Title: Entropic unification in ten trillion years from naturally selected dark matter

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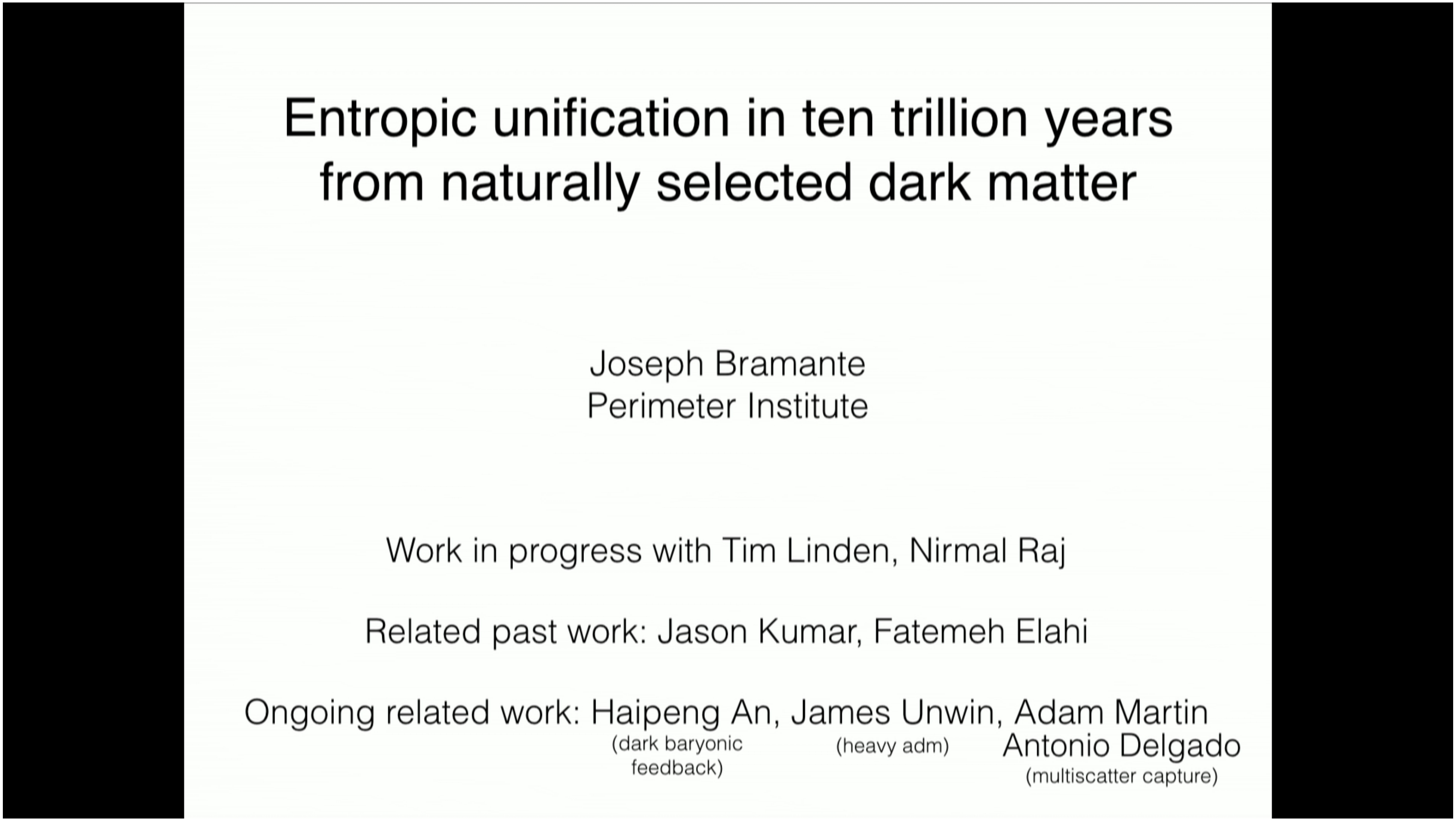
Abstract: <p>The fundamental constants of our universe may have been set to maximize the production of similar universes, through repeated parametric variation. In this context, I will advocate that by the time the maximum entropy producer in our universe has reached maximum complexity, the majority of its energy should be re-purposed towards the production of additional universes. This builds on elements of prior proposals, including cosmological natural selection, the nonsingular universe, and the causal entropic principle. The phenomena and properties of dark matter, which realizes this proposal by copious conversion of halo baryons to black holes in ten trillion years, will be discussed.</p>



# Entropic unification in ten trillion years from naturally selected dark matter

Joseph Bramante
Perimeter Institute

Work in progress with Tim Linden, Nirmal Raj

Related past work: Jason Kumar, Fatemeh Elahi

Ongoing related work: Haipeng An, James Unwin, Adam Martin
(dark baryonic feedback) (heavy adm) Antonio Delgado
(multiscatter capture)

# Naturalness

All terms in Lagrangian
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Scalar VEVs distributed across universes ($u_i$), our VEVs selected to give the observed universe.

## Example: Higgs

$$\delta m_h^2 = \Lambda^2/32\pi^2(6\lambda - y_t^2 + ...)$$

Need new states at Λ to preserve naturalness.

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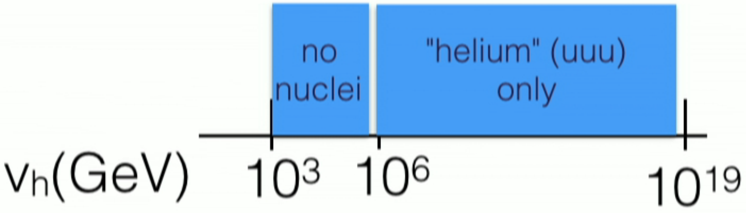
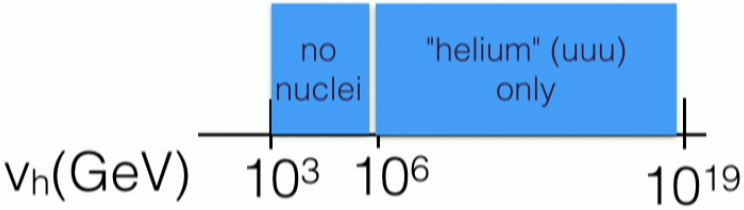


If higgs vev heavier, no atoms, $|m_n - m_p| >$ MeV

Donoghue et al. '96

# Selection parametric ping pong



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Agrawal, Barr, Donoghue, Seckel '96

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**Weakless Universe**

-Increase the higgs vev to its natural $\sim m_{pl}$ value.

-Decrease the (technically natural) u, d, s quark, and electron yukawa couplings to maintain observed fermion masses.

-Atoms and stellar burning possible in more natural universe.

Harnik, Kribs, Perez '06

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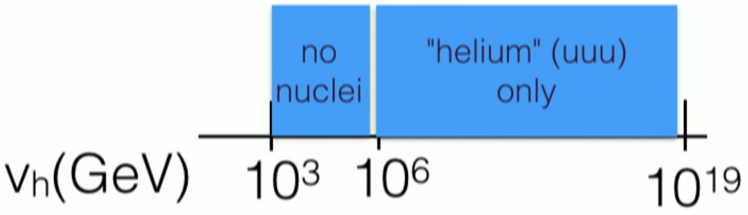

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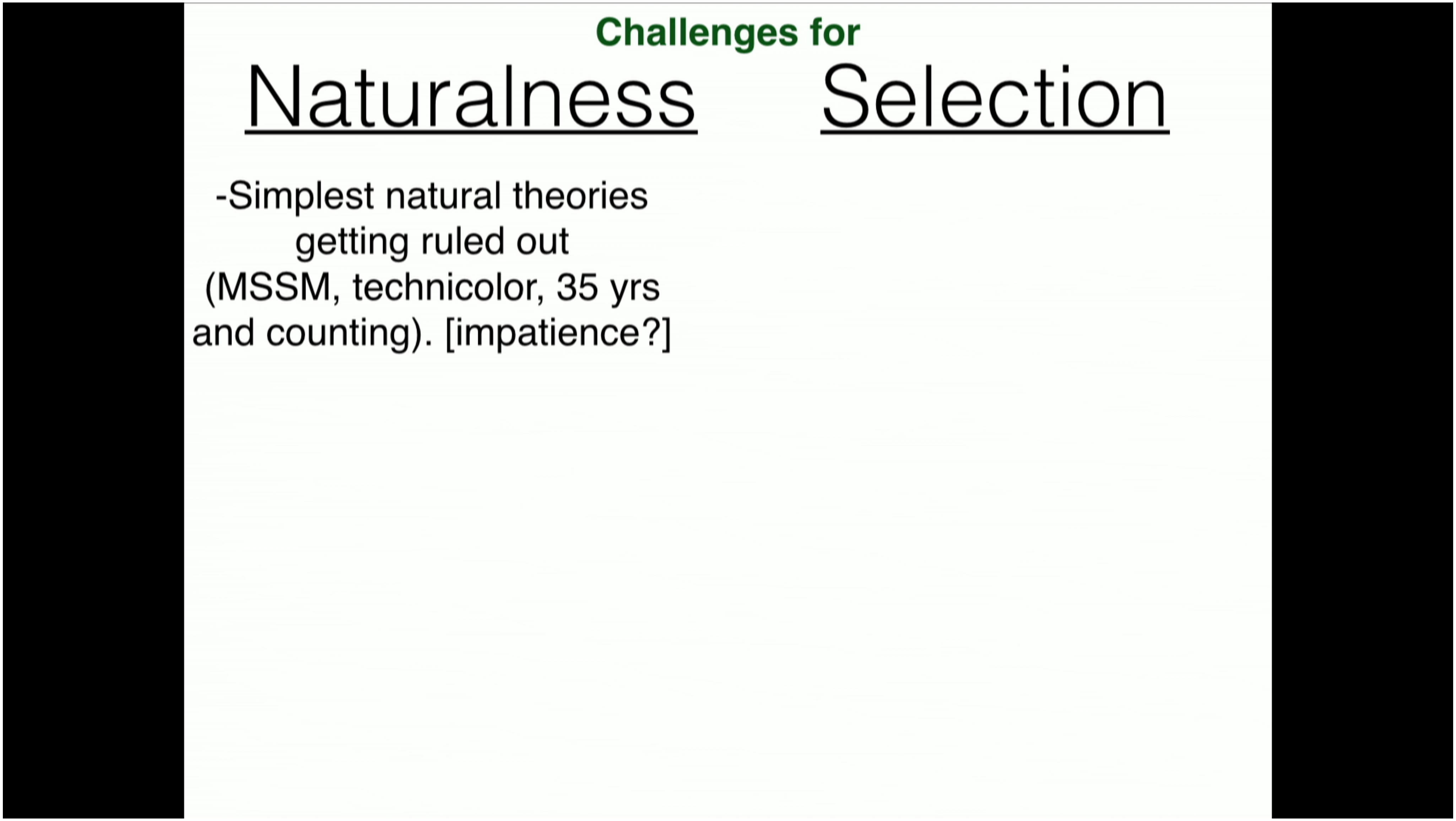
**Oxygen deficient weakless universe?**

-Possible problems propagating oxygen, carbon in a universe lacking core collapse supernovae (no neutrino emission).

Clavelli, White '06



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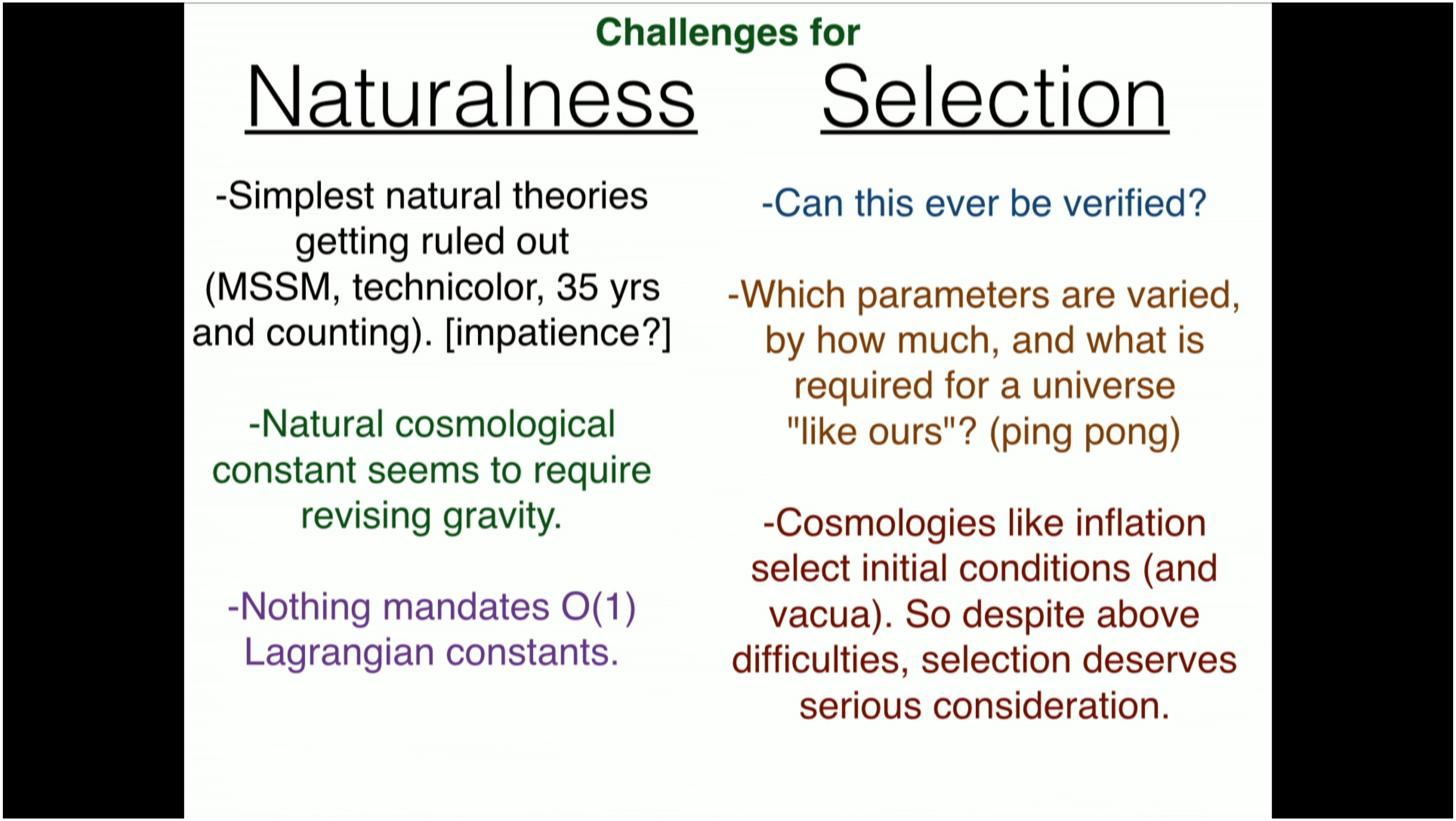


## Challenges for

## Naturalness

-Simplest natural theories getting ruled out (MSSM, technicolor, 35 yrs and counting). [impatience?]

-Natural cosmological constant seems to require revising gravity.

-Nothing mandates O(1) Lagrangian constants.

## Selection

-Can this ever be verified?

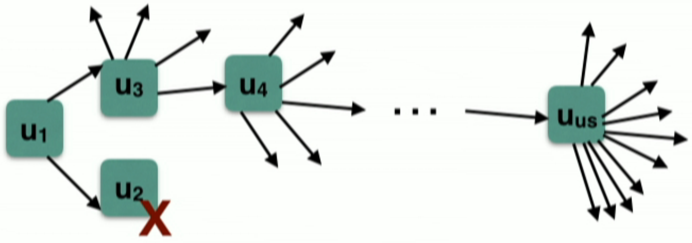
-Which parameters are varied, by how much, and what is required for a universe "like ours"? (ping pong)

-Cosmologies like inflation select initial conditions (and vacua). So despite above difficulties, selection deserves serious consideration.

# Natural Selection

Constants (scalar VEVs) selected through repeated variation, akin to biological evolution.

-Nambu ’85
(brief musing)
-Smolin
(most subsequent development)



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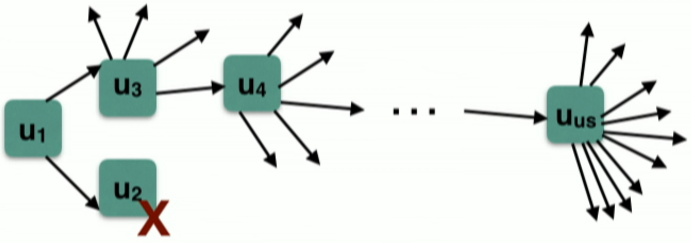

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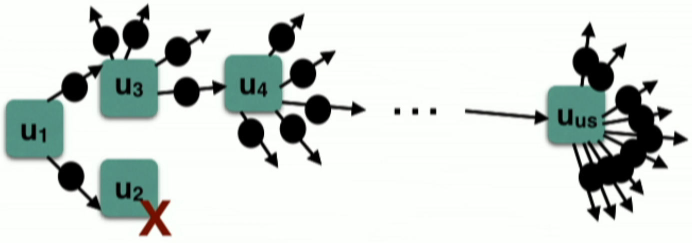


More specifically:

Black holes best candidate sites for de Sitter patch creation.

- only known sites with >BBN density
- max GR curvature ➜ de Sitter in BH interior

Brandenberger, Mukhanov, Sornborger, Markov, Frolov ~'90

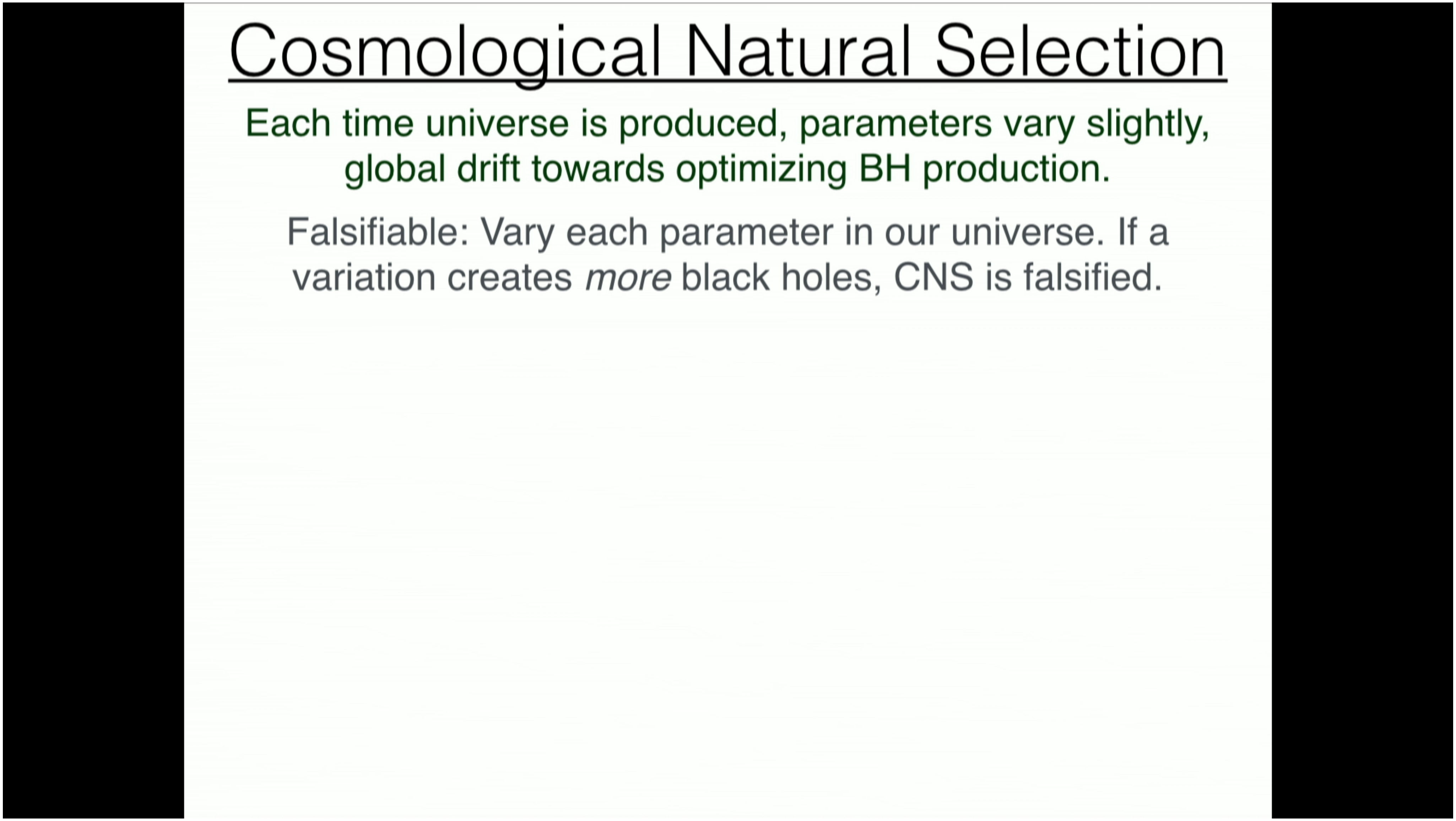
Hence our universe should maximize black hole production.

-Smolin ~'90

# Cosmological Natural Selection

Each time universe is produced, parameters vary slightly, global drift towards optimizing BH production.

Falsifiable: Vary each parameter in our universe. If a variation creates *more* black holes, CNS is falsified.



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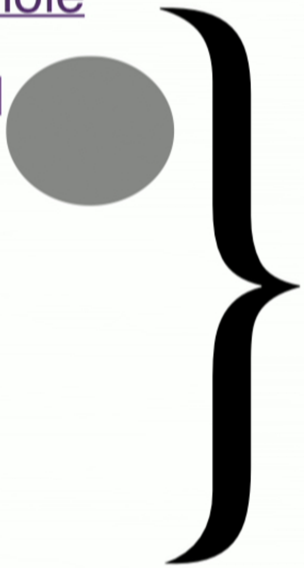
CCSN to black hole

>20 $M_\odot$ gas cloud condenses



# Finding an explicit model of cosmological natural selection

An explicit model of cosmological natural selection could be constructed with 2 ingredients:

1. Black hole interiors should contain a de Sitter (inflating) spacetime.

2. The parameters of the underlying theory (moduli fields) should vary a small amount in each inflating spacetime.

# 1. BH interior — de Sitter

1. Limit on maximum curvature: $R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} \leq \dfrac{\alpha}{\ell^4}$

-Simplest (classical GR) prescription, which solves the Penrose-Hawking singularity problem.

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-Simplest (classical GR) prescription, which solves the Penrose-Hawking singularity problem.

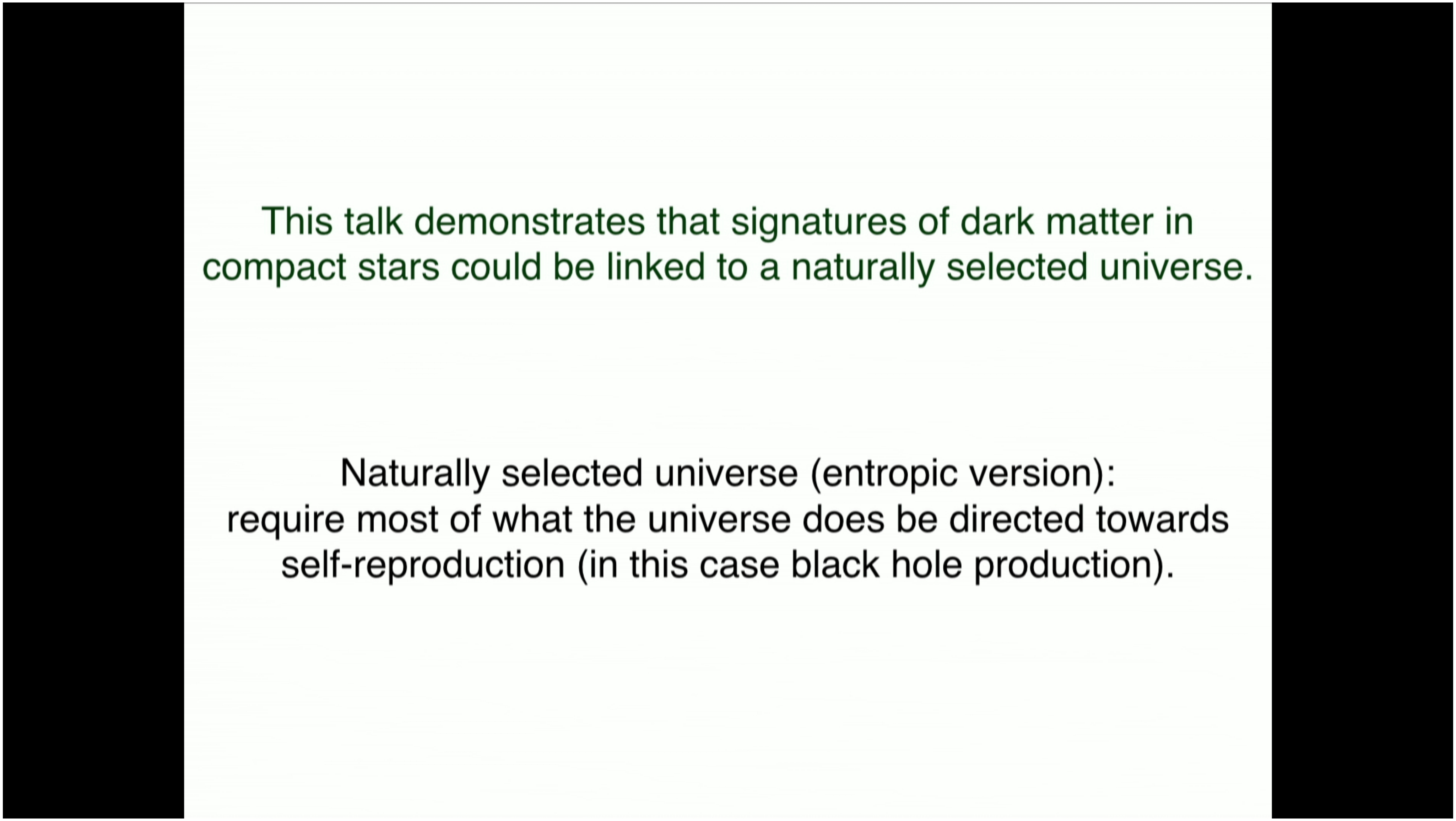
2a. Can construct classical GR transition to inflating spacetime when $R^2 \sim \ell^{-4}$.

Frolov, Markov, Mukhanov '90

2b. Or show that when a finite number of invariants take on limiting values, any solution of the Einstein field equations will asymptote to de Sitter. (Using Lagrange parameters to set maximum curvature limitation.)

Brandenberger, Mukhanov, Sornborger '93

This talk demonstrates that signatures of dark matter in compact stars could be linked to a naturally selected universe.



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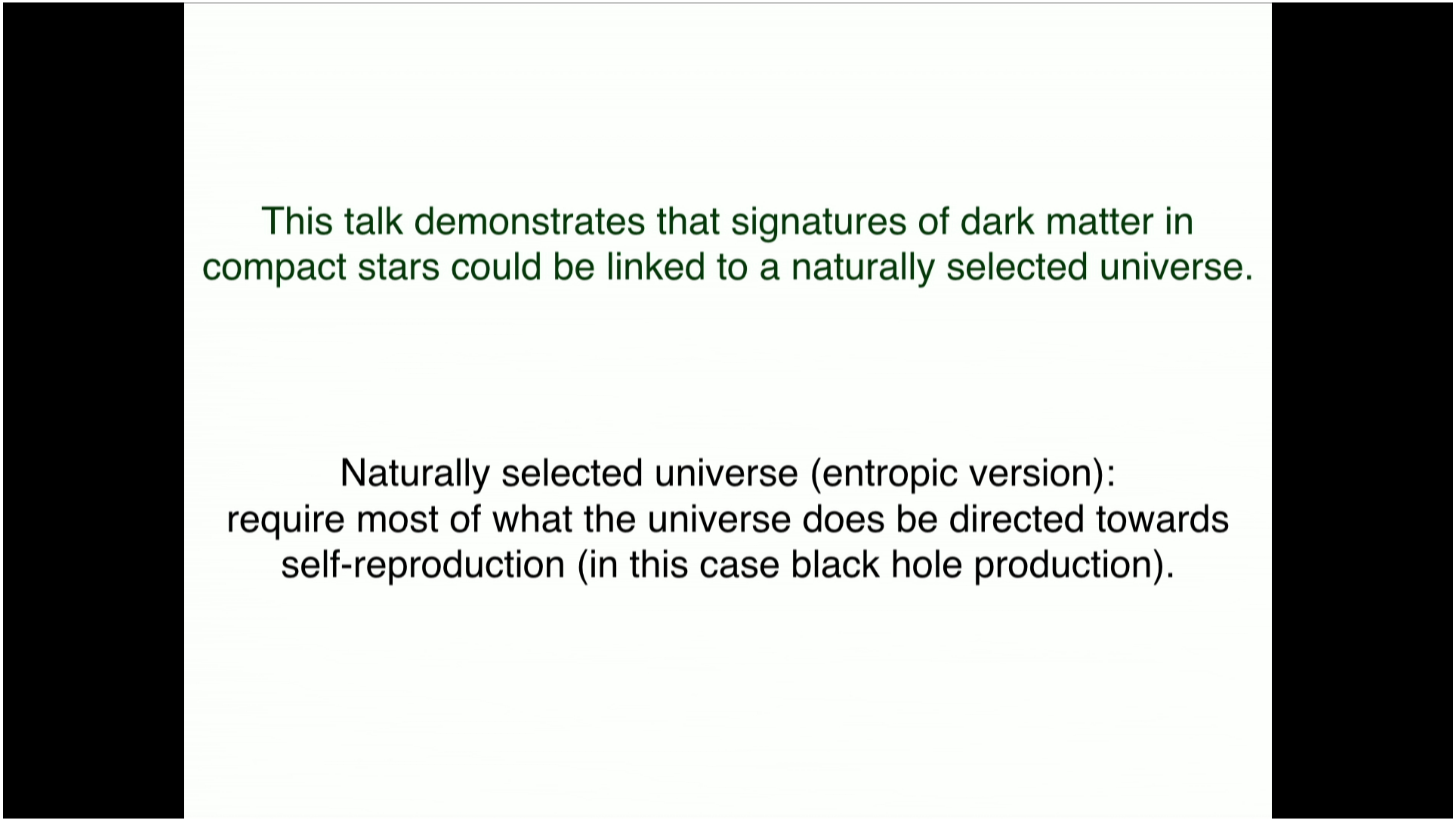

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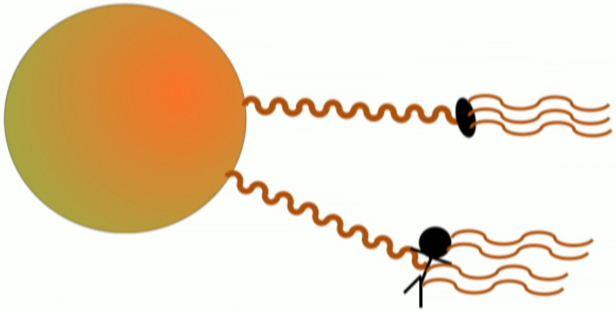

Most entropy increase comes from starlight,
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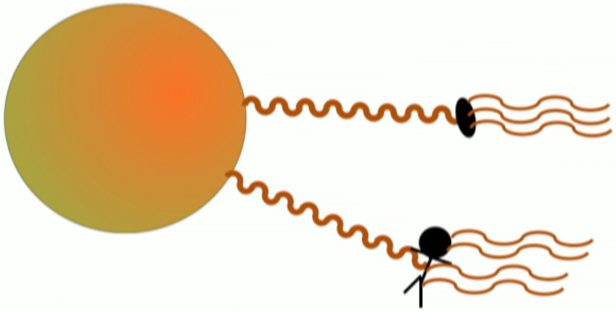

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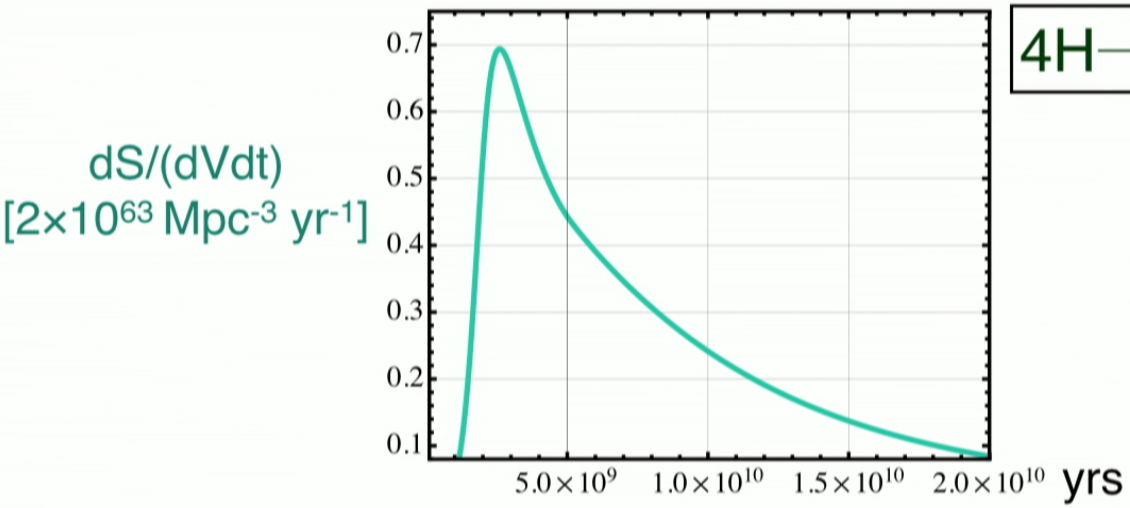

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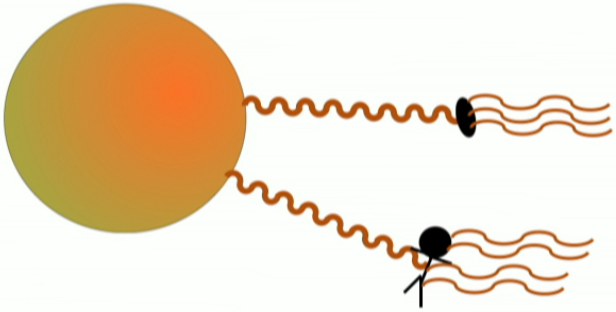

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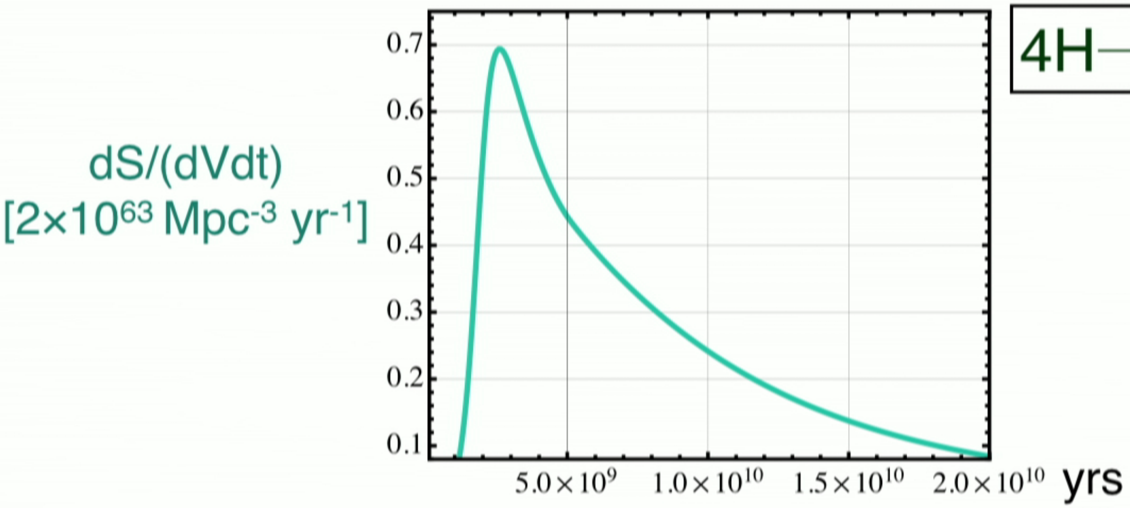

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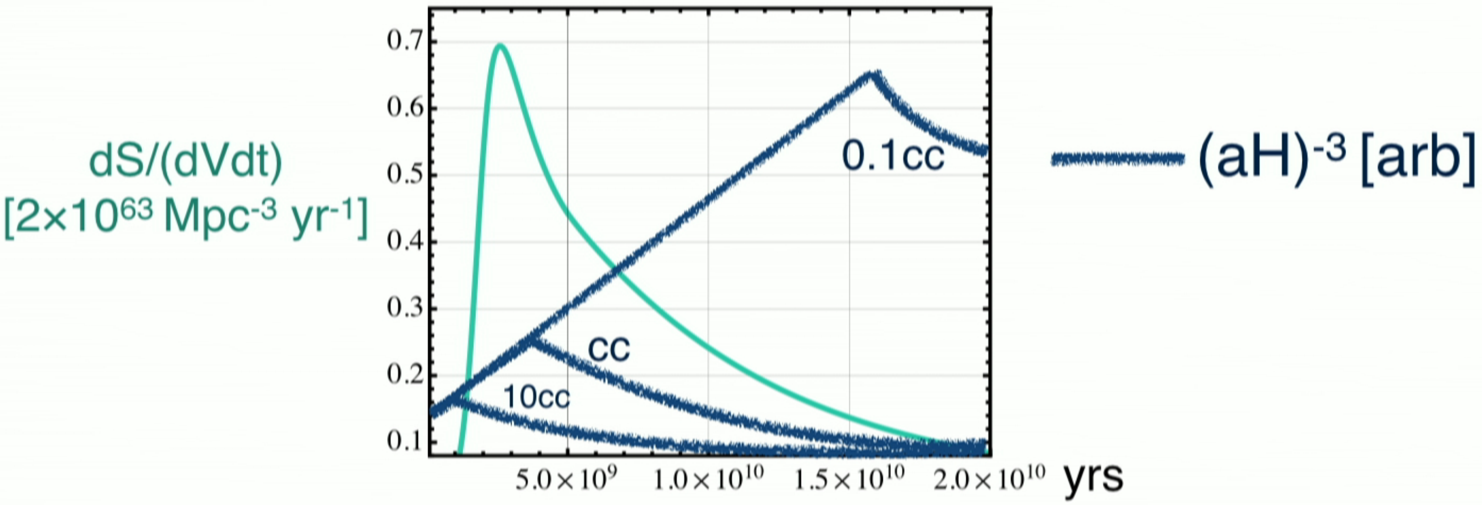
Brief aside:

Causal entropic principle: maximum entropy production (observation) at maximum comoving horizon (causally connected spacetime volume). BHKP '06



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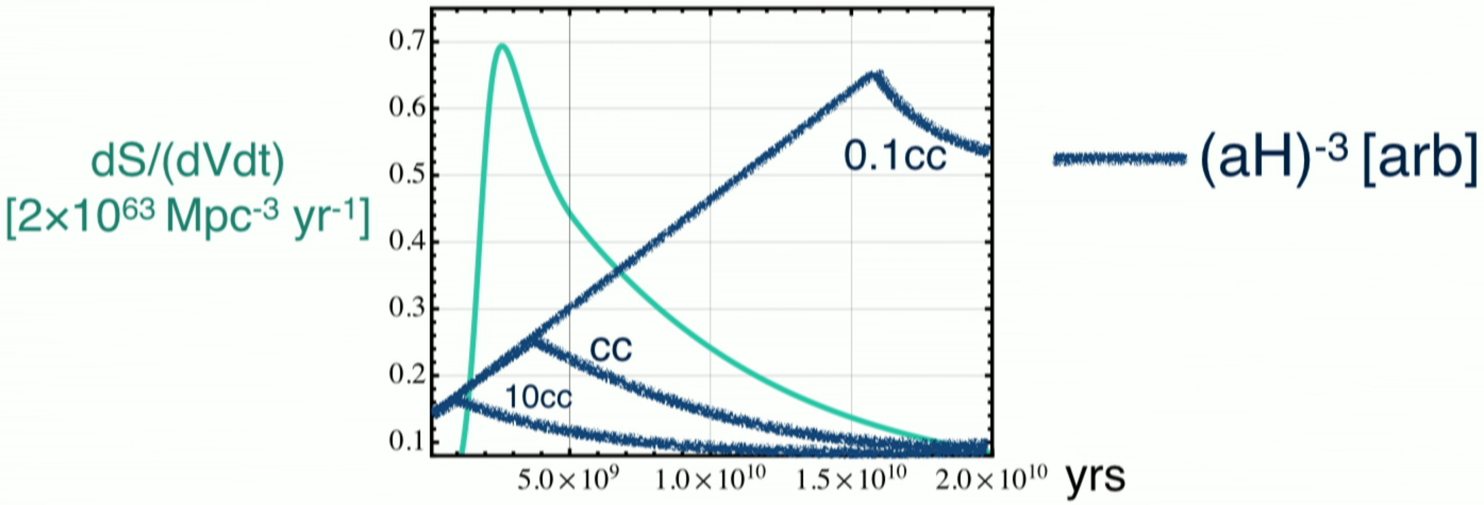

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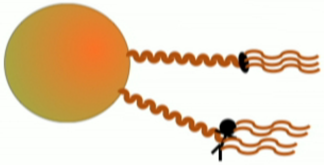

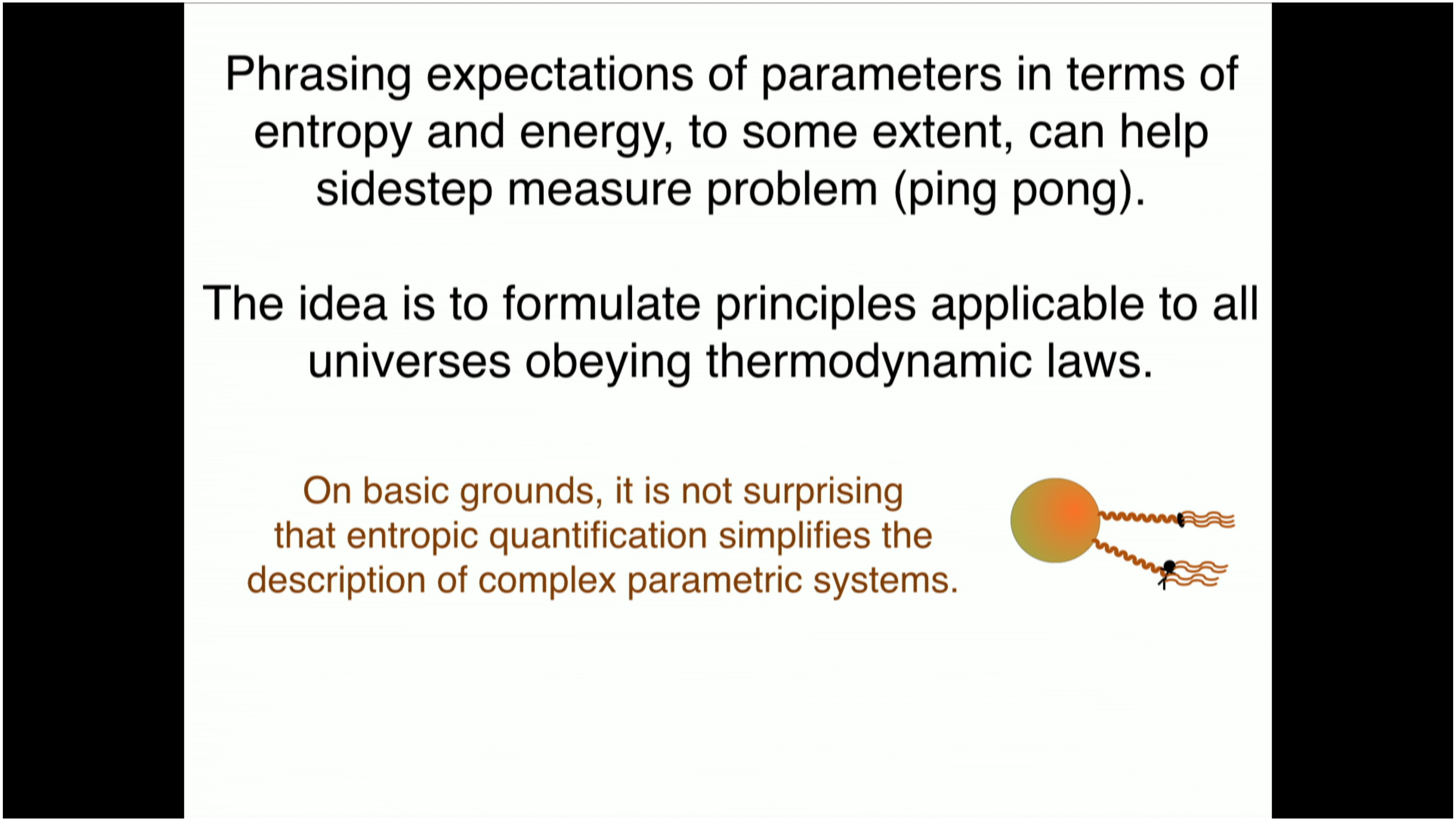

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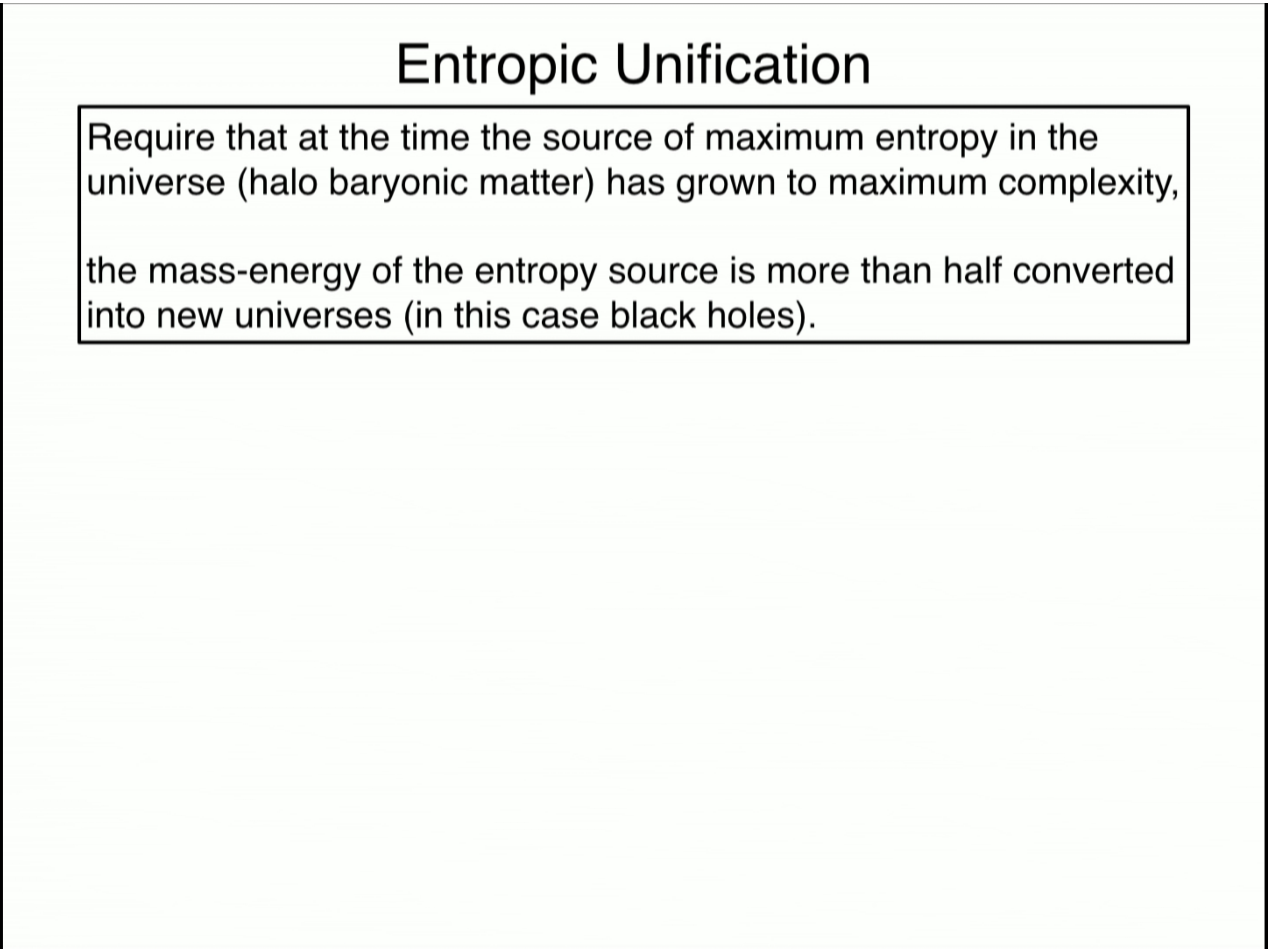

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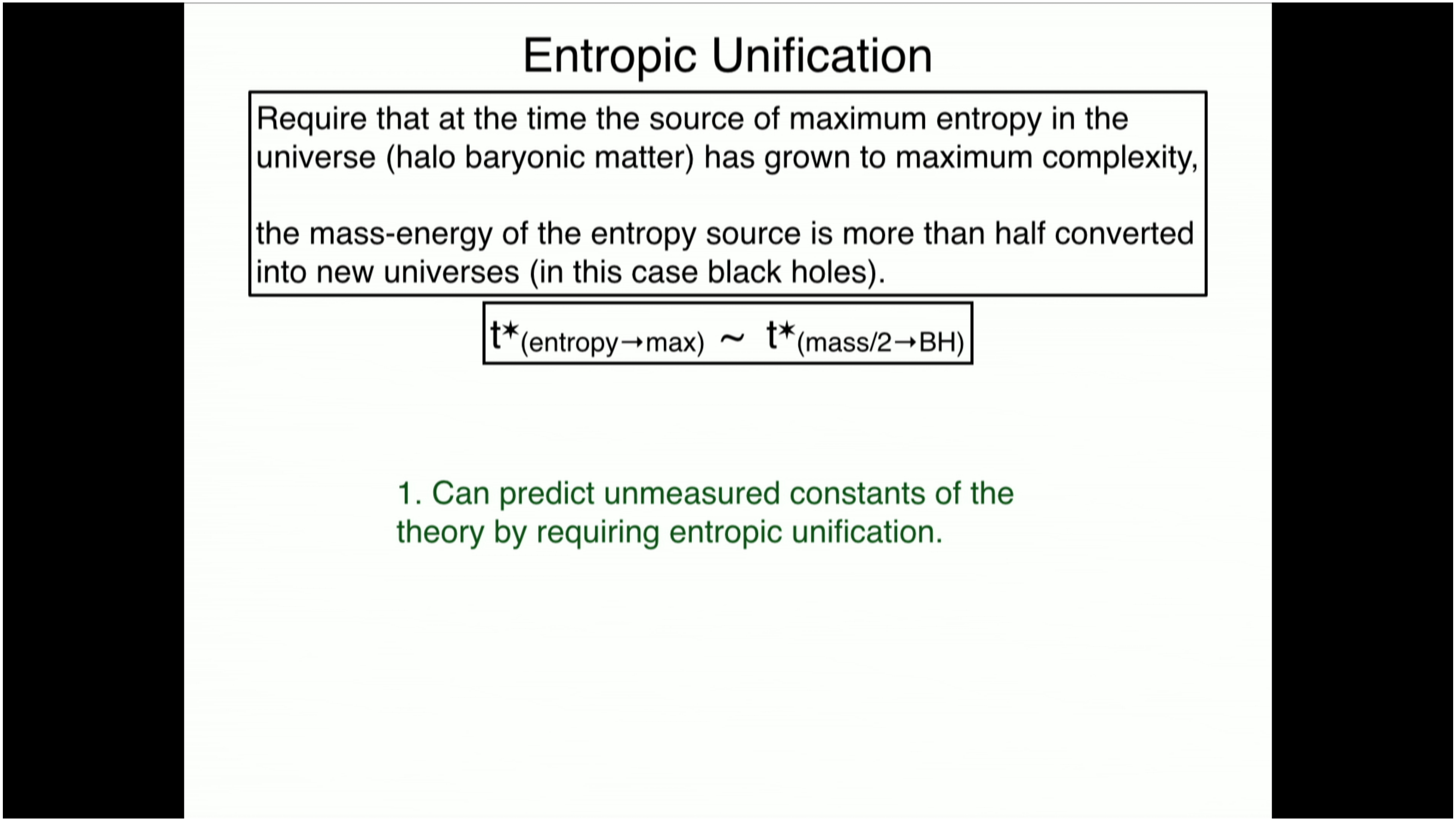
($\star$=max entropy producer in universe)



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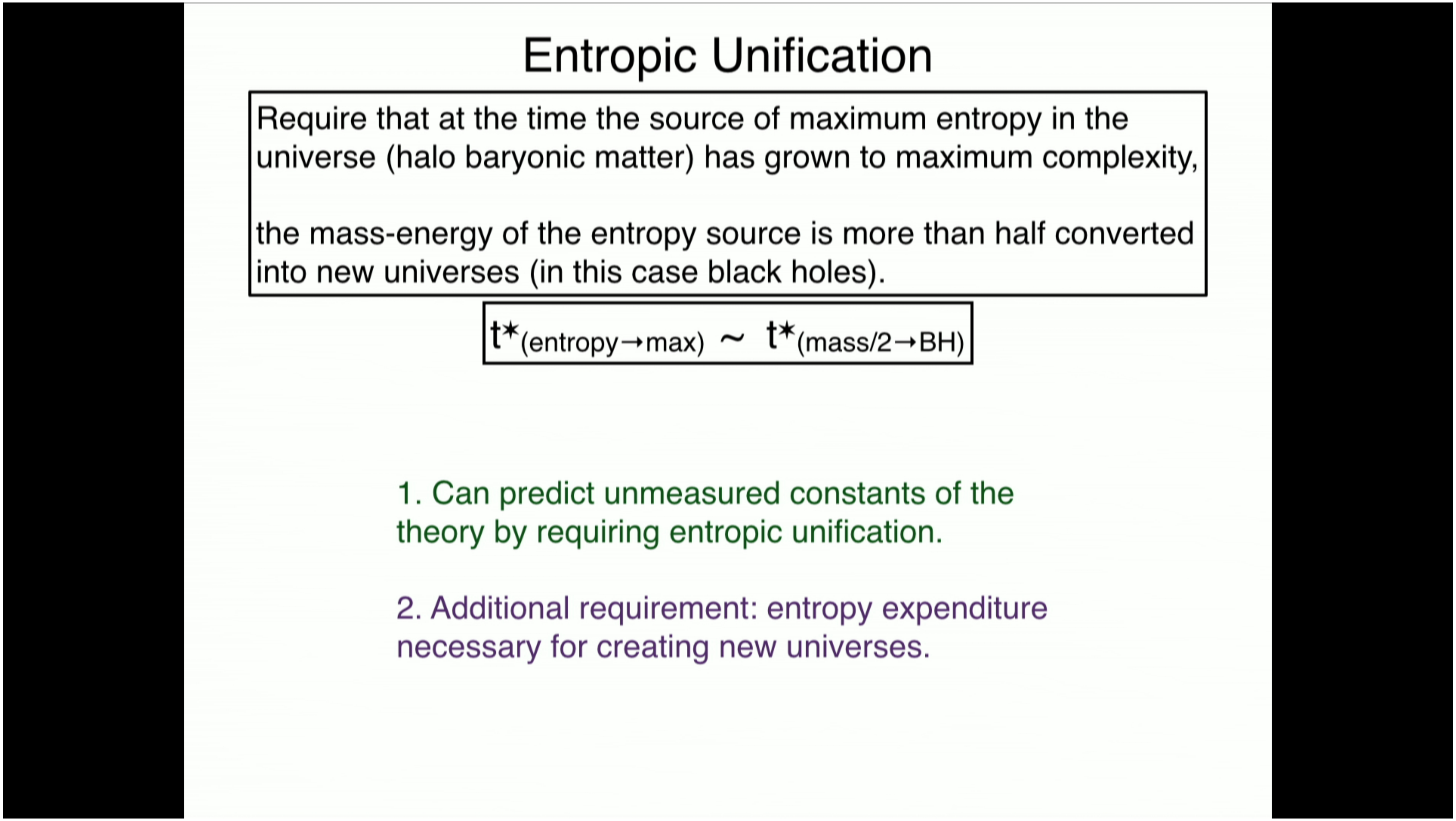

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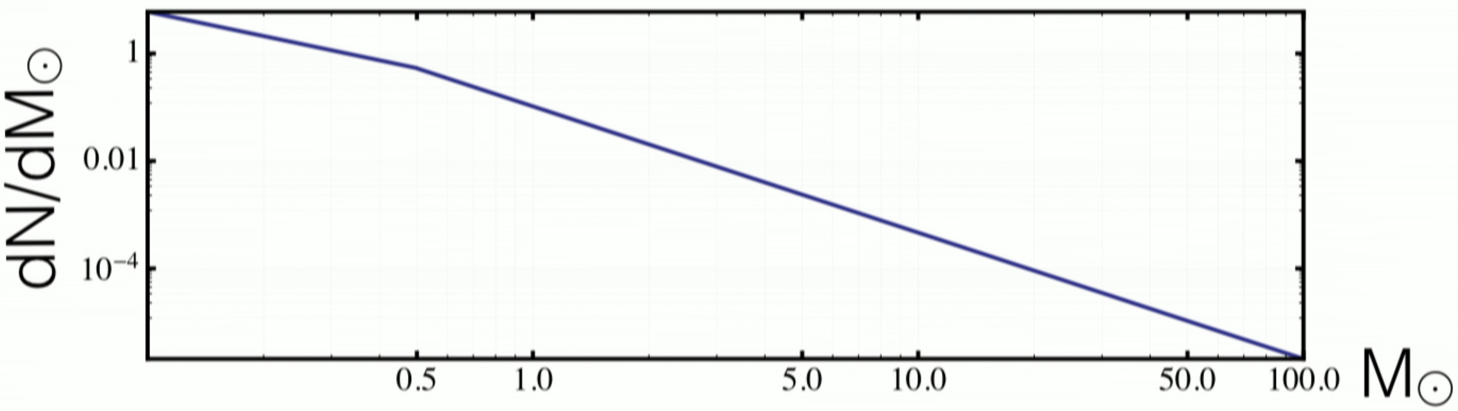
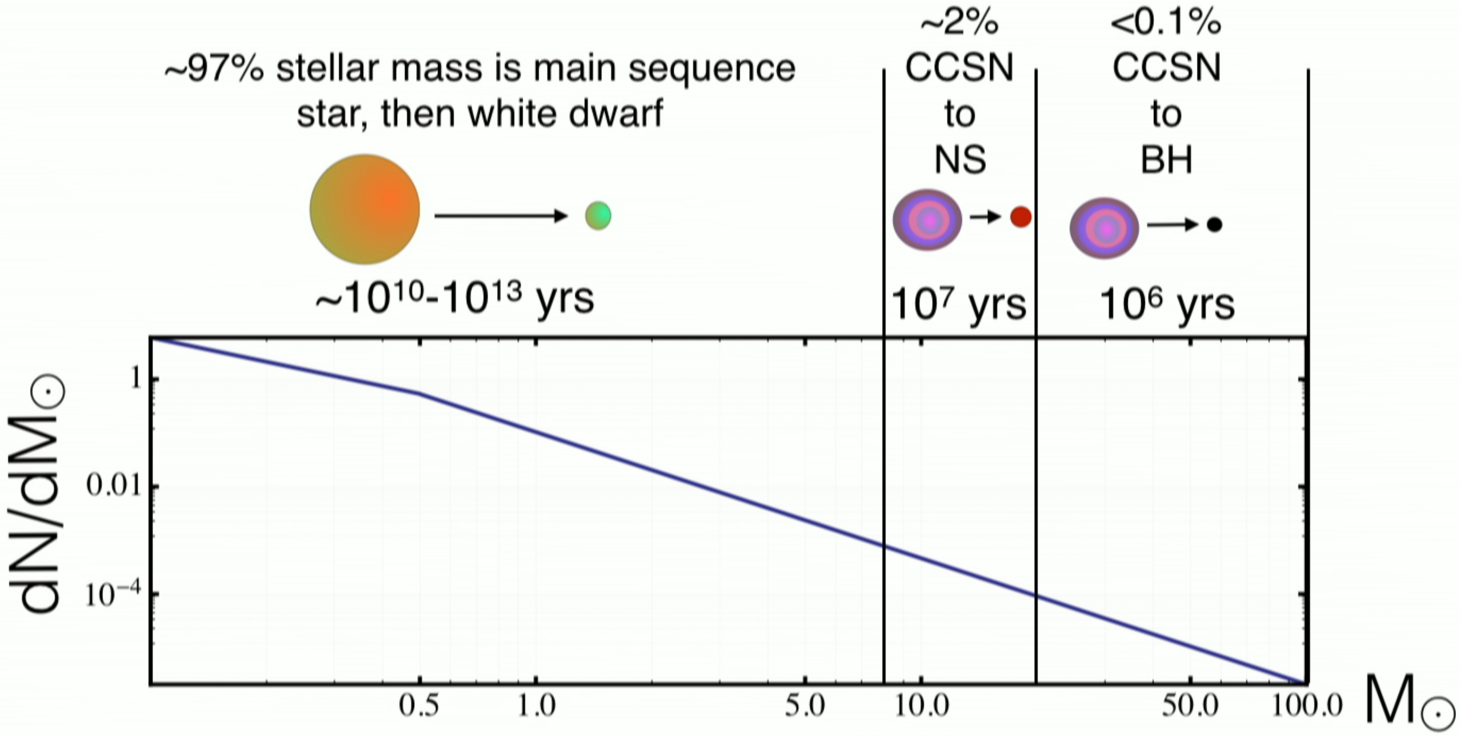
2. Additional requirement: entropy expenditure necessary for creating new universes.



Star masses follow an observationally-fit spectrum, weighted towards low mass (non-BH producing) stars.



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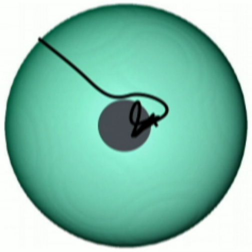
More massive stars burn faster.

$$t(m) = \left(\frac{m_\odot}{m}\right)^{2.5} 10^{10} \text{ yrs}$$

# Compact Stars → Black Holes via Asymmetric Dark Matter

1. DM captured



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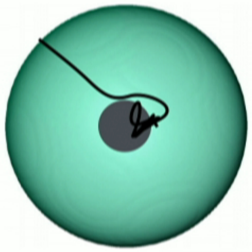
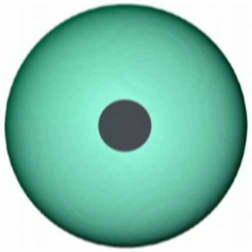


2. DM and star reach thermal equilibrium, DM forms core



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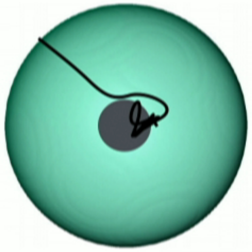

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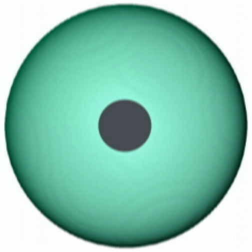
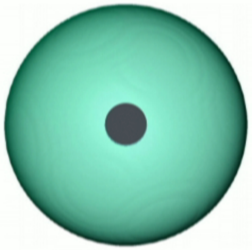
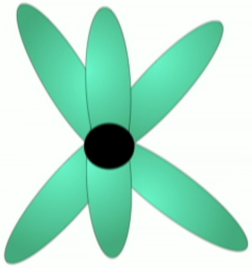


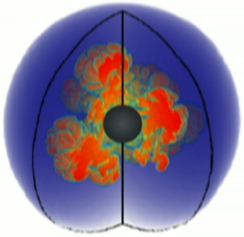
3. DM collapses once $\rho_{dm} \sim \rho_s$



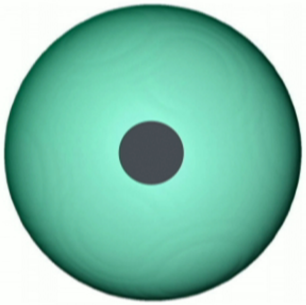
4a. large BH formed as BH composed of DM accretes star



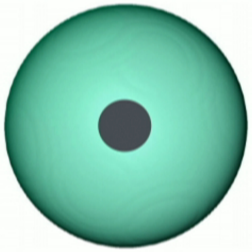
4b. DM collapse ignites thermonuclear burning, star explodes, halo metallicity increases, more efficient giant molecular cloud cooling



In order to implode in a compact star, the dark matter must collect into a *small* enough core within the star, and collect *enough* DM to self-gravitate — $\rho_{dm} \sim \rho_s$. Even tiny self-annihilation cross-sections make this impossible — hence the DM must have some asymmetry.



# Dark matter that implodes in compact stars



$m_X$

✗ GeV mass, asymmetric dark fermions — fermi degeneracy pressure stabilizes up to a solar mass of dark matter.

Even in $10^{13}$ yrs, at most $\sim 10^{-9}\, M_\odot$ of DM accumulate

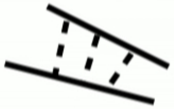
**KeV-EeV**

✓ Bosonic dark matter without repulsive self interactions — requires very small effective quartic self-coupling (λ).

$$M_{crit}^{bos} \simeq \frac{M_{pl}^2}{m_X}\left(1+\frac{\lambda M_{pl}^2}{32\pi m_X^2}\right)^{1/2}$$

**MeV-PeV**

✓ Higgs portal dark matter with ~MeV scalar portal mediator — provides attractive Yukawa force that prompts collapse.



$$\frac{N_X^{1/3}}{r} - \alpha\frac{e^{-m_s r}}{r} \sim 0$$

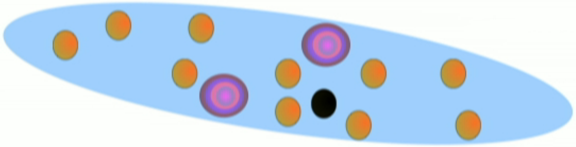
**PeV-EeV**

✓ **Heavy** dark matter, fermionic or bosonic — fewer particles, less degeneracy pressure.

$$M_{crit}^{ferm} \simeq M_{pl}^3/m_X^2$$

# Abridged Timeline of Galactic Halos, with and without compact star imploding dark matter

~$10^9$ yrs galaxies form



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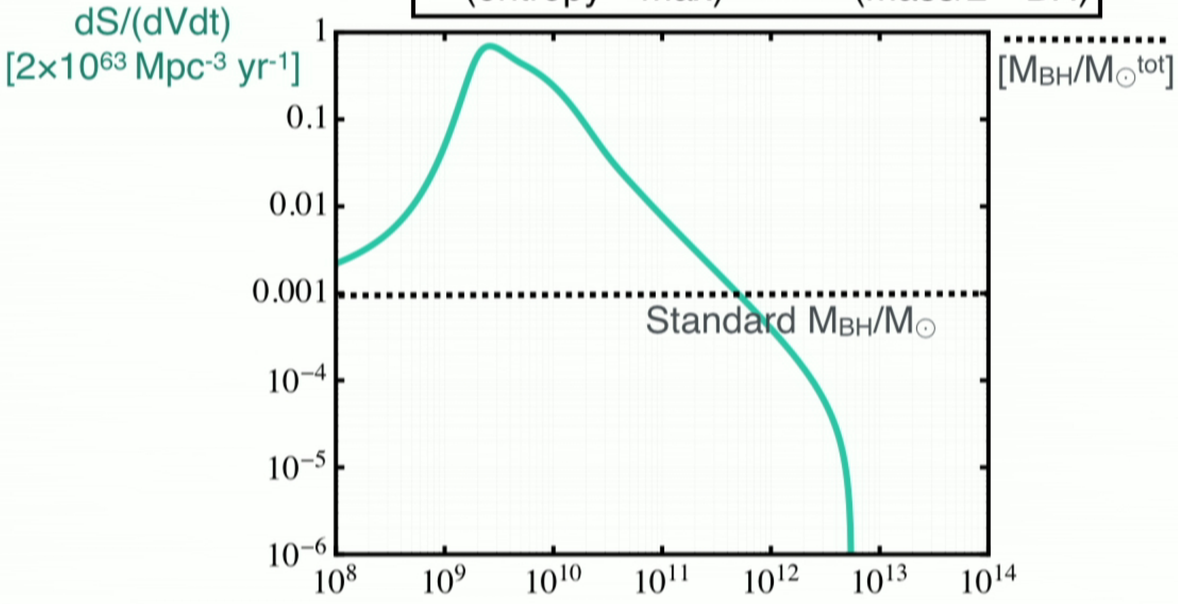

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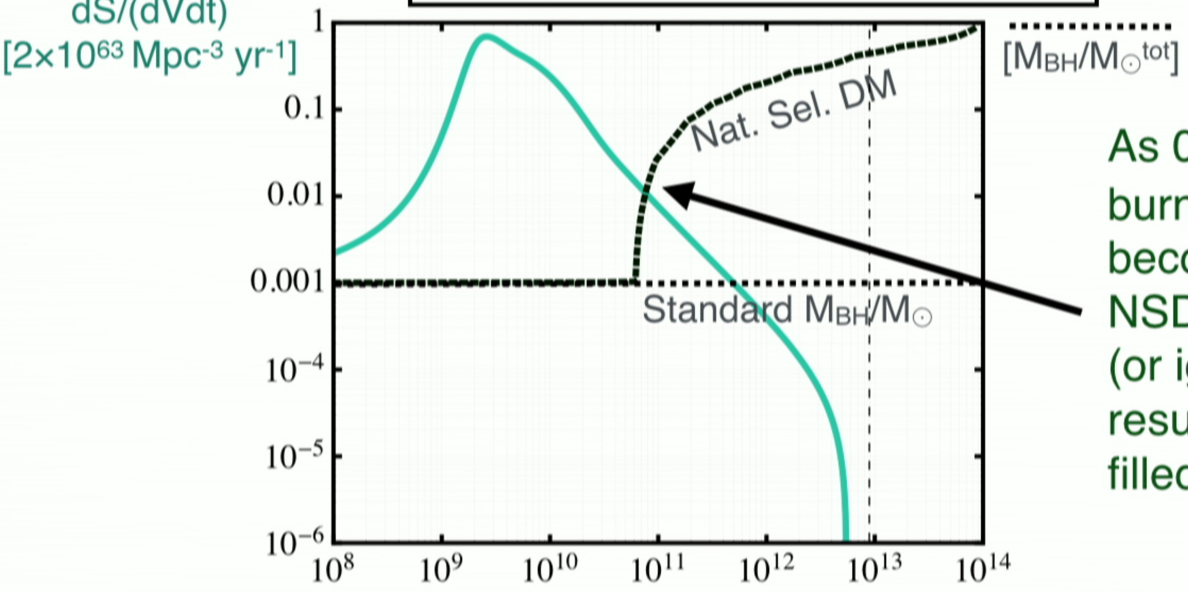
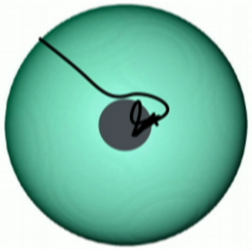


As 0.1-1$M_\odot$ stars burn out, they become compact, NSDM will collapse (or ignite) them, resulting in halos filled with BHs

# Signals of DM in Compact Stars



DM particle capture rate
in Milky Way galactic halo:

$$C_X \sim \frac{\boxed{\rho_x}}{m_x \bar{v}} \frac{M_{\rm wd}^2}{R_{\rm wd} m_t} \sigma_{\rm nx}$$

# Entropic Unification

Require that at the time the source of maximum entropy in the universe (halo baryonic matter) has grown to maximum complexity,

the mass-energy of the entropy source is more than half converted into new universes (in this case black holes).

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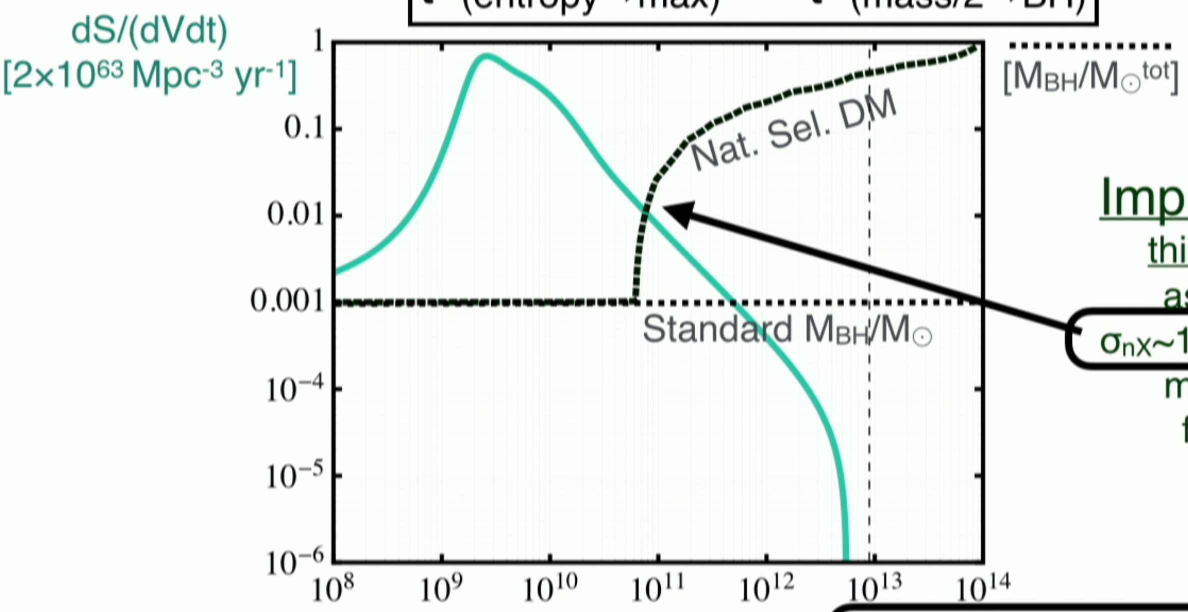

**Implosive DM**

this example:

asymmetric

$\sigma_{nX}\sim10^{-40}$-$10^{-42}$ cm$^2$

$m_X\sim30$ PeV

fermionic

Dependent on late time metallicity.

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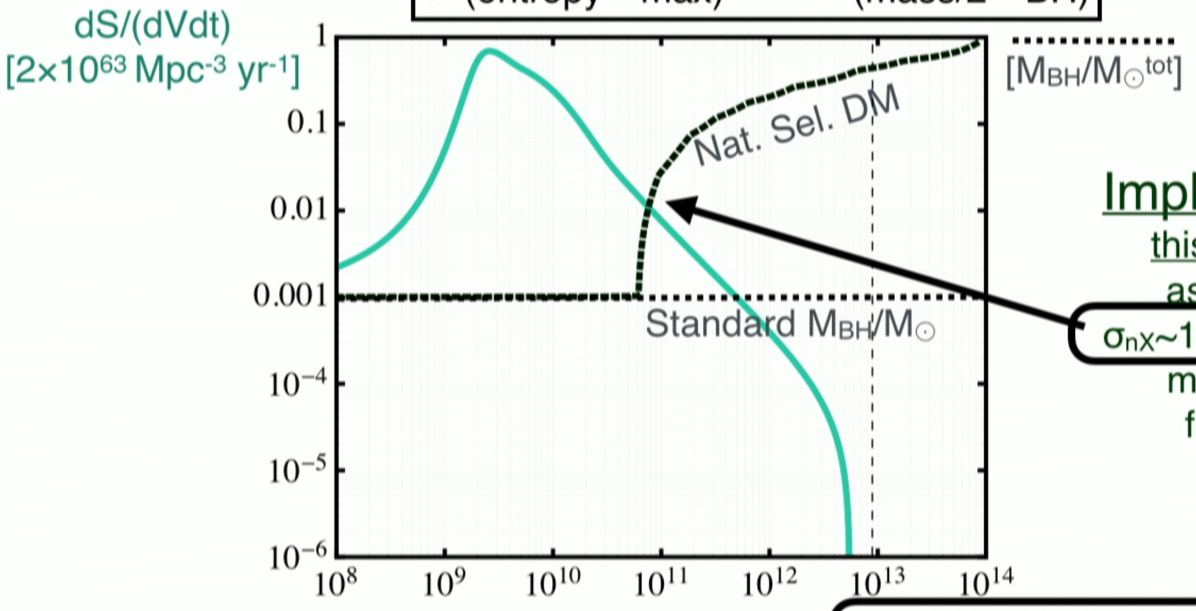

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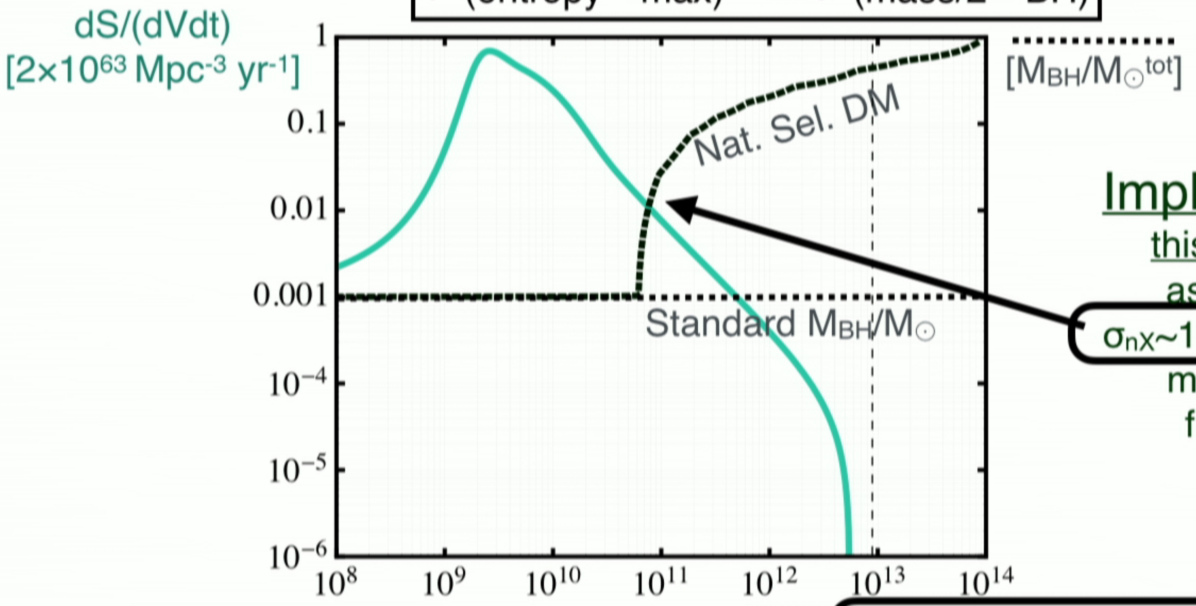

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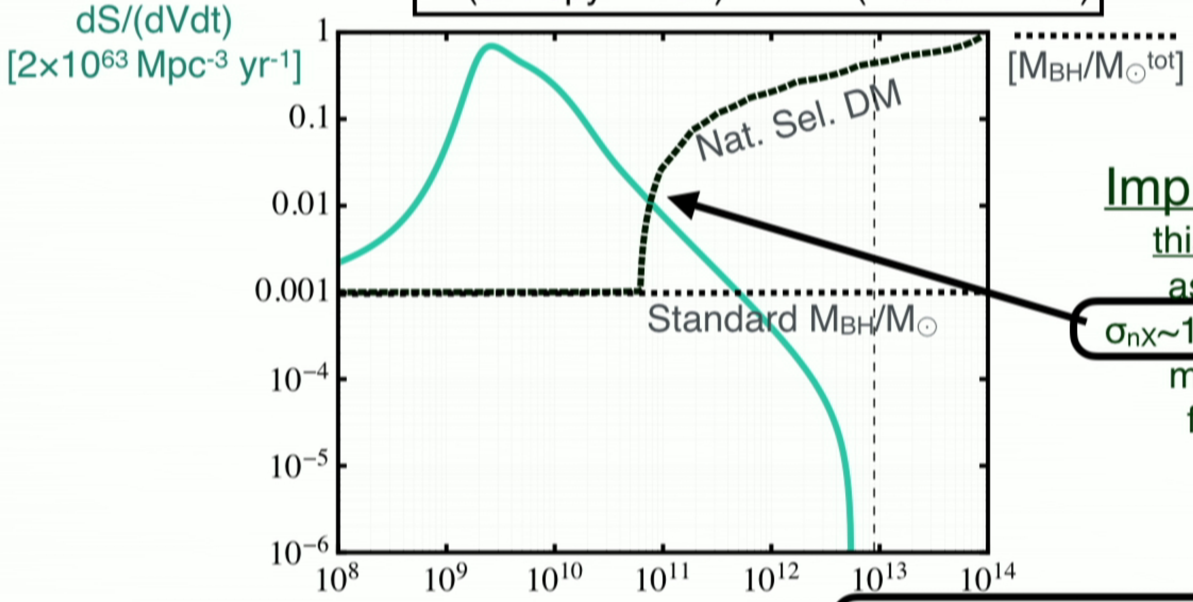

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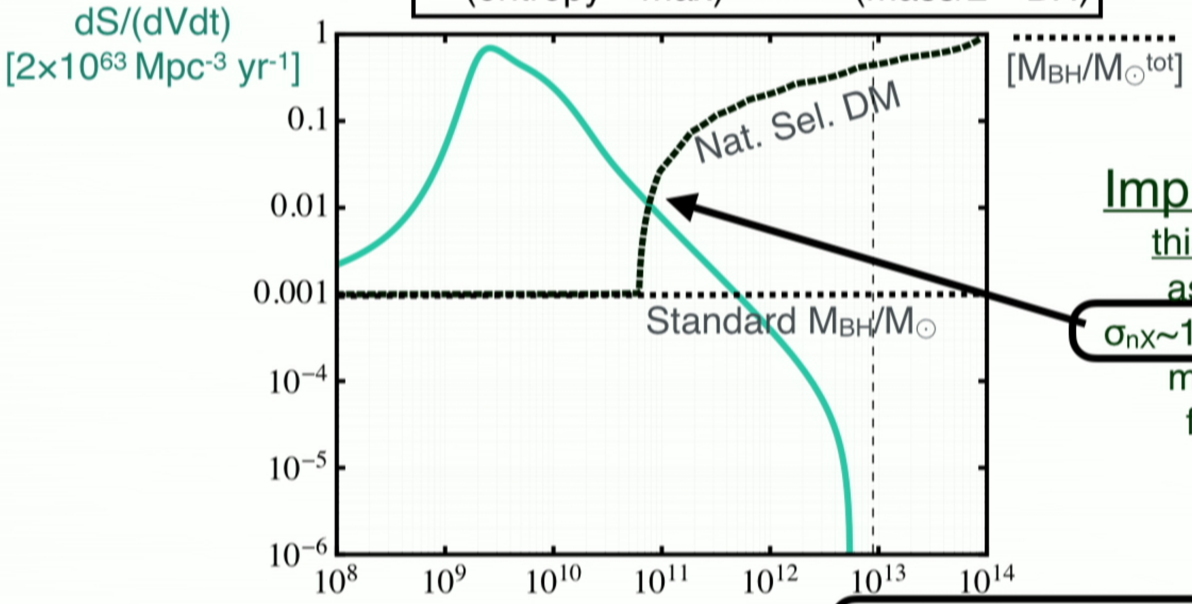

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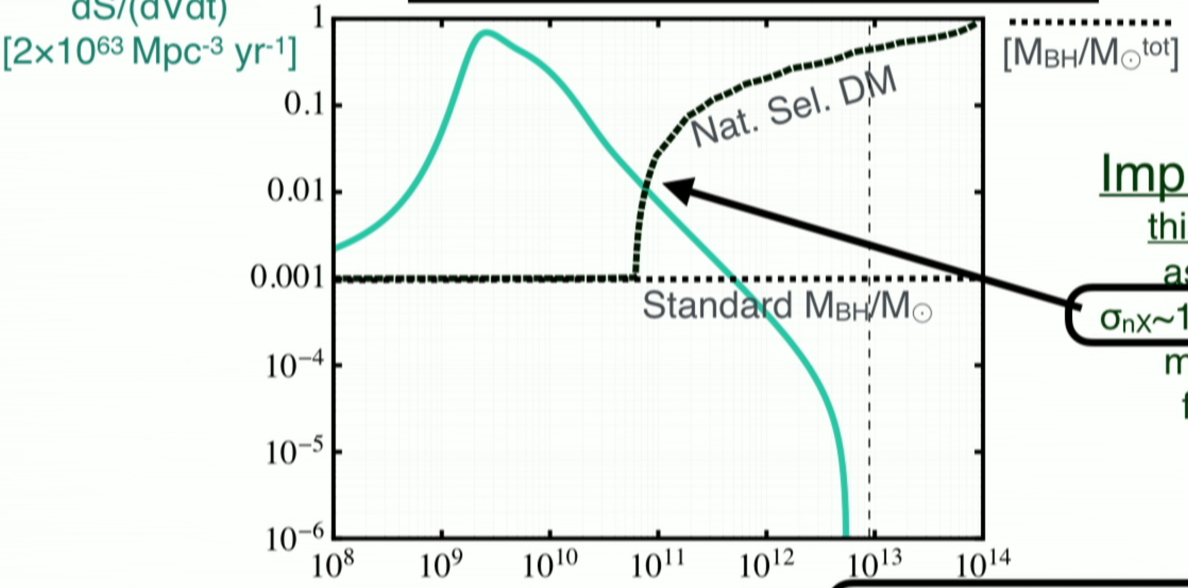

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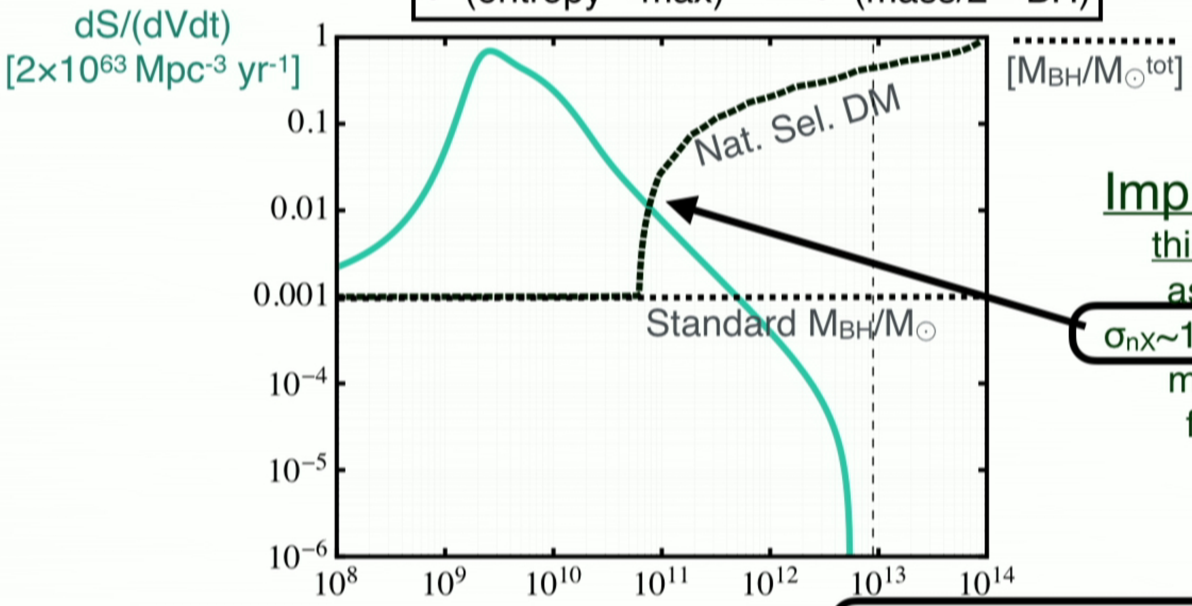

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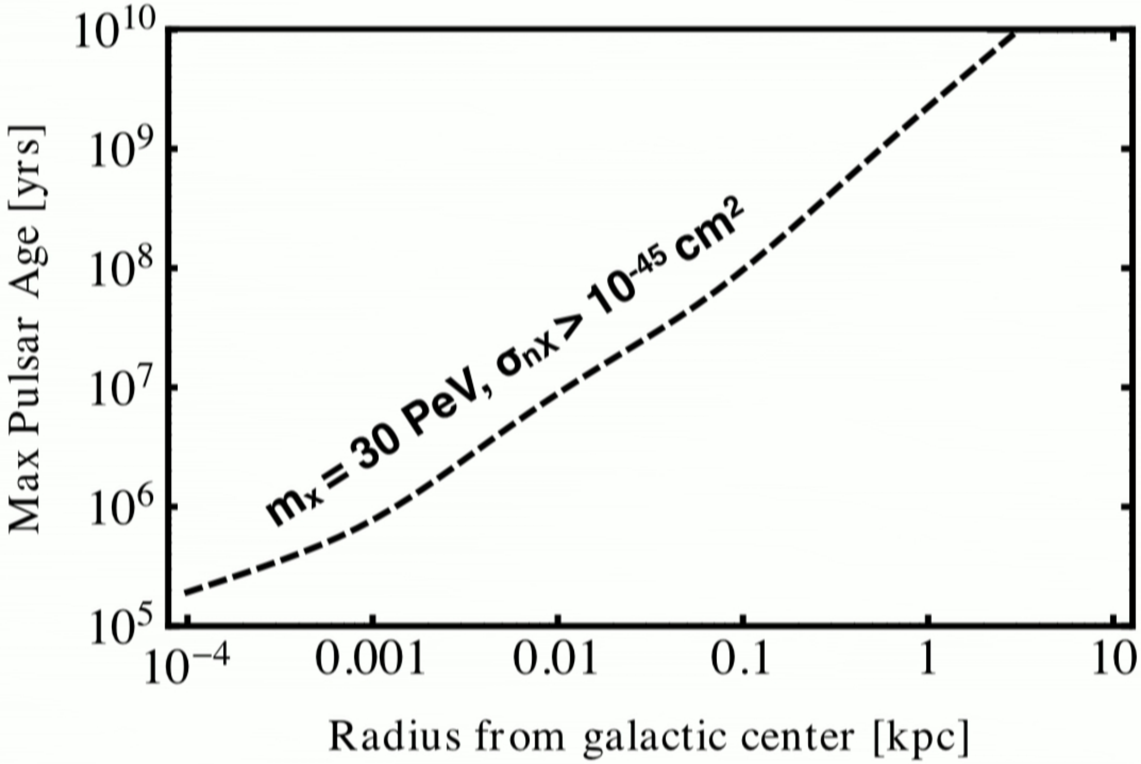
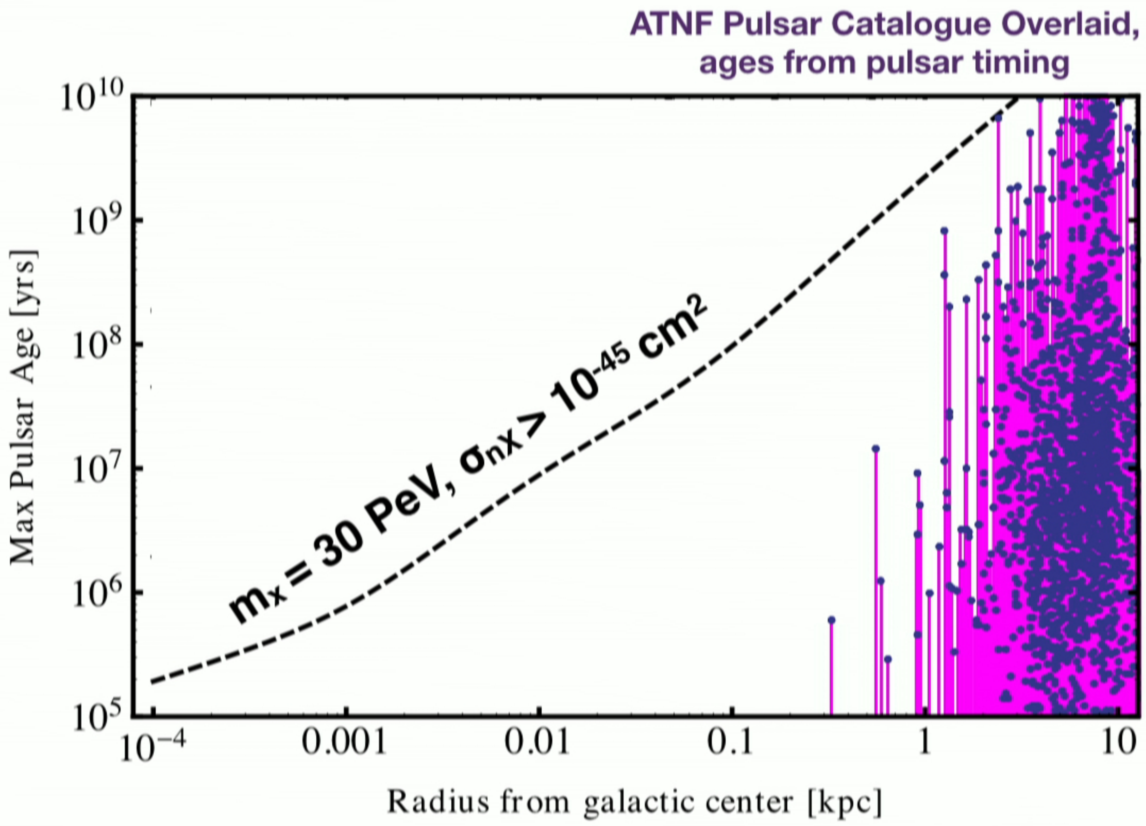
# Dark Matter and Maximum Pulsar Age Curves



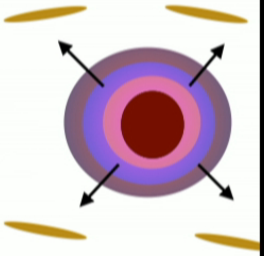
Naturally selected dark matter that converts halo baryons to black holes in ten trillion years could show up as a maximum pulsar age dependent on distance from the galactic center.

# Dark Matter and Maximum Pulsar Age Curves



**The Milky Way's 1-500 pc center will be surveyed in the coming decade (SKA). Thus far, the central parsec has been searched.**

# Plausible r-process sites:



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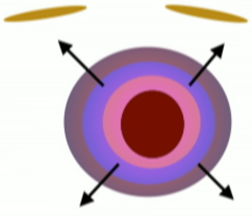

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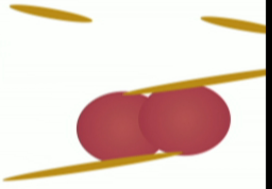
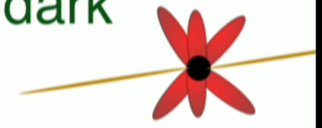


-Merging neutron star binaries tidally blowing off dense neutron fluid (rare, ~1/$10^4$ years)



-Neutron star falling into a black hole made of dark matter at its core.

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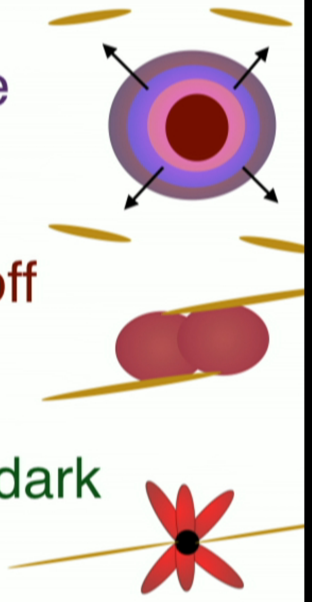

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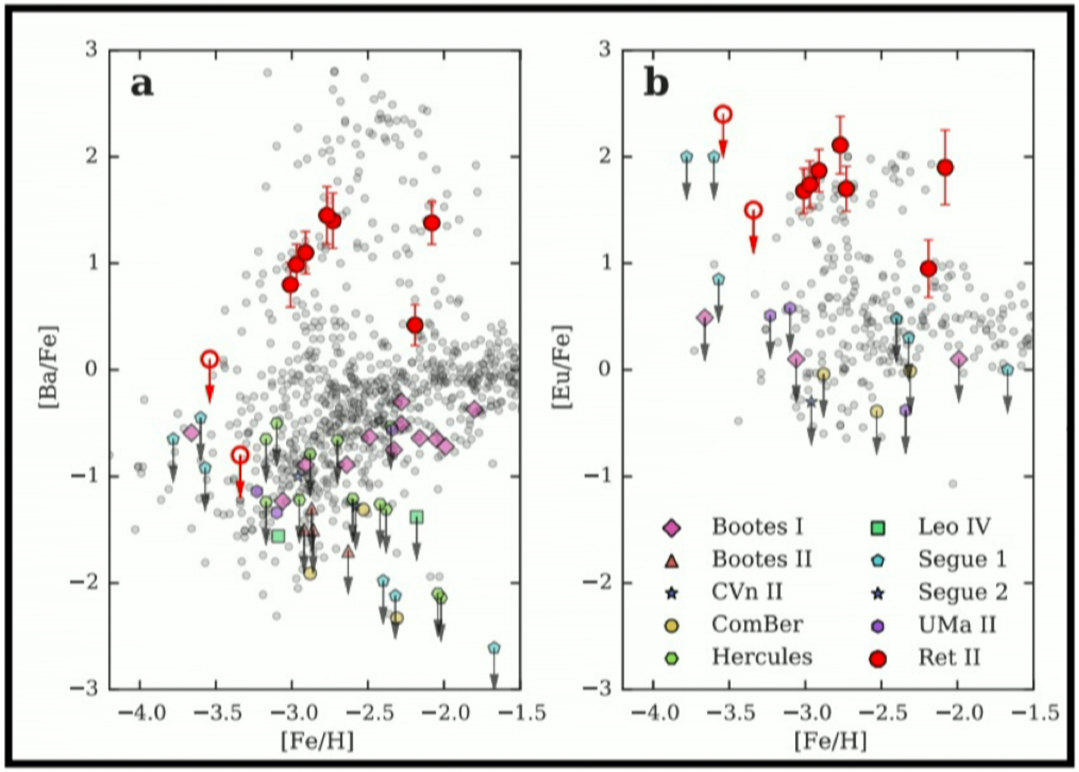
In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.

Ultra Faint Dwarf Spheroidals are rapidly formed during the first few billion years, and have a high mass-to-light ratio



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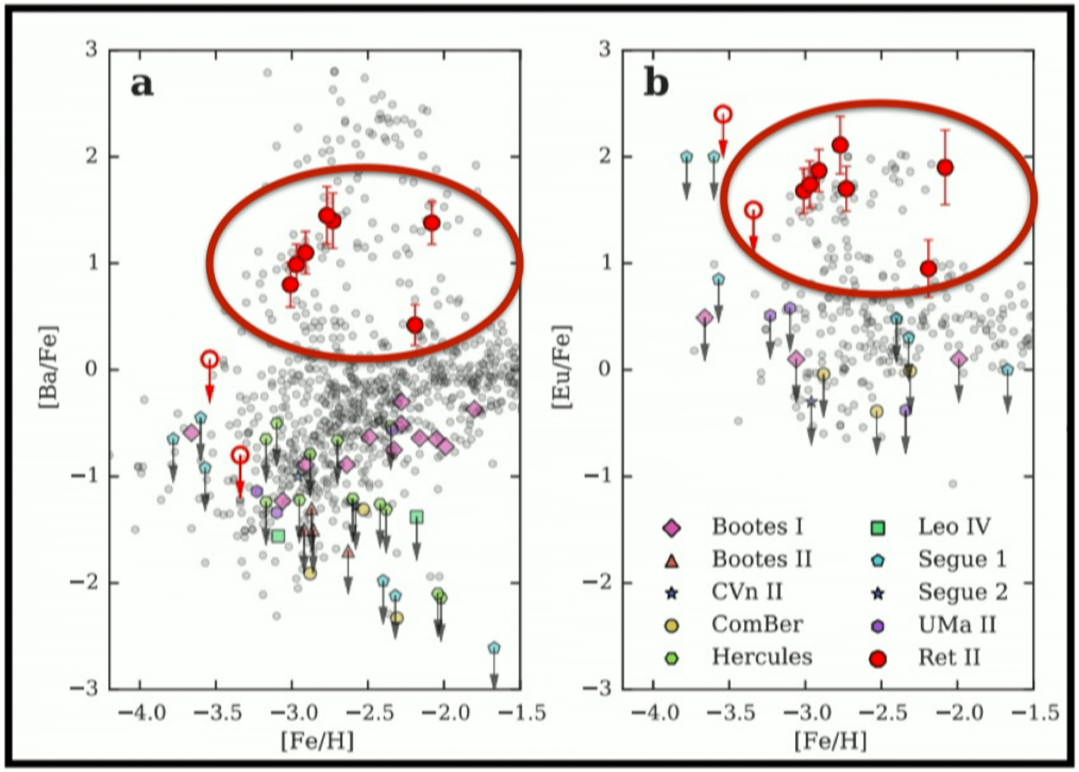
Reticulum II
high r-process
abundance



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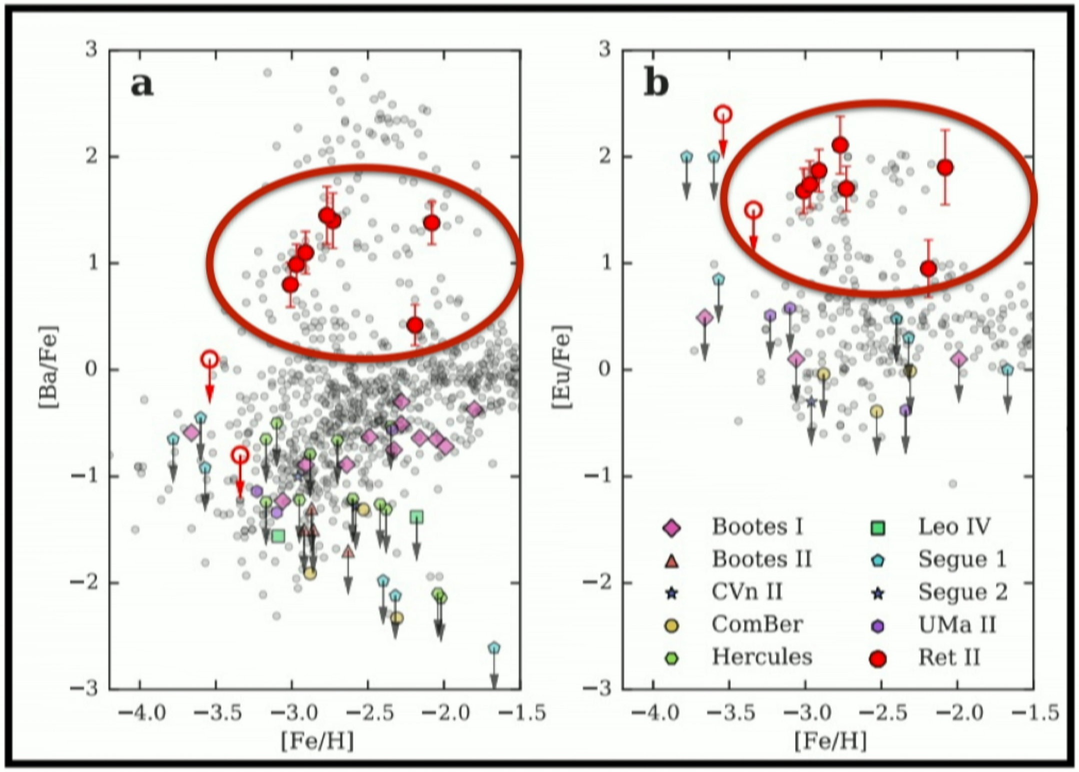

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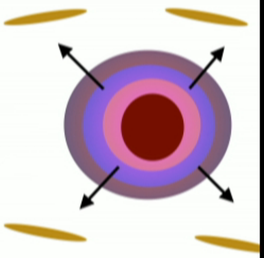

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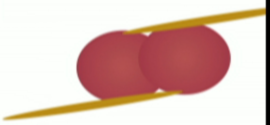

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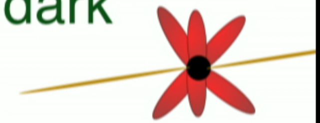


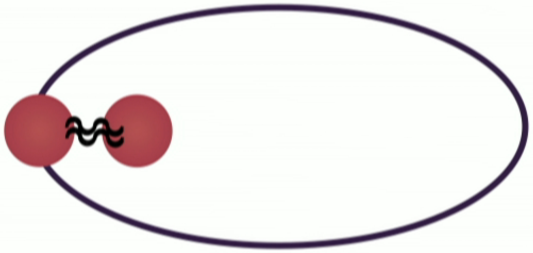
-Neutron star falling into a black hole made of dark matter at its core.

In each case, neutron rich fluid beta decays, forms heavy neutron-rich elements.

But one UFD with r-process, and 9 without, points towards rare events.

# Reticulum II r-process from NS-NS merger?

high eccentricity
for quick merger



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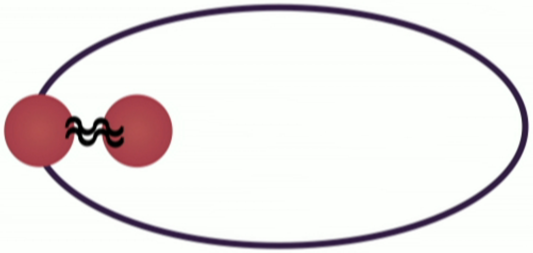
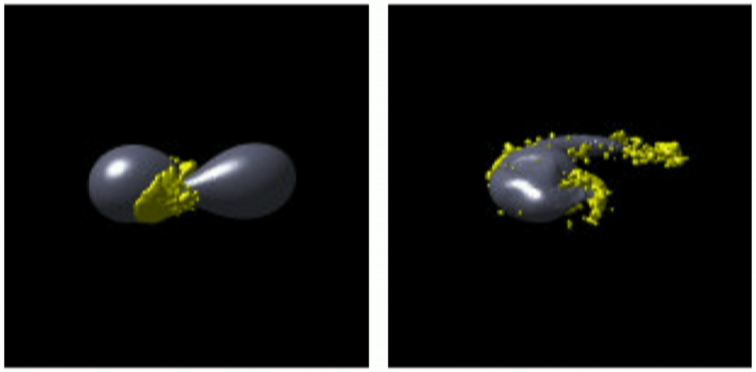




Picture from 1107.0899

**Milky Way NS-NS r-process numbers:**

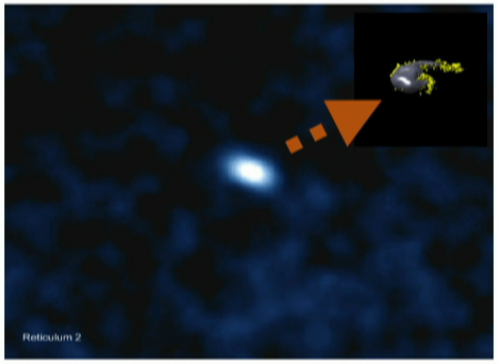
$10^{-2}$ solar masses
from a merger every $10^4$ years
explains Milky Way r-process abundance…

# Rapidly merging NS-NS systems are kicked out of ultra faint dwarf spheroidal galaxies

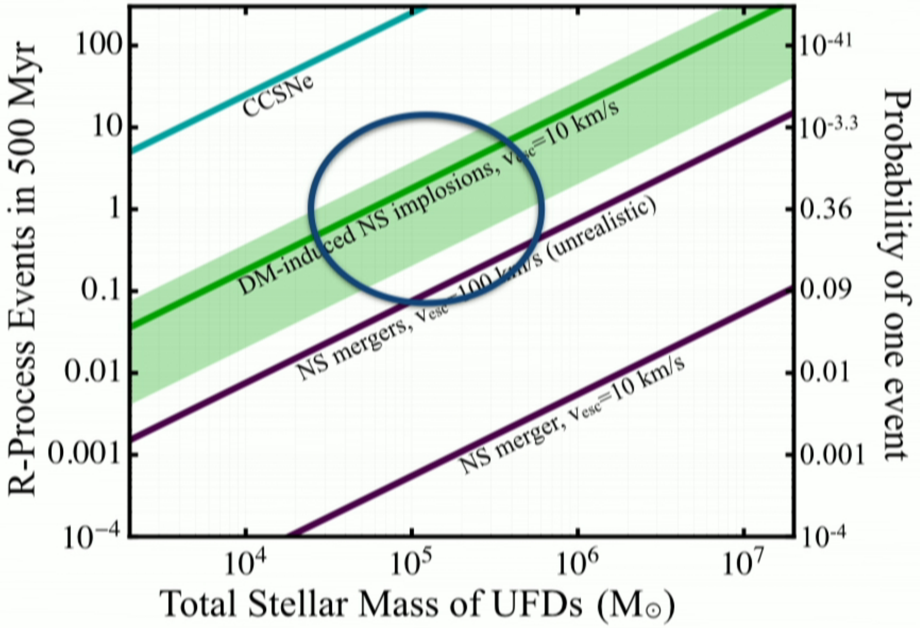
***The required orbital eccentricity to merge within $10^9$ years necessitates ~100 km/s kicks from parent supernovae.

***This in turn kicks the NS binary system to ~50 km/s in the UFD rest frame.

***So merging NSs would not stay inside dwarf spheroidals — the exit velocity of Reticulum II is about 10 km/s.



# UFD r-process rates



DM-NS implosions match observed rate in dwarf spheroidals:

expect O(1) events for the 10 UFDs observed.

# DM-induced NS implosions

Roche limit: radius at which self-gravity of NS fluid is less than tidal force from the black hole.

$$R_{\mathrm{Roche}} \simeq 20 \left( \frac{M_{\mathrm{BH}}}{10^{-10}\ \mathrm{M}_{\odot}} \right)^{1/3} \left( \frac{10^{14}\ \mathrm{g\ cm^{-3}}}{\rho_{\mathrm{NS}}} \right)^{1/3}\ \mathrm{m}$$

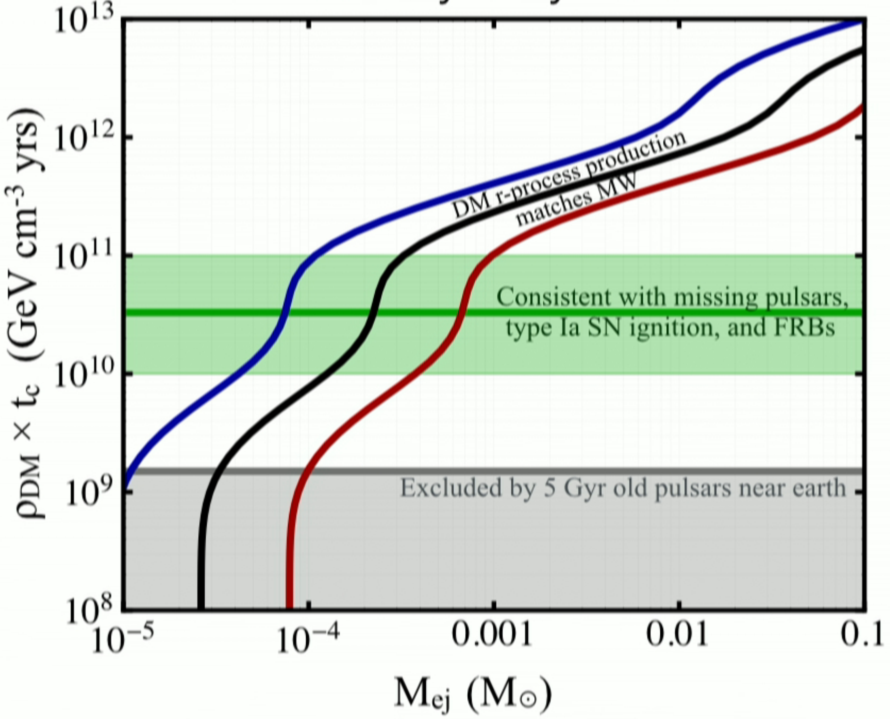
-Neutron star sucked into a small black hole,

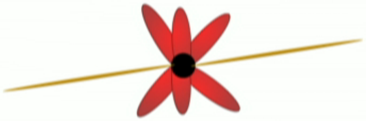
-"Tube of toothpaste" affect ejects neutron star fluid.

-Same timescale as NS-NS, BH-NS mergers — 1 ms.

Y-axis: a neutron star surrounded by DM density $\rho_{DM}$ collapses in time $t_c$.

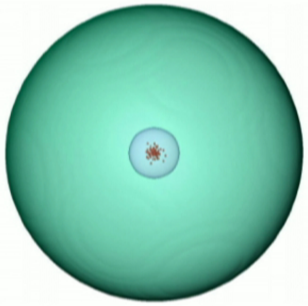
## r-process from NS implosion in milky way halo





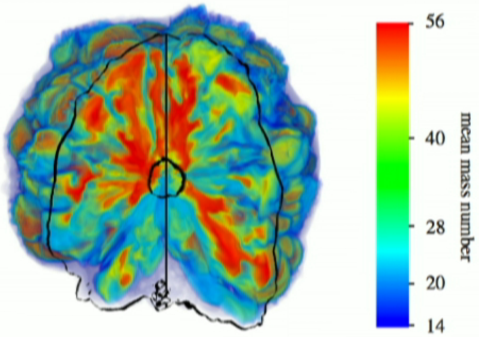
# Type Ia Supernova Ignition

Type Ia supernovae erupt when a portion of white dwarf becomes heated, igniting a thermonuclear fusion flame-front that sweeps through the star, followed by an explosion.



Ignition region inside WD

ignition



nuclei fuse ($^{56}$Ni)

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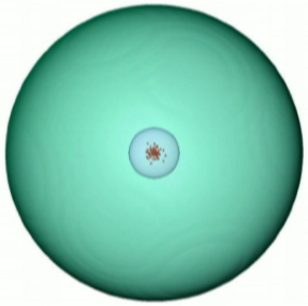

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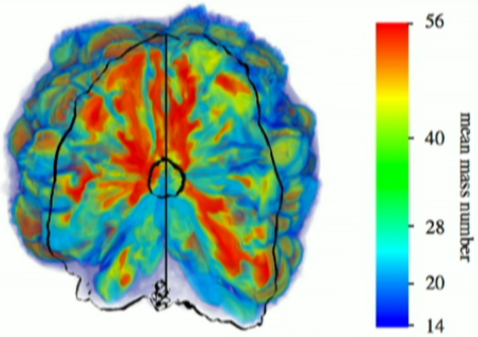

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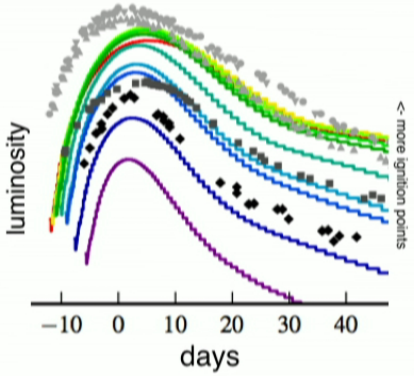
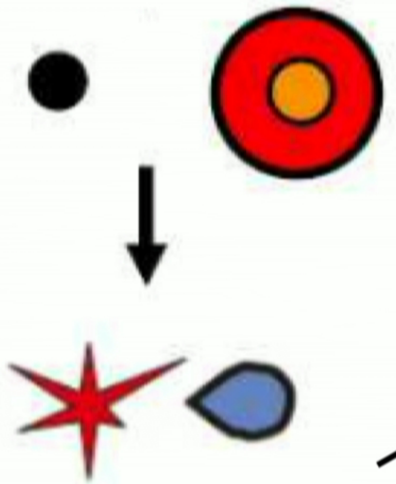


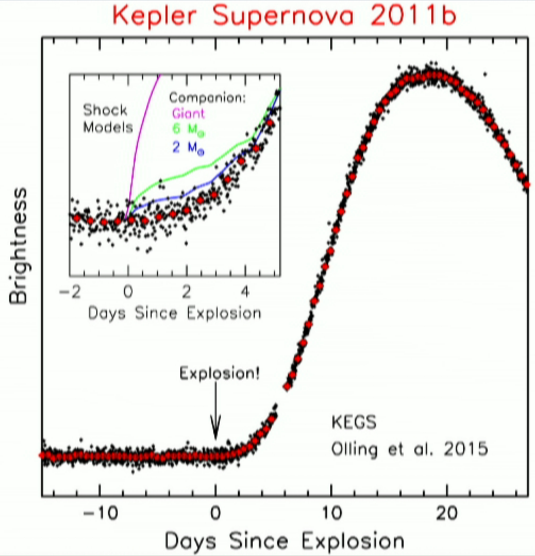
nuclei decay

e.g. 1308.3257 (figures), 1308.4833, 1309.4042

It is not clear what ignites type Ia supernovae. Candidates include binary accretion to critical mass (a.k.a. Chandrasekhar mass), and white dwarfs merging.



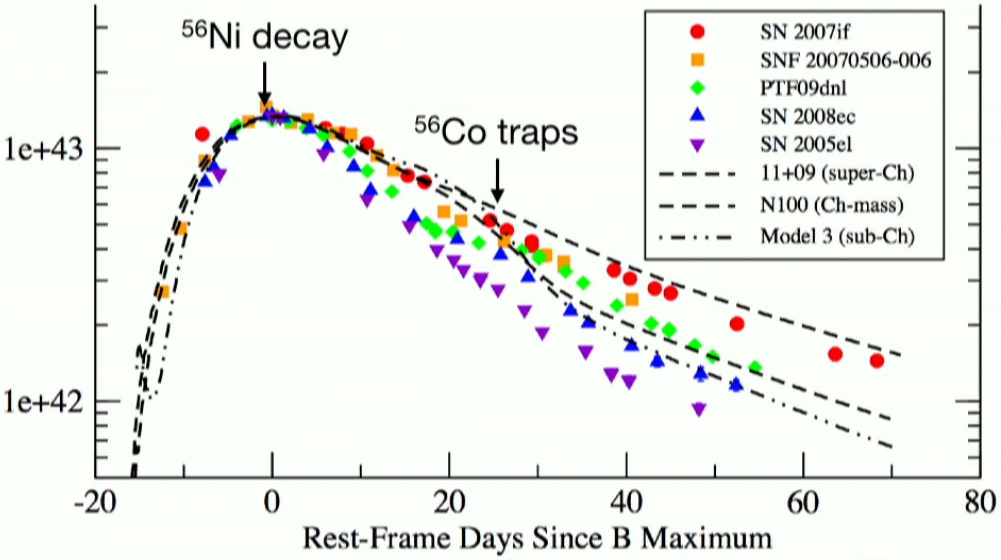
implied shocks
not seen



Binary ignition is disfavored by some observations, notably a lack of companion star "shocks" in SNIa light curves and the non-observation of H or He lines in type Ia spectra. White dwarf mergers may not match the high rate of type Ia supernovae.

Maoz et al. 1312.0628 (Review), Olling et al. Nature 2015

Recent observations indicate that half of type Ia supernovae originate from a sub-Chandrasekhar (< 1.4 solar mass) white dwarf. This implies that "sub-critical" white dwarfs are igniting.

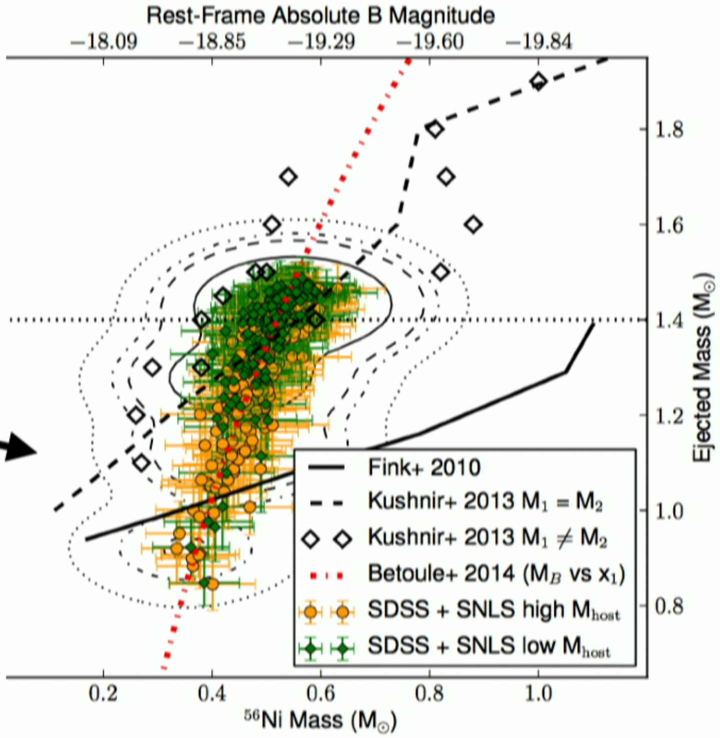


1402.6842

By measuring the maximum luminosity (dominated by $^{56}$Ni→$^{56}$Co decay) and the luminosity tail (shaped by $^{56}$Co decay and bulk optical trapping), the masses of type Ia progenitors can be inferred.

Strizinger et al. 2006, Scalzo et al. 1402.6842, Scalzo Ruiter Sim 1408.6601

# The apparent existence of sub-Chandrasekhar supernovae presents a quandary for ignition by binary accretion.



Long tail of
sub-Chandrasekhar mass SNIa

1408.6601

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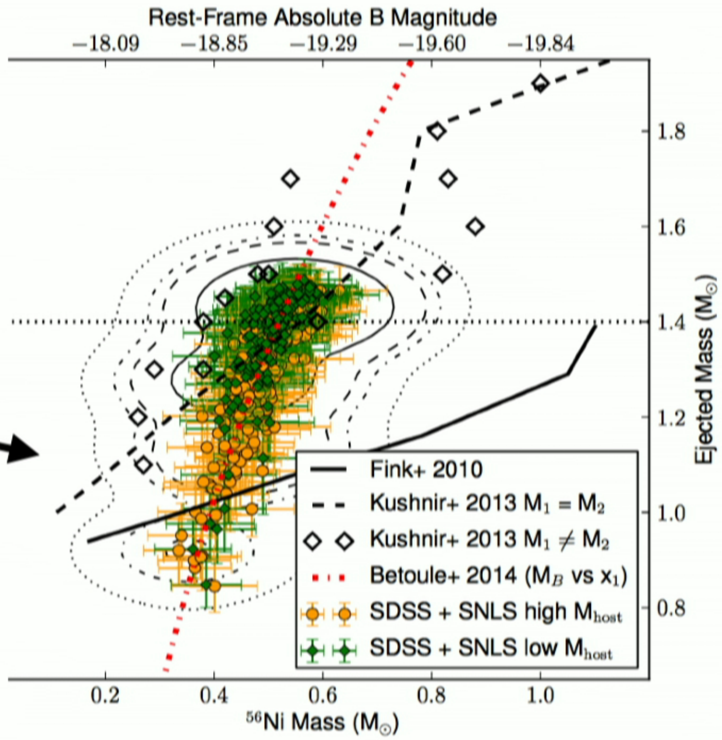

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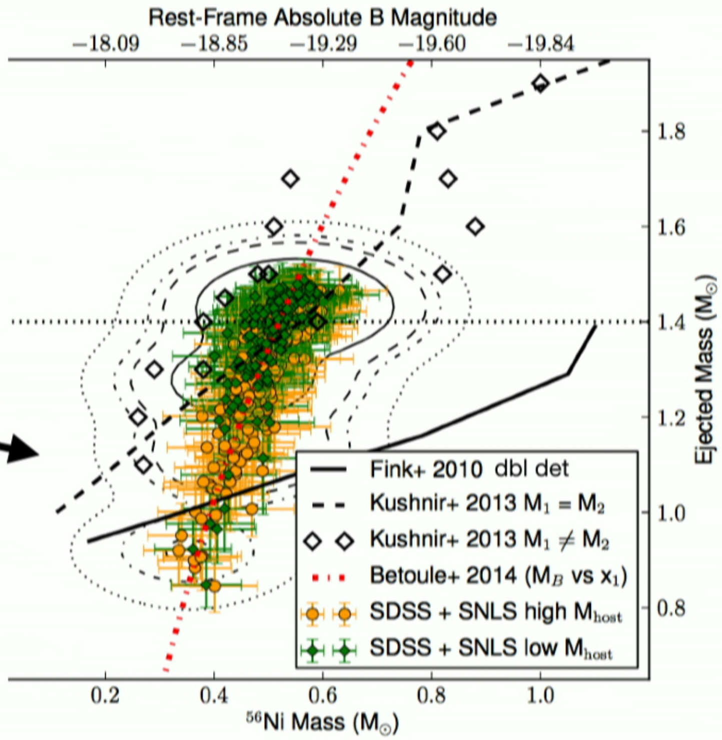
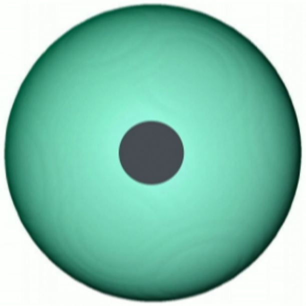


1408.6601

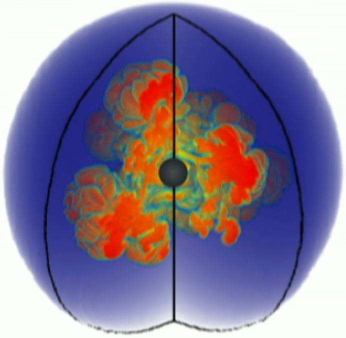
**Compare Chandrasekhar mass (1.4 solar mass) to**

$$\frac{M_{\rm ej}}{M_\odot} = (1.322 \pm 0.022) + (0.185 \pm 0.018)x_1, \quad x_1 = [-3, 2]$$

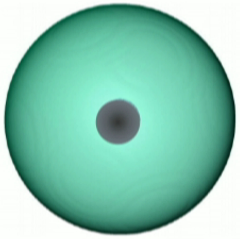
In order to ignite a carbon-oxygen white dwarf, the dark matter must collect to the point of self-gravitation within ~$10^9$ years.



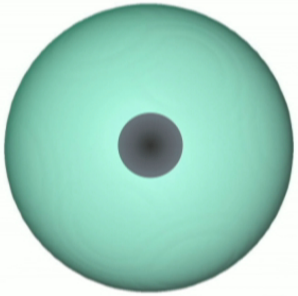
DM collects to the point of self-gravitation.



DM collapses, shedding gravitational potential energy, igniting a SNIa.



more massive WD,
DM collapses sooner



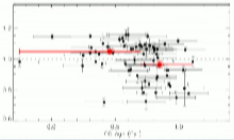
less massive WD,
DM collapses later

$$N_{sg} \sim \frac{T_w^{3/2}}{m_X^{5/2}\,\rho_w^{1/2}}$$

-More massive white dwarfs collect dark matter faster.

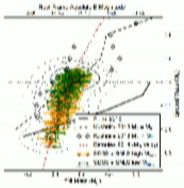
-Because the more massive white dwarf has a larger central density, dark matter collects into a smaller ball, and collapses sooner.

-Altogether, this shortens the time for dark matter collapse in more massive white dwarfs.



1311.6344

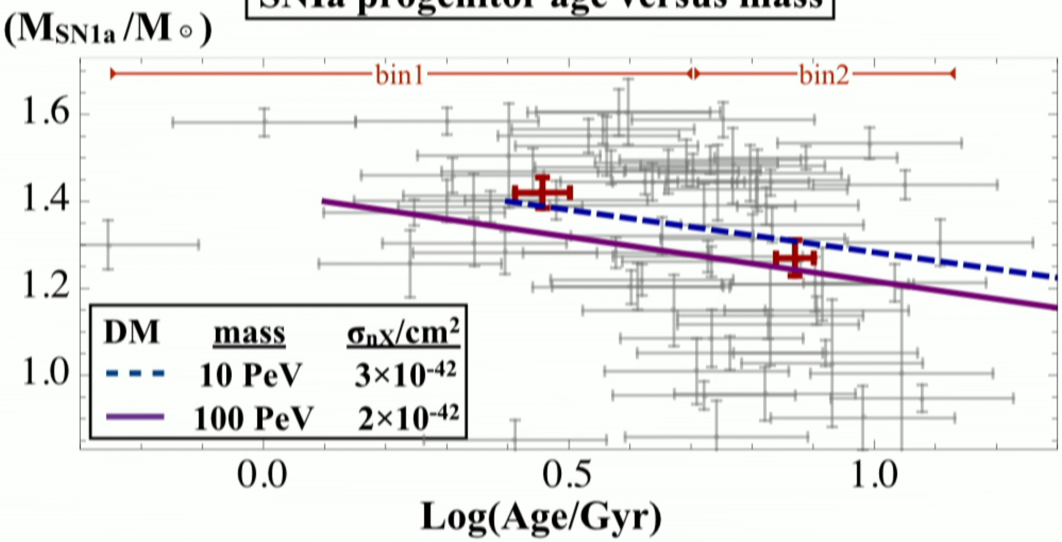
Data on the ages of stars adjacent to type Ia supernovae



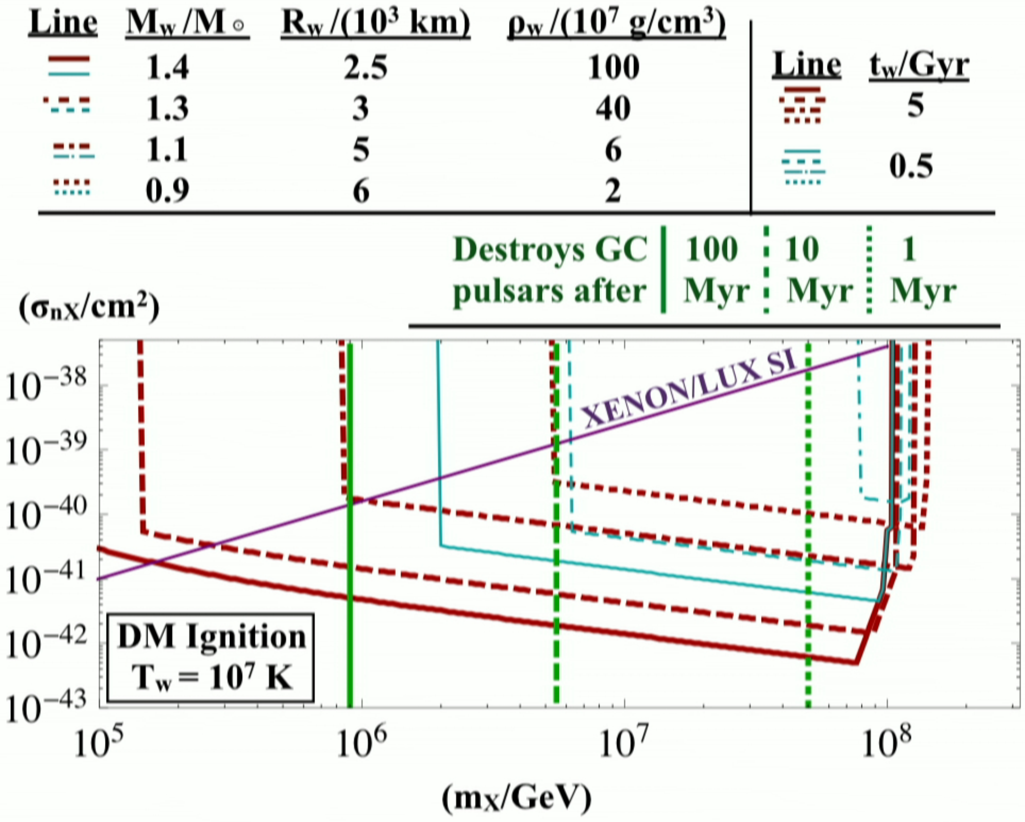
1408.6601

Data on the mass of type Ias inferred from luminosity

**SNIa progenitor age versus mass**



# PeV mass asymmetric dark matter can account for sub-Chandraskhar mass type Ia supernovae and missing pulsars.



| Line | $M_w/M_\odot$ | $R_w/(10^3\ \mathrm{km})$ | $\rho_w/(10^7\ \mathrm{g/cm^3})$ |
|---|---|---|---|
| — | 1.4 | 2.5 | 100 |
| -·- | 1.3 | 3 | 40 |
| -- | 1.1 | 5 | 6 |
| ···· | 0.9 | 6 | 2 |

| Line | $t_w$/Gyr |
|---|---|
| 🟥 | 5 |
| 🟦 | 0.5 |

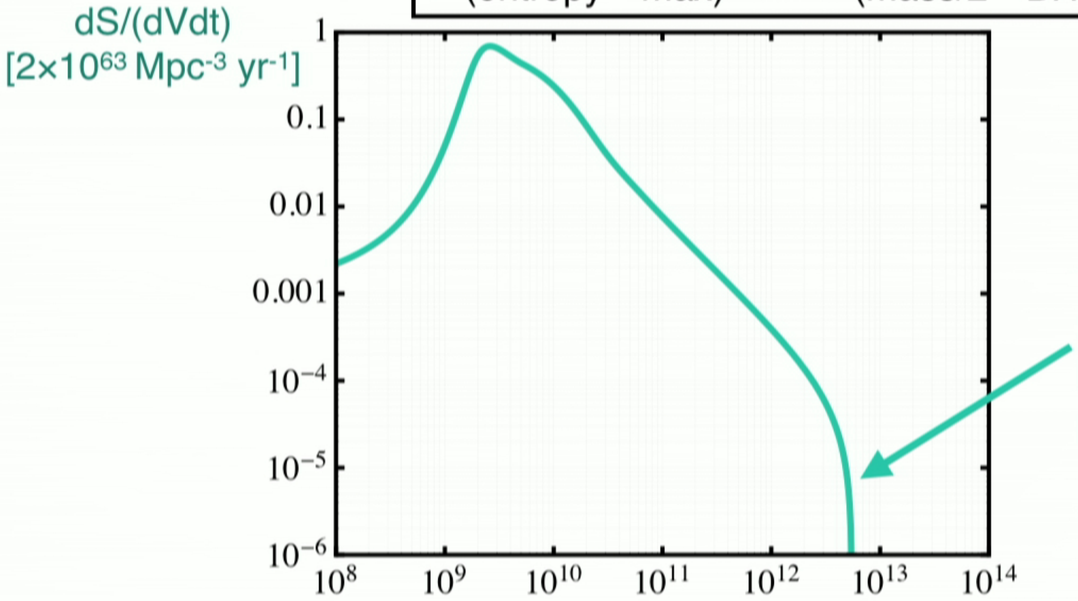
| Destroys GC pulsars after | 100 Myr | 10 Myr | 1 Myr |
|---|---|---|---|

# Entropic Unification

Require that at the time the source of maximum entropy in the universe (halo baryonic matter) has grown to maximum complexity,

the mass-energy of the entropy source is more than half converted into new universes (in this case black holes).

$$t^{\star}_{(\text{entropy}\rightarrow\text{max})} \sim t^{\star}_{(\text{mass}/2\rightarrow\text{BH})}$$



~$10^{13}$ yrs for 0.1 $M_{\odot}$ stars to burn out, become compact helium white dwarves