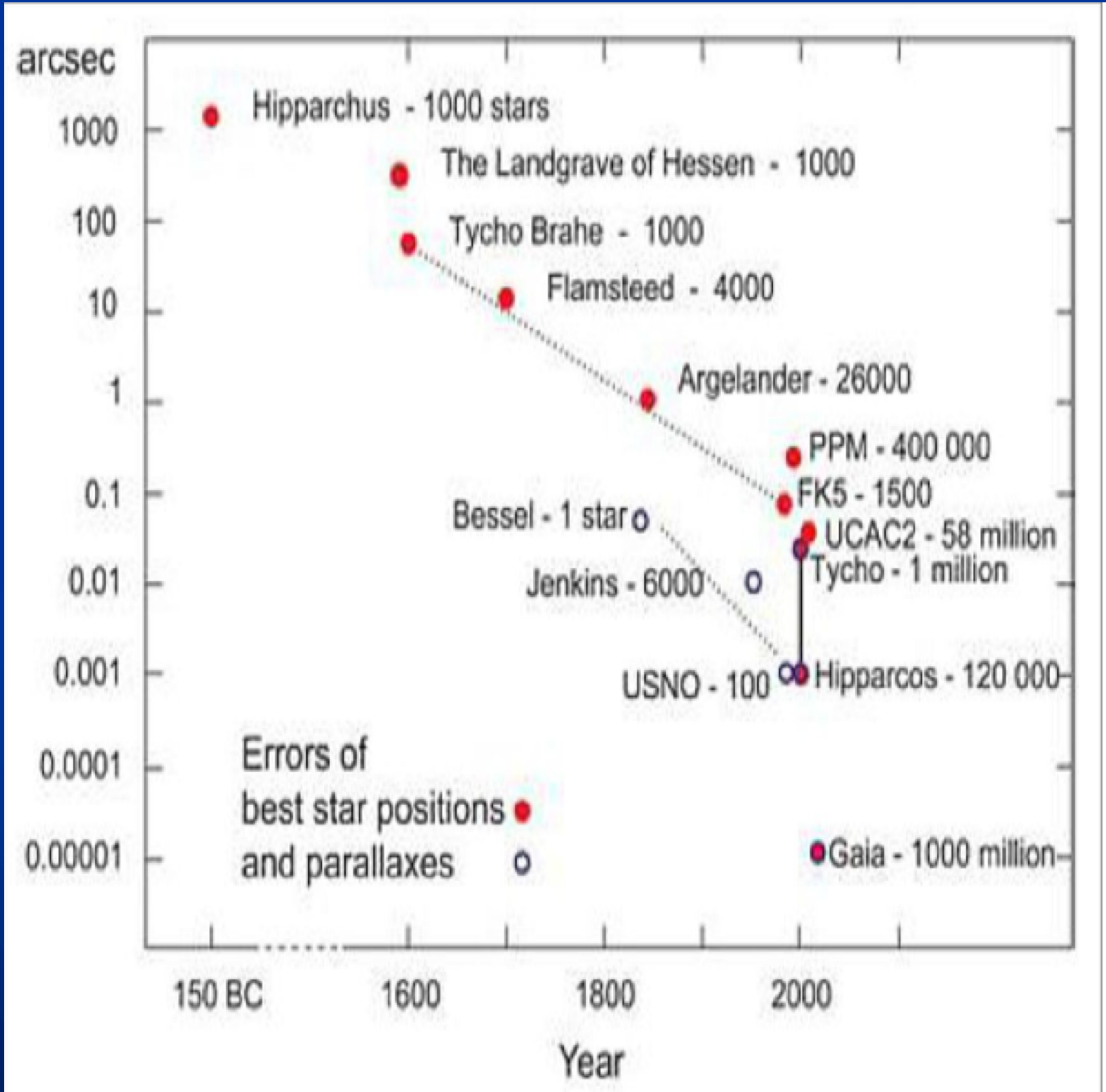


Looking for Dark Stars

4) New ways to test nature of DM: use GAIA data



Measures positions and velocities of 1.3 billion stars in the Milky Way. Stellar kinematics determined by gravitational potential of Dark Matter



arcsec
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Hipparchus - 1000 stars
The Landgrave of Hessen - 1000
Tycho Brahe - 1000
Flamsteed - 4000
Argelander - 26000
PPM - 400 000
FK5 - 1500
Bessel - 1 star
UCAC2 - 58 million
Tycho - 1 million
Jenkins - 6000
USNO - 100
Hipparcos - 120 000
Errors of
best star positions
and parallaxes
Gaia - 1000 million
150 BC
1600
1800
2000
Year

COLD DARK MATTER (including WIMPs and axions

“Cusp/core” problem: window to the nature of DM

CDM simulations

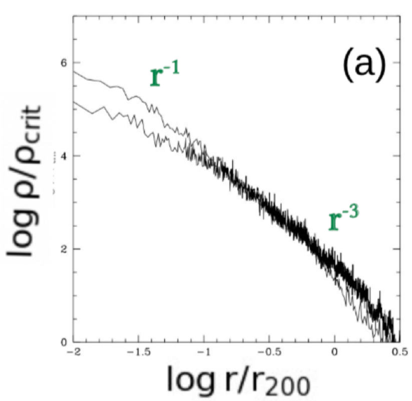
Hypothesis: DM is non-relativistic (“cold”), collisionless, massive

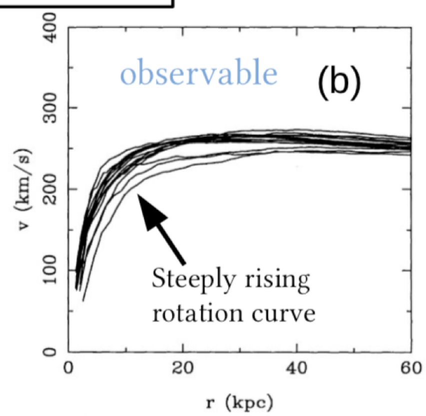
Outcome:

Shapes of DM halos

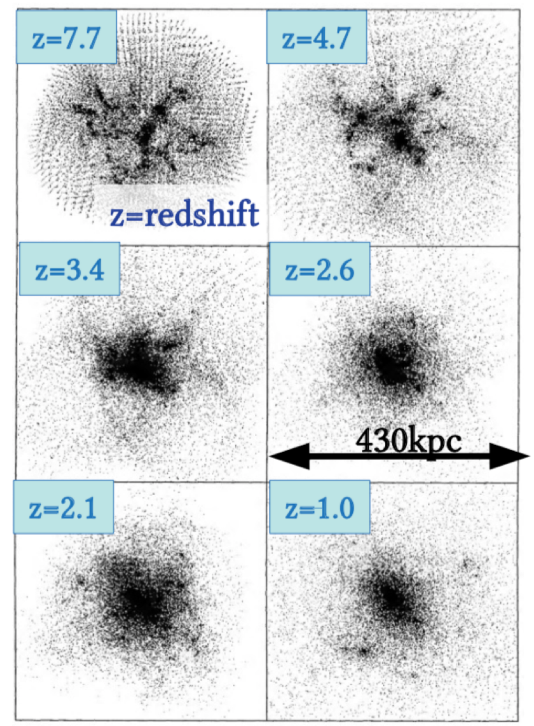
- Dark halos are triaxial (and could be both oblate and prolate)
- Density profiles are “universally” cuspy:

$$\boxed{\rho(r) \propto r^{-\gamma} \text{ (with } \gamma = 1)}$$





Dubinski & Carlberg (1991), Frenk et al. (1995), NFW (1996)



Density profiles of DM halos fit power law, and they are strongly triaxial in shape

Small-scale observations are not quite consistent with CDM

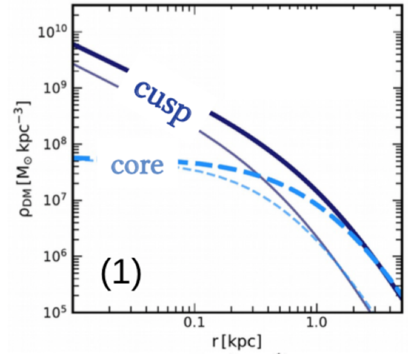
Small-scale=> M_{halo} ~$\mathbf{10^{9\text{-}12}\,M_\odot}$, length scale ~ **1 kpc-1 Mpc**

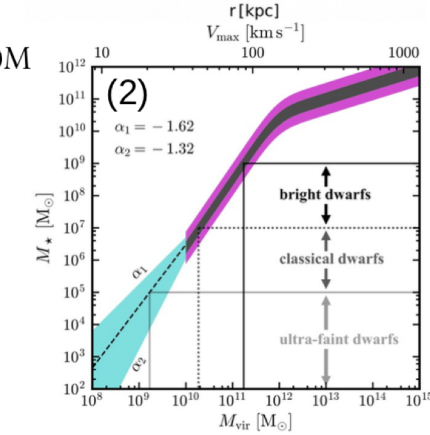
Problems

1. Prediction: The central-DM profiles of individual halos are steeply-rising and form high-density "cusps"
   Observations: Central-DM profiles are low-density "cores"

2. Prediction: >1000 subhalos (dwarf galaxies, physical size ~ 1-3 kpc) should orbit any Milky Way like galaxy
   Observations: only ~60-70 known galaxies with M_{halo}~$10^{8\text{-}9}\,M_\odot$ (M_* > 300M within 300 kpc of the Milky Way

3. Prediction: The local universe should have galaxies with M_{vir} ~ $10^{10}M_\odot$
   Observations: "Too-Big-to-Fail"





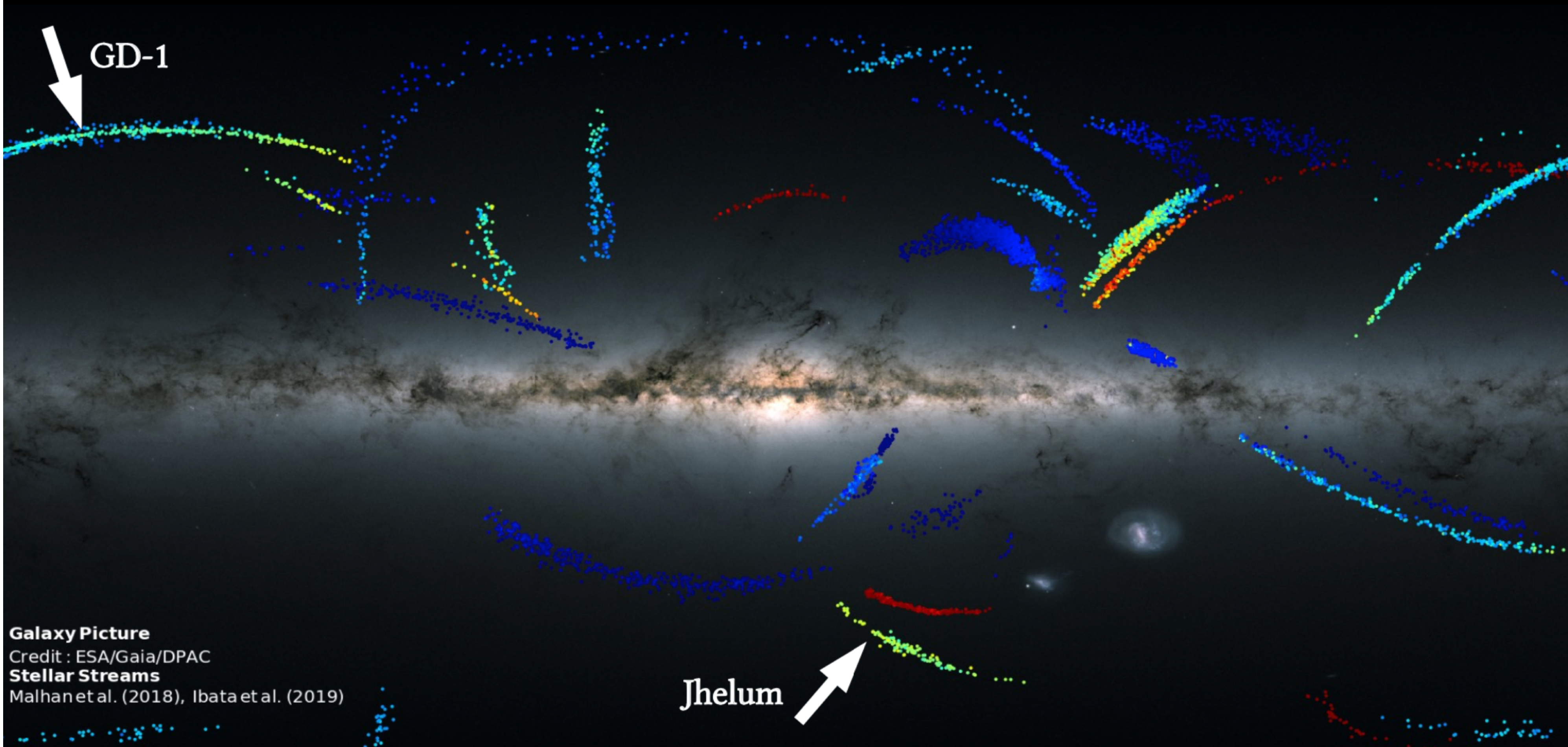
Bullock & Boylan-Kolchin (2017)

Probing Nature of DM with Streams in GAIA data

- We know of 70 stellar streams in the Milky Way. With GAIA data, more are being found, and their properties can tell us about the nature of DM.
- Streams form by tidal stripping of Dwarf Galaxies (e.g. the Sagittarius Stream) or by tidal stripping of Globular Clusters of stars inside halos
- GCs are dense and old star clusters (formed at redshifts $z \sim 2{-}4$) with $M \sim 10^5\, M_\odot$ and a physical sizes of a few tens of pc that reside in the halos of galaxies.

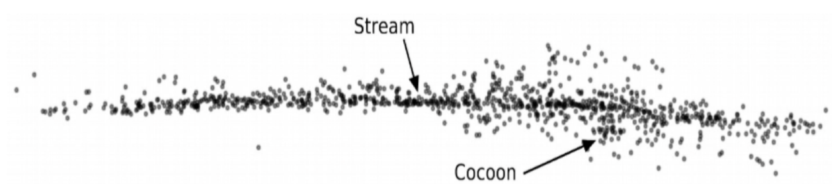
Stellar Streams in the Milky Way

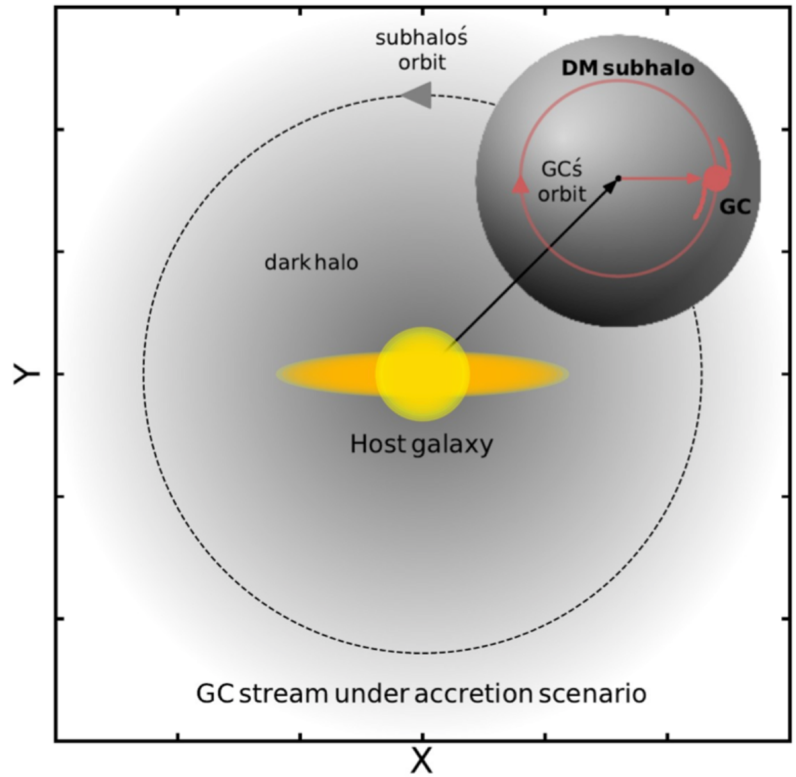
<u>Question</u>: Can the present day physical properties of such accreted GC streams provide information about the DM density of their parent subhalos?



Accreted GC streams as direct probes of dark matter

Can the present day physical properties of such accreted GC streams provide information about the DM density of their parent subhalos?



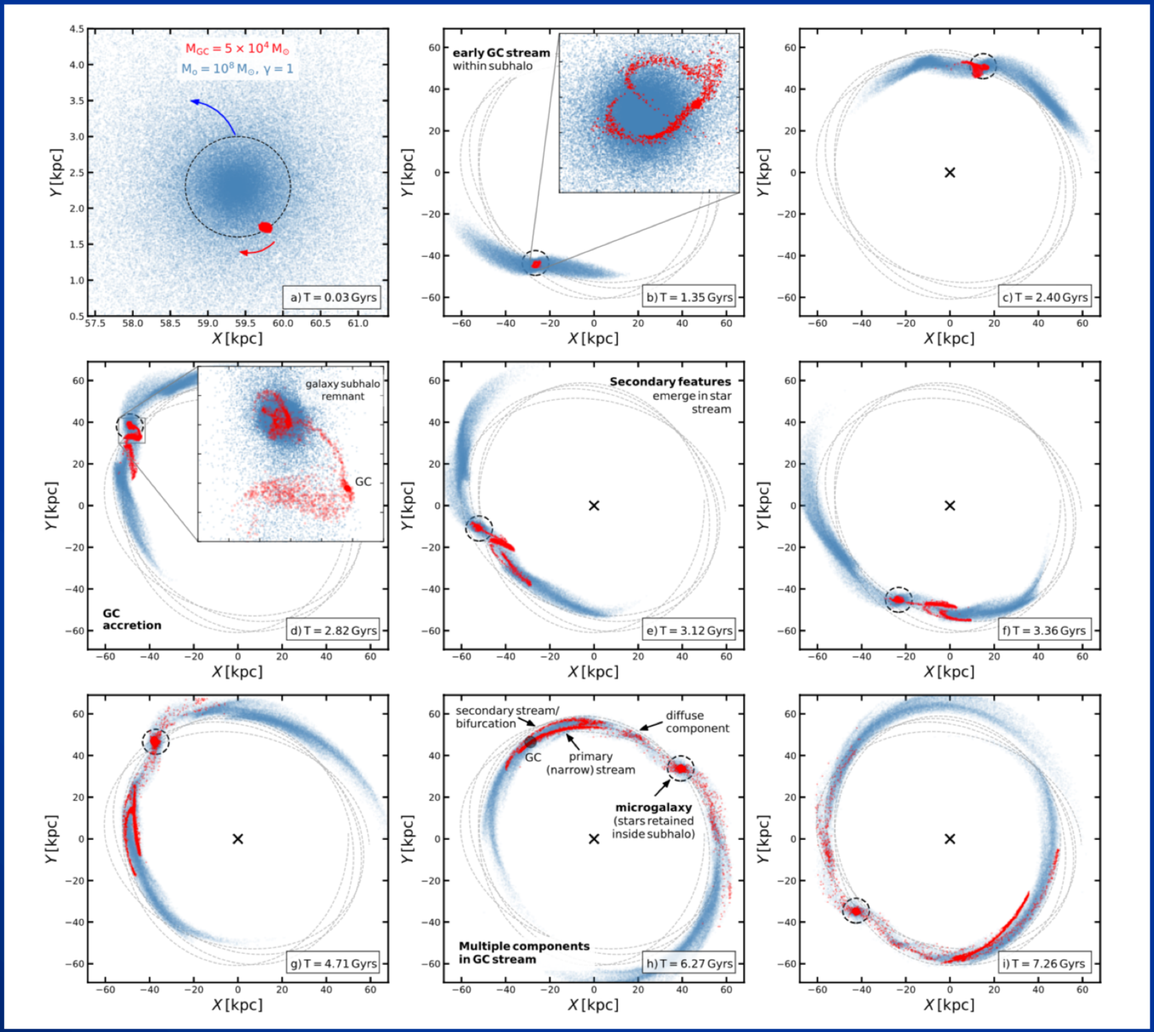


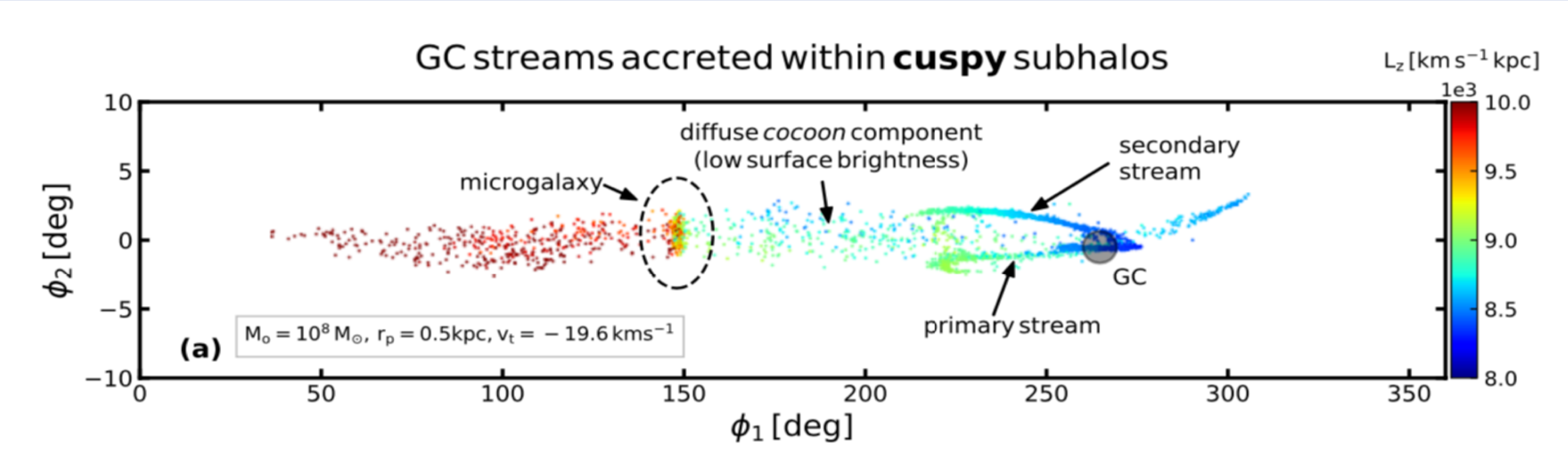
Khyati Malhan

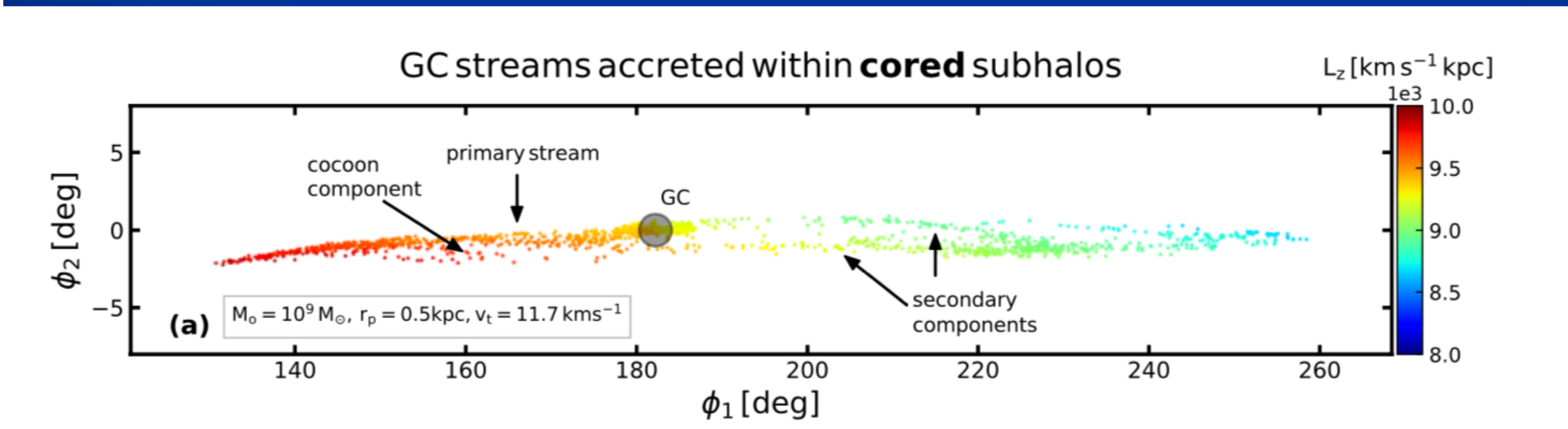
Monica Valluri

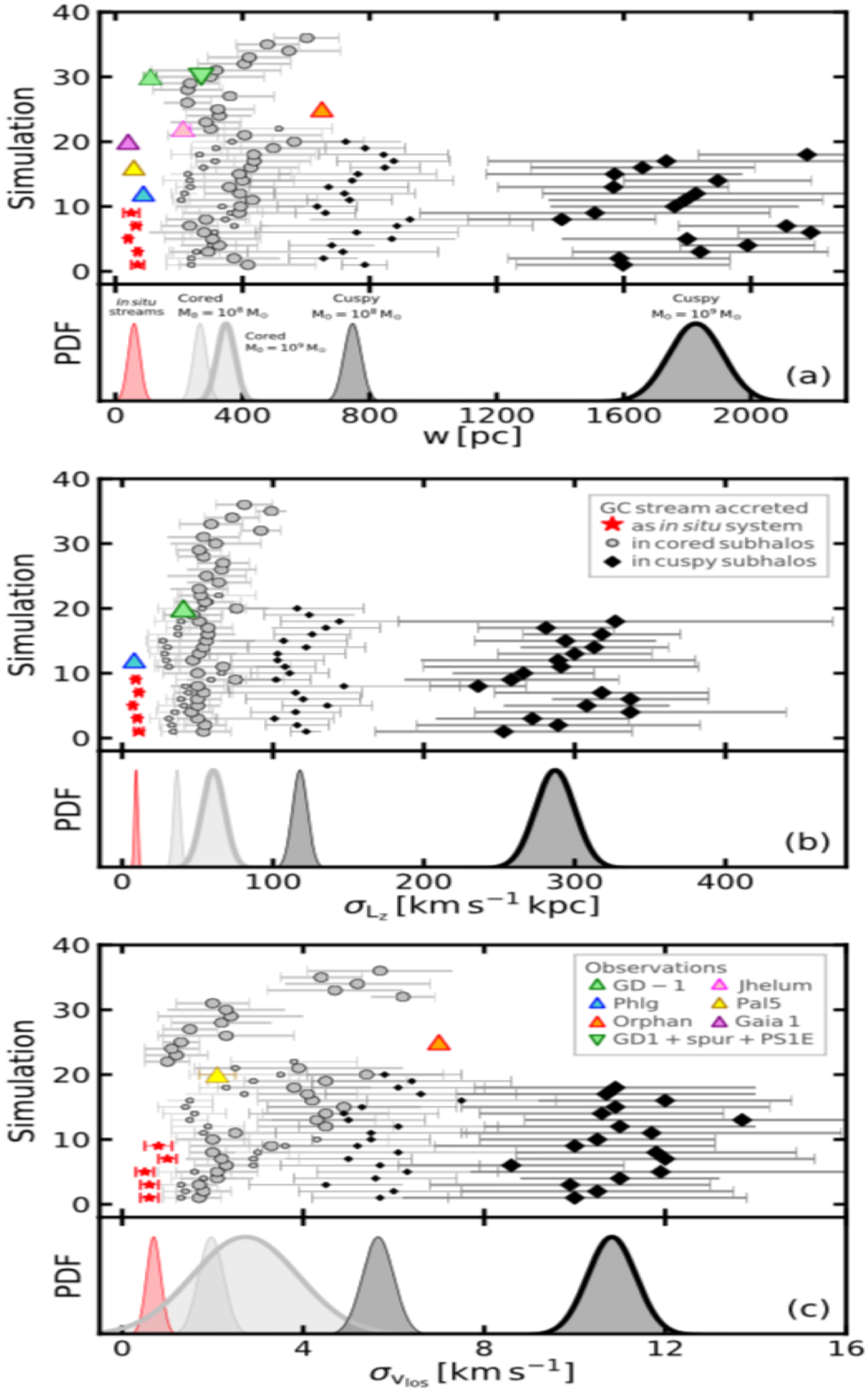
Malhan, Valluri, Freese 2020

Formation of stream by tidal stripping of accreted GC




GC streams accreted within **cuspy** subhalos
L_z [km s^{-1} kpc]
1e3
10.0
9.5
9.0
8.5
8.0
diffuse *cocoon* component
(low surface brightness)
secondary
stream
microgalaxy
GC
primary stream
(a)
$M_o = 10^8 M_\odot$, $r_p = 0.5$kpc, $v_t = -19.6$ kms^{-1}
ϕ_2 [deg]
ϕ_1 [deg]
10
5
0
−5
−10
0
50
100
150
200
250
300
350


GC streams accreted within **cored** subhalos
L_z [km s^{-1} kpc]
1e3
10.0
9.5
9.0
8.5
8.0
cocoon
component
primary stream
GC
secondary
components
(a)
$M_o = 10^9 M_\odot$, $r_p = 0.5$kpc, $v_t = 11.7$ kms^{-1}
ϕ_2 [deg]
ϕ_1 [deg]
5
0
−5
140
160
180
200
220
240
260



Streams coming from cuspy subhalos are wider physically and dynamically hotter than those from cored subhalos

First comparison with observed streams GD-1 and Jhelum indicates a preference for cored subhalos

If this result holds up, then either there was baryonic feedback or must go beyond CDM

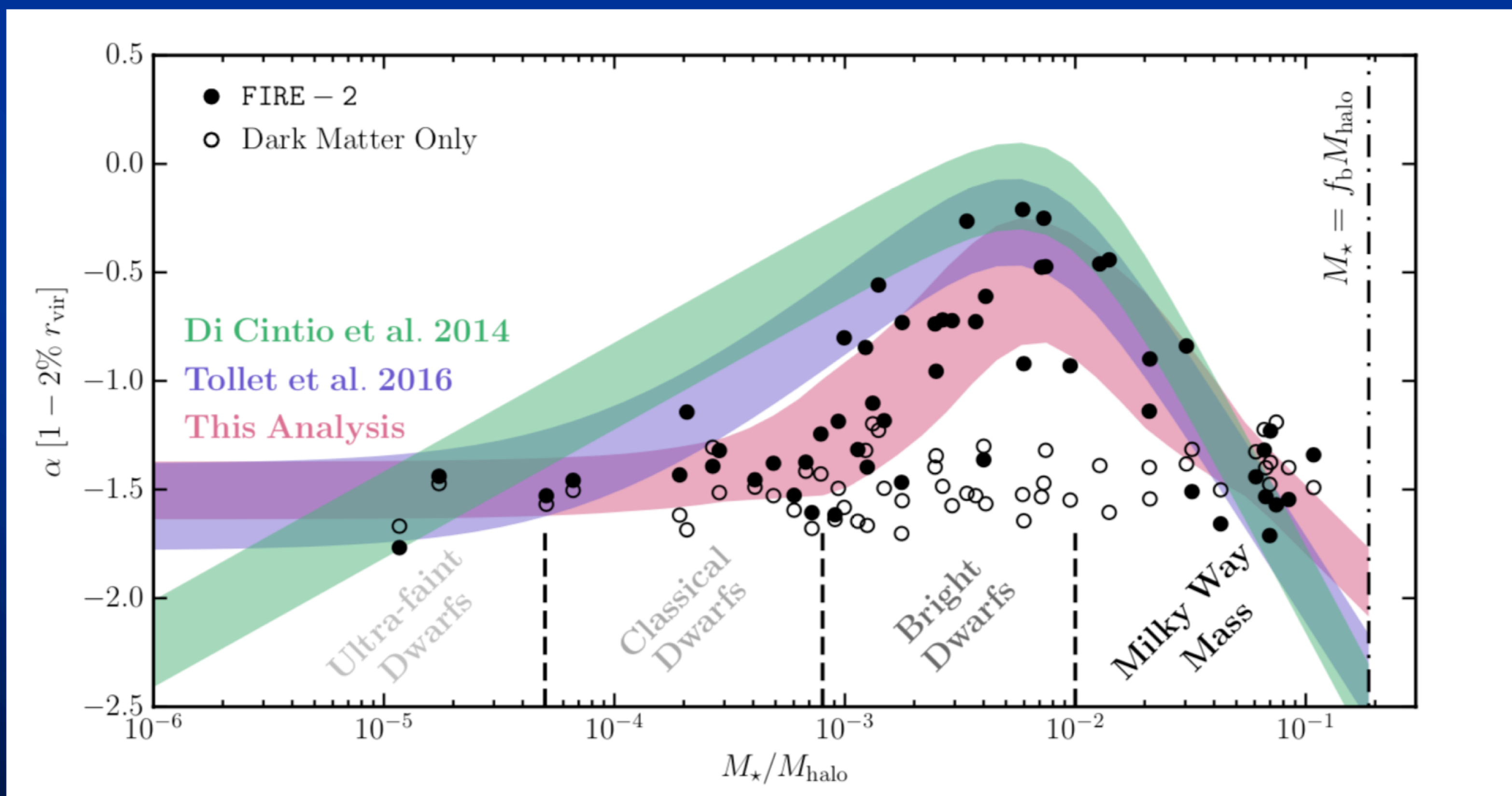
What's new In Cold Dark Matter Simulations:

- Impact of stellar feedback on core/cusp of inner DM density most effective at ~5 x 10^10 M☉

$$\rho(r) \propto r^{\alpha}$$

CORE
α ~ 0

CUSP
α ~ −1



Lazar, Bullock, Boylan-Kolchin etal arXiv:2004.10817

Self-Interacting Dark Matter

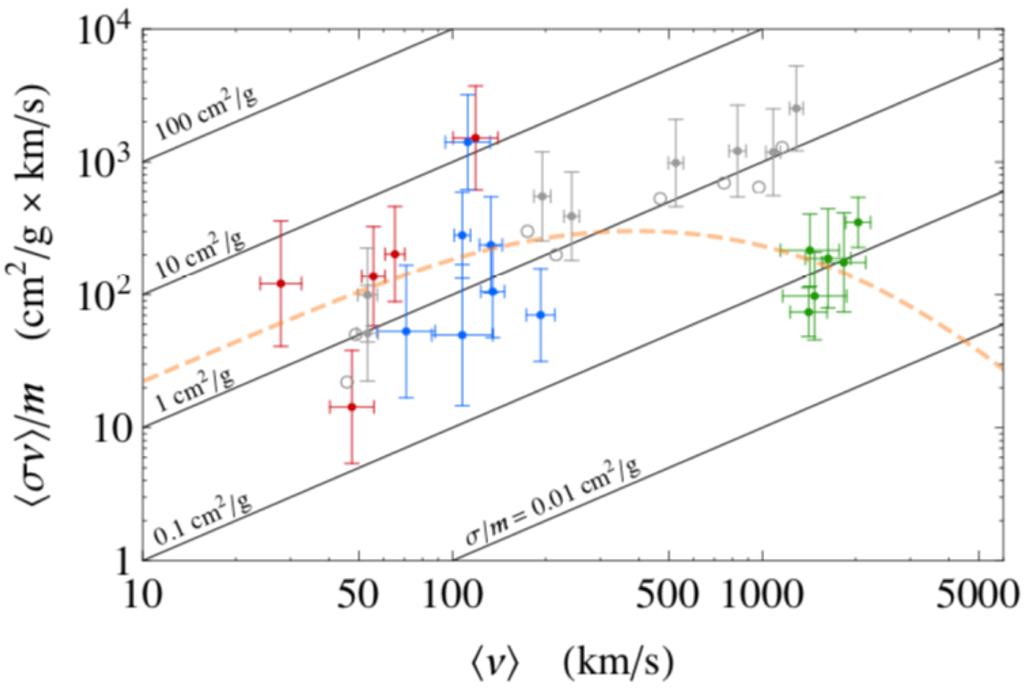


FIG. 1: Self-interaction cross section measured from astrophysical data, given as the velocity-weighted cross section per unit mass as a function of mean collision velocity. Data includes dwarfs (red), LSBs (blue) and clusters (green), as well as halos from SIDM N-body simulations with $\sigma/m = 1 \ \mathrm{cm}^2/\mathrm{g}$ (gray). Diagonal lines are contours of constant σ/m and the dashed curve is the velocity-dependent cross section from our best-fit dark photon model (Sec. V).

Can turn
Cusps
Into Cores

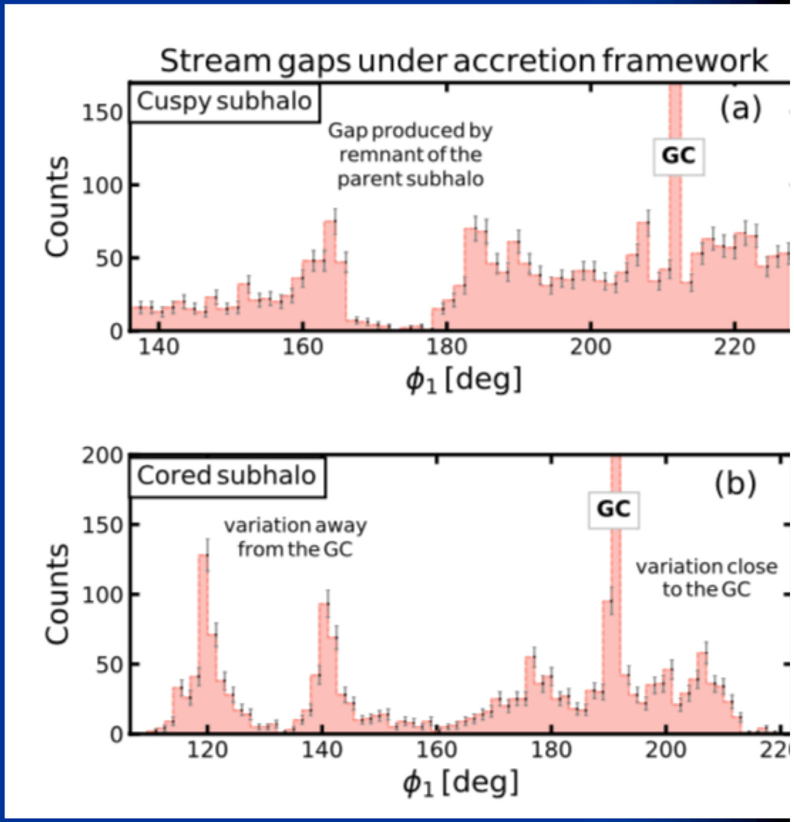
Kaplinghat,
Tulin, Yu,
1508.03339

Gaps in Stellar Streams as probes of DM

- When subhalos pass through stellar streams, they can create gaps. CDM predicts hundreds or thousands of subhalos.

Evidence of passage of subhalos ~ 10^7 M⊙ or less would strongly favor CDM over alternatives.

Our mechanism: longer, stronger interactions when microgalactic remnant of accreted subhalo passes through its own GC stream (they are on the same orbit).



(Bonaca etal for GD-1 stream, must be very compact million solar mass subhalo)

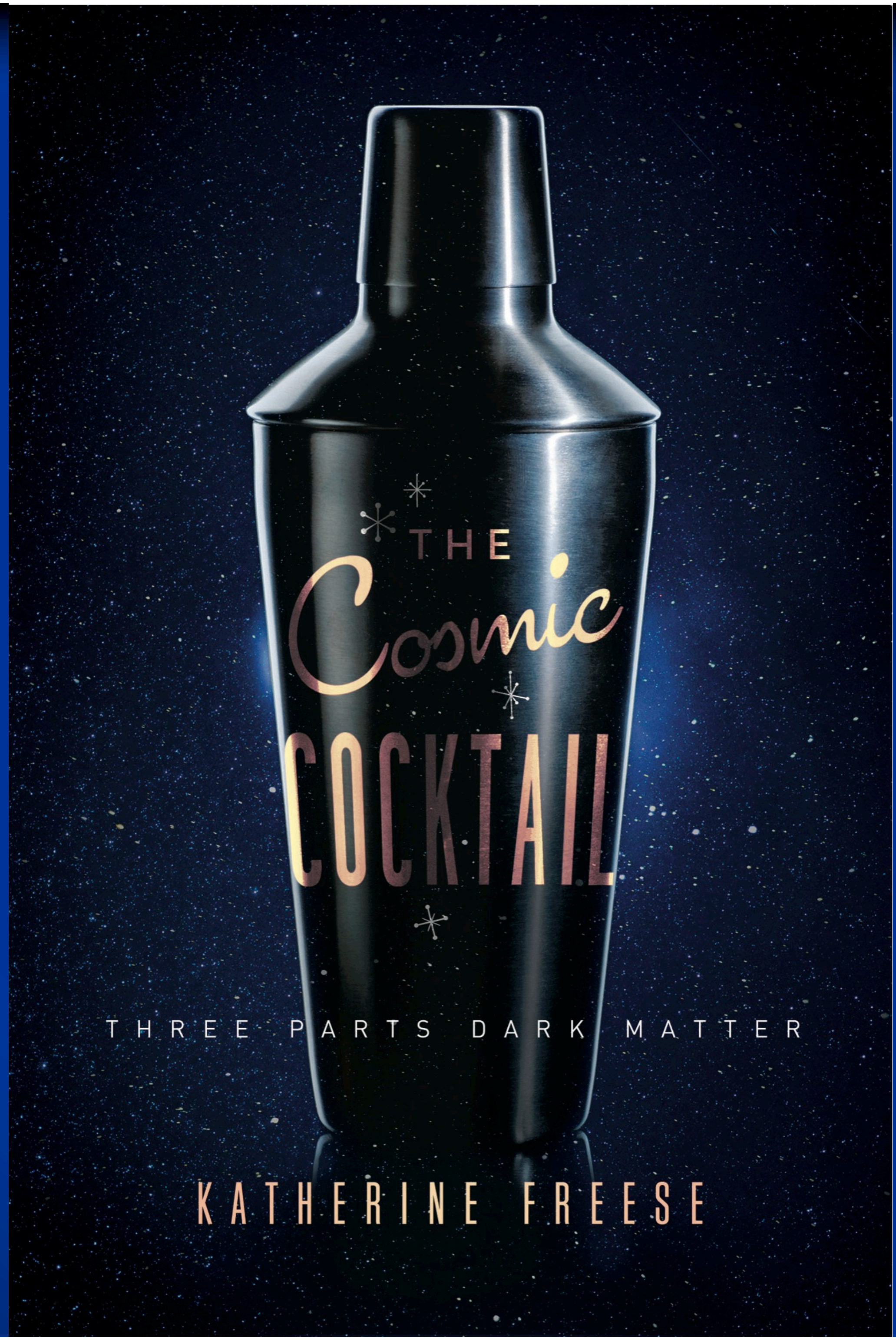
GAIA tests Cold Dark Matter hypothesis

- 1) Cored vs. cuspy (as predicted by CDM) subhalos produce streams of different widths
- 2) Gaps in streams: if produced by substructure of less than $10^7 M_\odot$, then it cannot be SIDM or WDM but CDM is good fit.
- 3) Shape of Milky Way Halo.
  CDM predicts triaxial. (Vasiliev, Valluri in progress)
- 4) Better estimates of local dark matter density
  ~0.3 GeV/cm^3 (Pablo Fernandez deSalas, Sofia Sivertsson) using Jeans equation

Summary

- 1) Neutrino mass ~ 0.1 eV. We are close to knowing the answer. Cosmology is very powerful.
- 2) WIMP searches: what is going on with DAMA? It is not Spin-Independent.

  COSINE-100 is testing it.
- 3) Dark Stars: the first stars could have been powered by Dark Matter rather than by fusion. Powered by WIMPs or SIDM or …
- 4) New ways to test nature of DM: GAIA satellite and stellar streams as a test of Cold Dark Matter


THE
Cosmic
COCKTAIL
THREE PARTS DARK MATTER
KATHERINE FREESE