OCA Seminar
17 October 2017

Spin alignment of stars in old open clusters

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OUTLINE

PART I
- Star and Stellar Cluster formation

PART II
- Stellar oscillations

PART III
- Observations, analysis & new results

PART I

STAR AND STELLAR CLUSTER FORMATION

INTRODUCTION

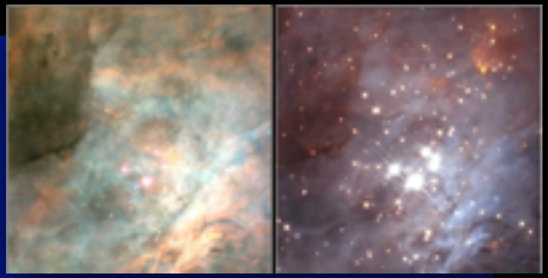
STAR FORMATION

- ***Fundamental*** problem in Astrophysics
  SHU ET AL. 1987; MCKEE & OSTRIKER 2007
- Gravitational collapse of turbulent molecular clouds (MC)
- Physical and chemical properties and dynamics of star forming regions (SFR)
- Origin of stellar mass distribution (IMF)
- Star and planet formation rates
- Link to stellar evolution and planet formation
- Formation, structure, and evolution of galaxies

BARNARD 68 DARK CLOUD. © ESO

Very difficult to access:

- SFR are dense and obscured by dust (only IR and Radio)
- MC change density by 10 orders - Hierarchical step approaches required



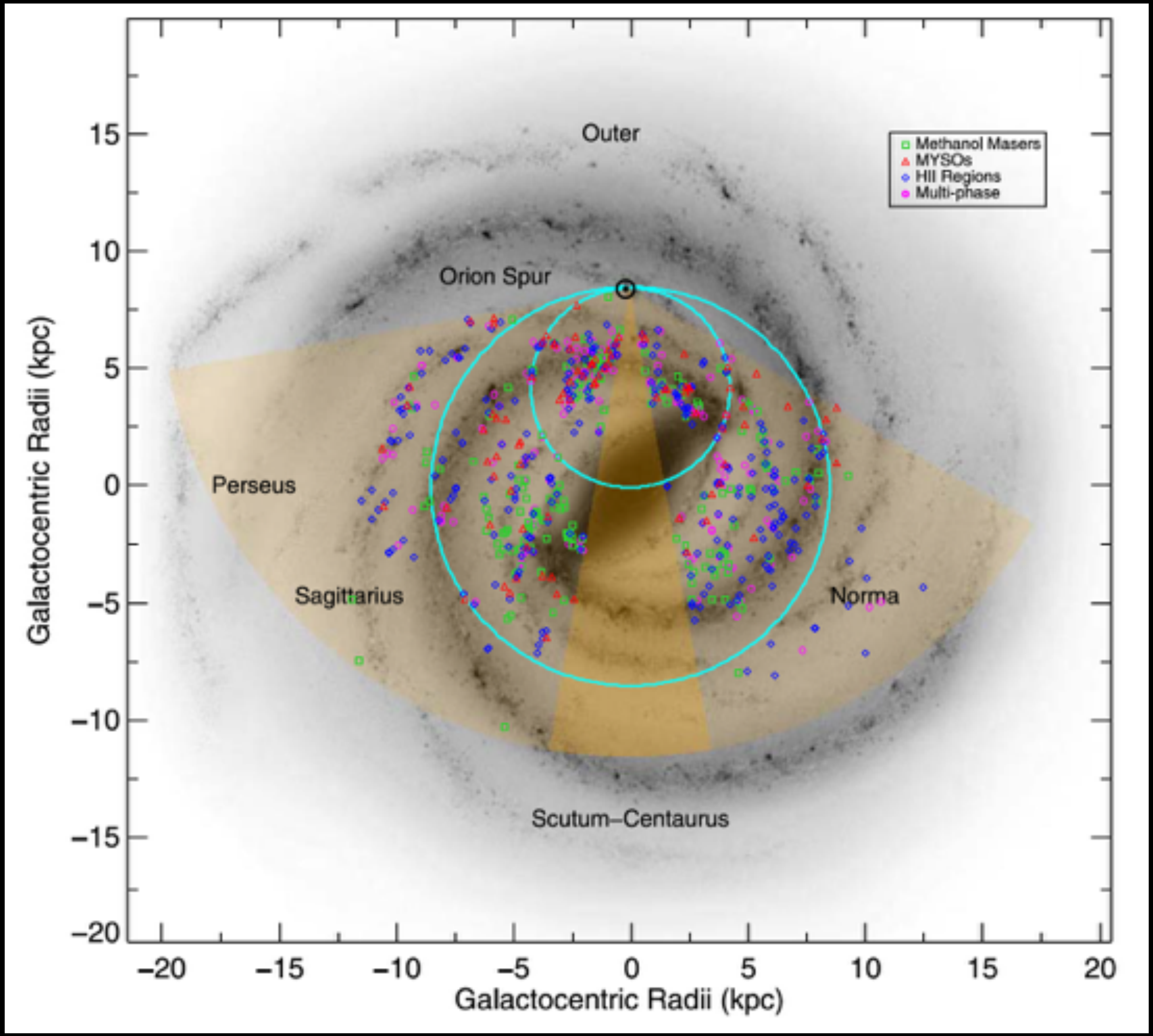
INTRODUCTION

MASSIVE SFR

- Star formation very diffused in Galaxy

- ~1300 massive SFR identified with IR, sub-mm, radio surveys across inner Galaxy

URQUHART ET AL. 2014



ATLASGAL © URQUHART ET AL. 2014

- Half star formation in Milky Way occurring in 24 giant MC (up to **10^7 M_{Sun}** each)

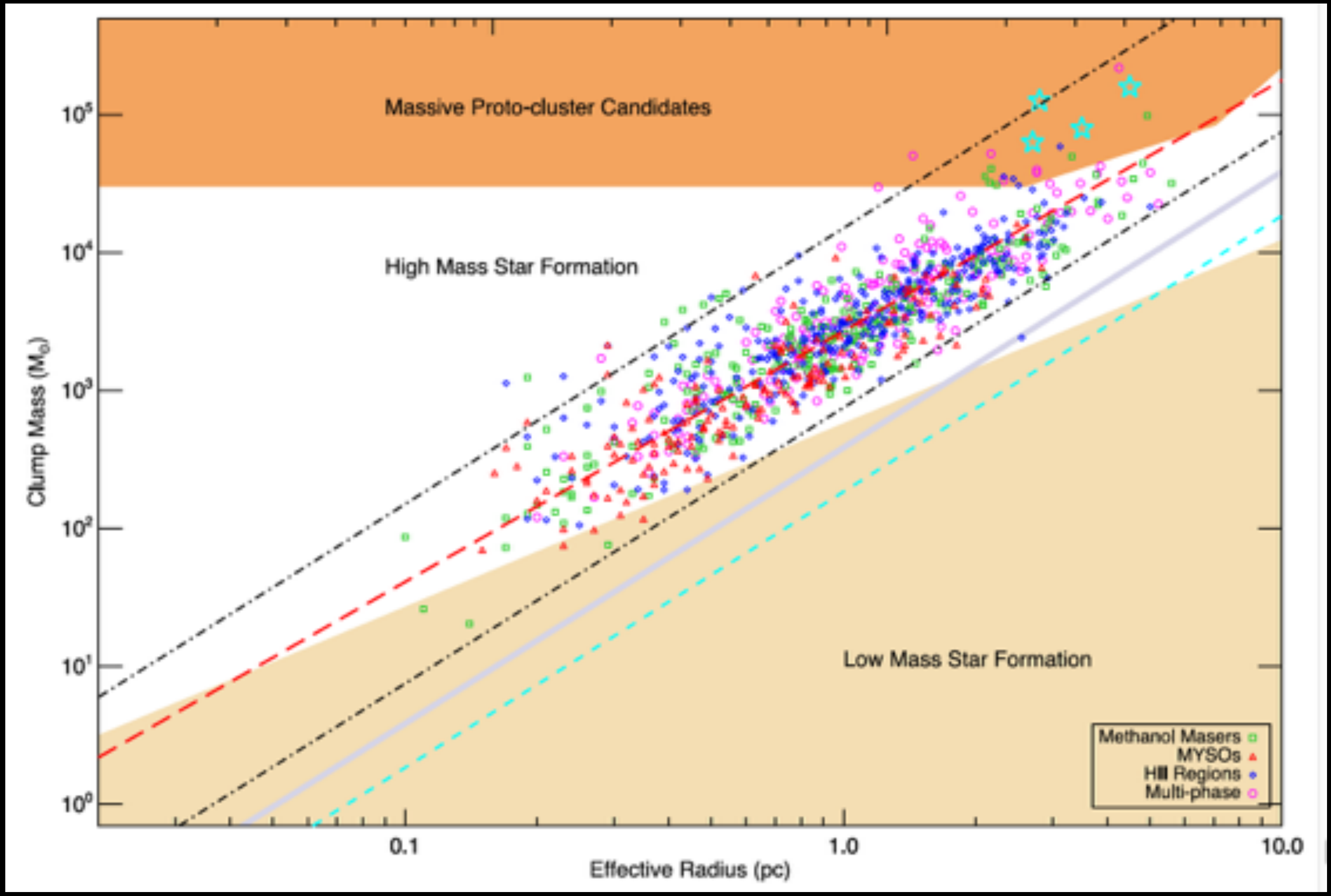
LEE ET AL. 2012; LONGMORE ET AL. 2014

INTRODUCTION

PROTO-CLUSTERS

- Giant MC can form hundreds of proto-clusters each with up to **10^5 M_{Sun}** (many Jeans masses!)
  IMMER AL. 2012; LONGMORE ET AL. 2012
- Stellar clusters are ***common*** and likely to form (high mass clumps)

ATLASGAL © URQUHART ET AL. 2014



- Understand cluster formation is critical to understand star formation
- Sun and Solar System likely originated from a cluster
  ADAMS 2010

BENCHMARKS OF STAR FORMATION

OPEN CLUSTERS

OPEN CLUSTER NGC 265 © NASA/ESA

- Open clusters (OC) ***important***:

  LADA & LADA 2003; LONGMORE ET AL. 2014

  - **Can be observed in multi bands because no or little ISM (not embedded)**

    Not possible in SFR because covered by dust

  - **Stars are sparse (~1 M_{Sun} pc^{-3}) —> precise follow-up studies possible**

    Not possible in e.g. Globular Clusters, too dense!

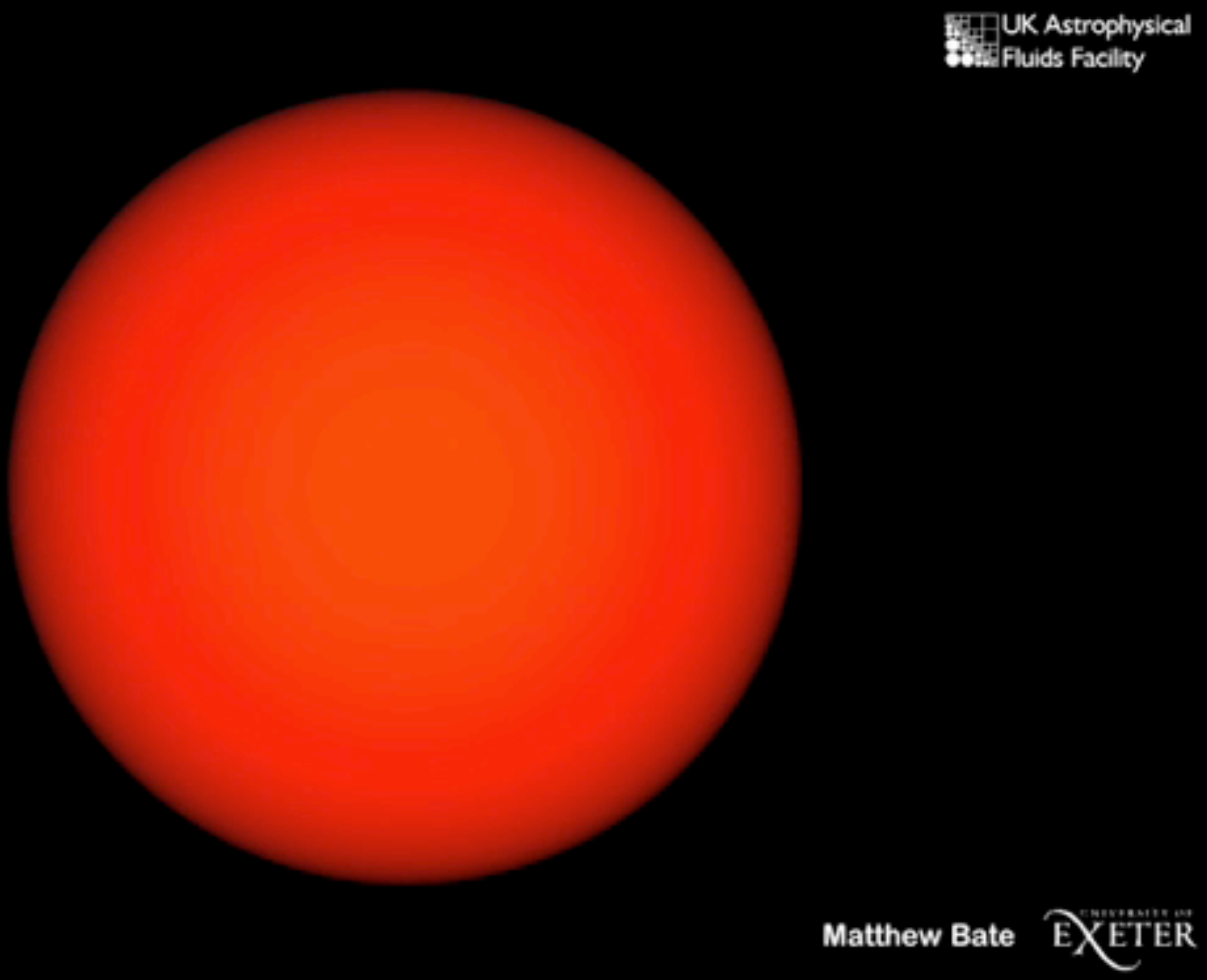
  - **Stars in cluster can preserve imprint of initial cdts of progenitor MC**

    Not possible with field stars because from dissolved small stellar systems

STELLAR CLUSTERS AND 3D SIMULATIONS

IMPRINT OF INITIAL CONDITIONS?

- 3D numerical simulations of MC collapse and cluster formation to study ***morphology*** and ***dynamics***
  BATE ET AL. 2009; KUZNETSOVA ET AL. 2015
- Stars can form either isolated, in filaments or in clusters (more common)
- Kinematic signatures of MC might not live long enough to be observed



CLOUD COLLAPSE © BATE ET AL. 2009

CLOUD'S ANGULAR MOMENTUM

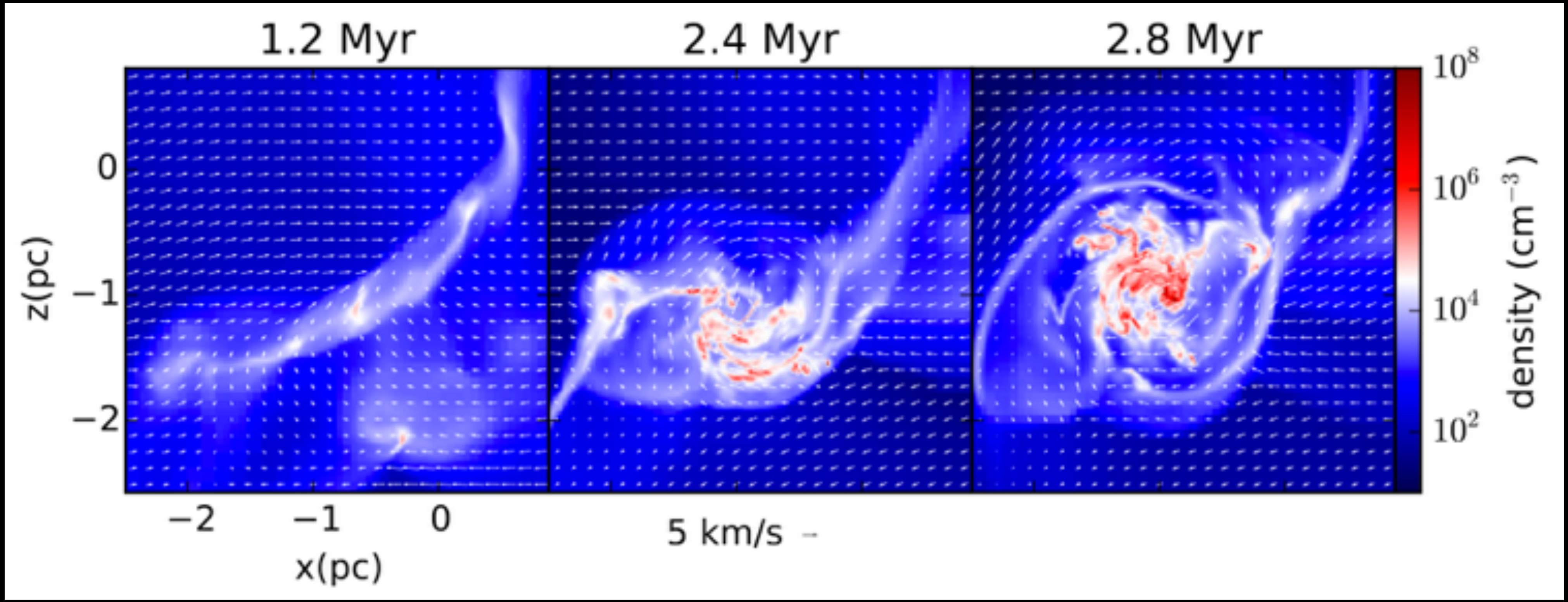
- From 3D MHD simulations of proto-cluster formation
  LEE & HENNEBELLE 2016

$$E_{\rm kin} = E_{\rm tur} + E_{\rm rot}$$

$$\boxed{E_{\rm rot} < \frac{1}{2} E_{\rm tur}}$$

- Angular momentum from the cloud is not efficiently passed to stars
- Less general cloud's rotation at scales of forming stars (several AU)

PROTO-CLUSTER FORMATION © LEE & HENNEBELLE 2016



CLOUD'S ANGULAR MOMENTUM

OBSERVATIONAL RESULTS

- Evolution of cloud's AM not well understood
  E.G. SHU, ADAMS & LIZANO 1987; DONG LAI 2014
- Stellar-spin axis ***randomly distributed*** in nearby OC Pleiades and Alpha Persei (d ~ 150 pc, Age~80 Myr)
  JACKSON & JEFFRIES 2010
- Clouds' average AM scrambled by turbulence at different scales
- Imprint of cloud's global rotation lost during star formation

PLEIADES WITH DSS © NASA/ESA

Turbulence fields counteract cloud's global rotation in producing spin alignment

CLOUD'S ANGULAR MOMENTUM

OBSERVATIONAL LIMITATIONS

- Observational technique requires combination of several observations:
  JACKSON & JEFFRIES 2010
  - P_{rot} from light curve spot modulation (***active stars!***)
  - ***v sini*** measurement from spectroscopic observations
  - ***stellar radius R*** from cluster distance + angular diameter
  - cluster ***distance*** from ***parallax*** (Hipparcos)
  - ***angular diameter*** from magnitude (de-reddened) + color index relation recalibrated with interferometry on MS and SG stars
    KERVELLA ET AL. 2004

$$\sin i = \frac{v \sin i P_{\mathrm{rot}}}{2\pi R}$$

Only young active stars possible
Strong sensitivity to cluster distance
Prone to large systematics

PART II

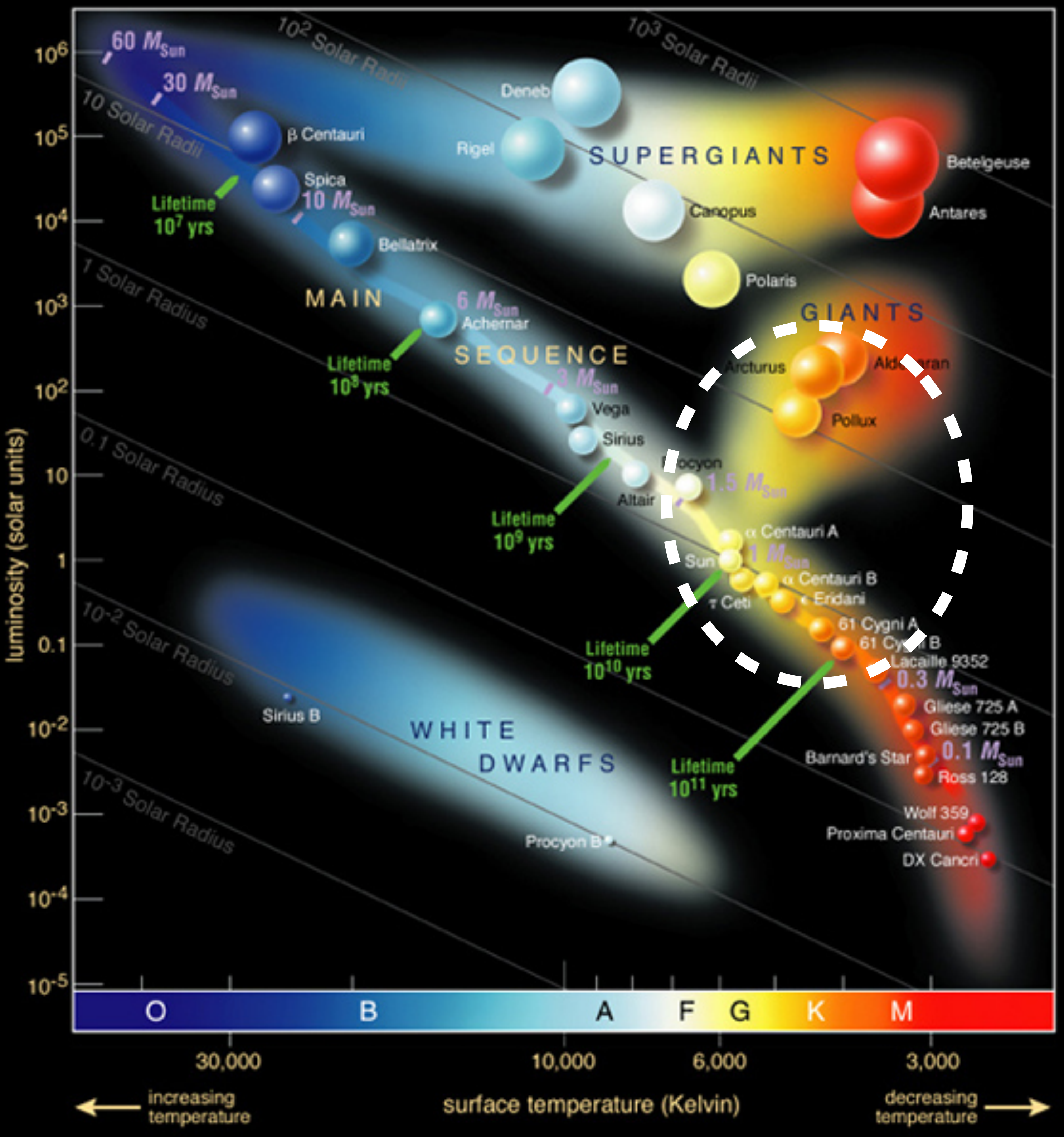
STELLAR OSCILLATIONS

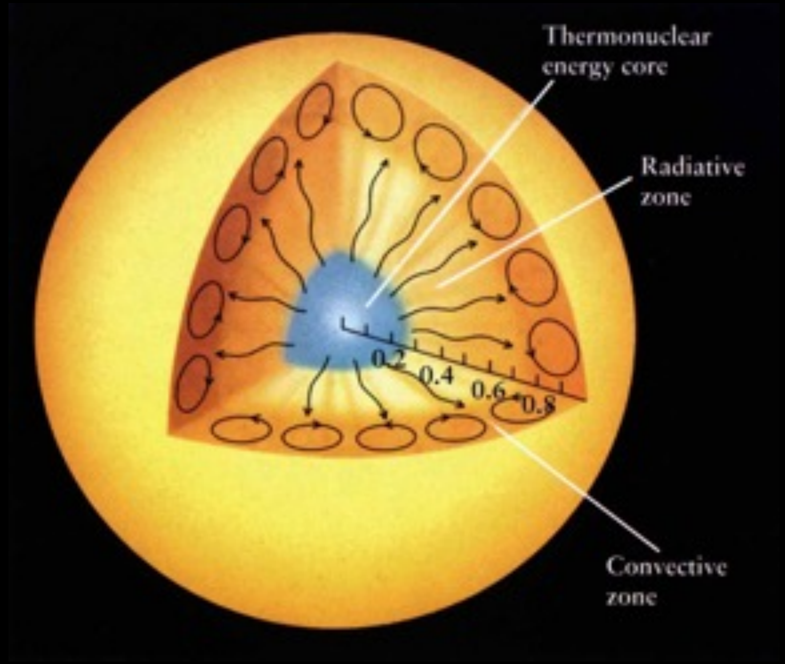
PROBING THE INTERIOR OF STARS

ASTEROSEISMOLOGY

- Most stars with M ~ 1-3 M_{Sun} oscillate like the Sun (helioseismology)
  CHRISTENSEN-DALSGAARD 1987
- ~ 100 K known today
- Space missions MOST, CoRoT, NASA's *Kepler* & K2
- More to follow: NASA TESS, ESA PLATO space missions

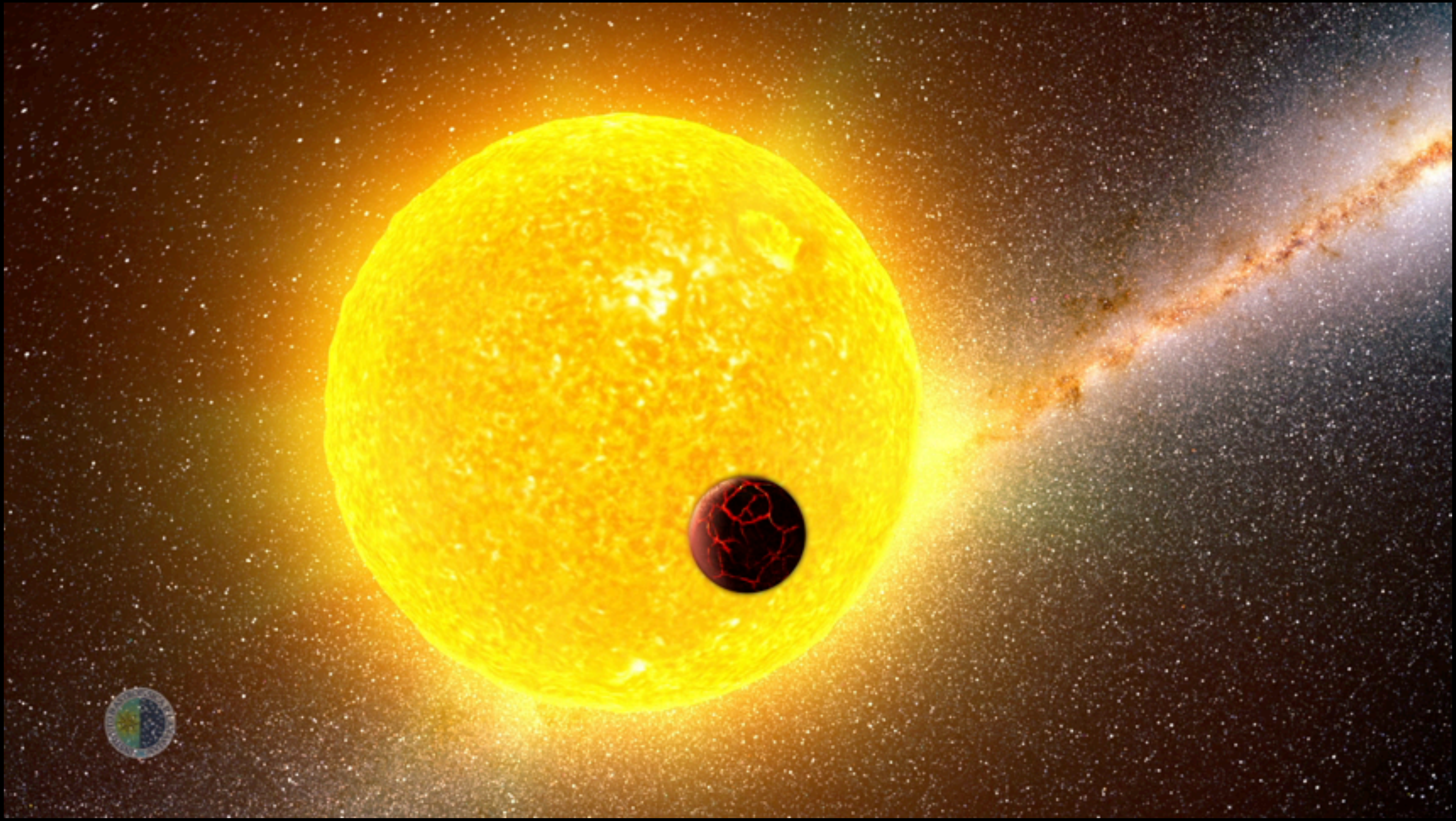
© ESO





SOLAR-LIKE OSCILLATIONS

Acoustic waves (***p modes***) propagate in outer CZ



© CREDIT: GABRIEL PEREZ DIAZ, IAC (MULTIMEDIA SERVICE)

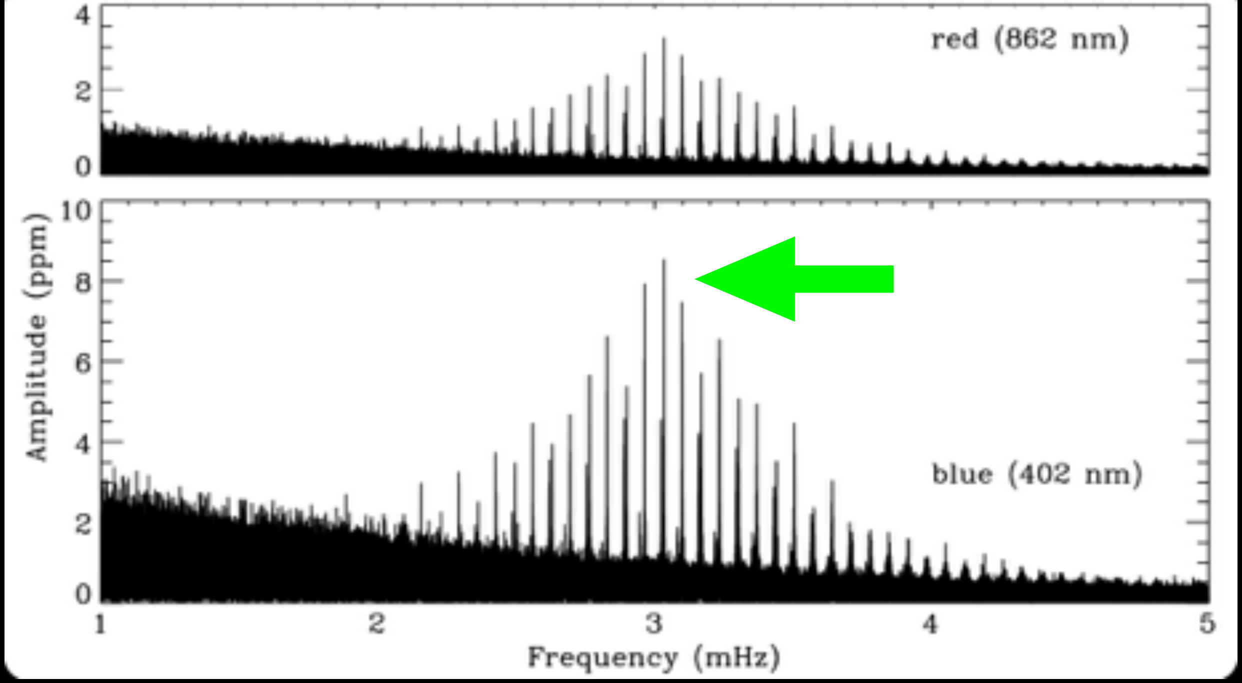
PROBING THE INTERIOR OF STARS

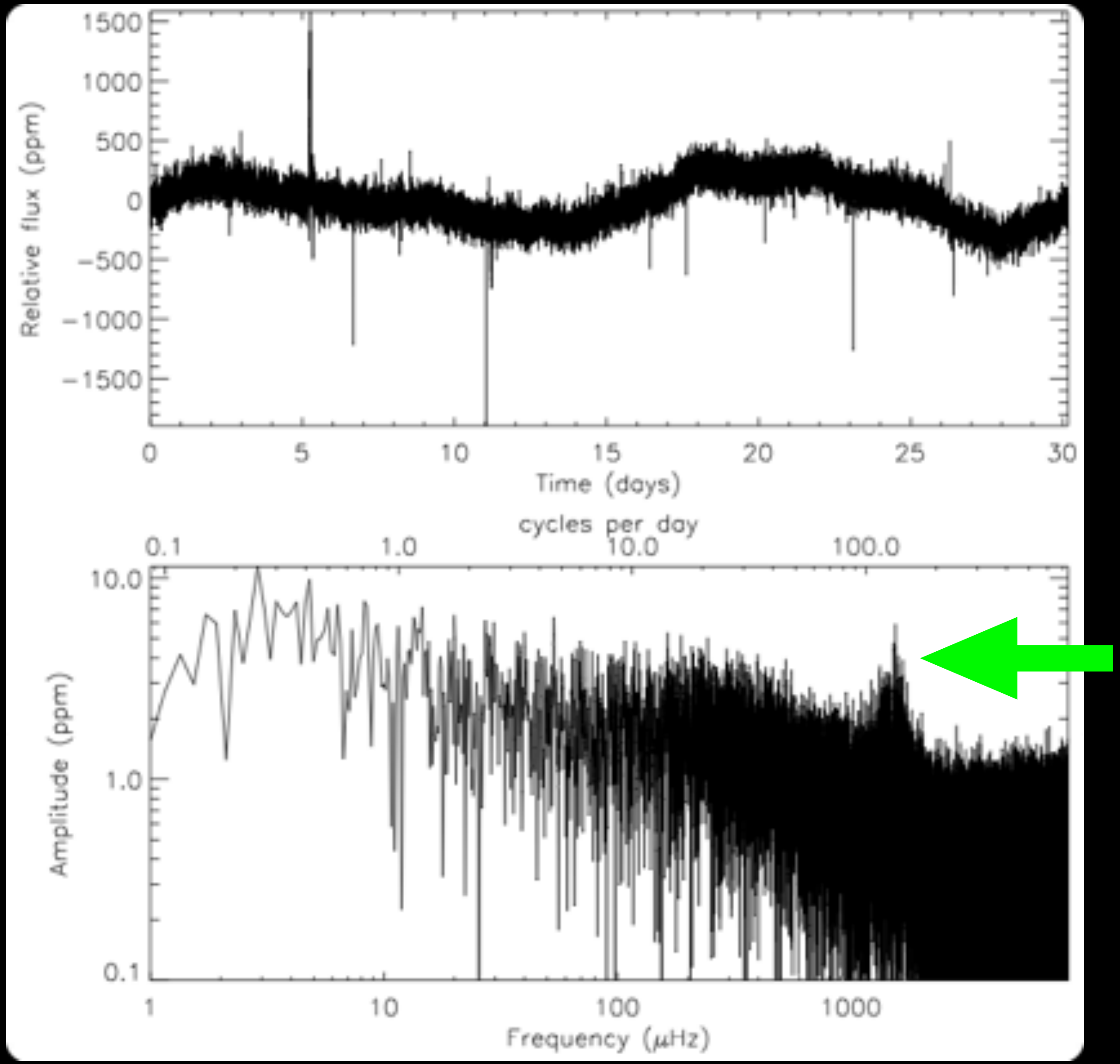
SOLAR-LIKE OSCILLATIONS

- Produce tiny brightness variations (from few ppm to ppt) in light curve
- Fourier analysis (***Power Spectrum***) reveals Gaussian envelope of oscillations

$$\nu_{\rm max} \propto g/\sqrt{T_{\rm eff}}$$

© VIRGO/SPM ONBOARD SOHO

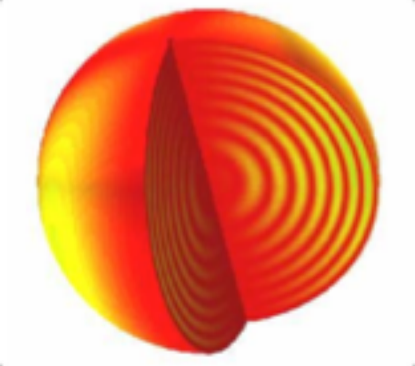




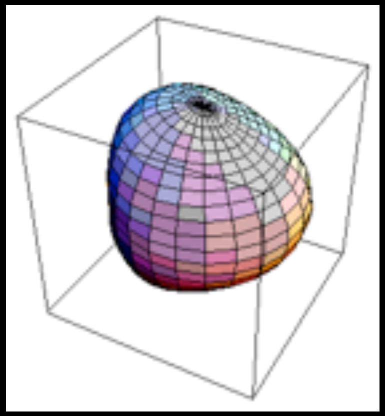
PROBING THE INTERIOR OF STARS

OSCILLATION MODES

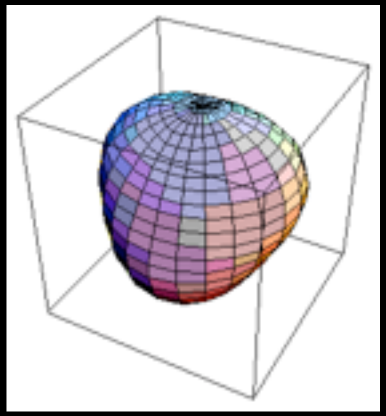
- Oscillation mode identified by 3 quantum numbers (***n***, ***ℓ***, ***m***, for spherical harmonic)
- Surface distribution depends on oscillation mode



$n \sim 10$-20



$\ell = 3$, $m = 1$



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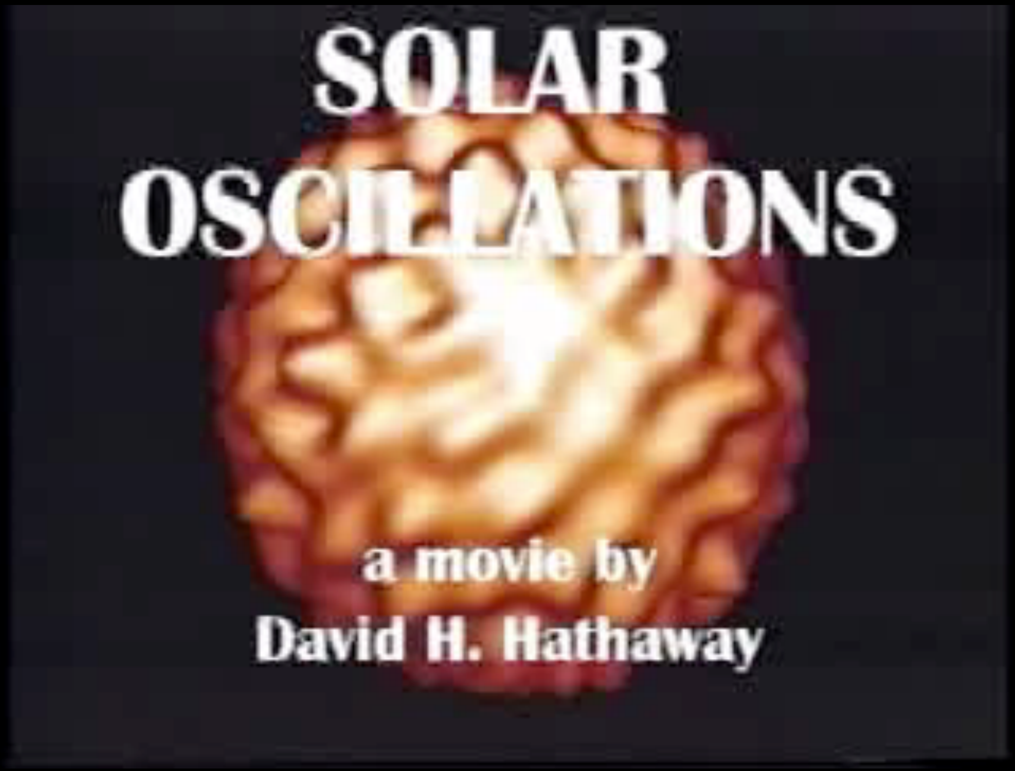
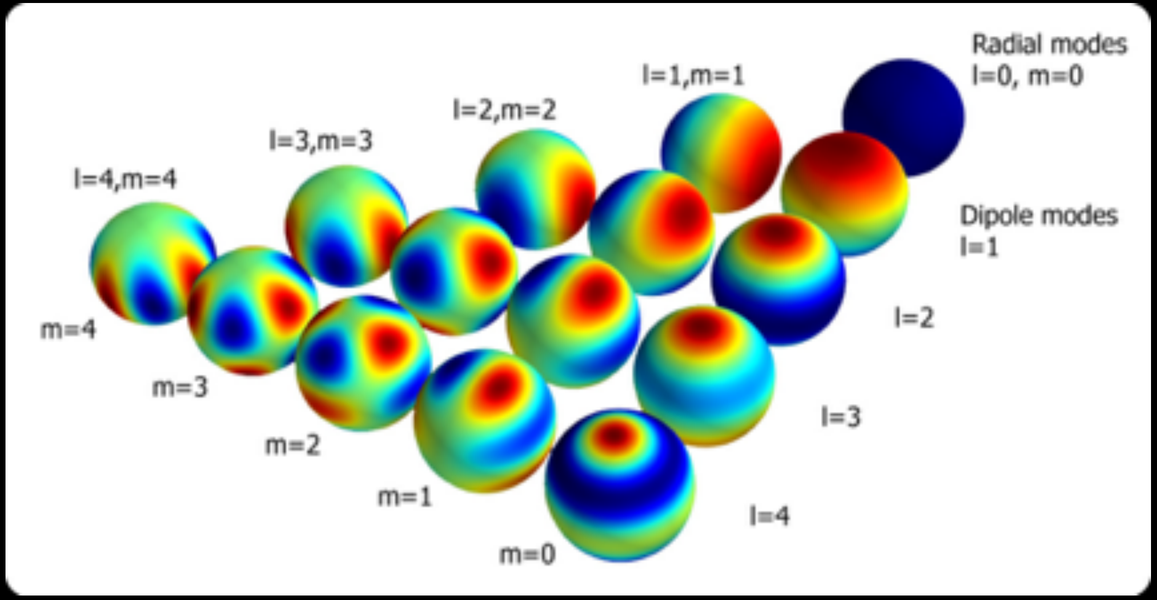




© BECK & KALLINGER, 2013 S&W

PROBING THE INTERIOR OF STARS

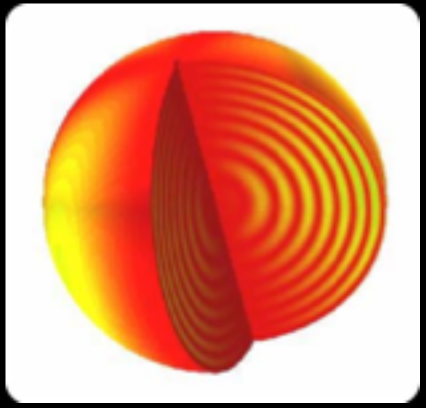
ASYMPTOTIC PATTERN

- When radial order ***n >> 1***, regime becomes asymptotic
- Modes with same ***angular degree ℓ*** are equally spaced in frequency
- Large frequency separation Δν probes mean stellar density

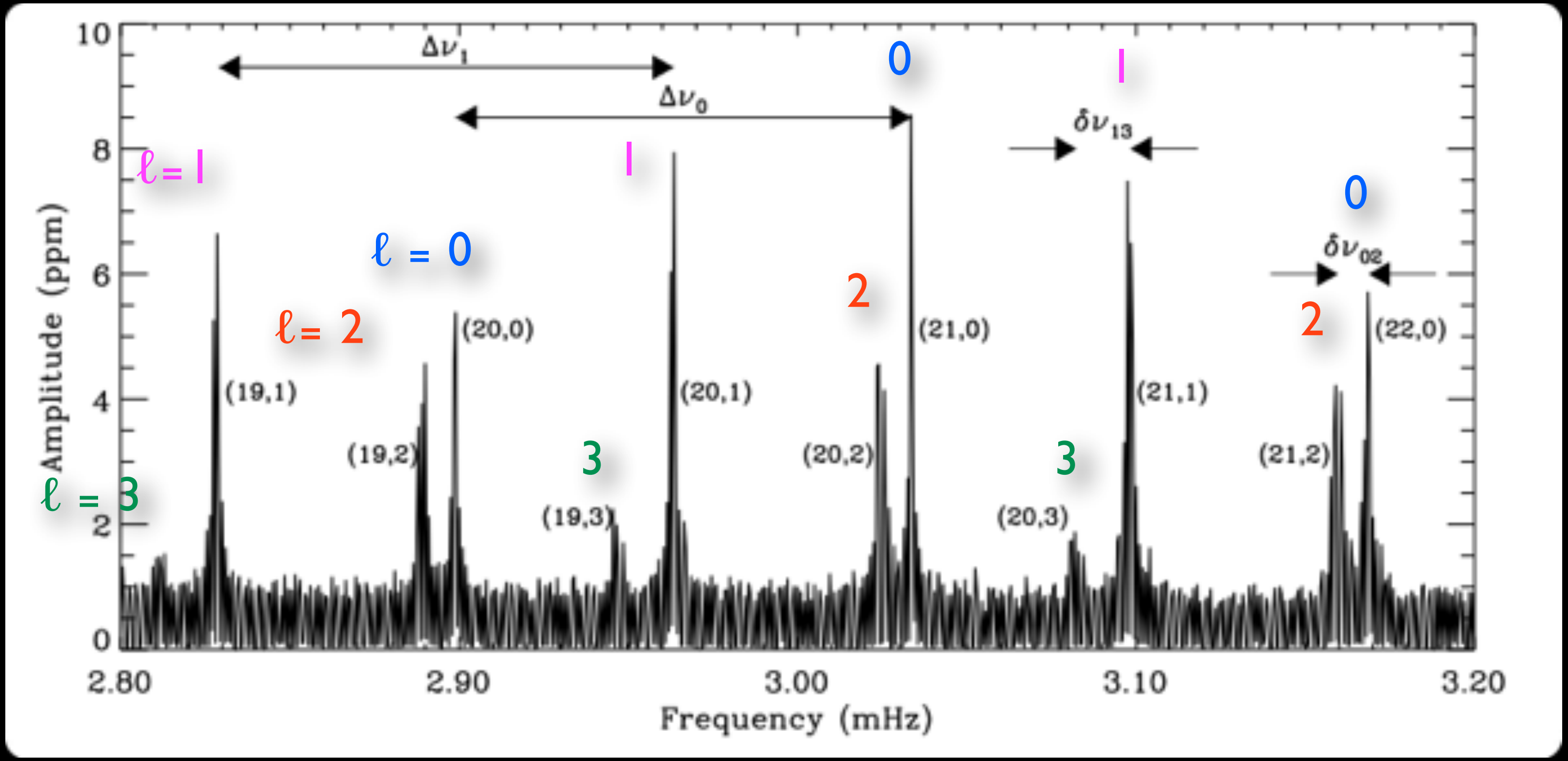
$$\nu_{\max} \propto g/\sqrt{T_{\text{eff}}}$$

$$\Delta\nu \propto \overline{\rho}$$

$$M, R$$



n ~ 10-20



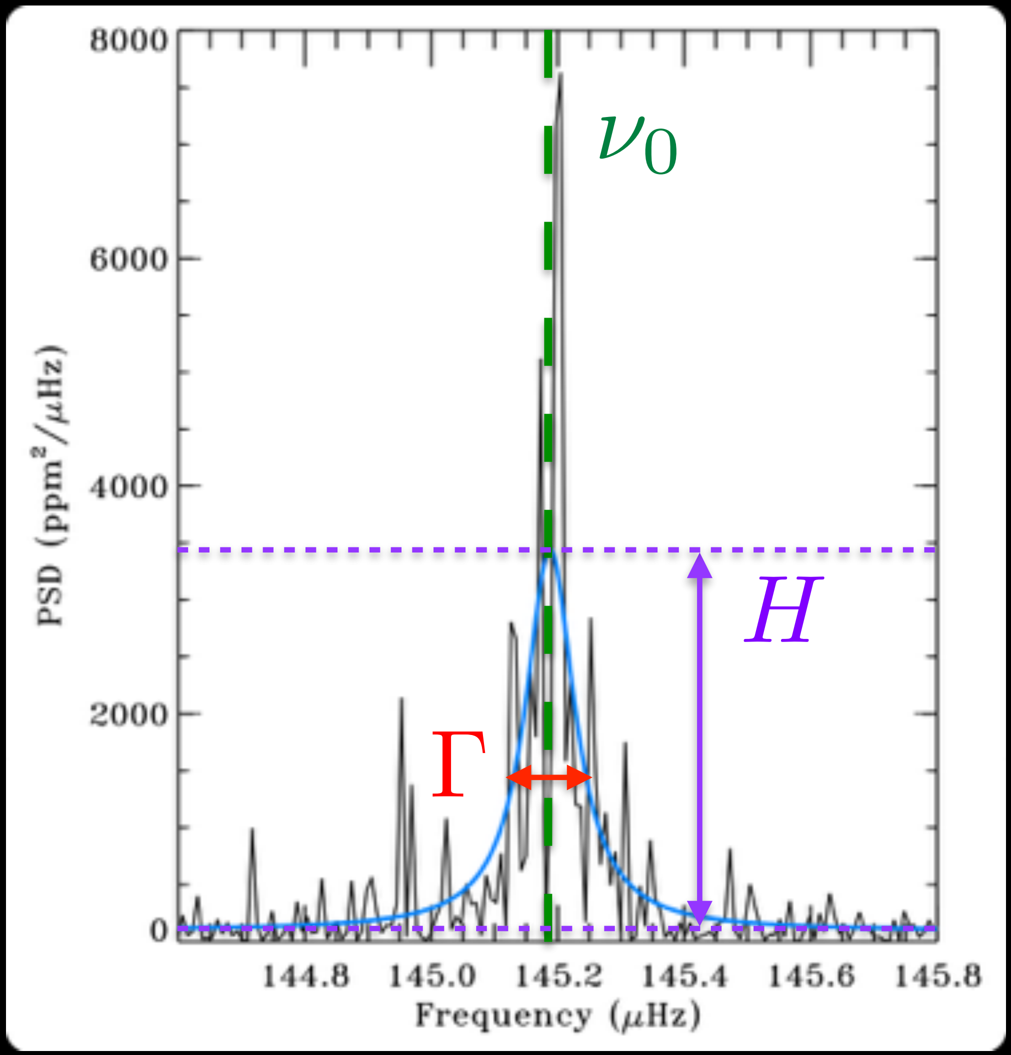
© BEDDING, KJELDSEN ET AL. 2003

PROBING THE INTERIOR OF STARS

DETAILED MODE PROPERTIES

- Each oscillation mode is characterized by ***3*** parameters

- An individual ***PS*** can require hundreds of free parameters to be modeled



Damped oscillation

Lorentzian profile

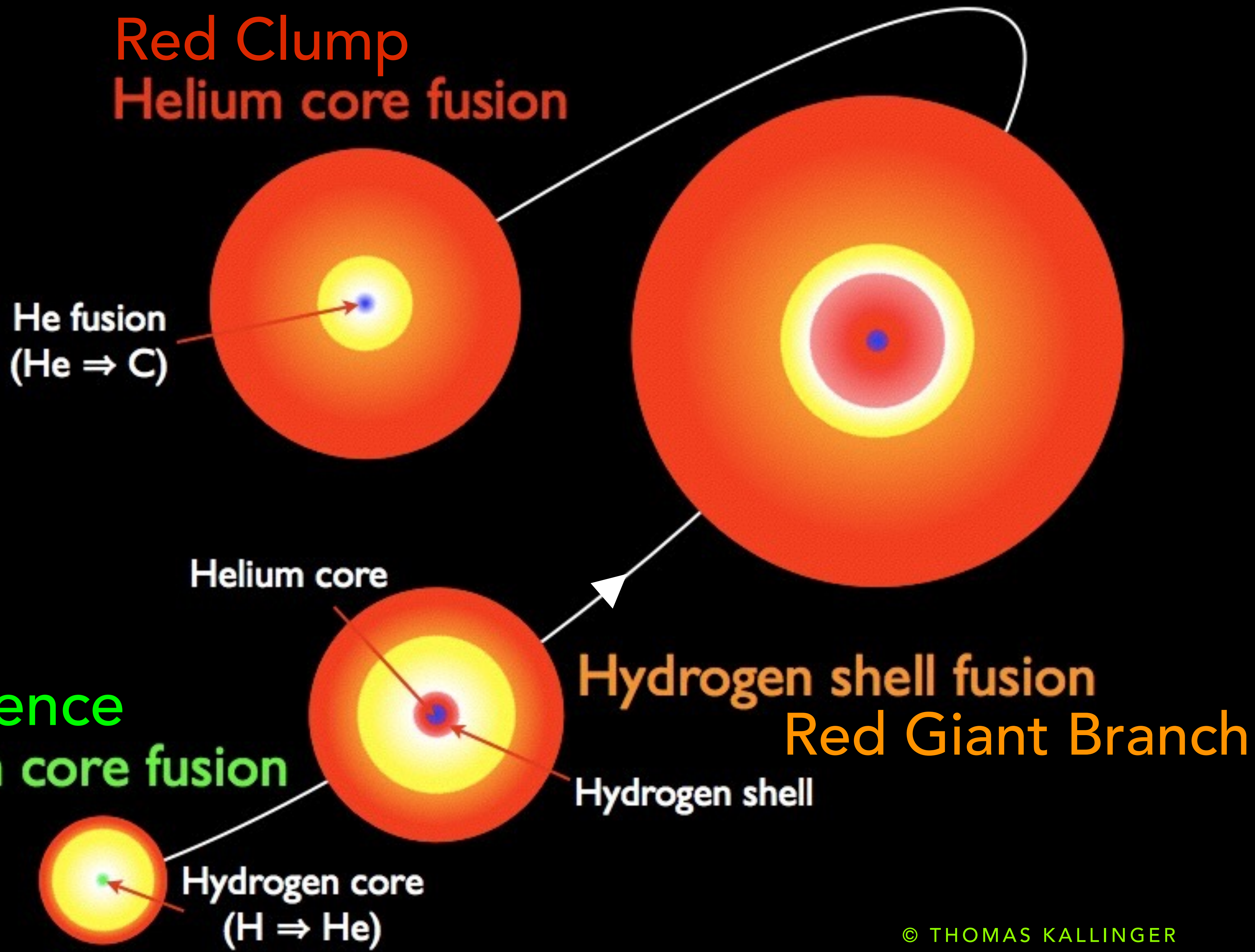
$$T_{\mathrm{obs}} \gg \tau$$
$$\Gamma \propto \tau^{-1}$$

$$\nu_0, \Gamma, H$$

EVOLVED SOLAR-TYPE STARS

RED GIANTS

(sizes not to scale!)



Red Clump

Helium core fusion

Main Sequence

Hydrogen core fusion

Hydrogen shell fusion

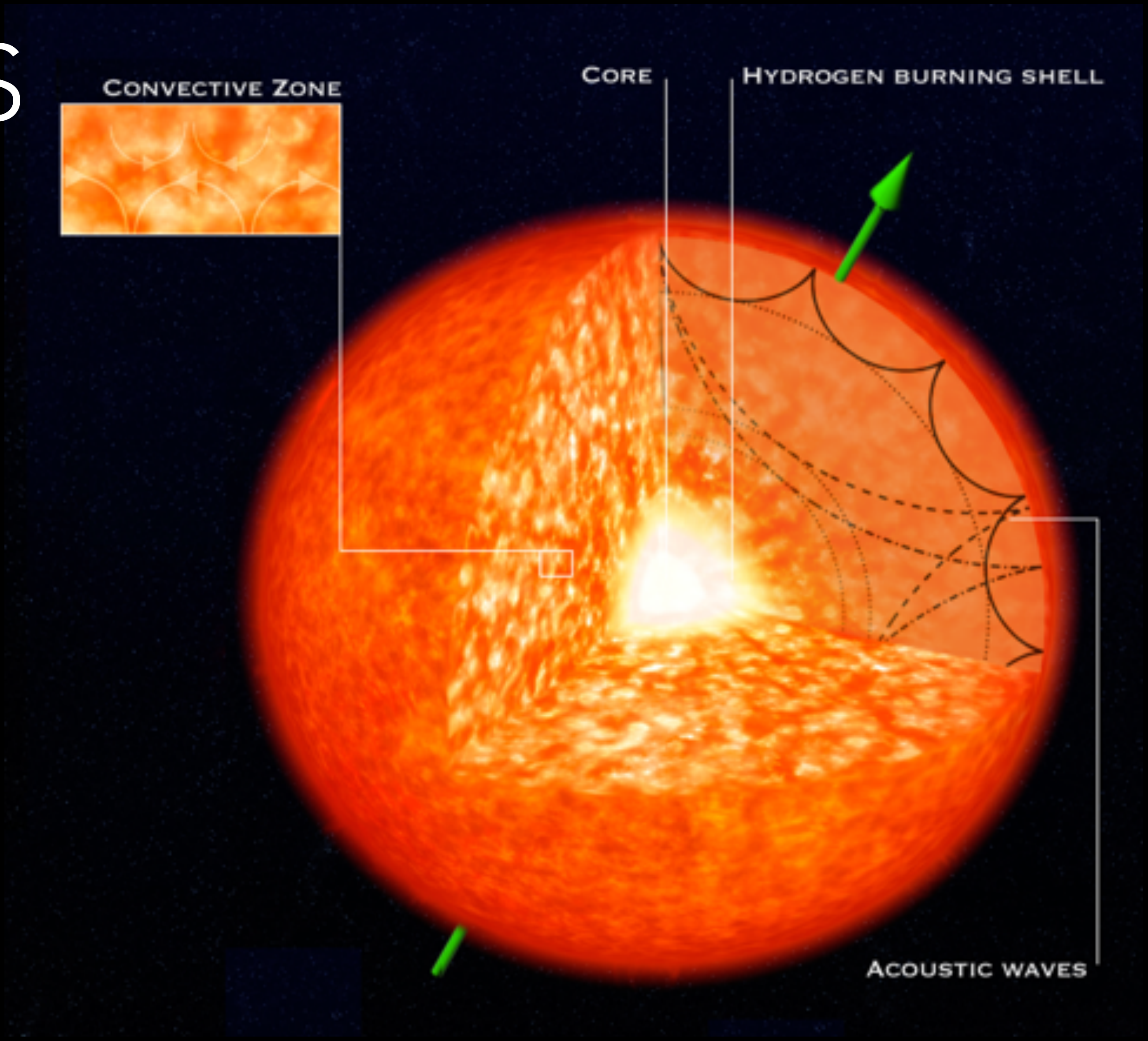
Red Giant Branch

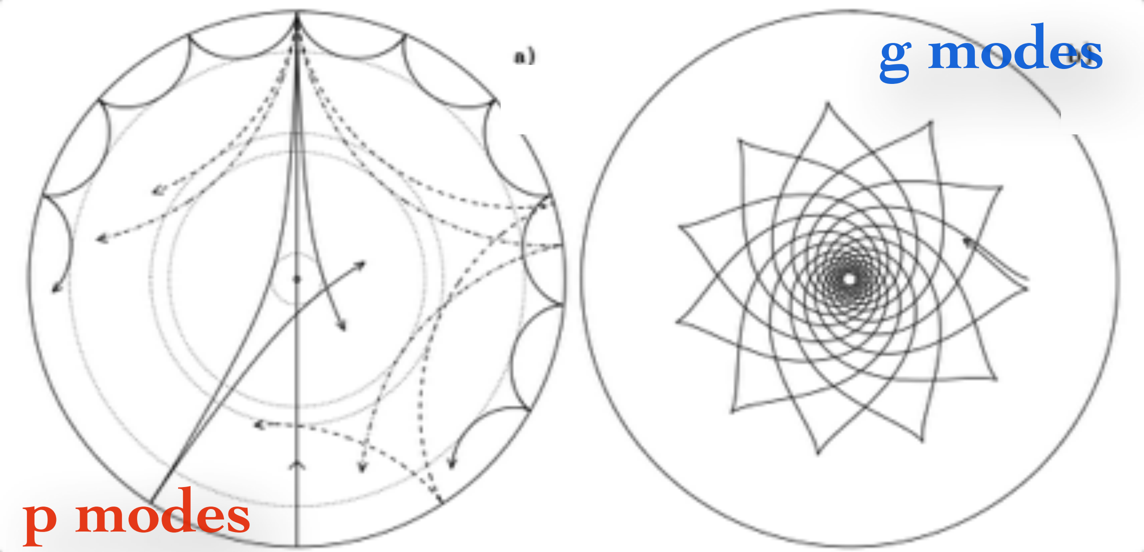
© THOMAS KALLINGER

EVOLVED SOLAR-TYPE STARS

RG OSCILLATIONS

- Giants are very luminous: can be observed more far away than MS (dwarfs)
- Useful for ***Galactic Archeology***: map Galaxy structure and evolution, Globular Clusters
  MIGLIO ET AL. 2013, 2016
- Solar-like oscillations in outer CZ
- Couple with ***gravity waves*** from RZ
- Dipole (ℓ=1) mixed modes observable, with both g- and p- character





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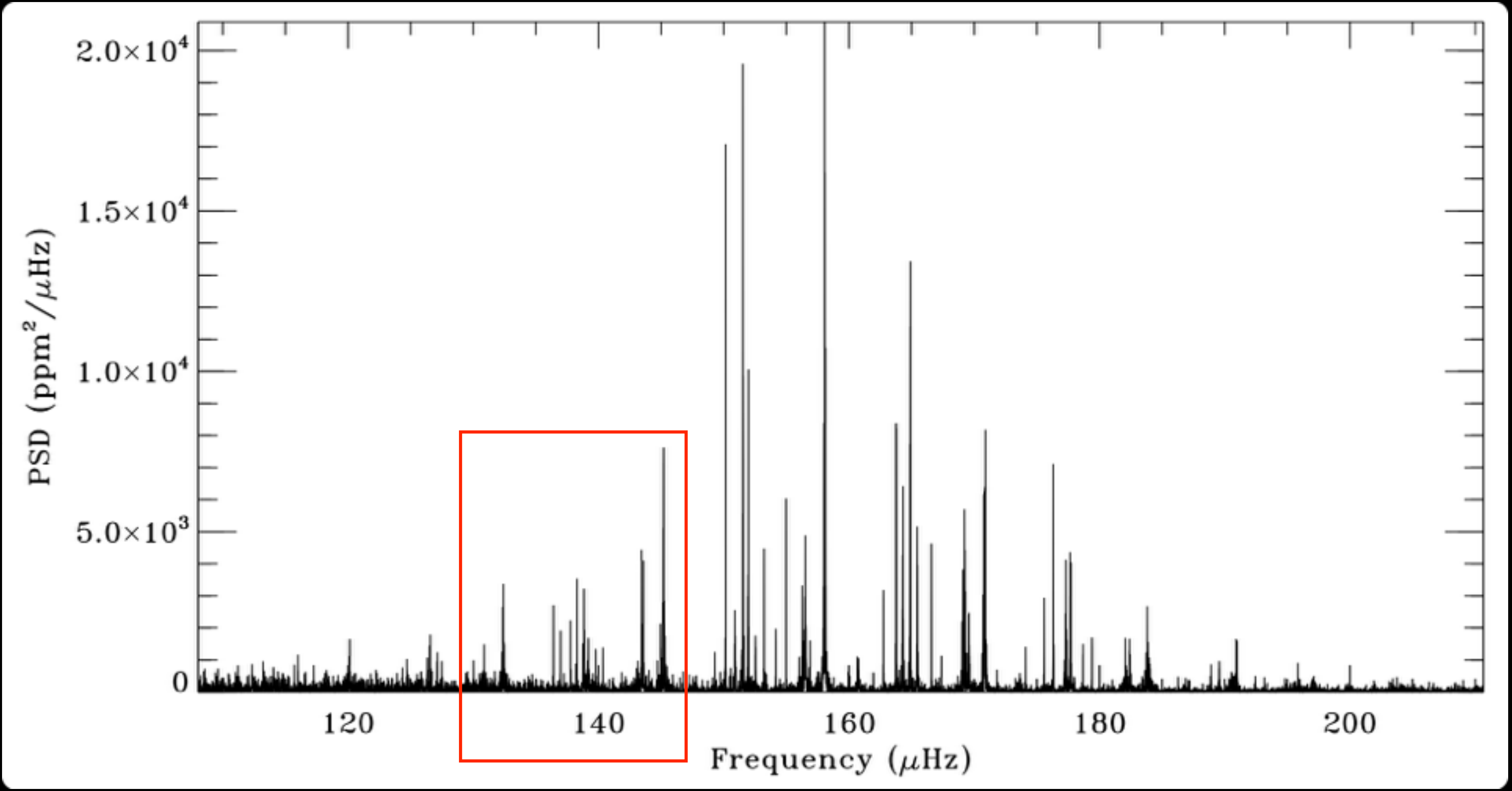
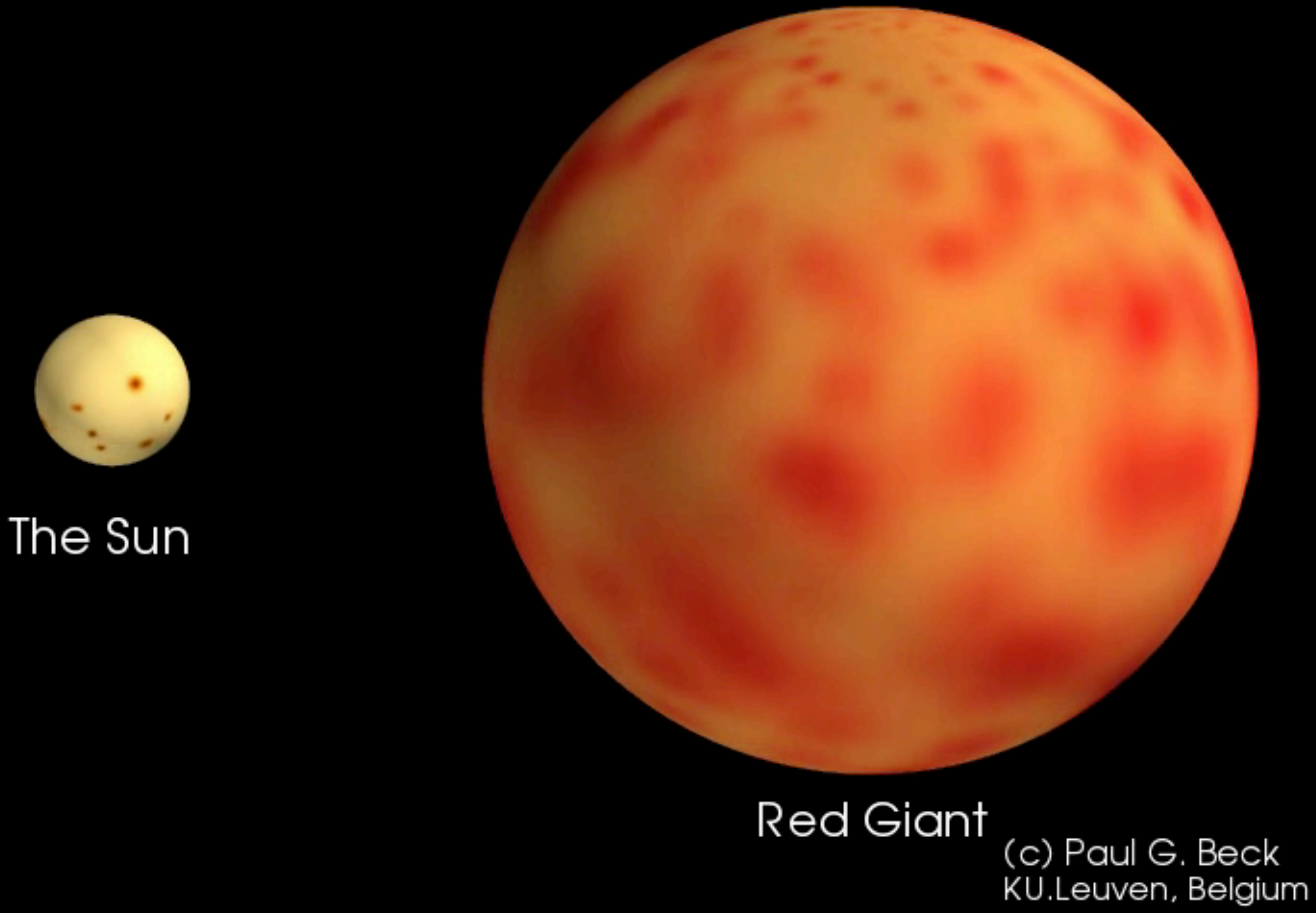
EVOLVED SOLAR-TYPE STARS

MIXED MODES PATTERN



MEASURING STELLAR AM

INTERNAL ROTATION

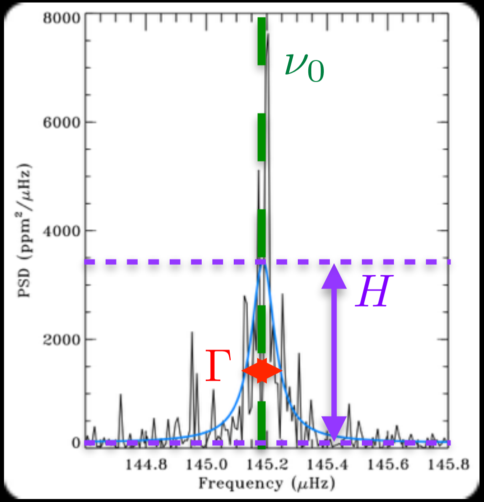


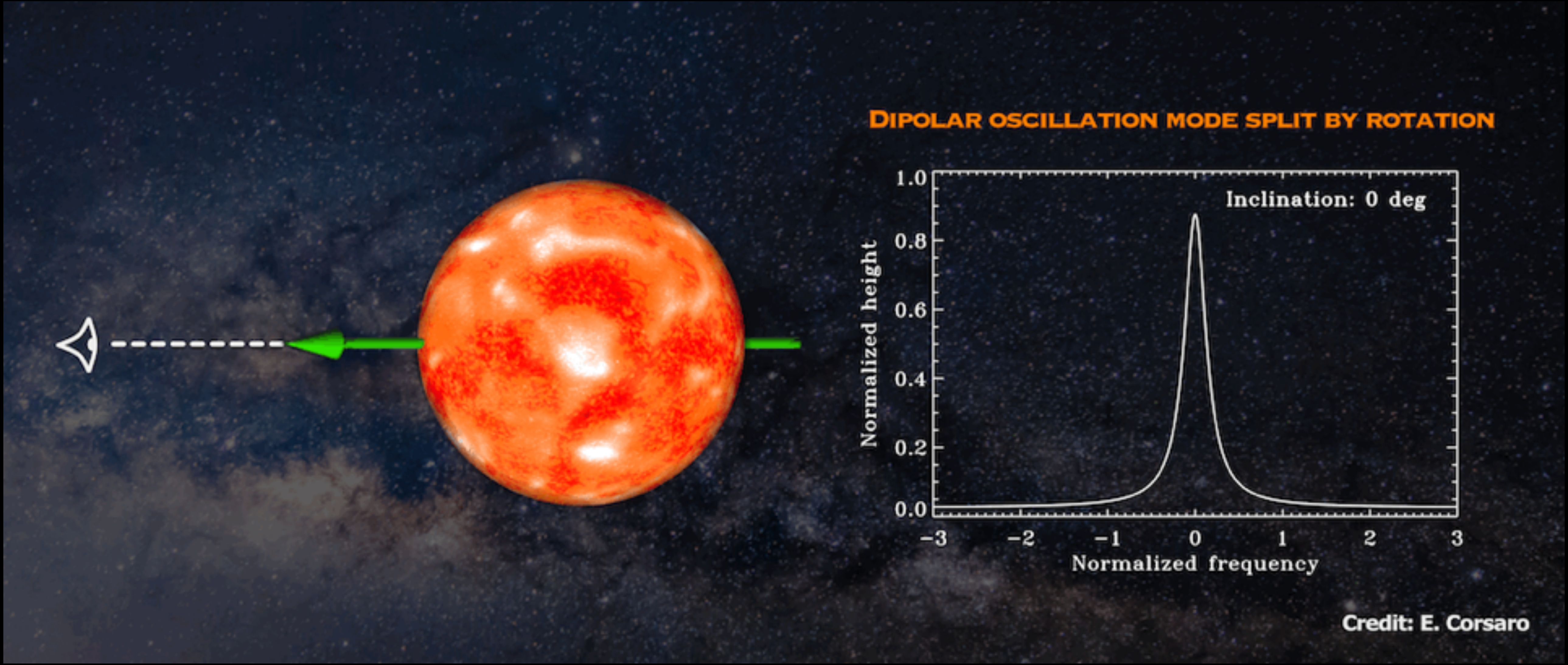
BECK ET AL. 2011 SCIENCE;
MOSSER ET AL. 2012

MEASURING STELLAR AM

SPIN INCLINATION ANGLE

- Stellar oscillations accurately probe rotation rate and spin axis inclination
  GIZON & SOLANKI 2003; BALLOT ET AL. 2006; BECK ET AL. 2012 NATURE; DEHEUVELS ET AL. 2012; HUBER ET AL. 2013 SCIENCE
- Rotational degeneracy of $\ell=1$ (dipolar) modes gives $(2\ell + 1)$ m-components





Credit: E. Corsaro

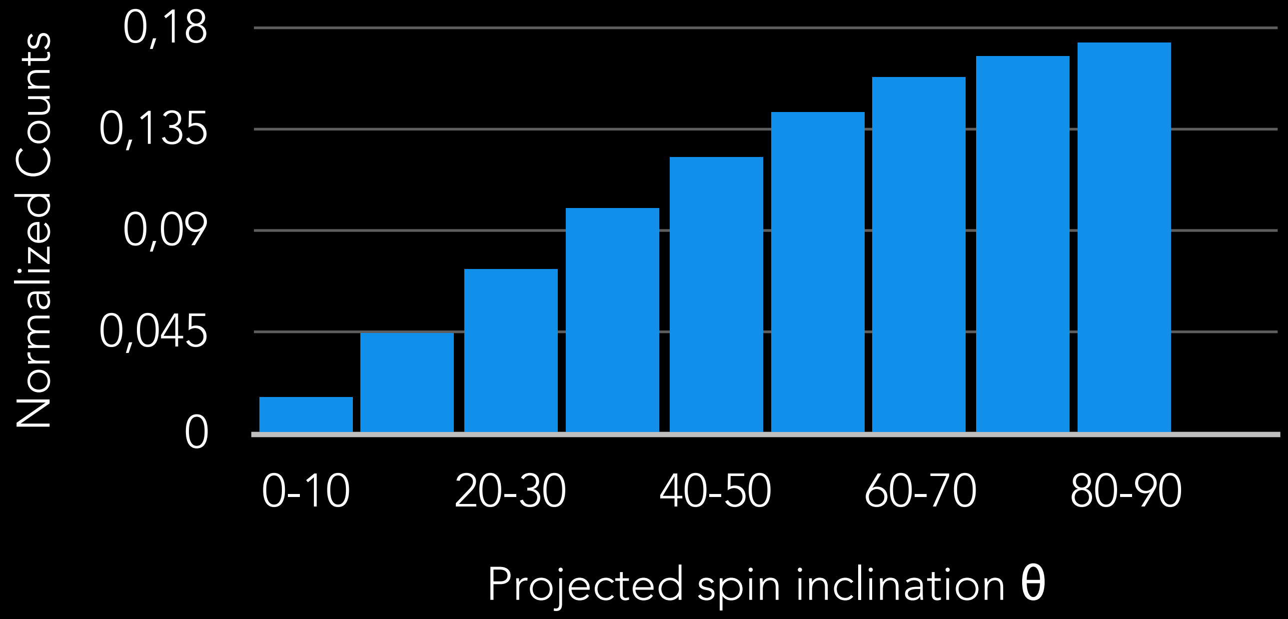
MEASURING STELLAR AM

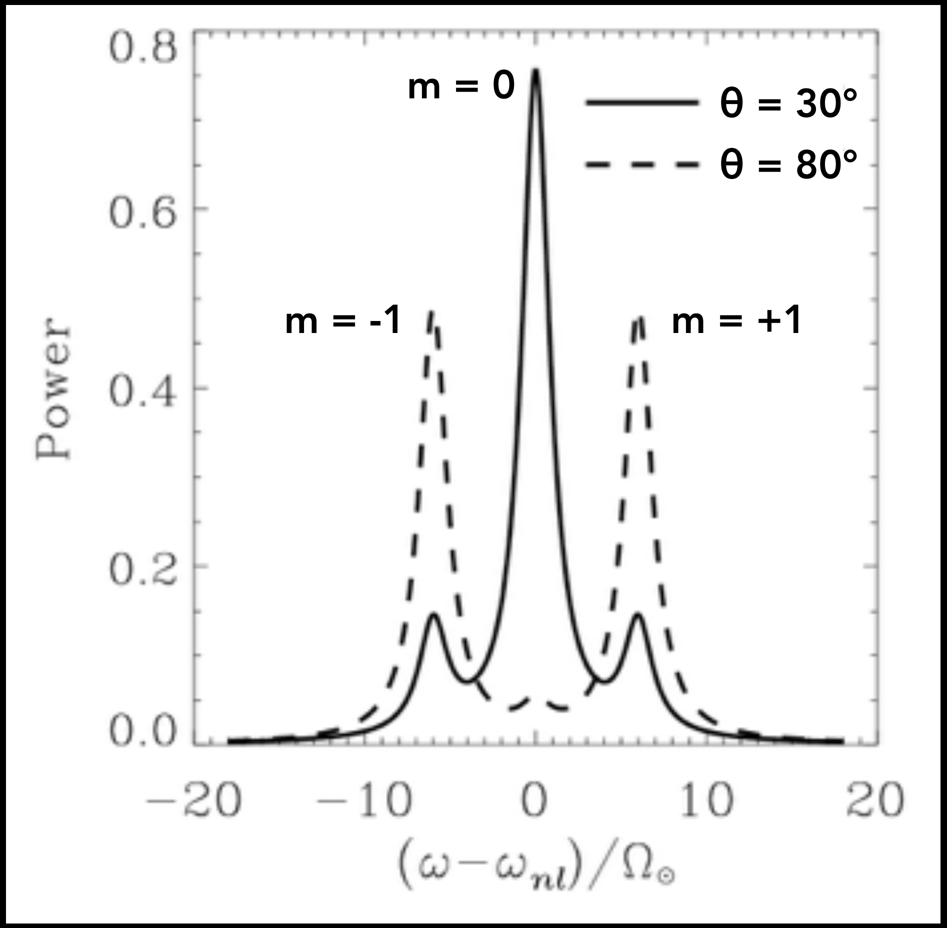
PROJECTION EFFECT

High angles are easier to observe
(projection effect from 3D space)

$$d\Omega = sin(\theta)d\theta$$

3D RANDOM DISTRIBUTION





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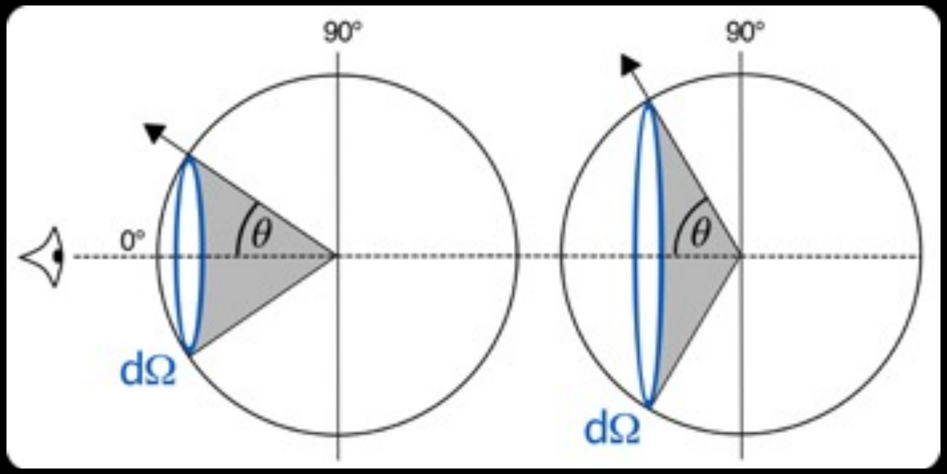

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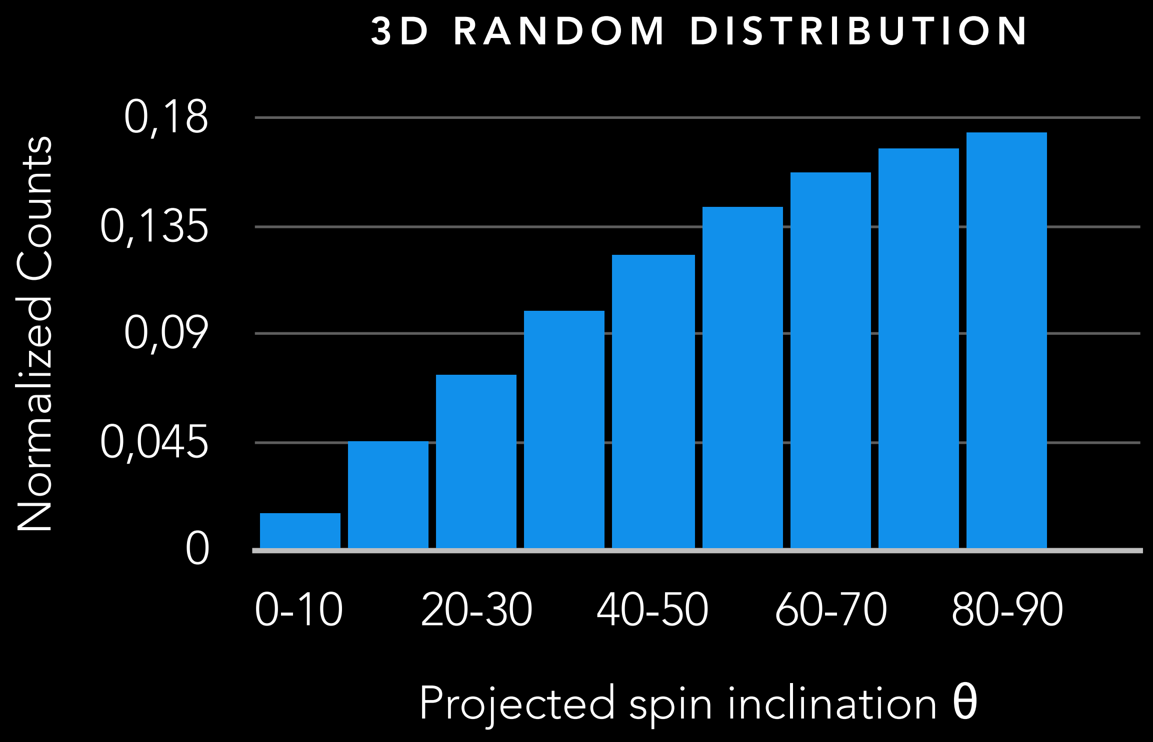
MEASURING STELLAR AM

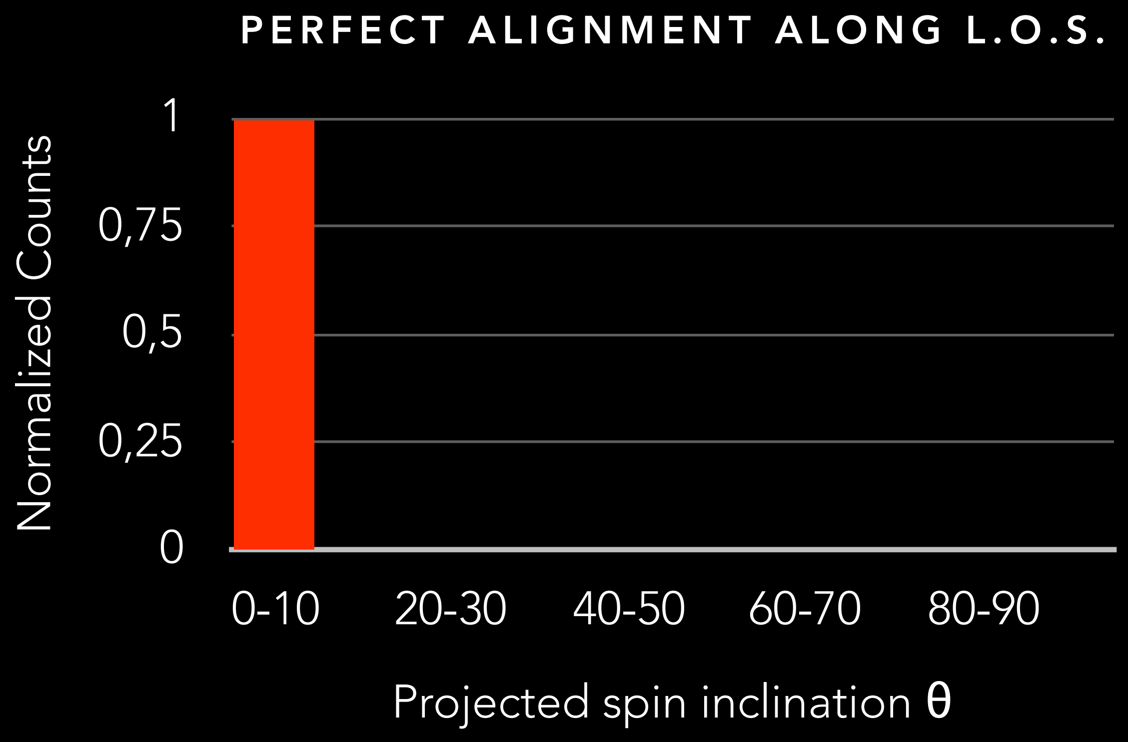
DEGREE OF SPIN ALIGNMENT



3D Random

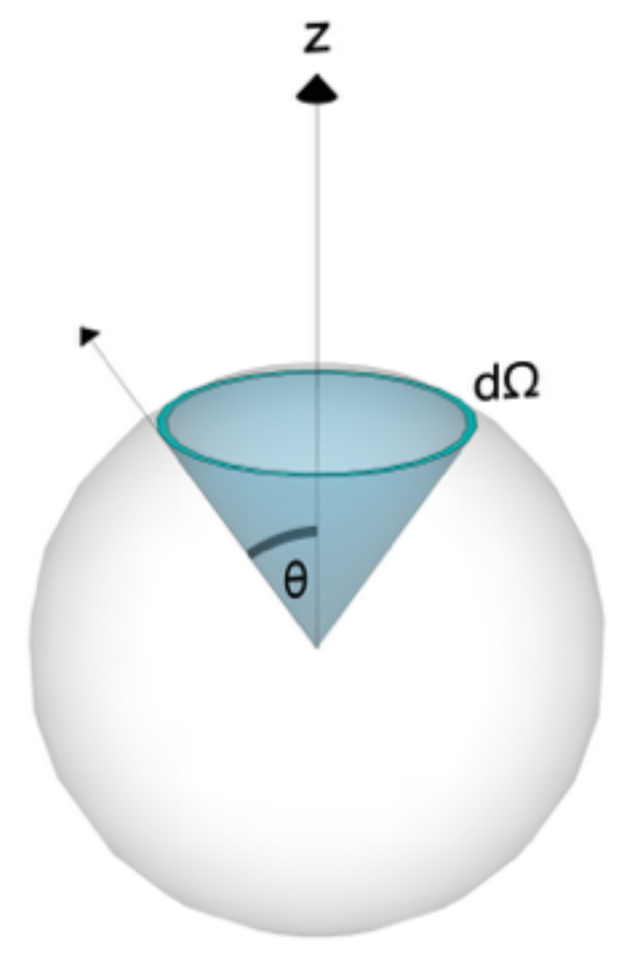
$$\alpha = \frac{1}{3}$$

$$\alpha = \frac{1}{N}\sum_{i=1}^{N}\cos^2(\theta_i)$$



Perfect alignment

$$\alpha = 1$$



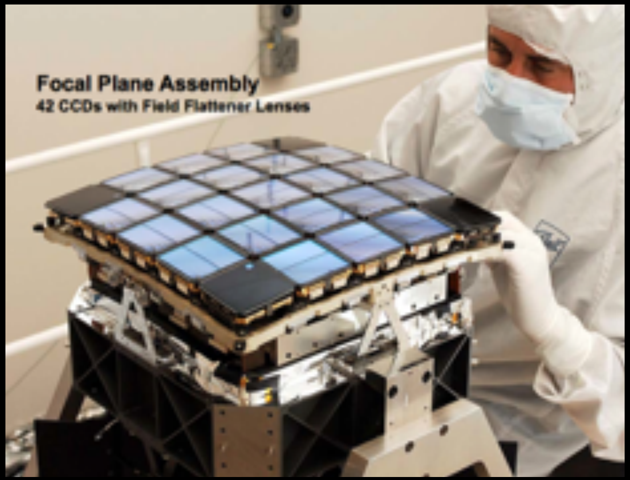
PART III

OBSERVATIONS, ANALYSIS & NEW RESULTS

SPACE MISSION

NASA KEPLER

- Launched 2009 - End nominal mission in 2013
- Mission devoted to exoplanets discovery
- 150,000 stars observed in the Cygnus - Lyra constellations
- Kepler photometric band: 430-890 nm



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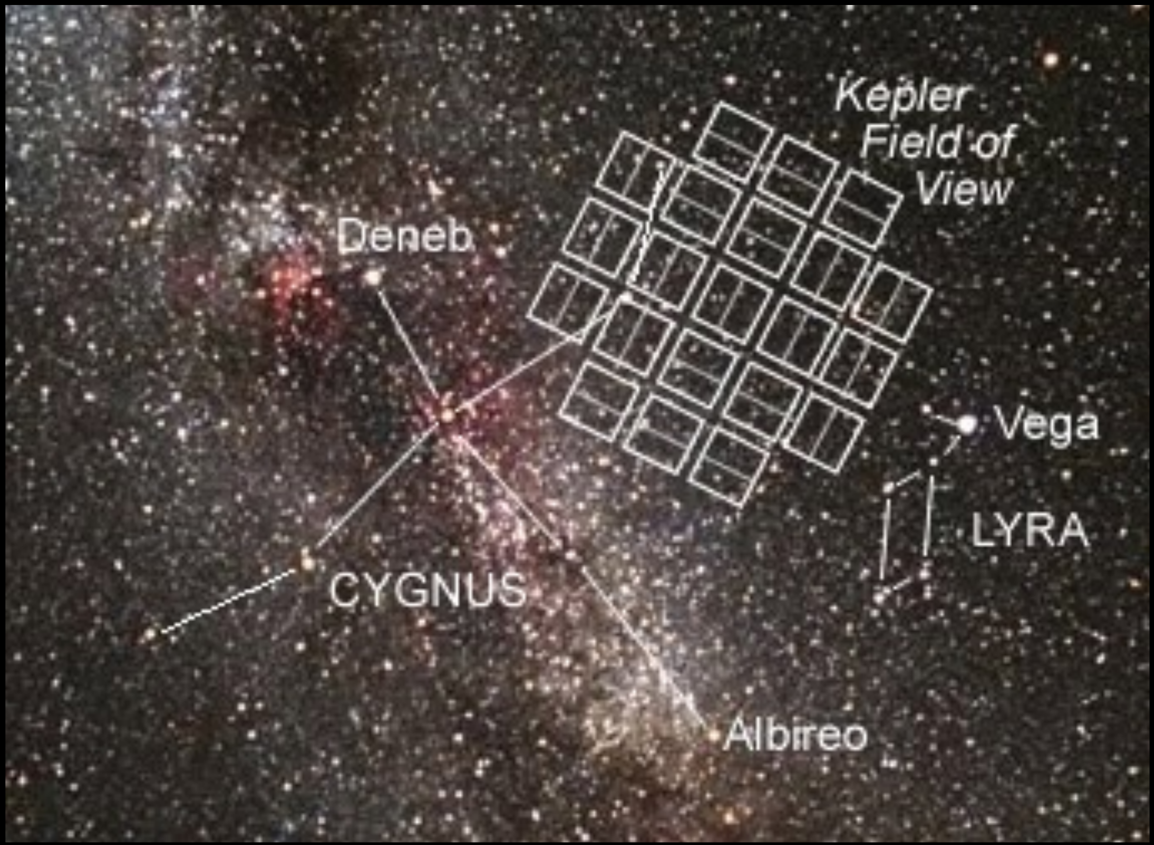
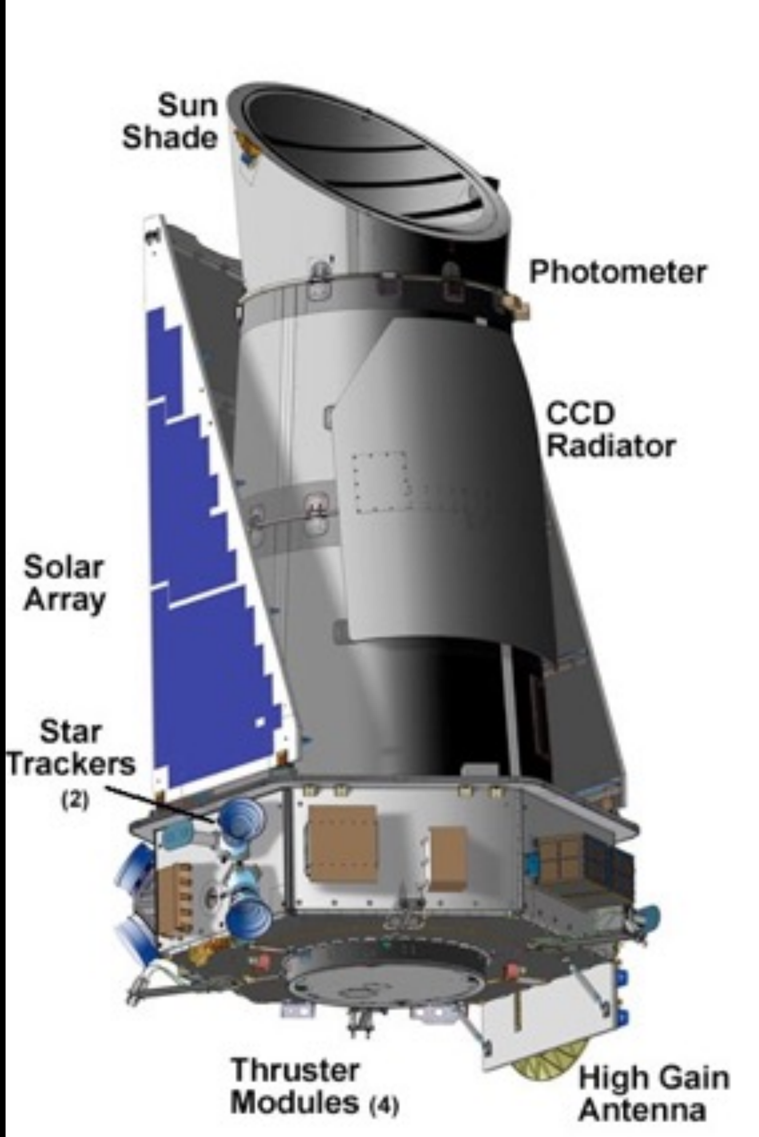


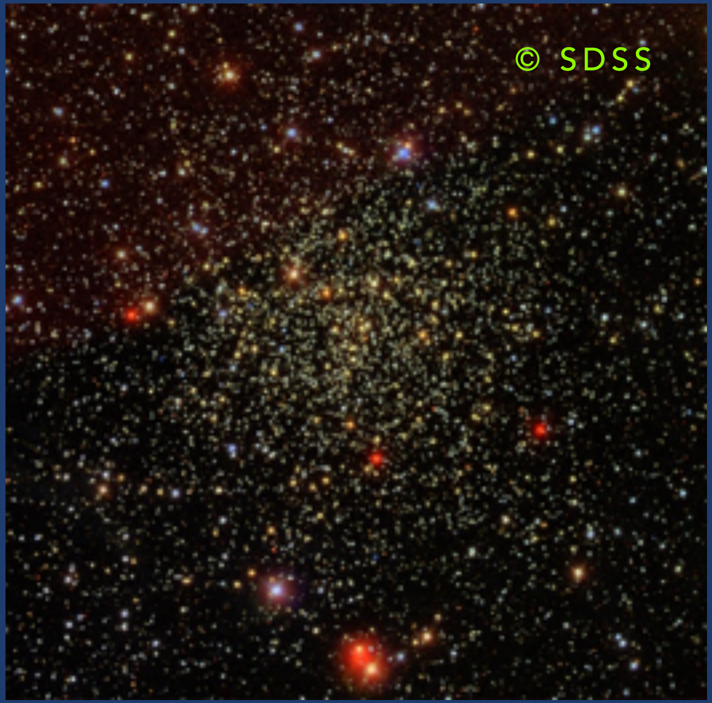


OC FROM NASA'S *KEPLER* MISSION

OBSERVATIONAL PROPERTIES

NGC 6791

- Total mass ~ 5000 M_{Sun}
  PLATAIS ET AL. 2011
- Distance ~ 4187 pc
  BASU ET AL. 2011
- Size ~ 10 pc
- Age ~ 8.3 Gyr
  BROGAARD ET AL. 2012
- M_{RG} ~ 1.1 M_{Sun}
  MIGLIO ET AL. 2012
- Class: II3r


© SDSS

4 YEARS PHOTOMETRY

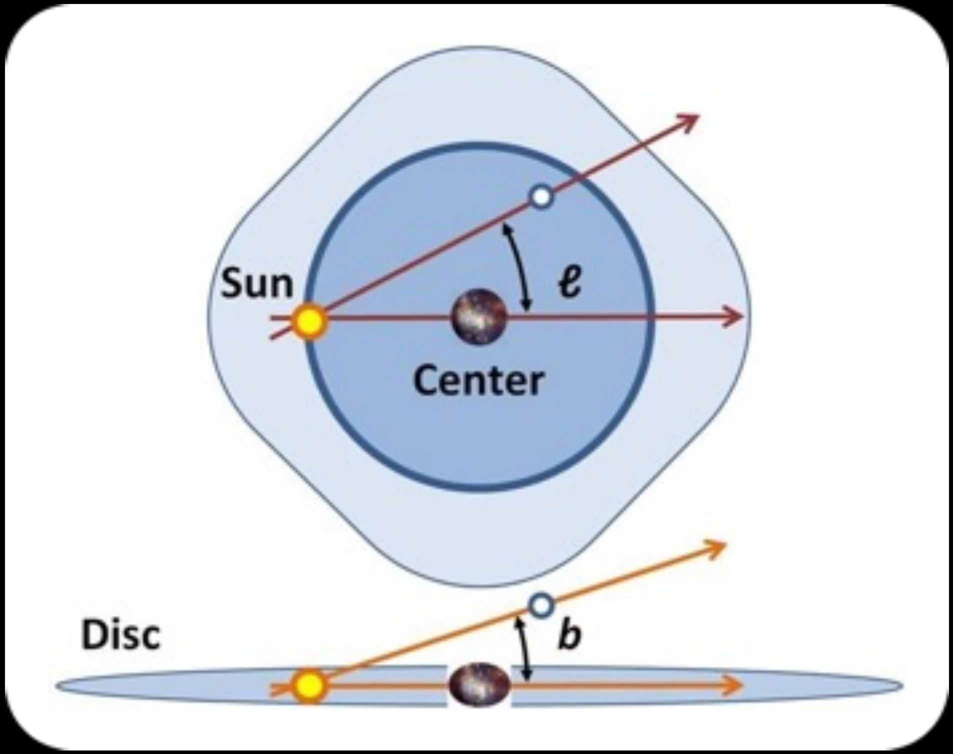

© DSS

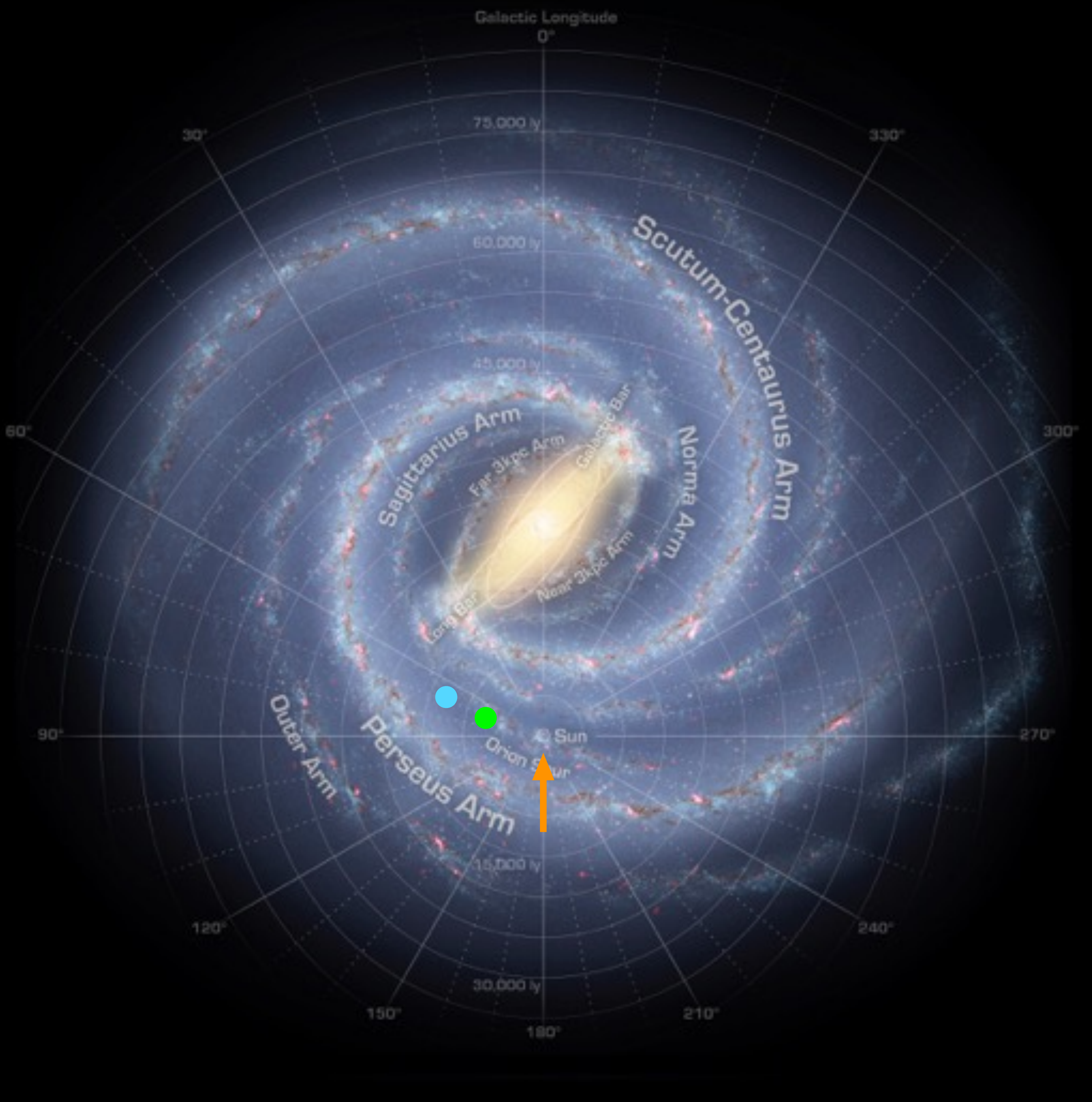
NGC 6819

- Total mass ~ 2600 M_{Sun}
  KALIRAI ET AL. 2001
- Distance ~ 2344 pc
  BASU ET AL. 2011
- Size ~ 7 pc
- Age ~ 2.4 Gyr
  BREWER ET AL. 2016
- M_{RG} ~ 1.7 M_{Sun}
  MIGLIO ET AL. 2012
- Class: I1m

OC FROM NASA'S *KEPLER* MISSION

GALACTIC POSITIONS





Annotated Roadmap to the Milky Way

(artist's concept)

NASA / JPL-Caltech / R. Hurt (SSC-Caltech) ssc2008-10b

NGC 6791

Gal. lat. 10.9°
Gal. long. 69.95°
h ~ 700 pc

NGC 6819

Gal. lat. 8.5°
Gal. long. 73.98°
h ~ 300 pc

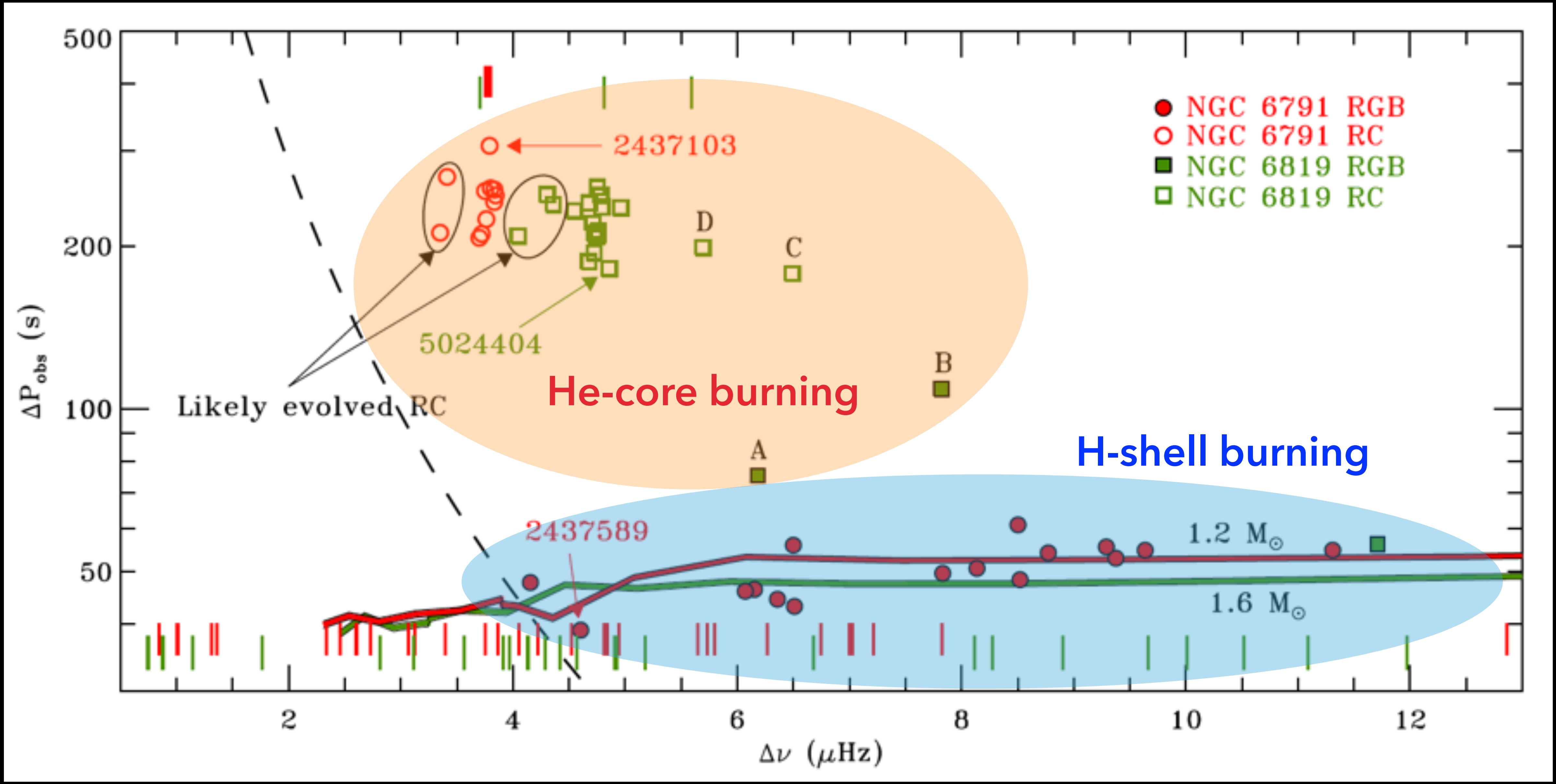
$h_{\text{thin disk}} \sim 350$ pc

TARGET SELECTION

CLUSTER RED GIANTS

- **48 cluster red giants** with clear evolutionary stage from period spacing of $\ell = 1$ mixed modes $\Delta\Pi_1$

BEDDING ET AL. 2011; MOSSER ET AL. 2012
CORSARO ET AL. 2012;



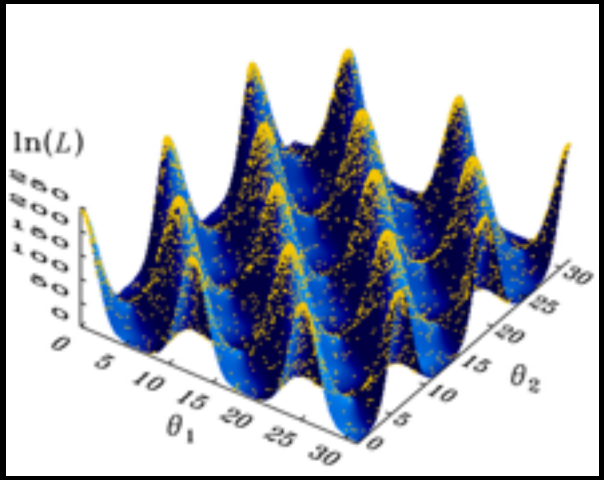
EVOLUTIONARY STAGE OF RED GIANTS © CORSARO ET AL. 2012

ANALYSIS OF STELLAR OSCILLATIONS

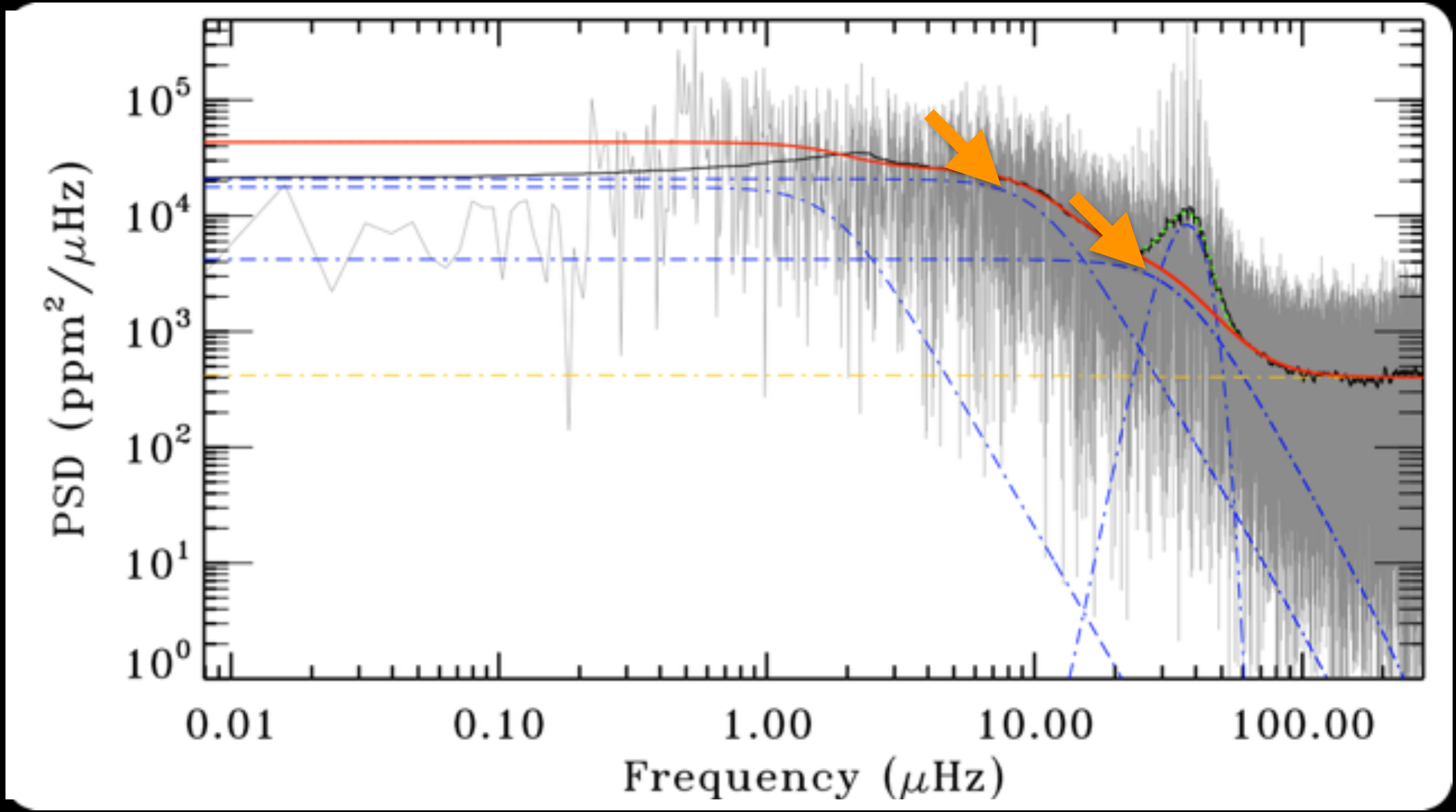
BACKGROUND SIGNAL

- Bayesian inference code ***DIAMONDS***: public code
  https://github.com/EnricoCorsaro/DIAMONDS
  CORSARO & DE RIDDER, 2014, A&A, 571, 71
  CORSARO, DE RIDDER, GARCIA, 2015, A&A, 579, 83

- Background signal modeled with **granulation and mesogranulation components** in 48 cluster red giants
  CORSARO ET AL. 2017, IN PREP.



© CORSARO & DE RIDDER, 2014



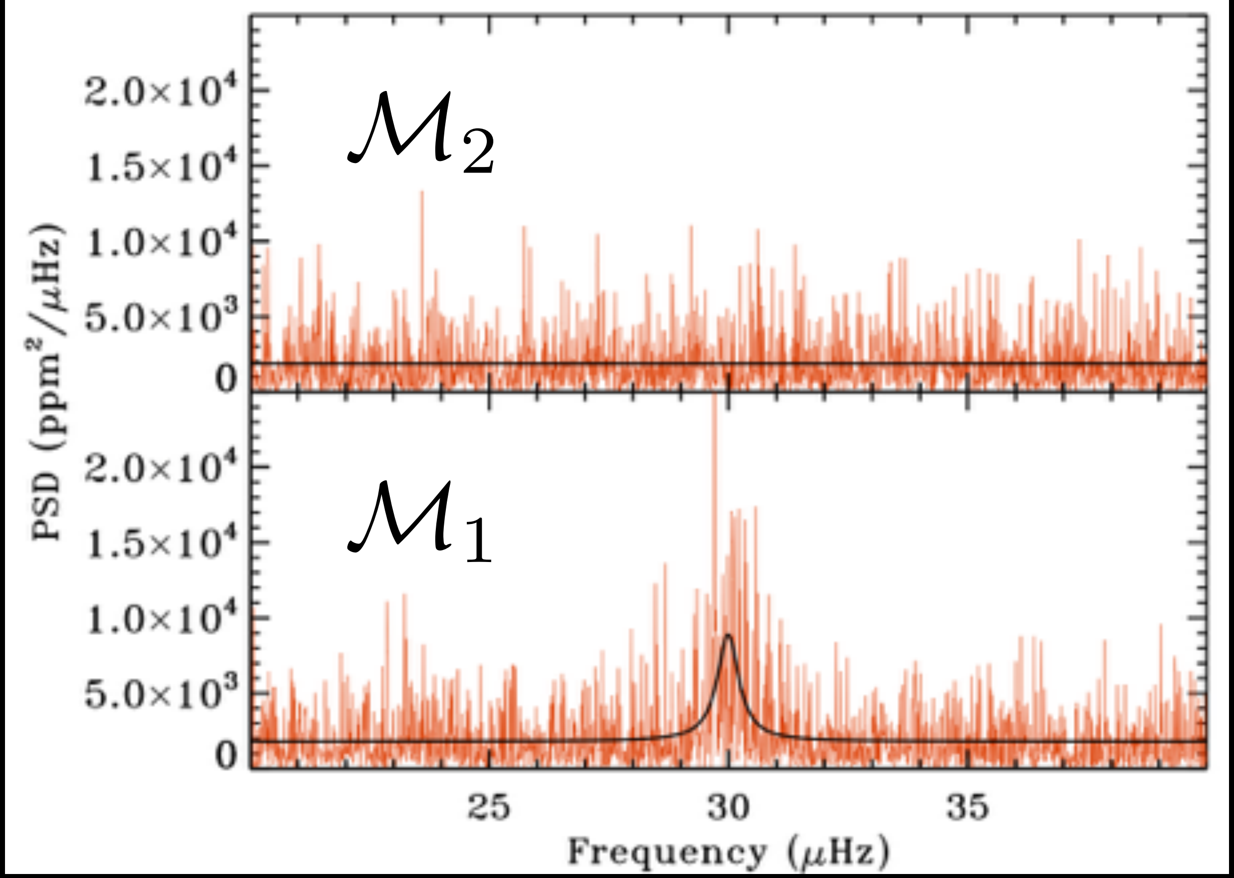
ANALYSIS OF STELLAR OSCILLATIONS

BAYESIAN PEAK BAGGING

- **3900** oscillation modes fitted and identified from **48 red giant stars** in NGC 6791 and NGC 6819

CORSARO ET AL. 2016, IN PREP.

- **380** rotationally split $\ell=1$ mixed modes used to measure spin-axis inclinations



© CORSARO ET AL. 2015

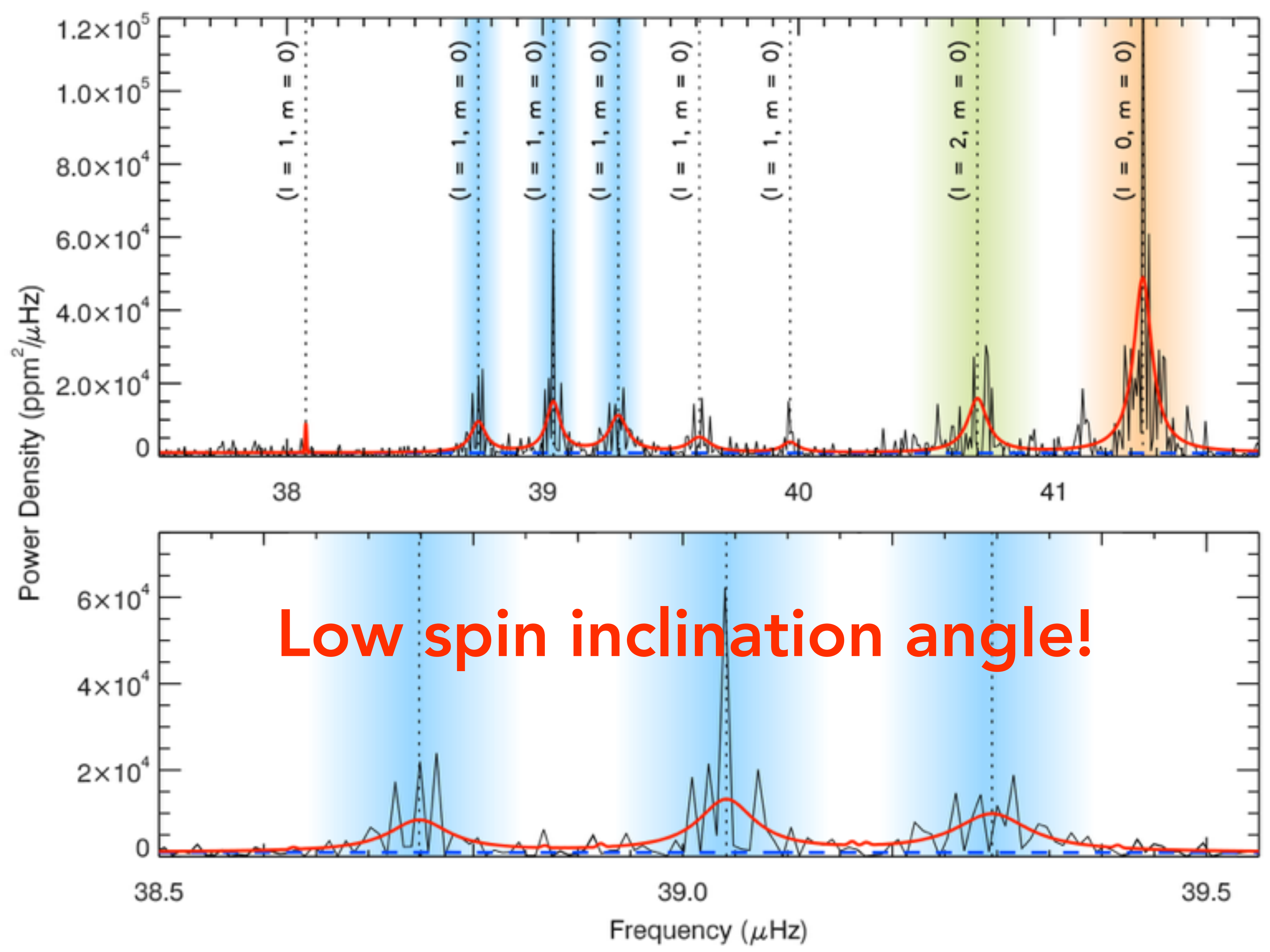
- Only significant peaks considered with peak significance test

- Bayesian model comparison with Bayesian evidence computed with DIAMONDS

$$\mathcal{E}_1/\mathcal{E}_2 \simeq 150$$

ANALYSIS OF STELLAR OSCILLATIONS

BAYESIAN PEAK BAGGING



Low spin inclination angle!

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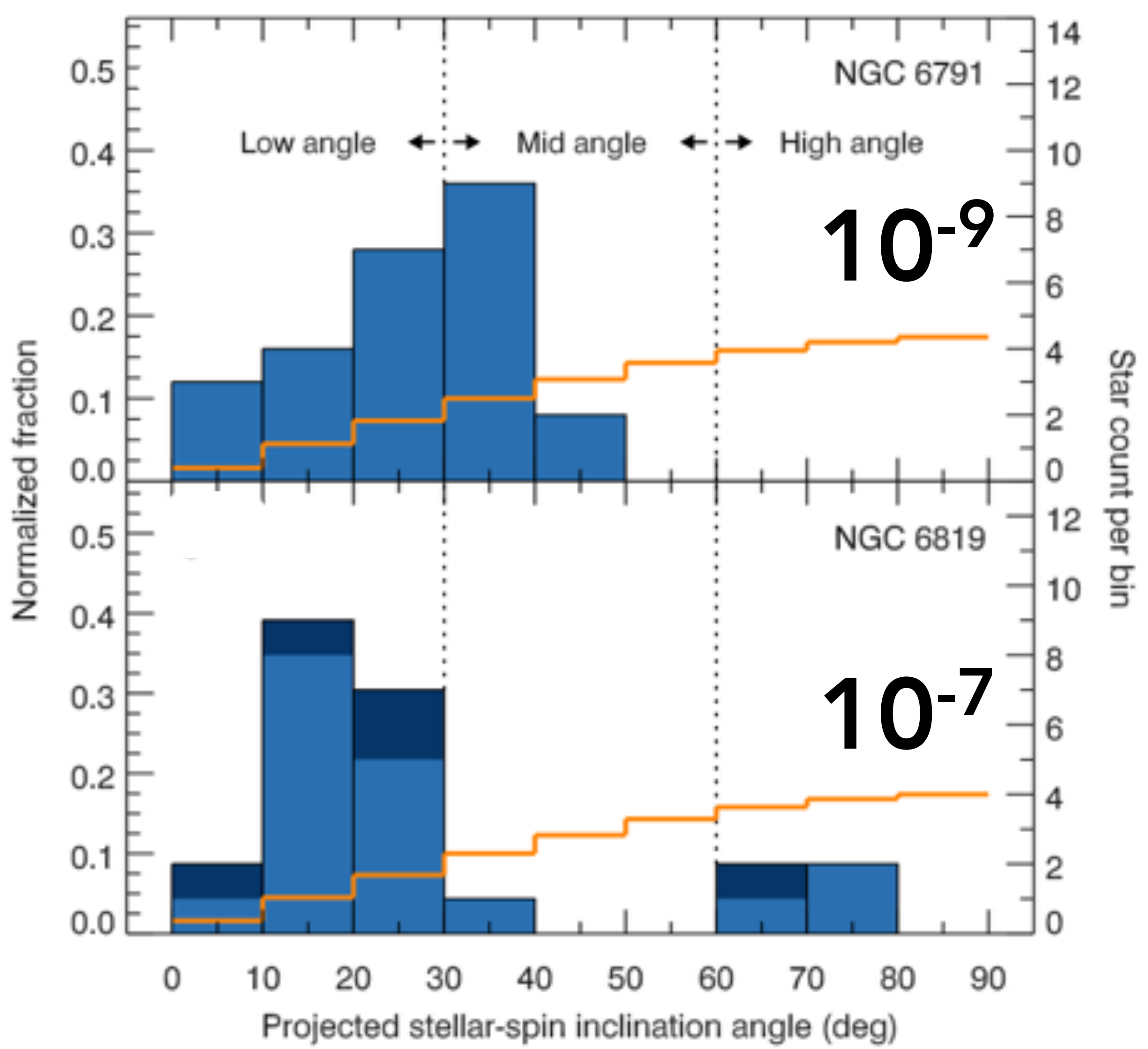
MEASURING STELLAR-SPIN INCLINATIONS

OBSERVATIONAL RESULTS

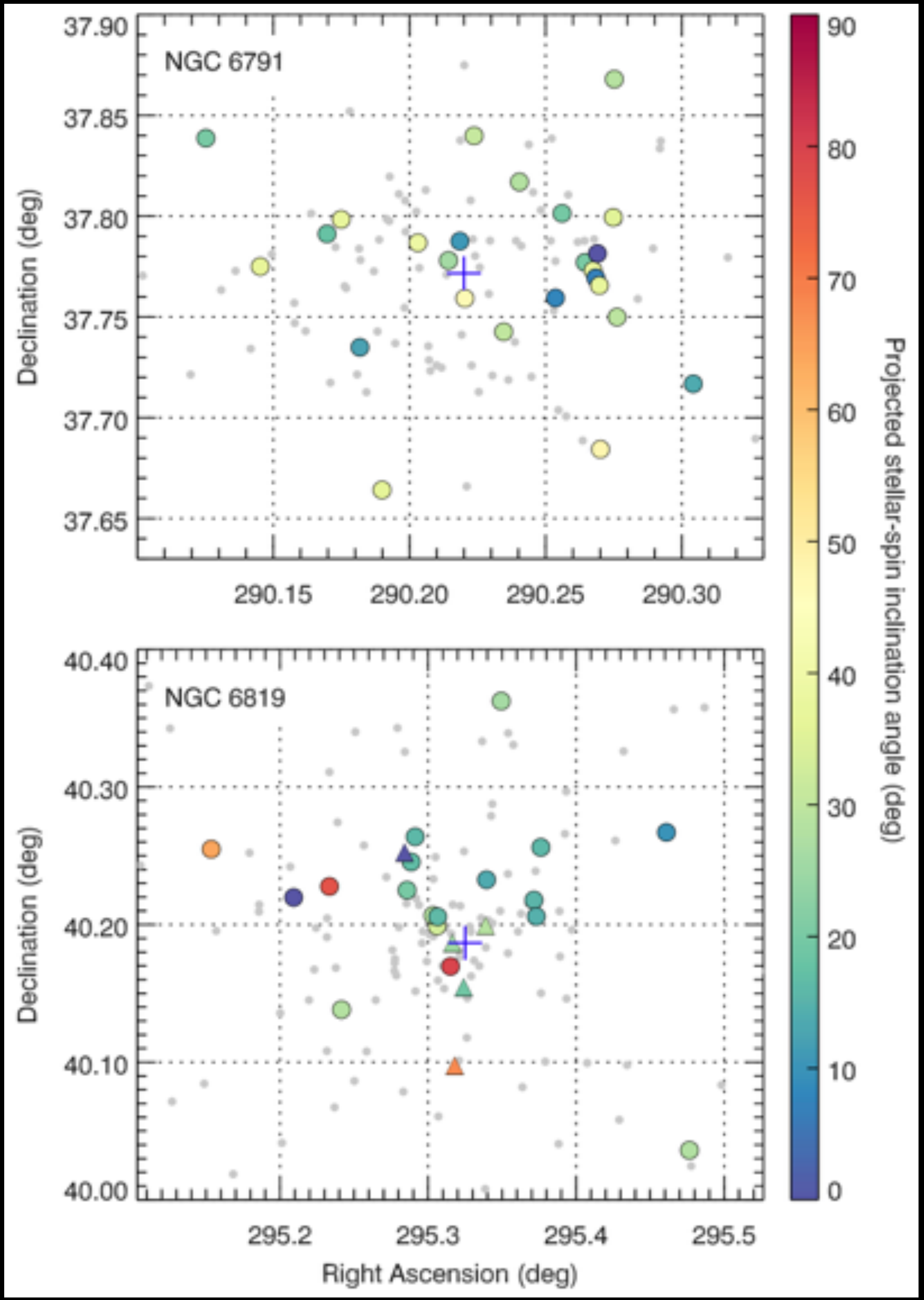
- ***Strong*** spin alignment in both clusters!

$\alpha \simeq 0.75$



10^{-9}

10^{-7}



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ORIGIN OF SPIN ALIGNMENT

N-BODY INTERACTIONS?

- N-body simulations for old open clusters can reproduce observed populations of single and multiple stars

  GELLER ET AL. 2013

- Individual stars undergo spin down over time: magnetic braking, stellar winds, tidal friction

  MEIBOM ET AL. 2011 NATURE; VAN SADERS ET AL. 2016 NATURE

- Main force influencing spin orientation and orbital configuration is ***tidal***

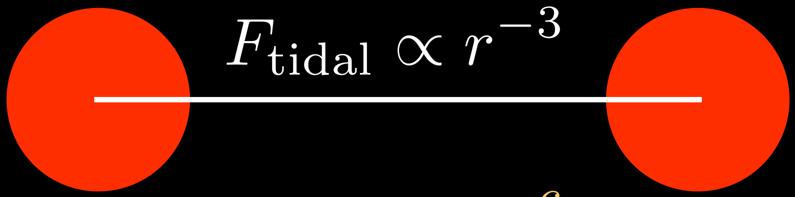
- But OC stars are sparse (**~1 M_{Sun} pc^{-3}**)

  LADA & LADA 2003

- Tidal forces among stars are negligible already over a few AU (~ 10^{-5} pc) and on given timescales

  HUT 1981

- Spin alignment possible ***only*** during cluster formation epoch



$$F_{\rm tidal} \propto r^{-3}$$

$$\frac{d\theta}{dt} \propto \left(\frac{R}{a}\right)^6$$

3D HYDRODYNAMICAL SIMULATIONS

PROTO-CLUSTER FORMATION

- MC is treated as compressible fluid and evolution resolved with Navier-Stokes equations
- RAMSES: 3D MHD code with adaptive mesh refinement
  TEYSSIER 2002; FROMANG ET AL. 2006
- Compact (**~0.2 pc**) and dense (**10^7 H_2 cm^{-3}**) MC with **10^3 M_{Sun}** and isothermal at **T = 10 K**
  LEE & HENNEBELLE 2016
- Bonnor-Ebert-like spherical MC with density profile

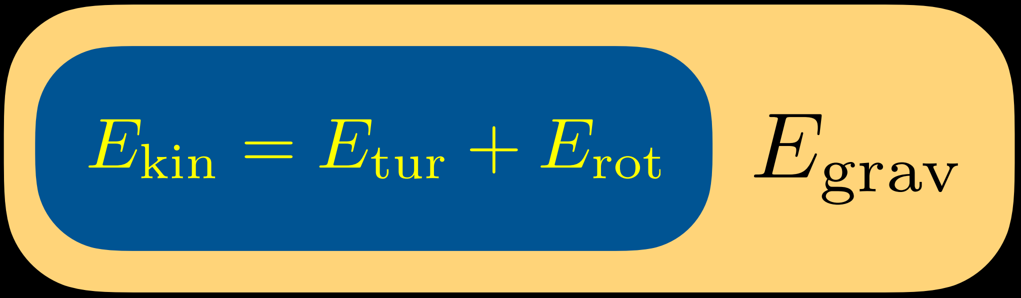
$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_0} \right)^2 \right]^{-1}$$

3D HYDRODYNAMICAL SIMULATIONS

PROTO-CLUSTER FORMATION

- Evolution by gravitational collapse + turbulent velocity field (Kolmogrov spectrum) + solid body global rotation

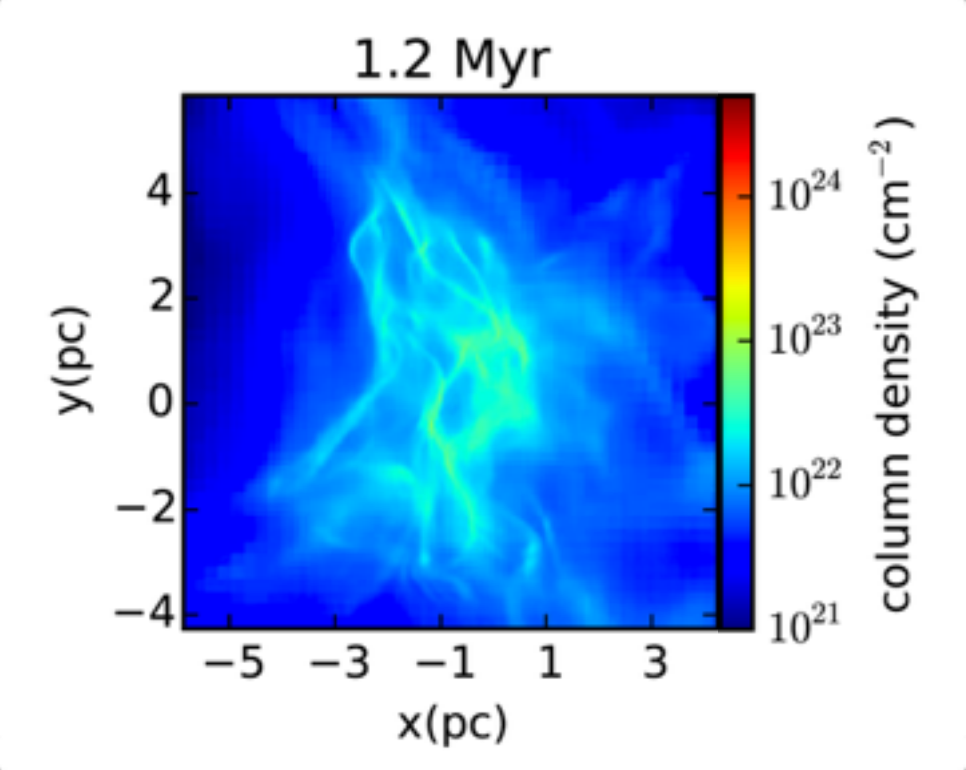
- ***Sink particles*** algorithm used to add AM from gas to sink (***pre-stellar cores***): track evolution of AM at scales of several AU



$E_{\rm kin} = E_{\rm tur} + E_{\rm rot}$

$E_{\rm grav}$

3D hydrodynamics



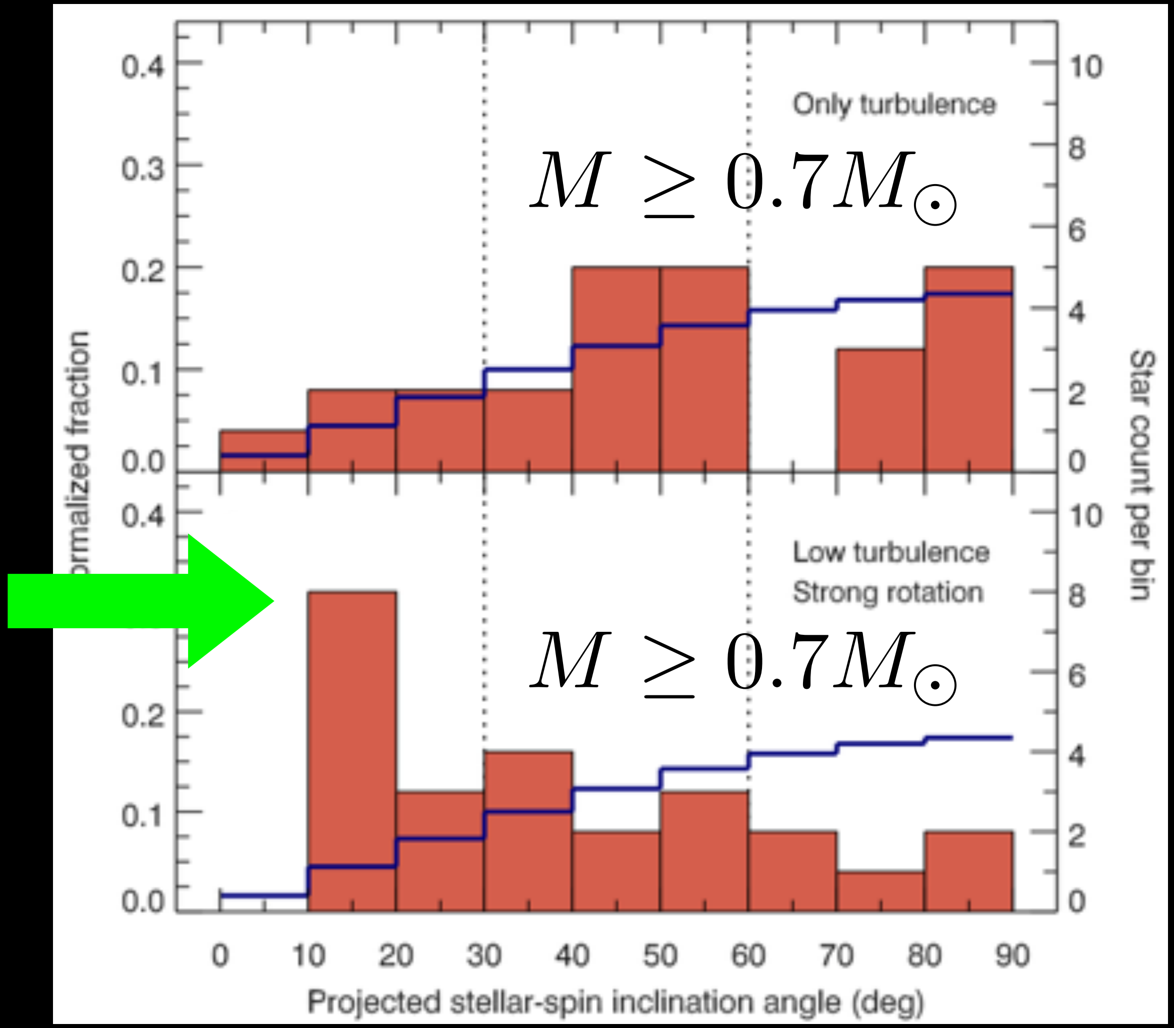
PROTO-CLUSTER FORMATION

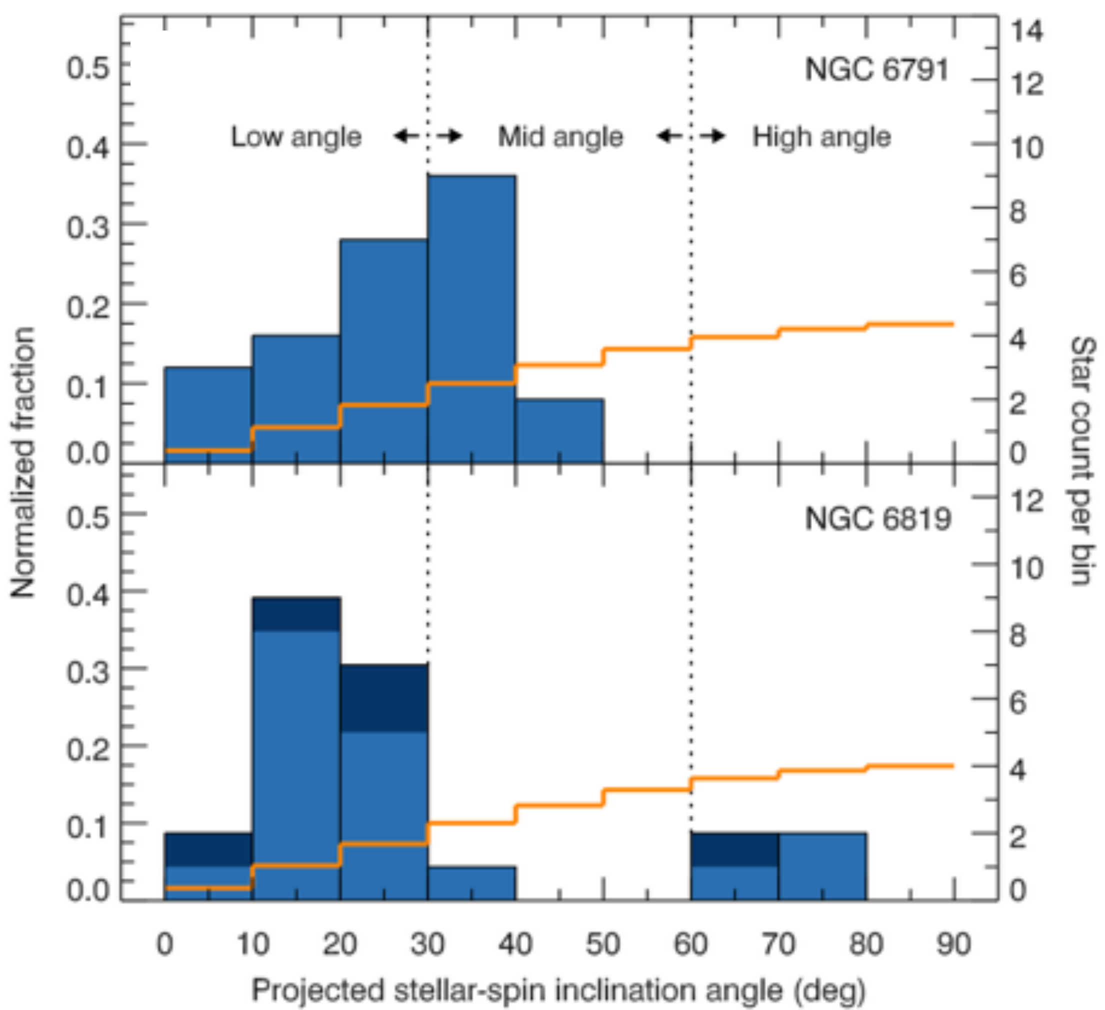
3D SIMULATION RESULTS

- If cloud rotation **absent** or **low**: no spin alignment (random)
- If **strong** cloud rotation present: significant spin alignment
- Stars with **$M < 0.7 M_{Sun}$** show no alignment even with strong rotation

$$E_{\rm rot}/E_{\rm tur} < 1$$

$$E_{\rm rot}/E_{\rm tur} \simeq 1$$





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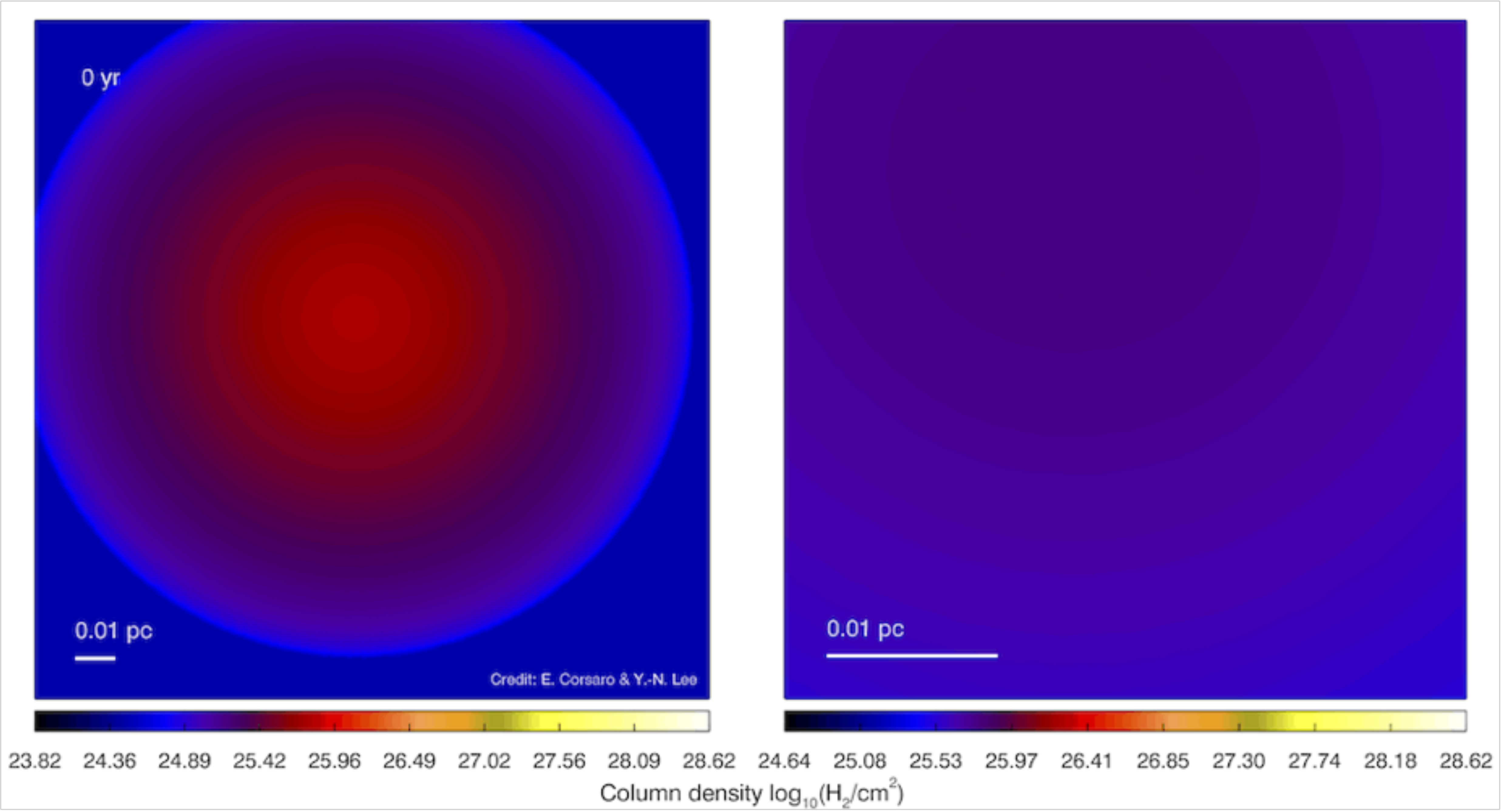
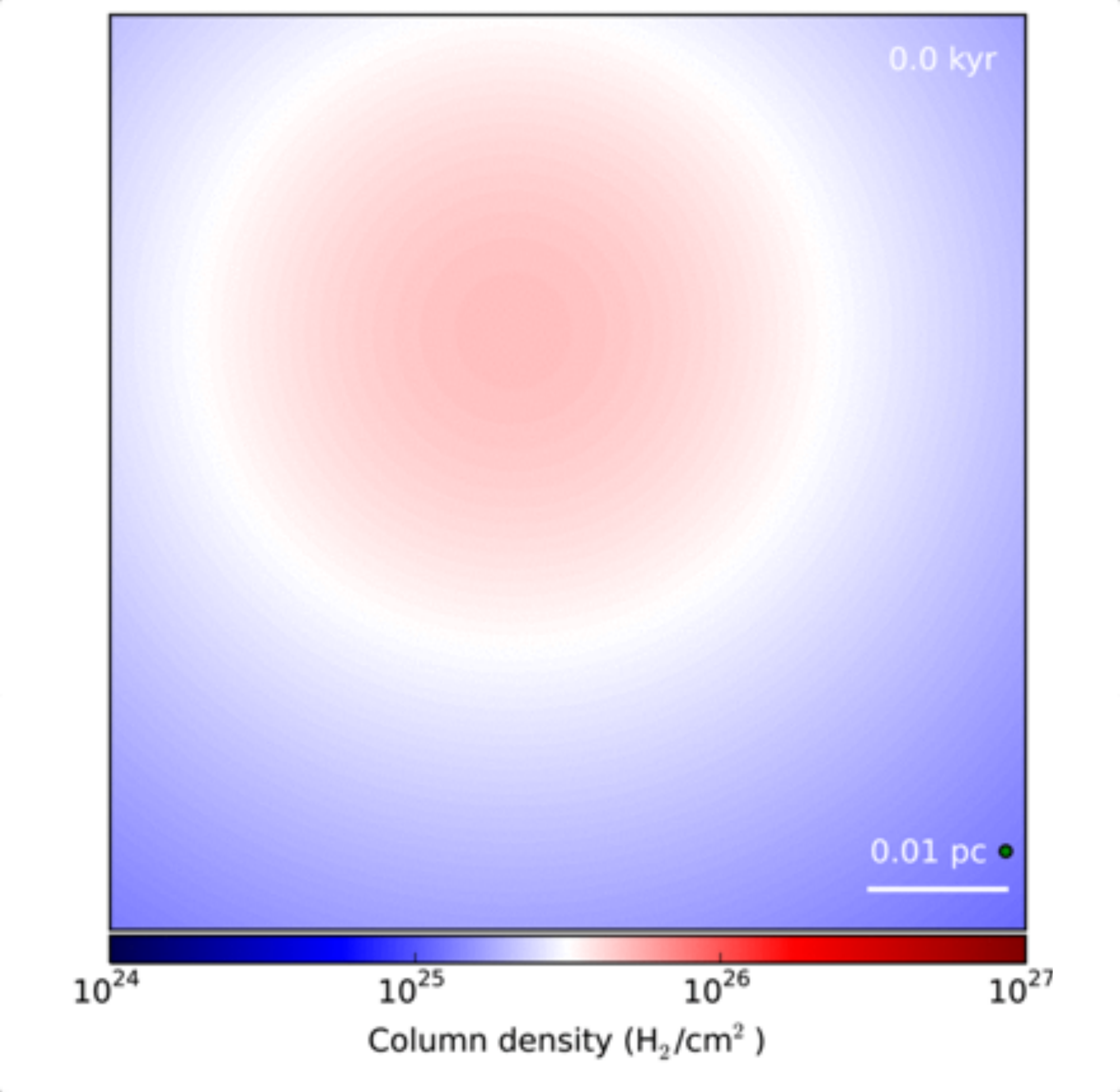
PROTO-CLUSTER FORMATION

3D SIMULATION RESULTS



PROTO-CLUSTER FORMATION

3D SIMULATION RESULTS



$M \geq 0.7\ M_{Sun}$

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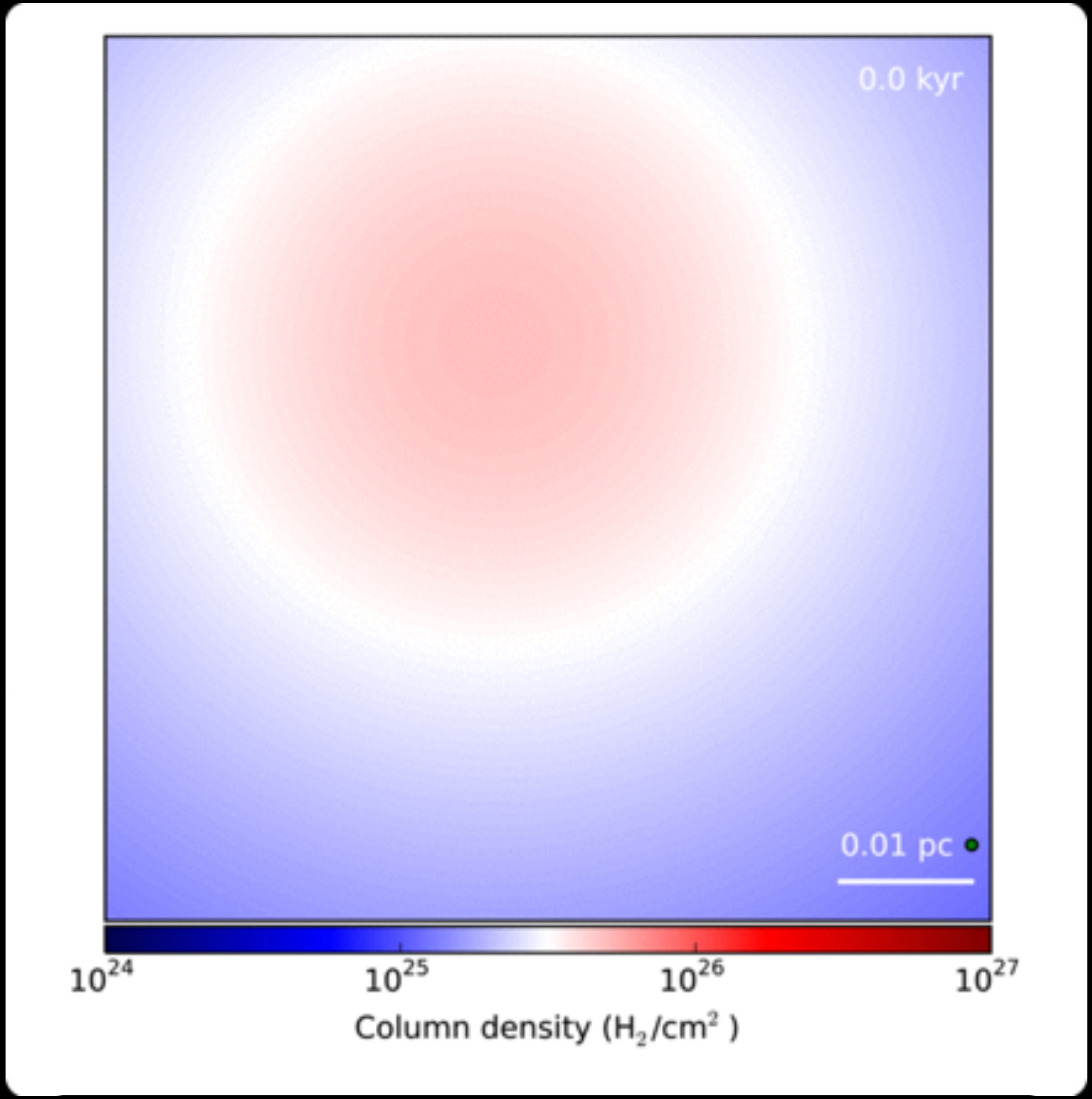
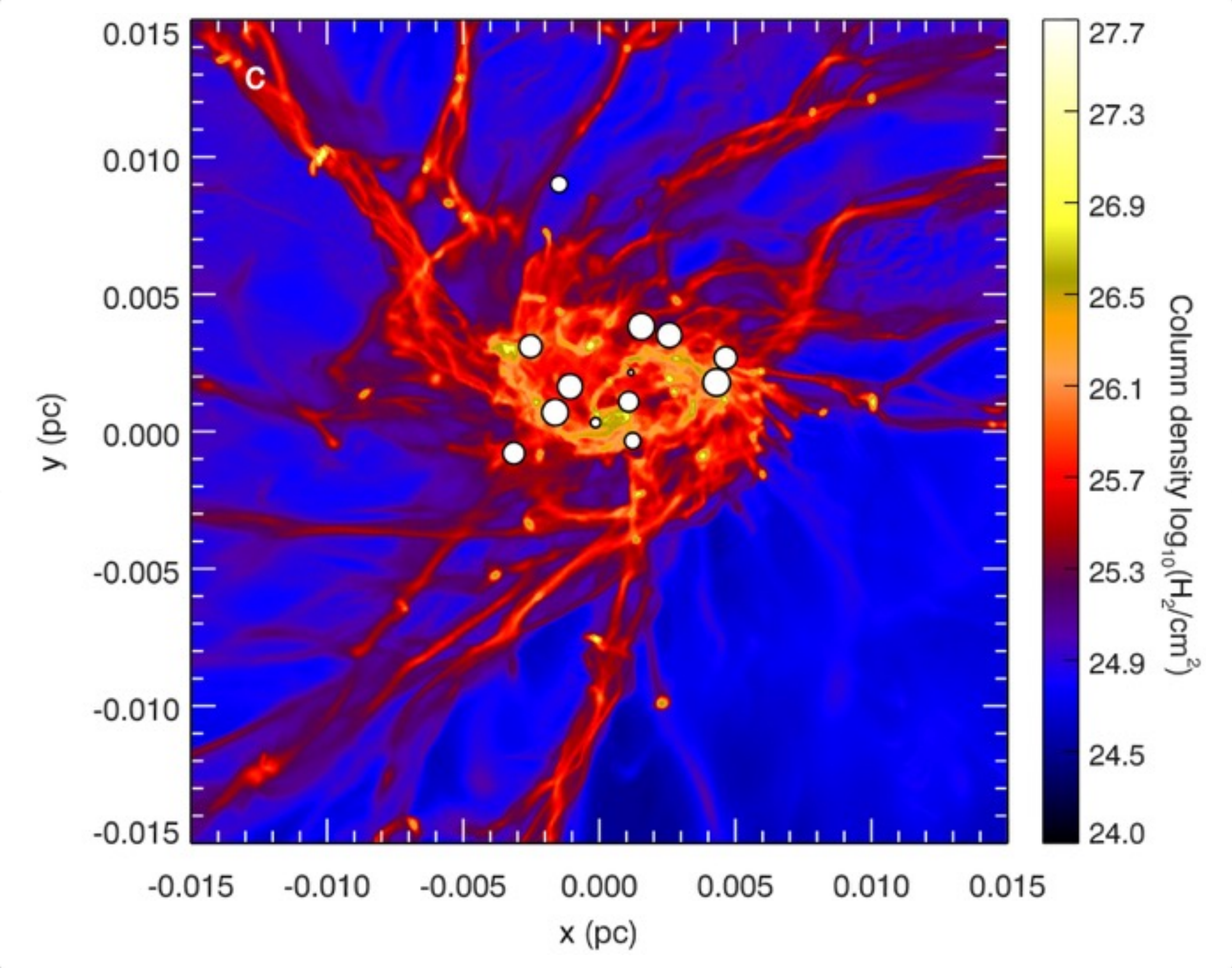


All masses

Sink particles simulate pre-stellar cores

PROTO-CLUSTER FORMATION

3D SIMULATION RESULTS



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SUMMARY & CONCLUSIONS

Direct observations

Strong stellar-spin alignment (~70%) within a stellar cluster

Detection through asteroseismology

+

3D hydrodynamics

Proto-cluster has strong rotational energy component

Proto-cluster AM efficiently passed down to individual stars

Imprint of cloud's global rotation has survived for more than 8 Gyr!

$E_{\mathrm{tur}} > 2E_{\mathrm{rot}}$ **Proto-cluster**

$$E_{\mathrm{kin}} = E_{\mathrm{tur}} + E_{\mathrm{rot}}$$

$E_{\mathrm{rot}} \gtrsim E_{\mathrm{tur}}$ **Proto-cluster**

$M \geq 0.7 M_{\odot}$ **Stars**

FUTURE PROSPECTS

- Enlarge the sample of open clusters, e.g. M44 and M67 with ***NASA K2***
- Possibly include globular clusters with future space missions ***NASA TESS*** and ***ESA PLATO*** using asteroseismology
- Compare with astrometric and kinematic observations from ***ESA Gaia*** to study global rotation properties in clusters
- Extend study using standard methods from ***v sini*** using spectroscopic surveys for accessible open clusters from e.g. ***APOGEE***, ***Gaia ESO***
- Search for prototypes of forming regions in IR with strong rotational components using ***JWST*** and ground facilities such as ***GIARPS@TNG***

We can use *detailed* asteroseismology
(coupled with simulations)
to probe the physics of star and
stellar cluster formation!

Thank you!

ENRICO CORSARO


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