TWO-DIMENSIONAL STELLAR EVOLUTION : **2DStars**

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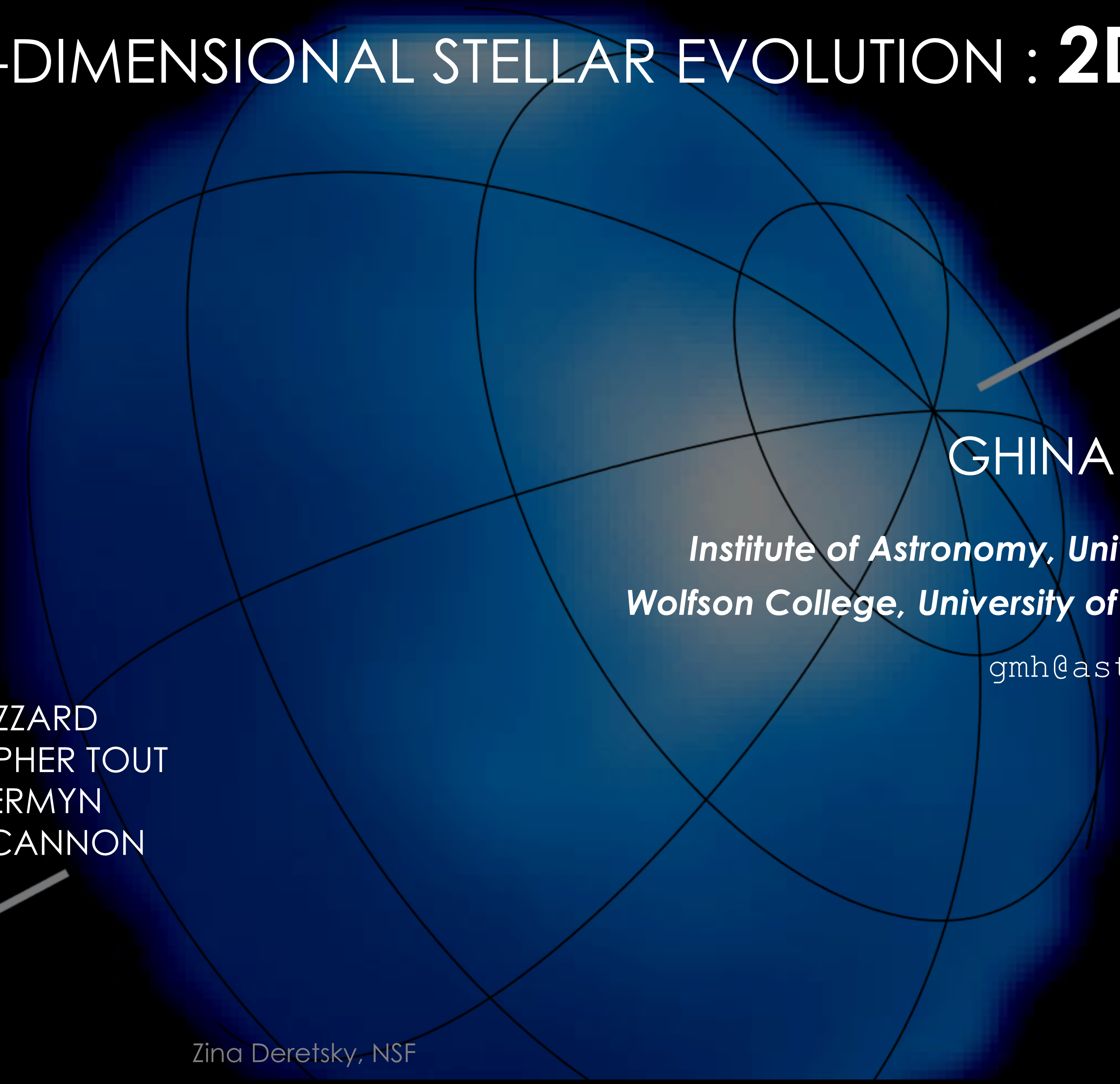


Zina Deretsky, NSF

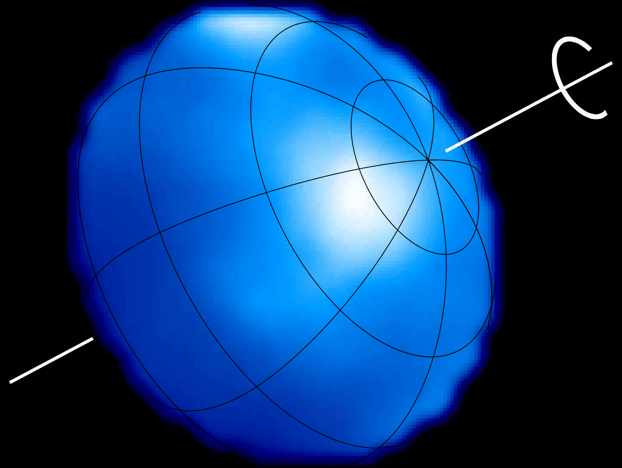
The AGB-Supernovae Mass Transition

27th – 31st March 2017, Rome, Italy

OUTLINE

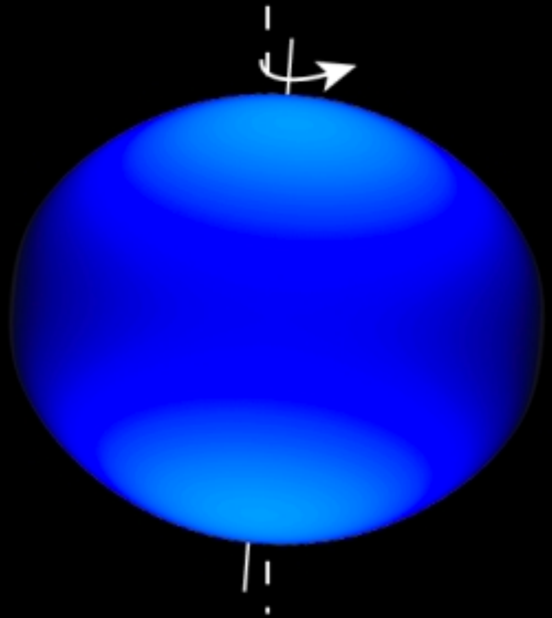
- Why 2D
- Rotating stars
  - Structure
  - Effects of rotation
  - Observable consequences
- How do we do this? **2DStars**
- Numerical challenges
- Further work

STELLAR ROTATION



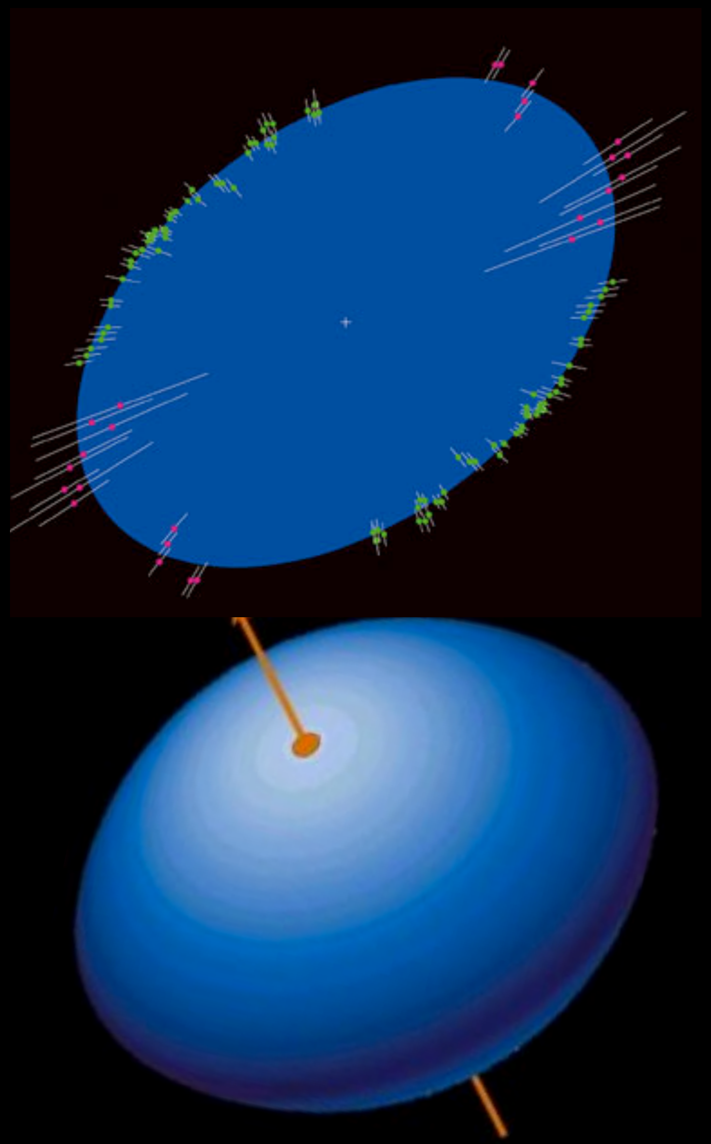
Altair (CHARA)

Monnier+ (2007)



Vega (CHARA)

J.Aufdenberg, NOAO (2006)



Achernar (VLT, ESO)

Domiciano+ (2003)

THERMAL STRUCTURE : NO ROTATION

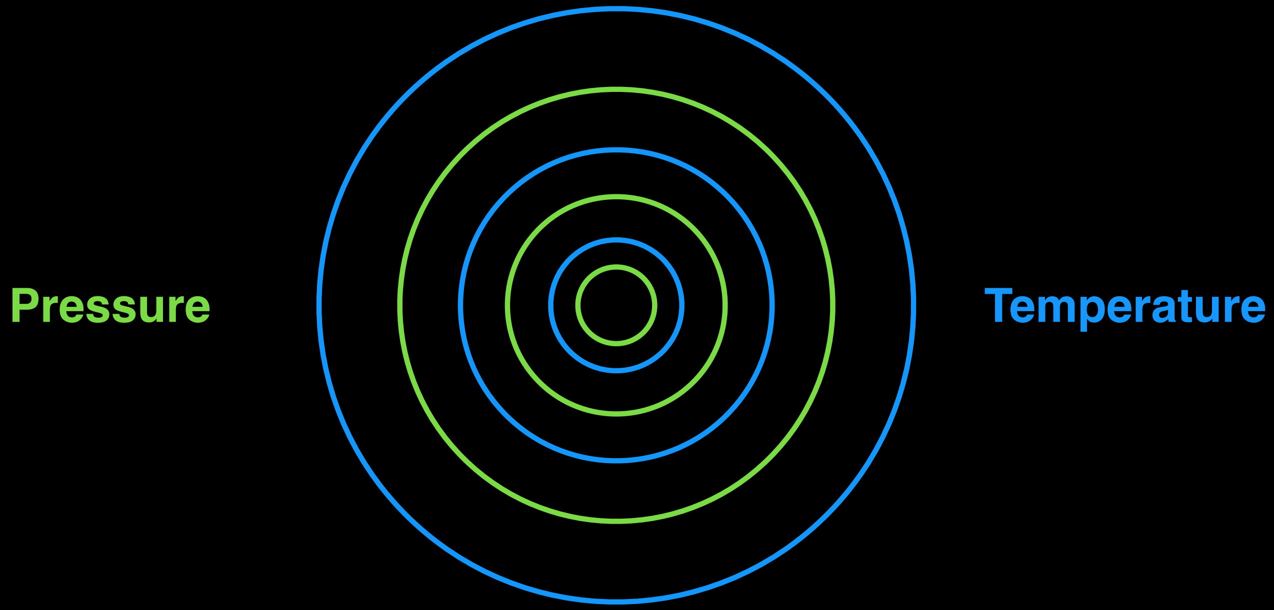
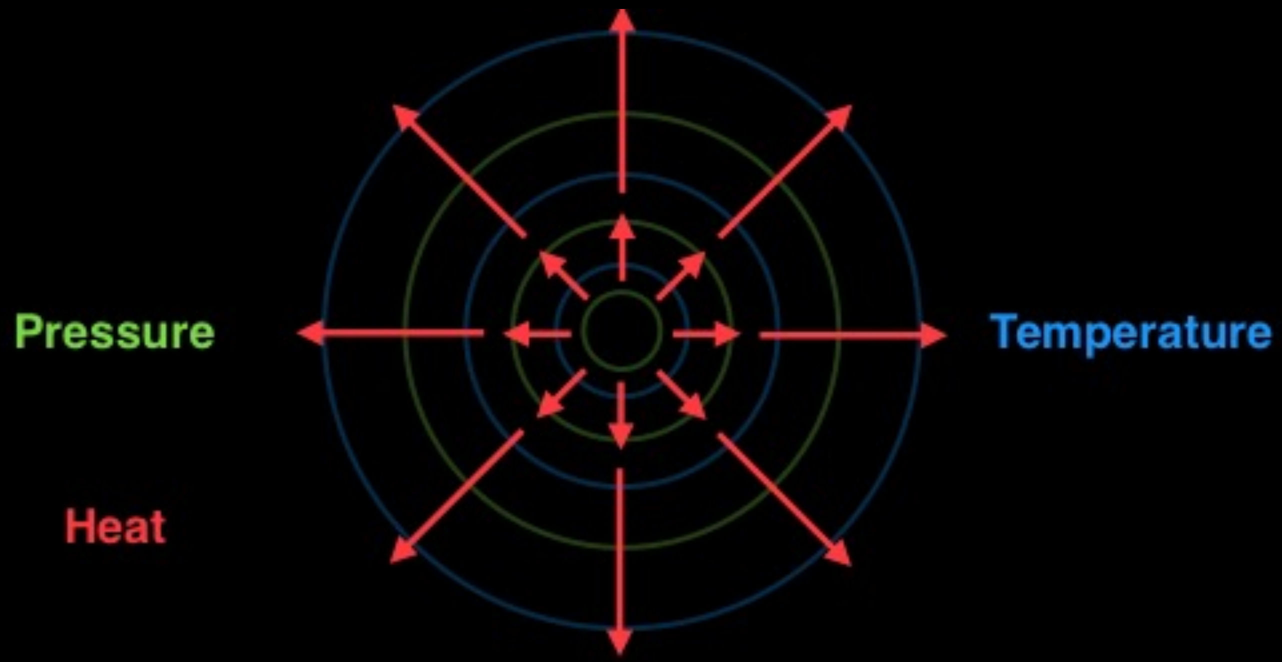


figure by Adam Jermyn

THERMAL STRUCTURE : NO ROTATION



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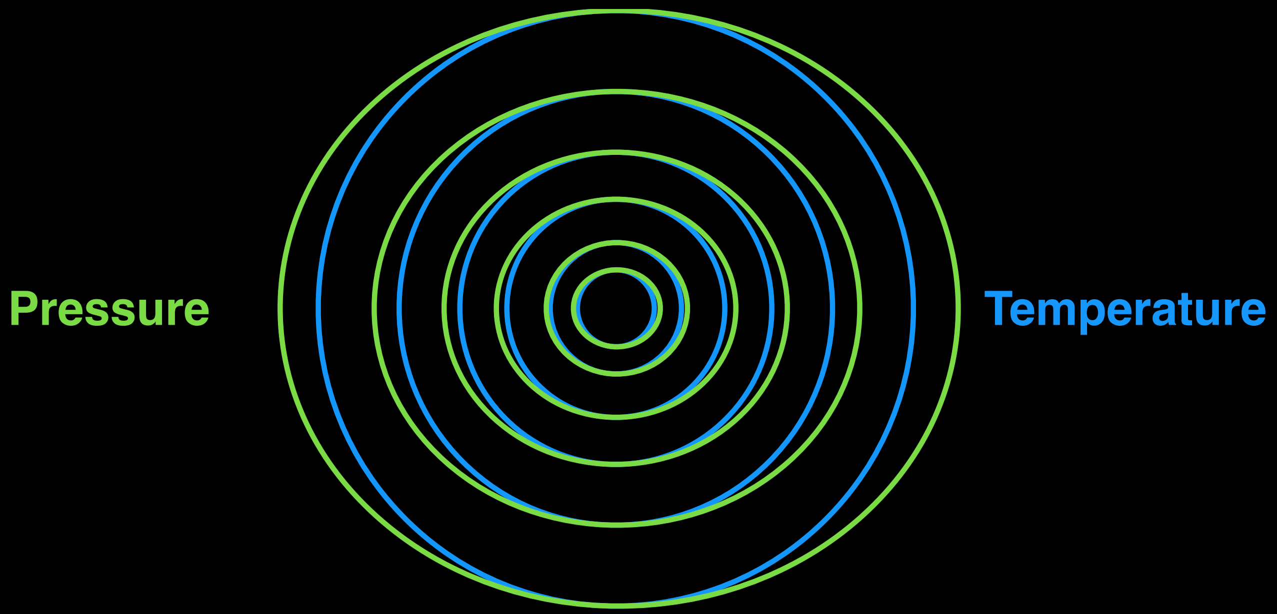
THERMAL STRUCTURE : ROTATING STARS



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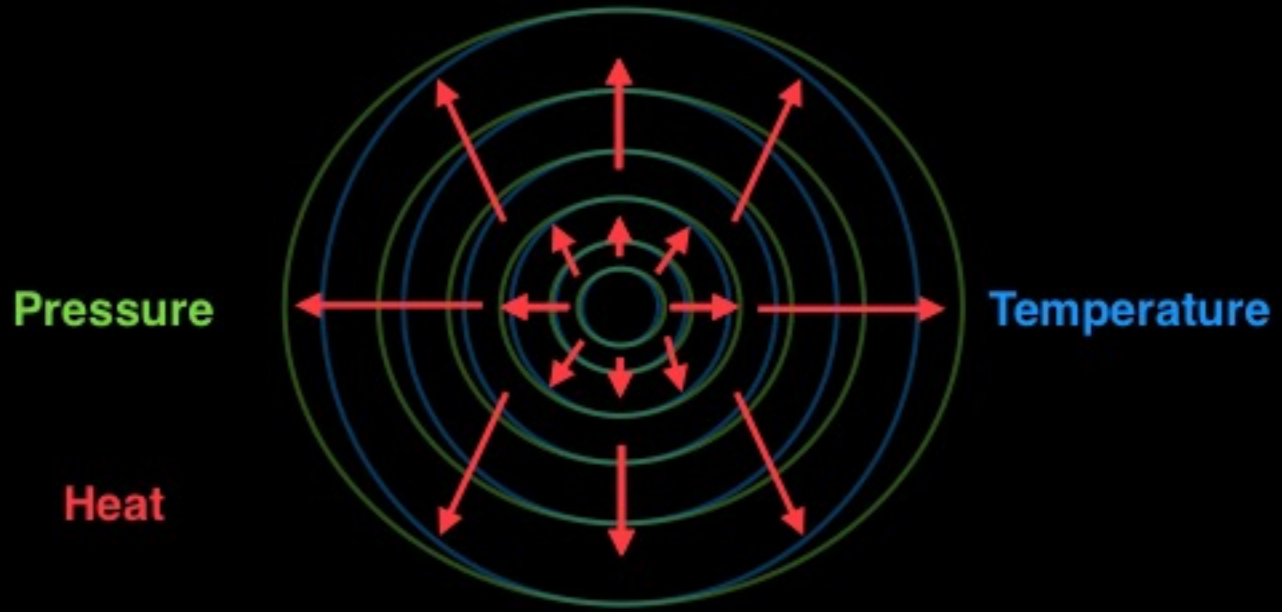

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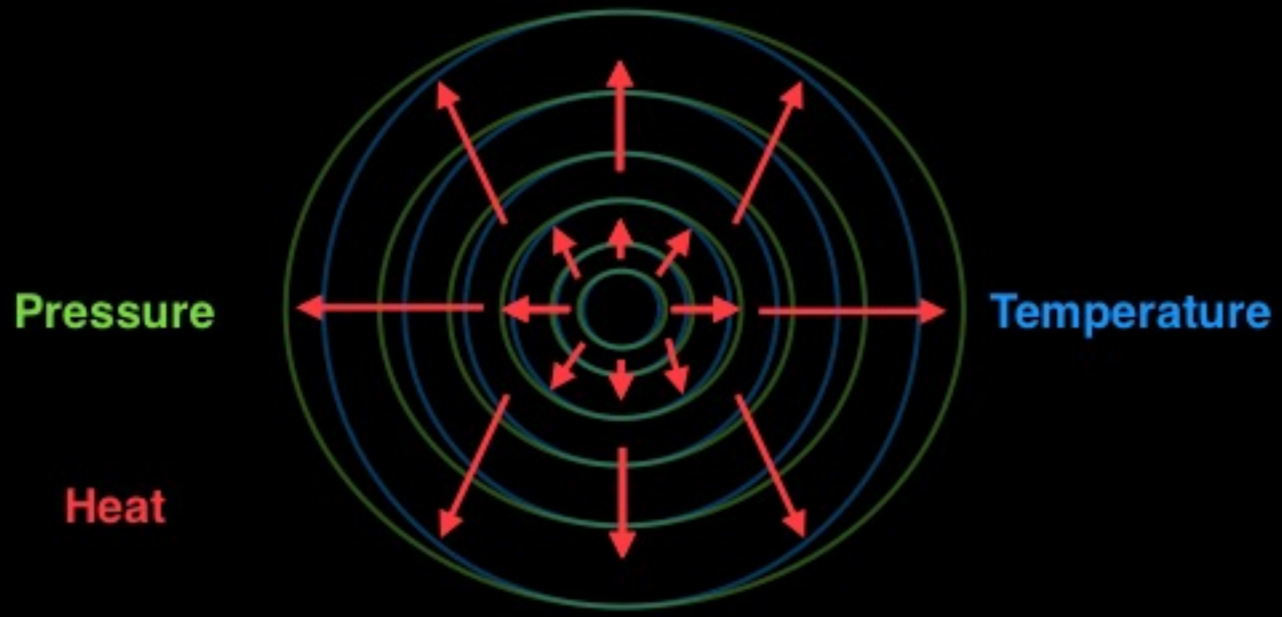
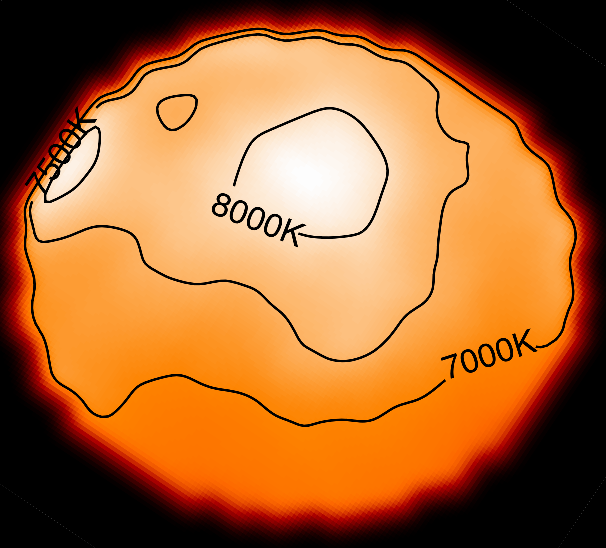


I_{eq} = 60% I_{pole} in Altair

brightness asymmetry
gravity darkening (von Zeipel 1924)



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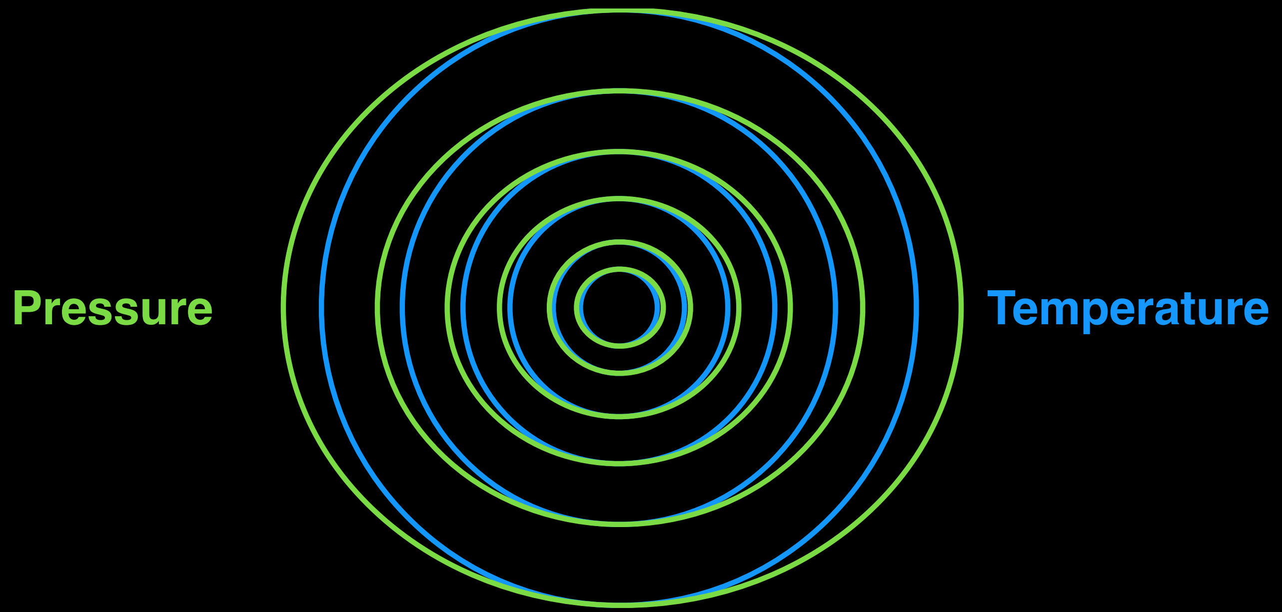
THERMAL STRUCTURE : ROTATING STARS



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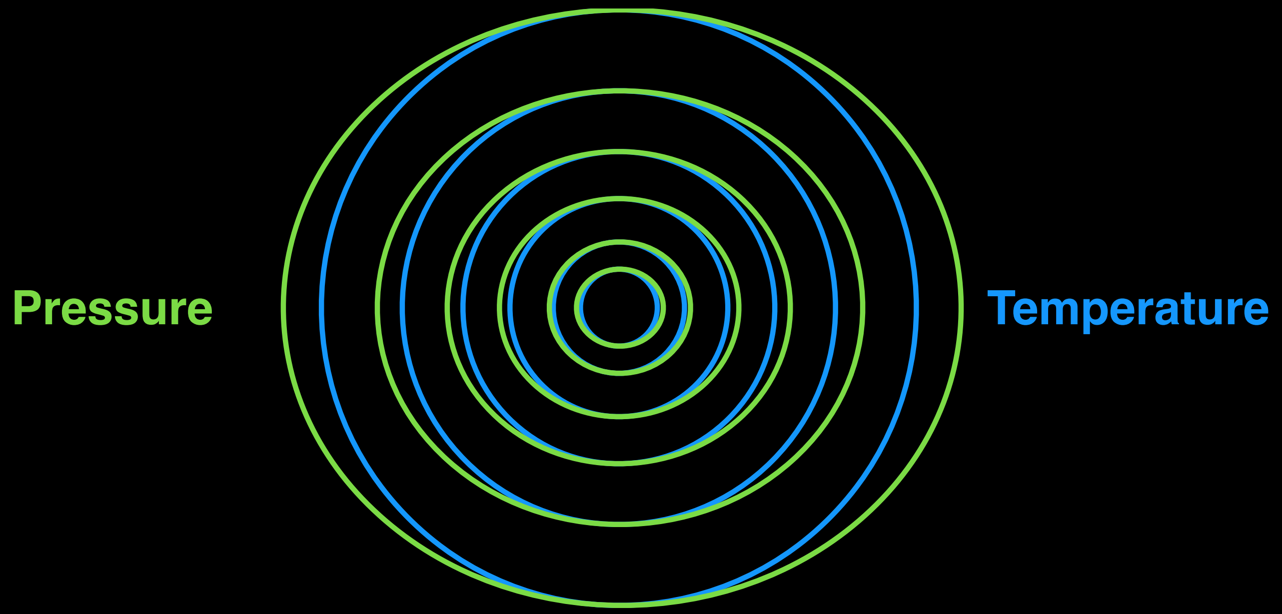
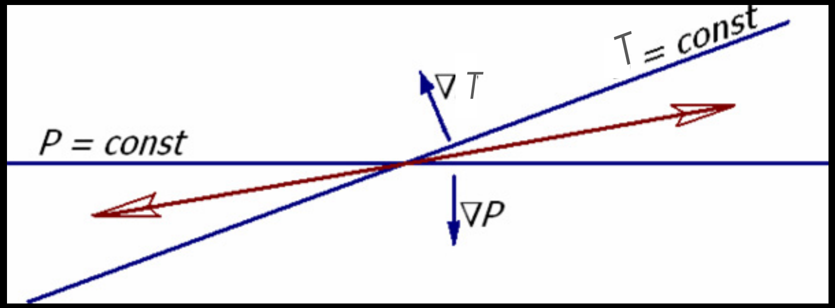


Baroclinic instability



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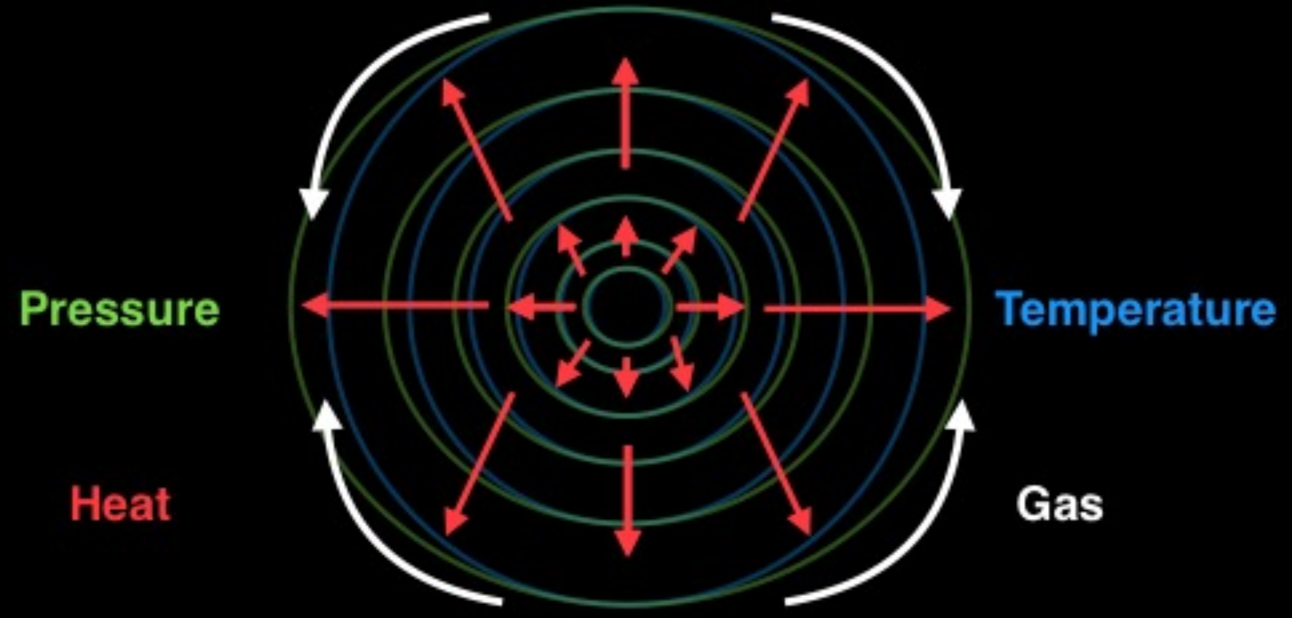
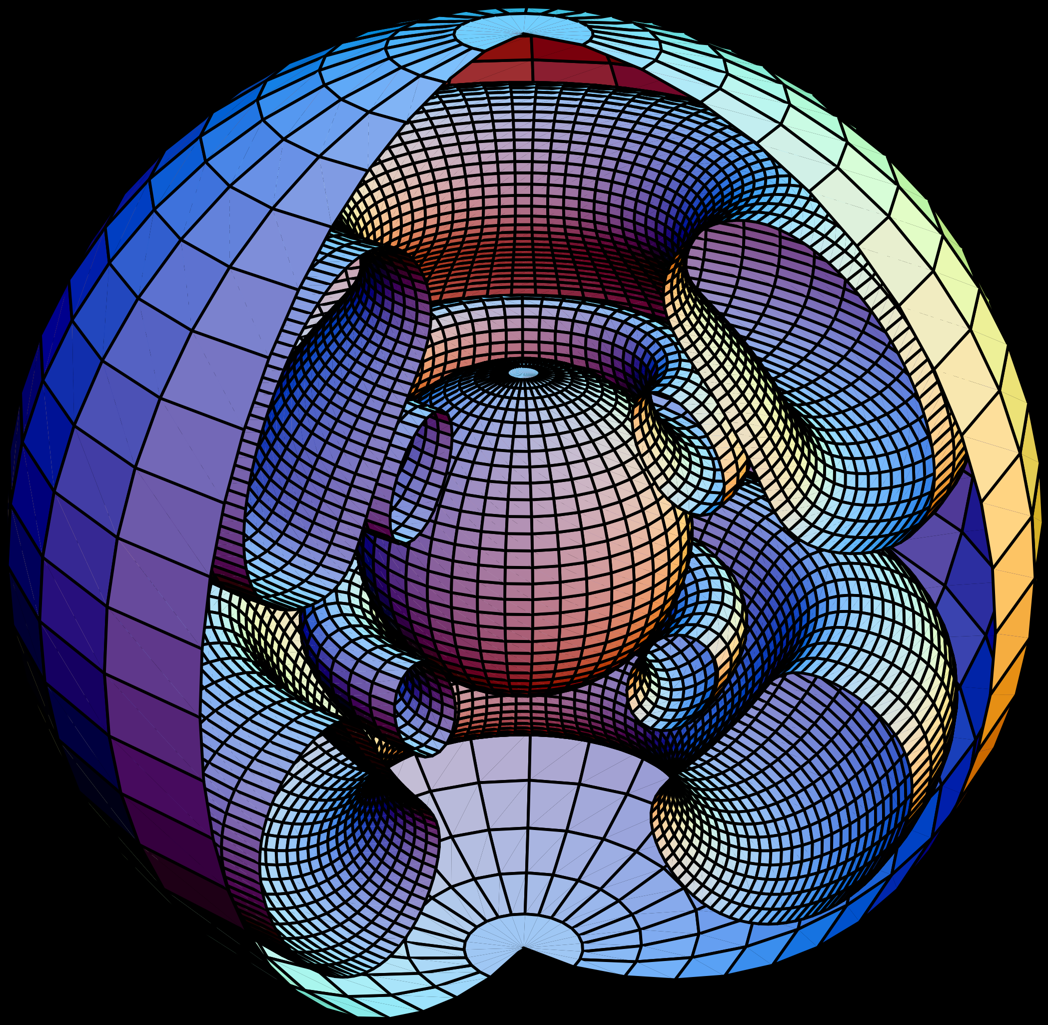


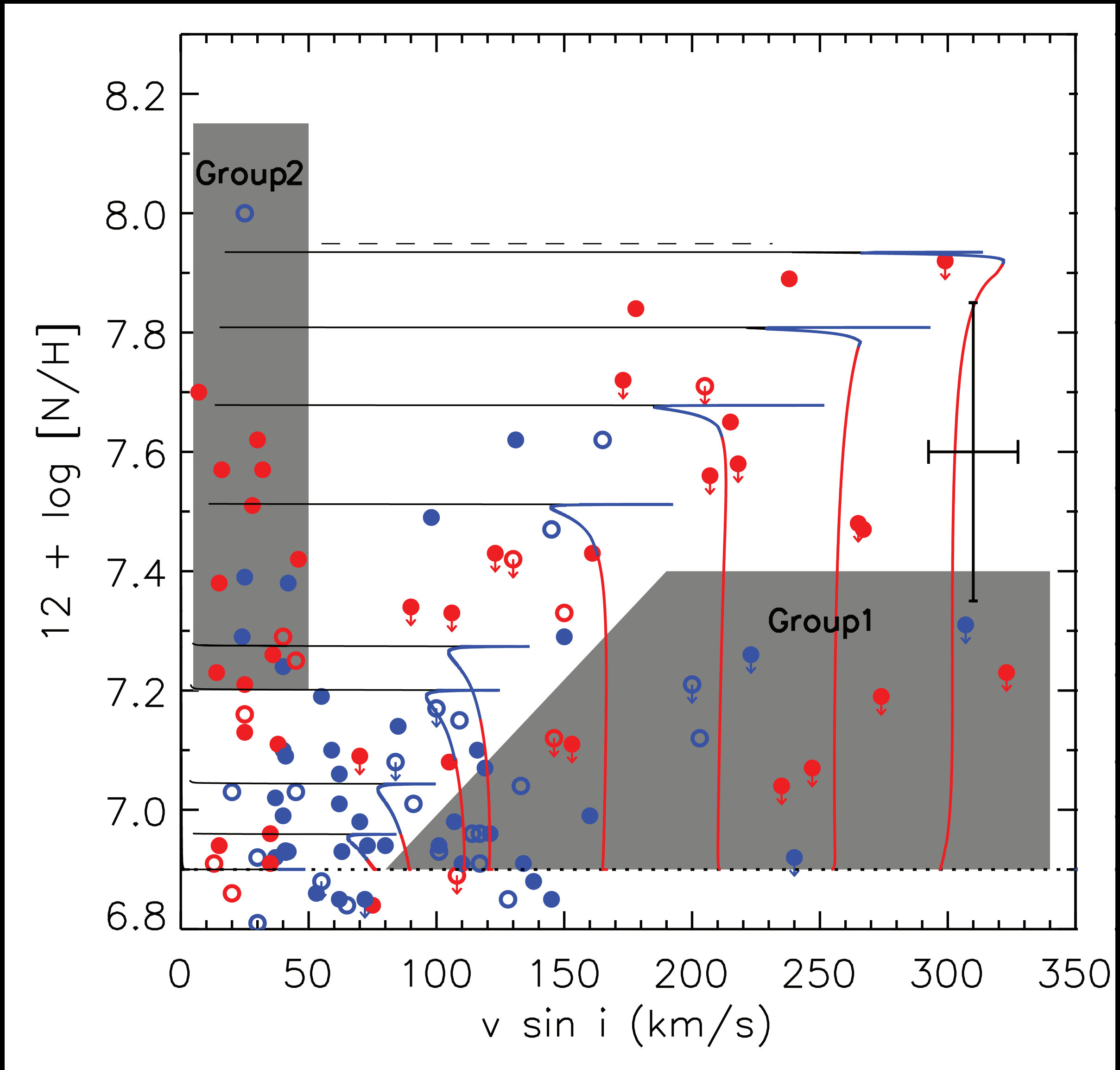
meridional circulation in radiative envelopes

THERMAL STRUCTURE : ROTATING STARS



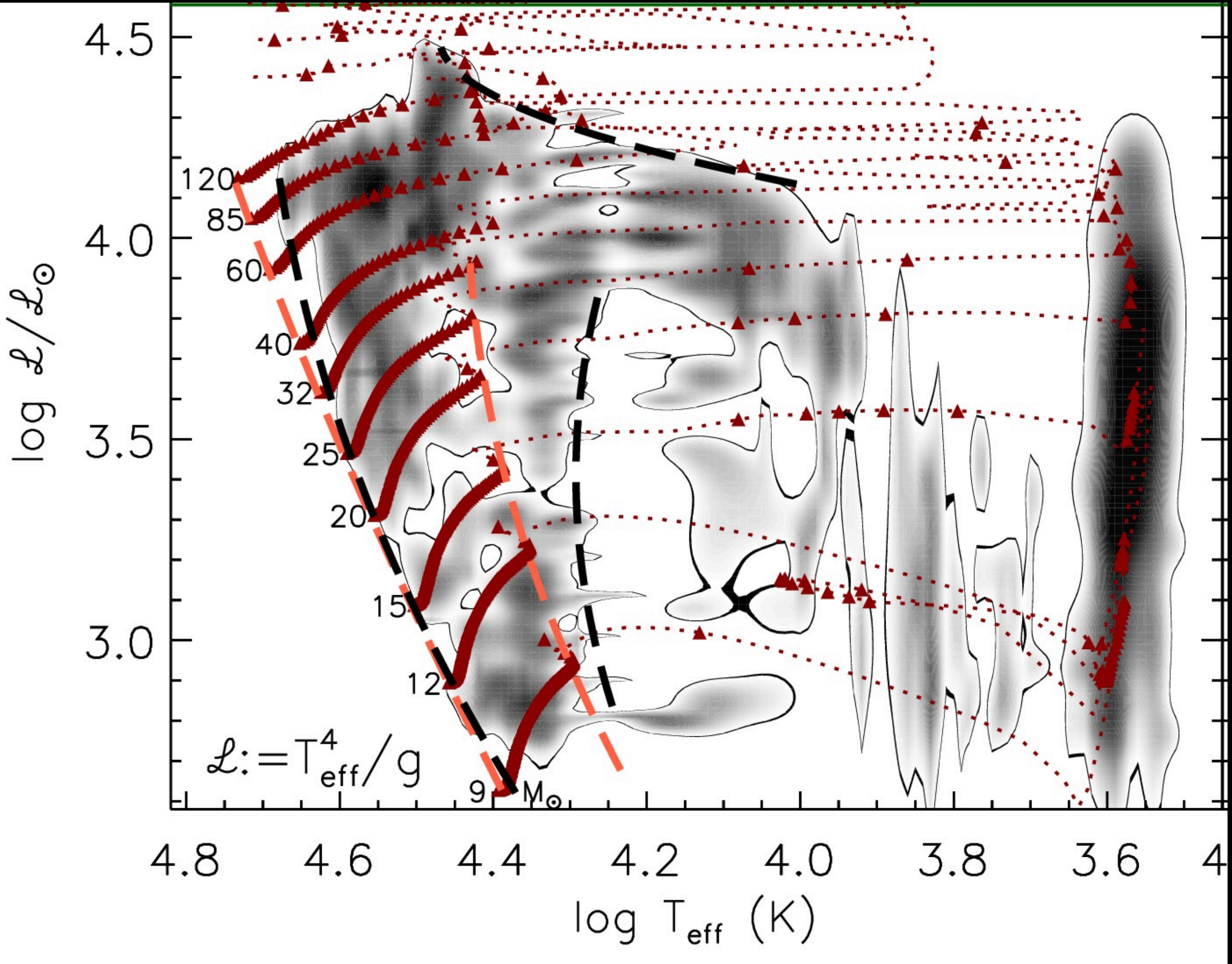
Meynet & Maeder (2002)

CONSEQUENCES : CHEMICAL MIXING!



VLT flames survey of massive stars in the LMC (Hunter+ 2008)

CONSEQUENCES : WIDTH OF MAIN SEQUENCE



Castro et al. (2014)

CONSEQUENCES : …

asteroseismology

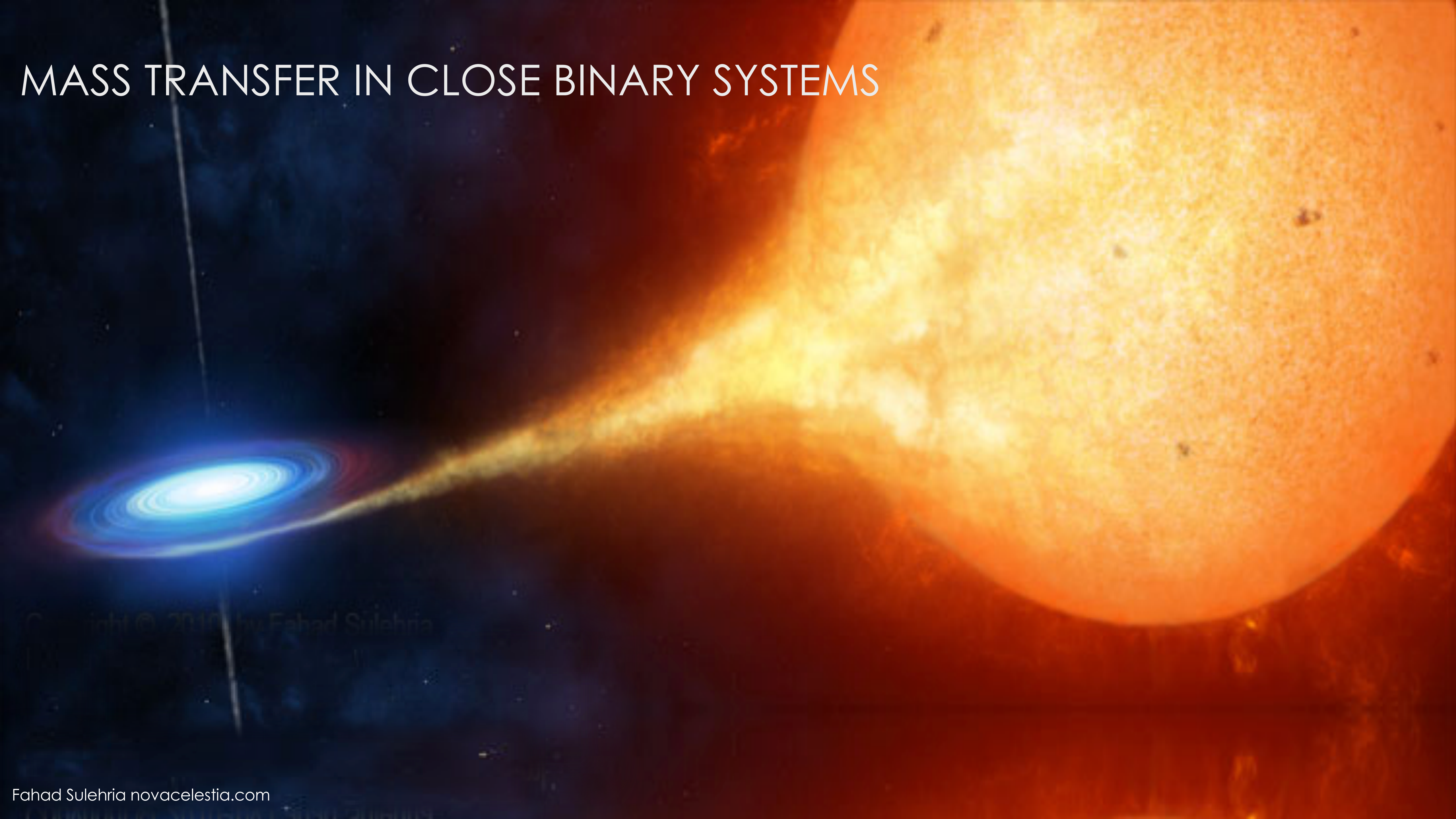
AGB chemical yields

SN rates

composition of ejecta

formation of black holes

MASS TRANSFER IN CLOSE BINARY SYSTEMS



Fahad Sulehria novacelestia.com

2DStars

in spherical polar coordinates:

Poisson equation: $\nabla^2 \Phi = 4\pi G \rho$

Continuity equation: $\vec{\nabla}.(\rho \vec{v}) = 0$

momentum equation: $\vec{\nabla}.(\rho \vec{v}\vec{v}) = -\vec{\nabla} P - \rho \vec{\nabla} \Phi + \vec{\nabla}.\vec{\sigma}$

equation of state: $P = K\rho^\gamma$

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2DSTARS

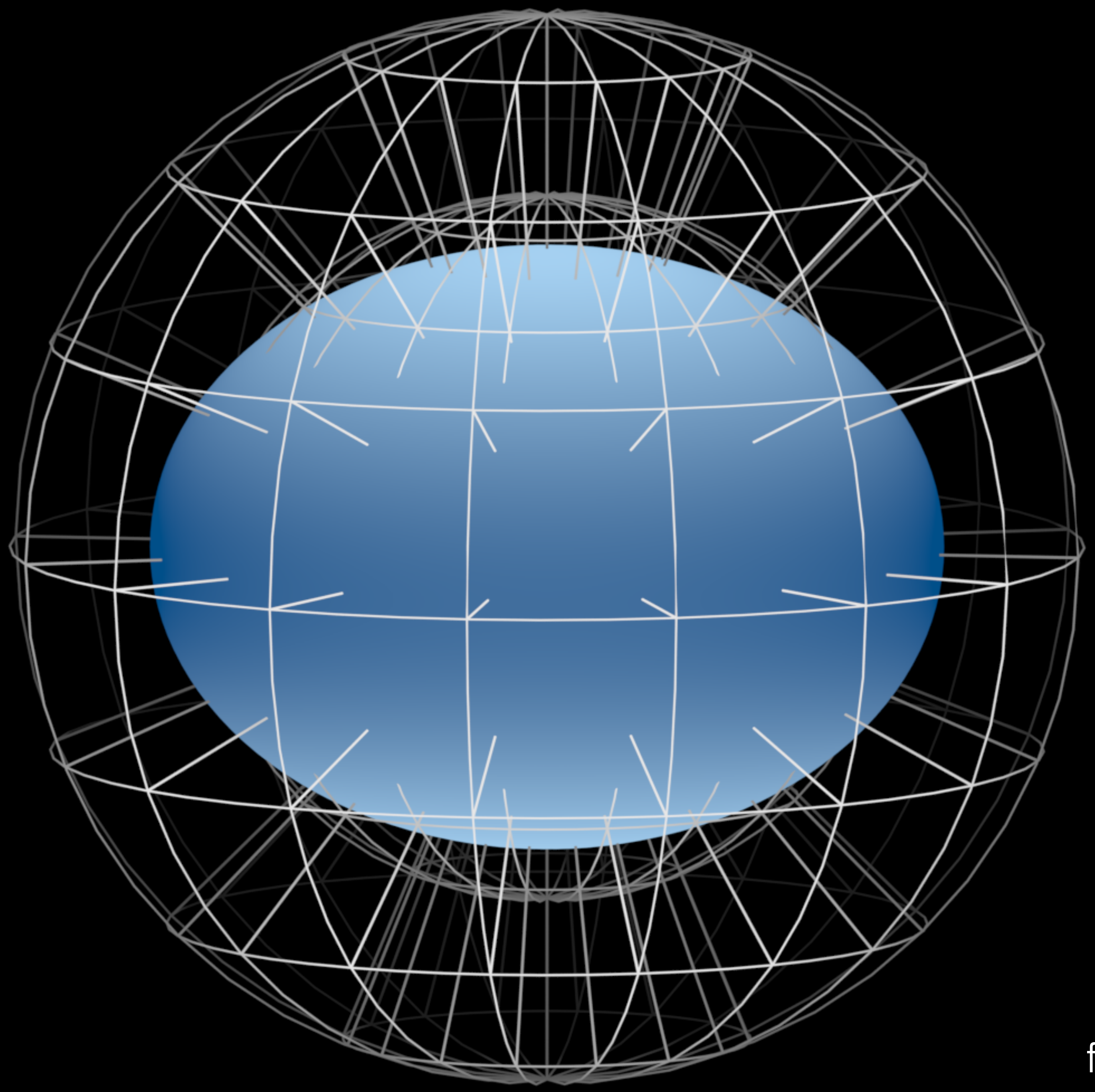
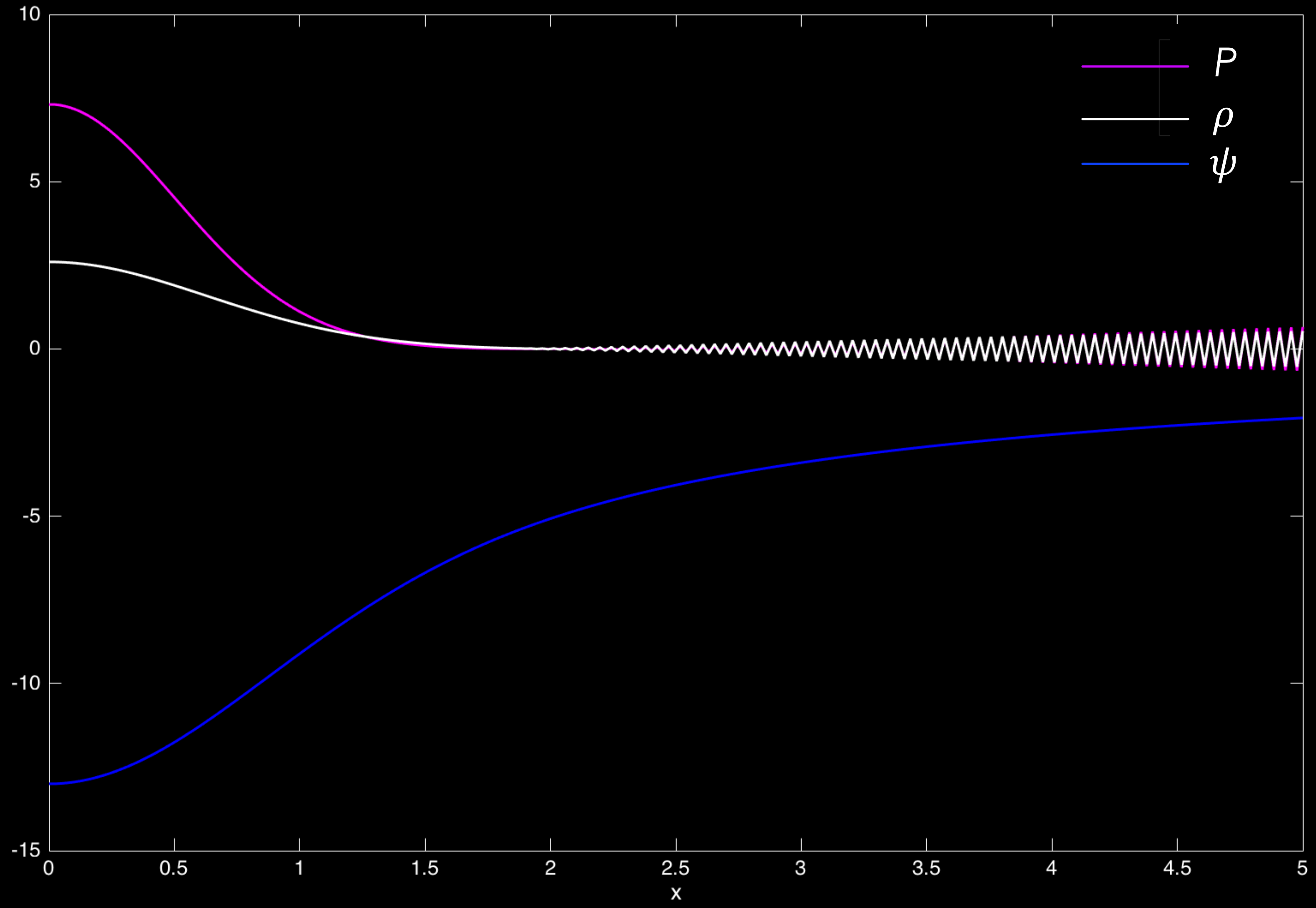


figure by Tom Comerford

2DSTARS : NUMERICAL CHALLENGES



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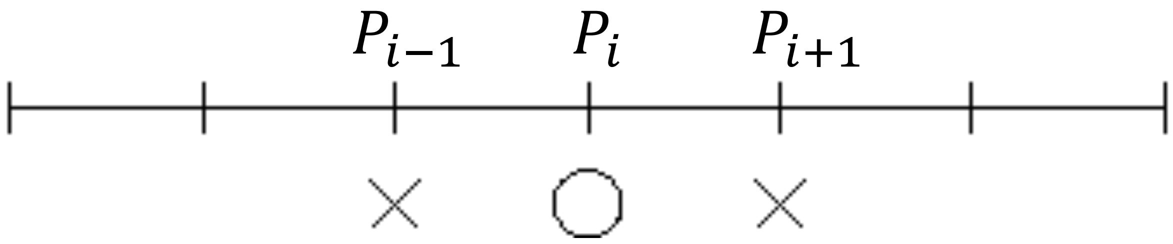

$$\frac{\partial P}{\partial r} = -\rho \frac{\partial \Phi}{\partial r}$$

$$\frac{P_{i+1,j} - P_{i,j}}{r_{i+1,j} - r_{i,j}} + \frac{P_{i,j} - P_{i-1,j}}{r_{i,j} - r_{i-1,j}} = -\rho_{i,j} \left(\frac{\Phi_{i+1,j} - \Phi_{i,j}}{r_{i+1,j} - r_{i,j}} + \frac{\Phi_{i,j} - \Phi_{i-1,j}}{r_{i,j} - r_{i-1,j}} \right)$$

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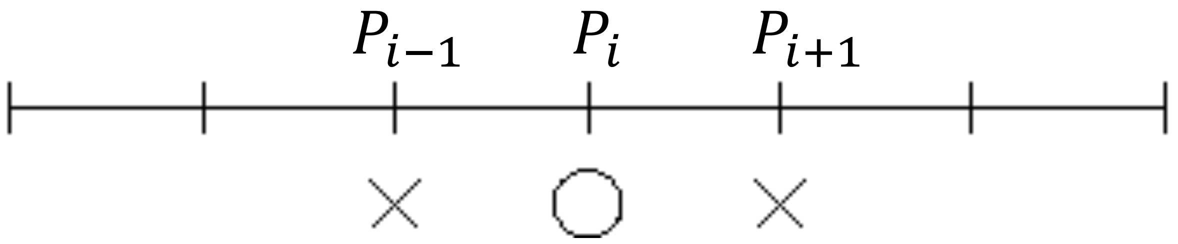

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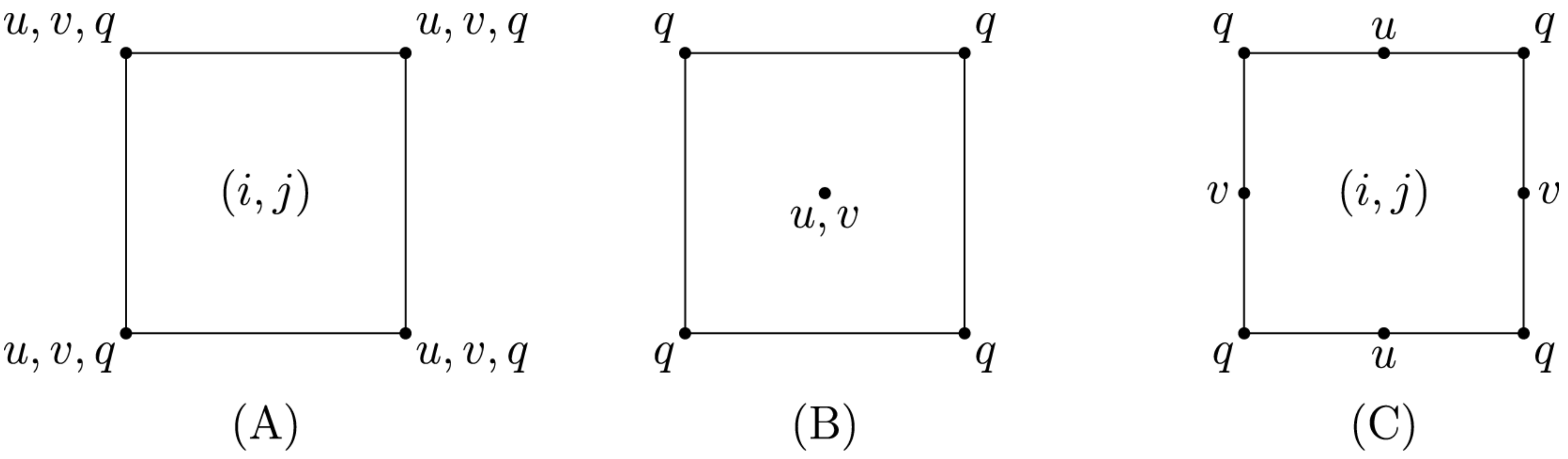
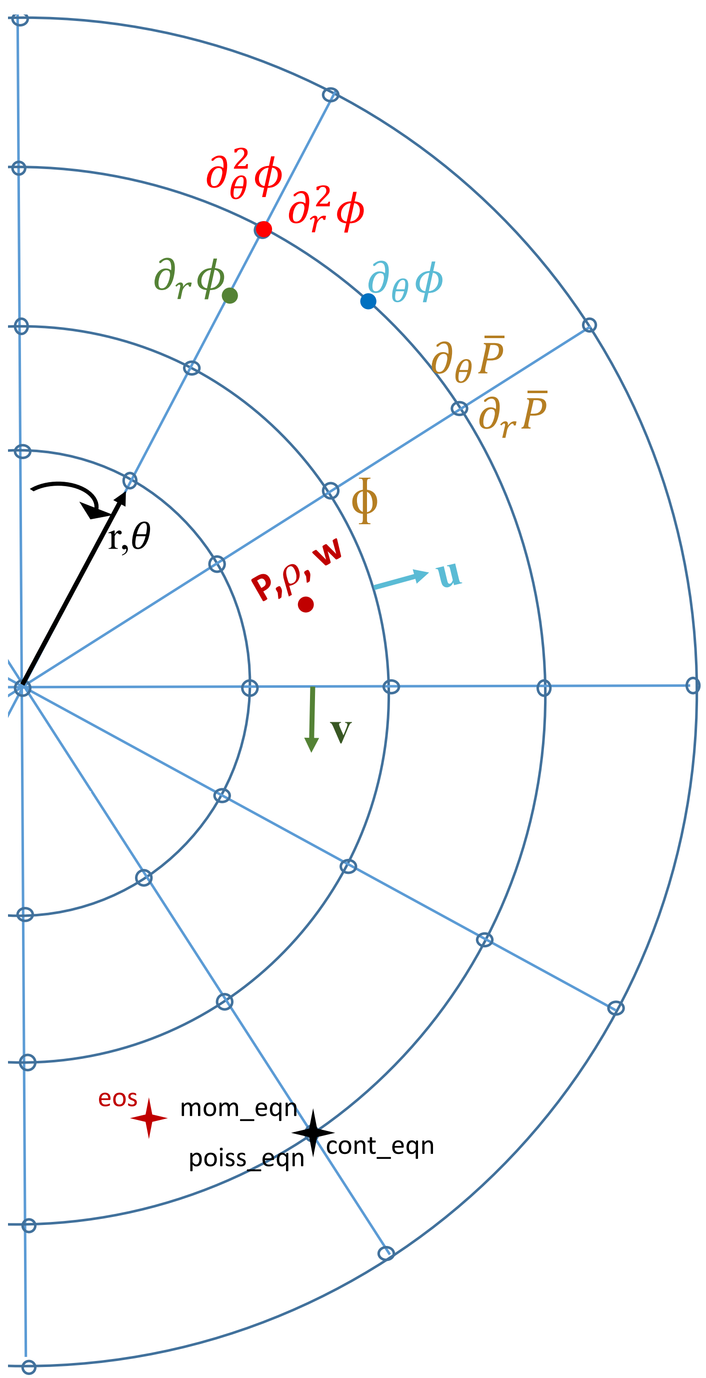
2DSTARS : STAGGERED GRID



unstaggered grid **staggered grid** **staggered grid**

2DSTARS : STAGGERED GRID



2DSTARS : FINITE ELMENT METHOD