

# Physics of Stars

Ken Chen, ASIAA



19 - 2013: IAC-CIPIER Fellow, Department of Astrophysics and Astronomy, UC Santa Cruz, USA  
13: Ph.D., Physics, University of Minnesota at Twin Cities, Minnesota, USA

search Interests:

research interest in computational astrophysics focuses on modelling the supernovae explosions.



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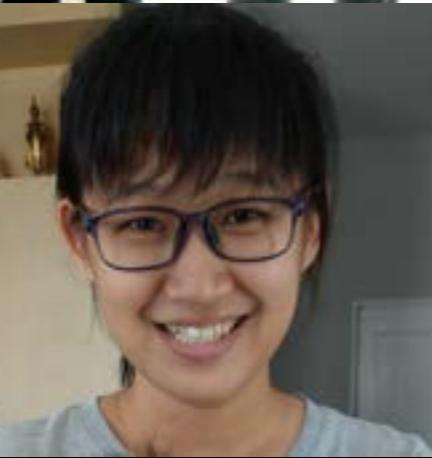
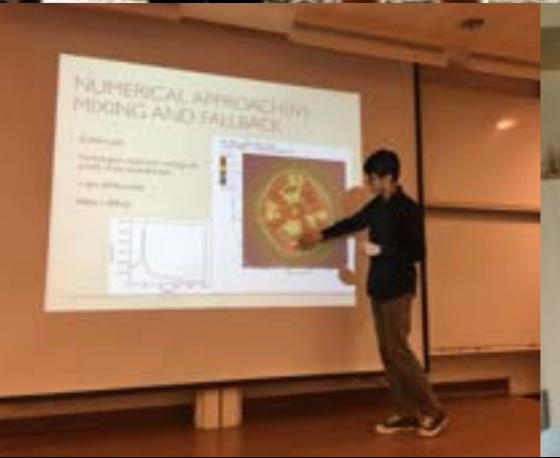
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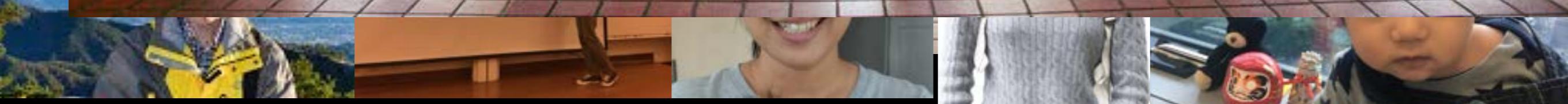


# The Explosion Group at ASIAA

Since Sep. 2018 ~



# The Explosion Group at ASIAA



# 爆炸小組首頁

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Explosion

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# Cosmic Explosion

Ken's Group for Explosive Astrophysics and Cosmology

Get Started



Let's Chat!

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# Motivations

1. Why do we care about stars?
2. How do they form and evolve?



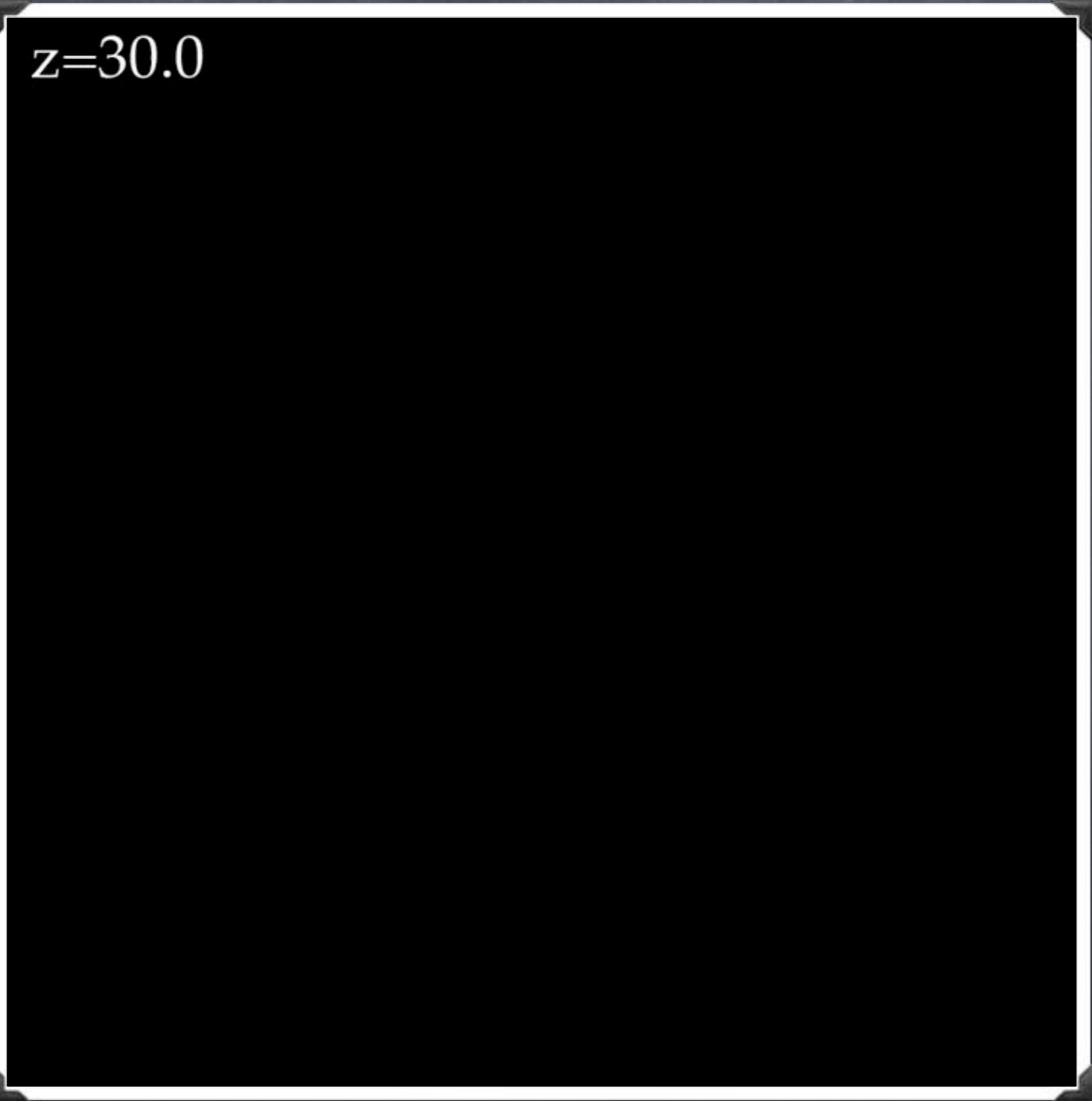




Magnificent Galaxies and Little Stars

# Magnificent Galaxies and Little Stars

z=30.0



# Magnificent Galaxies and Little Stars



# Magnificent Galaxies and Little Stars

## Milky Way Galaxy

About 13.2 billion years old.

200–400 billion Stars, with at least 100 billion Planets, 500 million of which may support Life

125,000 Light Years  
in Diameter.

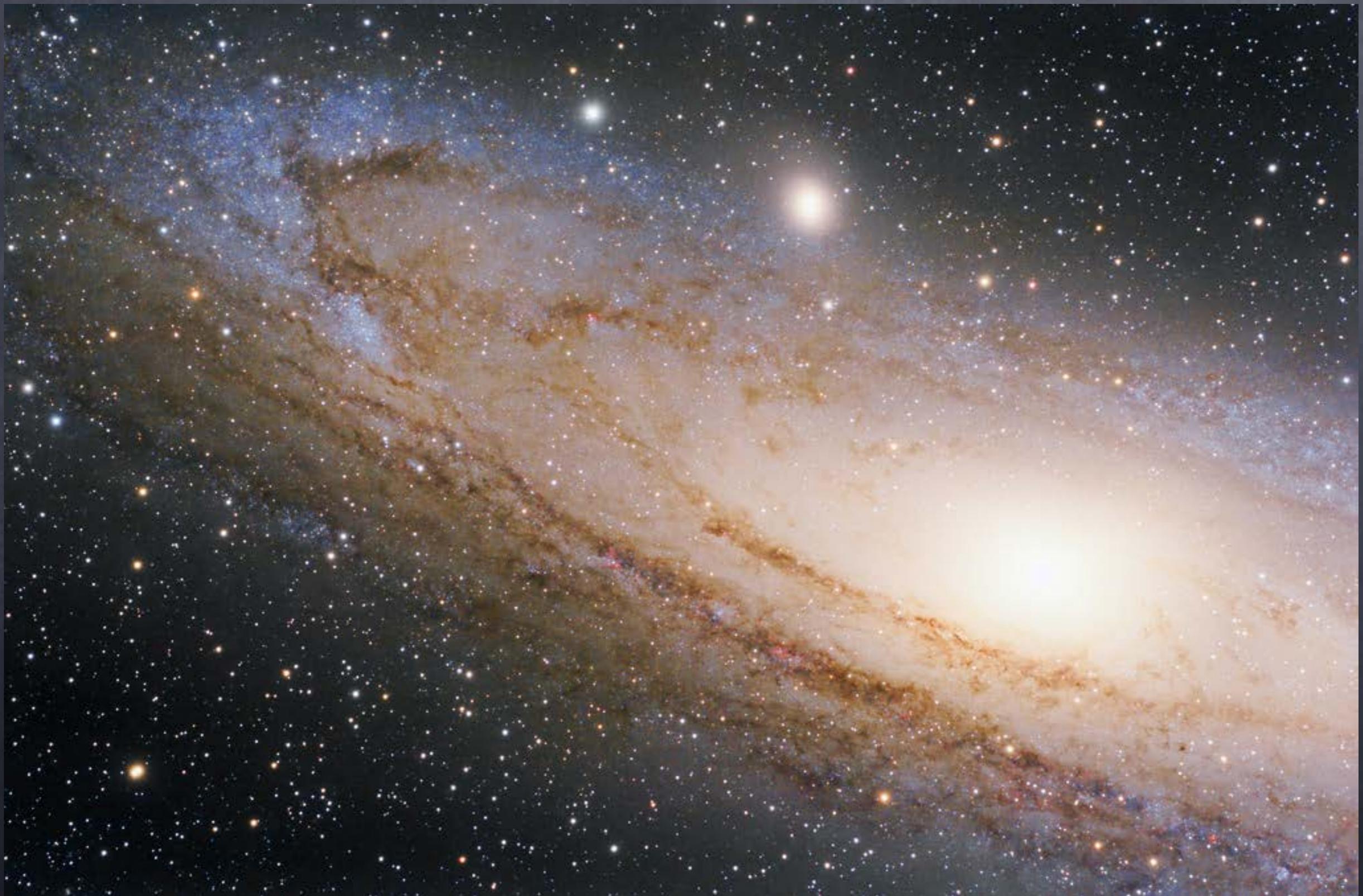
The Milky Way is moving at a rate of 552 to 630 km per second, being pushed away from the Local Void at 600,000 mph. Our Solar System travels at 447,000 MPH and takes 250 Million years to complete one Galactic Rotation.



You Are Here

26,000 light years away from the Black Hole at the center of the Milkyway

Stars are atoms of cosmos



Stars are atoms of cosmos



# Stars are atoms of cosmos









Molecular Cloud

R, M, ρ, T



Molecular Cloud

R, M, ρ, T

Gravitational Binding Energy > Total gas energy (Collapse!)



Molecular Cloud

R, M, ρ, T

Gravitational Binding Energy > Total gas energy (Collapse!)

$$\frac{GM^2}{R} \approx PV \approx V(nkT) \approx \frac{M}{m_p} kT \quad \text{With } R \approx \left(\frac{M}{\rho}\right)^{\frac{1}{3}}, n \approx \frac{\rho}{m_p}$$



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$$M_{\text{jeans}} \approx 1.26 M_{\text{sun}} \left(\frac{T}{10K}\right)^{\frac{3}{2}} \left(\frac{n}{10^4 \text{cm}^{-3}}\right)^{-\frac{1}{2}}$$



Free Fall Time

## Free Fall Time

$$g = \ddot{R} = \frac{d^2 R}{dt^2} \approx \frac{R}{t_{ff}^2} = \frac{GM}{R^2} \Rightarrow t_{ff} \approx (G\rho)^{-\frac{1}{2}}$$

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for the Sun is 30 min

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Kelvin-Helmholz Time

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Time scale to radiate gravitational energy

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How old is our Sun?



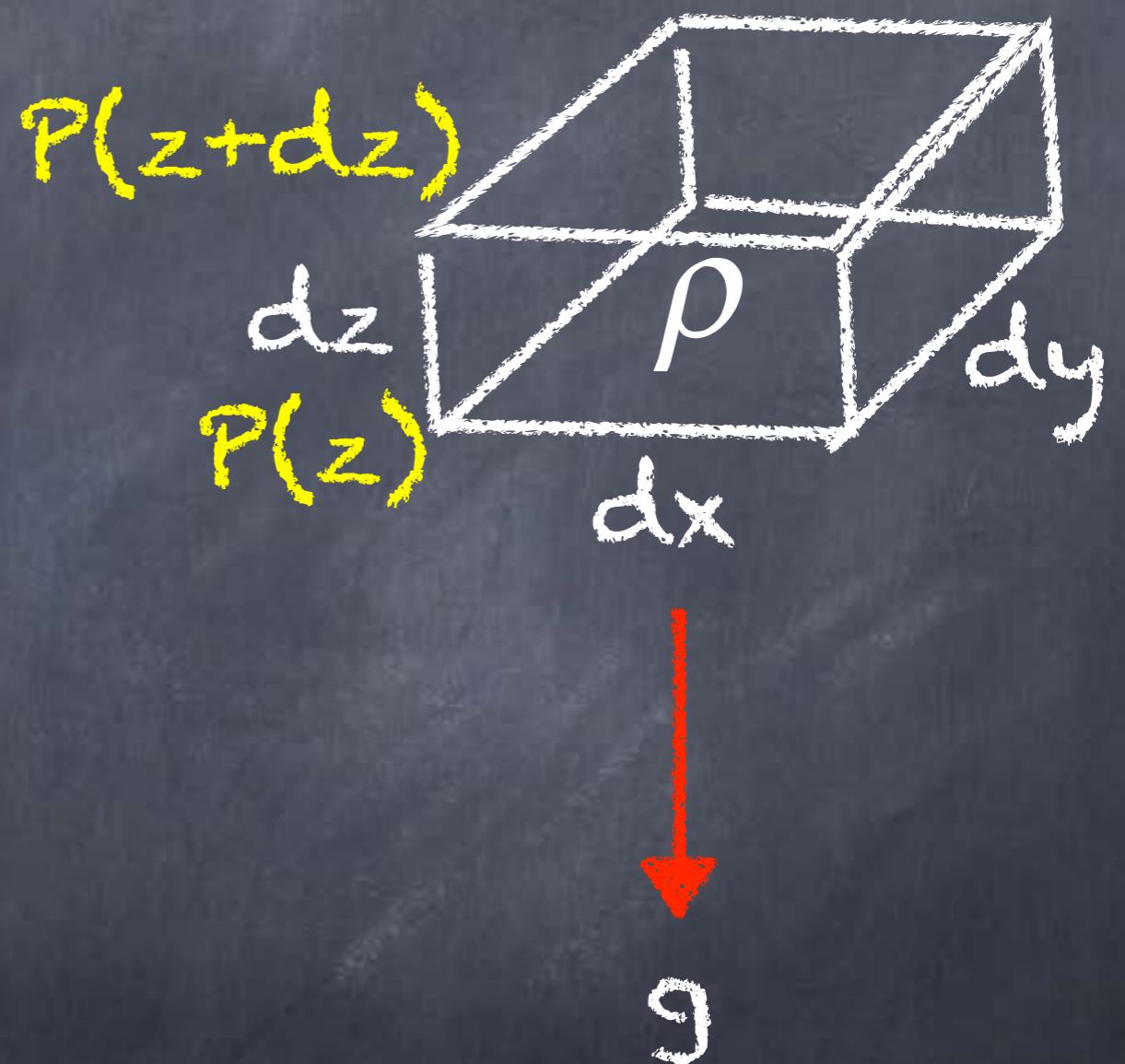
# Hydro Equilibrium

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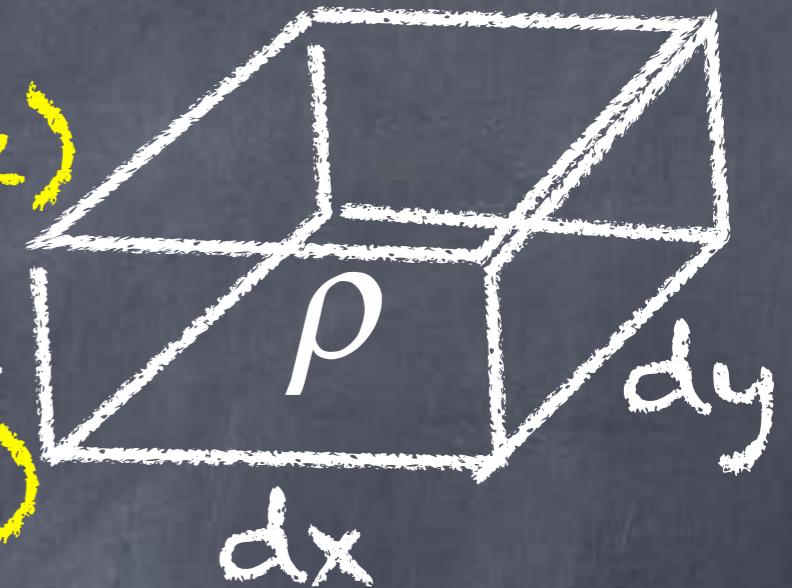
# Hydro Equilibrium

$$F_g \approx \frac{GMdm}{z^2} \approx g(z)dm \approx \rho g dx dy dz$$

$P(z+dz)$

$dz$

$P(z)$



$g$

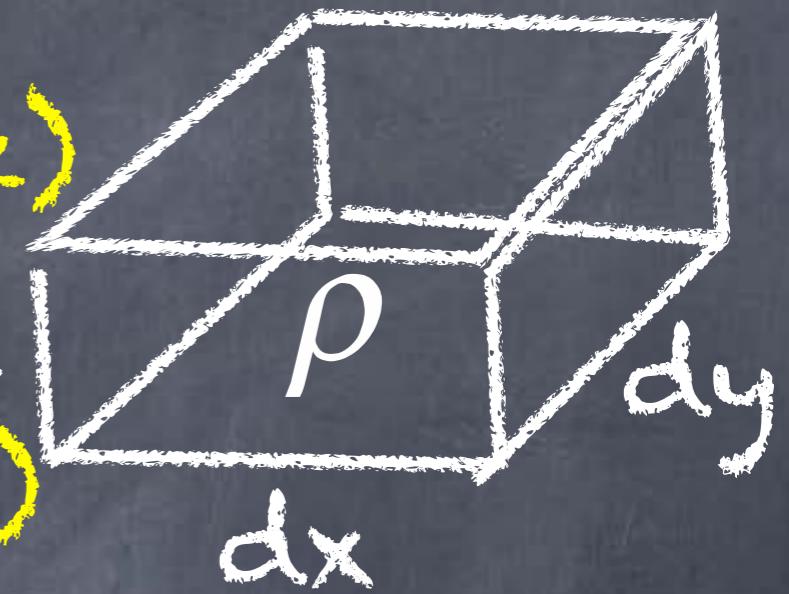
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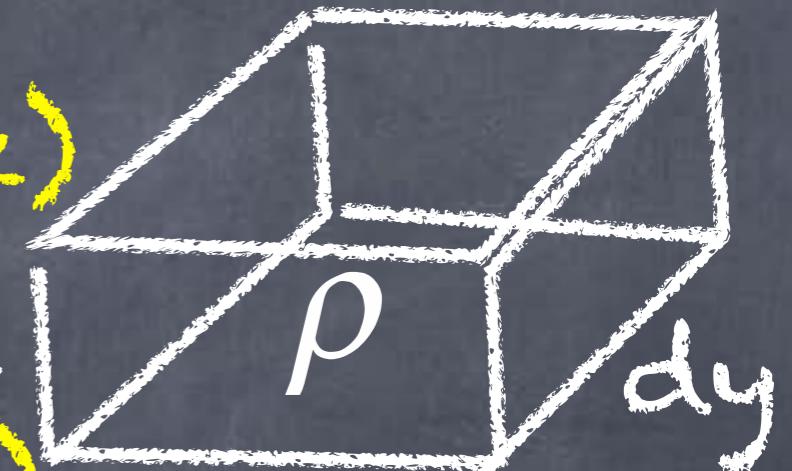
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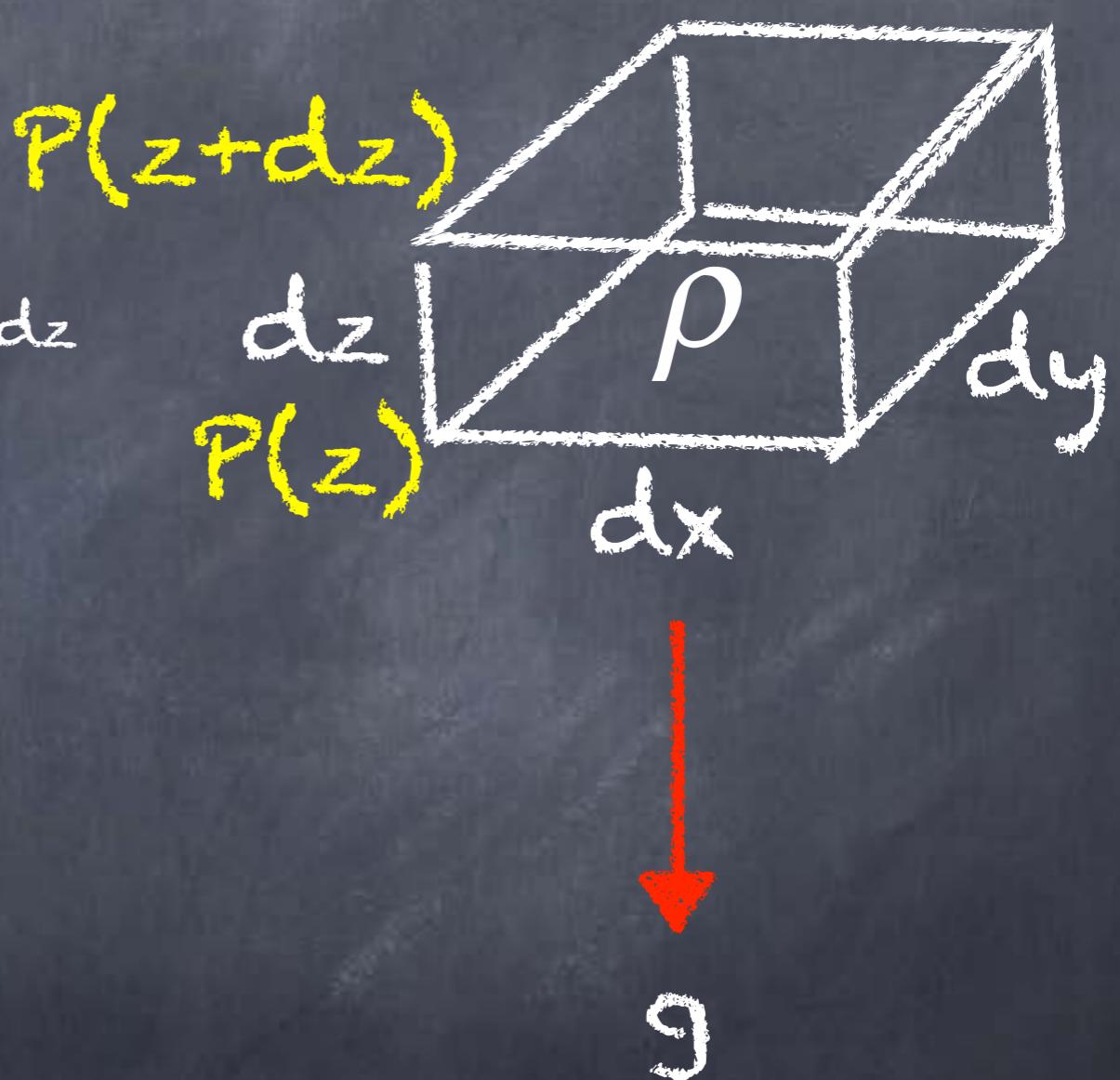
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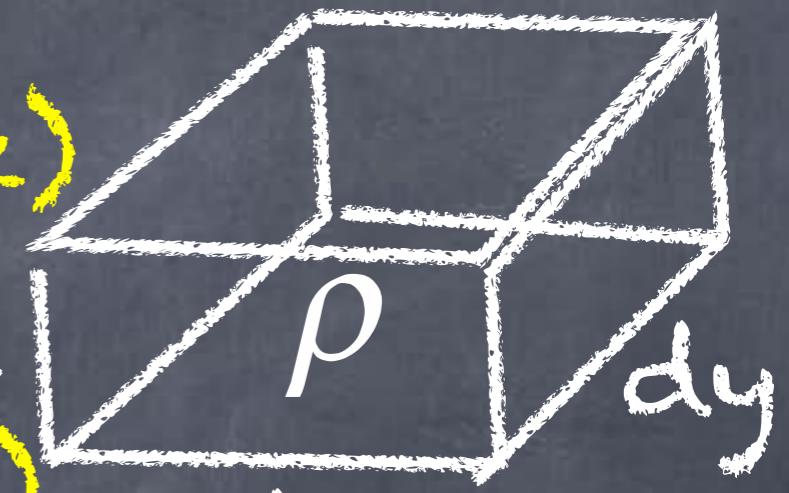
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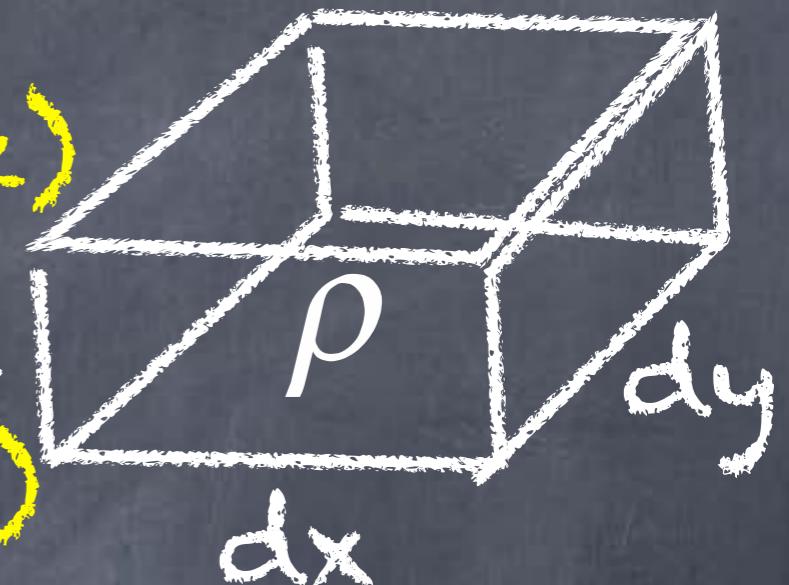
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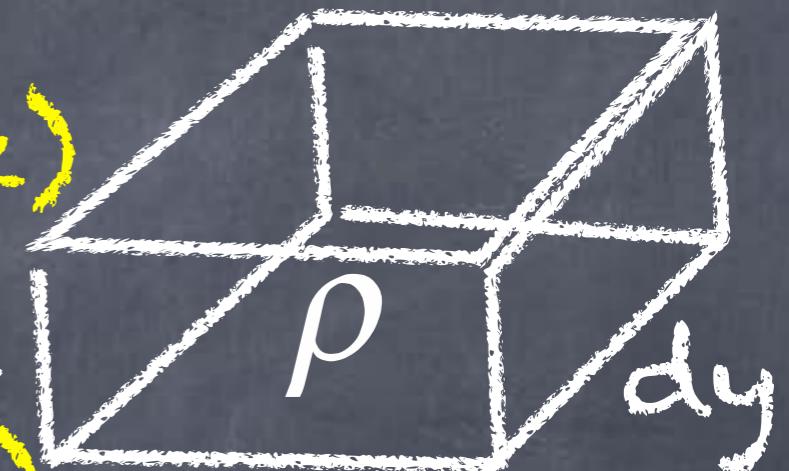
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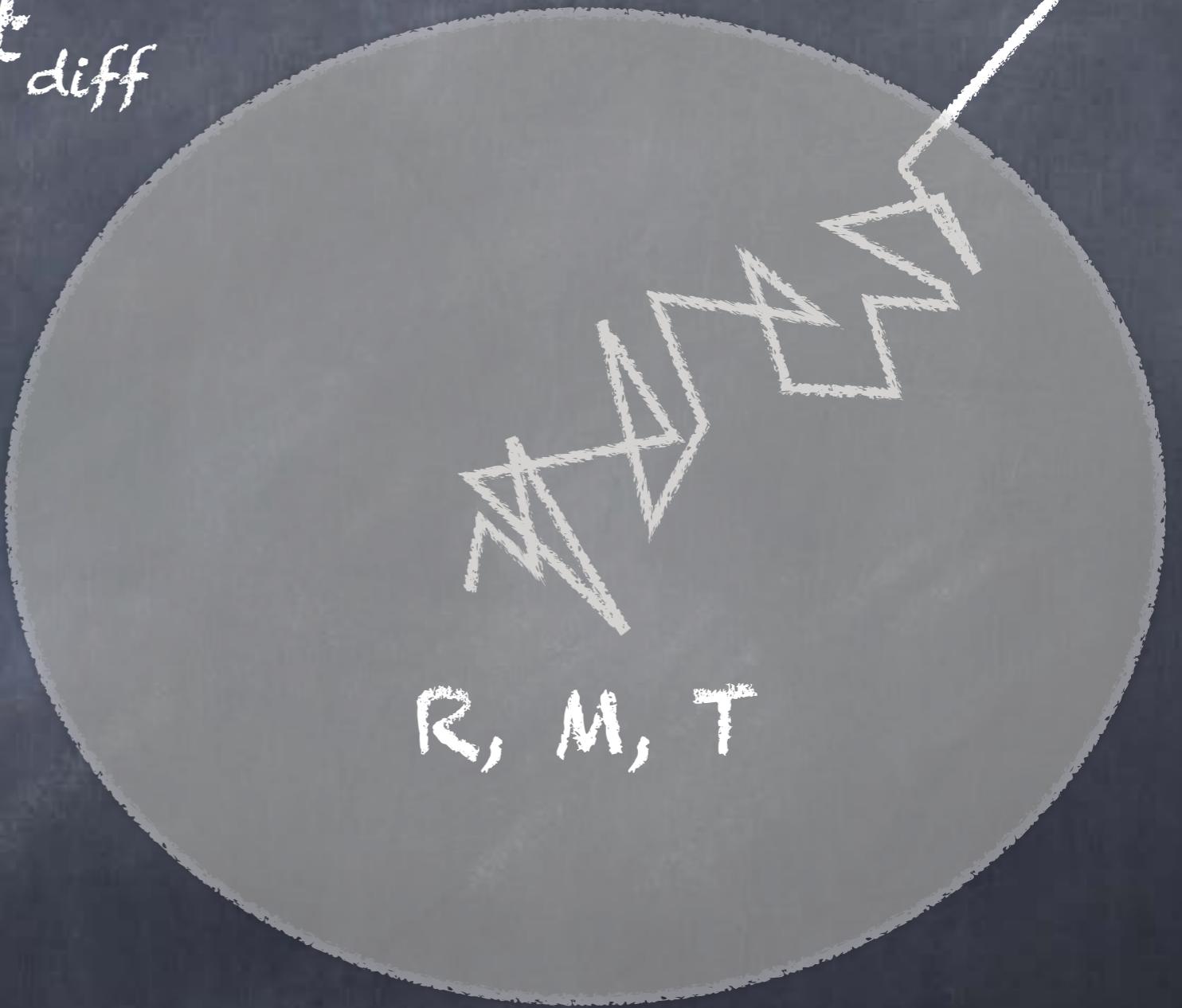
R, M, T

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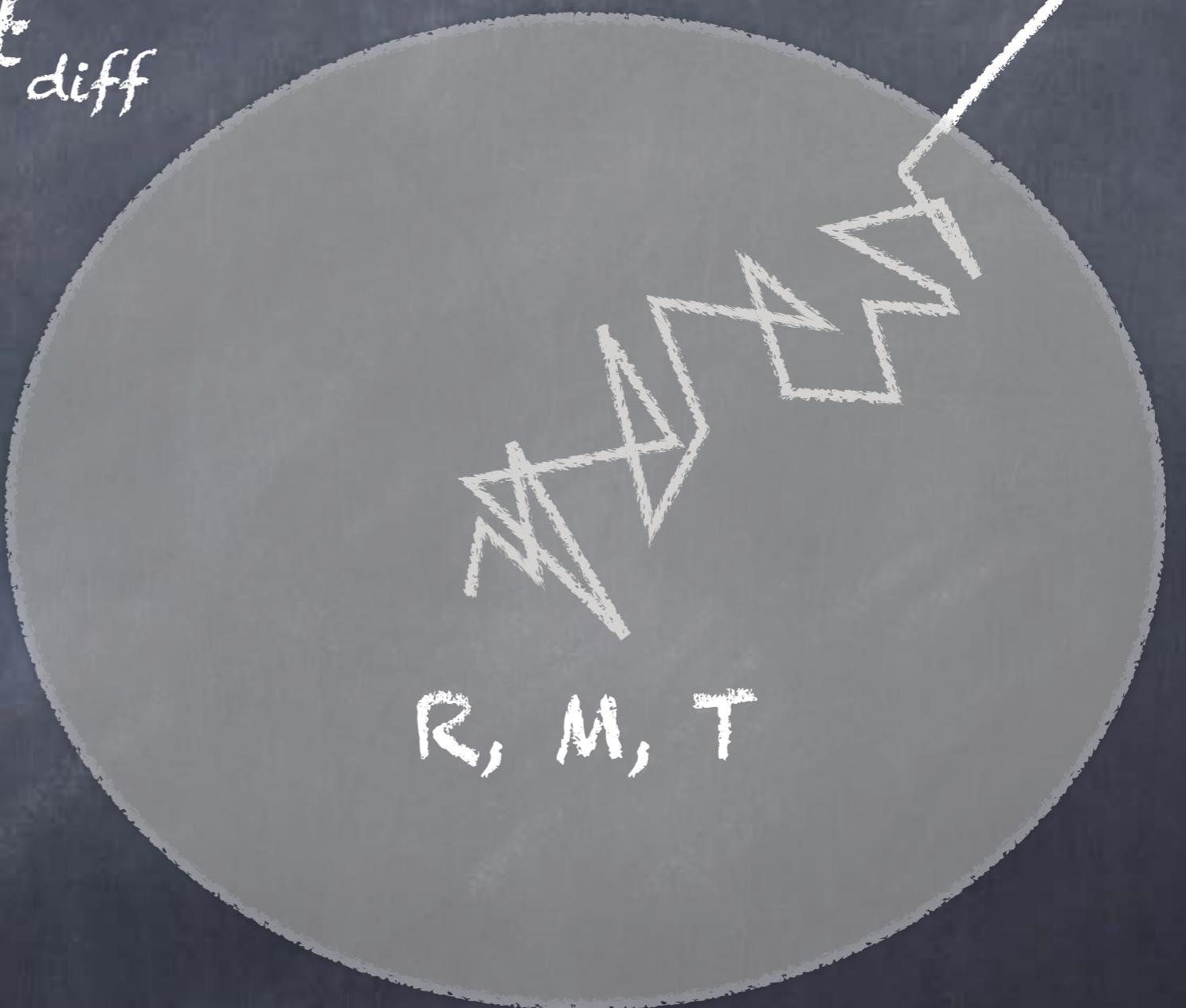
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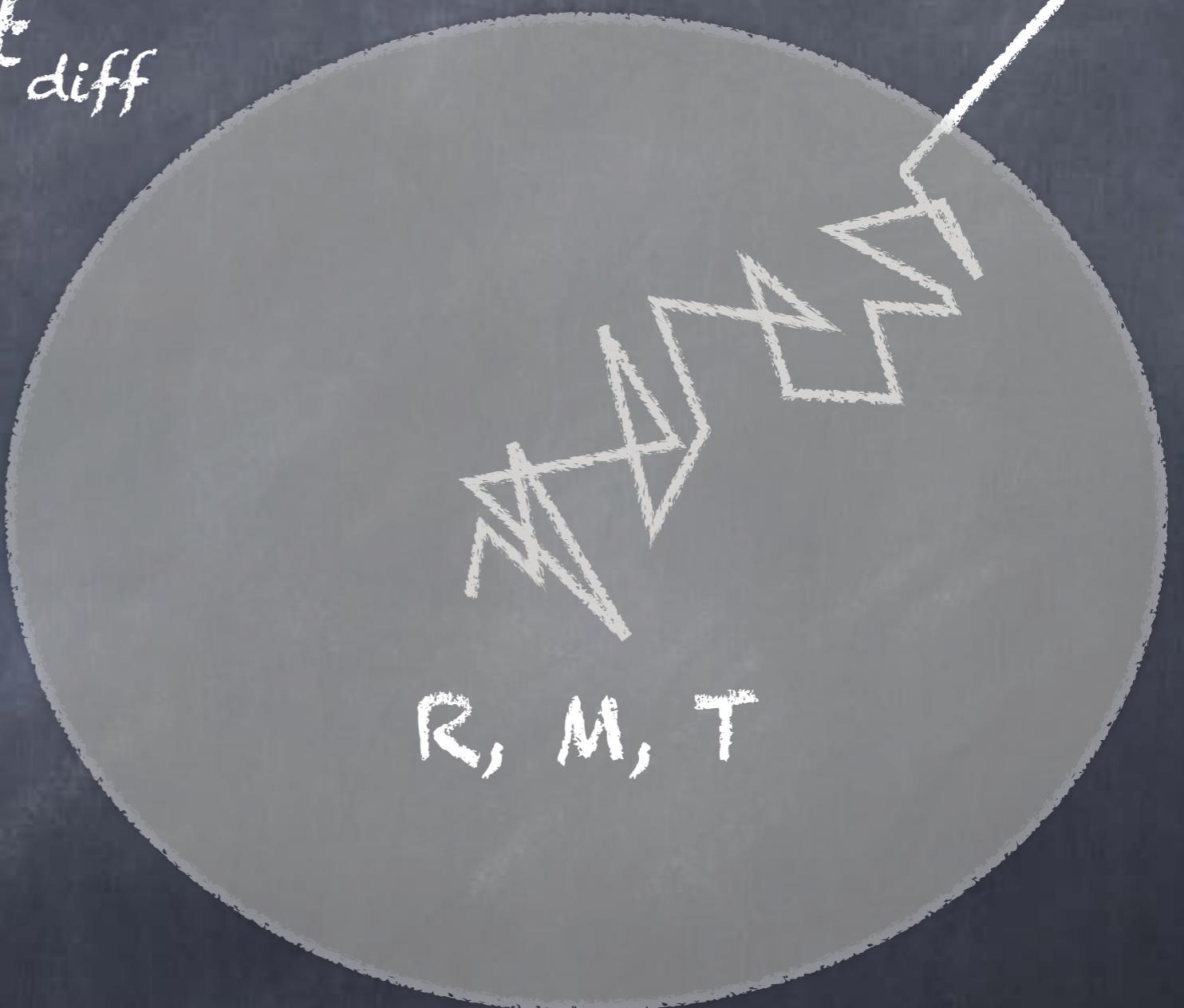


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$$\vec{R} \sim \vec{l}_1 + \vec{l}_2 + \vec{l}_3 + \dots + \vec{l}_N$$



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R, M, T

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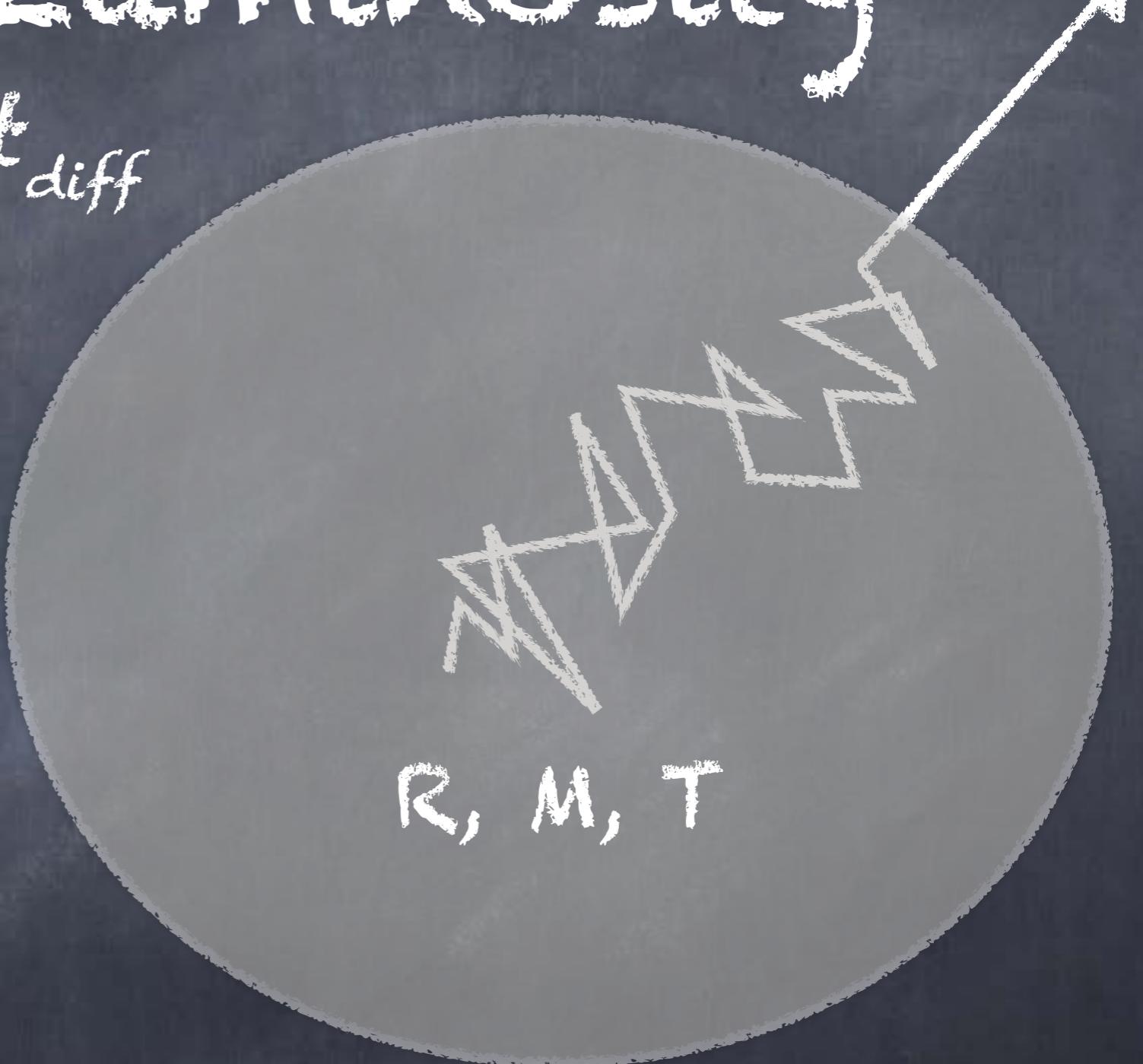
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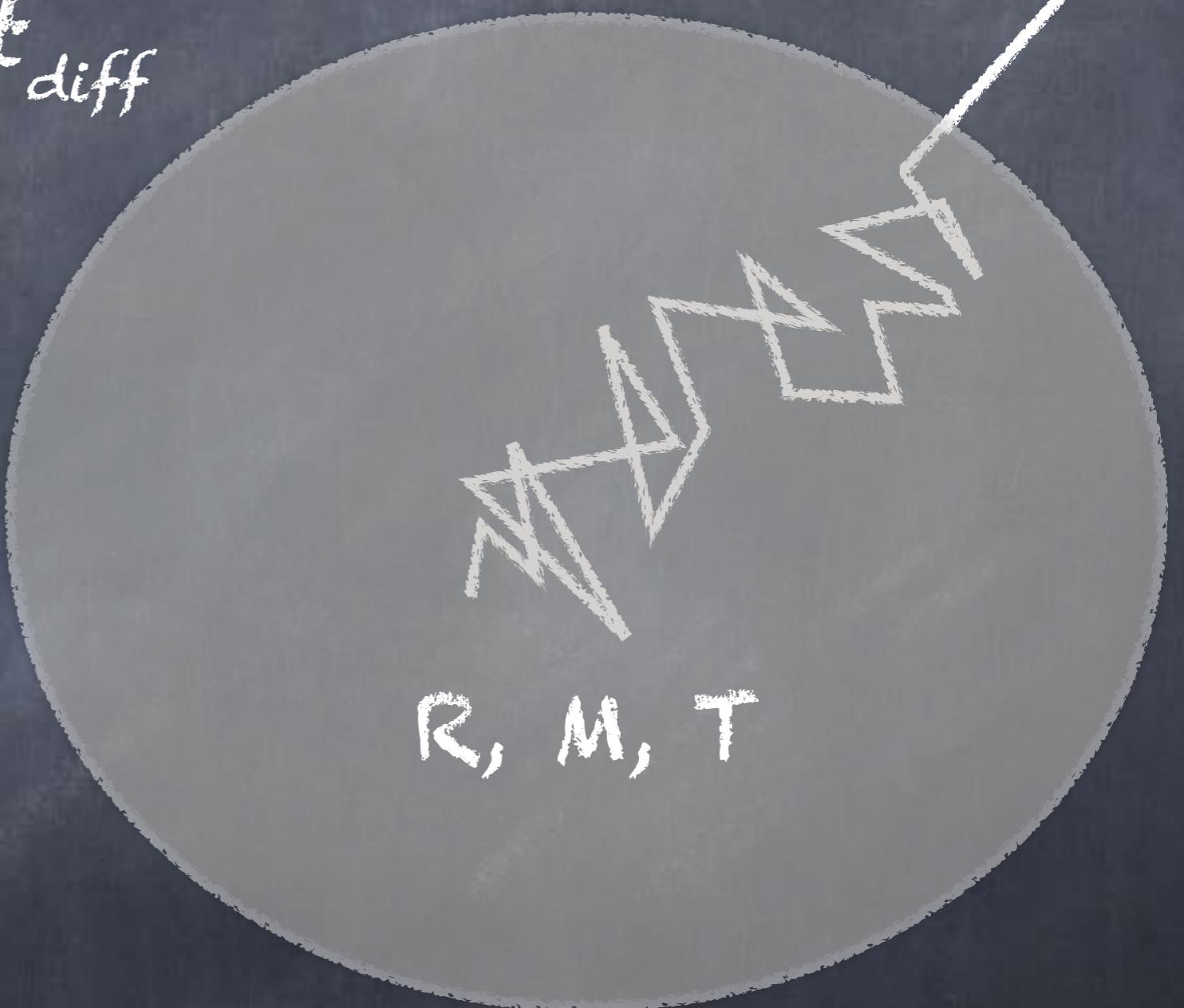
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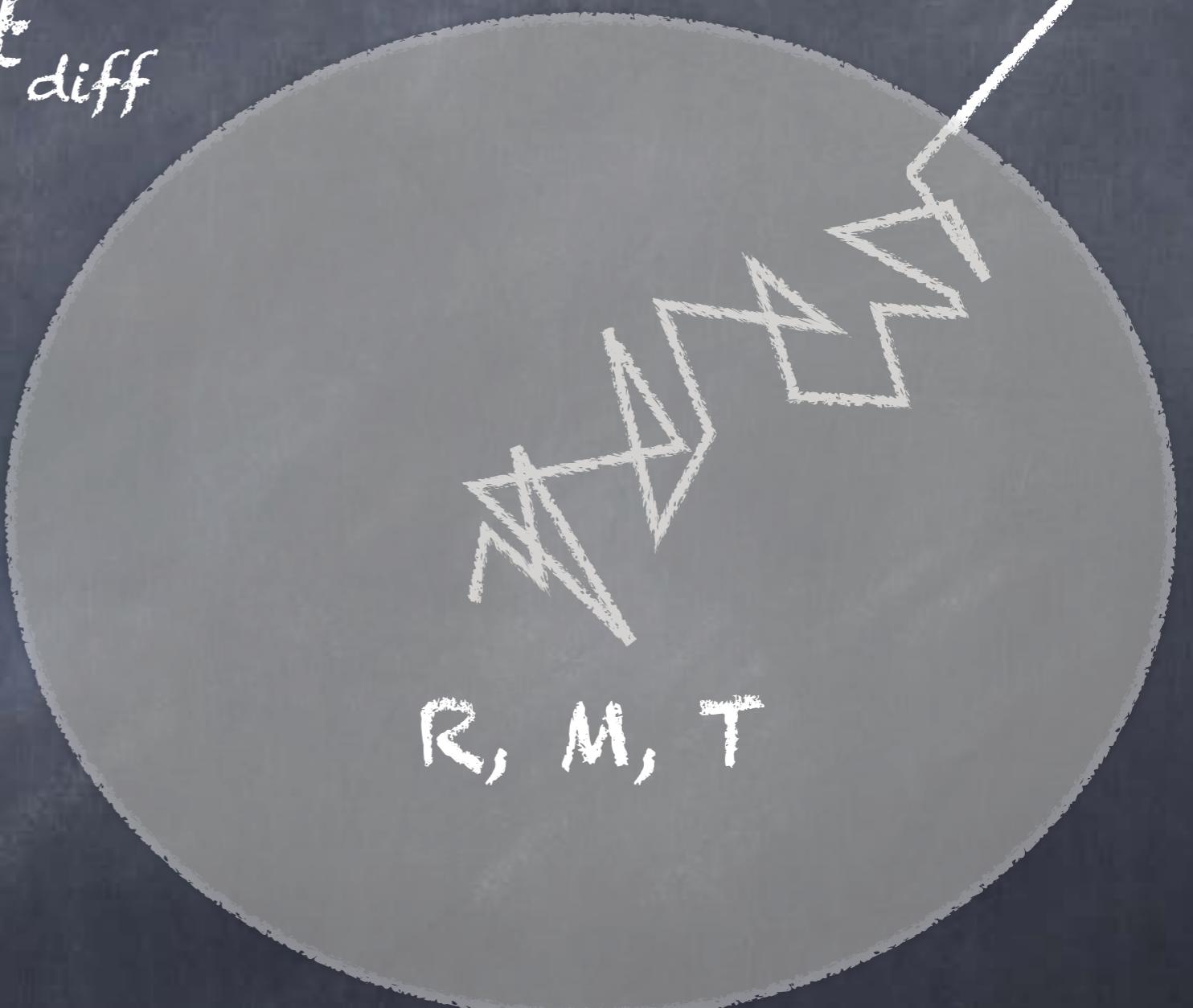
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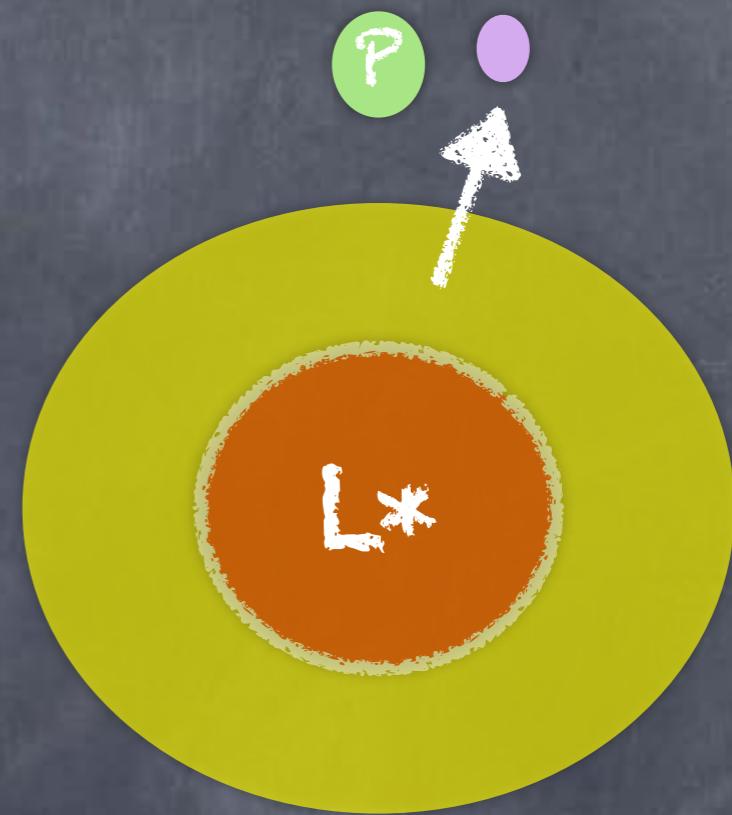
$$t^* \sim \frac{\epsilon M c^2}{L^*} \propto M^{-2}$$





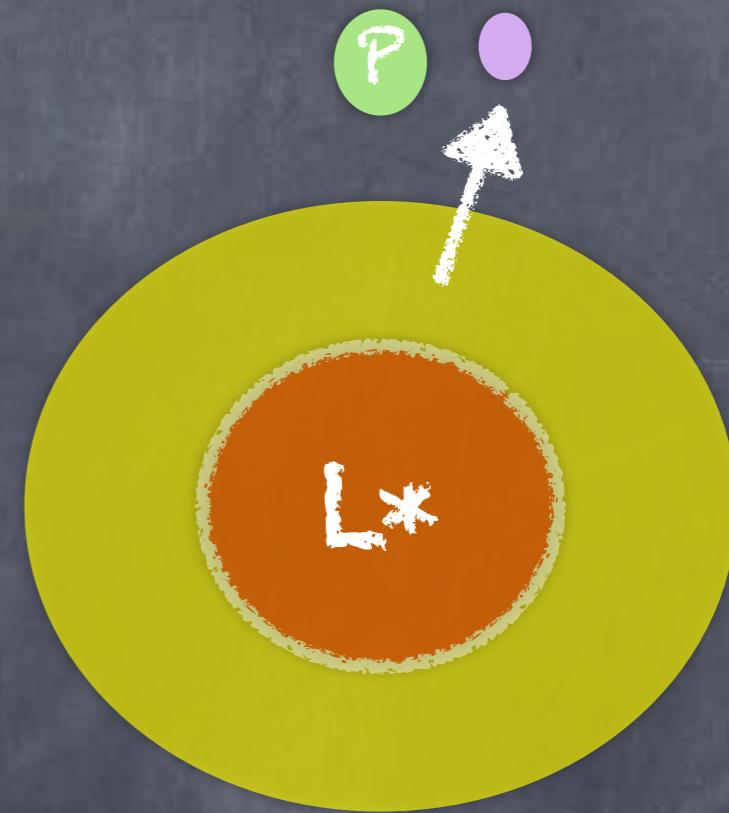
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$$F_g \approx F_r$$

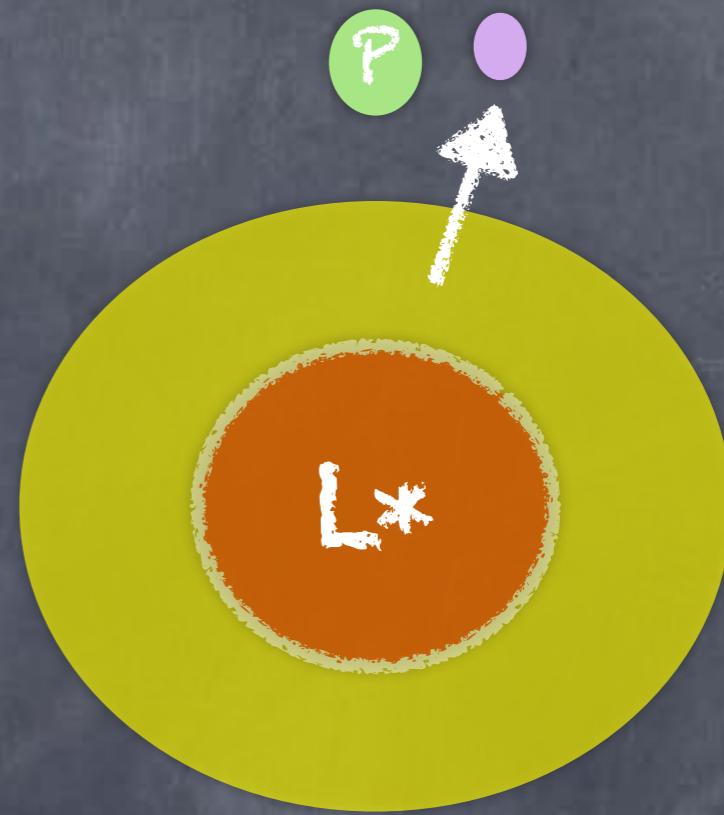


# Eddington Luminosity

$$F_g \approx F_r$$

$$\frac{GMm_p}{R^2} = \frac{dP_r}{dt} \approx \frac{\sigma_t L}{4\pi R^2 c}$$

$$\Rightarrow L_{ed} = \frac{4\pi m_p c M}{\sigma_t} \propto M$$



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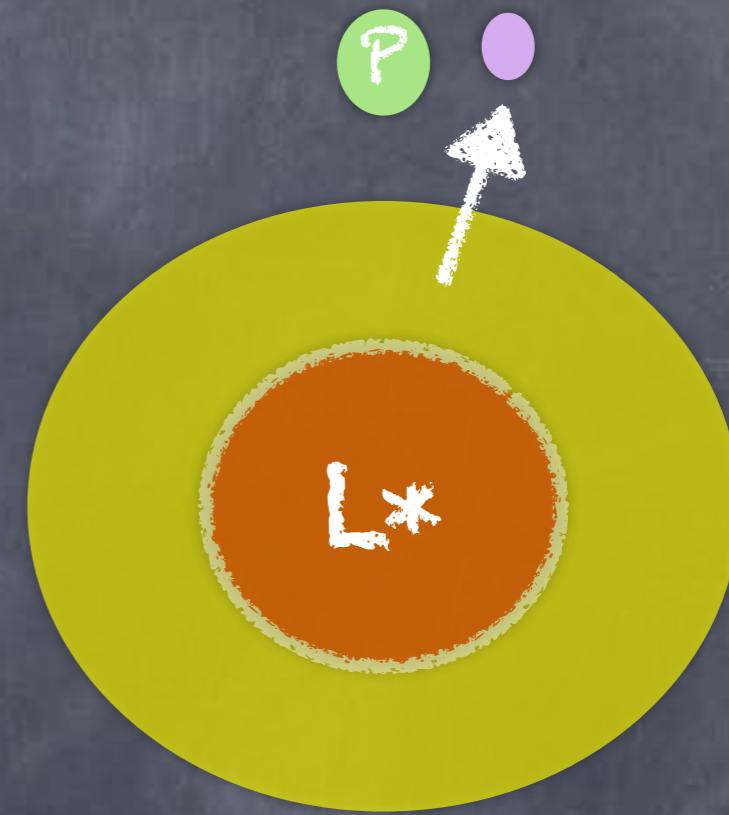
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$$L_{ed} \approx \epsilon m c^2 = \frac{4\pi m_p c M}{\sigma_t}$$

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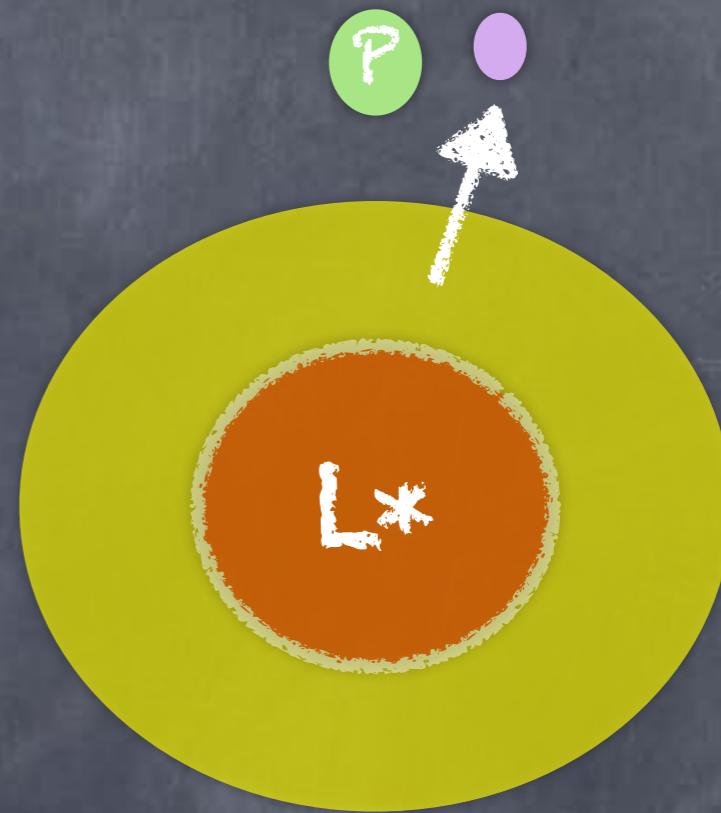
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Very massive stars shine close to Eddington Luminosity



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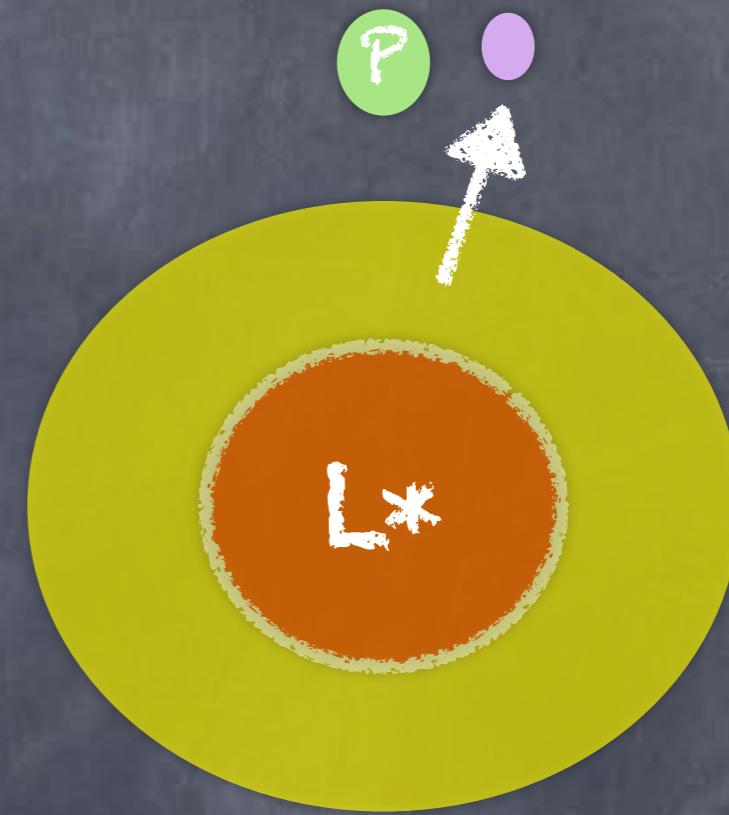
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$$L_{ed} \approx \epsilon Mc^2 = \frac{4\pi m_p c M}{\sigma_t}$$

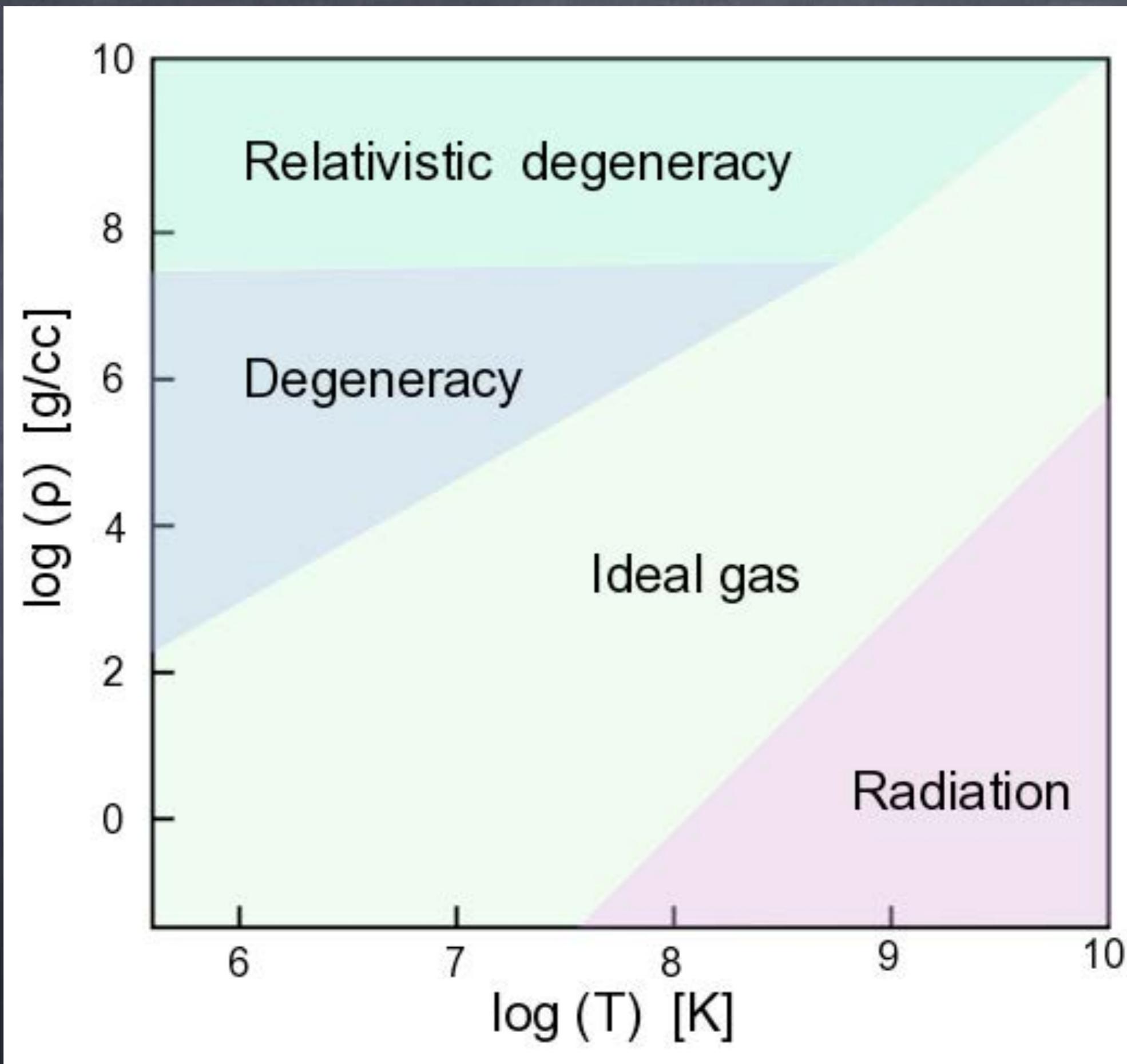
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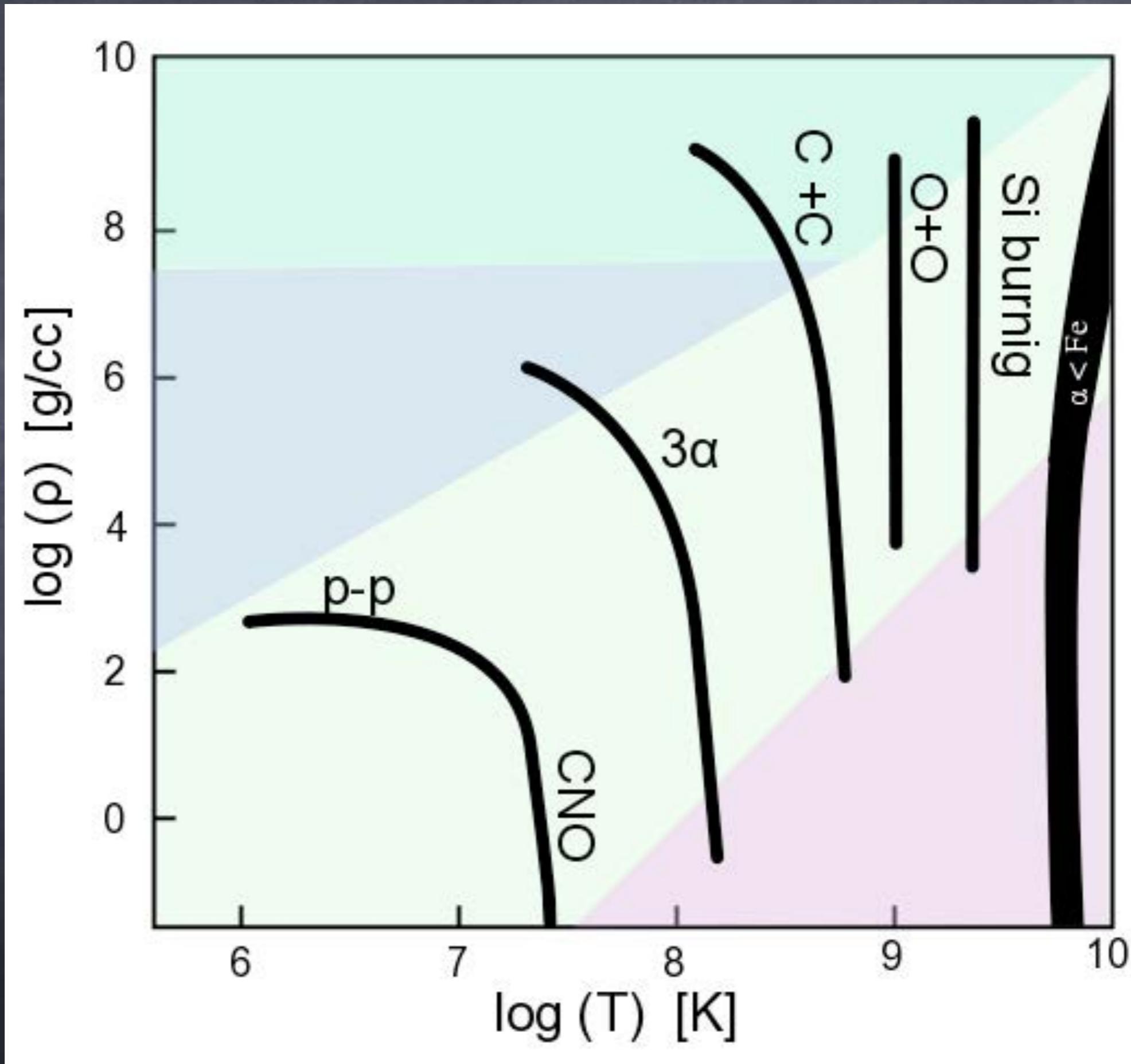
$$t^* \approx \frac{\epsilon Mc^2}{L_{ed}} \approx \text{constant}$$



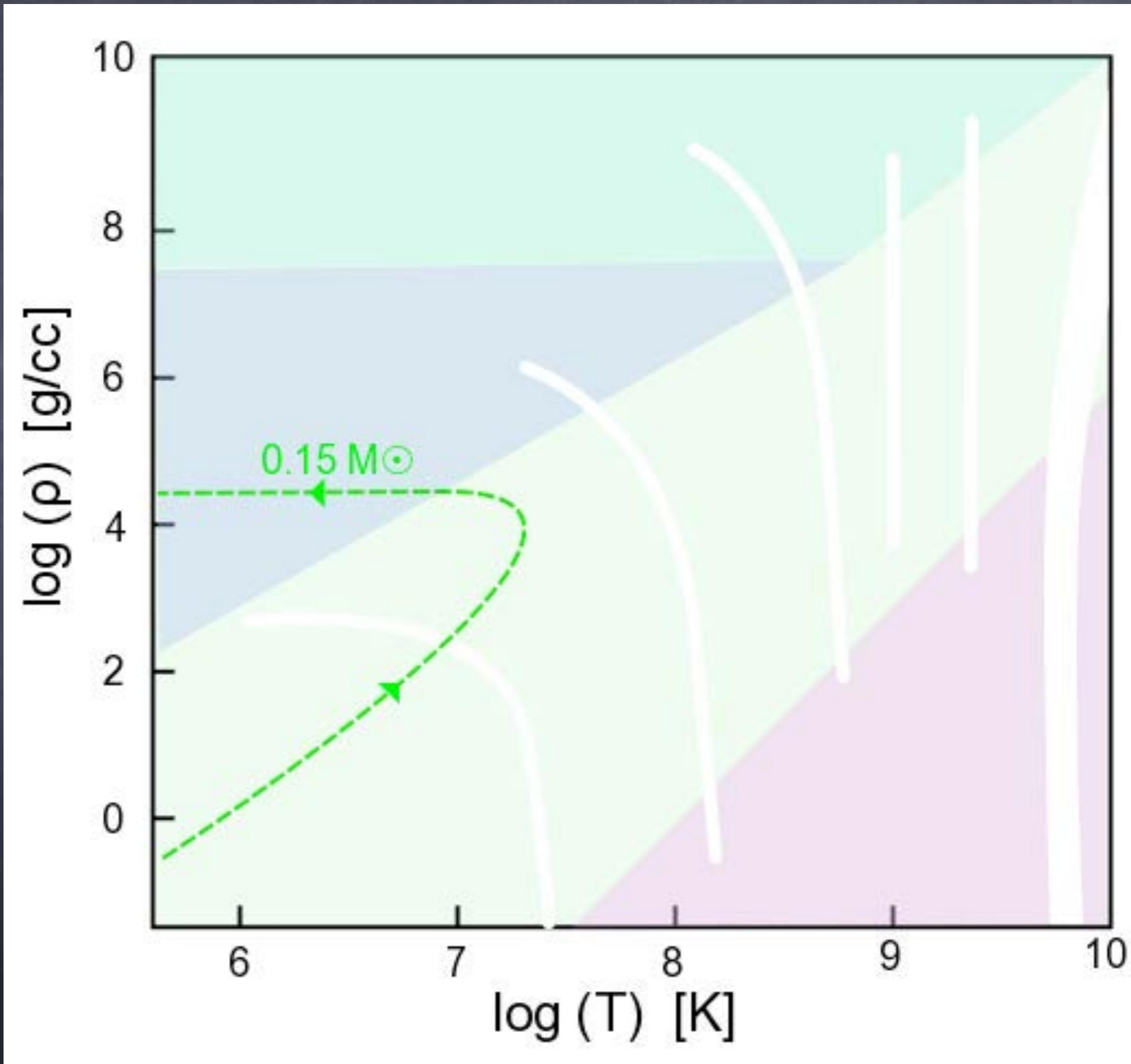
# Temperature-Density Diagram of Stellar Evolution



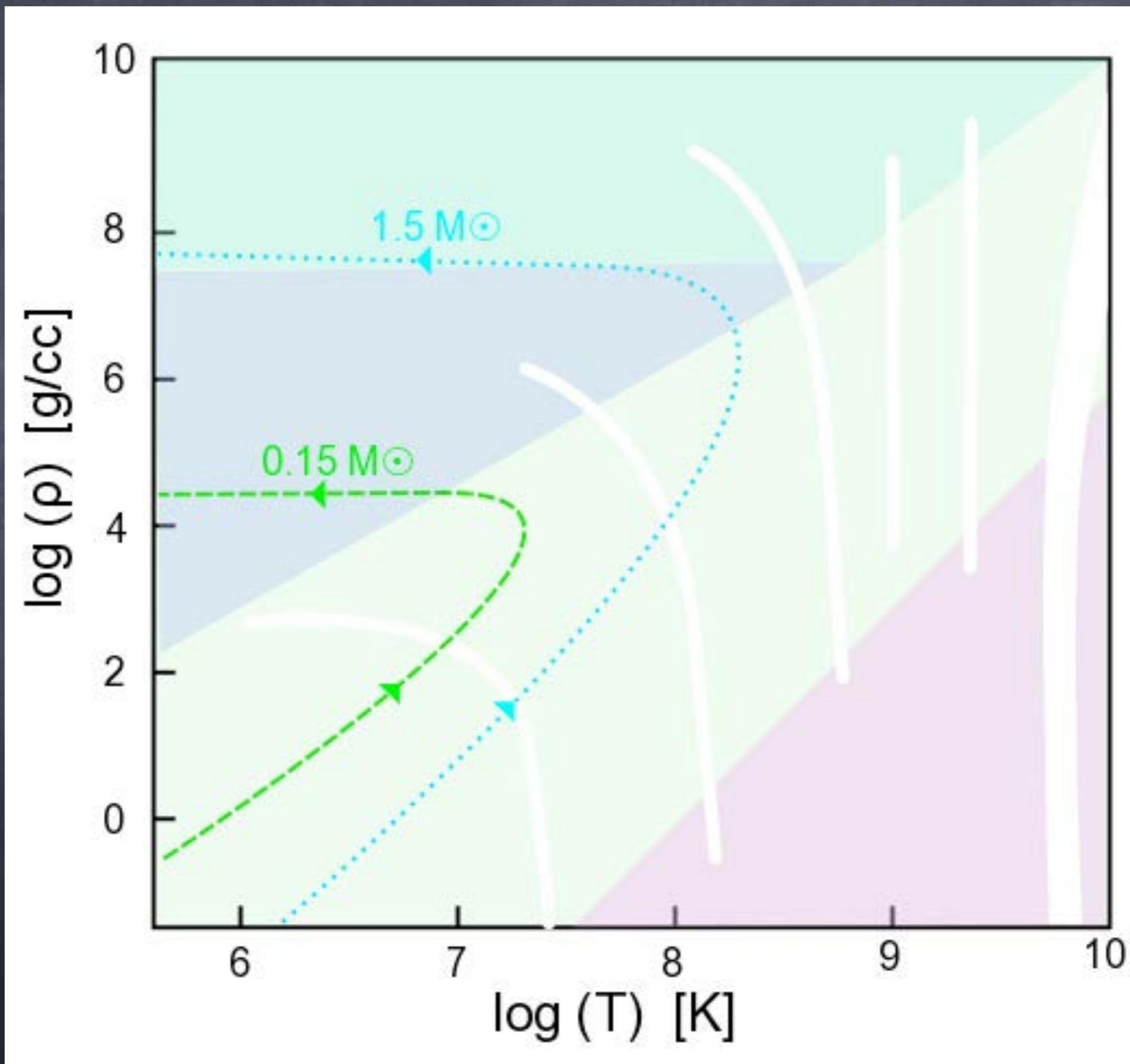
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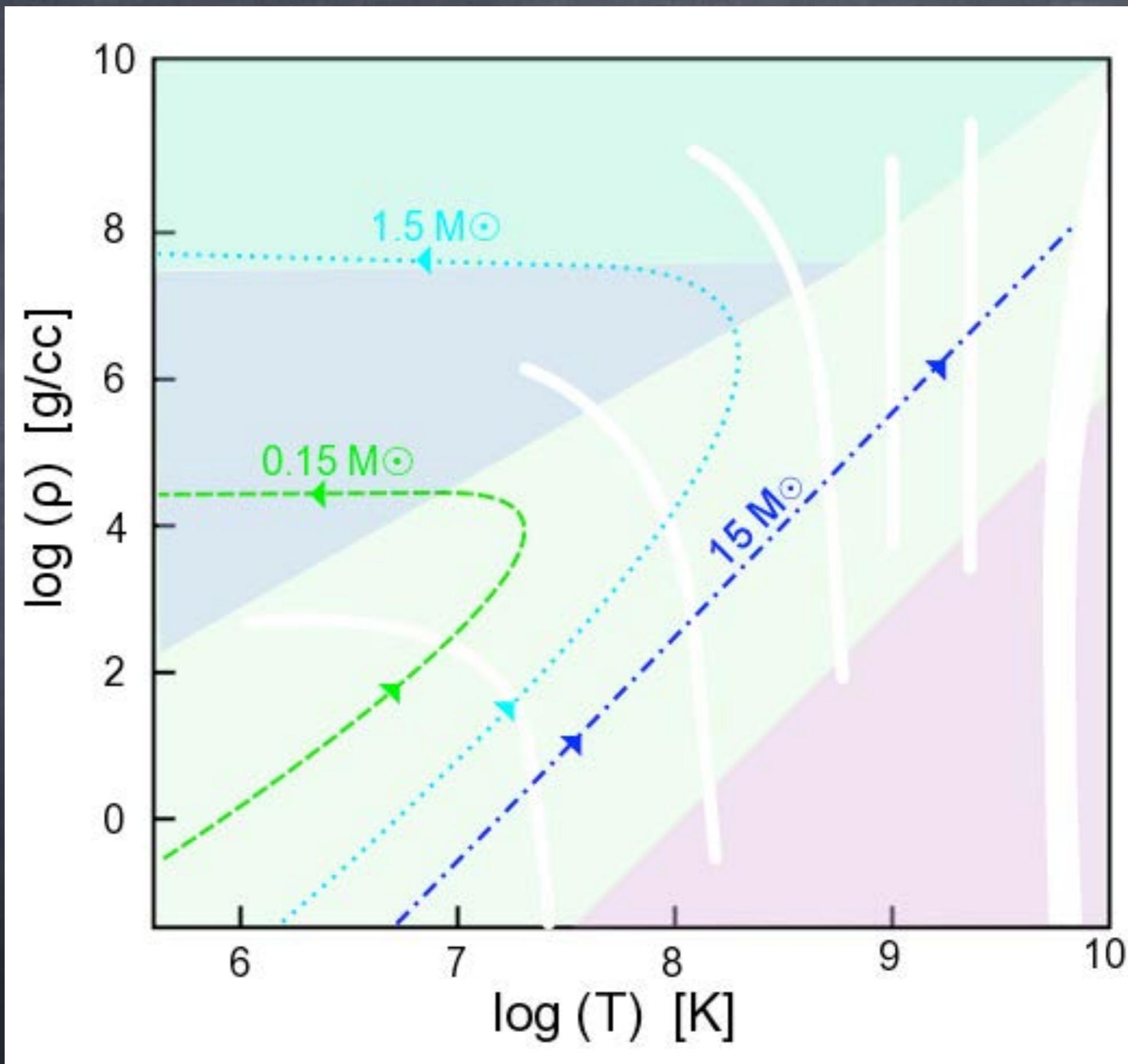
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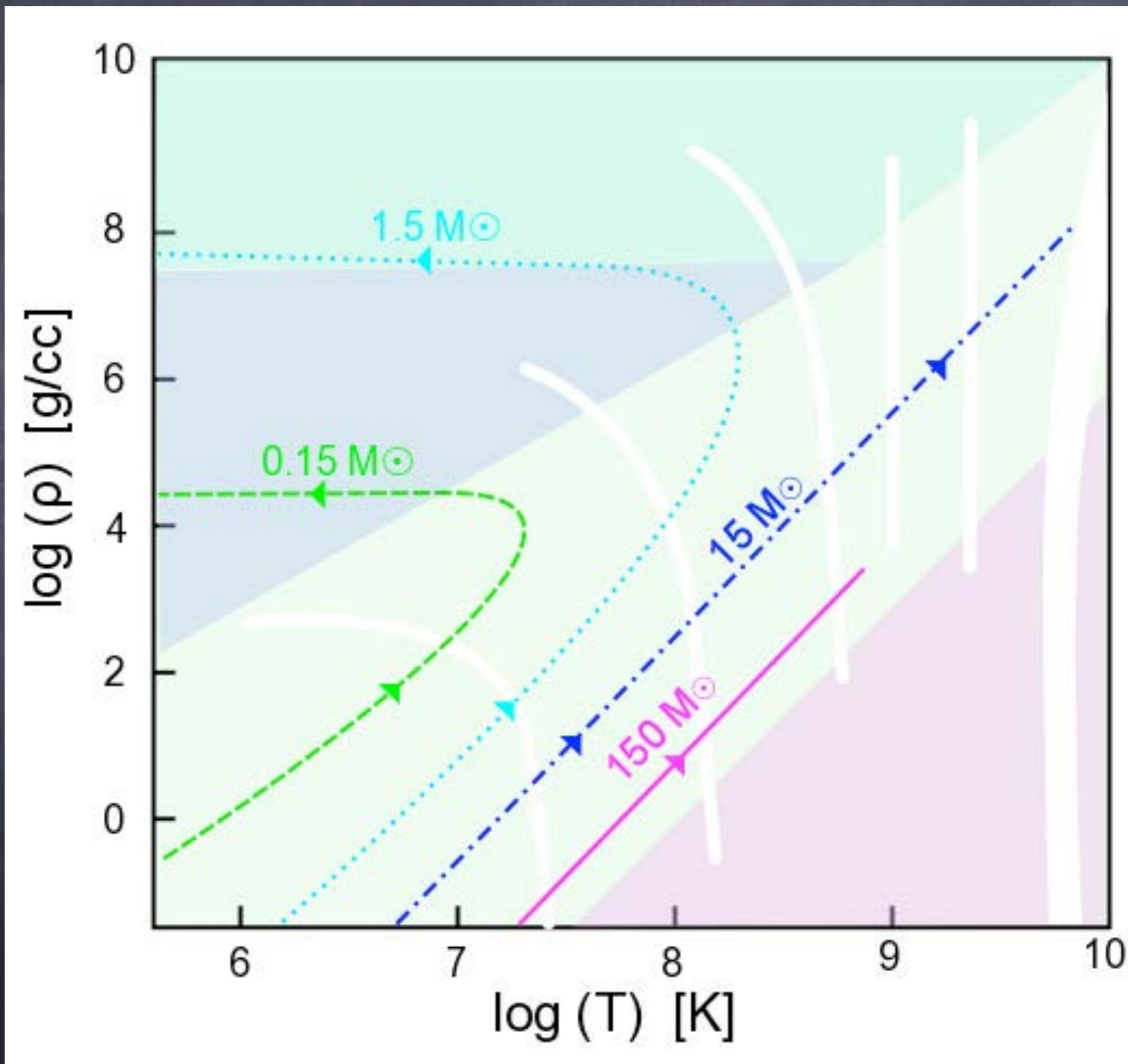
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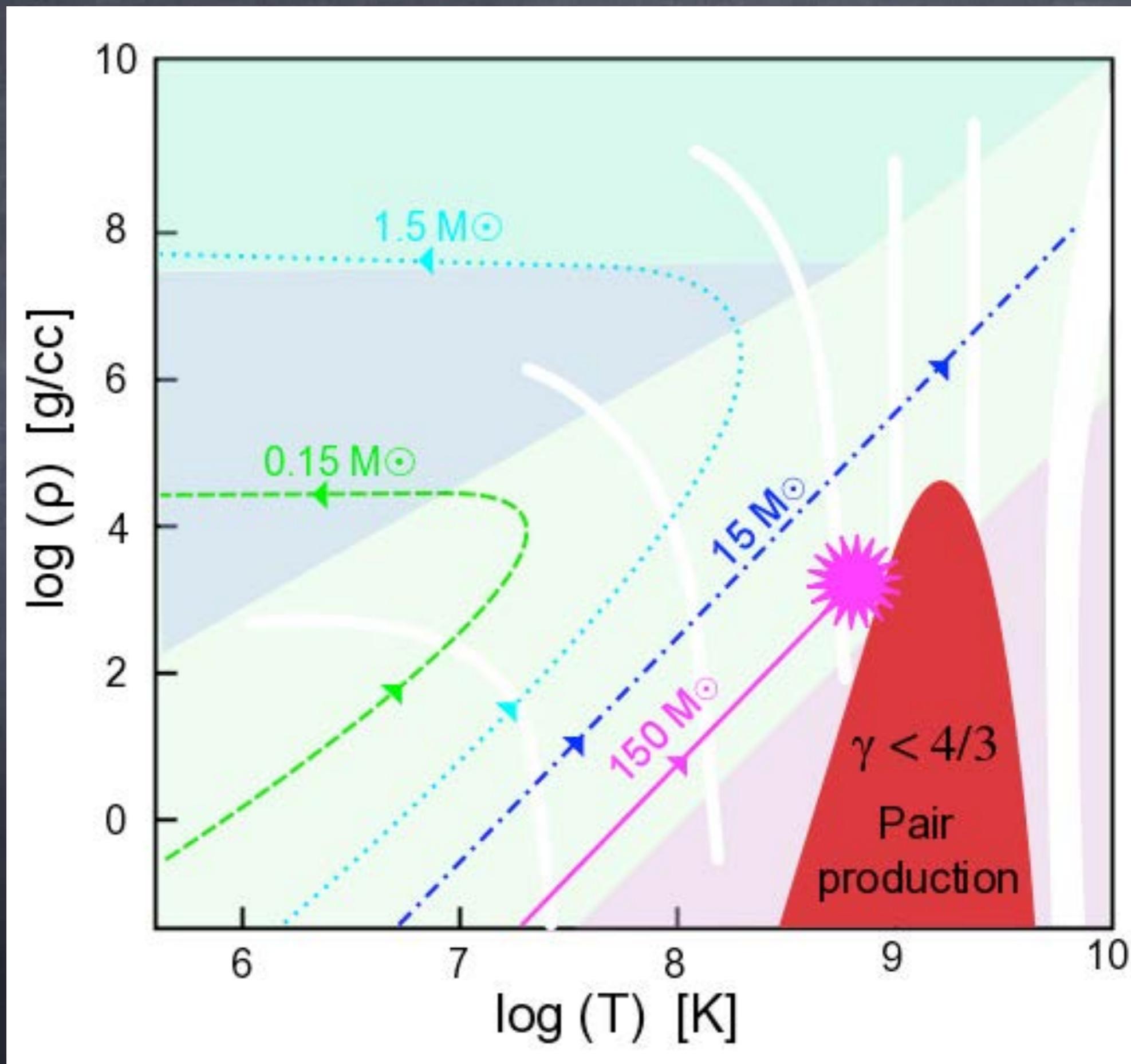
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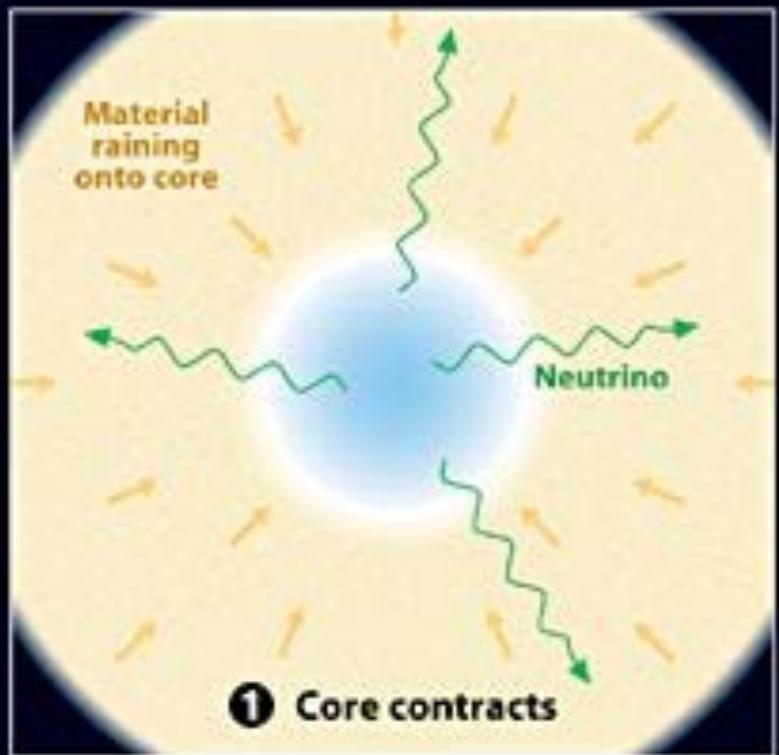
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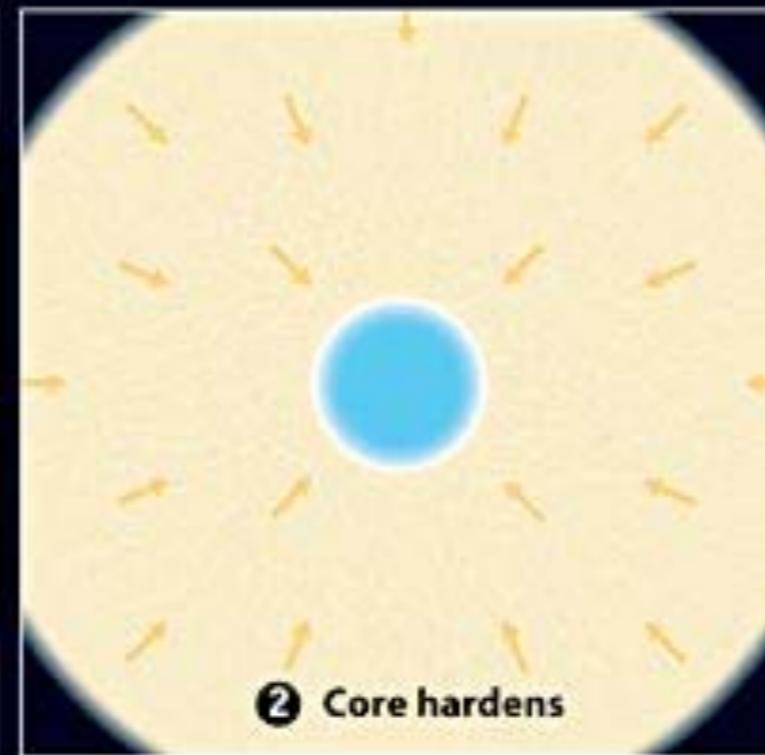
## Advanced Nuclear Burning Stages (e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp ( $10^9$ K)	Time (yr)
H	He	$^{14}\text{N}$	0.02	$10^7$
He	C,O	$^{18}\text{O}, ^{22}\text{Ne}$ s- process	0.2	$10^6$
C	Ne, Mg	Na	0.8	$10^3$
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

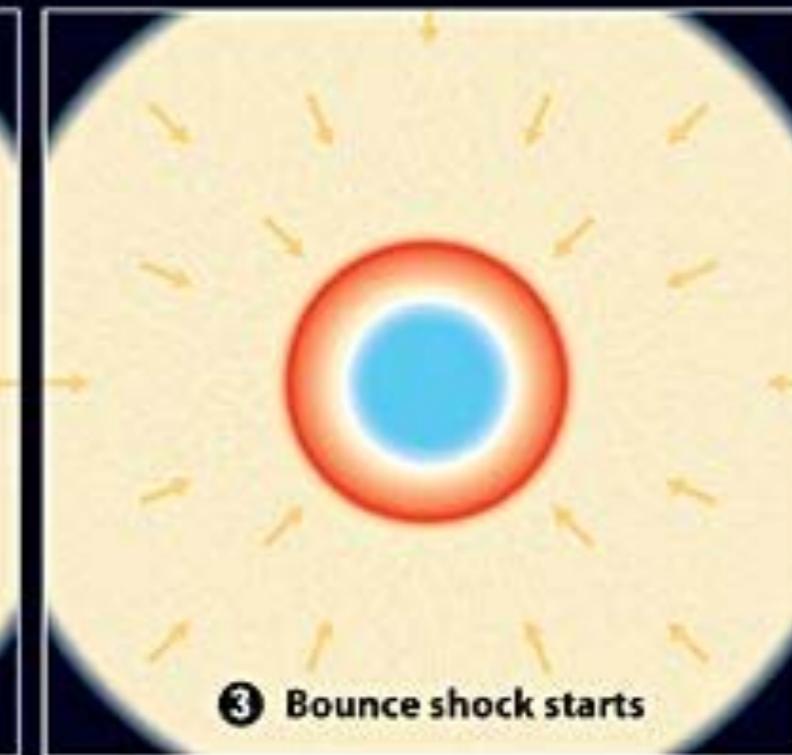
# Physics of Supernovae



① Core contracts



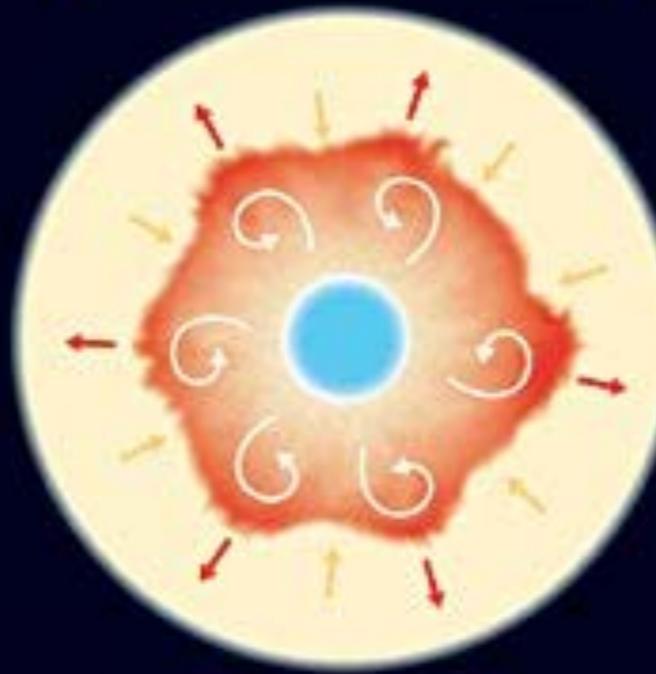
② Core hardens



③ Bounce shock starts



④ Shock stalls



⑤ Instabilities raise shock



⑥ Explosion proceeds

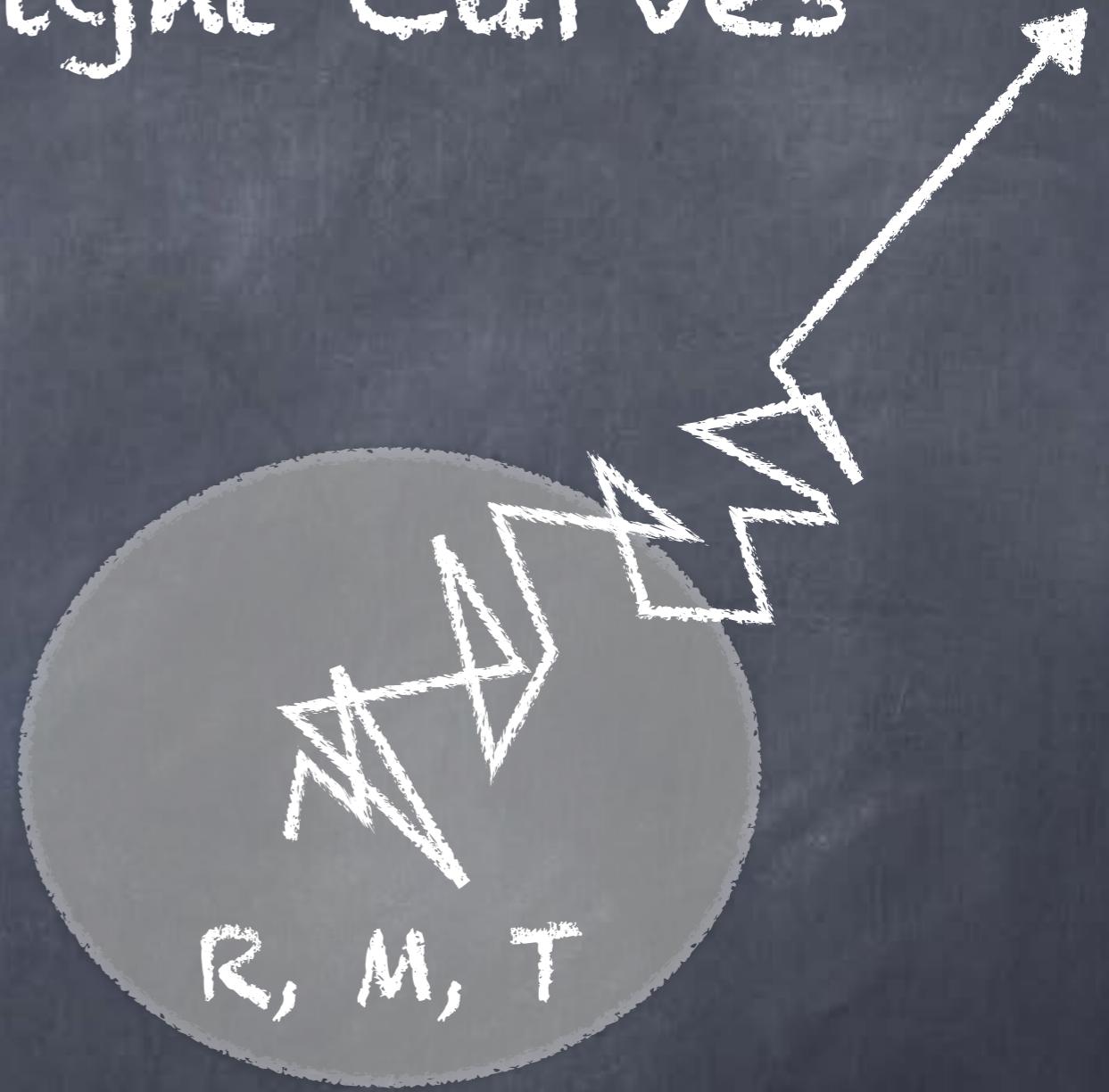




# Supernovae Light Curves

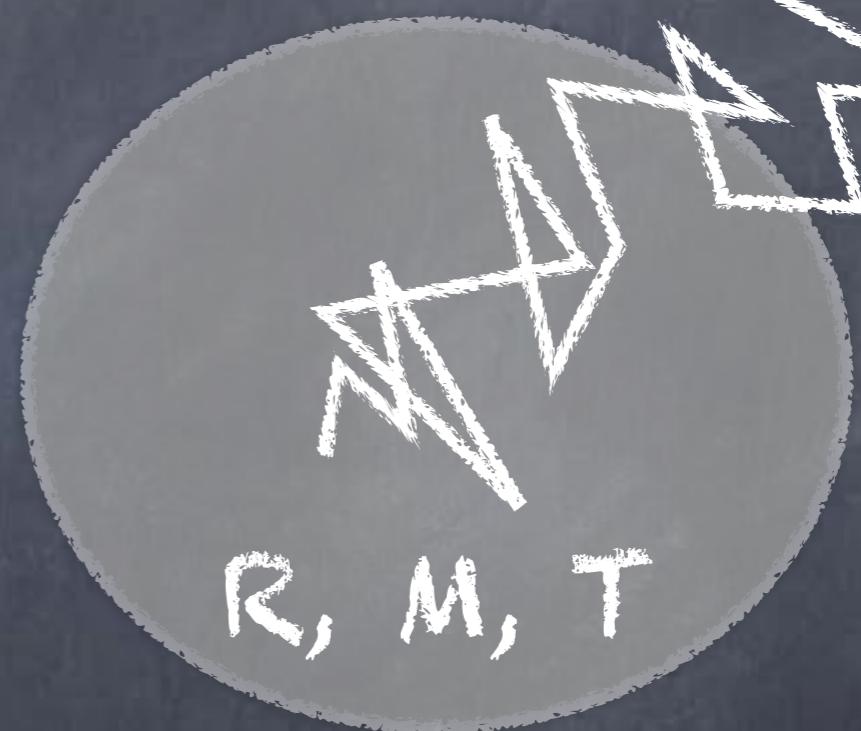


# Supernovae Light Curves



# Supernovae Light Curves

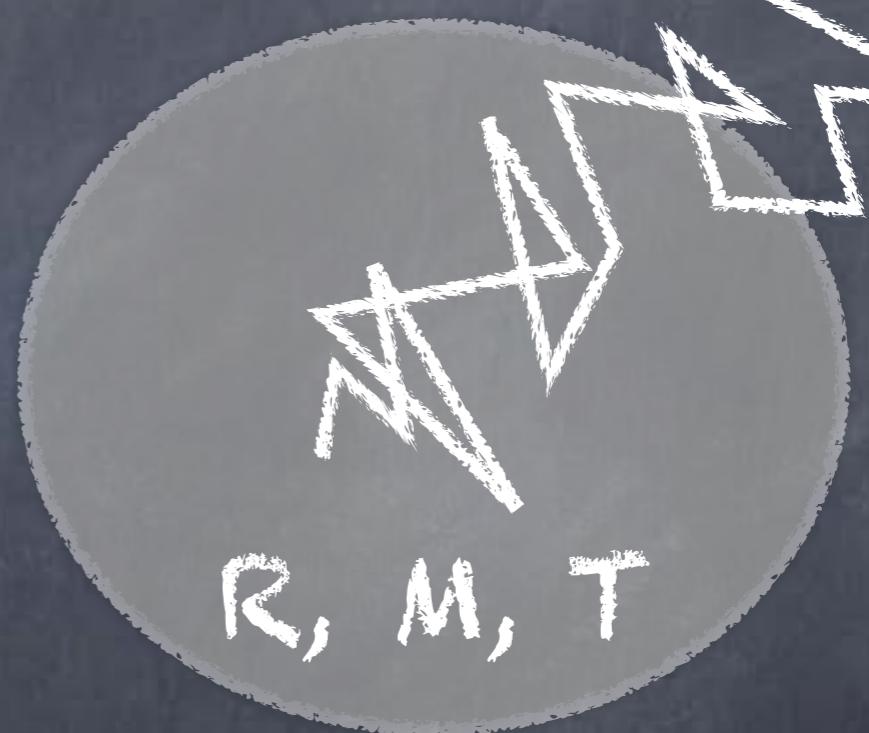
Diffusion Time = Expansion Time:



# Supernovae Light Curves

Diffusion Time = Expansion Time:

$$t_{\text{diff}} = t_{\text{exp}}$$

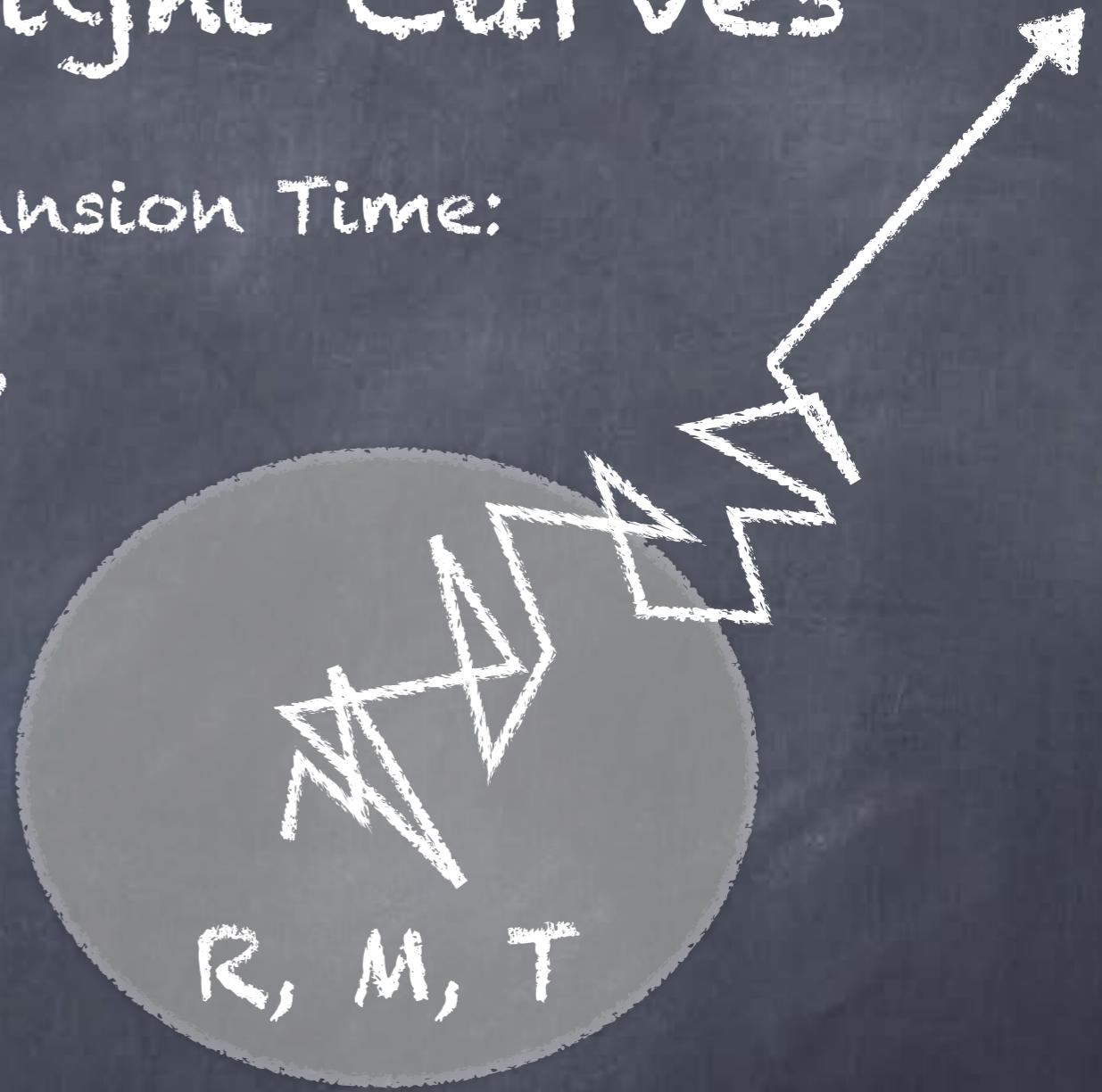


# Supernovae Light Curves

Diffusion Time = Expansion Time:

$$t_{\text{diff}} = t_{\text{exp}}$$

$$t_{\text{exp}} \approx \frac{R}{V}$$



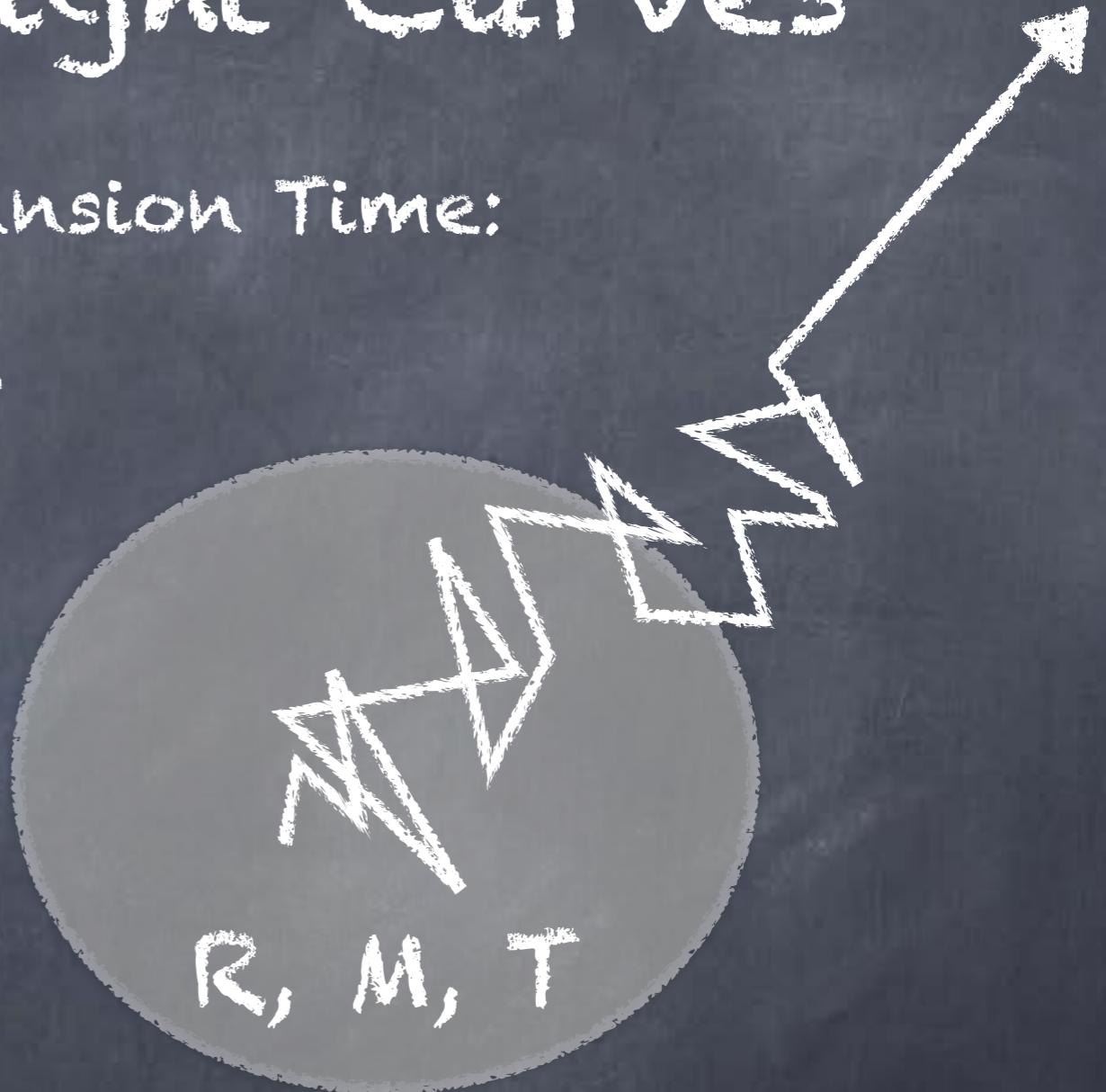
# Supernovae Light Curves

Diffusion Time = Expansion Time:

$$t_{\text{diff}} = t_{\text{exp}}$$

$$t_{\text{exp}} = \frac{R}{V}$$

$$t_{\text{diff}} \approx \tau\left(\frac{R}{c}\right) \approx \kappa\rho R\left(\frac{R}{c}\right) \approx \frac{\kappa M}{Rc}$$



# Supernovae Light Curves

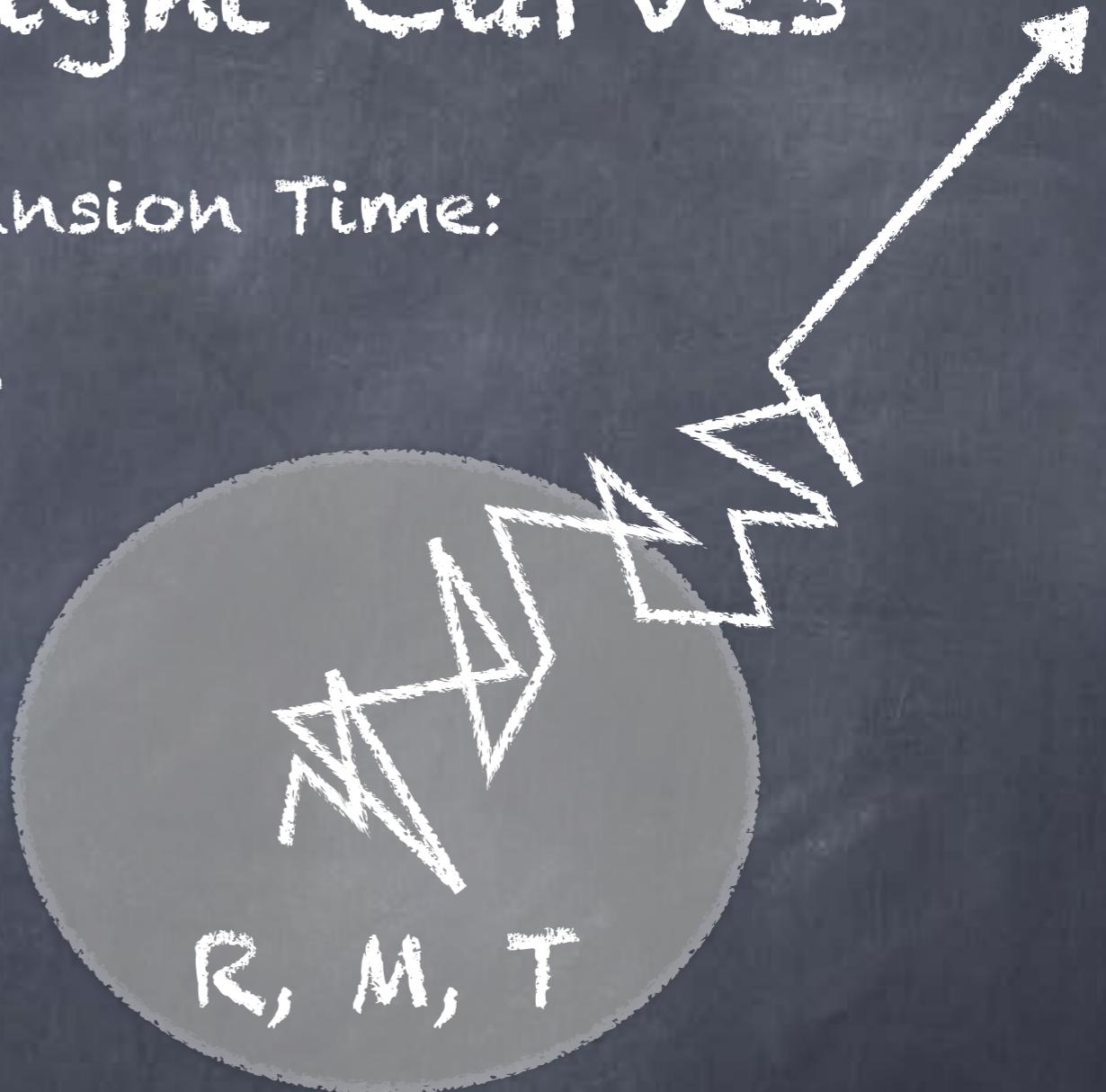
Diffusion Time = Expansion Time:

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$$t_{\text{diff}} \approx \tau\left(\frac{R}{c}\right) \approx \kappa\rho R\left(\frac{R}{c}\right) \approx \frac{\kappa M}{Rc}$$

$$t_{\text{sn}} \approx \sqrt{\frac{\kappa M}{Vc}} \quad V \approx \sqrt{\frac{E}{M}}$$



# Supernovae Light Curves

Diffusion Time = Expansion Time:

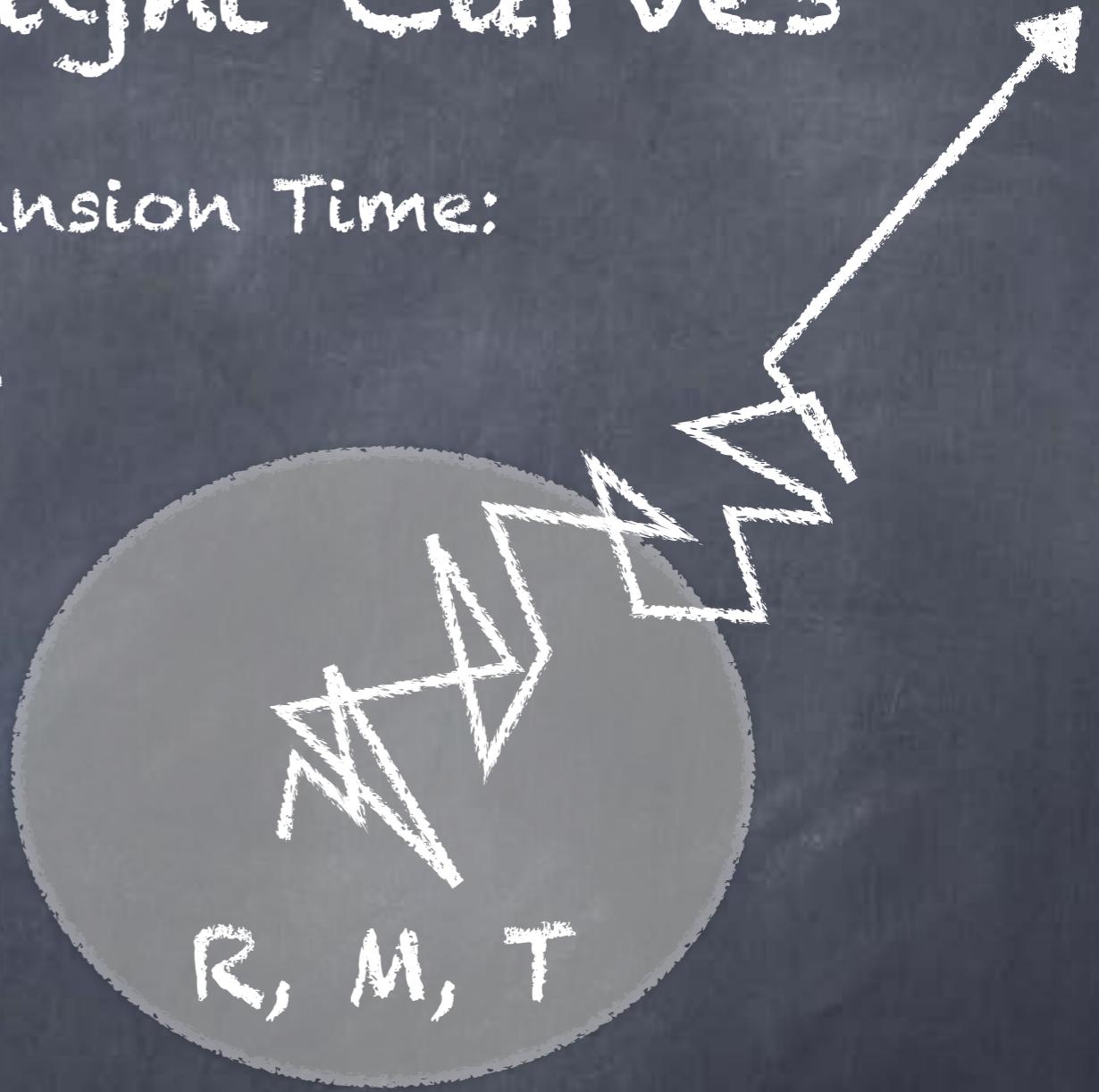
$$t_{\text{diff}} = t_{\text{exp}}$$

$$t_{\text{exp}} = \frac{R}{V}$$

$$t_{\text{diff}} \approx \tau\left(\frac{R}{c}\right) \approx \kappa\rho R\left(\frac{R}{c}\right) \approx \frac{\kappa M}{Rc}$$

$$t_{\text{sn}} \approx \sqrt{\frac{\kappa M}{Vc}} \quad V \approx \sqrt{\frac{E}{M}}$$

$$t_{\text{sn}} \approx 29 M_{\text{sun}}^{\frac{3}{4}} K_{0.4}^{\frac{1}{2}} E_{51}^{-\frac{1}{2}} \text{ days}$$



# Supernovae Light Curves

Diffusion Time = Expansion Time:

$$t_{\text{diff}} = t_{\text{exp}}$$

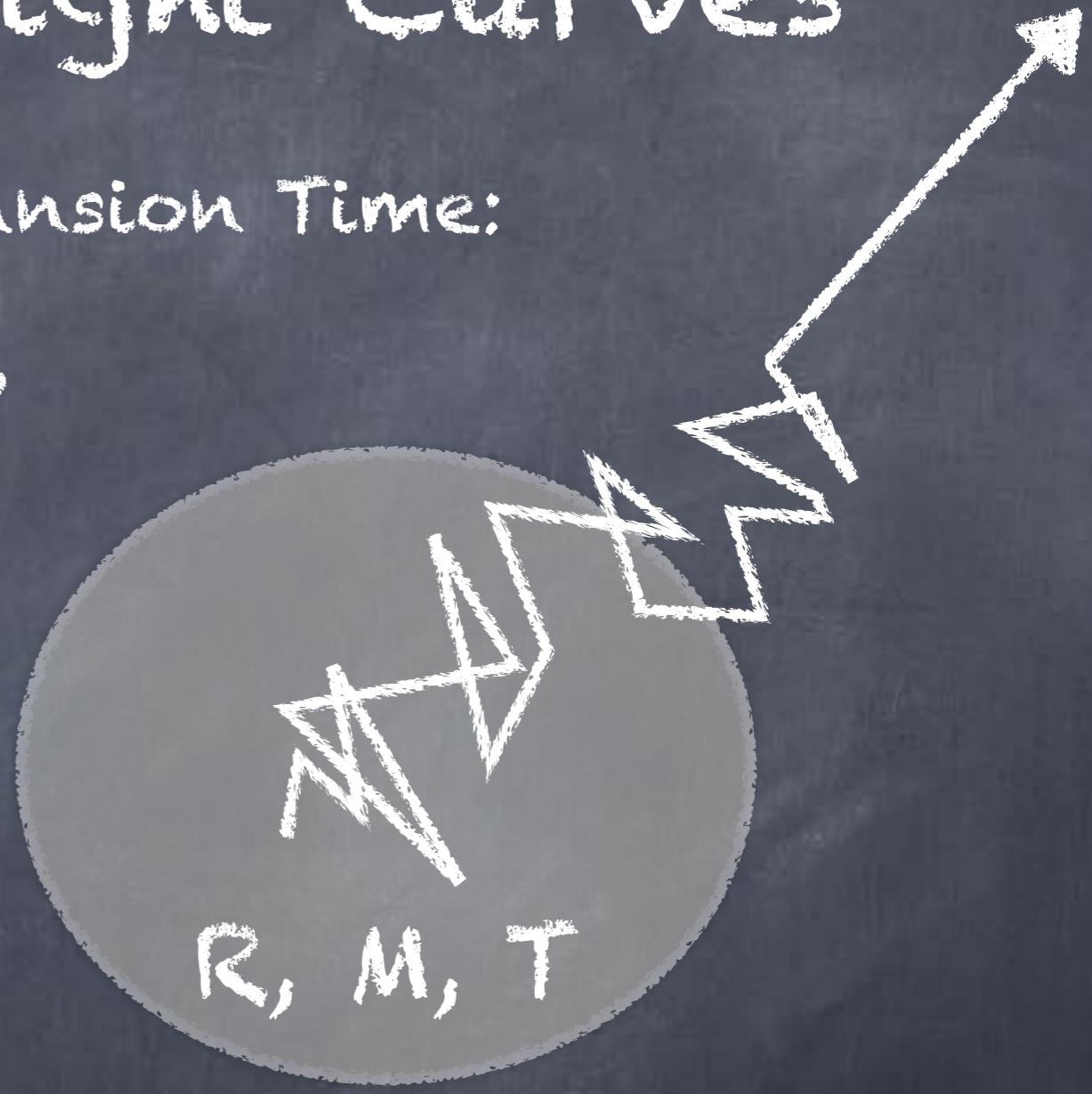
$$t_{\text{exp}} = \frac{R}{V}$$

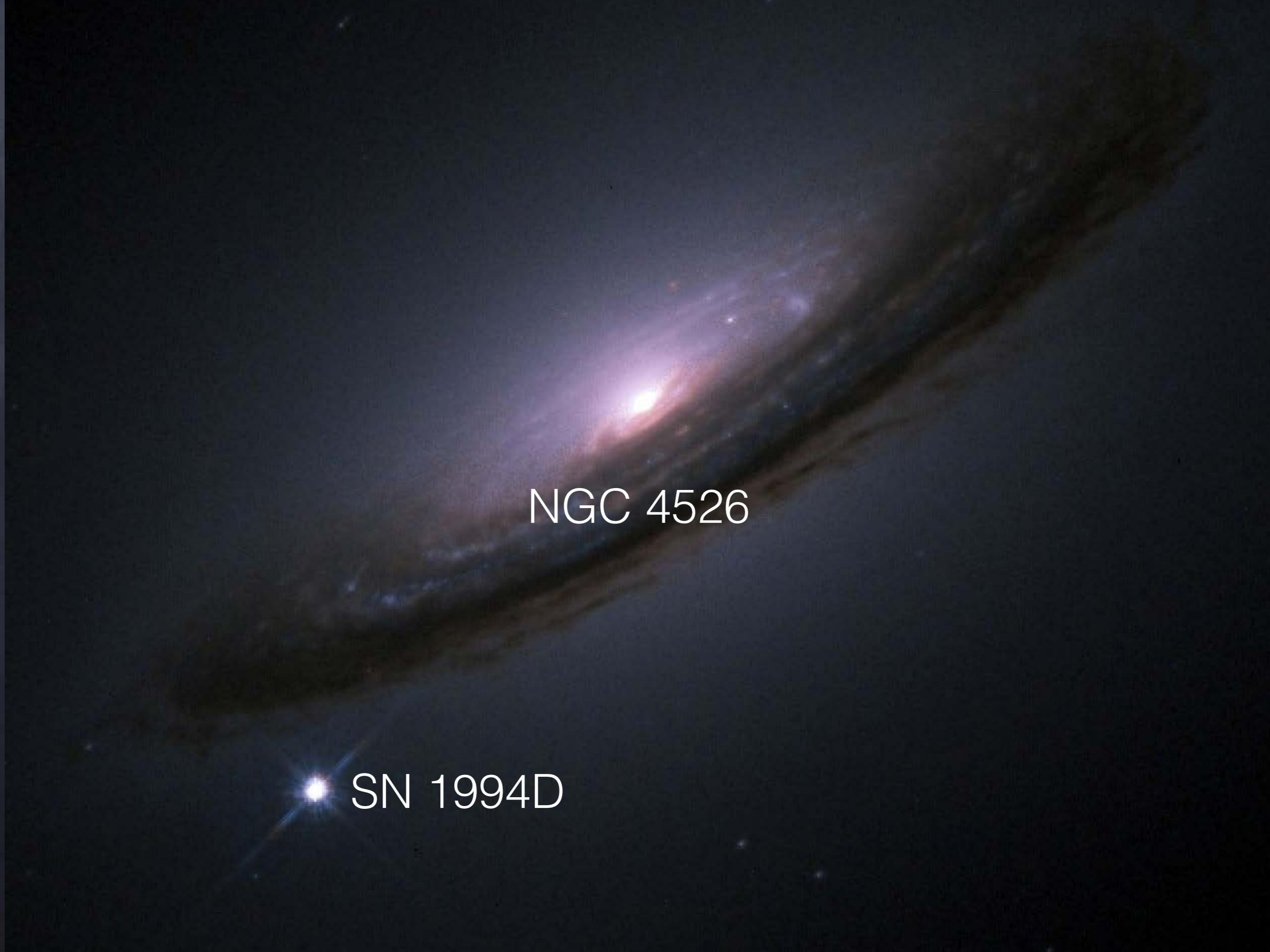
$$t_{\text{diff}} \approx \tau\left(\frac{R}{c}\right) \approx \kappa\rho R\left(\frac{R}{c}\right) \approx \frac{\kappa M}{Rc}$$

$$t_{\text{sn}} \approx \sqrt{\frac{\kappa M}{Vc}} \quad V \approx \sqrt{\frac{E}{M}}$$

$$t_{\text{sn}} \approx 29 M_{\text{sun}}^{\frac{3}{4}} K_{0.4}^{\frac{1}{2}} E_{51}^{-\frac{1}{2}} \text{ days}$$

$$L_{\text{sn}} \approx \frac{E_r}{t_{\text{diff}}} \approx \frac{E_o \left( \frac{R_o}{V t_{\text{diff}}} \right)}{t_{\text{diff}}} \approx \frac{E_o R_o}{K M} \approx 10^{41} M_{\text{sun}}^{-1} K_{0.4}^{-1} E_{51}^1 \text{ erg / s}$$





NGC 4526



SN 1994D



Want to be an Astronomer?

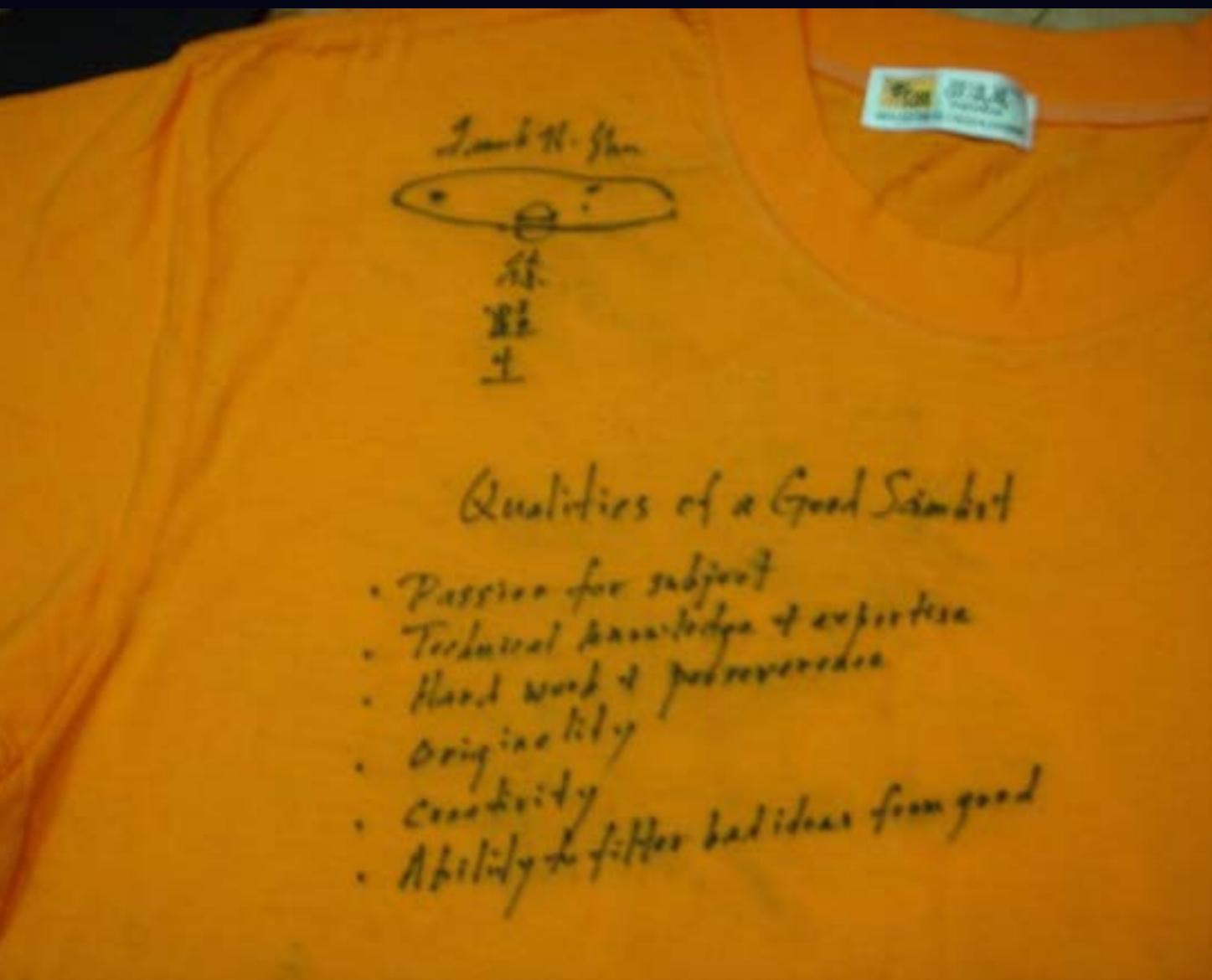
Want to be an Astronomer?

I have some stories and advices to  
share with you!!

# 注意事項

我分享的天文學家生活,是根據我自己的研究生活經驗,不能代表所有的天文學家,所以我下面提到的資訊,謹供大家做參考用。

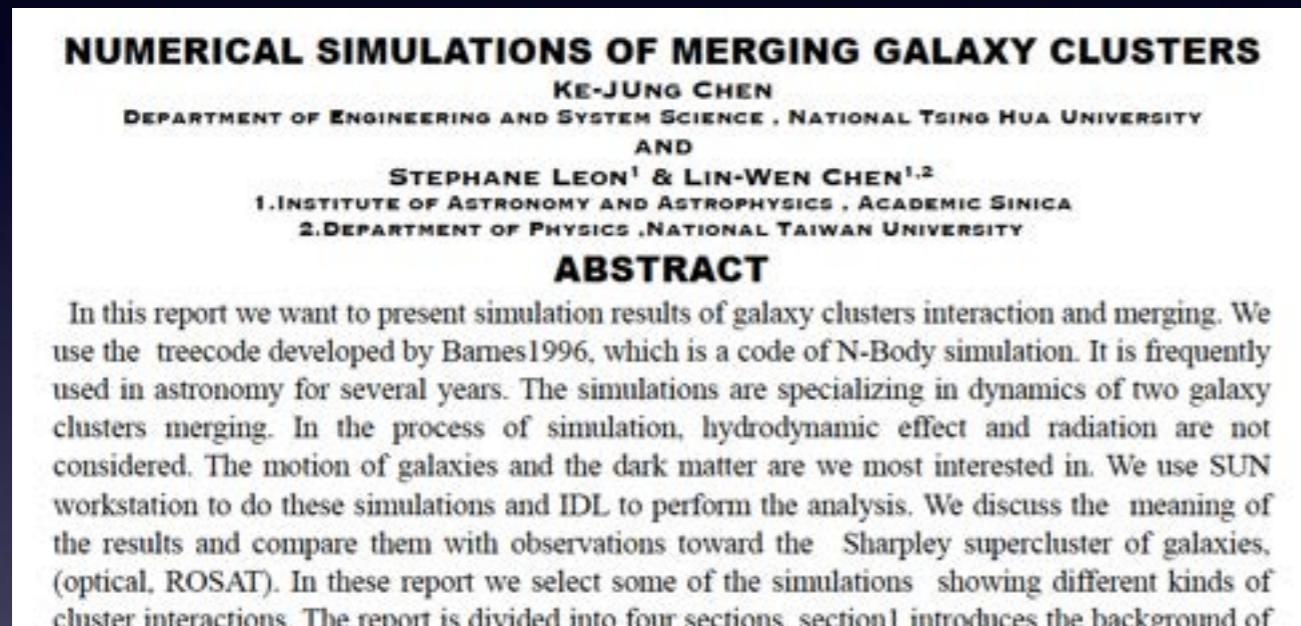
# 研究天文的動機？誤入歧途？？



徐遐生院士

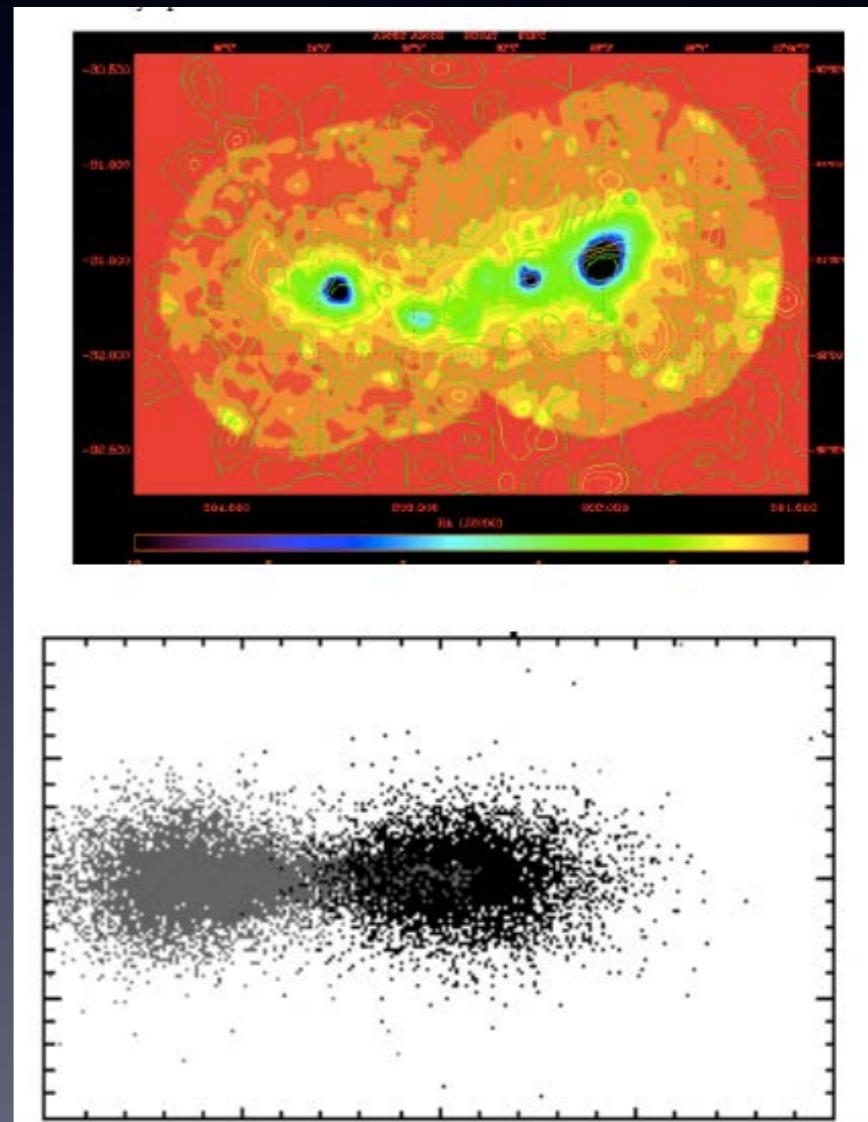
1. 對研究主題充滿熱誠
2. 具有相關的專業知識
3. 努力工作並能持之以恆
4. 原創力
5. 創造力
6. 有能力判斷點子的好壞

# 大學第一個天文專題



## 專題研究報告

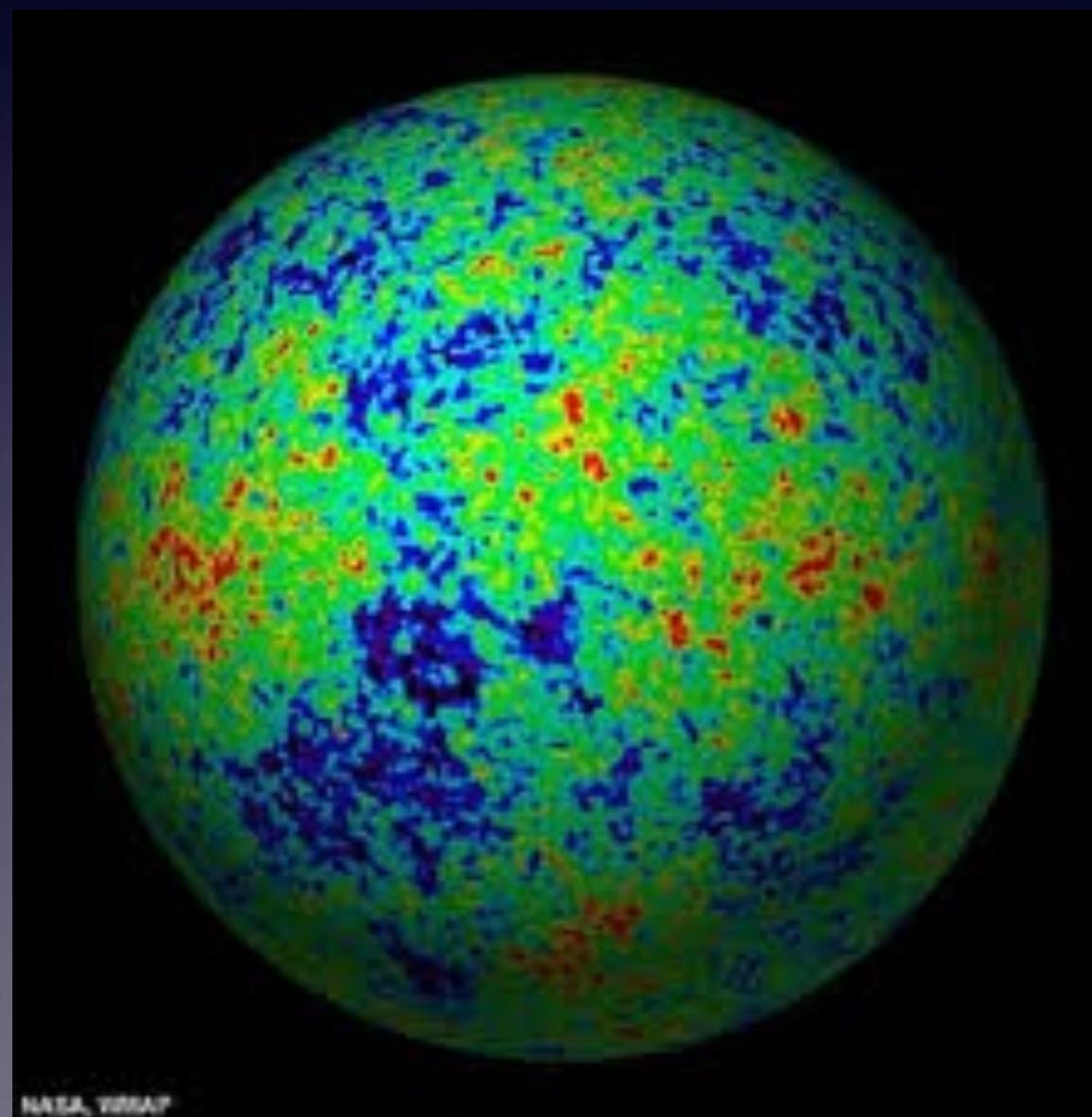
非科班出身,我大學本來念工程然後  
修了一堆物理的課,對天文有興趣的,  
所以想成為天文學家大學的主修可能不是  
最重要的,但是強烈推薦多修一些物理的課



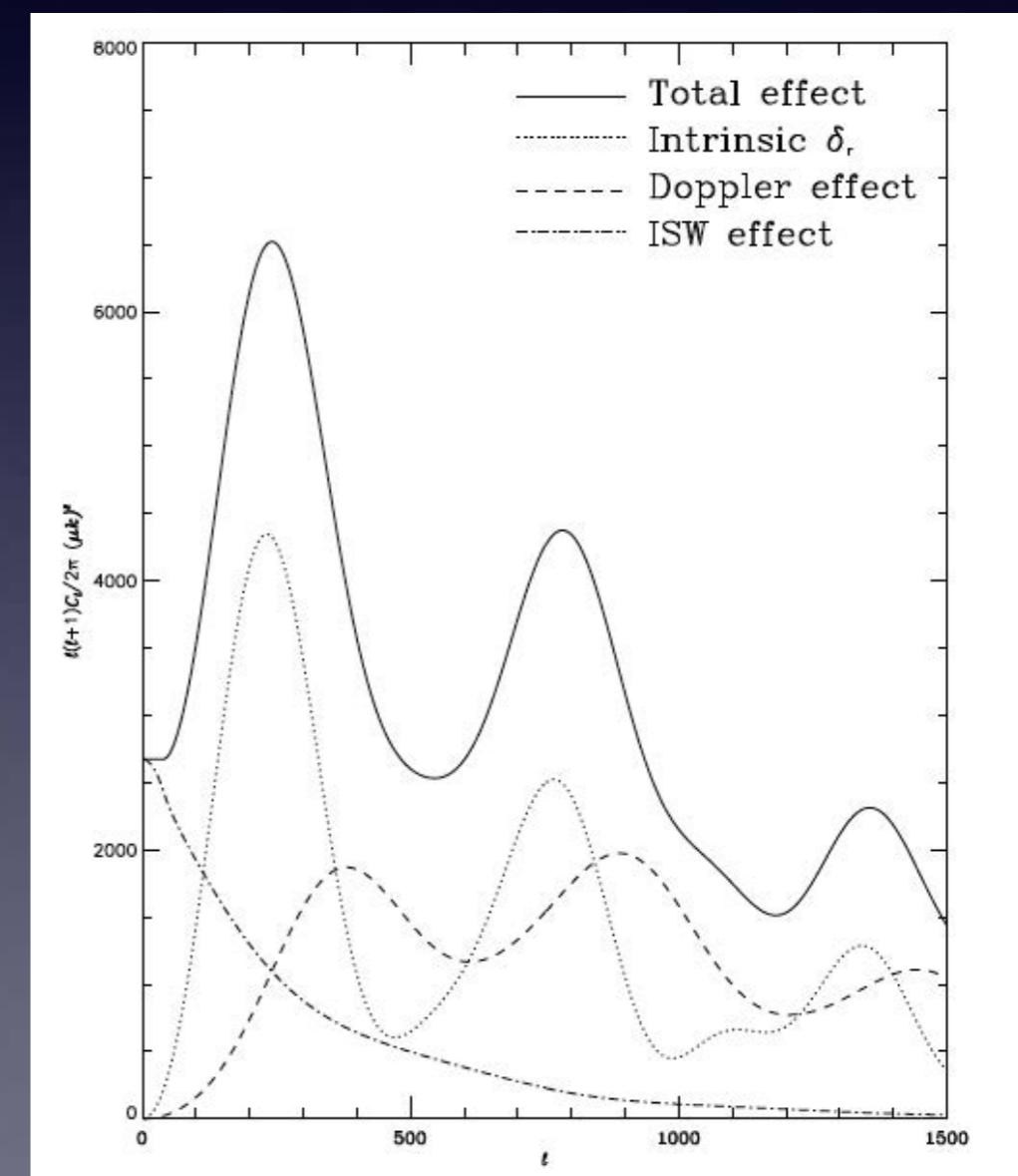
星系團模擬

# 碩士研究

# 宇宙背景輻射的物理



CMB

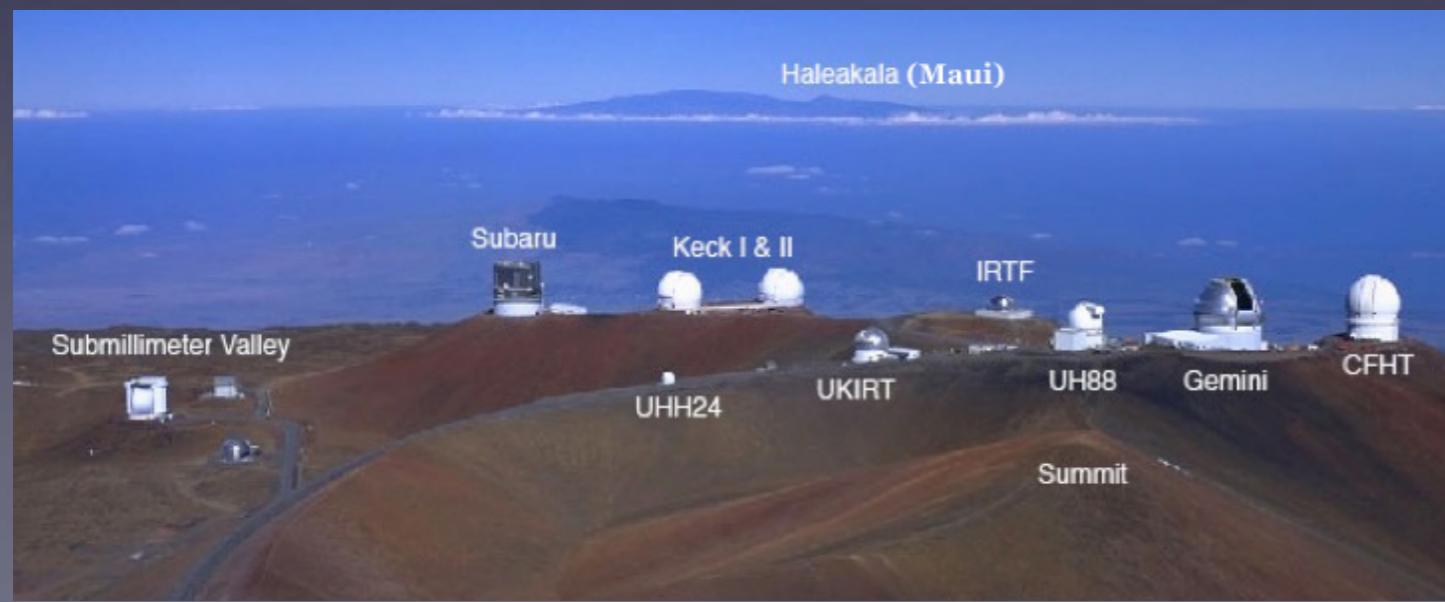


手算CMB頻譜

# 理論還是觀測? 我在夏威夷火山上的一天



AMiBA



Summit

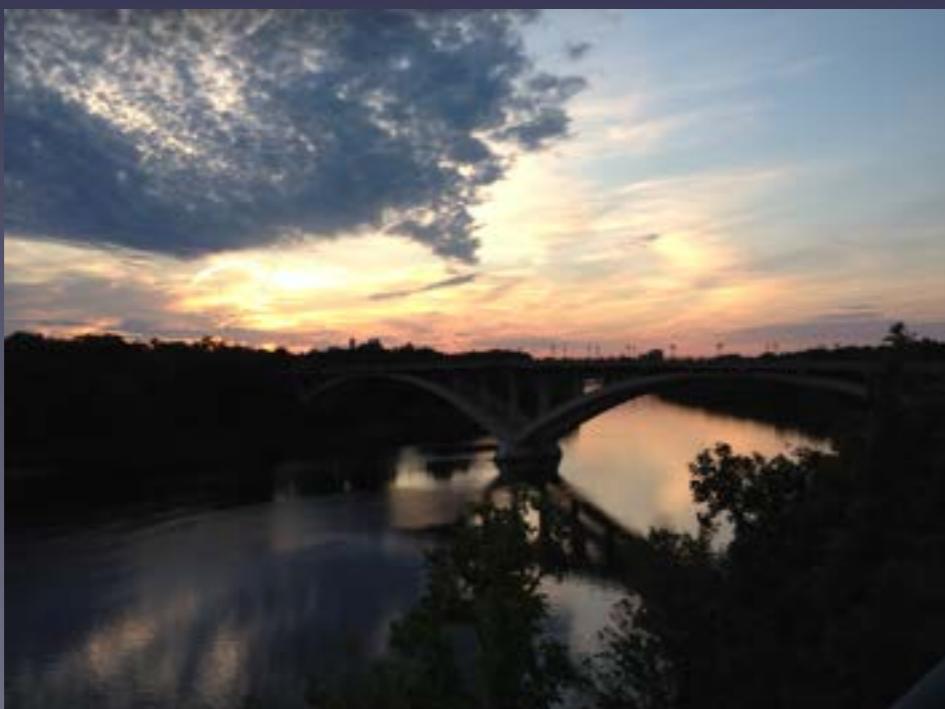


Ken and AMiBA

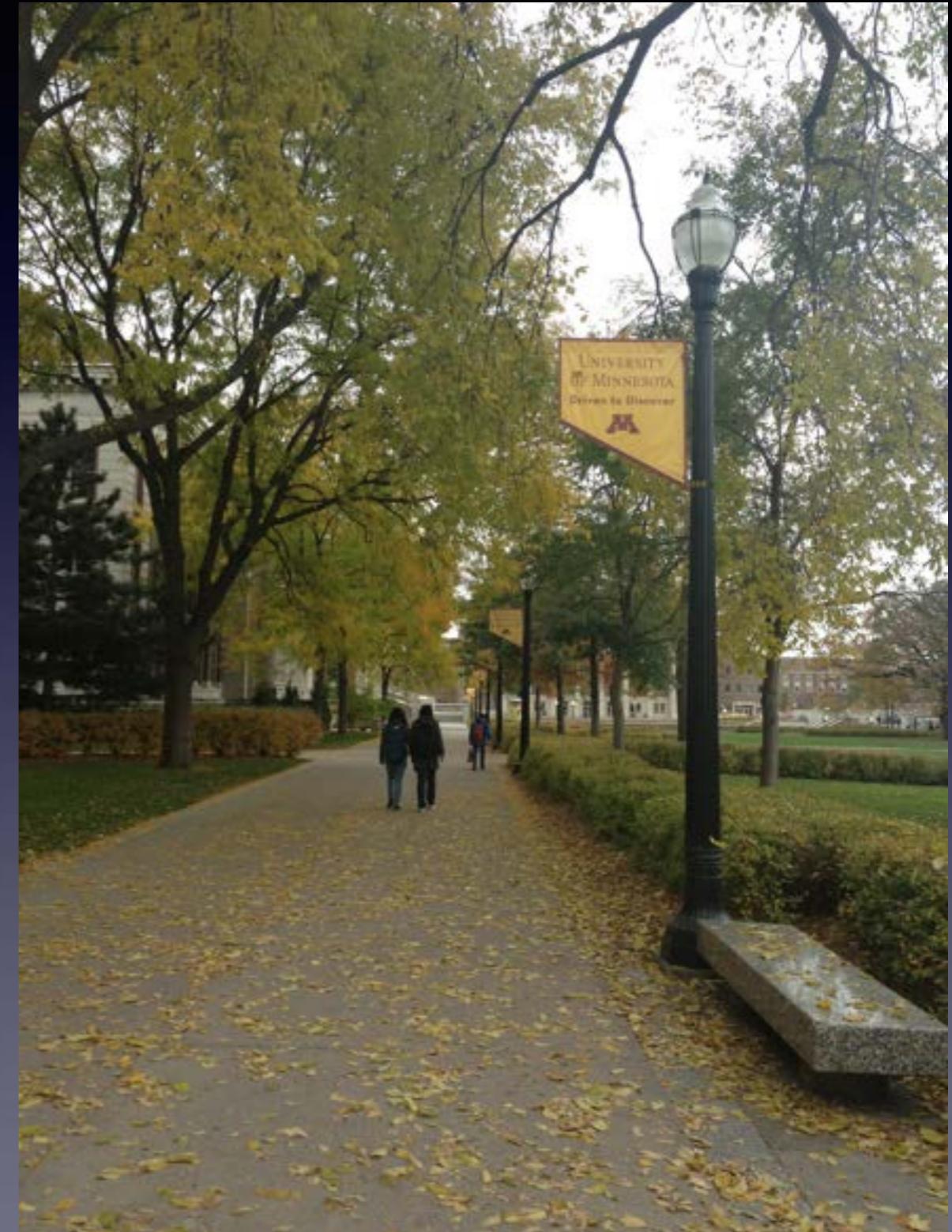
# 念博士班的歲月 — 明尼蘇達大學



物理系館



密西西比河



雙城校區

冬天是超乎想像的冷.... (零下20-30 C)



被雪埋住的愛車



被雪埋住的行人道

# 研究生.....



Itasca



coding, debuging, running, and getting crazy

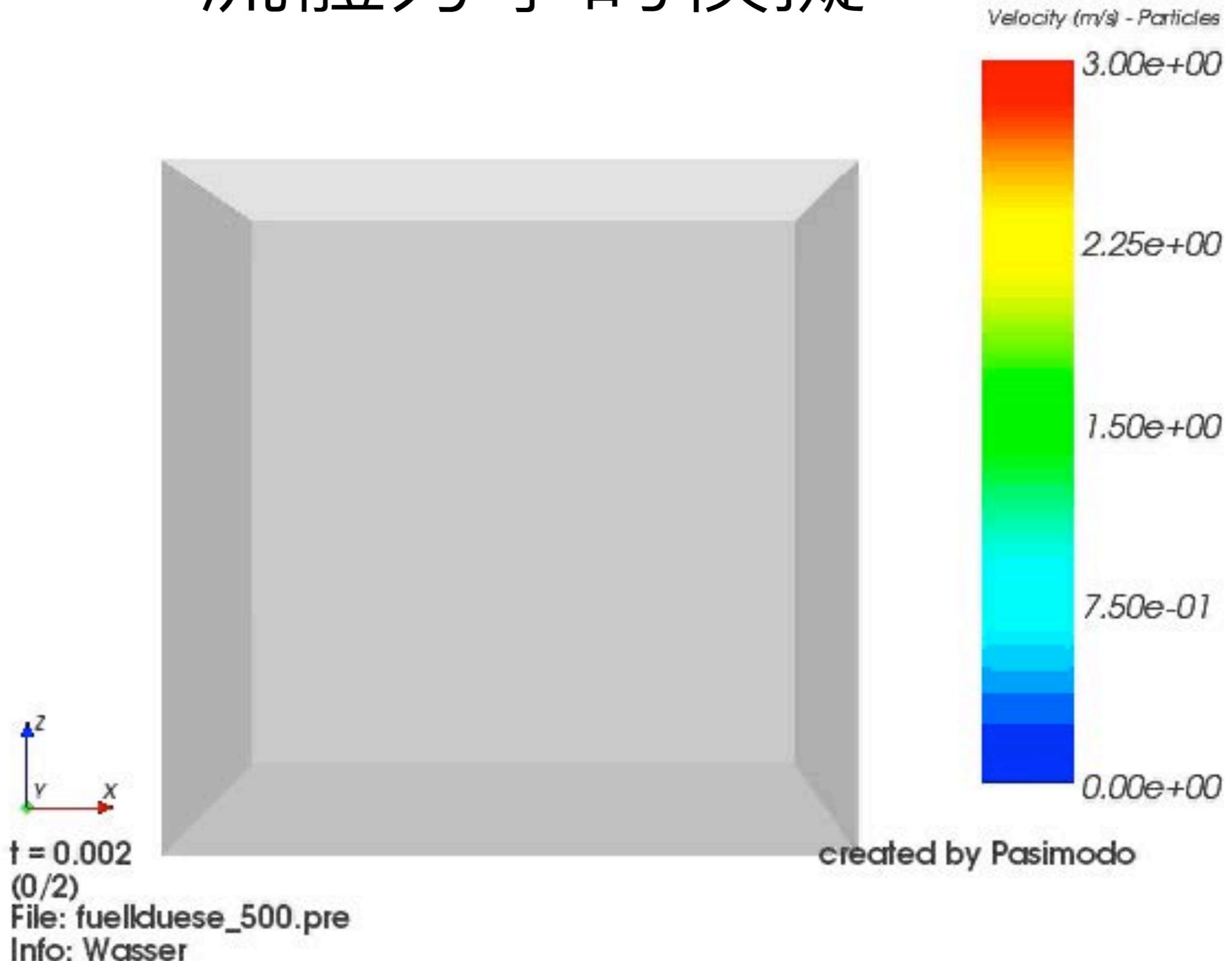


Franklin



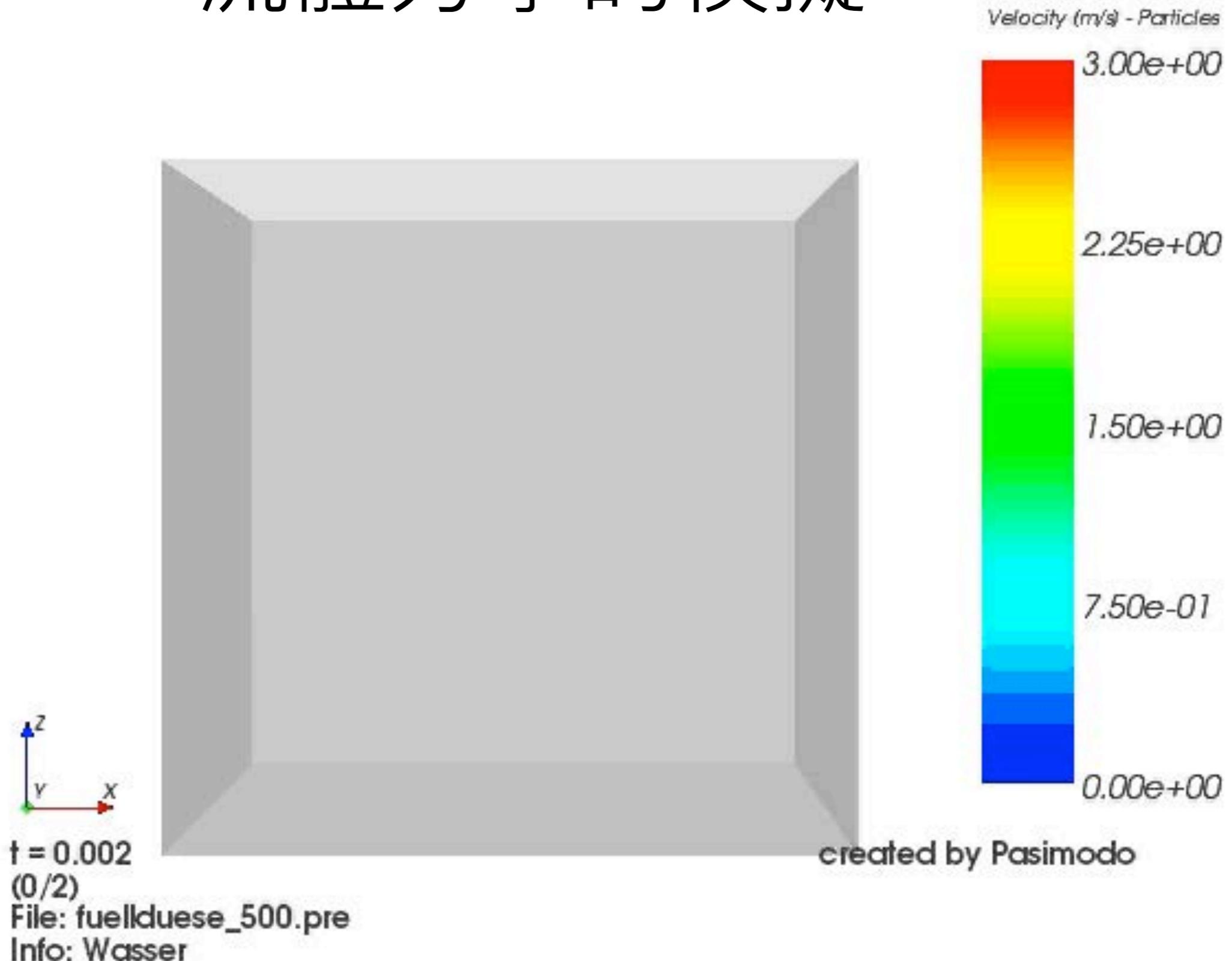
Hopper

# 流體力學的模擬



Lehnart, et al. (2009)

# 流體力學的模擬



Lehnart, et al. (2009)

# Milk and Coffee



Courtesy of Volker Springel (AREPO code, 2009)

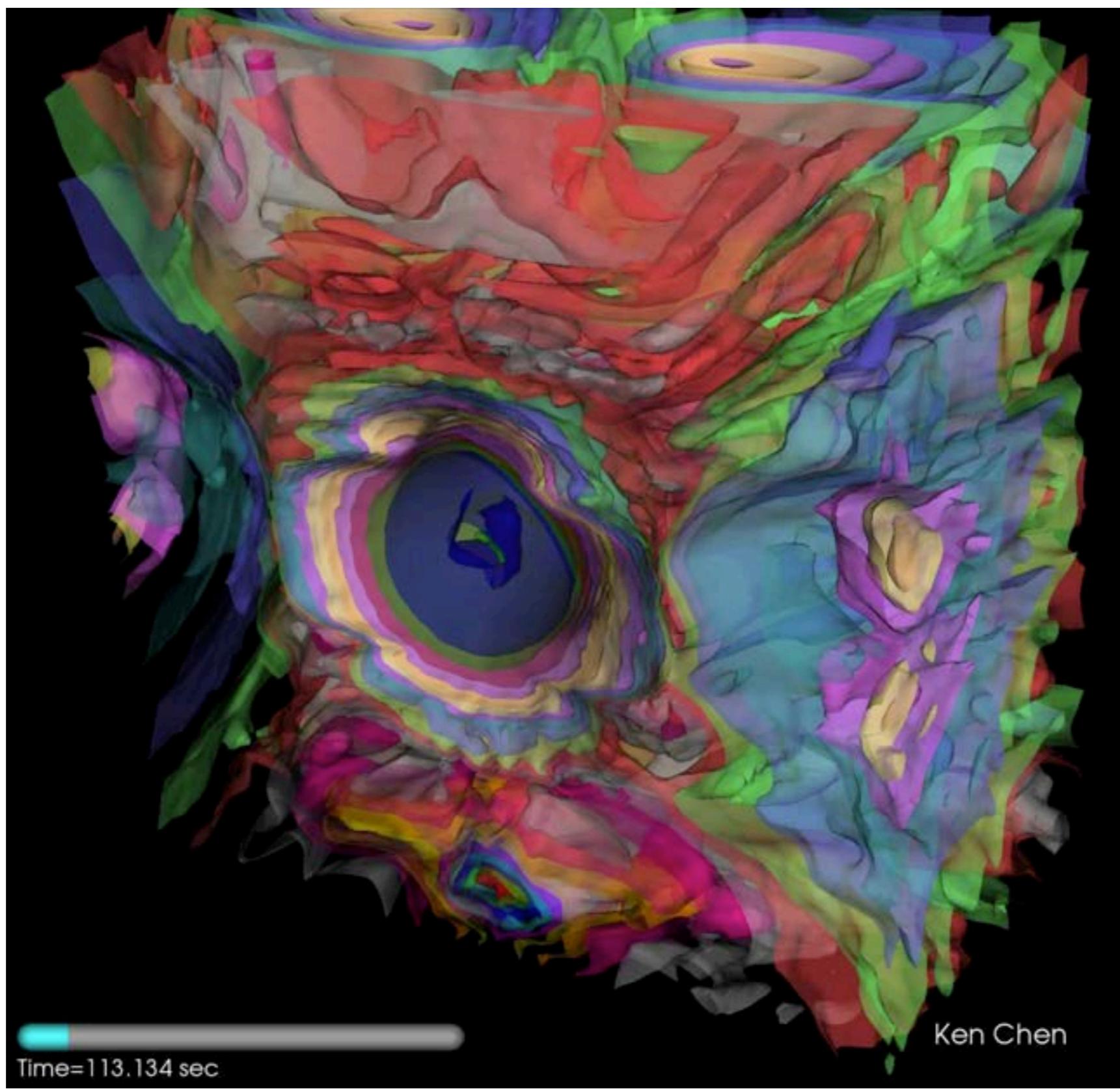
# Milk and Coffee

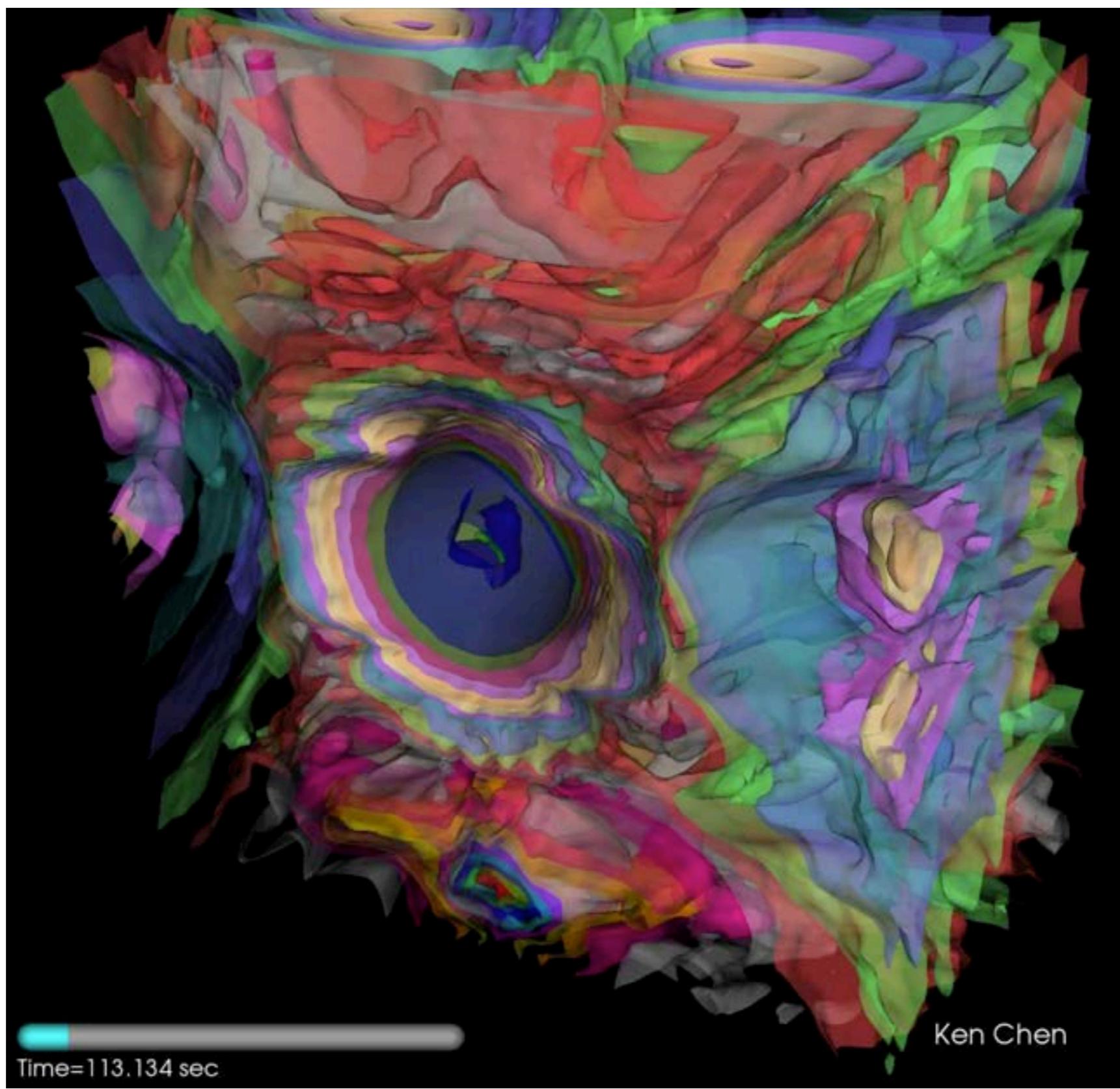


Courtesy of Volker Springel (AREPO code, 2009)

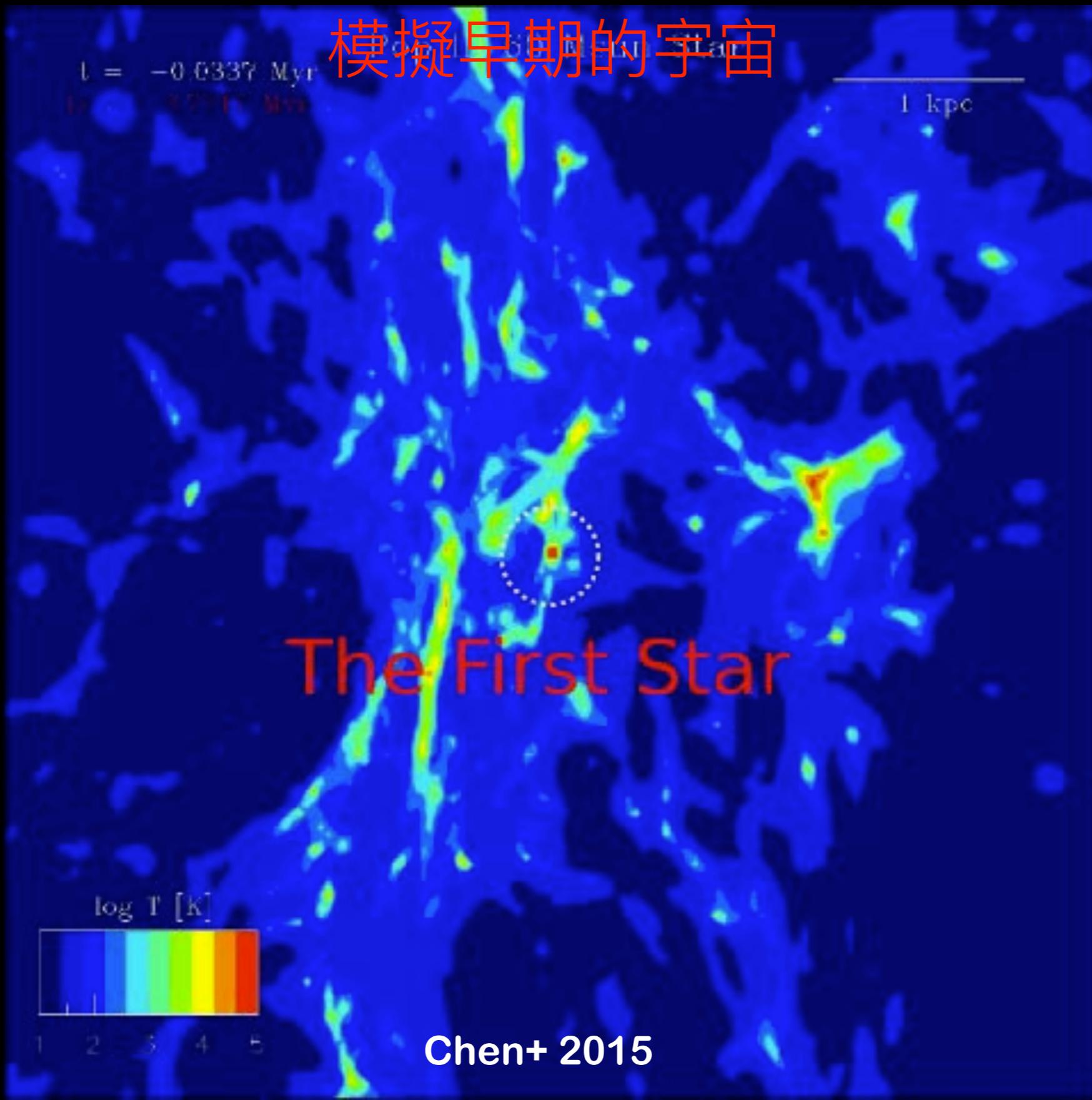
# Milk and Coffee



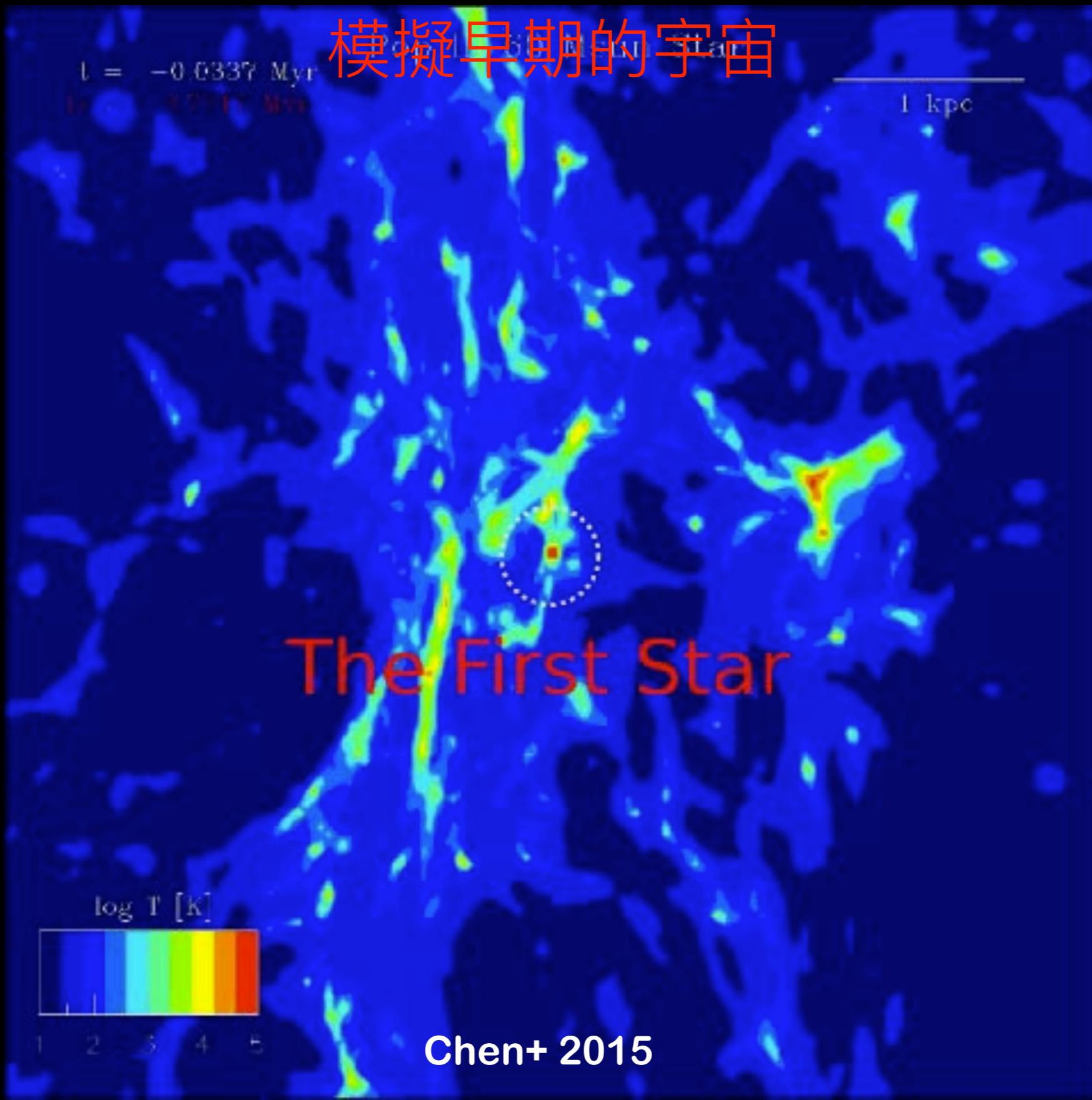




# 模擬早期的宇宙



# 模擬早期的宇宙



# 做研究需要朋友

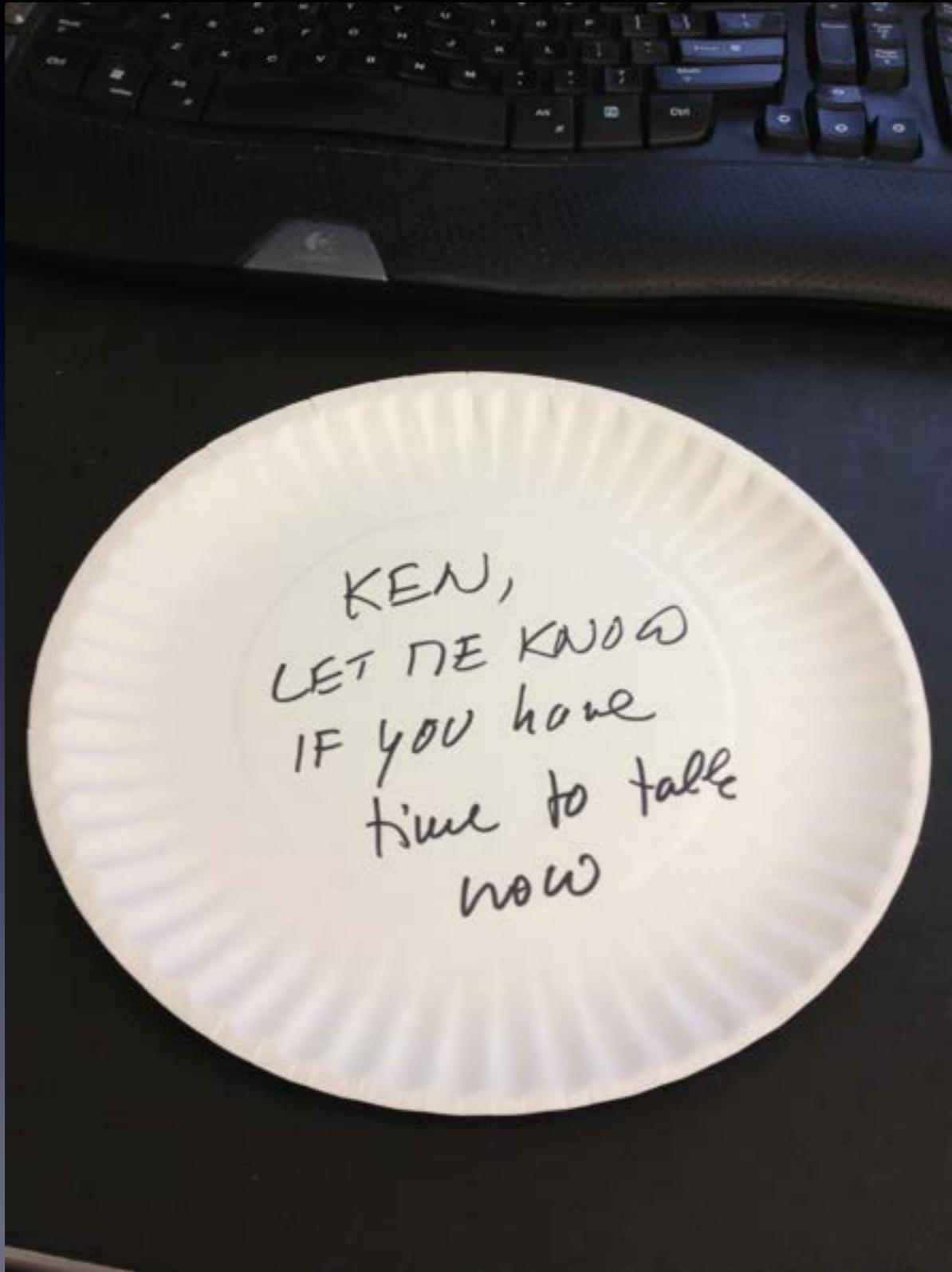


三五好友



朋友做的卡片

# 研究需要小樂趣



老師的留言方式



模擬快打旋的波動拳

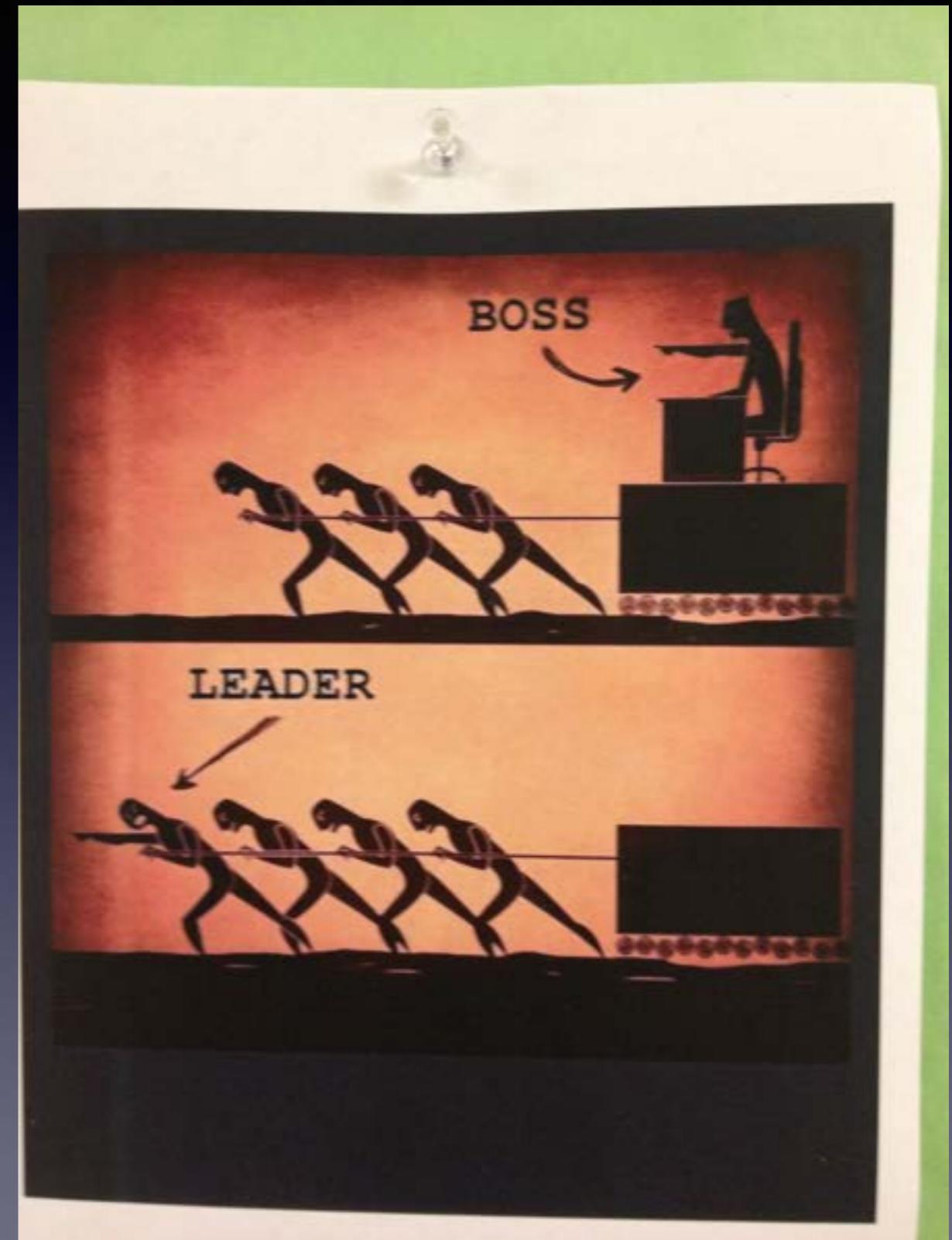
# 訪問德州大學



UT Austin



天文系的辦公室

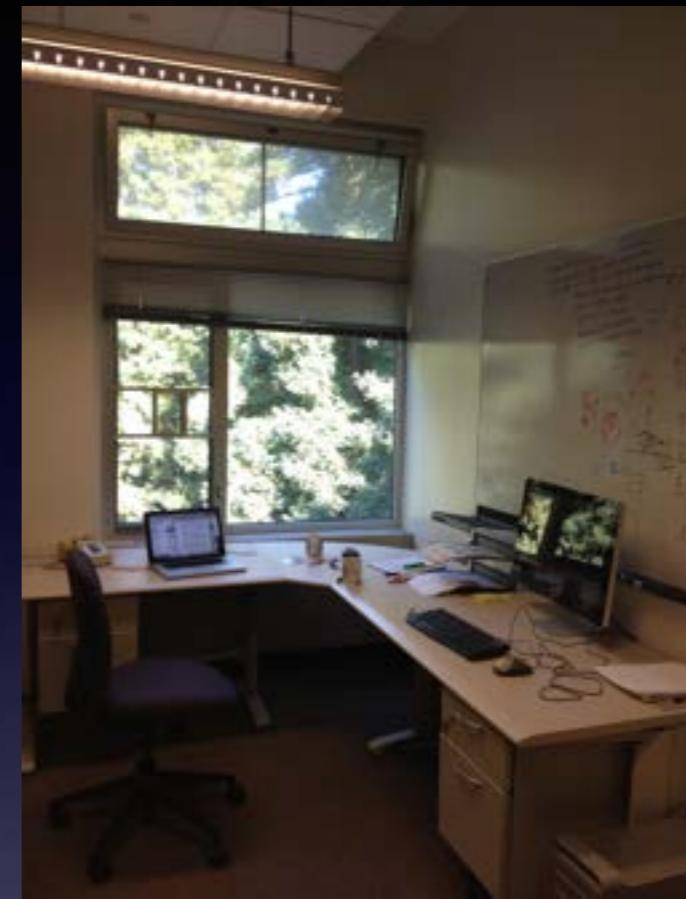


某研究生的貼圖

# 博後生活—UCSC



UCSC大門



辦公室



另類學生



可怕的另類學生



辦公室窗外景色

# 科學山丘上的生活



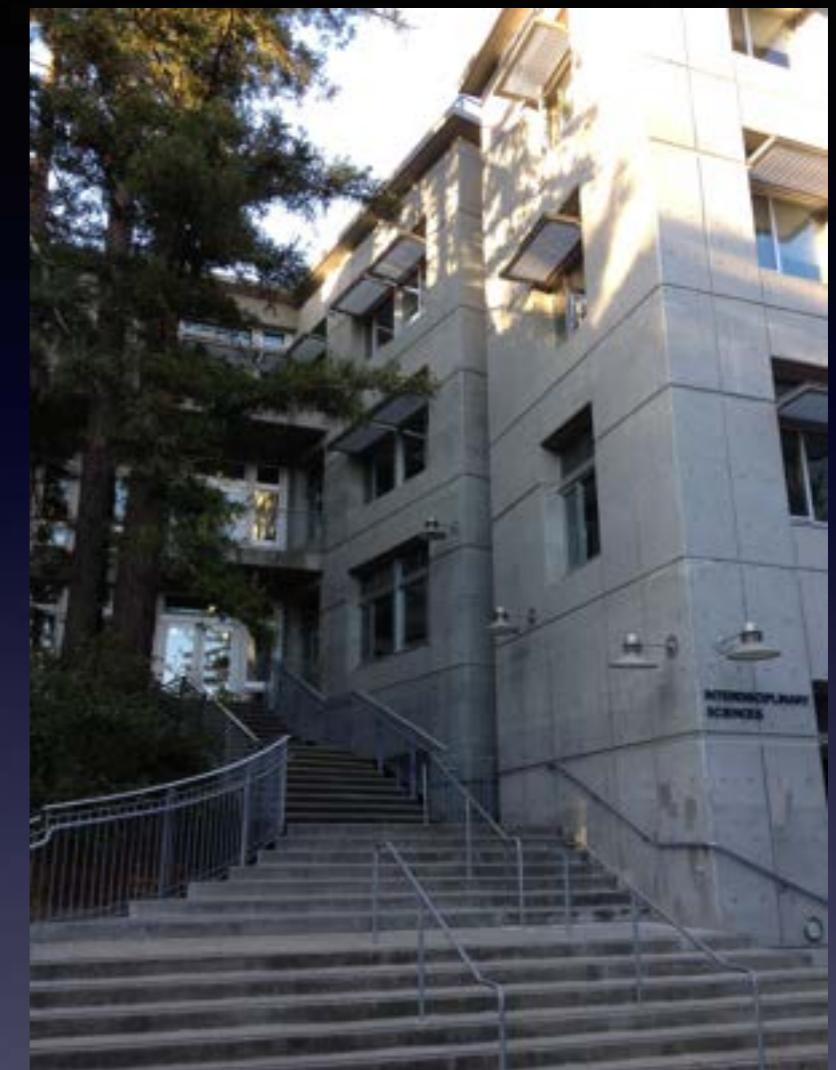
遠眺太平洋



小精靈



浣熊們



天文系館

# 到處演講訪問



專屬停車位



自製名牌 (Intel Inside)



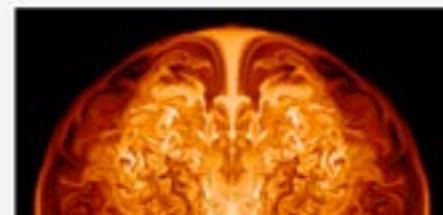
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## Slice Through the Interior of a Supermassive Star



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LiveScience Staff  
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研究受到注意—博版面

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UNIVERSITY OF MINNESOTA

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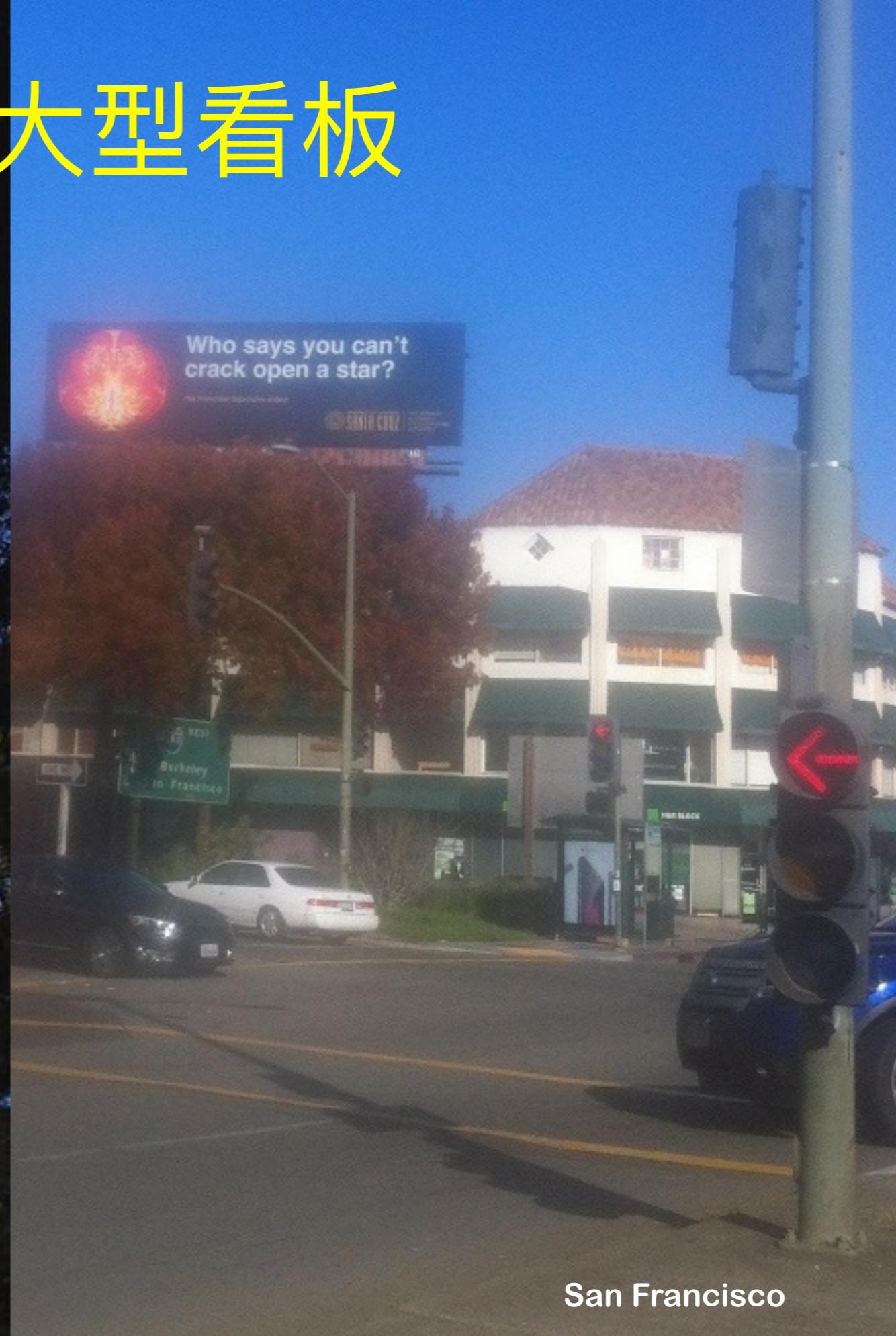
Volume 27 Number 1



# 研究旗幟與大型看板



UCSC Campus



San Francisco

# 旅行是天文學家的福利



海濱遊樂園



太平洋衝浪



紅木大樹



樹隧道



滑雪

# 經驗分享與建議

多數取自我自己的臉書 :D



歡迎跟在臉書上做我朋友, Find “Ken Chen”

# 申請美國學校 — 越來越難

建議有志出國攻讀博士的同學，其實可以先在國內拿到碩士學位。首先，碩士已經具備基礎的研究能力，會比較受國外大學歡迎，而且台灣的訓練很不錯，碩士也都有了寫論文的經驗。再者，年紀成熟一點，再到國外那樣全然陌生的環境，總是比較容易克服一些生活上的挫折。還有一個重要因素就是fellowship，尤其是一些大學像Stanford、Michigan、Berkeley等，想直攻博士的話，GPA沒有4.0或3.9真的很難申請。

# 申請美國學校

每次deadline一來,就要開始寄提醒信請大家準時交資料,順便提醒今年申請學校或找工作的朋友,記得早點跟幫忙寫推薦信的老師說,讓他們可以及早準備你的推薦信,如果你到最後一刻才找老師,他們會很不開心的,就像今天出的習題叫你明天交出來一樣,所以現在就可以開始問老師了啦:D

給學生：建議大家把要申請學校的名單先弄出來並註記學校送件截止日期,然後把它與cv一併寄給老師們做參考,這樣老師也比較好安排他們的推薦信與送達時間。

# 申請美國學校不為人知的一面

如果台灣出國念博士的人越來越少,以後要出去難度也會越來越高,造成這種情況的原因是,一個系如果有收過台灣學生,然後這些人的學業研究表現優良,系上就會喜歡錄取台灣學生,反言之如果這個系都沒收過台灣學生或很久沒招過台灣人,審查委員們的對台灣學生沒印象,錄取台灣人的機會自然大大降低。

# 找指導教授

給未來的博士班學生一個建議,指導教授的話和爸媽一樣,選擇你覺得合理的建議聽,會這樣說有兩個原因,第一是爸媽與教授,除了年紀比你大之外,並不見得一定比你厲害,更重要的是你的未來前途由你自己負責,所以你有權利自己決定,但是千萬不要意見不和而跟指導教授與爸媽吵架,到頭來你只會是吃虧的一方。

# 念博士班的經費



給在念博士班的學弟妹一點建議,如果想要畢業以後長期從事學術工作,務必設法在博士班或博士後期間拿到研究fellowships,這不但讓你有自己的研究經費與自由,也對你未來找教職會有很大的幫助。

# 博士班生存



閒聊--研究生如何跟指導教授要資源

以前在美國唸博士班晚期的時候,我指導教授的DOE與NSF經費的progress reports,超級電腦時間的proposals主要都是我寫的,以前同學們常抱怨沒錢出去參加研討會,我早就每年出國開會4-5次,飛到變成航空公司的白金卡會員,比老師的金卡還高,看到跟自己研究相關的研討會,就跑去跟老師說, I am interested in this conference. 老師通常會說: Yes, you should go. Our grants can cover your travel expense. 與大家分享一個心得,當研究生除了自身研究,如果可以也要努力幫老師爭取資源,一旦拿到各式補助,當你需要什麼東西要跟老師要的時候,老師也沒有藉口說不行。

努力爭取研究資源

# 努力爭取研究資源

1. University of Kyoto, Japan, Conference Travel Grant, 2012: \$705
2. American Astronomical Society, International Travel Grant, 2012: \$1,362
3. University of Göttingen, Germany, Conference Travel Grant, 2012: \$780
4. International Astronomical Union, Travel Grant, 2012: \$313
5. American Astronomical Society, International Travel Grant (IAU GA), 2012: \$1,378
6. American Physical Society, Travel Award for Excellence in Graduate Research, 2012: \$500
7. American Physical Society, Division of Nuclear Physics—Travel Award, 2012: \$300
8. American Physical Society, Division of Astrophysics Physics—Travel Award, 2012: \$600
9. Sigma Xi Foundation, Research Grant, 2012: \$675
10. UC High-Performance AstroComputing Center, Travel Grant, 2011: \$1,267
11. National Science Foundation, Head Meeting Registration Fee Waiver, 2011: \$450
12. American Physical Society, Division of Astrophysics Physics—Travel Award, 2011: \$300
13. American Astronomical Society, International Travel Grant, 2011: \$2,138
14. International Astronomical Union Travel Grant, 2011: \$365
15. American Physical Society, International Travel Grant, 2011: \$800
16. American Physical Society, FPD Scholar Award, 2011: \$1,000
17. University of Minnesota, Thesis Research Grant, 2010: \$2,500
18. CECAM, Conference Travel Grant, 2010: \$1,668
19. University of Texas at Austin, Conference Travel Grant, 2010: \$950
20. University of Minnesota, Lump-Sum Travel Fellowship, 2009: \$600
21. National Science Foundation, International Travel Grant, 2009: \$1,000

# 研究獎金與肯定

# 研究獎金與肯定

1. NSF, Scientific Visualization Competition, the Finalist in Graphics, 2016
2. University of Minnesota, Best Dissertation in Physical Science, 2015
3. Berkeley National Laboratory, NERSC Achievement Award, 2015
4. East Asian Core Observatories Association, EACOA Fellowship, 2015
5. International Astronomical Union, Gruber Fellowship, 2013
6. The University of Minnesota, Johnston Fellowship, 2012
7. Kavli Institute for Theoretical Physics, Graduate Fellowship, 2012:
8. Advances in Computational Astrophysics, Best Paper Prize, 2011
9. MSI Research Exhibition, Best Poster Prize, 2011
10. University of Minnesota, Edmond Franklin Fellowship, 2008

# 發表論文與找工作

閒聊--博士生的論文數

發表論文對於一位科學家就好像製造產品對於一家公司,我們都希望產品的質與量都能越高越好,所謂好的標準是因人而異並且很難定義的,我覺得當一位博士生已發表2-3篇第一作者國際期刊論文,他具有獲得博士學位的資格,也具有競爭一般博士後工作的門票,然而想要競爭高度自主與較好待遇的博士後研究獎金,最好建議還是能衝到4-5篇論文,這帳面上的論文數字其實只算是資本額,實質上的效益必須考慮一個很重要的因素---推薦信,尤其是你博士導師的推薦信,導師研究口碑,為人處事,是否高徒滿天下...都是考慮的因素,曾經聽一位老師說過,他寫推薦信的時候,一開頭就說他指導過十幾位博士生,到目前為止大約有七成的都變成名校教授,我目前所推薦的這位學生,在我所指導過的學生裡面,大約排Top 10%,委員們覺得這位學生的程度如何? 如果有一封這樣的推薦信,對申請絕對是大大加分,所以我覺的有效論文是應該這樣定義:

有效論文數 = 推薦力x實際論文數

推薦力: 是介於0.5 - 2

如果老師真的很推你,然後老師本身名氣大,公信力強,這推薦力可是超過1以上,但是如果你每天跟老師互看不順眼,或老師自己不太會推薦別人,那這個推薦力可能會小於1,結論在好好研究,努力出論文之餘,也設法培養你未來寫推薦信的人選吧。

# 想一直看星星，找教職？

美國研究型大學的教授是怎麼被選出來的？？

UCSC天文系有不少老師歲數已逼近退休年齡,所以近幾年都有在招新老師舉動,史丹老師也常跟我聊到系上招新老師的情況,以去年為例,系上招聘一位宇宙學的老師,收到大約152份申請資料,老師說約三分之一的人直接刷掉,他們不見得是申請資料不好而是今年找的是宇宙理論方向,領域差太遠的申請資料直接資源回收,通常主要有三位老師負責審資料,一個人讀 $152*2/3*1/3 \sim 33$ 份,每個老師列出自己心目中前最佳十人名單,然後聚在一起討論把三十人名單縮小至五~十人,這個名單稱之為short list,在名單上的人會被正式邀請到系上面試與發表演講,然後從面試表現,最後再決定要聘誰,基本上能進來這個名單的人,單論研究資格已經算是合格的候選者,面試主要是考察候選人的臨場反應與系上人員互動情況。

史丹老師個人審核的標準

## 1. 推薦信

先看推薦信才決定要在這份申請資料上花多久時間,推薦人的來歷很重,如果老師不認識或沒聽過推薦者,那這封推薦信對他而言很難有很強的說服力,接著看推薦人有沒有用到BEST, OUTSTANDING 等關鍵字。

## 2. 研究成果

主要看申請者研究發表的論文,通常只算“第一作者的文章”數目和引用次數,審的人標準不一,但是以老師的標準看的話,這數字非常驚人.....

## 3. 研究經歷

看看是不是在名校或重要的機構作研究,是否有拿過各類研究獎金,這個指標是評量申請者未來申請外界經費的潛力。

## 4 .最後才是研究計畫,教學理念與指導學生的經驗。

這些指標主要是針對研究型大學適用,教學型大學的順序是剛好想反,對不同學校與審核人,上述條件可能不盡相同。

# 教職前哨戰

以我之見,在主要研究型大學得到終身職研究工作的人,主要分成三種類型的研究者

- 1 頂級名校博士(Top5) > 一或兩任有獎博後 > 教職 (佔50%)
- 2 一流大學博士(Top50) > 知名機構一般博後 > 有獎博後 > 教職 (佔40%)
3. 愛因斯坦路線與其他 (佔10%)

名校指標:通常名校的學生素質原本就好,知名大學通常能提供比一般學校更佳的師資與學習資源,所以名校學生的成功率自然就比較高,但這不是絕對。

博後指標:博後是一個學生變成教職員的一個重要階段,能獲得博後研究獎金通常代表這個學生做了很不錯的博士論文,在該領域獲得專家與大老們的認同,有機會能成為該領域的領導者,另一方面該學生能拿到博後獎金也表示他以後能爭取外在研究經費的潛力,這是一點在經費緊縮的現在,是非常重要的。

我想表達一個訊息,一個做研究人的track比他的起跑點還重要,不論他是不是名校畢業,博士讀多久,博後做多久,只要他的track走勢往上,這裏指研究的質與量,工作的重要性與學界風評,最後都會有拿到學術工作的機會。

# 如果不只想看星星,還能做什麼?

我從東尼身上學到的事情

因為研究的關係,我認識了東尼這個年輕人,他算是半個台灣人,父母來自台灣而他在美國加州出生,東尼繼承了台灣父母的優良血統從小在學業上的表現就很突出,他2007年以破紀錄的成績(GPA 4.35/4.00)畢業於史丹佛大學物理系,也是當屆畢業生代表,但是成績優異的東尼並沒有繼續念研究所,反而是跑到著名的投顧公司高盛當了顧問,做了兩年之後,不巧遭遇美國金融風暴,他決定回來唸書,他申請到哈佛的天文物理博士班,在哈佛的時候,他是著名赫茲獎學金暨NSF研究生獎金的得主,然後他又以短短四年的時間從哈佛拿到了博士學位,也做了幾篇很不錯的論文,畢業之後東尼就在學術界消失了,原來是他老兄跑去自己開公司了,他現在不寫論文反而是猛發專利,他現在的目標是研究新材料應用在未來能源科技上,我很看好他的點子,說不一定很快就可以造福全人類,寫了這些有關東尼的事,不是要說明東尼有多棒,而是我從他身上學到了幾件事,第一件事,就是年輕人不能驕傲,總以為自己很聰明而不去努力,當你有機會看到類似像東尼的人,你會發現聰明的人還真不少而且越聰明的人越努力,第二件事情是我們必須從新思考什麼叫學以致用? 東尼的博士論文是研究超新星爆發,跟他現在研發材料的工作完全無關,為什麼東尼還是做的一樣好,因為東尼在大學與研究所的訓練給他打下很好的思考邏輯基礎,所以他學新的東西一下就上手,更重要的事,東尼一點都不在乎別人的眼光,他老兄做他自己覺得重要感興趣的事,然後把它做到最好,東尼這樣精神值得好好學習。

# 送給大家的兩句話

科學研究工作最大的報酬不是金錢,名聲或權力,而是研究中所得到樂趣,了解從來沒人理解的自然現象,拓展人類知識的版圖。

-Ken's random thoughts

如果你要學習一個技能,最好的方式就是從實作去學,如果你要變強,最好的方式就是跟比你強的人一起工作,學習他們的觀念與態度,通常這就是他們比你強的原因。

-Ken's random thoughts

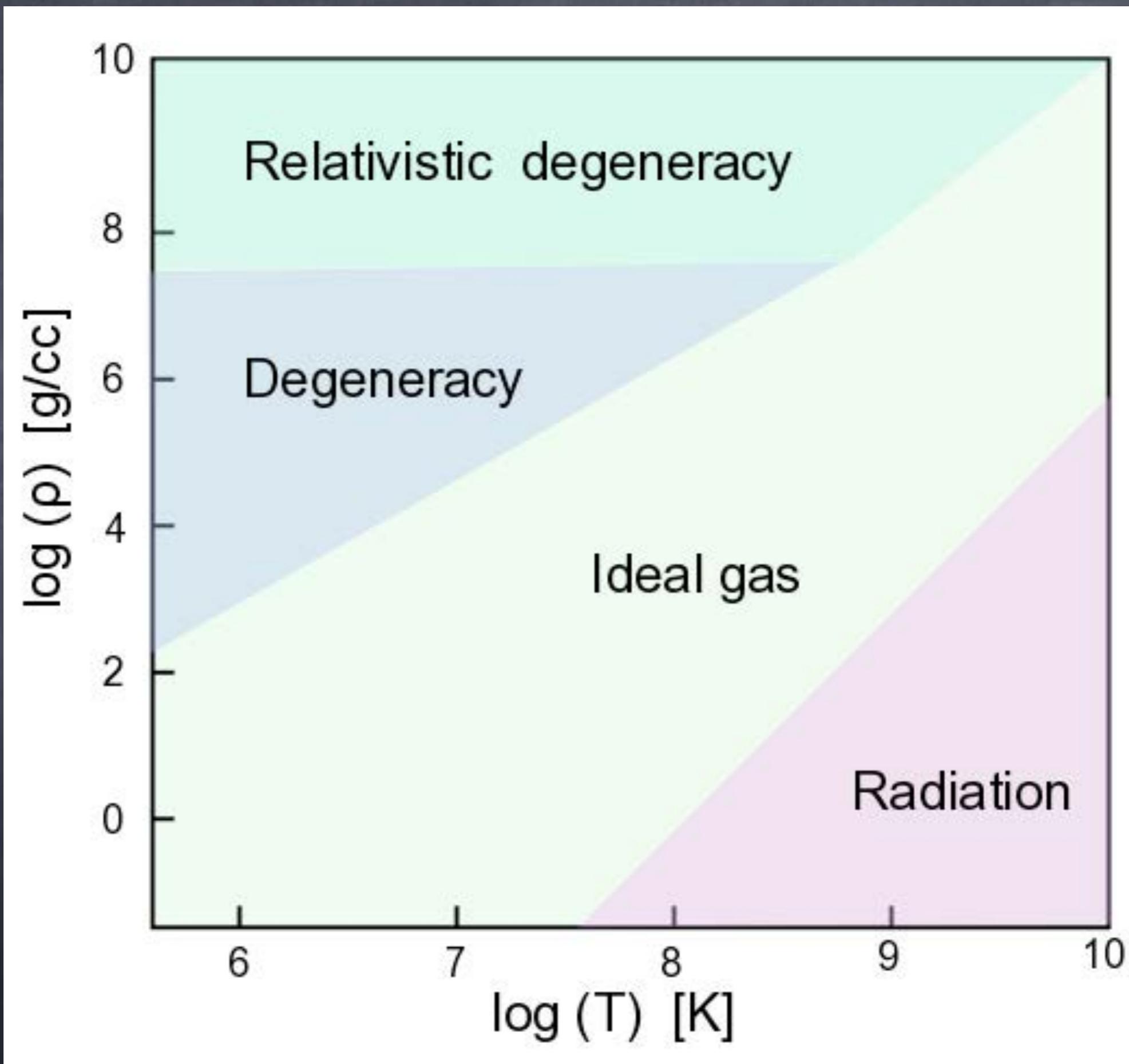
告訴我你的想法？？

Q&A

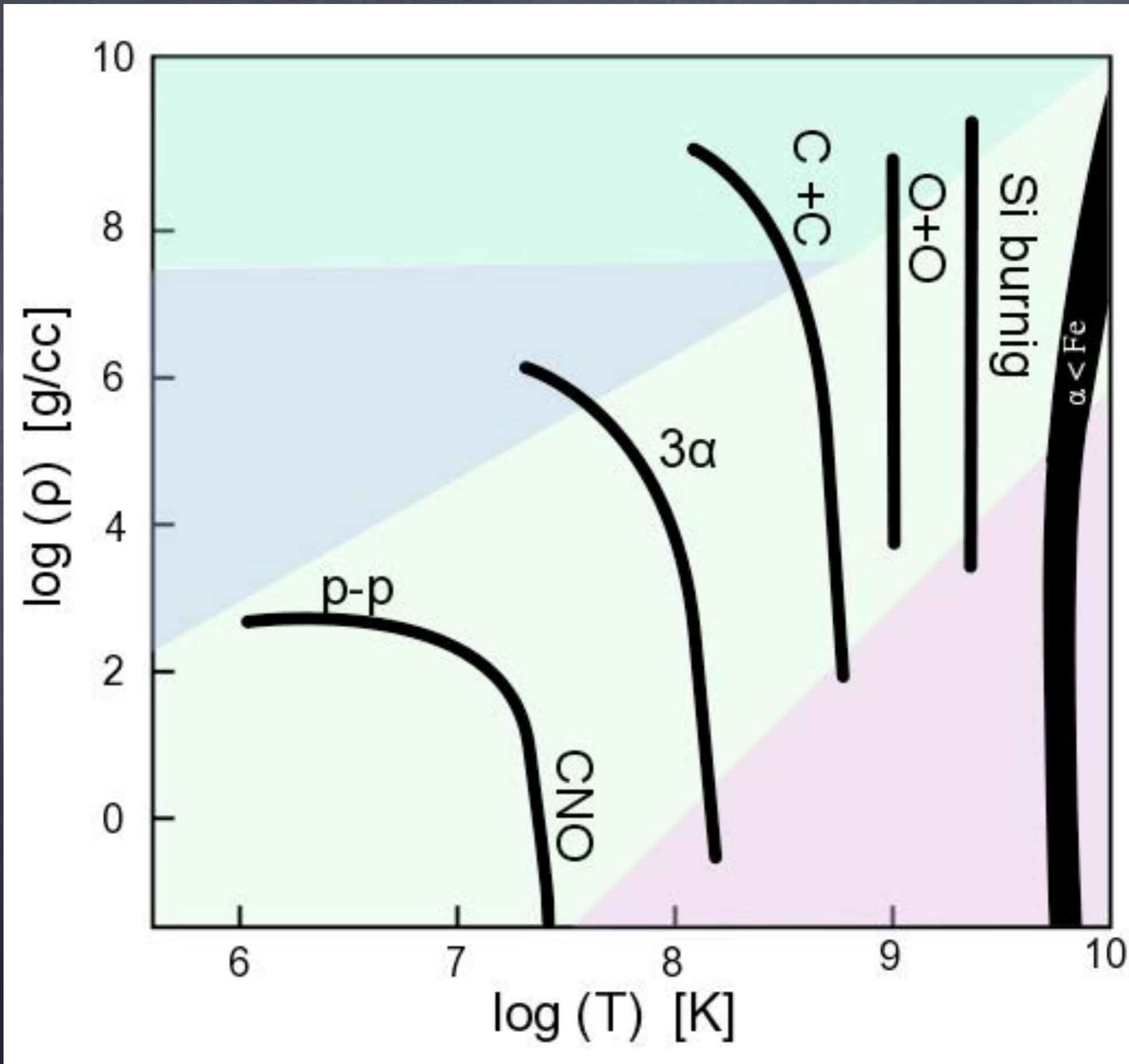
## Advanced Nuclear Burning Stages (e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10 <sup>9</sup> K)	Time (yr)
H	He	<sup>14</sup> N	0.02	10 <sup>7</sup>
He	C,O	<sup>18</sup> O, <sup>22</sup> Ne s- process	0.2	10 <sup>6</sup>
C	Ne, Mg	Na	0.8	10 <sup>3</sup>
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

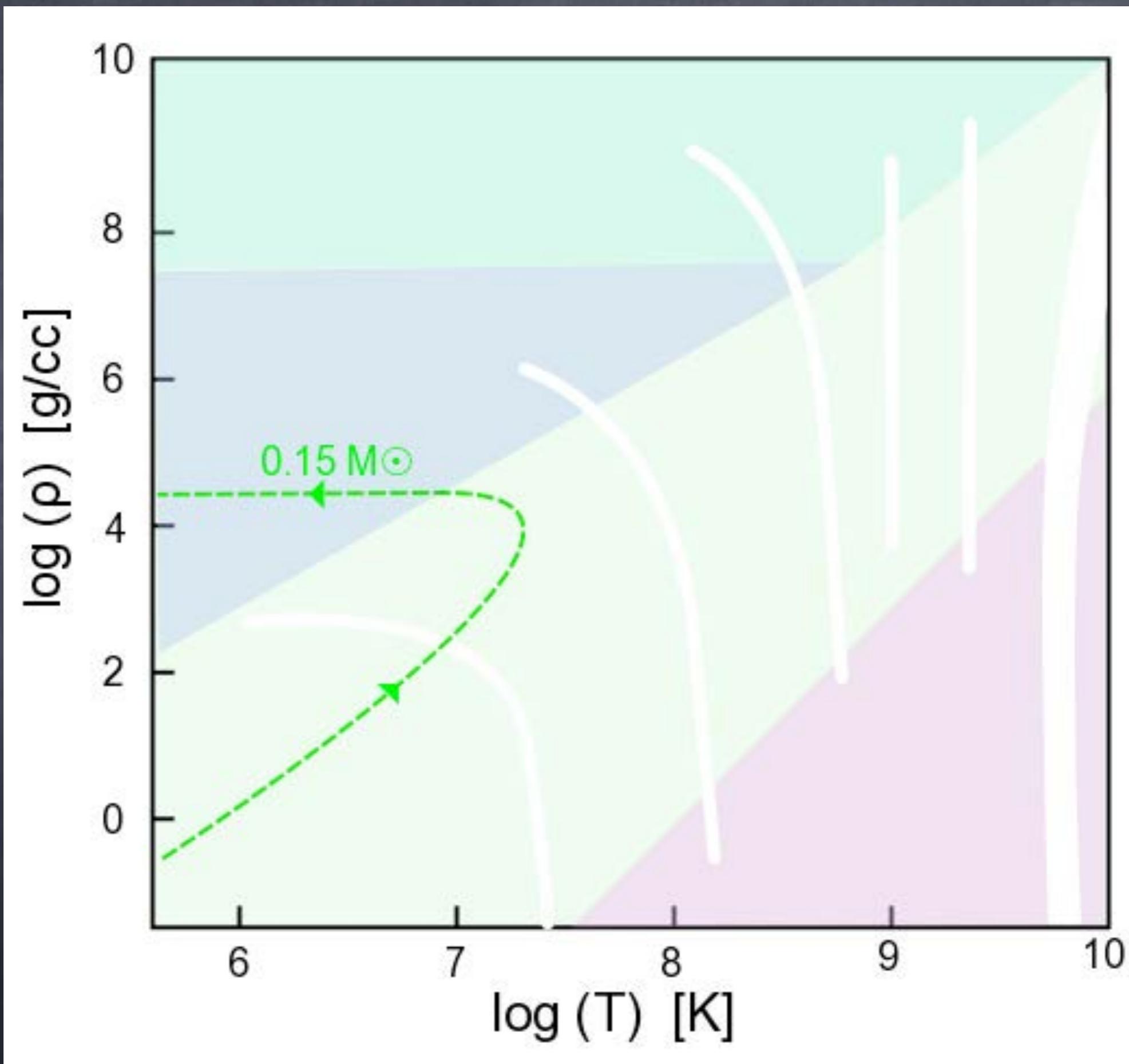
# Temperature-Density Diagram of Stellar Evolution



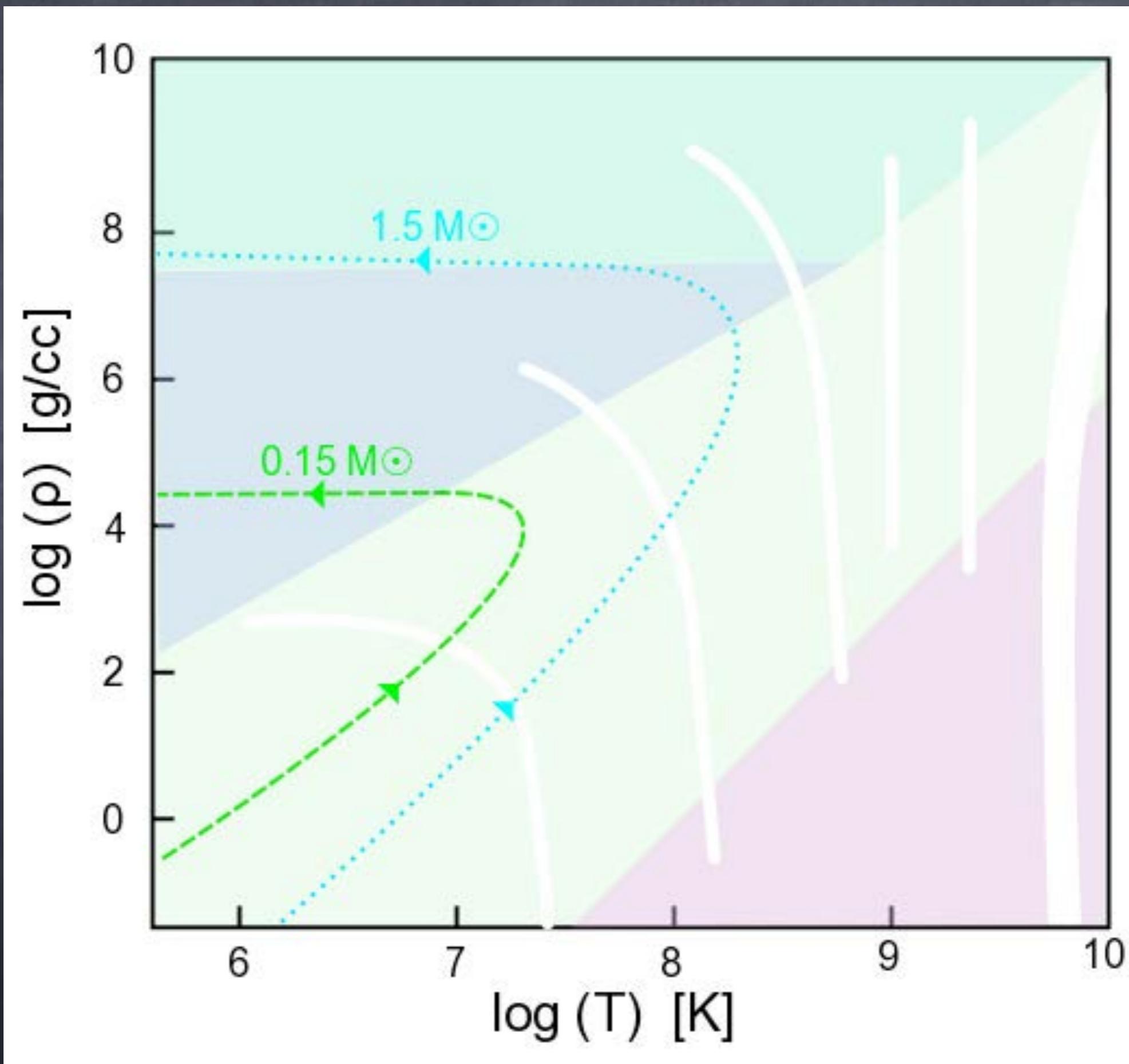
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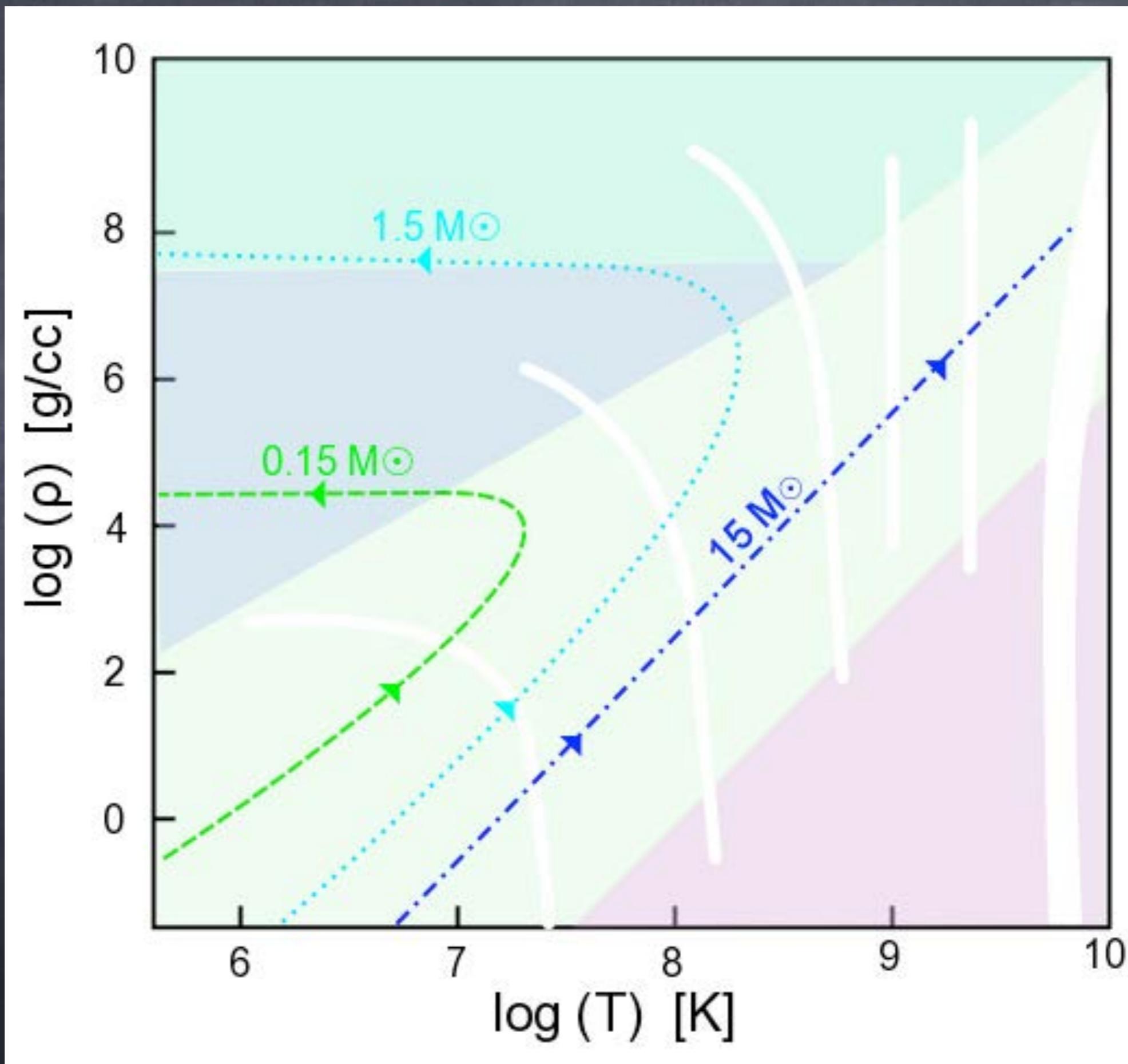
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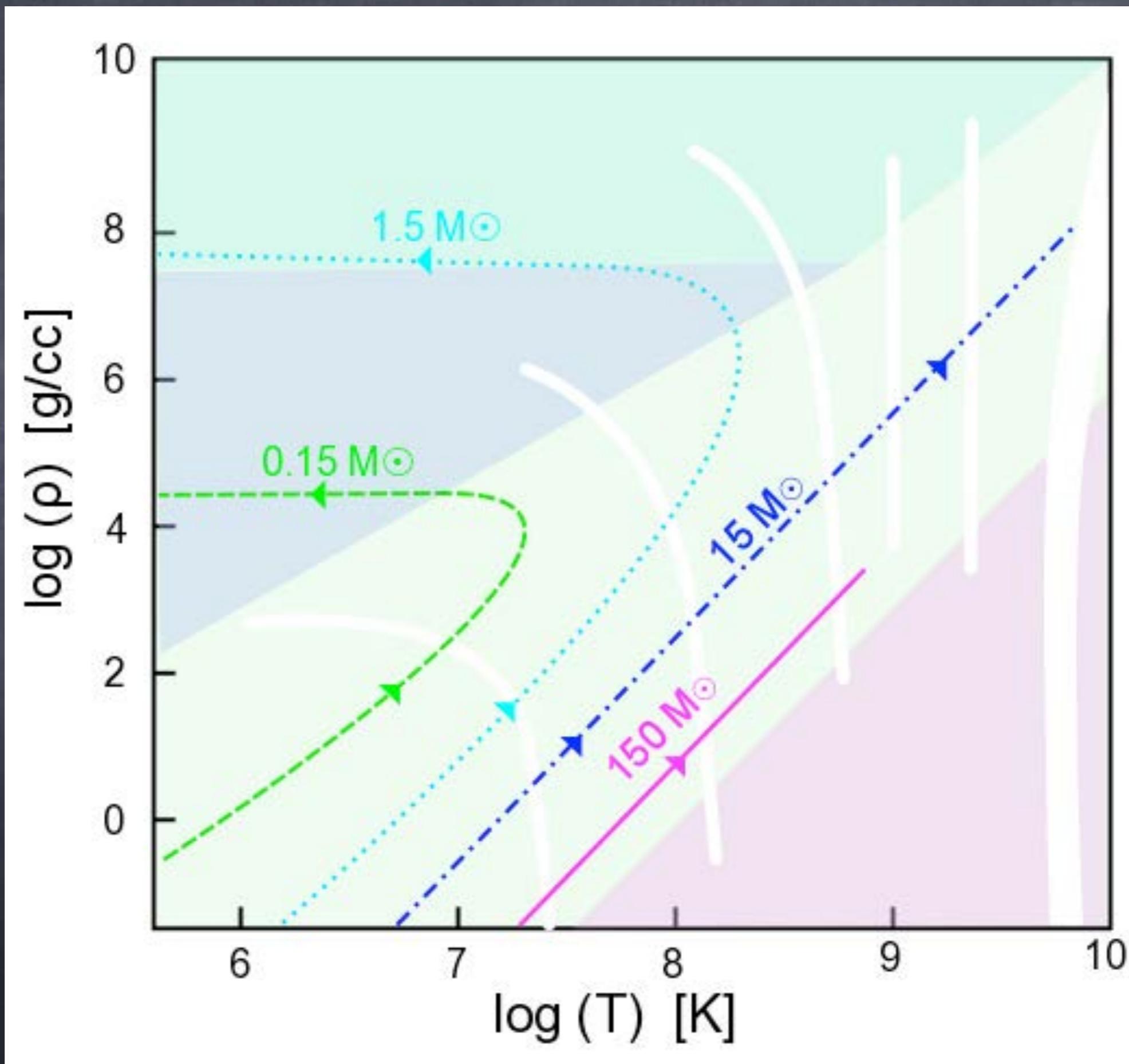
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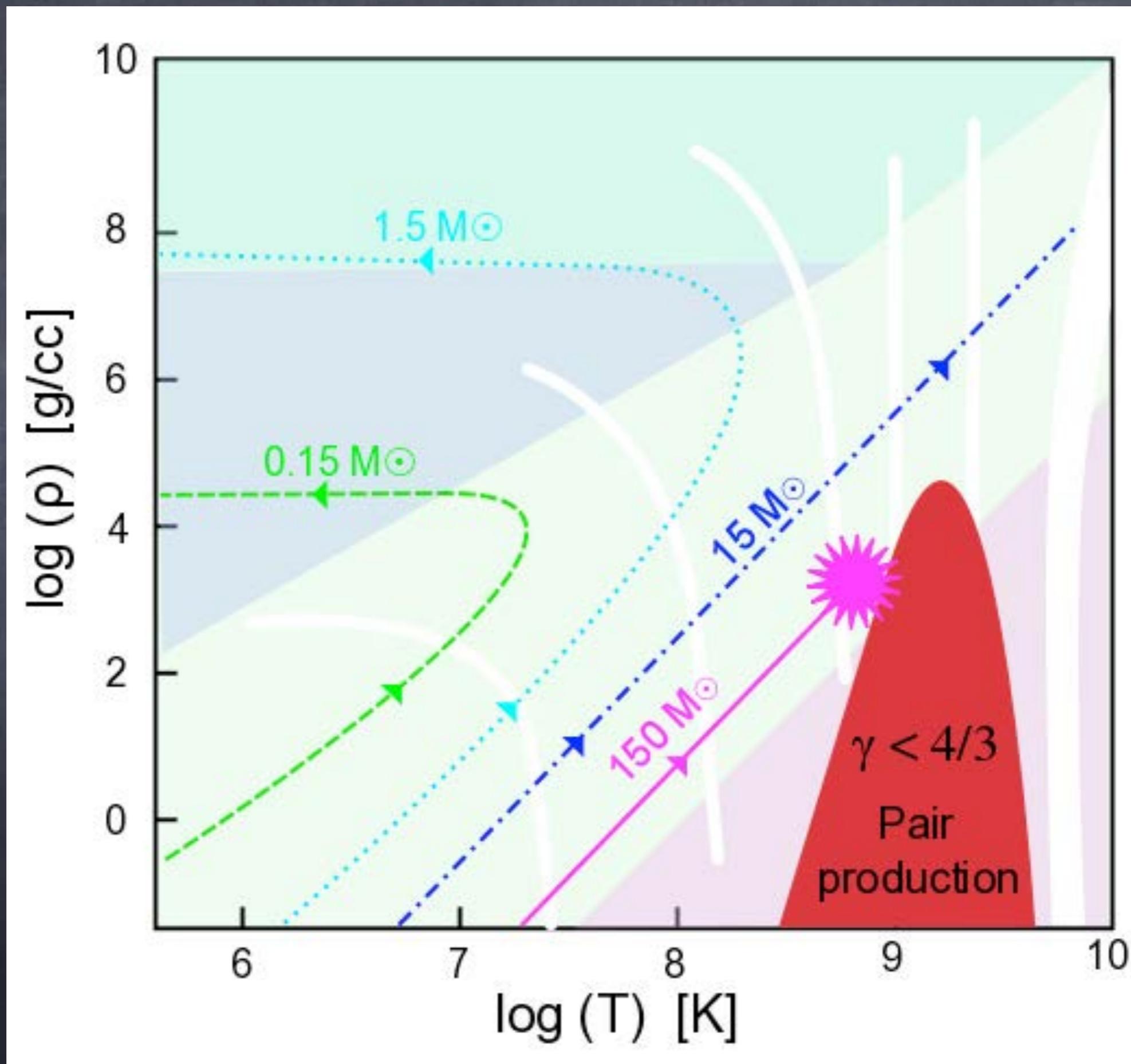
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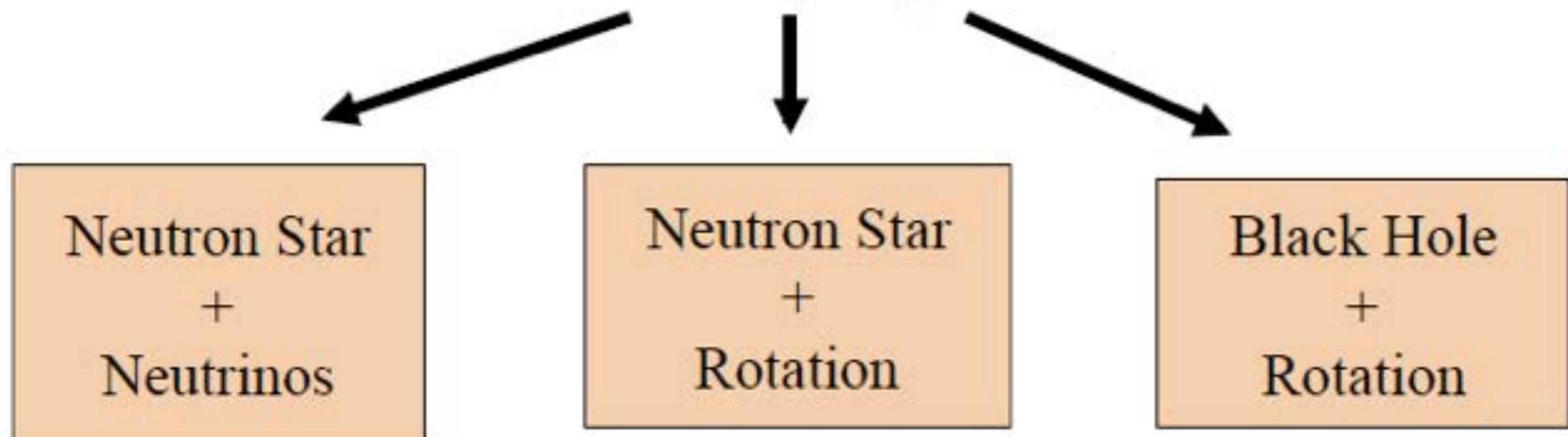
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## *When Massive Stars Die, How Do They Explode?*



Colgate and White (1966)

Arnett

Wilson

Bethe

Janka

Herant

Burrows

Fryer

Mezzacappa

etc.

Hoyle (1946)

Fowler and Hoyle (1964)

LeBlanc and Wilson (1970)

Ostriker and Gunn (1971)

Bisnovatyi-Kogan (1971)

Meier

Wheeler

Usov

Thompson

etc

Bodenheimer and Woosley (1983)

Woosley (1993)

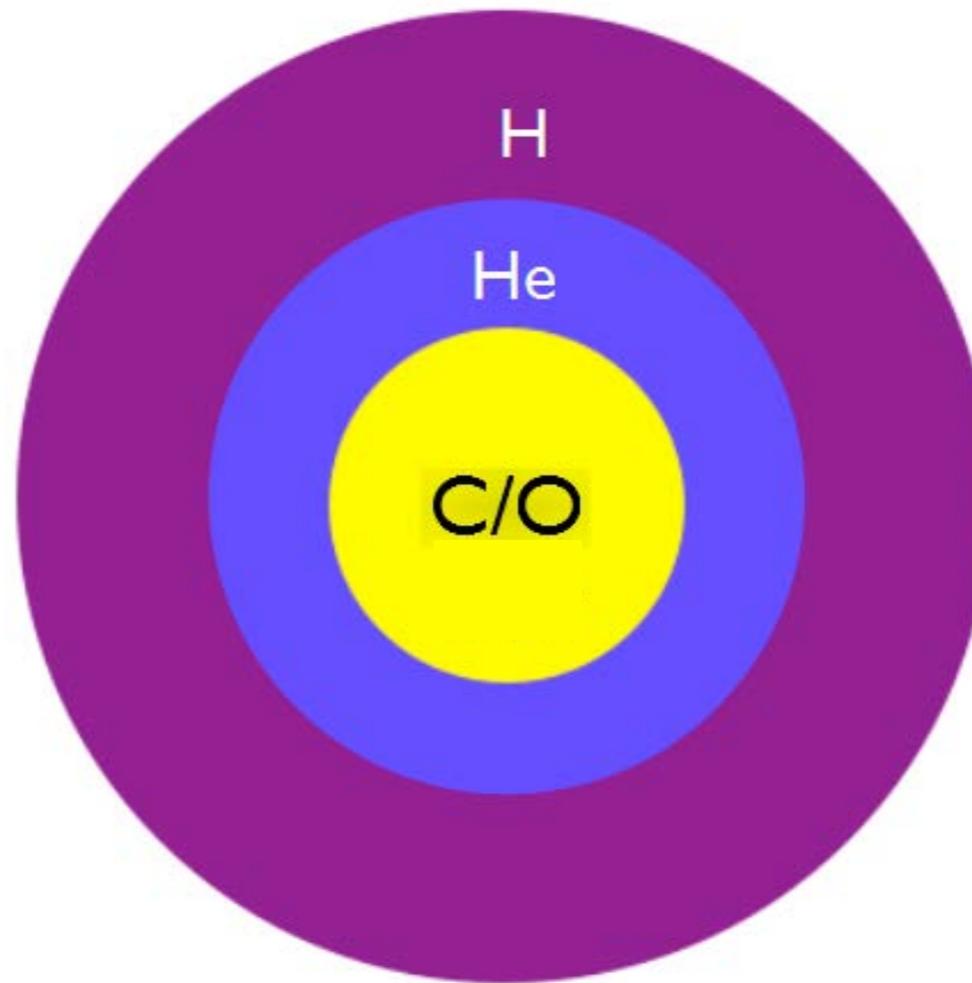
MacFadyen and Woosley (1999)

Narayan (2004)

*All of the above?*

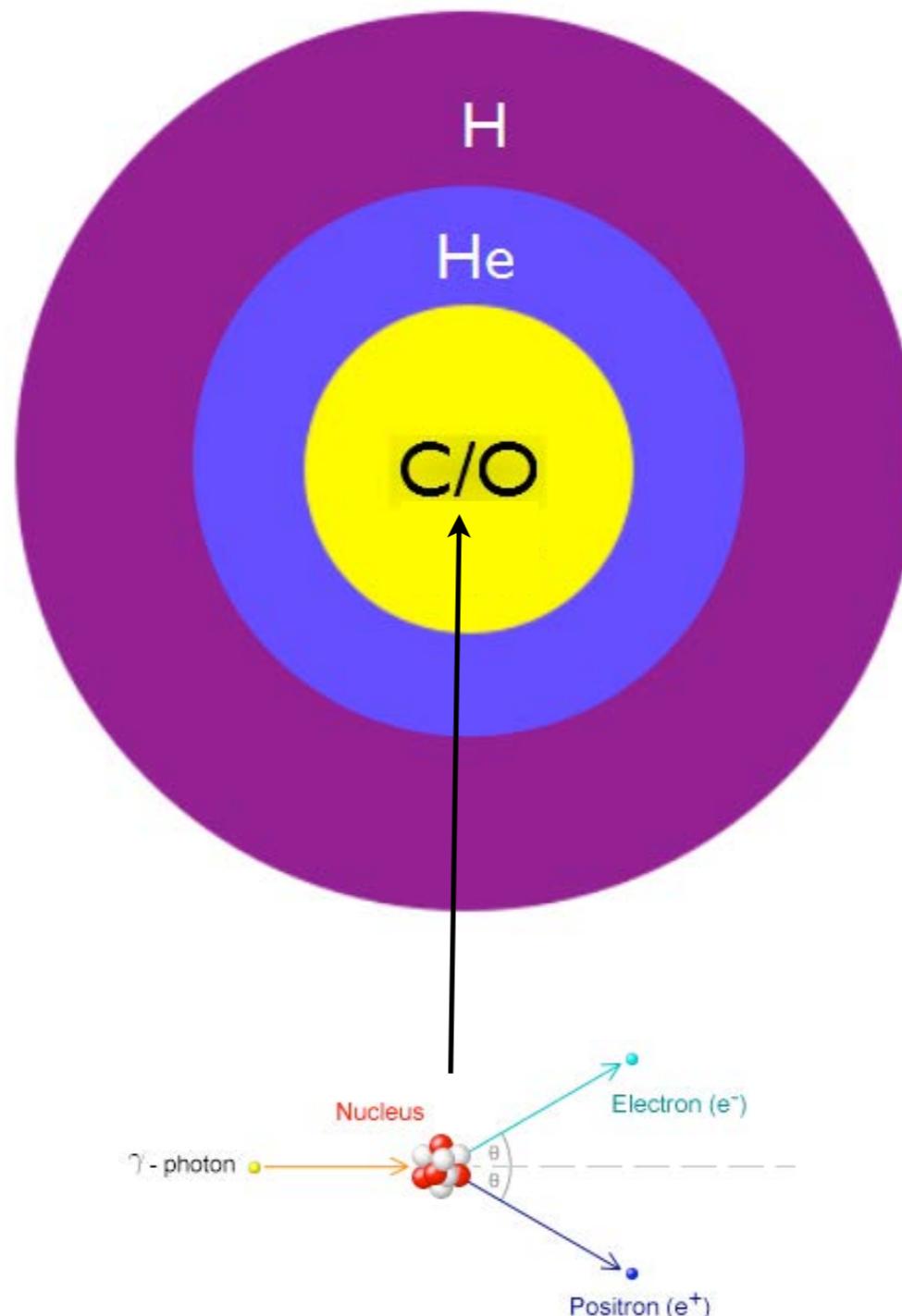
# Fate of Very Massive Stars

Star  $> 80 M_{\odot}$



# Fate of Very Massive Stars

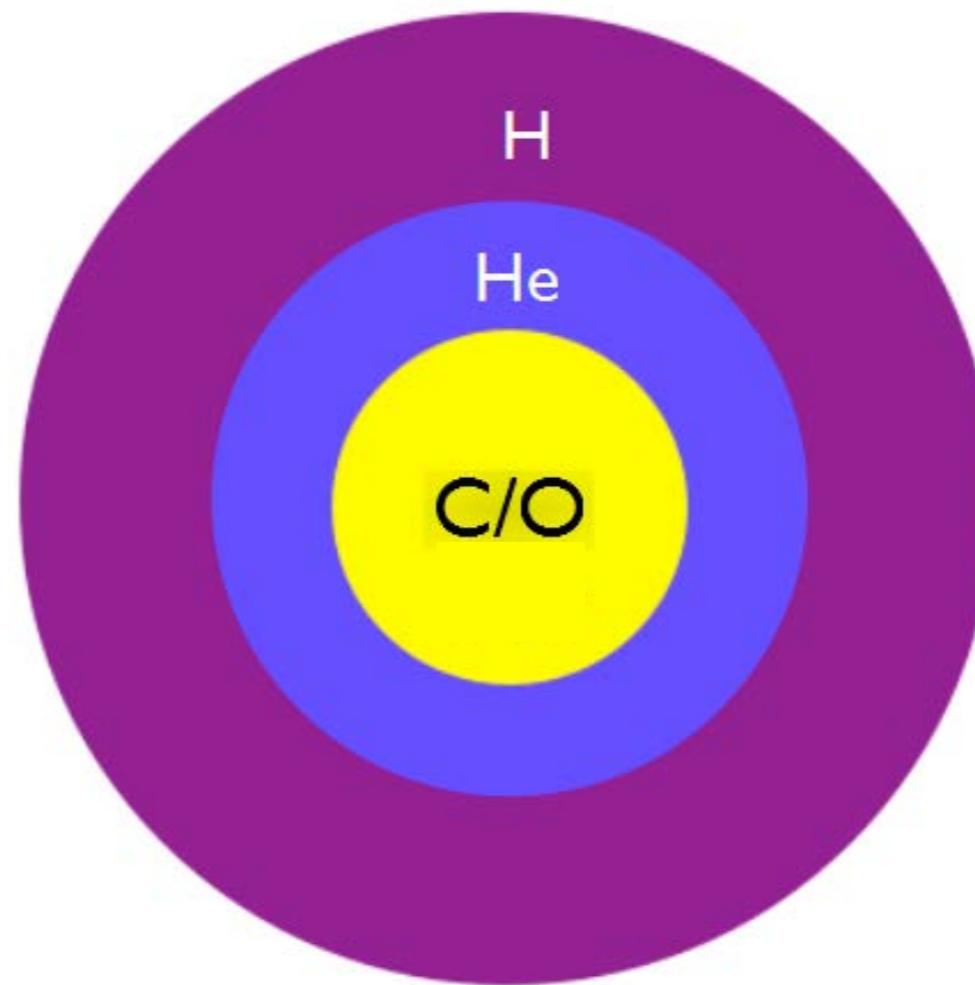
Star  $> 80 M_{\odot}$



$E_o > 2m_0c^2$ , where  $m_0$  is  
the electron rest mass

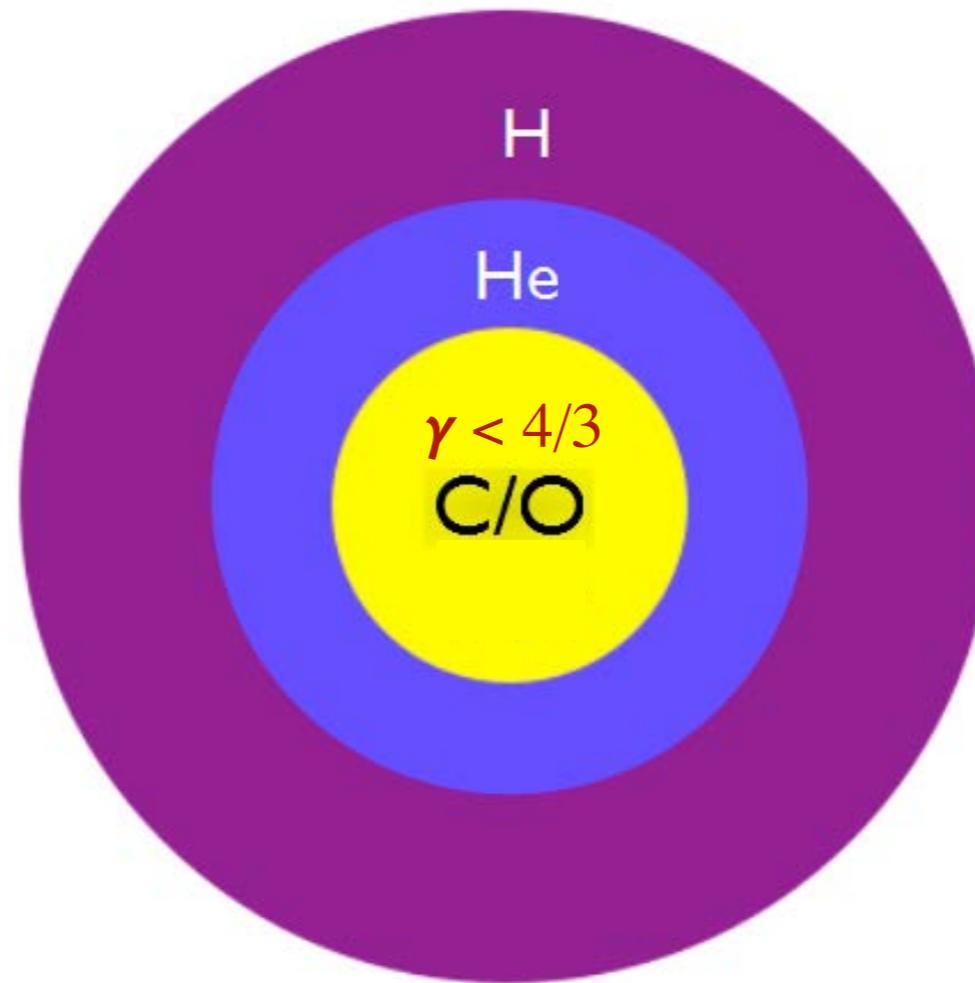
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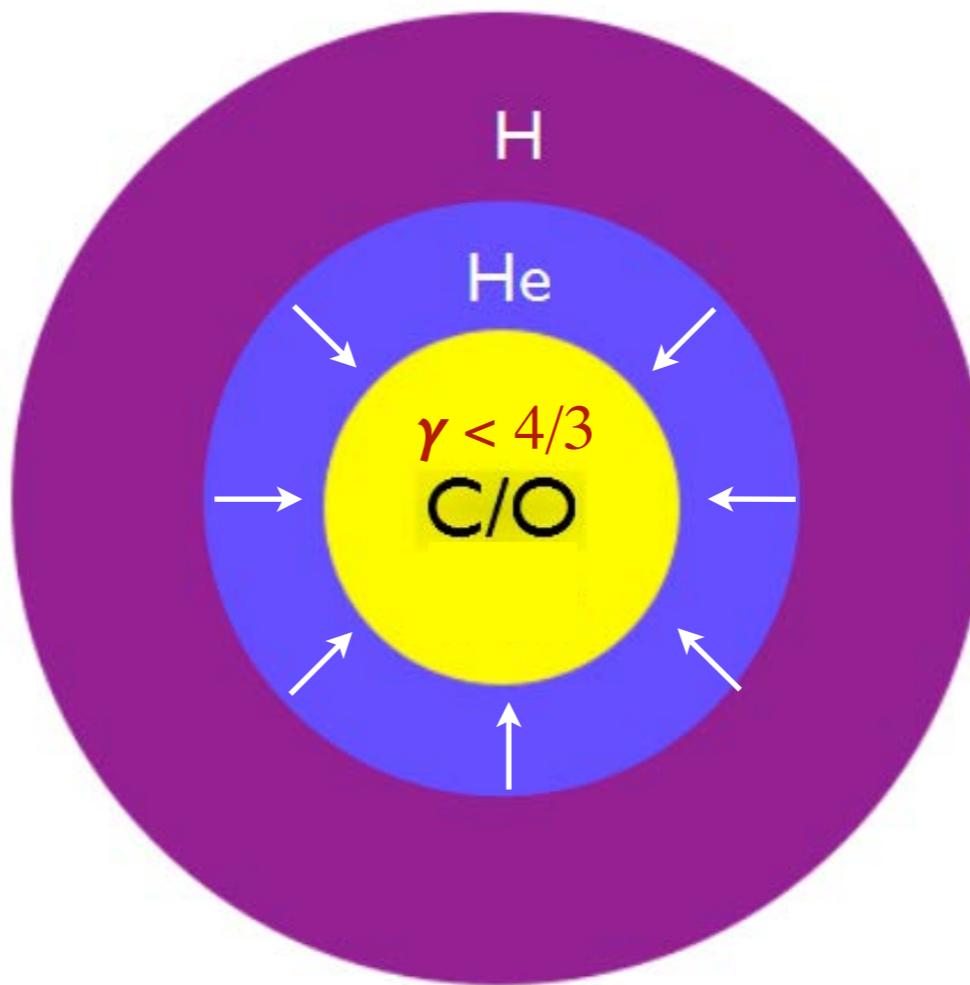
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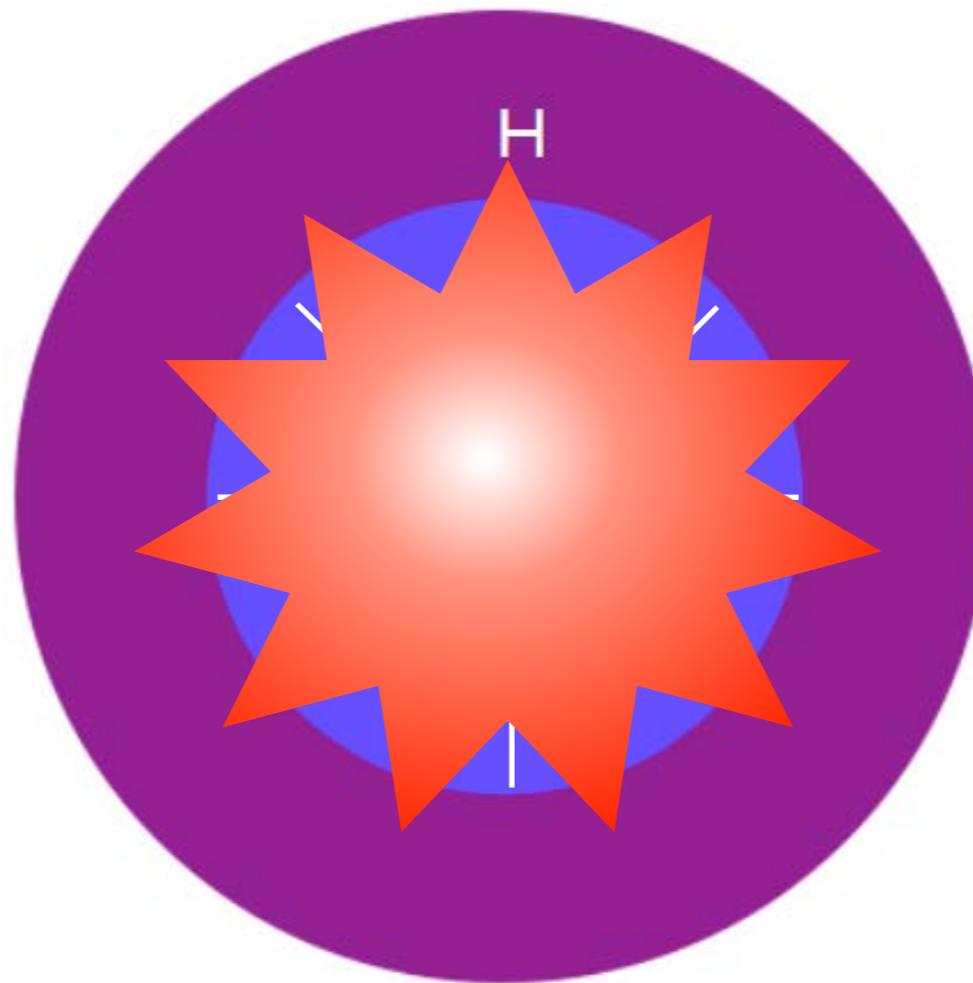
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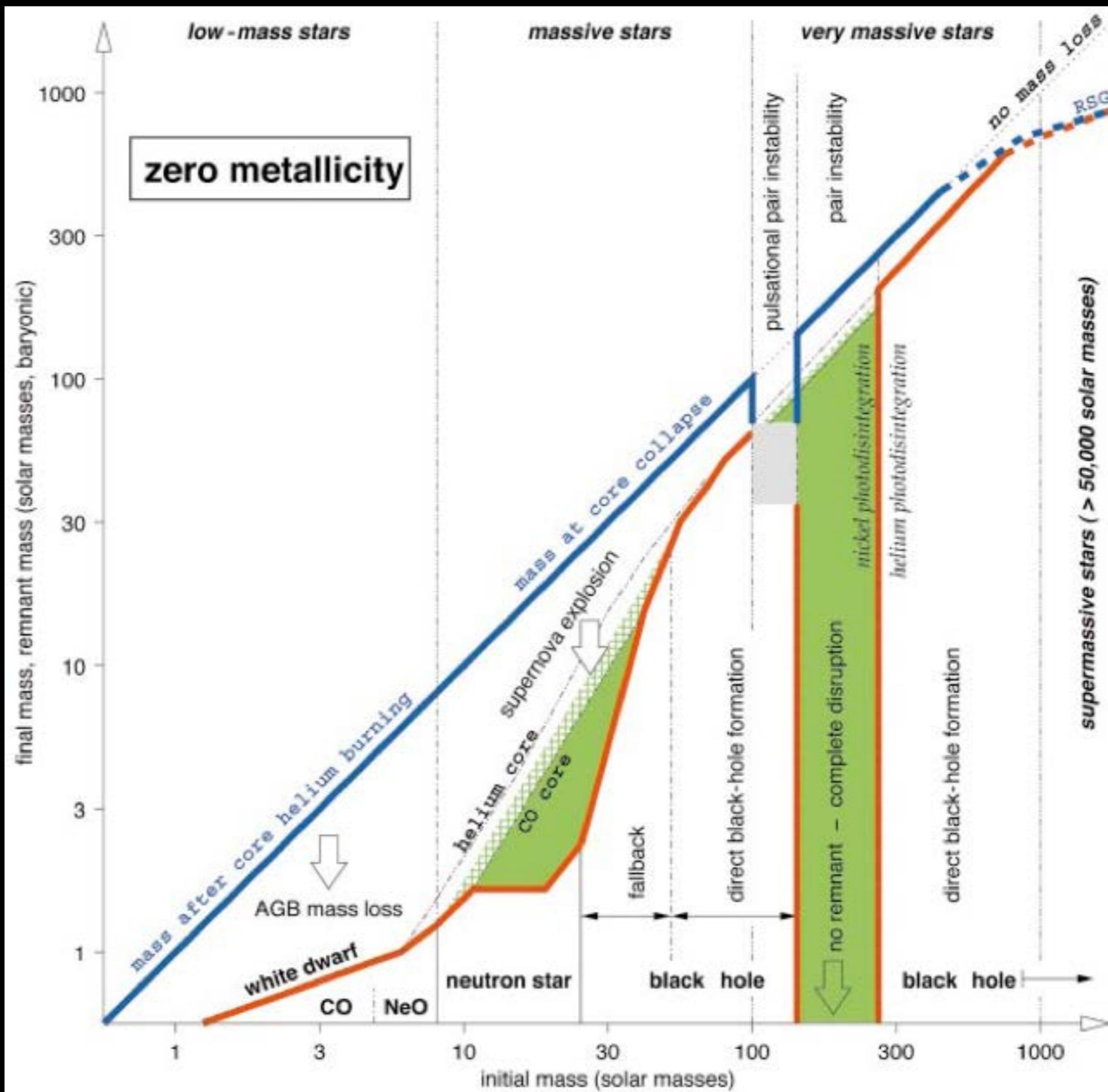
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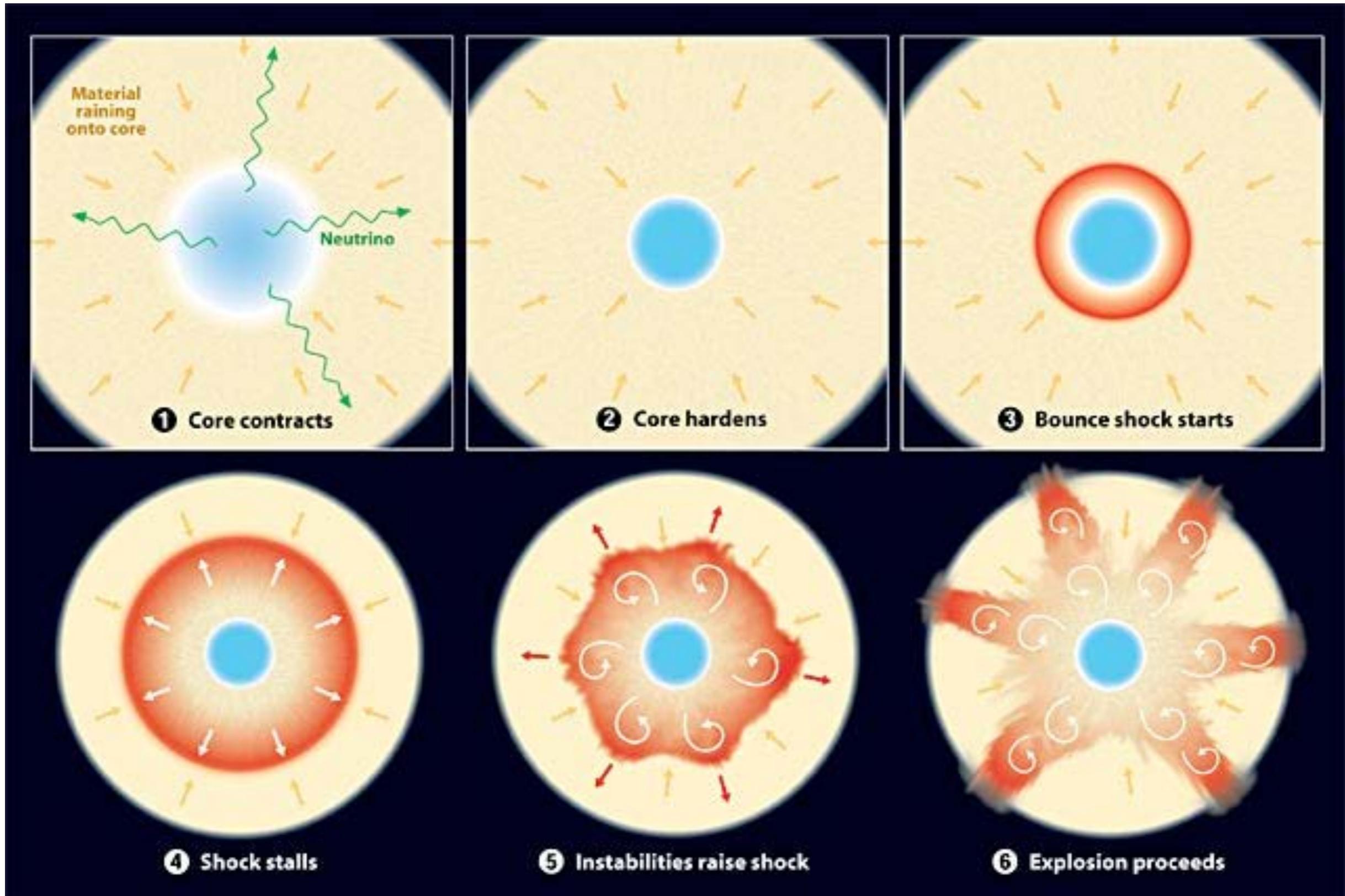


# The Death of Massive Stars

Woosley, Heger, & Weaver (2002)



$$20 \text{ M}_\odot > M^* > 10 \text{ M}_\odot$$



## Neutrino Burst Properties:

$$E_{\text{tot}} \sim \frac{3}{5} \frac{GM^2}{R}$$

$M = 1.5 M_{\odot}$

$\sim 3 \times 10^{53} \text{ erg}$

$R = 10 \text{ km}$

emitted roughly equally in  $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_\mu$ ,  $\bar{\nu}_\mu$ ,  $\nu_\tau$ , and  $\bar{\nu}_\tau$

### Time scale

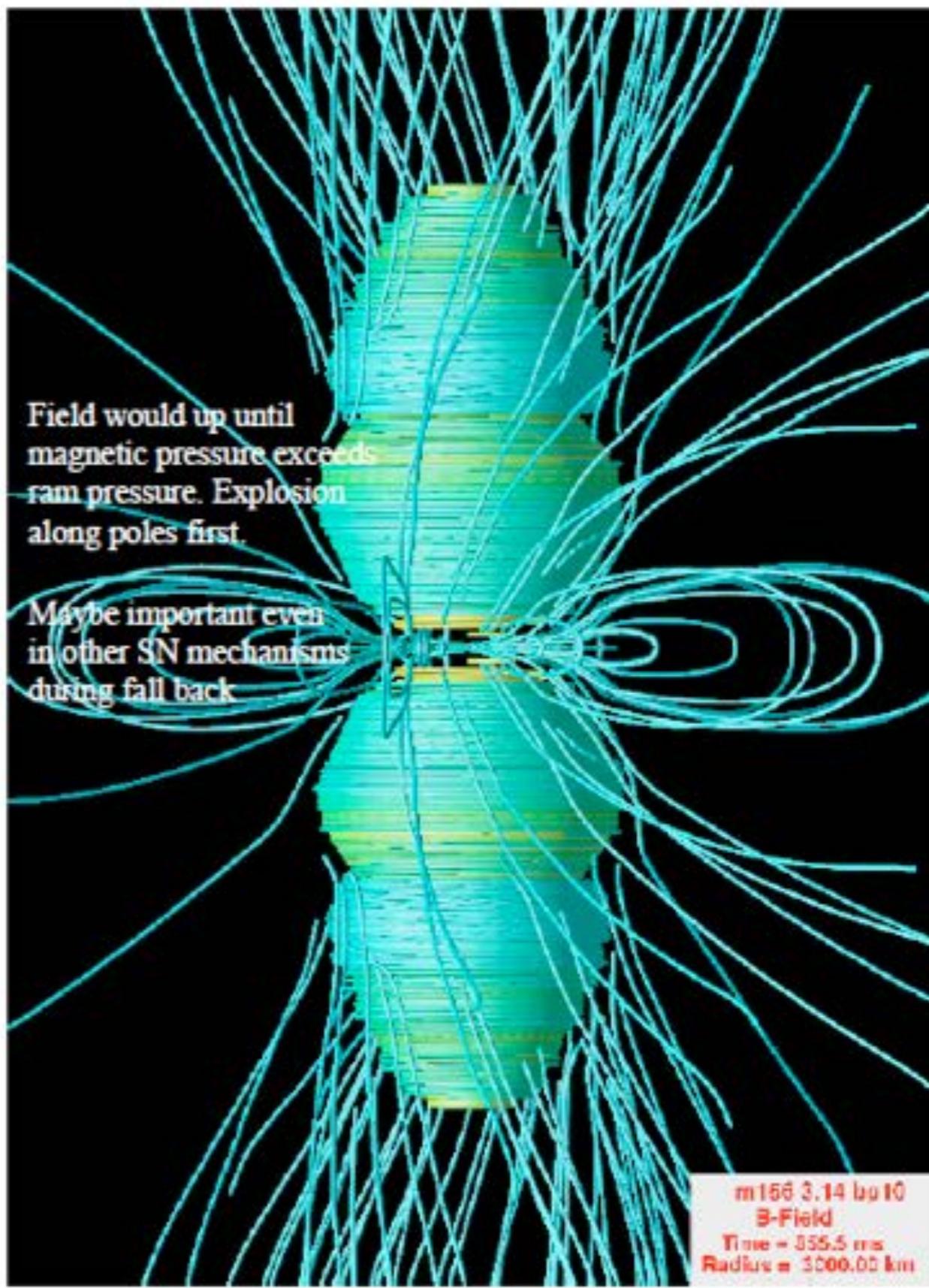
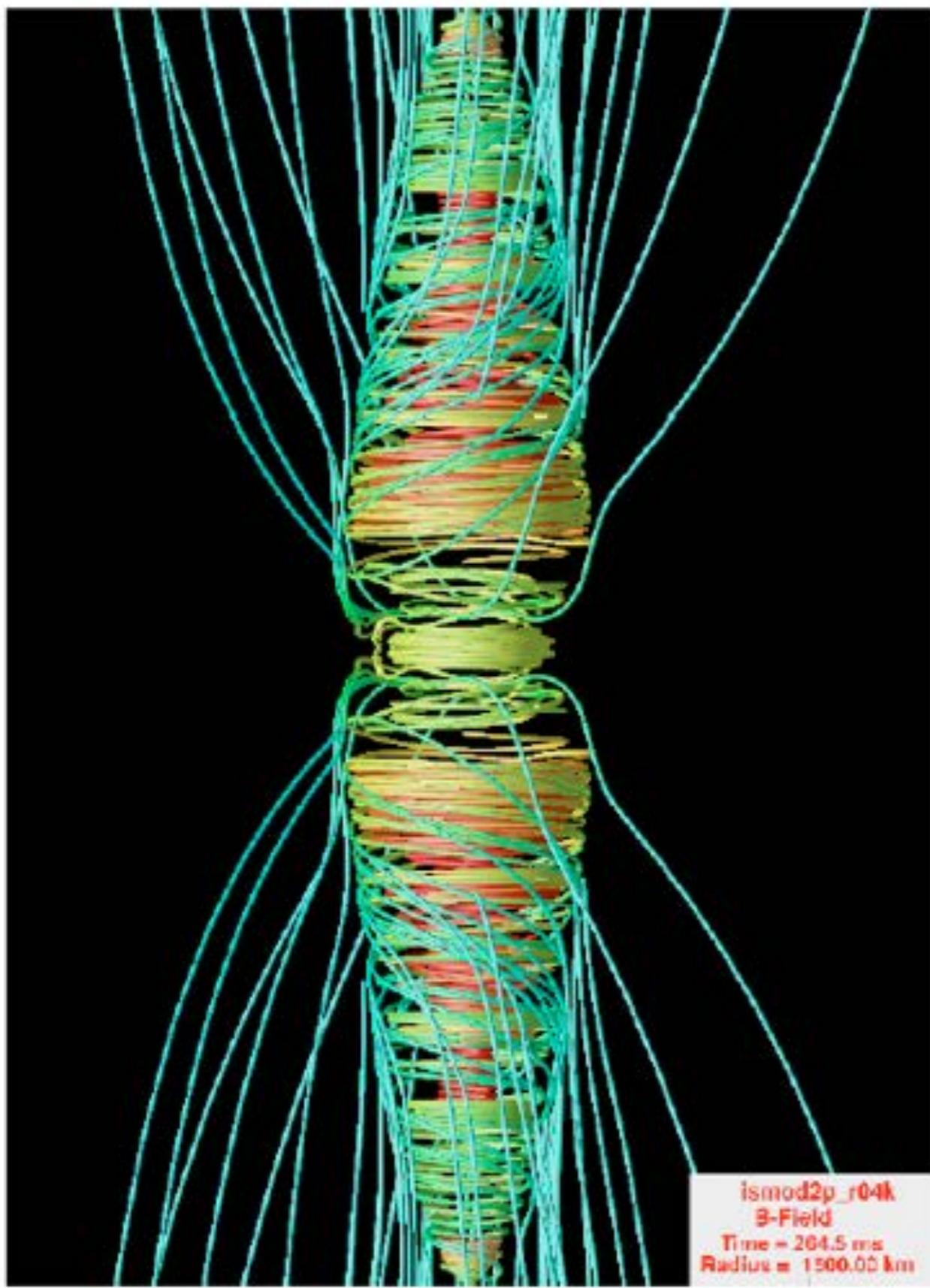
$$\tau_{\text{Diff}} \sim \left( \frac{R^2}{l c} \right) \quad l = \frac{1}{\kappa_v \rho} \quad \text{Scattering: } \kappa_{vs} \approx 1.0 \times 10^{-20} \left( \frac{E_v}{\text{MeV}} \right)^2 \text{ cm}^2 \text{ gm}^{-1}$$

$\kappa_v \sim 10^{-16} \text{ cm}^2 \text{ gm}^{-1}$  for  $\varepsilon_v = 50 \text{ MeV}$       Absorption:  $\kappa_{va} \approx 4 \kappa_{vs}$

$\rho \sim 3 \times 10^{14} \text{ gm cm}^{-3}$        $\Rightarrow$        $l \sim 30 \text{ cm}$        $R \sim 20 \text{ km}$

$$\tau_{\text{Diff}} \sim \left( \frac{(2 \times 10^6)^2}{30 \cdot 3 \times 10^{10}} \right) \sim 5 \text{ sec}$$

*Very approximate*



Assuming the emission of high amplitude ultra-relativistic MHD waves, one has a radiated power

$$P \sim 6 \times 10^{49} (1 \text{ ms}/P)^4 (B/10^{15} \text{ gauss})^2 \text{ erg s}^{-1}$$

and a total rotational kinetic energy

$$E_{\text{rot}} \sim 4 \times 10^{52} (1 \text{ ms}/P)^2 (10 \text{ km}/R)^2 \text{ erg}$$

*For magnetic fields to matter one thus needs magnetar-like magnetic fields and rotation periods (for the cold neutron star) of < 5 ms. This is inconsistent with what is seen in common pulsars. Where did the energy go?*

## Challenges

- Tough physics – nuclear EOS, neutrino opacities
- Tough problem computationally – must be 3D (convection is important). 6 flavors of neutrinos out of thermal equilibrium (thick to thin region crucial). Must be followed with multi-energy group and multi-angles
- Magnetic fields and rotation may be important
- If a black hole forms, problem must be done using relativistic (magneto-)hydrodynamics (general relativity, special relativity, magnetohydrodynamics)

# Why do We Care about SNe ?

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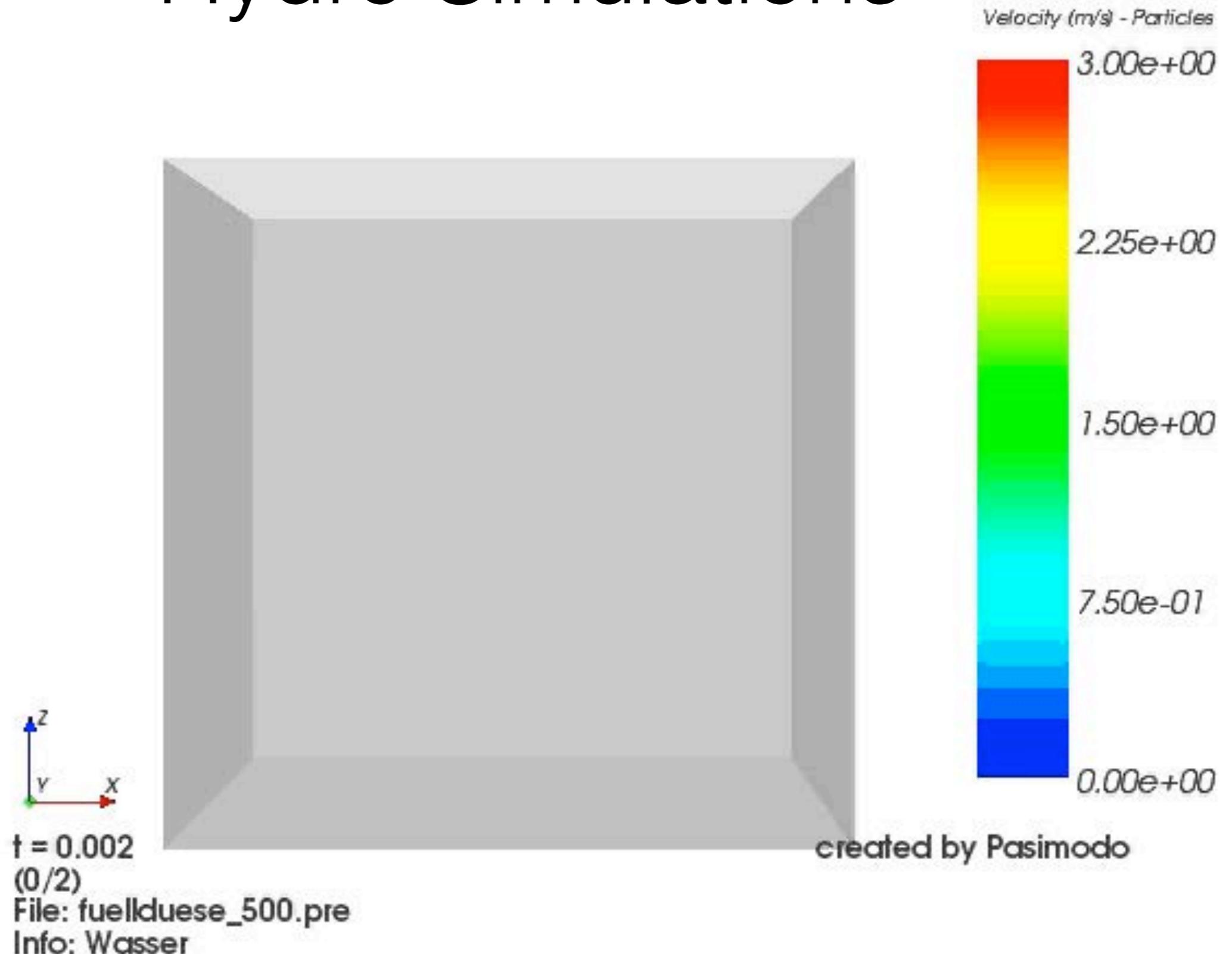
- Exceptional explosion and brightness
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- Fundamental physics (GR, HEP)
- Accessibility in Research (models and observations)

# The Telescope for Simulators



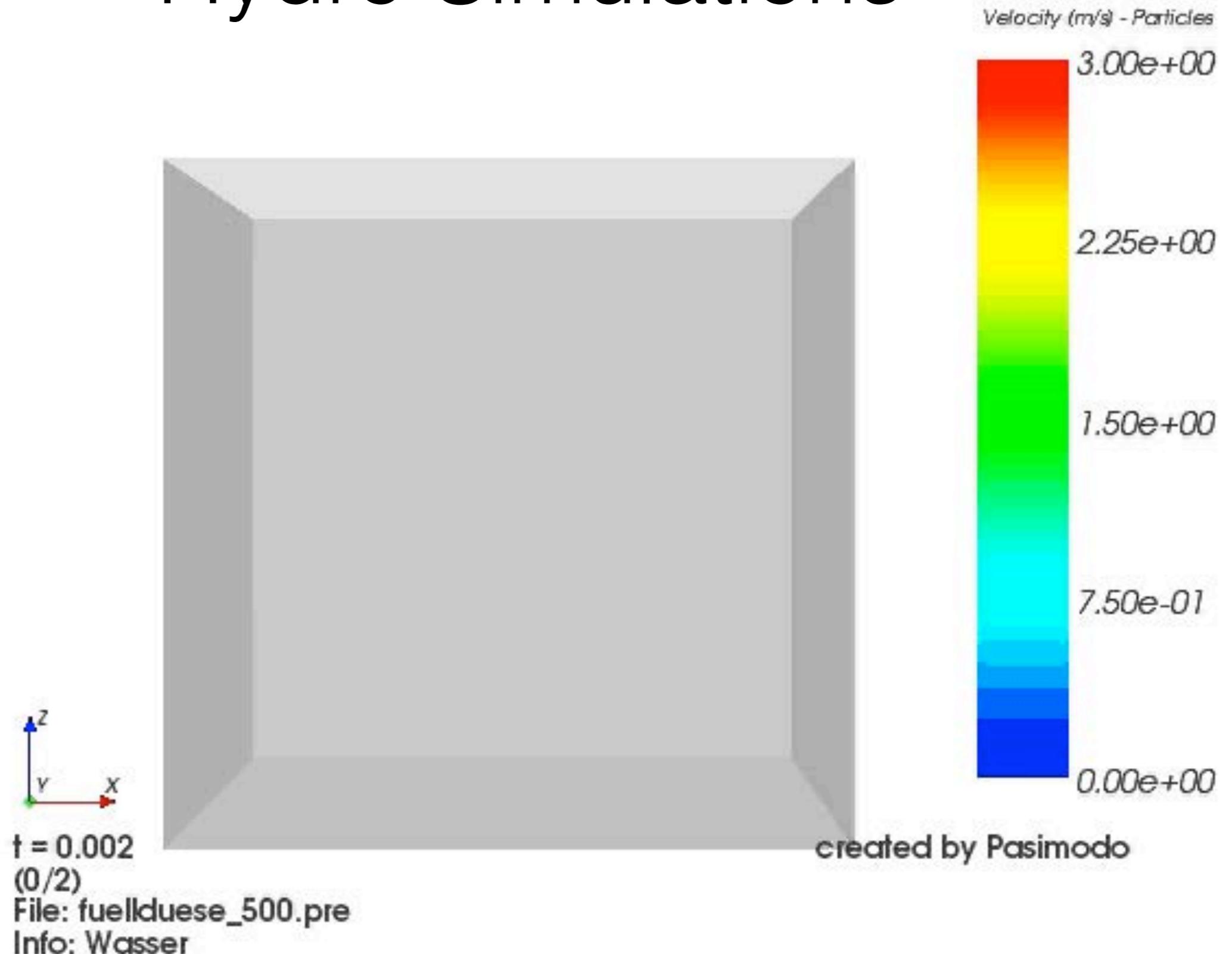
ATERUI II

# Hydro Simulations



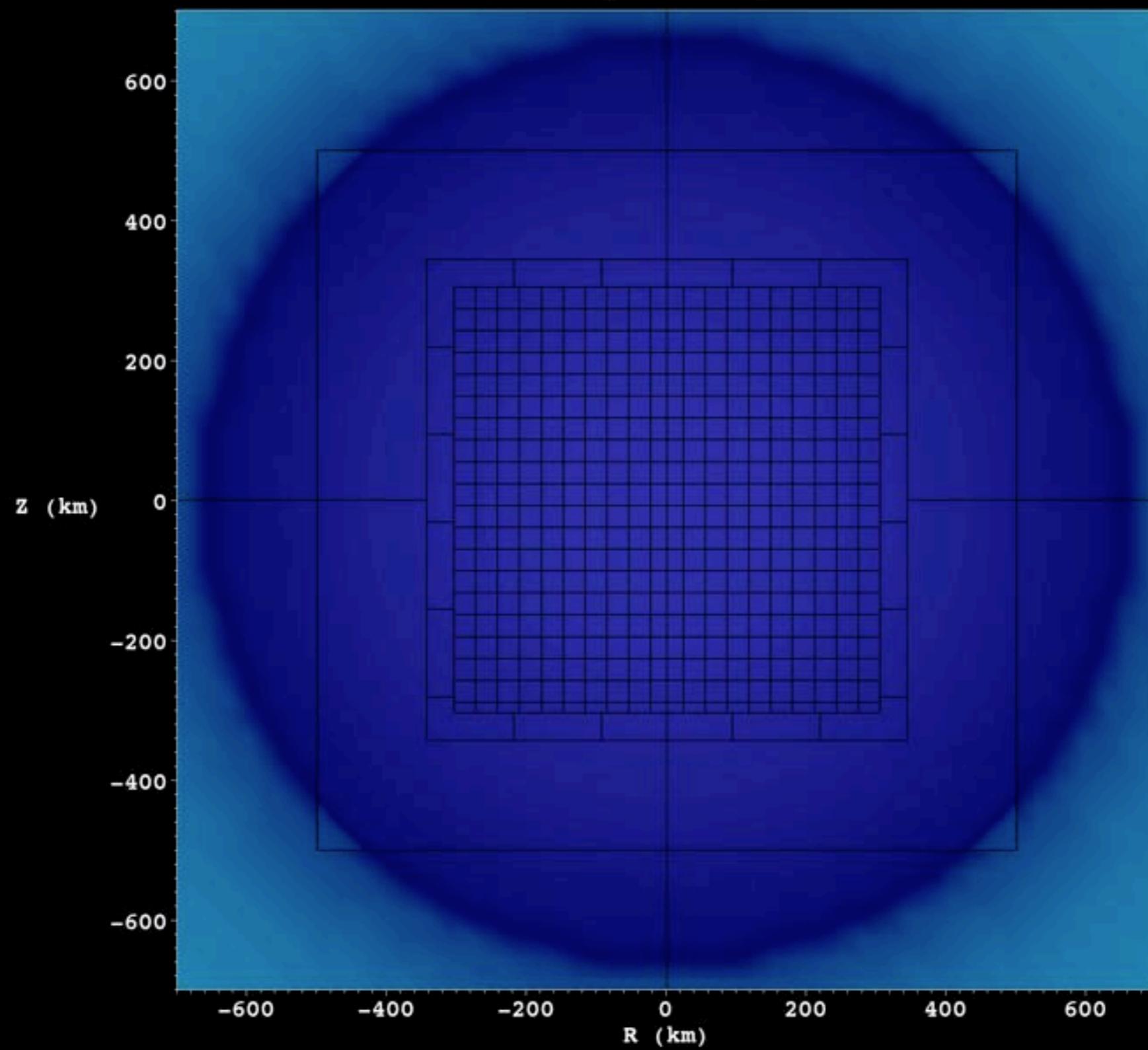
Lehnart, et al. (2009)

# Hydro Simulations

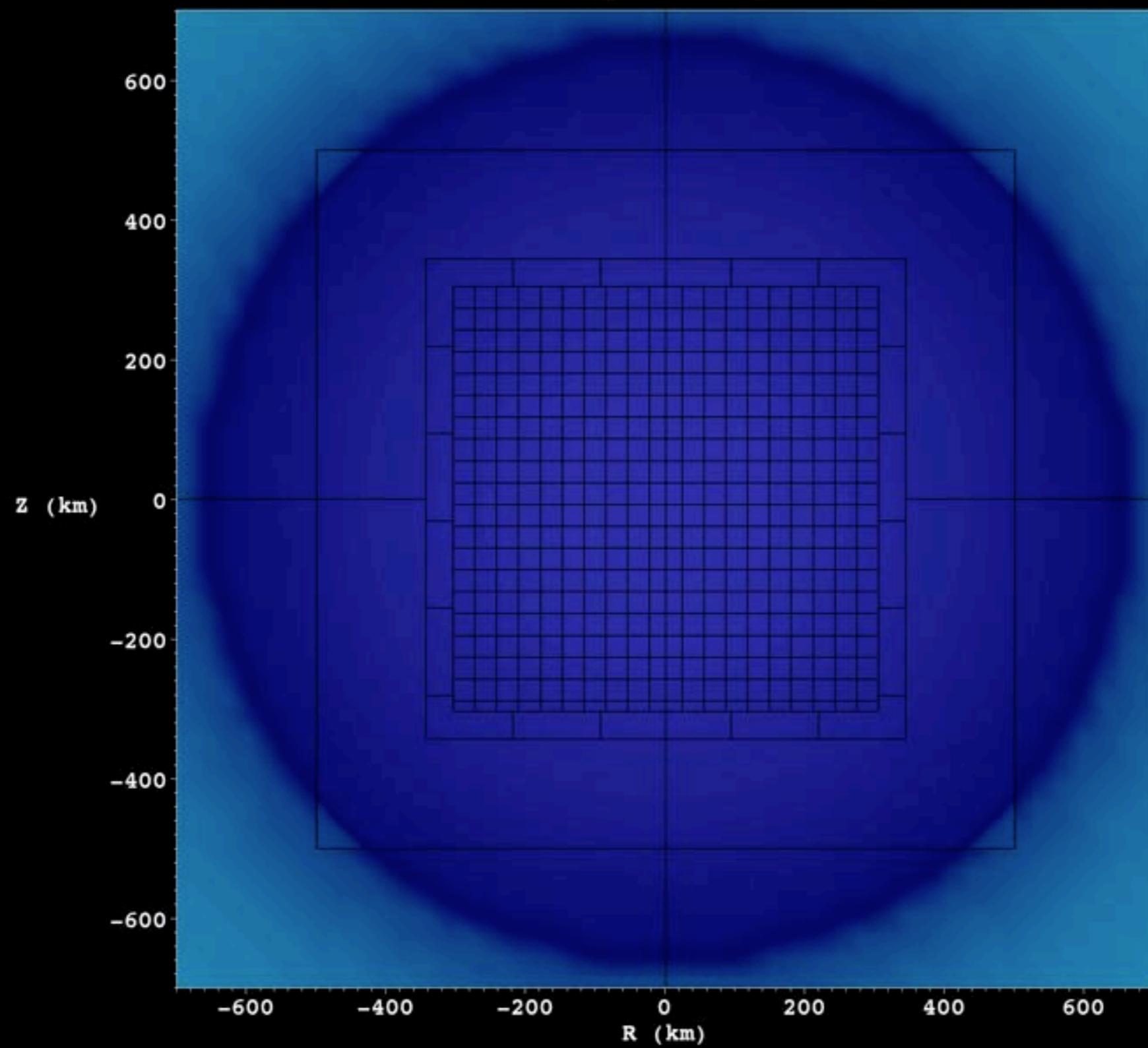


Lehnart, et al. (2009)

Time = U



Time = U



# Explosions from the heart of star



# Explosions from the heart of star



# Explosions from the heart of star



Fe-core Collapse SNe  
Nordhaus+ 2010  
Using CASTRO

# Magnetar

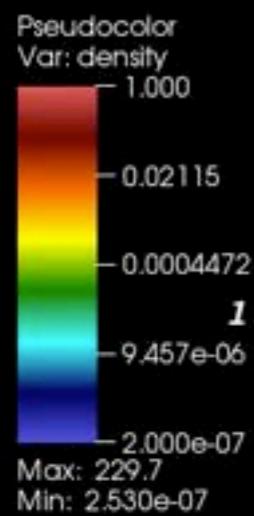
$30 M_{\odot} > M^* > 20 M_{\odot}$

DB: Header

Cycle: 0

Chen+ 2016

Time: 0



1.0

0.5

0.5

1.0  
R-Axis ( $\times 10^{12}$  cm)

1.5

# Magnetar

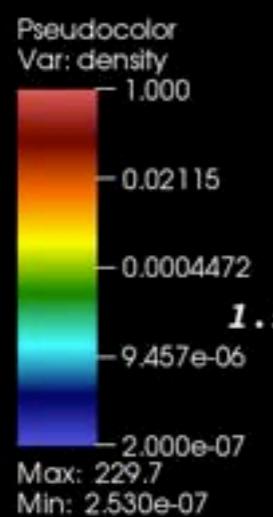
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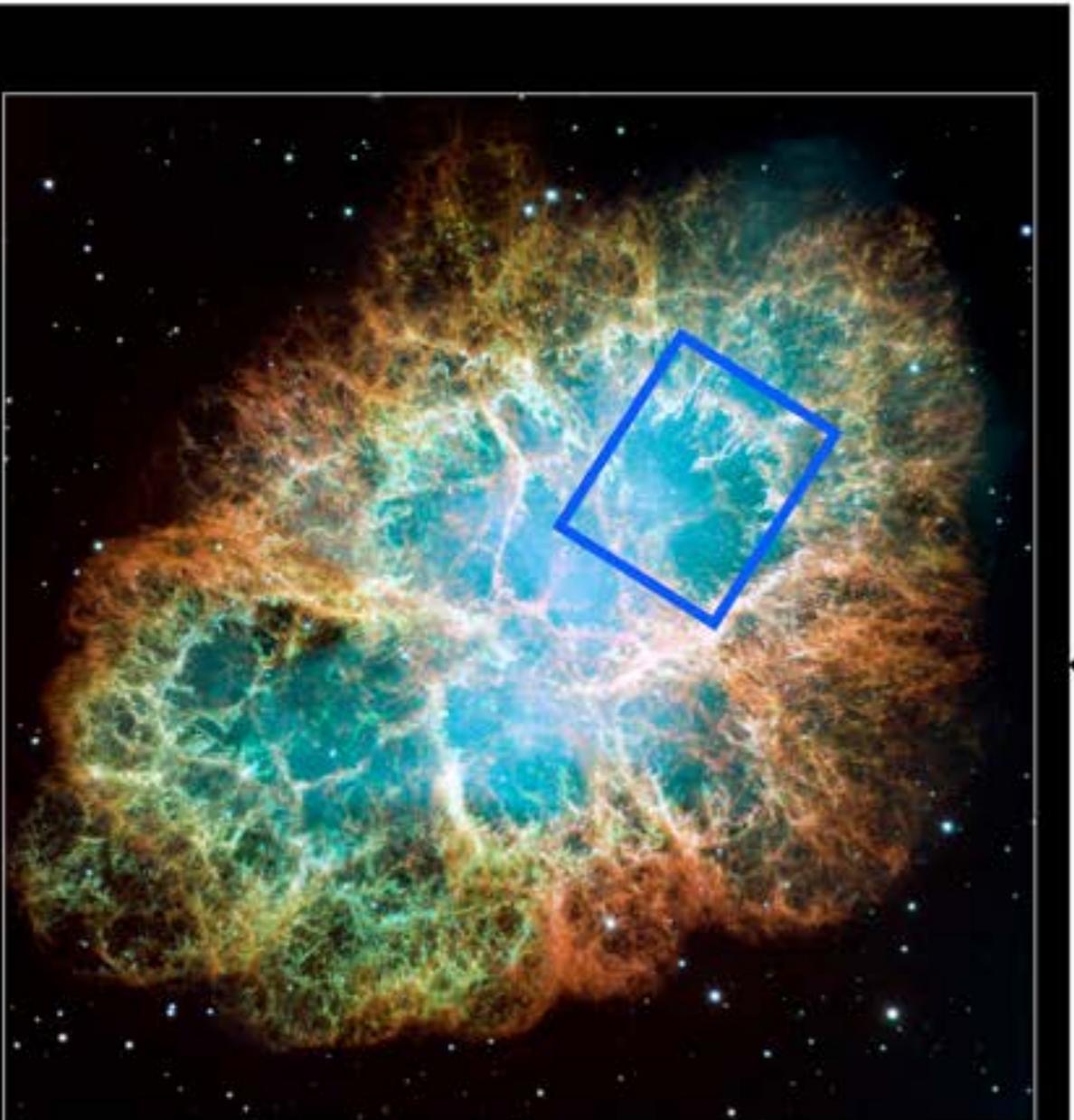
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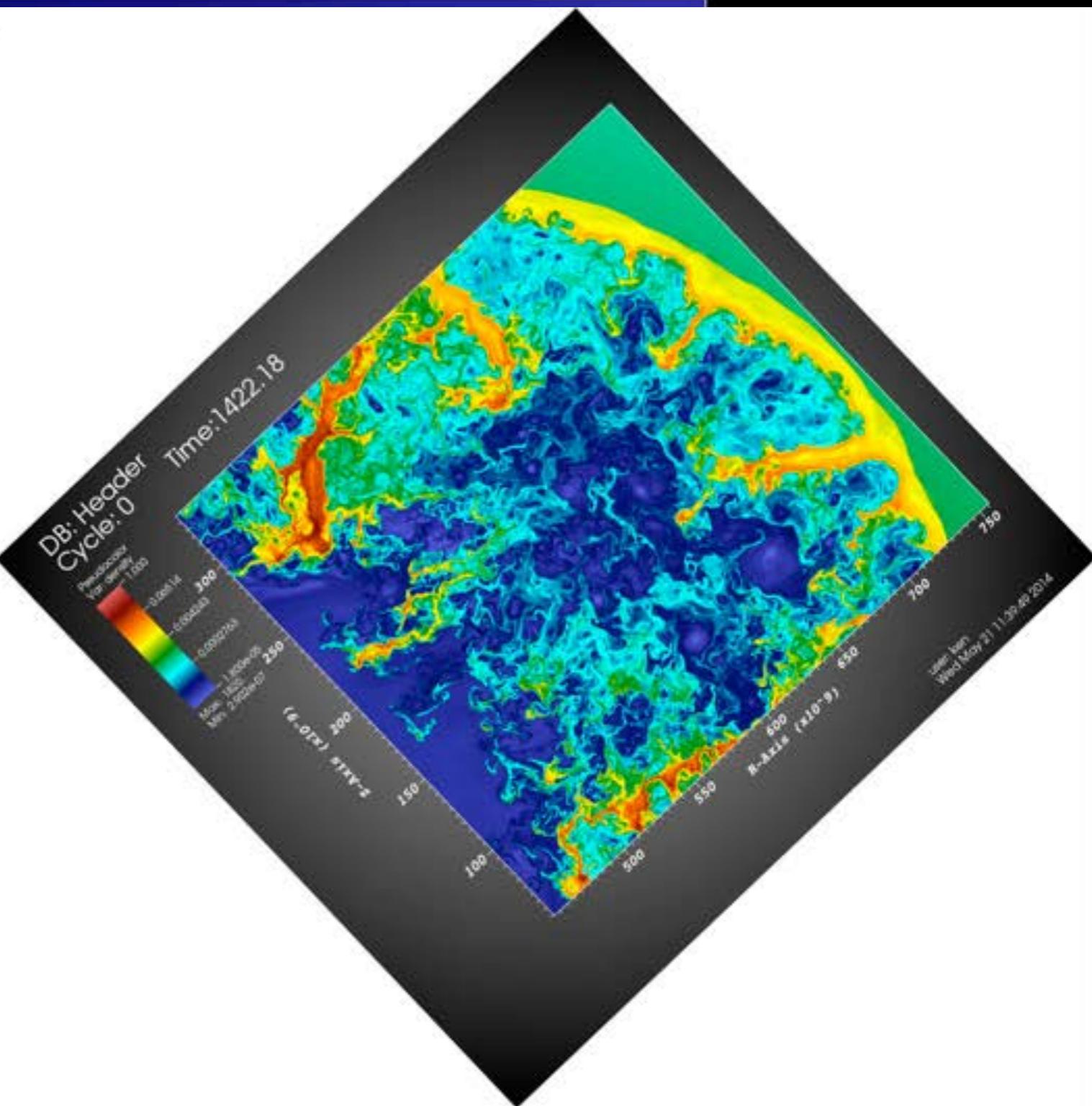
Cycle: 0

Time: 0

Chen+ 2016



Crab Nebula • M1  
Hubble Space Telescope • WFPC2



# Hypernovae and Collapsars

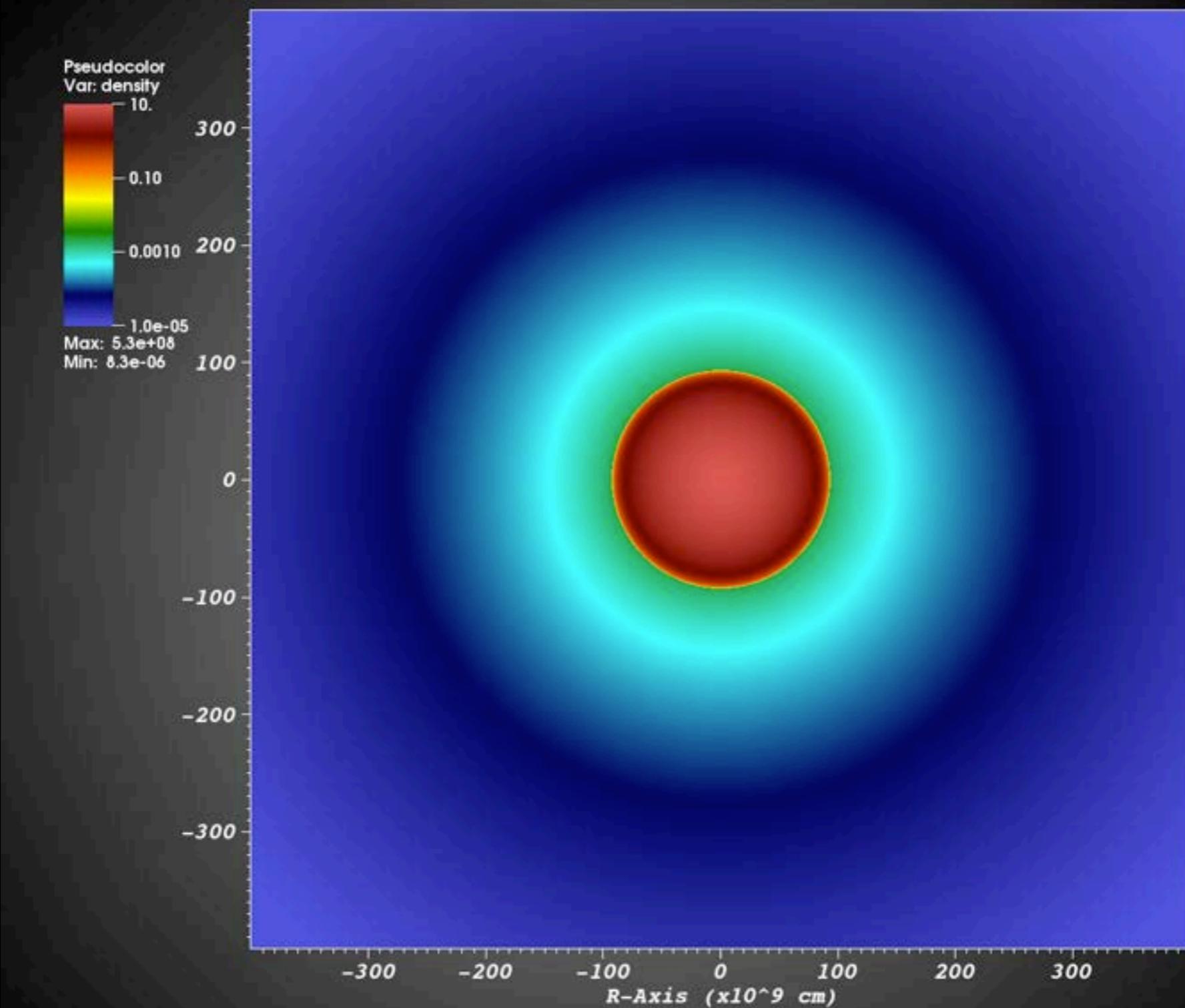


NASA JPL

# Hypernova and GRB !!!

$60 M_{\odot} > M^* > 30 M_{\odot}$

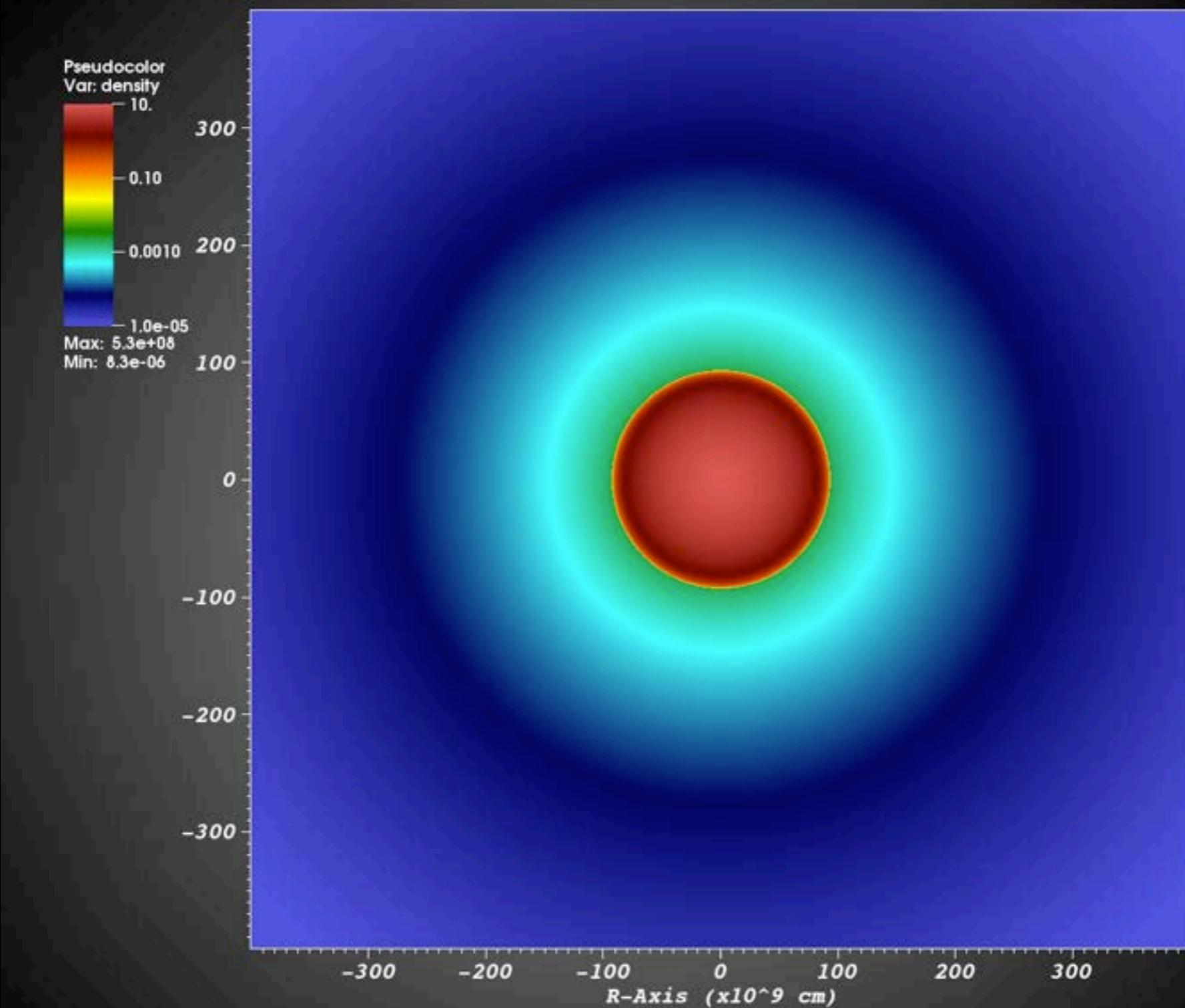
Chen+ 2017



# Hypernova and GRB !!!

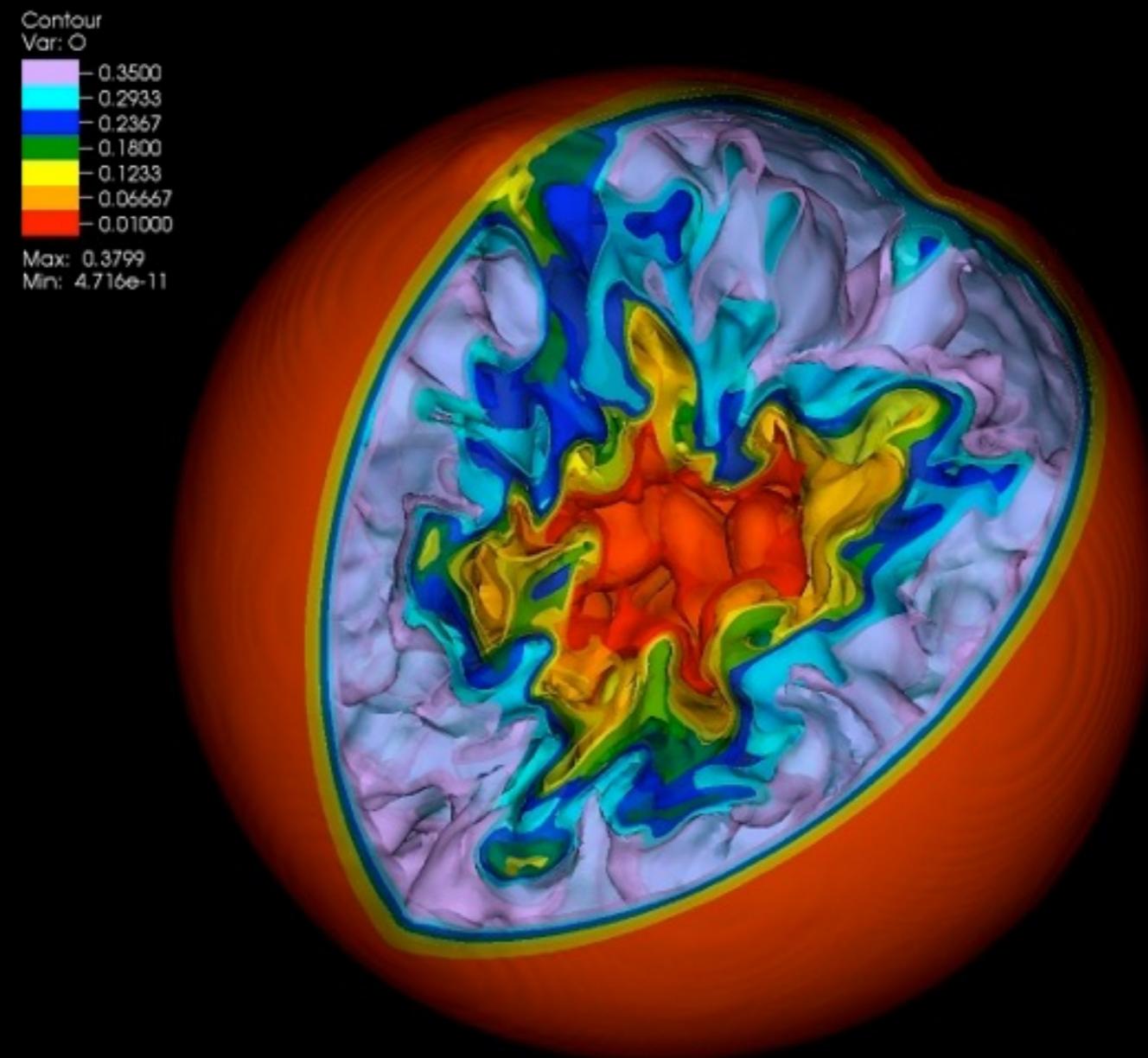
$60 M_{\odot} > M^* > 30 M_{\odot}$

Chen+ 2017



# GR Instability Supernovae (GSNe)

$M^* \gg 100 M_\odot$



Chen+ ApJ 790 162 (2014)