EXPLOSIONS AS TRIGGERS OF SEISMIC VIBRATIONS

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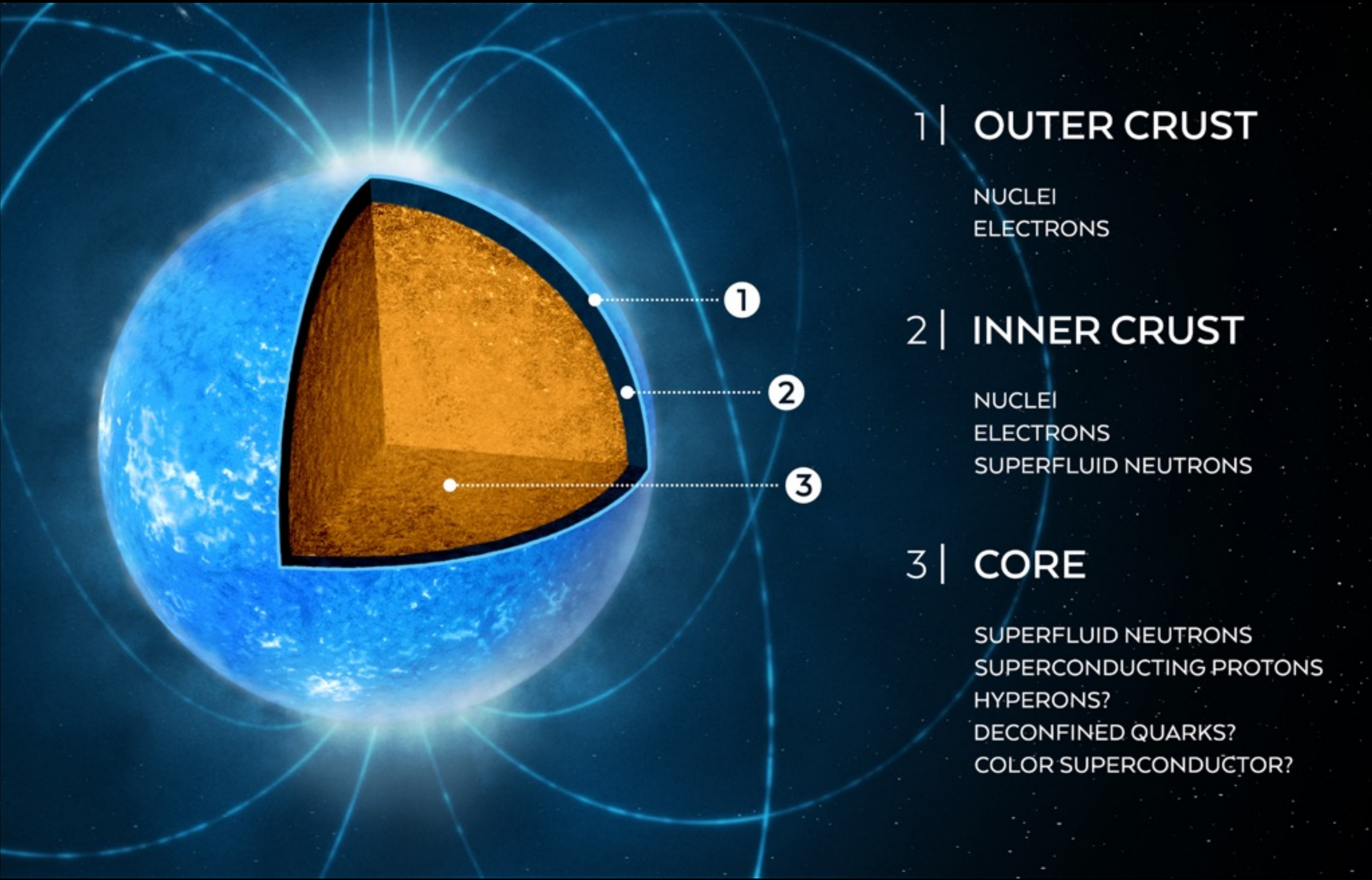


Figure from Watts et al. 2016

The neutron star ocean

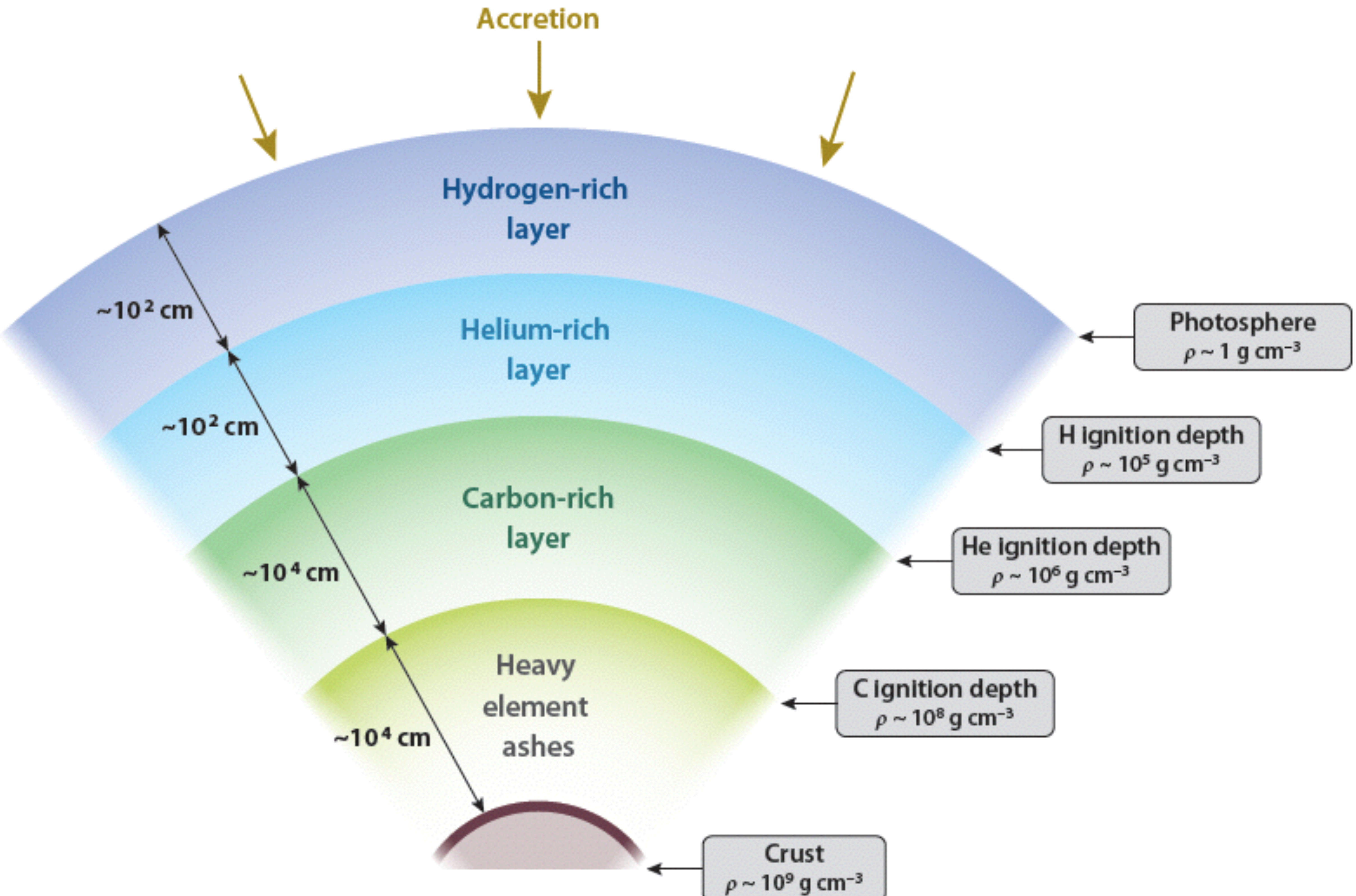
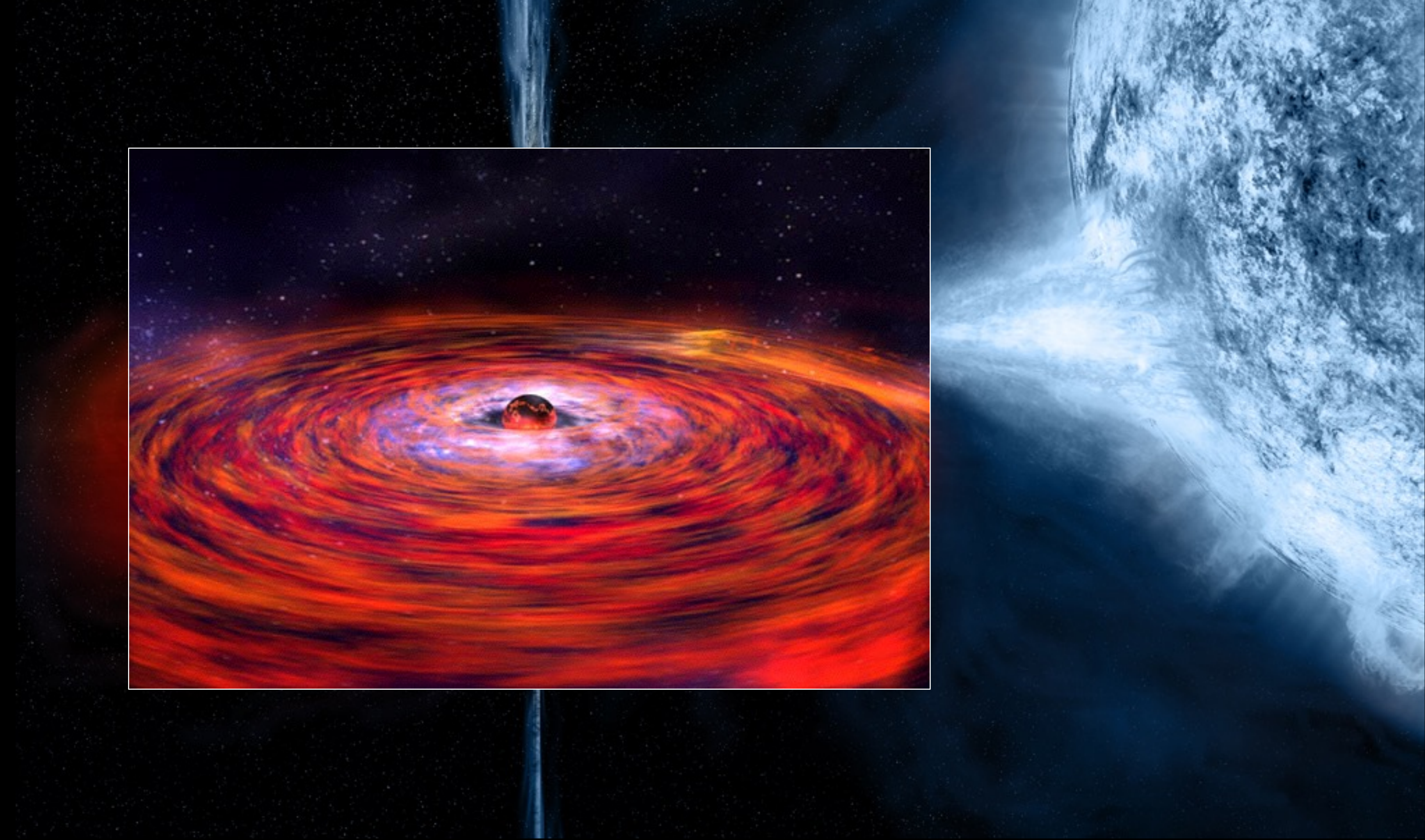


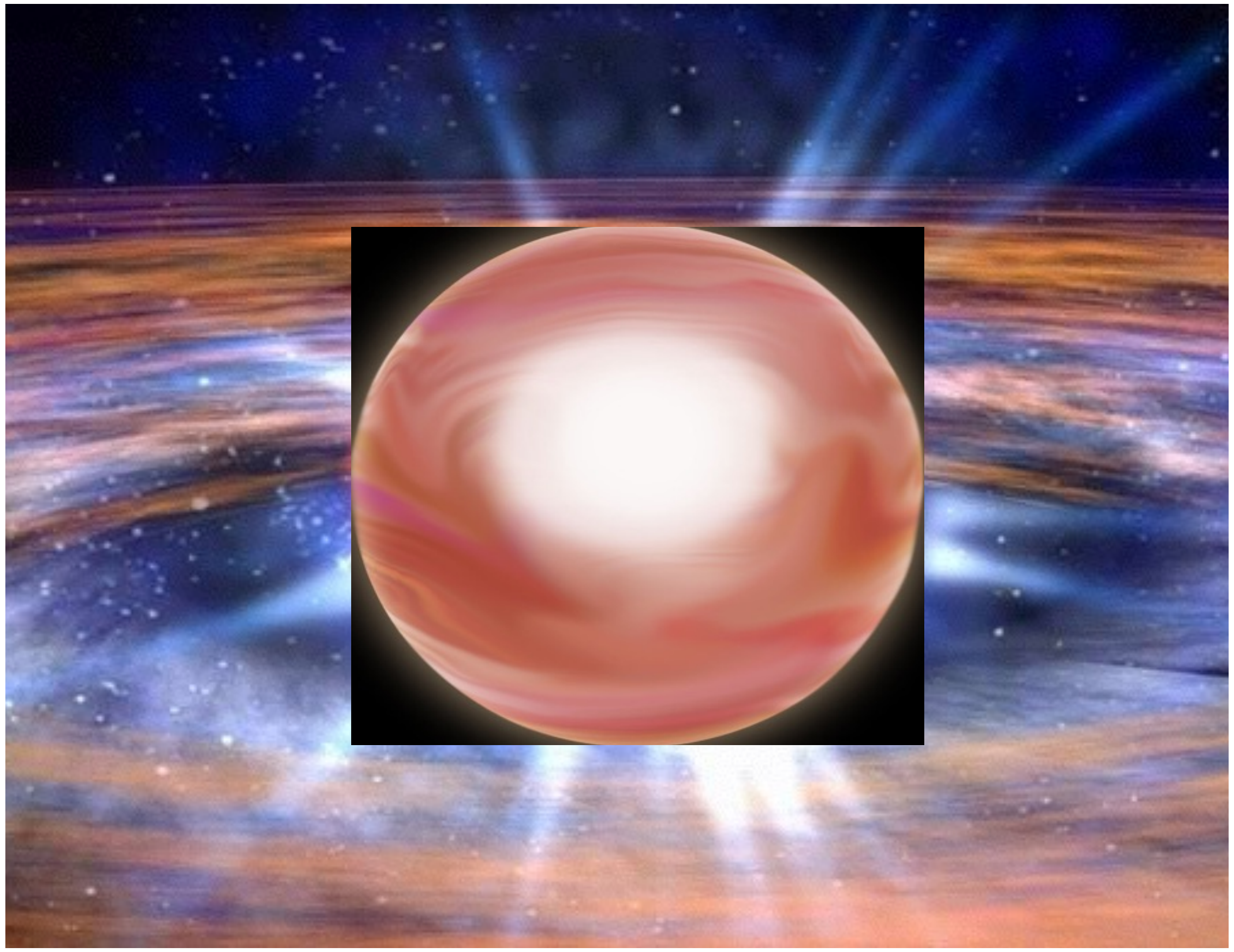
Figure from Watts 2012

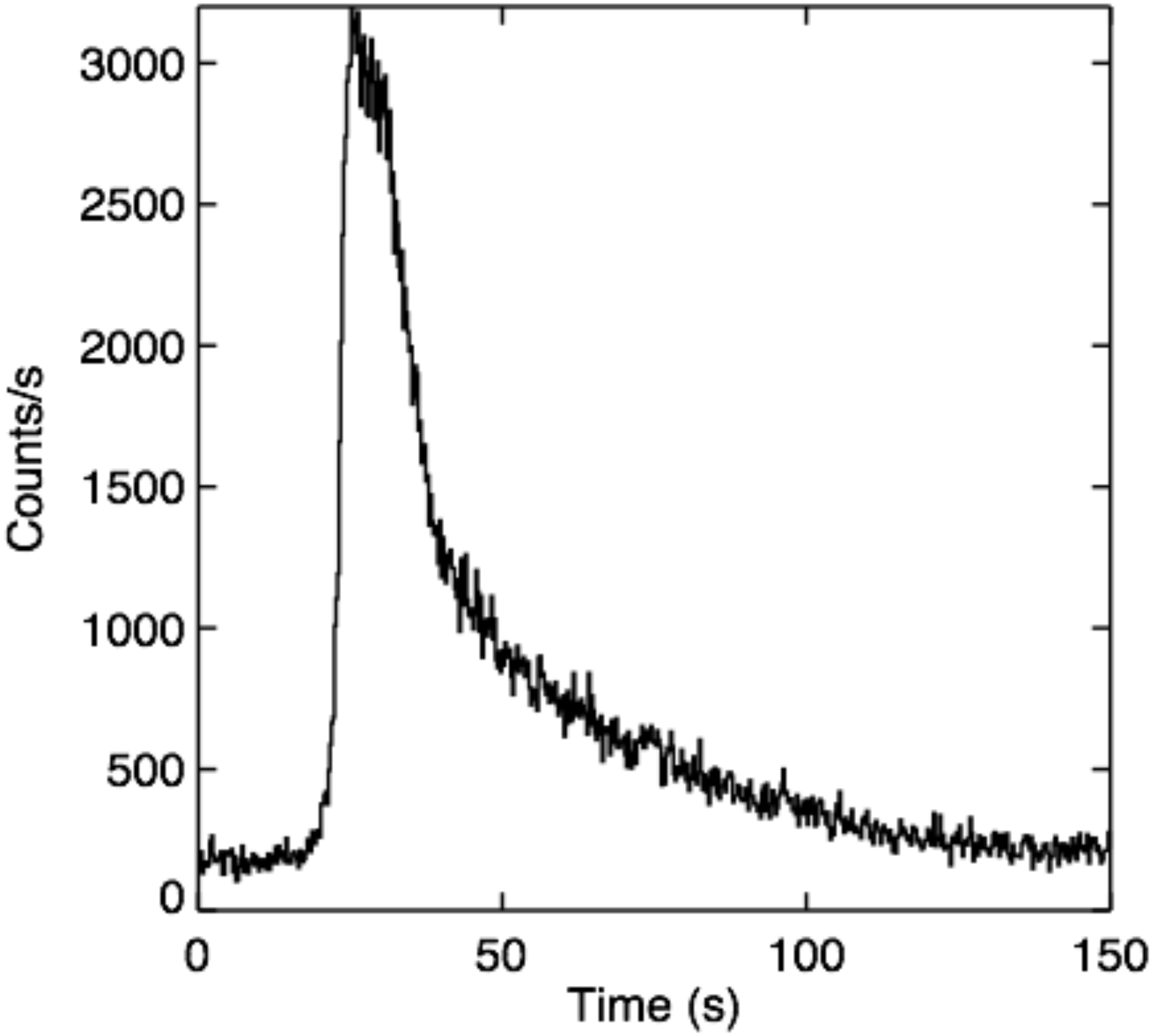
THERMONUCLEAR EXPLOSIONS AND OCEAN MODES



THERMONUCLEAR EXPLOSIONS AND OCEAN MODES

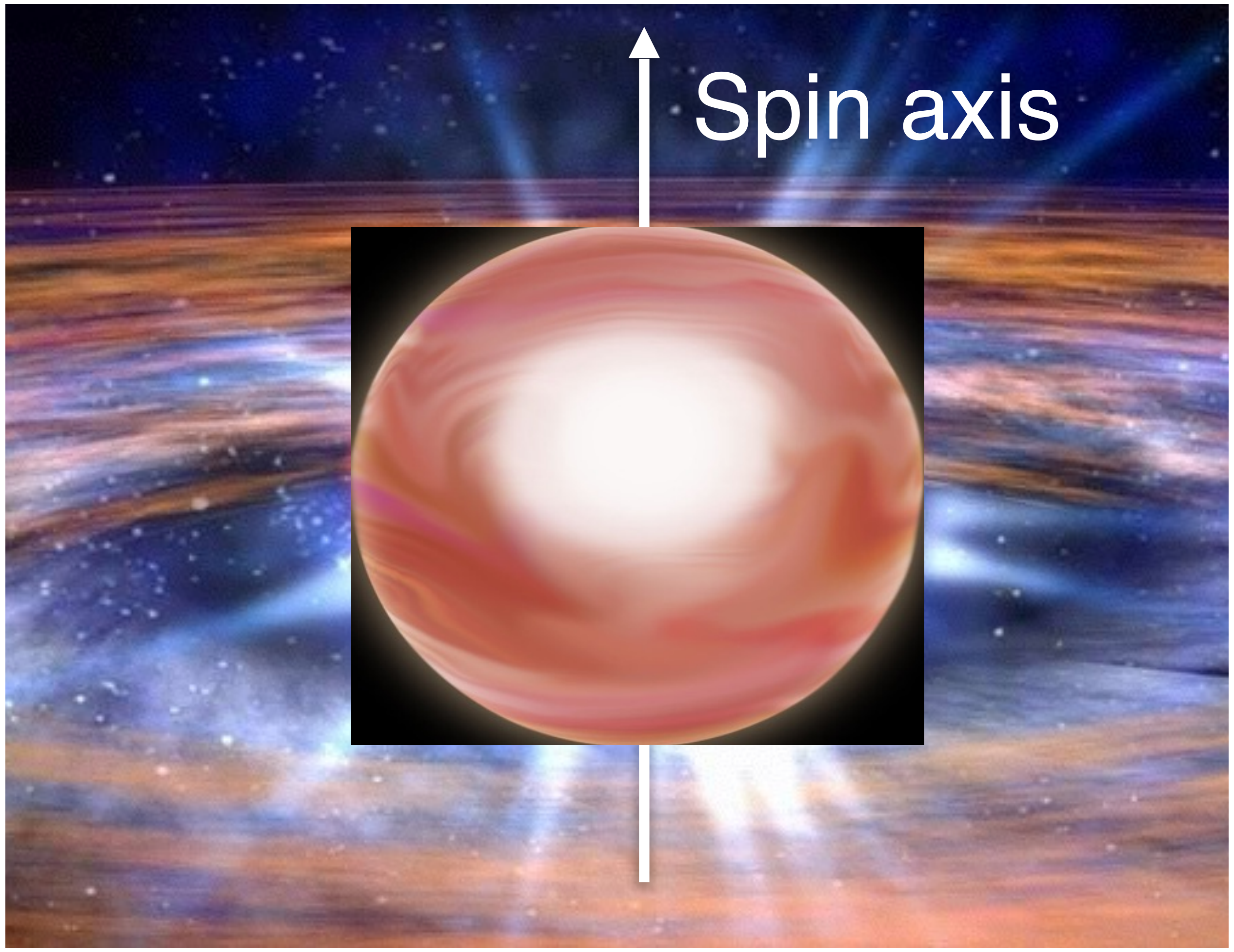
Burst oscillations

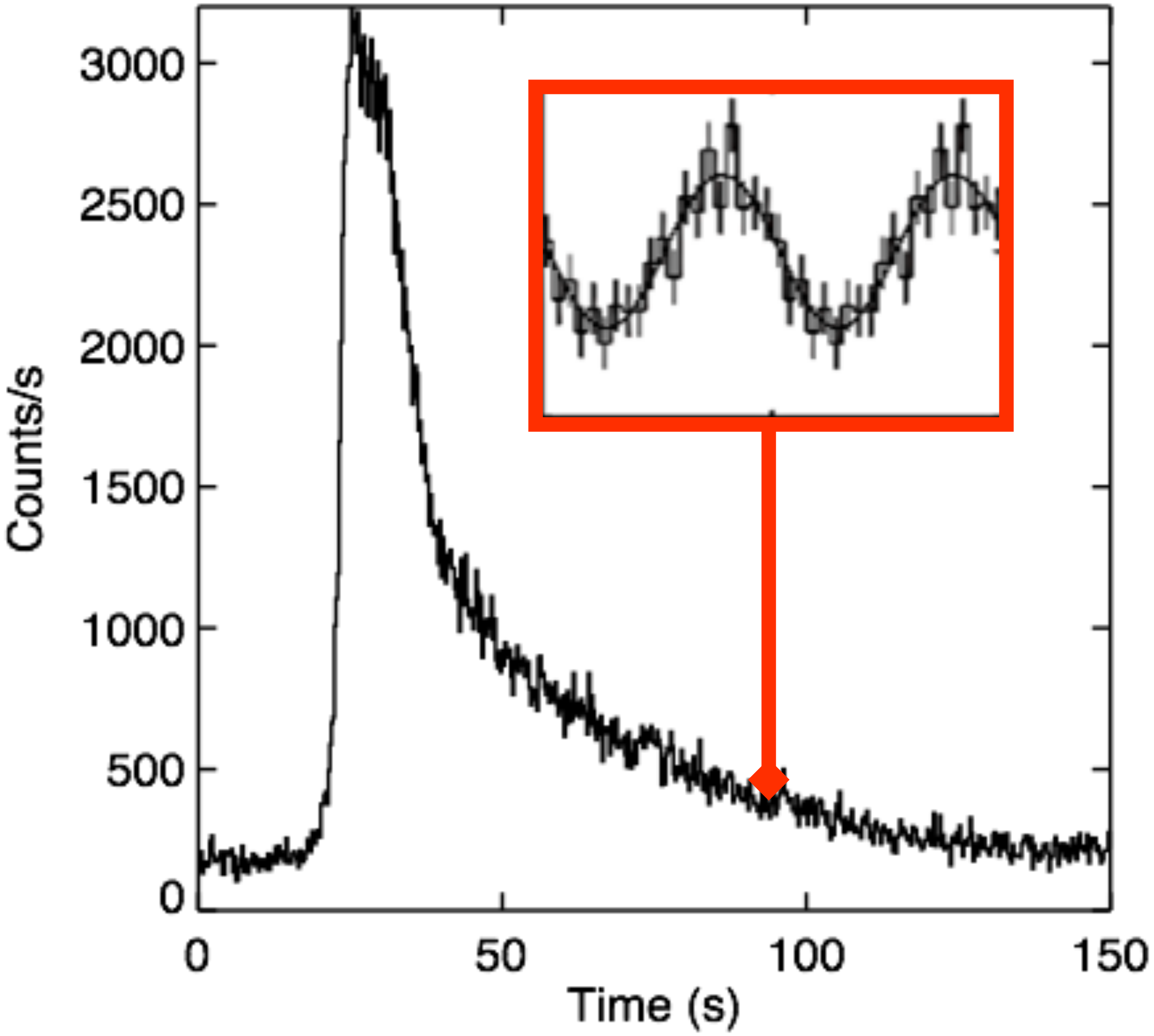




IN SOME BURSTS ANOMALOUSLY BRIGHT PATCHES FORM.
THESE ARE KNOWN AS BURST OSCILLATIONS

Burst oscillations

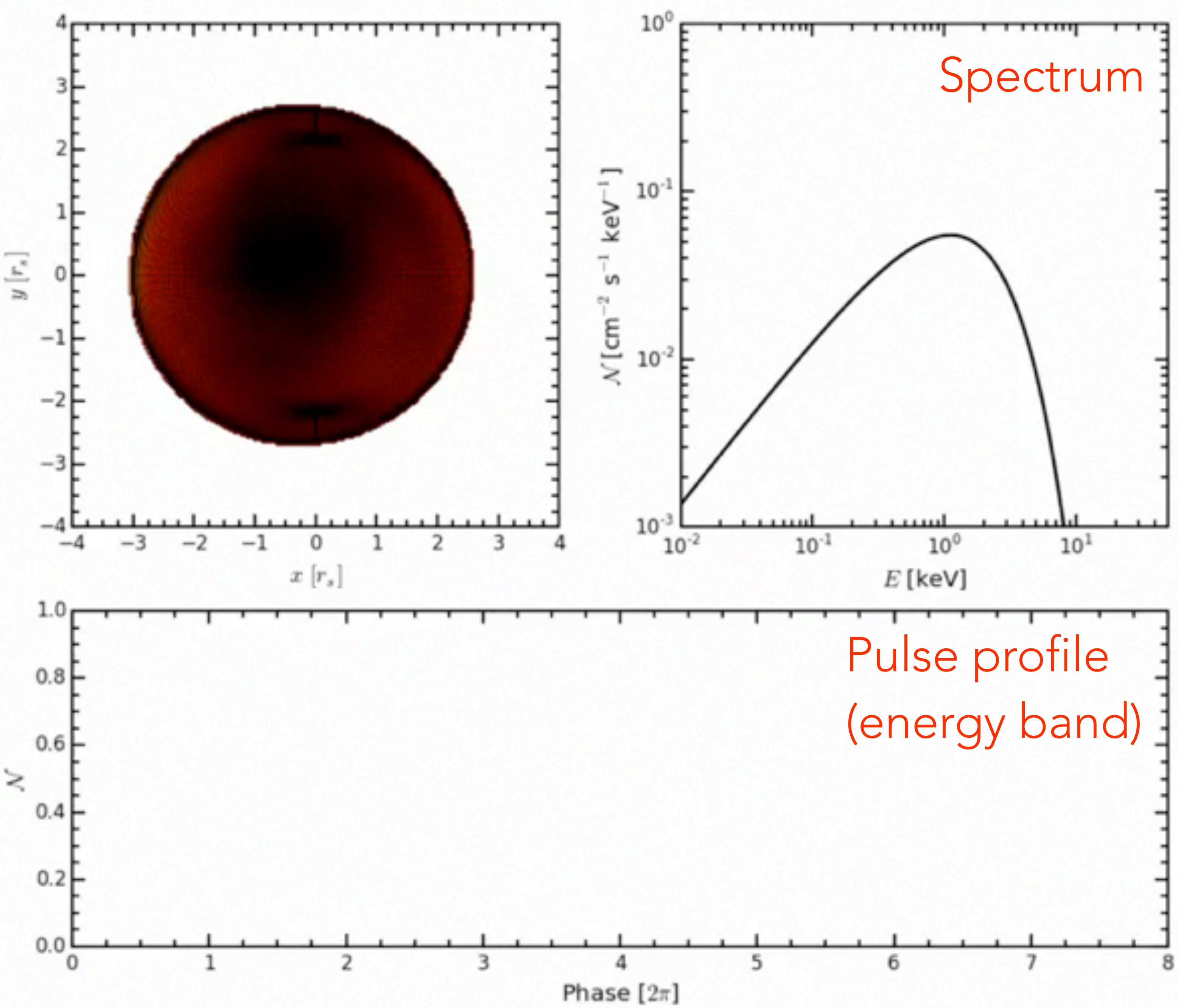




IN SOME BURSTS ANOMALOUSLY BRIGHT PATCHES FORM. THESE ARE KNOWN AS BURST OSCILLATIONS

Discovered in 1996 by Strohmayer et al., for review see Watts, ARAA, 2012

BY FITTING PULSE PROFILE PROPERTIES WE CAN RECOVER MASS AND RADIUS, WITHOUT NEEDING DISTANCE/COMPOSITION.



ıulations (Hartle-Thorne spacetime)
by Tom Riley

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HOWEVER WE DO NOT (YET) UNDERSTAND THE MECHANISM RESPONSIBLE FOR GENERATING BURST OSCILLATIONS. THIS MEANS UNDERLYING SURFACE PATTERN IS UNCERTAIN.

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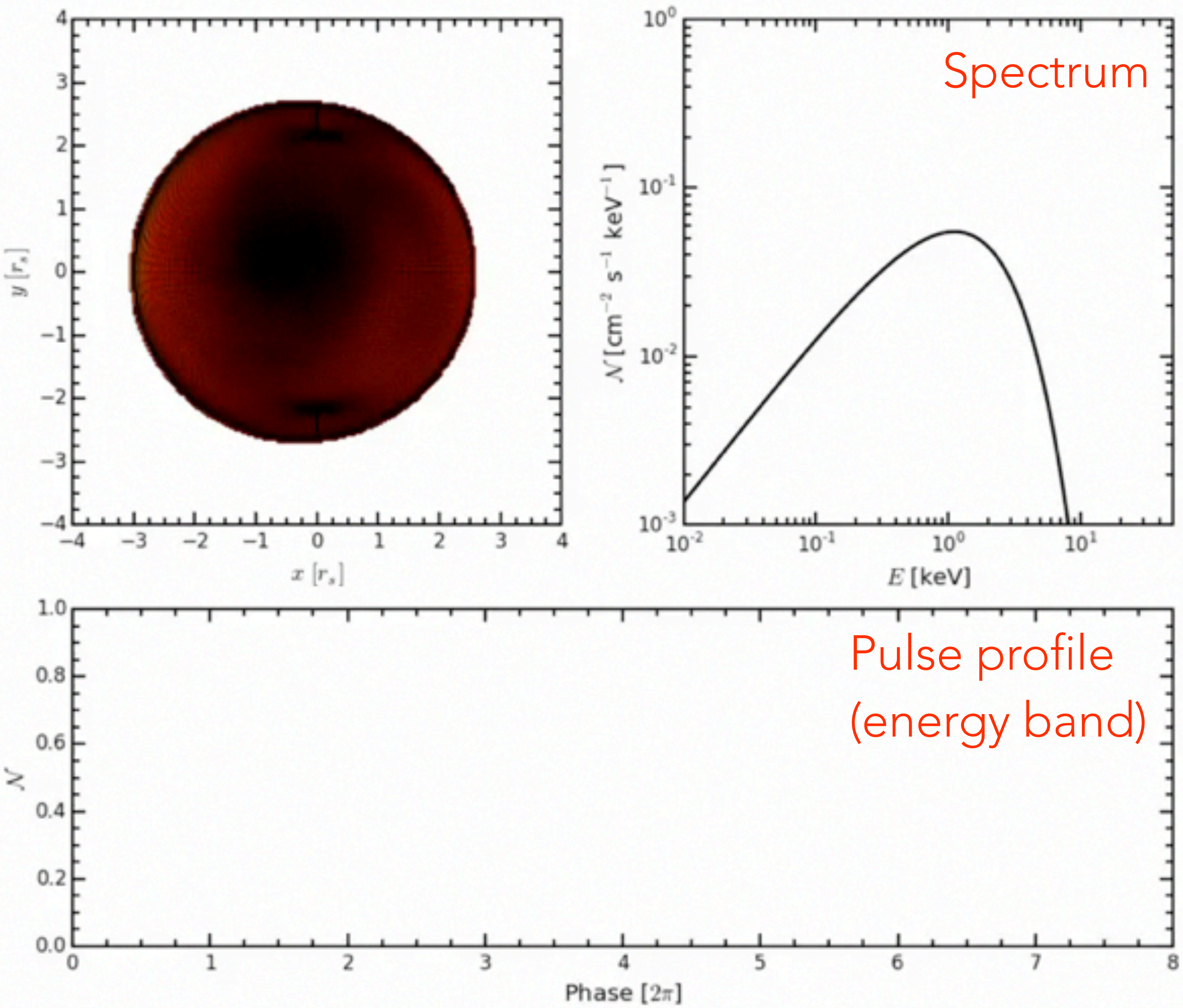

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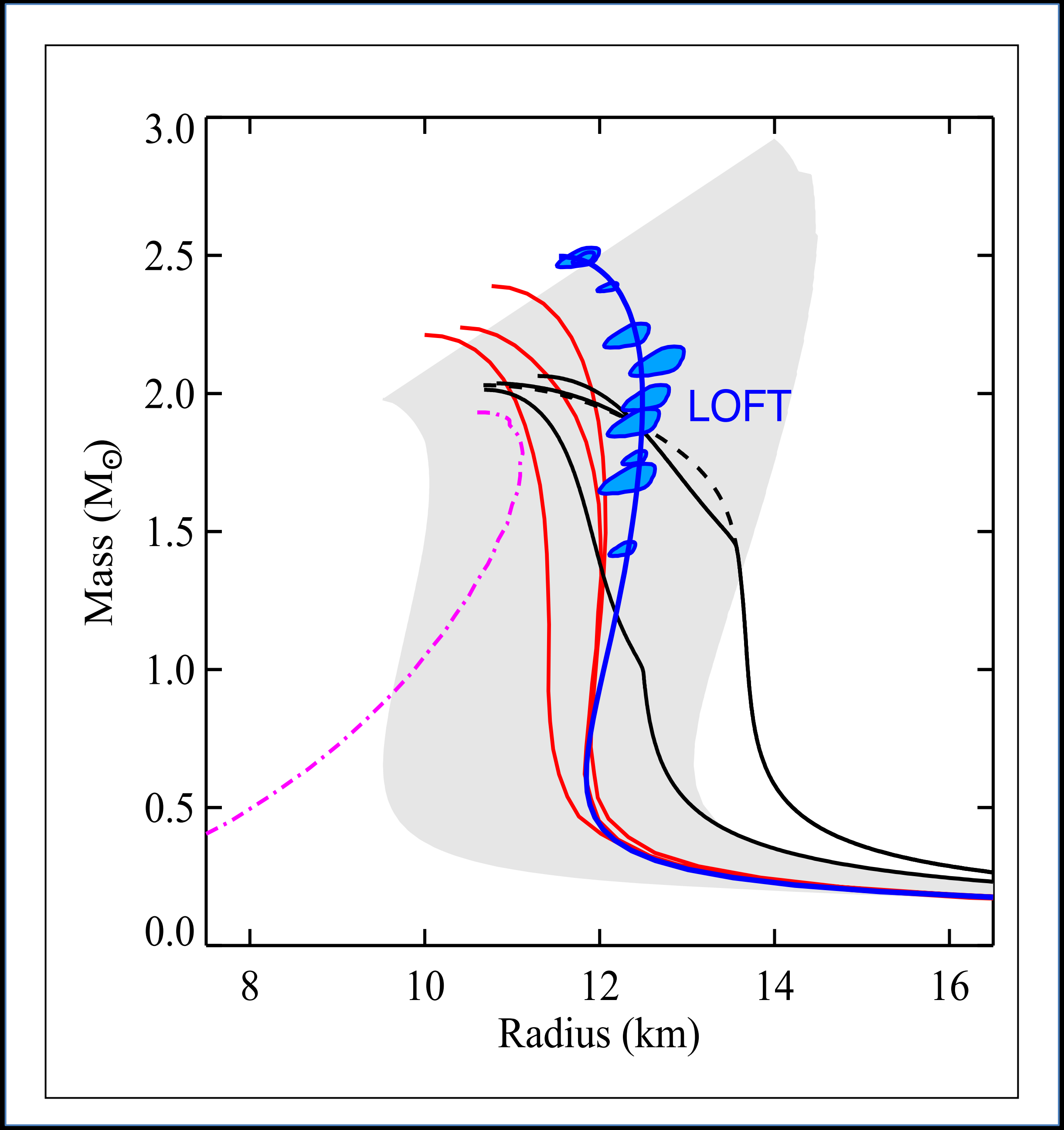
Hard X-ray telescope concepts

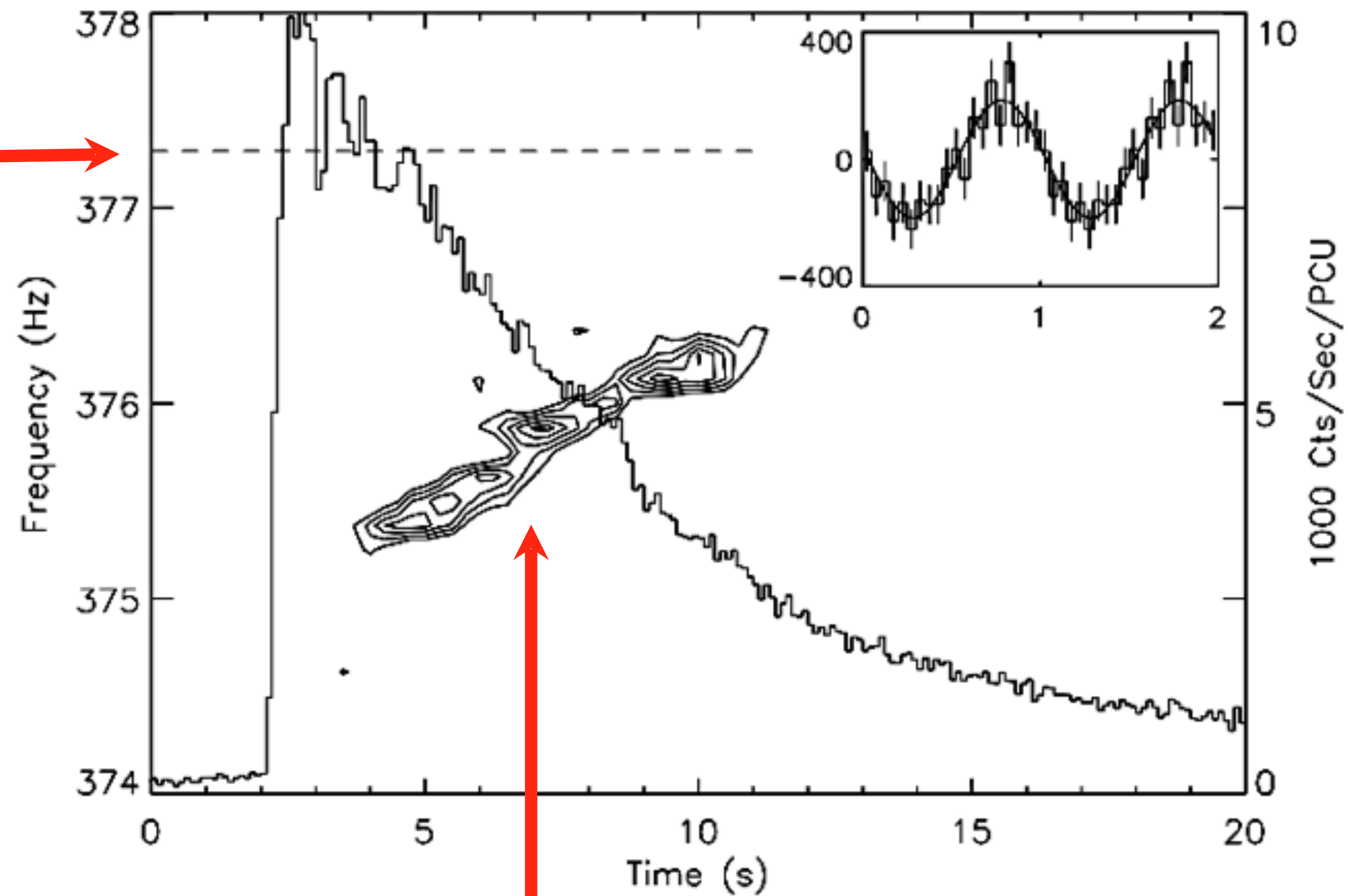
Hard X-ray opens up new source classes with reduced systematics, and more options for cross-checks.



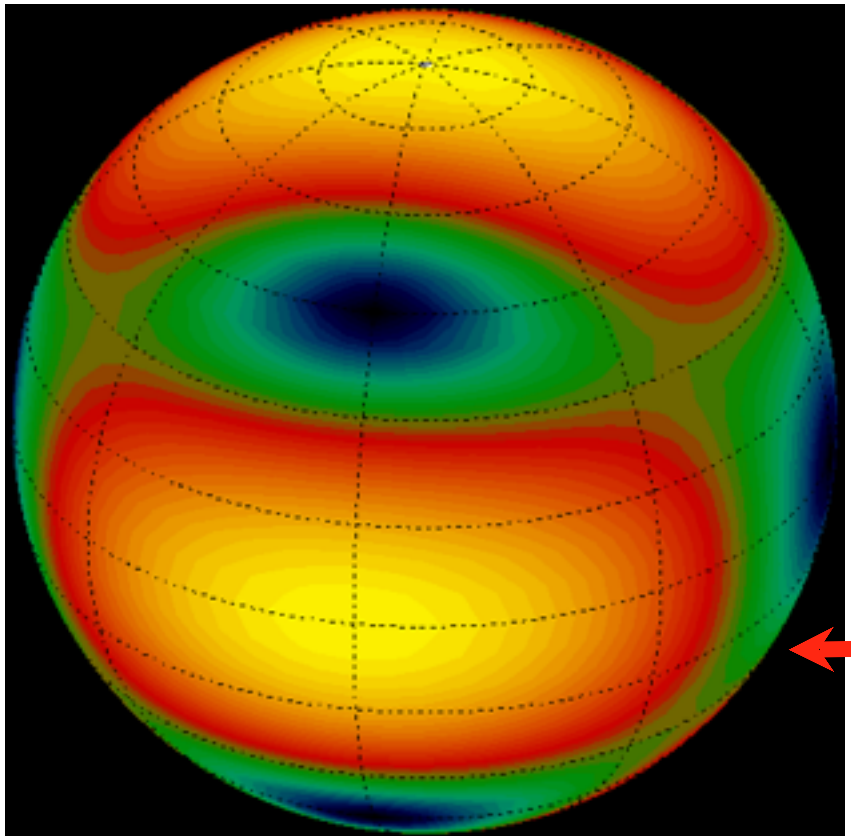
- Large Observatory for X-ray Timing (LOFT/LOFT-P), ESA M-class/NASA PROBE candidate
  - ~10 m^2 hard X-ray
  - Targets burst oscillation sources
  - See Watts et al. 2016, Reviews of Modern Physics Colloquium
- Enhanced XTP – Chinese Academy of Sciences/European concept
  - ~1m^2 soft X-ray + polarimeter
  - ~3m^2 hard X-ray
  - Polarimeter helps to offset impact of area reduction
  - Targets accretion-powered millisecond pulsars, especially those with burst oscillations

Relation to spin frequency

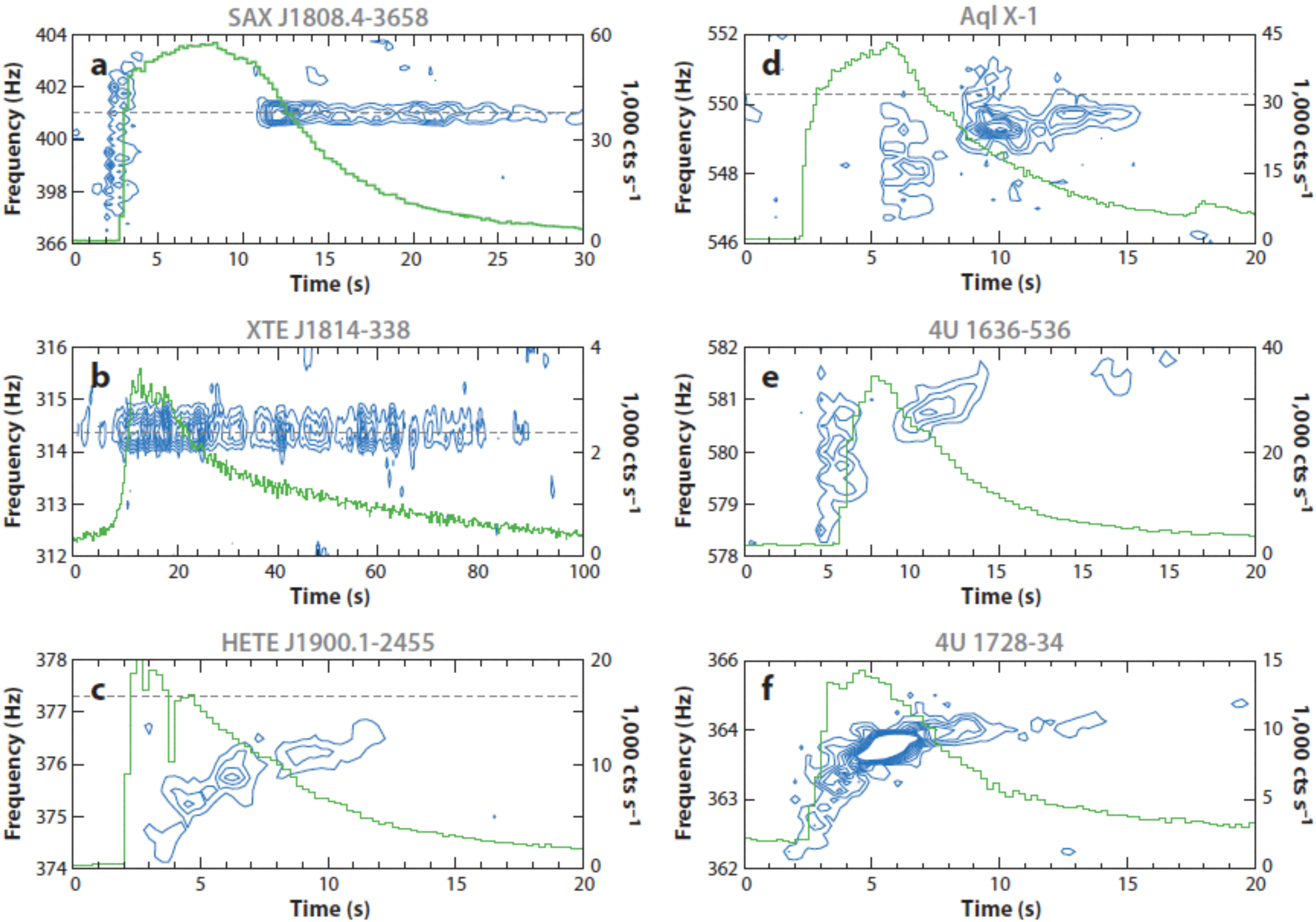
Spin frequency



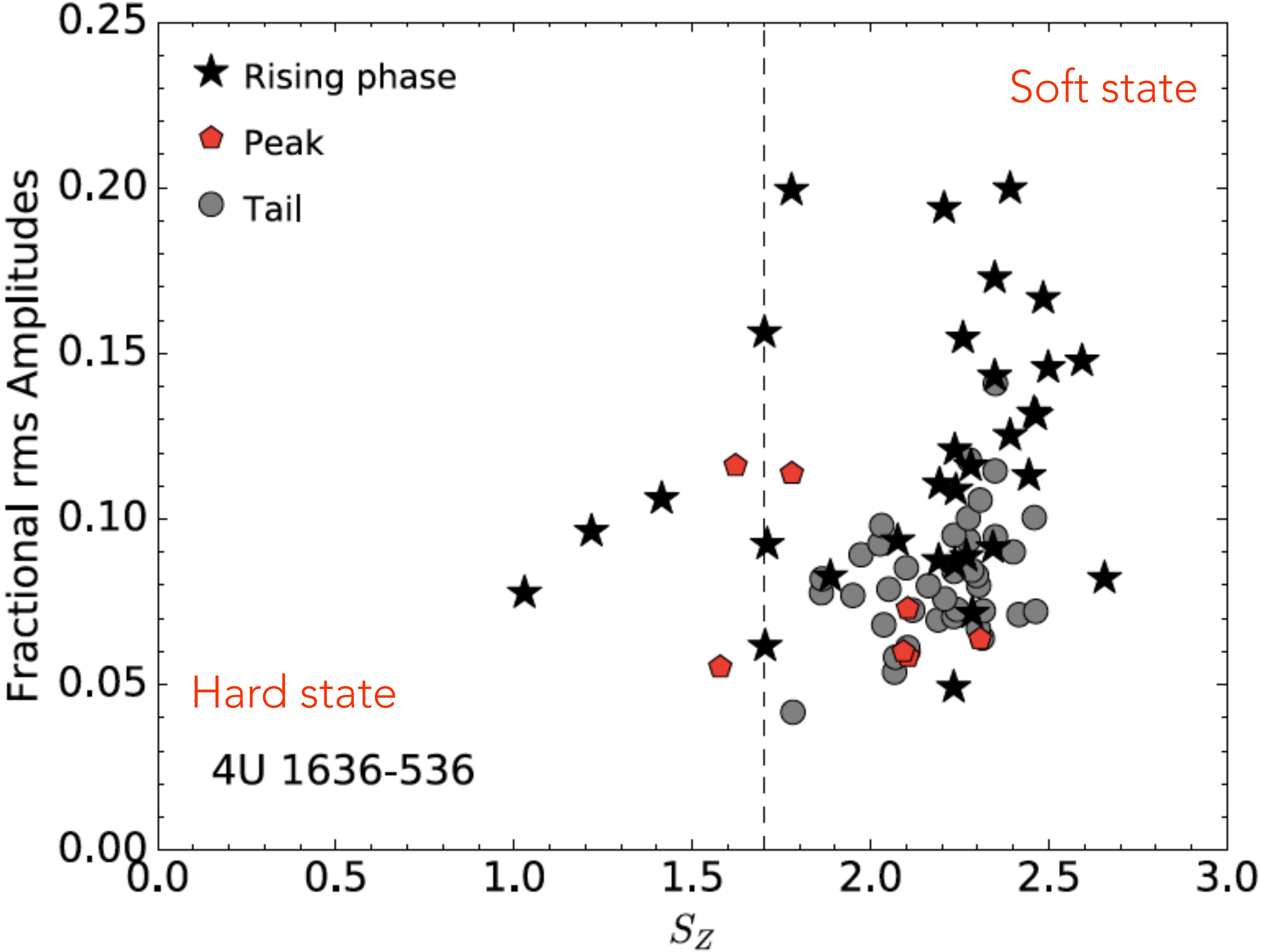
Intermittent accretion-powered pulsar, HETE J1900.1-2455, Watts et al. 2009



Drifting hotspot

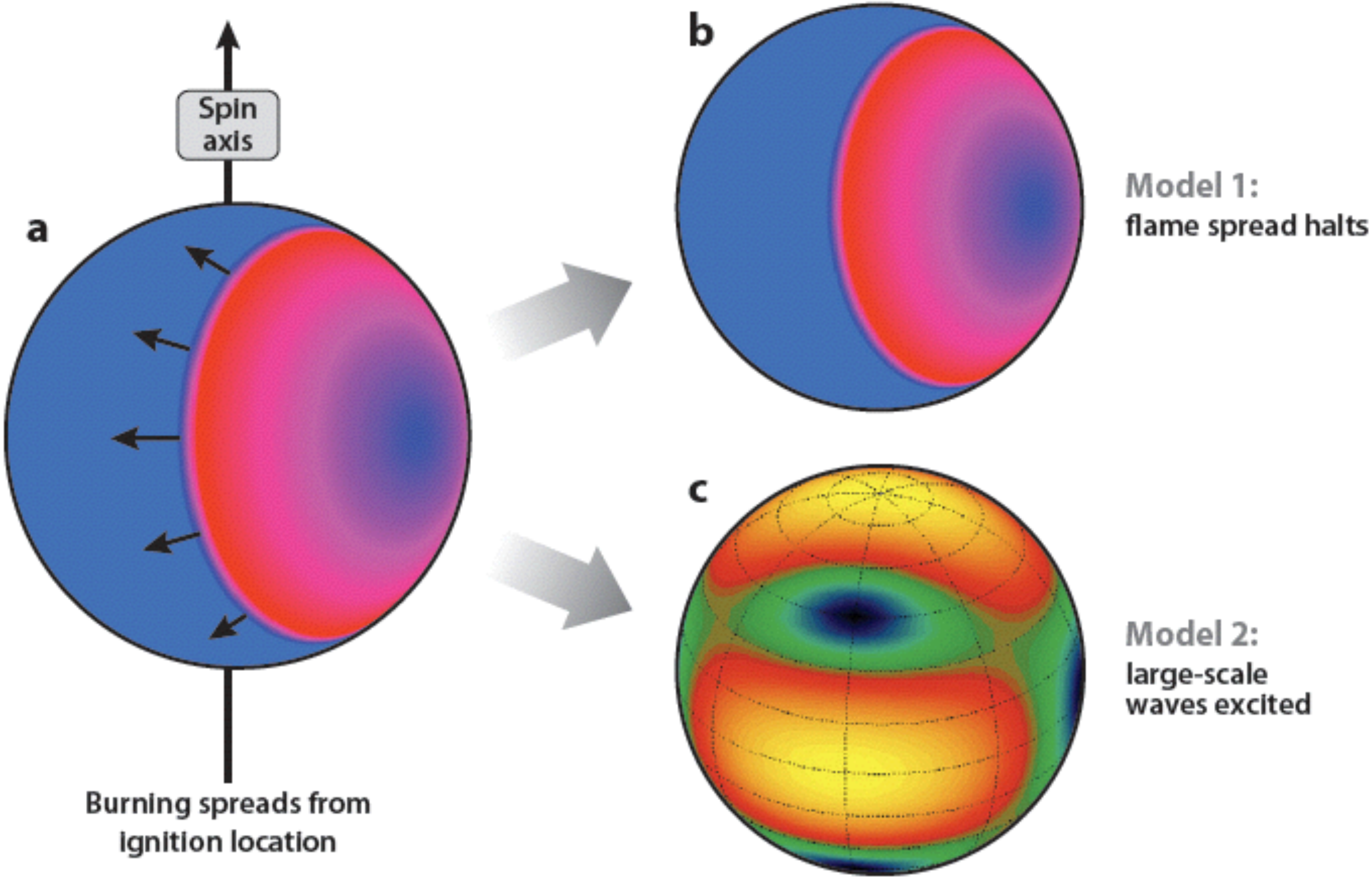


Watts 2012. Burst oscillations also seen in a superburst (Strohmayer & Markwardt 2002, see Simin's talk)



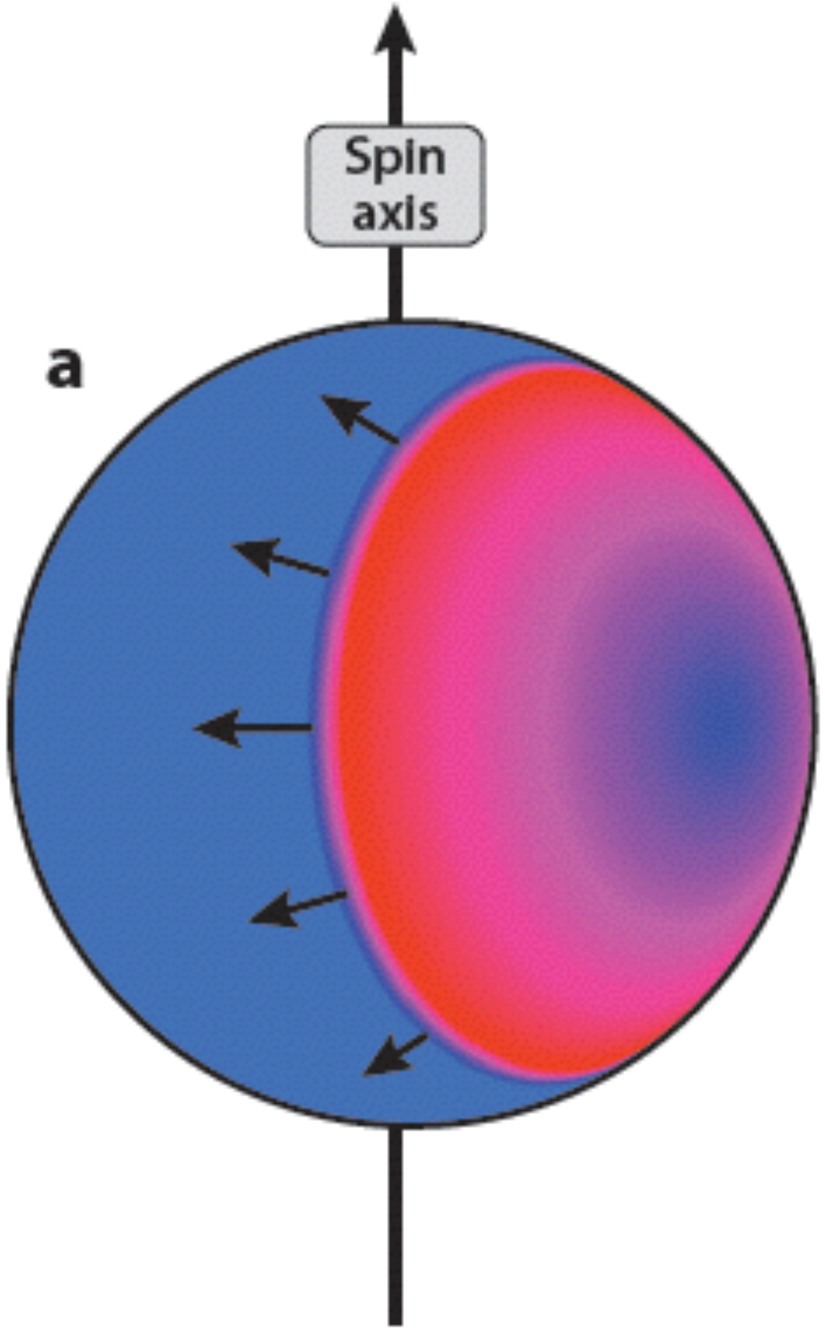
Strongest amplitude dependence on accretion state,
Ootes, Watts, Galloway & Wijnands 2016

Burst oscillation models



Watts 2012

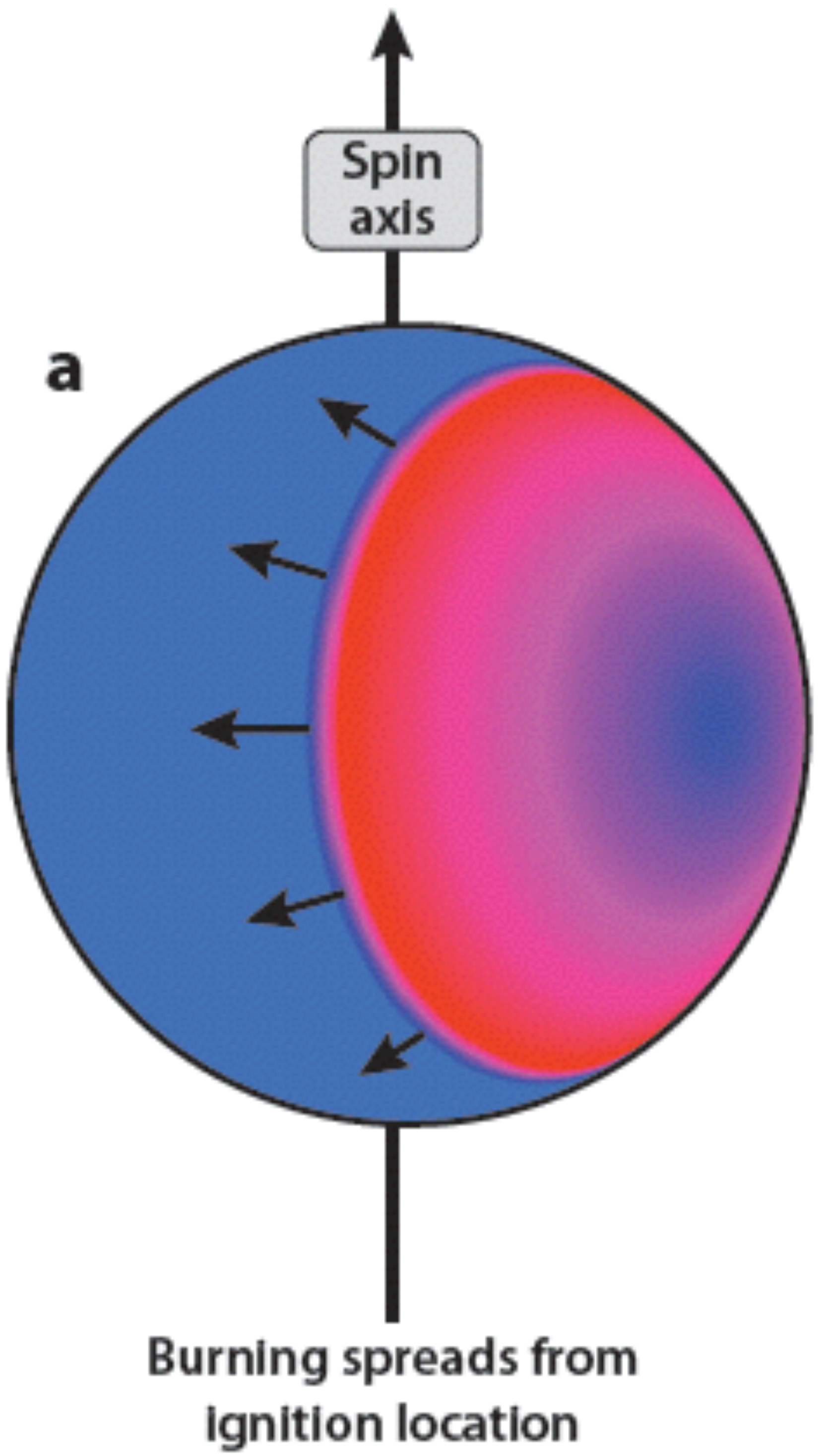
Burst oscillation models



Where does ignition take place?

- Equator, where local accretion rate is highest (Spitkovsky et al. 02)?
- Off-equator near burning regime boundaries (Cooper & Narayan 07, Maurer & Watts 08)?
- Magnetic pole ignition (Watts et al. 08, Cavecchi et al. 11)?
- Importance of (Coriolis) confinement (Cavecchi et al. 15).

Burst oscillation models



How does flame spread?

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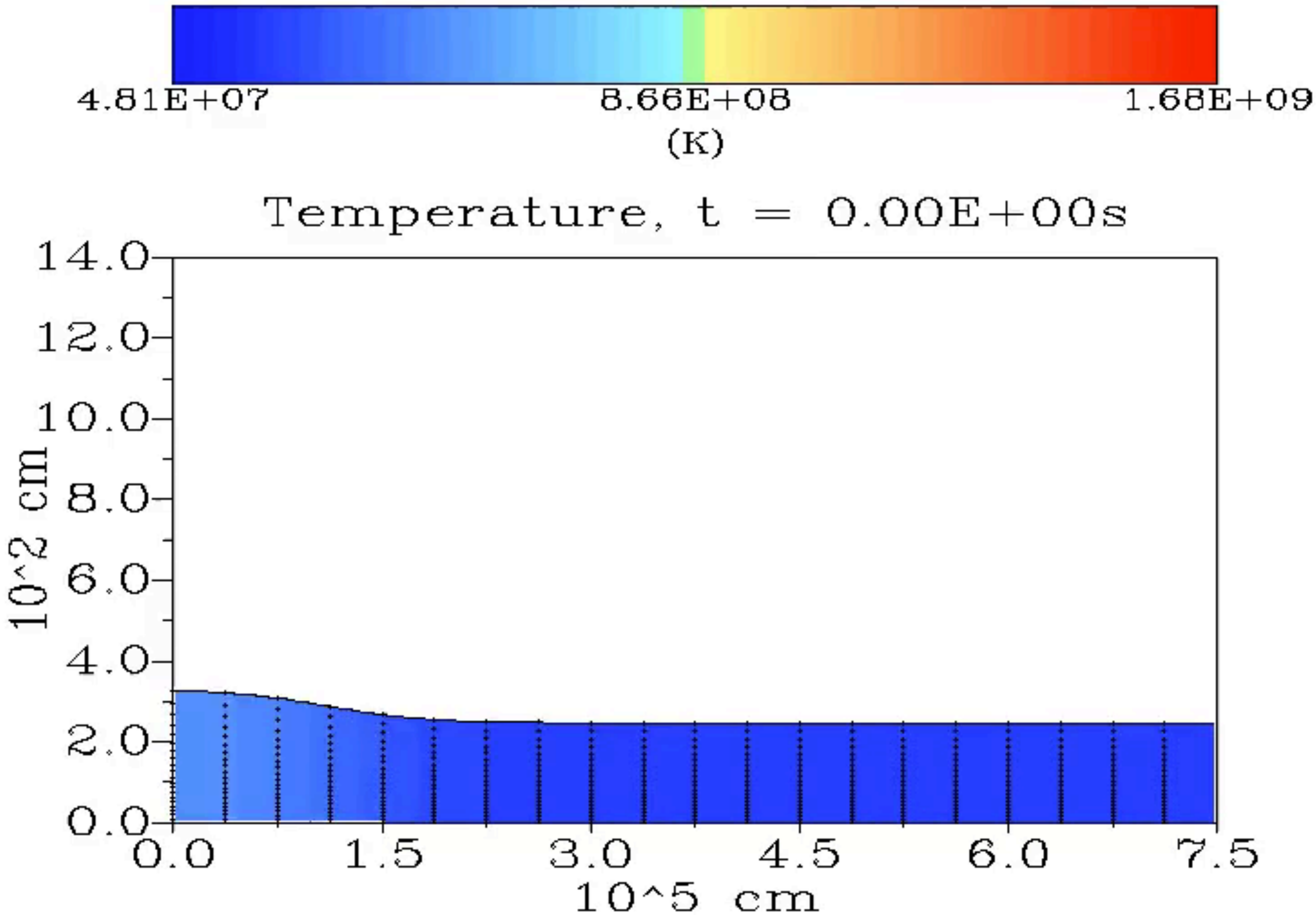
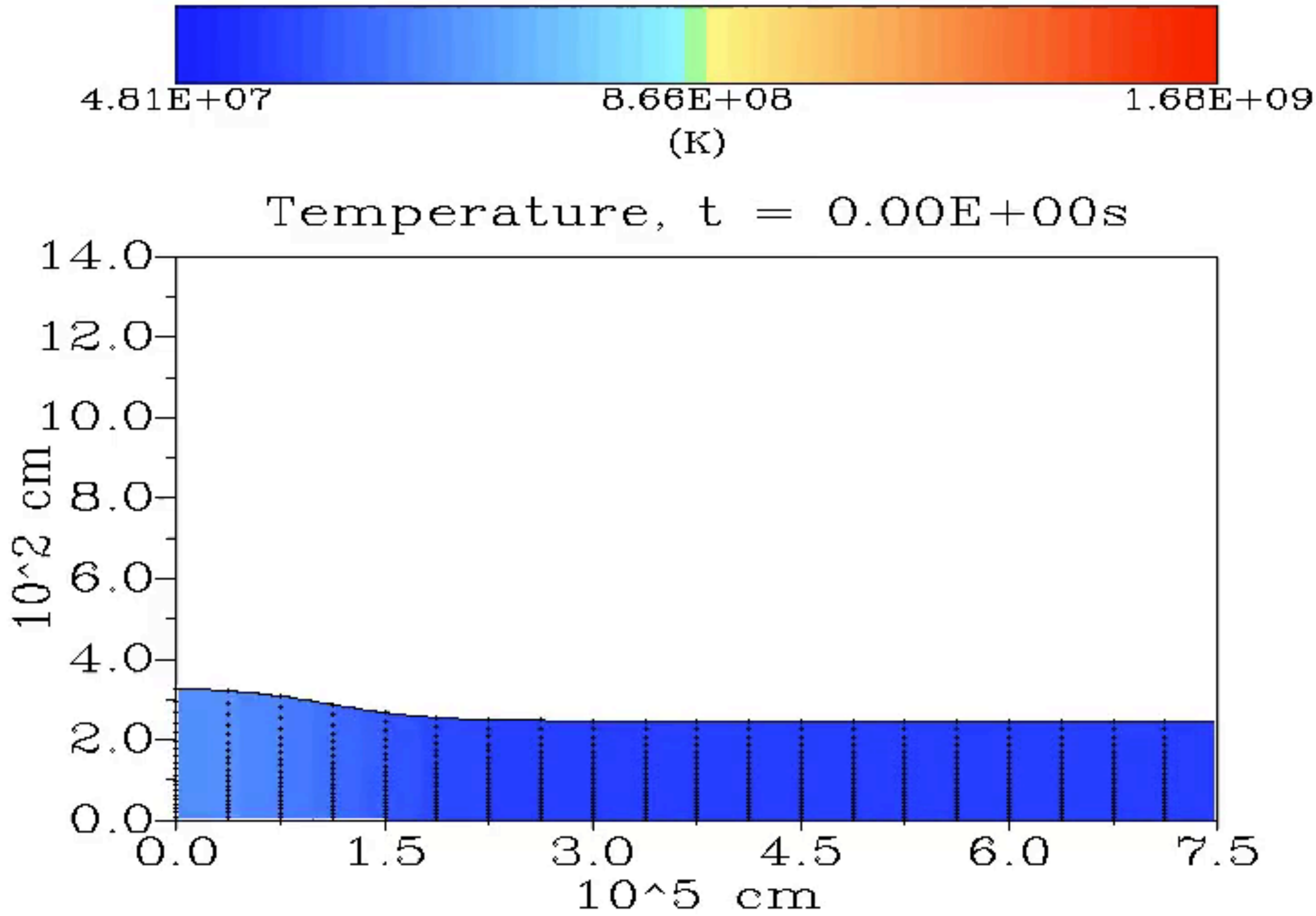


Cavecchi et al. 2013: fixed Coriolis parameter.



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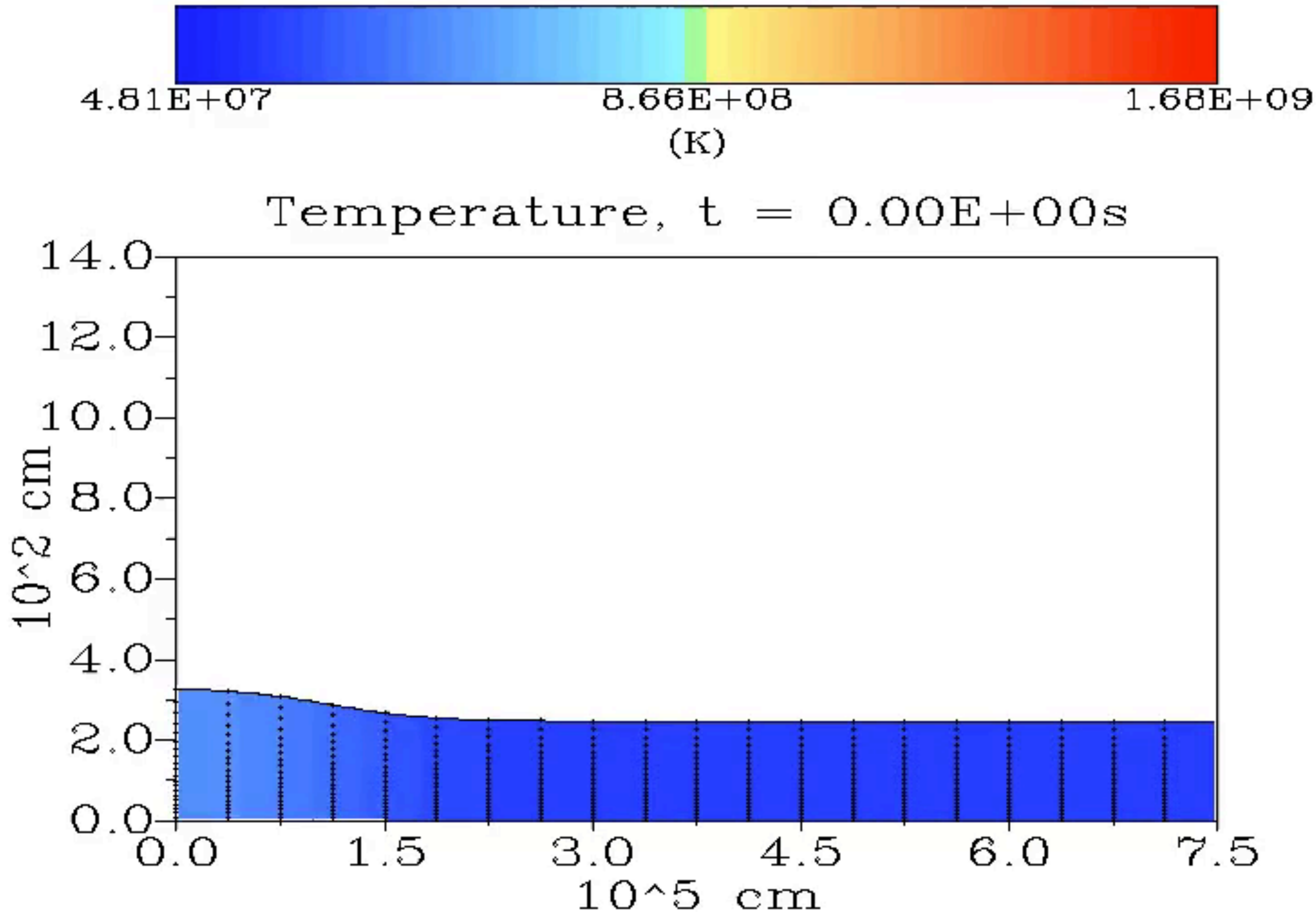

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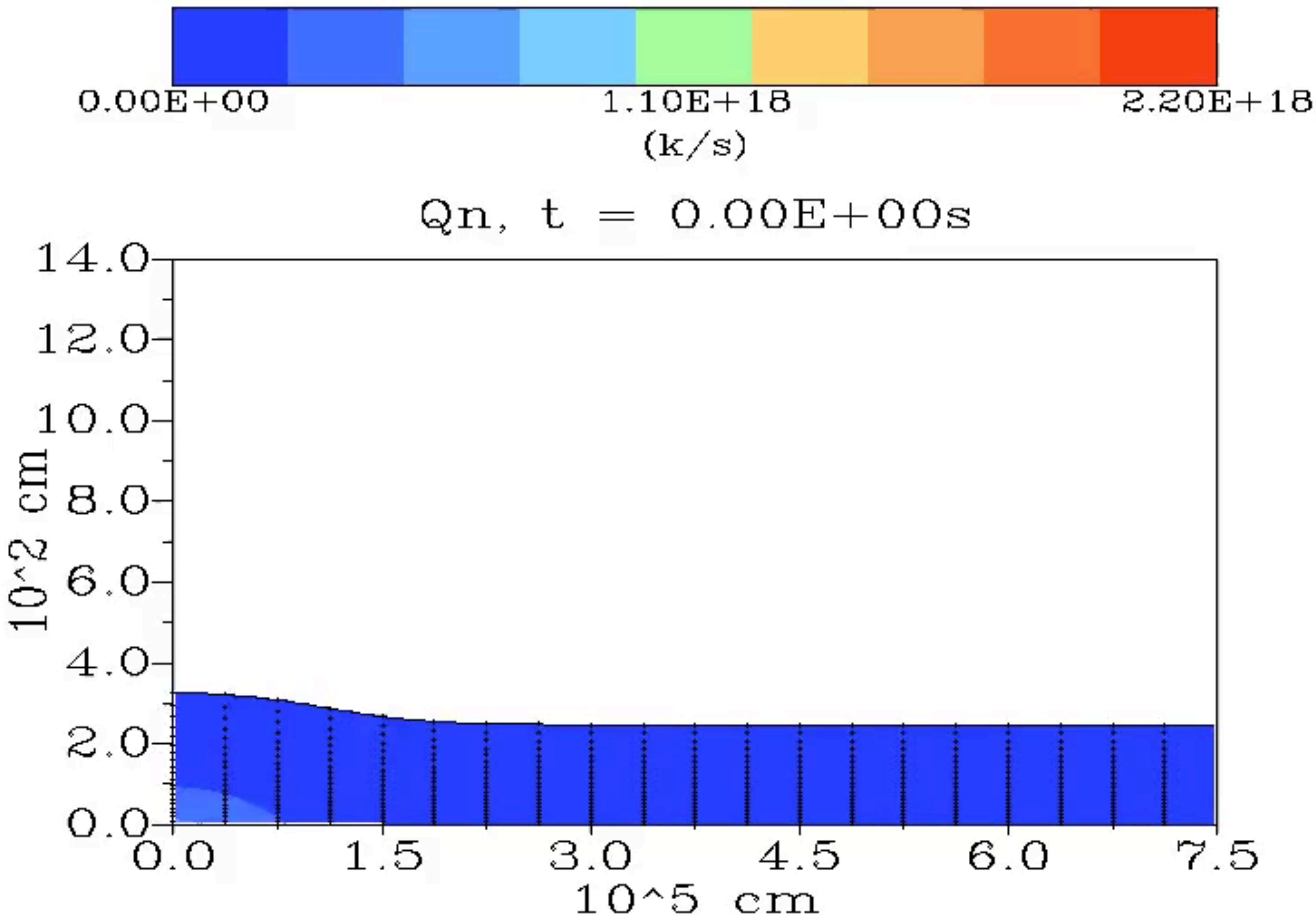

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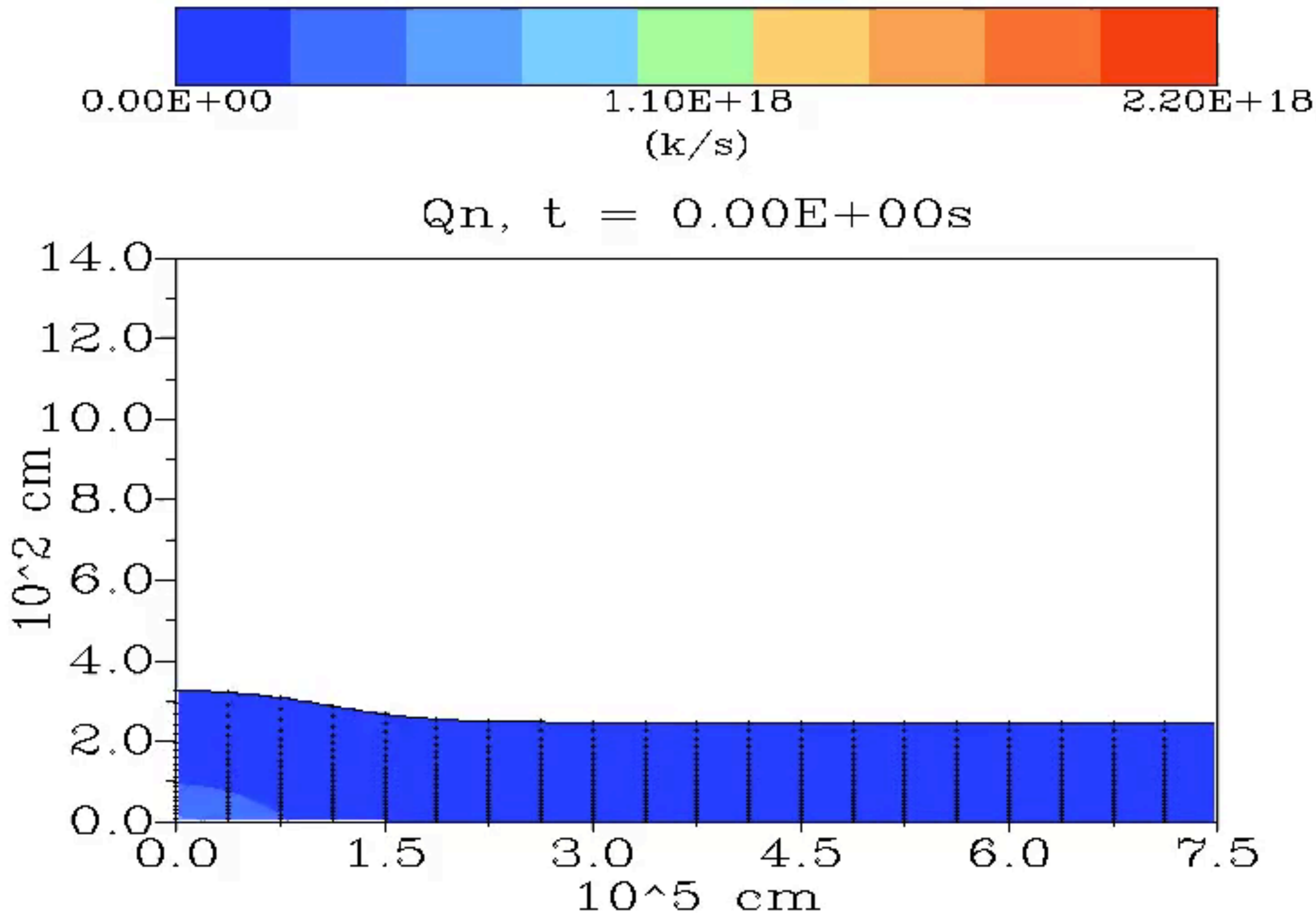

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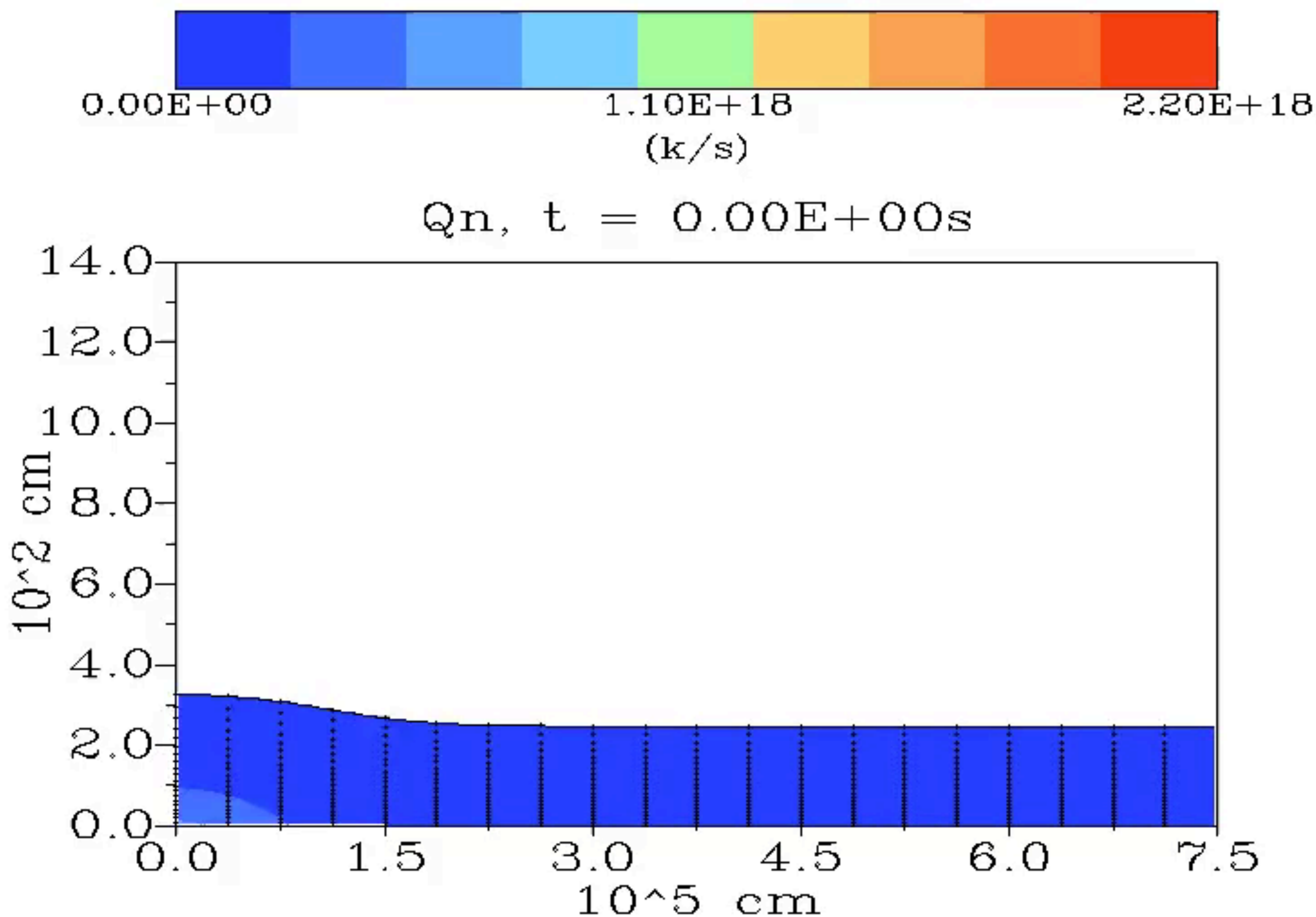

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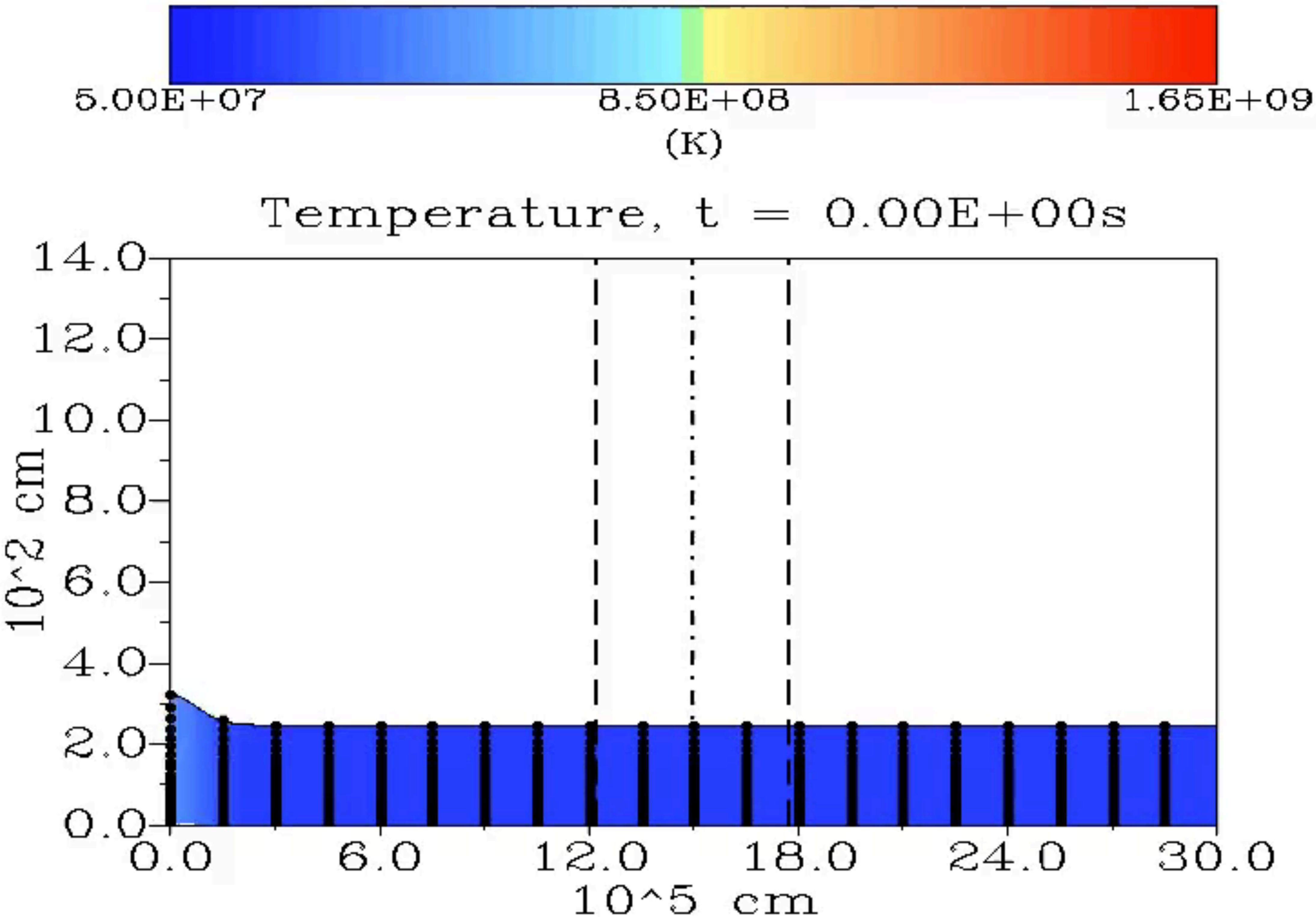
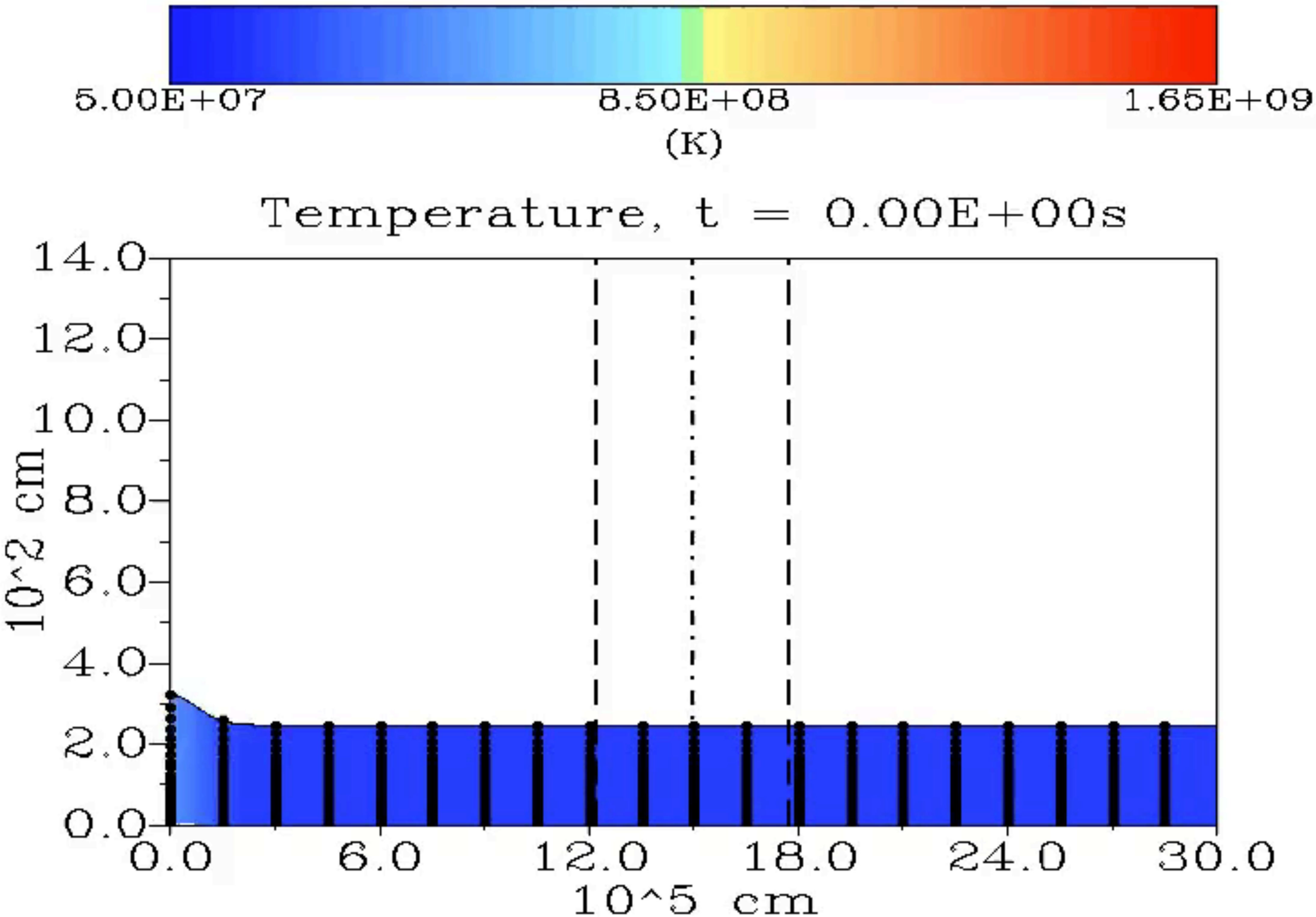


Cavecchi et al. 2015: varying Coriolis parameter



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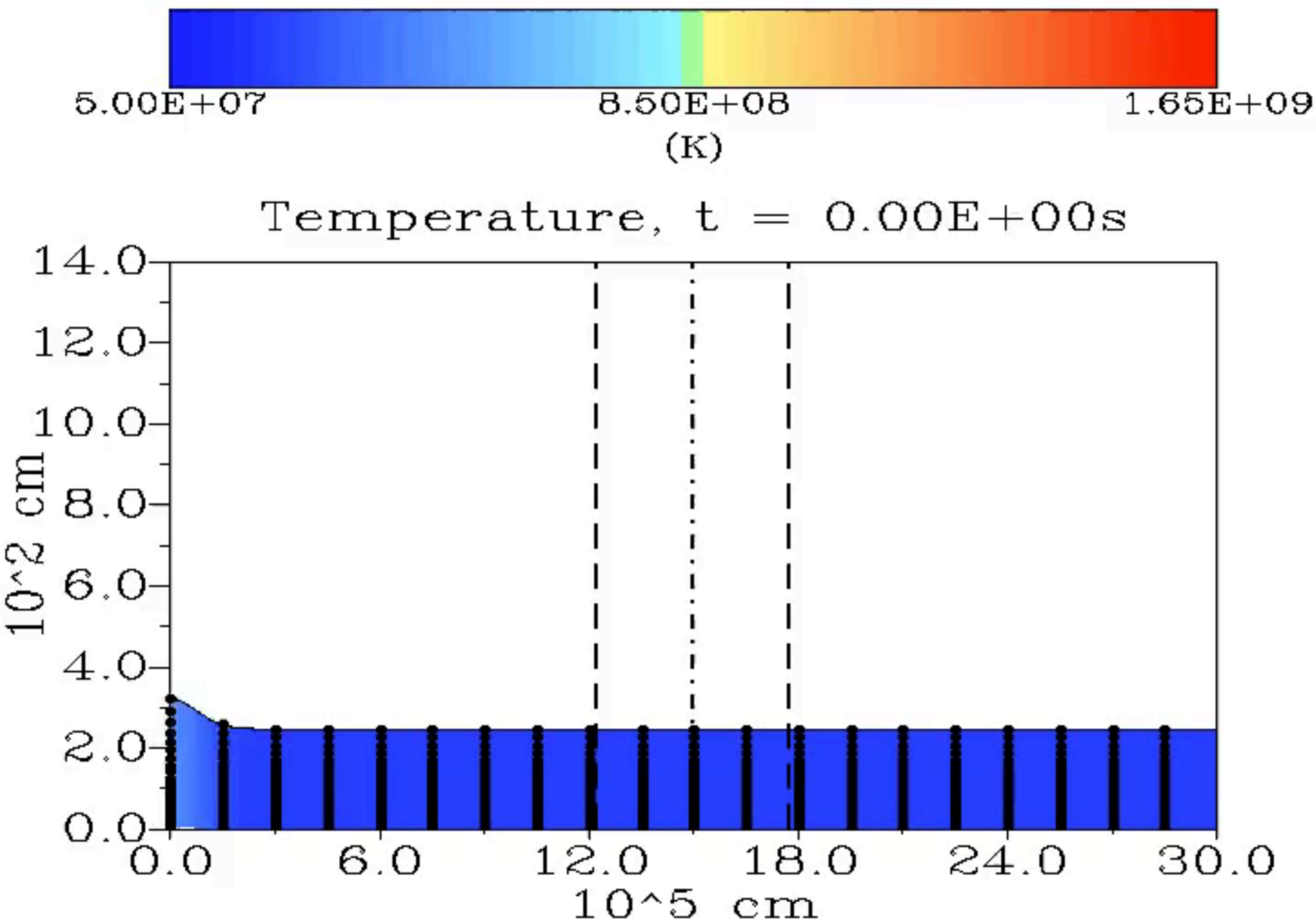

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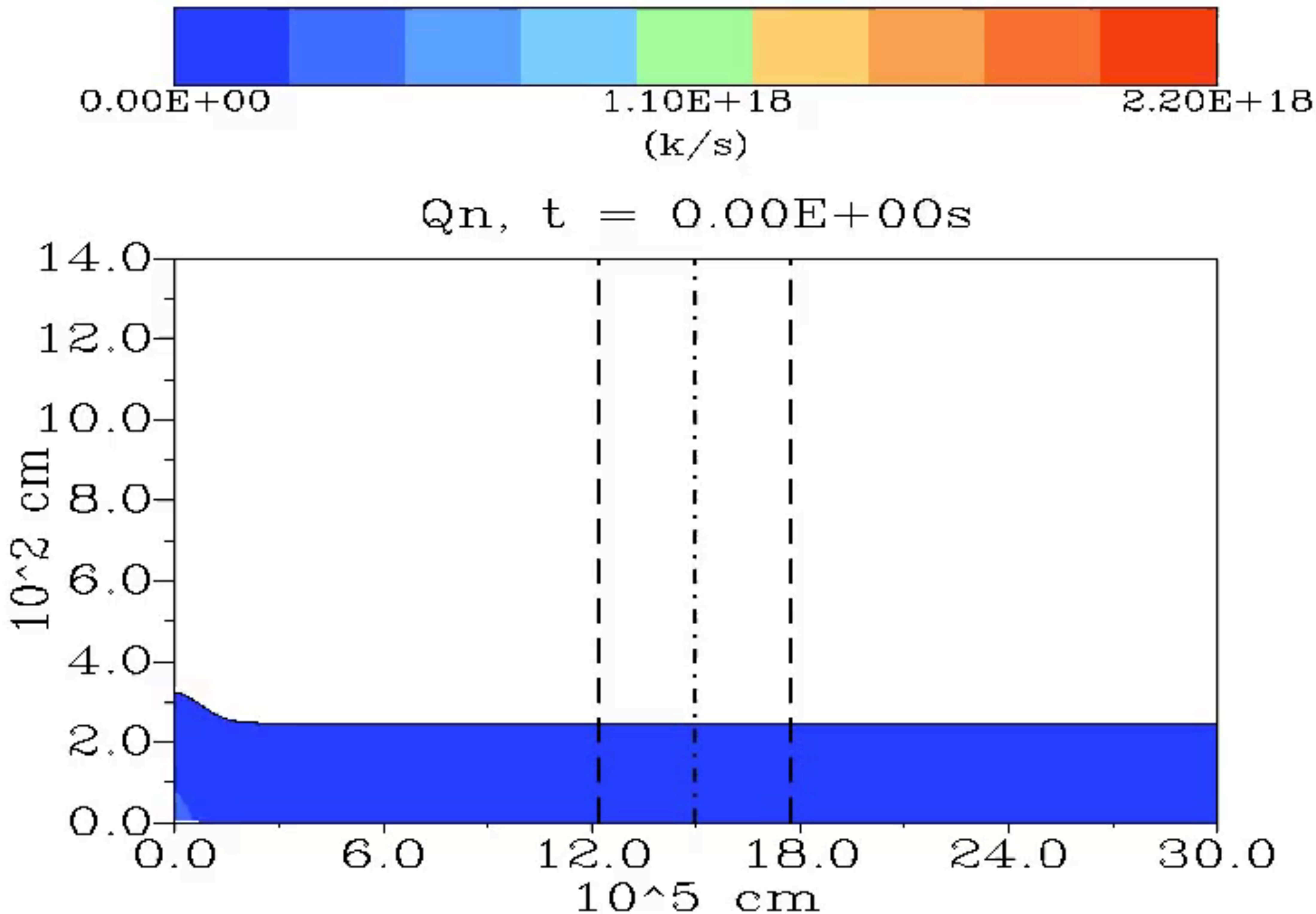

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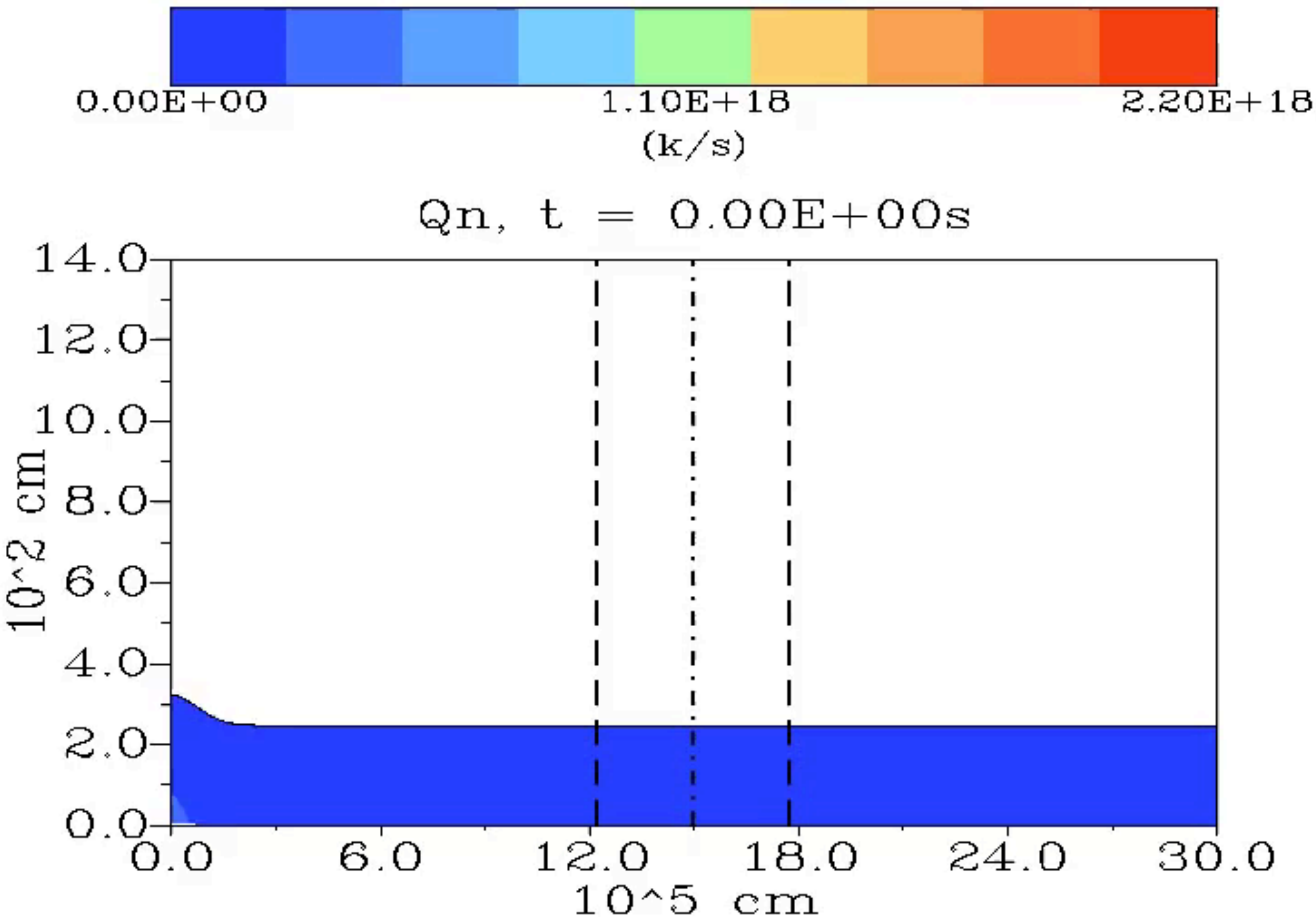

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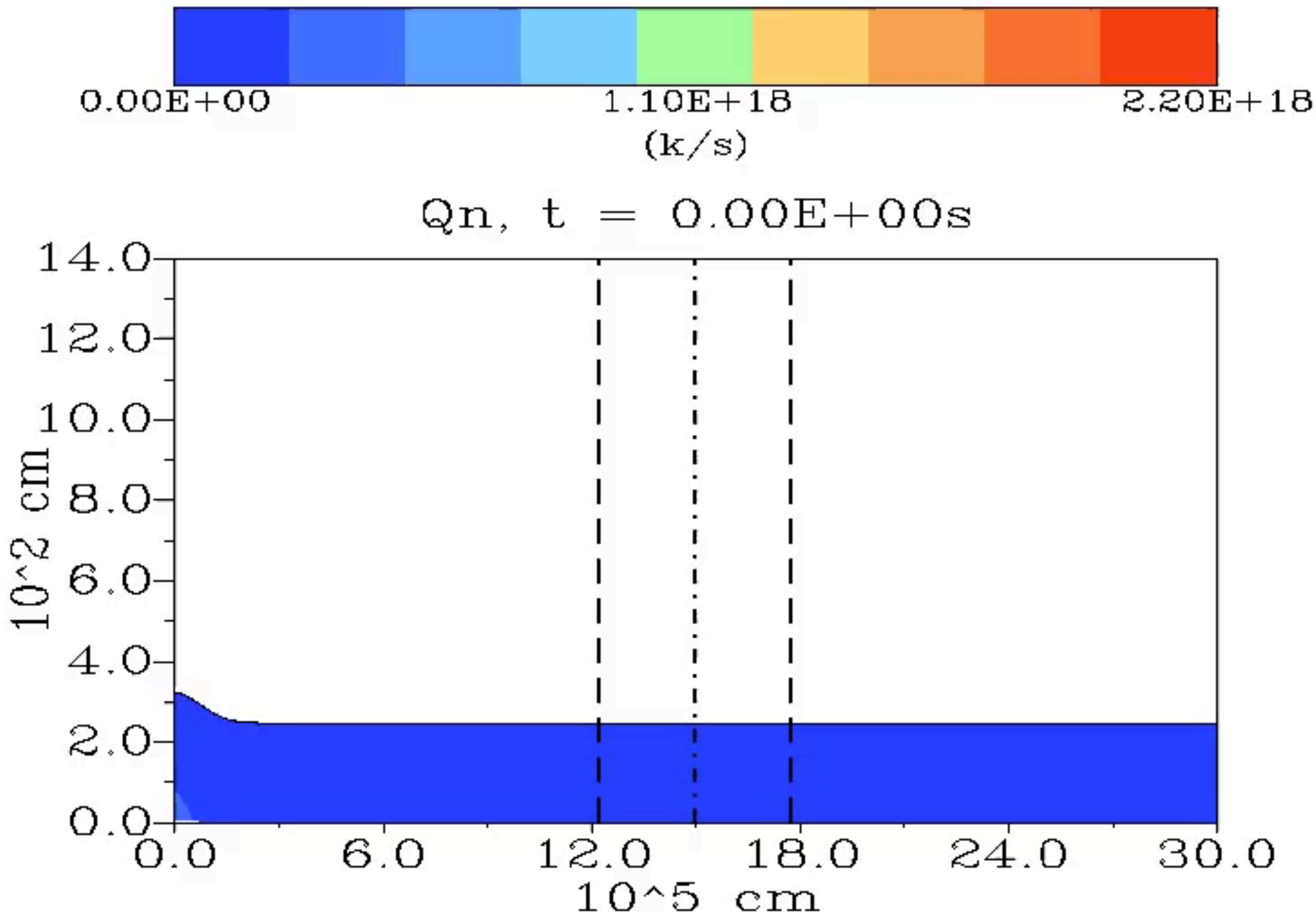

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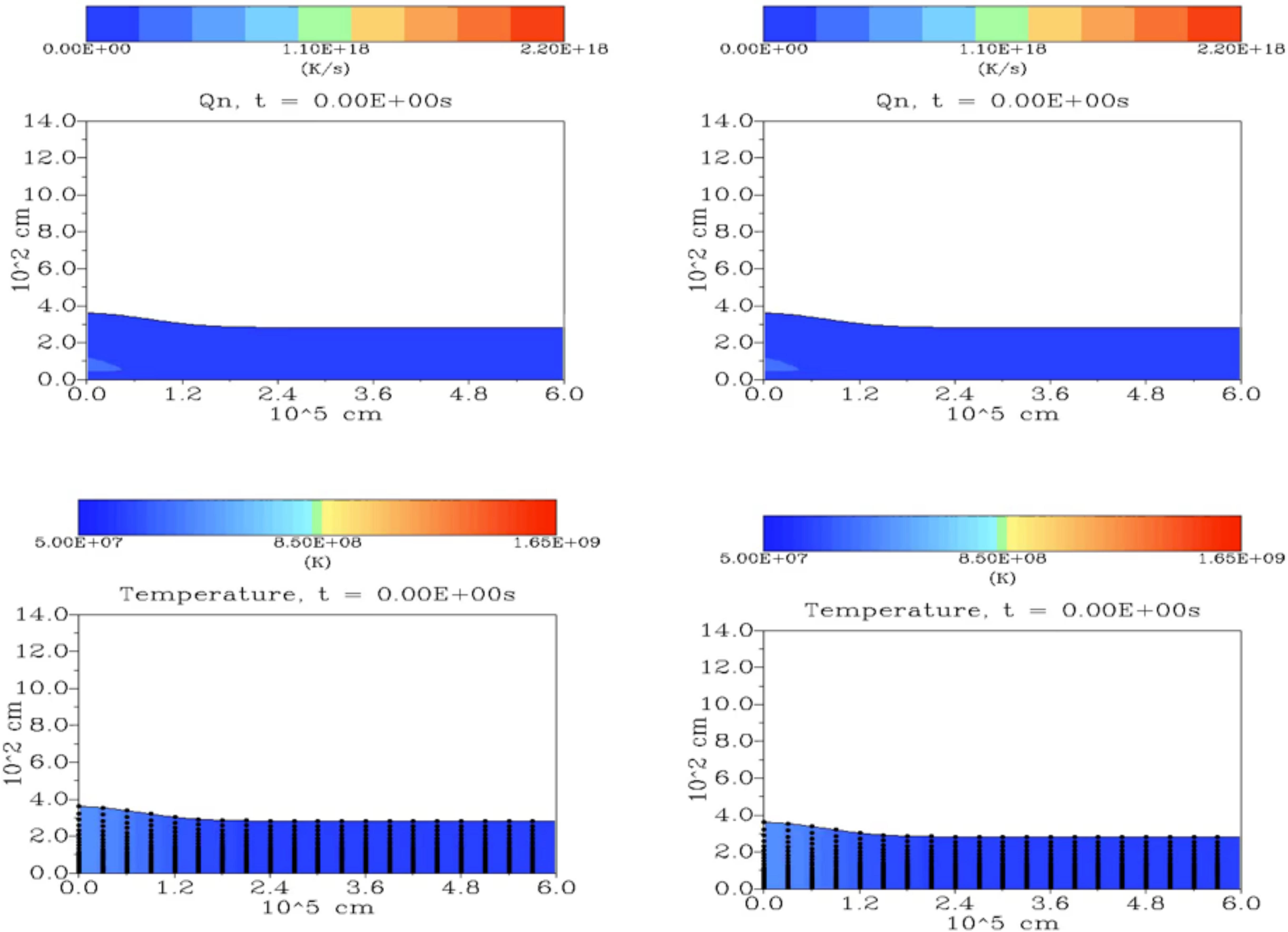
Low field (10^7 G) High field (10^{10} G)



Magnetic field effects, Cavecchi et al. 2016

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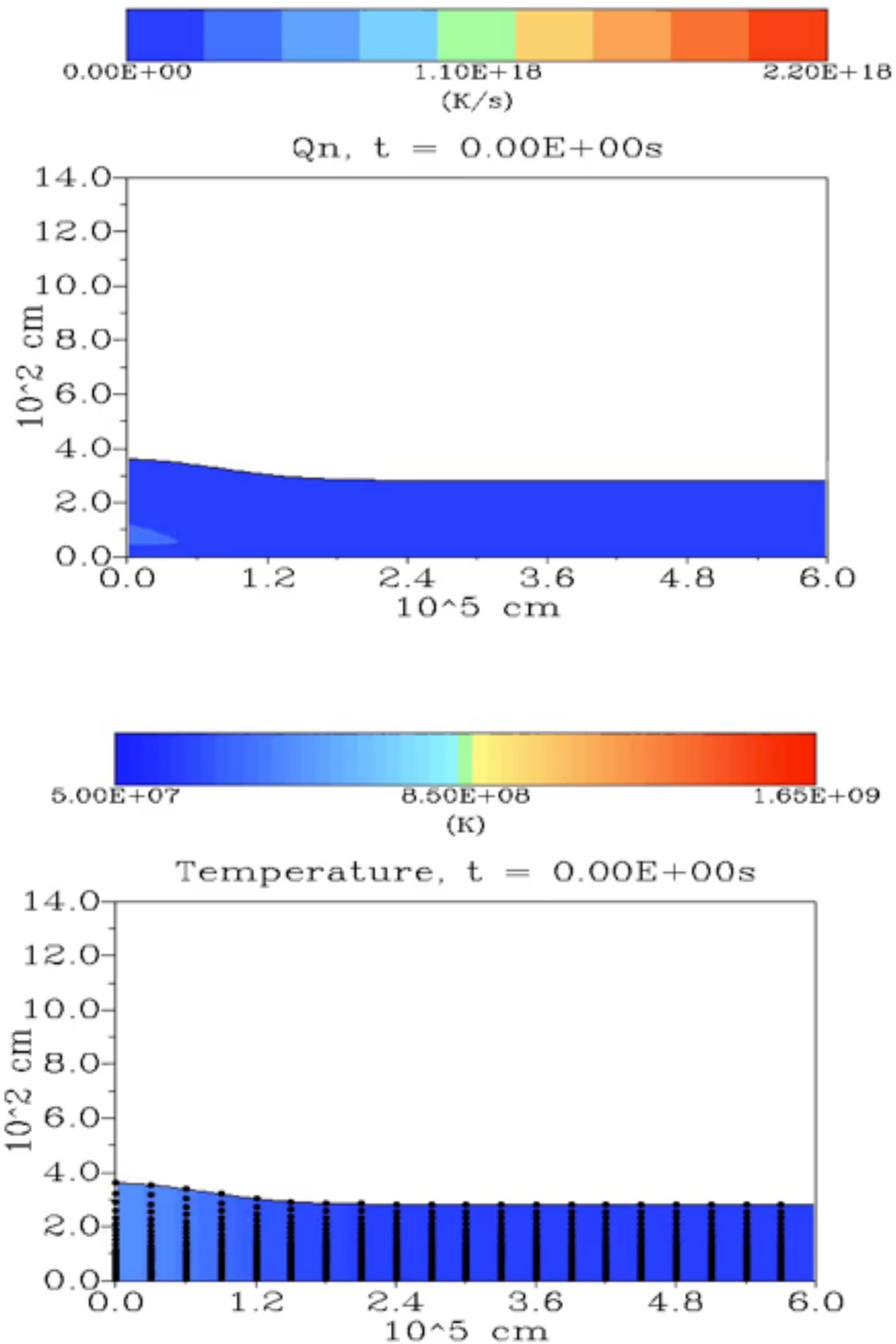

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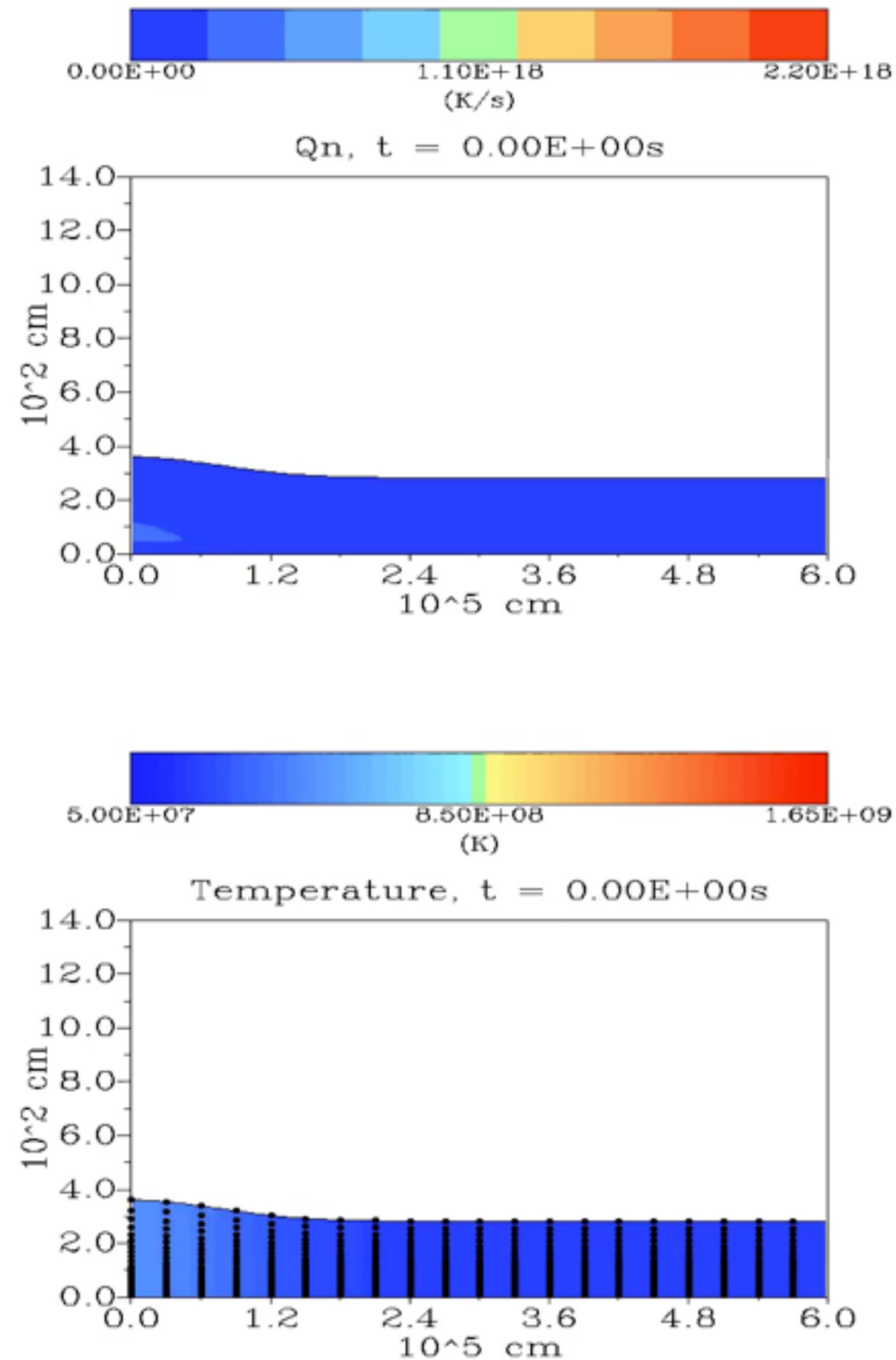

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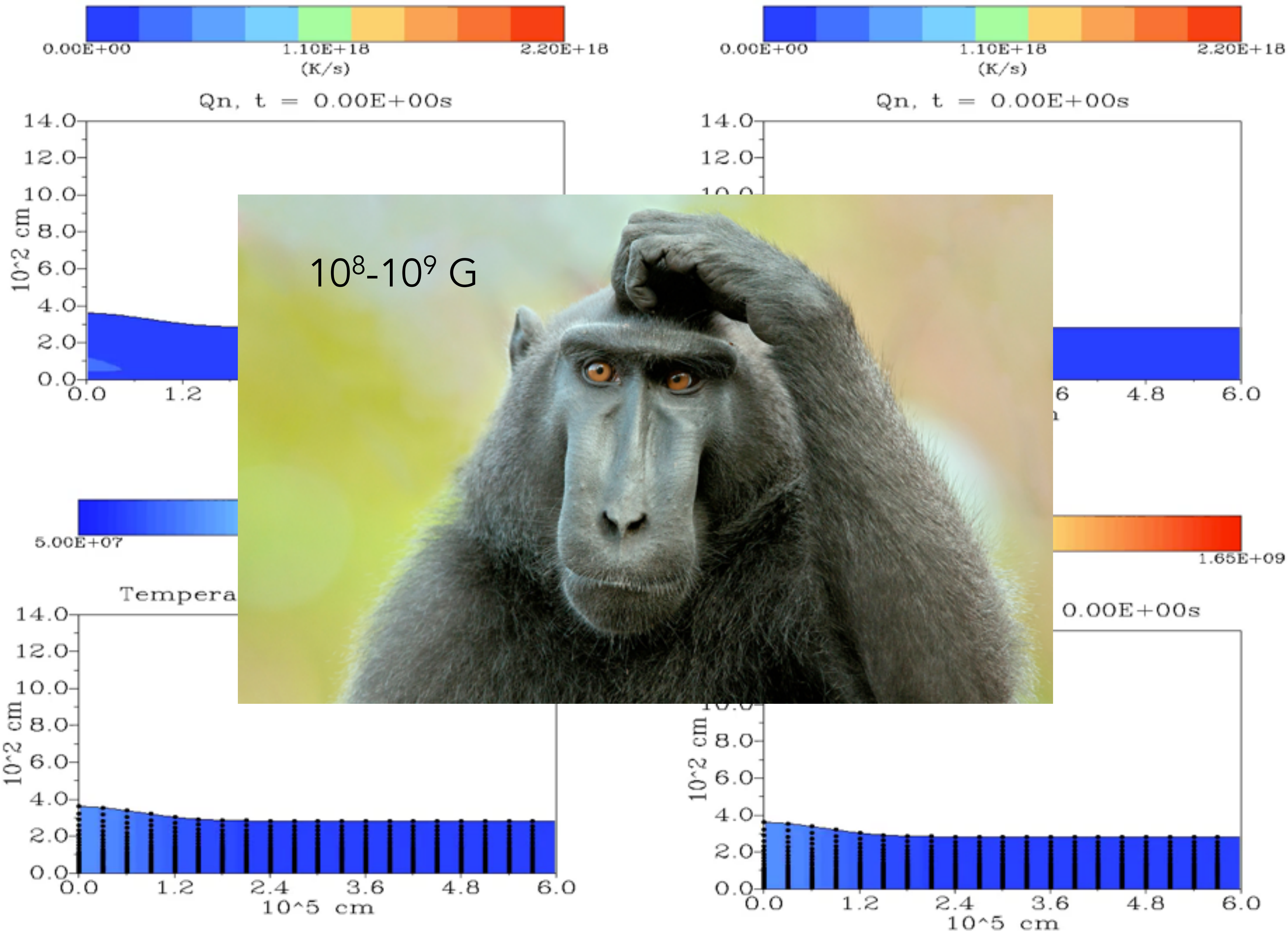

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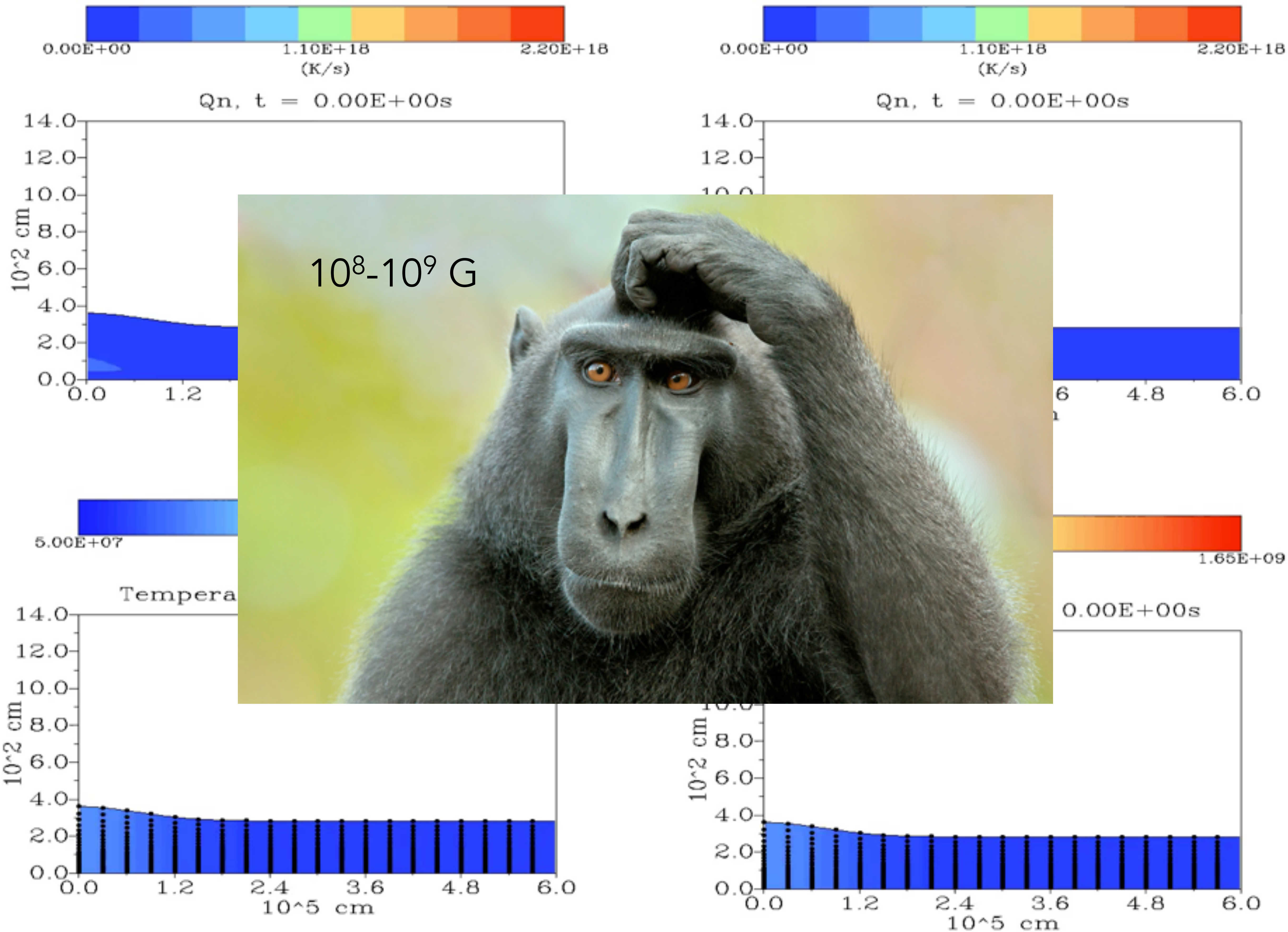

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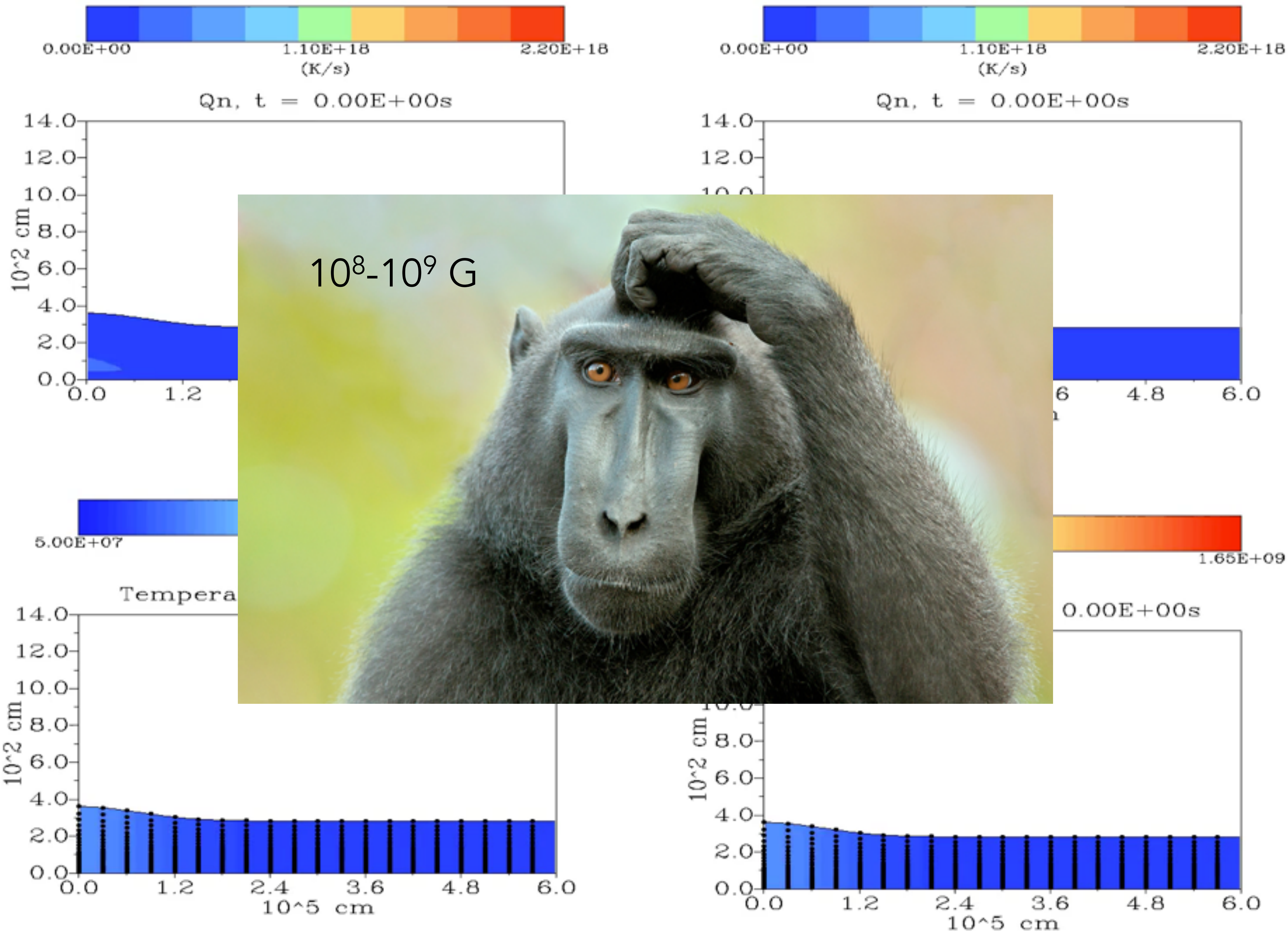

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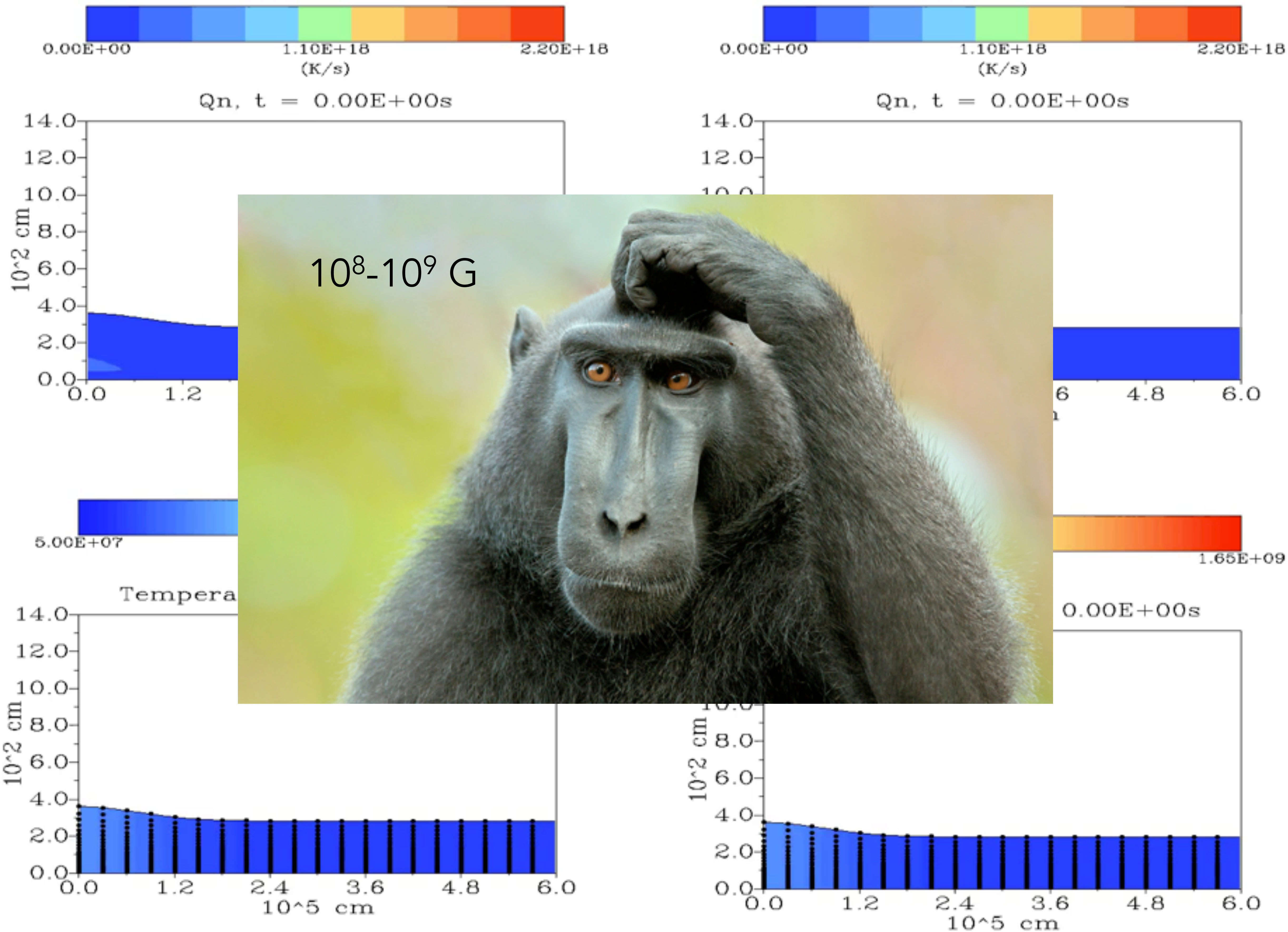

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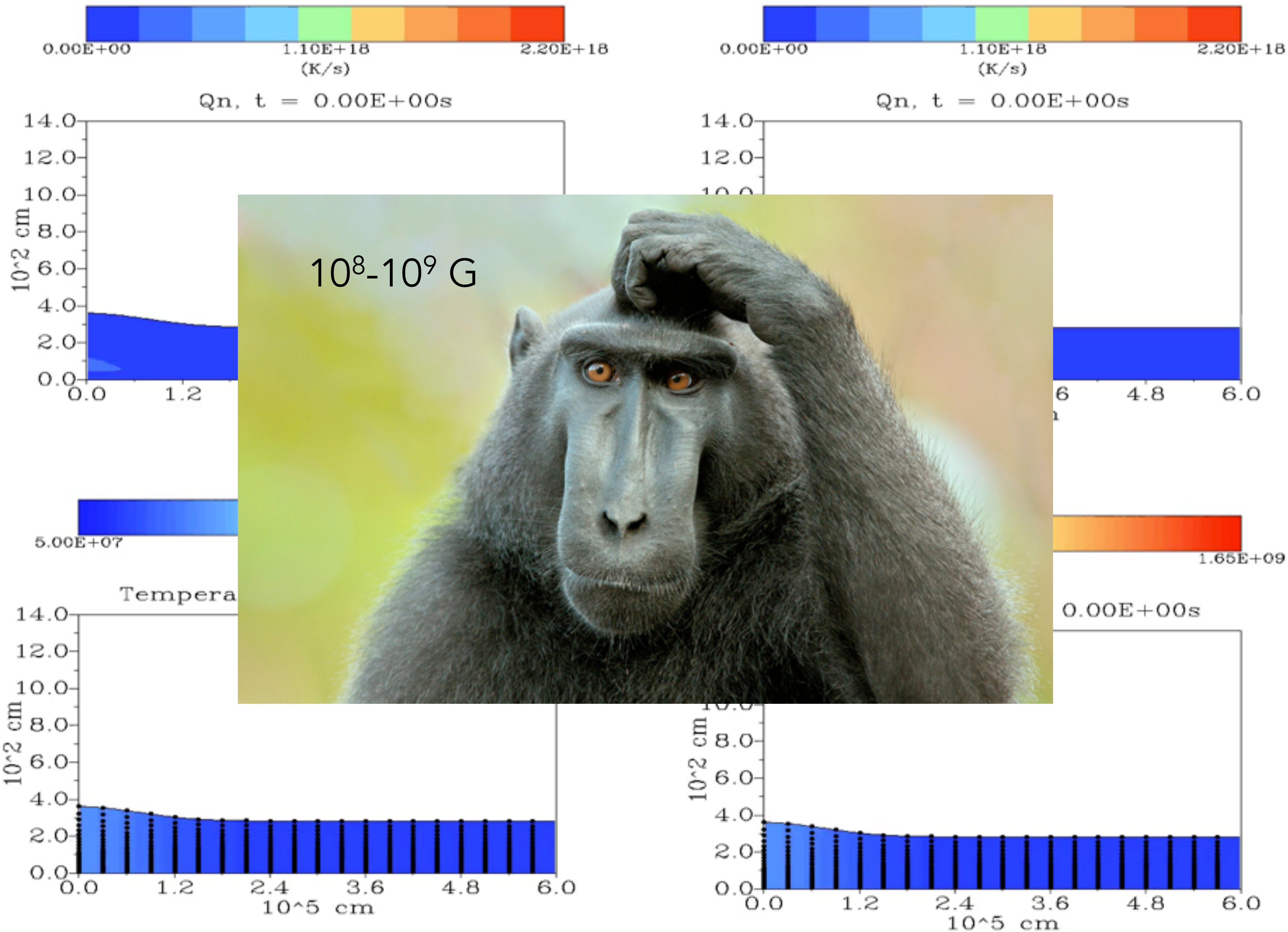

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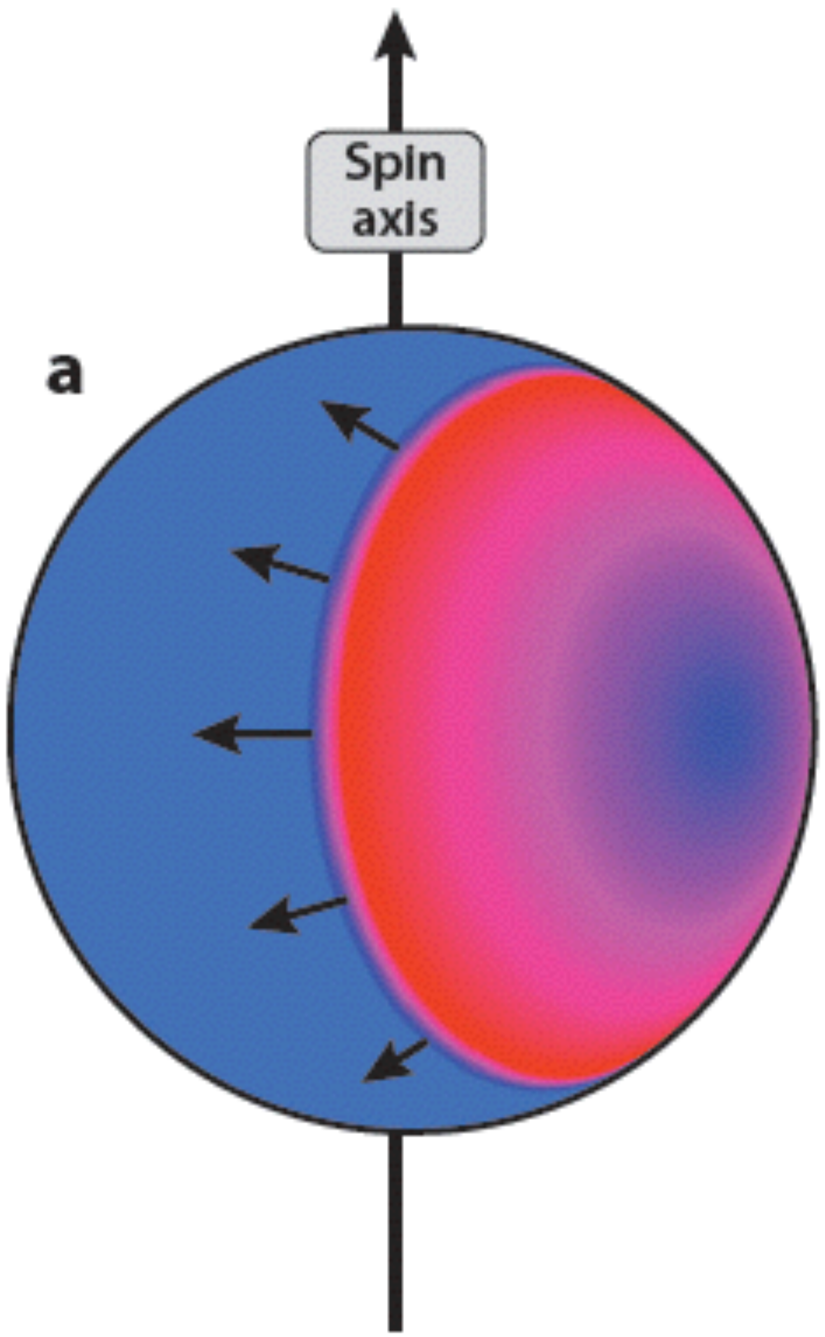
Burst oscillation models



Burning spreads from ignition location

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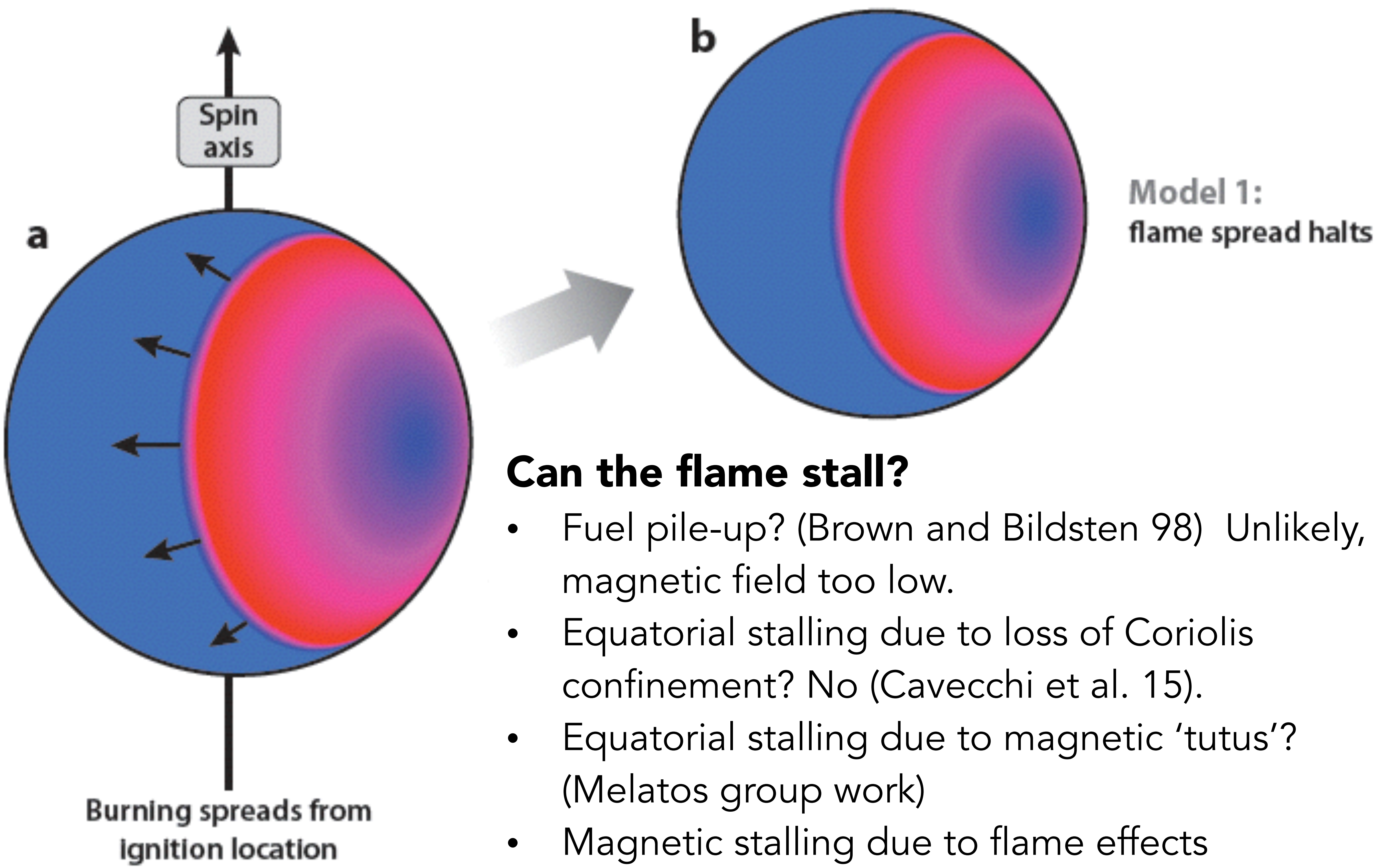


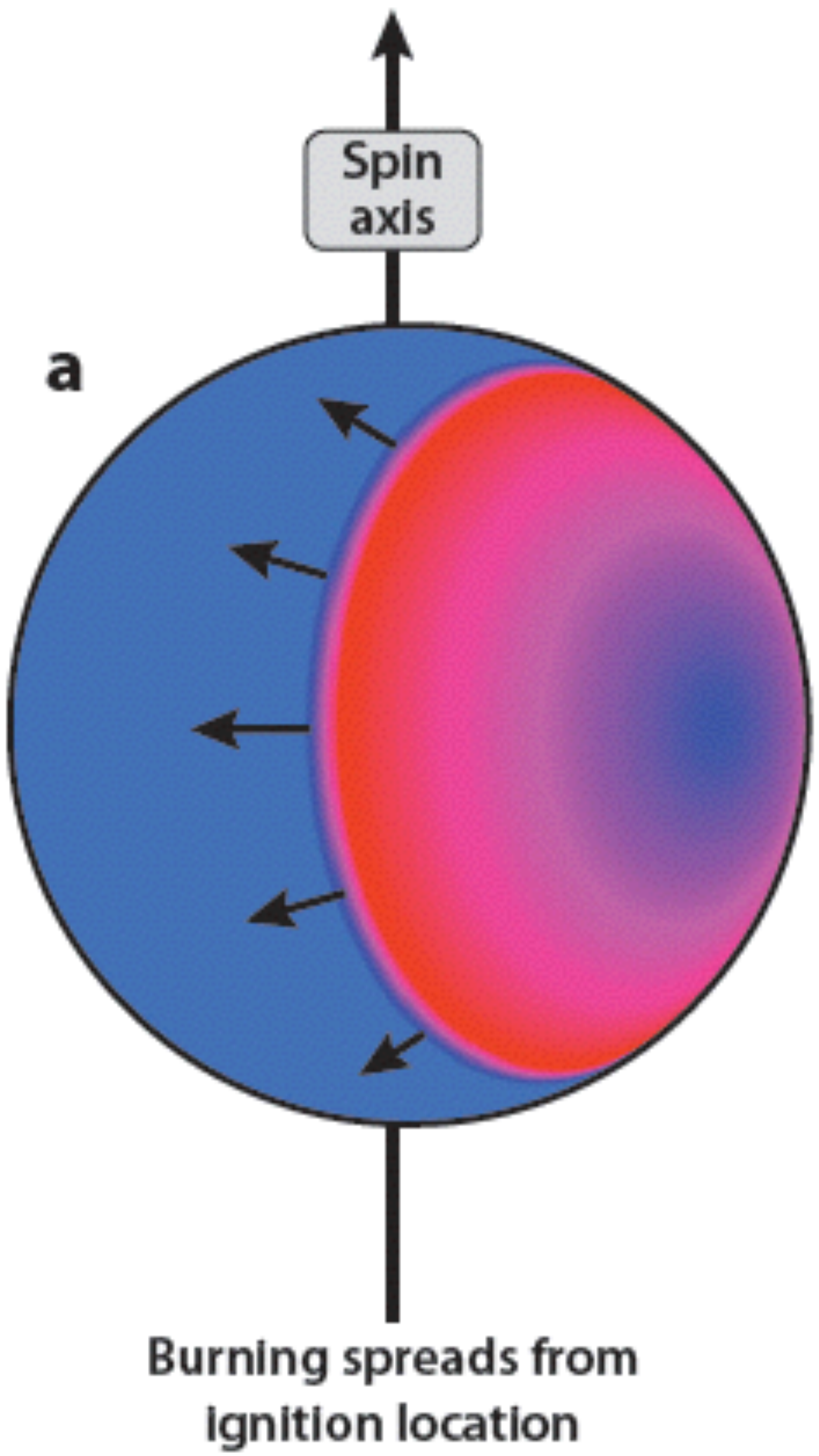
Can the flame stall?

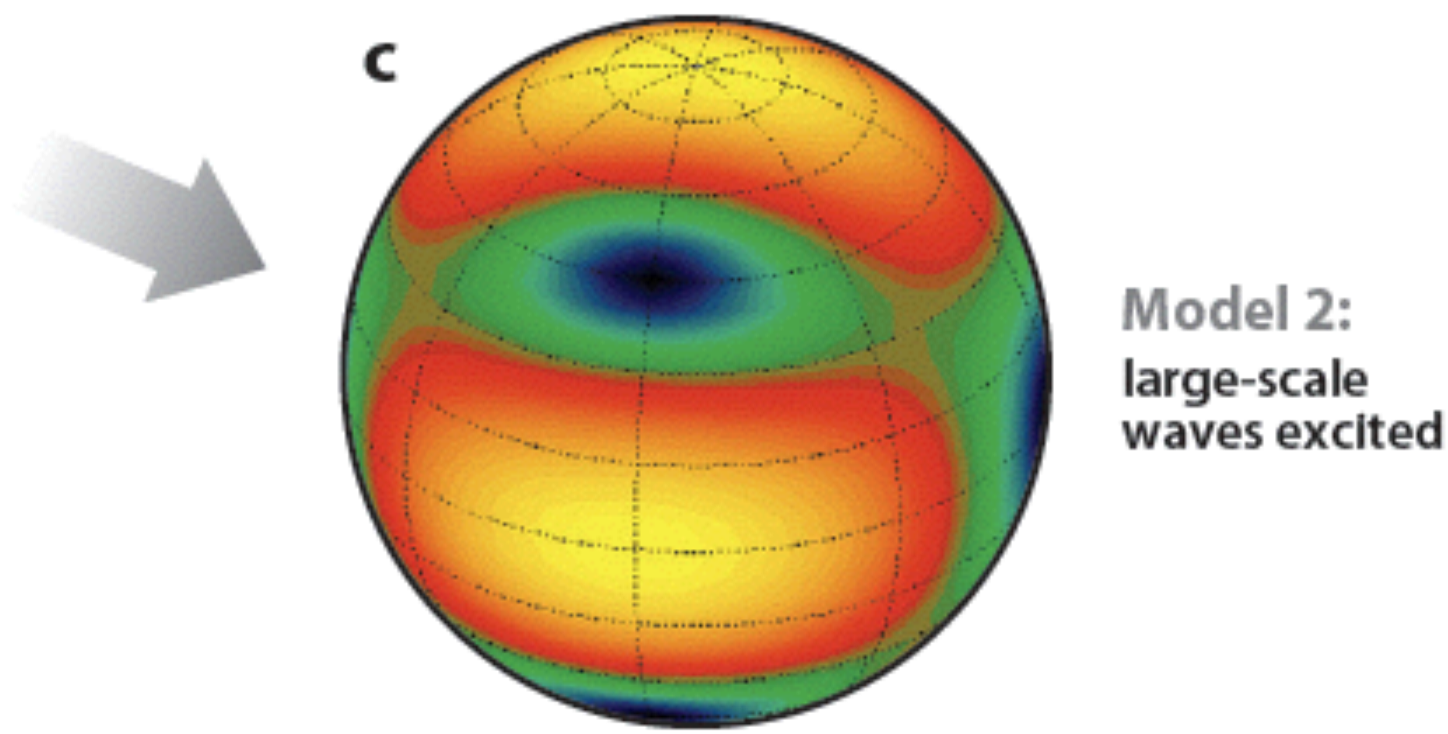
- Fuel pile-up? (Brown and Bildsten 98) Unlikely, magnetic field too low.
- Equatorial stalling due to loss of Coriolis confinement? No (Cavecchi et al. 15).
- Equatorial stalling due to magnetic 'tutus'? (Melatos group work)
- Magnetic stalling due to flame effects (Cavecchi et al. 11, 16)?

Burst oscillation models

Can large-scale mode patterns form?

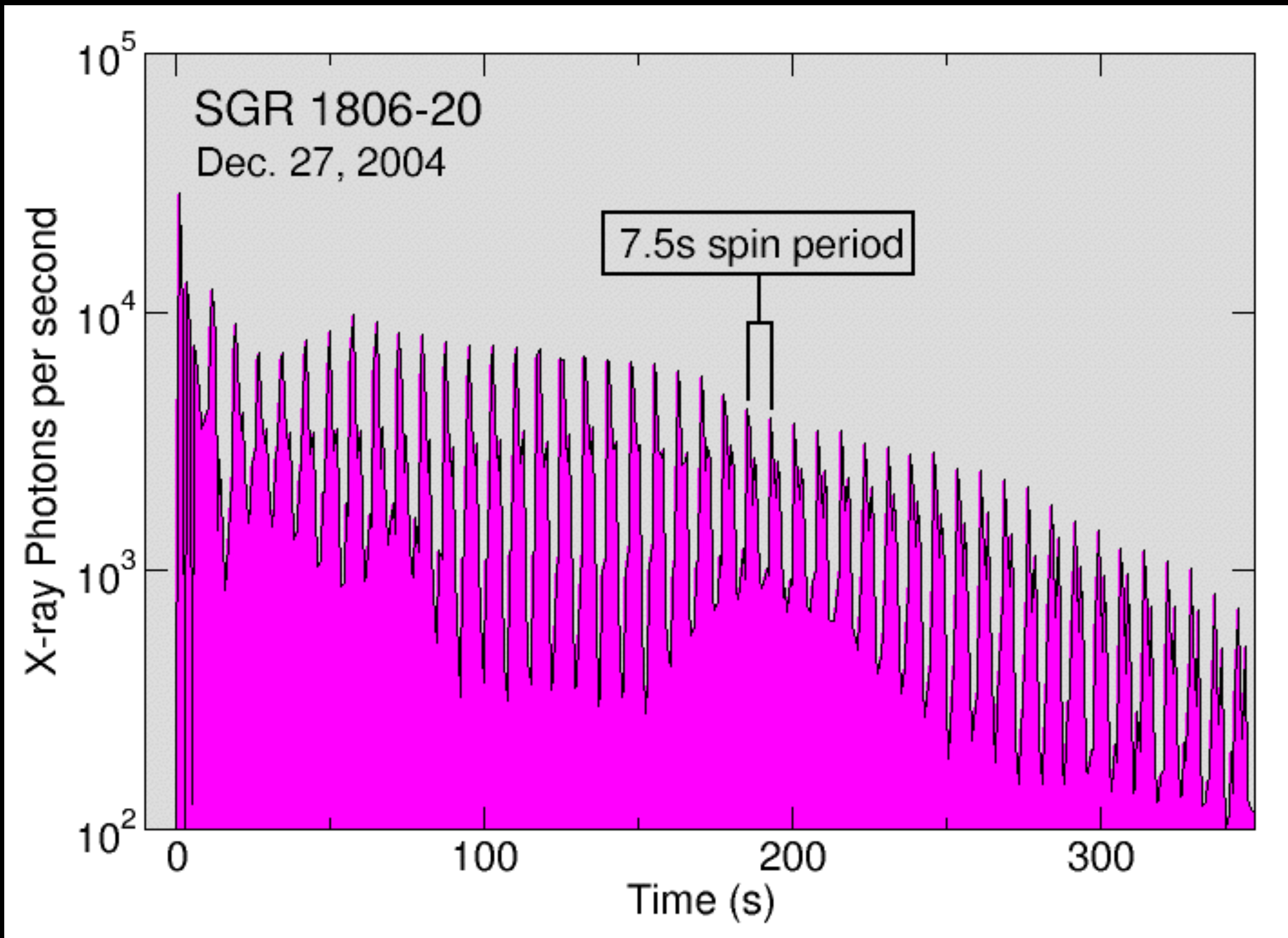
- Buoyant r-mode fits frequency (Heyl 04)
- Drifts over-predicted (Berkhout & Levin 08).
- Does not fit pulsars (Watts et al. papers).
- Shear modes (Cumming 05)?
- Magnetic modes (Heng & Spitkovsky 09)?
- Other frequencies? (see Simin's talk)
- Photospheric/convection/deep burn effects?
- Excitation/link to flame spread?
- Characterizing 'allowed' patterns.





MAGNETIC EXPLOSIONS AND MAGNETO-ELASTIC MODES

GIANT FLARE ASTEROSEISMOLOGY



Giant flare QPOs: Israel et al. 2005, Strohmayer & Watts 2005,6, Watts & Strohmayer 2006

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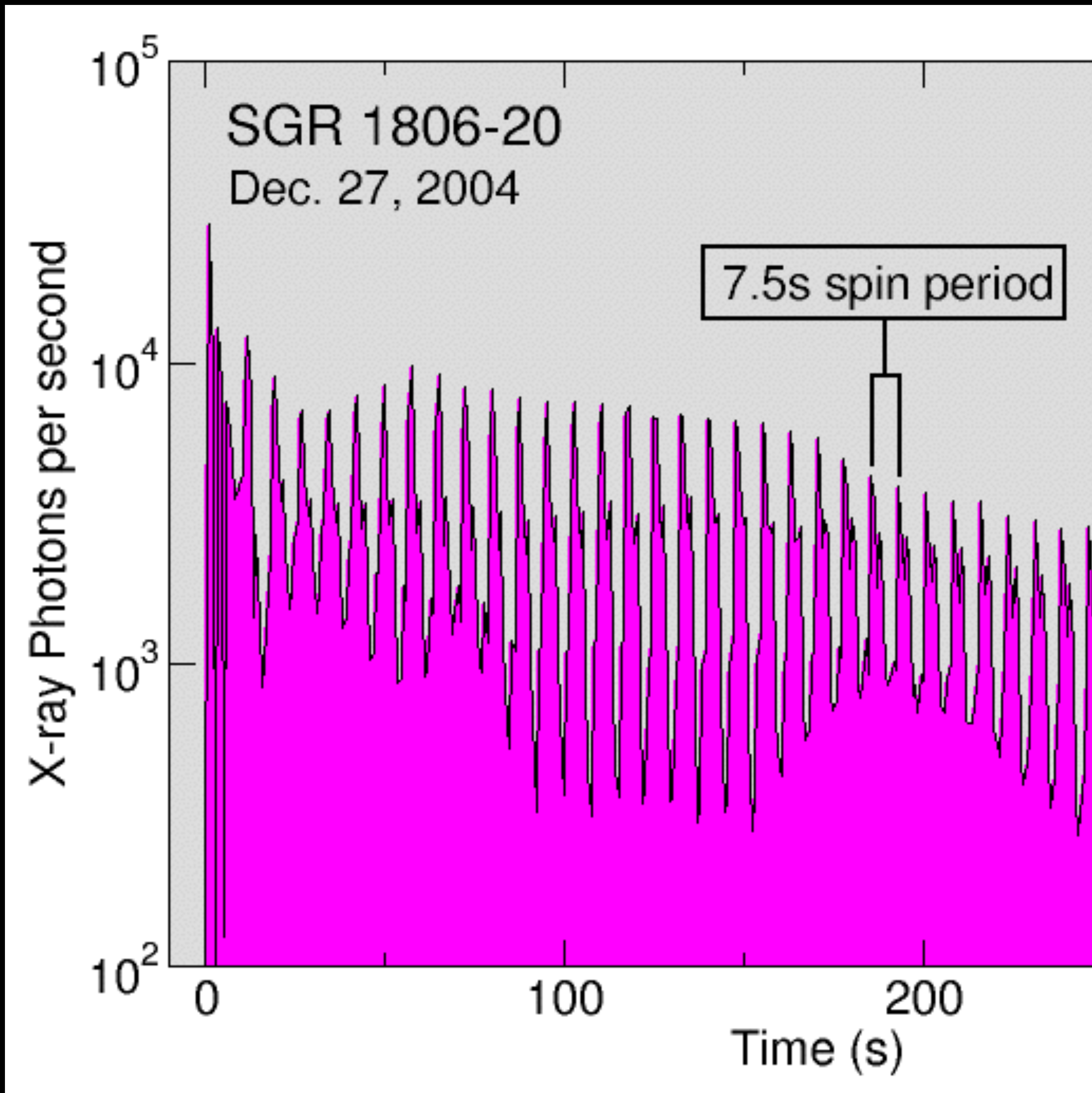
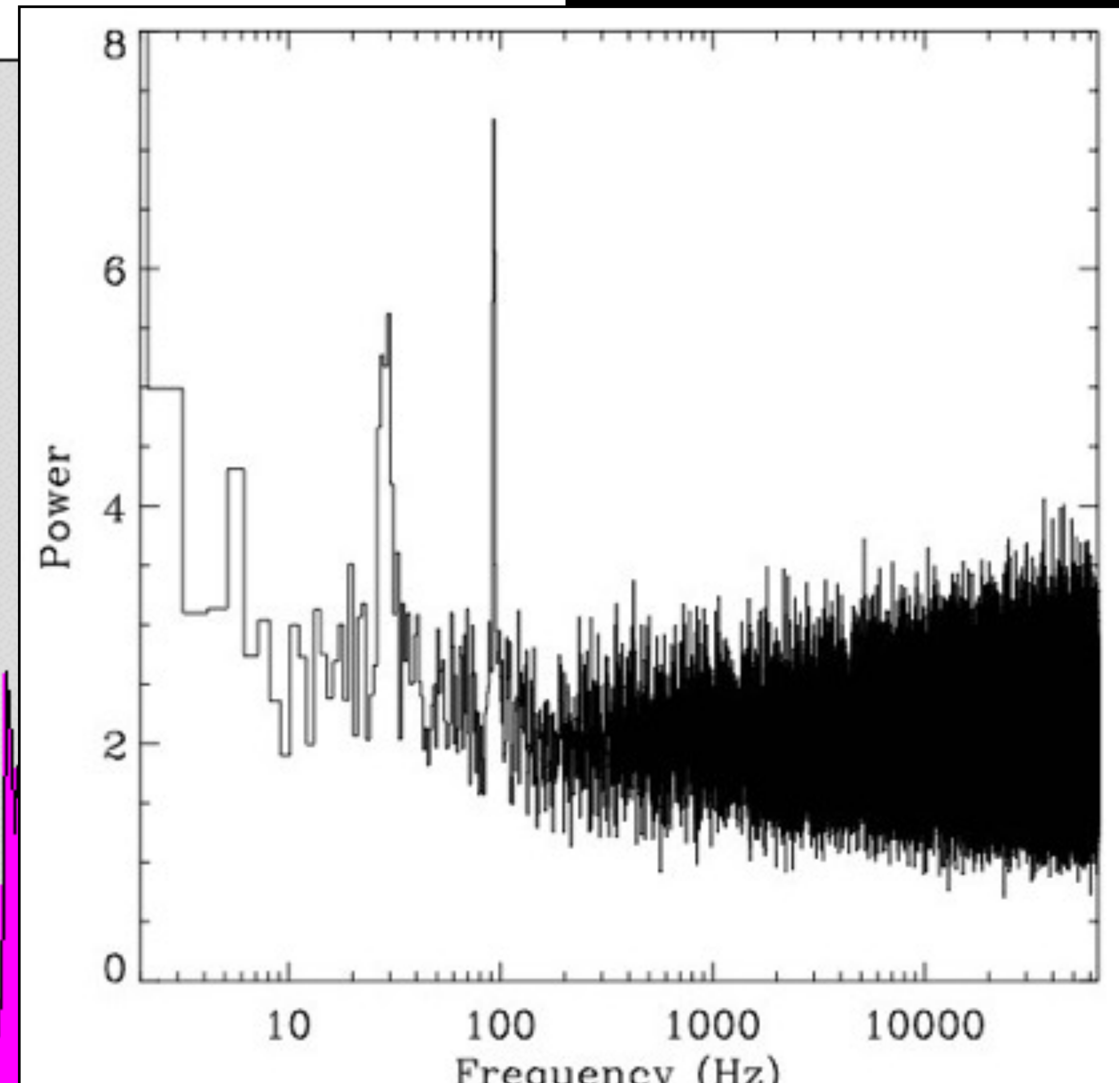
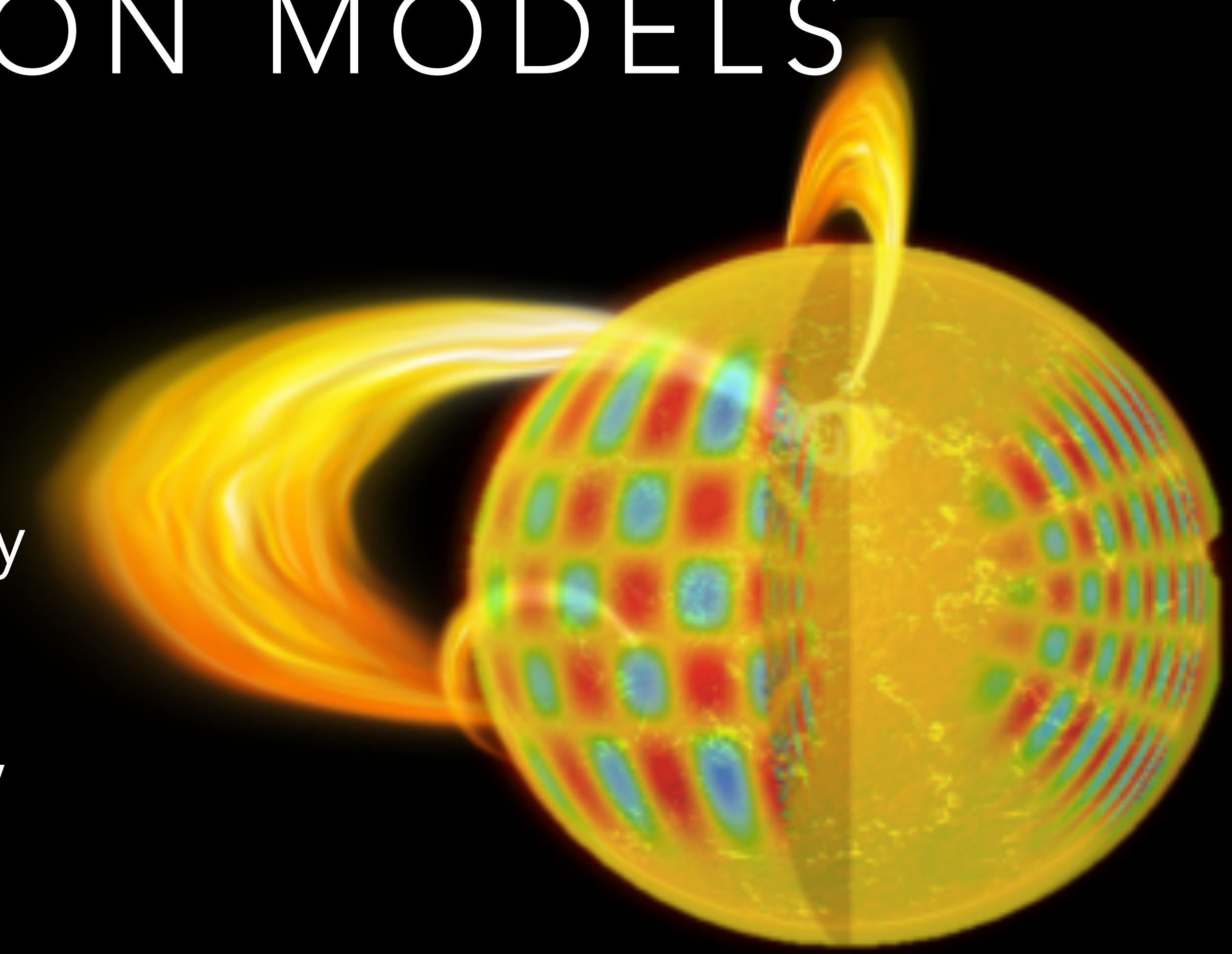




18-1800 Hz Quasi-Periodic Oscillations (QPOs) seen in two giant flares.

Giant flare QPOs: Israel et al. 2005, Strohmayer & Watts 2005,6, Watts & Strohmayer 2006

SEISMIC VIBRATION MODELS

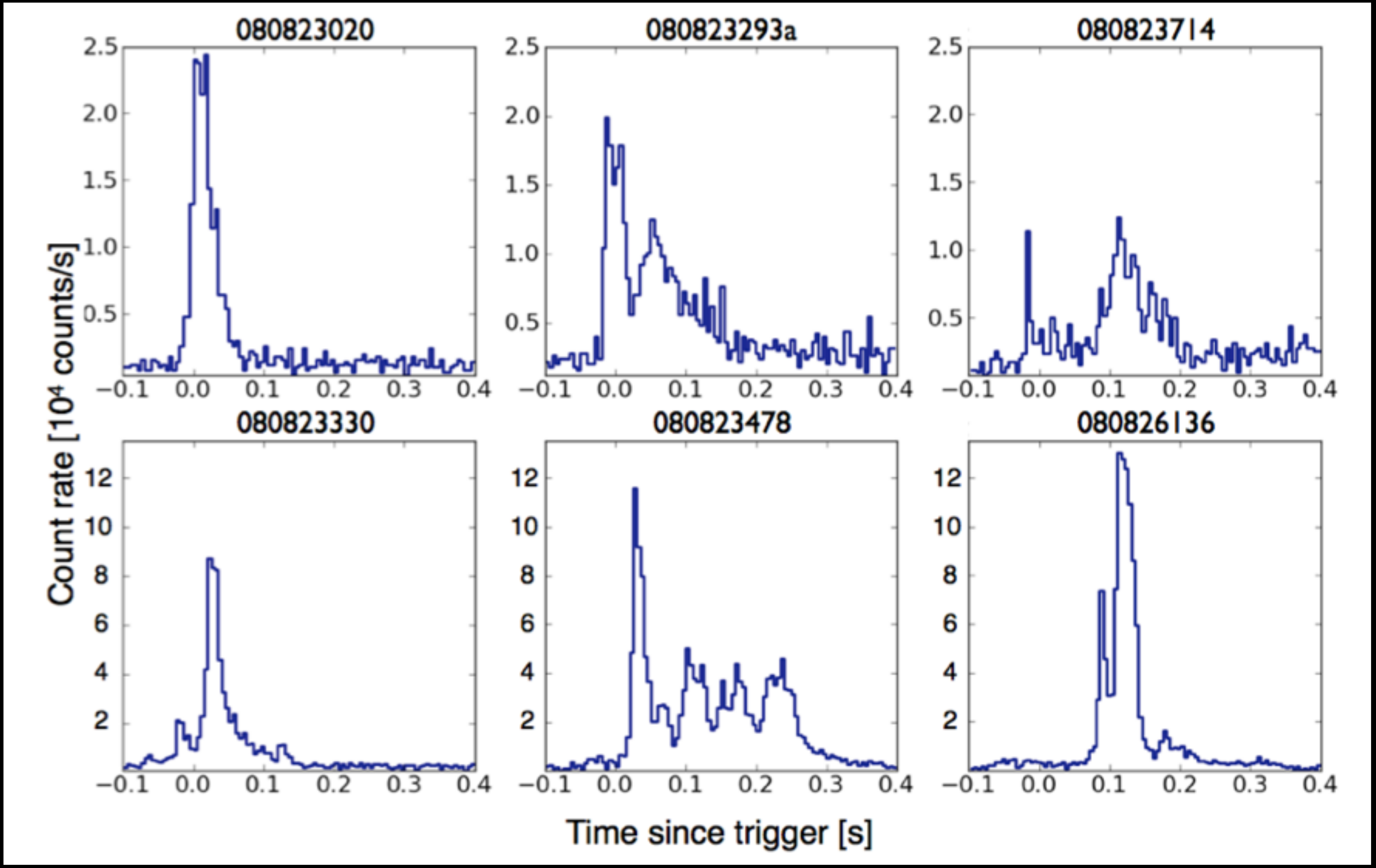


- Coupled magneto-torsional oscillations of crust/core.
- Alfven modes are continua: frequency drifts intrinsic.
- Frequencies depend on mass, radius, superfluidity, crust composition, magnetic field strength and geometry.
- Decay times important (Huppenkothen, Watts & Levin 14) .
- Associated GW emission? Seems unlikely (see work by Kalmus, van Hoven, Levin).

See for example: Duncan 1998, Levin 2006, 7, Samuelsson & Andersson 07, Glampedakis et al 2006, Lee 2008, Sotani et al. 2008 Andersson et al 2009, Steiner and Watts 2009, Colaiuda and Kokkotas 2011, 12, van Hoven and Levin 2011, 2012, Gabler et al 2012, 13, 14, Passamonti and Lander 2013, 14, Asai and Lee 2014, Glampedakis and Jones 2014...

Review: Turolla, Zane & Watts 2015, Reports on Progress in Physics.

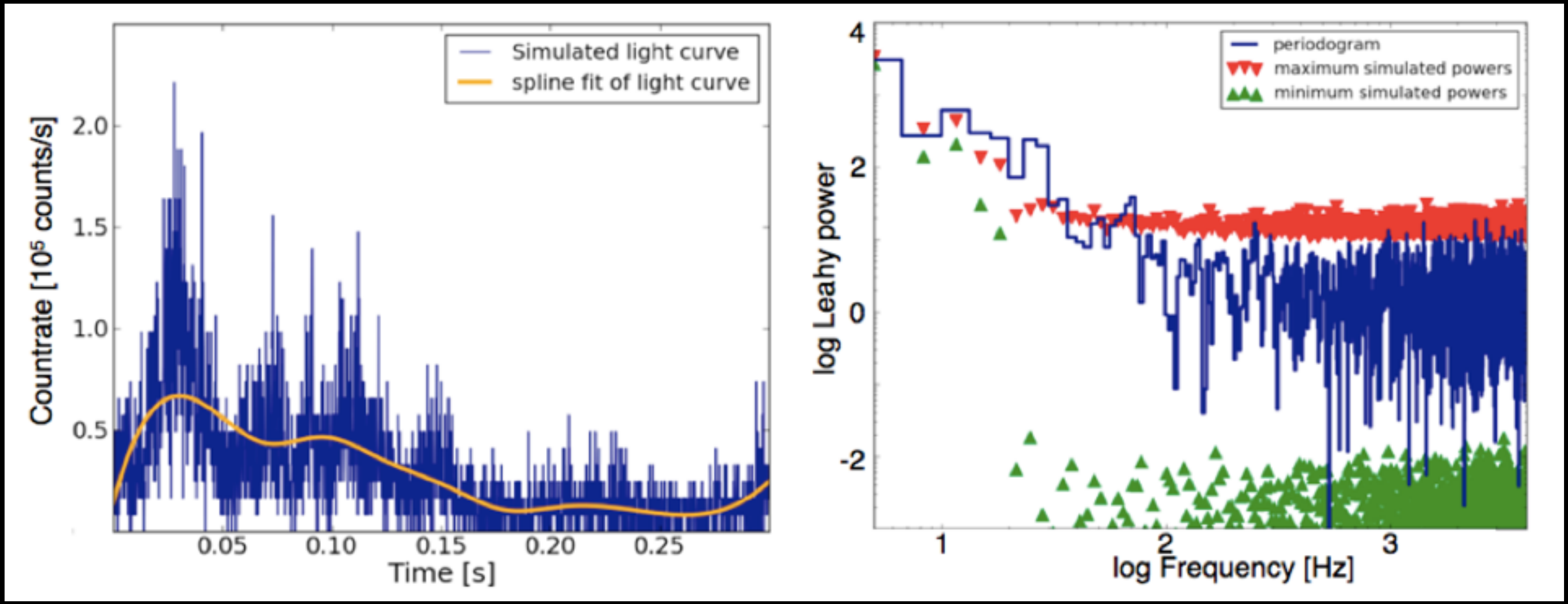
SMALL BURST ASTEROSEISMOLOGY



Fermi GBM bursts from SGR 0501+4516 (Huppenkothen et al. 2013)

SMALL BURST ASTEROSEISMOLOGY

- QPO searches are complicated by the 'burst envelope'.
- Traditional method (Monte Carlo simulations of smoothed lightcurves) fails in absence of simple functional model for emission.

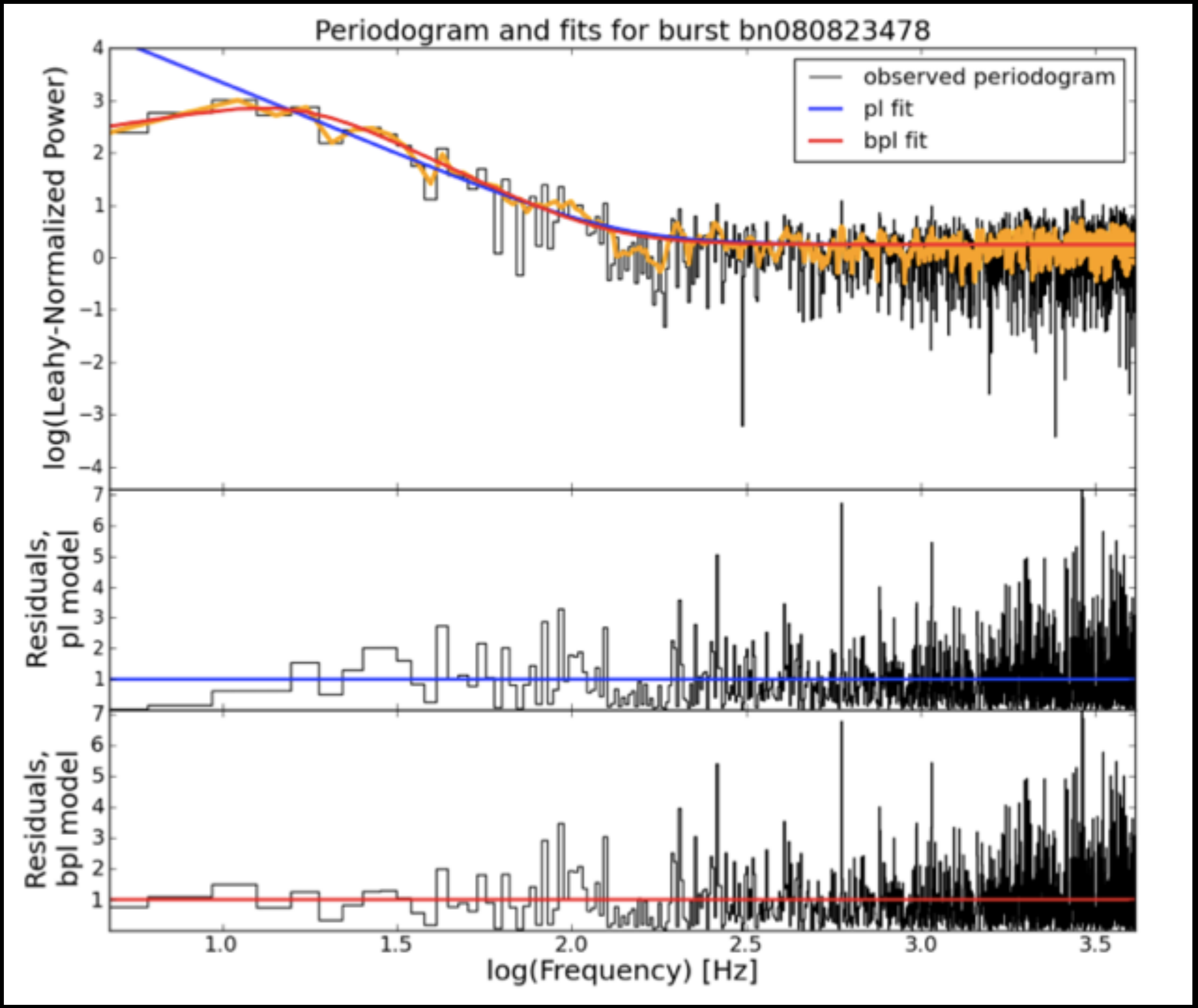


Huppenkothen et al. 2013

SHORT BURST ASTEROSEISMOLOGY

- We use a Bayesian procedure for modelling the periodogram, assuming a red noise process.

- Method is highly conservative.



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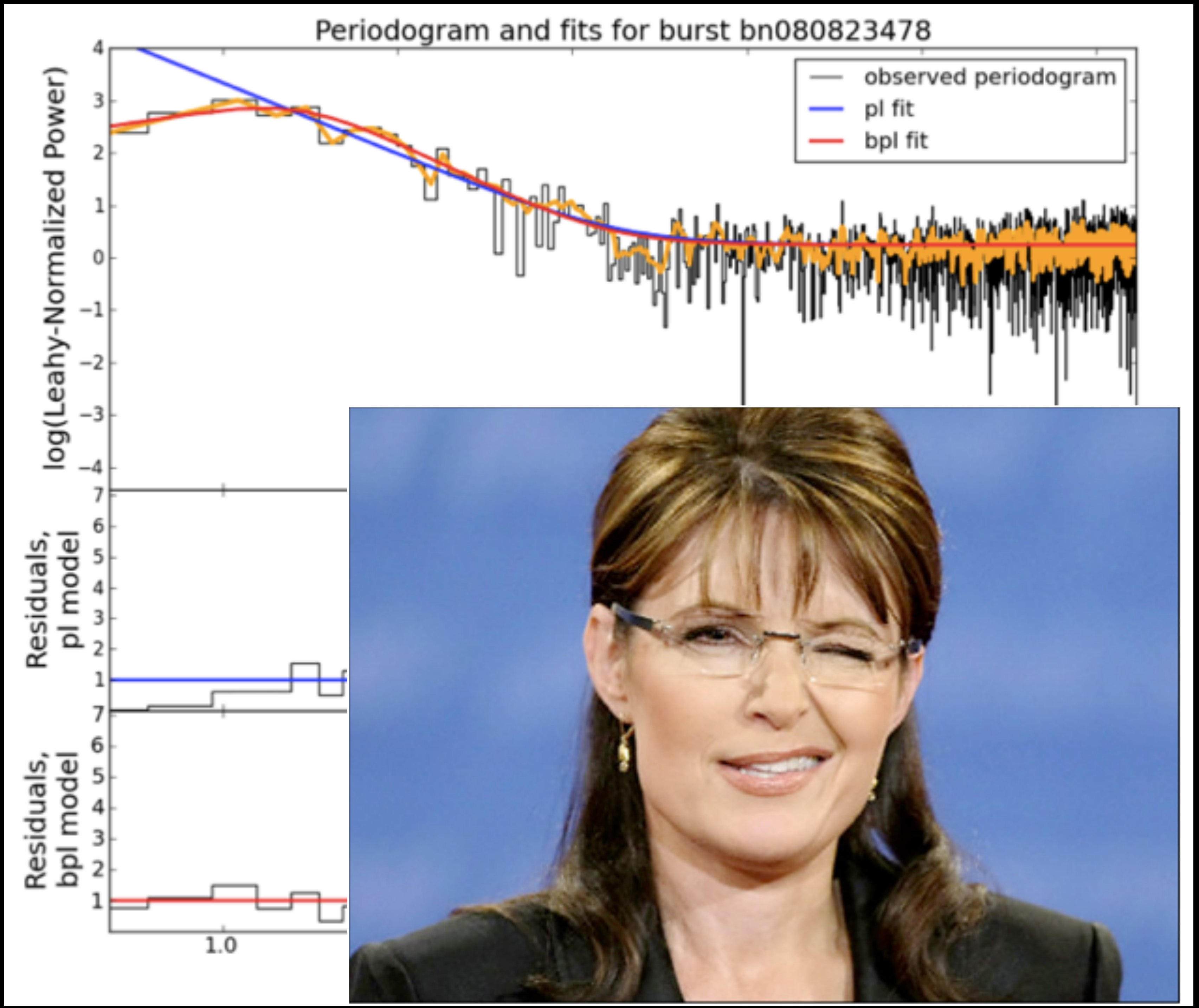
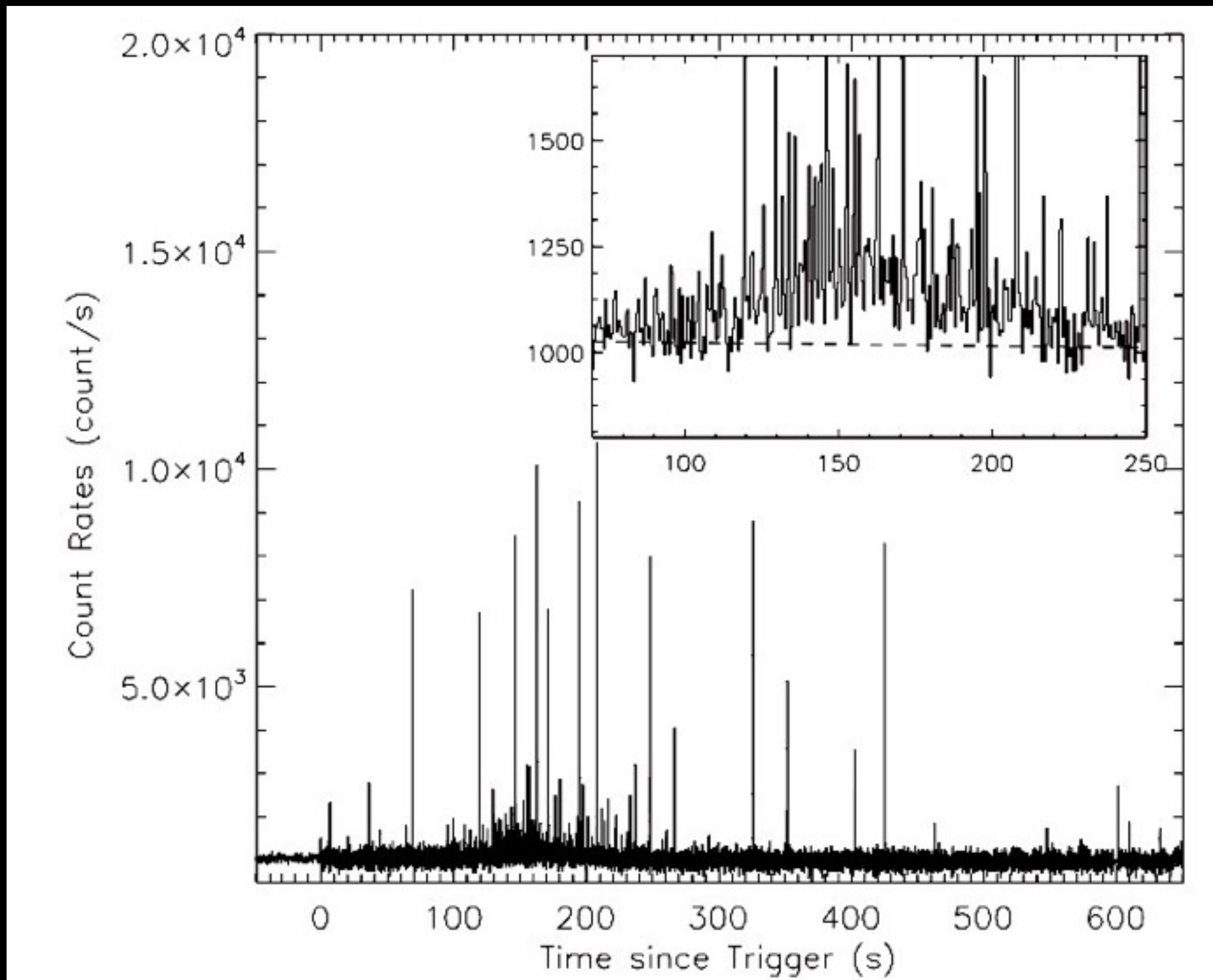


Unofficially known as the 'Palin Method'

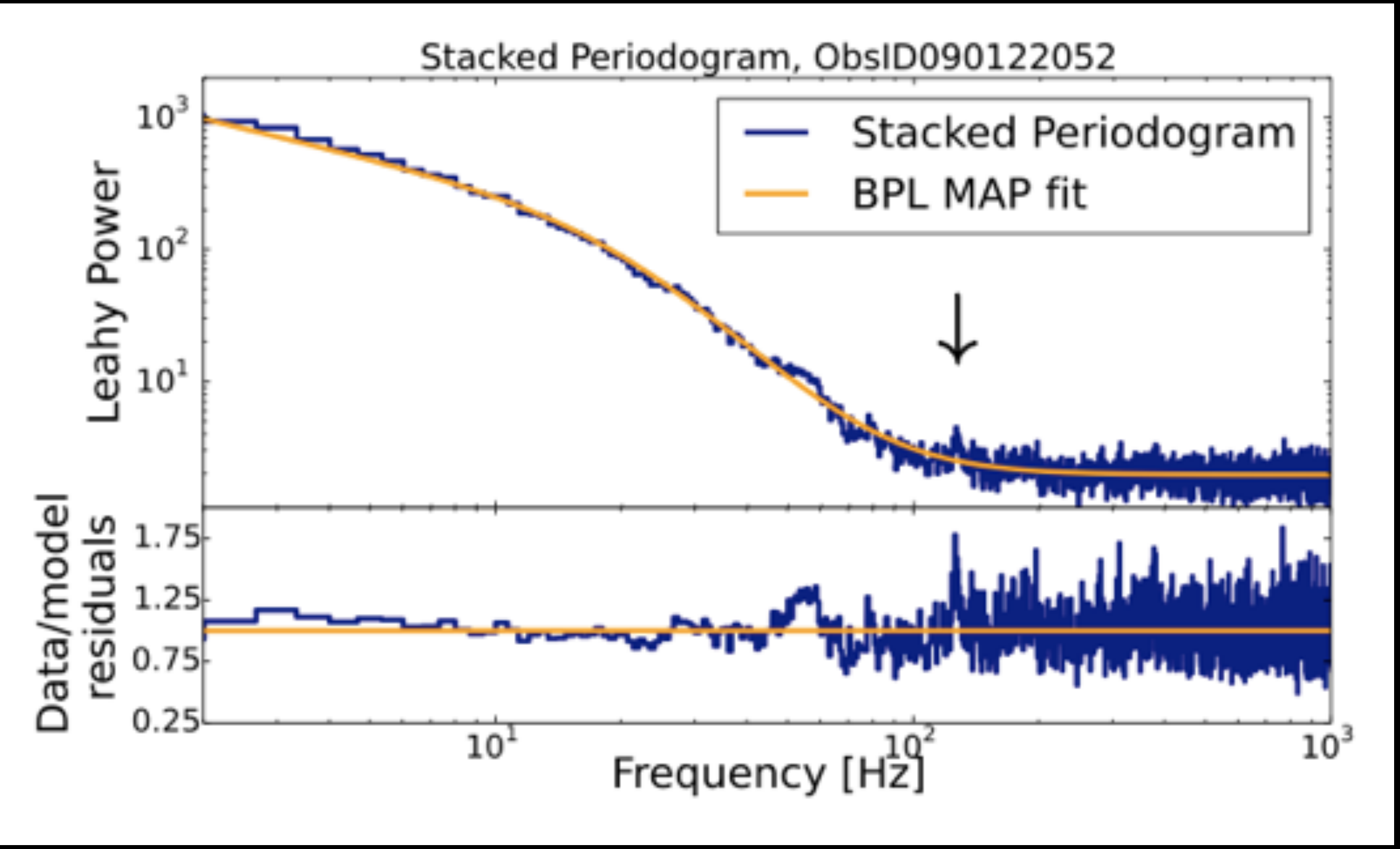
THE SGR J1550-5418 BURST STORM



Fermi GBM burst storm, January 2009 (Kaneko et al. 2010, van der Horst et al. 2012)

THE SGR J1550-5418 BURST STORM

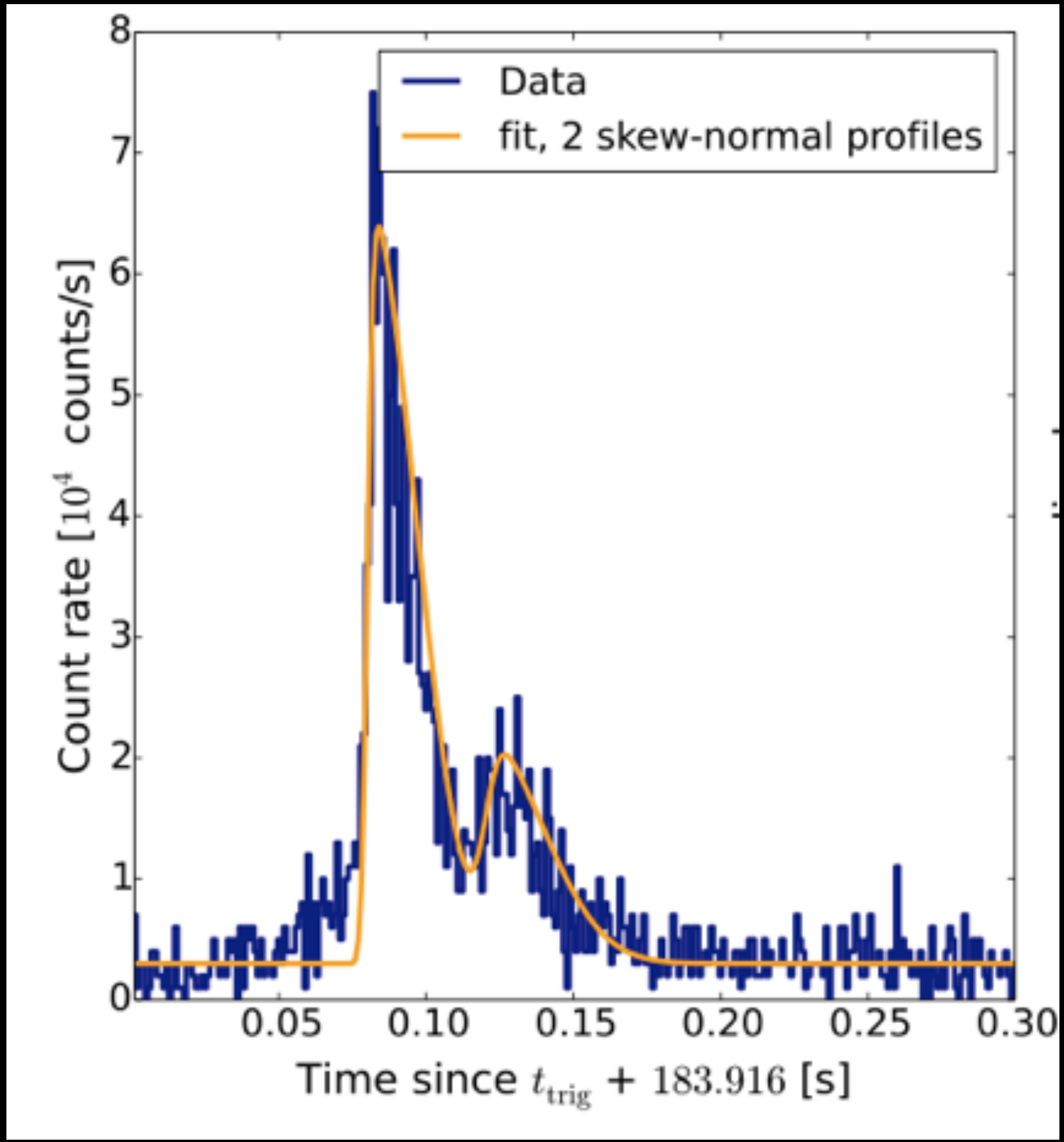
- Stacking consecutive bursts in most active periods: Significant QPOs (final $p < 0.001$) in frequency range (93-127 Hz) found in giant flares.
- Similar signals in RXTE data of SGR 1806-20/ SGR 1900+14 bursts.
- **Global modes excited by burst storms? Excitation threshold?**



Huppenkothen et al. 2014a, b

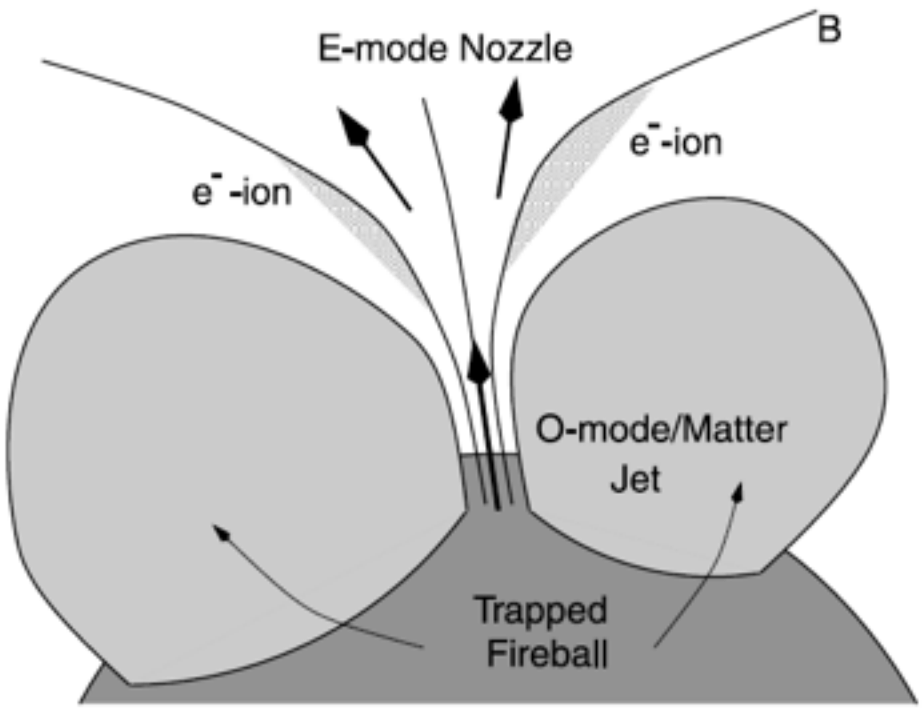
THE SGR J1550-5418 BURST STORM

- Single burst: Candidate (final $p < 0.025$) QPO at 260 Hz, different frequency range and broader than giant flare QPOs.
- **Core damping? In line with theoretical predictions.**
- **Signature of trigger mechanism, similar to variability claimed in giant flare peaks?**

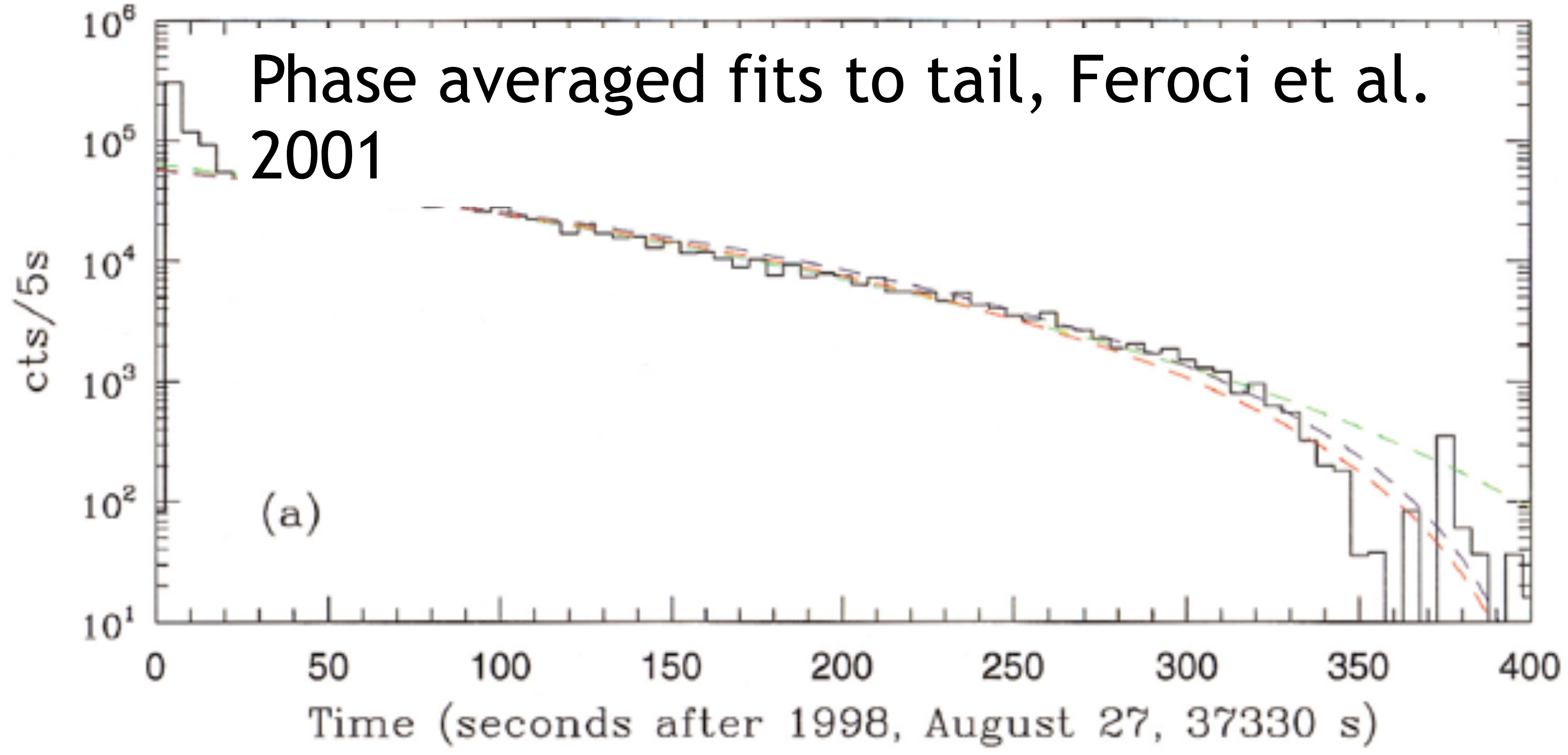


Huppenkothen et al. 2014a

Giant flares



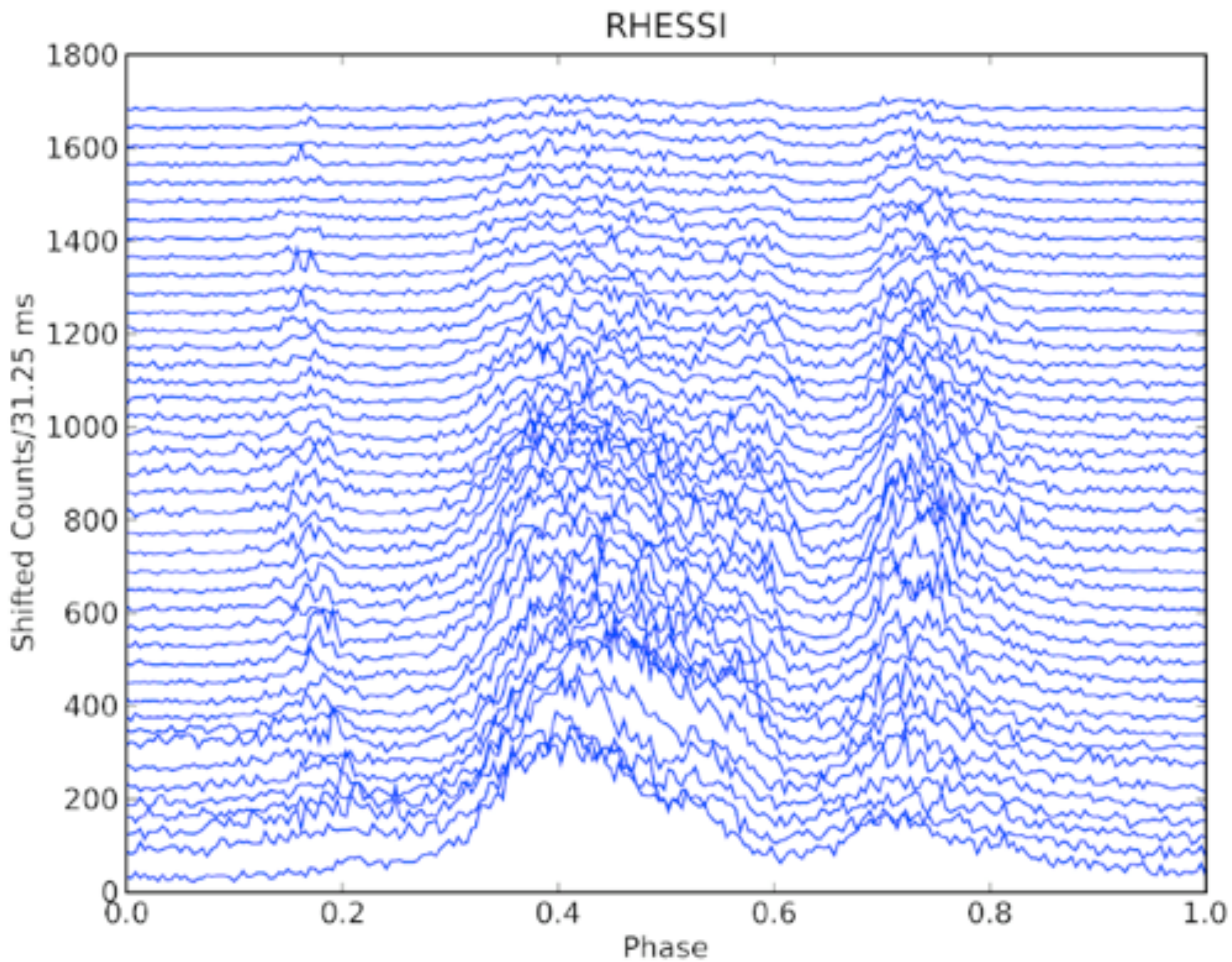
Fireball model, Thomson & Duncan 01



Phase averaged fits to tail, Feroci et al. 2001

Emission components

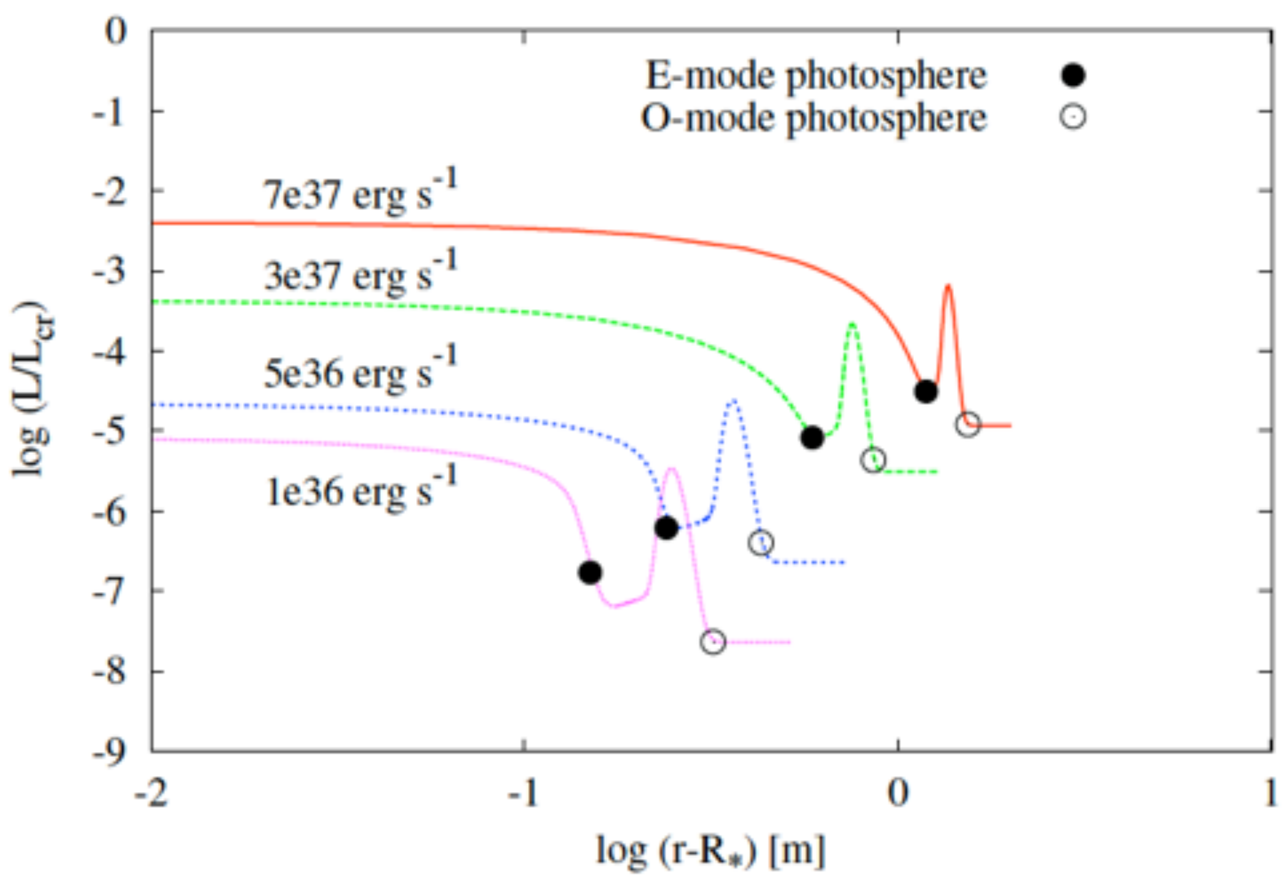
- Direct emission from reconnection.
- Outflow interaction w/ environs.
- Fireball formation, evaporation.
- Seismic vibration contribution?
- Heating of crust, afterglow

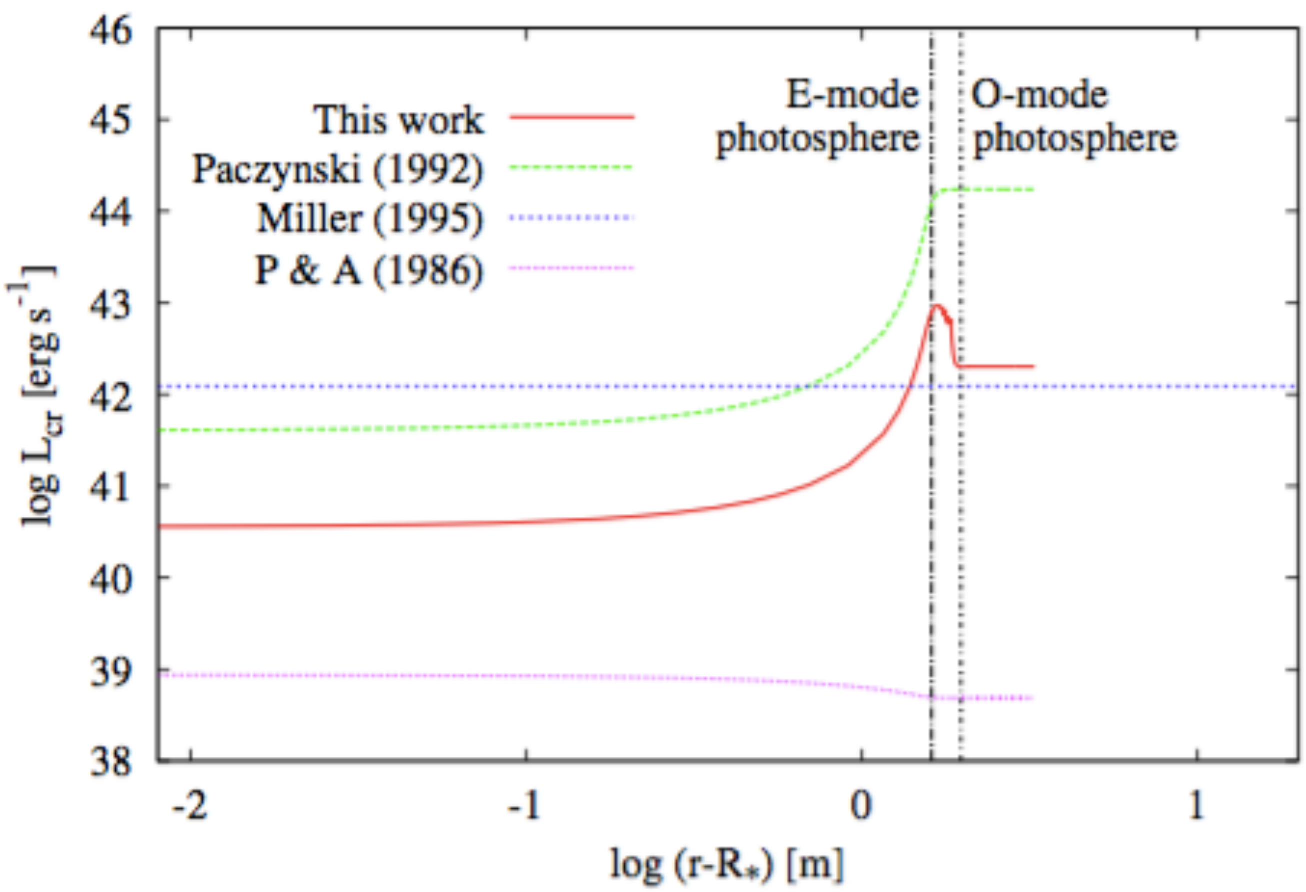


Strong evolving pulse, SGR 1806-20 GF (plot from Dekker MSc thesis)

Magnetic Eddington limit effects

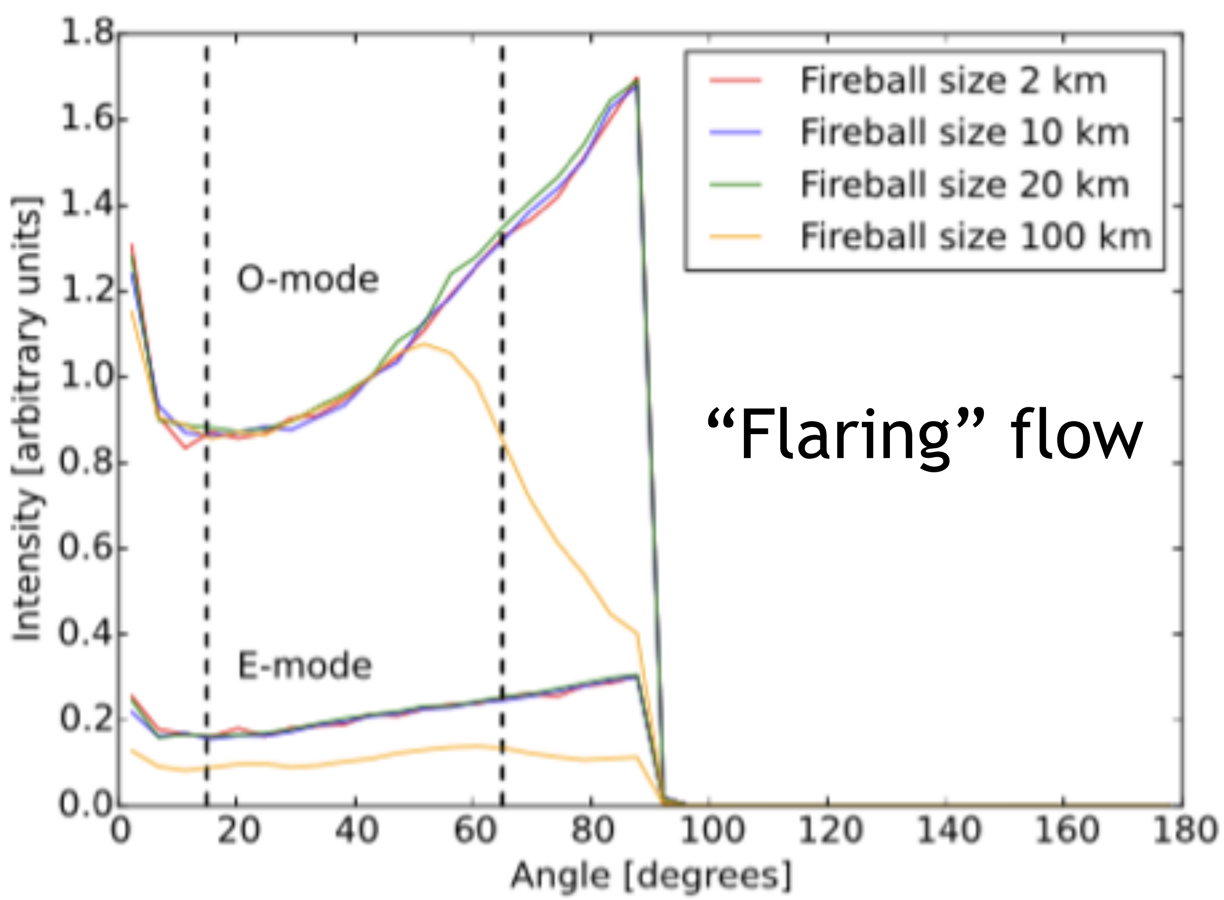
- Could we identify Eddington limit effects like Photospheric Radius Expansion? Could constrain EOS and magnetic field (Watts et al. 2010).
- van Putten, Watts et al. 2013: simple open field line model.
- Extended atmospheres don't form (no PRE), magnetic Eddington limit lower than expected, outflows seem likely (subsequent work so far fails to find stable outflow solutions) – what are their effects?

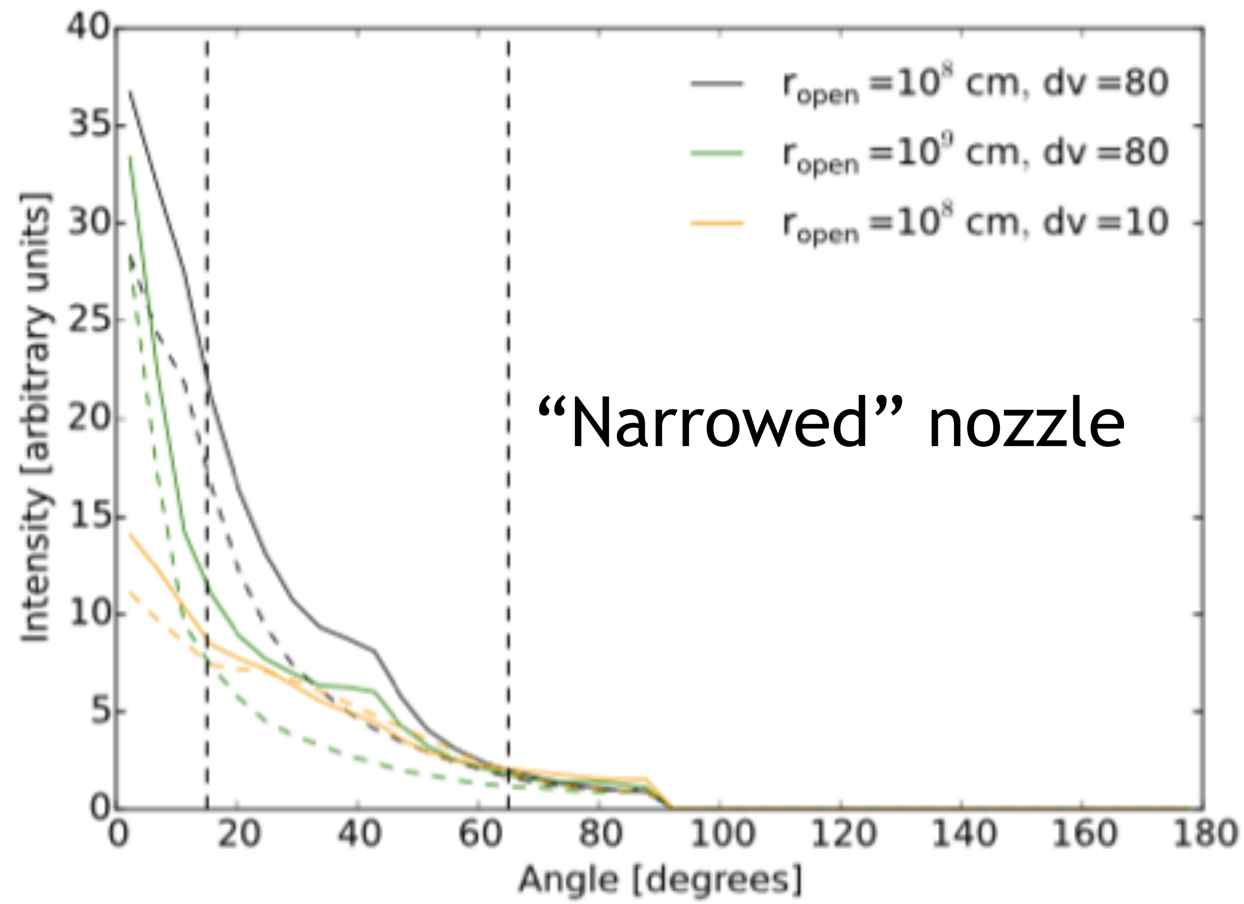




Peaks, tails and wobbles

- Initial peak - much focus on lightcurve timescales , but without considering radiation processes (Elenbaas, Watts et al. 2016).
- Seismology – `waving the beam' not enough explain high amplitudes of QPOs (D'Angelo & Watts 2012)
- Tail – how does one get the strong pulsed emission?





van Putten, Watts & Wijers 2016, radiative transfer simulations, outflow imposed a priori

Summary

Burst (ocean) oscillations excited by thermonuclear bursts

- Understanding mechanism/permitted patterns will remove a source of uncertainty for pulse profile modelling M, R technique.
- Substantial progress, esp. using pulsars and flame spread models.
- Multiple mechanisms may be in operation: whether these include surface modes is still unclear.

Magneto-elastic oscillations excited by magnetar flares

- Oscillations detected in both giant flares and short bursts.
- Seismic models complex, but would deliver much more than just M, R
- Understanding emission processes crucial to understanding how to link X-ray variations to seismology, including excitation.