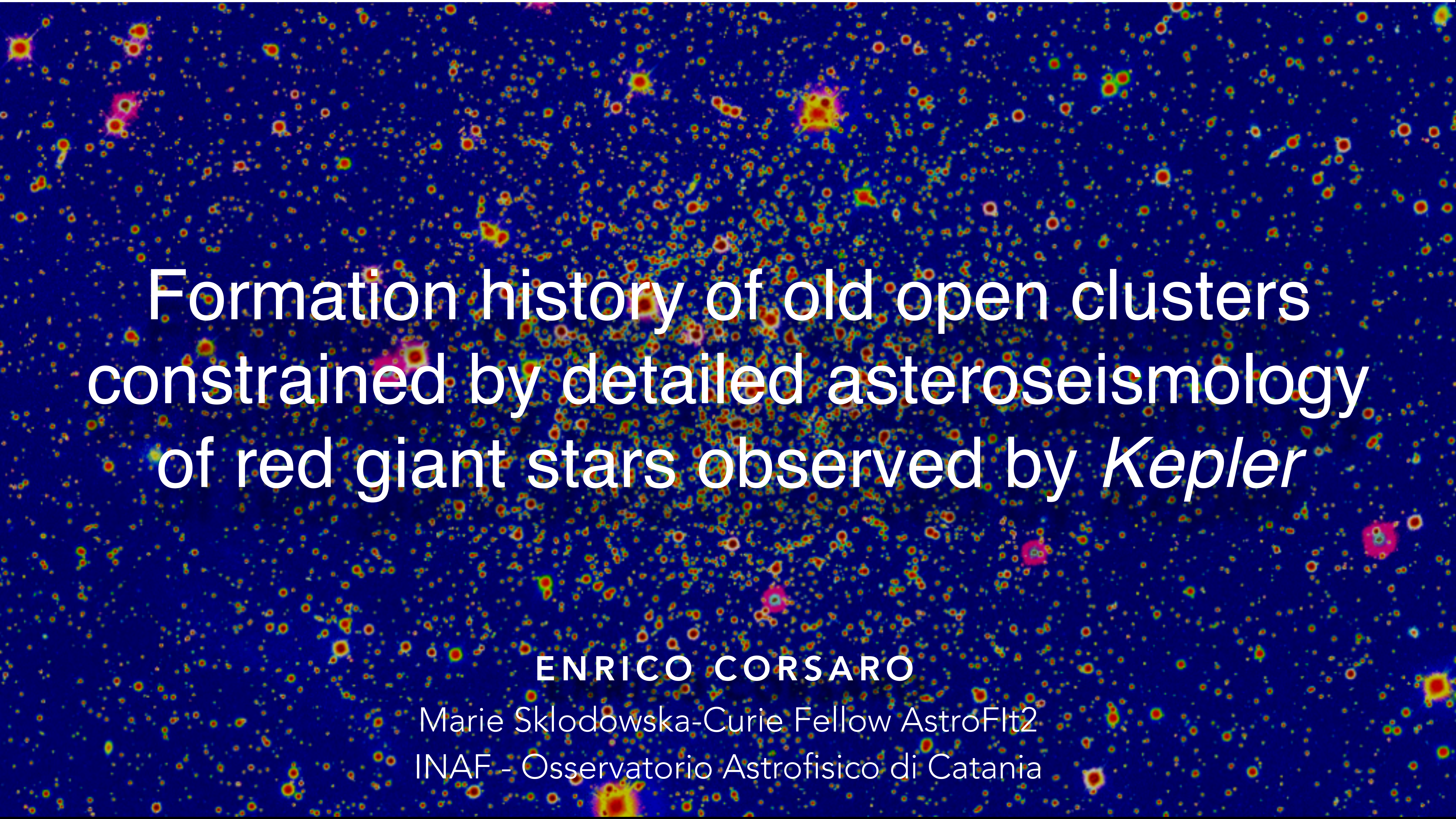
CEPS Seminar
17 January 2017



Formation history of old open clusters constrained by detailed asteroseismology of red giant stars observed by *Kepler*

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INAF - Osservatorio Astrofisico di Catania

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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

BARNARD 68 DARK CLOUD. © ESO

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

Very difficult to access:

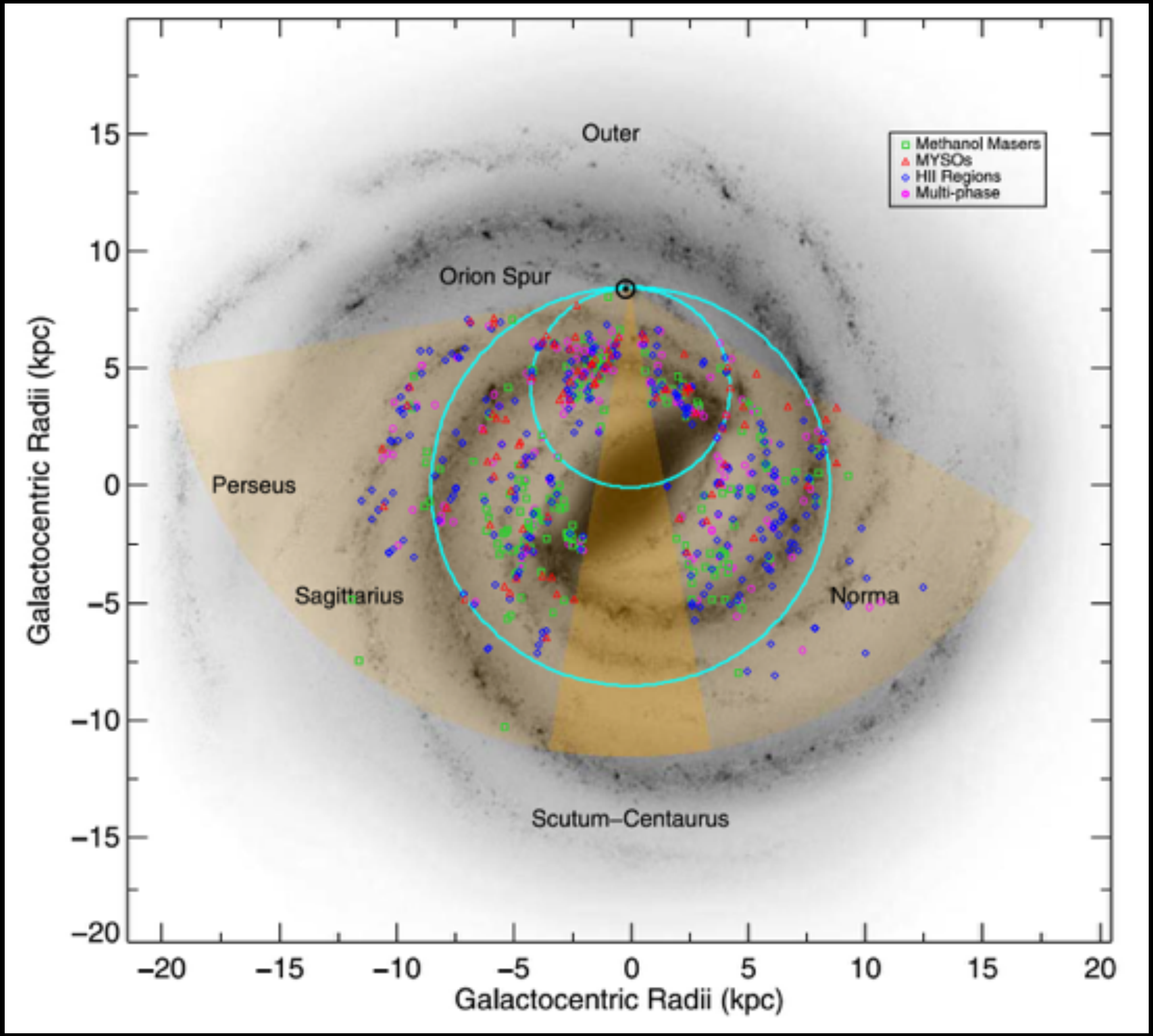
- SFR are dense and obscured by dust (only IR and Radio)
- MC change density by 10 orders - Hierarchical step approaches required

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

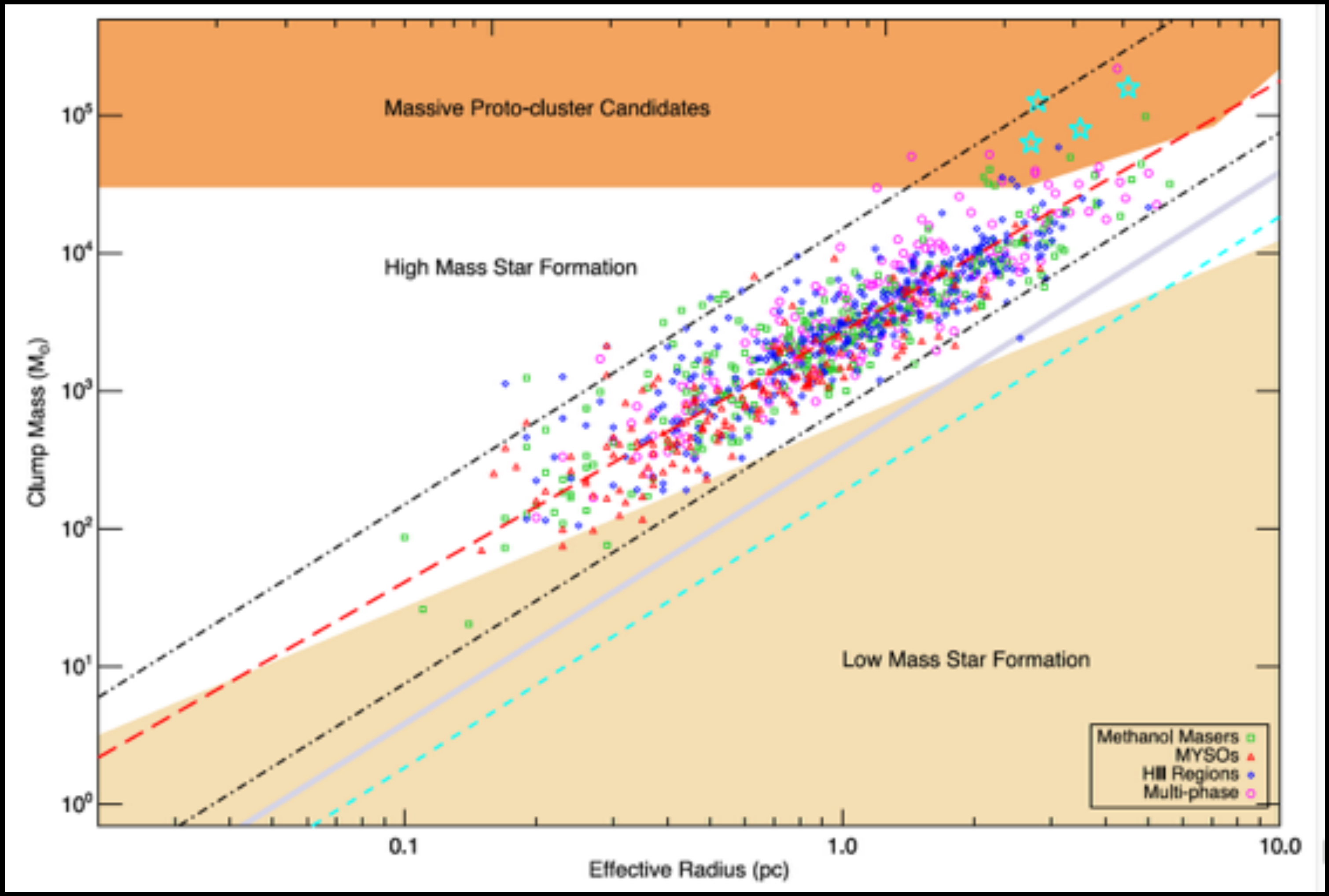
- Stellar clusters are common and likely to form (high mass clumps)

- Understand cluster formation is critical to understand star formation

- Sun and Solar System are likely originated from a cluster

  ADAMS 2010

ATLASGAL © URQUHART ET AL. 2014



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!

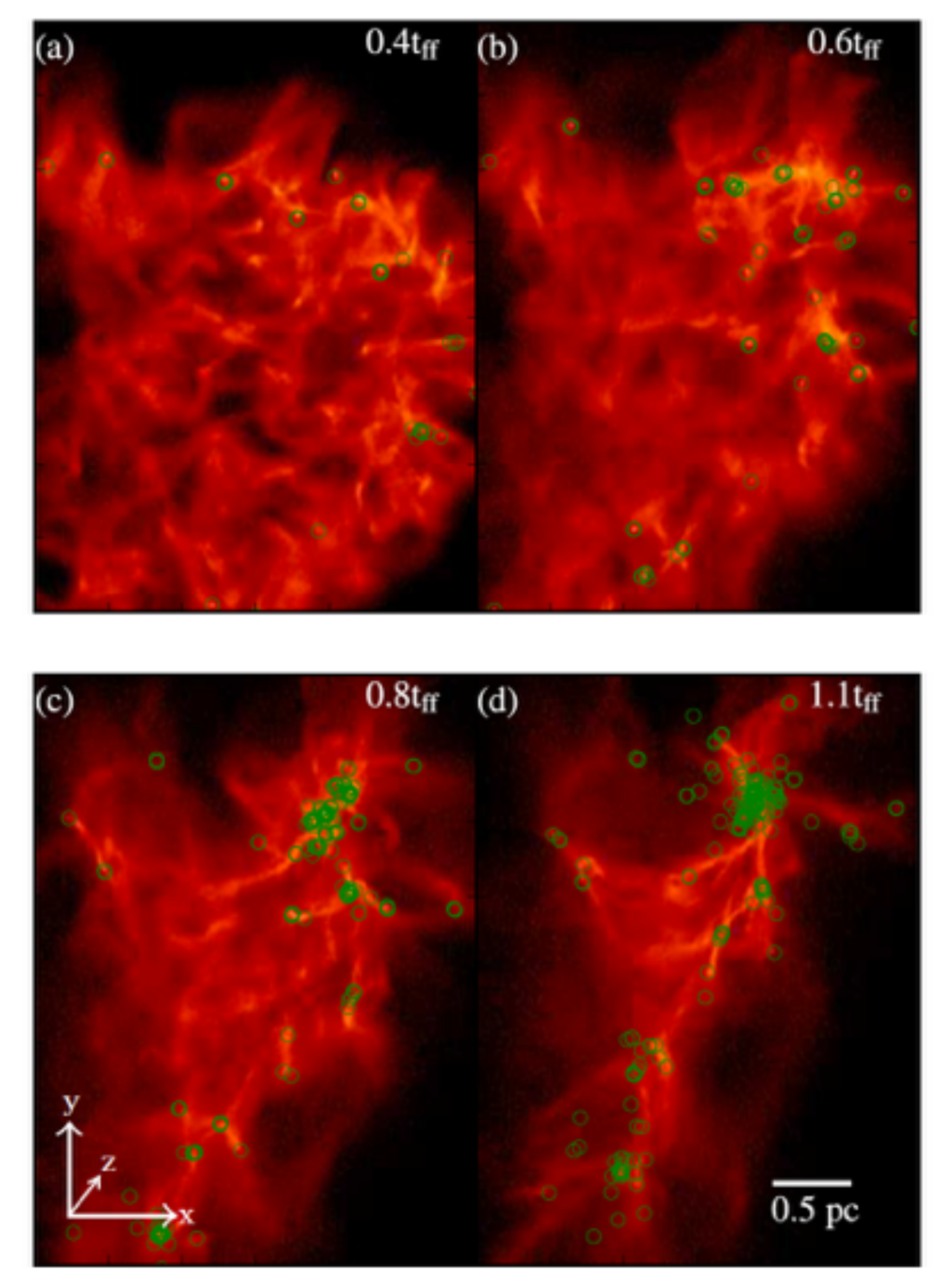
  - **Stars in cluster can preserve imprint of initial cdts of progenitor MC**

    Not possible with field stars because from dissolved small stellar systems

STELLAR CLUSTERS

IMPRINT OF INITIAL CONDITIONS?

- 3D numerical simulations of MC collapse and cluster formation to study morphology and dynamics
  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
- Only very young clusters could show imprint of initial conditions



CLOUD COLLAPSE © KUZNETSOVA ET AL. 2015

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
  - ***v sin i*** 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

CLOUD'S ANGULAR MOMENTUM

PROTO-CLUSTER FORMATION

- From 3D MHD simulations
  LEE & HENNEBELLE 2016

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

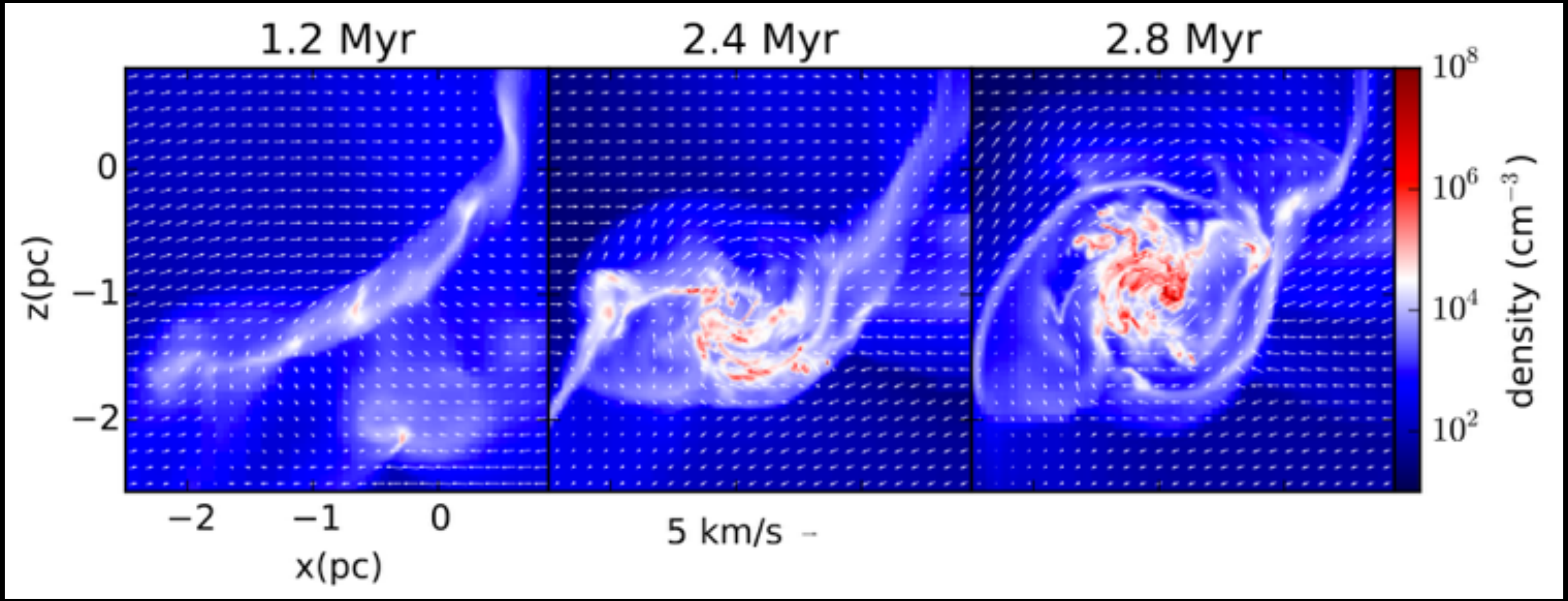
$$\boxed{E_{\text{rot}} < \frac{1}{2} E_{\text{tur}}}$$

- Pre-stellar cores however show

$$\boxed{E_{\text{tur}} \gg E_{\text{rot}}}$$

- 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



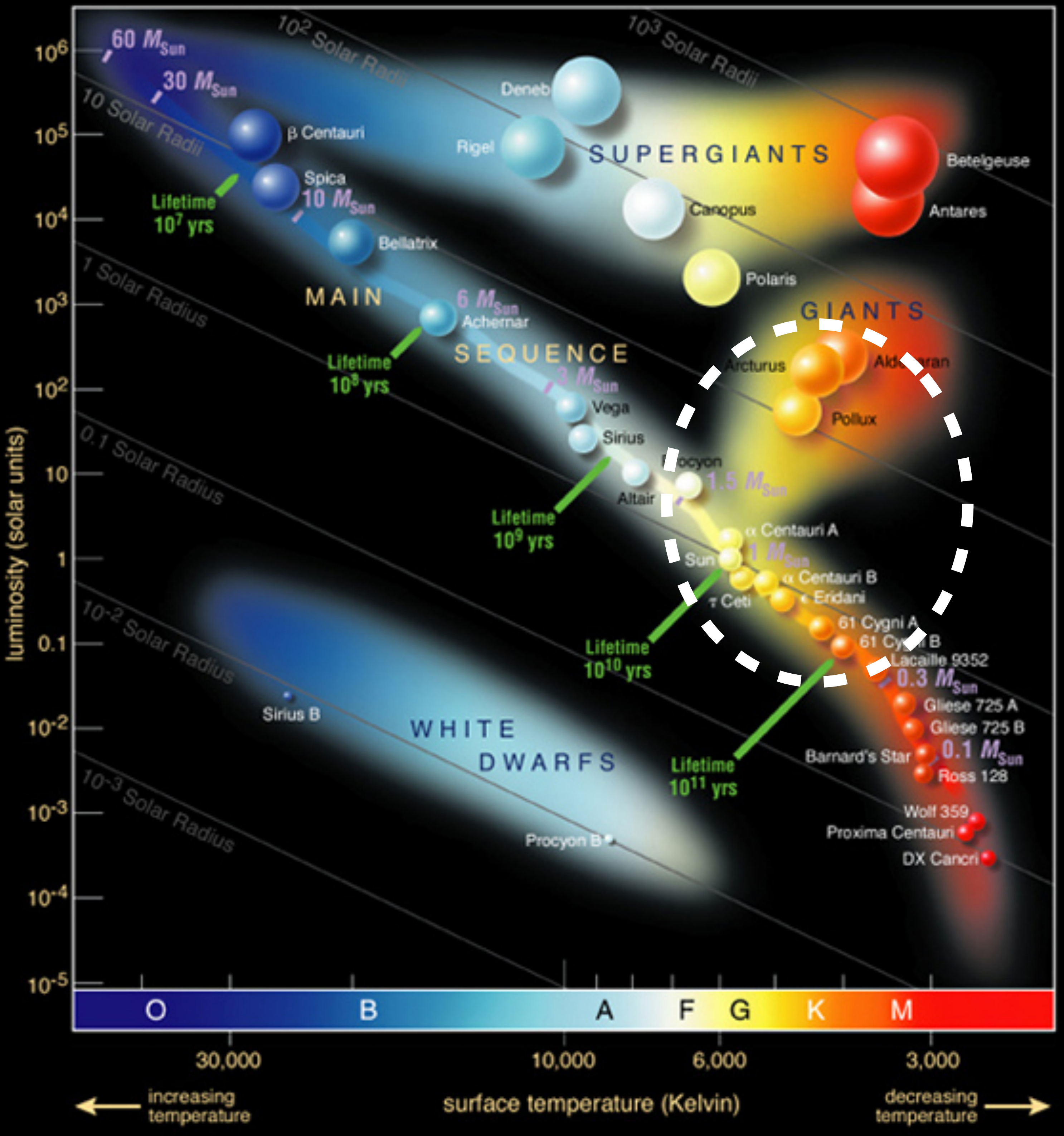
PART II

STELLAR OSCILLATIONS

PROBING THE INTERIOR OF STARS

ASTEROSEISMOLOGY

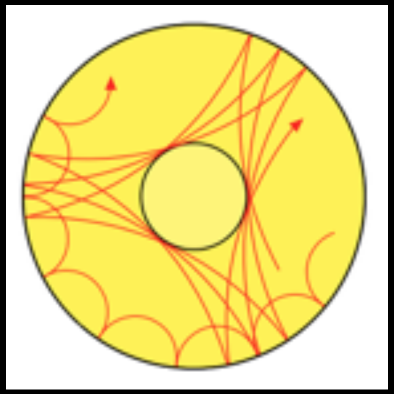
- Most stars with M ~ 1-3 M_{Sun} oscillate like the Sun (helioseismology)
  CHRISTENSEN-DALSGAARD 1987
- ~ 100K known today
- Observed with ground-based RV (e.g. SONG)
- Space missions MOST, CoRoT, NASA's *Kepler* & K2
- More to follow: NASA's TESS, ESA PLATO space missions



© ESO

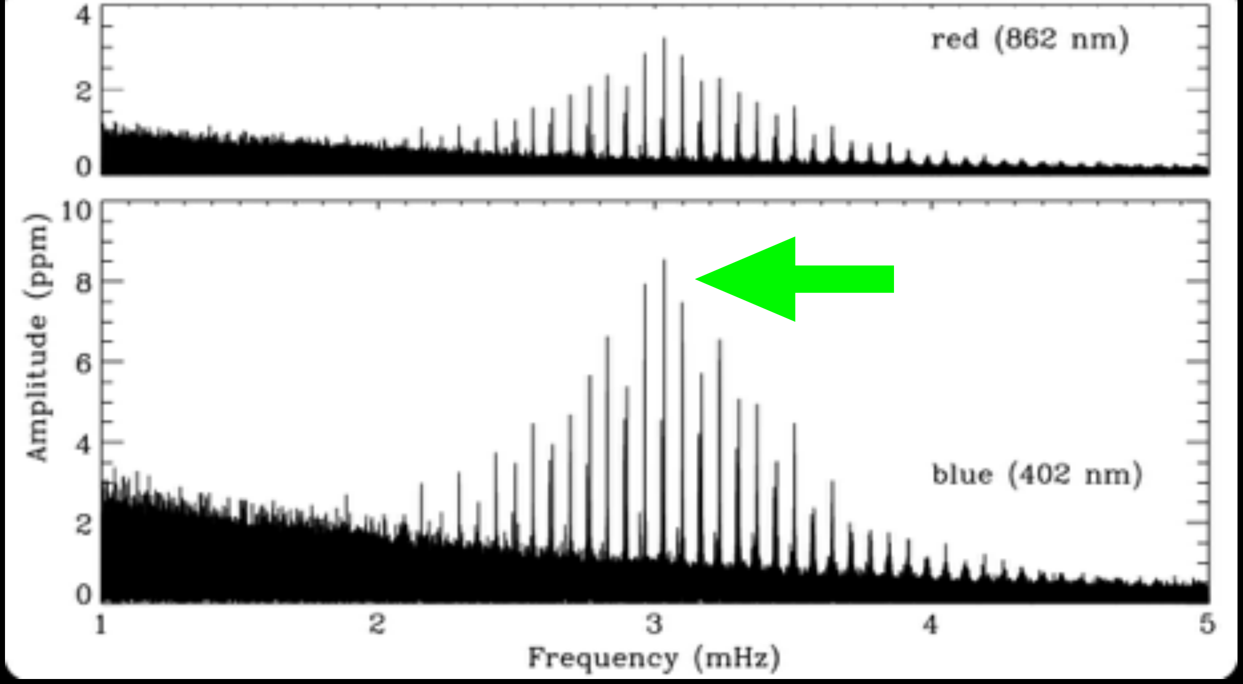
PROBING THE INTERIOR OF STARS

SOLAR-LIKE OSCILLATIONS

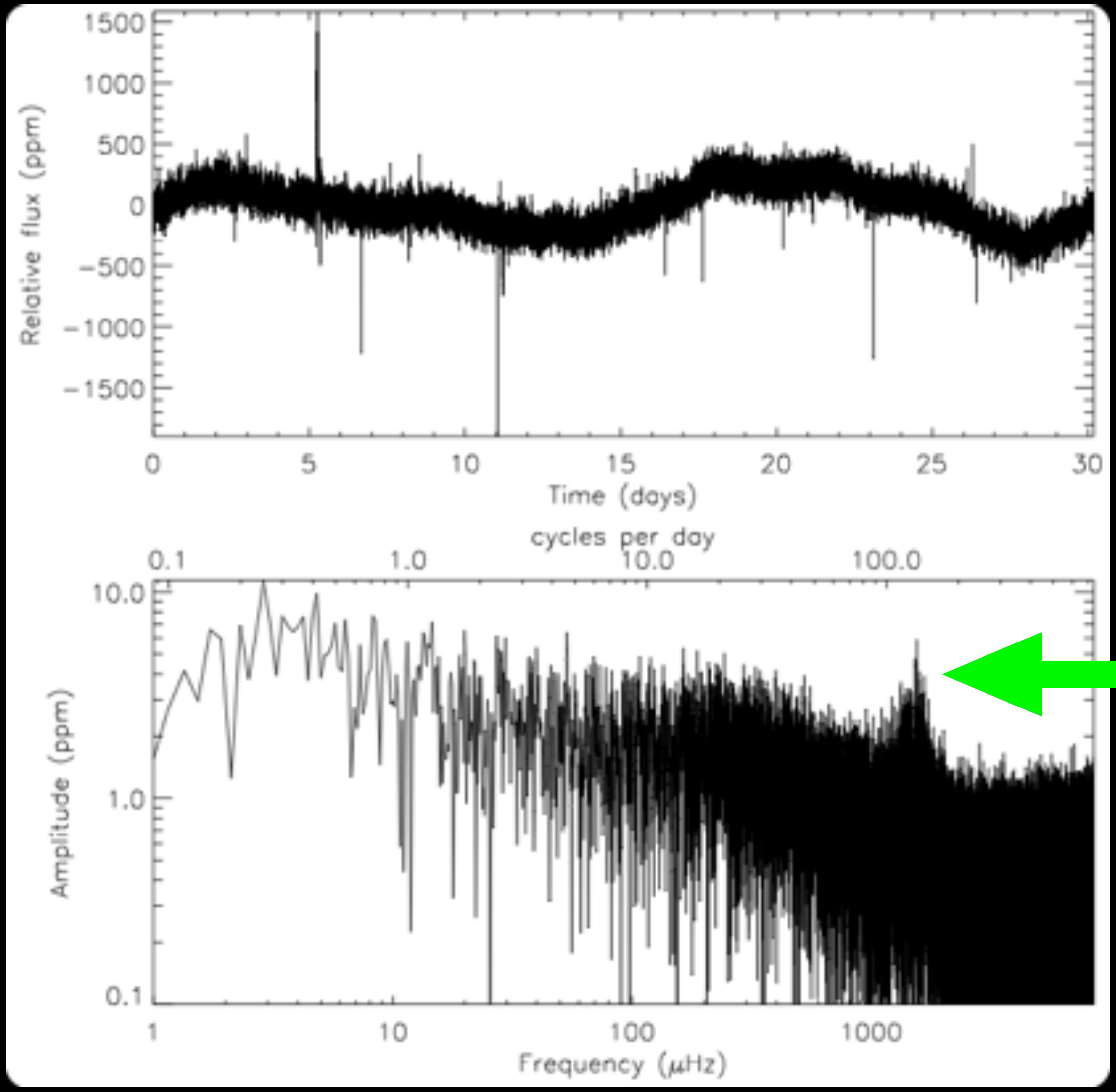


- Acoustic waves propagate in outer CZ
- Produce tiny brightness variations (from few ppm) in light curve
- Fourier analysis reveals Gaussian envelope of oscillations (PS)

$\nu_{\max} \propto R, M, T_{\rm eff}$



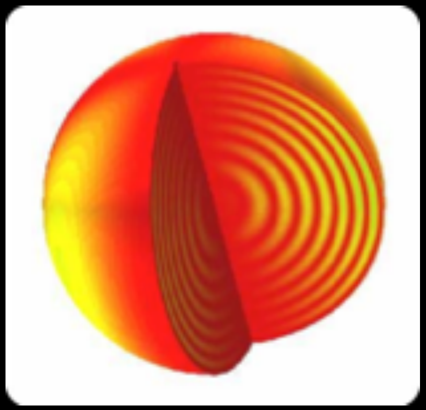
© VIRGO/SPM ONBOARD SOHO



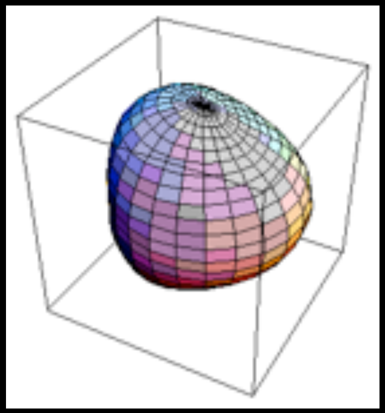
PROBING THE INTERIOR OF STARS

ASYMPTOTIC PATTERN

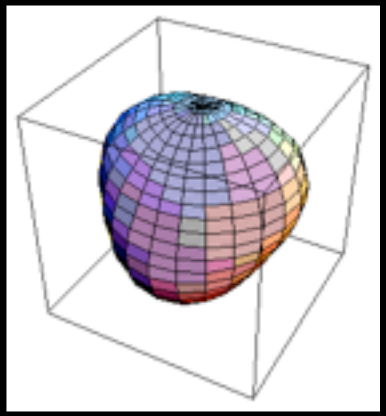
- Oscillation mode identified by 3 quantum numbers (n, l, m)
- Surface distribution depends on which oscillation mode
- Up to ~50 different oscillation modes in MS in regular position



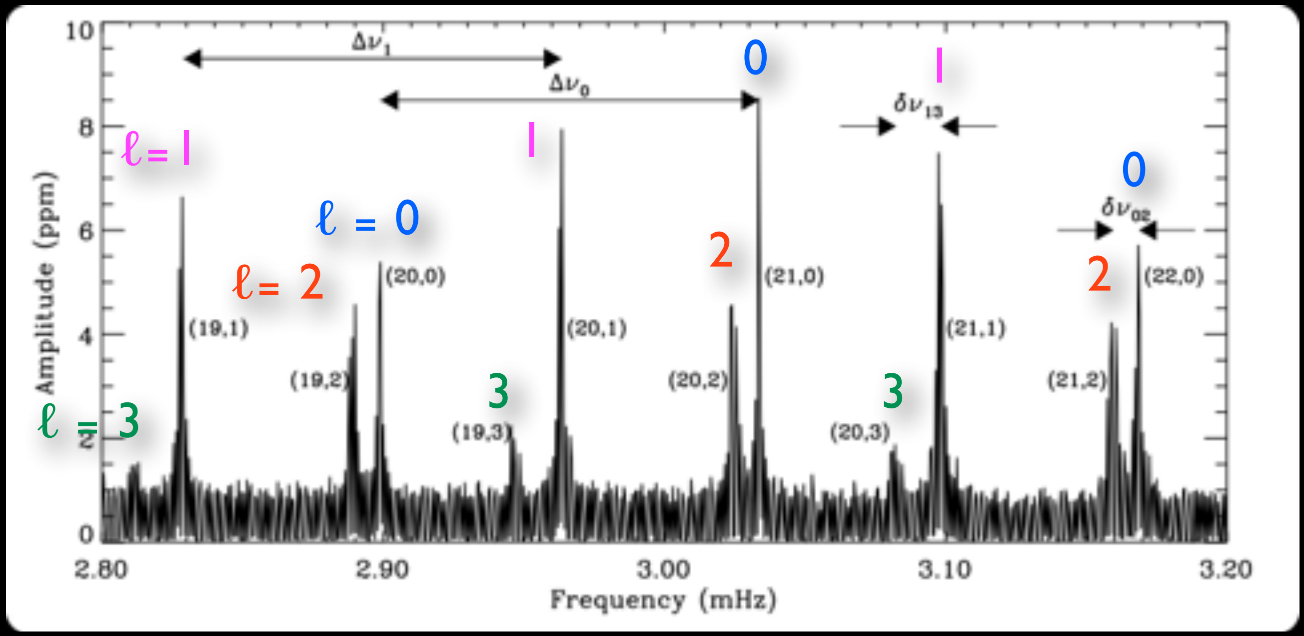
n > 10



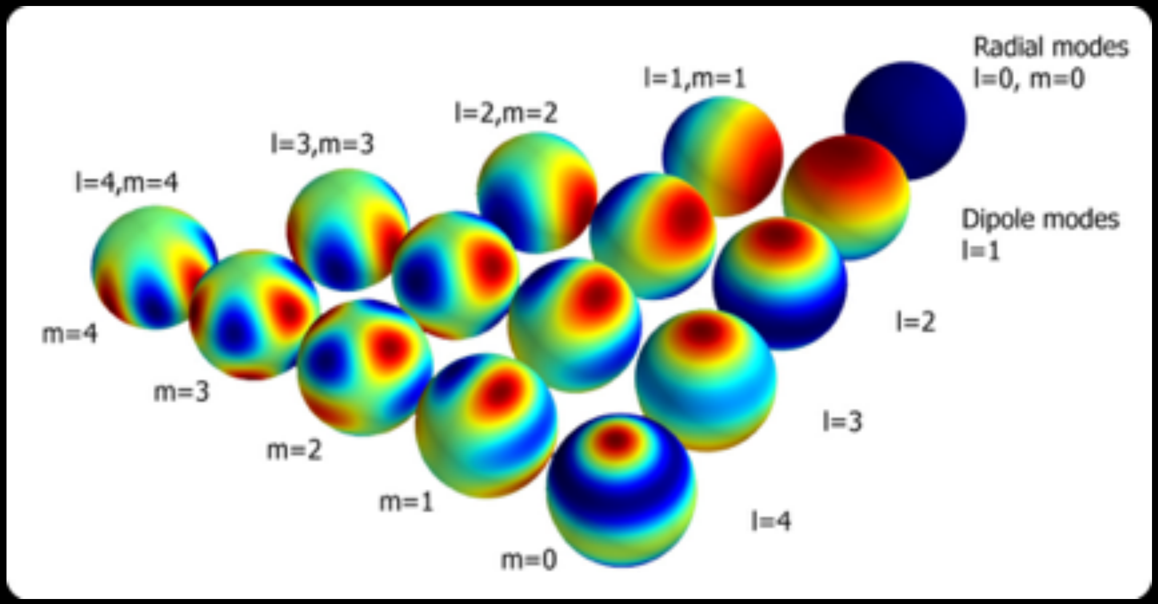
ℓ = 3, m = 1



ℓ = 3, m = 2



© BEDDING, KJELDSEN ET AL. 2003



© BECK & KALLINGER, 2013 S&W

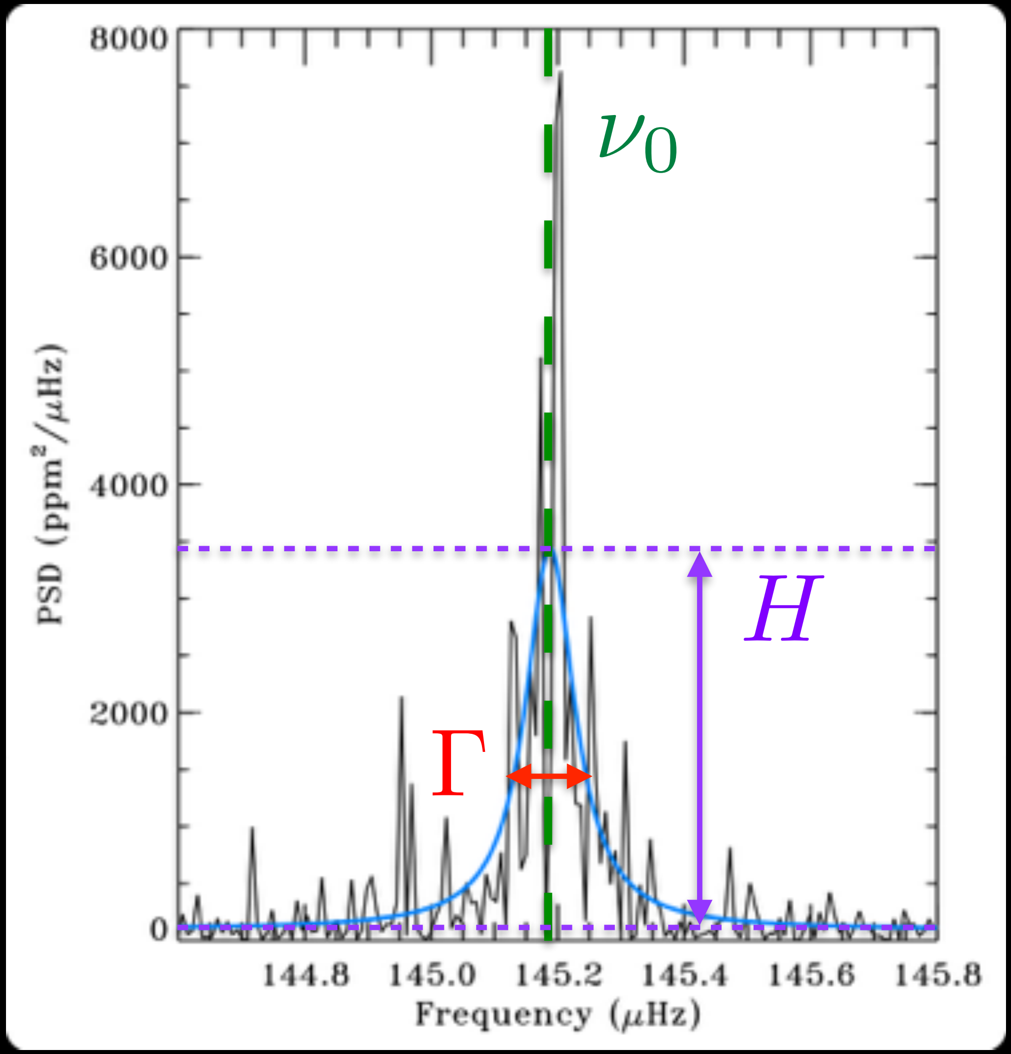
$$\Delta\nu \propto \overline{\rho}$$
$$\nu_{\max}$$

$$\rightarrow \quad M, R$$

PROBING THE INTERIOR OF STARS

OSCILLATION MODES

- Each oscillation mode is characterized by 3 asteroseismic parameters
- An individual PS can require hundreds of free parameters to be modeled



Damped oscillation

↓

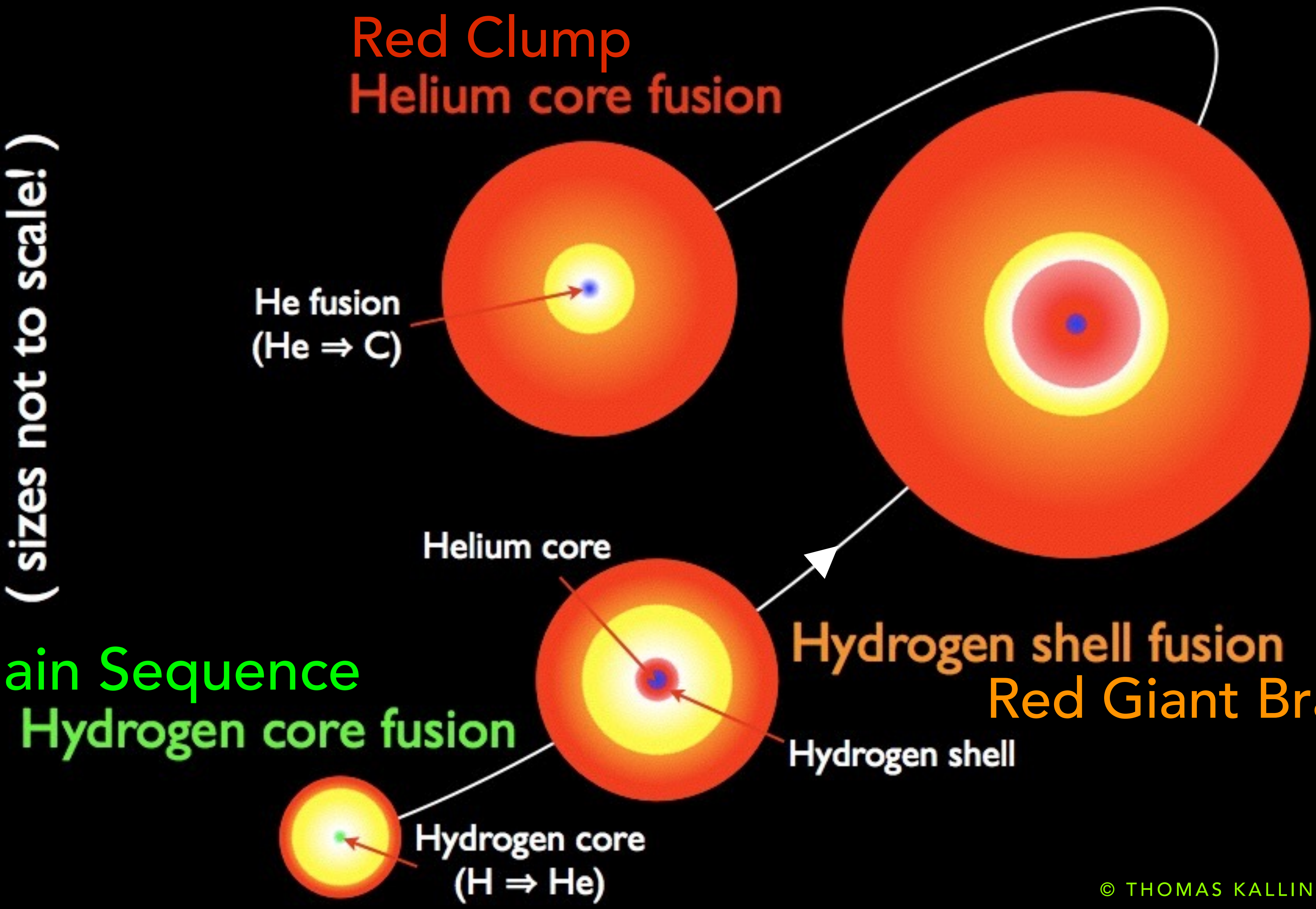
Lorentzian profile

$$T_{\rm obs} \gg \tau$$
$$\Gamma \propto \tau^{-1}$$
$$A^2 = \pi H \Gamma$$

$$\nu_0, \Gamma, A$$

EVOLVED SOLAR-TYPE STARS

RED GIANTS



© THOMAS KALLINGER

EVOLVED SOLAR-TYPE STARS

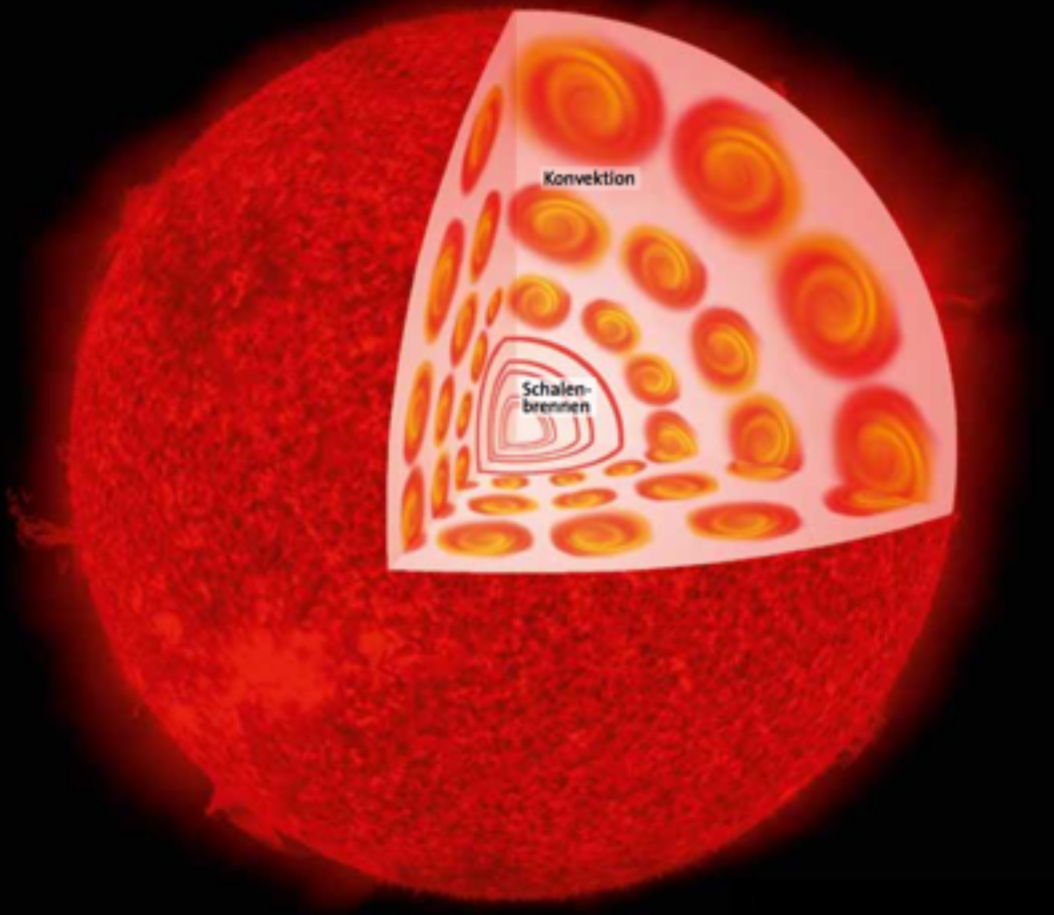
RG OSCILLATIONS

- Solar-like oscillations in outer CZ
- Couple with gravity waves from inner RZ
- Dipole ($\ell=1$) mixed modes observable, with both g- and p- character
- Mixed modes reveal internal structure and dynamics up to core level

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

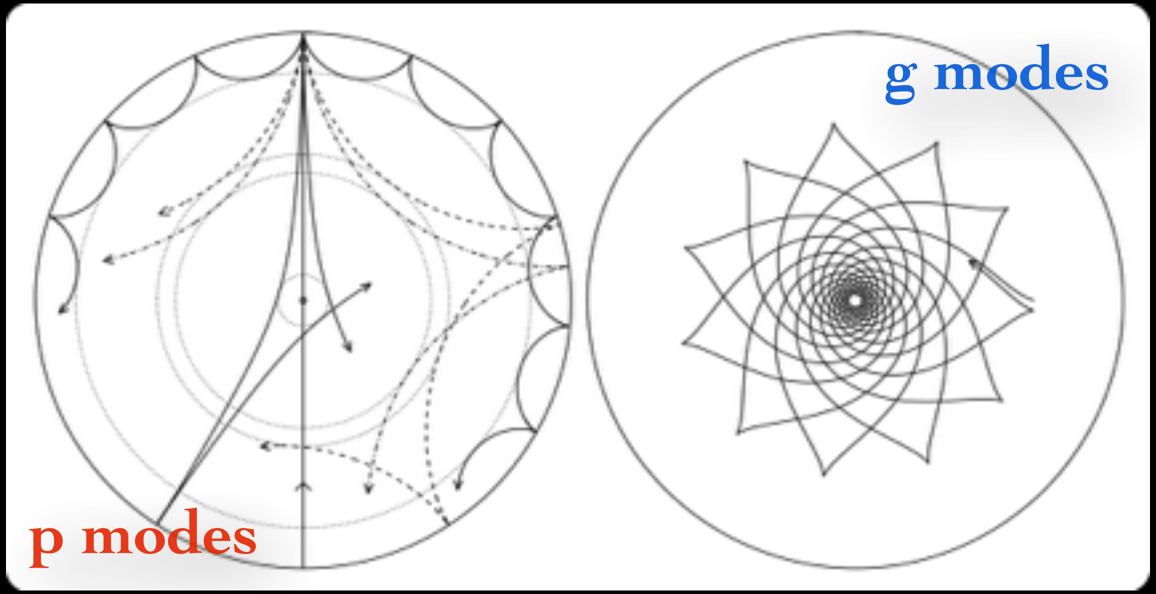
- Very luminous: can be observed more far away than MS
- Useful for Galactic Archeology: map Galaxy structure and evolution, Globular Clusters

MIGLIO ET AL. 2013, 2016



© BECK & KALLINGER, 2013 S&W

© CHRISTENSEN-DALSGAARD



EVOLVED SOLAR-TYPE STARS

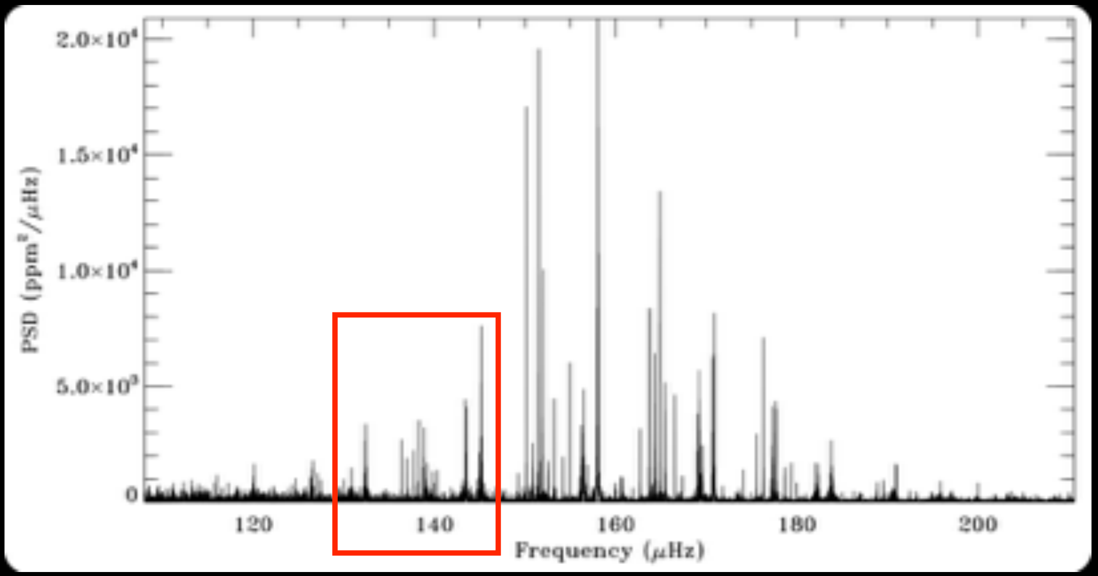
MIXED MODES PATTERN

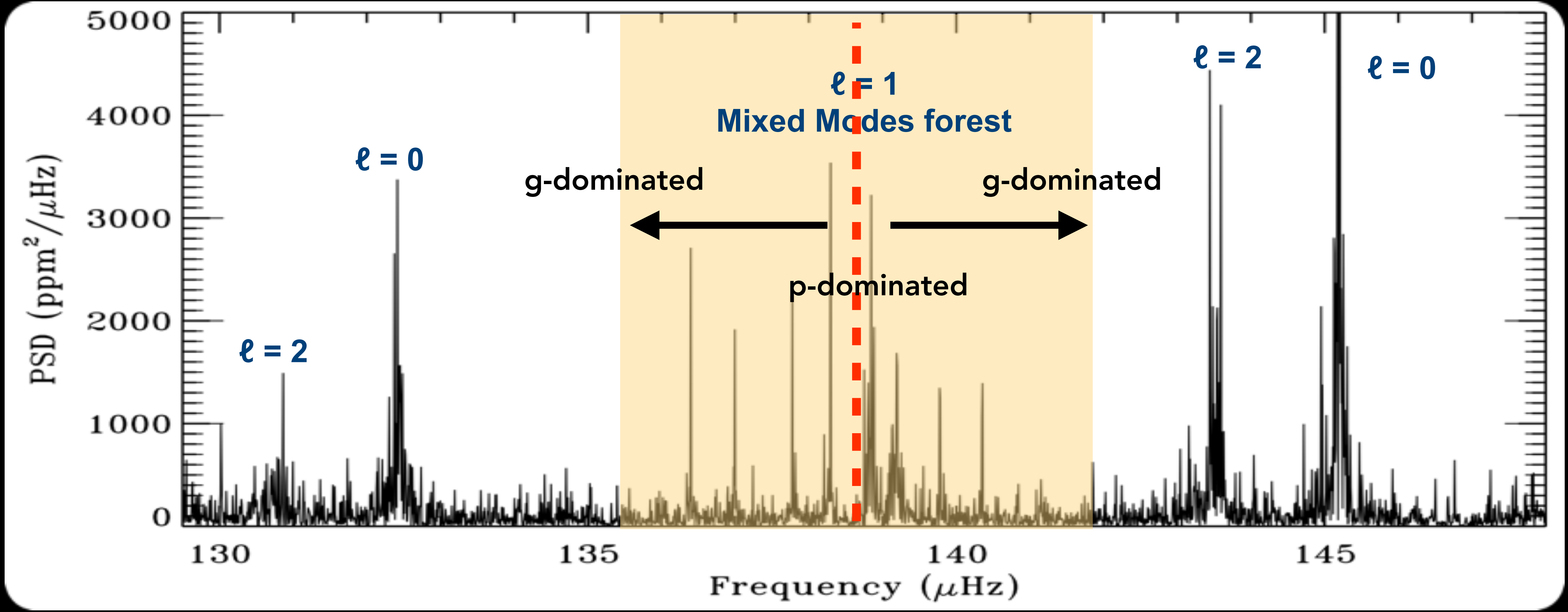
- Mixed dipole modes have regular separation in period

$\Delta\Pi_1$ → **He-core burning**

H-shell burning

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





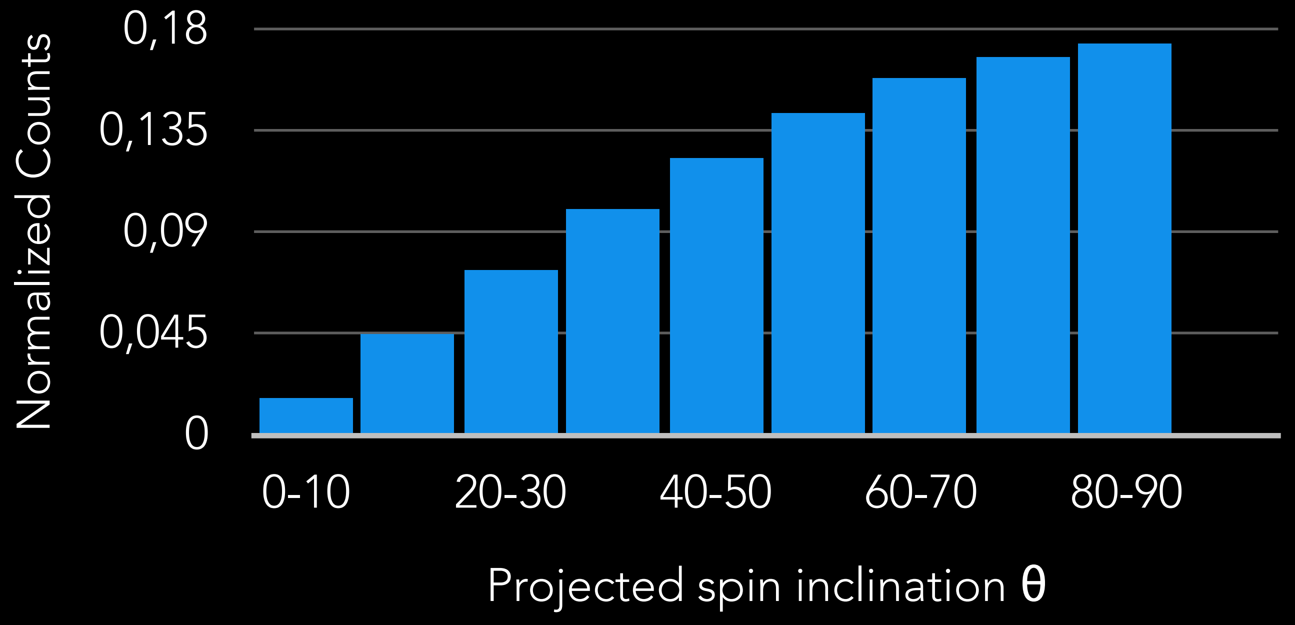
MEASURING STELLAR AM

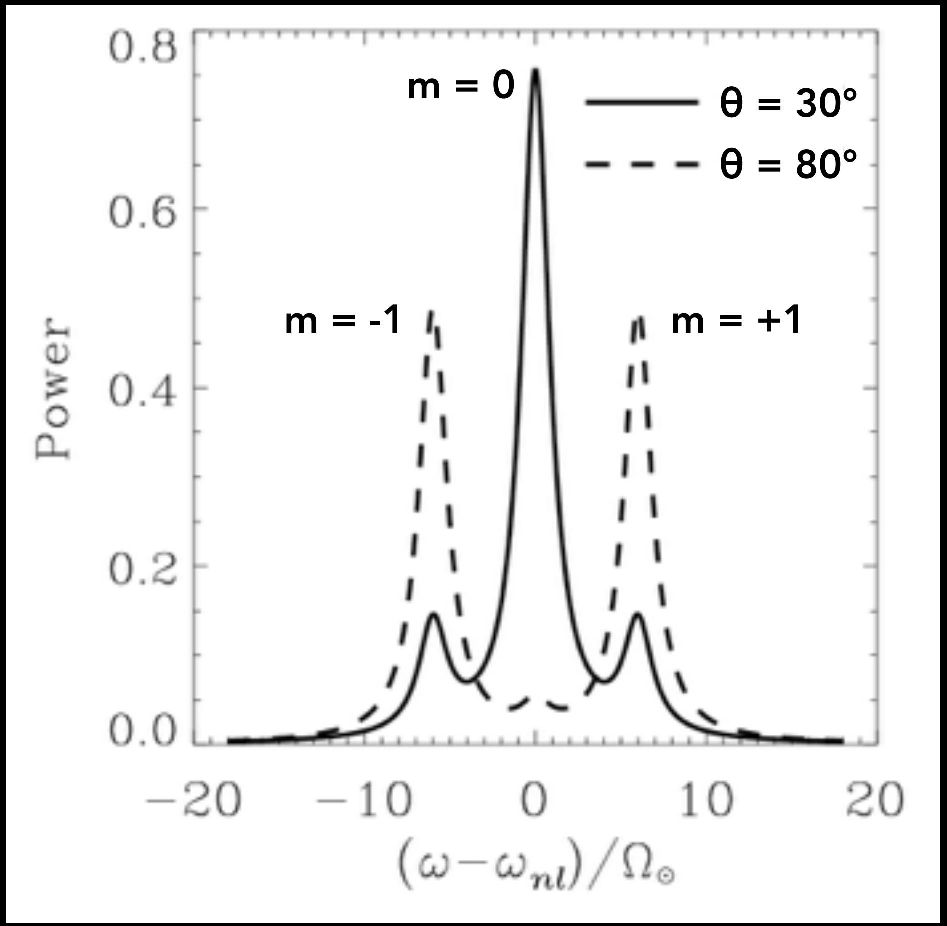
ROTATIONALLY SPLIT MODES

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

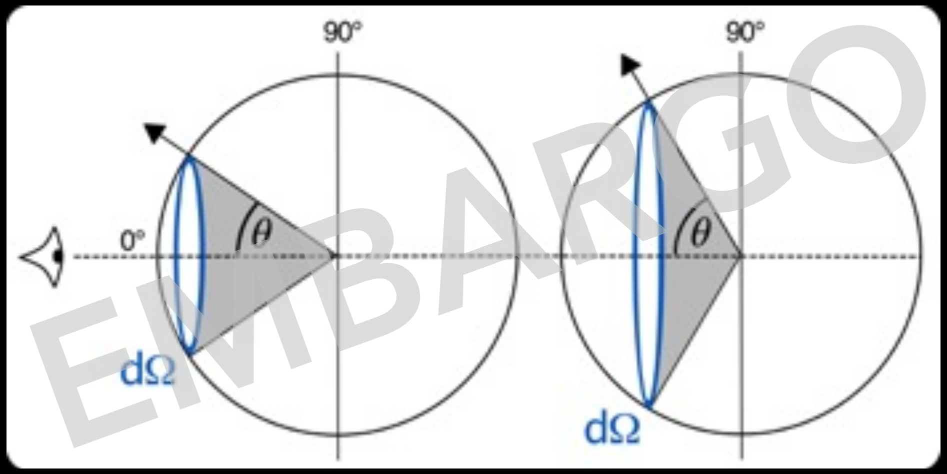
$$d\Omega = sin(\theta)d\theta$$

3D RANDOM DISTRIBUTION





© GIZON & SOLANKI 2003



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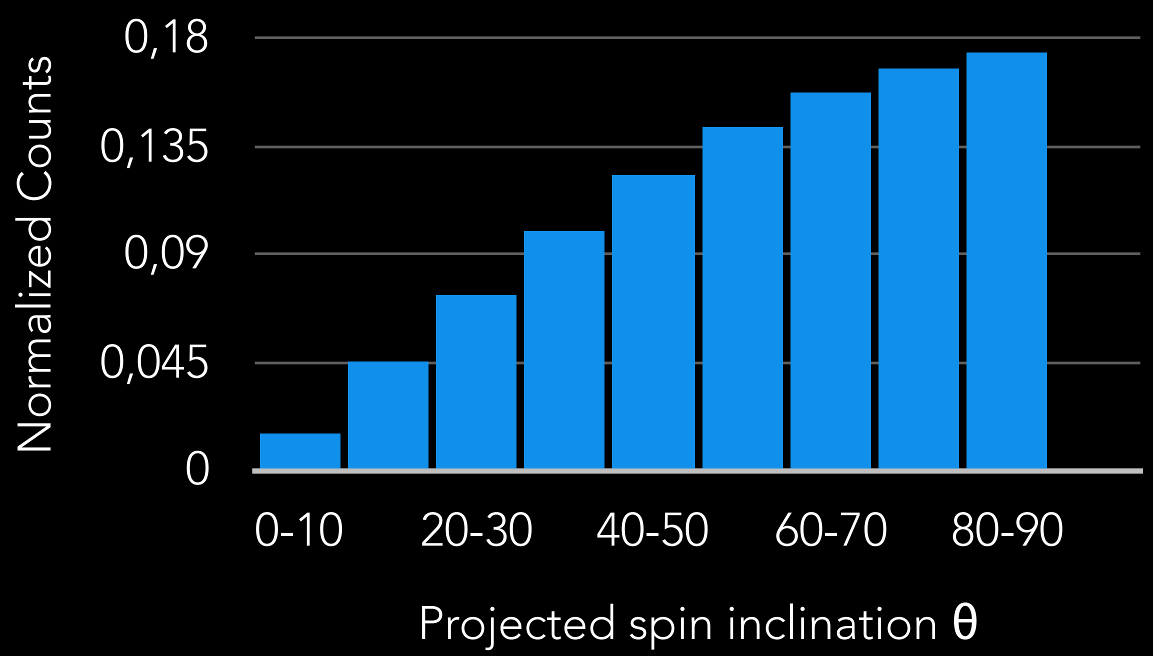
MEASURING STELLAR AM

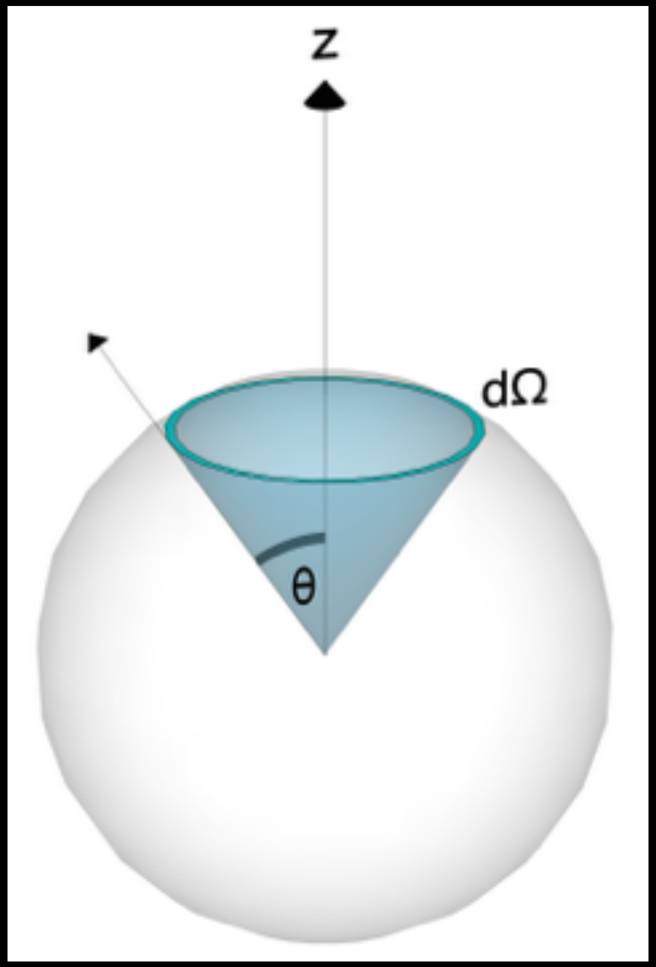
DEGREE OF SPIN ALIGNMENT

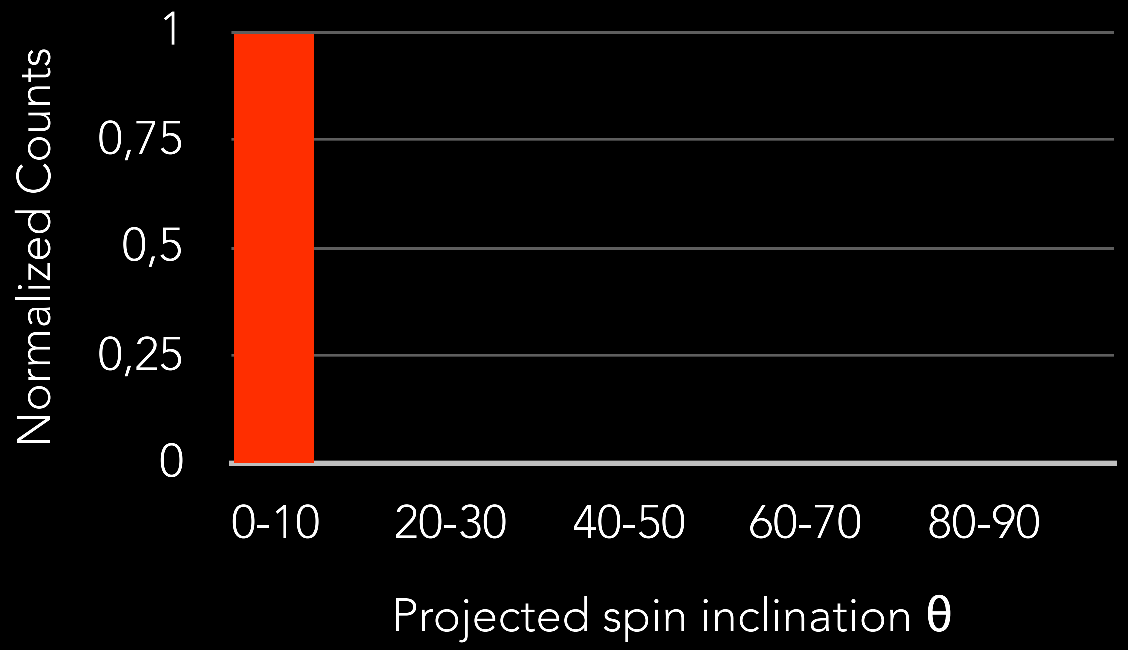

3D RANDOM DISTRIBUTION

3D Random

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

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




PERFECT ALIGNMENT ALONG L.O.S.

Perfect alignment

$$\alpha = 1$$

PART III

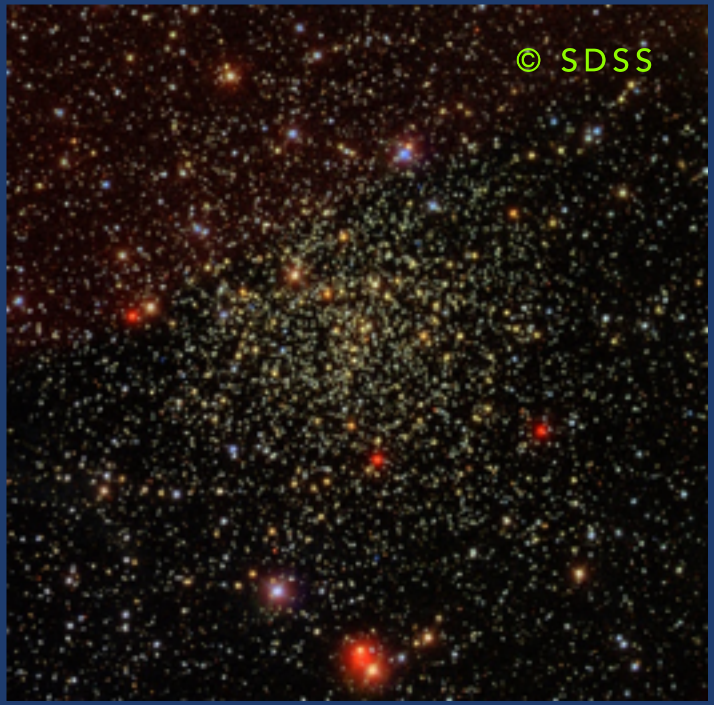
OBSERVATIONS, ANALYSIS & NEW RESULTS

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

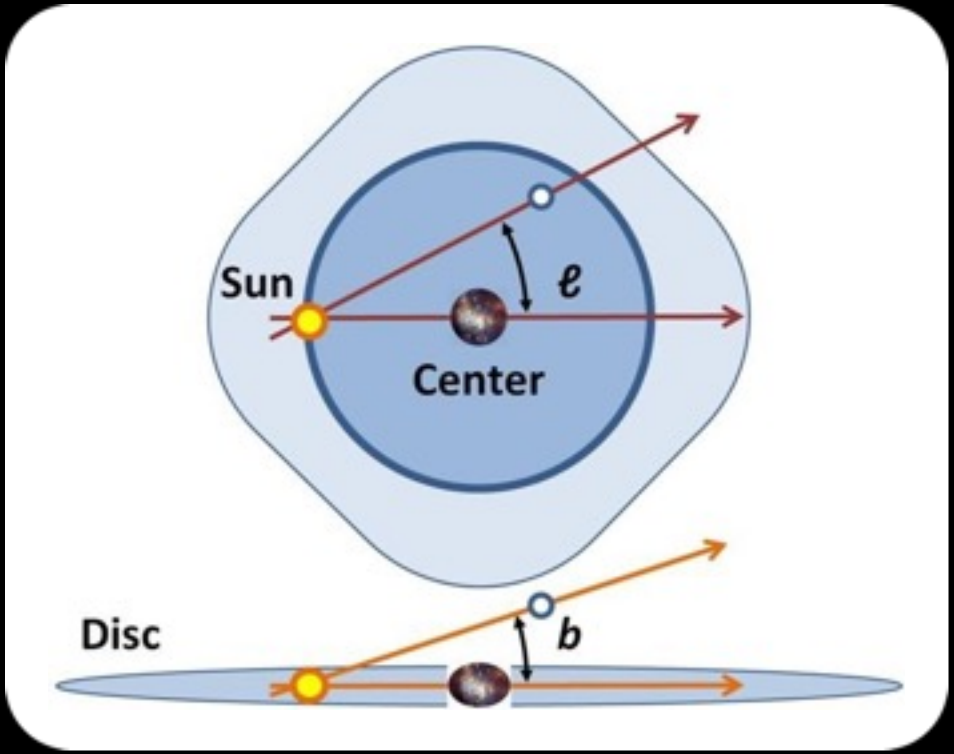
4 YEARS PHOTOMETRY

© 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



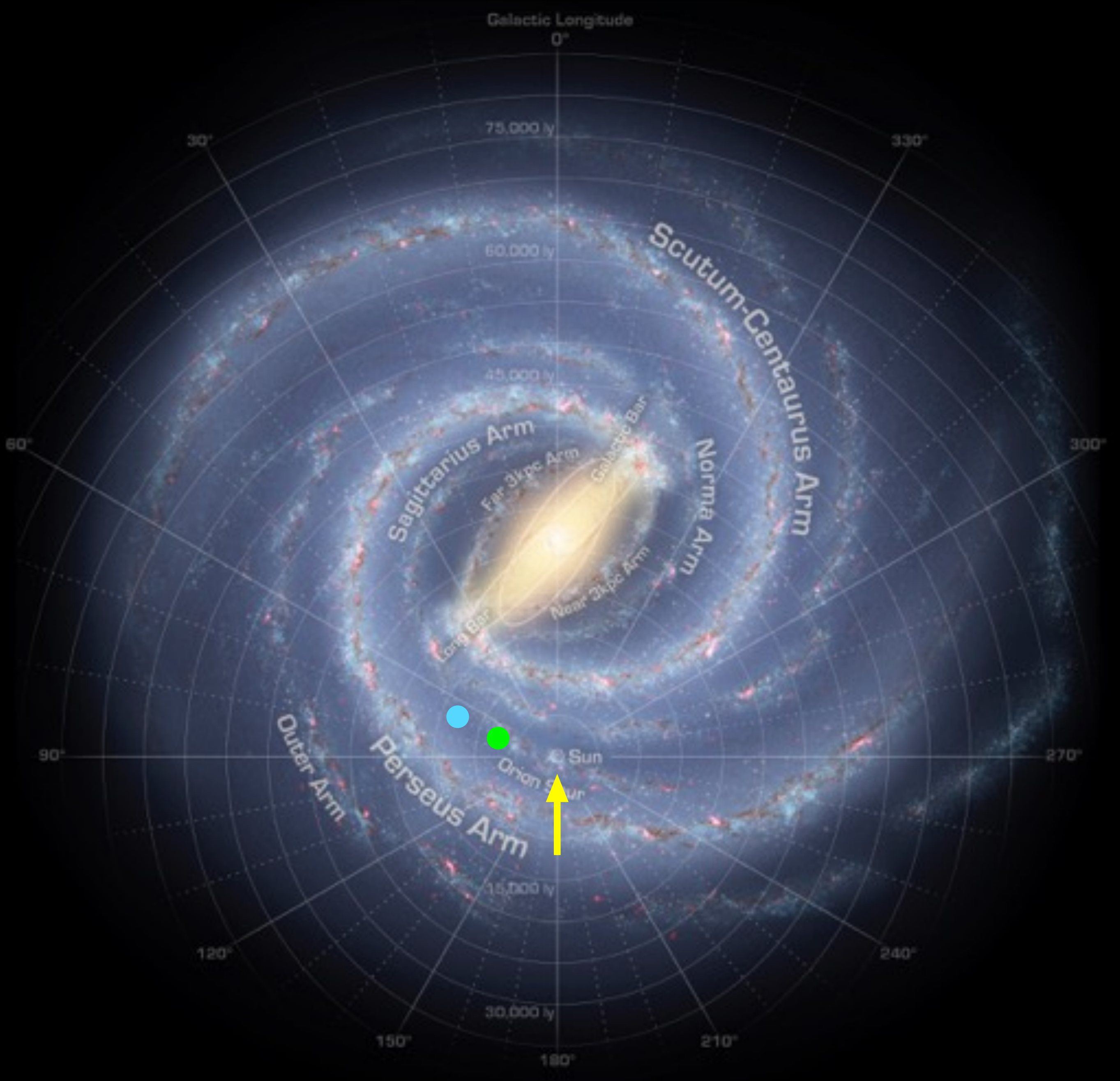
NGC 6791

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



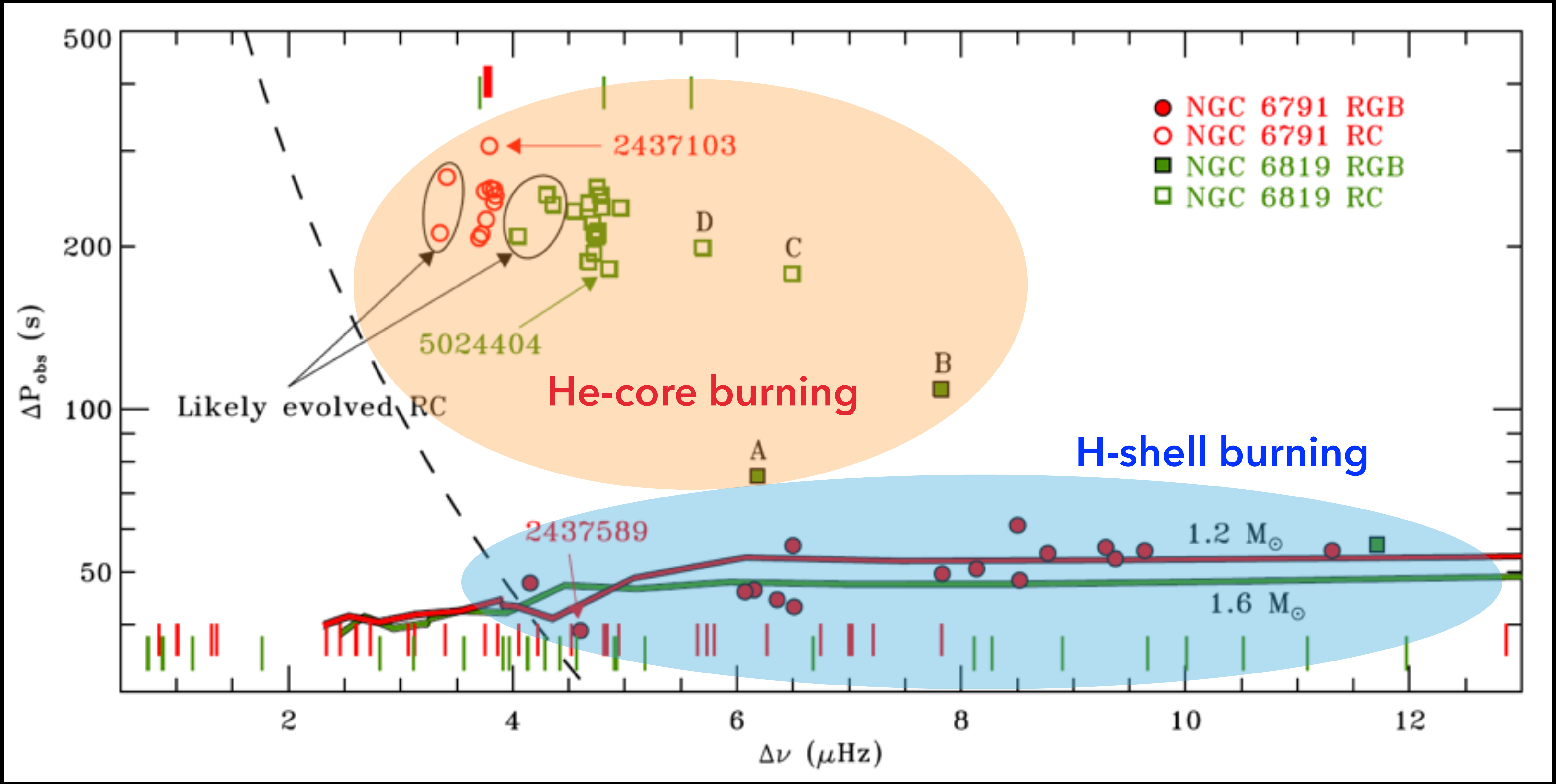
Annotated Roadmap to the Milky Way
(artist's concept)

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

TARGET SELECTION

CLUSTER RED GIANTS

- **48 cluster red giants** with clear evolutionary stage from period spacing of $\ell = 1$ mixed modes $\Delta\Pi_1$ CORSARO ET AL. 2012; MOSSER ET AL. 2012

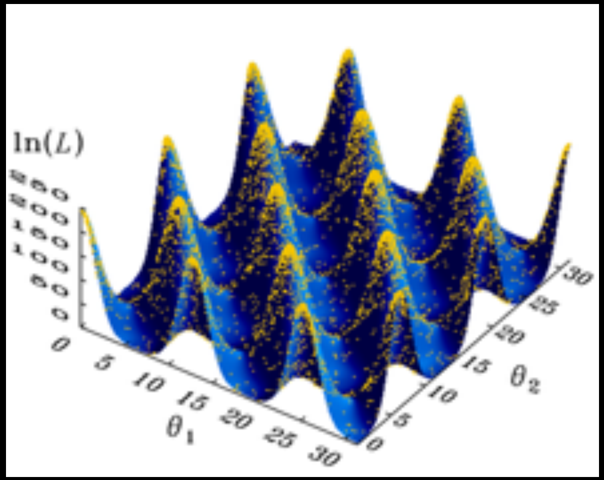


EVOLUTIONARY STAGE OF RED GIANTS © CORSARO ET AL. 2012

ANALYSIS OF STELLAR OSCILLATIONS

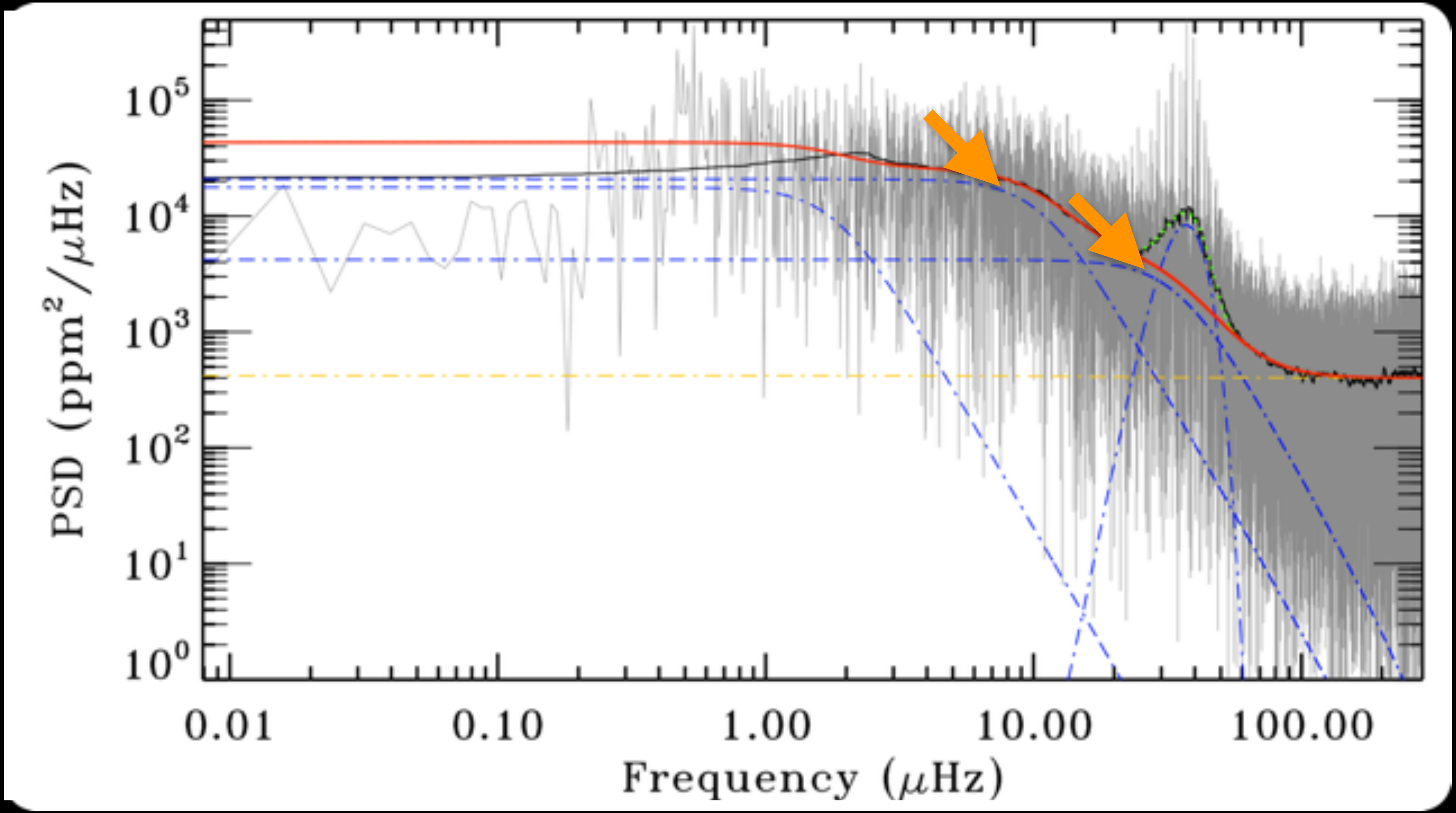
BACKGROUND SIGNAL

- Bayesian inference code DIAMONDS: public code available at https://fys.kuleuven.be/ster/Software/Diamonds/
  CORSARO & DE RIDDER, 2014, A&A, 571, 71
  CORSARO, DE RIDDER, GARCIA, 2015, A&A, 579, 83



© CORSARO & DE RIDDER, 2014

- Background signal modeled with **2 granulation components** in 48 cluster red giants
  CORSARO ET AL. 2016, IN PREP.



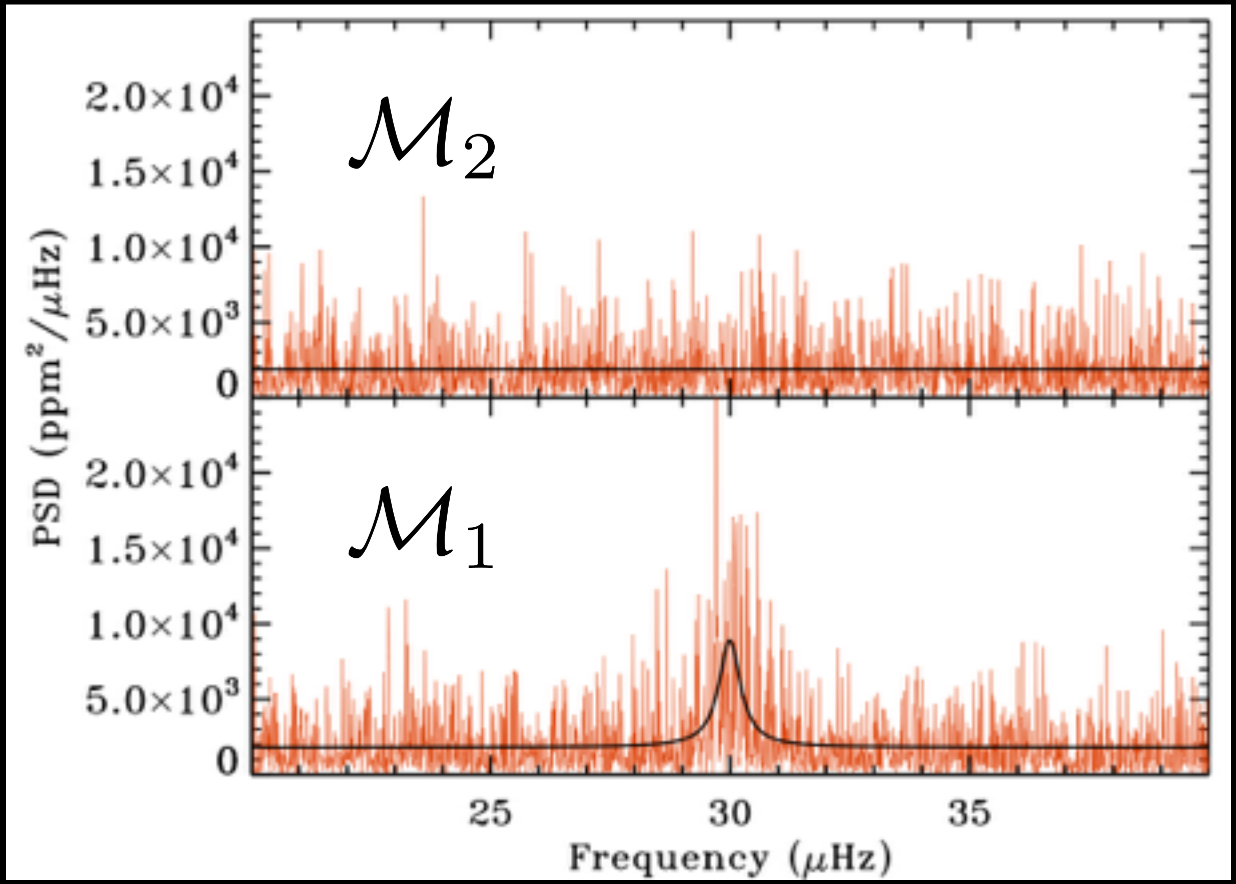
ANALYSIS OF STELLAR OSCILLATIONS

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



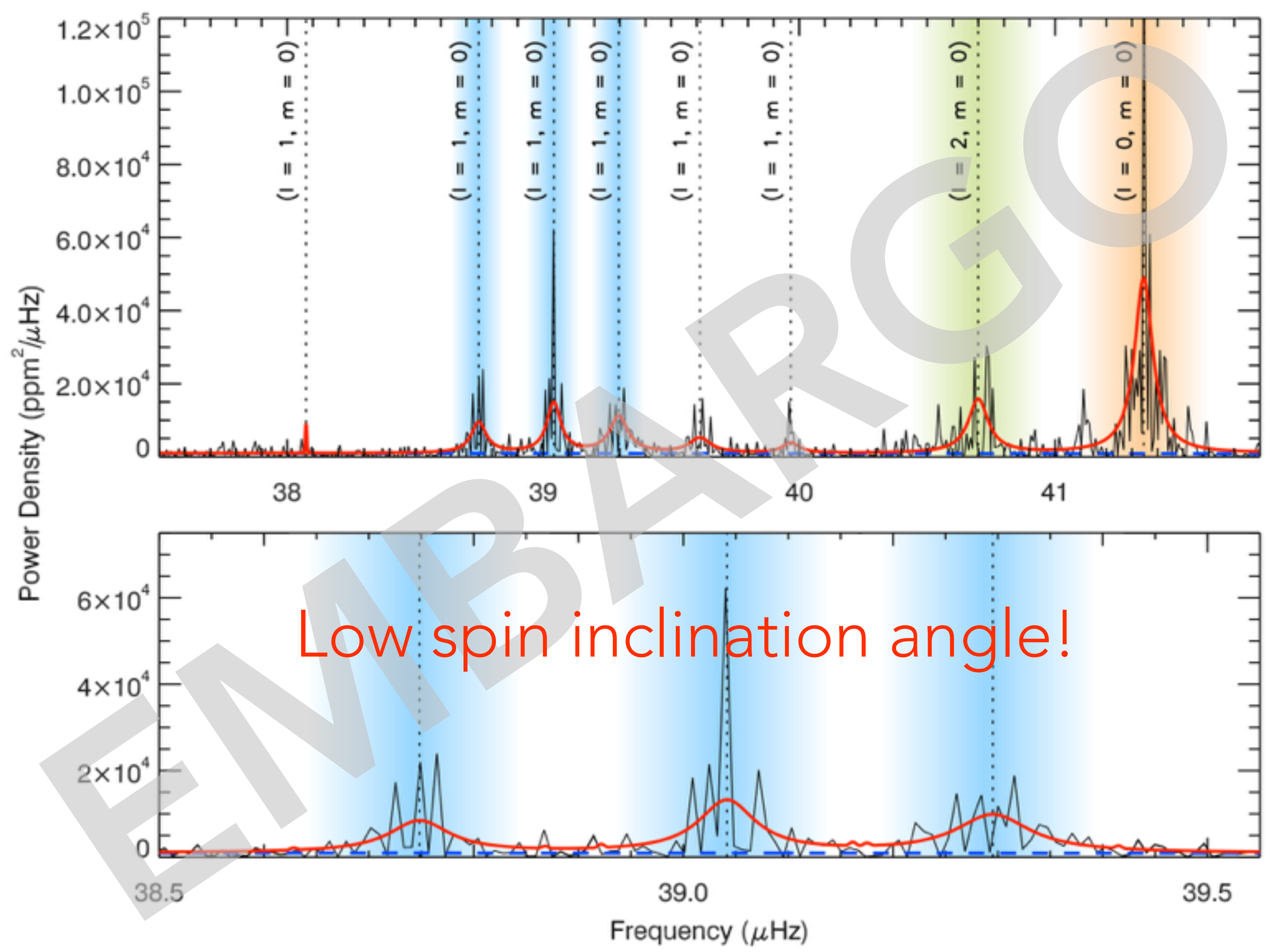
© CORSARO ET AL. 2015

- 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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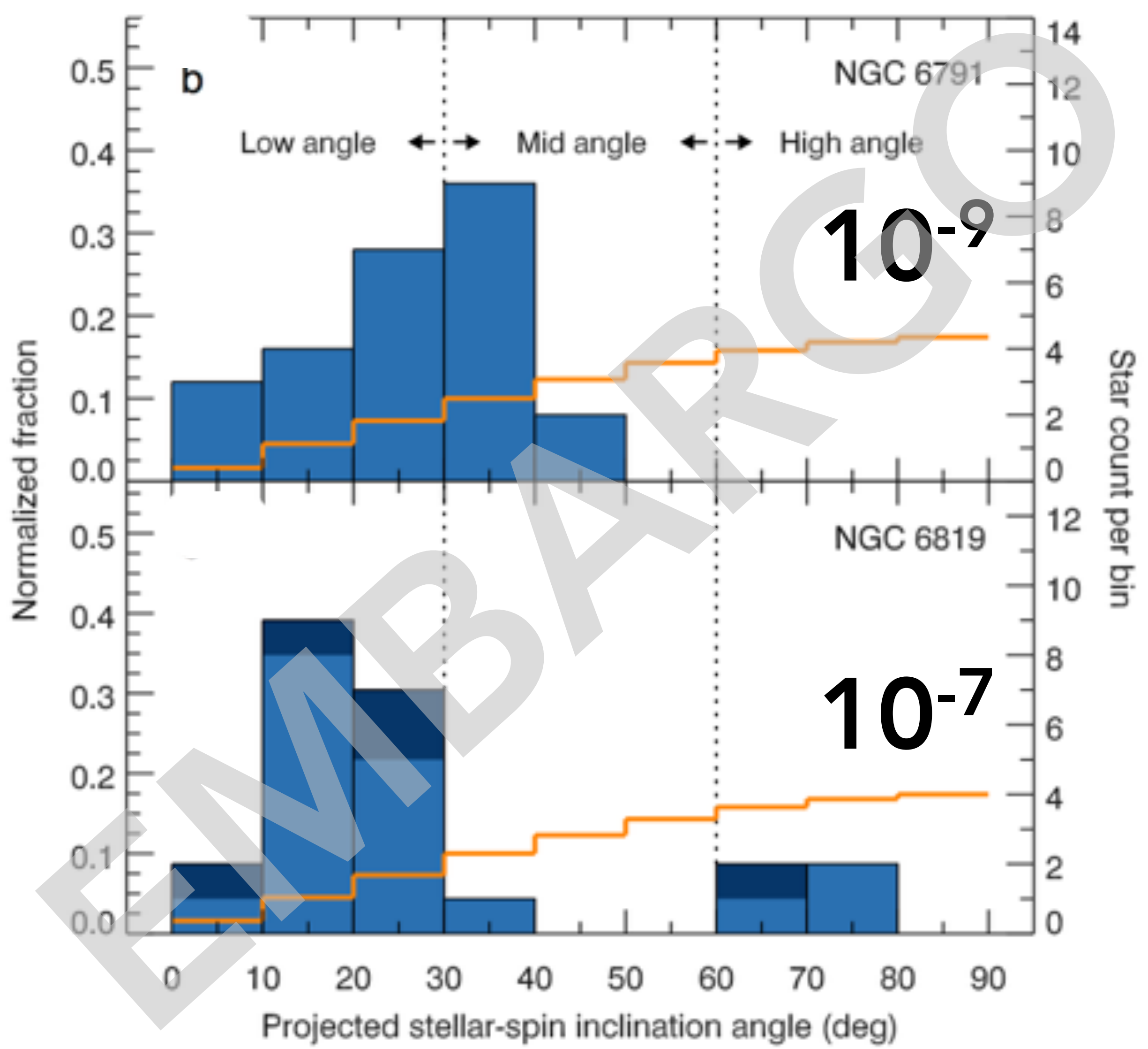
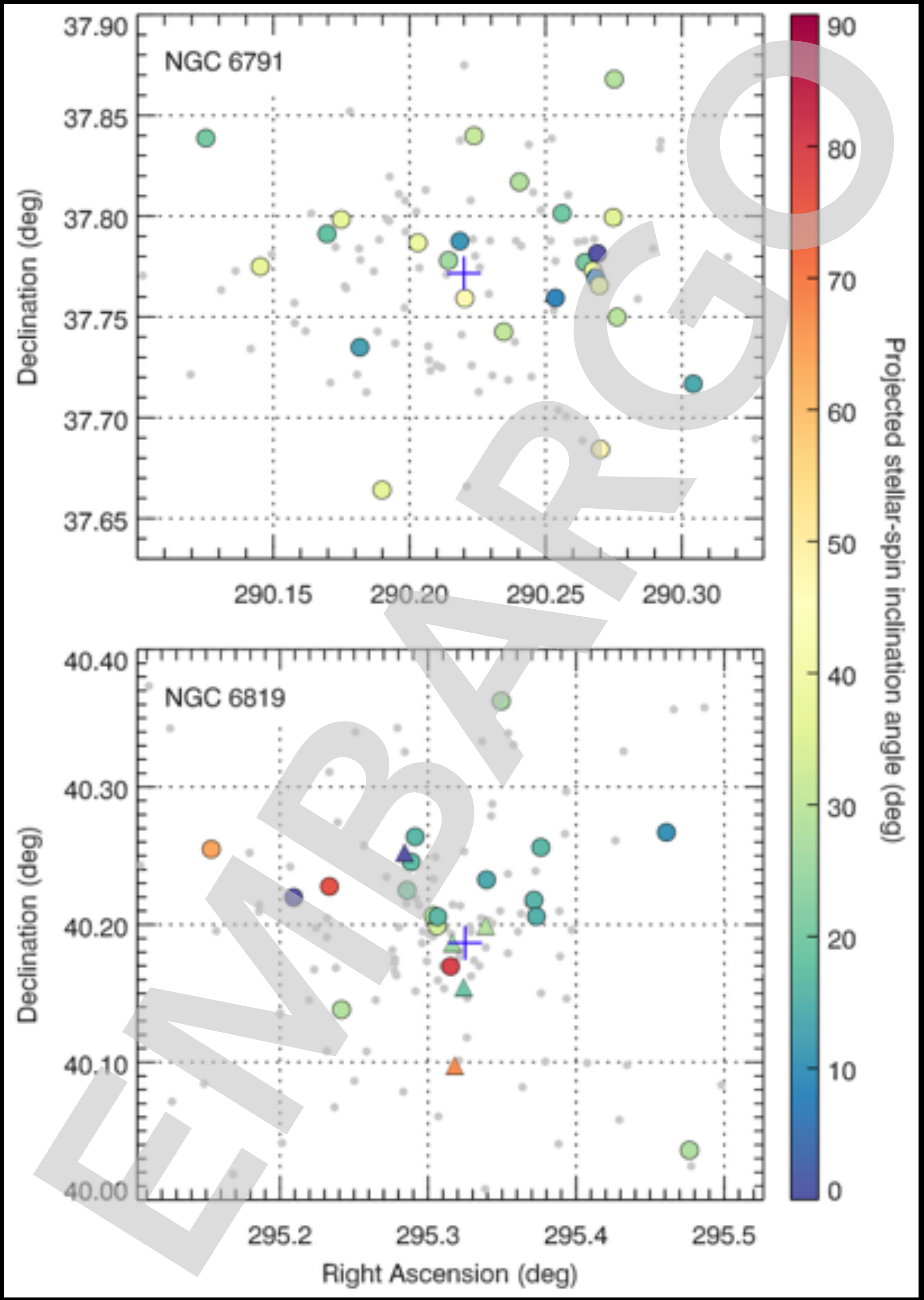
MEASURING STELLAR-SPIN INCLINATIONS

OBSERVATIONAL RESULTS

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

$\alpha \simeq 0.75$





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ORIGIN OF SPIN ALIGNMENT

N-BODY INTERACTIONS?

- N-body interactions are related to colliding stars or multiple stellar systems
- 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 ($\sim 1\ M_{Sun}\ pc^{-3}$)

  LADA & LADA 2003
- Tidal forces among stars can negligible already over a few AU (~ 10^{-5} pc)

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

3D 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

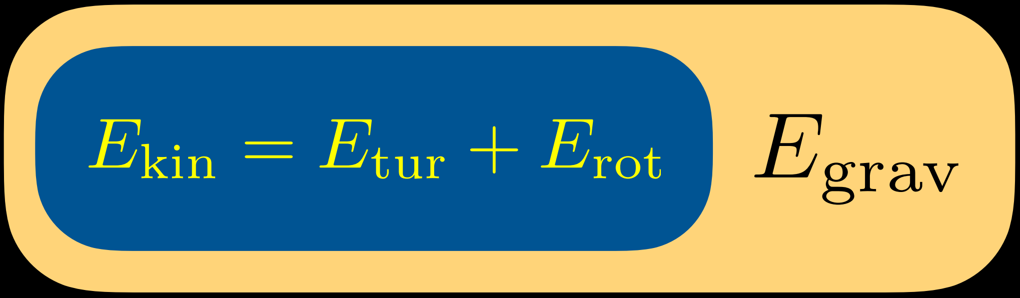
$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_0} \right)^2 \right]^{-1}$$

3D SIMULATIONS

PROTO-CLUSTER FORMATION

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

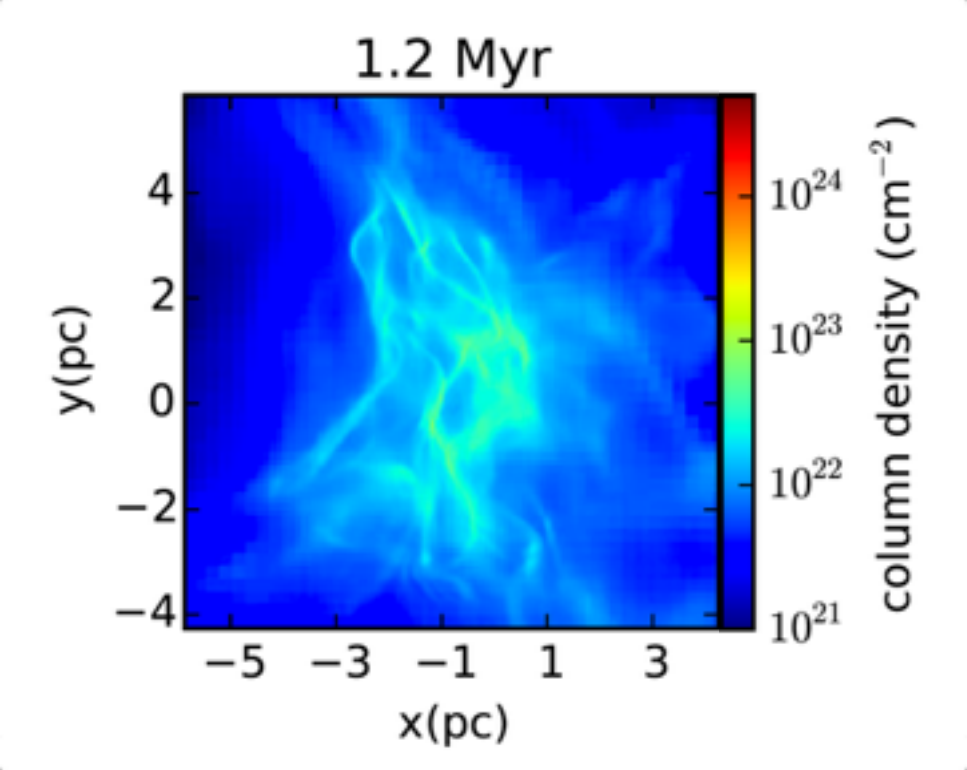
- Sink particles algorithm used to add angular momentum from gas to sink: track evolution of AM at scales of several AU



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

$$E_{\mathrm{grav}}$$

3D hydrodynamics



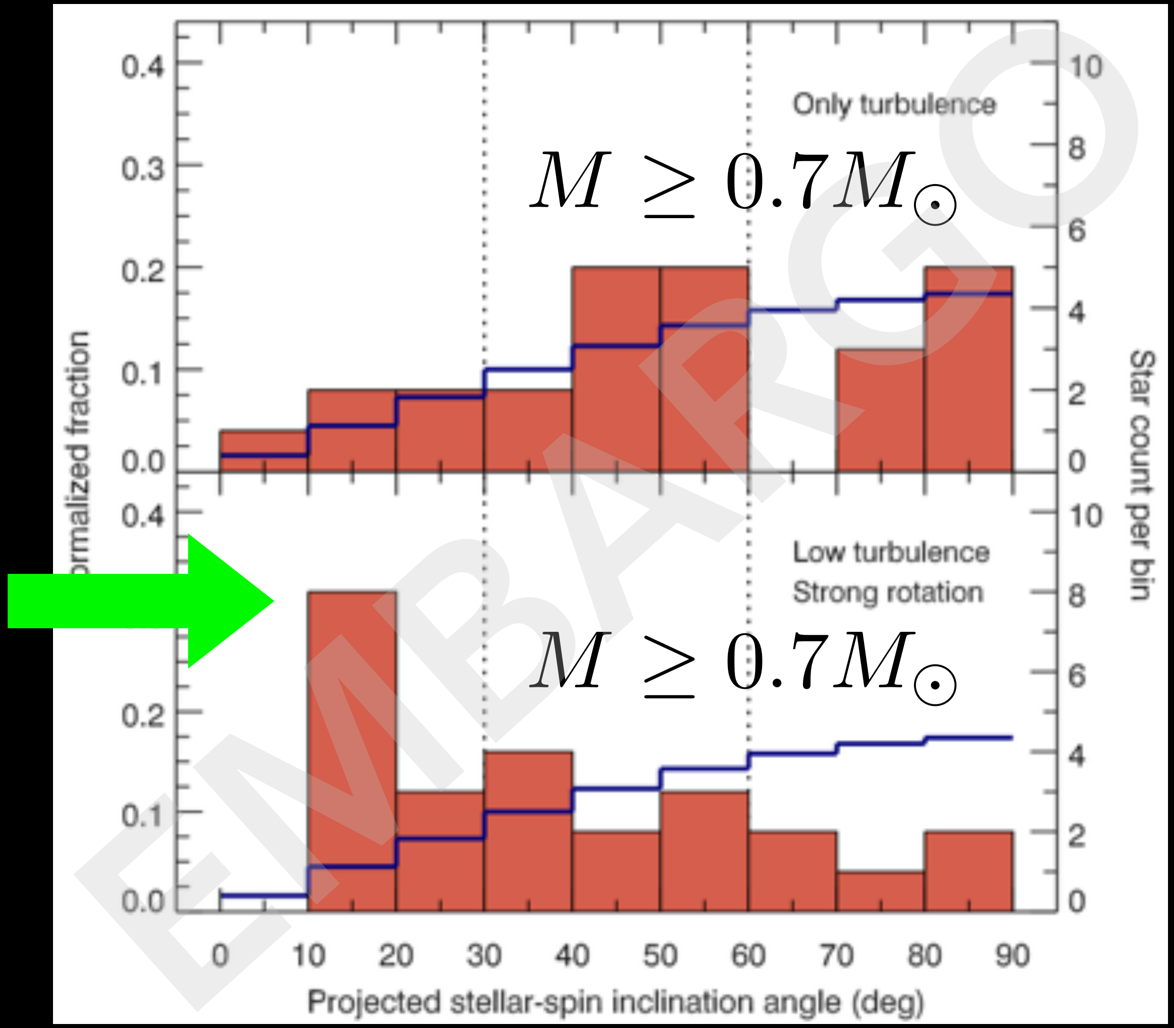
PROTO-CLUSTER FORMATION

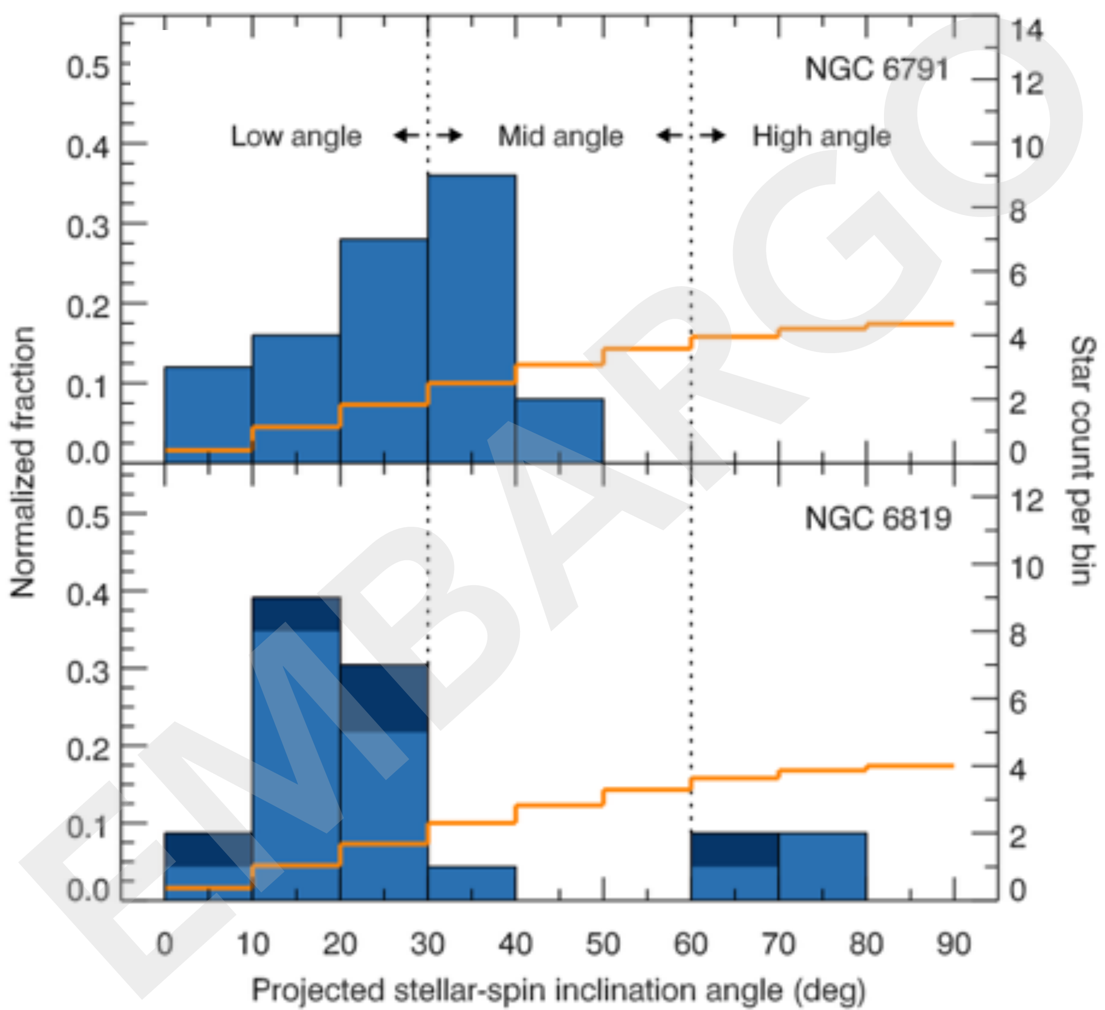
3D SIMULATION RESULTS

- 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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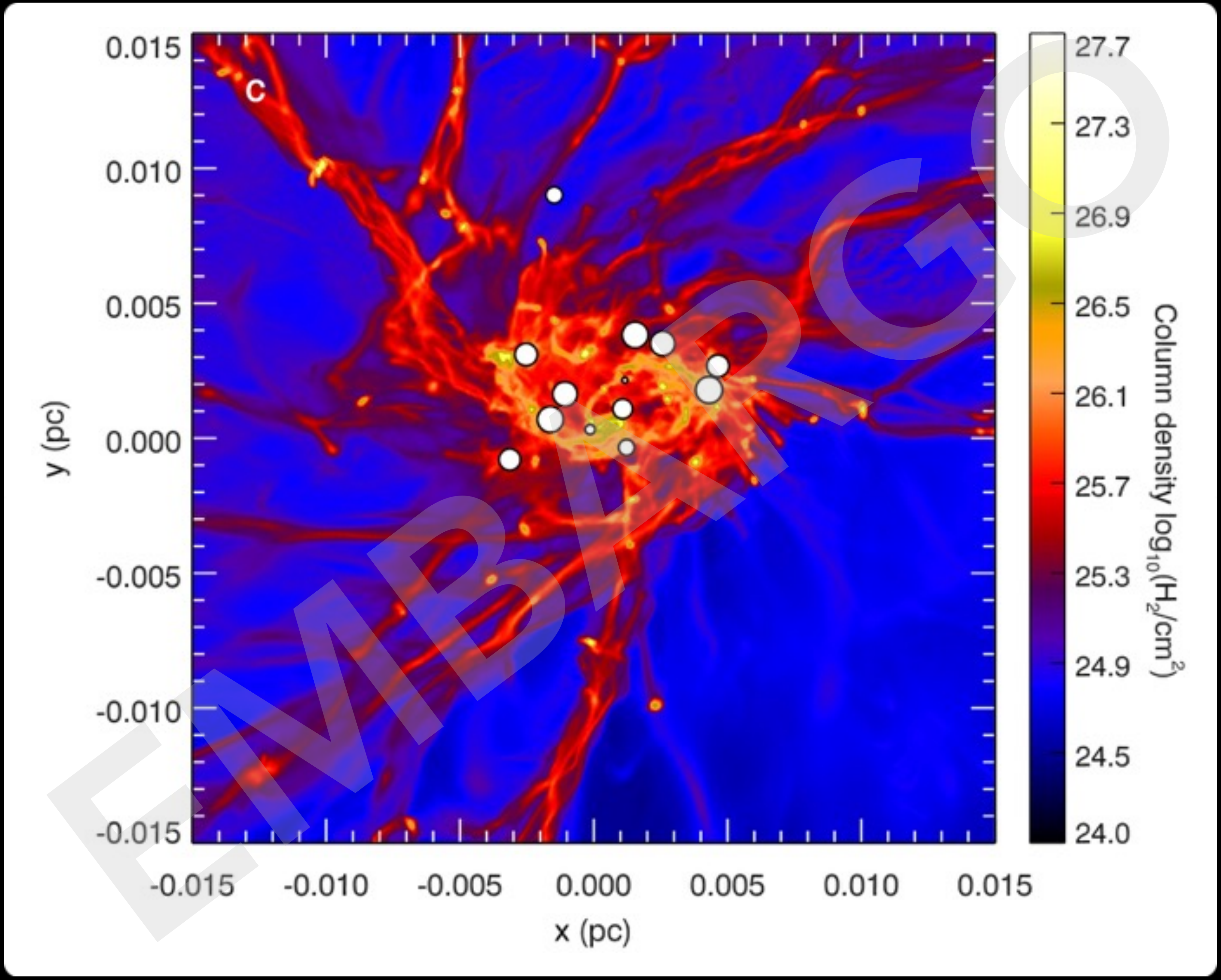
PROTO-CLUSTER FORMATION

3D SIMULATION RESULTS



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

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

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

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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