Long GRB progenitors

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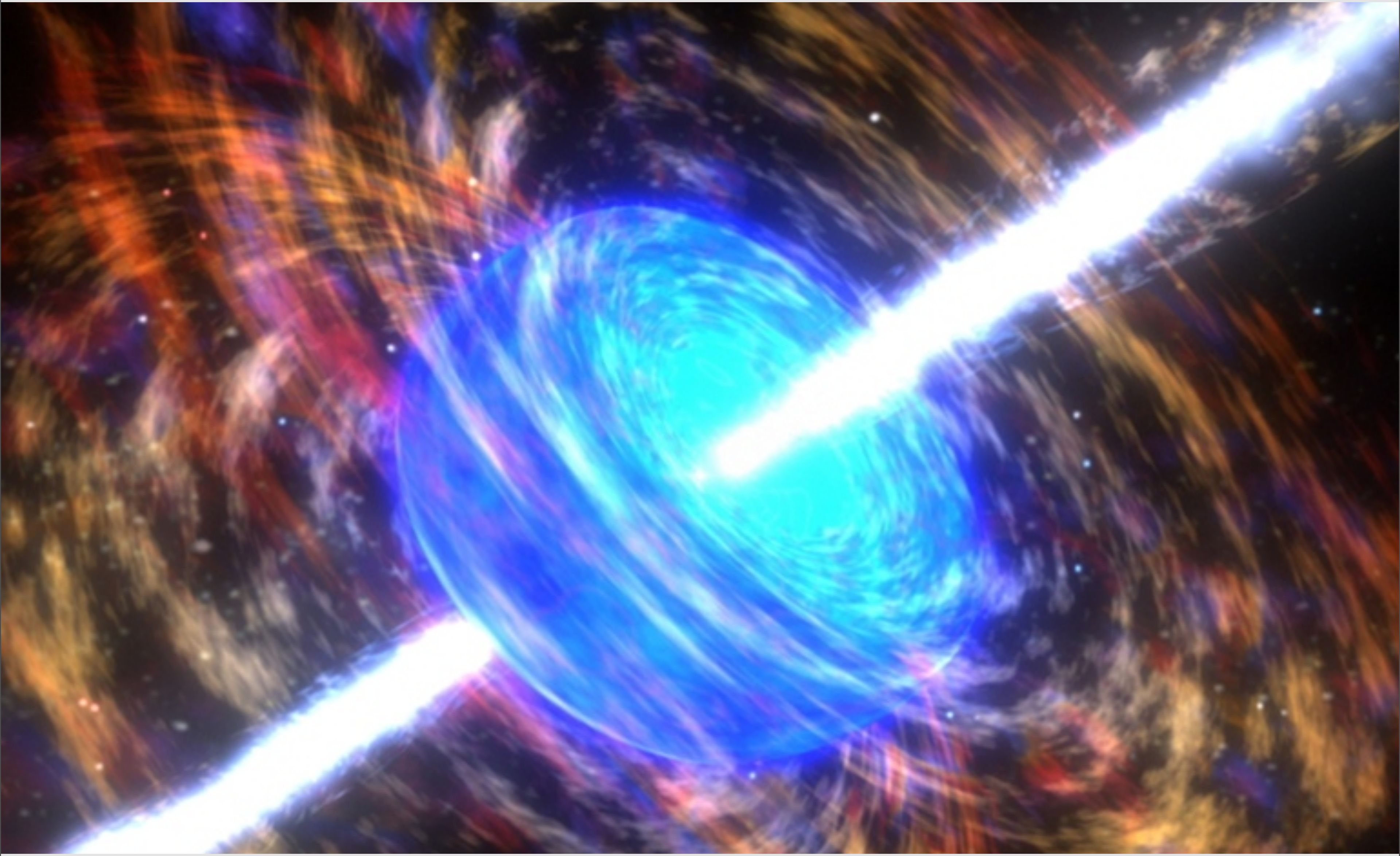
Gamma Ray Bursts

- Central Engines
- Massive Stars Evolution with Rotation and B-fields
- Single Star Progenitors of GRBs
- Binary Star Progenitors of GRBs
- Relevant Observations of Massive Stars
- Predictions from the progenitor models
- Where we stand?

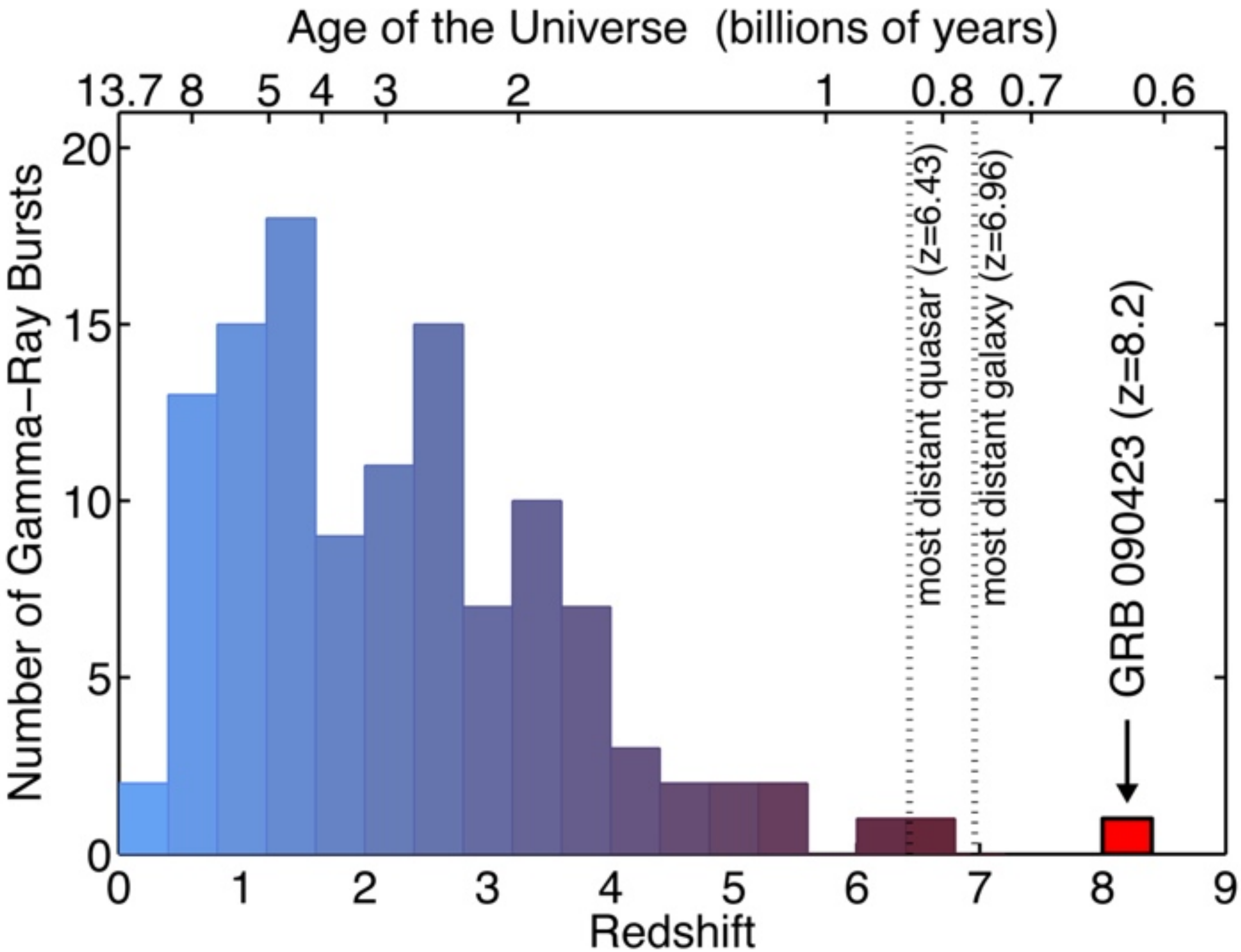
Gamma Ray Bursts



Gamma Ray Bursts

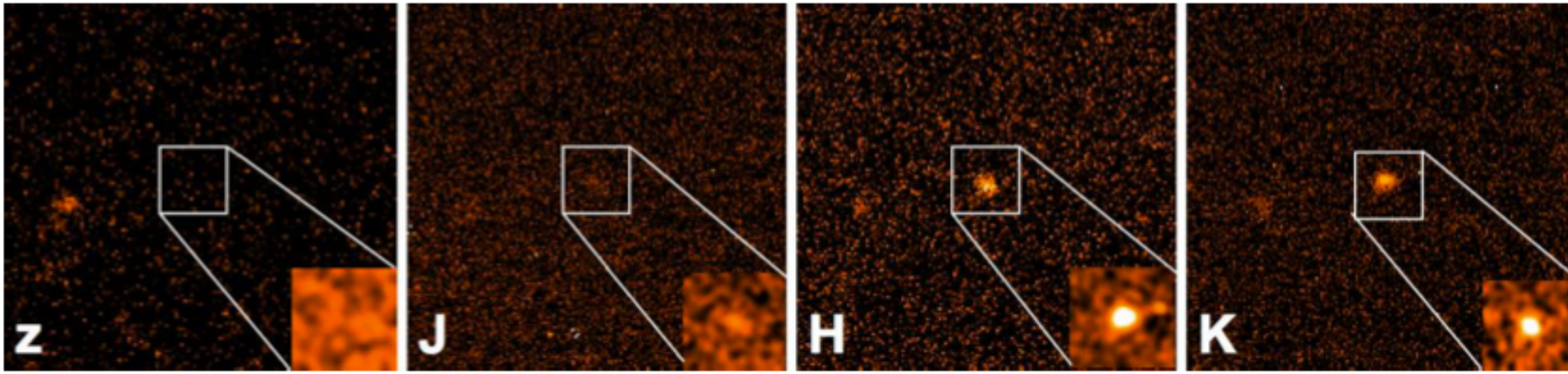
The most luminous electromagnetic transients in the universe

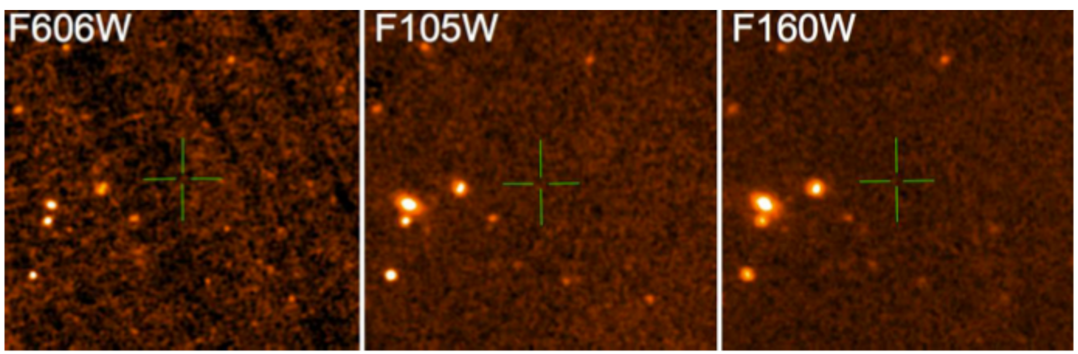
SWIFT GRBs

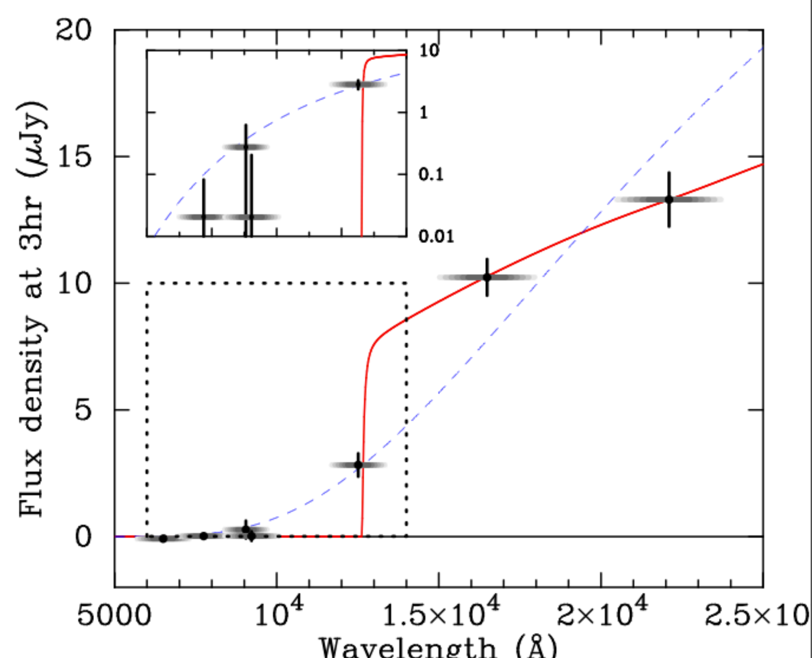


Credit: Edo Berger (Harvard-Smithsonian CfA)

GRB 090429B



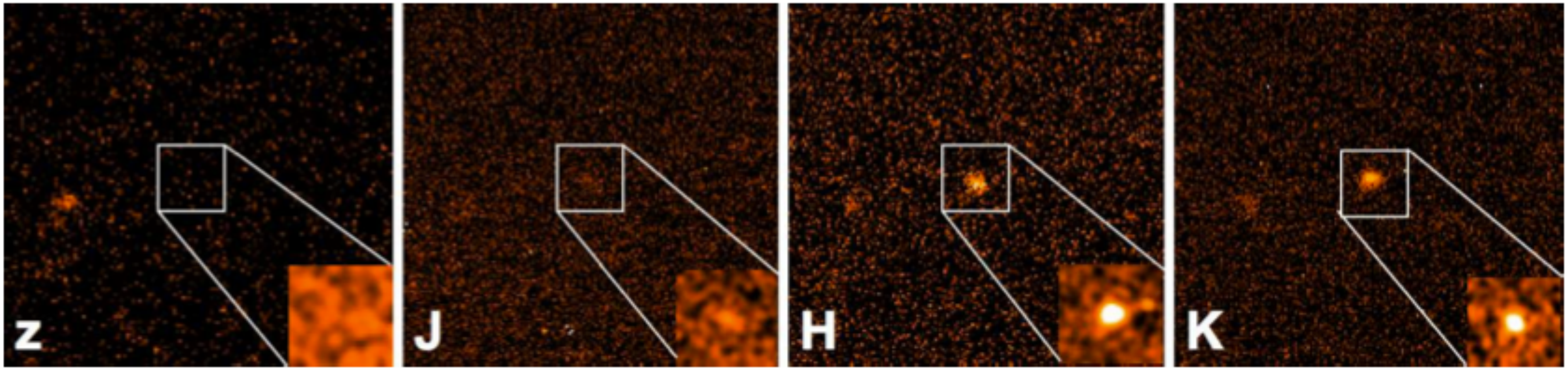


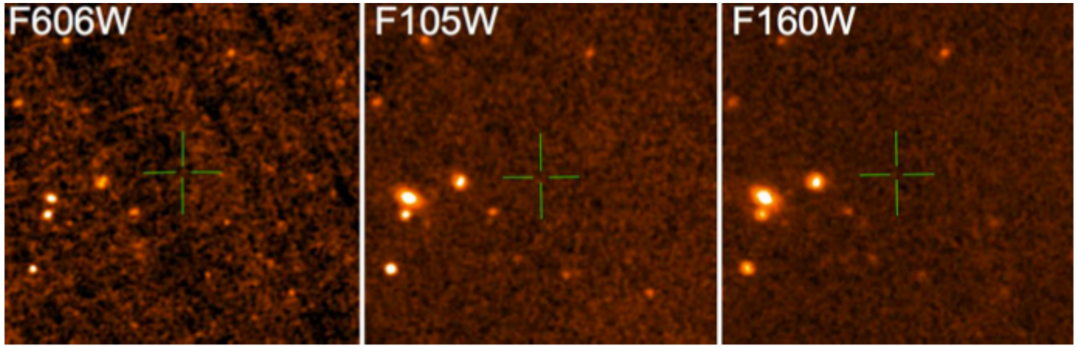


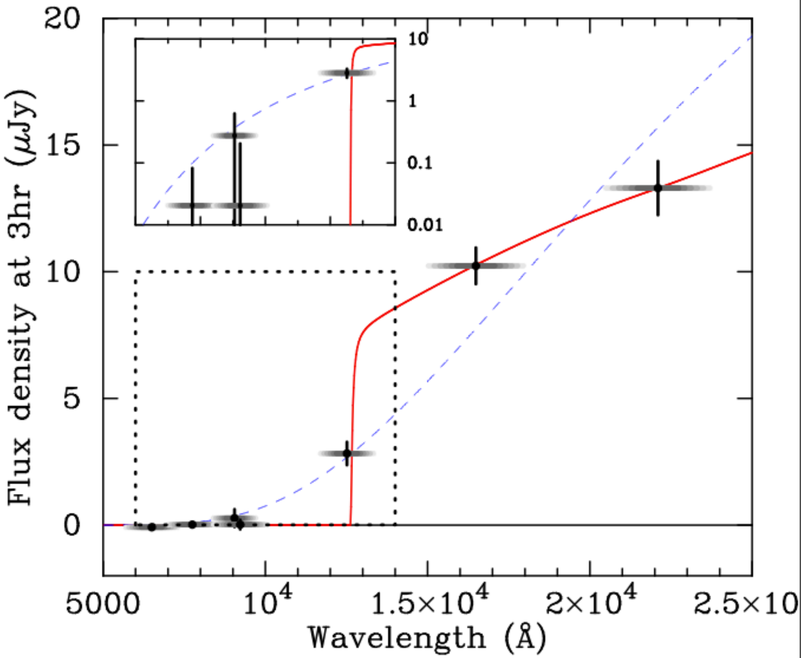
$z \sim 9.4$ ($t_{Universe} \sim 520$ Myrs)

Cucchiara et al. 2011

GRB 090429B







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Cucchiara et al. 2011

Two classes of GRBs

- **70% Long** (t > 2s)
- Associated with the death of massive stars (e.g. Nomoto et al. 2011)

- **30% Short** (t < 2s)
- Merger of compact objects? (e.g. Berger 2011)

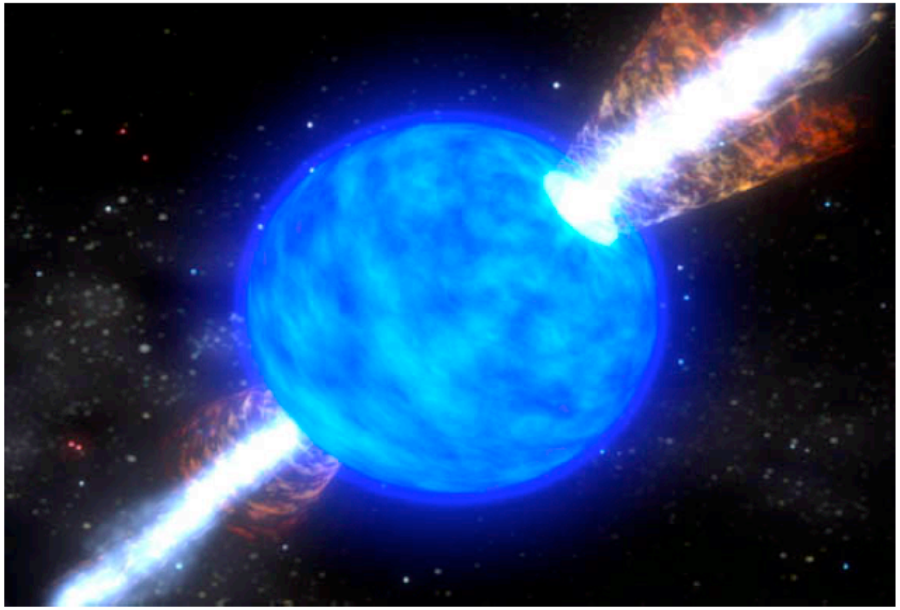

Image credit: NASA / SkyWorks Digital

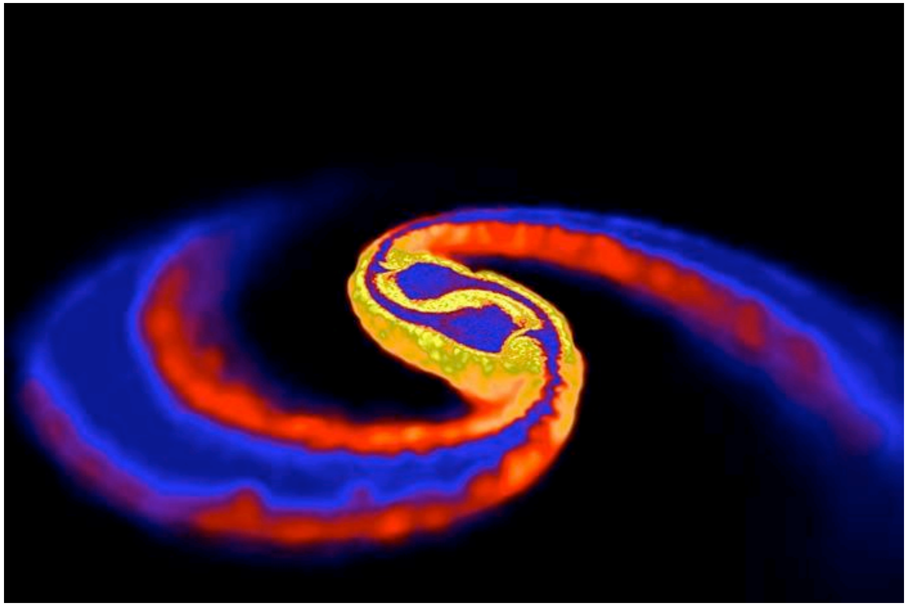

Image credit: Price & Rosswog

Long GRBs

Long GRBs

- SN (Type Ic, BL) - GRB connection (e.g Stanek et al. 2003, Nomoto et al. 2003, Modjaz et al. 2006, see also Soderberg et al. 2010)
- Found in regions of massive star formation (Bloom et al. 1999, Fruchter et al. 2006)
- Most (all?) long GRBs produced by the death of massive stars (Woosley & Bloom 2006)

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Which massive stars explode as Long Gamma-Ray Bursts?

Central Engines

Central Engines 101

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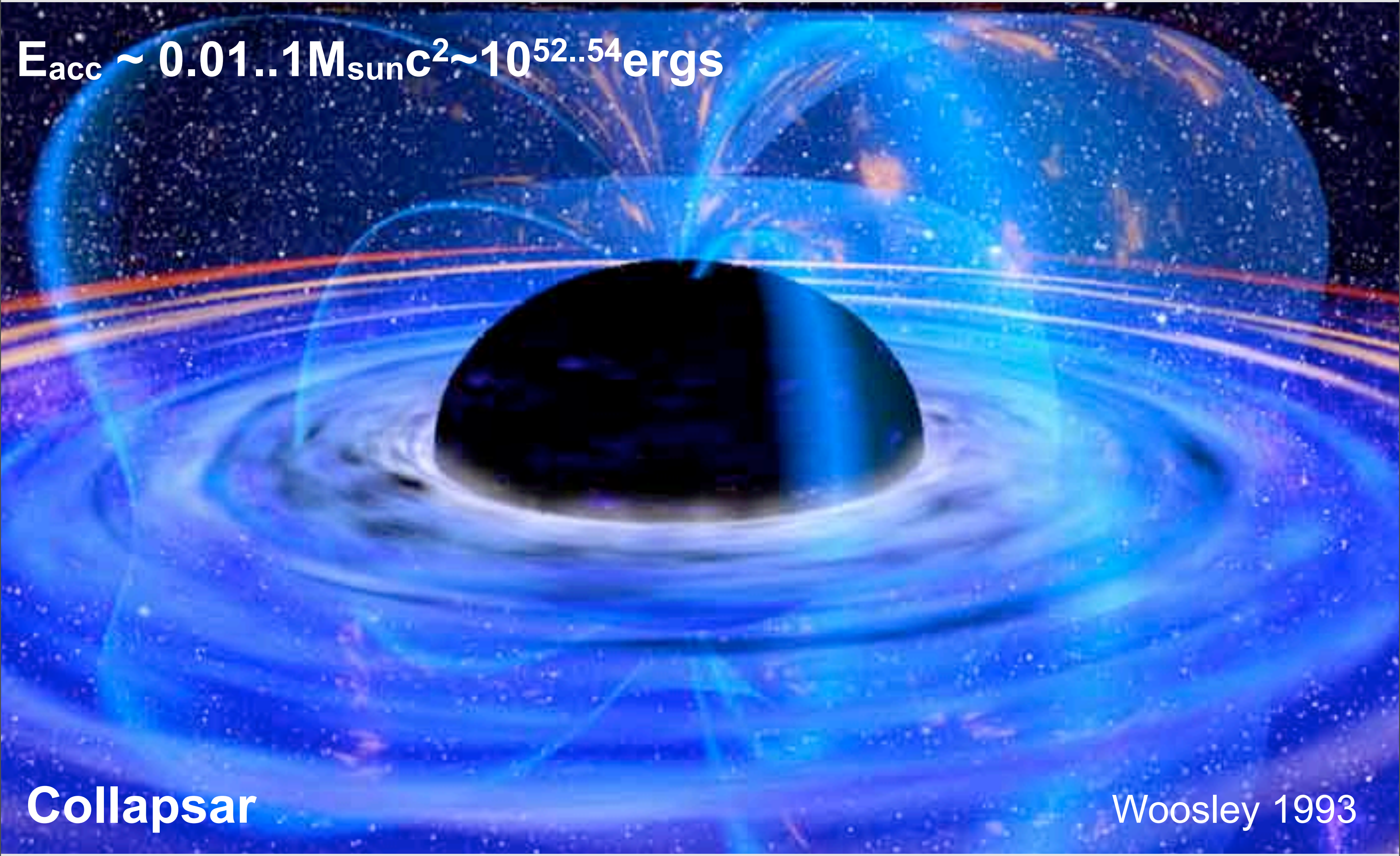

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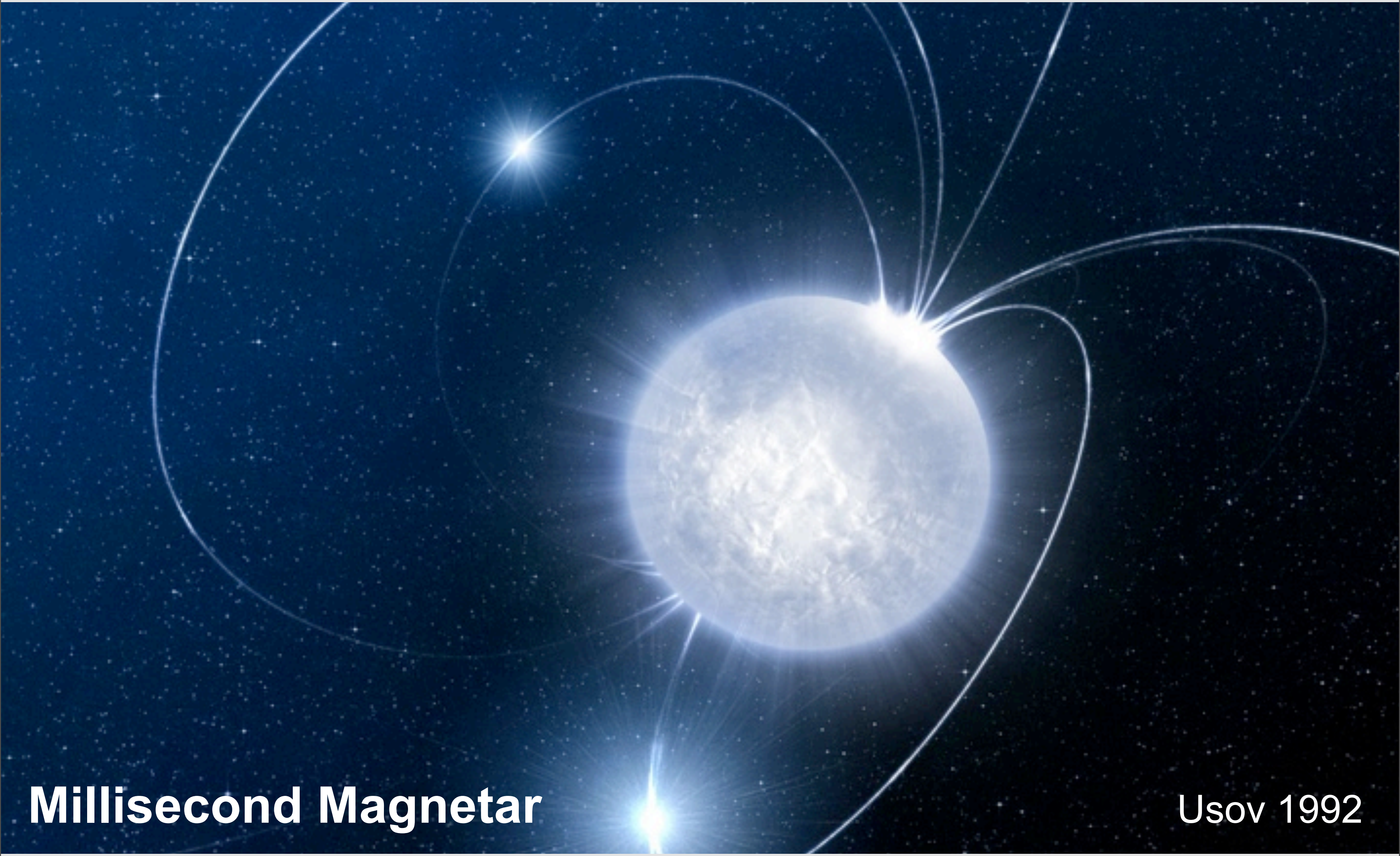

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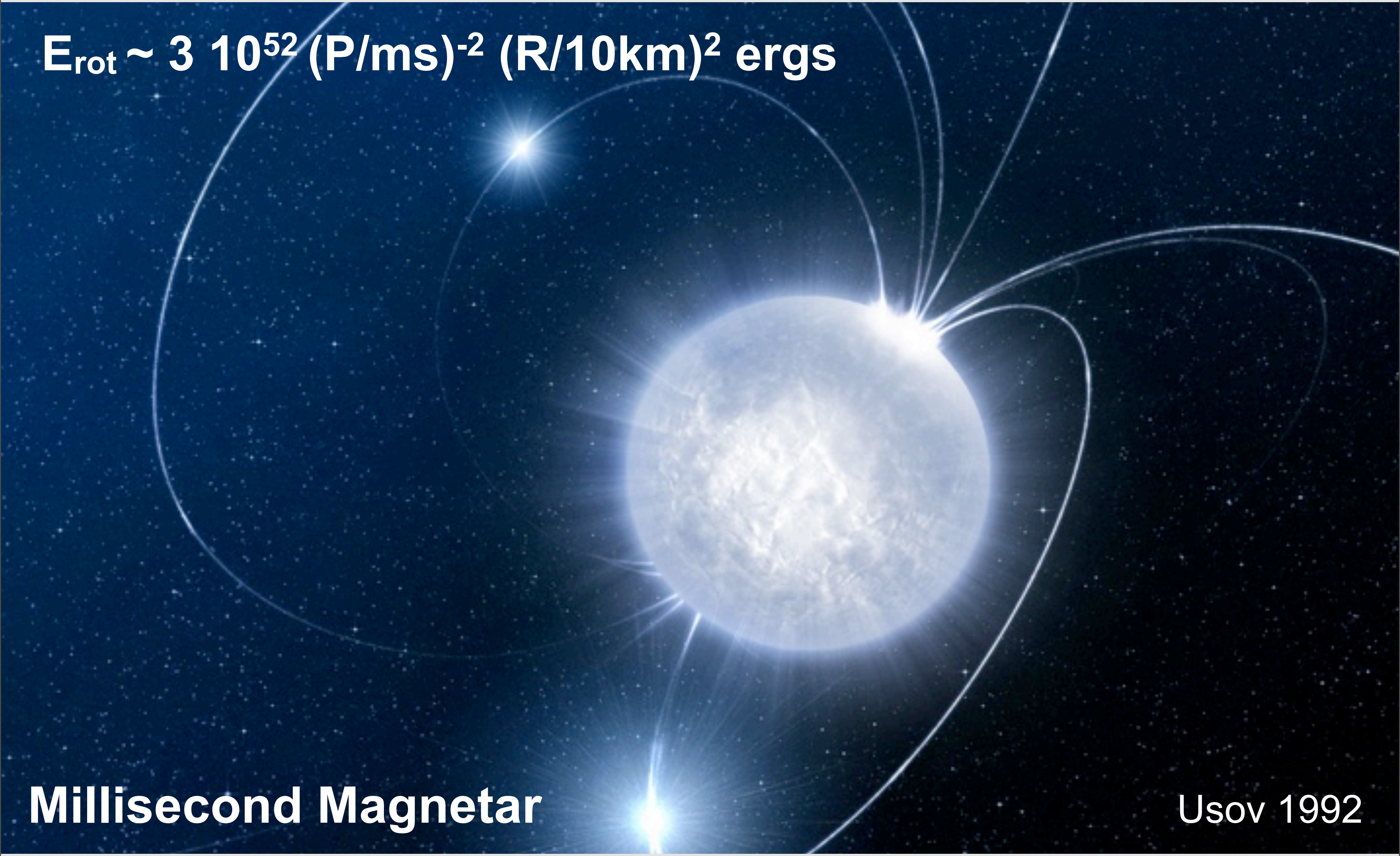

$E_{rot} \sim 3\ 10^{52}\ (P/ms)^{-2}\ (R/10km)^{2}$ ergs

Millisecond Magnetar

Usov 1992

Central Engines 101

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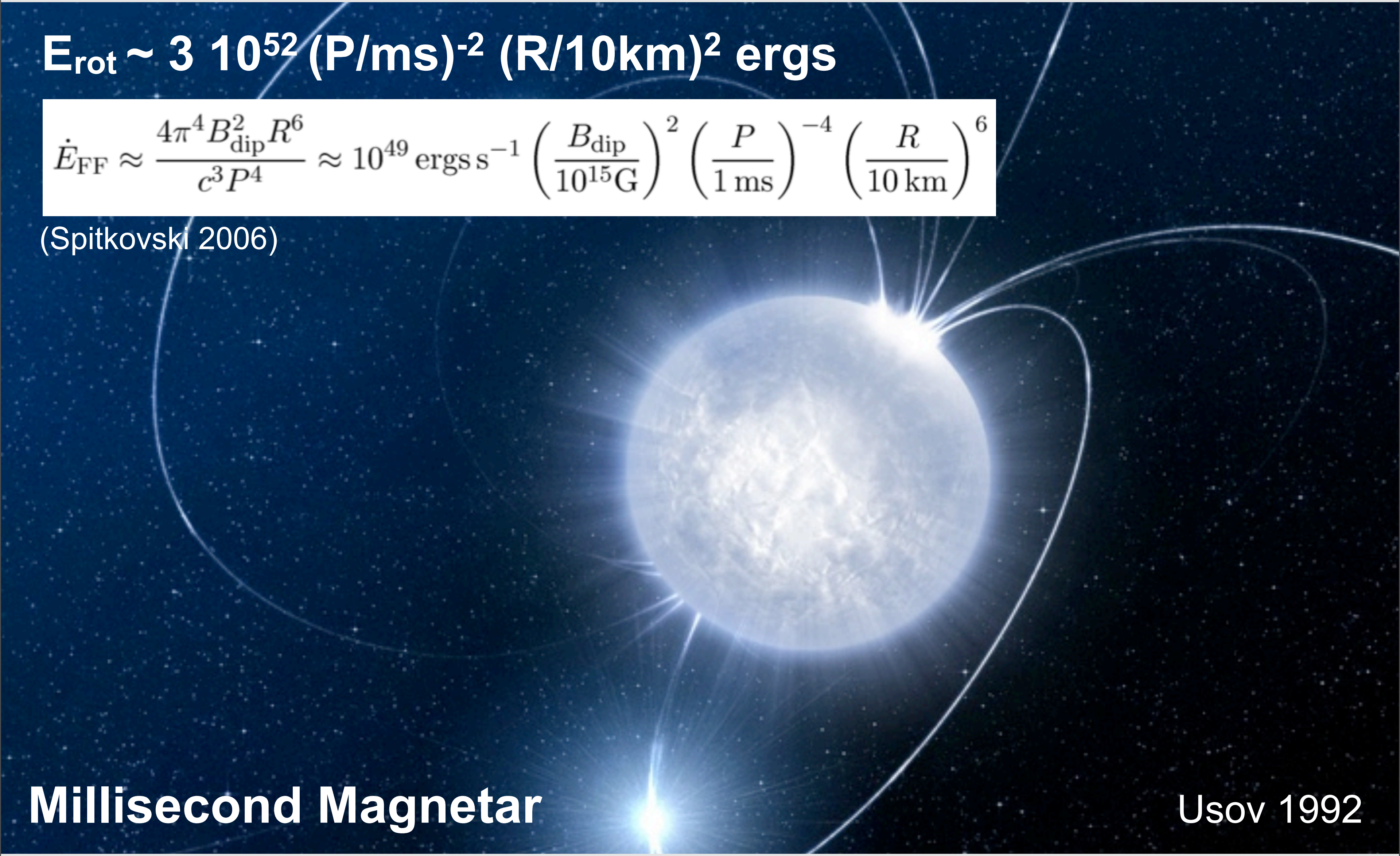
$$\dot{E}_{\rm FF} \approx \frac{4\pi^4 B_{\rm dip}^2 R^6}{c^3 P^4} \approx 10^{49}\,{\rm ergs\,s^{-1}} \left(\frac{B_{\rm dip}}{10^{15}{\rm G}}\right)^2 \left(\frac{P}{1\,{\rm ms}}\right)^{-4} \left(\frac{R}{10\,{\rm km}}\right)^6$$

(Spitkovski 2006)

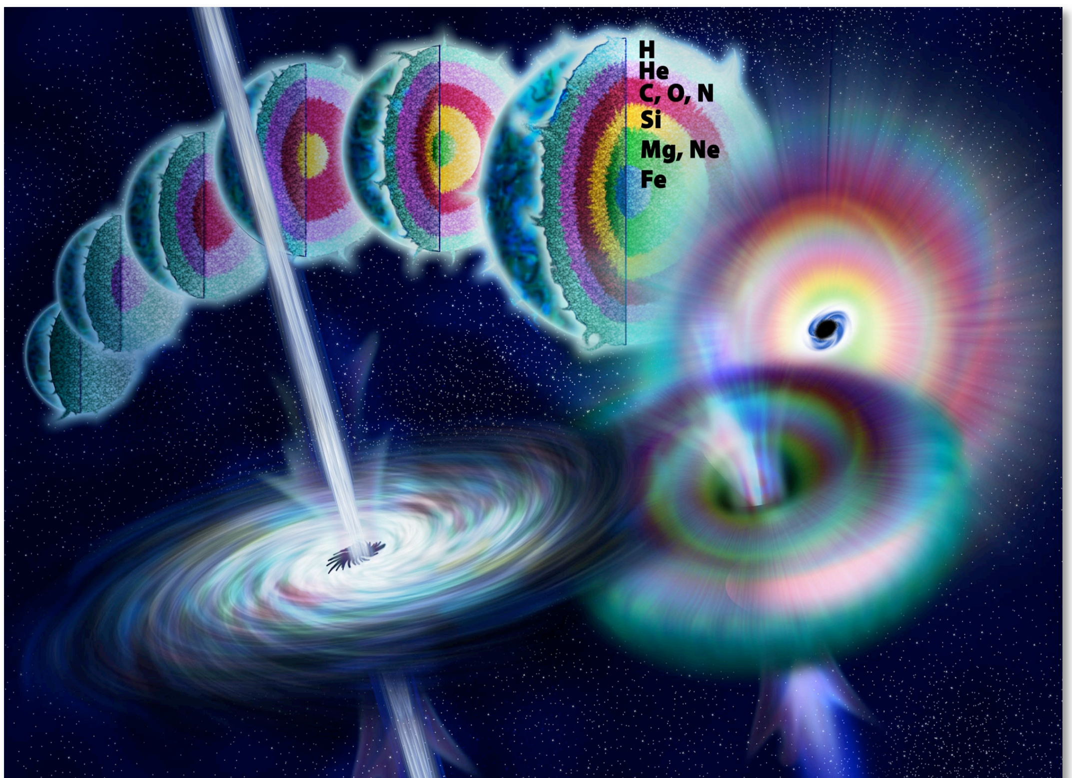


Millisecond Magnetar

Usov 1992

Recipe to make a long GRB

- Collapsar Scenario (e.g. Paczinski, Woosley, Macfadyen...)
- Magnetar Scenario (e.g. Usov, Thompson, Duncan, Wheeler, Metzger, Bucciantini...)



- Massive core (BH - NS)
- Rapidly rotating core (accretion disk/magnetar)
- Compact size $R_* / c \approx \tau_{engine}$

Stellar Evolution

Stellar progenitors of GRBs

- Observationally GRB/SN ~ 1/1000
- Collapsar need compact progenitor with massive, fast rotating core
- Canonical evolution of single stars including rotation and B fields can not do it

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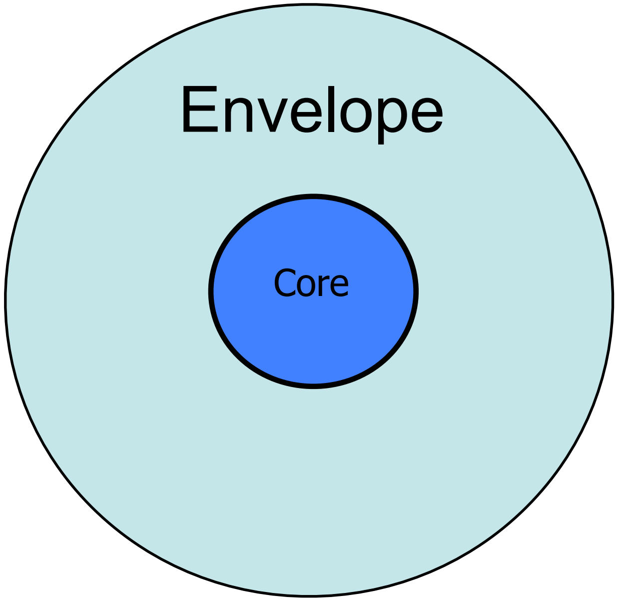

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A possible solution:

Chemically Homogeneous evolution

(Yoon & Langer 2005 - Heger & Woosley 2006)

Key-ingredient: **fast rotation**

How to avoid the core-envelope structure?
Rotational "instabilities" can efficiently mix a massive star

If $$\frac{\tau_{Mix}}{\tau_{MS}} < 1$$

→ The star can not build a compositional gradient and evolves **quasi chemically homogeneous**

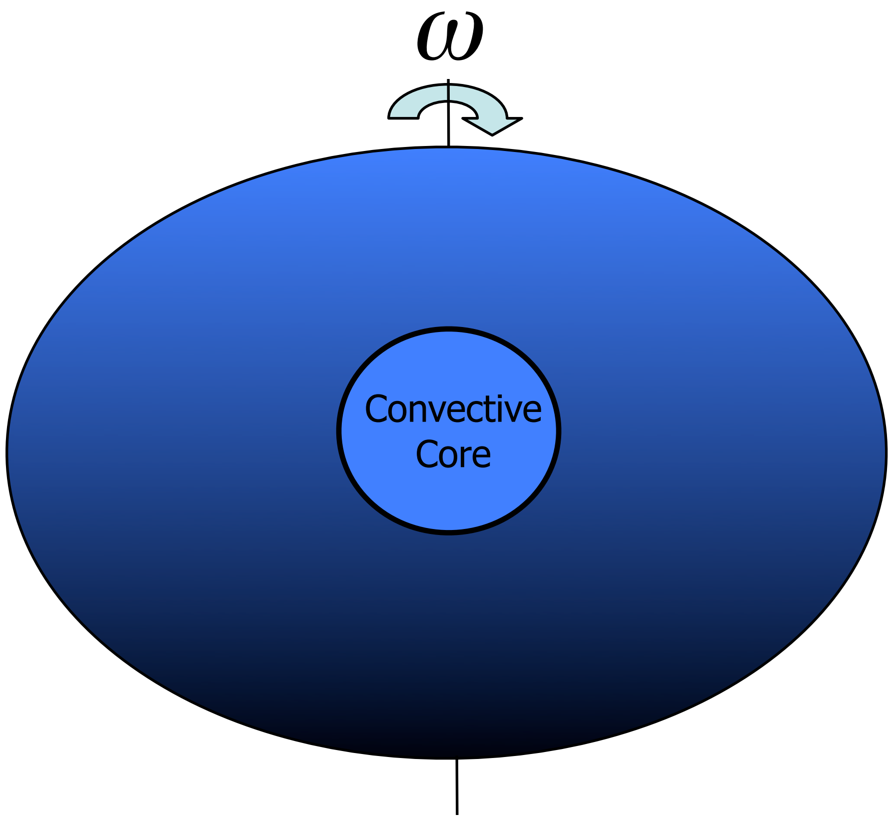
Key-ingredient: **fast rotation**

The unstable interiors of rotating stars

- Differential rotation is expected to arise in stars because of hydrostatic **structural evolution**, **mass loss** and **meridional circulation**. As a consequence, stars are subject to a number of local hydrodynamic instabilities.

- These instabilities arise and cause diffusion of angular momentum (and chemicals) while they try to bring the star back to solid body rotation, its lowest energy state.

Rotational Mixing: Von Zeipel



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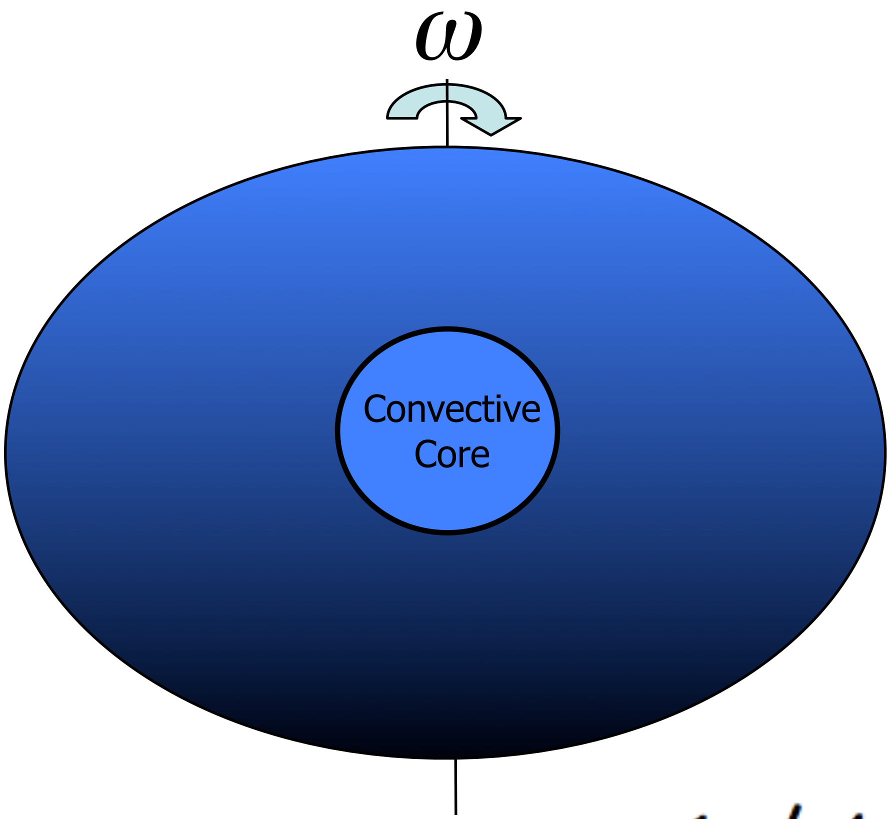
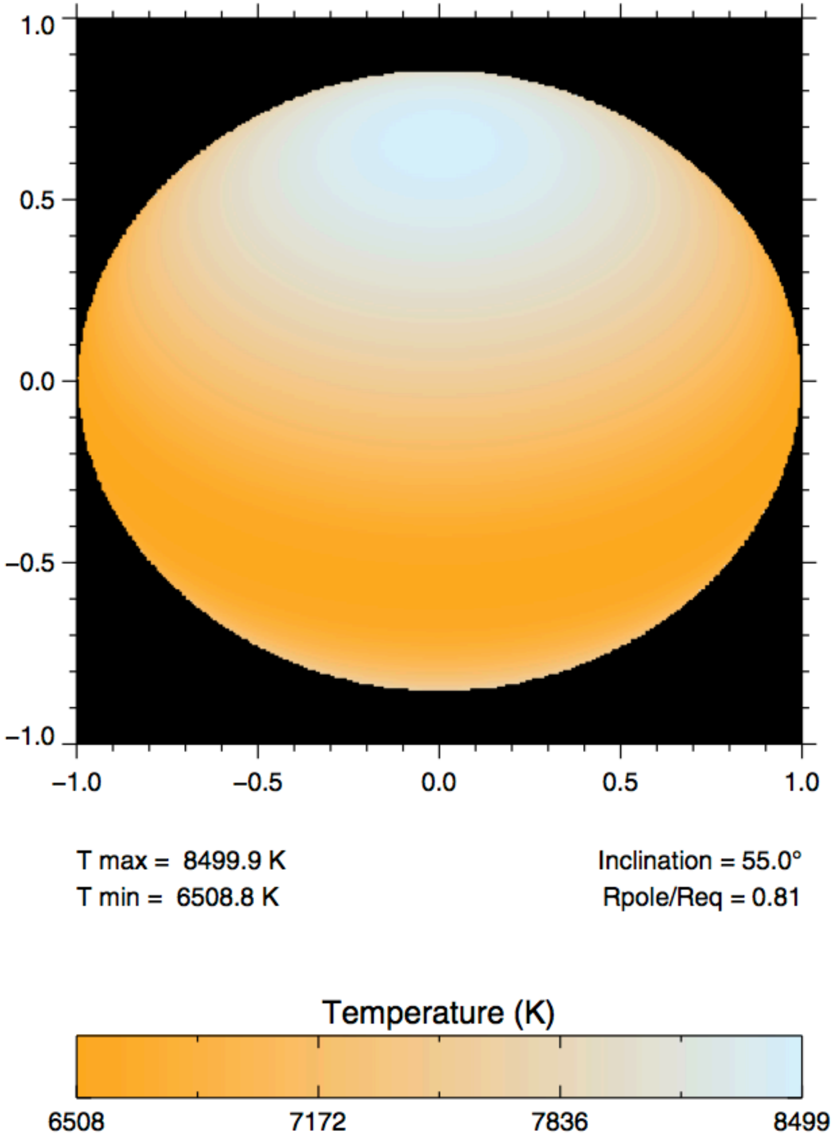


$$T_{\rm eff}(\vartheta) \sim g_{\rm eff}^{1/4}(\vartheta)$$

Interferometry of rotating stars



Altair (A7IV-V Star)
VLTI Observations

Von Zeipel 'gravity darkening' Confirmed

Domiciano Da Souza et al.2005

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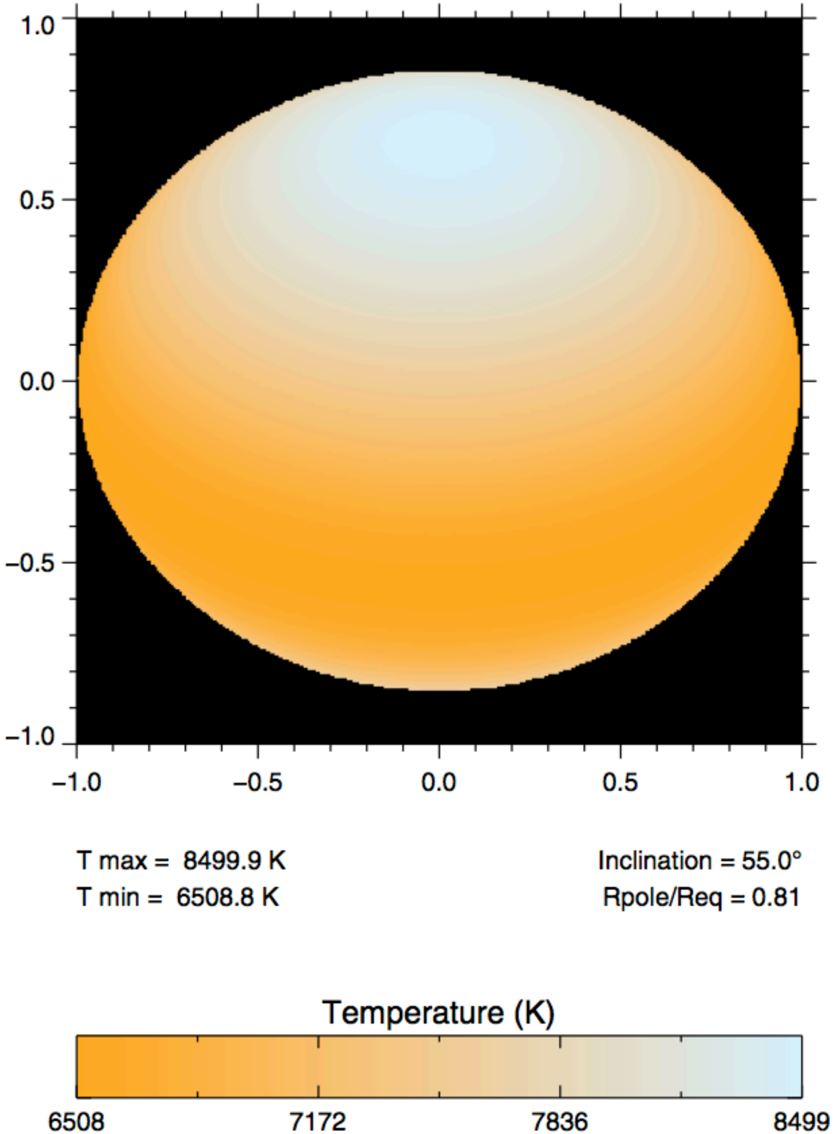

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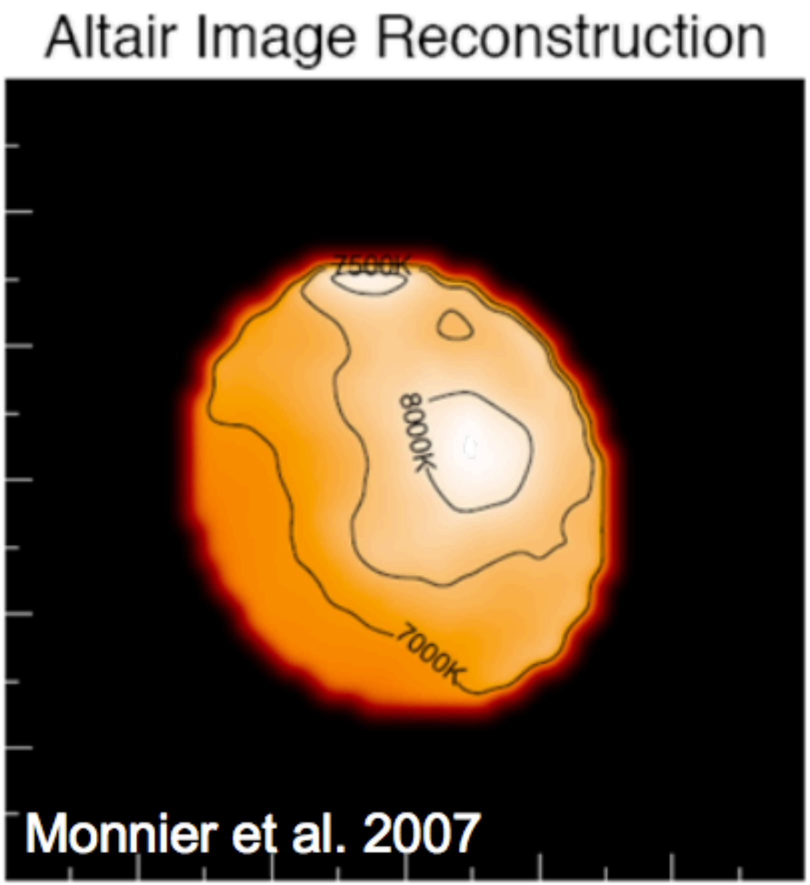

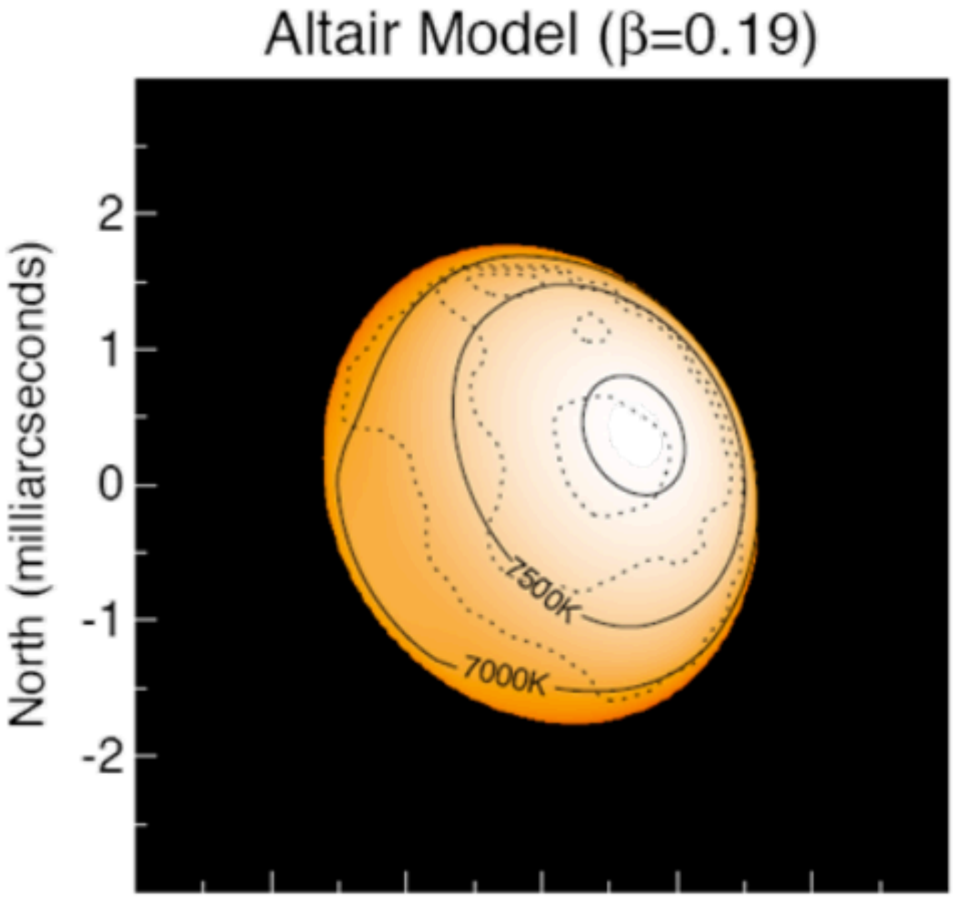

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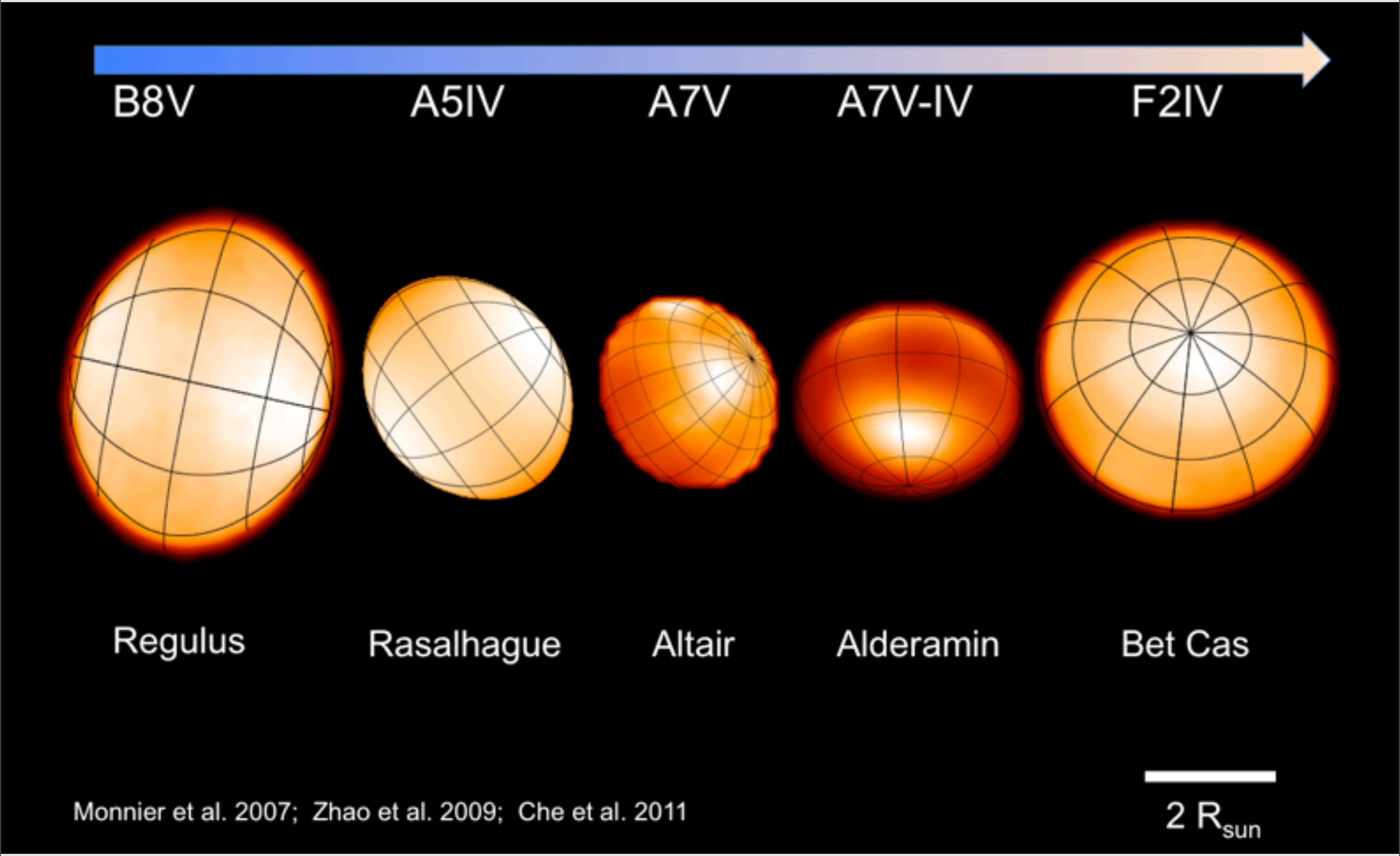
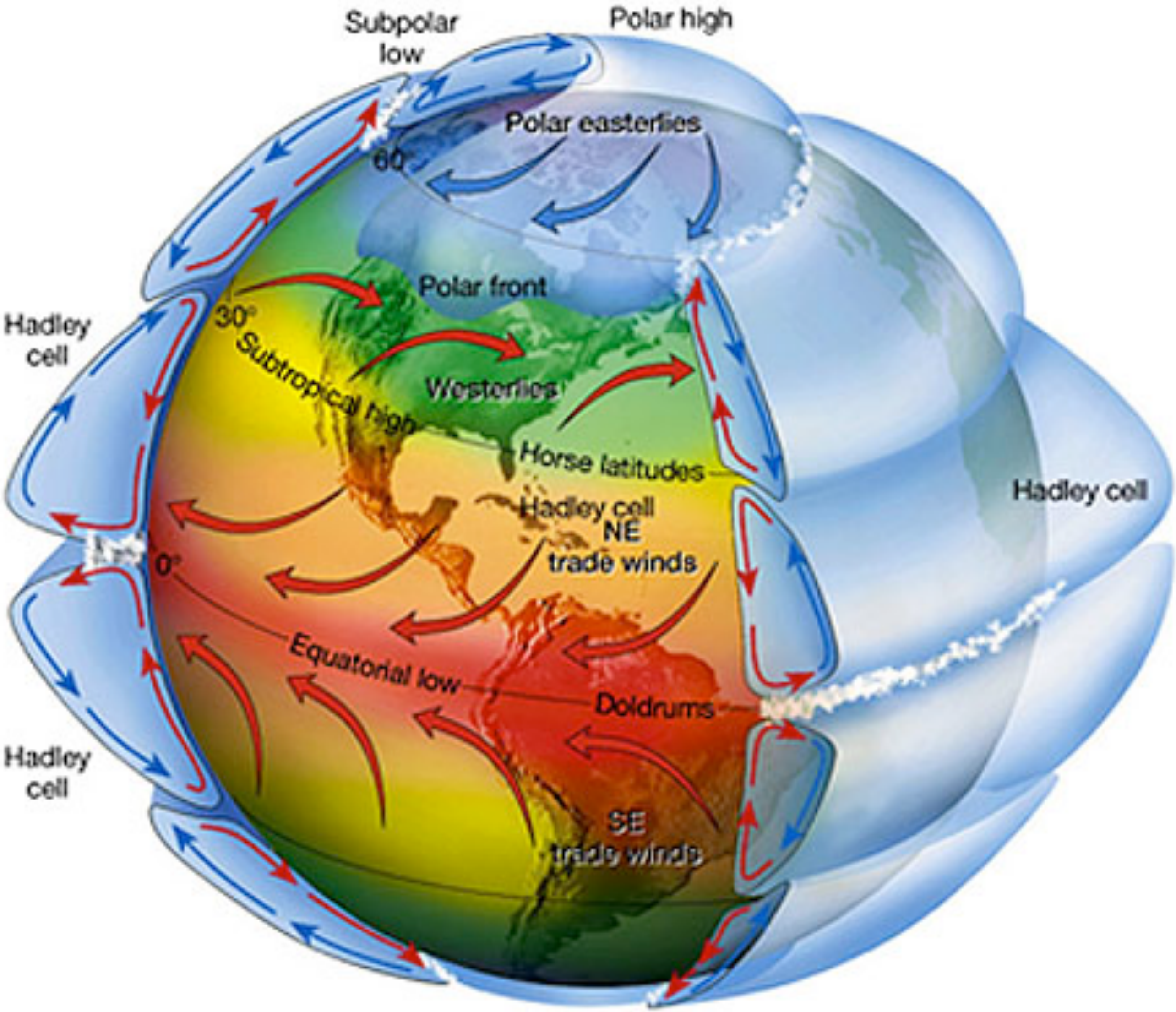


Thermal imbalance drives circulations



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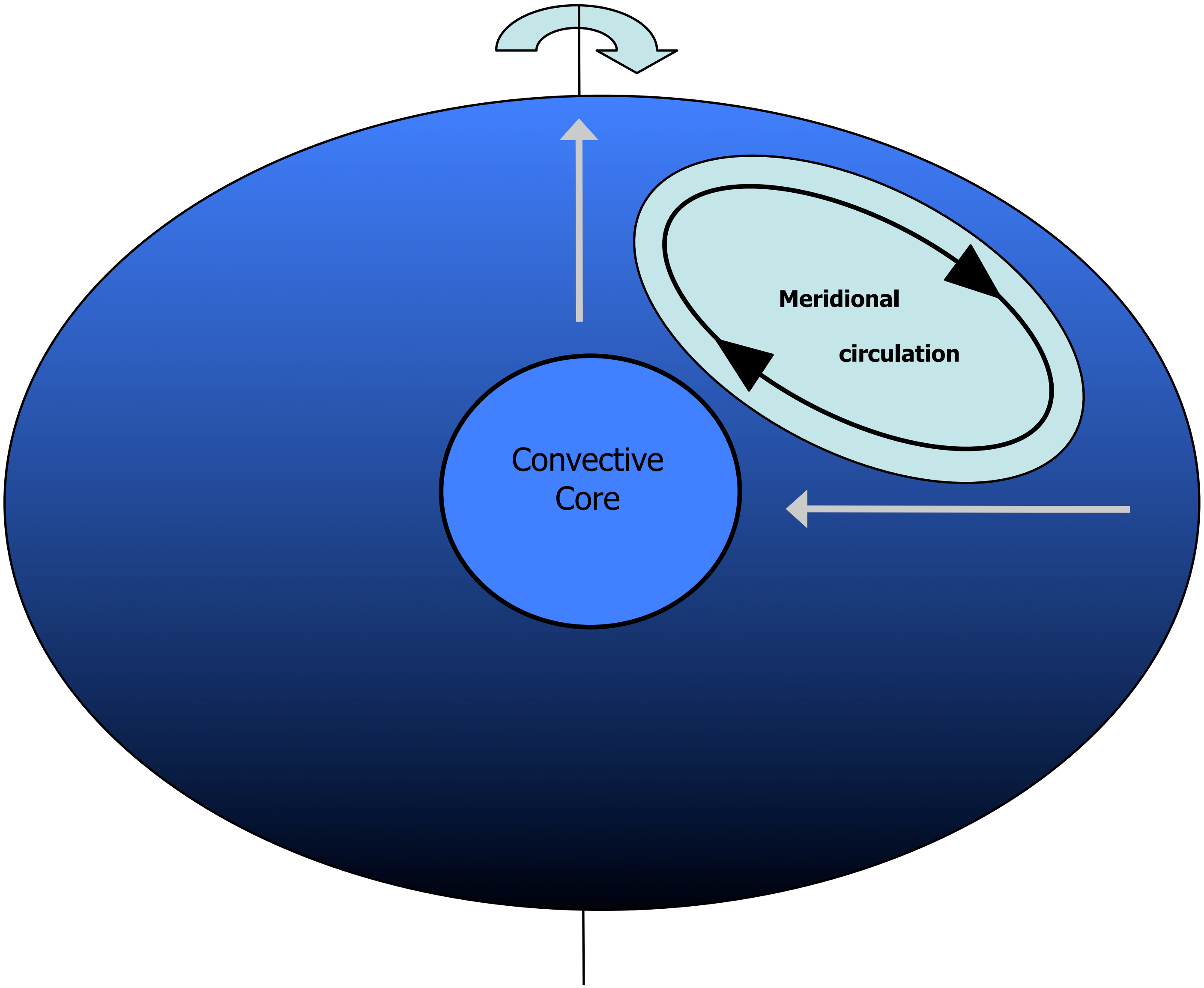
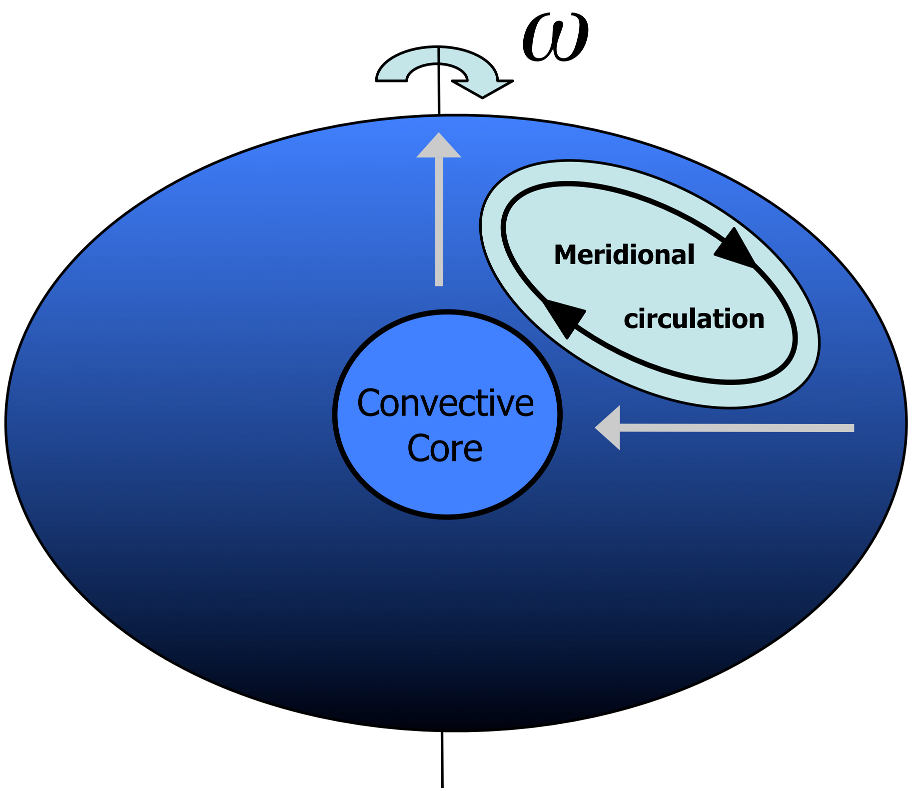


Rotational Mixing

- Rotational "instabilities" mix rotating massive stars
- Eddington-Sweet circulation most efficient process
- Mixing process on t_{KH}



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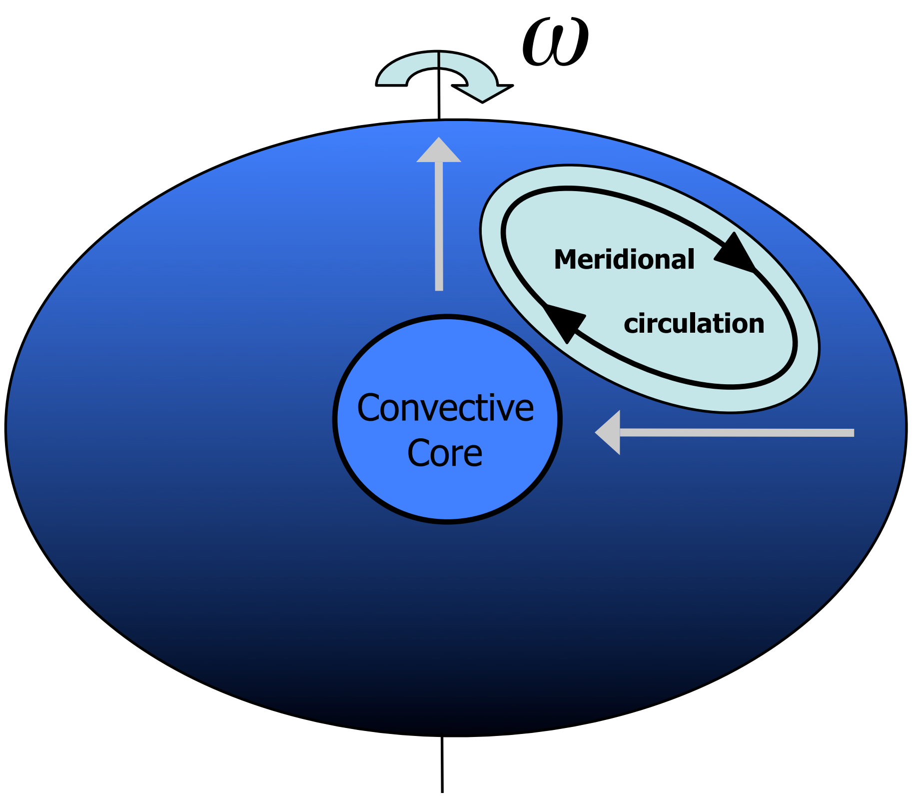
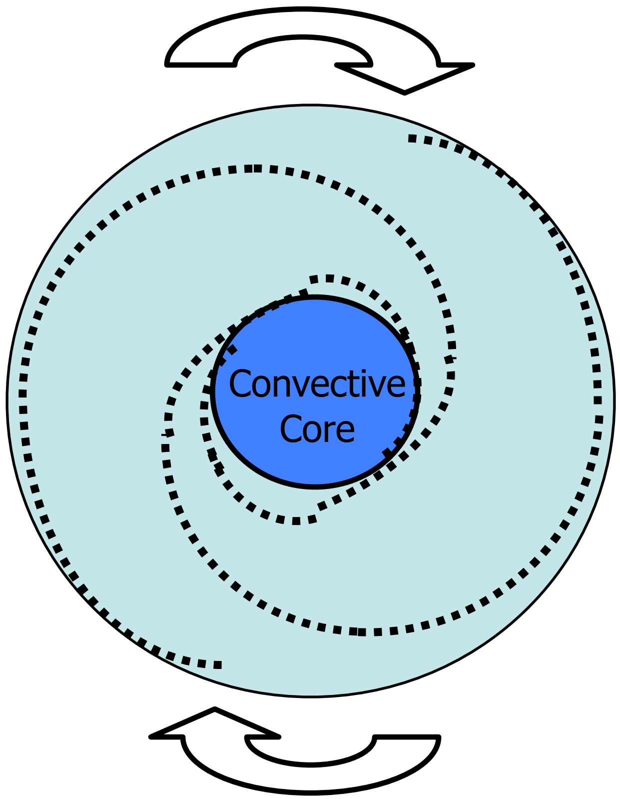
$$\tau_{ES} \propto \tau_{KH} \left(\frac{\omega_K}{\omega} \right)^2$$

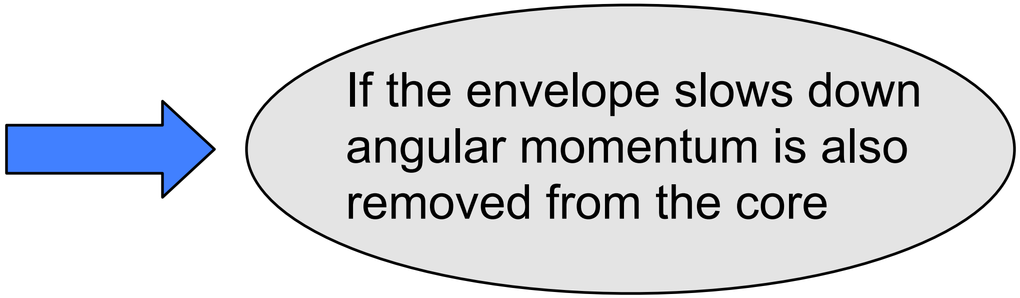


Magnetic fields

- Spruit-Tayler Dynamo (Spruit 2002)
- Core - Envelope coupling



1. Differential rotation winds up toroidal component of B
2. Magnetic torques tend to restore rigid rotation



Magnetic fields

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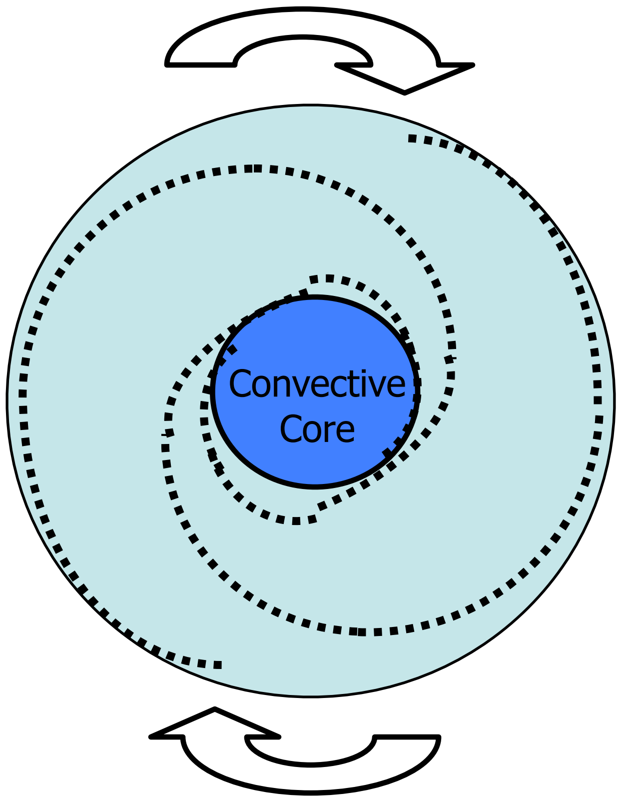
- Core - Envelope coupling

Required to explain the slow spin of NS/WD
(Heger et al. 2005, Suijs et al. 2008)



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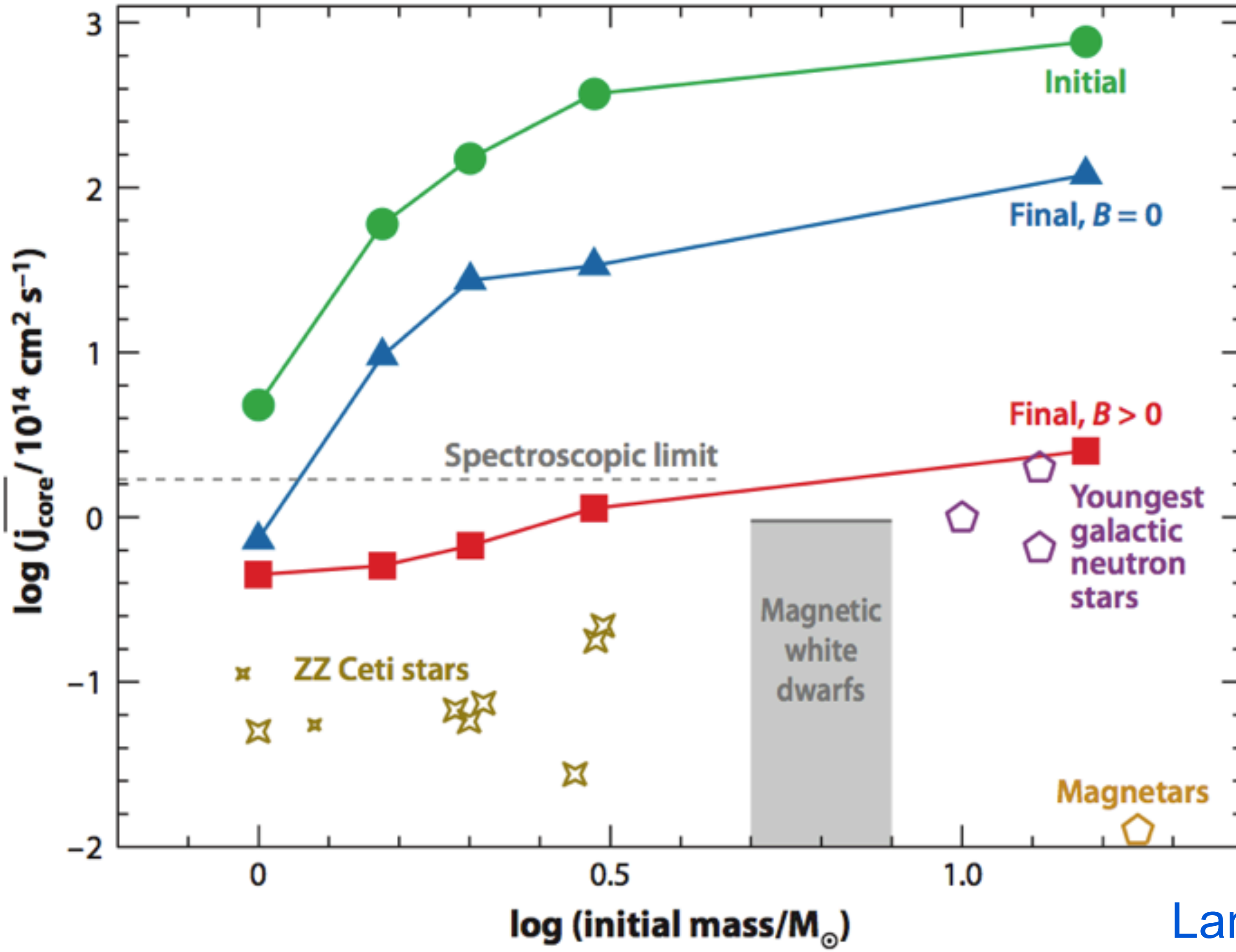
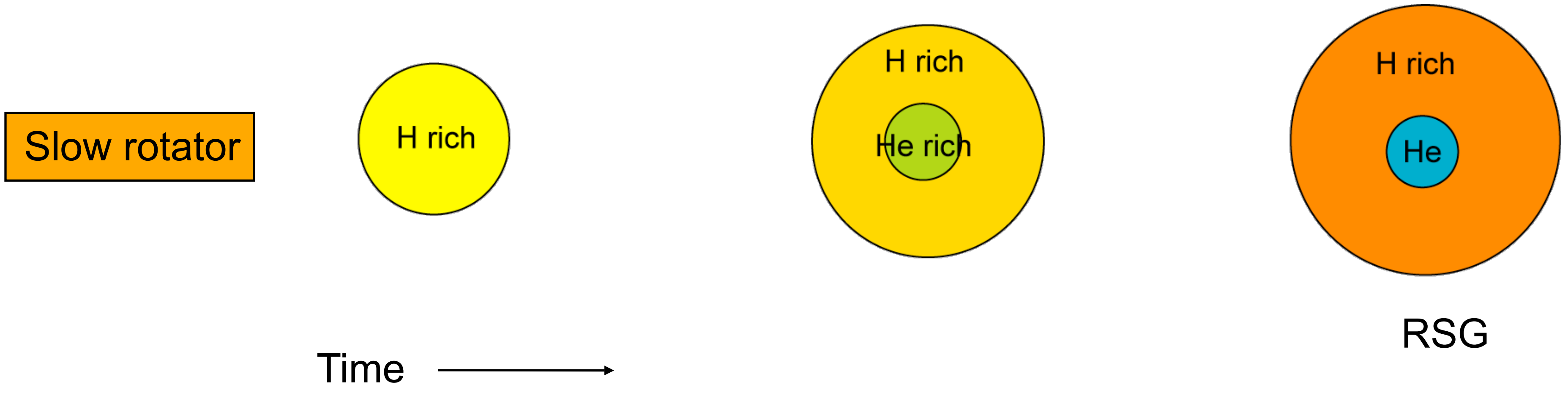
If the envelope slows down angular momentum is also removed from the core

Need for magnetic torques



Langer 2012

Chemically Homogeneous Evolution I



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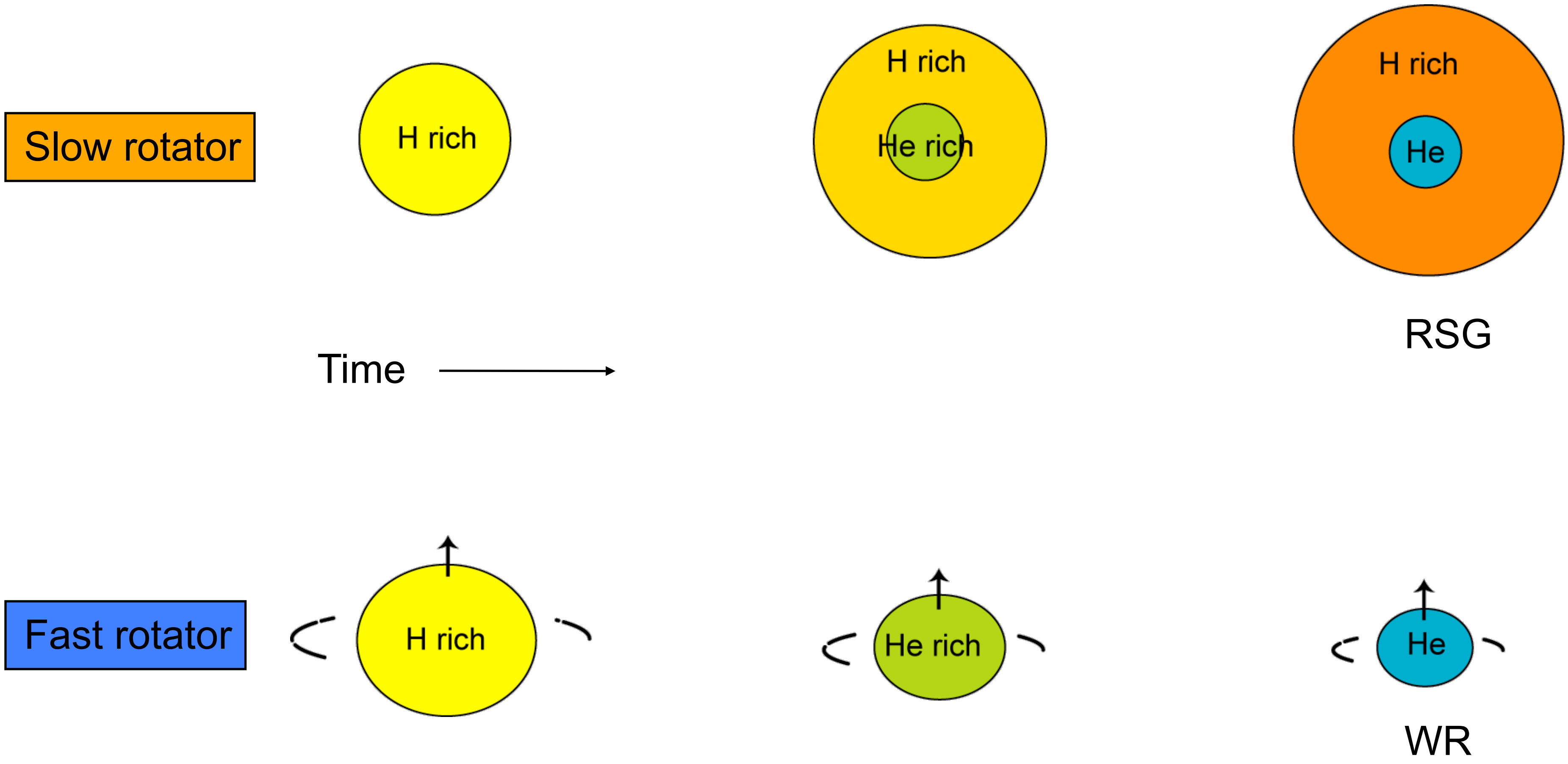
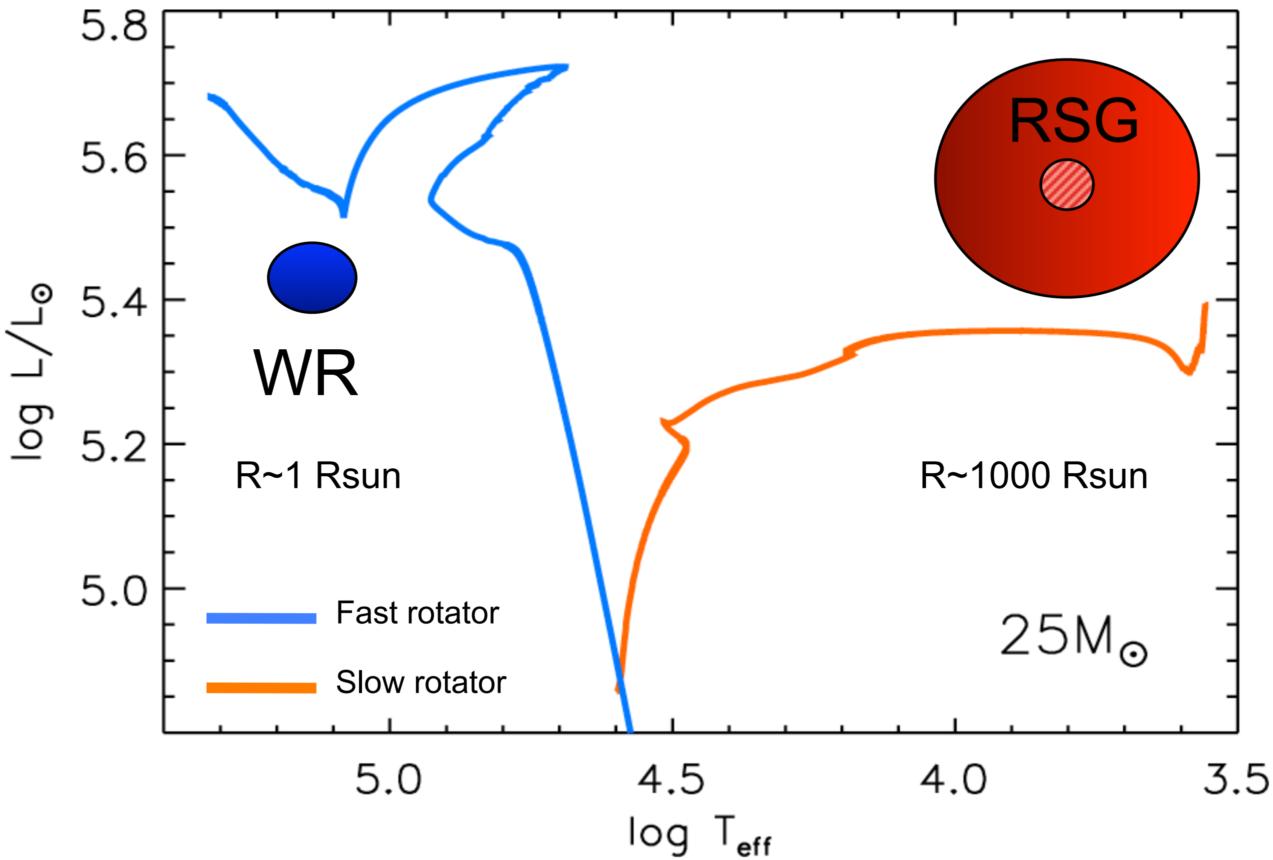


Chemically Homogeneous Evolution II



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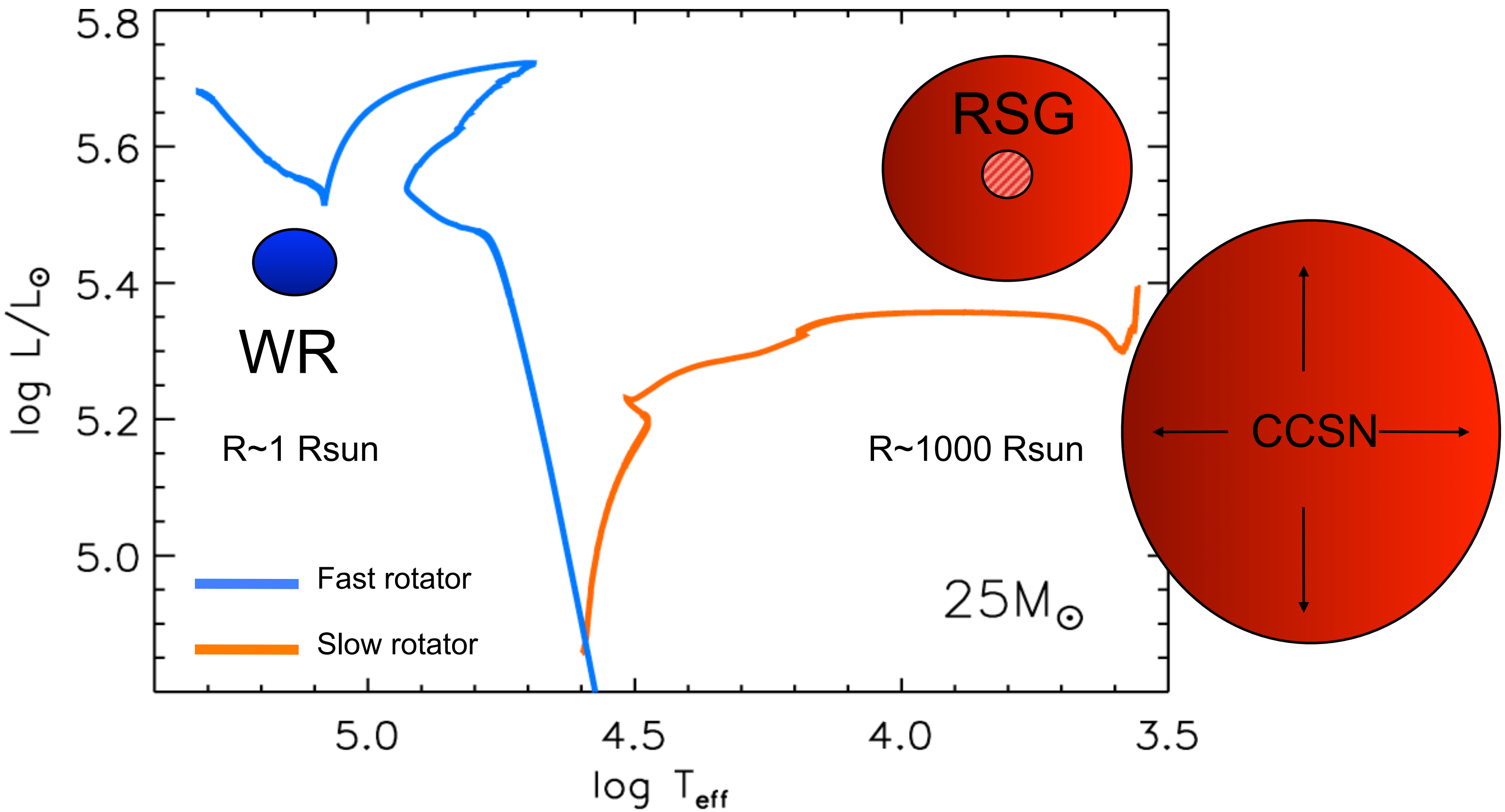

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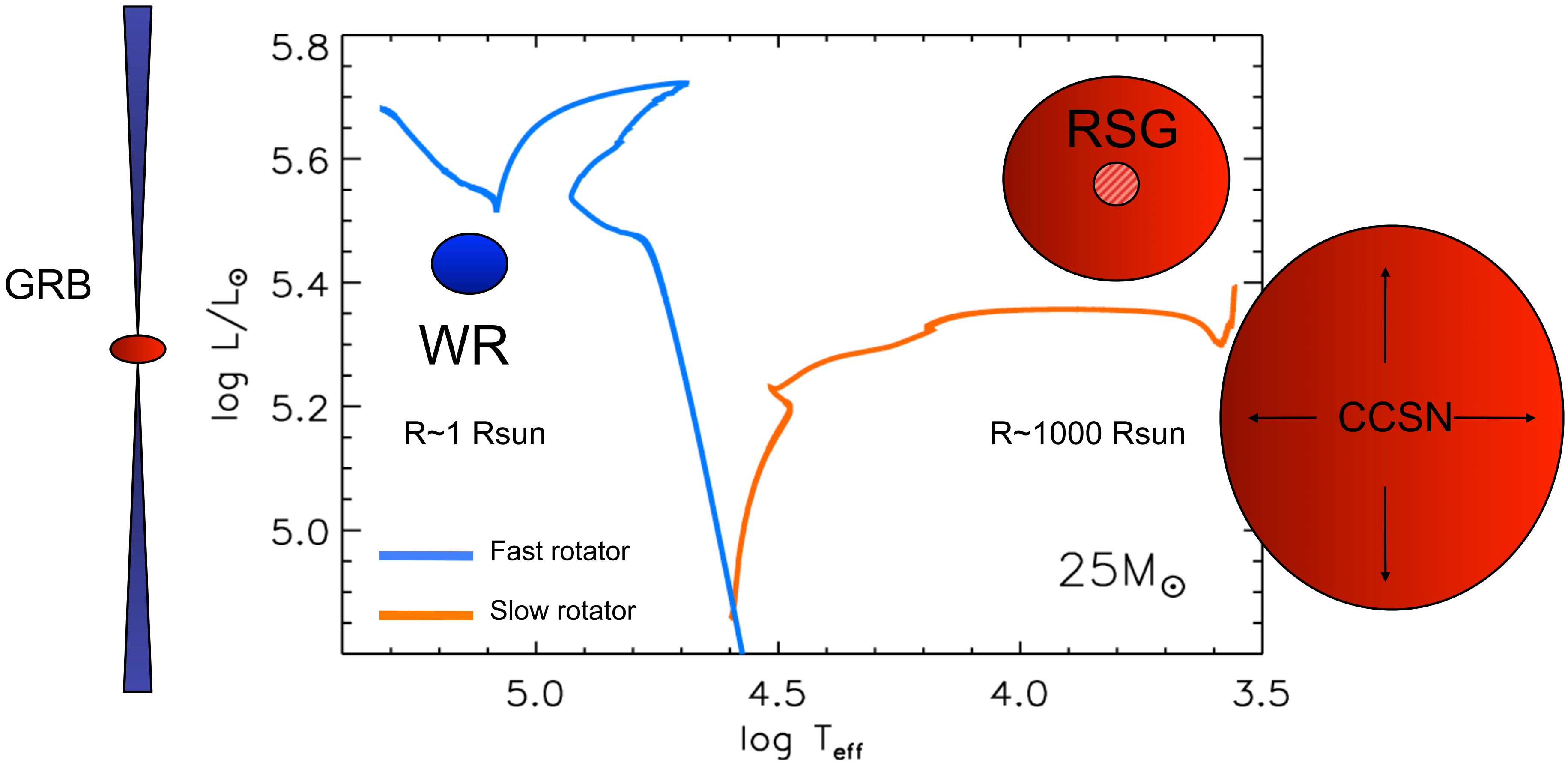

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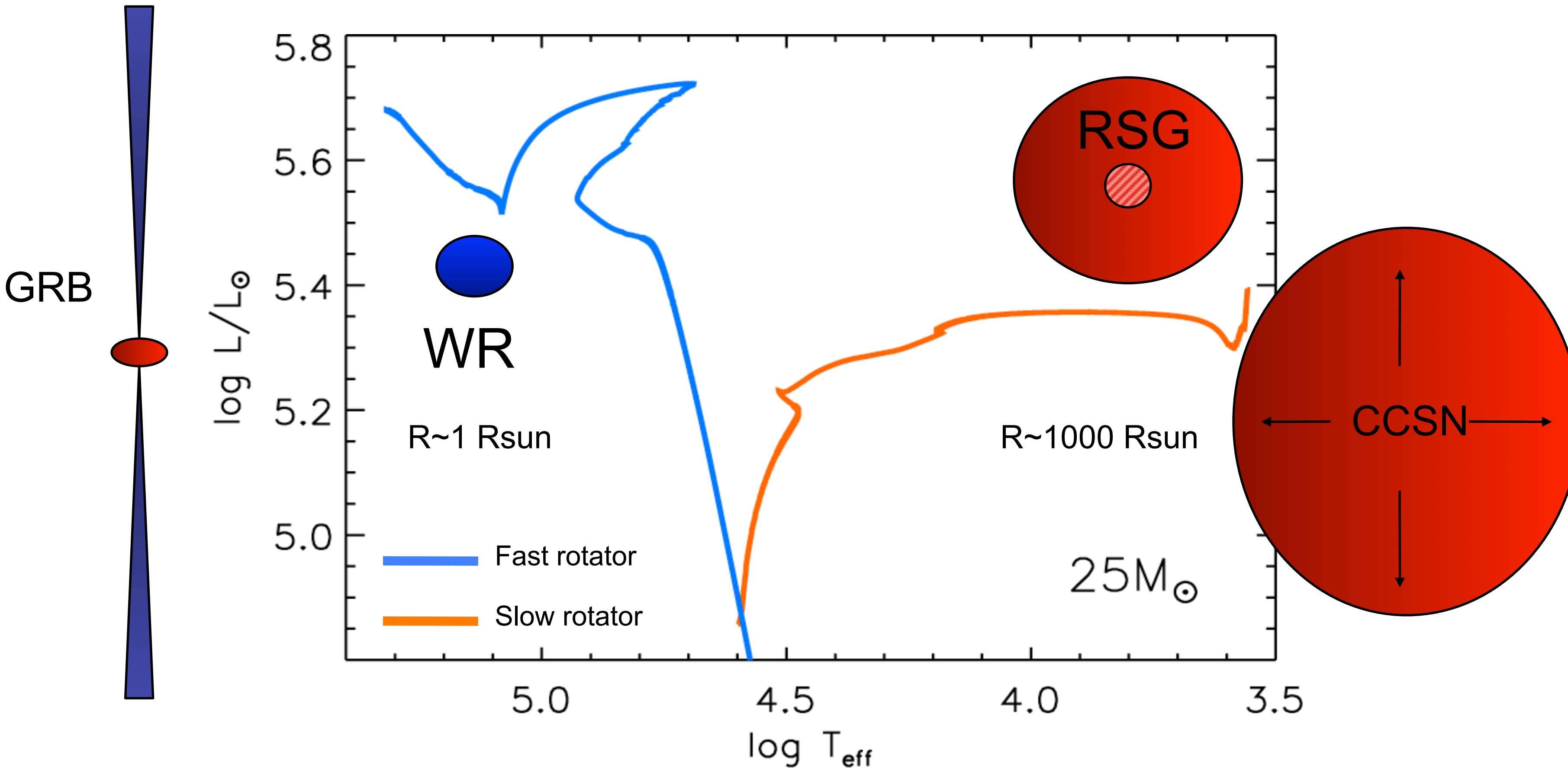

- Fast rotating massive stars can evolve chemically homogeneous
- If mass loss is not too high (**Low Z**) -> Long GRB

Any candidates for this evolutionary scenario?

VLT-Flames Tarantula Survey

VLT-FLAMES Tarantula Survey (PI: Evans): ~ 900 OB stars observed spectroscopically in 30 Dor (LMC) region.
Multi-epoch observations to separate binaries from single stars.

(Evans et al. 2010)

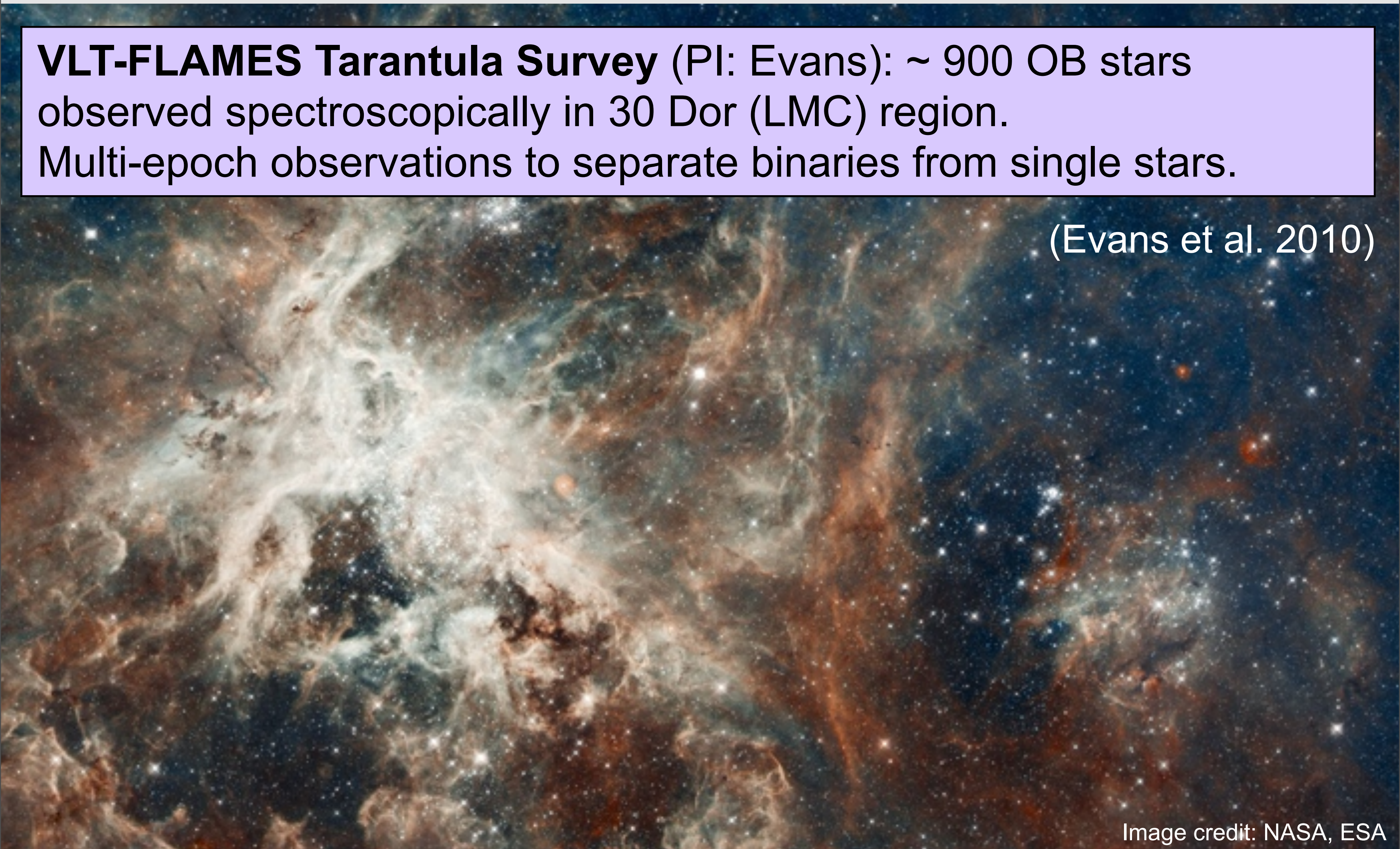

Image credit: NASA, ESA

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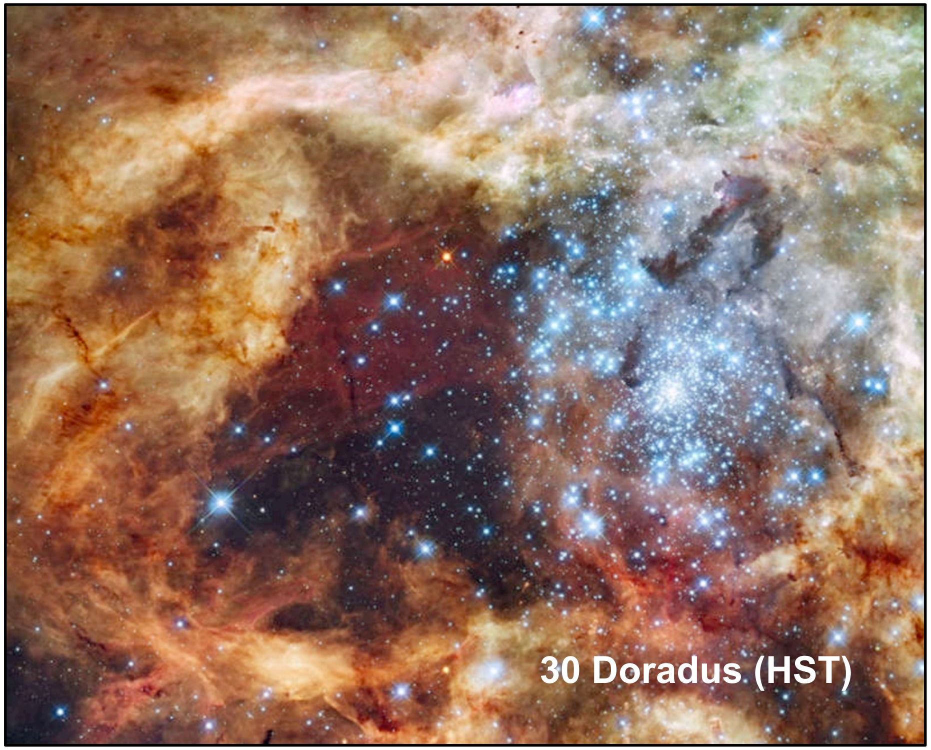
(Evans et al. 2010)

- Nitrogen surface abundances
- Rotational velocities
- Binary fraction

- A statistically significant sample of the most massive stars
(see e.g. Crowther et al. 2010)



VLT-Flames Tarantula Survey:
A Chemically Homogeneous Star

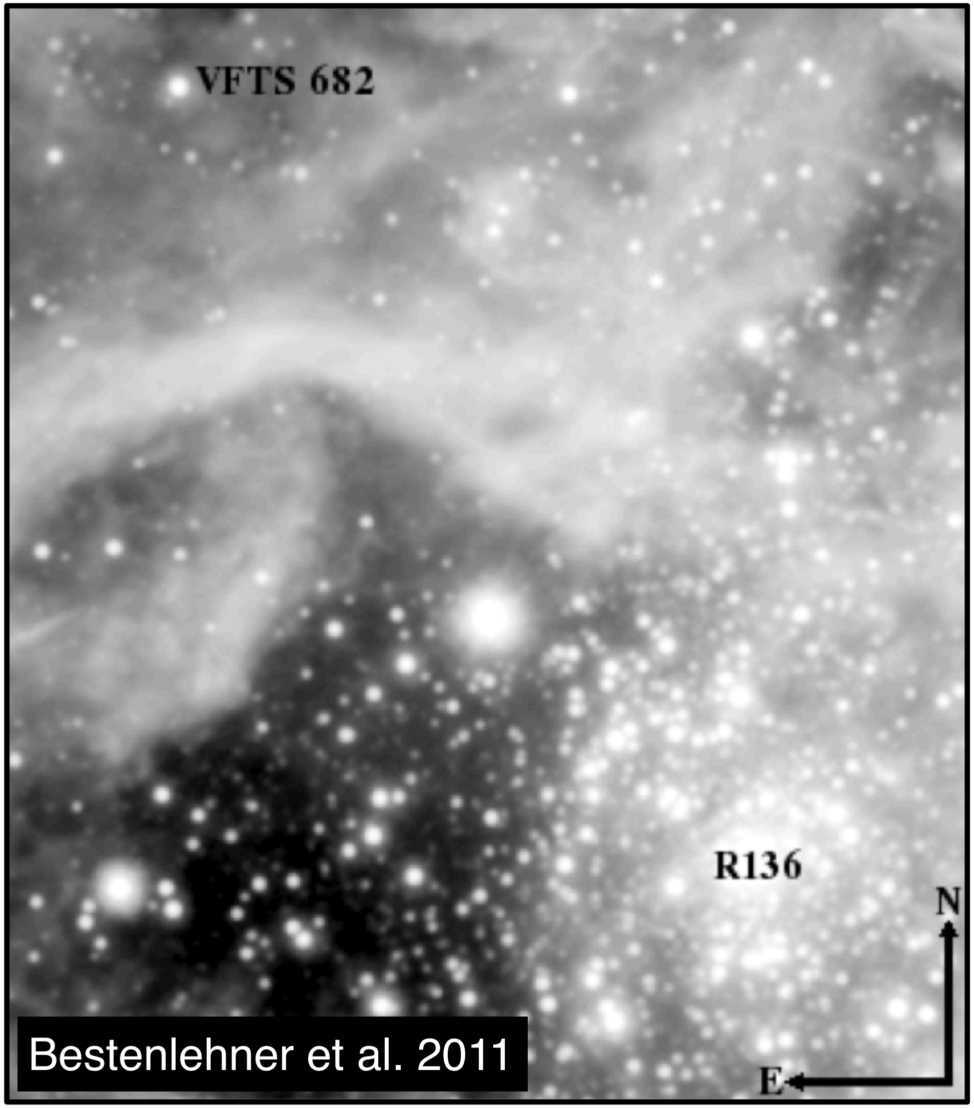
VFTS 682
H-rich WR Star (WN5h)
~30 pc away from R136
in the LMC (Tarantula Nebula)

T_{eff}~53kK
$\log(L/L_{sun})$~6.5

Can be explained with a chemically homogeneous M_{ini}~[120-210] M_{sun} star

Requires initial rotation V_{eq}>200 km/s

See **Martins et al. 2009** for other 2 CH candidates



Rotational velocity

- Chemically homogeneous evolution needs **high rotational velocity**

Rotational velocity

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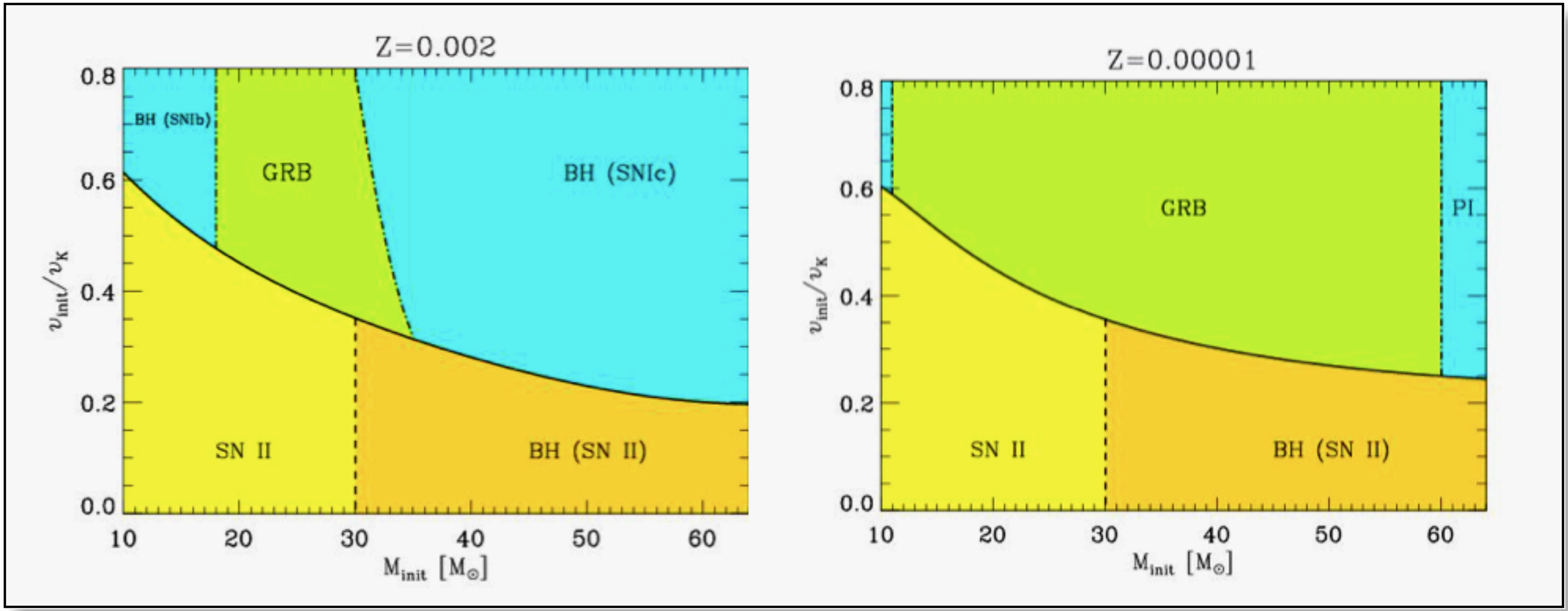
⇒ Stars born with high rotational velocity
Single star progenitors (Yoon at al. 2006)

Single star progenitors



(Yoon, Langer & Norman, 2006)

- Long GRBs prefer low metallicity (i.e. weaker winds) **$Z \lesssim$~ 1/5 Z_{Sun} (SMC)**
- This **metallicity threshold** is sensitive to mass-loss efficiency

Rotational velocity

- Chemically homogeneous evolution needs **high rotational velocity**

→ Stars born with high rotational velocity
Single star progenitors (Yoon at al. 2006)

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Binary star progenitors (Cantiello et al. 2007)

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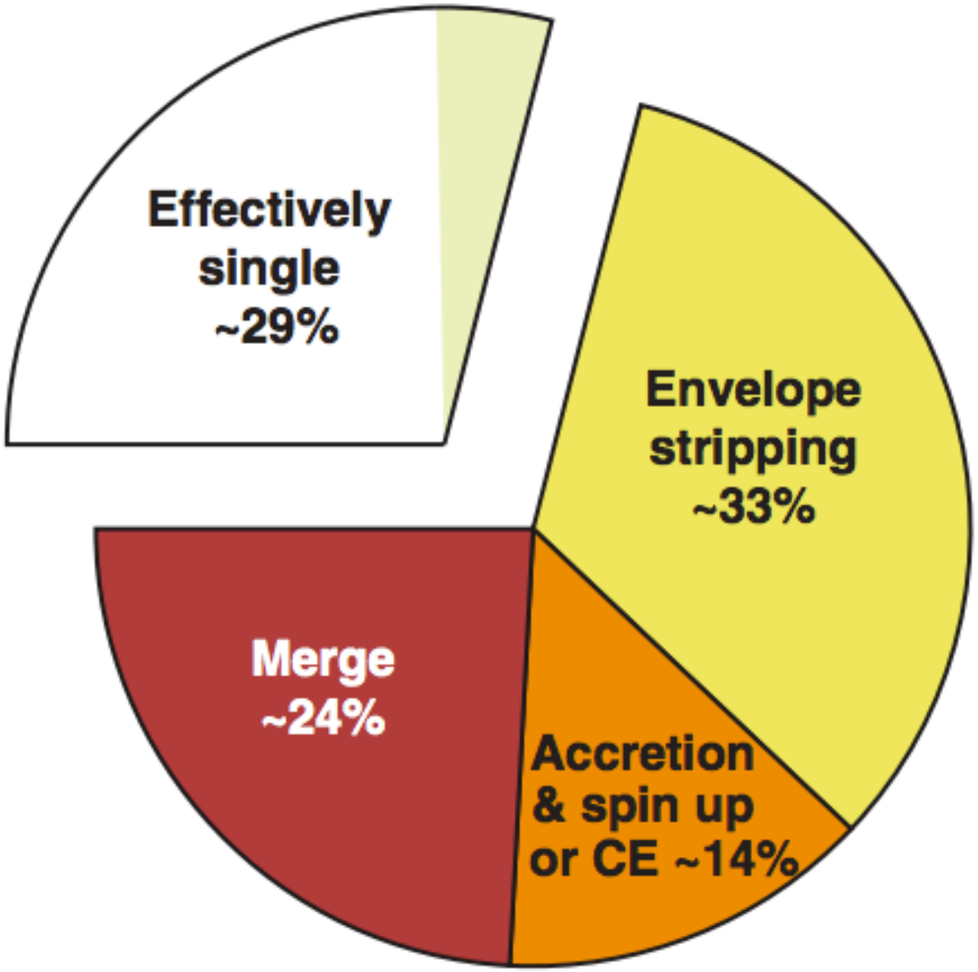
Other binary progenitor models of long GRB
(e.g.: Tidal spin up, Binary Mergers, Explosive Common-Envelope Ejection)

Binary interactions are the norm

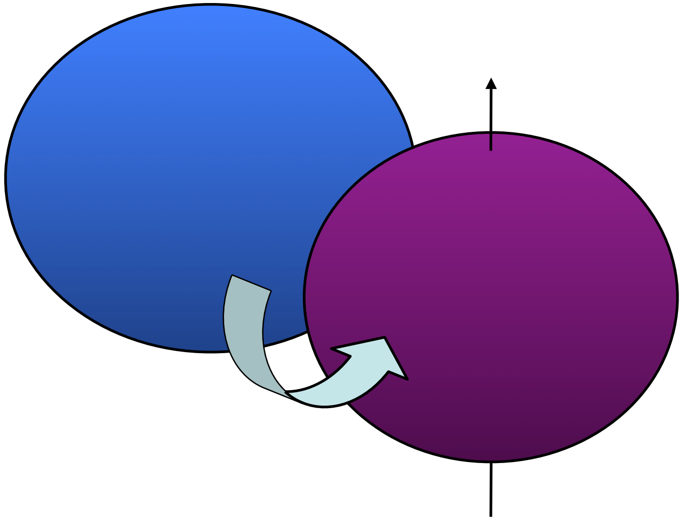
"71% of all stars born as O-type interact with a companion, over half of which do so before leaving the main sequence"



Sana et al. 2012 (Science)

Binary star progenitors

- We want to spin-up a star and induce chemically homogeneous evolution



Mass (angular momentum) accretion

Binary star progenitors

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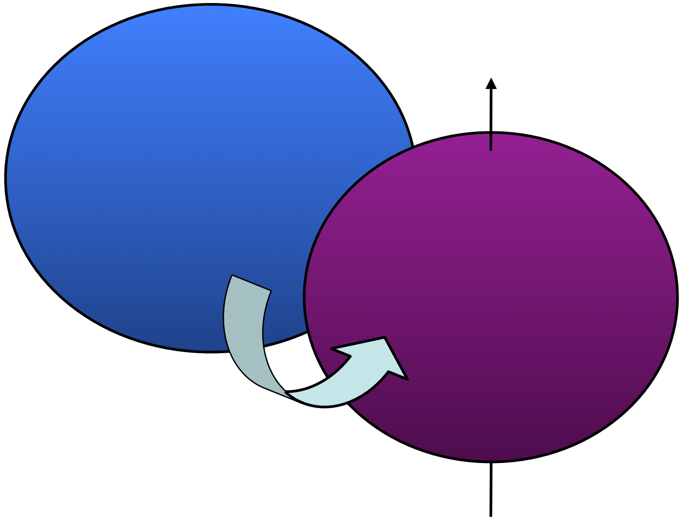
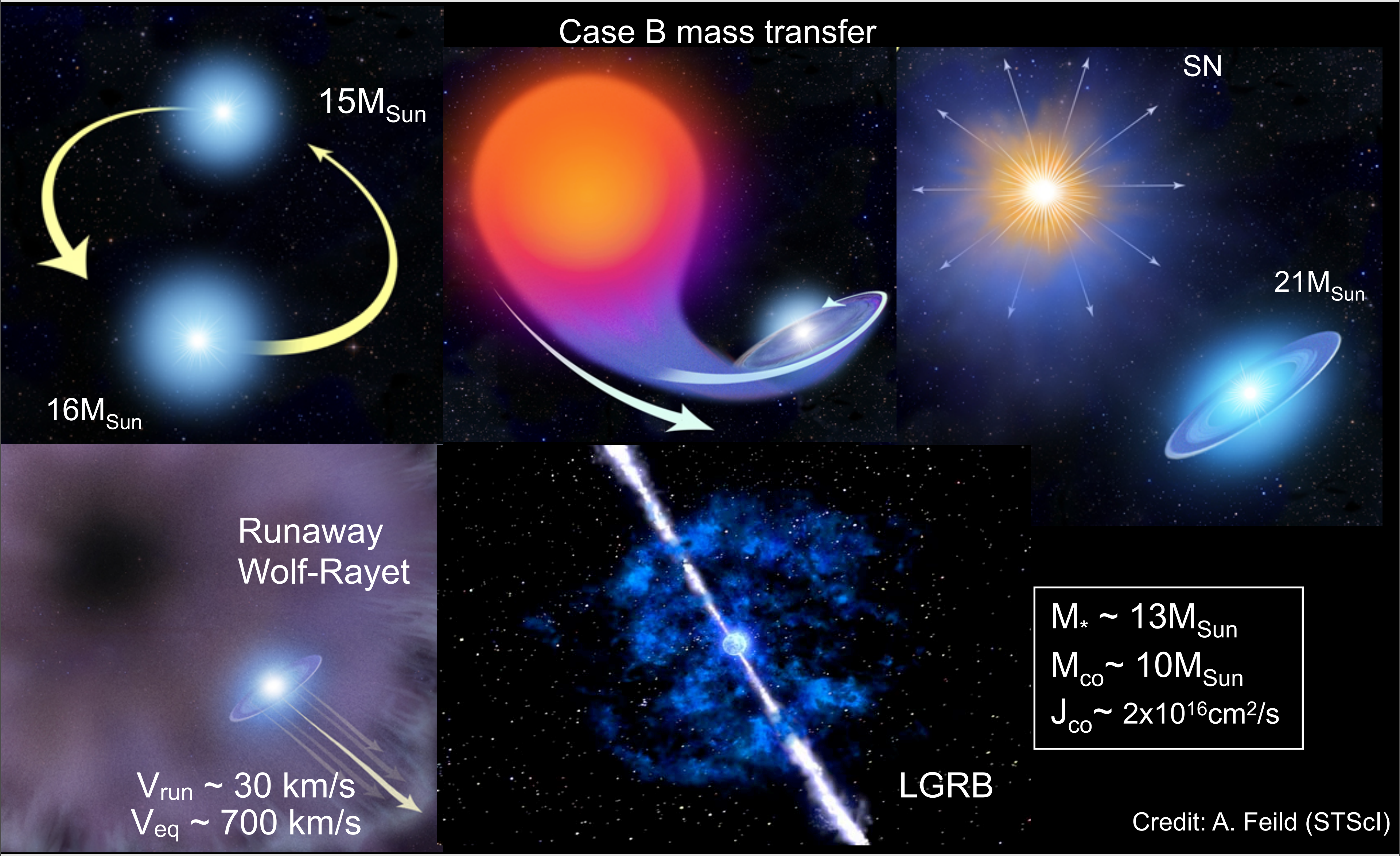


Mass (angular momentum) accretion

- A merger is also a possible way to obtain a single, fast rotating massive star (e.g. Fryer et al., Podsiadlowski et al.)

Spin up by accretion



Any candidates for this binary evolutionary scenario?

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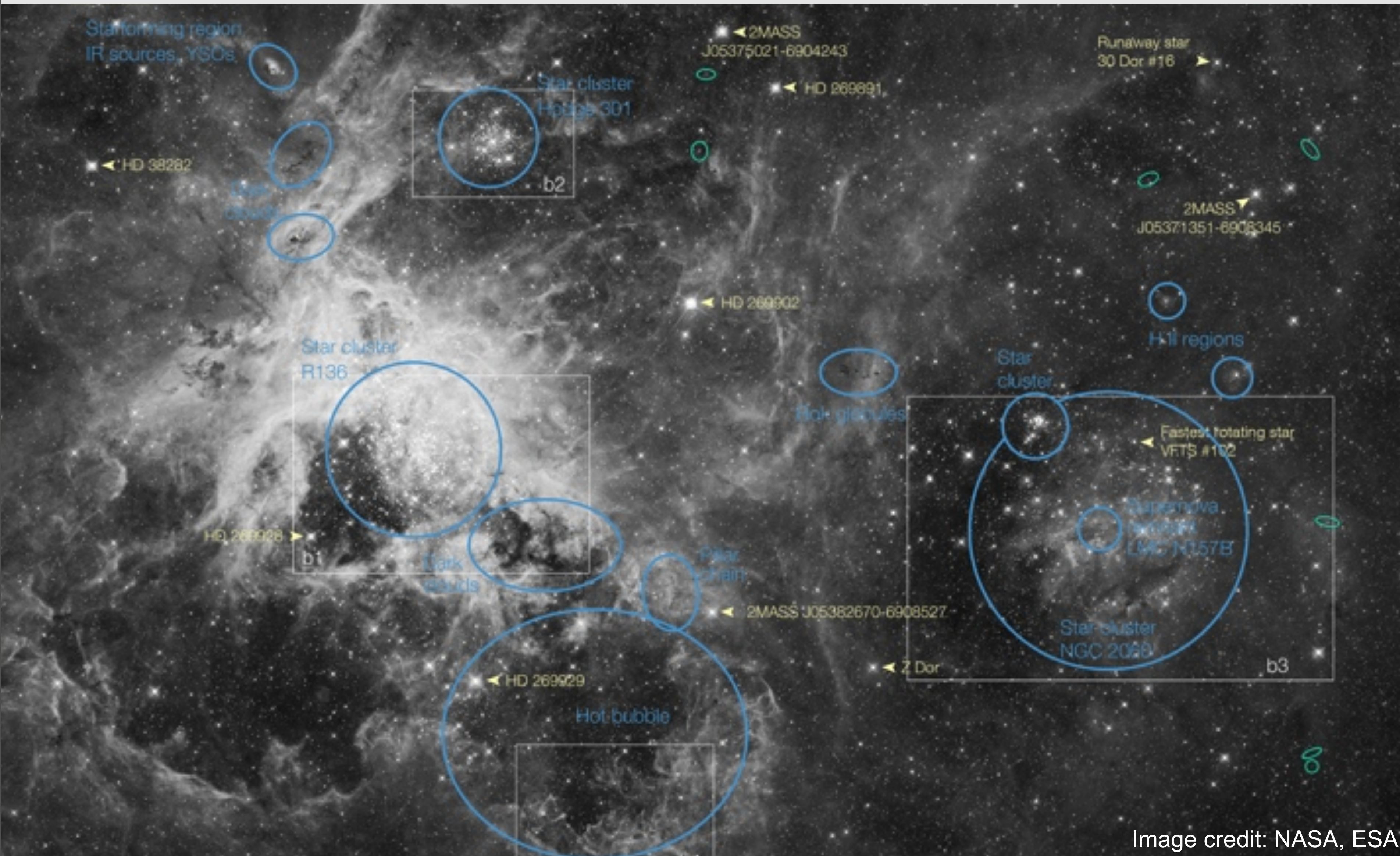

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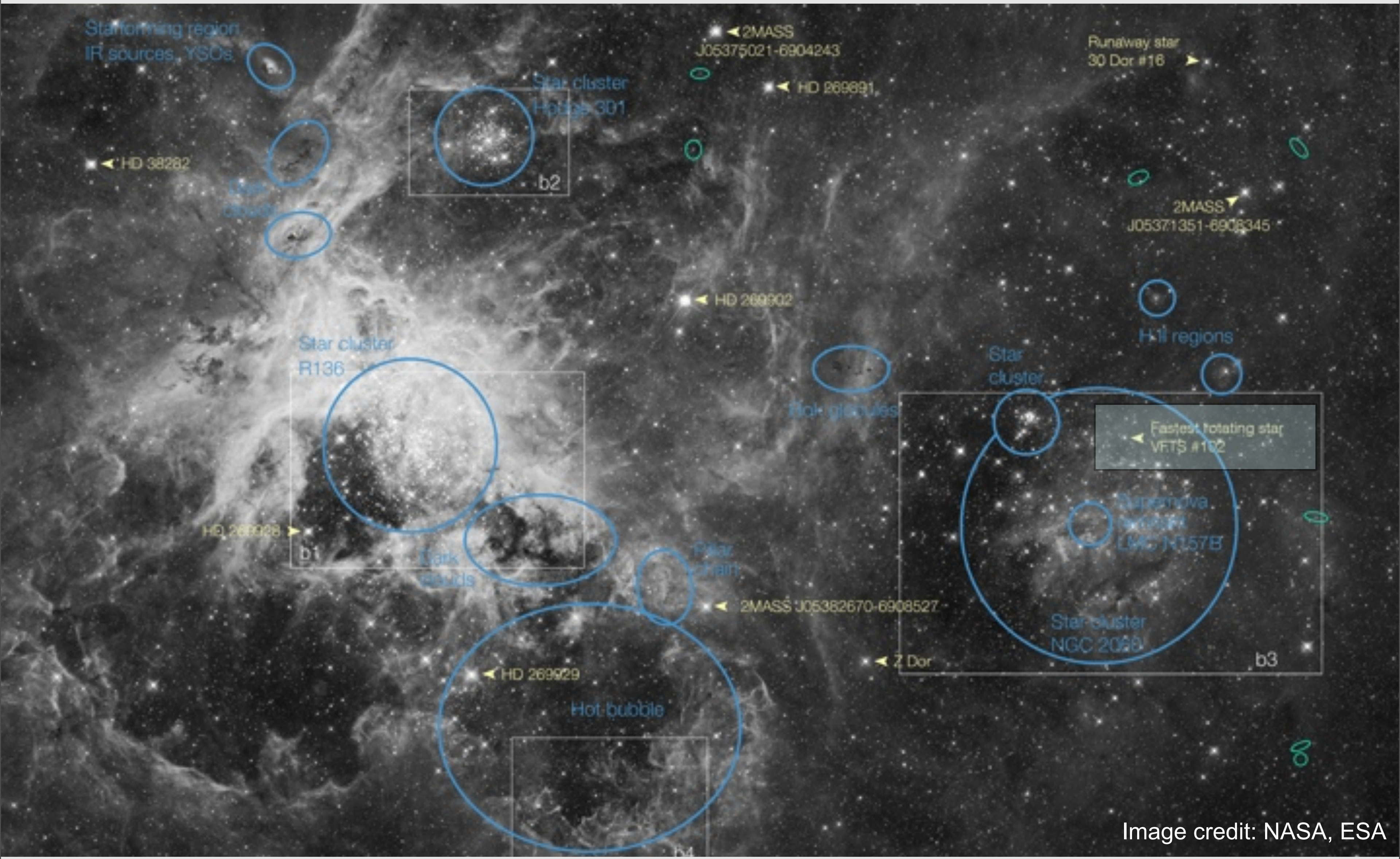
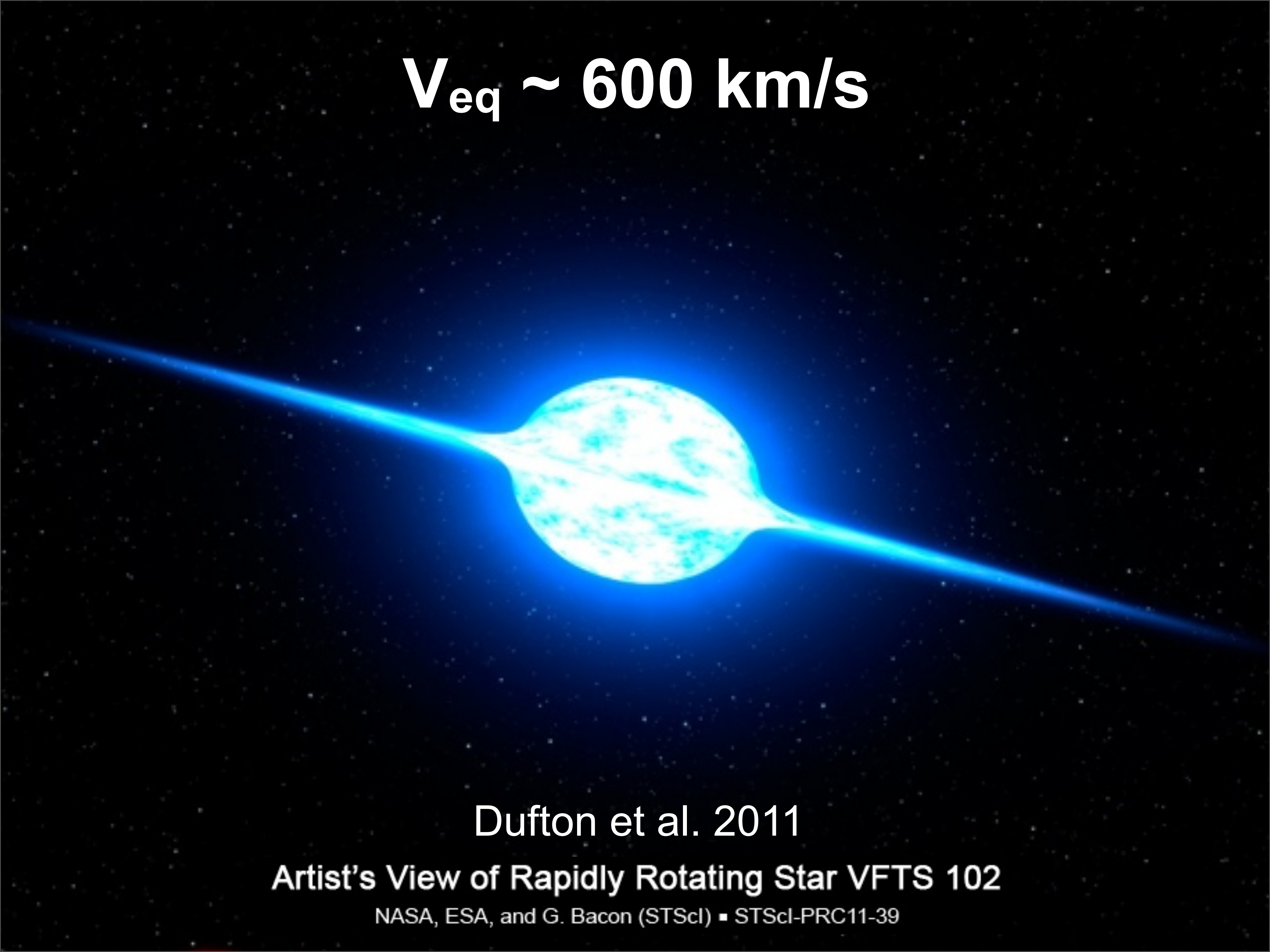


Image credit: NASA, ESA


Dufton et al. 2011
Artist's View of Rapidly Rotating Star VFTS 102
NASA, ESA, and G. Bacon (STScI) ▪ STScI-PRC11-39

V_{eq} ~ 600 km/s



Dufton et al. 2011

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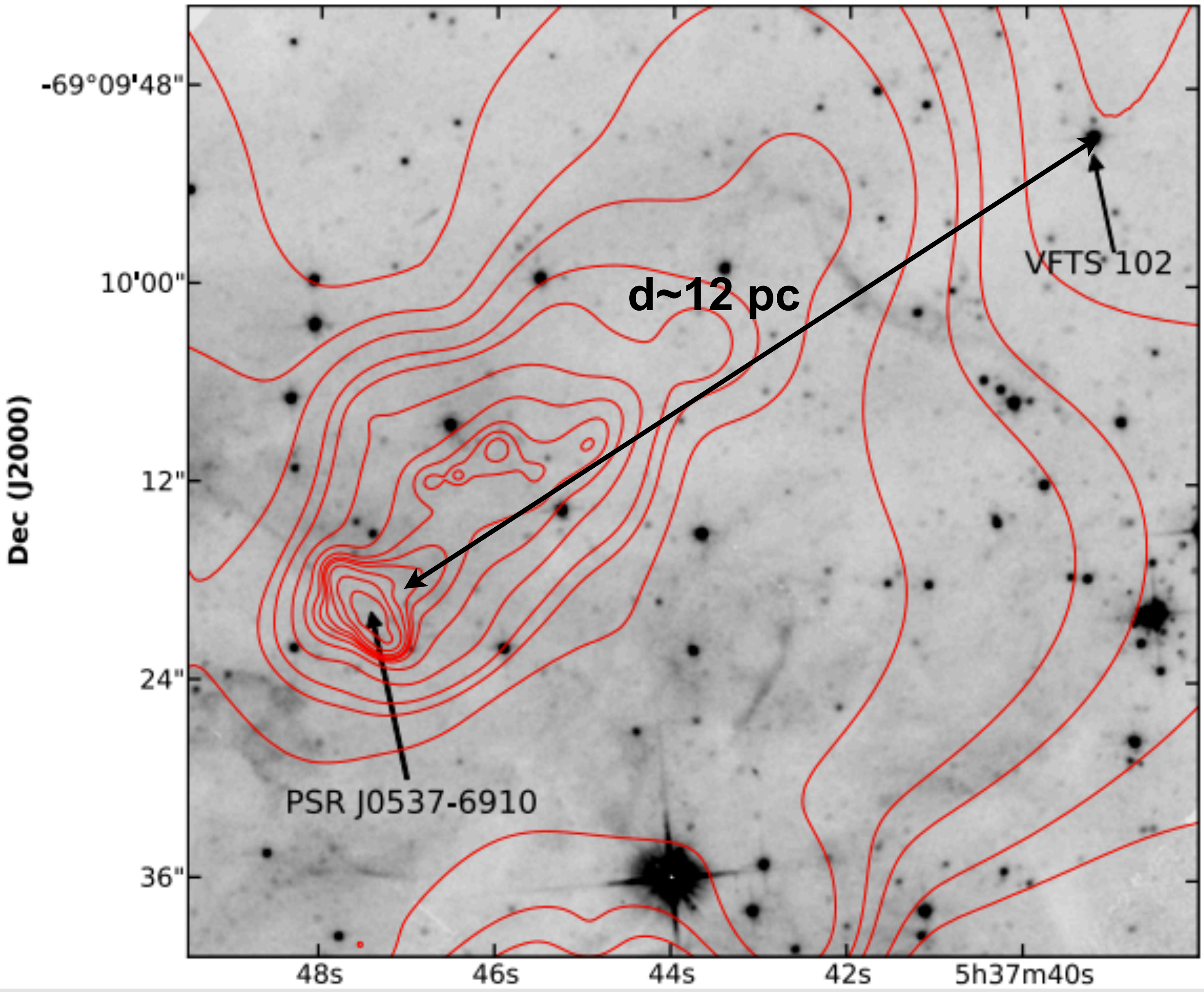
V_{eq} ~ 600 km/s
It’s a Runaway

Lies close to a young Pulsar

Dufton et al. 2011

Lies close to a Pulsar and a SNR



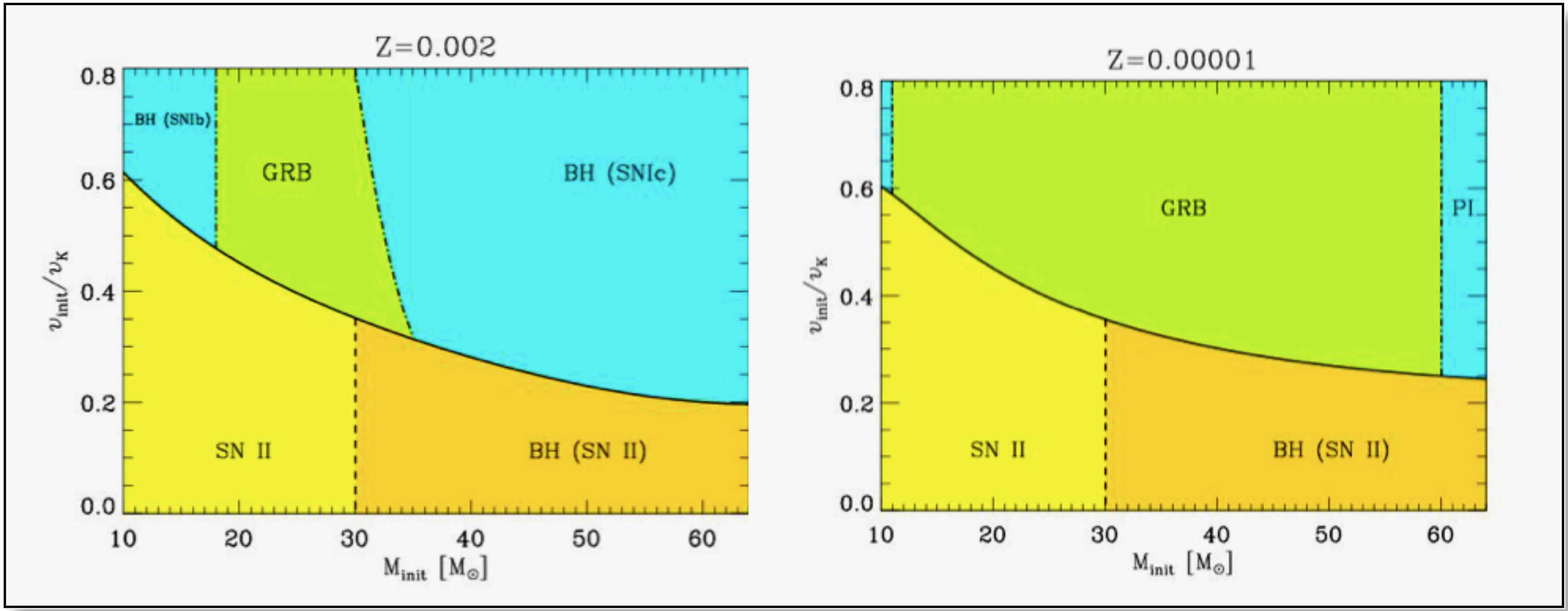
Dufton et al. 2011

Pulsar - VFTS102 Connection

- Diffuse X-ray emission consistent with bow-shock if pulsar is moving at ~1000 km/s
  Wang & Gotthelf (1998)
- Adopting estimated age of pulsar (5000-24000 yrs Marshall et al. 1998, Chu et al. 1992), velocity for being casually connected to VFTS102 is 500-2500 km/s
- An attractive scenario, but needs to be confirmed (HST proper motion study PI: Lennon)
- Other scenarios are possible (e.g dynamical ejection)

GRB Observations

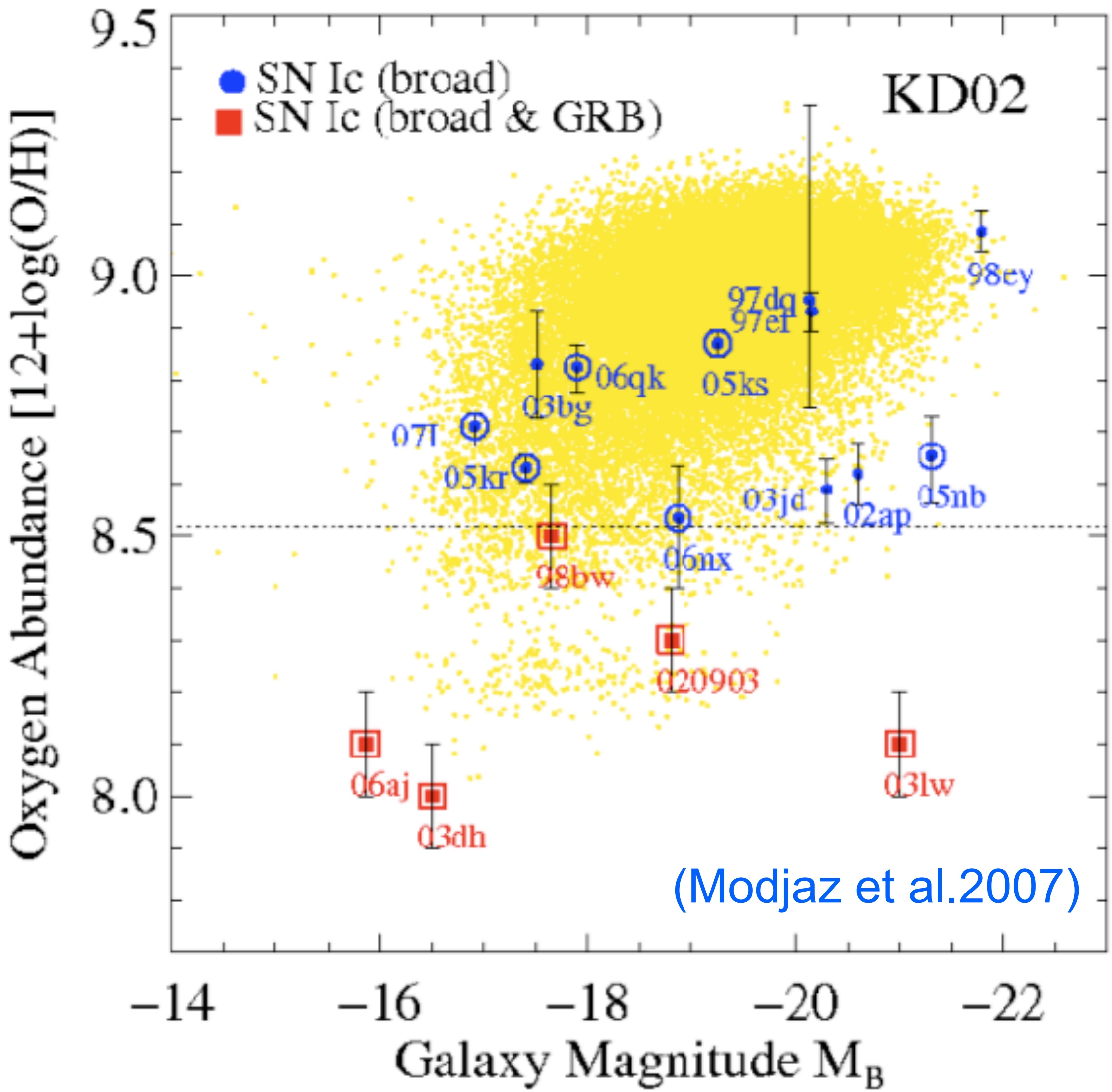
Prediction: Metallicity Threshold



(Yoon, Langer & Norman, 2006)

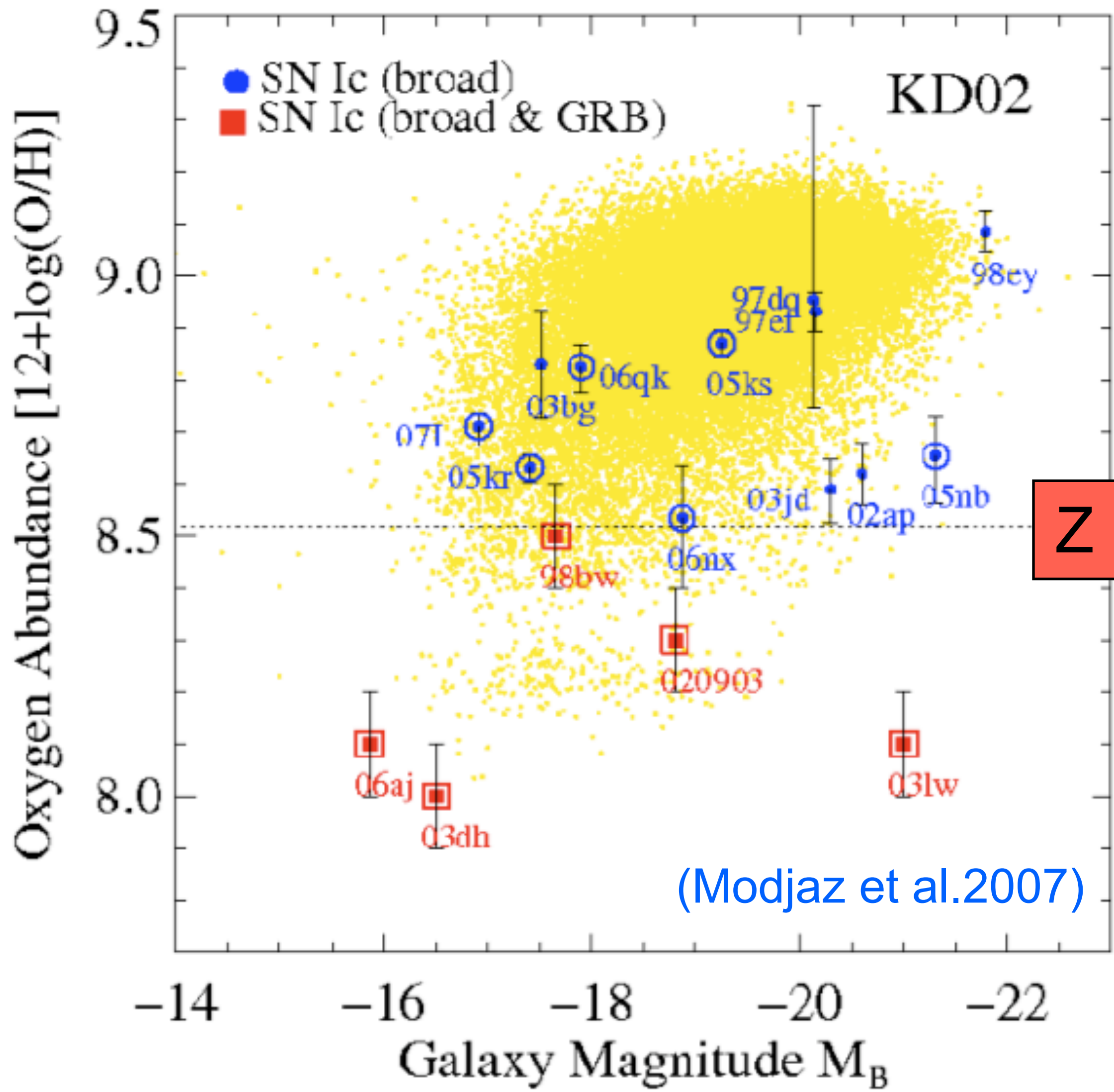
- Long GRBs prefer low metallicity (i.e. weaker winds) **$Z \lesssim 1/5\ Z_{Sun}$ (SMC)**
- This **metallicity threshold** is sensitive to mass-loss efficiency

Observations: Metallicity Threshold?



Diagnostic: KD02

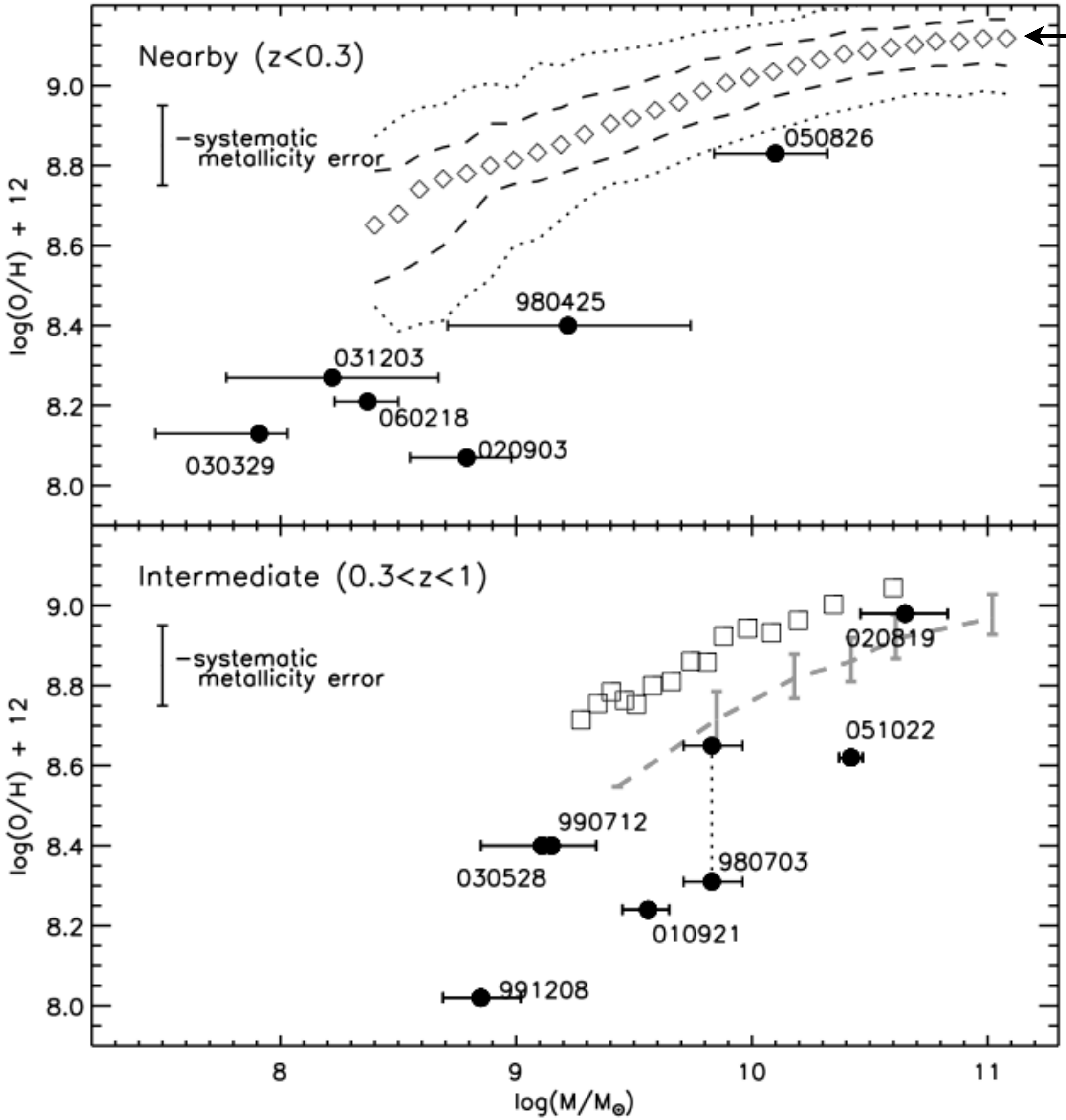
Observations: Metallicity Threshold?



Z ~ 0.2 - 0.6 Z_{Sun}

Diagnostic: KD02

Observations: LGRBs prefer low Metallicity?

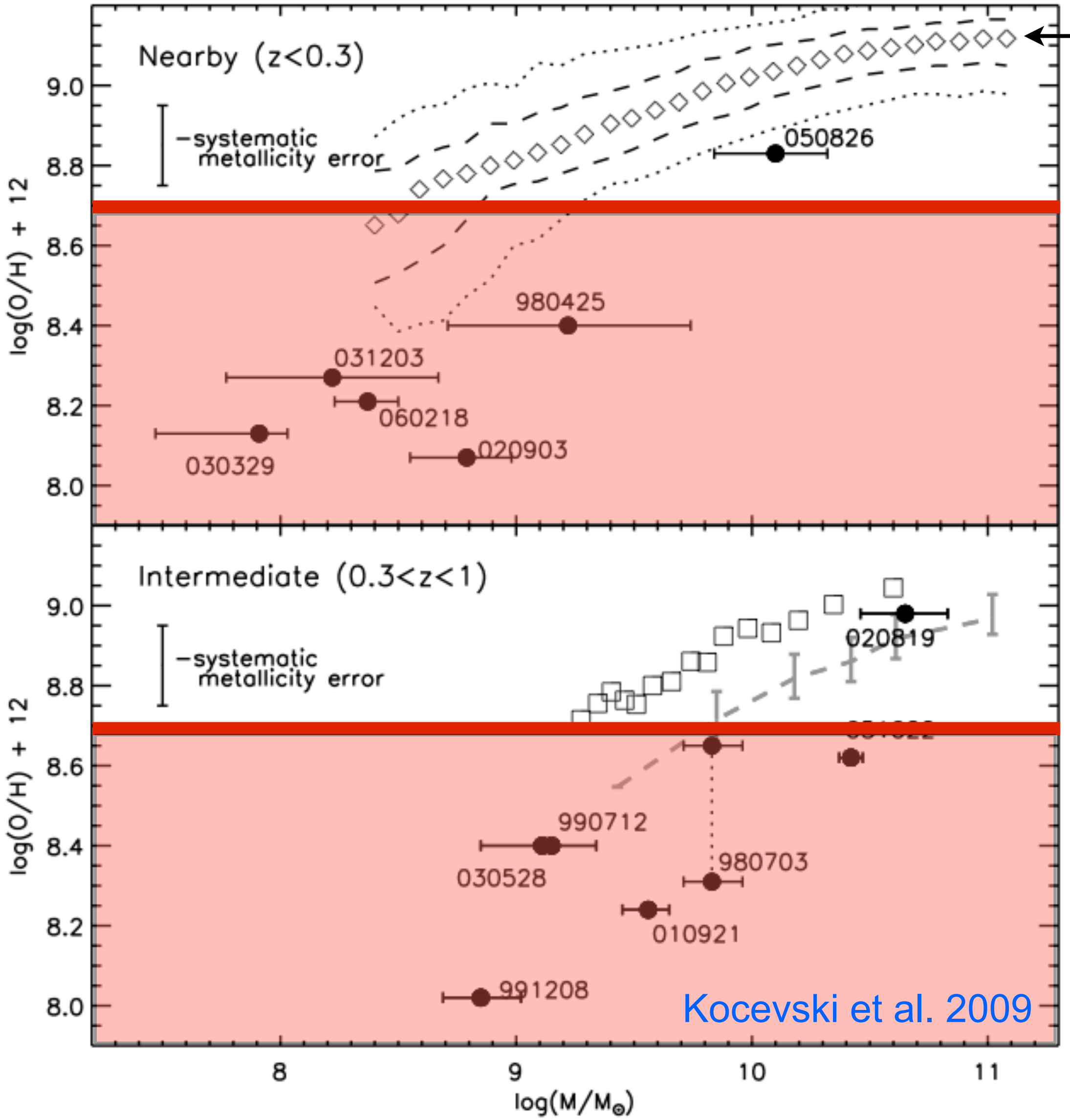


Tremonti et al. 2004 M-Z relation

Diagnostic: KK04

(Levesque et al.2010)

Observations: LGRBs prefer low Metallicity?

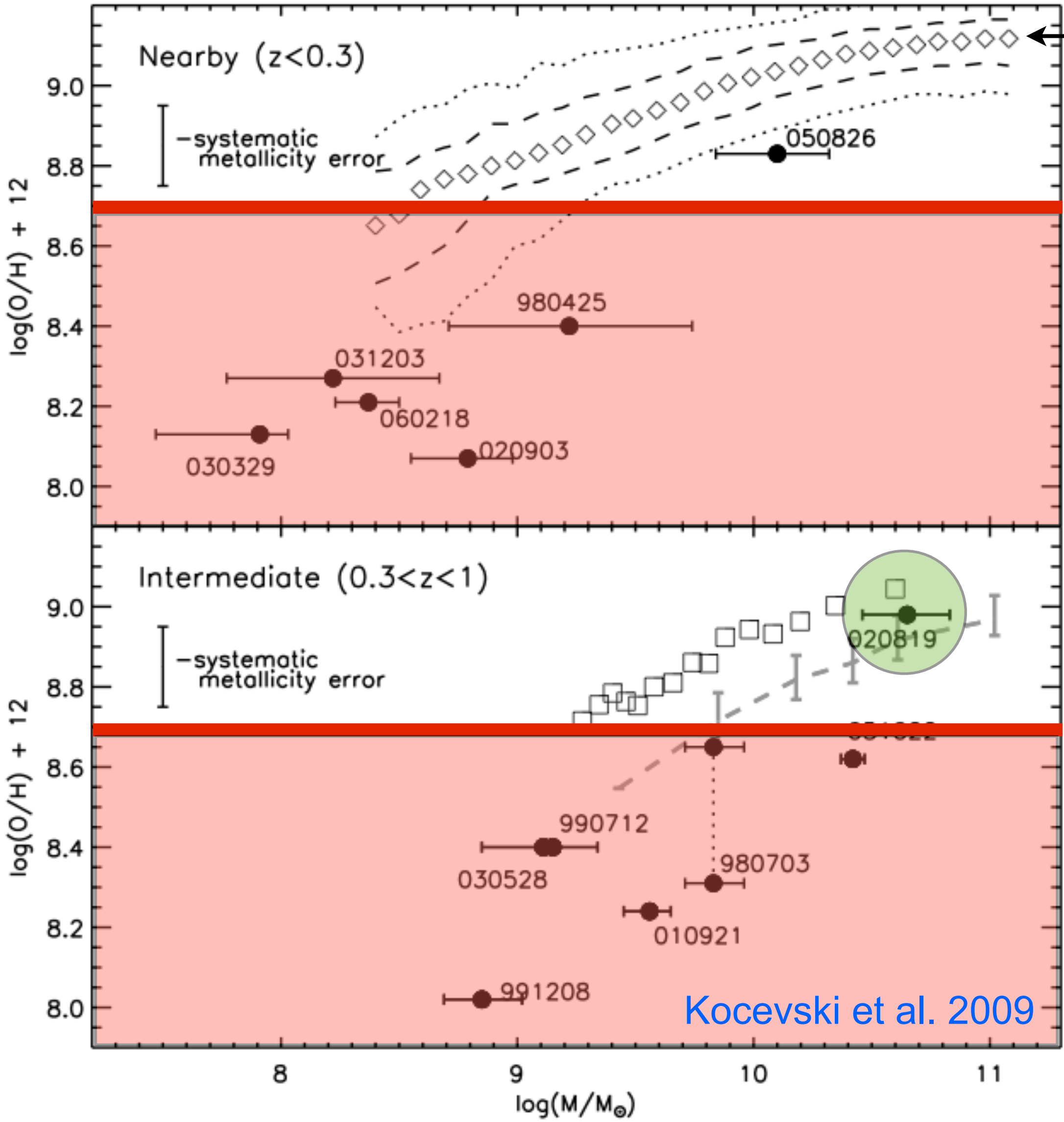


Tremonti et al. 2004 M-Z relation

Diagnostic: KK04

(Levesque et al.2010)

Observations: LGRBs prefer low Metallicity?

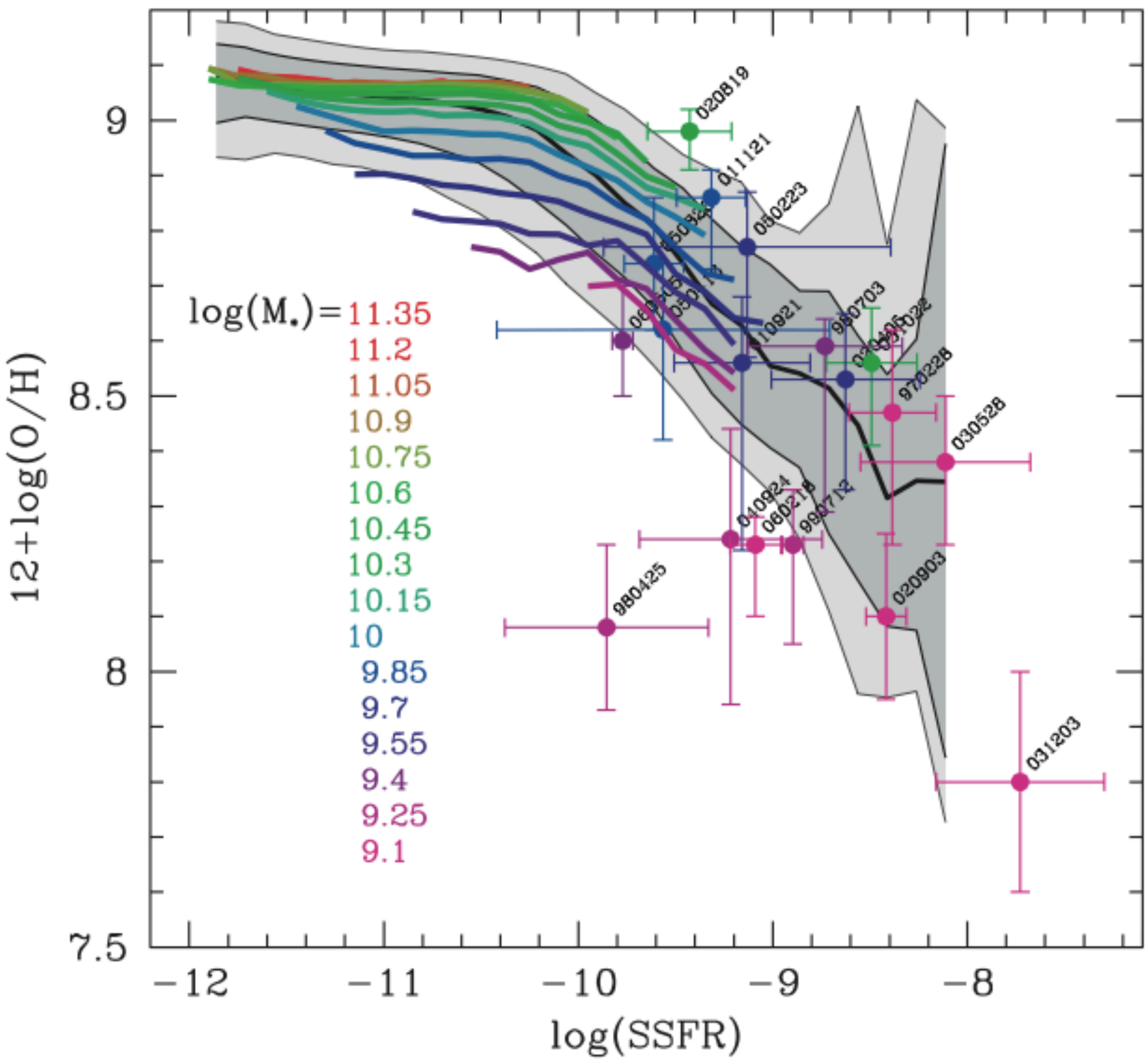


Tremonti et al. 2004 M-Z relation

Diagnostic: KK04

(Levesque et al.2010)

Or maybe even something else...



- The low metallicity observed in long GRB host galaxies is just a consequence of the observed correlation between SSFR and Z (Mannucci et al. 2011)

Conclusions

- Long GRBs? Fast rotating massive stars that evolve **chemically homogeneous**
- Two classes of progenitors: single and binary stars
- In massive binaries it is possible to **spin up** a star and form a rapidly rotating collapsing core
- This scenario is likely to produce a **runaway** WR which travels several hundred pc before collapse
- Both single and binary progenitors prefer **low Z**
- The origin of observed low-metallicity trend for GRB host galaxies is currently debated
- VLT-Flames Tarantula Survey: chemically homogeneous star and most rapidly-rotating O-star


WARNING
DO NOT TRY
THIS AT HOME


WARNING
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Open Source, State-of-the-art Stellar evolution

MESA
Modules for Experiments in Stellar Astrophysics

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getting started
how to use MESA star
mailing list
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MESA Council
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MESA

mesa.sourceforge.net

Welcome

... to the homepage of ***MESA***, modules for experiments in stellar astrophysics.

Why A New 1D Stellar Evolution Code?
What Can It Do?
Instrument Paper
Manifesto
Download, install, and run
MESA C++ Interface and Interactive Python Driver
How do you say that?
What does thread-safe mean?

Open Source, State-of-the-art Stellar evolution

Openness: anyone can download sources from the website.

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Wide Applicability: capable of calculating the evolution of stars in a wide range of environments.

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MODULES FOR EXPERIMENTS IN STELLAR ASTROPHYSICS (MESA)

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ABSTRACT

Stellar physics and evolution calculations enable a broad range of research in astrophysics. Modules for Experiments in Stellar Astrophysics (MESA) is a suite of open source, robust, efficient, thread-safe libraries for a wide range of applications in computational stellar astrophysics. A one-dimensional stellar evolution module, MESA star, combines many of the numerical and physics modules for simulations of a wide range of stellar evolution scenarios ranging from very low mass to massive stars, including advanced evolutionary phases. MESA star solves the fully coupled structure and composition equations simultaneously. It uses adaptive mesh refinement and sophisticated timestep controls, and supports shared memory parallelism based on OpenMP. State-of-the-art modules provide equation of state, opacity, nuclear reaction rates, element diffusion data, and atmosphere boundary conditions. Each module is constructed as a separate Fortran 95 library with its own explicitly defined public interface to facilitate independent development. Several detailed examples indicate the extensive verification and testing that is continuously performed and demonstrate the wide range of capabilities that MESA possesses. These examples include evolutionary tracks of very low mass stars, brown dwarfs, and gas giant planets to very old ages; the complete evolutionary track of a 1 $M_\odot$ star from the pre-main sequence (PMS) to a cooling white dwarf; the solar sound speed profile; the evolution of intermediate-mass stars through the He-core burning phase and thermal pulses on the He-shell burning asymptotic giant branch phase; the interior structure of slowly pulsating B Stars and Beta Cepheids; the complete evolutionary tracks of massive stars from the PMS to the onset of core collapse; mass transfer from stars undergoing Roche lobe overflow; and the evolution of helium accretion onto a neutron star. MESA can be downloaded from the project Web site (http://mesa.sourceforge.net/).

Key words: methods: numerical – stars: evolution – stars: general

Online-only material: color figures

ありがとうございます