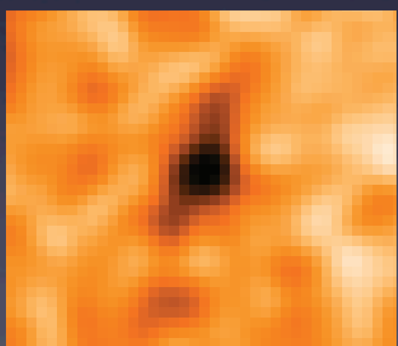
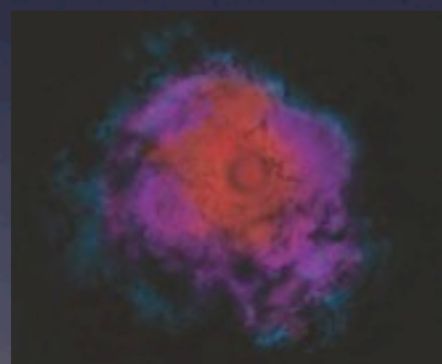
Dark Matter and Light

Douglas Spolyar

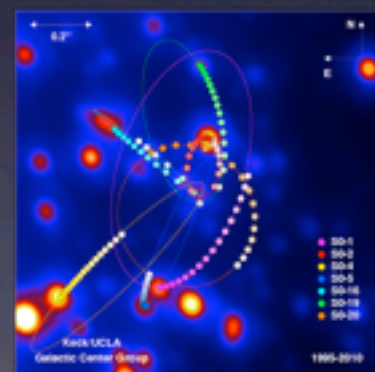
IAP



Dark Star?



Dark Stars then

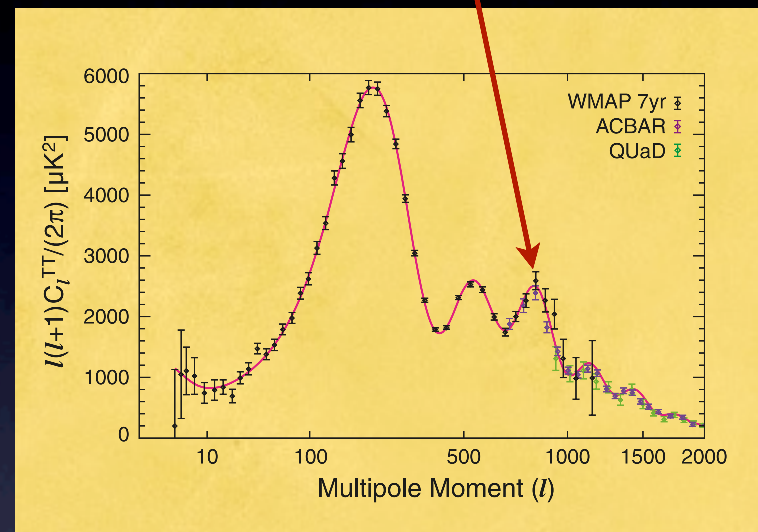


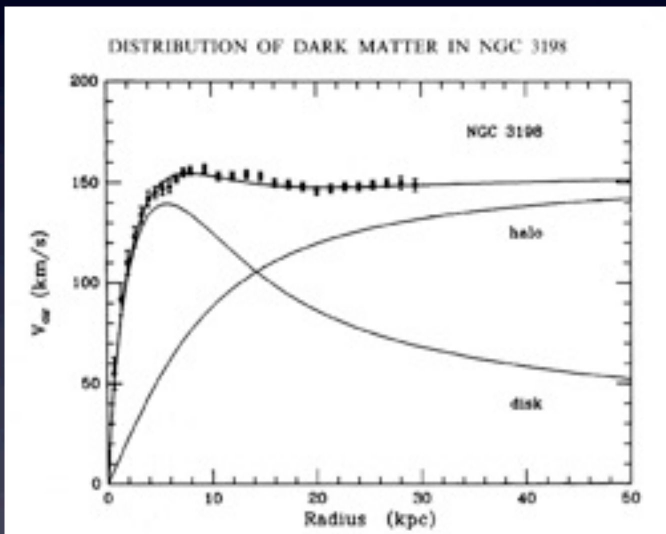
Dark Stars Now

Invisible Effects of DM

The gravitational effects of DM are well know from rotation curves, the bullet cluster, the CMB, etc...

CMB
3rd Peak DM





rotation curves

lensing

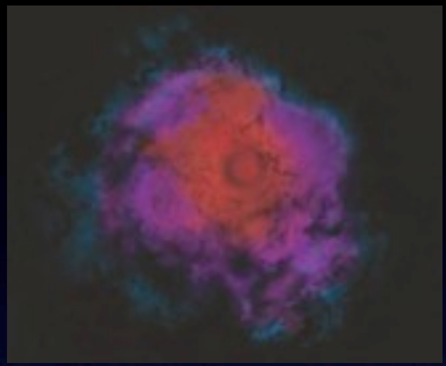
bullet Cluster

Instead, we will see how DM can change the evolution of Universe beyond purely its gravitational effect.

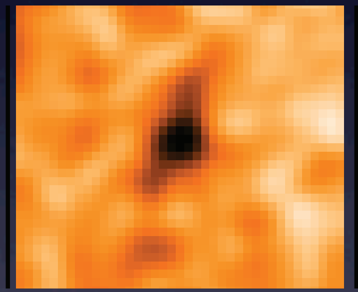
Possible Visible Effects

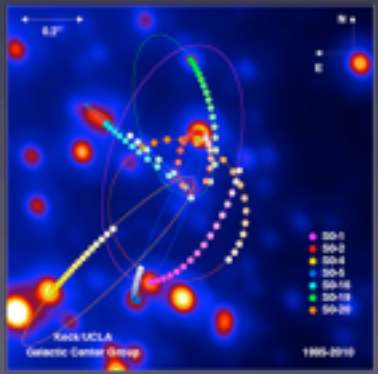
1. DM (dark matter) can dramatically alter the nature of the first stars, by powering the first stars. ie dark stars
2. Dark Stars may also live TODAY at the galactic center of our own galaxy

OutLine



- DarkStars Then (red shift 10-20)
- Review DM and first stars
- Basic Scenario
- Observational Effects HST/JWST
- DM spikes
- DarkStars Now (Galactic Center)
    - Time Permitting





WIMP Primer

- Weakly-Interacting Massive Particles (one type of CDM)
- Dark because no electromagnetic interactions
- Cold because very massive ($\sim$10 GeV to $\sim$10 TeV)
  $\Longrightarrow$ good for structure formation
- Non-baryonic and stable - no problems with BBN or CMB
- Weak-scale masses and annihilation cross-sections *naturally* lead to a relic abundance of the right order of magnitude
- Many theoretically well-motivated particle candidates (e.g. lightest neutralino in R-parity conserving supersymmetry, lightest Kaluza-Klein boson in extra-dimensional models)
- Weak interaction means scattering off nuclei $\rightarrow$ direct detection experiments
- Almost all WIMPs are Majorana particles (own antiparticles) $\Longrightarrow$ self-annihilation cross-section

Other good CDM candidates exist axions, primordial BHs, etc

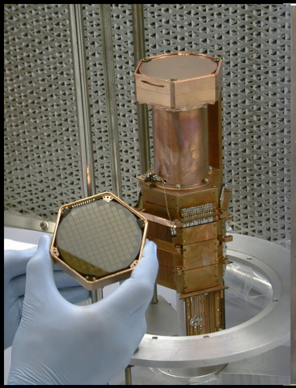
P. Scott

Current searches for WIMP Dark Matter

- Accelerators
- Direct detection
- Indirect detection (neutrinos)
  - Sun
  - Earth
- Indirect detection (gamma-rays, positrons, antiprotons)
  - Milky Way halo
  - External galaxies
  - Galactic Center

LHC

CDMS



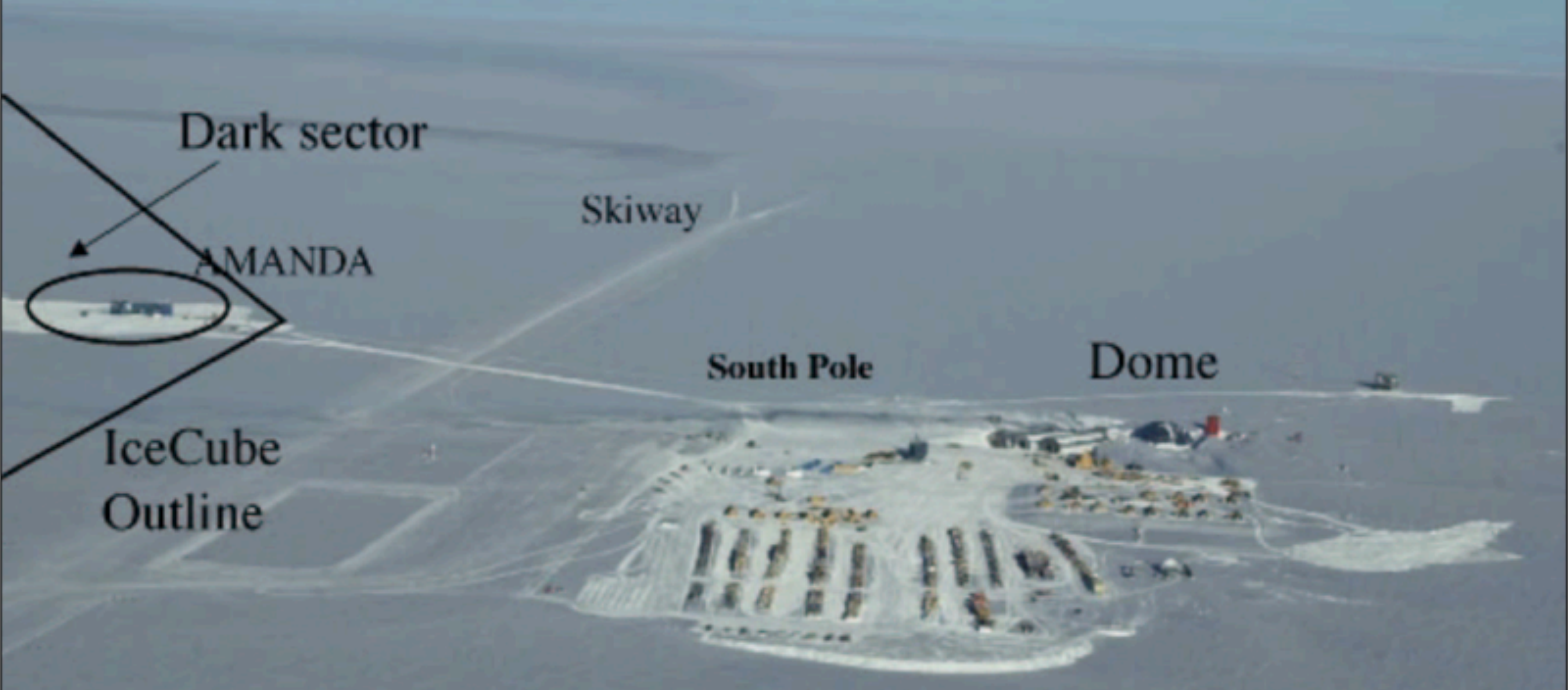
XENON

Fermi

IceCube

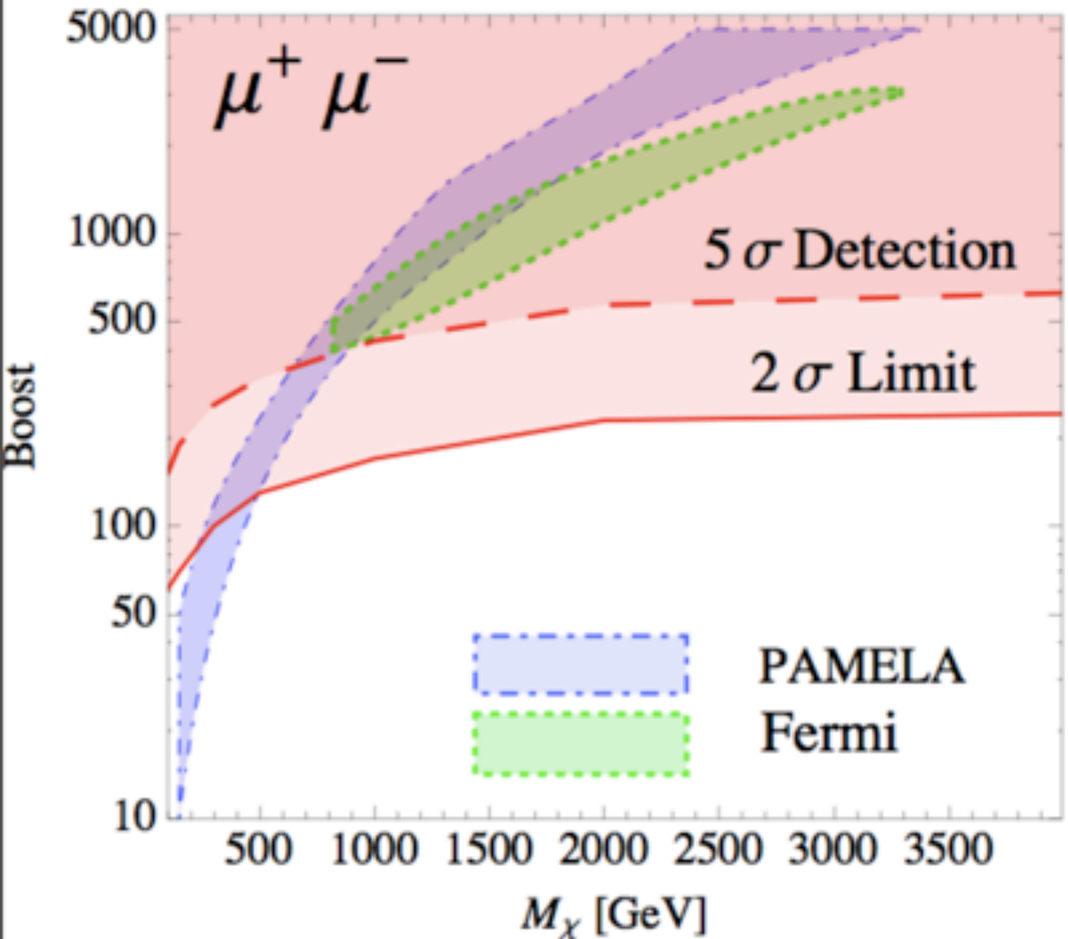
PAMELA

IceCube at the South Pole



Dark Matter Can produce neutrinos
Detectable by IceCube

Neutrino Bounds



- 5 years of Data
- assume NFW profile
  - similar to Isothermal sphere factor of 2 smaller
- no Substructure (additional boost of 2)

Bounds calculated with poisson statistics assuming a few sigma excess over background

with M. Buckley, K. Freese, D. Hooper, S. Mandal, & H. Murayama

Calculate background with Honda etal 2006

Dark-Star Spotter's Guide to the Universe

a definition of a 'Dark Star': any star whose structure or evolution has ben effected by DM annihilation

→ There are Many kinds of dark stars....

- **Main Sequence stars**- fed by scattering (salati, Spergel, Press, Scott, Fairbairn, iocco, Freese)

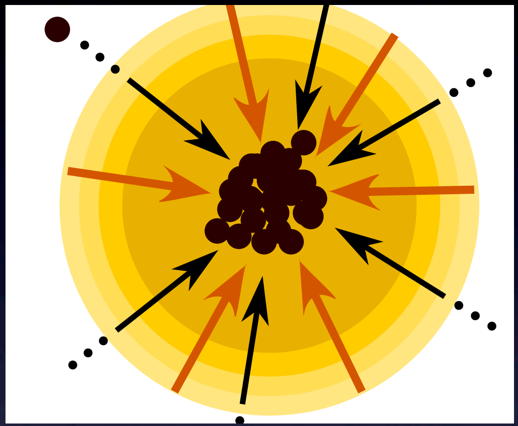
- **White dwarfs**- fed by scattering (Moskalenko, Wai, Fairbairn, etc.)

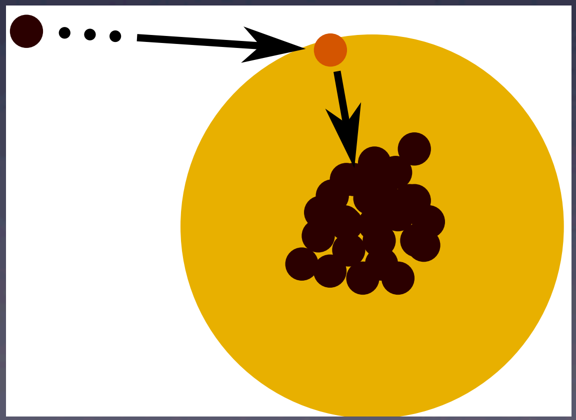
- Nuetron stars in the MIlky Way -fed by scattering (Fairbairn, Bertone)-considered any compact star

- The first stars in the early Universe - fed by scatter and by gravitational contraction (Spolyar, Freese, Iocco, Gondolo)

Two ways of concentrating dark

- *Gravitationally*:

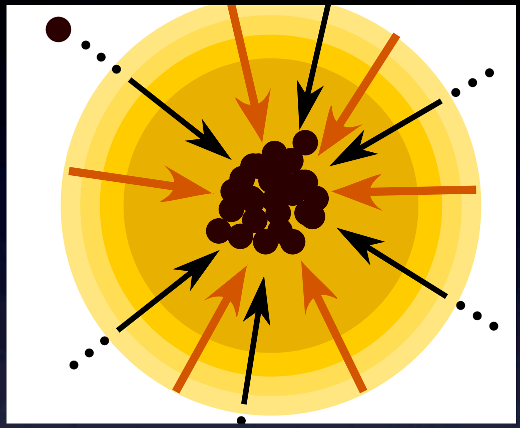


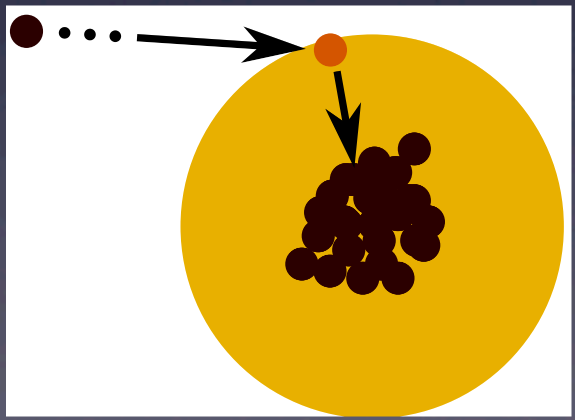


graphics P. Scott

Two ways of concentrating dark

- *Gravitationally*: when object forms, dark matter is dragged in deeper and deeper into the potential well
  - adiabatic contraction of galactic halos due to baryons (e.g. Blumenthal et al 1986)
  - dark matter concentrations around black holes (Gondolo, Silk 1999) Important for dark stars at the galactic center
  - dark matter contraction during formation of first stars (Spolyar, Freese, Gondolo 2007)





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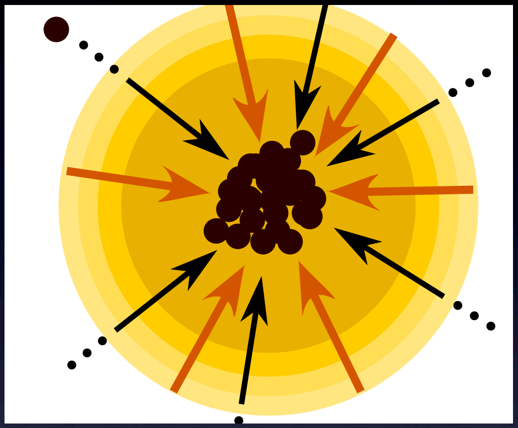
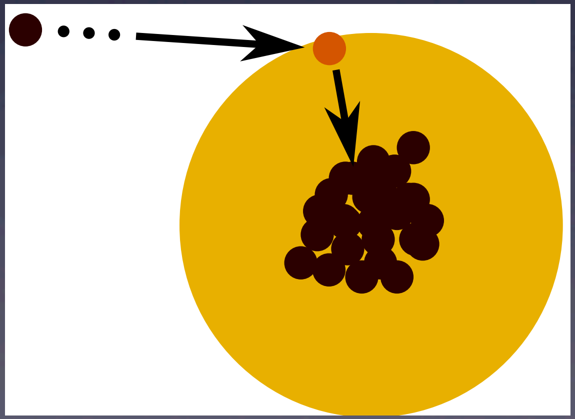


- Dark matter scatters elastically off baryons and is eventually trapped
  - Sun and Earth, leading to indirect detection via neutrinos
  - stars embedded in dense dark matter regions ("dark matter burners" of Moskalenko & Wai 2006, Fairbairn, Scott, Edsjo 2007)
  - dark matter in late stages of first stars (Freese, Spolyar, Aguirre; Iocco; Iocco et al; Taoso et al 2008)



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Dark Stars in the early universe

- Dark Stars modify the *reionization history of the universe*, and thus the expected signals in future 21 cm surveys
- Dark Stars change the production of heavy elements and the *chemical abundances of the oldest stars*
- Dark Stars may evolve into *intermediate-mass or supermassive black holes*, providing a mechanism for their early formation
- Dark Stars are a *new indirect detection method* to search for WIMPs

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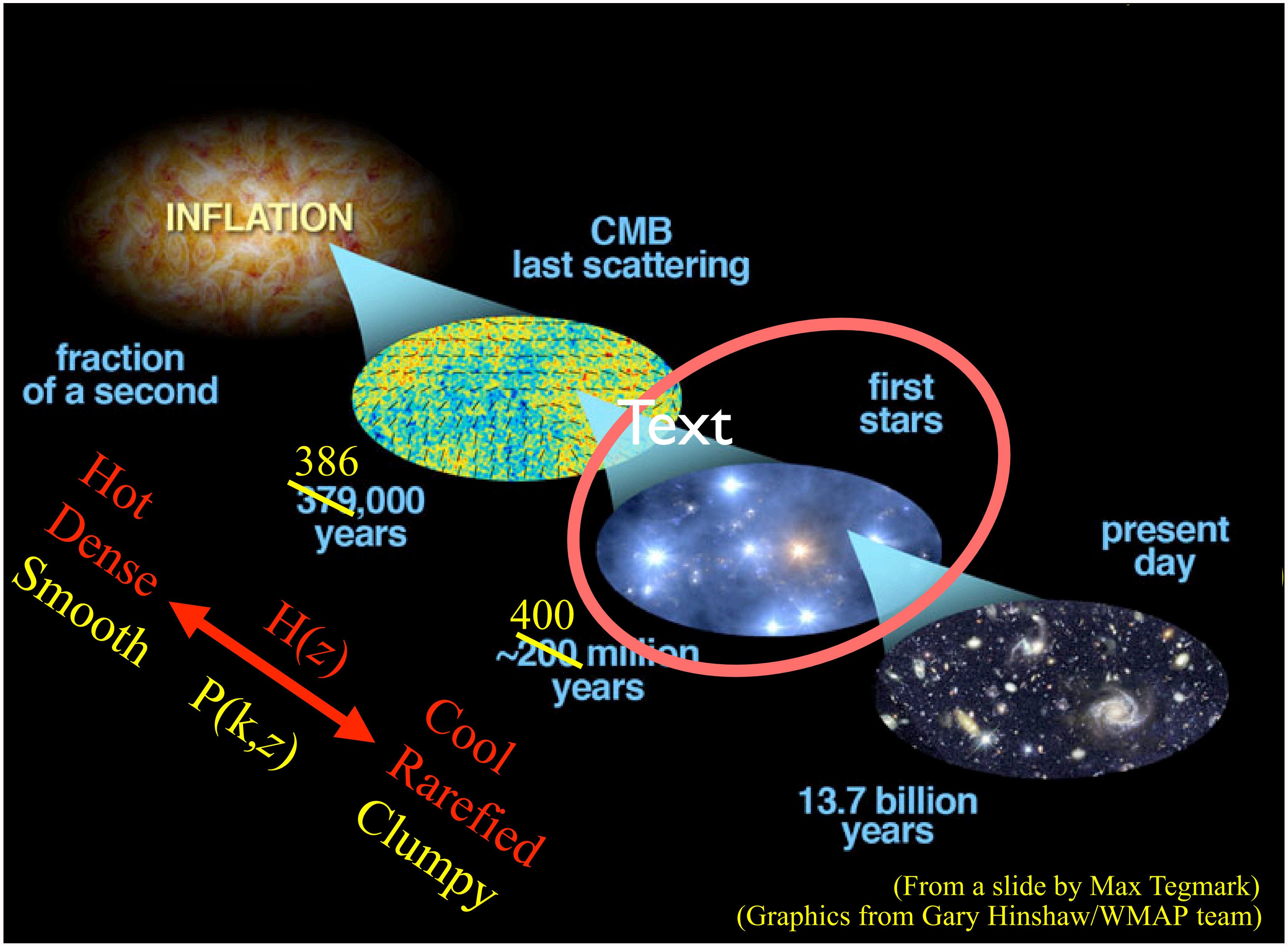
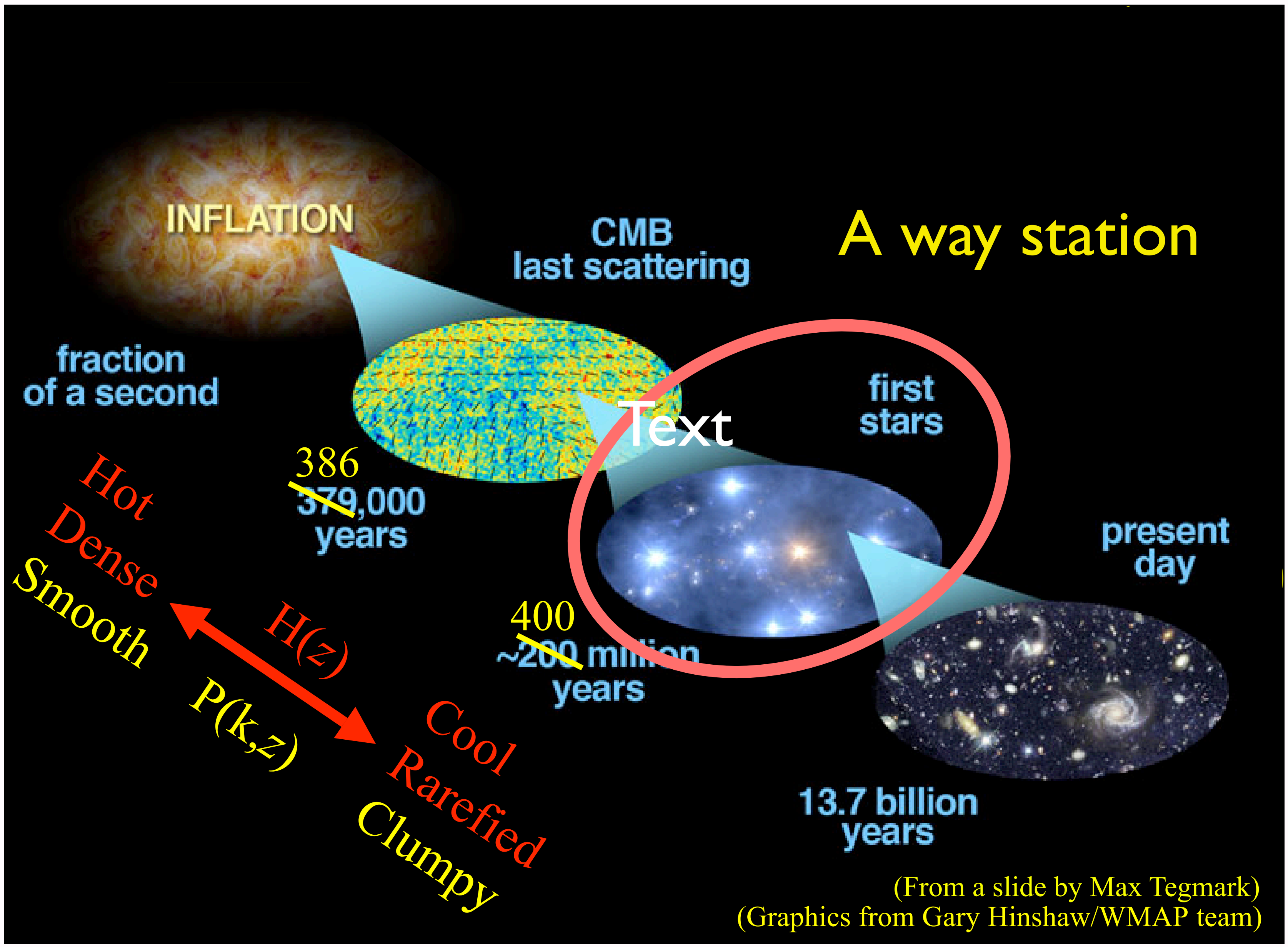
Dark Matter annihilation can dramatically alter the formation of the first structures in the universe.

The First Stars (Population III stars)

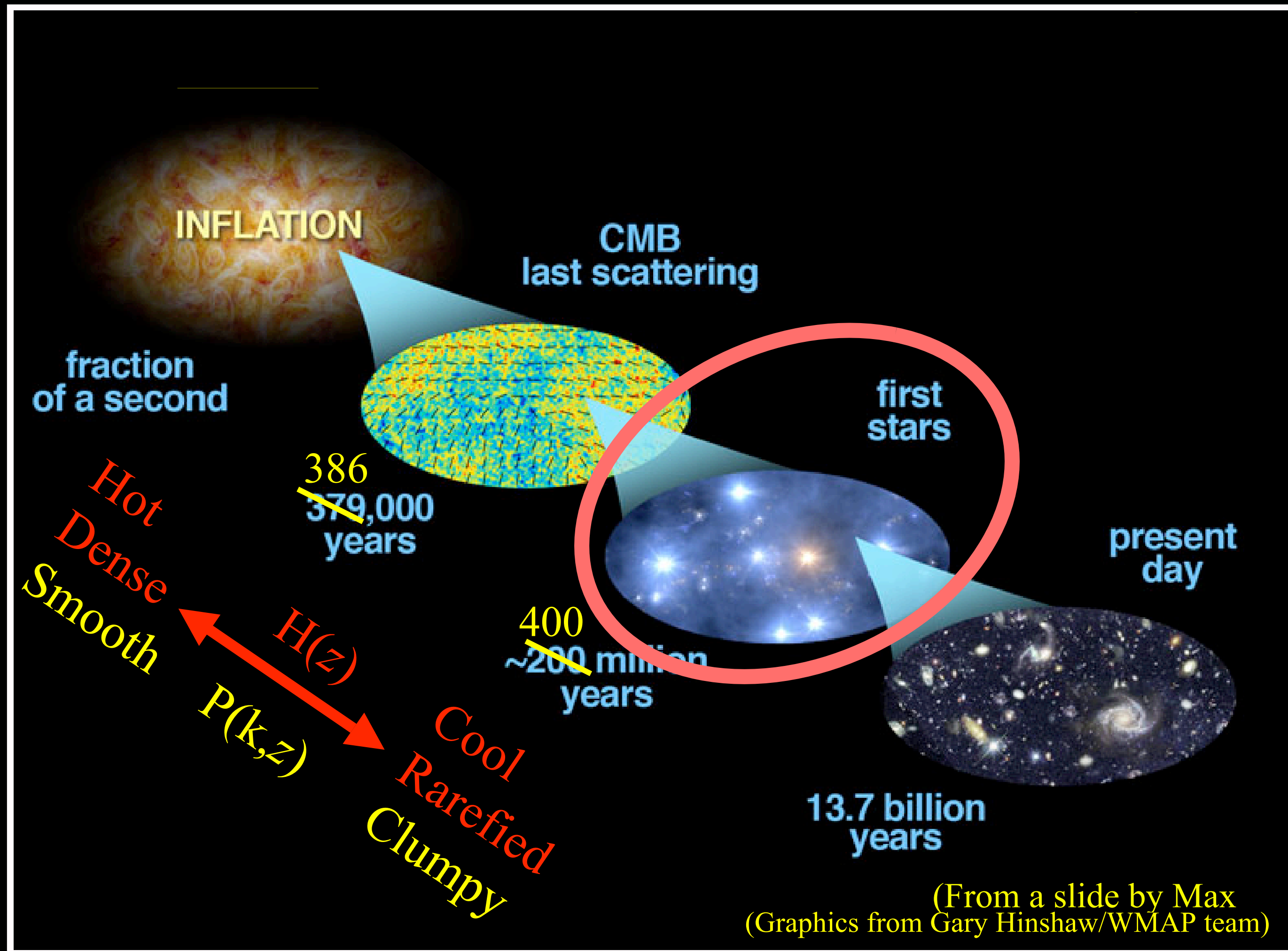


The First Stars (Population III stars)



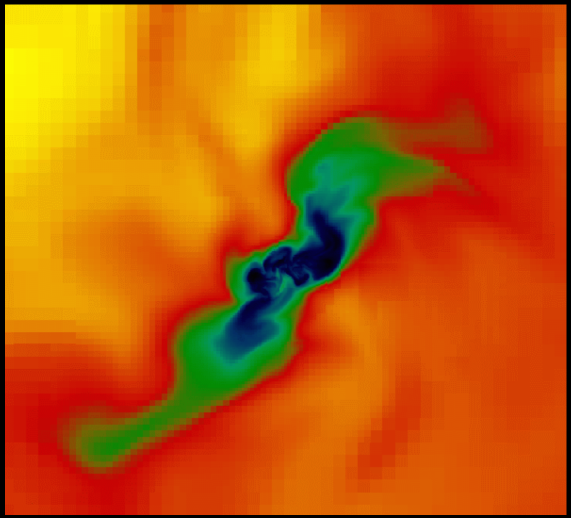
The First Stars (Population III stars)

- Important for
  - end of Dark Ages
  - reionize the universe
  - provide enriched gas for later stellar generations

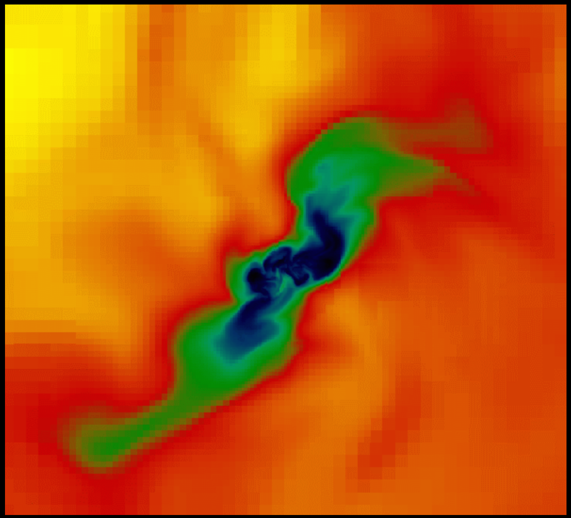


(From a slide by Max
(Graphics from Gary Hinshaw/WMAP team)

First Stars: Standard Picture



First Stars: Standard Picture



- Formation Basics
  - first luminous objects ever
  - made only of H/He
  - form inside DM halos of 10^5-10^6 $M_\odot$
  - at redshift z=10-50
  - baryons initially even distributed over halo
    - 15% of the halo mass
  - formation is a gentle process
- Dominant cooling mechanism to allow collapse into star is H_2 cooling (Hollenbach & McKee 1979)

Hierarchical Structure

Smallest objects form first (sub earth mass)

Merge to ever larger structures

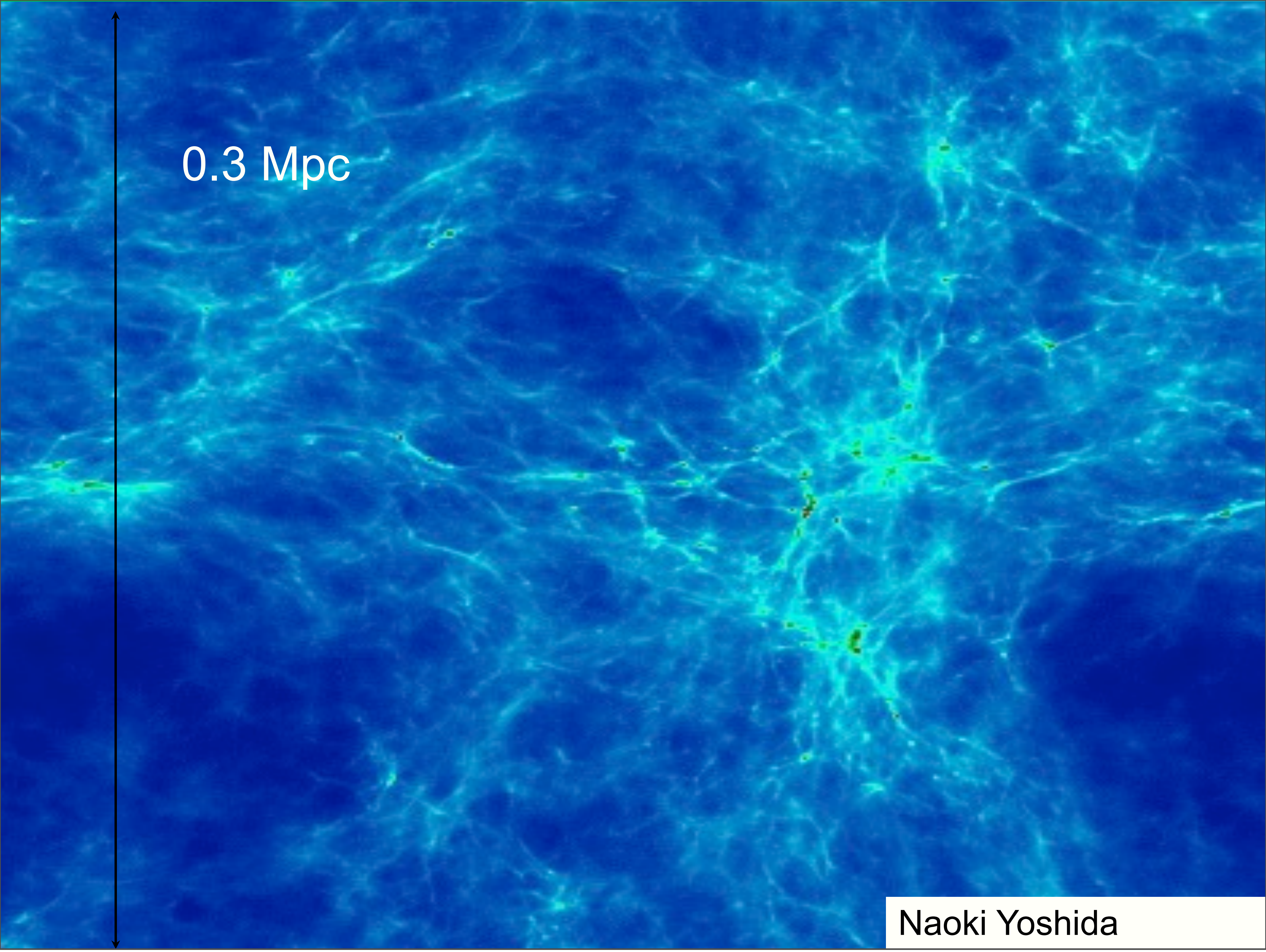
Pop III stars (inside $10^6\,M_\odot$ haloes) first light

Merge → galaxies

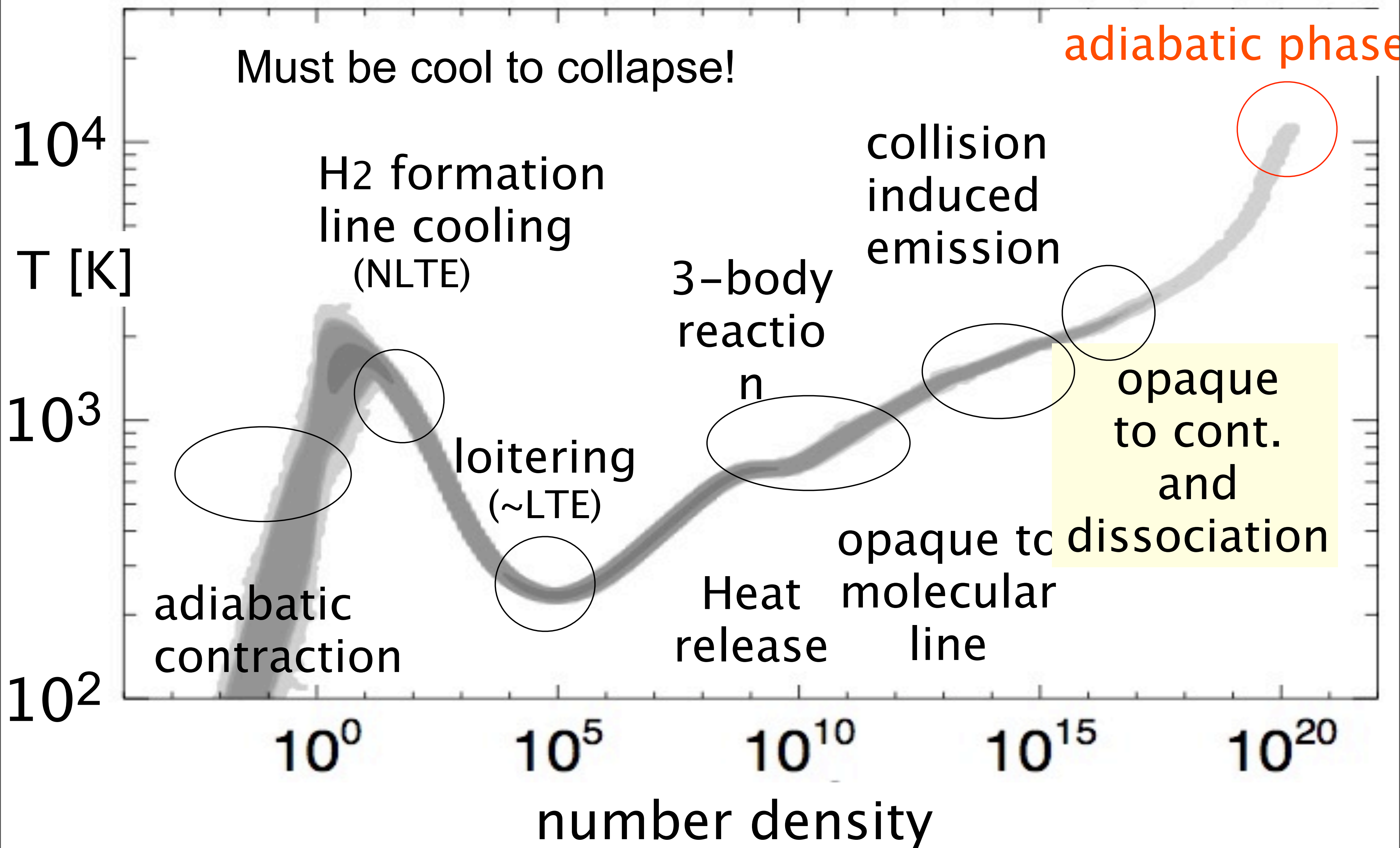
Merge → clusters

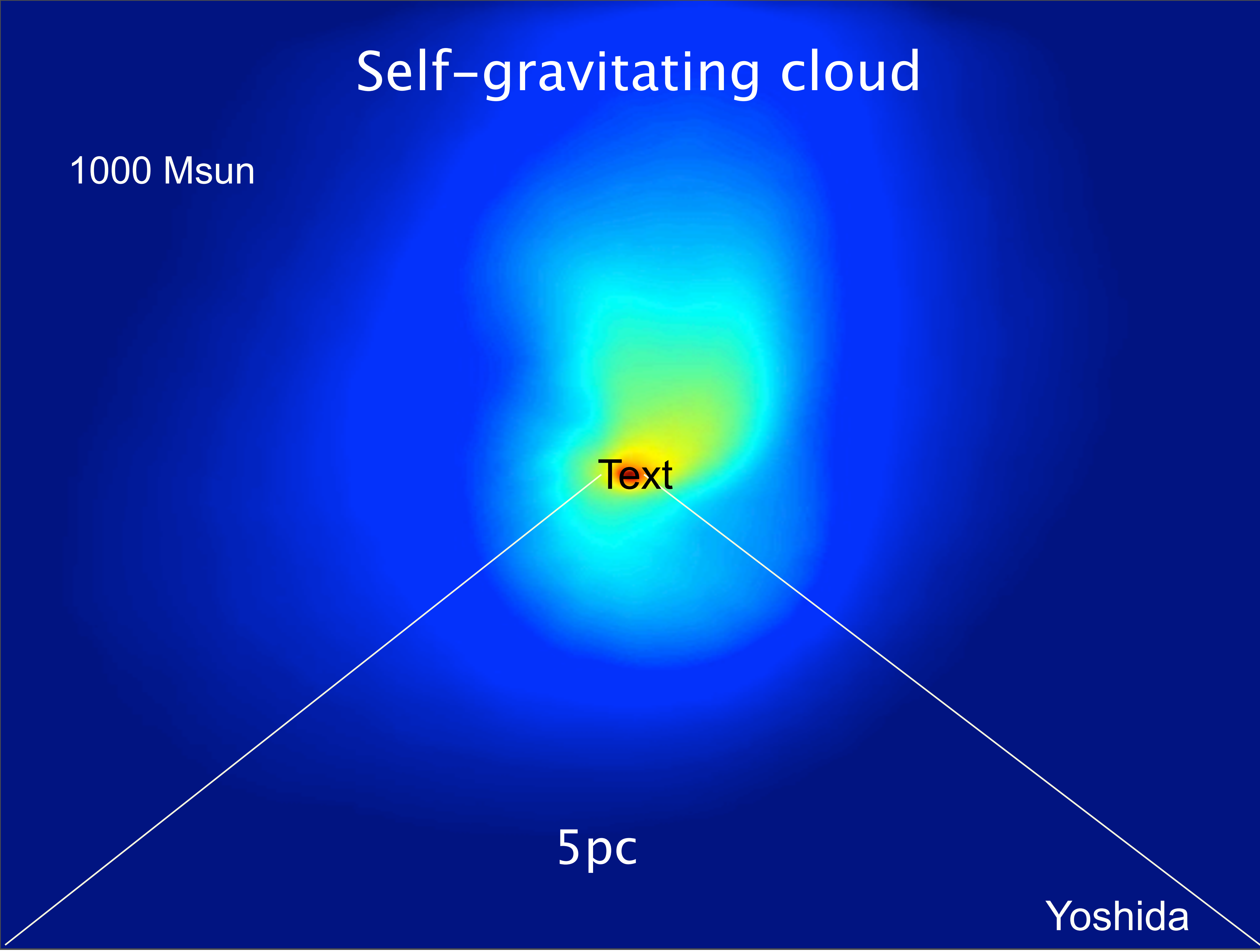
→

→

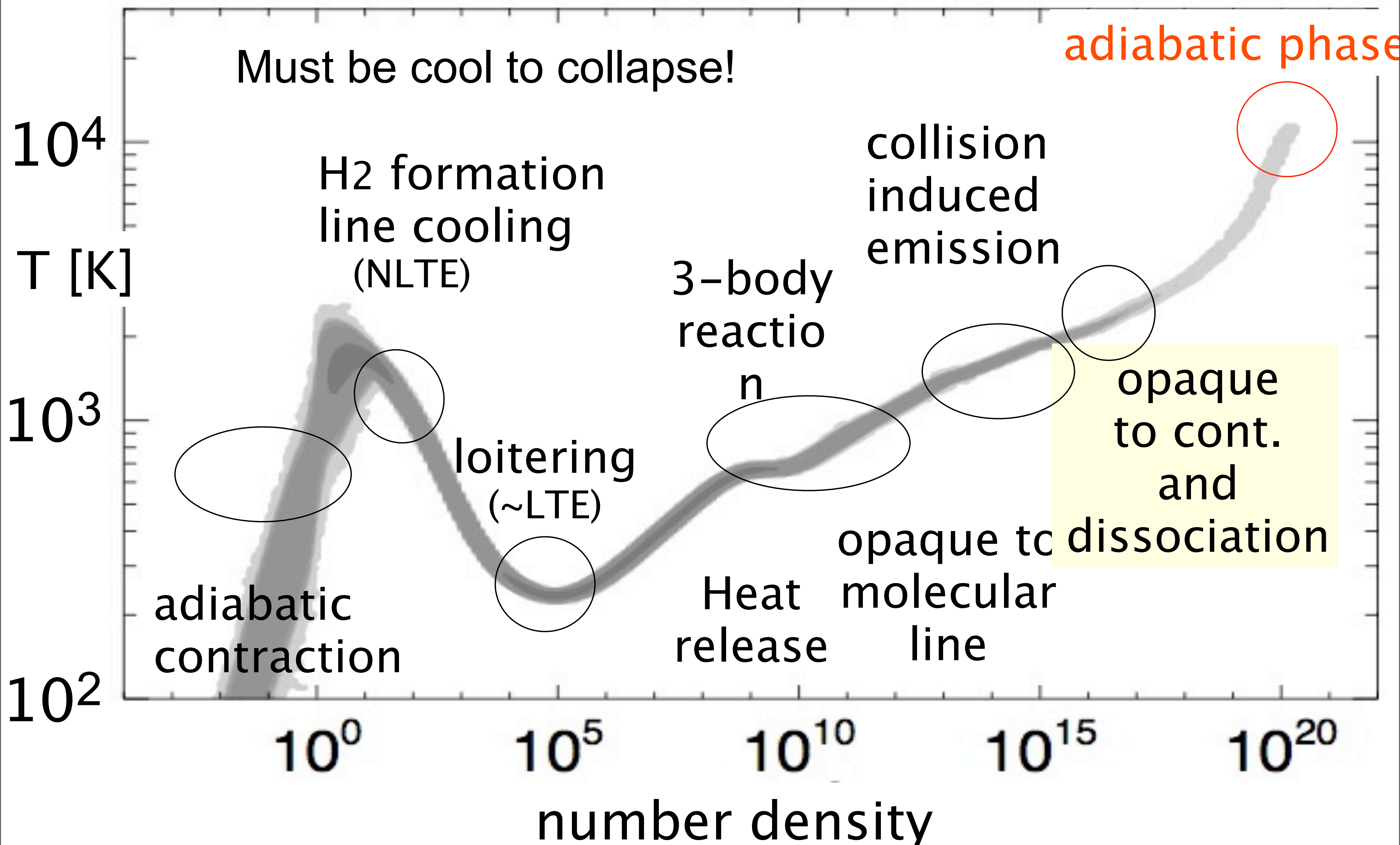

0.3 Mpc
Naoki Yoshida

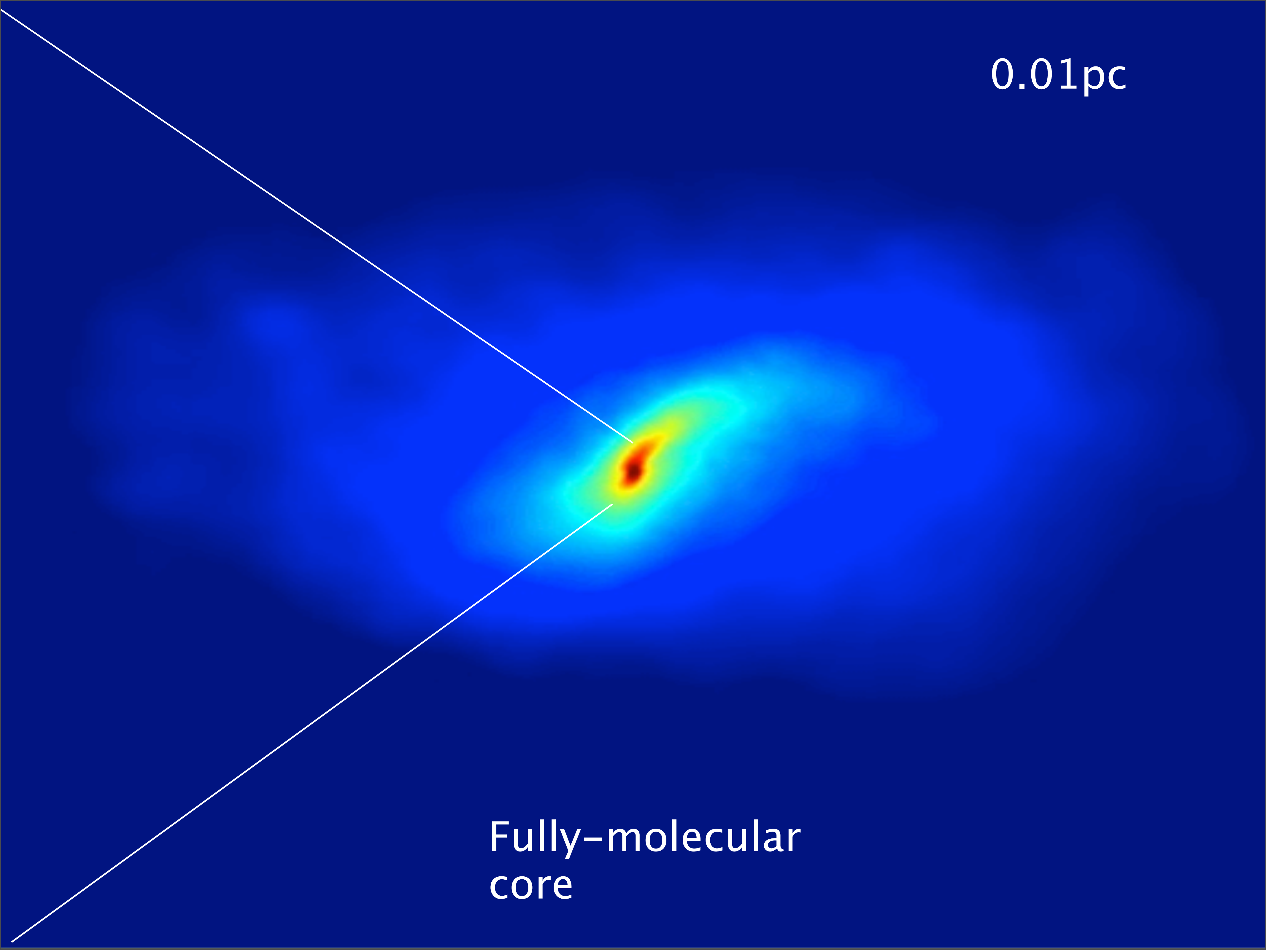
Thermal evolution of a primordial gas



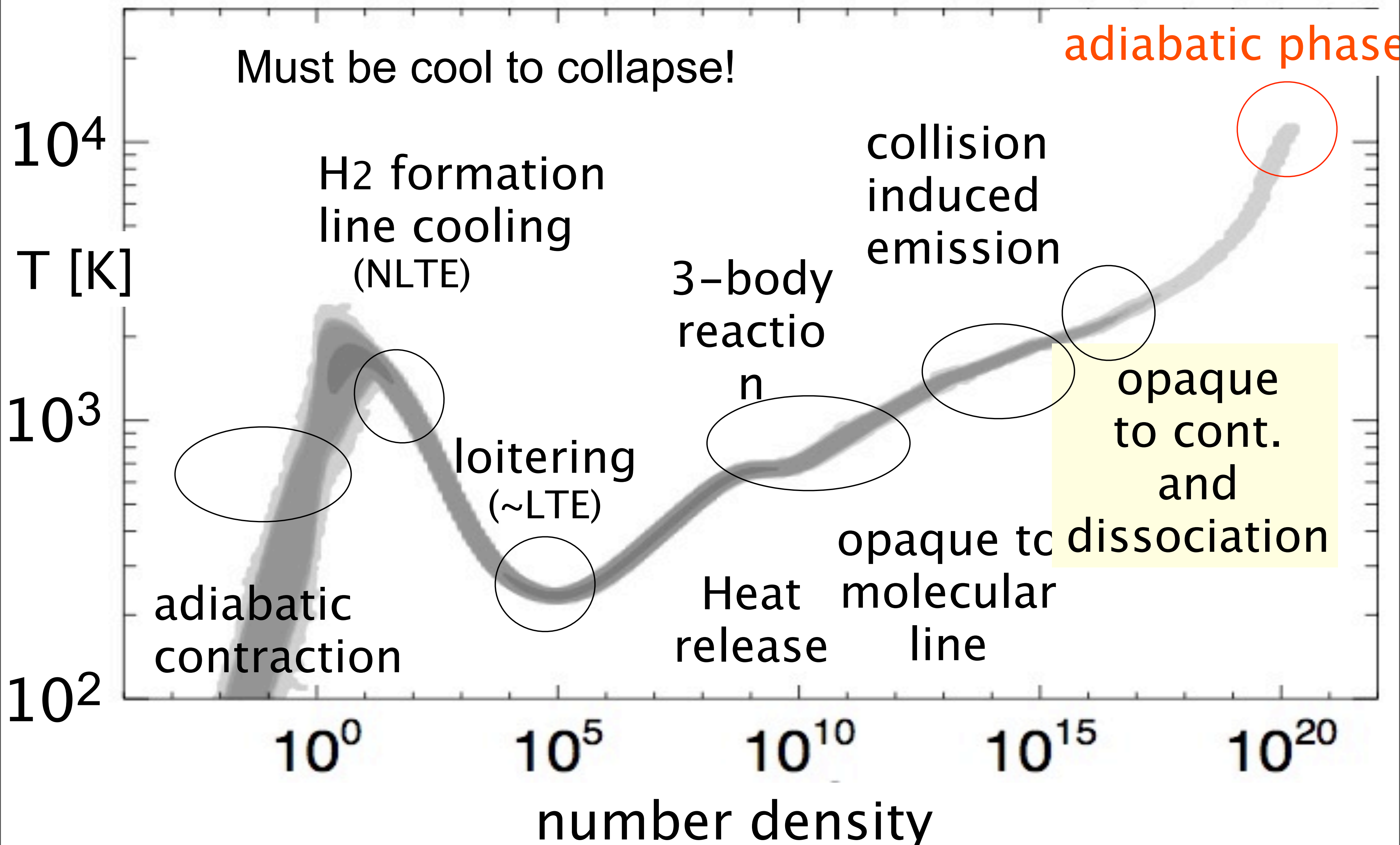

Self-gravitating cloud
1000 Msun
Text
5pc
Yoshida

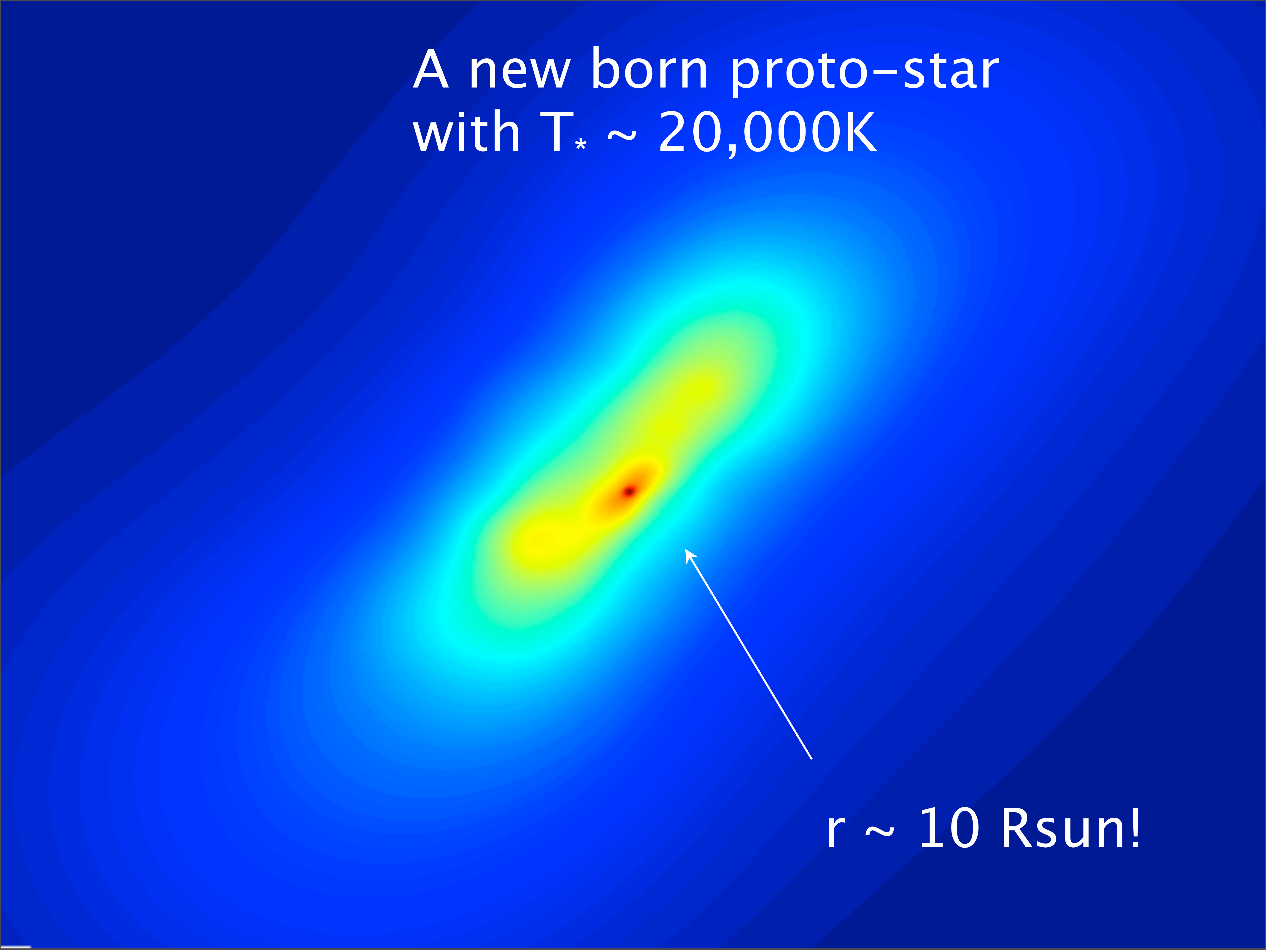
Thermal evolution of a primordial gas




0.01pc
Fully-molecular
core

Thermal evolution of a primordial gas




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

Scales

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

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

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

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

feedback effects
McKee and Tan 2008

Accretion

With DM heating
Much more massive

Final stellar Mass??

$100M_\odot$ Standard Picture

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

Dark Matter in Pop III Stars

- DM in protostellar halos alters the formation of Pop III stars
  - dark matter annihilation heats the collapsing gas cloud impeding its further collapse and halting the march toward the main sequence
- a new stellar phase results, powered by DM annihilation instead of nuclear fusion

WIMP Cold Dark Matter

Our canonical case:

$$\langle \sigma v \rangle_{\mathrm{ann}} = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \qquad m_\chi = 100 \text{ GeV}$$

- We consider
  - a range of masses (1 GeV - 10 TeV)
  - a range of cross sections
- Our results apply to various WIMP candidates
  - neutralinos
  - Kaluza-Klein particles
  - sneutrinos

Three conditions for Dark Stars

Spolyar, Freese, Gondolo, 2008 Paper I

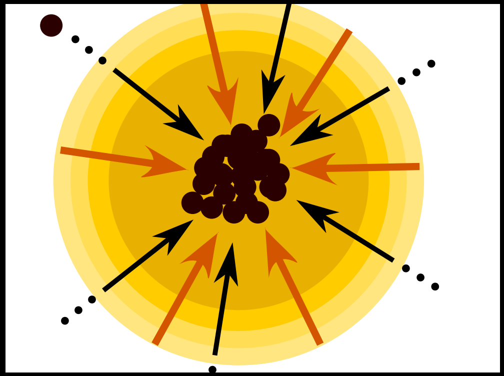
(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

Dark Matter Density Profile



- Adiabatic contraction
  - as baryons fall into core, DM particles respond to potential well
  - using prescription from Blumenthal, Faber, Flores, & Primack 1986

$$r\,M(r) = \mathrm{constant}$$

- We find a contracted profile

$$\rho_\chi(r) = k r^{-1.9} \text{ outside core}$$

$$\rho_\chi(\mathrm{core}) = 5\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}\left(\frac{n}{\mathrm{cm}^{-3}}\right)^{0.8}$$

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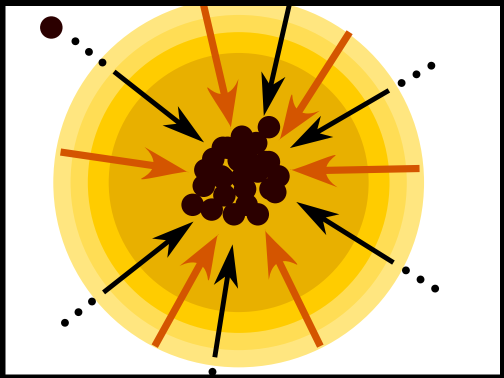

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vs. r^{-1}
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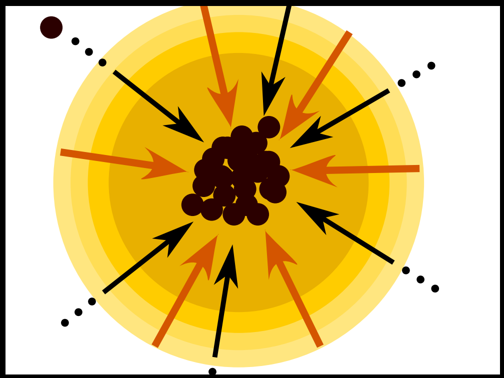

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(NFW profile)

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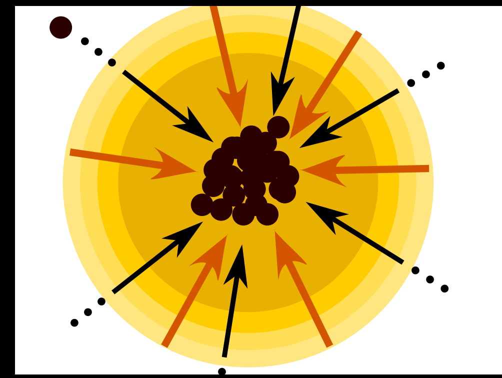

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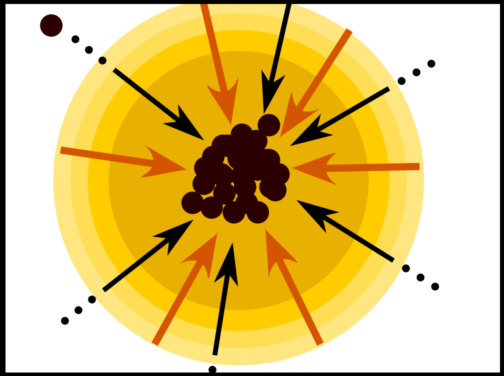
$\rho_\chi(r) = k r^{-1.9}$ outside core — vs. r^{-1} before contraction (NFW profile)

$$\rho_\chi(\text{core}) = 5\,\frac{\text{GeV}}{\text{cm}^3}\left(\frac{n}{\text{cm}^{-3}}\right)^{0.8}$$

(DM tracks the Baryons!)

Dark Matter Density Profile



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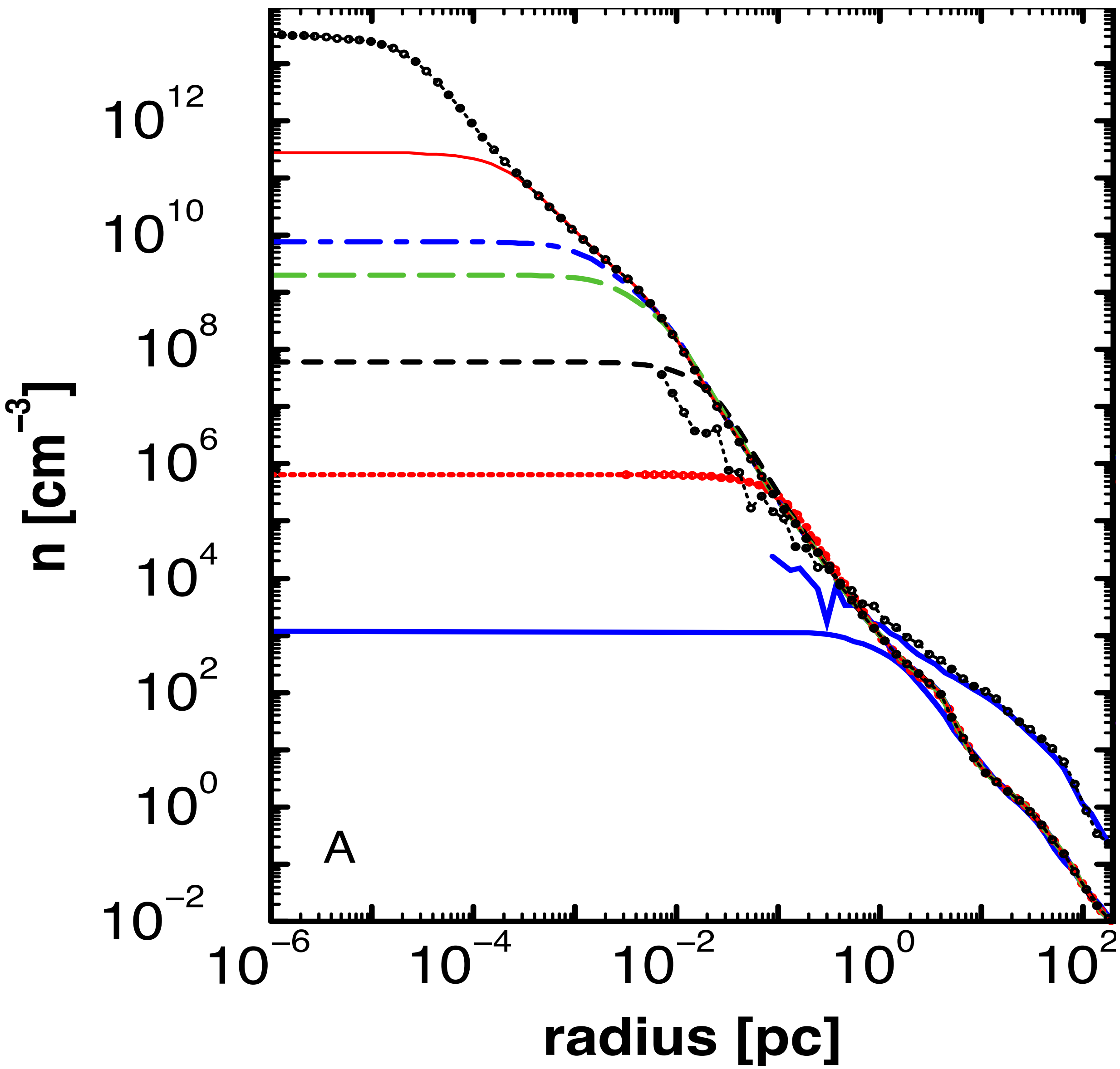
(DM tracks the Baryons!)

High Dark Matter densities!

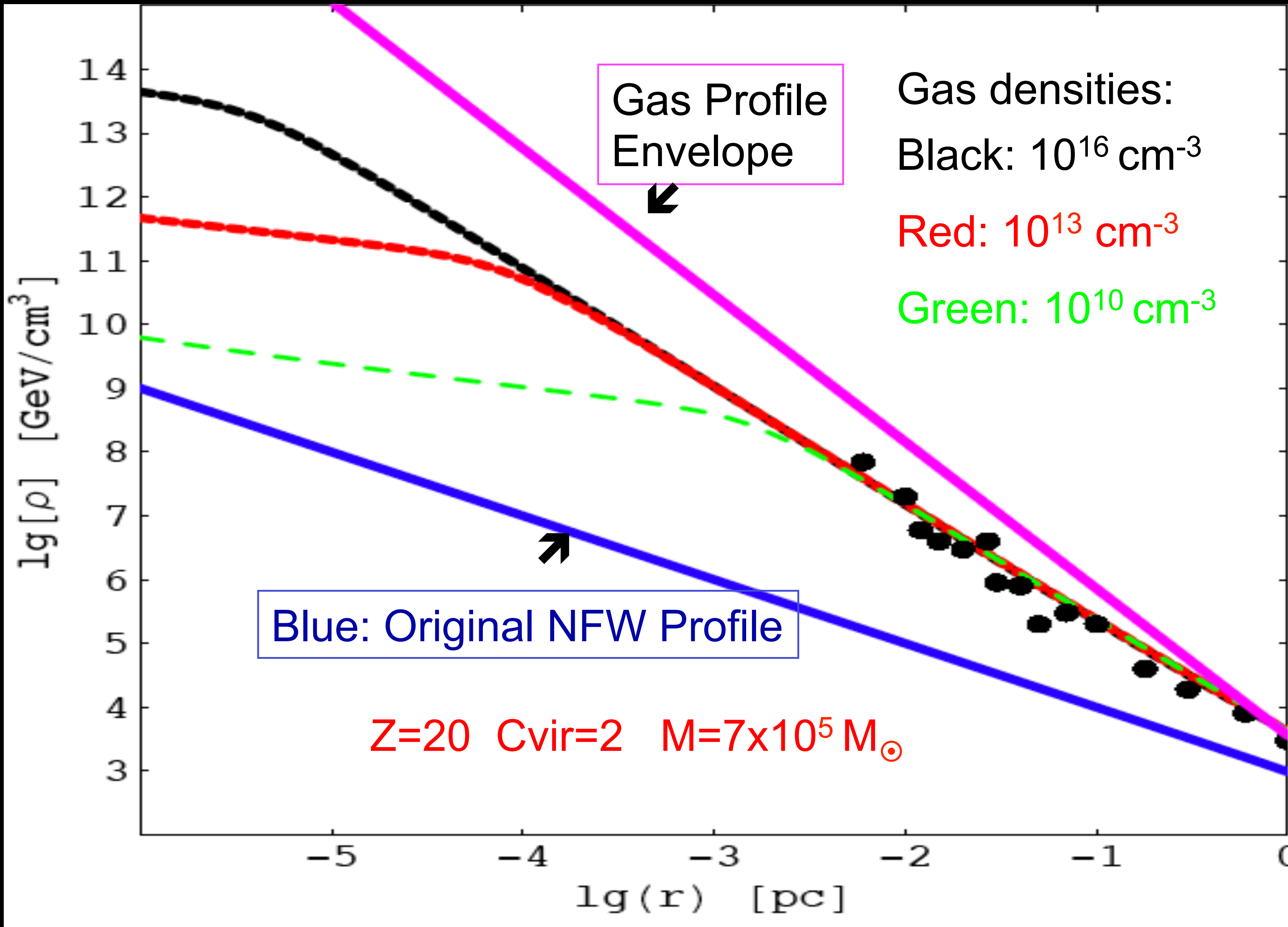
Dark Matter and Simulations



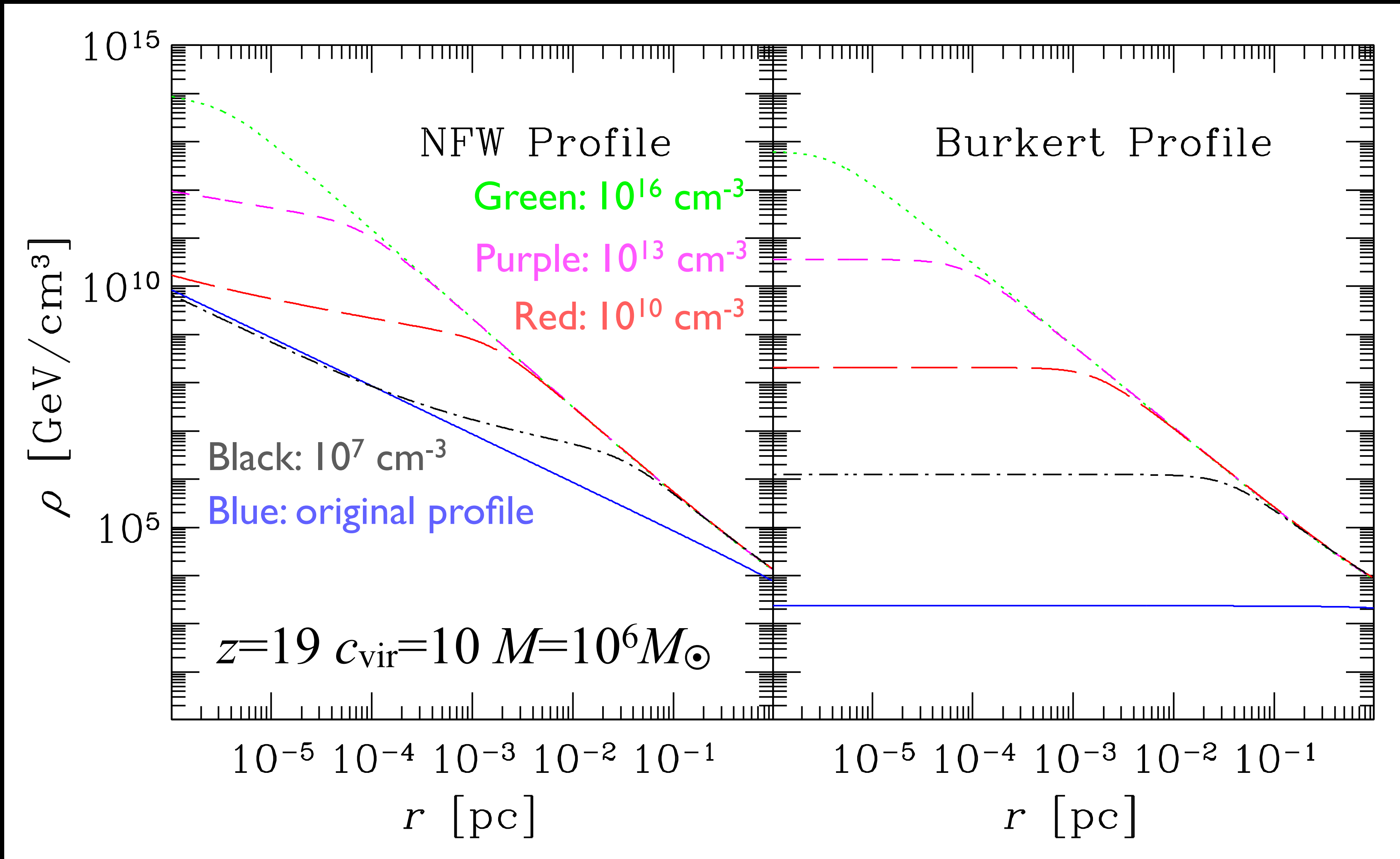
Central gas density increase
Dark Matter Density follows

Abel, Bryan, & Norman 2002

Dark Matter and Gas Profile



Dark Matter Profile: Adiabatic Contraction



Outer profile matches Abel, Bryan, & Norman 2002

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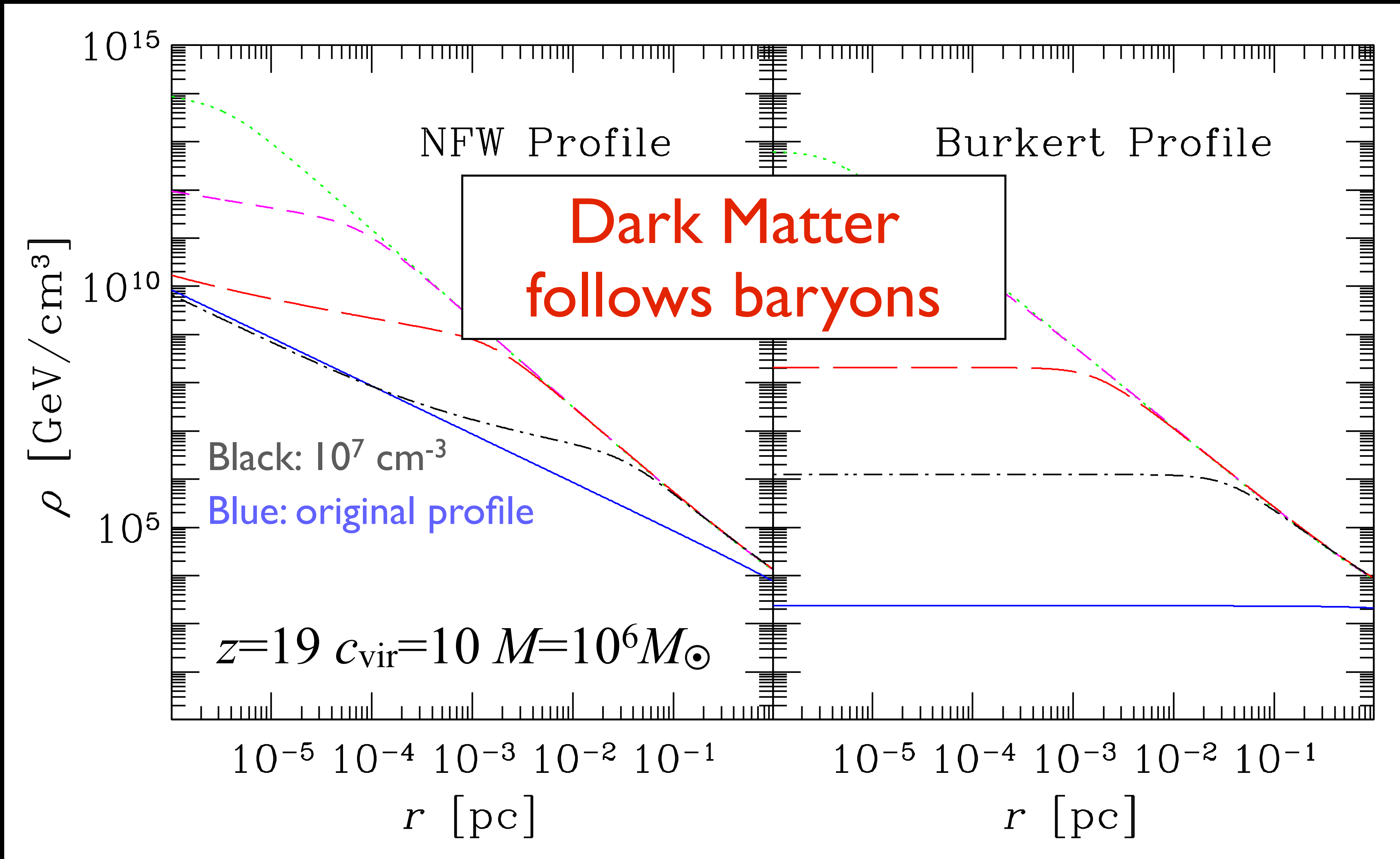

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Three conditions for Dark Stars

Spolyar, Freese, Gondolo 2007 aka Paper I

(1) Sufficiently high dark matter density to get large annihilation rate

(2) Annihilation products get stuck in star

(3) Dark matter heating beats H_2 cooling

Leads to new stellar phase

Dark Matter Heating

Heating rate $\Gamma_{\mathrm{DM\ heating}} = f_Q\, Q_{\mathrm{ann}}$

Rate of energy production from annihilation $Q_{\mathrm{ann}} = n_\chi^2 \langle \sigma v \rangle m_\chi = \dfrac{\rho_\chi^2 \langle \sigma v \rangle}{m_\chi}$

Fraction of annihilation energy deposited in gas f_Q (see next slide)

Previous work noted that at $n \leq 10^4$ cm^{-3} annihilation products simply escape (Ripamonti, Mapelli, & Ferrara 2007)

Annihilation energy deposited into gas

Estimate f_Q (better calculation in progress)

- 1/3 neutrinos, 1/3 photons, 1/3 electrons/positrons
- Neutrinos escape
- Electrons $\gtrsim E_\mathrm{c} \approx 280$ MeV $\longrightarrow$ electromagnetic cascades
  $\lesssim E_\mathrm{c} \approx 280$ MeV $\longrightarrow$ ionization
- Photons $\gtrsim$ 100 MeV $\longrightarrow$ electromagnetic cascades
  $\lesssim$ 100 MeV $\longrightarrow$ Compton/Thomson scattering

Annihilation energy deposited into gas

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  $\lesssim E_c \approx 280$ MeV $\rightarrow$ ionization
- Photons $\gtrsim 100$ MeV $\rightarrow$ electromagnetic cascades
  $\lesssim 100$ MeV $\rightarrow$ Compton/Thomson scattering

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

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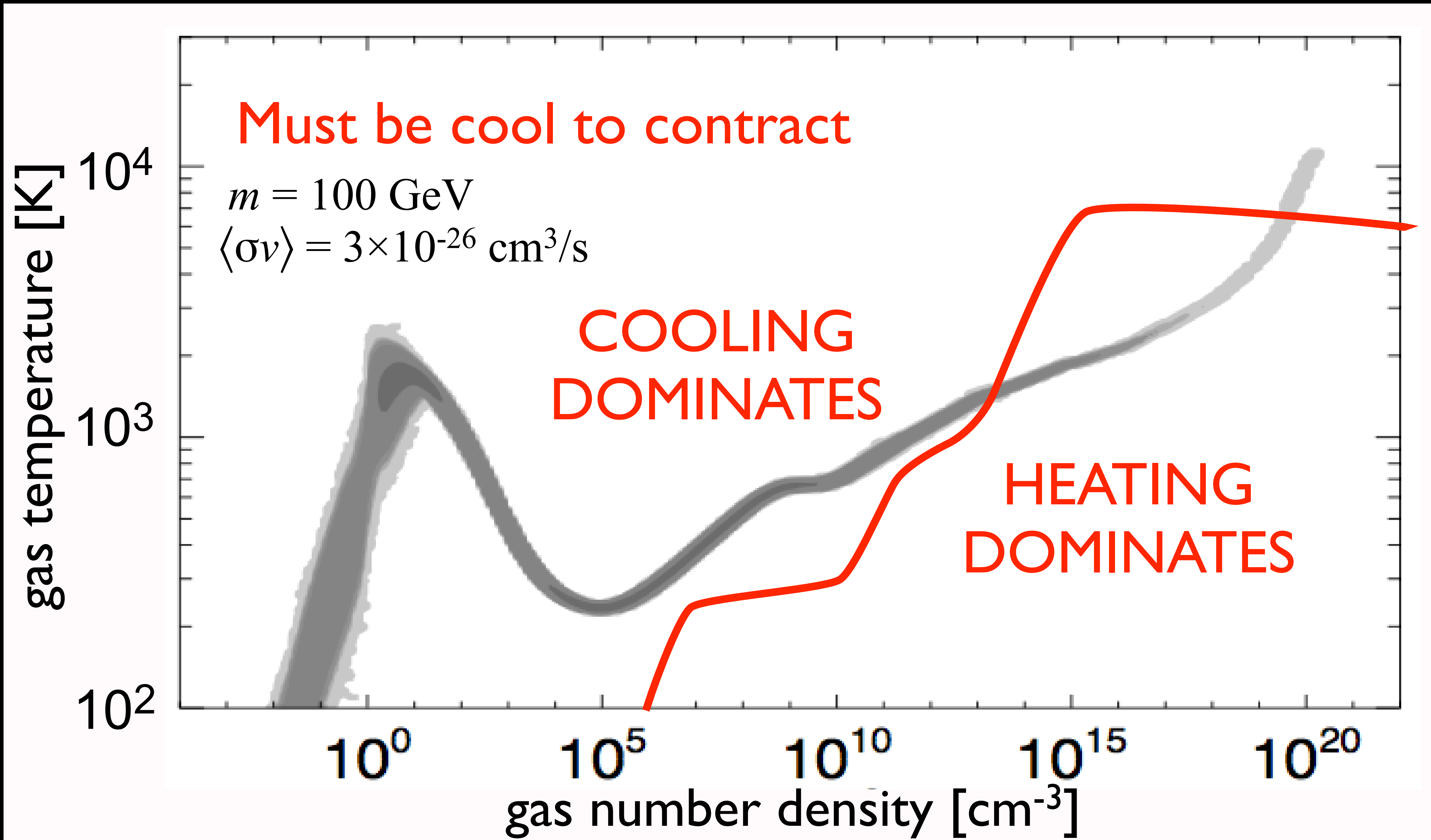
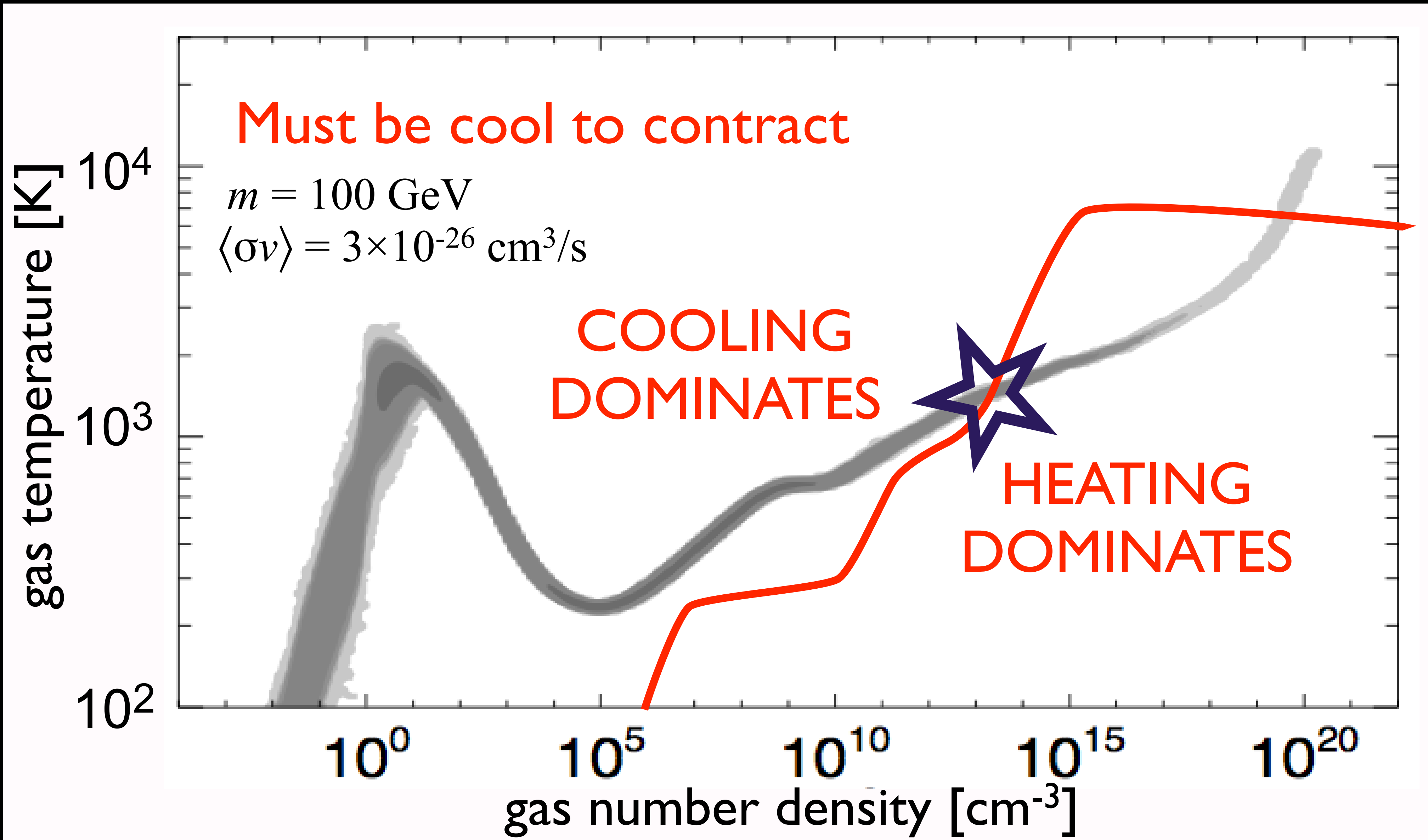
Crucial transition



Crucial transition



Crucial transition

- When

$$m_\chi \approx 1 \text{ GeV} \quad \longrightarrow \quad n \approx 10^9 \text{cm}^{-3}$$

$$m_\chi \approx 100 \text{ GeV} \quad \longrightarrow \quad n \approx 10^{13} \text{cm}^{-3}$$

$$m_\chi \approx 10 \text{ TeV} \quad \longrightarrow \quad n \approx 10^{15.5} \text{cm}^{-3}$$

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

Solving the 4 Equations of Stellar Evolution

$$\frac{dr}{dM} = \frac{1}{4\pi r^2 \rho}$$

$$\frac{dL}{dM} = \varepsilon$$

$$\frac{dP}{dM} = -\frac{GM}{4\pi r^4}$$

$$\frac{dT}{dM} = \frac{3\kappa_R L}{64\pi^2 r^4 \sigma T^3}$$

With boundary conditions:

R=0, L=0 at M=0

ρ=0, T=0 at M=M_s

$$P = \frac{\Re \rho T}{\mu}$$

Equation of State

Equilibrium Structure

- Pre-main sequence stars are well described as polytropes in hydrostatic equilibrium

$$P = K\rho^{1+1/n}$$

- ρ is baryon density, P is the Pressure, K is determined Once the Mass and Radius is found. n is the polytropic index which ranges between n=1.5 (fully convective) and n=3 (fully radiative).
- We have varied the adiabatic index to account for the transition from convective to radiative energy transport.

(Chandrasekhar 1939)

Solving Stellar Structure

$$\frac{(n+1)K}{4\pi nG}\frac{1}{r^2}\frac{d}{dr}\left(\frac{r^2}{\rho^{\frac{n-1}{n}}}\frac{d\rho}{dr}\right)=-\rho$$

- Lane-Emden Equation

$$P=\frac{\Re\rho T}{\mu}$$

- Equation of State

$$P=K\rho^{1+1/n}$$

- Polytropic relationship

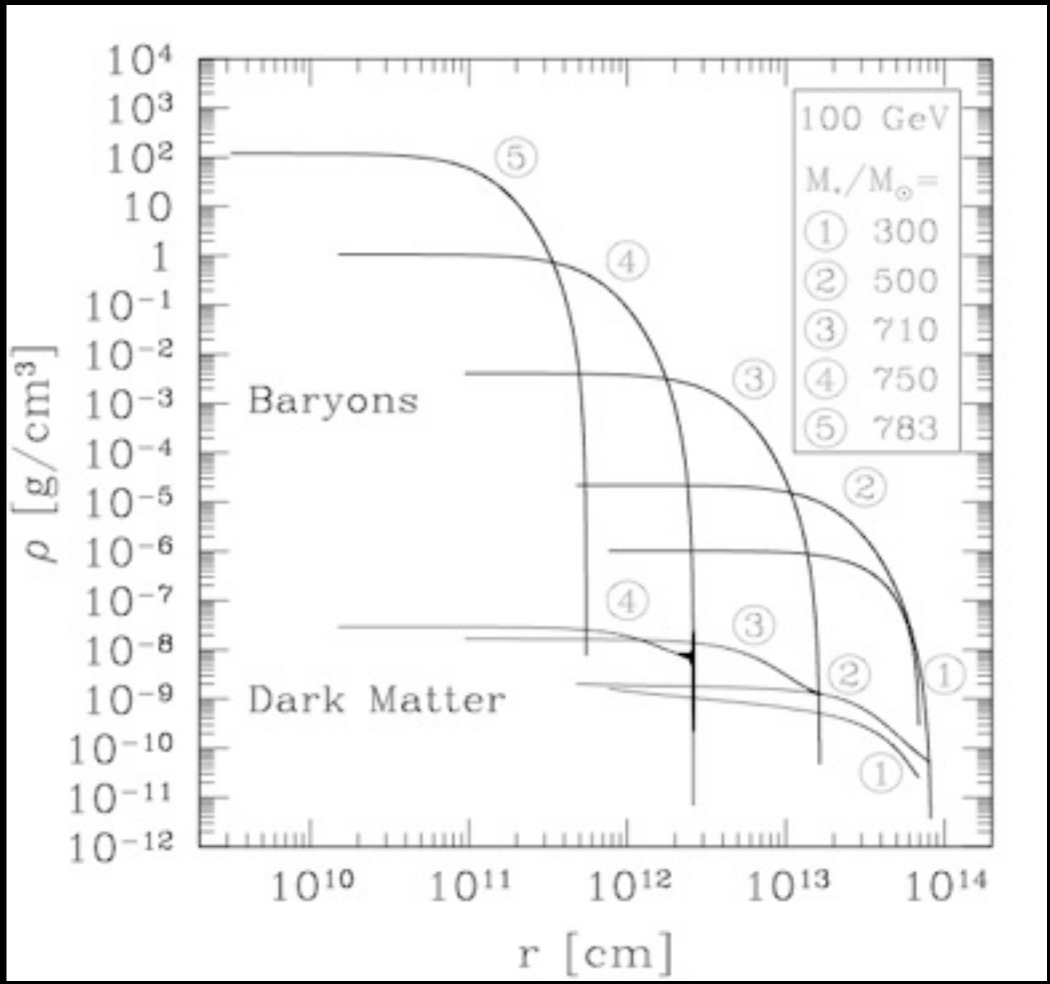
- We can now completely solve for the density, pressure, and temperature profile of the star! Can also now solve for the DM density profile.

Stellar Structure

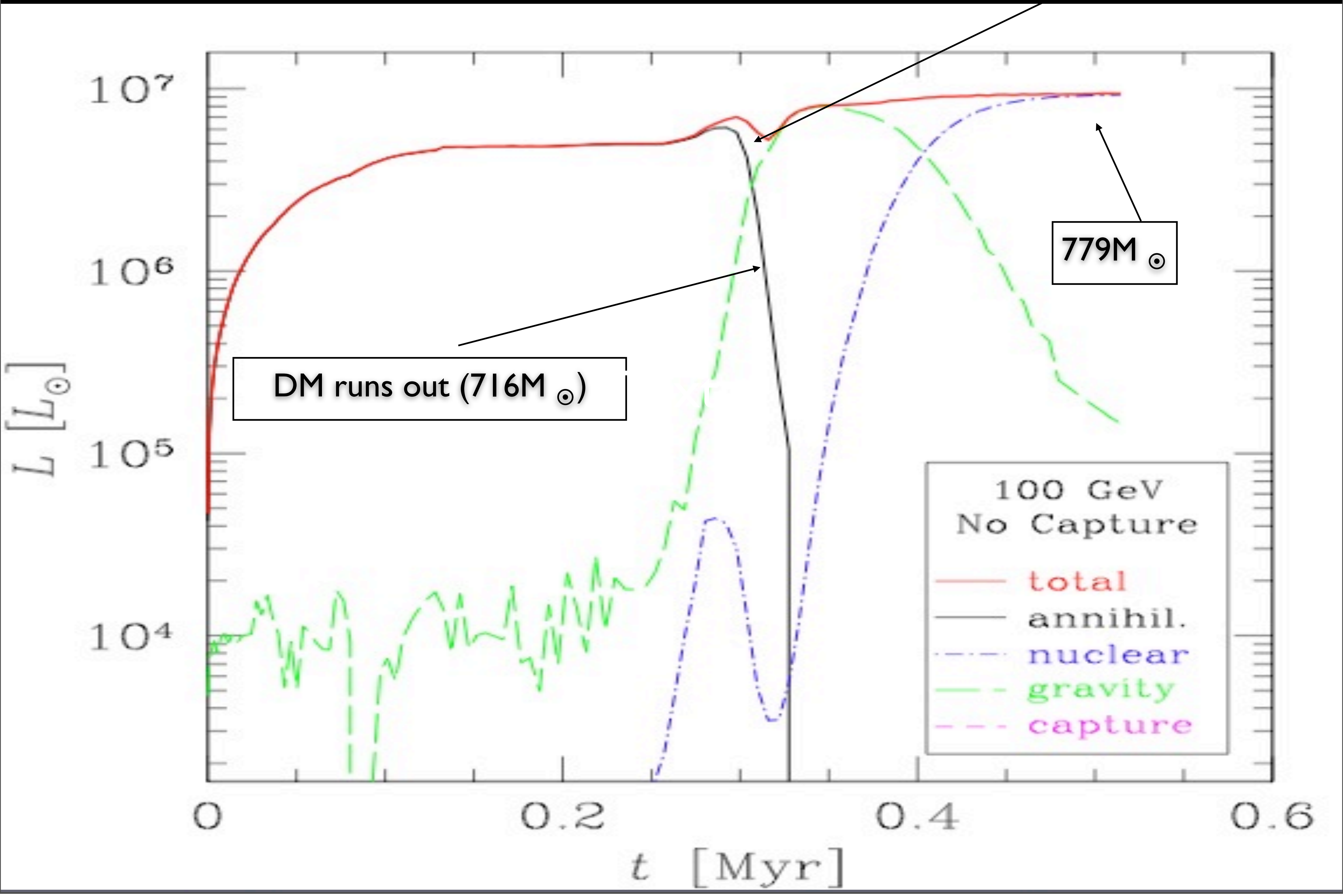
- Variable accretion rate account more accurate accretion rate based upon rates by Tan and McKee 2008 and O'Shea and Norman 2007
- Feedback (McKee and Tan 2008)
- Variable polytropic index
  - (convective to Radiative)
- Gravity
- Nuclear burning
- Dark matter capture

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
    - as gas accretes
  - (Conservatively) DM in spherical halo. We later relax this condition

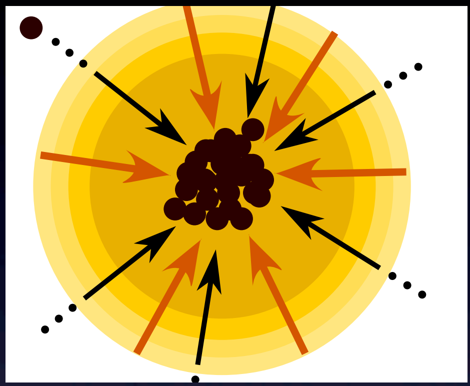


Vary Radius until Stellar luminosity Matches Power sources

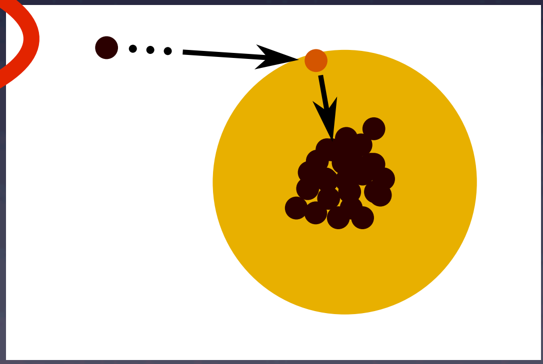


Two ways of concentrating dark

- *Gravitationally*: when object forms, dark matter is dragged in into deeper and deeper potential
  - adiabatic contraction of galactic halos due to baryons
    (e.g. Blumenthal et al 1986)
  - dark matter concentrations around black holes
    (Gondolo, Silk 1999) Important for dark stars at the galactic center
  - dark matter contraction during formation of first stars
    (Spolyar, Freese, Gondolo 2007)

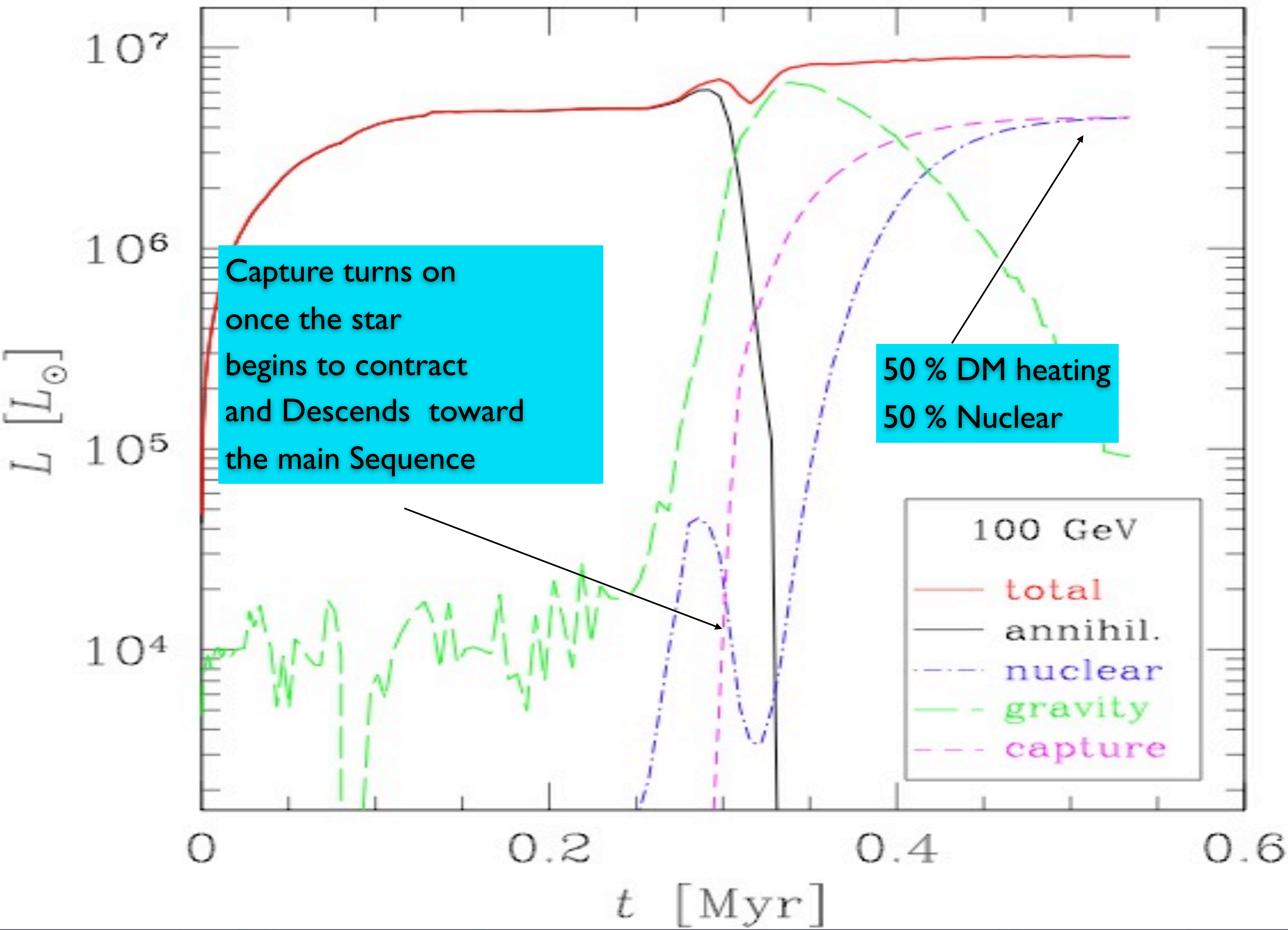


- *Through collisions*: dark matter scatters elastically off baryons and is eventually trapped
  - Sun and Earth, leading to indirect detection via neutrinos
  - stars embedded in dense dark matter regions
    ("dark matter burners" of Moskalenko & Wai 2006, Fairbairn, Scott, Edsjo 2007)
  - dark matter in late stages of first stars
    (Freese, Spolyar, Aguirre; Iocco; Iocco et al; Taoso et al 2008)

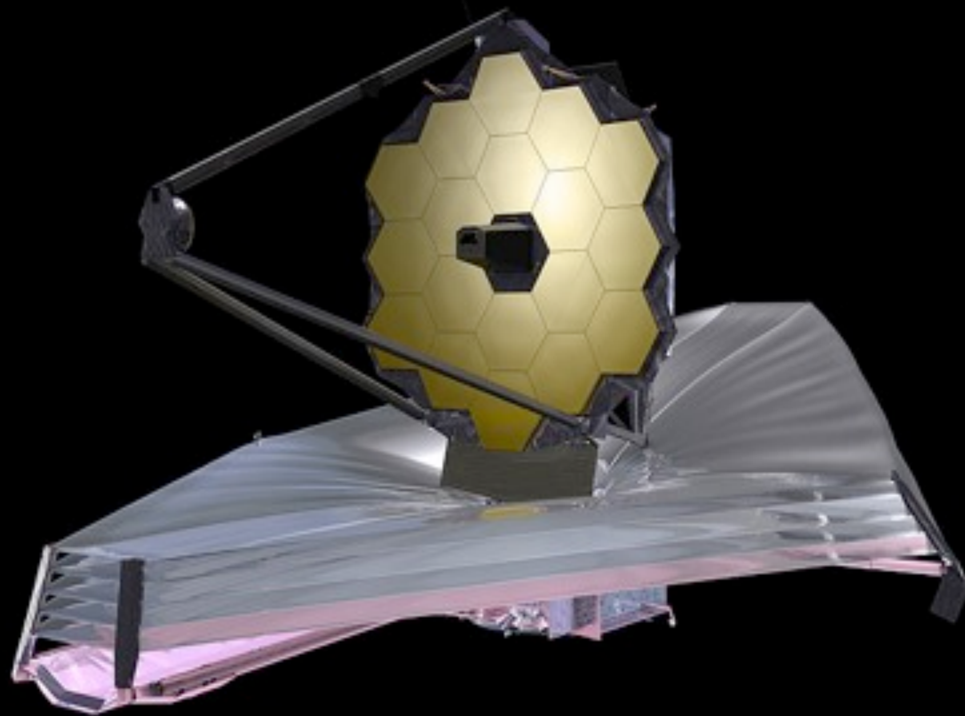


P Scott

graphics P. Scott


Capture turns on
once the star
begins to contract
and Descends toward
the main Sequence
50 % DM heating
50 % Nuclear
100 GeV
total
annihil.
nuclear
gravity
capture
10^7
10^6
10^5
10^4
$L\ [L_\odot]$
0
0.2
0.4
0.6
t [Myr]

JWST

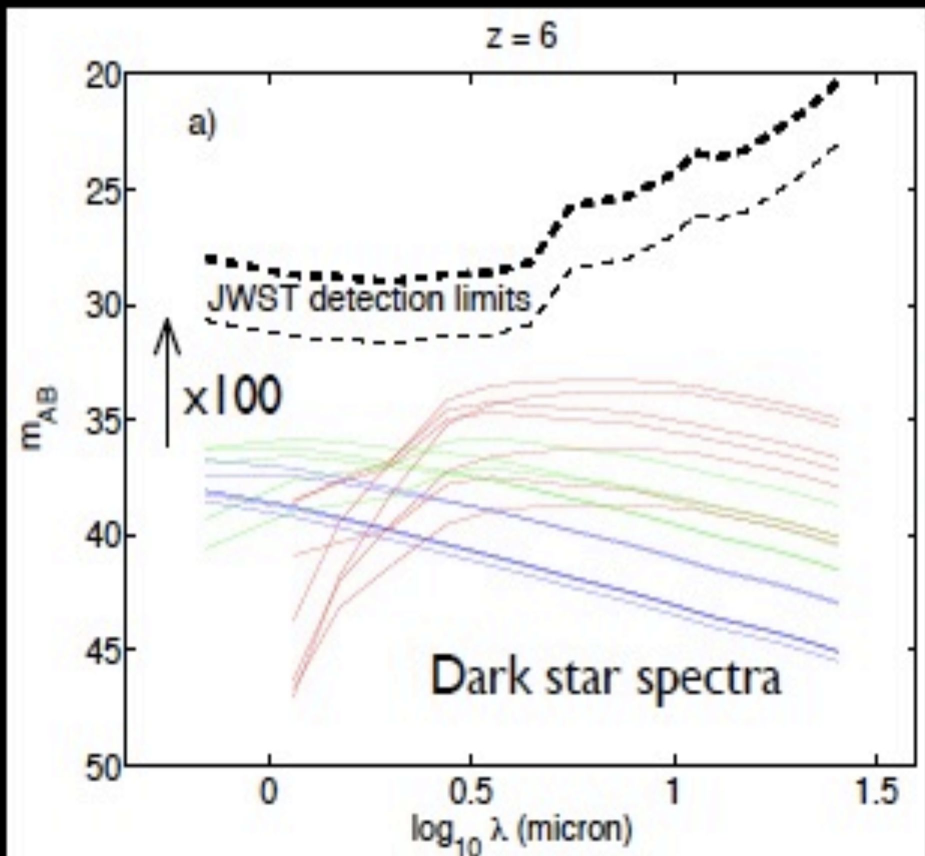


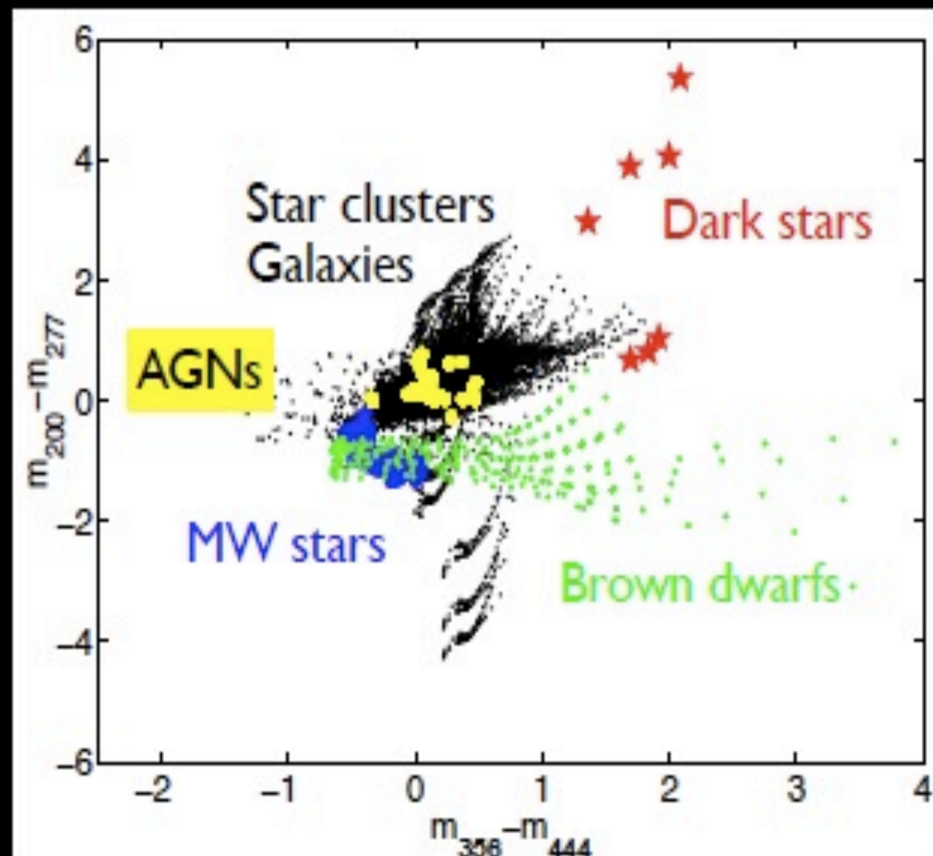
- 6.5 meters
- L2 point
- Hubble Replacement
- Pricey and counting (uncertain future)
- Far infrared
  - designed to go after the first galaxies and stars

Detecting 1000 Msun Dark Stars via Lensing

Idea: Use a magnifying lens *Zackrisson et al 2010*

Detectable with JWST via gravitational lens magnification ~100





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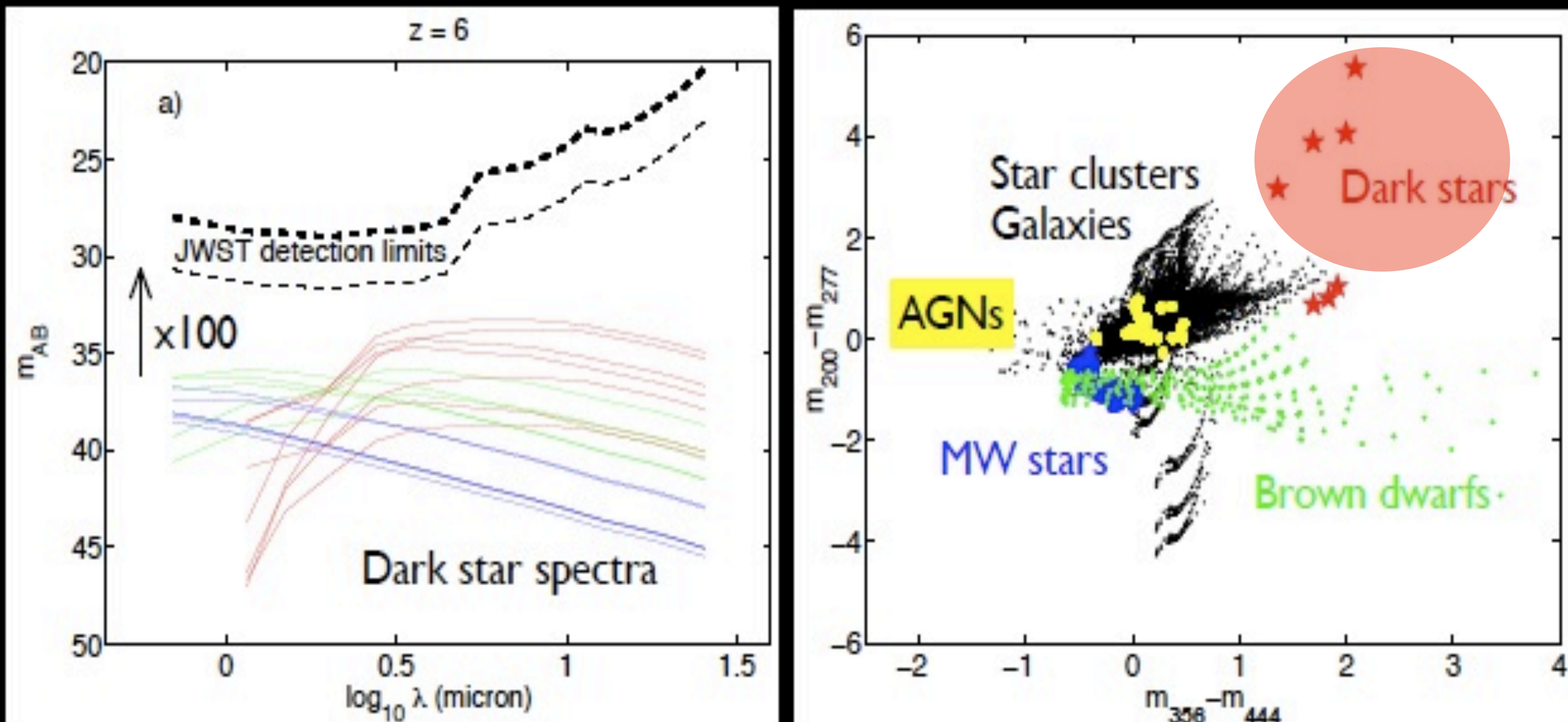

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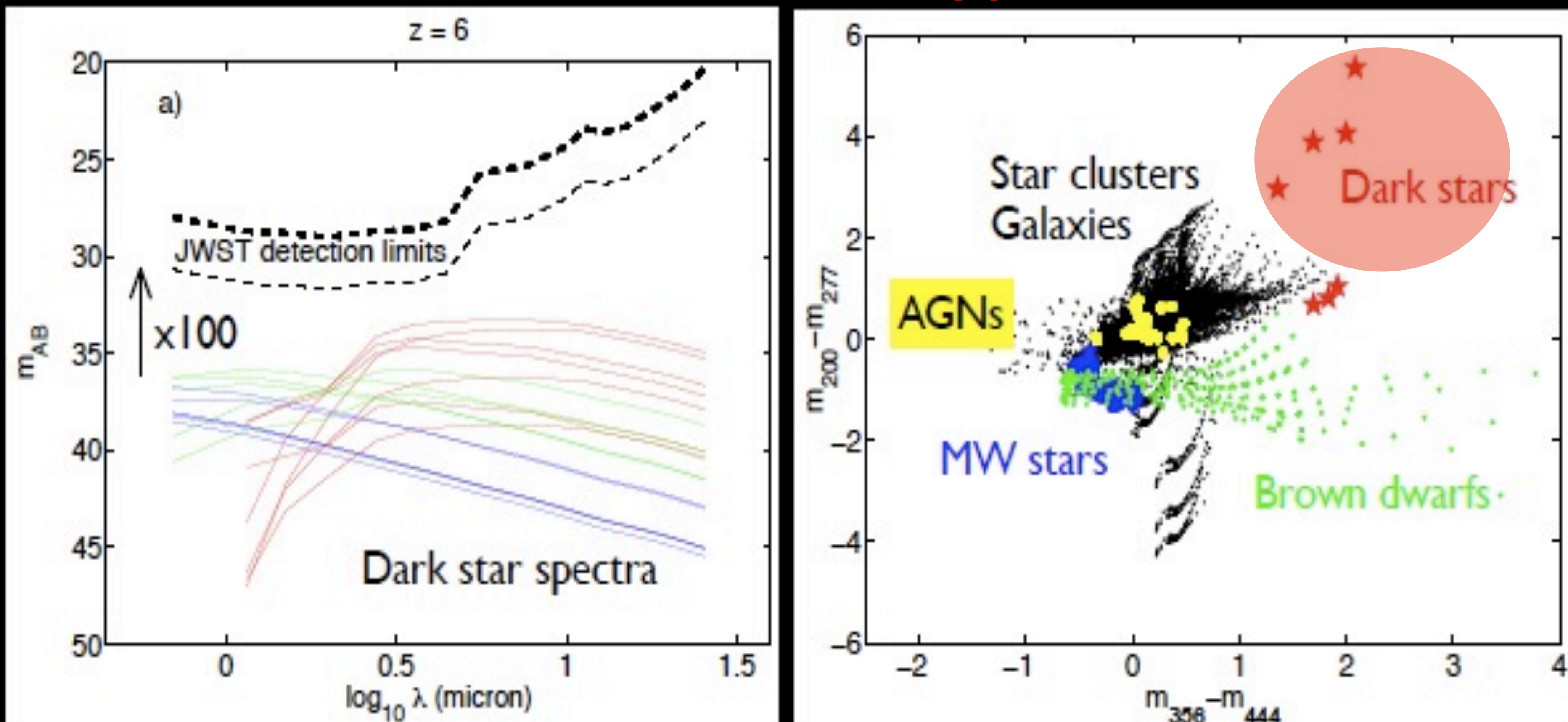
Distinctive Appearance



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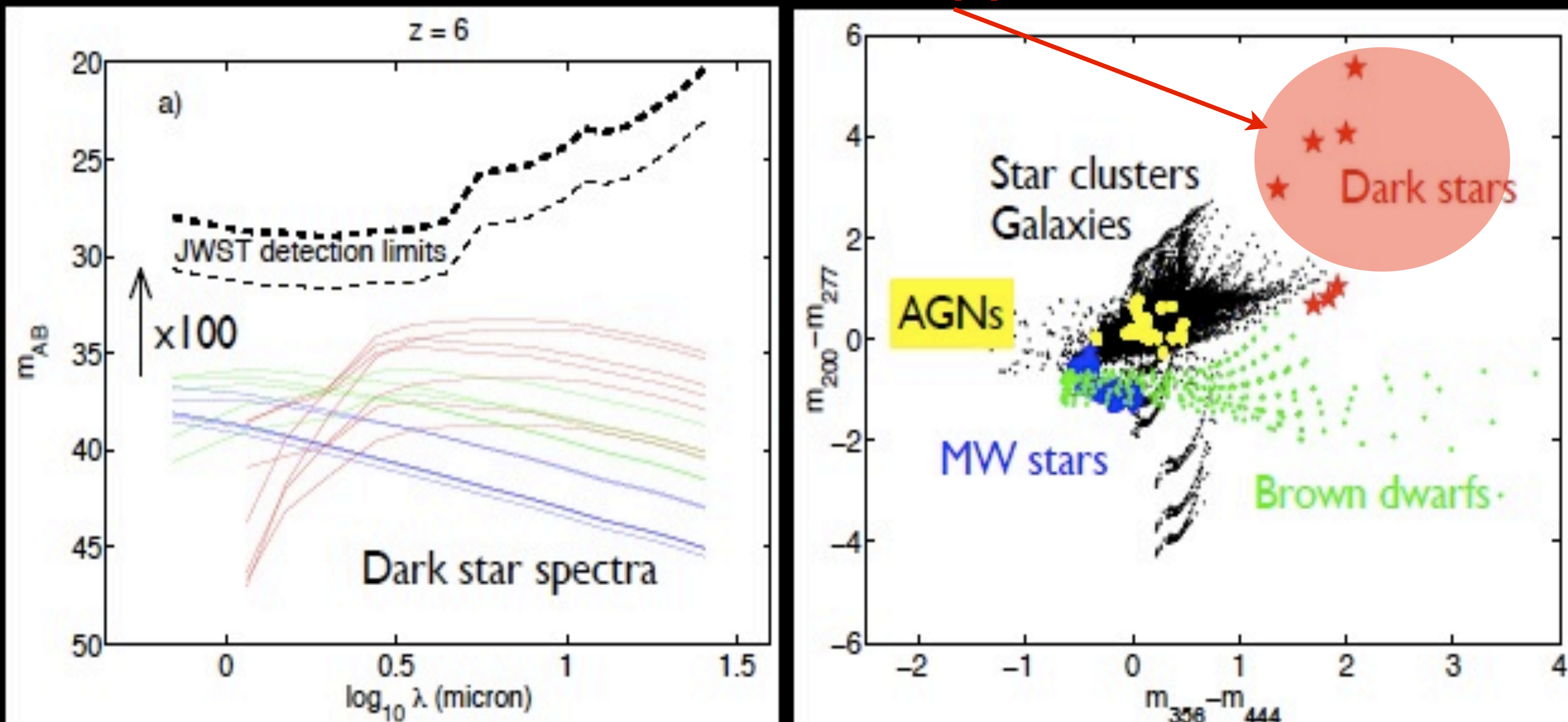


A First Phase of Dark Star Evolution

Freese, Bodenheimer, Spolyar, Gondolo 2008

- Initial star is a few solar masses
- Accrete more baryons $\sim 1000 M_\odot$
- Becomes very luminous, between $10^6 L_\odot$ and $10^7 L_\odot$
- Cool: 10,000 K vs usual 100,000 K and plus
  Very few ionizing photons - just too cool
  - (in principle accrete all baryons in the halo)
- Lifetime: a few million years

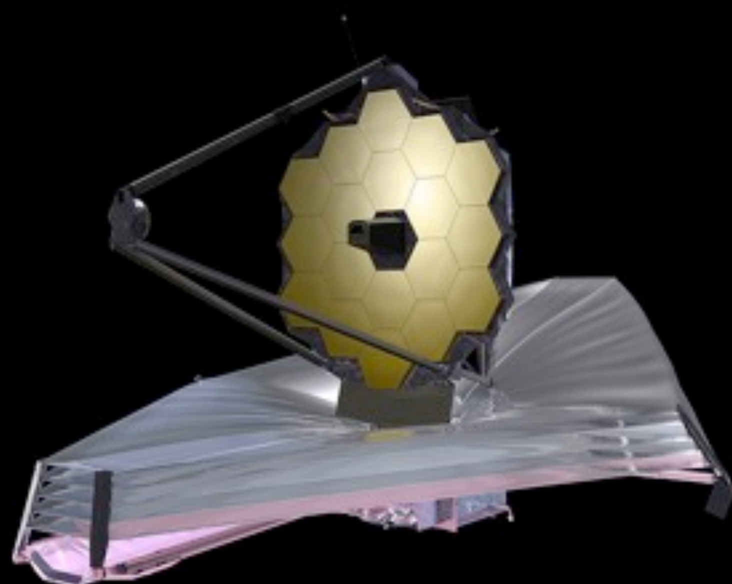
  With capture or non-circular orbits, could be very different

How Big can They grow?

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.

Even after adiabatic contraction fails, capture can refuel the star's dark matter reservoirs



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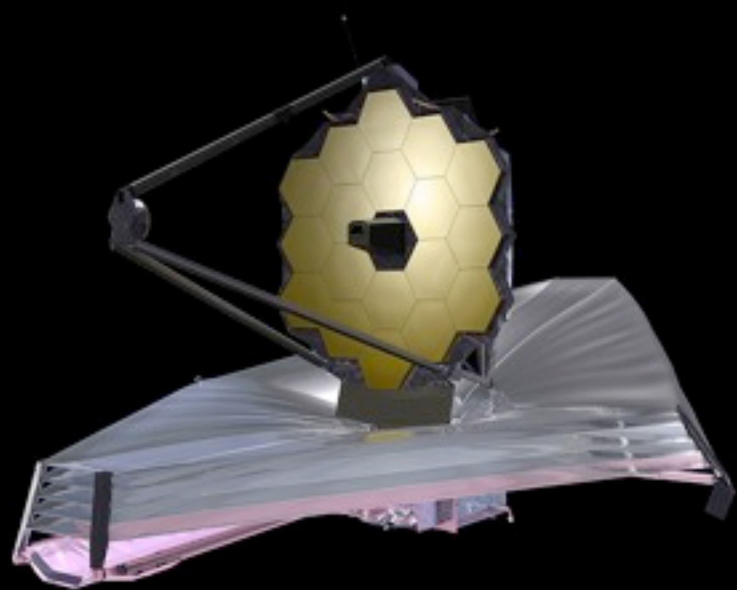
Detect with JWST?
Seen already?



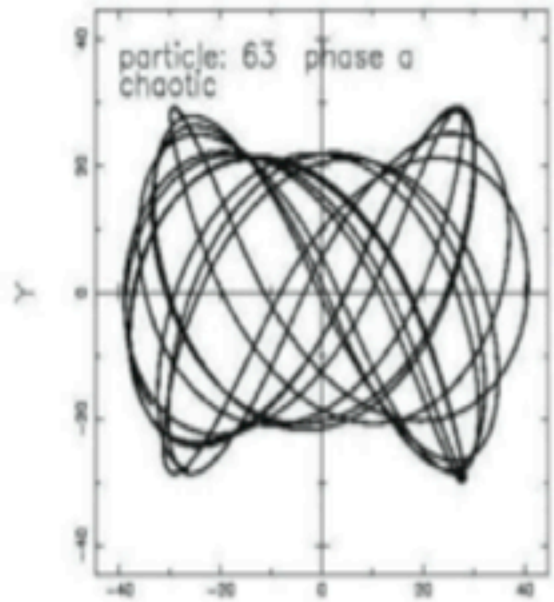
Is there enough DM?

Spherical Halos

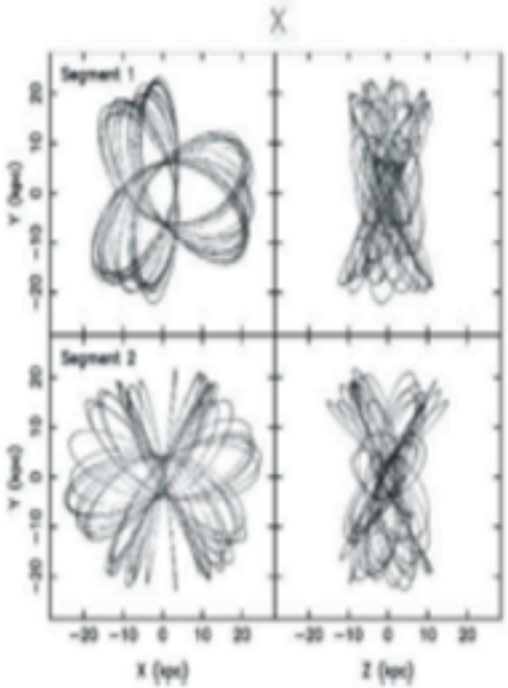
- DM orbits are planar rosettes (Binney & Tremaine '08).
- The Dark Star creates a loss cone that cannot be refilled.

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

Super Massive Dark Star

In general one power source will dominate
- Previously artificially matched DM heating with fusion

If DM heating Dominates:
- DM densities sufficiently high or scattering cross sections sufficiently large then:
  - Star cool (50,000K)
  - Very massive (10^5 M)
  - Very Luminous (10^9L)
- **Similar result as with**
  - **Umeda, Yoshida, Nomoto, Tsuruta, Sasaki, and Ohkubo (2009)**
  - **Consider Only capture**

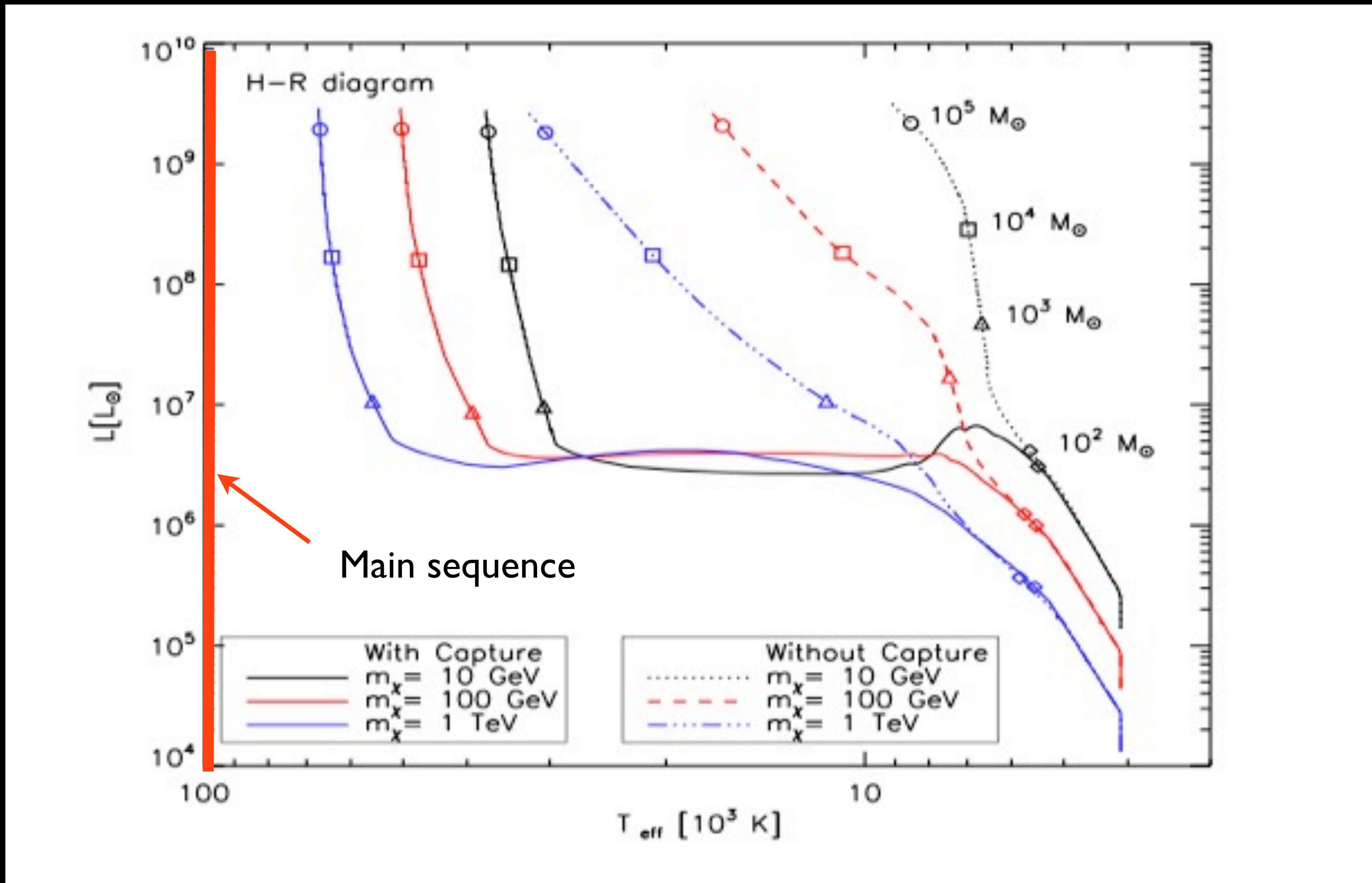
(Assuming Sufficient DM)

- GR Instability (not likely DM helps stabilize star)
- Avoids fusion and re-ionization?
  - Until DM reservoir depleted or disrupted
  - Maximum time Scale
    (10-100Myrs) due to mergers

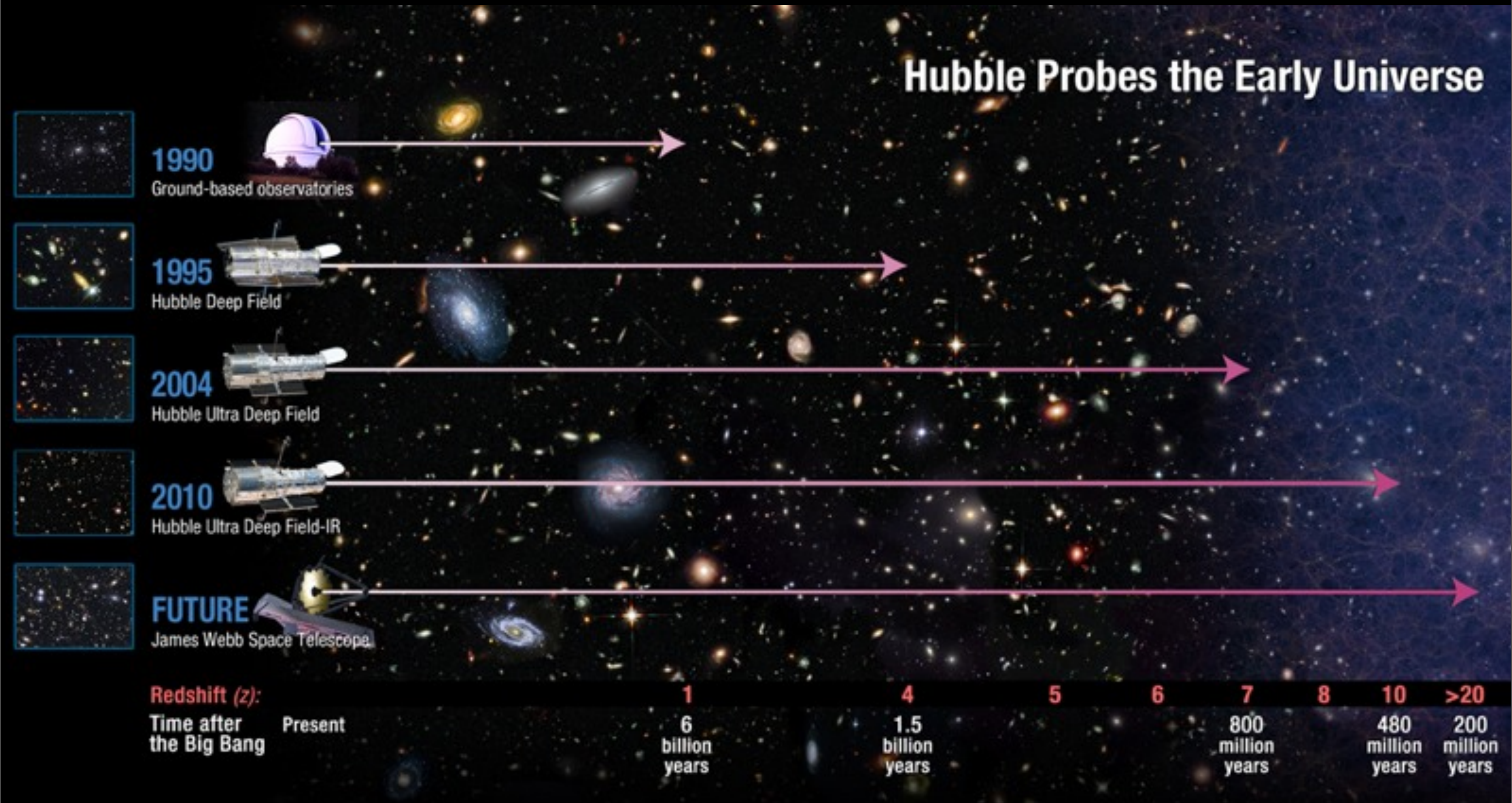
Super Massive Dark Star

Dark matter reservoir has been replenished due to triaxial halo orbital structure

Assume all baryons in a $10^6 M_\odot$ halo have been accreted



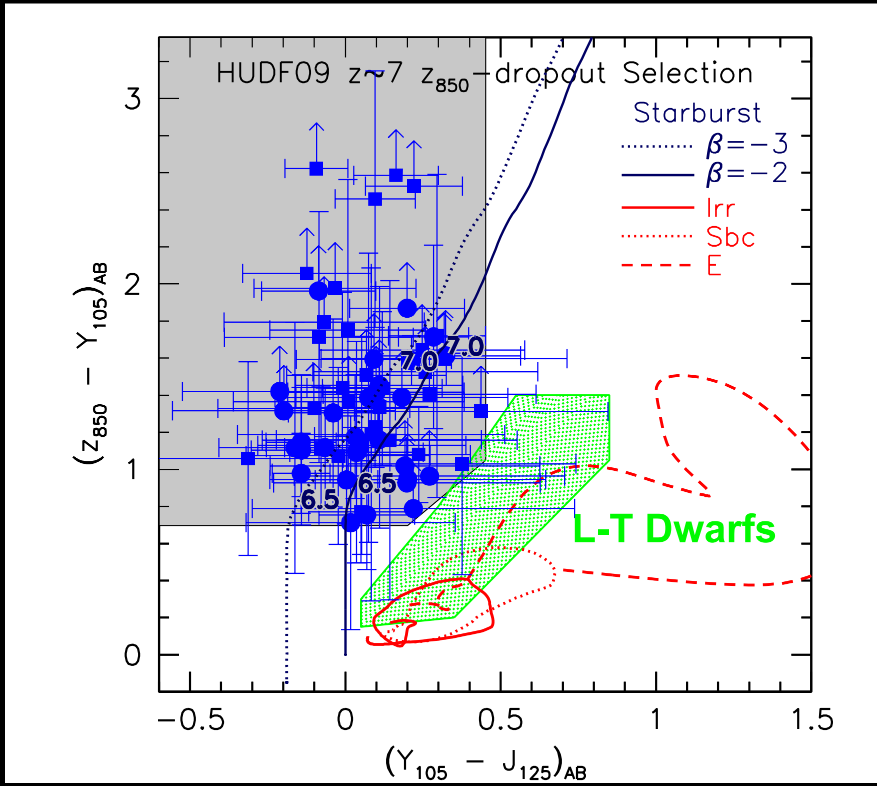
Spolyar et al 2011


Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

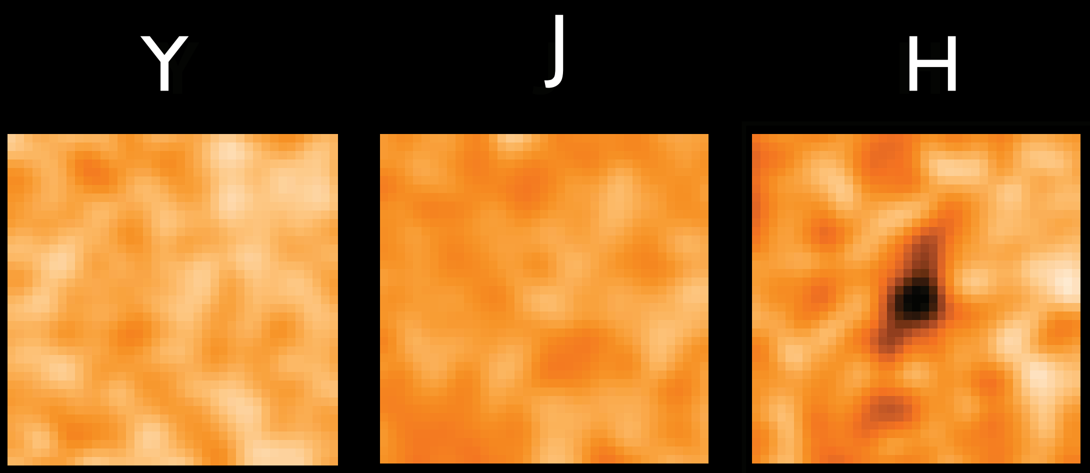
How to Look for High redshift objects

- Use the two-color Lyman-Break galaxy method pioneered by Steidel and collaborations in the mid 90s
- Require non-detection on flux data blueward of break
- Expect only small number of contaminants, from
  - low-mass stars, SNe, Photometric Scatter

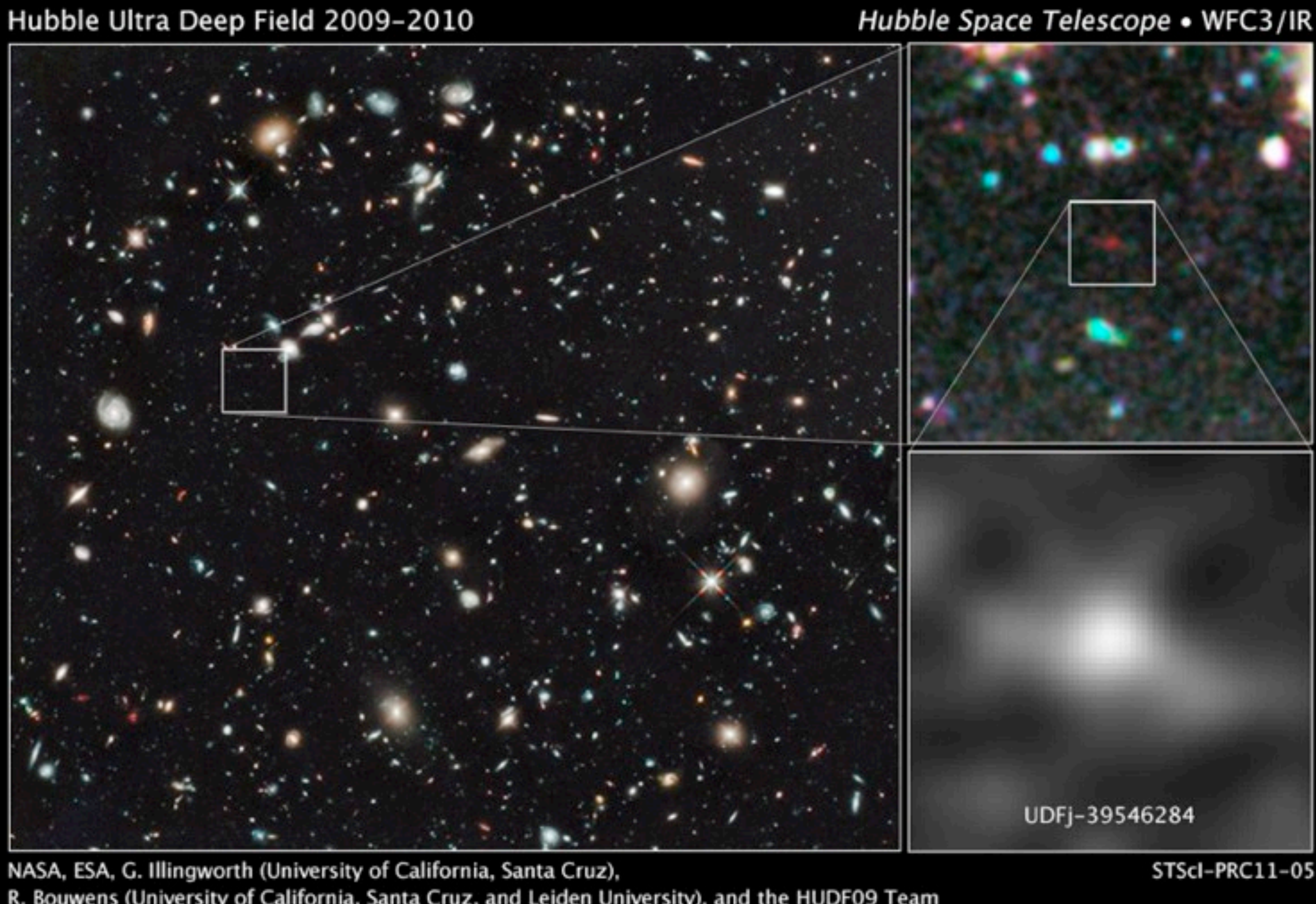
z~7 selection



Bouwens 2012



Redshift 10 Dropout: Galaxy or Dark Star?



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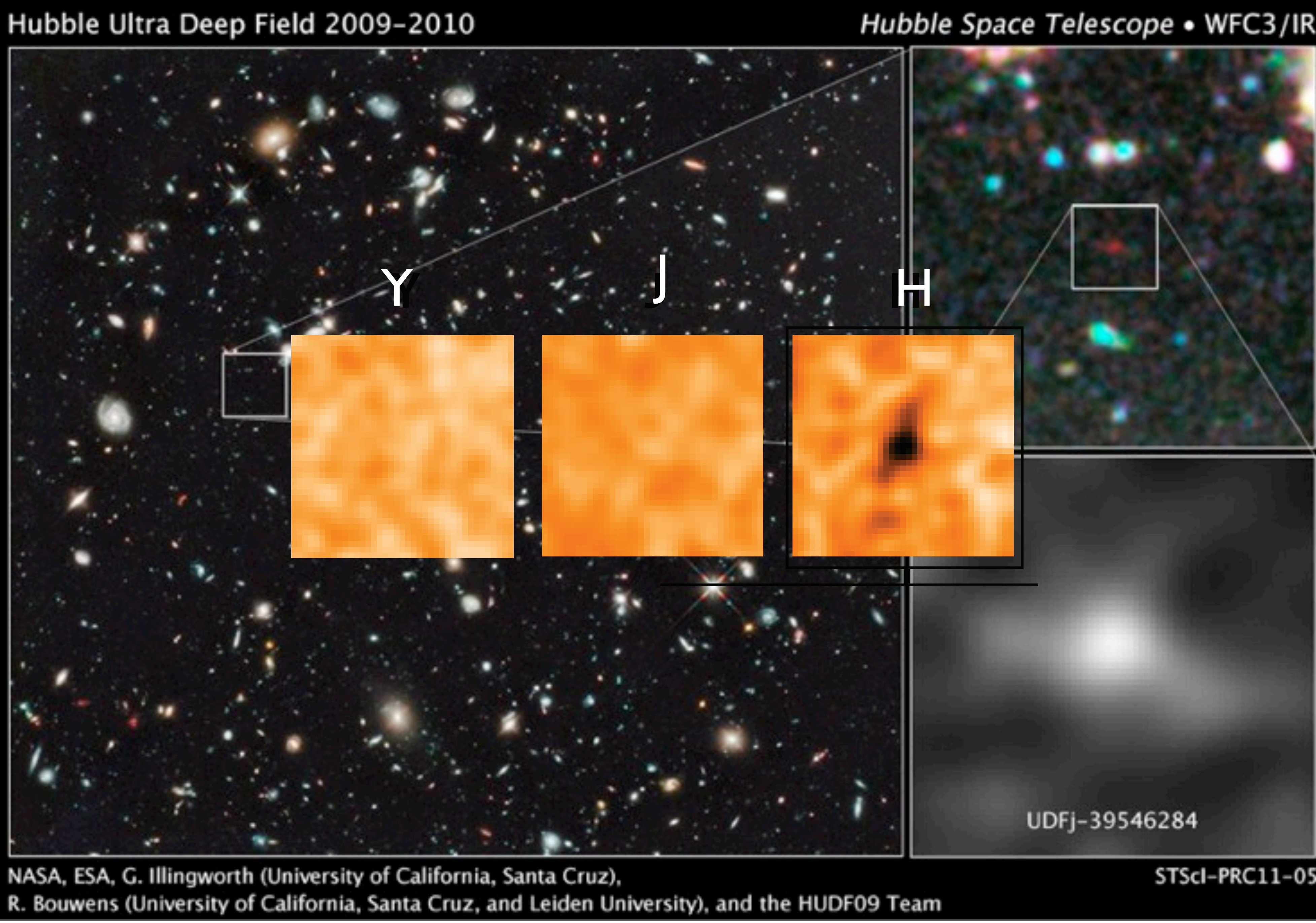
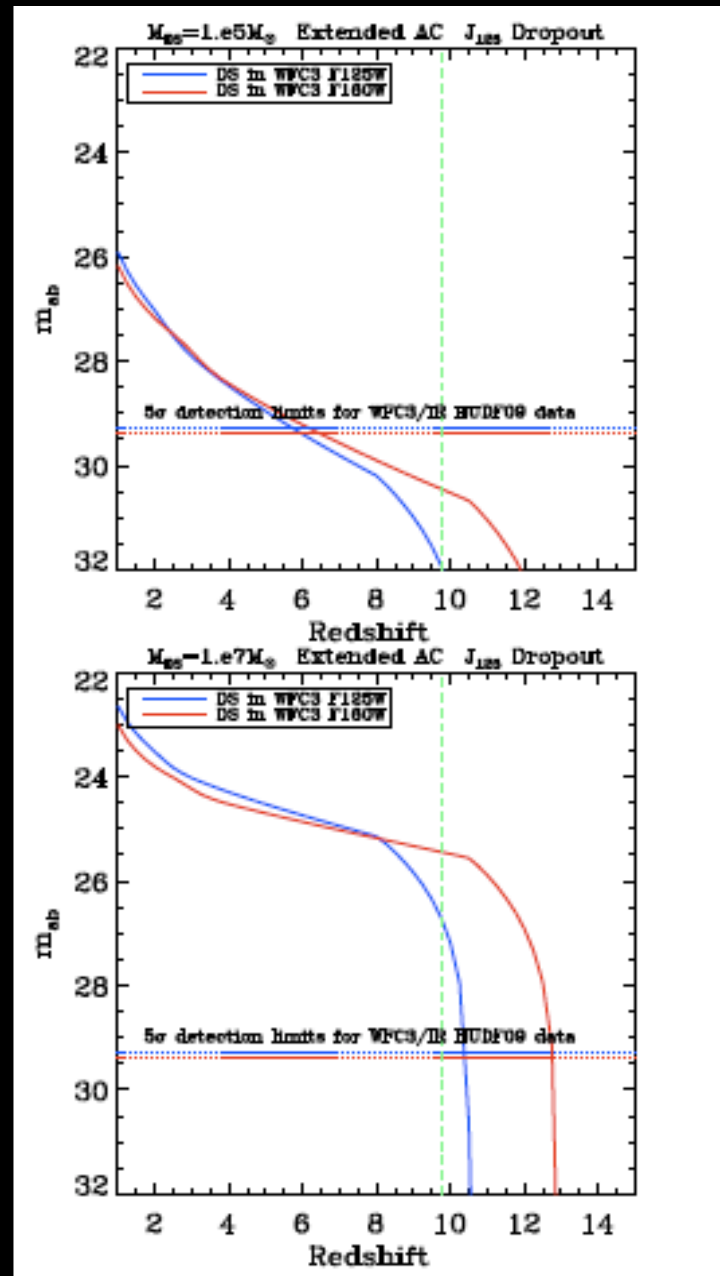


Dark Stars in HST

Heaviest ones would be visible in HST as Jband dropouts (observable in 1.6 micron band but not in 1.25 micron band due to Ly-alpha absorption in the intervening gas), yet only one object was found at z=10.
Thus we can bound the numbers of 10^7 solar mass SMDS.

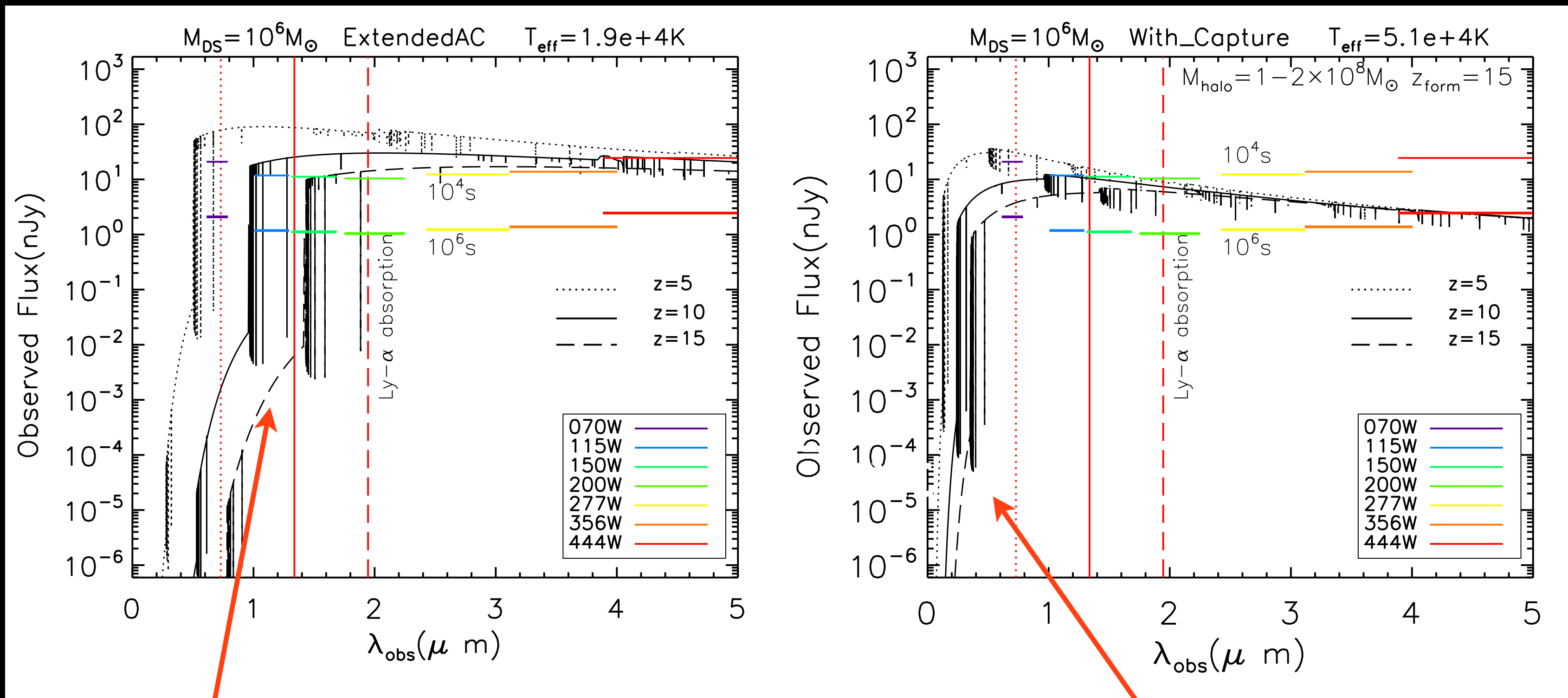


$$\log f_{smds}(M_{DS} = 10^7 M_\odot) \leqslant \begin{cases} -4.5 - \log(f_{surv} \times f_{\Delta t}), & \text{A} \\ -3.4 - \log(f_{surv} \times f_{\Delta t}), & \text{B} \\ -2.1 - \log(f_{surv} \times f_{\Delta t}), & \text{C} \end{cases}$$

A,B,C: zform=10,12,15

See also Zackrisson etal 2011

Super Massive Dark Star with JWST



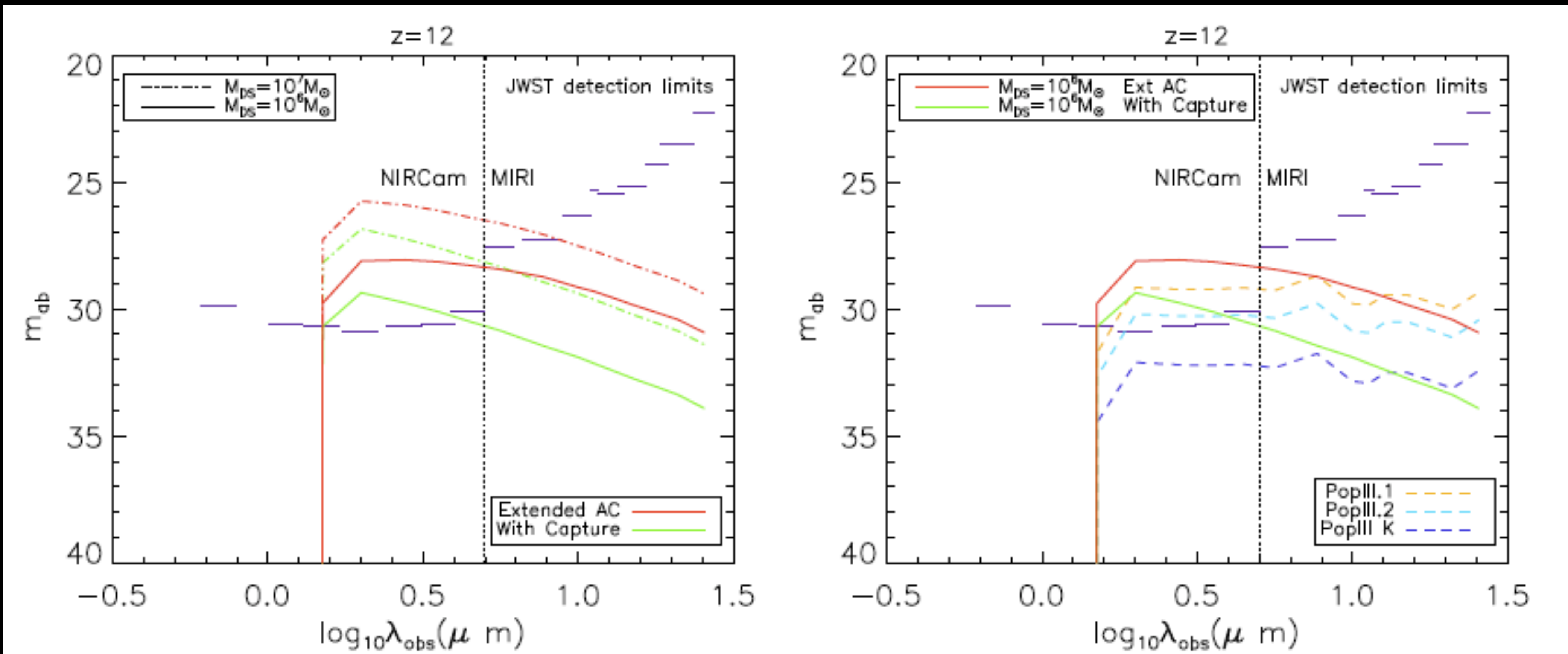
Lower Temperature (longer wavelength)
ExtendedAdiabatic Contraction

Higher Temperature (shorter wavelength)
capture

Ilie etal. 2011

Super Massive Dark Stars
vs

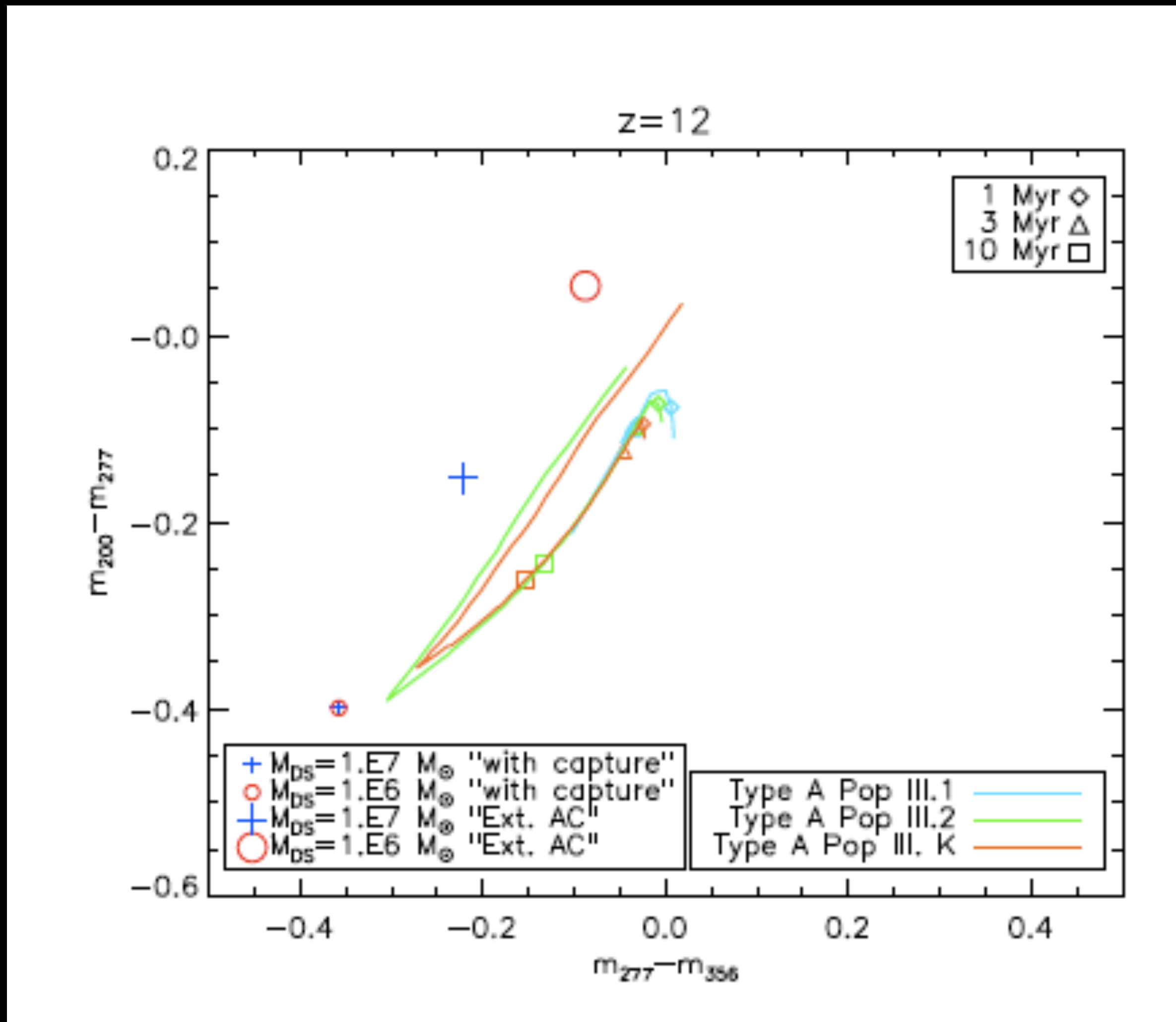
Dark Stars   Galaxies



SMDS are brighter and have a different spectral slope.

Ilie etal. 2012

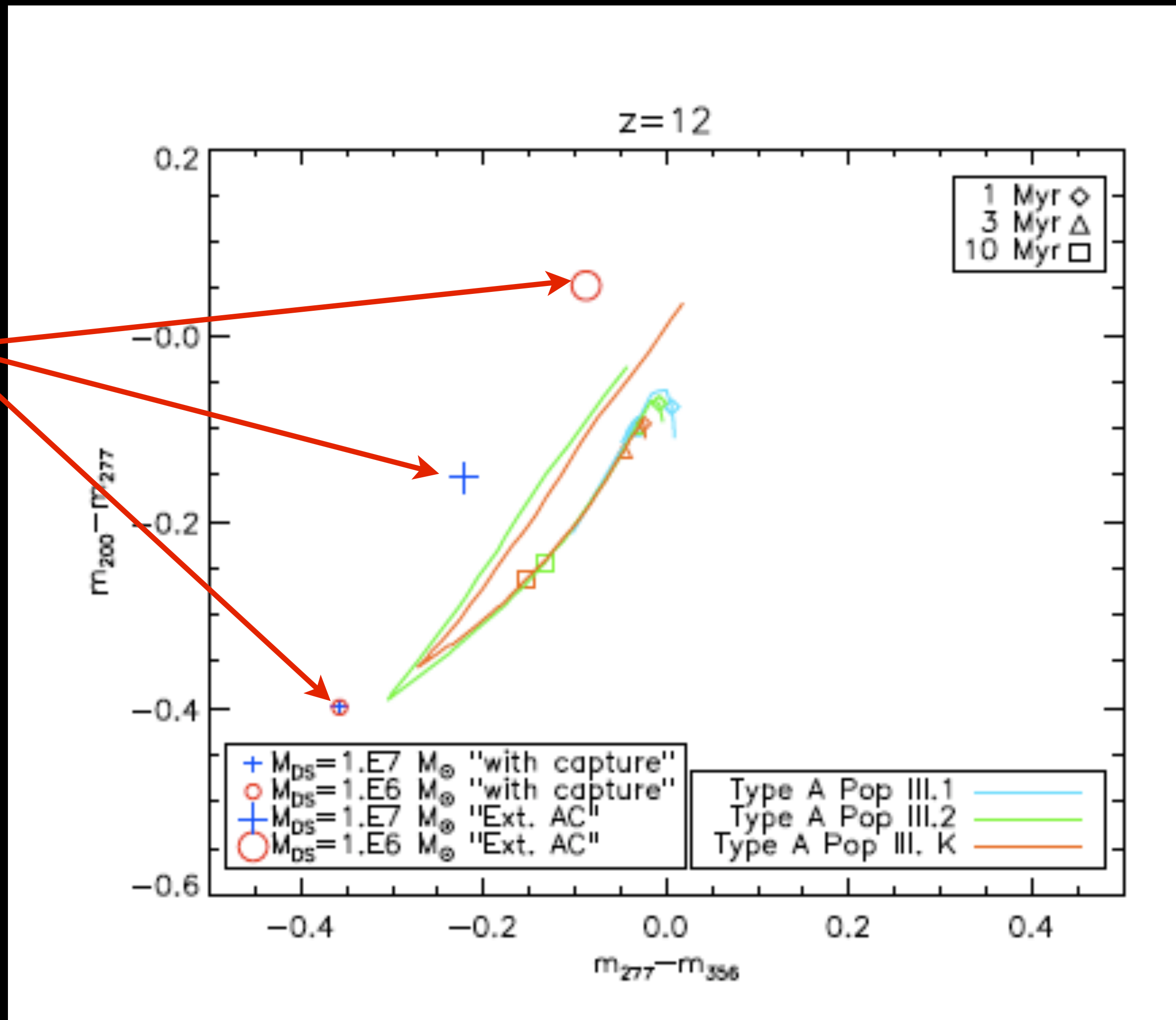
Galaxies vs. Super Massive Dark Stars



Ilie etal. 2012

Galaxies vs. Super Massive Dark Stars

Dark Stars



Ilie etal. 2012

Fermi constrain dark stars

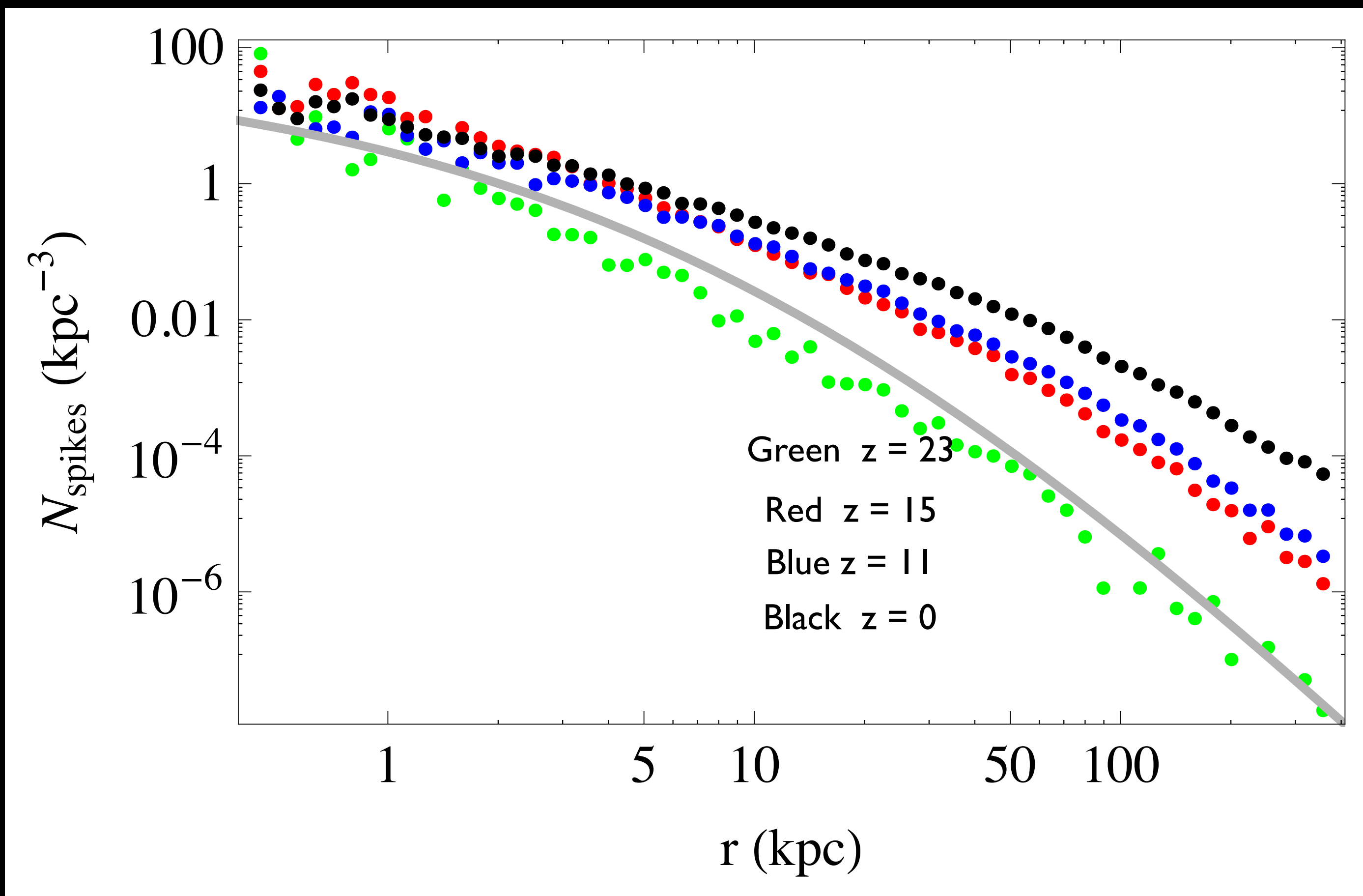
- If the first stars (powered by DM or Not) collapse to form BH, the remnant BH still holds onto a spike of DM
  - When the star formed, the in falling gas adiabatically contracted the DM, which boosted and tightly bound DM around the future Black, which can lurk in our galaxy today.

Pearl Sandick 2011 etal.

Bringmann,Lavalle, and Salati 2009

Intact DM Halos

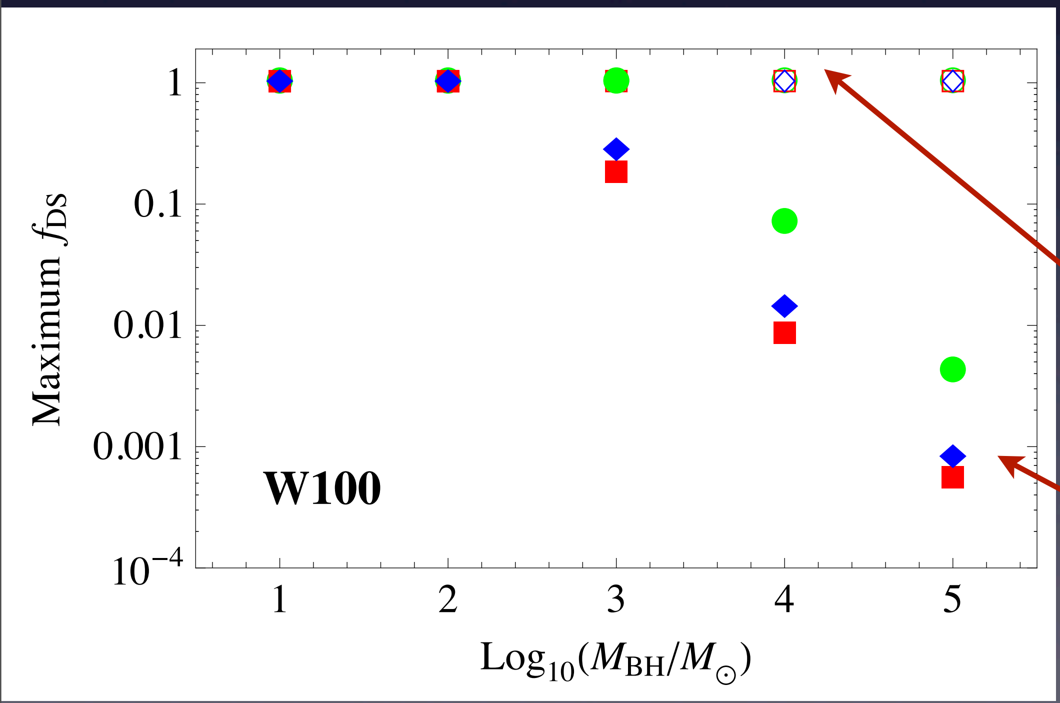
- from Via Lactea, we have been able to count the number of halos which might have hosted Pop III stars. (these halos formed at the right red shift and have the right mass to host a first star)



P. Sandick etal 2011

Fermi Constraints on Fraction of DM spikes

- DM =100 GeV
- Decays into b-mesons
- different colors correspond to different end of DS formation



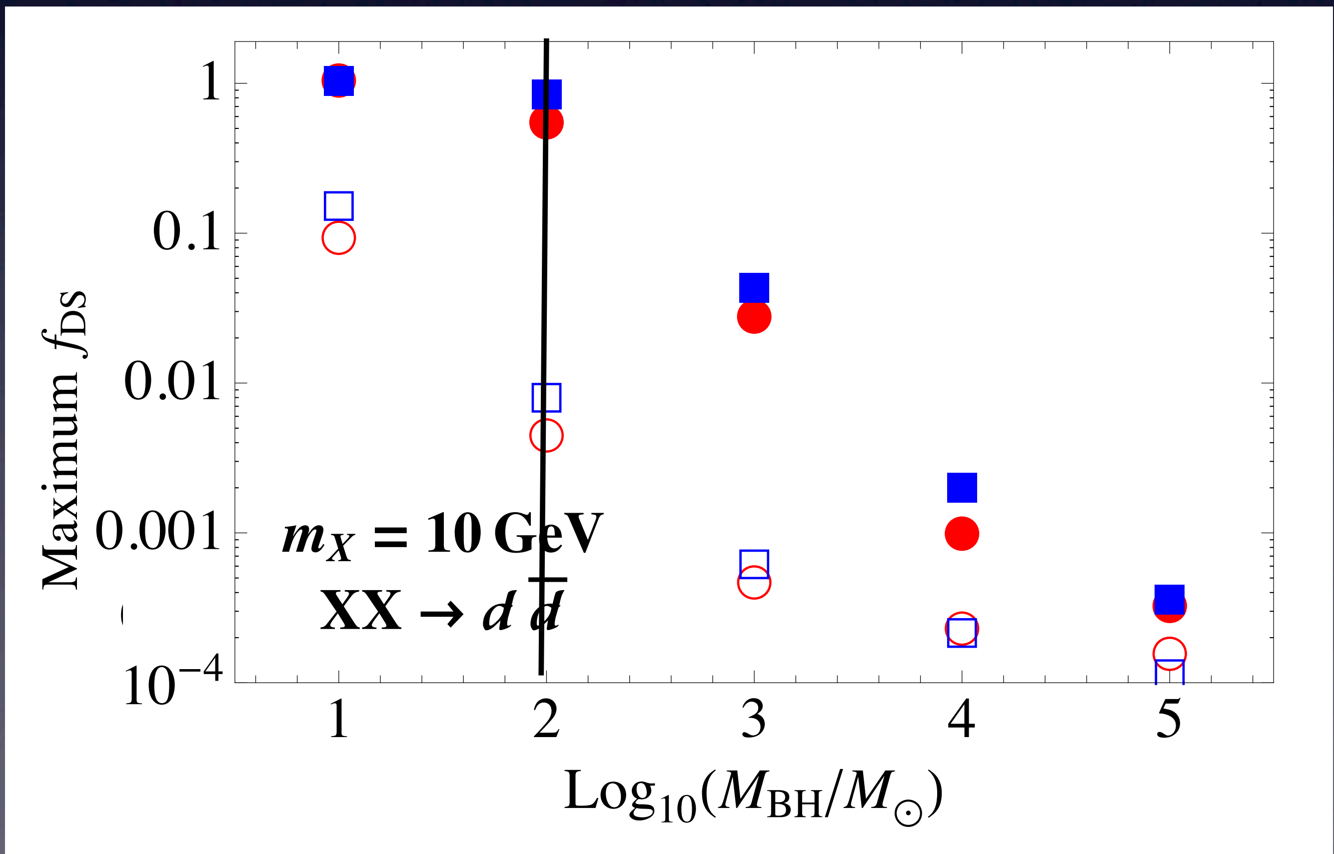
open - diffuse background

closed - point sources

P. Sandick etal 2011

Strong Constraints on Low Mass WIMPs

- Motivated by DAMA, Cogent, CREST, Fermi GC excesses, etc.



Tension between low mass DM and standard first stars

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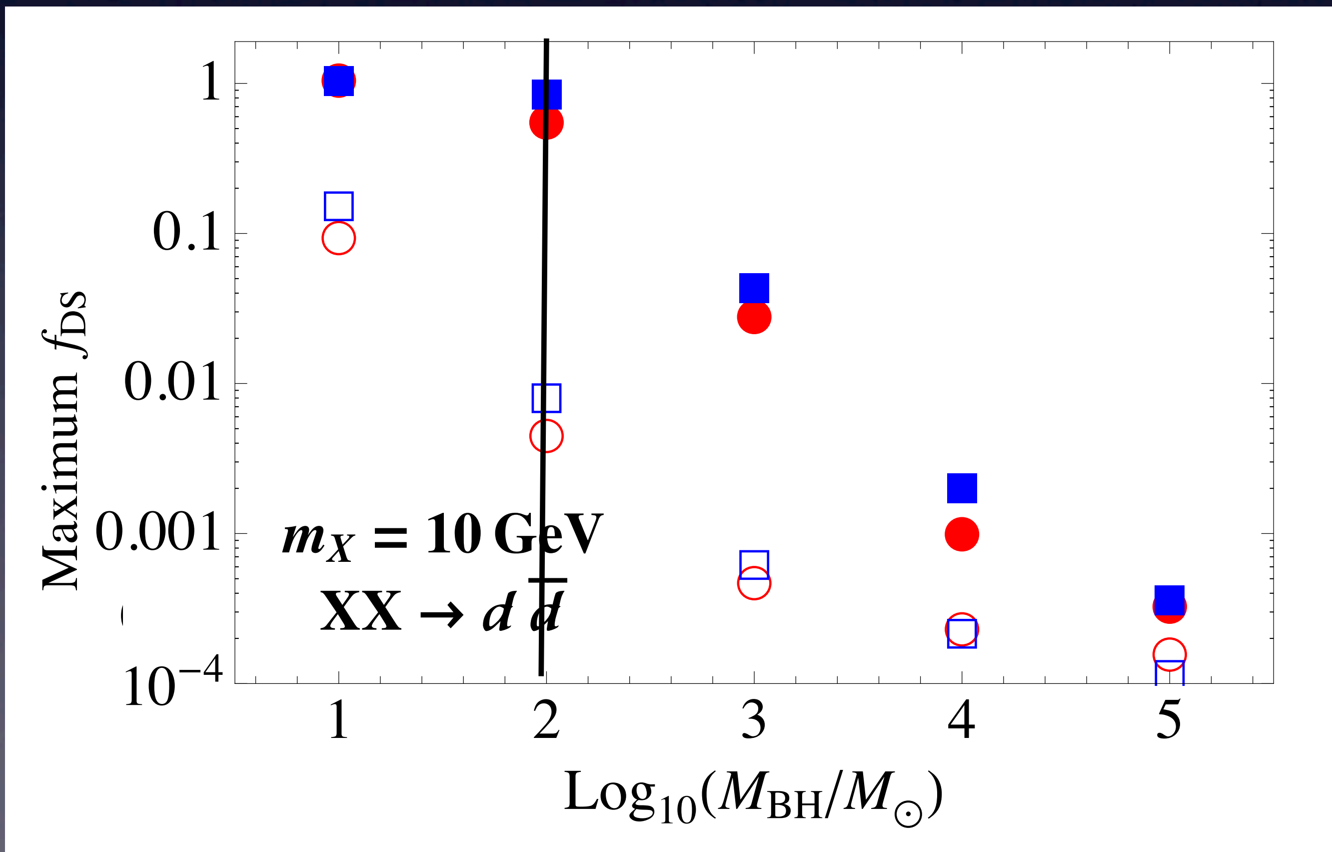

Standard first star BH

Tension between low mass DM and standard first stars

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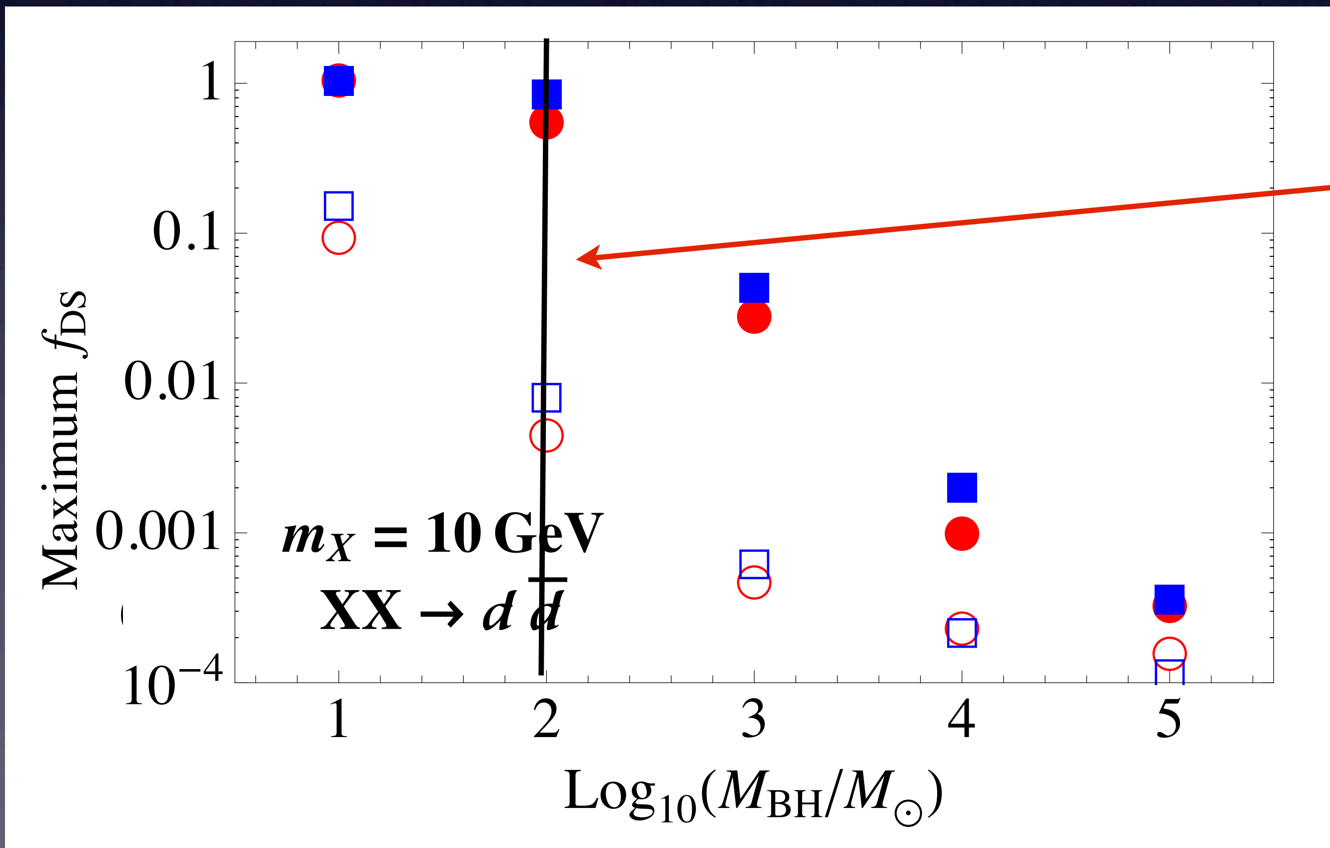
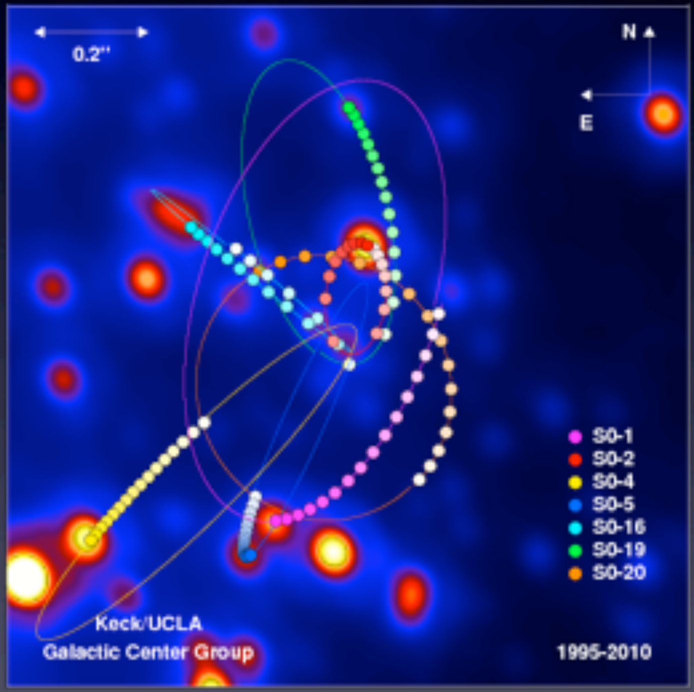


Standard first star BH

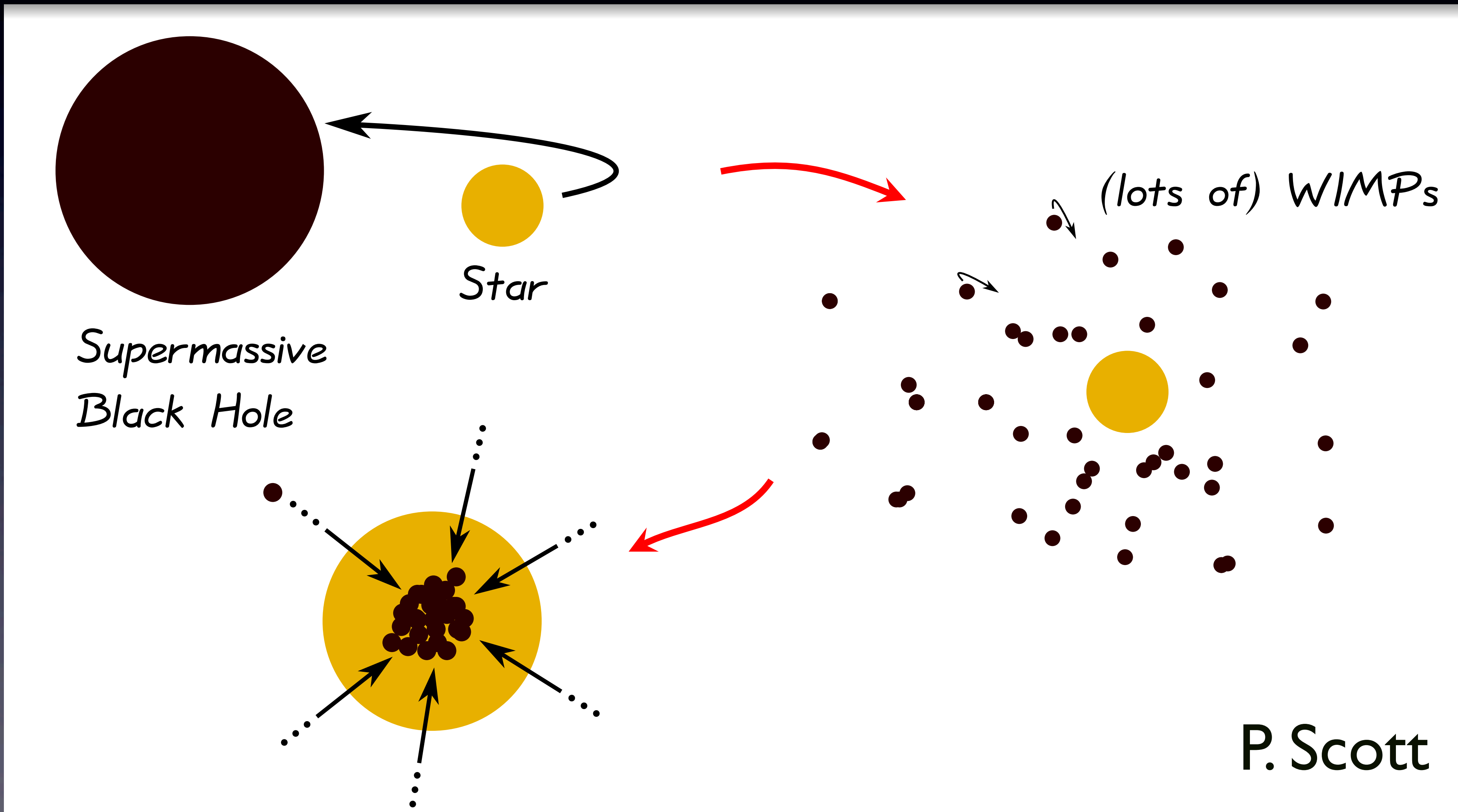
Tension between low mass DM and standard first stars

Galactic Center

- difficult to study but recent progress A. Ghez etal 2008
- apparently quiescent super massive black hole $\cong 10^6 M_{\odot}$
  - May also have a DM spike which boost the local DM density by several orders of Magnitude due to baryonic



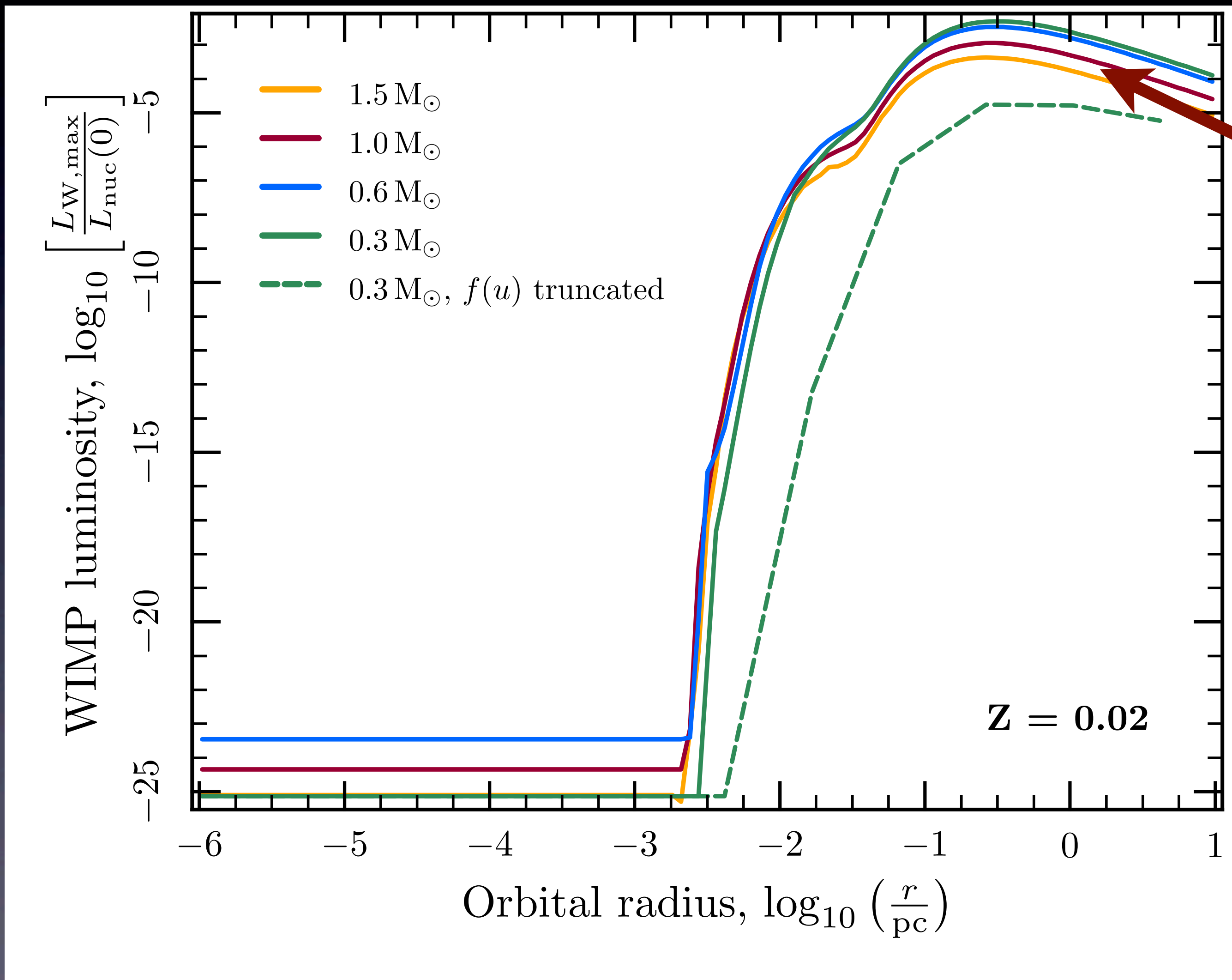
Cartoon of Dark Stars around the Galactic Center



Pameters used in stellar structure of DS at galactic center

- Nuclear-scattering cross-sections: $\sigma_{\mathrm{SI}} = 10^{-44}\,\mathrm{cm}^2$, $\sigma_{\mathrm{SD}} = 10^{-38}\,\mathrm{cm}^2$ (chosen to be consistent w current limits in 2009)
- Annihilation cross-section: $< \sigma_{\mathrm{a}} v >_0 = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$
- Stellar masses: 0.3–2.0 $M_{\odot}$, metallicities: Z = 0.0003 – 0.02
- Behaviour is qualitatively very similar at higher masses and $Z = 0$

Max WIMP Capture Rate in Star



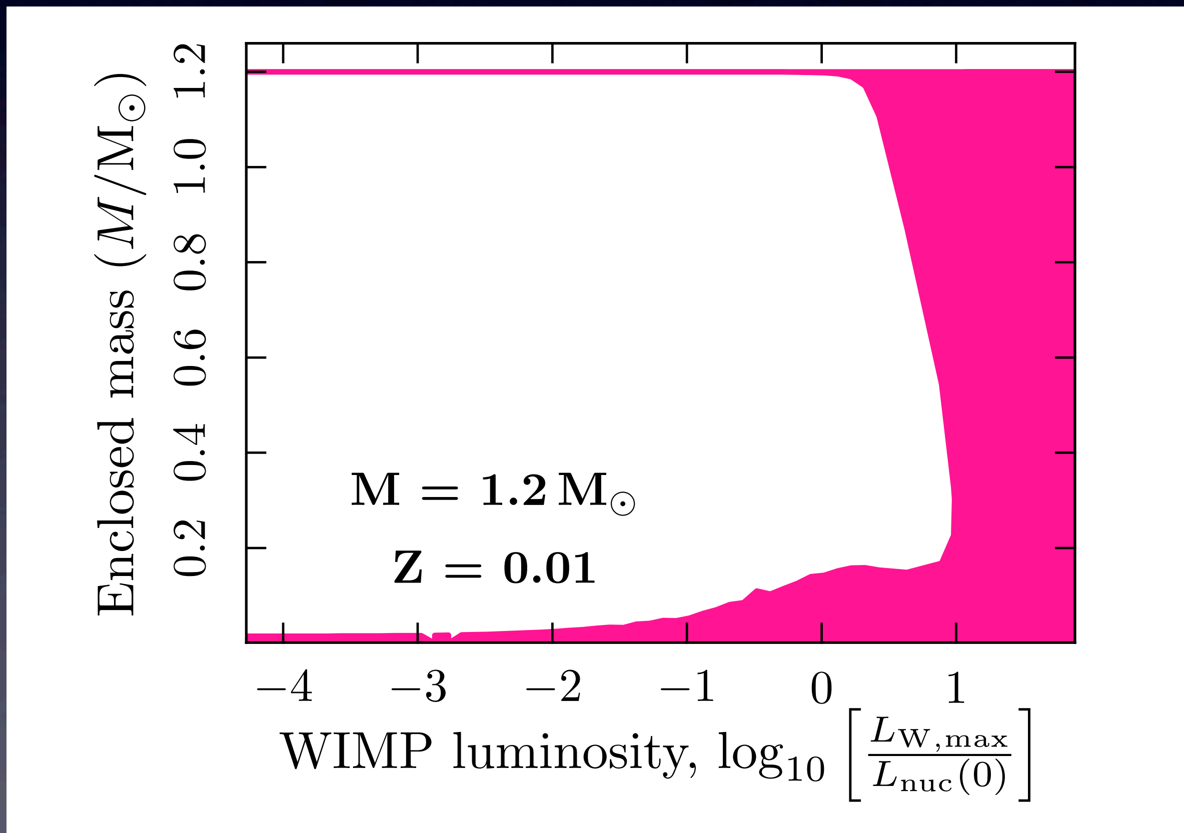
Velocity vs. DM density

Max Capture rate is at 0.3 pc from the center of the BH

Lower DM density compensated Since DM has lower velocity

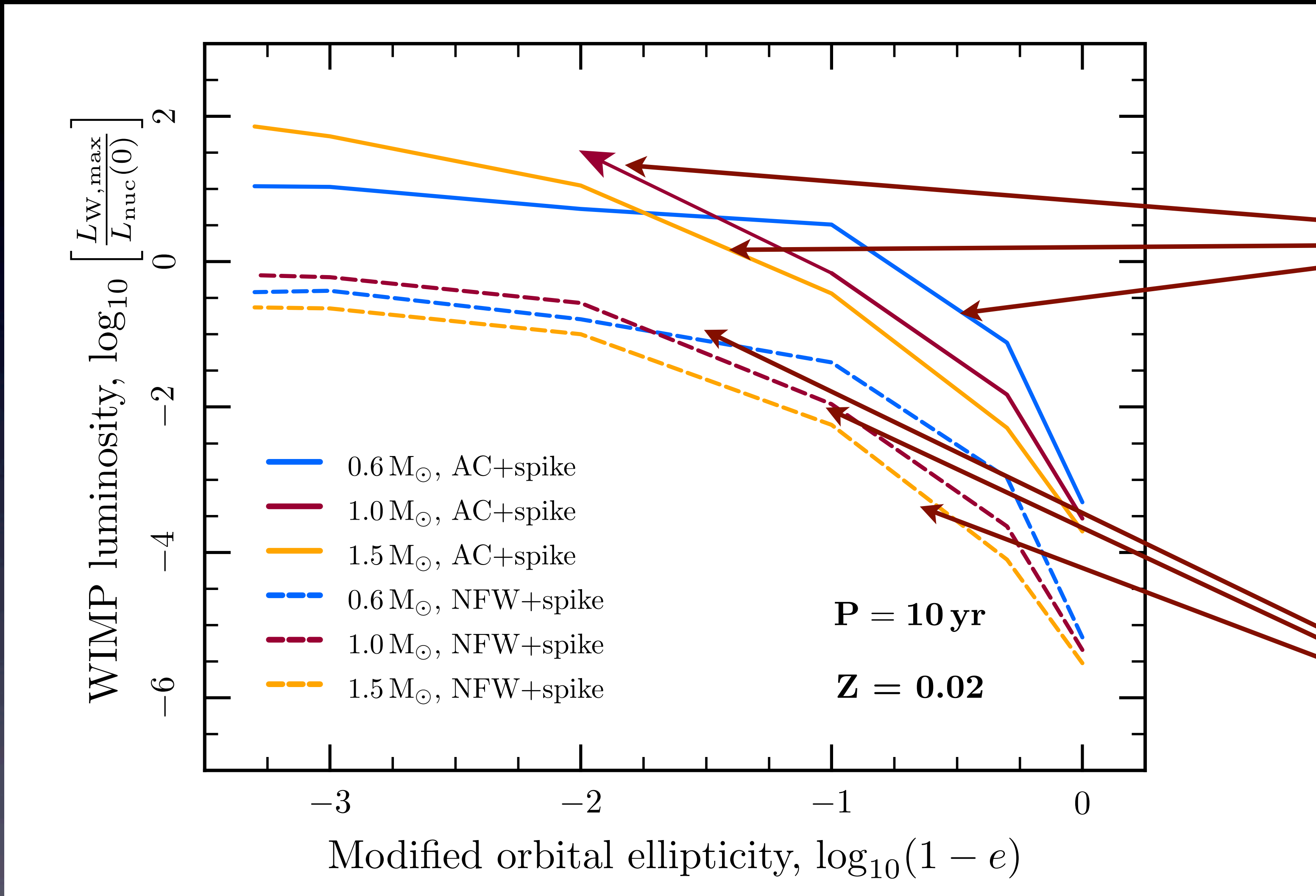
Scott Etal. 2009

Convection Zones of Star With Increasing DM heating



Edsjo, Fairbairn, and Scott 2008

DM Luminosity vs. Fusion



Adiabatically NFW contracted Halo

NFW profile alone

Since Capture happens mostly away from the DM spike.... AC has the most dramatic effect

P Scott etal 2009

TMT
30 Meter

- larger telescope will dramatically increase the sensitivity to low luminosity stars and may provide an opportunity to determine the dark matter density in terms of Machos (invisible baryonic matter) and WIMPs (A. Ghez etal 2010)
    - 2018 first science
- Also may allow for a survey of stars powered by DM or at least place interesting constraints on the properties of DM

Conclusion

- JWST and HST can constrain dark stars forming in the early universe and could be a way to discover dark stars
- Fermi can strongly constrain the dark star scenario and SMBH formation in general
- TMT has a chance to also constrain the capture rates of DM at the galactic center