# Stellar Evolution as a Probe for Light Dark Matter Particles

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Summer 2024 REU
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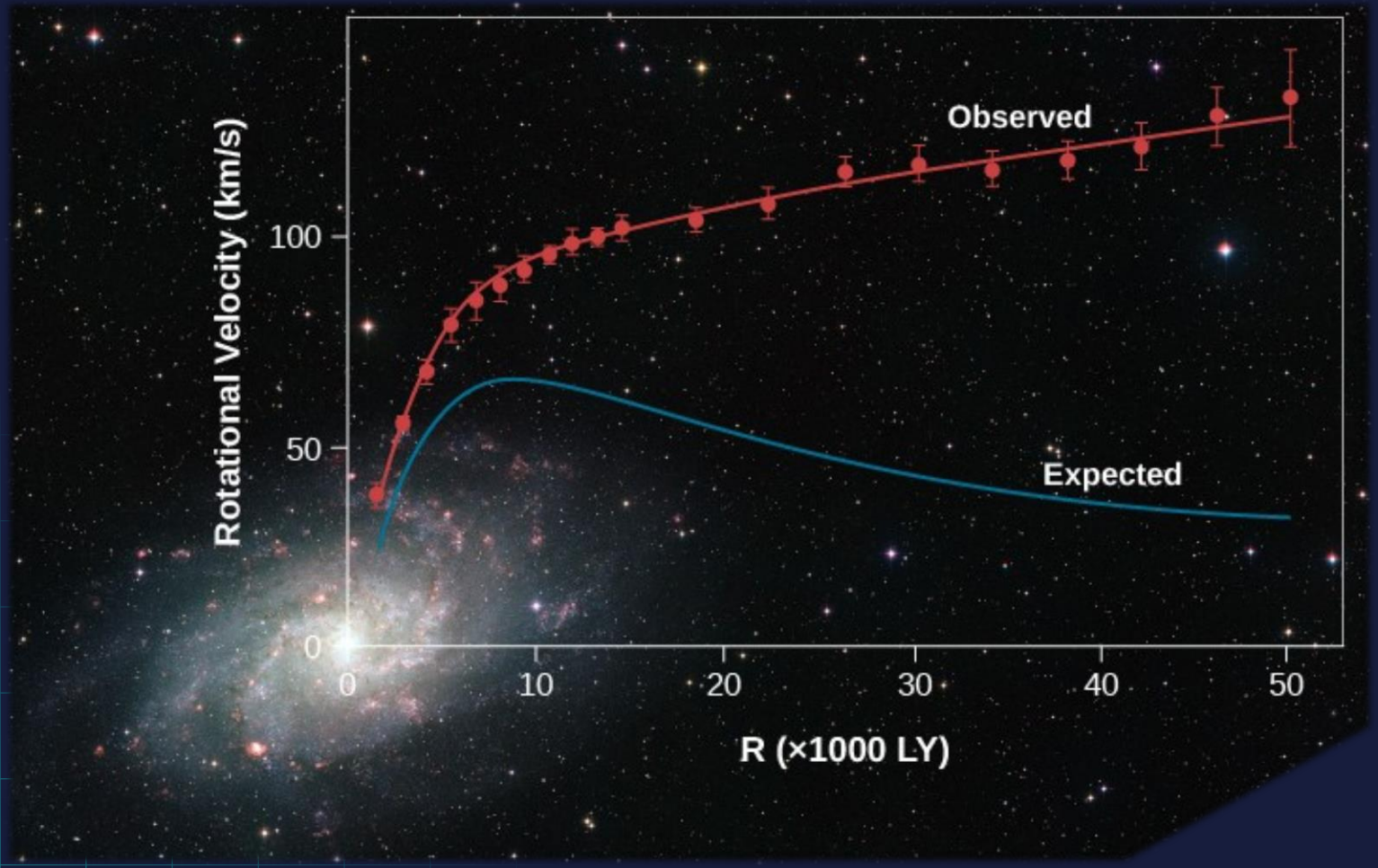
# Why is dark matter necessary?






**Virial Theorem**

- Friz Zwicki - 1933

**Rotation Curves**

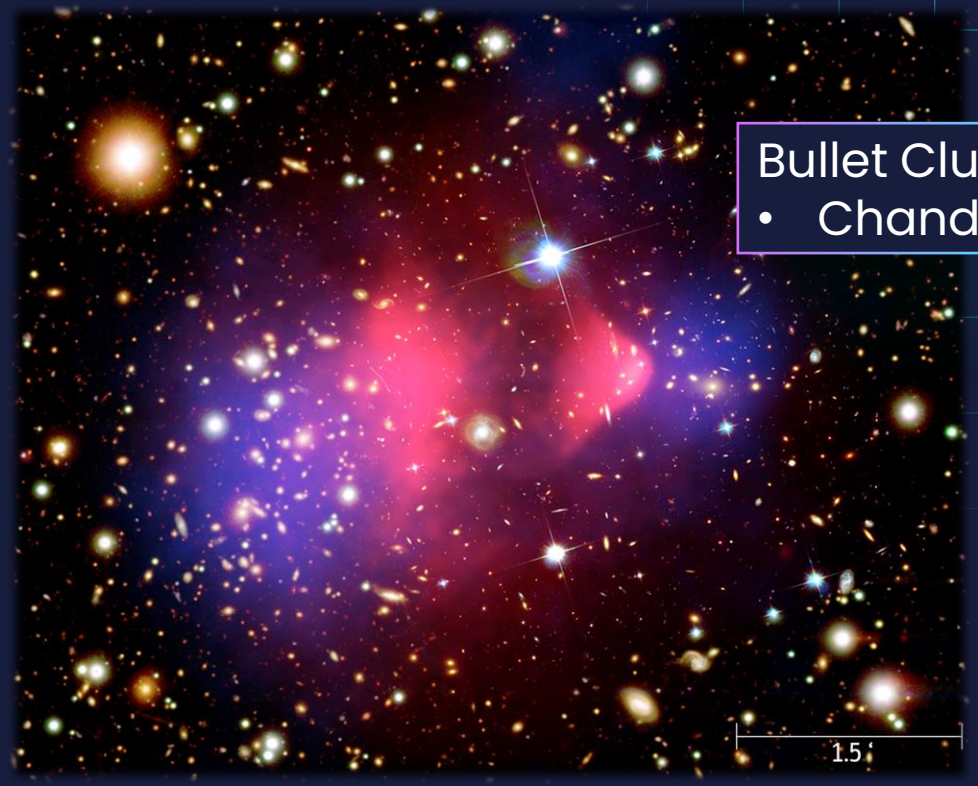
- Horace Babcock - 1939
- Vera Rubin – 1970s

$$\langle T \rangle = -\frac{1}{2}\langle U \rangle$$

# Why is dark matter necessary?

Gravitational Lensing
- 1980s – Now

Gravitational lensing. (n.d.). HubbleSite.

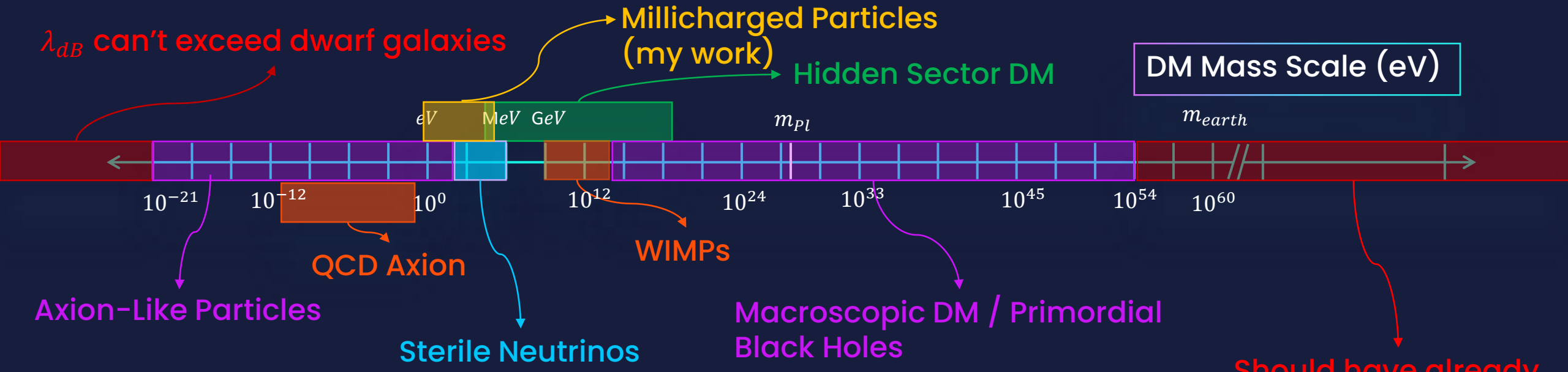



Bullet Cluster Merger
- Chandra (2006)

X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al

Early Structure Formation
- Radiation pressure prevents early structure formation

# Dark Matter Candidates?




Arguments from naturalness point to:

- WIMPs
- QCD Axions

## Is it time for a different approach?

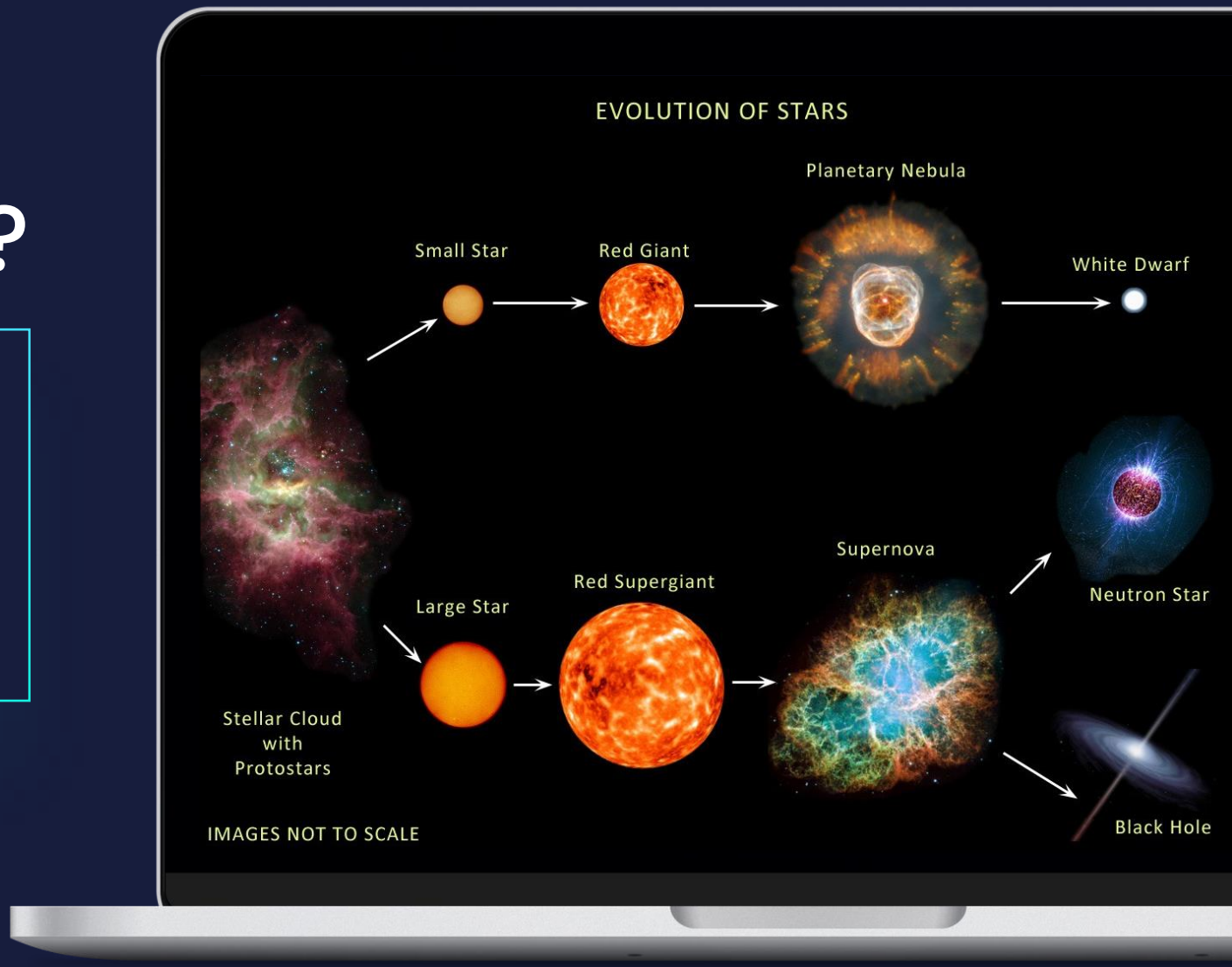
# How can we use Stellar Evolution to Probe Dark Matter?

**Indirect Detection at Population Level:**

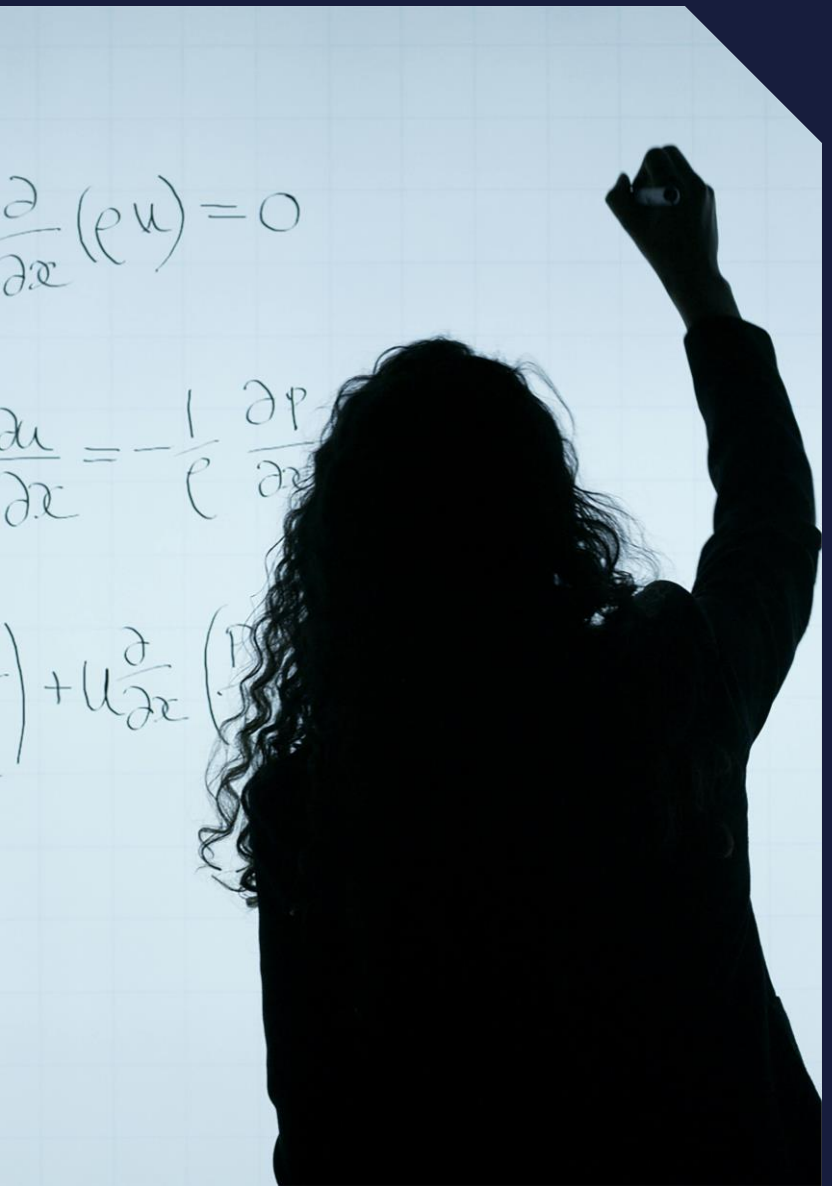
- White Dwarf Cooling
- Helium Flash
- Horizontal Branch and Cepheid Variable Stars

Raffelt, Georg G. Stars as laboratories for fundamental physics: The astrophysics of neutrinos, axions, and other weakly interacting particles. University of Chicago press, 1996.

## Ground Up Approach



# What is my role?



- Learn to Write Down a Model for Light DM Interactions
- Run Stellar Evolution Simulations
- Check Model Predictions Against Data
- Constrain Light DM Properties

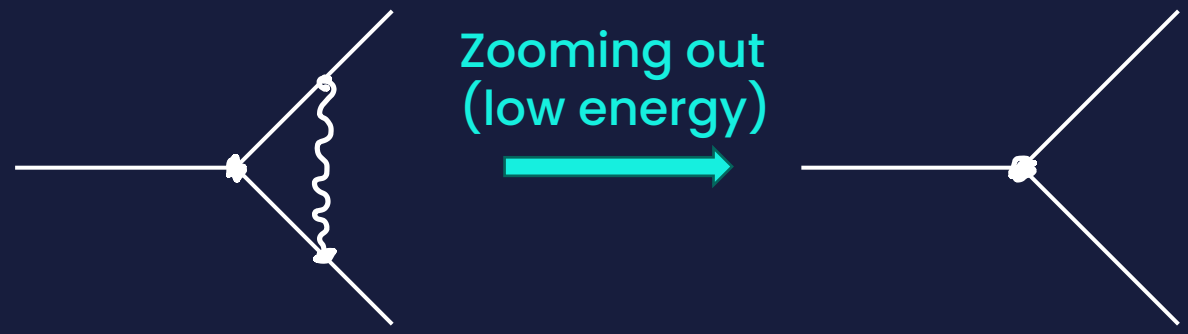
# What is an effective model?

- ✓ Extension of the Standard Model Lagrangian
- ✓ Effective Interaction Term
- ✓ Applicable below some energy scale

# What does an interaction term look like?

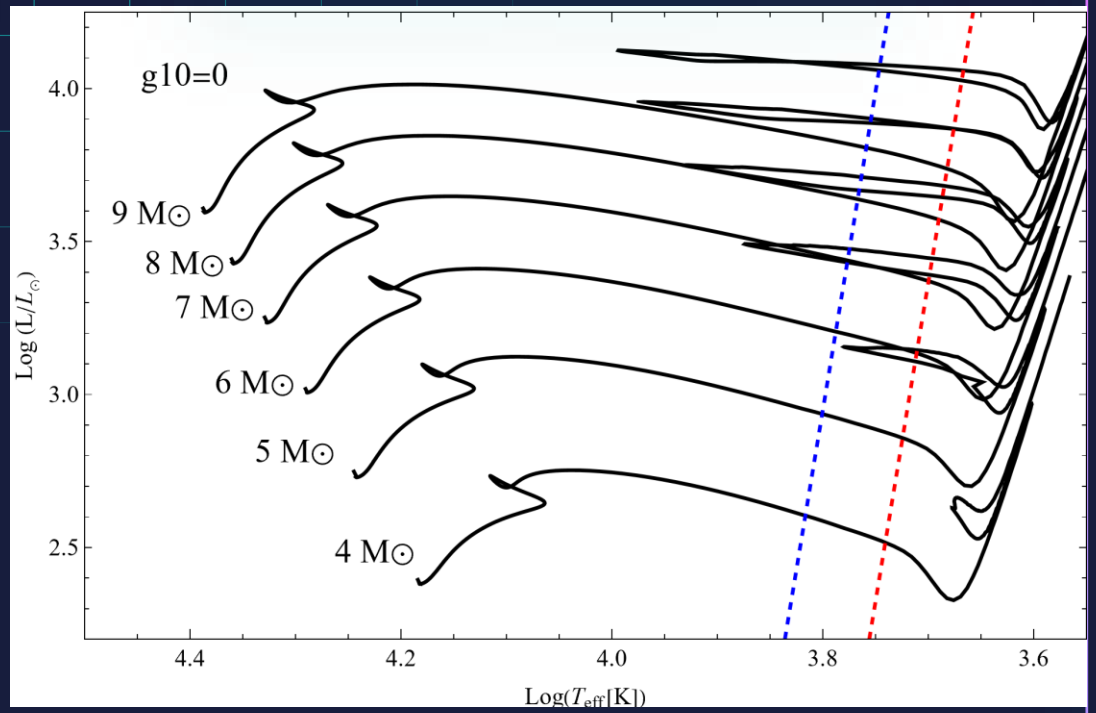
$$\mathcal{L}_{int,axion} \supset -ig\bar{\psi}_e\gamma_5\psi_e\phi$$

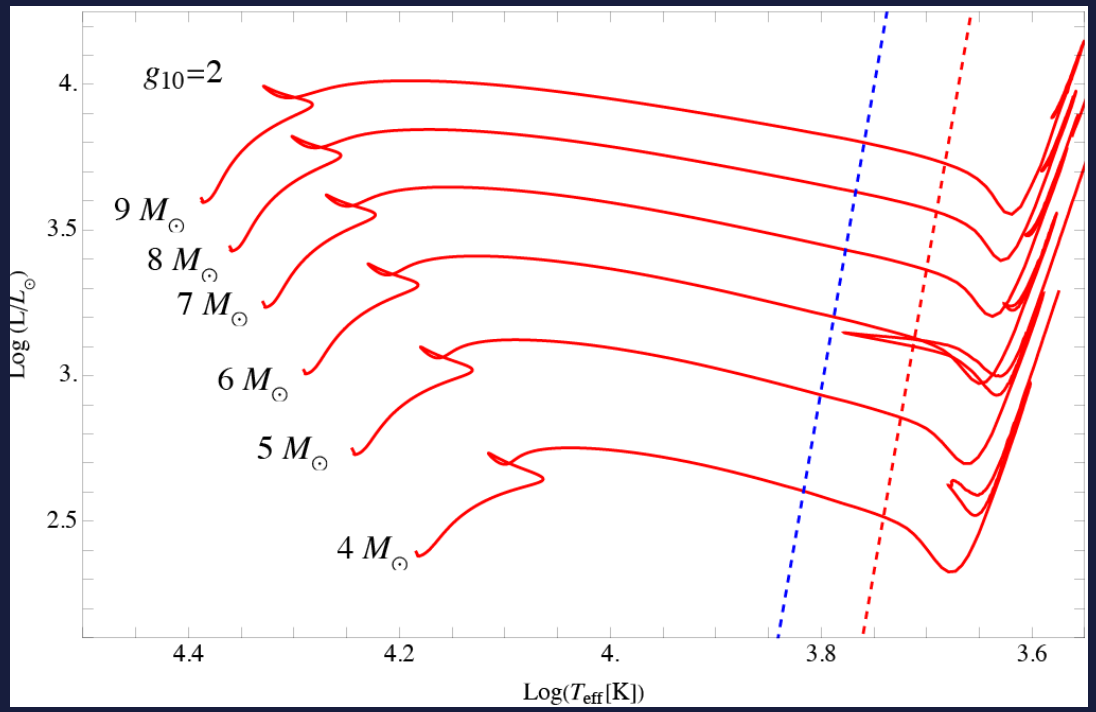
- Three or more fields
- Coupling is related to the energy cutoff scale



# Axion Constraints from Cepheid Variable Stars

Current work by Dr. Sinha's group, and specifically TJ German




$$\mathcal{L}_{int} \supset -ig_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

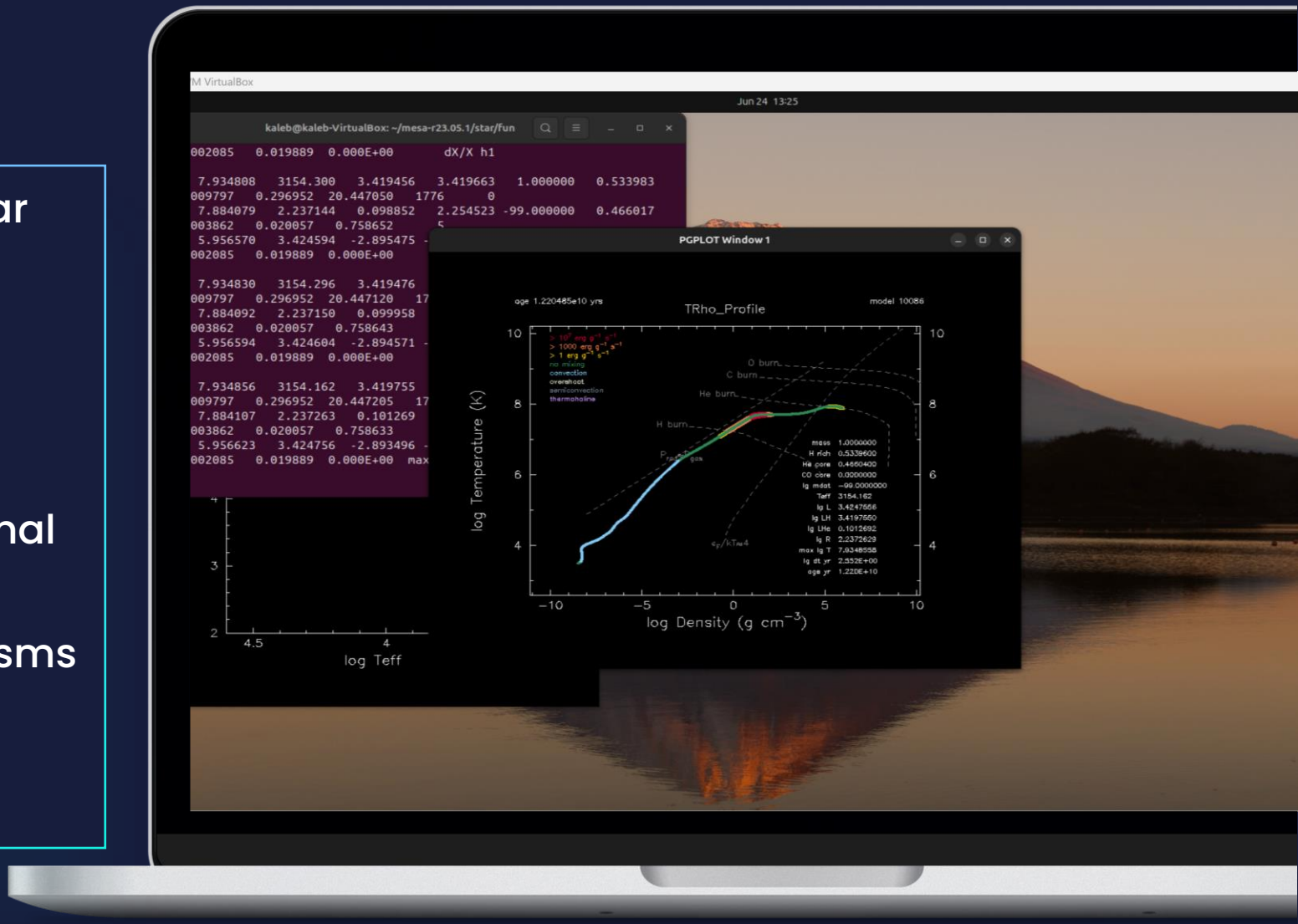
Sufficient energy loss would prevent the increase in temperature that occurs during helium burning

# How is the work accomplished?

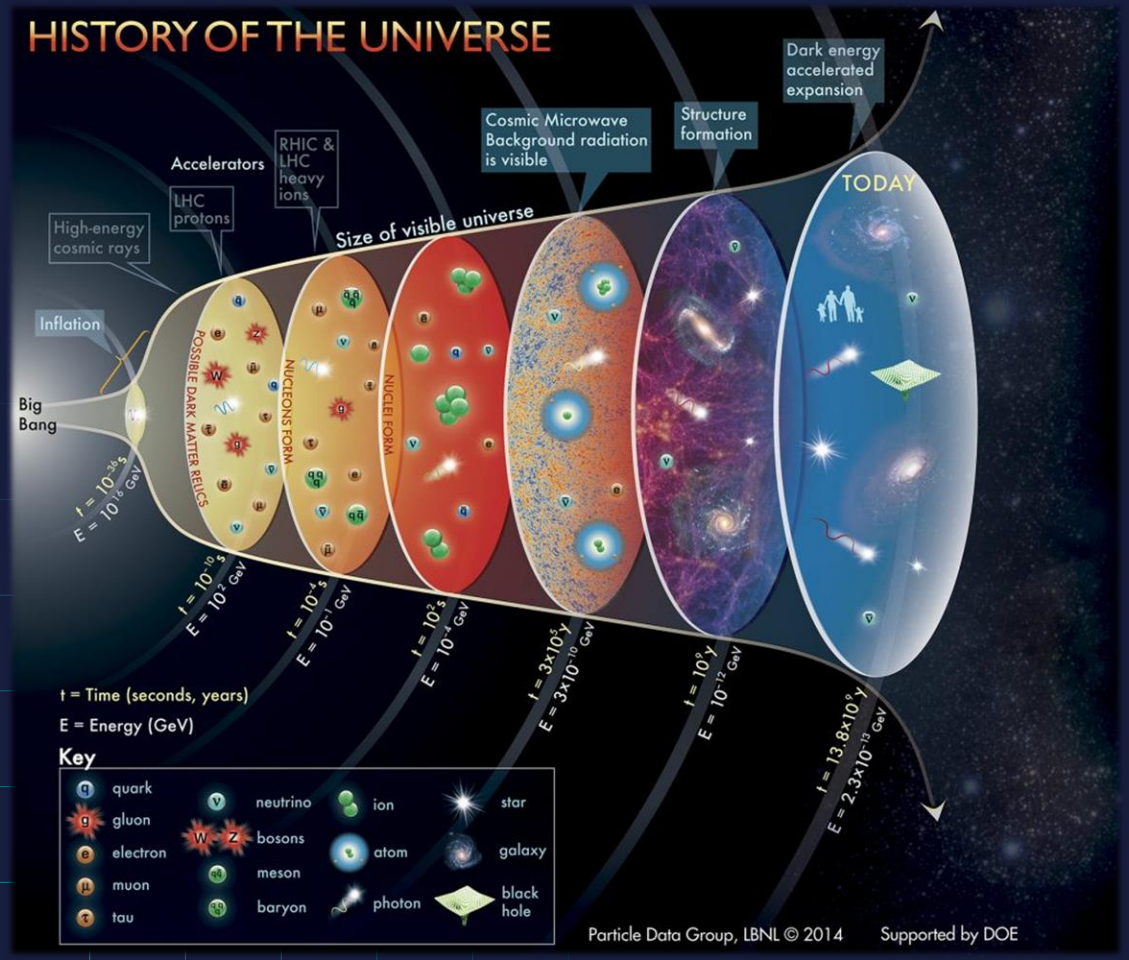
Using Modules for Experiments in Stellar Astrophysics (MESA):

- Work within $4M_{\odot} - 9\,M_{\odot}$
- Match the stellar properties of the desired population
- Extend the model to include additional energy loss mechanisms
- Extend the data collection mechanisms
- Run a simulation
- Vary relevant stellar parameters

The development of MESA was led by Bill Paxton at UC Santa Barbara (one of the founders of Adobe Systems)



# Millicharged Particles ⟶ What are they?




MCPs

- Dark Matter Candidate
- Fermions
- Low-Mass (not ultralight)
- Couple to photons through small fractional charge
- Possibly produced in early universe

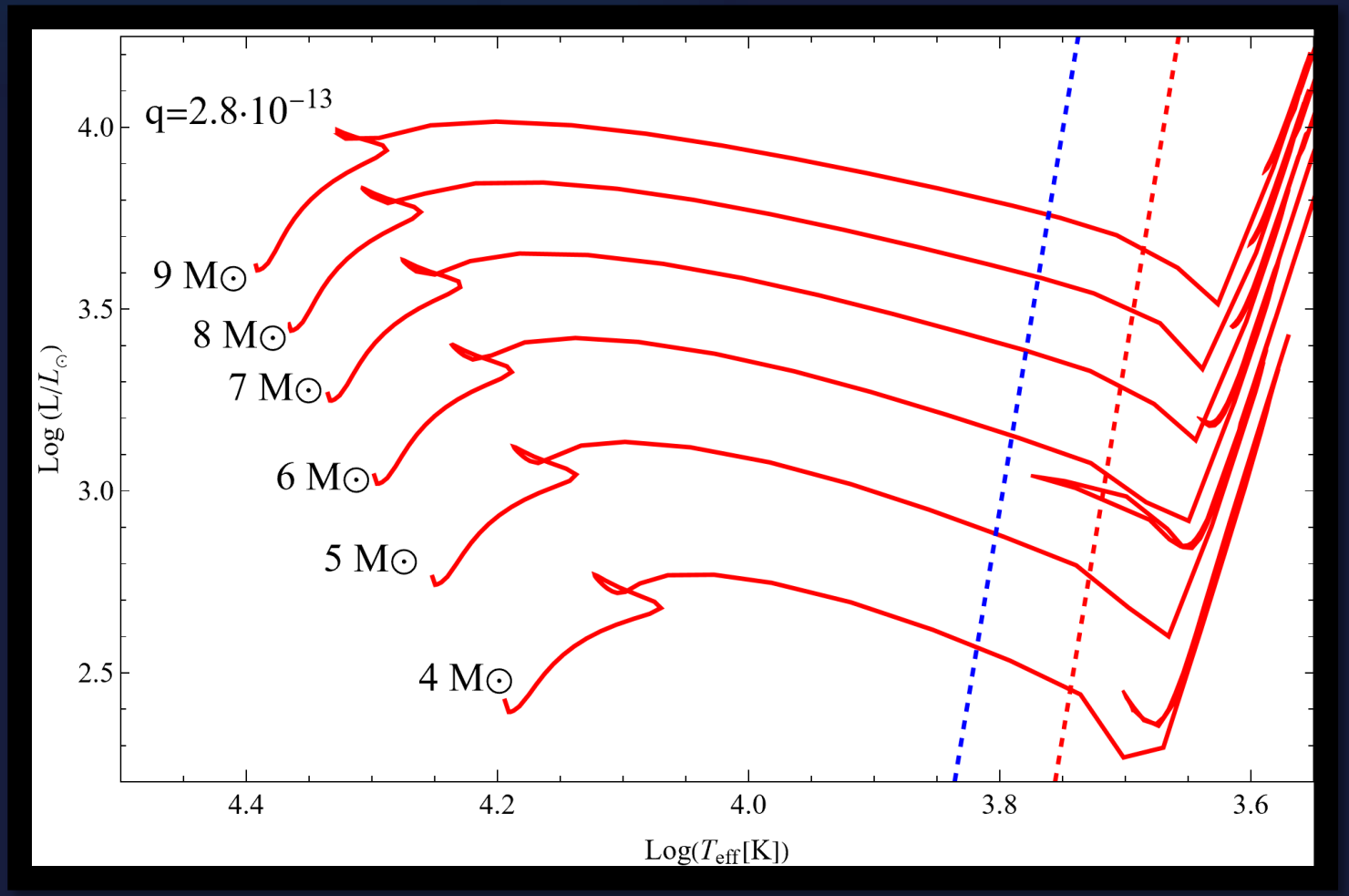
$$\mathcal{L}_{int,mcp} = qe\bar{\chi}\gamma_\mu\chi A^\mu$$

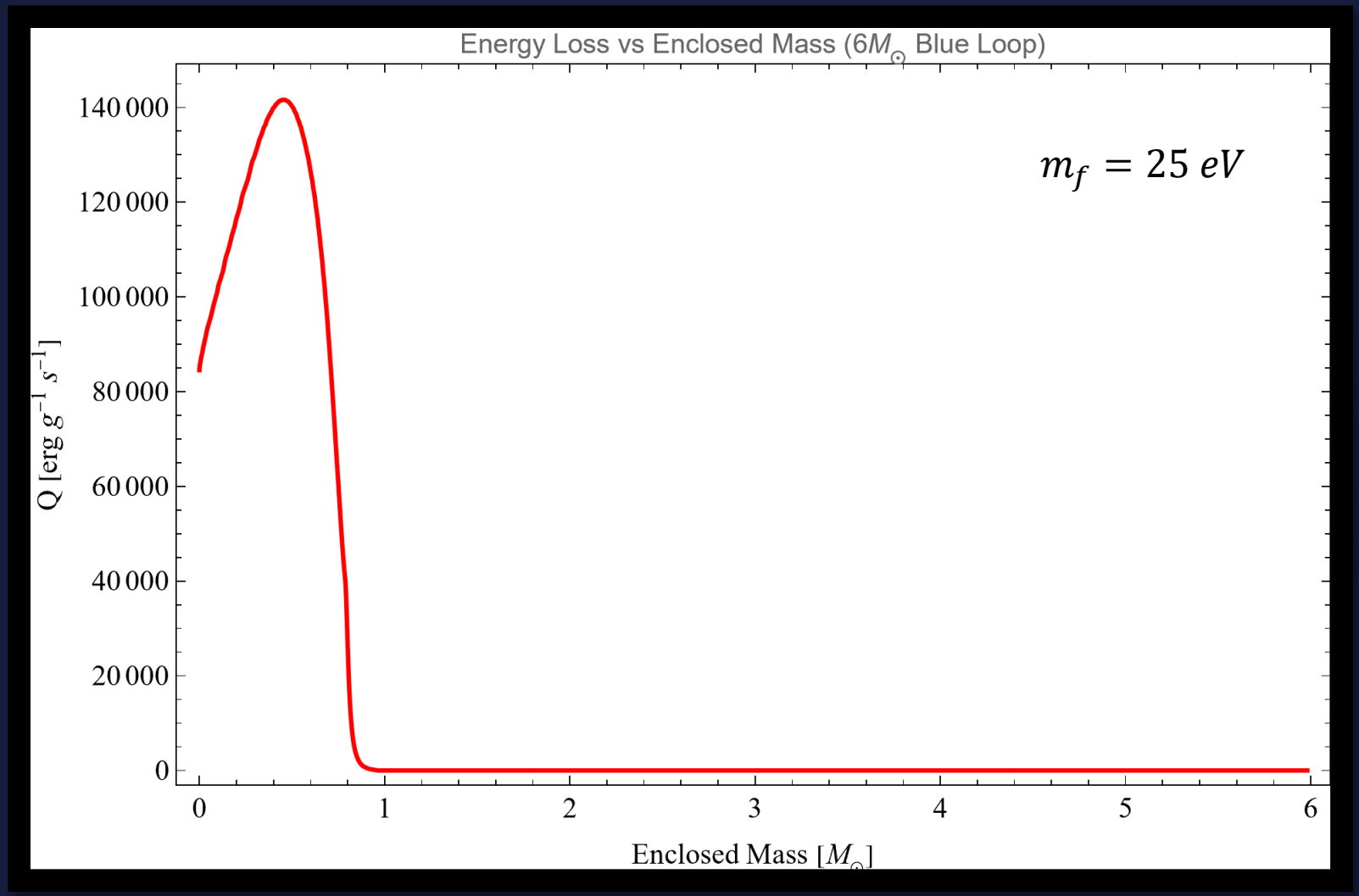
# My Results

Weak Bounds on Light Millicharged Particles

- Extend TJ German's work to millicharged particles
- MCPs produced through the on-shell decay of plasmons
- Relied heavily on work by Fung et al. as well as Vinyoles and Vogel

For this plot, $m_f = 25\ eV$






While off-shell plasmon decays would be suppressed, they could occur throughout the entire star.

Using only $9M_\odot$

| Mass | Weak q bound |
|---|---|
| 10 eV | 2E-13 |
| 25 eV | 2E-13 |
| 50 eV | 2E-13 |
| 100 eV | 2E-13 |
| 1000 eV | No Bound |

# Where are MCPs produced?

# Significance and Implications

Previous limits by Fung et al.

Preliminary results provide weak limits that are an order of magnitude worse than the most competitive bounds.

Cepheid Variable Stars may or may not be competitive with other methods of providing bounds on MCP charge

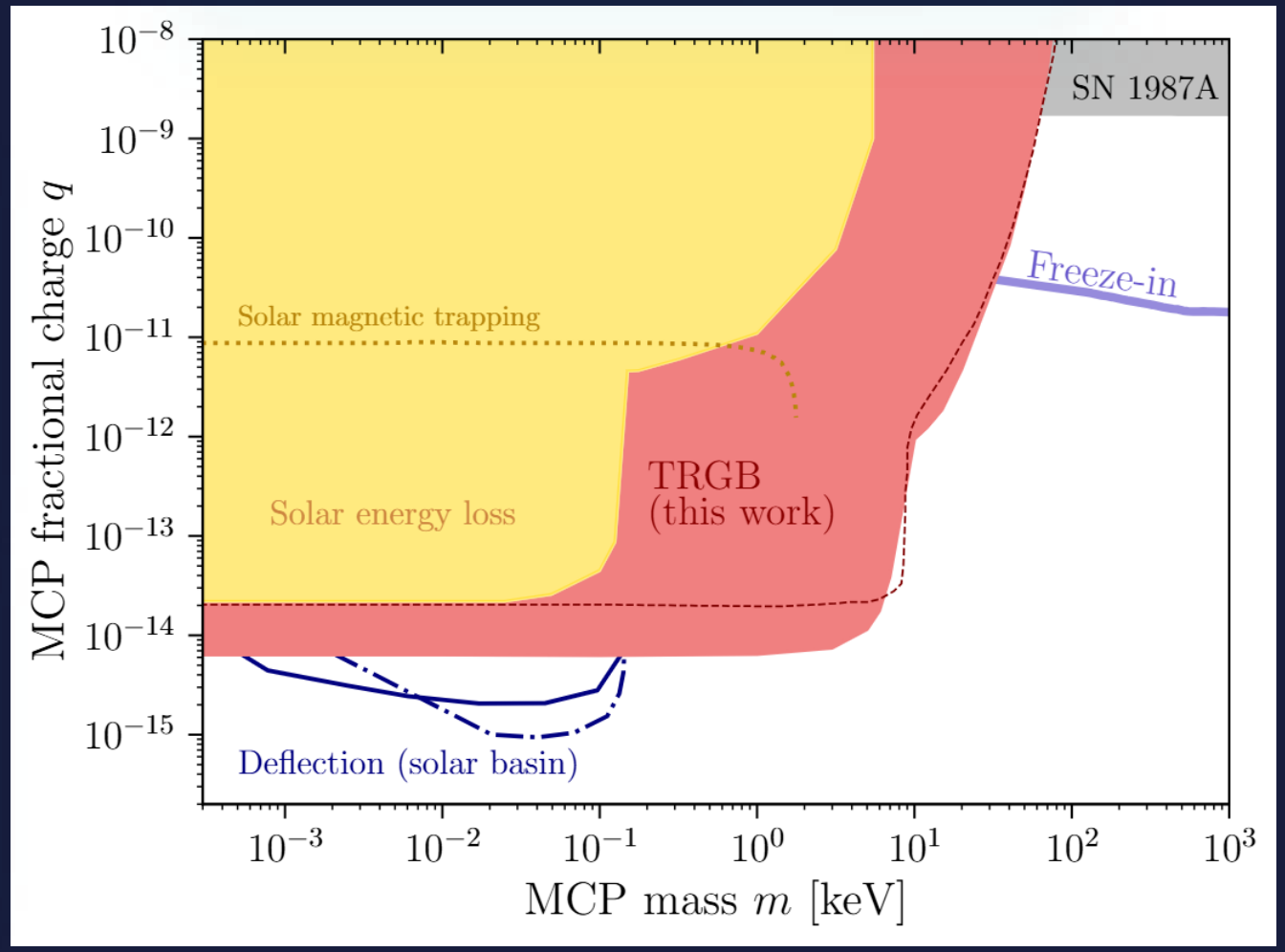
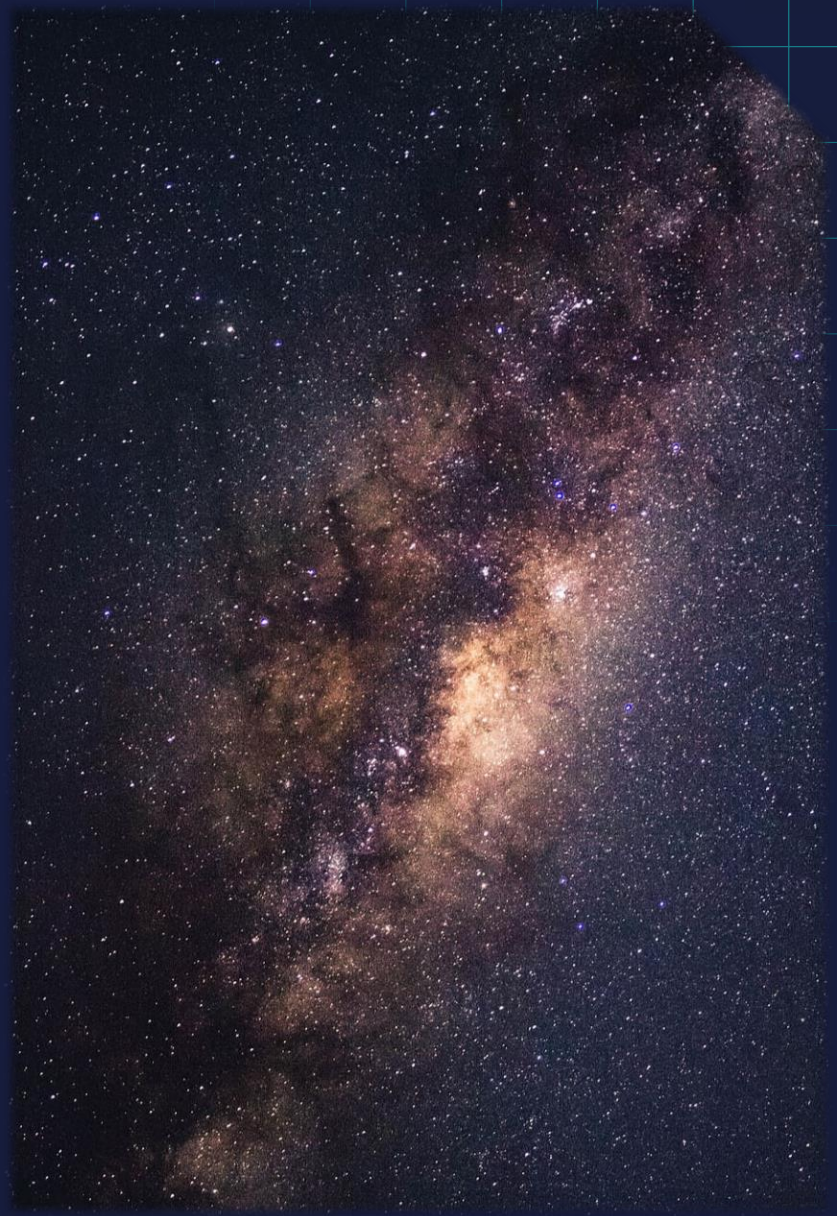



Fig. 1, Fung et al.



# Possible Future Work

- Improve bounds by introducing off-shell production
- Improve bounds through mass loss constraints
- Apply statistical methods
- Extend this work  with MCPs to rotating models
- Attempt alternative methods of constraining MCP properties

# Works Cited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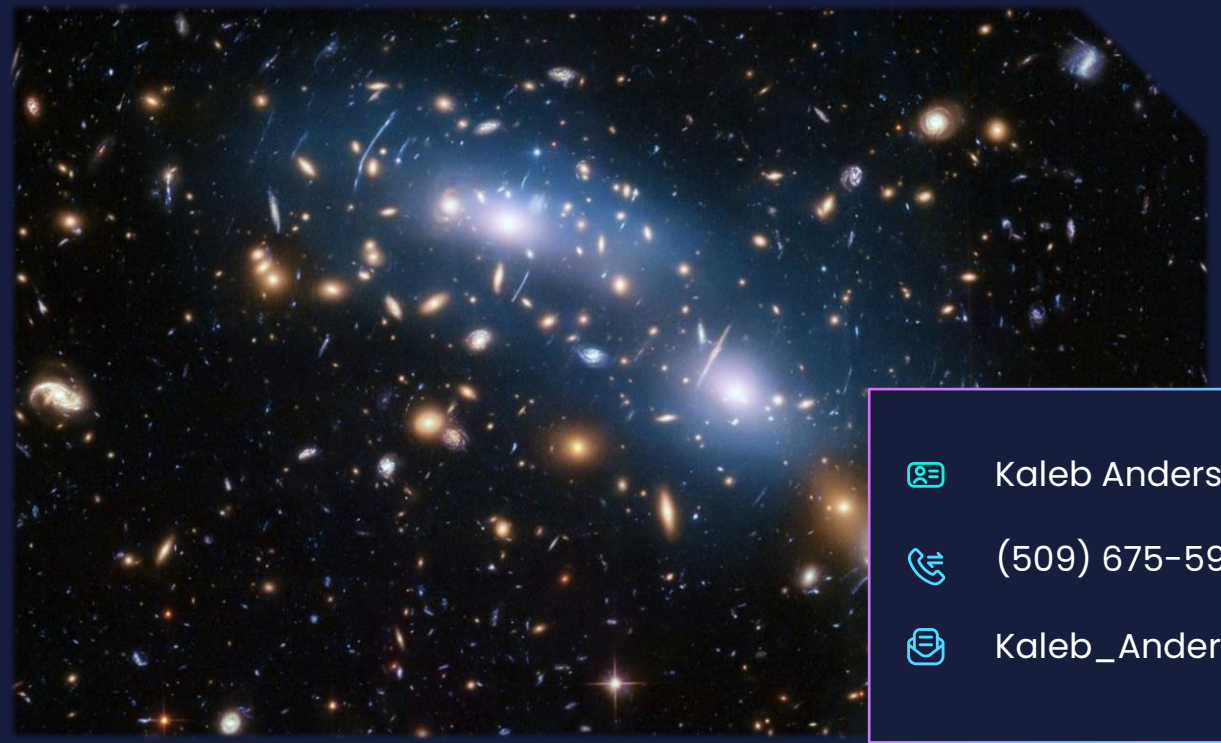
# Thank You for Listening

Please let me know if you have any questions.





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