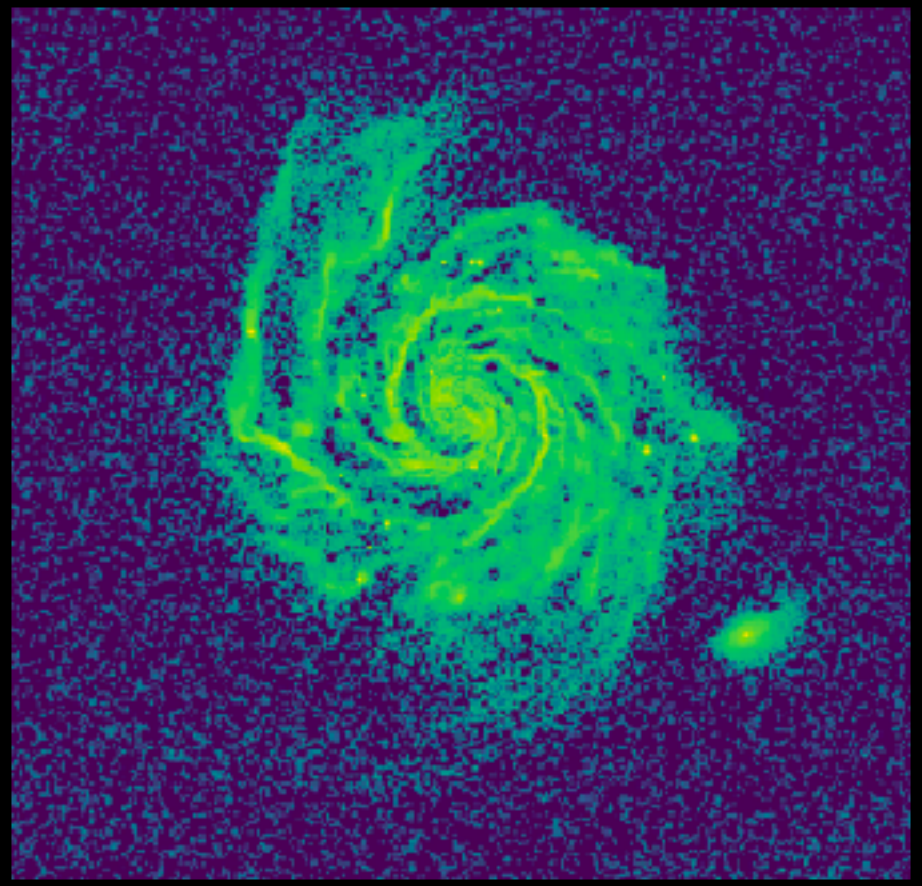
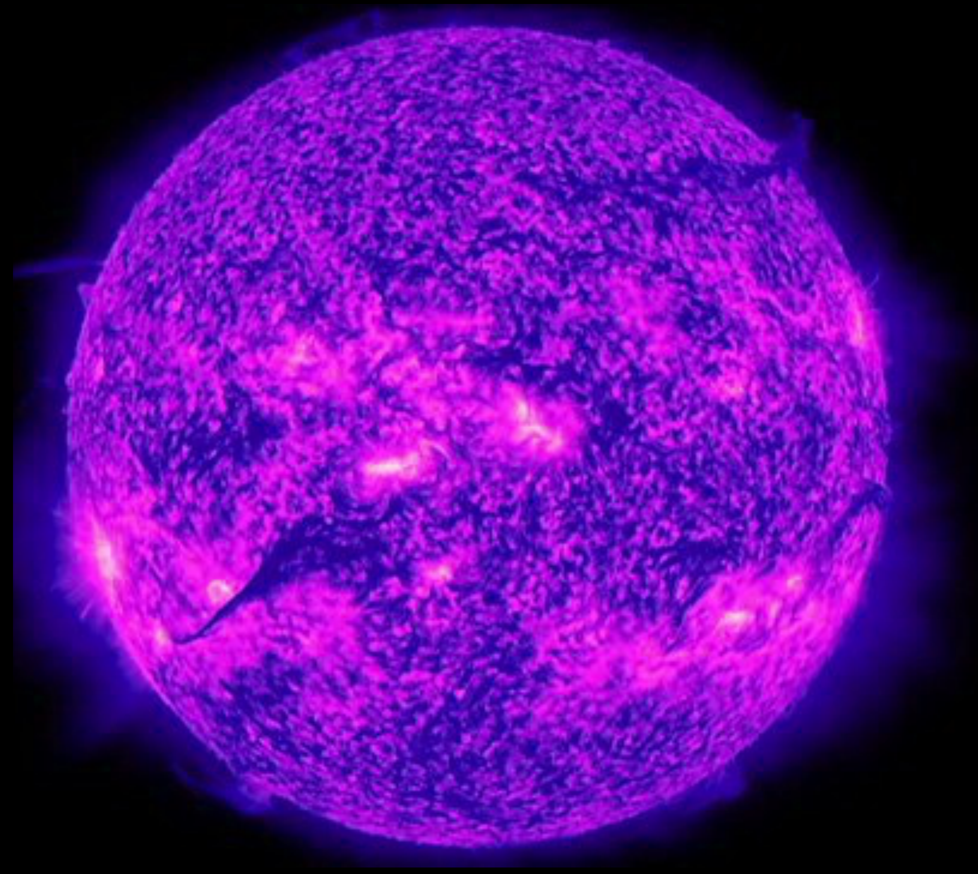


The Cosmology and Astrophysics of Dark Complexity



WNPPC2023 - 60th Winter Nuclear Particle Physics Conference

Banff Centre
Alberta, Canada

16 Feb 2023

David Curtin
University of Toronto

UNIVERSITY OF TORONTO

Complex Dark Matter

Most typical picture of dark matter: a single type of (astrophysically) mostly non-interacting particle (WIMP, axion, primordial-black-hole, etc…).

A different idea: consider a **hidden sector** with multiple stable particles and its own set of forces.

Minimal Benchmark model: Atomic Dark Matter as a FRACTION of DM
dark proton (mass m_{p_D}), dark electron (mass m_{e_D}), dark photon (coupling α_D)
Optional: dark nuclear physics (feature of some theories), dark He/Li/Be, …, etc

Much more rich behaviour:
- formation and dissociation of atoms
- pressure and acoustic oscillations
- dissipation, cooling, collapse

Theoretical Motivation

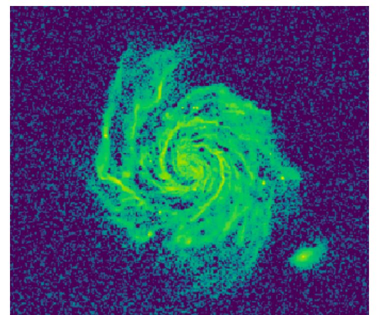
Why consider such a "complicated" scenario?

1. General Plausibility: the Standard Model is much more complicated. Why is the dark sector just one type of boring particle?
   Very minimal from QFT-POV: a few hidden sector fields give rich dynamics.

2. Hidden sectors can solve big problems in physics, like the Hierarchy Problem.
   The **Twin Higgs**: stabilizes Higgs mass from quantum corrections by introducing a hidden sector that is SM Z_2 copy, with dark higgs vev $f \sim (3 - 7) \times v$ → Does not give conspicuous LHC signatures of SUSY etc.
   → **Realizes particular atomic dark matter + dark nuclear physics**

3. In general, Hidden sector particles are either all unstable… or not (i.e. stable)
   → either have exotic LHC signatures (LLPs)… or **complex dark matter!**

MATHUSLA



Observational Signatures

Even for **minimal atomic dark matter benchmark**, highly varied and potentially spectacular! Think of all the interesting "signatures" of baryonic matter!

Difficulty lies in making predictions! Very large (cosmo) and very small (mirror stars) are easier, medium-scale is VERY hard (N-body simulations).

Cosmology

2212.02487 Saurabh Bansal, **Jared Barron**, David Curtin, Yuhsin Tsai

Jared is moving to YITP Stony Brook in September 2023

For Twin-Higgs specific analysis, see Bansal, Kim, Kolda, Low, Tsai 2110.04317

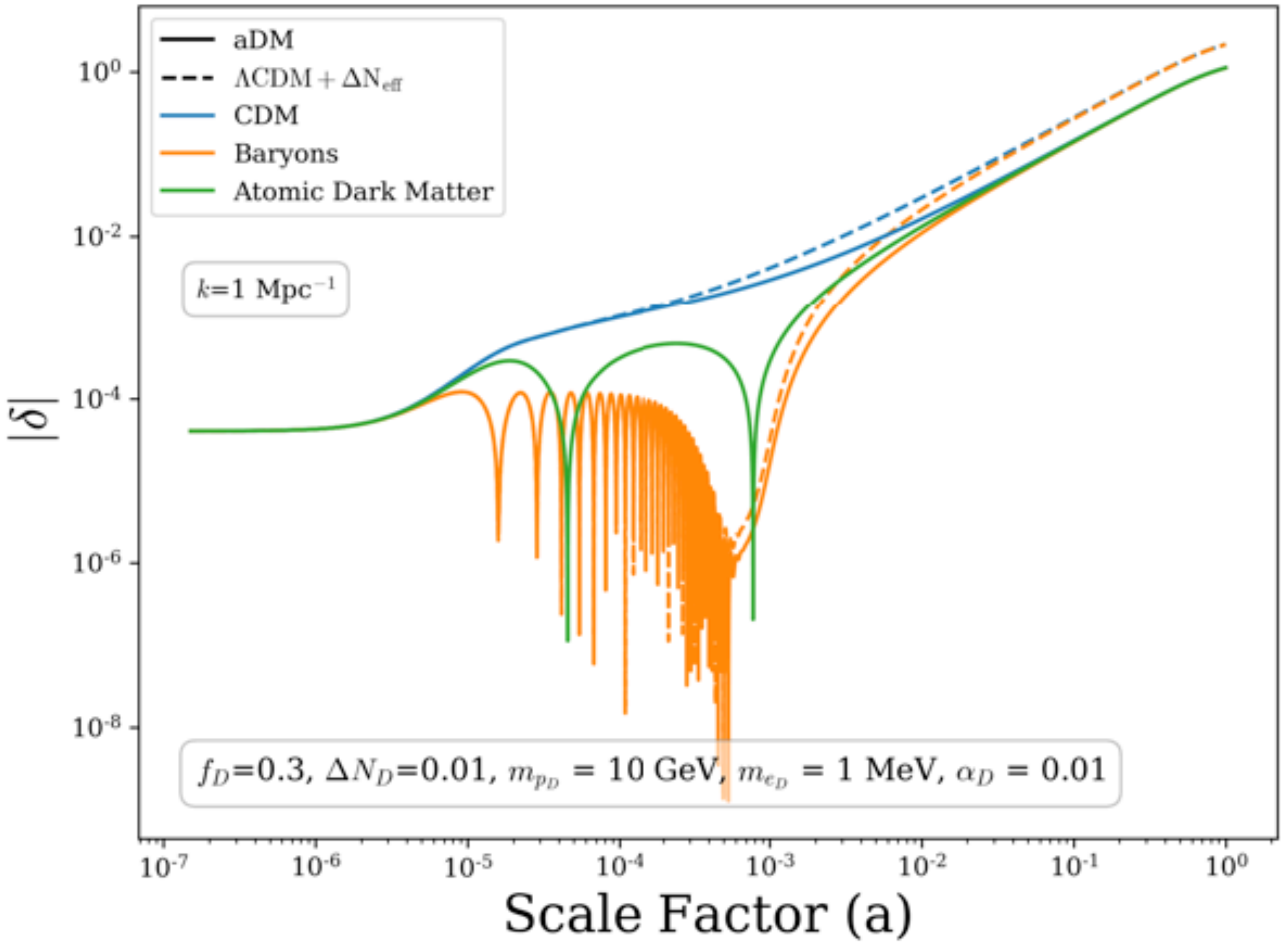
see also Cyr-Racine, de Putter, Raccanelli, Sigurdson 1310.3278 and several subsequent works by Cyr-Racine

Cosmology of atomic dark matter

Consider minimal atomic dark matter making up some fraction f_D of DM, the rest is CDM.

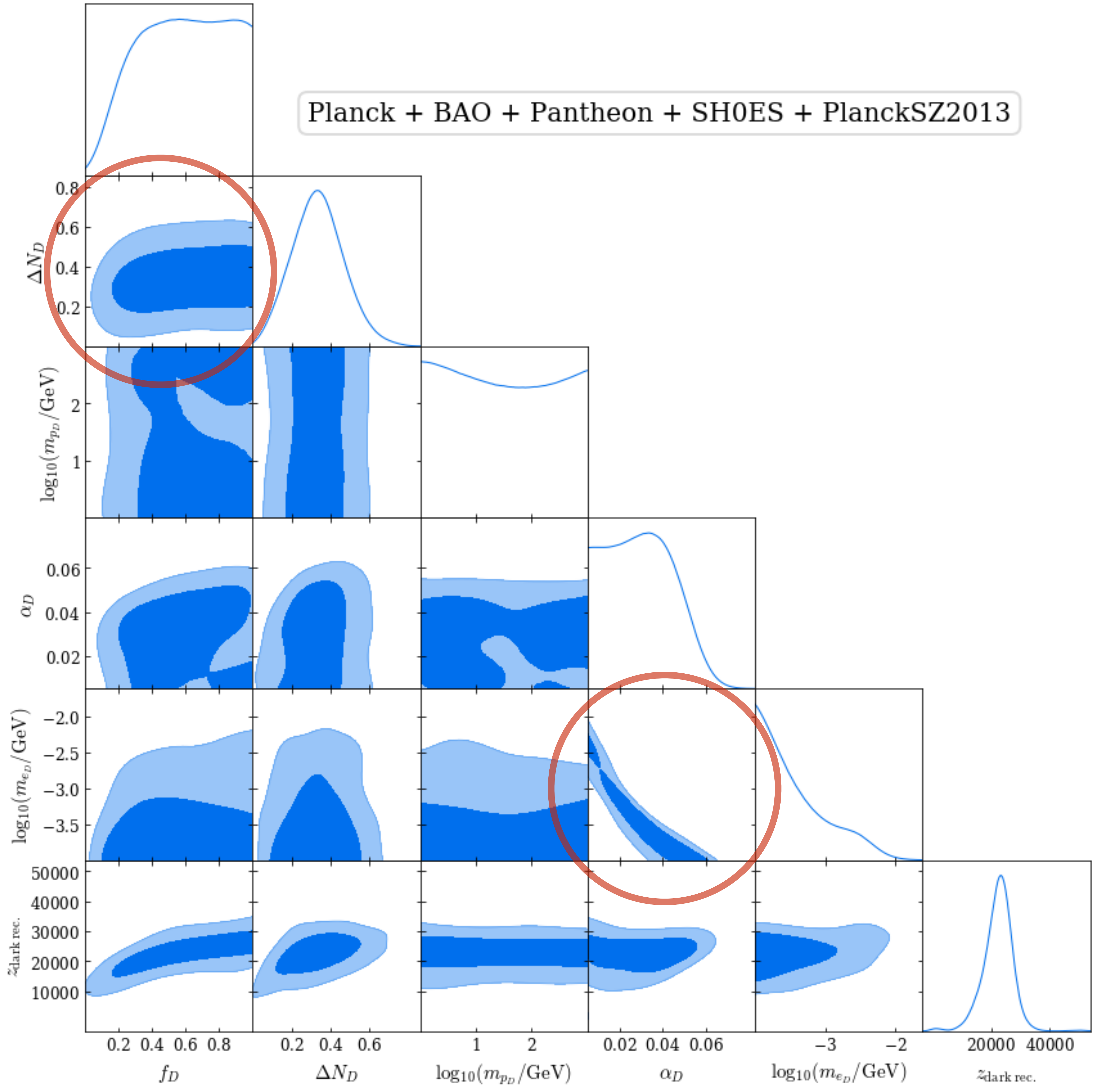
Let the aDM be colder than the SM by temperature ratio $\xi = T_D/T_{SM}$ at SM recombination (creation of CMB).

aDM behaves like SM baryons: it has pressure and oscillates after modes enter horizon, until it recombines and falls into CDM gravitational wells.



Two main CMB signatures:
dark radiation (ΔN_{eff}) +
Dark Acoustic Oscillations.

Constraints from CMB



Jared added an aDM module to CLASS code, significantly generalized recombination routines.

MCMC scan over aDM parameters gives **Constraints on aDM from CMB!**

⇒ aDM alleviates (H_0, σ_8) tension!

(H_0, σ_8) predicts non-zero ΔN_{eff} and f_D

Picks out aDM binding energy above SM:

$$B_D = \frac{1}{2}\alpha_D^2 m_{e_D} \sim (30 - 200)\ \mathrm{eV}$$

(right in the Twin Higgs range!)

confirms 2110.04317

What about Large Scale Structure?

Linear perturbation theory only allows us to predict structure formation at very large scales (k < 0.few h/Mpc). In that regime, LSS constraints do not affect constraints on aDM parameter space from CMB.

Dark Acoustic Oscillations **will** affect structure formation, but requires understanding structure growth in **non-linear regime.**

2011.05333 Munosz, Bohr, Cyr-Racine, Zavala, Vogelsberger

Requires simulations to take advantage of highly constraining Lyman-α and future 21cm data.

In progress!

with Zachary Gelles, Jared Barron, Mariangela Lisanto, Hongwan Liu, Sandip Roy, Julian Munoz

Galactic Dynamics

based on work in preparation with
Sandip Roy (Princeton),
***Xuejian (Jacob) Shen (Caltech)**,*
Philliip Hopkins, Mariangela Lisanti, Norman Murray

*… and follow up studies with above + **Caleb Gemmell**, …*

Galactic Astrophysics of Atomic Dark Matter

Stick with minimal aDM benchmark:
H-atoms arbitrary fundamental parameters but without nuclear physics.
→ have to generalize SM atomic physics (cooling, molecular bound states etc)

Rosenberg, Fan 1705.10341; Ryan, Shandera, Gurian, Jeong 2110.11971

What happens during Galaxy formation? aDM, just like baryons, falls into CDM gravity wells, shock heats, become ionized and pressure supported.

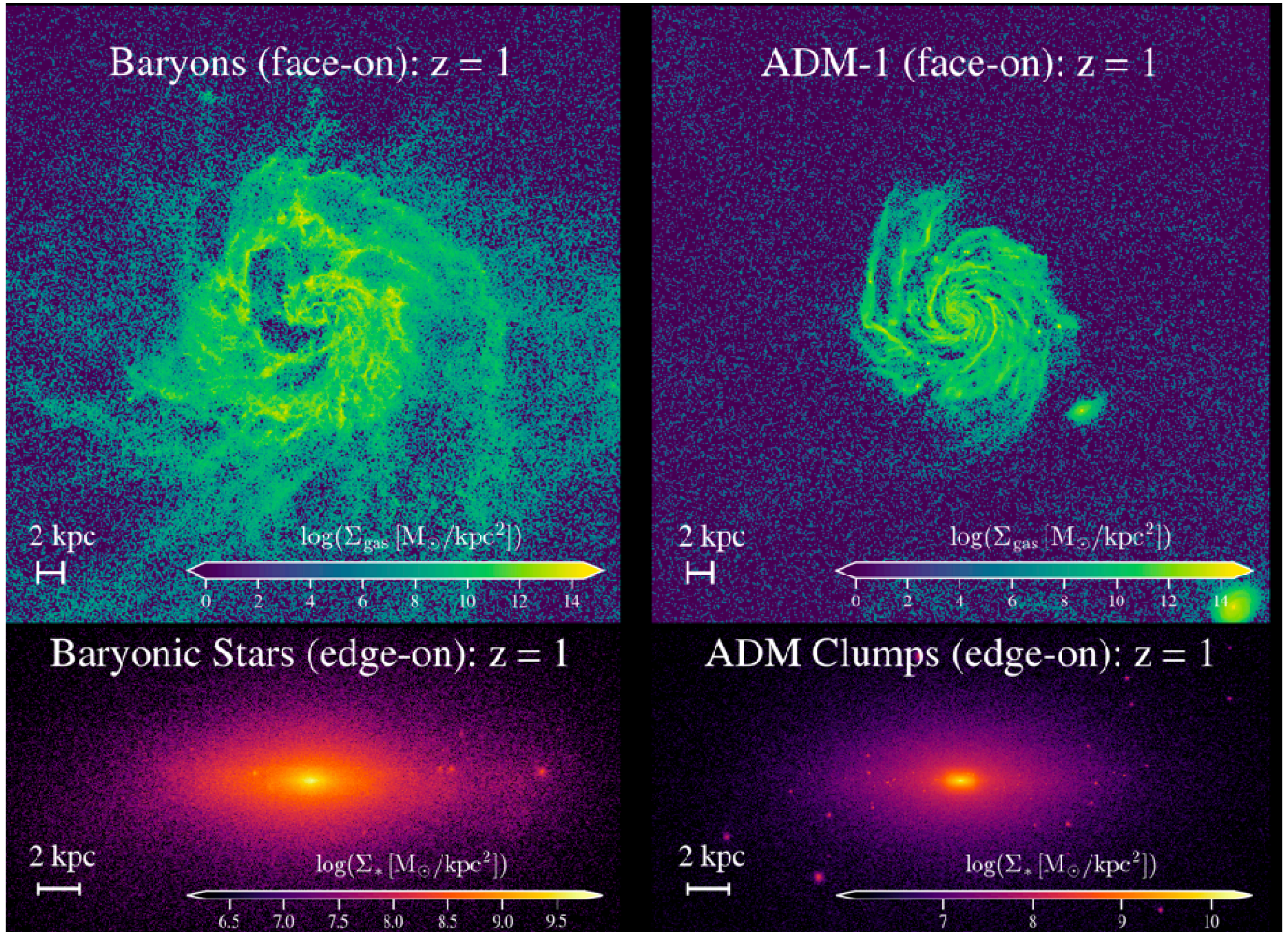
Then it starts to dissipate energy by emitting dark photons, eventually cooling enough to loose pressure support.

Cooling and collapse. Might expect a **dark disk** to form, but rapid collapse could disrupt this. **Can a dark disk form without "dark-SN" feedback? How does this affect the baryonic disk, i.e. our milky way?**

Fan, Katz, Randall, Reece 1303.1521 *Ghalsasi, McQuinn, 1712.04779*

Need full hydro N-body sims for baryons + CDM + aDM

Added full aDM module to GIZMO code with full dark gas and atomic physics, radiative transfer, formation of aDM "clumps" (in practice, BHs or mirror stars)



World's first full CDM + baryons + aDM hydro N-body simulations.

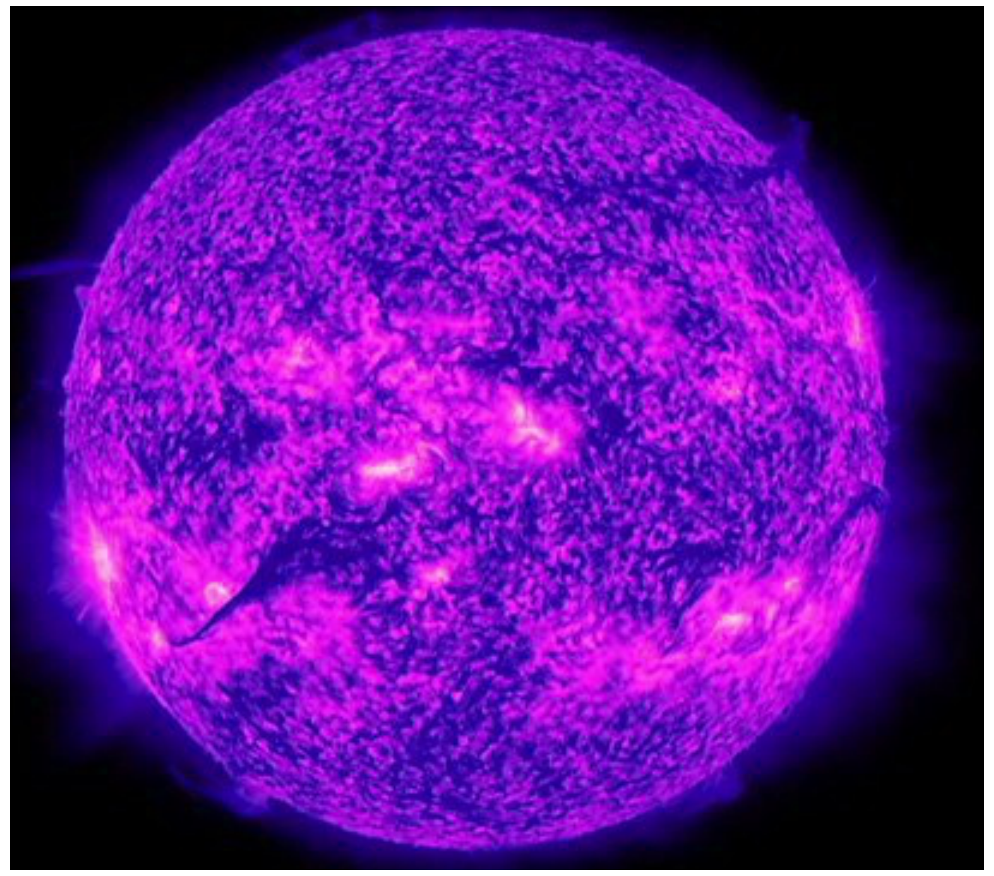
Code and first simulations complete. First paper out soon.

When/How does aDM form a disk?
How does this affect the baryonic disk?
What is impact on subhalo mass function?
Can also use this for structure formation studies etc…

Mirror Stars

What are Mirror Stars?

"Stellar scale" clumps of aDM that radiate their heat in dark photons.



Lifetime?

→ Kelvin-Helmholtz for minimal aDM

→ longer if aDM includes dark nuclear physics (fusion etc)

Robust consequence of atomic DM, and should occur where-ever aDM has cooled.

(Can also produce black holes, see 1802.08206, Shandera, Jeong, Gebhardt)

Precise abundance difficult to predict (see simulations!), but could be discovered with "single observation".

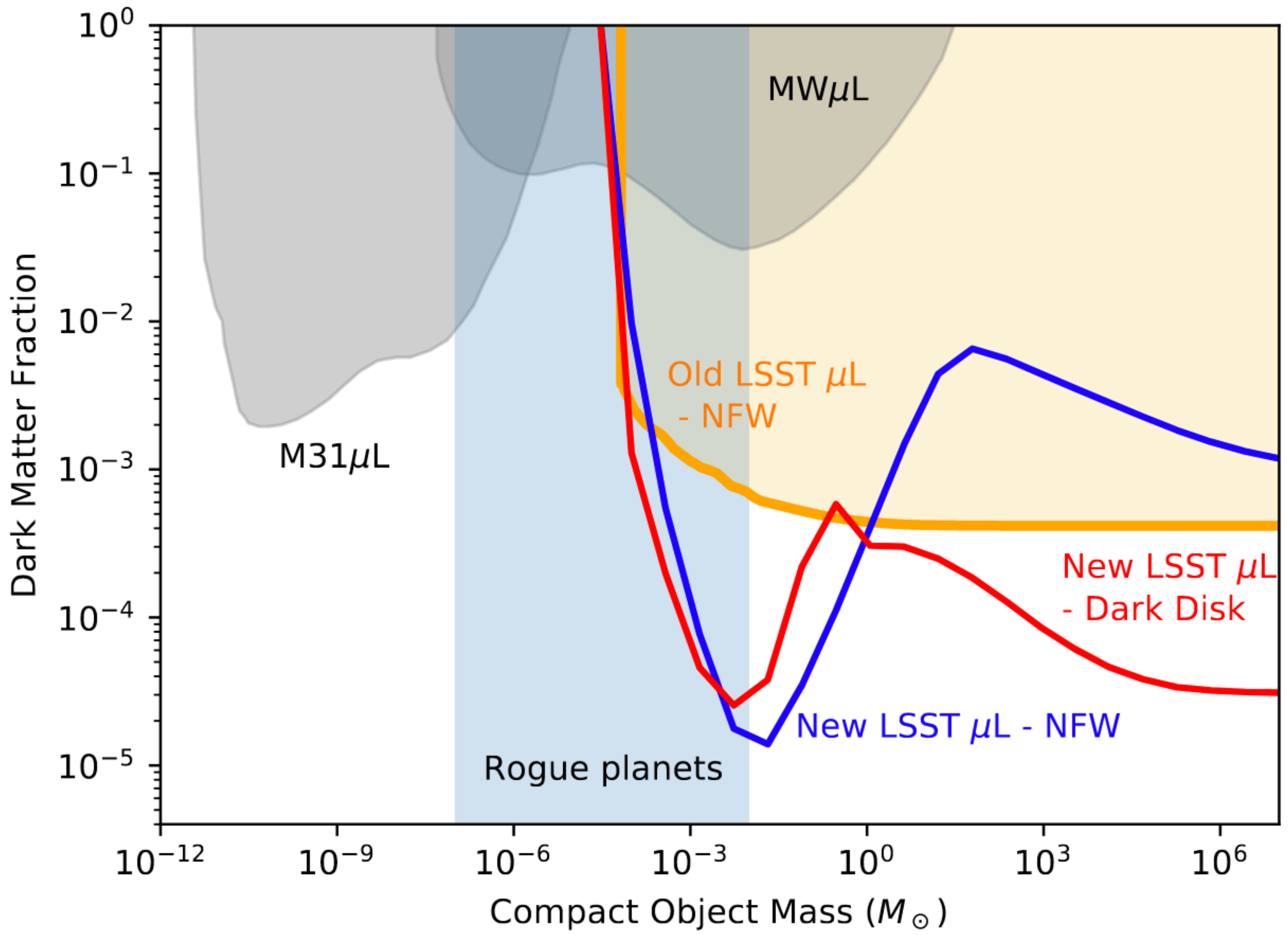
HOW CAN WE OBSERVE MIRROR STARS?

Microlensing Signals of Mirror Stars

2012.07136

Winch, Setford, Bovy, Curtin

LSST sensitivity to MACHOs and Mirror Stars



Significantly updated & improved MACHO sensitivity projection.

Derived mirror star sensitivities for disk distributions

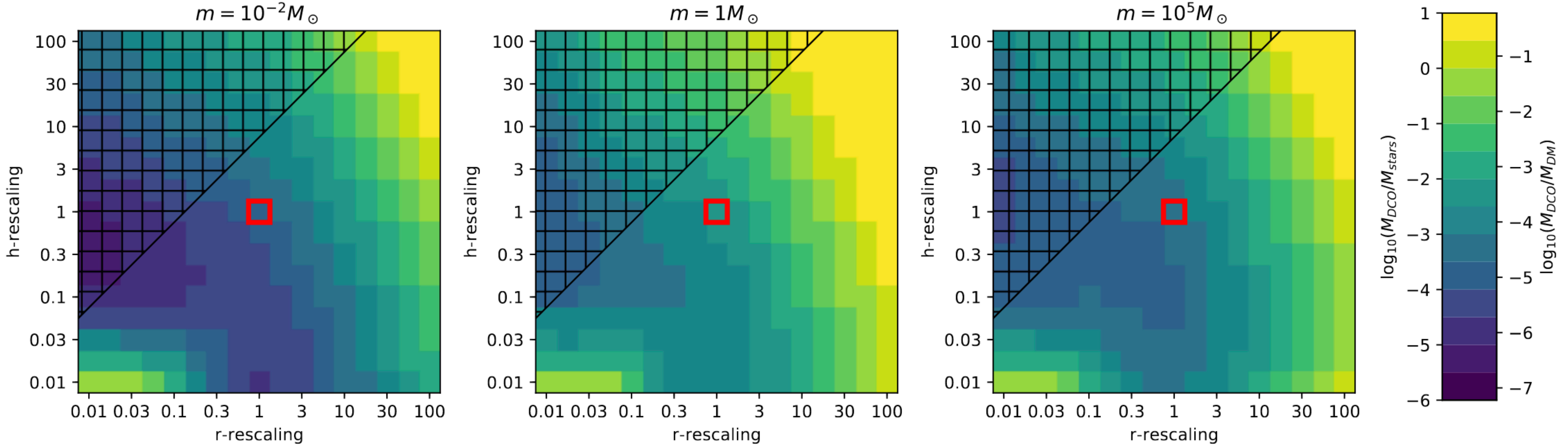
Example mirror star bounds for dark disk = milky way

Stunning 10^{-5} DM fraction sensitivities!

2012.07136 **Winch**, Setford, Bovy, Curtin

Dependence on Dark Disk properties

2012.07136 **Winch**, Setford, Bovy, Curtin



Increased density of sources closer to galactic centre means that sensitivity may exceed **10^{-5}** for "tighter" disks. (Center itself is too crazy and blinded.)

Even for very "fluffy" dark disks, probe **10^{-3} mirror star mass fractions**.

Applies for all aDM models, includes aDM-produced black holes!
But unclear how MS mass fraction correspond to cosmological aDM abundance.

Gravitational Waves from Mirror Neutron Stars

2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes
2211.08590 Hippert, Dillingham, Tan, DC, Norona-Hostler, Yunes

Mirror Neutron Stars

If mirror stars exist, and if there is dark nuclear physics, then the endpoint for some mirror stars may be a **mirror neutron star** with analogous but different properties to regular neutron stars. **Could we "hear" their mergers?**

For concreteness, focus on a naturalness-motivated possibility:
Mirror Twin Higgs

→ mirror baryons are SM copy, except fermion/W/Z masses higher by **f/v ~ 3-7**

Two questions:

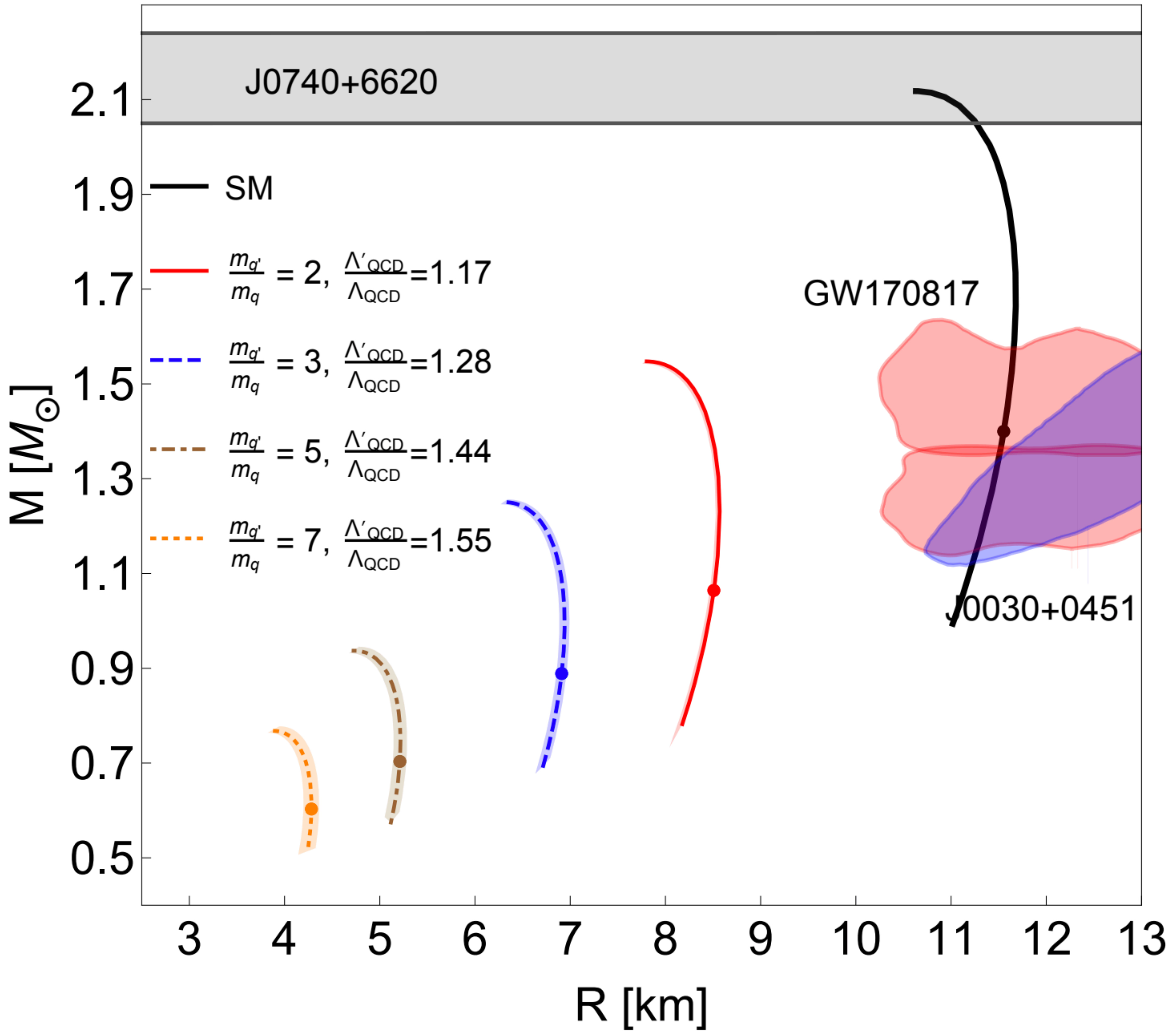
- what are the properties of Twin Higgs mirror baryon neutron stars?
- Could LIGO and other gravitational wave observatories detect them?

Mirror Neutron Star Properties

Rescale SM neutron star EOS using lattice results. Solve Einstein Equations (TOV) to get M(R) without rotation.

Mirror Neutron Stars in the MTH model are smaller and less massive than SM neutron stars!

Solving to 2nd order in ang. mom. gives moment of inertia, quadrupole moment and Love number of mirror neutron stars.



→GW signal distinct from SM neutron stars!

2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes

Electromagnetic Signals of Mirror Stars

Chris Matzner
U of T
(Astro)

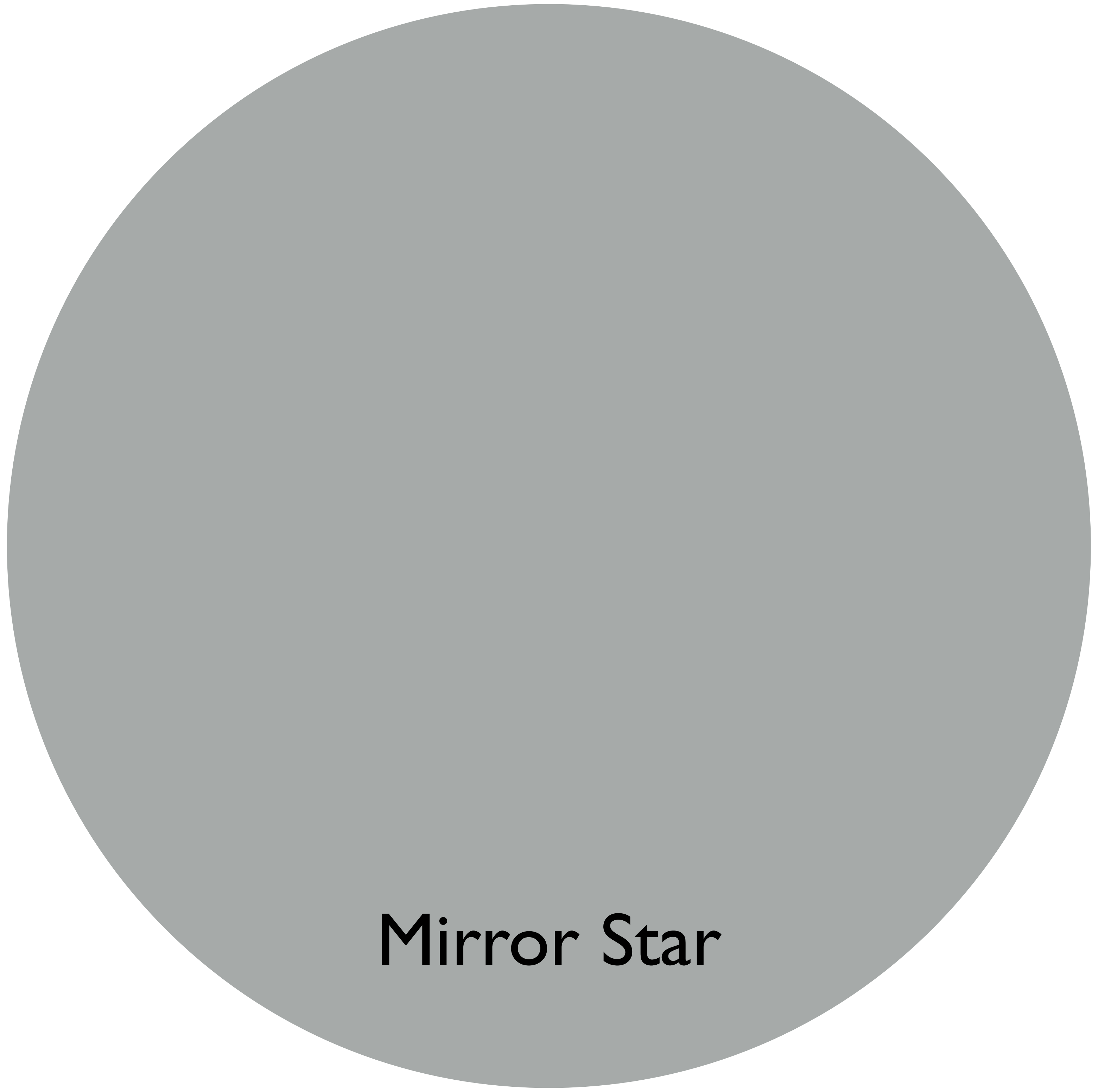
Basic mirror star signal:
DC, Setford, 1909.04071, 1909.04072

First Gaia search:
Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Realistic emission calculation:
ongoing with **Isabella Armstrong, Berkin Gorbuz**, Chris Matzner, DC

Life of a Mirror Star

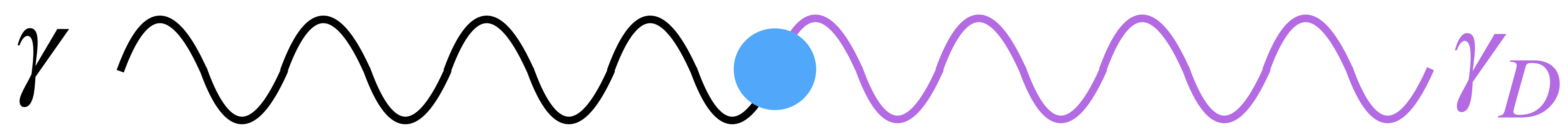
Once they form, mirror stars are a **dense** aDM object flying through our galaxy.



Life of a Mirror Star

Once they form, mirror stars are a **dense** aDM object flying through our galaxy.

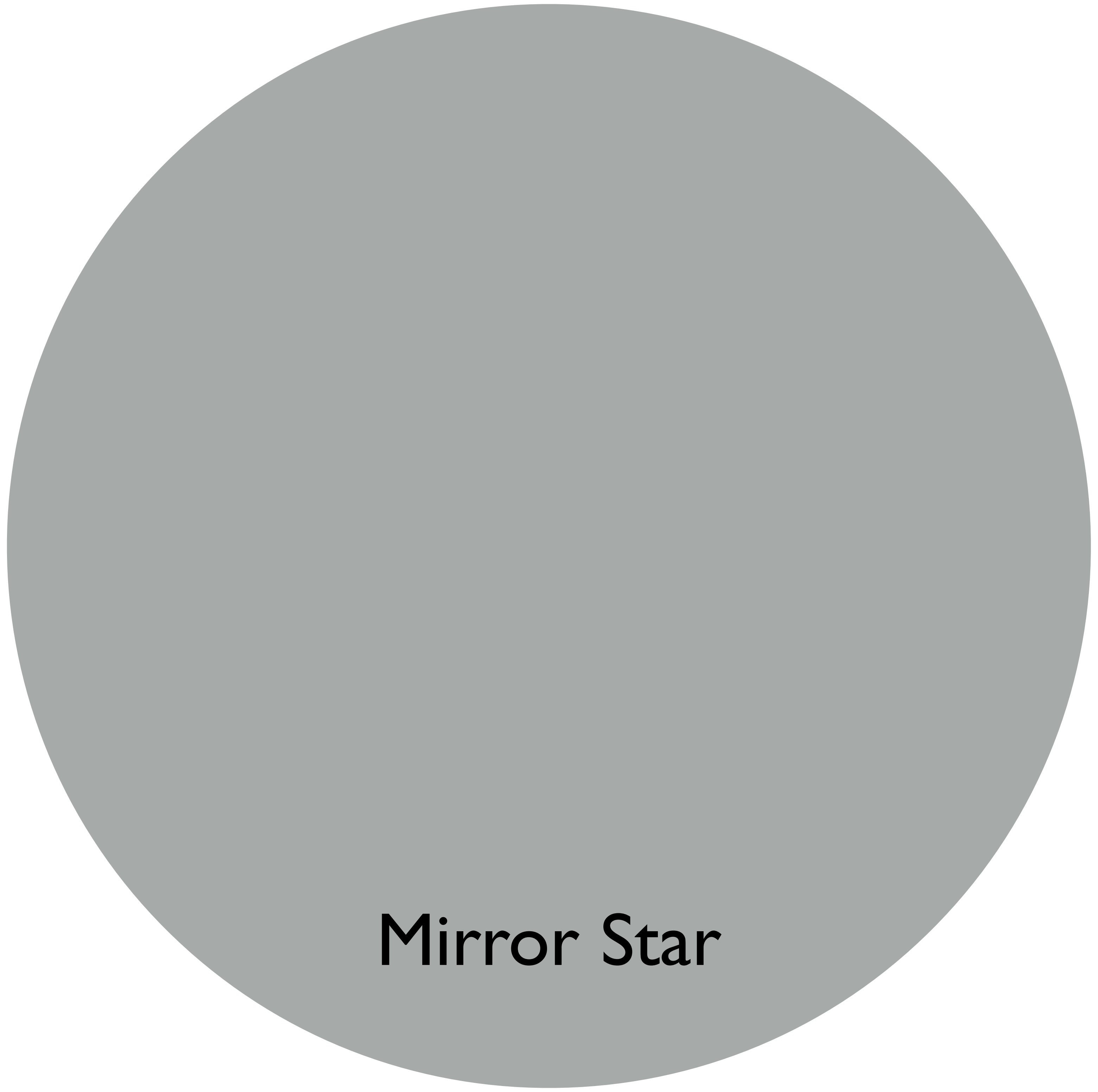
That density has important consequences in the presence of photon kinetic mixing.



$$10^{-13} \lesssim \epsilon \lesssim 10^{-9}$$

1909.00696 Gherghetta, Kersten, Olive, Pospelov

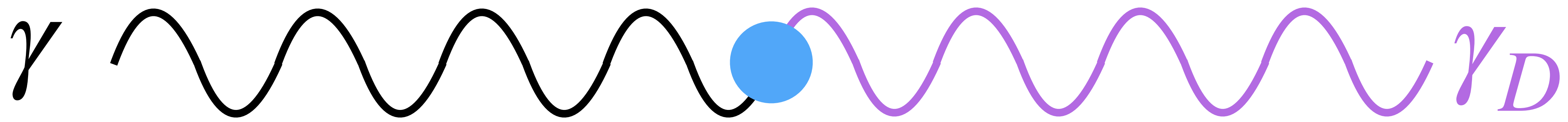
CMB ΔN_{eff} bounds (most recently, see Jared's talk)



Life of a Mirror Star

Once they form, mirror stars are a **dense** aDM object flying through our galaxy.

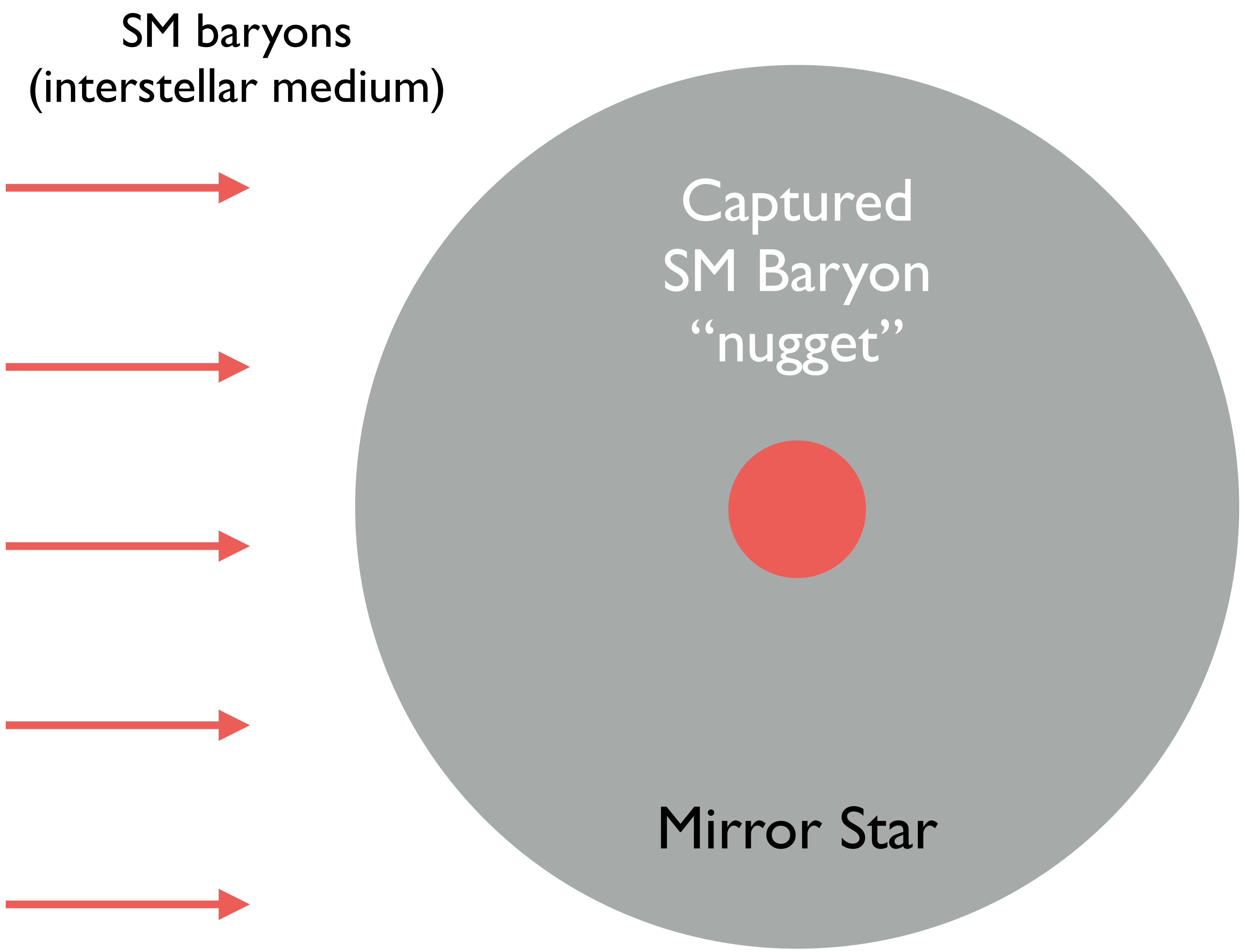
That density has important consequences in the presence of photon kinetic mixing. $M_{nugget} \sim \tau_{star}$

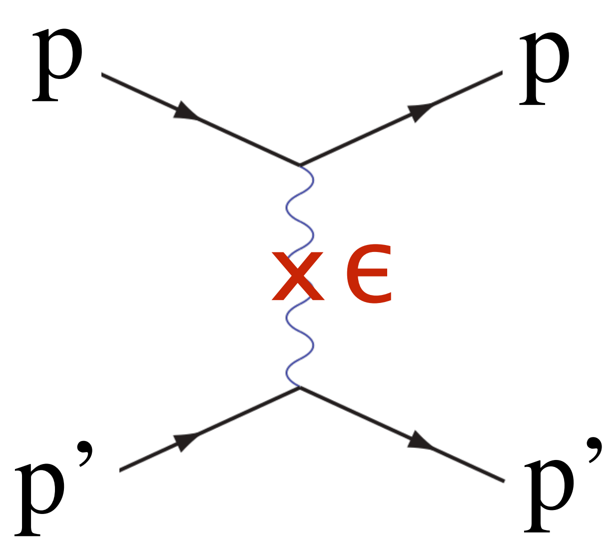


$$10^{-13} \lesssim \epsilon \lesssim 10^{-9}$$

1909.00696 Gherghetta, Kersten, Olive, Pospelov

CMB ΔN_{eff} bounds (most recently, see Jared's talk)

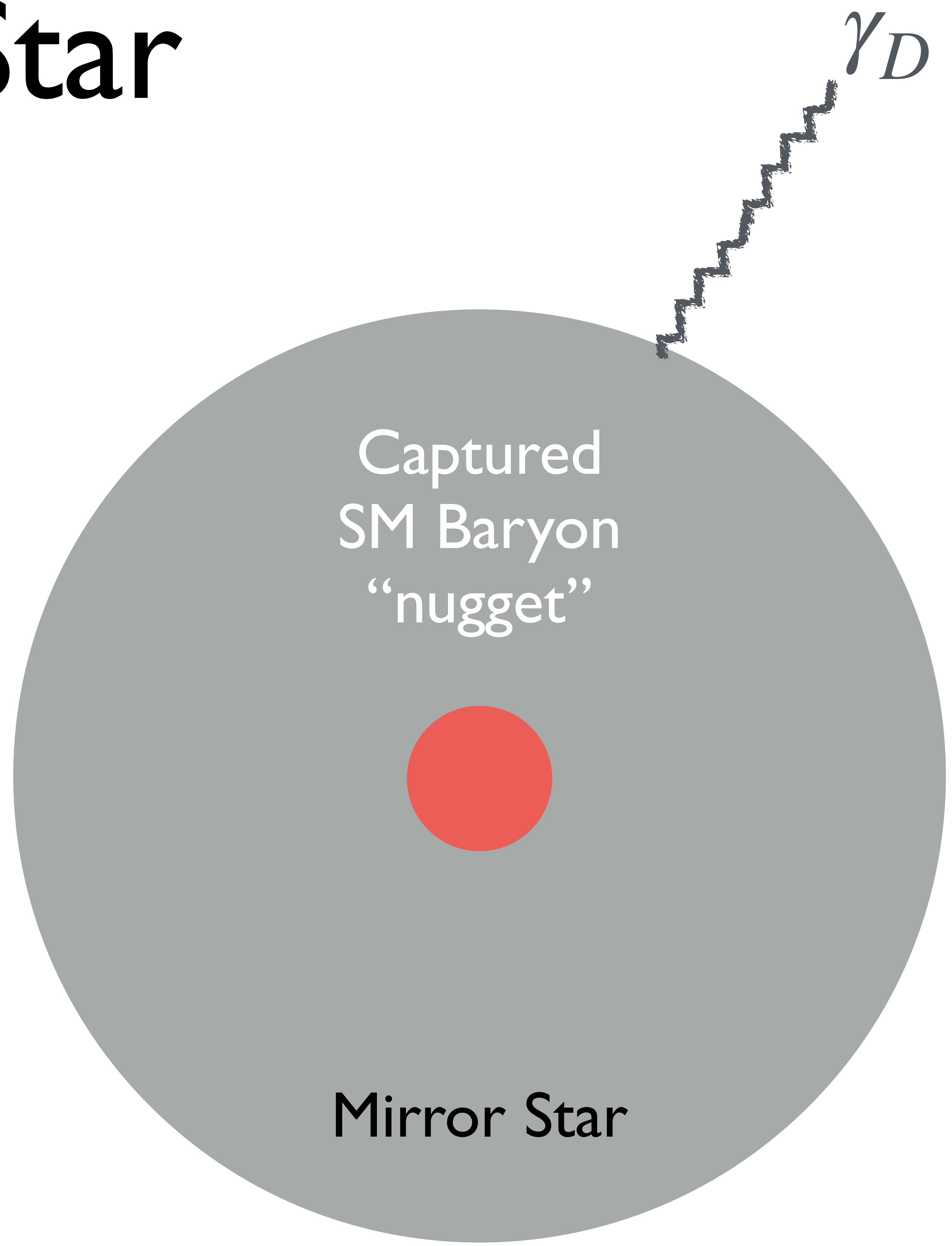




Life of a Mirror Star

For a time they are also very **hot**, radiating away heat in the form of dark photons.

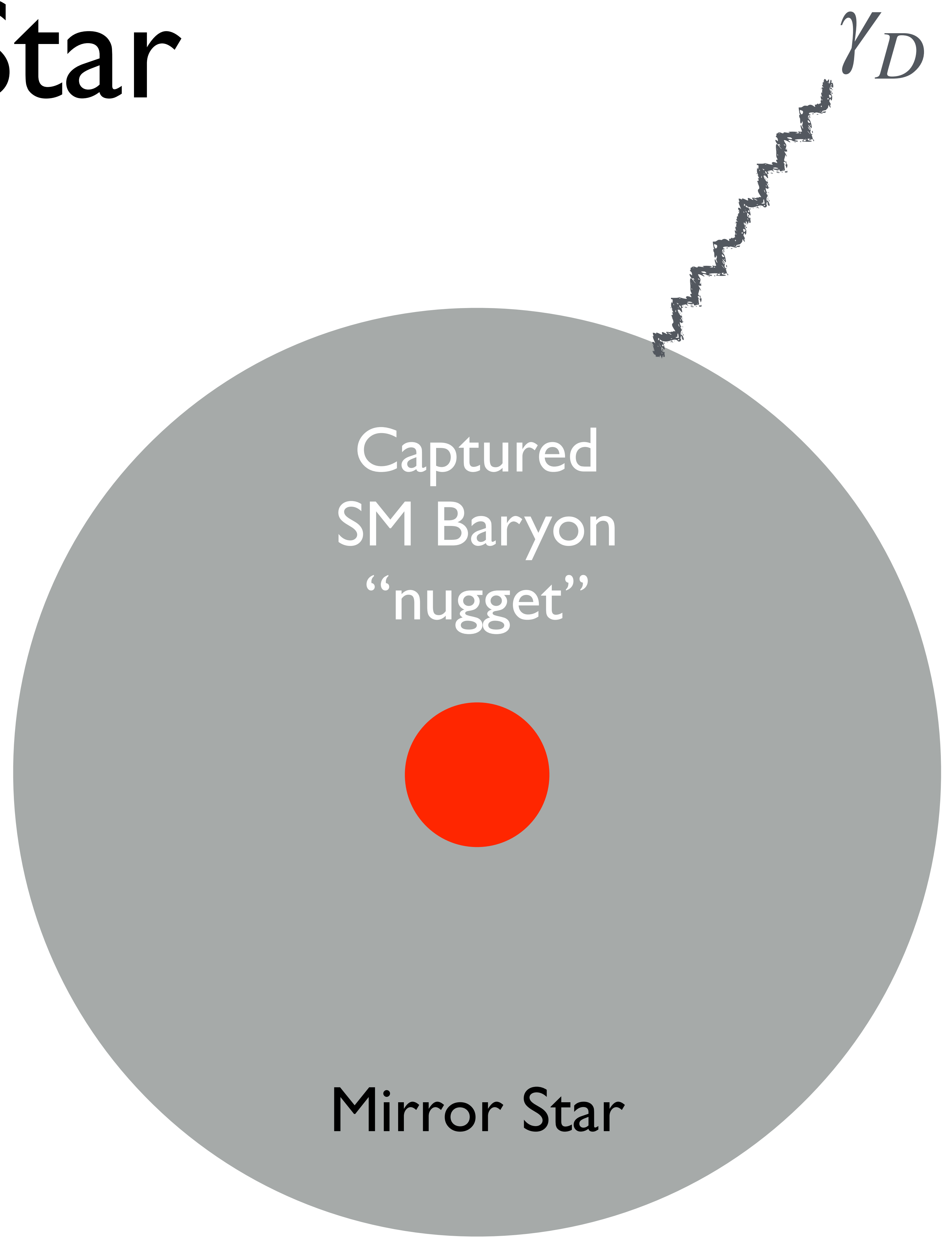
(This lifetime ranges from Kelvin-Helmholz to much longer than SM stars, depending on existence and parameters of dark nuclear physics.)



Life of a Mirror Star

For a time they are also very **hot**, radiating away heat in the form of dark photons.

This heats the captured SM nugget.

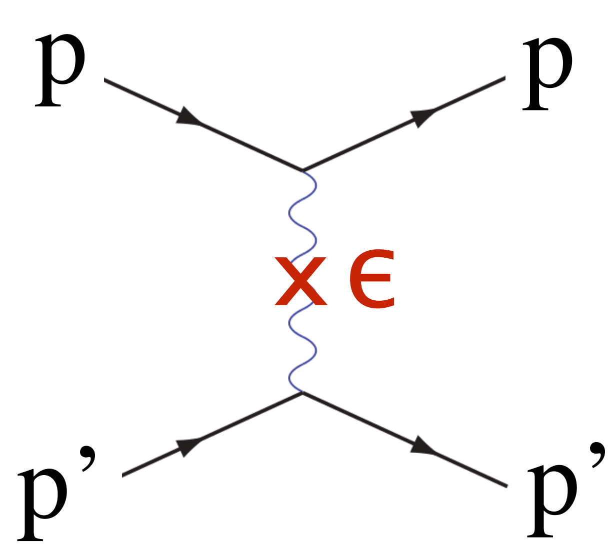


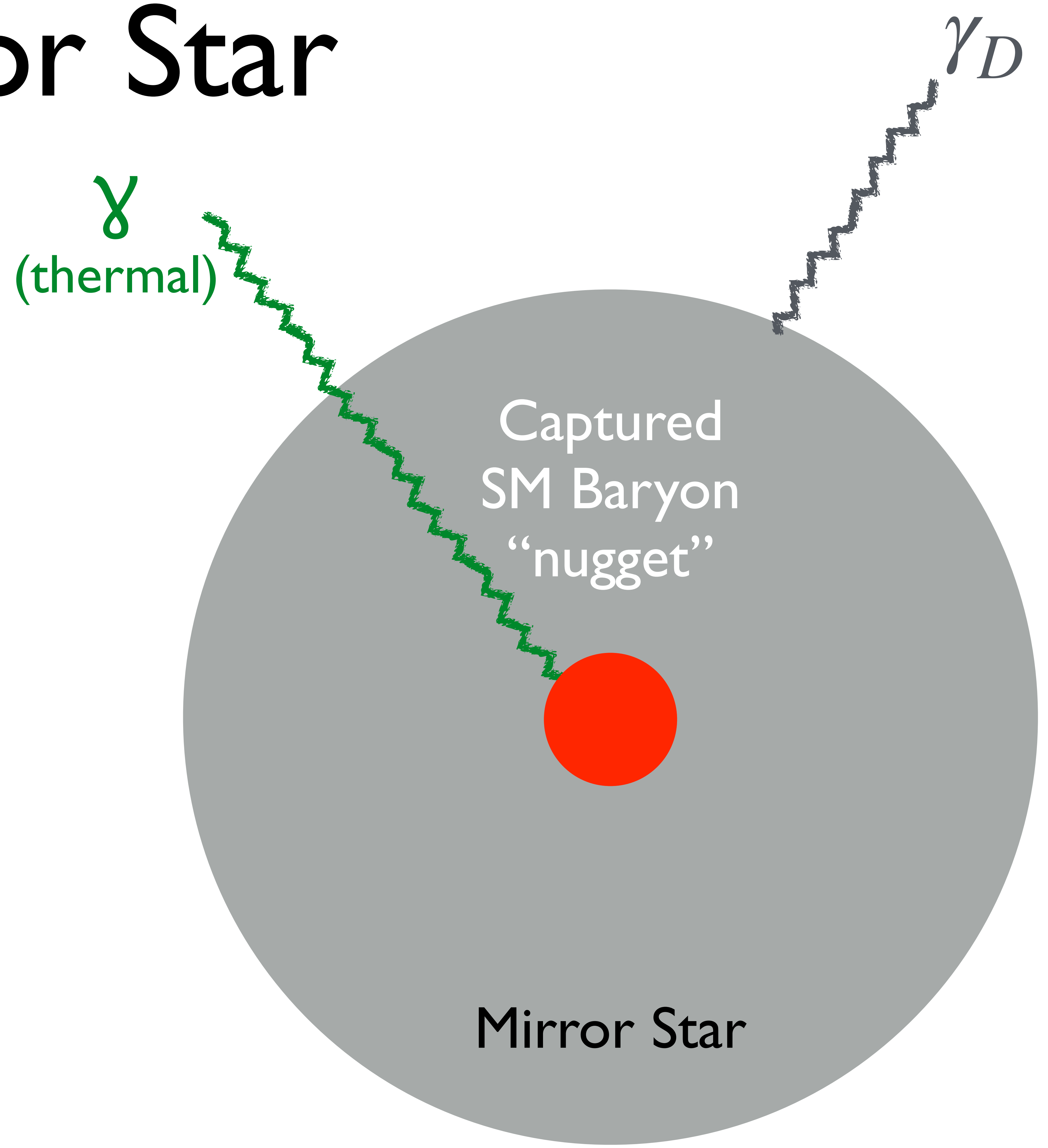
Life of a Mirror Star

For a time they are also very **hot**, radiating away heat in the form of dark photons.

This heats the captured SM nugget.

Optical/IR:
Thermal emission
of captured SM matter





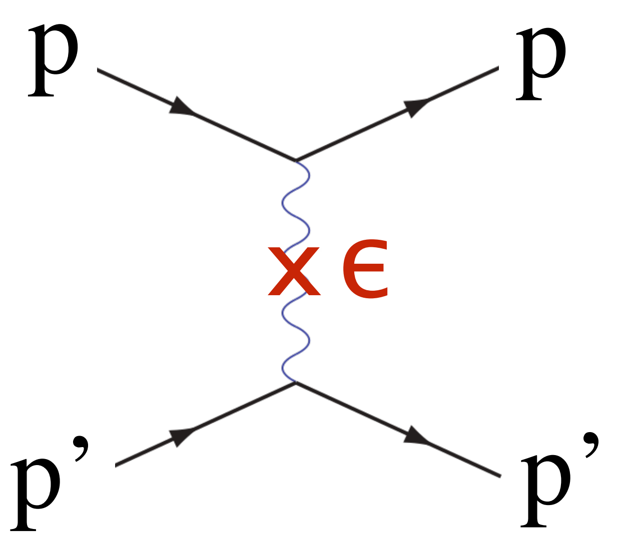
Life of a Mirror Star

For a time they are also very **hot**, radiating away heat in the form of dark photons.

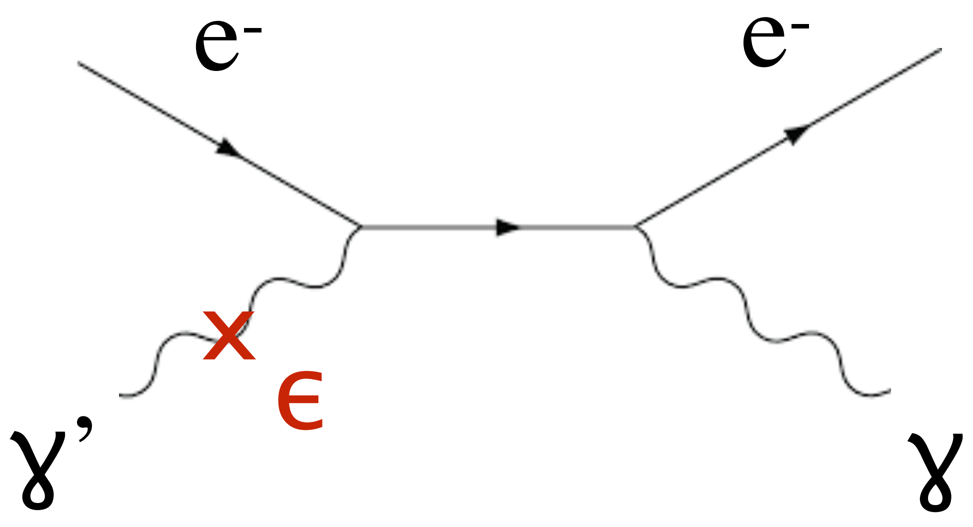
This heats the captured SM nugget.

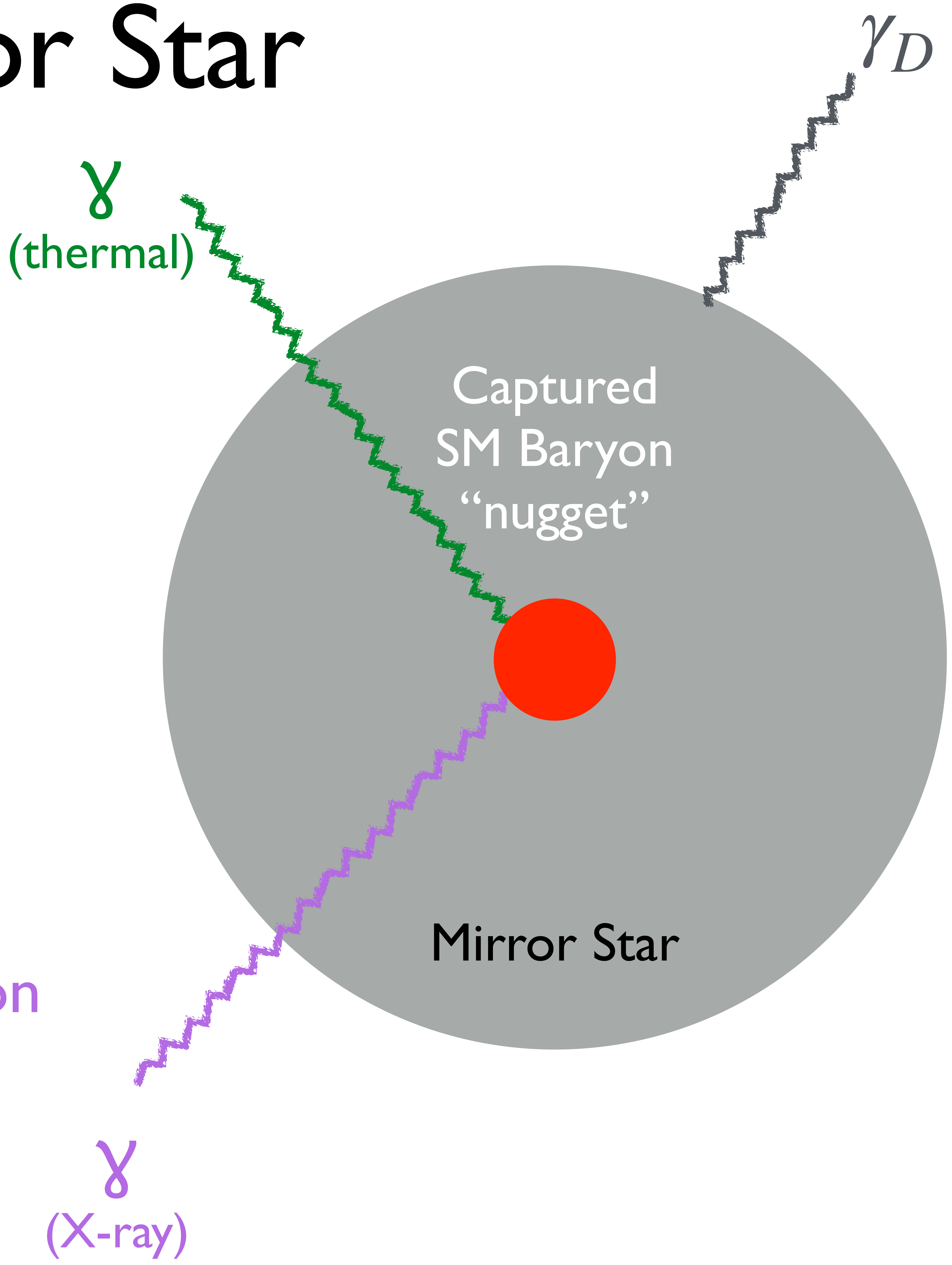
Captured SM matter acts as catalyst to convert dark photons from core directly to X-rays

Optical/IR:
Thermal emission
of captured SM matter



X-ray photons:
straight from core via
mirror-Thomson conversion





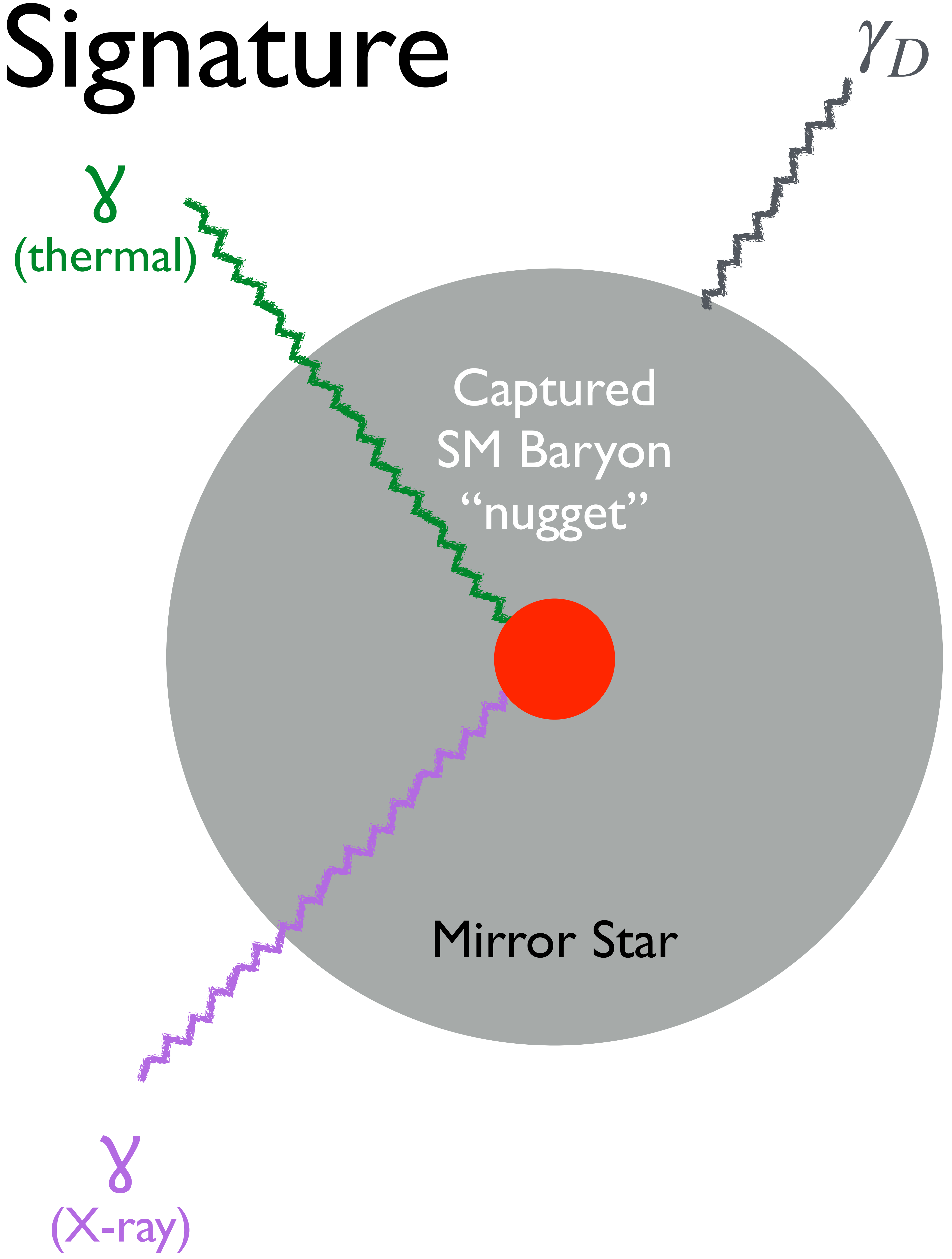
Electromagnetic Signature

What we see is not the mirror star, but the captured nugget of interstellar SM matter!

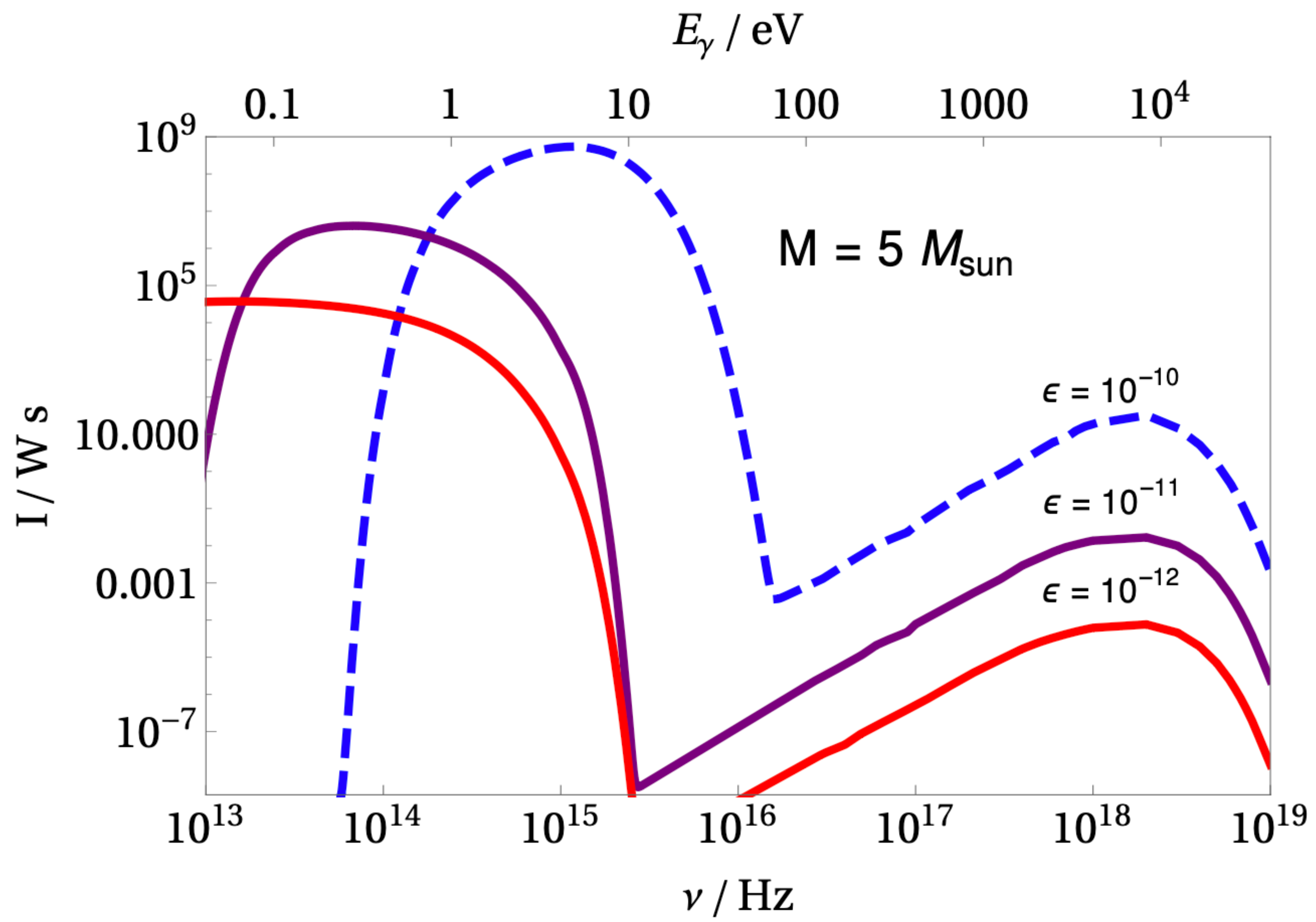
Two signals:

1) thermal emissions at $T_{nugget} \sim \mathcal{O}(10^4\text{K})$, characteristic of a given amount M_{nugget} of SM gas in gravitational potential set by ~ constant core density ρ_{core} of mirror star.

2) Mirror-conversion X-ray signal that reveals mirror star core temperature T_{core}.



Example calculation: SM-like mirror stars



Typical nugget properties for SM-star-lifetimes:
R ~ 5000km, M ~ 10^{16} - 10^{18} kg
= 10^{-8} - 10^{-6} earth masses = small-ish asteroids

Very primitive calculation of nugget structure and spectrum [bremsstrahlung + X-ray only].

Metals/Dust likely to have major impact on spectrum of signal.
Even so this gives idea of magnitude of emission.

1909.04071 DC, Setford
1909.04072 DC, Setford

Example calculation: SM-like mirror stars

0th order expectation:

Thermal part of spectrum relatively insensitive to mirror sector physics?

Roughly speaking, captured SM nuggets are HOT, like white dwarfs, but MUCH DIMMER + emit X-rays.
→ could distinguish in optical surveys with absolute magnitude measurement?

Astrophysically unique!

1909.04071 DC, Setford
1909.04072 DC, Setford

How to look for Mirror Stars in Gaia data

Chris Matzner
U of T
(Astro)

Basic mirror star signal:
DC, Setford, 1909.04071, 1909.04072

First Gaia search:
Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Realistic emission calculation:
ongoing with **Isabella Armstrong, Berkin Gorbuz**, Chris Matzner, DC

Demo: Agnostic mirror star search in Gaia

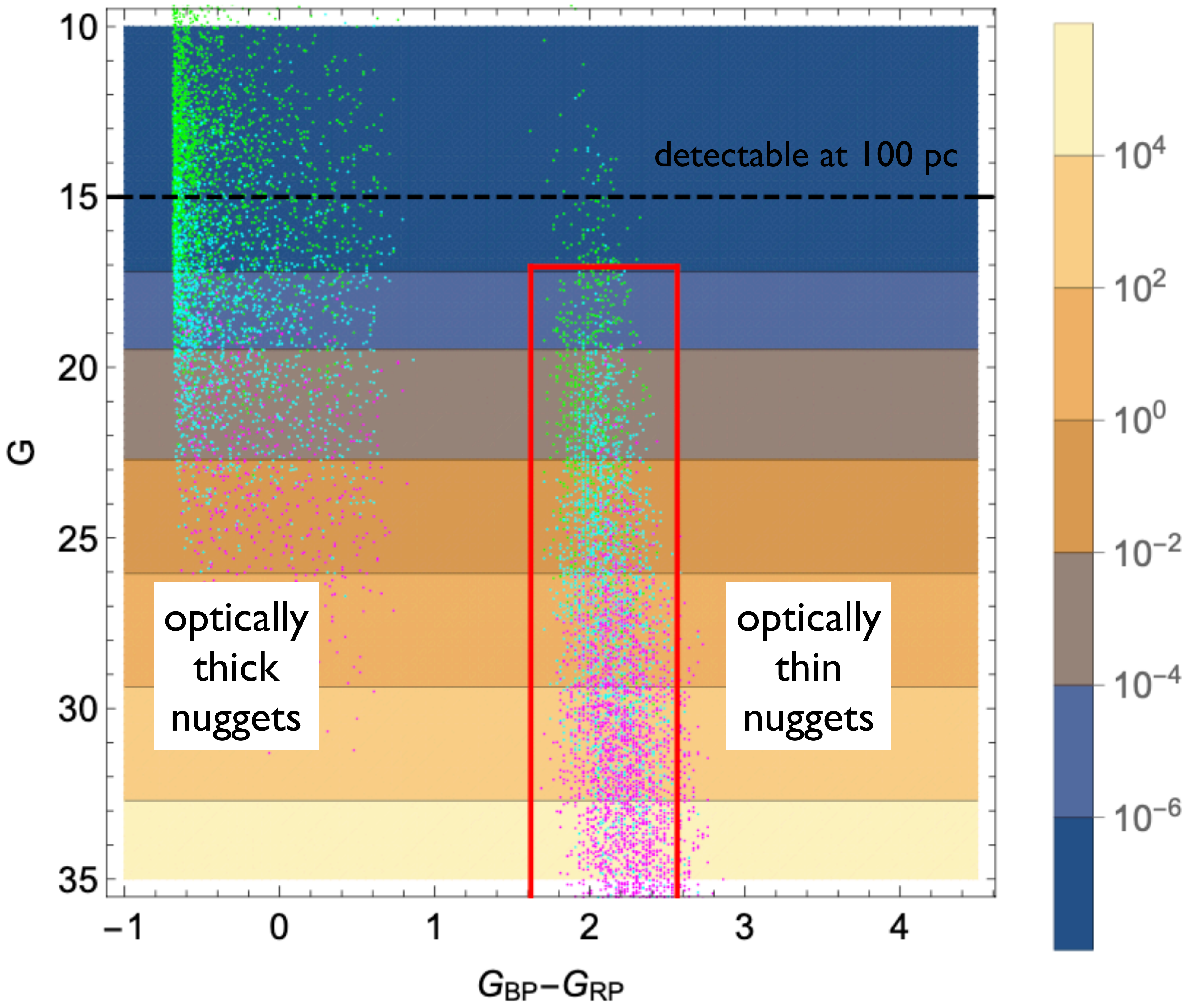
Let's believe our primitive nugget calculation for now.

Gaia would be the perfect tool to find dim but hot objects! *(measures absolute magnitude!)*

Where do general mirror stars live in the HR diagram?

Vary assumed mirror star masses, lifetimes, nucleon masses, kinetic mixing by many orders of magnitude.

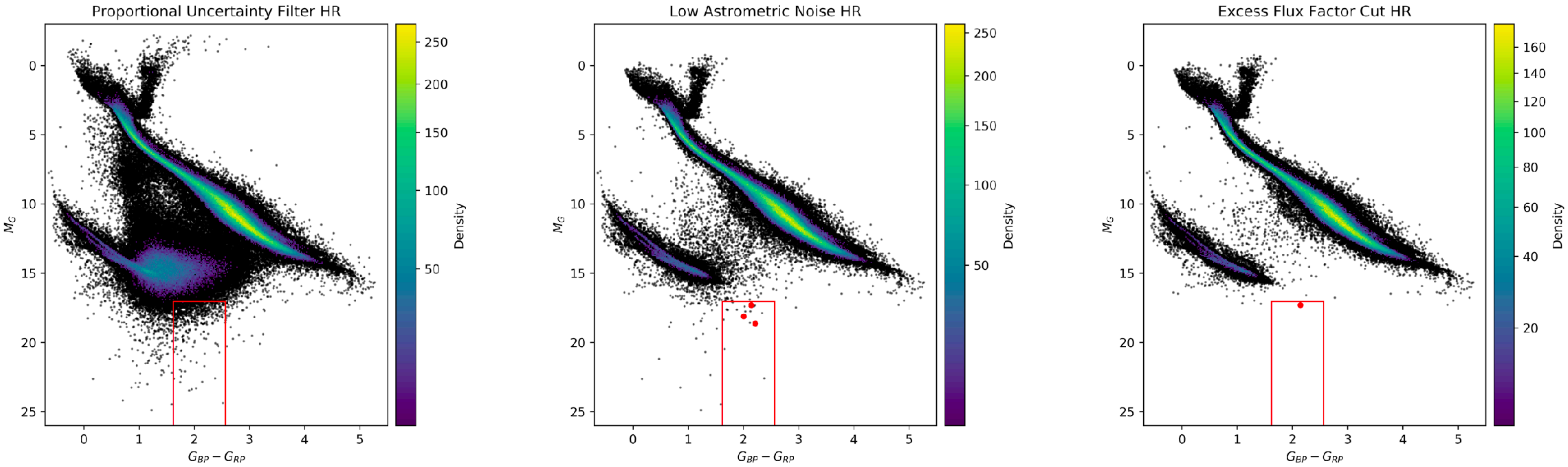
Two distinctive signal regions!



Mirror Star density (pc^{-3}) for Gaia to see 4 mirror stars

Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Look for "optically thin" mirror stars in Gaia data



Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Candidates?

Cross-check with other stellar catalogues!

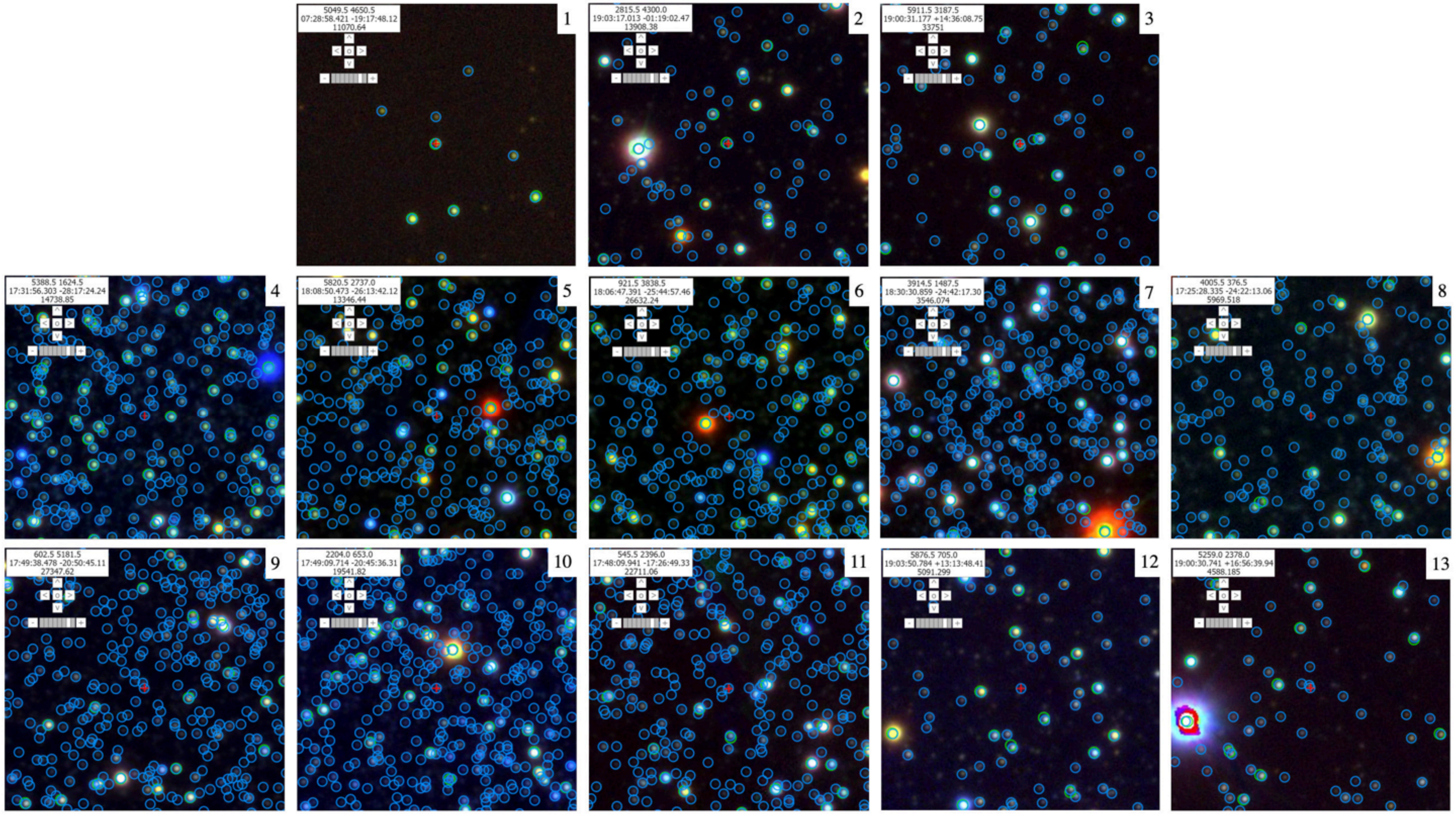


FIG. 4: Pan-STARRS sky images of mirror star candidates 1 - 13, each marked with a red cross. Blue and green circles indicate the known position of Gaia and 2MASS catalogue objects, respectively. Only the first three candidates were detected by the other surveys. Candidate 14 is not in a region of the sky imaged by Pan-STARRS. Each of these images is ~ 1 arcmin in height and width.

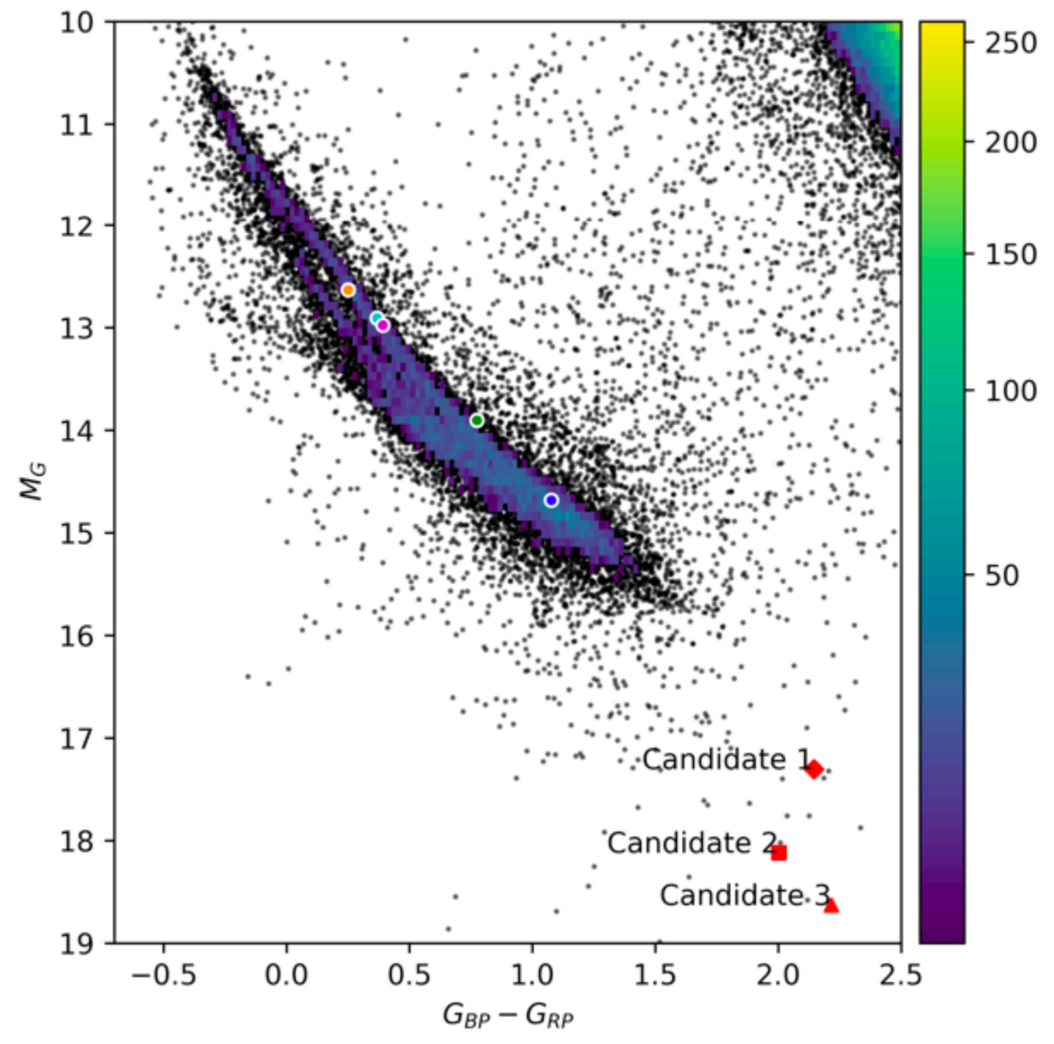
Candidates?

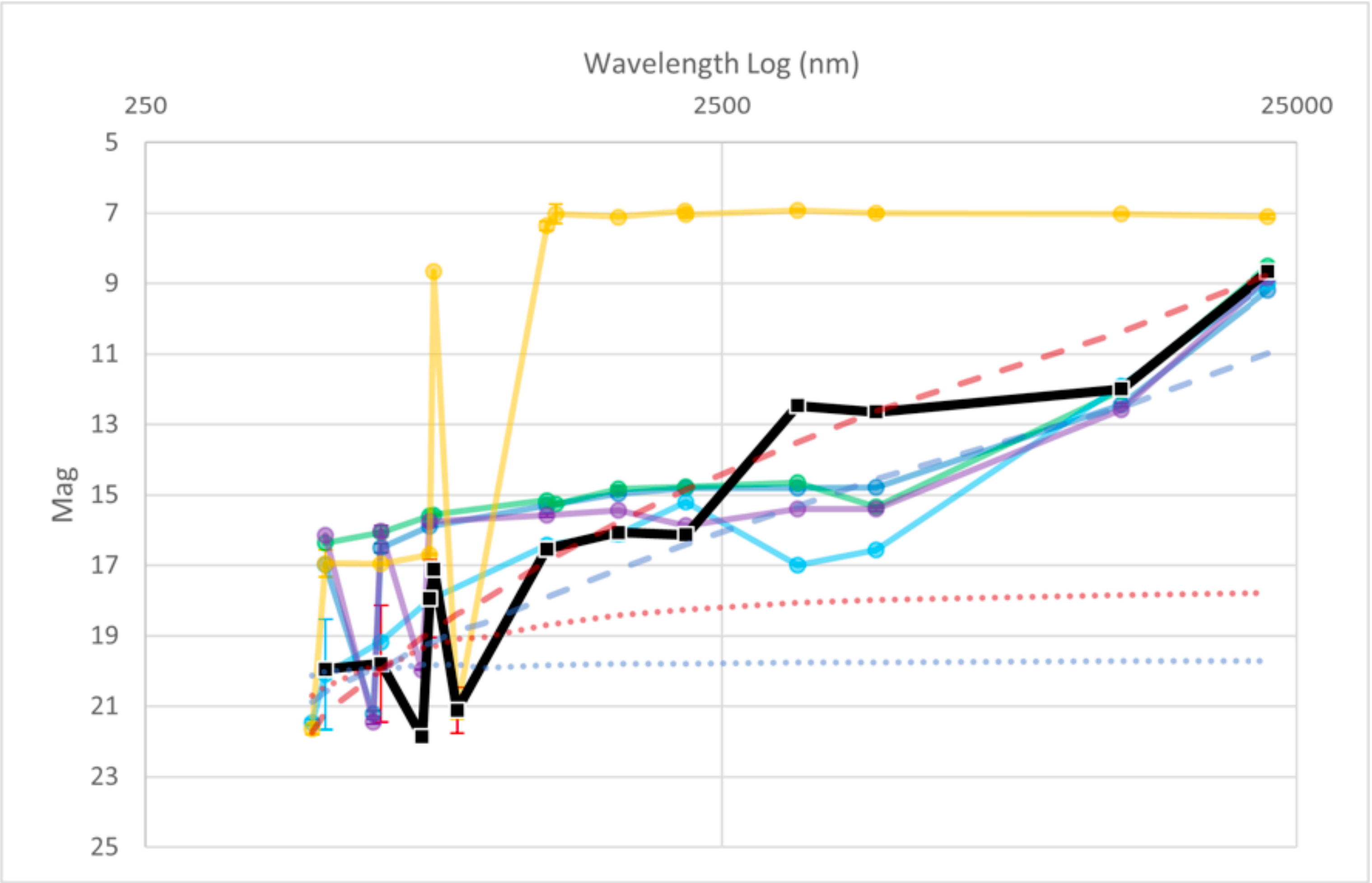
Cross-check with other stellar catalogues!

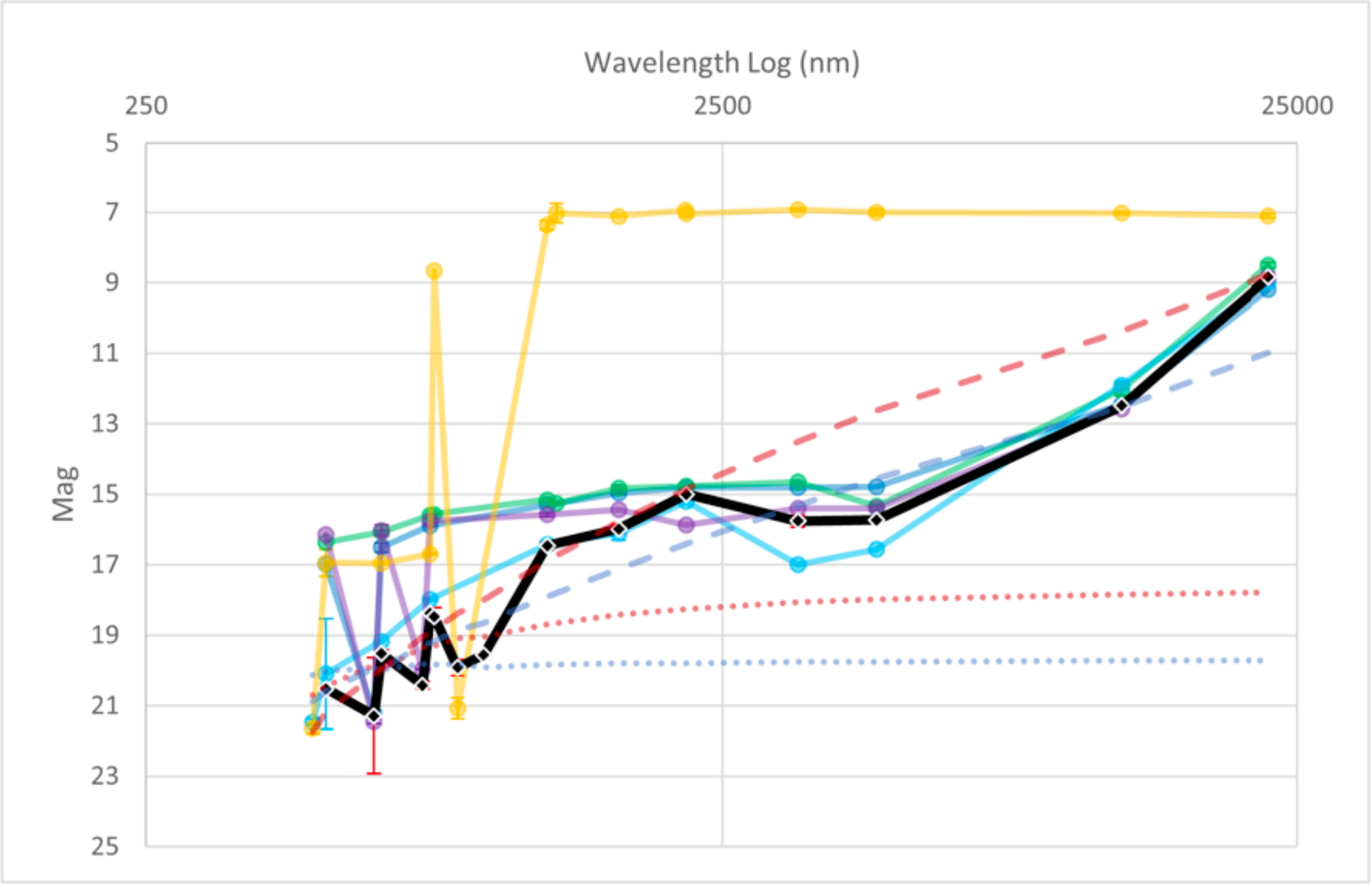
Assemble quasi-spectral info from magnitudes in different filters.

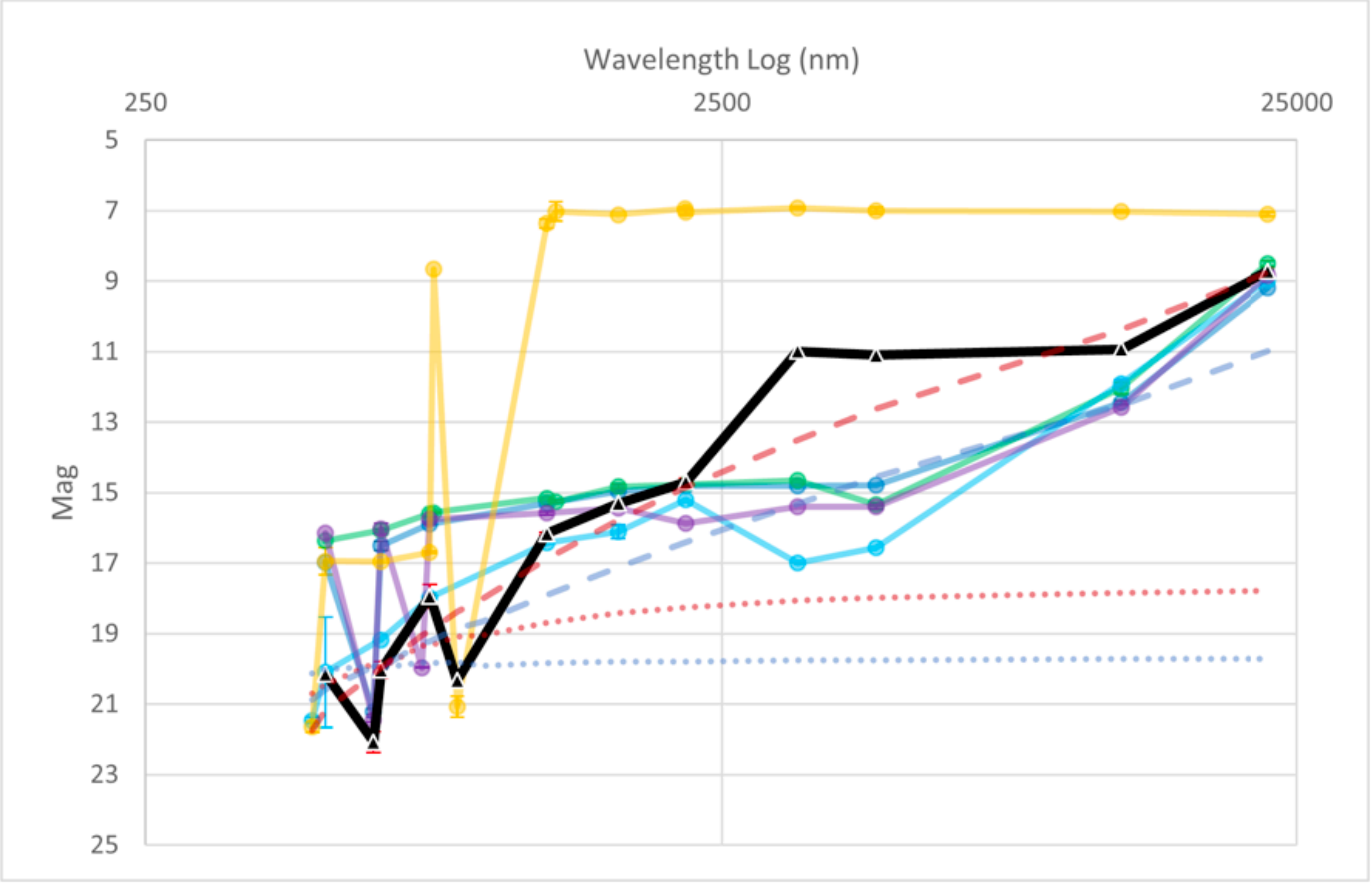
Look like dusty white dwarfs!

Lesson: detailed spectral information will be important in looking for mirror stars!



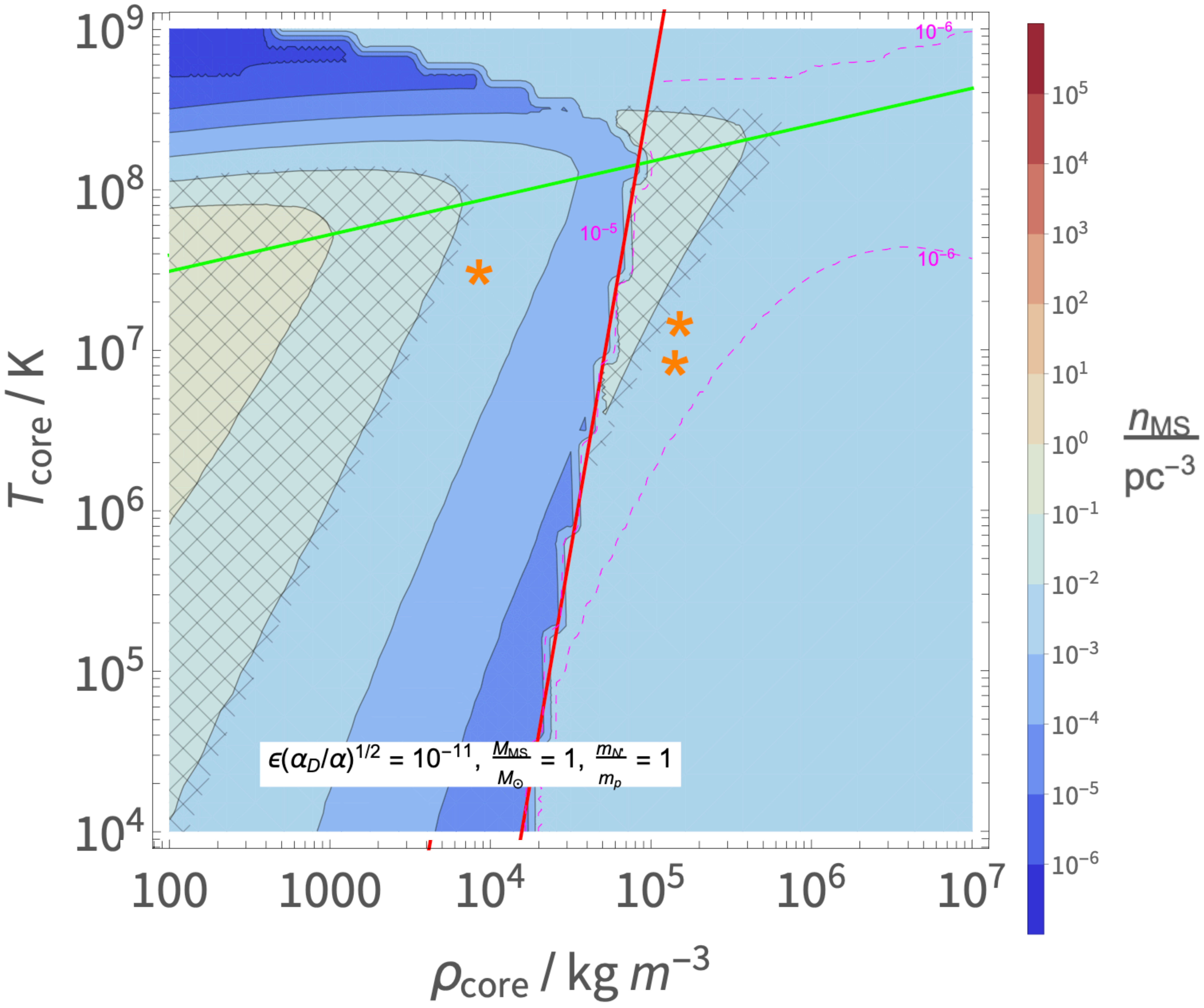






Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Constraints



Non-observation by Gaia can be used to set useful constraints on

- mirror star properties
- local abundance
- some hidden sector parameters

But this relies on accurate model of nugget properties and emissions!

Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

What do mirror stars *actually* look like?

Chris Matzner
U of T
(Astro)

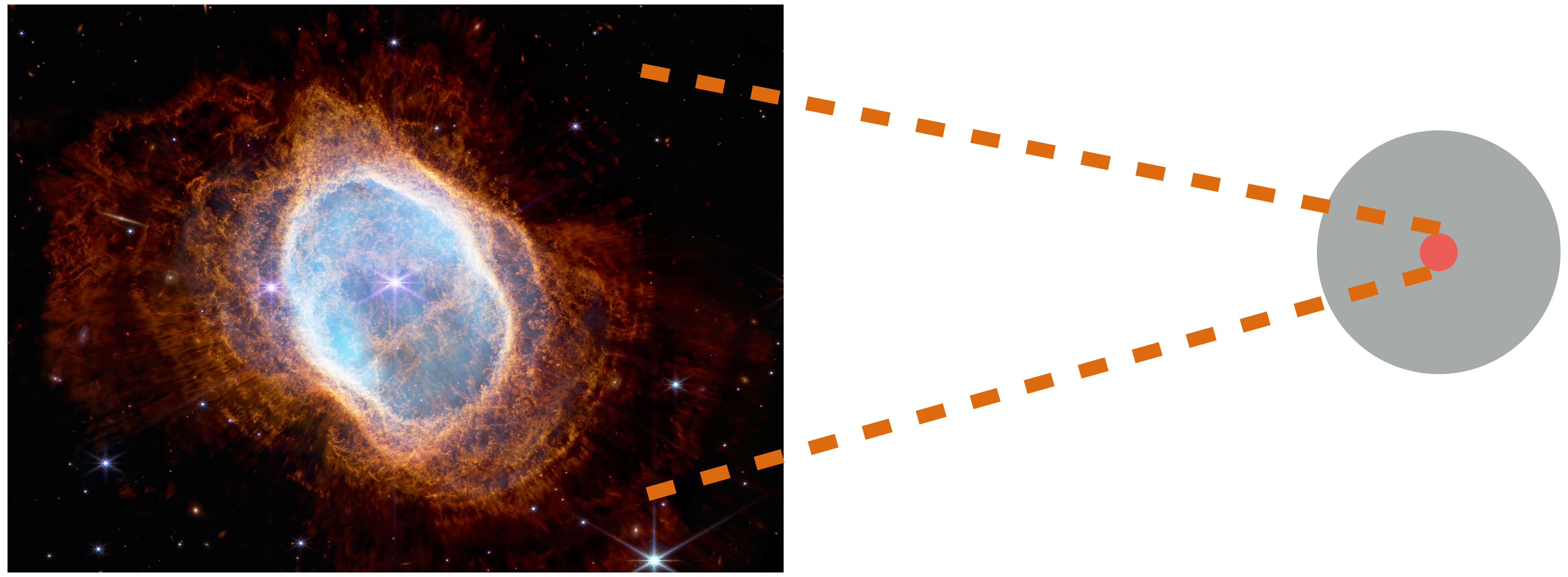
Basic mirror star signal:
DC, Setford, 1909.04071, 1909.04072

First Gaia search:
Aaron Howe, Jack Setford, Chris Matzner, DC, 2112.05766

Realistic emission calculation:
ongoing with **Isabella Armstrong, Berkin Gorbuz**, Chris Matzner, DC

Realistic prediction of SM Nugget Emission

SM Nuggets are a fun & weird astrophysical object, kinda like a planetary nebulae compressed to earth-size with magical local heating.



Just like for planetary nebulae, atomic emission lines, dust etc can completely dominate their emission.

→ use standard astrophysics tools like Cloudy and MESA to compute $T(r), \rho(r), \kappa(r), \dots$ profiles and resulting emission of SM nugget captured by mirror stars in a "fully realistic" way. Then do the real search!

[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Parameter space of Mirror Star emissions

Let's focus on optical emissions only for now (neglect X-ray emission and heating).

Captured SM nugget parameter space is to good approximation only 3D:

- heating rate $\zeta(\epsilon, T_{core}, m_{N'})$
- size of nugget M_{nugget}
- mirror star ρ_{core}

We can exhaustively map out mirror star EM signatures in this entire parameter space to inform searches!

$$\frac{dP^i_{coll}}{dV} \approx n^i_{mirror} n_{SM} \frac{2\pi\epsilon^2\alpha^2 Z^2_{SM} Z^2_i}{m_{SM}} \left\langle \frac{1}{v_{rel}} \left(\log \frac{8\mu^2 v^2_{rel}}{(1/a_0)^2} - 1 \right) \right\rangle$$

$$= \left(\zeta \ \frac{\text{Joules}}{sec} \right) \times \frac{n_{H,SM}}{cm^3} \times \frac{\rho_{core}}{160 g/cm^3}$$

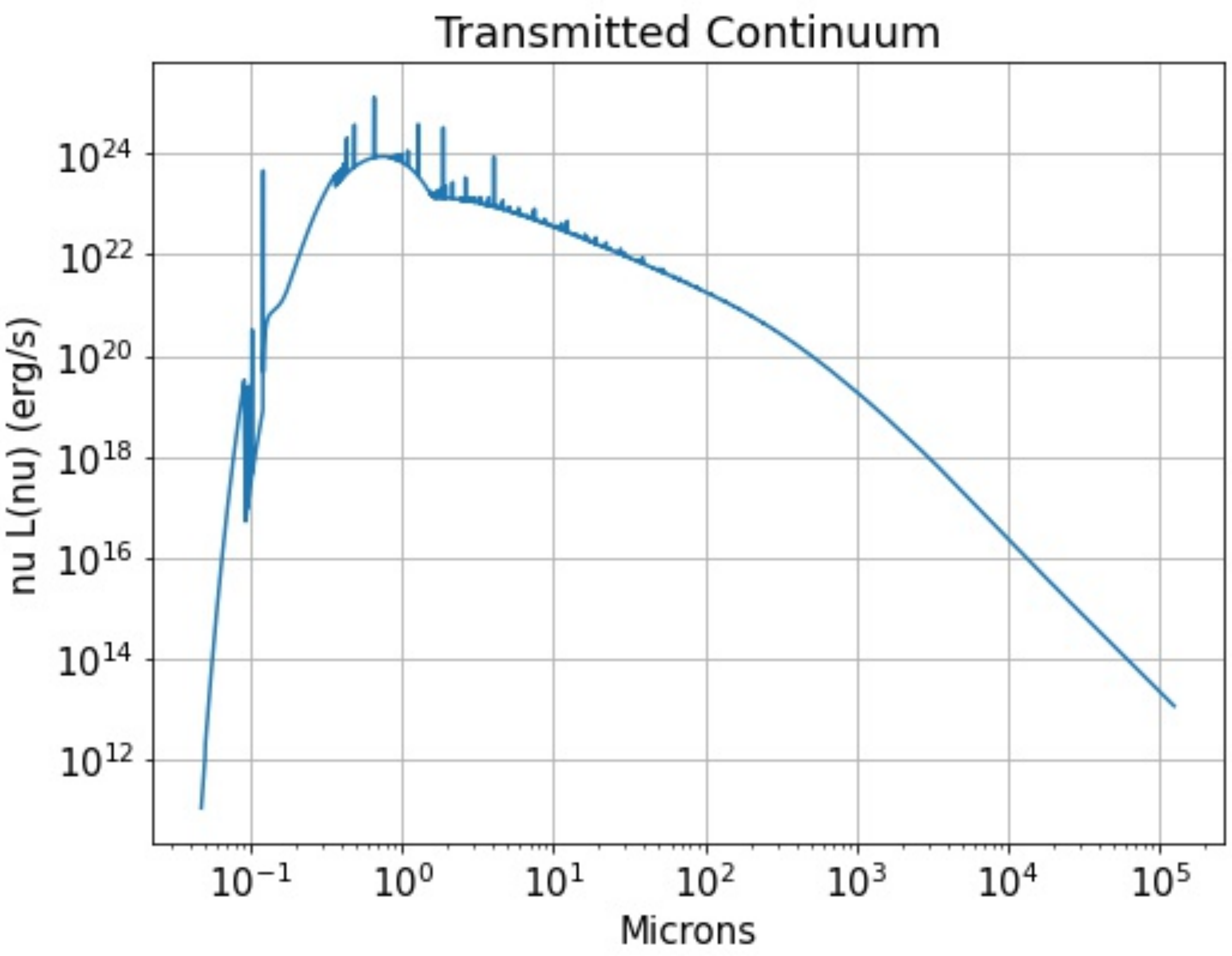
$$v_{rel} = \sqrt{3kT_{mirror}/\overline{m}_{mirror}}$$

$\zeta \sim 10^{-27} - 10^{-19}$ corresponds to $\epsilon \sim 10^{-13} - 10^{-10}$ and mirror star core temperatures within x 100 of the sun (for $m_N \sim m_{N'}$)

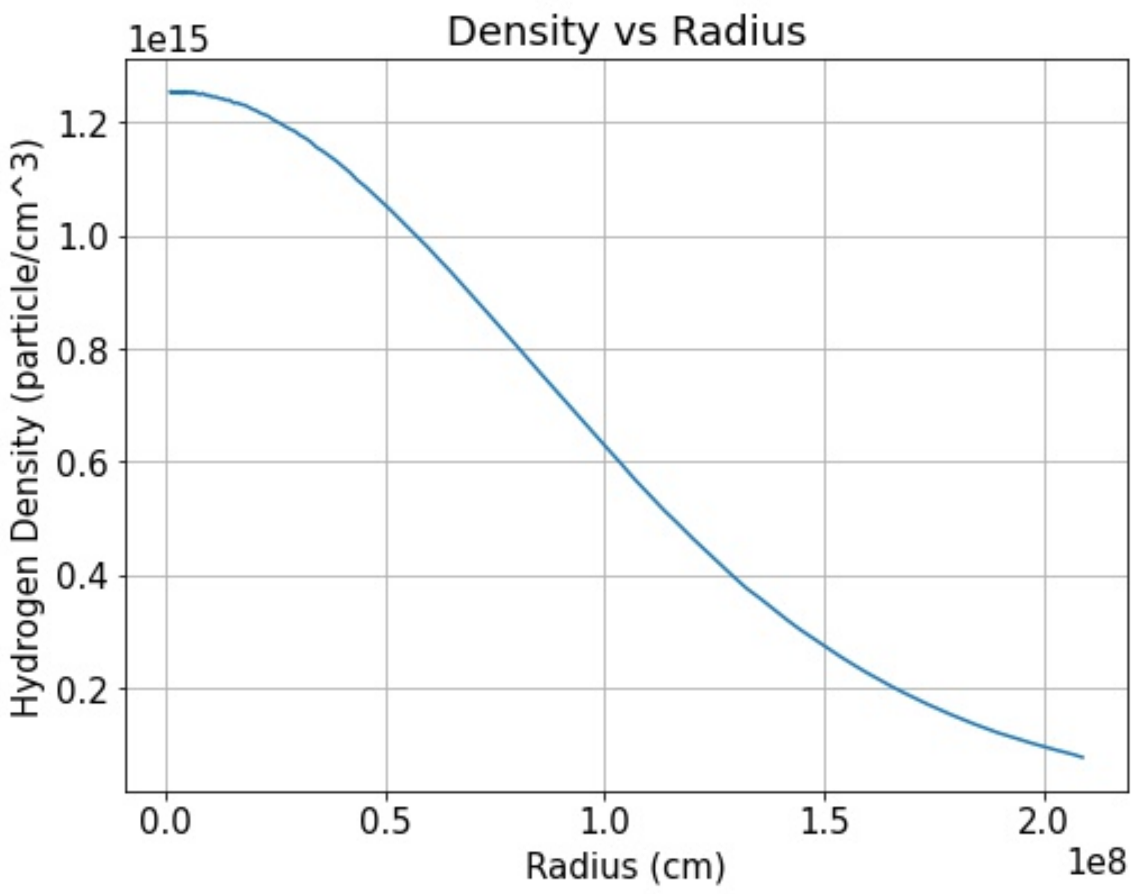
[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

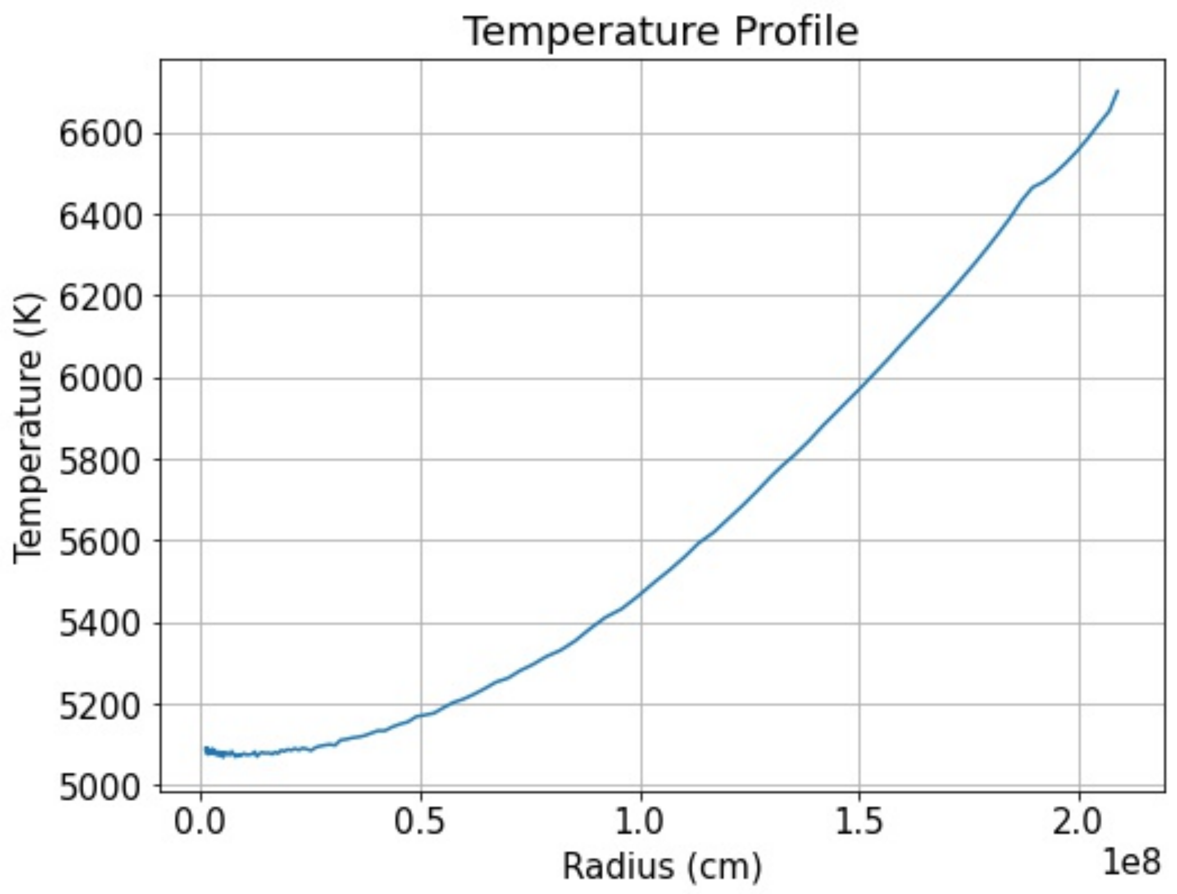
Optically thin nuggets in Cloudy

Emission spectrum. Peak around 700nm



Total mass: 2 x 10^{16} g
Radius ~ 2000 km





[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Roadmap for Realistic Nugget Emissions

Optically thin case almost completed:

- fix some issues with Cloudy
- run for realistic composition of captured gas: He, C, N, dust… (easy)
- compute huge grid of nuggets on cluster to build exhaustive library of mirror star spectra for searches.

Then, move on to optically thick nuggets:

- probably hack MESA
- again, run huge grid of nuggets

This will yield a library of realistic nugget emissions we can project into the HR plane, use as template for high-precision spectral searches, etc…

[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Conclusions

Conclusions

Complex Dark Matter has complicated dynamics but is theoretically simple and highly motivated.

Its effects are potentially spectacular at every scale. Explore with atomic DM benchmark model.

CMB measurements constrain aDM to favour particular binding energy and $\Delta N_{eff}, f_D \sim \mathcal{O}(0.1)$.

Coming up: world's first Nbody sims for aDM. Can then understand effects on baryonic disk and MW subhalos. Allow extension of cosmology constraints to non-linear regime.

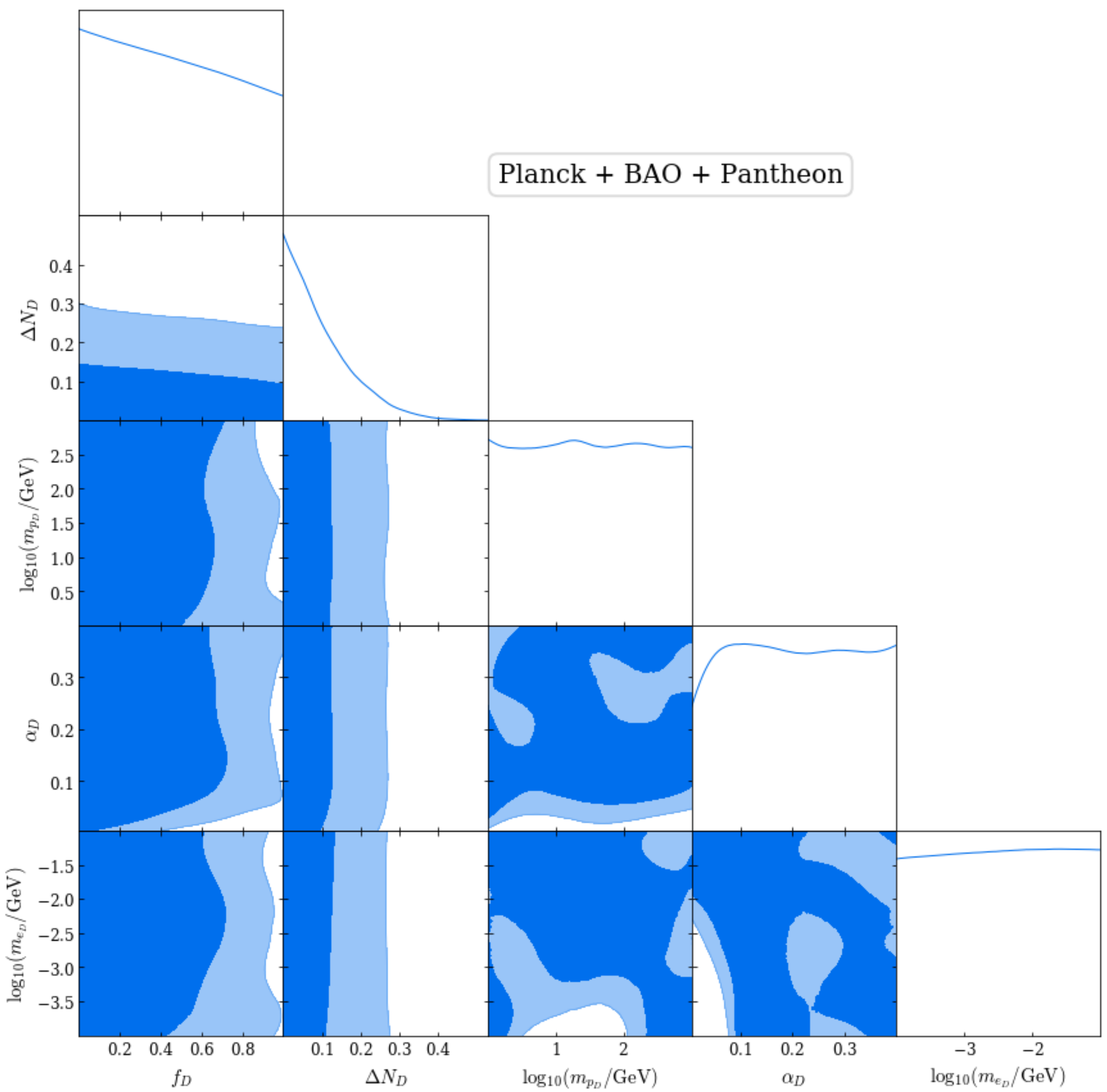
Mirror stars are a very robust consequence of aDM + generalizations.

- Microlensing: Vera Rubin sensitive to **<0.1% mirror star DM fractions** in our galaxy
- Gravitational Waves: **soon hear the whole universe!** If dark nuclear physics, then mirror neutron stars exist and can be distinguished from NS/BH.
- Electromagnetic signals and Telescope searches (Gaia etc) if dark & visible photons mix. Could discover mirror stars if there are any "close" to us (at least 100+ pc range ***)

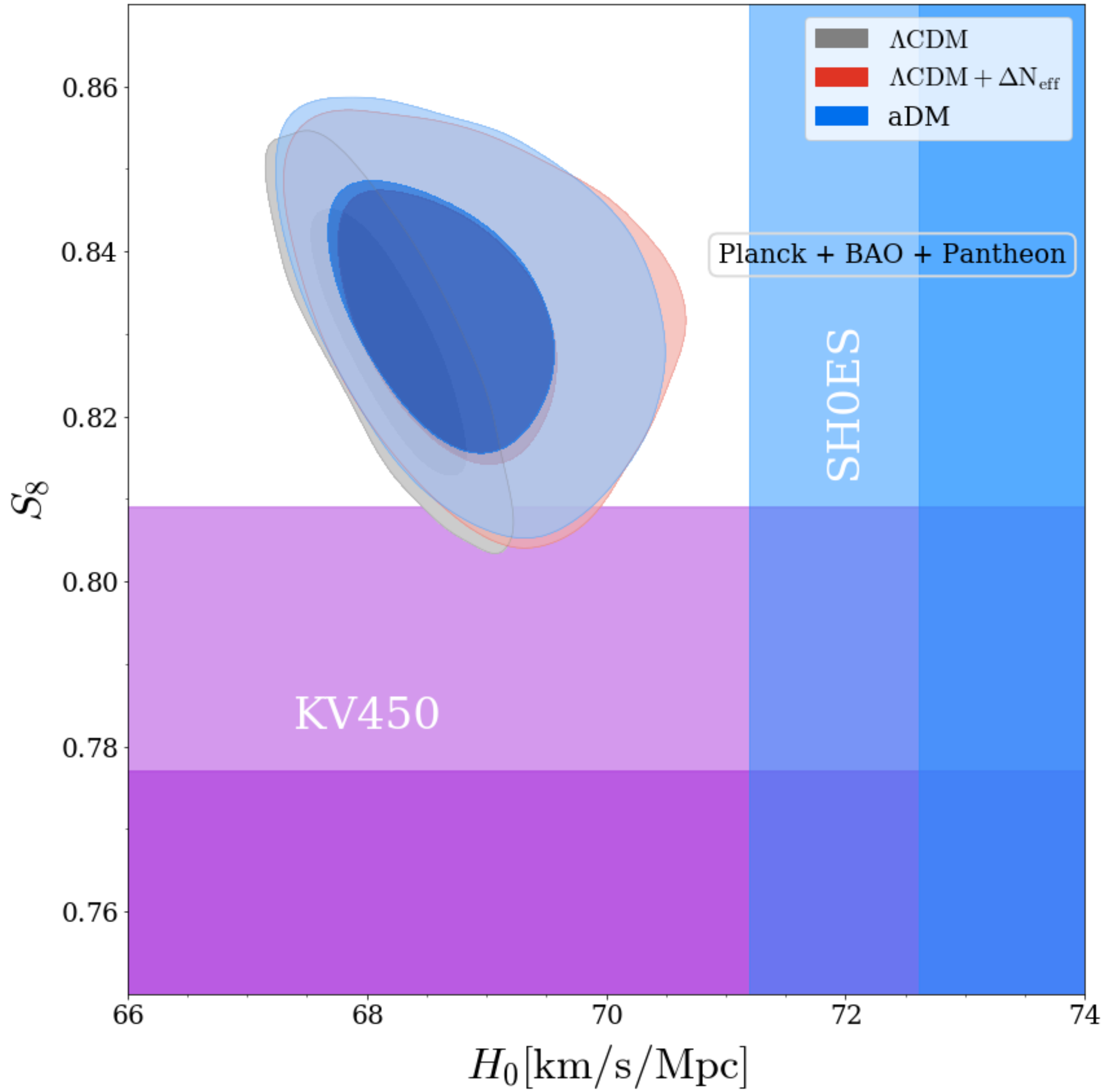
Interdisciplinary opportunity! Dark Complexity =
study of BSM particle/nuclear/chemistry/astro-physics!

Backup slides

Atomic Dark Matter Cosmology Plots

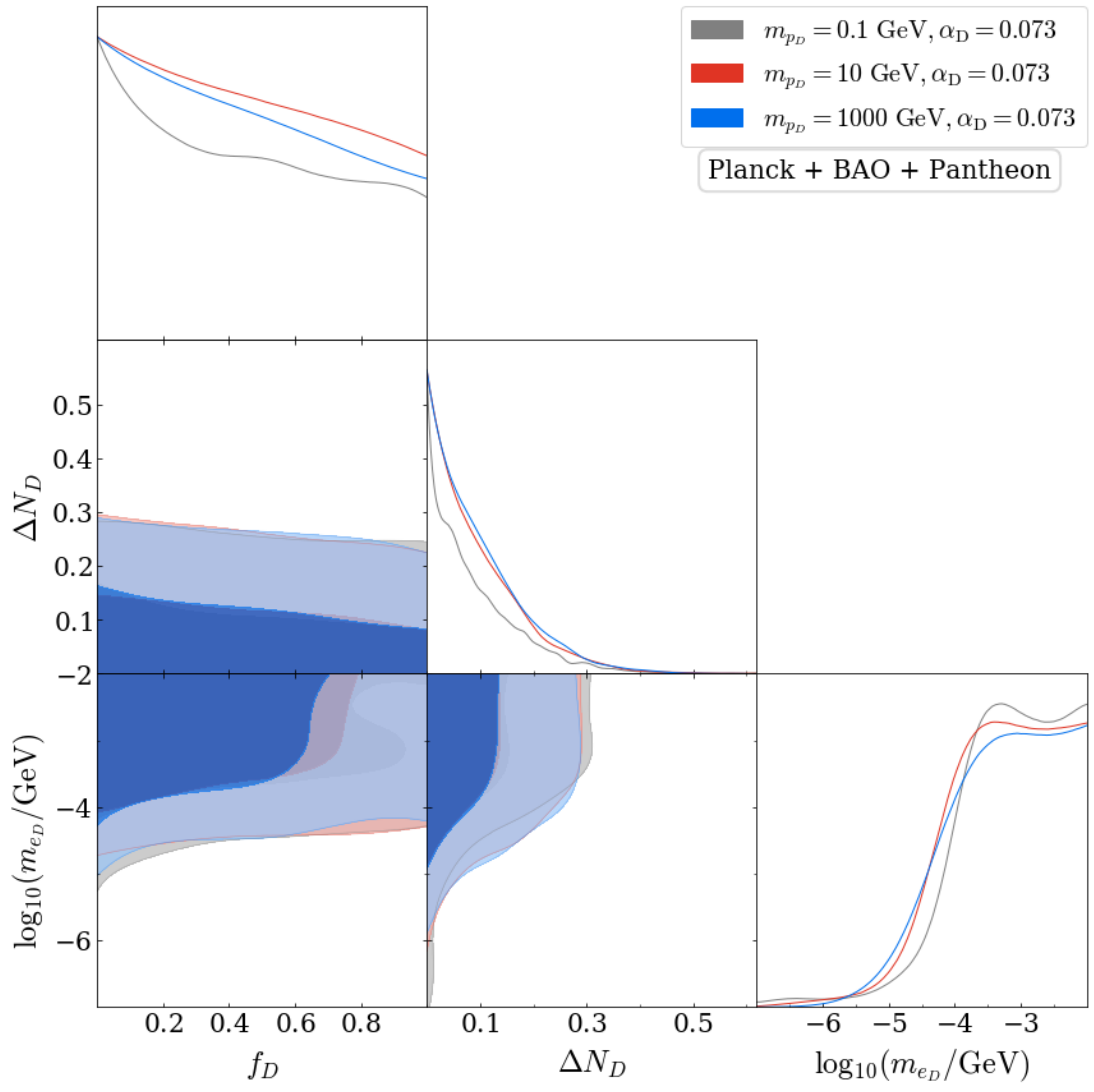


full 5D scan without H0, S8 and without LSS

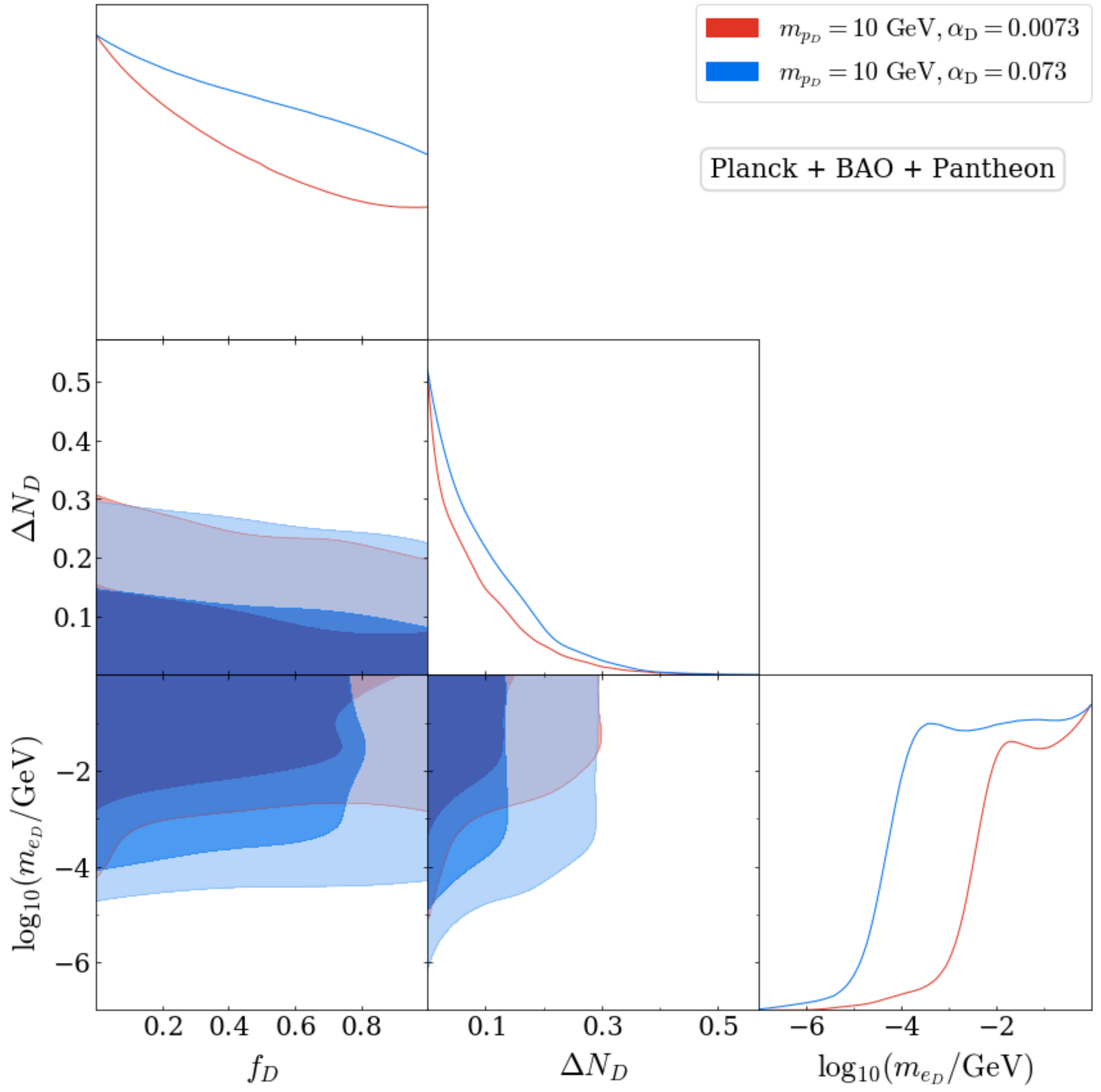


Atomic Dark Matter Cosmology Plots

full 5D scan without H0, S8 and without LSS



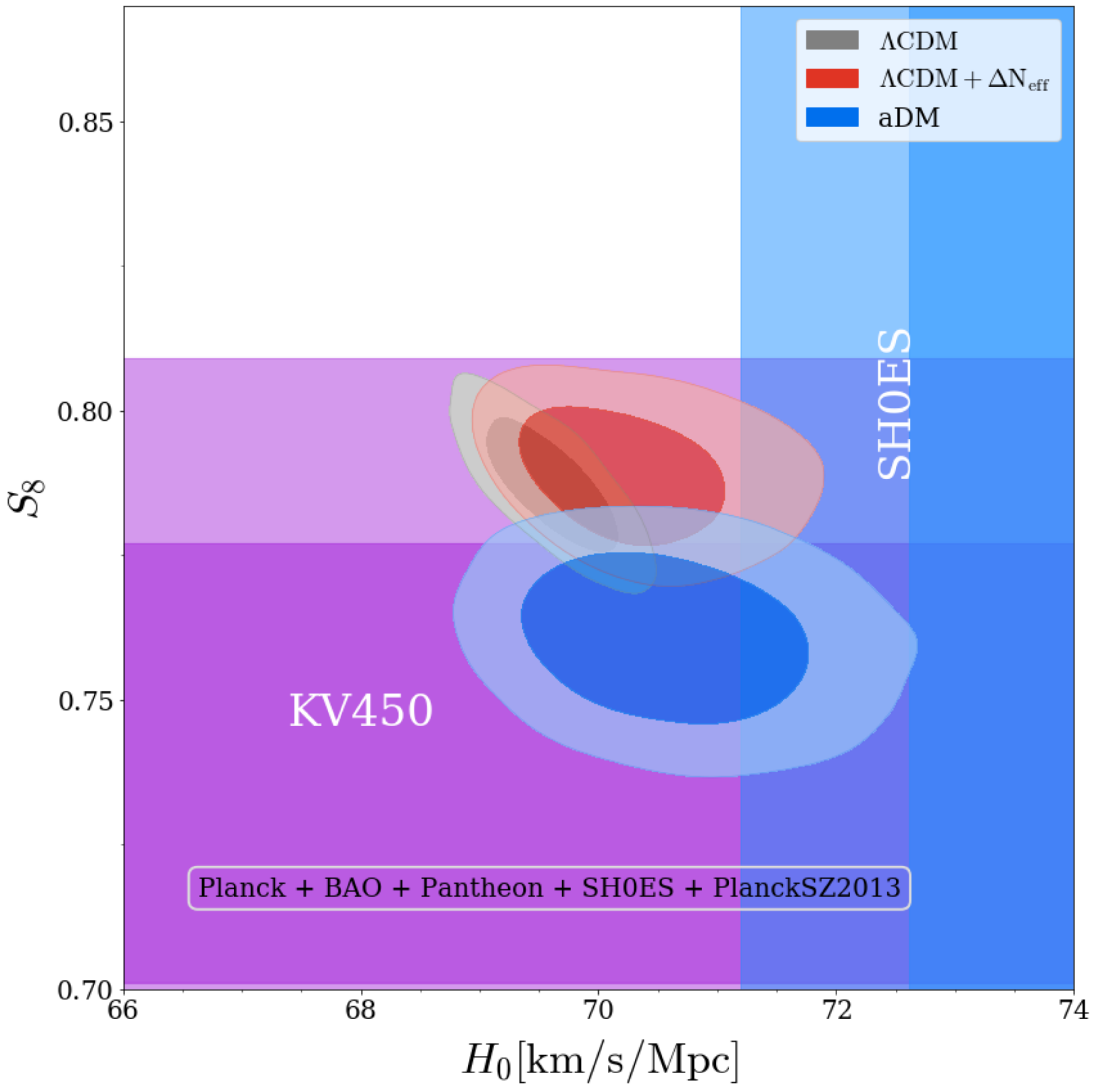
Dark proton mass doesn't matter



constraints become very tight below some m_{e_D}

Atomic Dark Matter Cosmology Plots

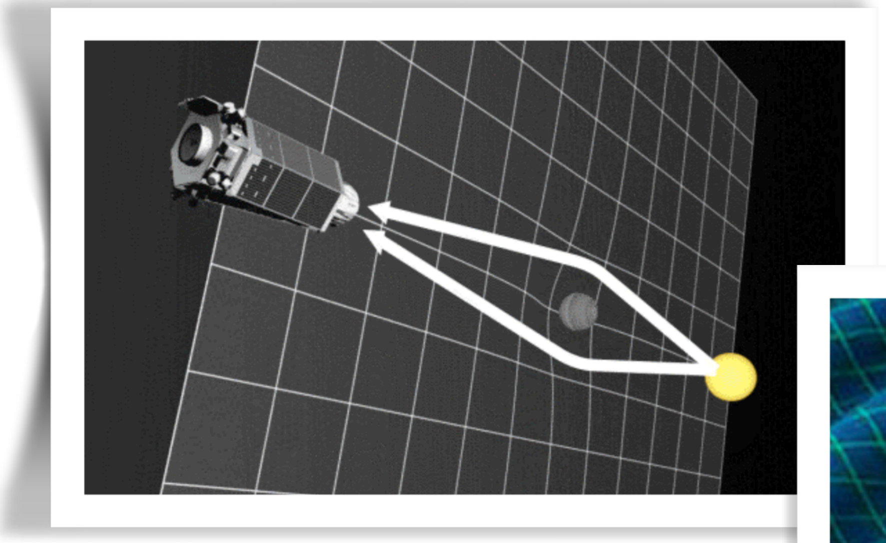
full 5D scan with local H0 and S8 measurements, 1-2sigma preferred contours

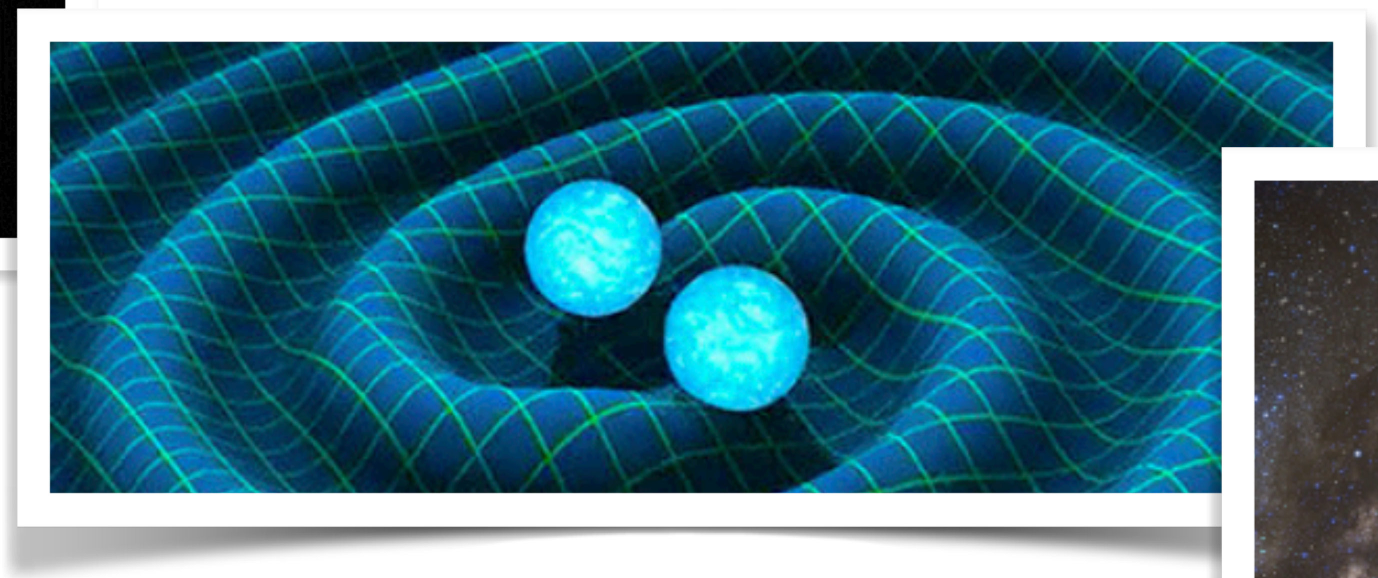


How do we "observe" Mirror Stars?

Purely gravitational probes

- microlensing
- gravitational waves





Electromagnetic probes (i.e. Telescope observations)

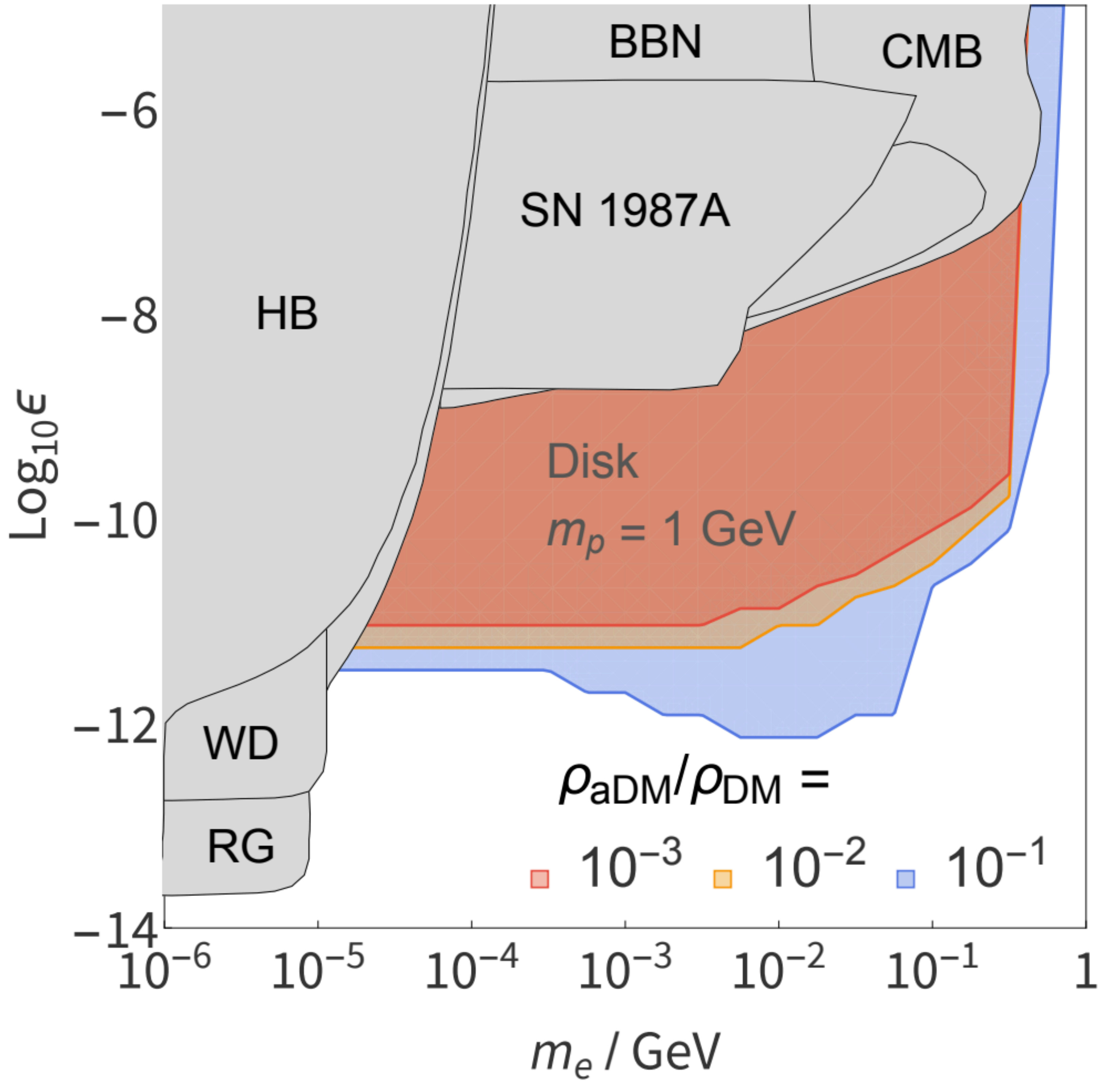
In general, dark photon will mix with SM photon. Incredibly faint interactions are not relevant for galaxy/stellar evolution, but produces electromagnetic signals!

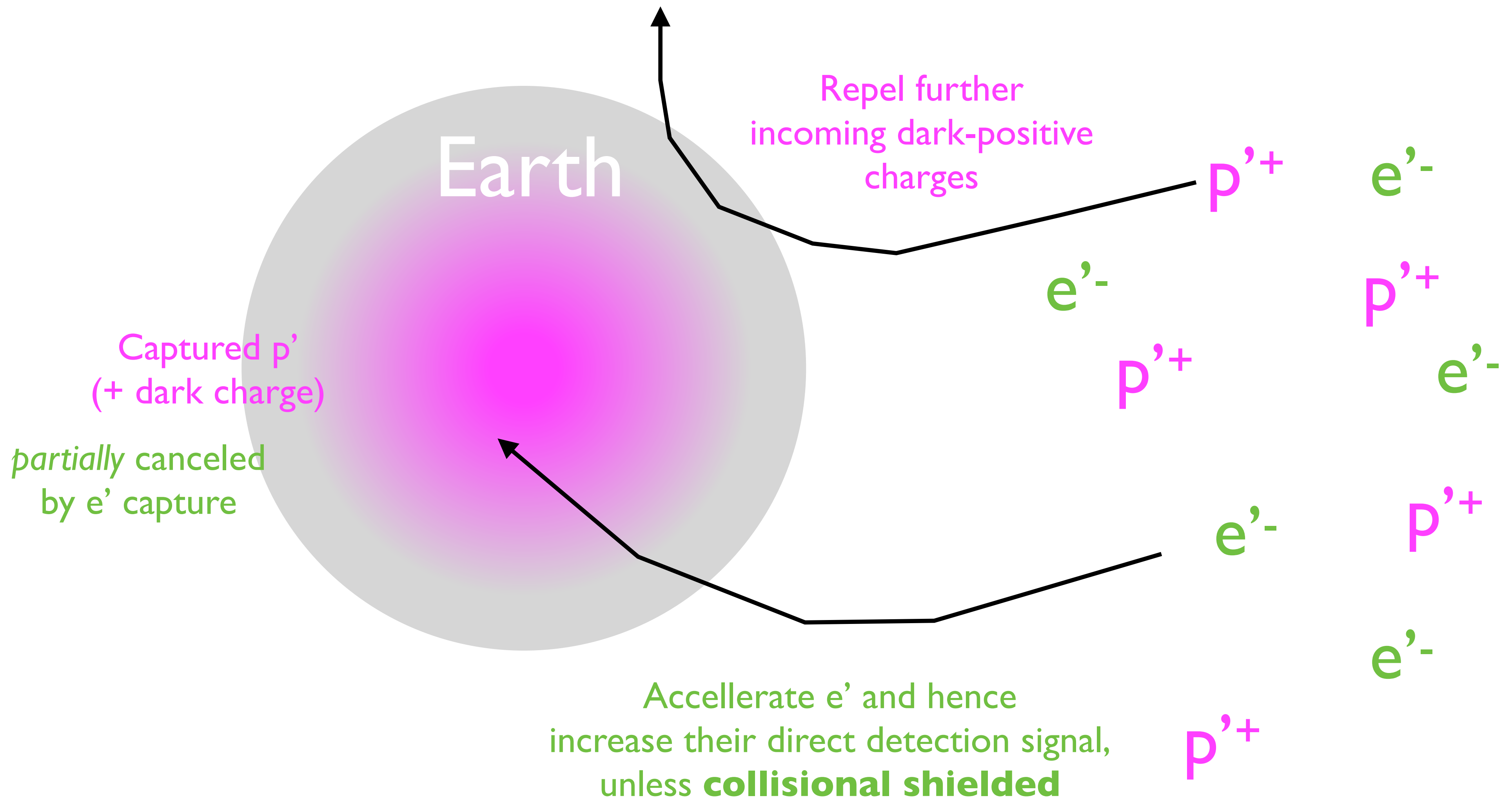
$$\mathscr{L} \supset \epsilon F_{\mu\nu} F_D^{\mu\nu}$$

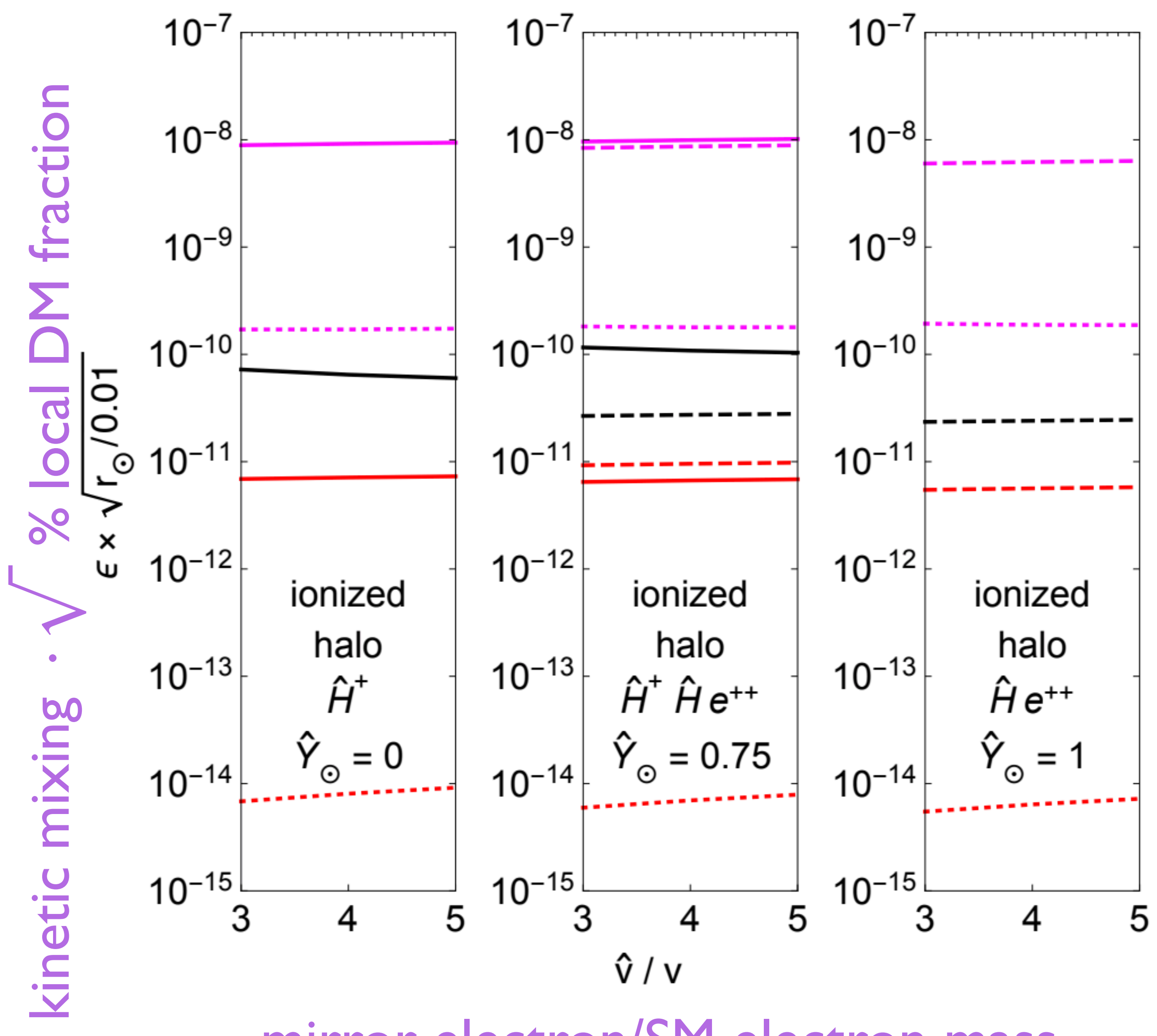
Stellar Cooling

Direct Detection

SM white dwarfs capture aDM and then radiate dark photons



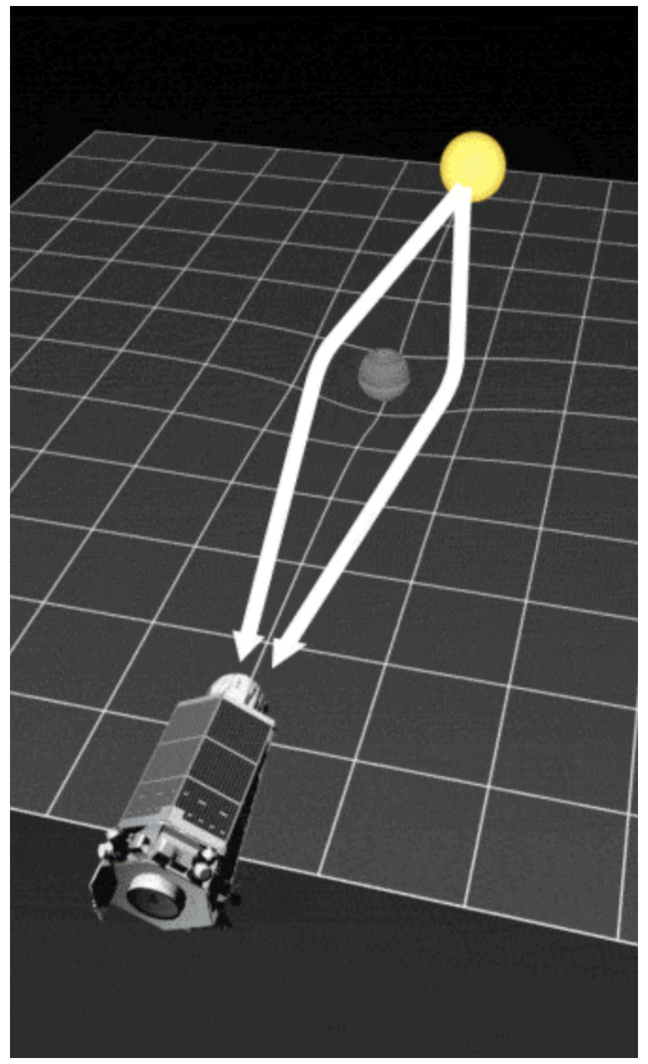




2010.00601 DC, Setford

2104.02074 Chacko, DC, Geller, Tsai

Just MACHOs?

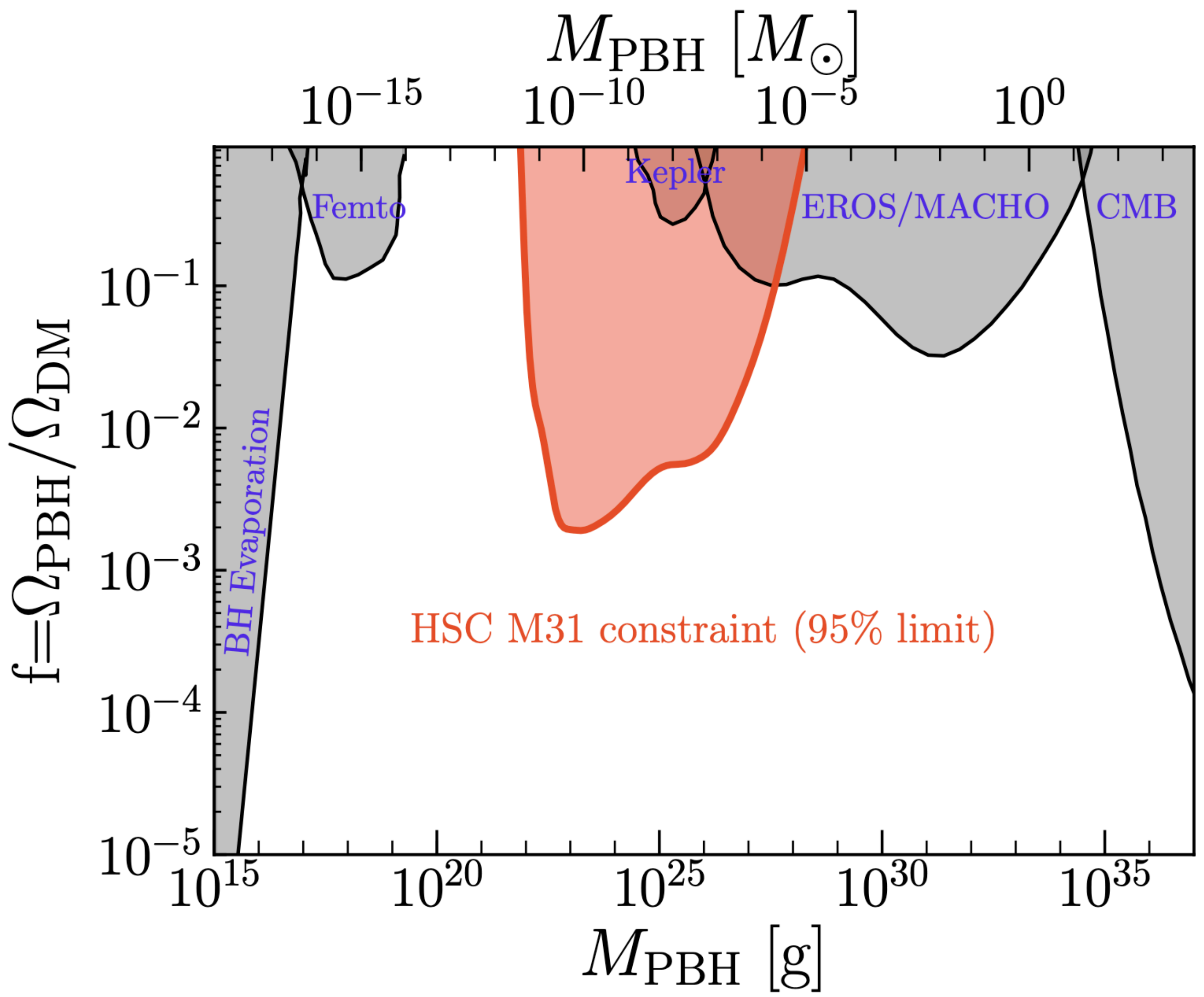


MACHOs (MAssive Compact Halo Objects) are an old idea.

For example: PBH component of collisionless cold dark matter.

Can search for them with gravitational microlensing: transient brightening of source star due to passing MACHO lens.

MACHOs live in the HALO, so best to look **through** milky way halo at sources **away** from the noisy milky way disk.



1803.09205 Calcino, Garcia-Bellido, Davis

1701.02151, Hiroko et al.

Image source: wiki

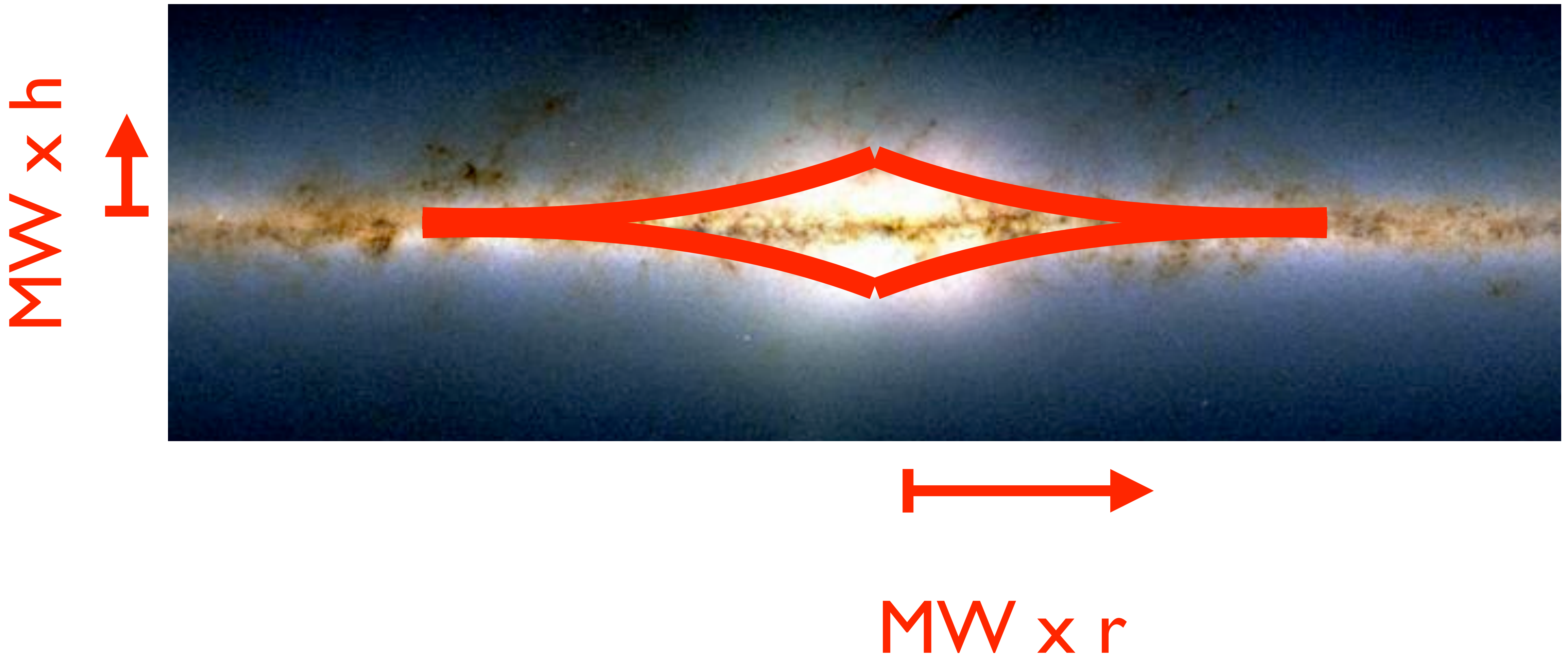
MACDOs!

Mirror stars are more likely to exist if aDM gas has already cooled and collapsed, which means they could populate a **dark disk** aligned with our milky way disk.

→ MACHO searches insensitive.
→ search for **MACDOs** (MAssive Compact **Disk** Objects).

We don't know mirror star distribution, so parameterize ignorance:

- rescaled exponential disk model
- delta function mass distribution
- velocity distribution same as MW



Seek to constrain mirror star mass fraction of DM in our milky way!

Image source: 2MASS

Vera Rubin Telescope

Projected staring contest world champion 2023 - ongoing

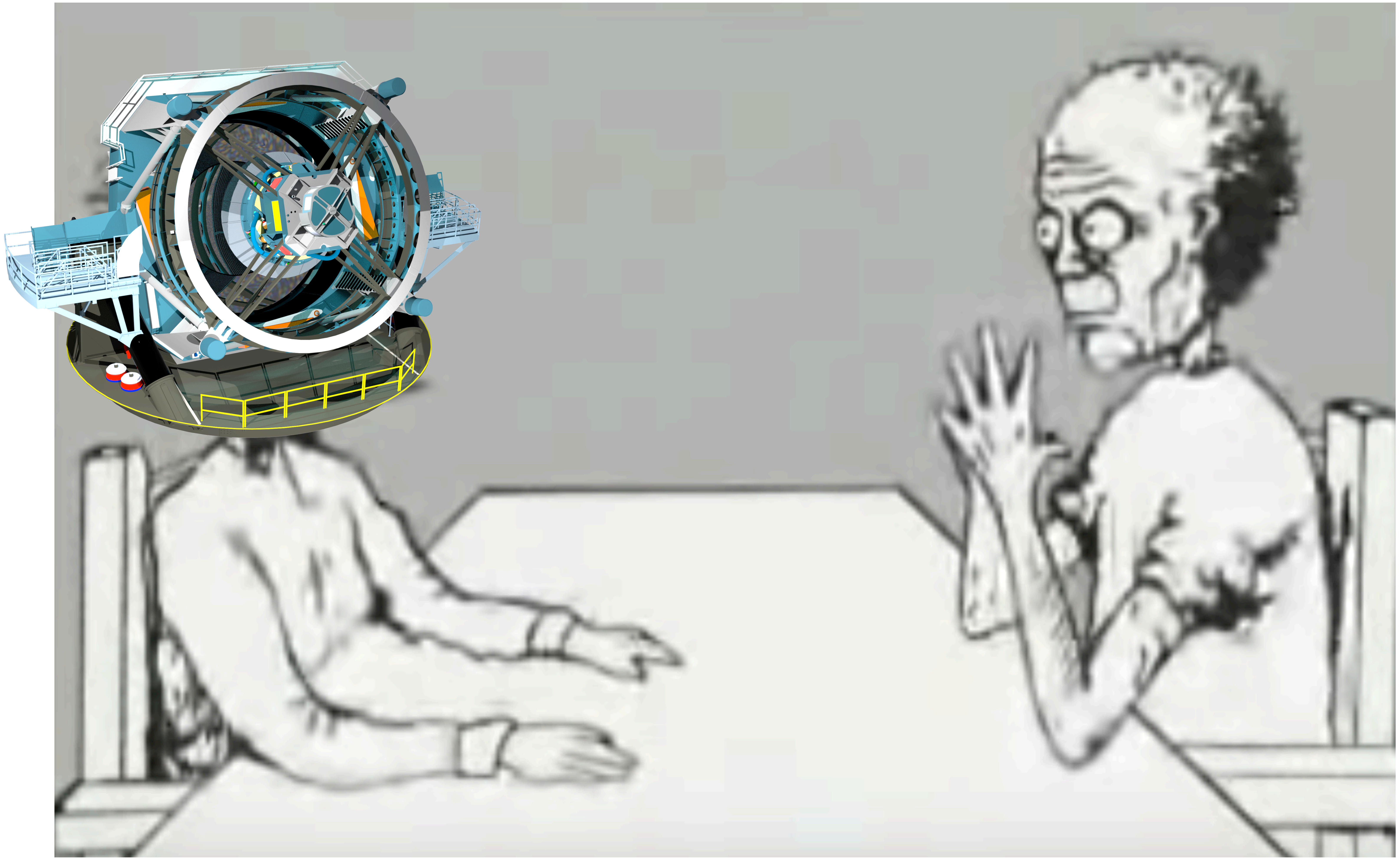


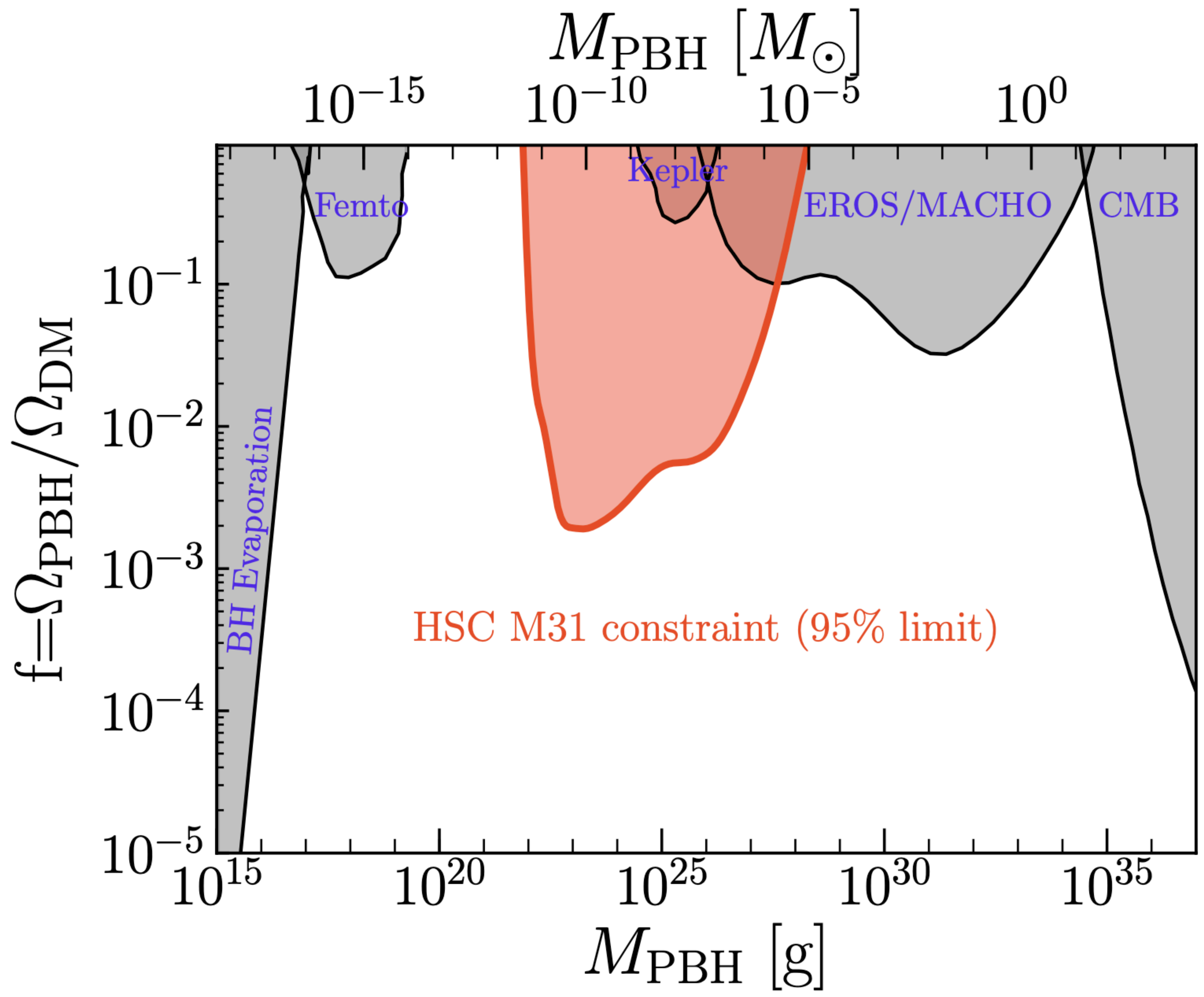
Image source: wiki, Big Train Sketch show

MACHO Constraints

MACHOs live in the HALO, so best to look **through** milky way halo at sources **away** from the noisy milky way disk.

EROS-2/MACHO surveys looked towards LMC, Subaru/HSC towards M31.

Constrain CDM fraction at 10% and 0.1% level in respective sensitive mass ranges
= sensitivity to transition time scale



1803.09205
Calcino, Garcia-Bellido, Davis

1701.02151, Hiroko et al.

Vera Rubin Telescope

Legacy Survey of Space and Time (LSST) observations of Milky Way disk should provide excellent sensitivity to mirror stars in a dark disk!

“We” (Harrison Winch) computed projected sensitivity for both traditional MACHOs* and mirror stars in a dark disk.

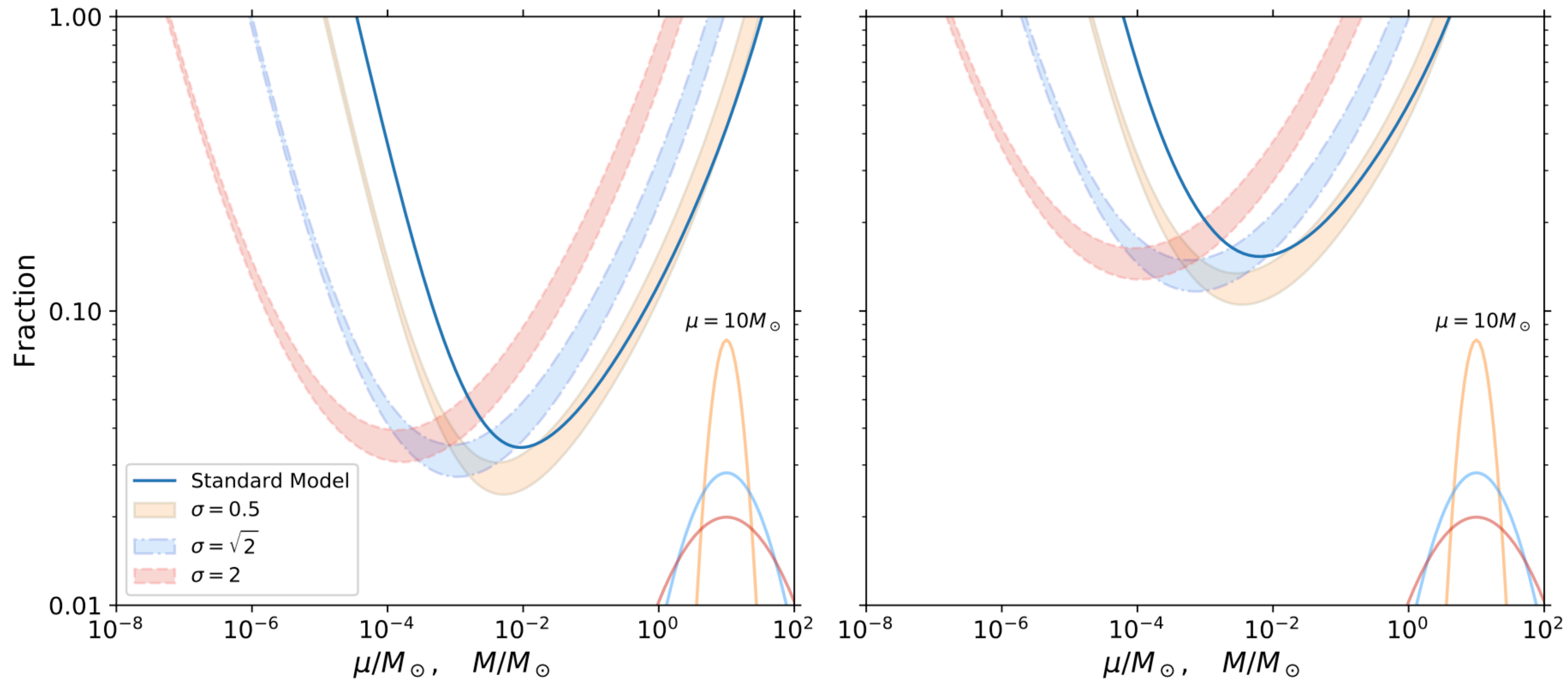
* previous estimates did not take into account

  - full observing runtime
  - baryonic microlensing background rates
  - multiple lines of sight
  - variable lens velocity distributions.

which we include for both MACHOs and MACDOs.

Image source: wiki

How important is unknown Mirror Star Mass Distribution?



1803.09205
Calcino, Garcia-Bellido, Davis

For comparison, the initial mass function (IMF) of SM stars is roughly log-normal with $\sigma \sim 2$ish

Judging from EROS-2/MACHO survey, sensitivity may only be degraded by factor of a few, so that part of uncertainty does not seem prohibitive (away from BGs).

Upshot: If mirror stars make up a per-mille of our MW total mass, Vera Rubin should find them!

Applies for all aDM models, includes aDM-produced black holes!

Equation of State

Need equation of state $P(\rho)$ for mirror nuclear matter.

Assume effective Lagrangian of SM hadrons

$$\mathcal{L} = \bar{\psi}\left[i\,\gamma_\mu\partial^\mu - m_B + \gamma^0\,\mu_B + \gamma_0\,\frac{\tau_3}{2}\,\mu_I - g_\omega\,\omega^\mu\,\gamma_\mu - g_\rho\,\gamma^\mu\,\vec{\rho}_\mu\cdot\frac{\vec{\tau}}{2} + g_\sigma\,\sigma\right]\psi$$
$$+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} - \frac{1}{4}\,\vec{\rho}_{\mu\nu}\cdot\vec{\rho}^{\mu\nu} - \frac{1}{2}m_\sigma^2\,\sigma^2 + \frac{1}{2}m_\omega^2\,\omega^\mu\omega_\mu + \frac{1}{2}\,m_\rho^2\,\rho^\mu\rho_\mu$$
$$-\frac{a_3}{3}\,m_B\,(g_\sigma\,\sigma)^3 - \frac{a_4}{4}\,(g_\sigma\,\sigma)^4 + g_{\omega\rho}\,(g_\omega\,\omega^\mu)^2(g_\rho\,\vec{\rho}^\mu)^2\,,$$

and rescale to mirror sector using known dependence of Λ_{QCD}, m_π on f/v

$$\frac{\Lambda'_{QCD}}{\Lambda_{QCD}} \approx 0.68 + 0.41\log\left(1.32 + \frac{f}{v}\right) \qquad m'_\pi \propto \sqrt{m'_q\Lambda'_{QCD}}. \qquad m_{q'} = \frac{f}{v}m_q$$

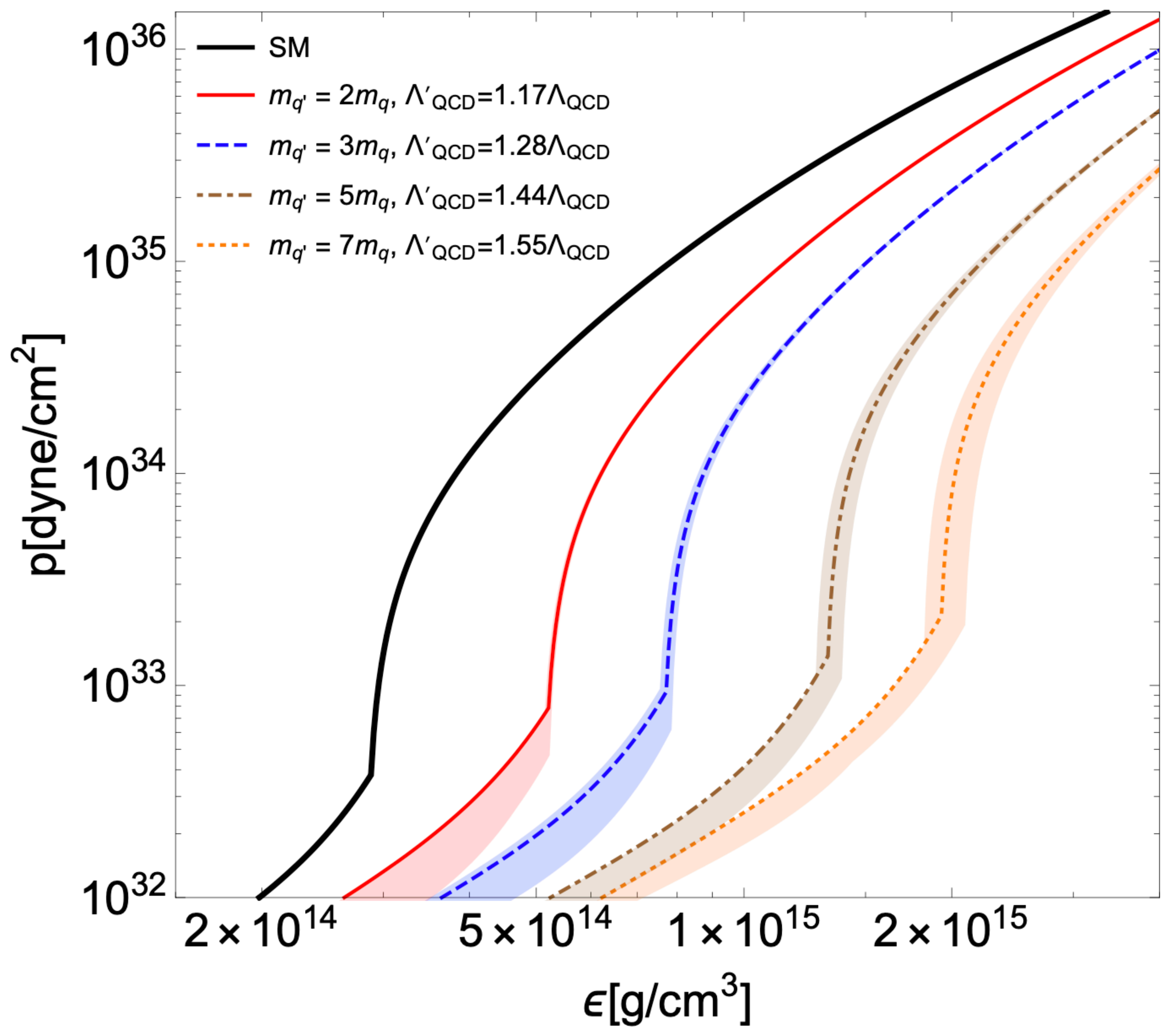
2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes

Recycling Lattice QCD Data

How to rescale? Use Lattice QCD, which routinely presents results for different m_π!

$$\frac{m'_i}{\Lambda'_{QCD}} = b_0 + b_1\left(\frac{m'^2_\pi}{\Lambda'^2_{QCD}}\right) + b_2\left(\frac{m'^2_\pi}{\Lambda'^2_{QCD}}\right)^2 + \dots,$$

Particle	Parameters	SM Value	Mirror pion mass scaling, Eqn (13) b_0	b_1	b_2	Source
π	f_π	92.07 ± 0.85 MeV [94]	$0.094^{+0.005}_{-0.005}$	$0.067^{+0.011}_{-0.011}$	$0.06^{+0.10}_{-0.10}$	[35, 112]
n, p	m_B	938.9 ± 0.6 MeV[a] [94]	$0.933^{+0.003}_{-0.006}$	$1.82^{+0.12}_{-0.09}$	$-1.35^{+0.25}_{-0.35}$	[35, 113–115]
σ	m_σ	400–550 MeV [94]	$0.408^{+0.012}_{-0.001}$	$2.42^{+0.40}_{-0.07}$	$-11.0^{+0.2}_{-6.6}$	[36, 116, 117]
	g_σ	7.95[b]	$g_\sigma \propto m_B/f_\pi$[c]			[34, 118, 119]
	a_3	0.0036[b]	Kept constant.[d]			—
	a_4	0.0059[b]	Kept constant.[d]			—
ω	m_ω	782.65 ± 0.12 MeV [94]	$0.773^{+0.015}_{-0.010}$	$0.573^{+0.120}_{-0.028}$	$0.659^{+0.004}_{-0.411}$	[120]
	g_ω	9.23[b]	$g_\omega \propto g_\rho$			—
ρ	m_ρ	775.26 ± 0.25 MeV [94]	$0.746^{+0.017}_{-0.013}$	$0.659^{+0.120}_{-0.028}$	$0.653^{+0.007}_{-0.391}$	[37]
	g_ρ	39.19[b]	$g_\rho \propto m_\rho/(\sqrt{2}\, f_\pi)$[e]			[37, 121, 122]
	$g_{\omega\rho}$	0.2[b]	Kept constant.[d]			—
e^-	m_e	0.511 MeV[f] [94]	$m_e \propto m_q$			—
μ^-	m_μ	105.658 MeV[f] [94]	$m_\mu \propto m_q$			—



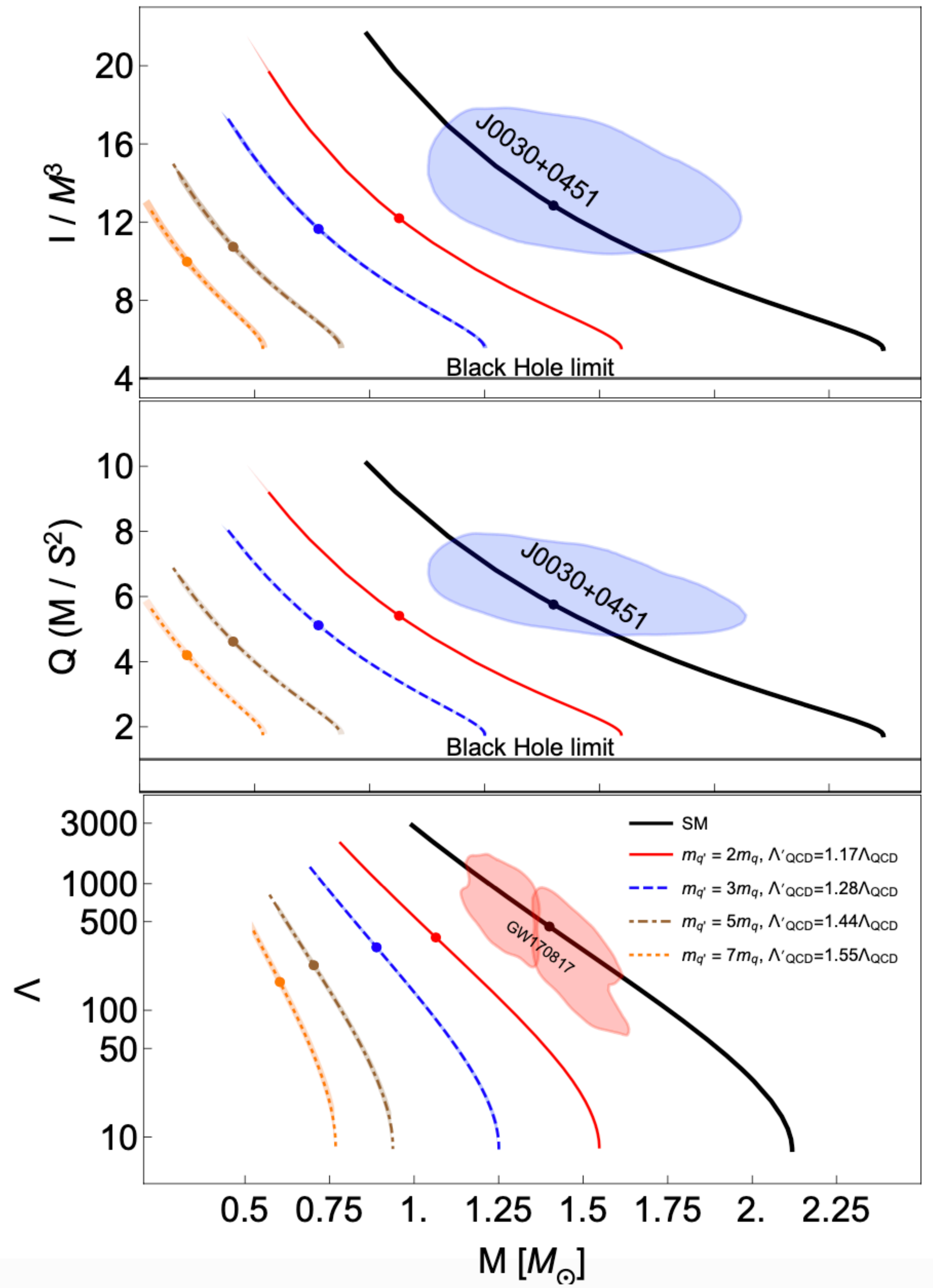
Gives mirror QCD equation of state!

2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes

Mirror Neutron Star Properties

Solving to 2nd order in angular momentum gives moment of inertia, quadrupole moment and Love number of mirror neutron stars.

Distinct from SM neutron stars, but still obeying certain universality relations that makes it easier for standard aLIGO analyses to pick up the signal.



2103.01965 Hippert, Setford, Tan, DC, Norona-Hostler, Yunes

Can also detect and distinguish SM-mirror hybrids!

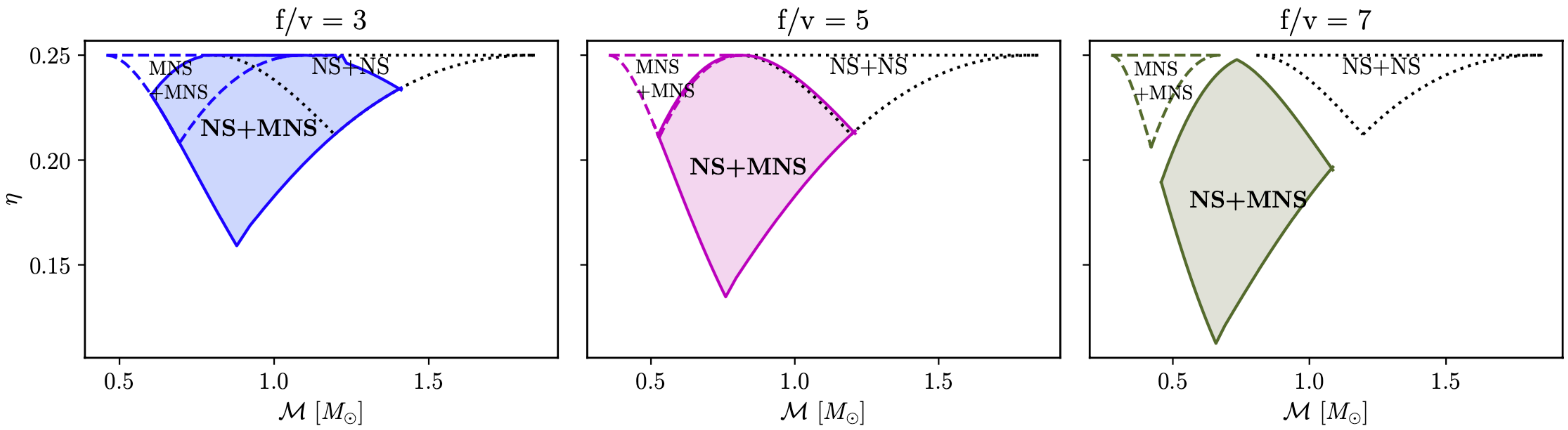
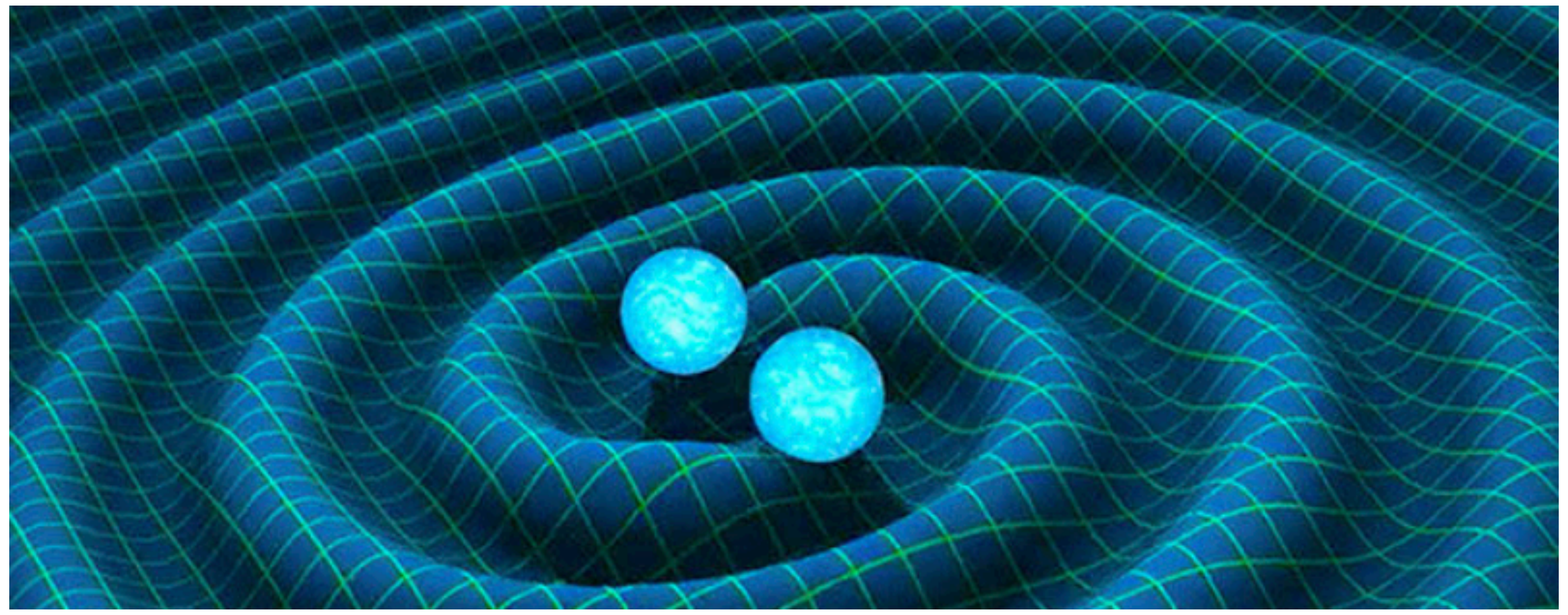


FIG. 13. Symmetric mass ratio η vs. chirp mass $\mathcal{M}$ of binary systems for three different values of f/v. The shaded region enclosed by solid lines corresponds to binaries composed of one NS and one MNSs, while the region delimited by dashed lines corresponds to binaries of two MNSs. For reference, we also show the region corresponding to SM NS binaries, delimited by the black dotted lines.

2211.08590 Hippert, Dillingham, Tan, DC, Norona-Hostler, Yunes

Upshot



Mirror neutron stars in mergers can be distinguished from both black holes and SM neutron stars!

For Mirror Twin Higgs, early and late inspirals are still in aLIGO sensitivity band.

Detection would provide unique information about hidden sector QCD.

Mirror neutron star merger rate is even harder to predict than mirror star distribution, but future GW sensitivity for NS mergers will include most of the observable universe. If they exist, excellent chance of hearing them!

Electromagnetic Signature

What we see is not the mirror star, but the captured nugget of interstellar SM matter!

Two signals:

1) thermal emissions at $T_{nugget} \sim \mathcal{O}(10^4\text{K})$, characteristic of a given amount M_{nugget} of SM gas in gravitational potential set by ~ constant core density ρ_{core} of mirror star.

2) Mirror-conversion X-ray signal that reveals mirror star core temperature T_{core}.

Optical/IR emissions are mostly determined by three parameters:

- heating rate $\zeta(\epsilon, T_{core}, m_{N'})$
- size of nugget M_{nugget}
- mirror star ρ_{core}

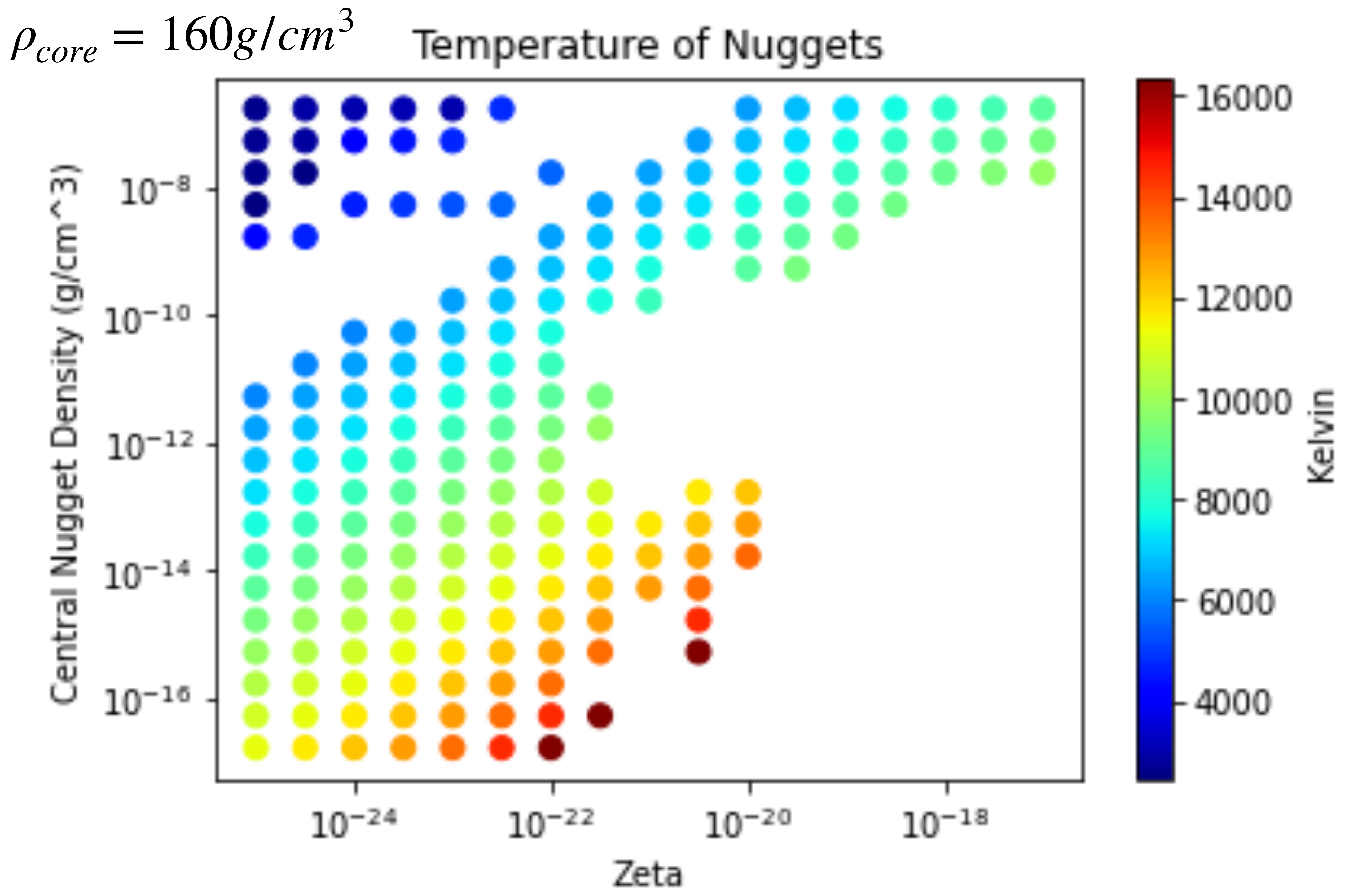
Size of nugget M_{nugget} depends on capture rate, i.e.

- kinetic mixing ϵ
- mirror star size (mostly just mass)
- mirror star age

Optically thin nuggets in Cloudy

For each ζ, ρ_{core} of mirror star, solve for hydrostatic optically thin nugget with M_{nugget}.

EARLY PREVIEW: $\rho_{core} = 160 g/cm^3$ slice of param space, **pure-H nugget**.

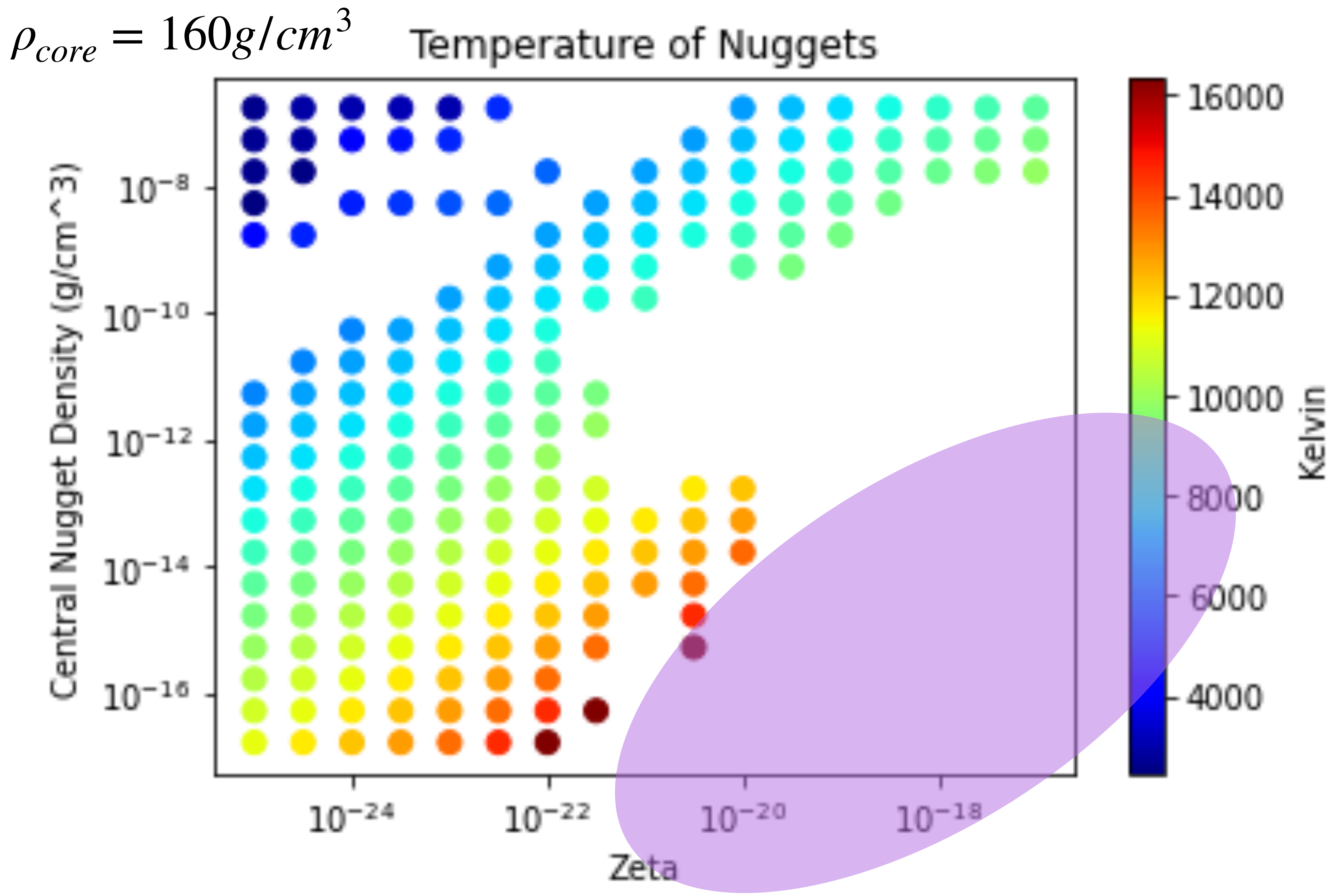


[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Optically thin nuggets in Cloudy

For each ζ, ρ_{core} of mirror star, solve for hydrostatic optically thin nugget with M_{nugget}.

EARLY PREVIEW: $\rho_{core} = 160 g/cm^3$ slice of param space, **pure-H nugget**.



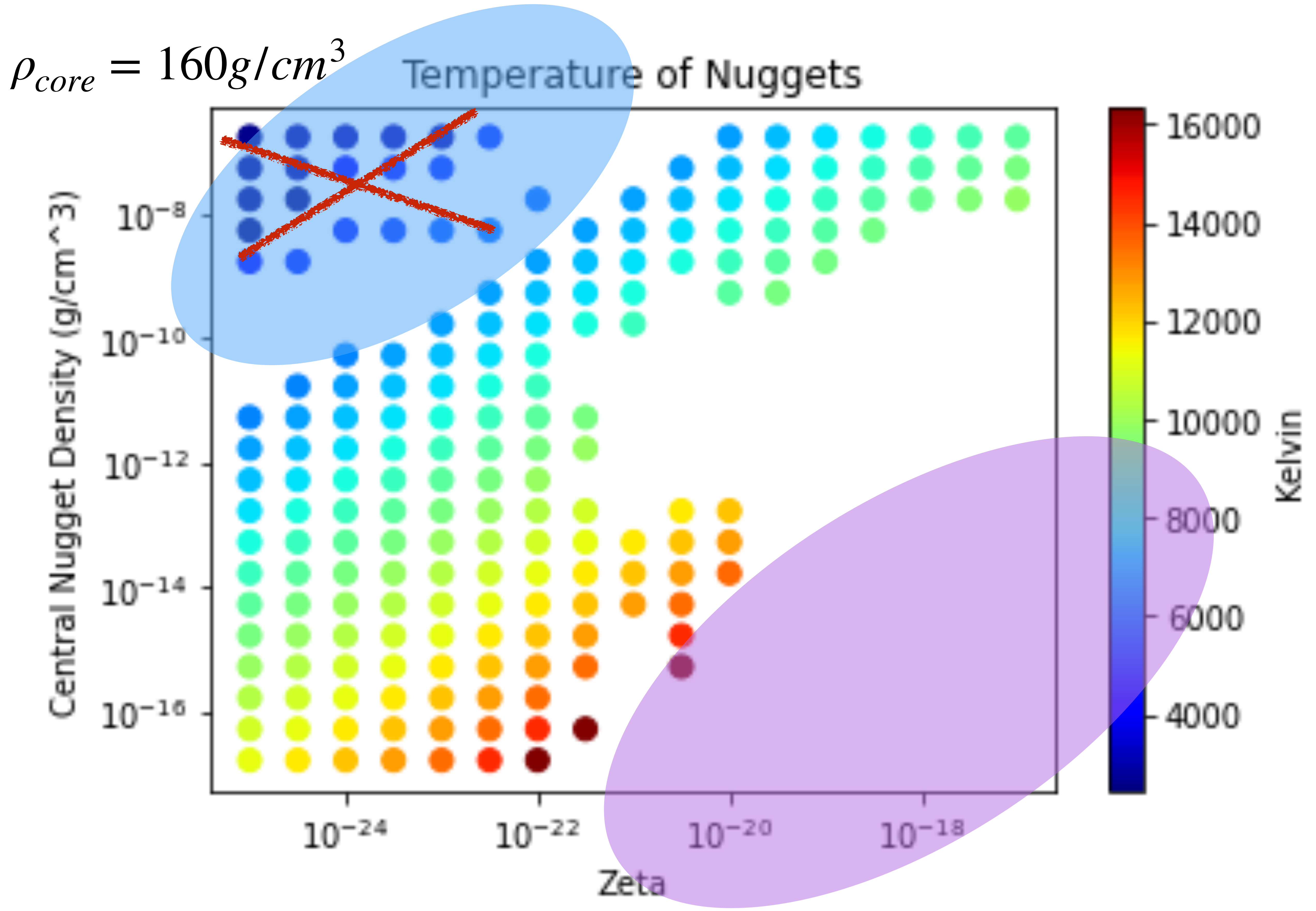
*Very low-mass nuggets cannot cool effectively and are **thermally unstable** (realistic size given by size of mirror star core region). Transient early accumulation regime.*

[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Optically thin nuggets in Cloudy

For each ζ, ρ_{core} of mirror star, solve for hydrostatic optically thin nugget with M_{nugget}.

EARLY PREVIEW: $\rho_{core} = 160 g/cm^3$ slice of param space, **pure-H nugget**.



*These points are numerical artifacts. Up here the nuggets start becoming **optically thick**.*

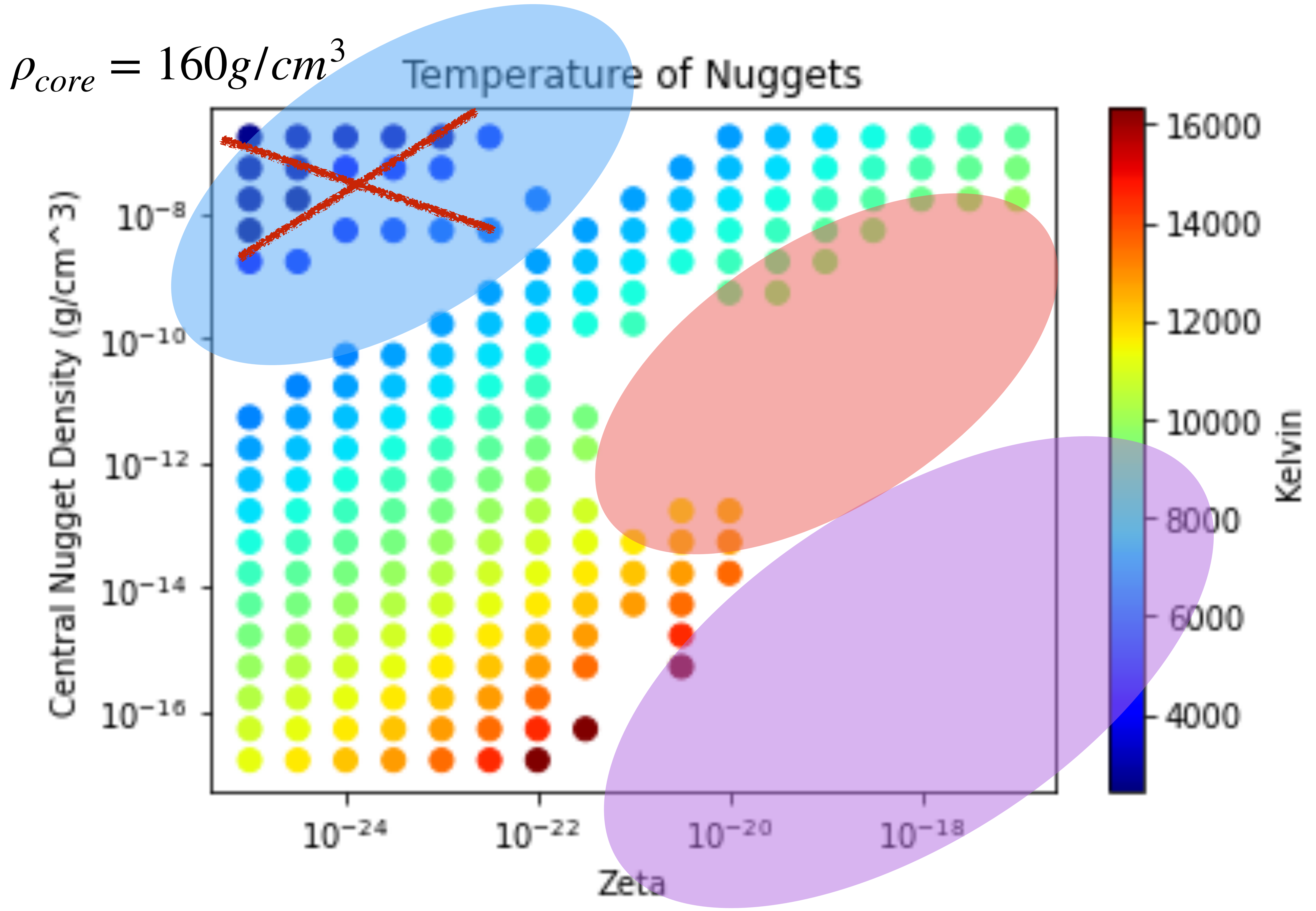
*Very low-mass nuggets cannot cool effectively and are **thermally unstable** (realistic size given by size of mirror star core region). Transient early accumulation regime.*

[in progress] **Isabella Armstrong, Berkin Gorbuz**, David Curtin, Chris Matzner

Optically thin nuggets in Cloudy

For each ζ, ρ_{core} of mirror star, solve for hydrostatic optically thin nugget with M_{nugget}.

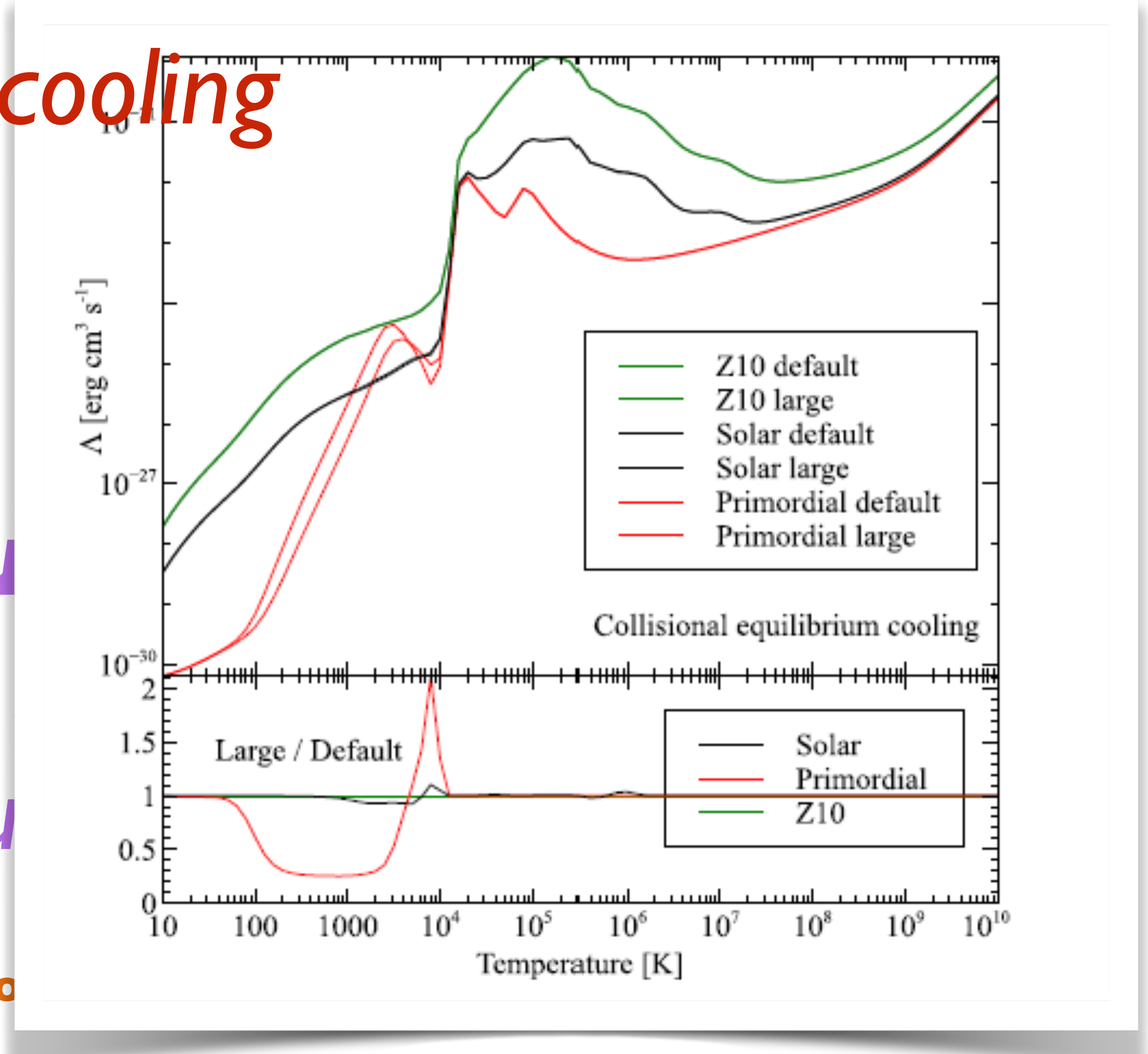
EARLY PREVIEW: $\rho_{core} = 160g/cm^3$ slice of param space, **pure-H nugget**.



These points are numerical artifacts. Up here the nuggets start becoming ***optically thick****.*

Not sure what's happening here yet.
May be associated with transition between atomic and molecular cooling

Very low-mass nuggets
and are ***thermally u***
given by size of mirror
Transient early accumu



[in progress] **Isabella Armstro**