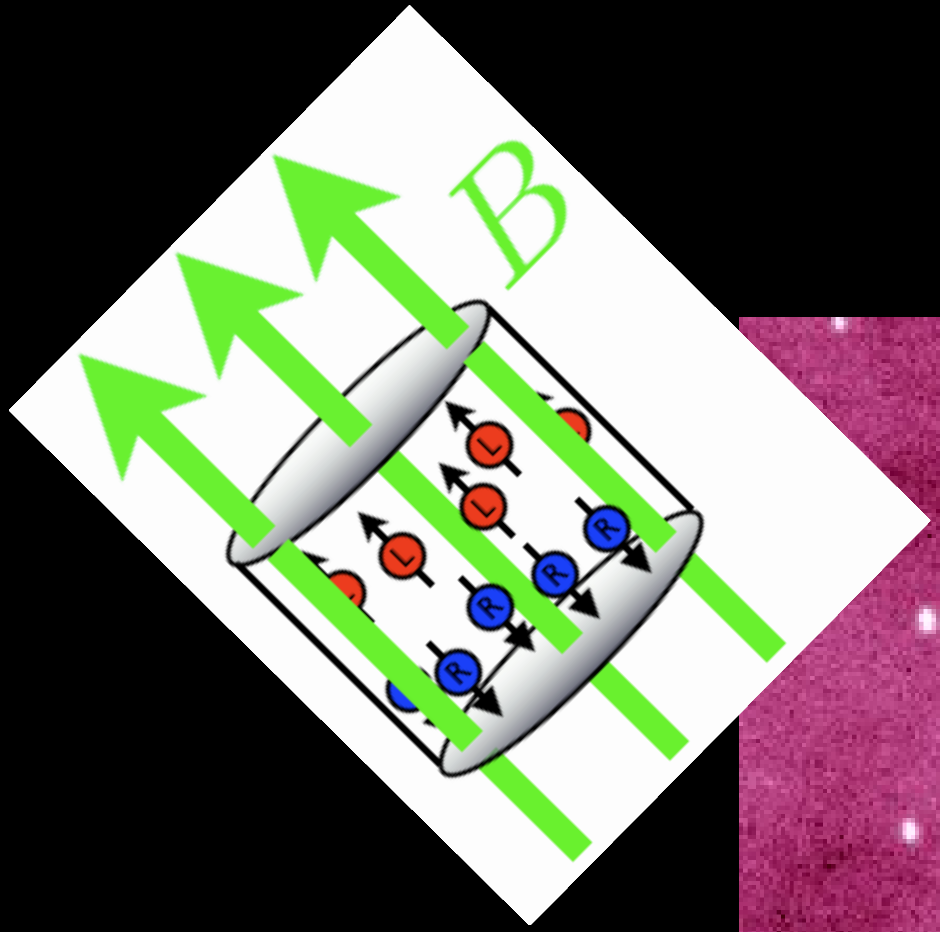
Discussion contribution: Chiral Hydrodynamics Kicks Neutron Stars

ECT* Workshop: Strongly interacting matter in extreme magnetic fields

ECT*, Trento, Italy

September 26=7th, 2023

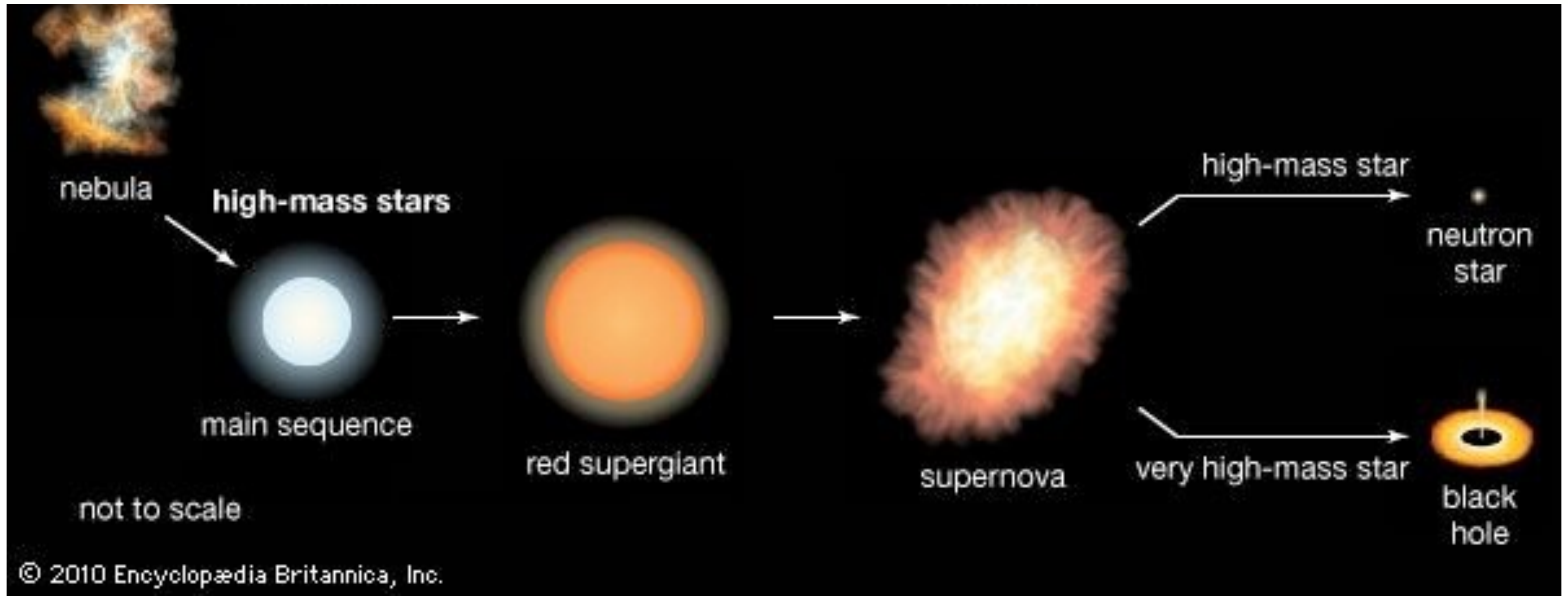


[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; Phys.Lett.B (2016)]

Matthias Kaminski
University of Alabama

U.S. DEPARTMENT OF ENERGY

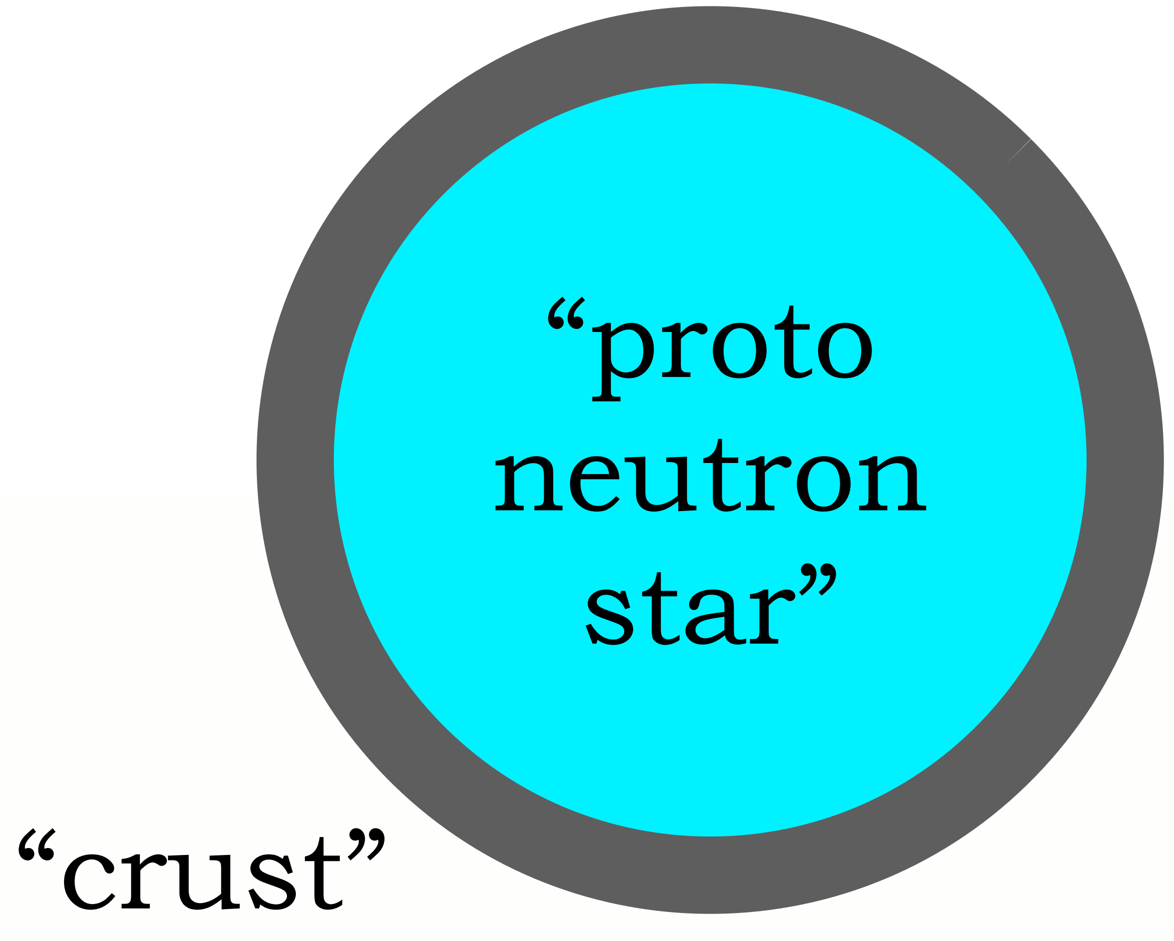
Neutron star picture

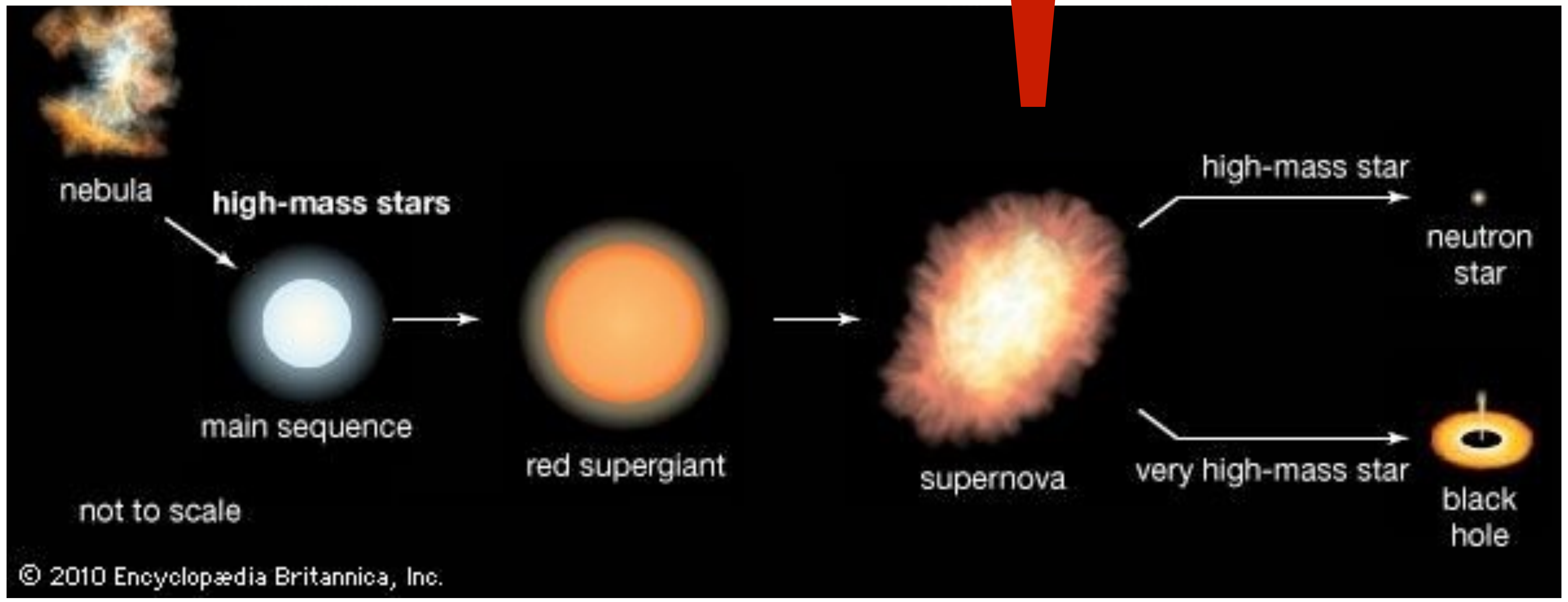


- compact star
  * small radius
  * large mass
  * high density
- quick rotation
- large B field

Neutron star picture

naive picture a short time interval immediately after the explosion:





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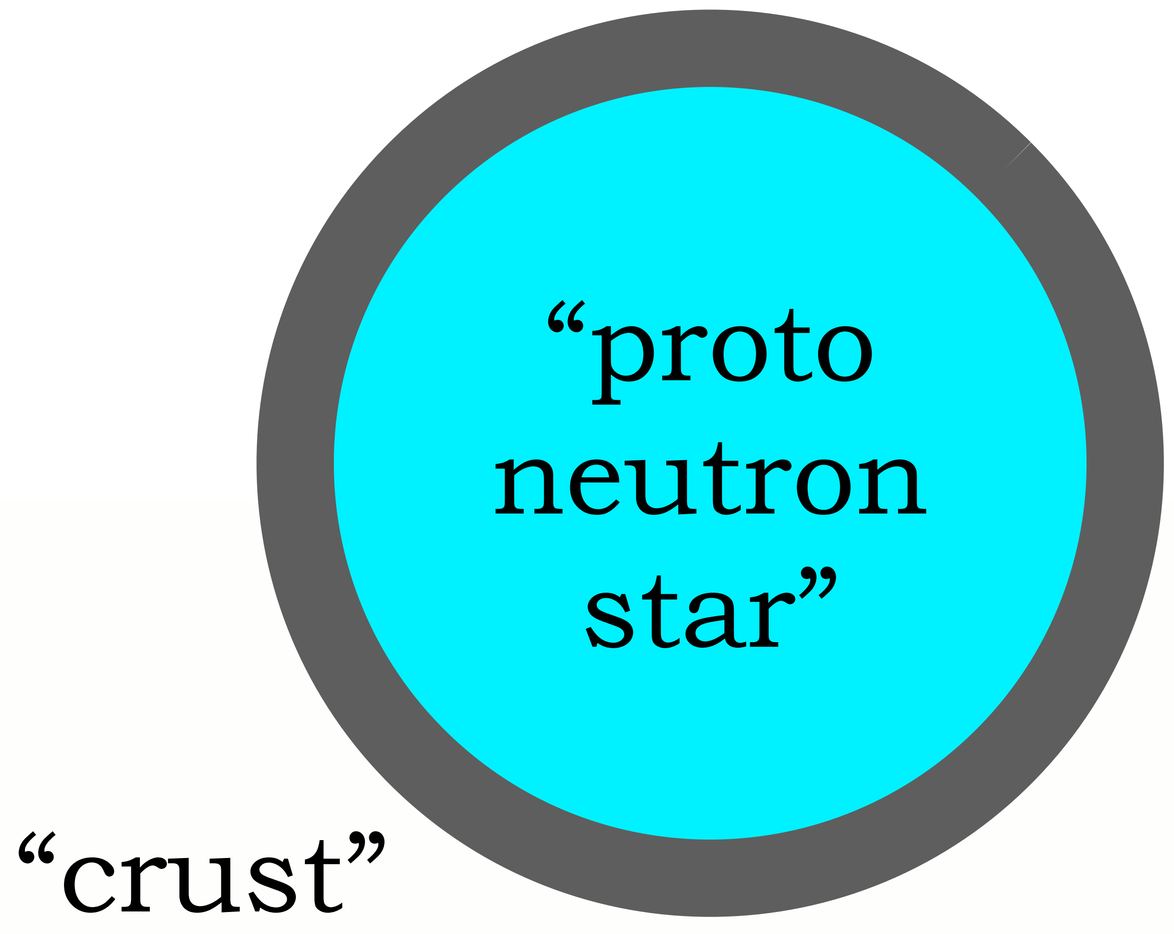

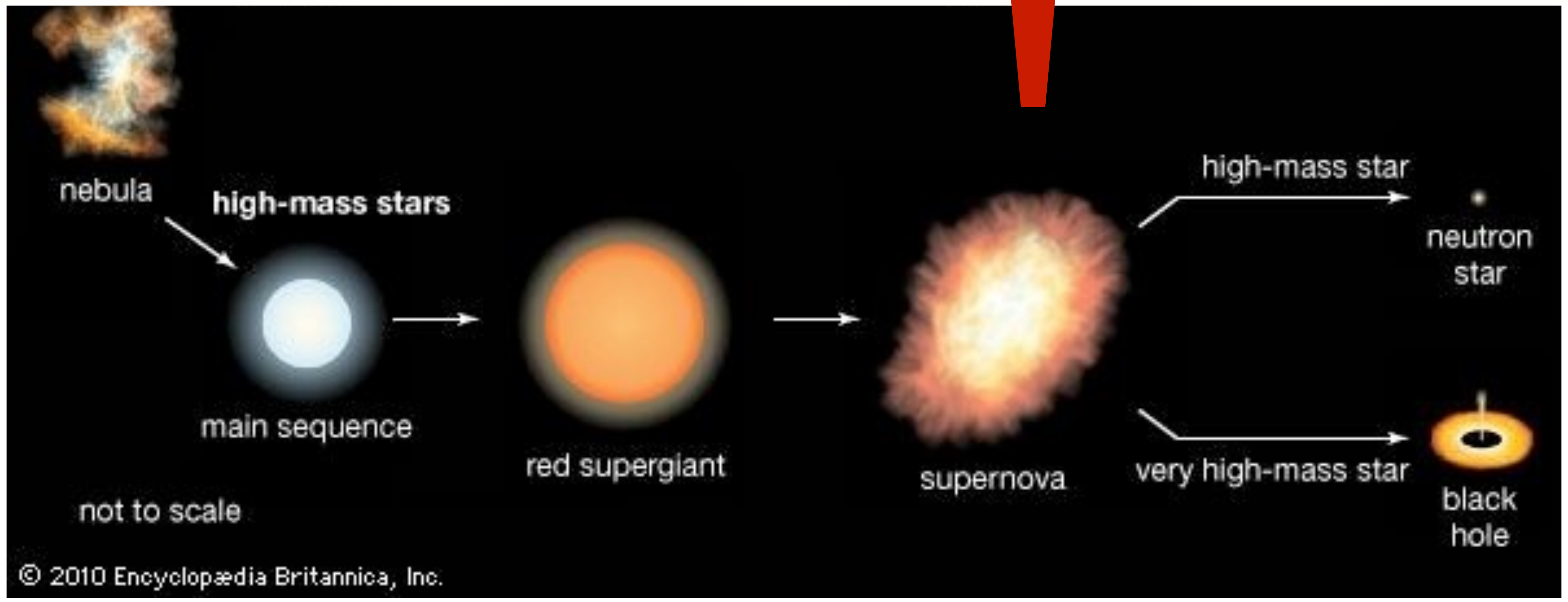

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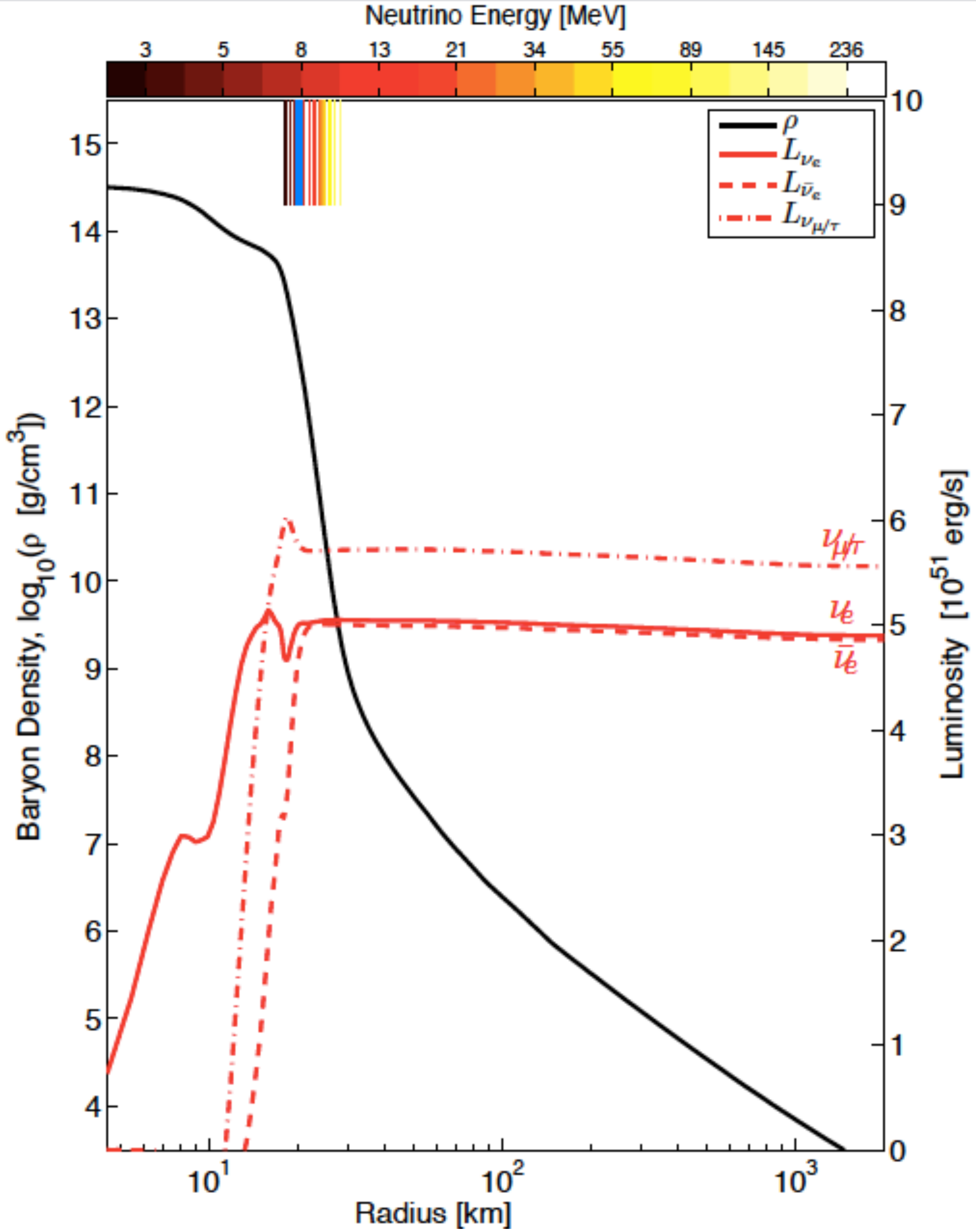
proto-neutron stars are dense objects with "crust" and preferred directions

First 10 seconds inside proto-neutron stars



[Fischer et al.; PRD (2011)]

cf. [Wongwathanarat, Janka, Muller; (2012)]

- baryonic matter: 10 km radius
- neutrinos: last scattering surfaces around 10 km
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- only electron flavor inside 10 km
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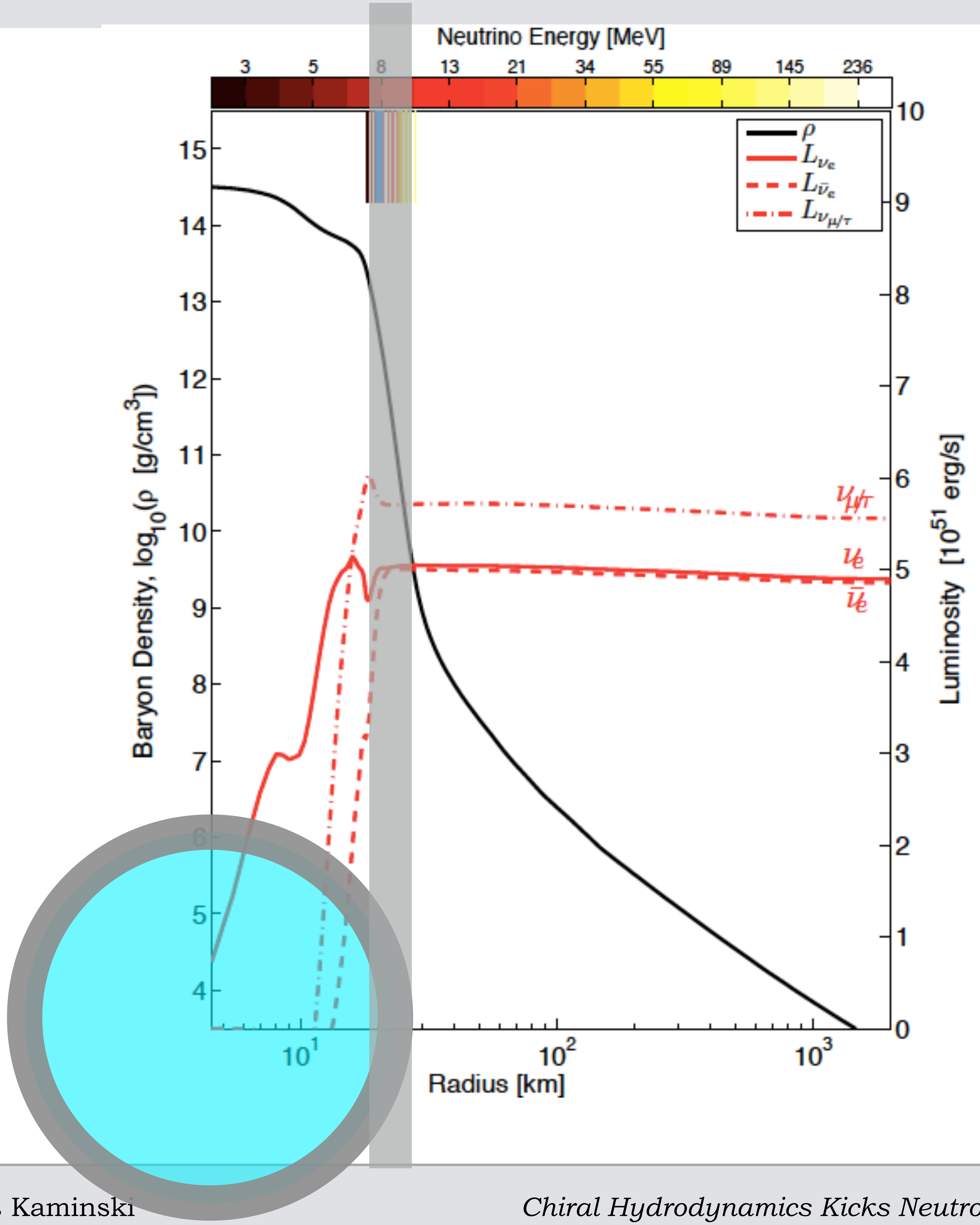

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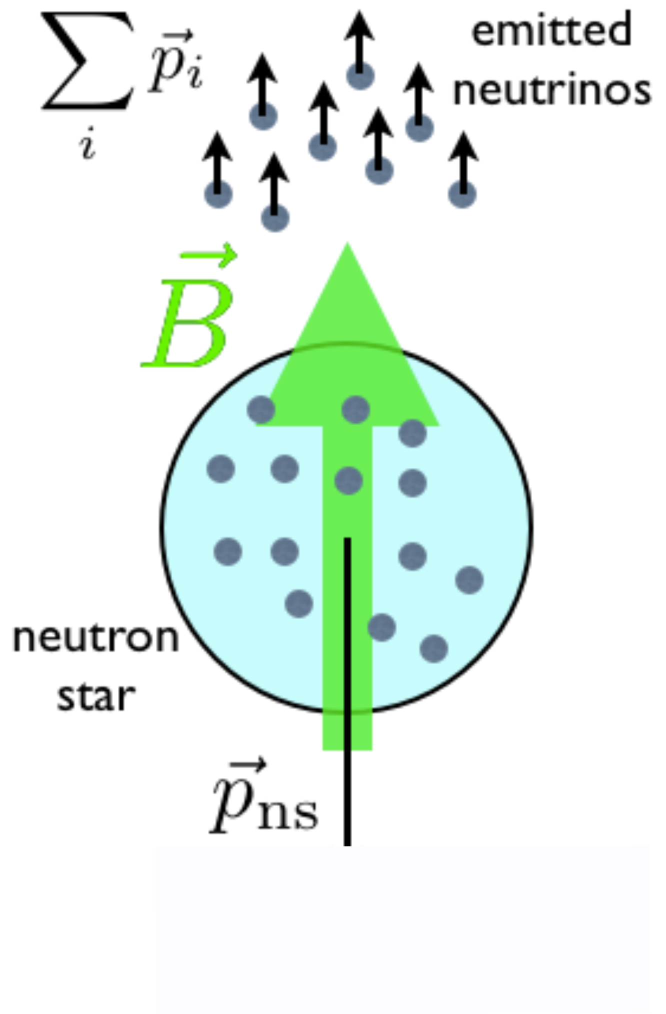
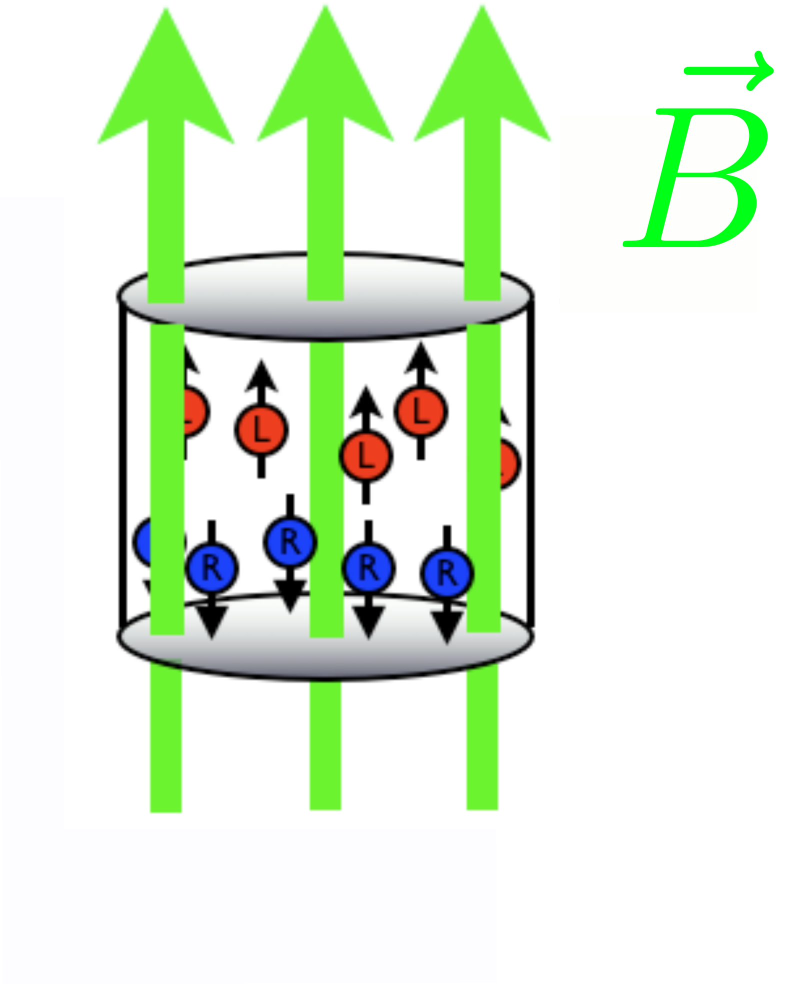
This simulation data confirms our naive picture; apply hydrodynamics!

Our assumptions

- simulation data from previous slide valid *[Fischer et al.; PRD (2011)]* *[Wongwathanarat, Janka, Muller; (2012)]*
- hydrodynamic approximation applicable
- strong magnetic field exists inside proto-neutron star for about 10 seconds

Result in kicks from chiral hydrodynamics





Dirty details: chiral effects in vector/axial currents

see e.g. [Jensen, Kovtun, Ritz; JHEP (2013)]
[Neiman, Oz; JHEP (2010)]

Vector current (e.g. QCD *U(1)*)

$$J_V^\mu = \cdots + \xi_V \omega^\mu + \xi_{VV} B^\mu + \xi_{VA} B_A^\mu$$

chiral magnetic effect

Axial current (e.g. QCD axial *U(1)*)

$$J_A^\mu = \cdots + \xi \omega^\mu + \xi_B B^\mu + \xi_{AA} B_A^\mu$$

chiral vortical effect

chiral separation effect

Note:

* hydrodynamic frame choice
  [Ammon, Kaminski et al.; JHEP (2017)]
* consistent vs covariant

[Landsteiner; APhysPolC (2016)]
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[Neiman, Oz; JHEP (2010)]
correcting and generalizing [Son,Surowka; PRL (2009)]

More than one current $\langle \partial_\mu J^\mu_a \rangle = \frac{1}{8} C_{abc} \epsilon^{\mu\nu\rho\sigma} F^b_{\mu\nu} F^c_{\rho\sigma}$

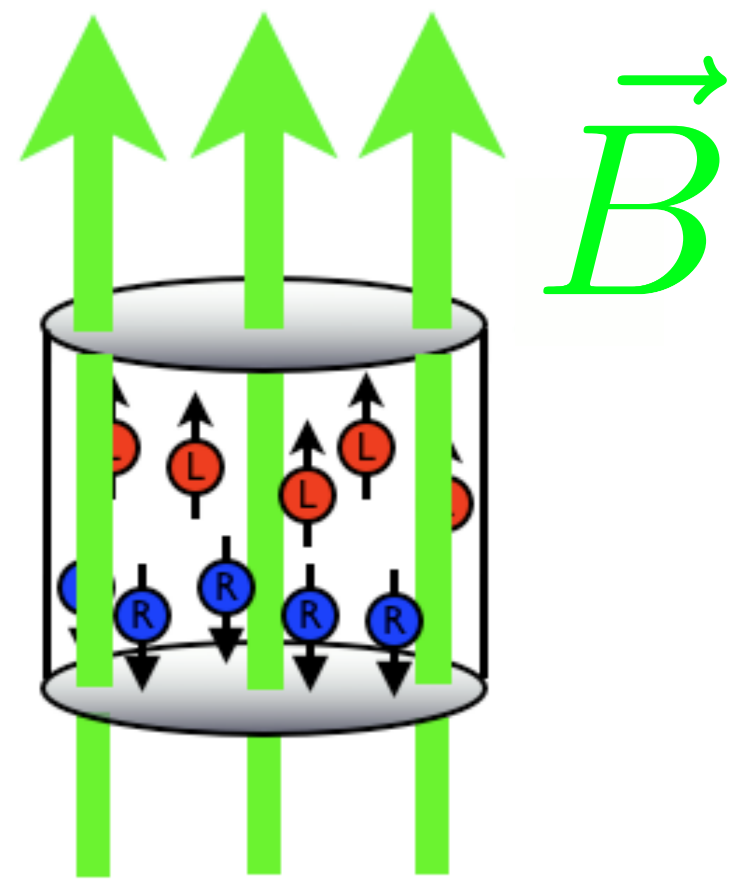
Constitutive relation:

$$J^\mu_a = n_a u^\mu + \sigma_a{}^b V^\mu_b + \sigma^V_a \omega^\mu + \sigma^B_{ab} B^{b\,\mu} + \mathcal{O}(\partial^2)$$

Chiral magnetic conductivity:

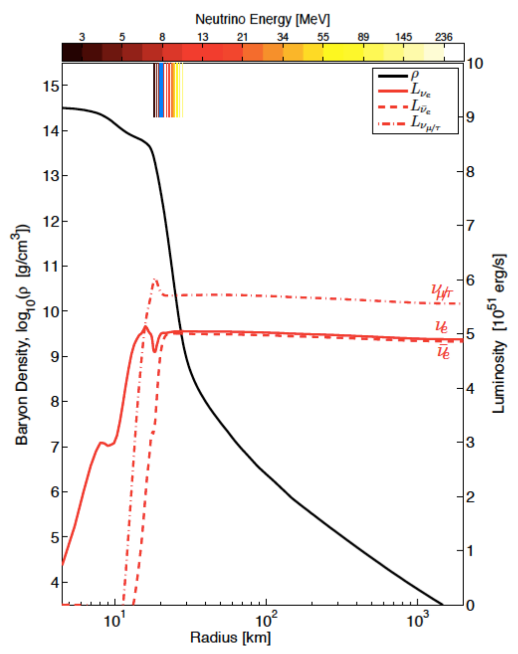
$$\sigma^B_{ab} = C_{abc}\, \mu^c$$

various charges
(e.g. lepton number,
electromagnetic charge, ...)

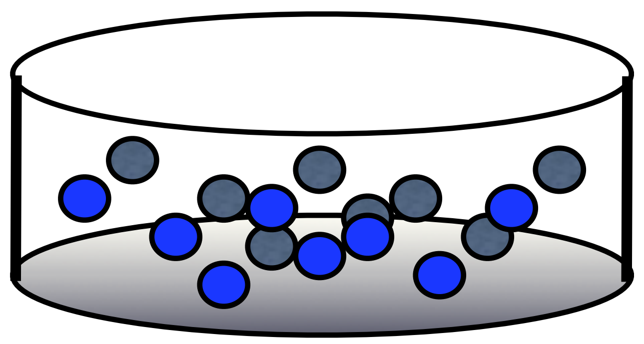


Relevant currents in neutron stars

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; PLB (2016)]



A bucket full of electrons and electron neutrinos with short mean free path



$B = 0.1\,\mathrm{MeV}^2$

$\mu^\ell \approx 300\,\mathrm{MeV}$

Microscopic (standard model) currents: lepton/axial/EM:

$$J^\mu_\ell = \bar{e}_L\gamma^\mu e_L + \bar{e}_R\gamma^\mu e_R + \bar{\nu}\gamma^\mu\nu$$
$$J^\mu_{\ell 5} = \bar{e}_L\gamma^\mu e_L - \bar{e}_R\gamma^\mu e_R + \bar{\nu}\gamma^\mu\nu$$
$$J^\mu_{EM} = \bar{e}_L\gamma^\mu e_L + \bar{e}_R\gamma^\mu e_R$$

neutrinos and electrons "inseparable"

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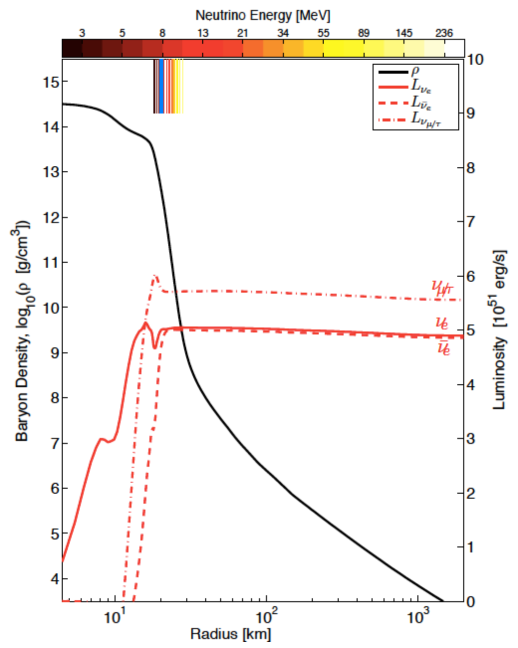

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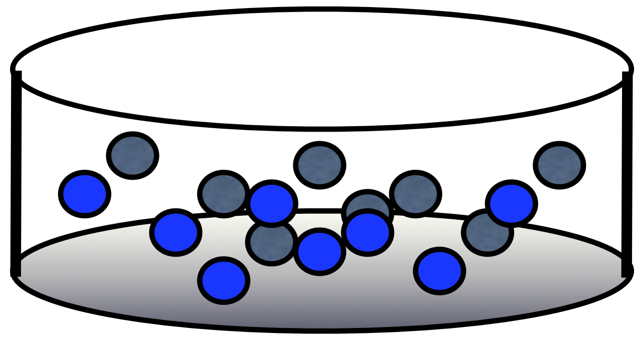

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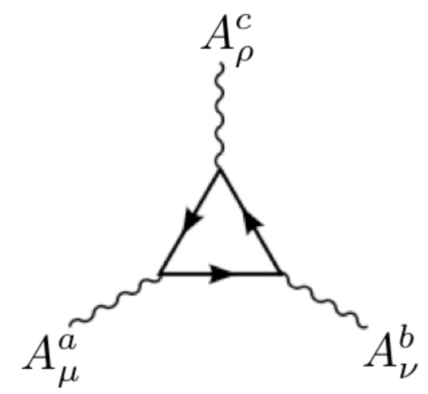
neutrinos and electrons "inseparable"

"crust"

Macroscopic (hydrodynamic) description: $\sigma^B_{ab} = C_{abc}\,\mu^c$

$$J_\ell \sim \sigma^B_{\ell,EM} B \approx C \mu^{\ell 5} B$$

$$J_{\ell 5} \sim \sigma^B_{\ell 5,EM} B \approx C \mu^{\ell} B$$



$$C_{\ell,\ell 5,EM} = \frac{1}{2\pi^2}$$

Estimate of the neutron star kick

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; PLB (2016)]

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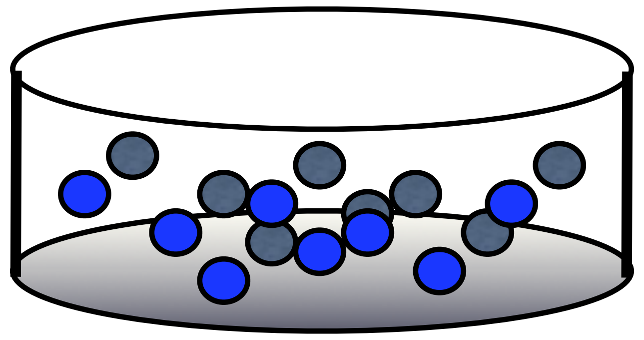

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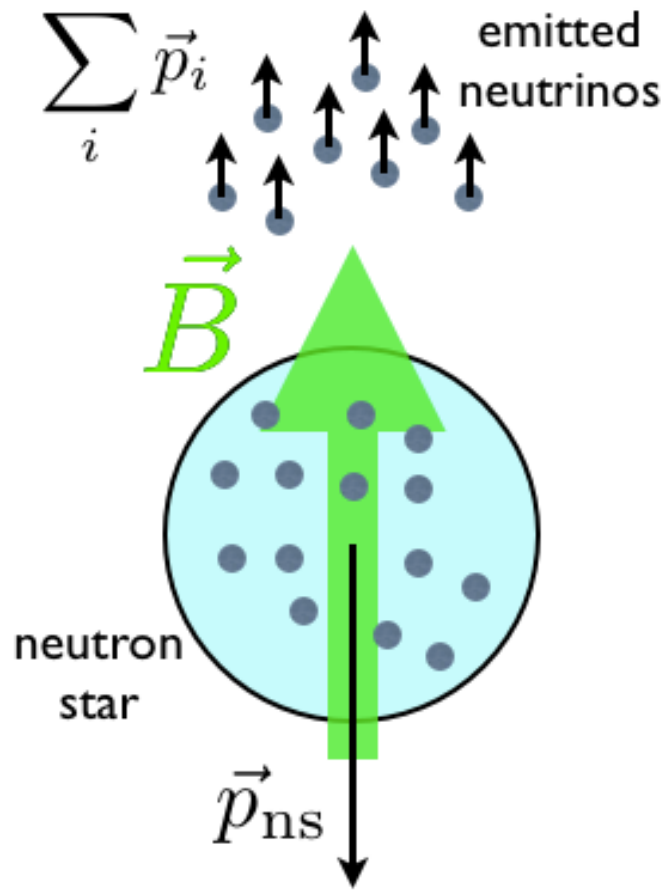

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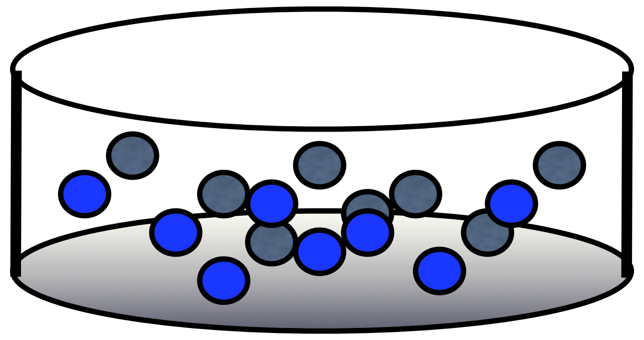

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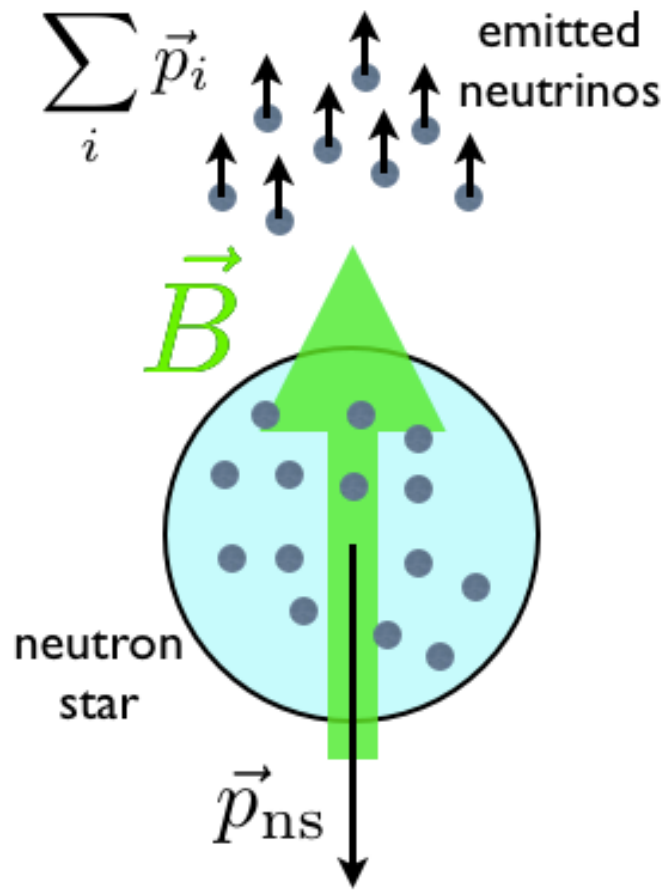

Chiral conductivity:

$$\sigma^B_{\ell 5, EM} = C_{\ell, \ell 5, EM}\, \mu^\ell = \frac{1}{2\pi^2} \mu^\ell$$

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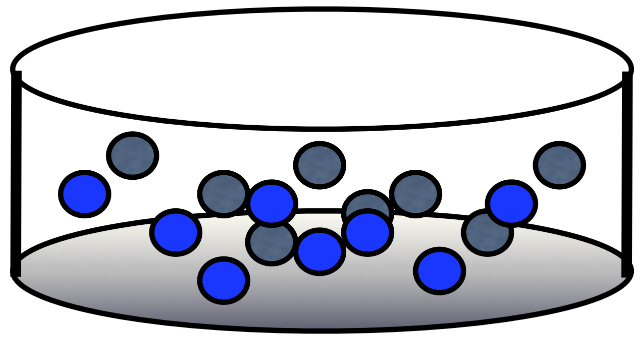

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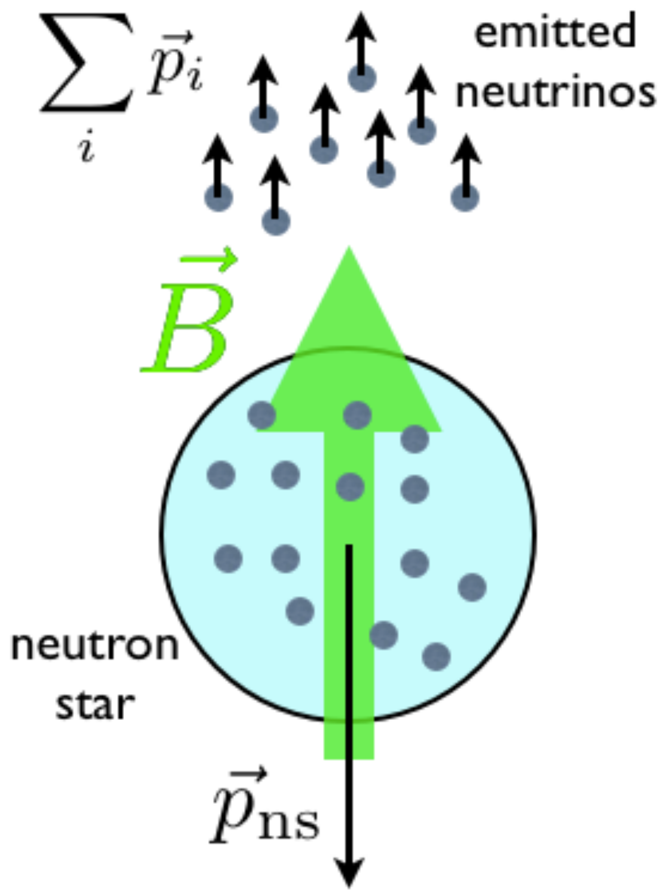

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$$\vec{J}_{\ell 5} = C\mu^\ell \vec{B} \approx \vec{e}_B \cdot 1\,\mathrm{MeV}^3$$

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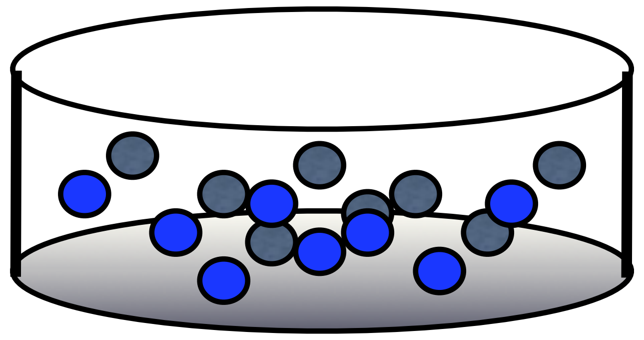

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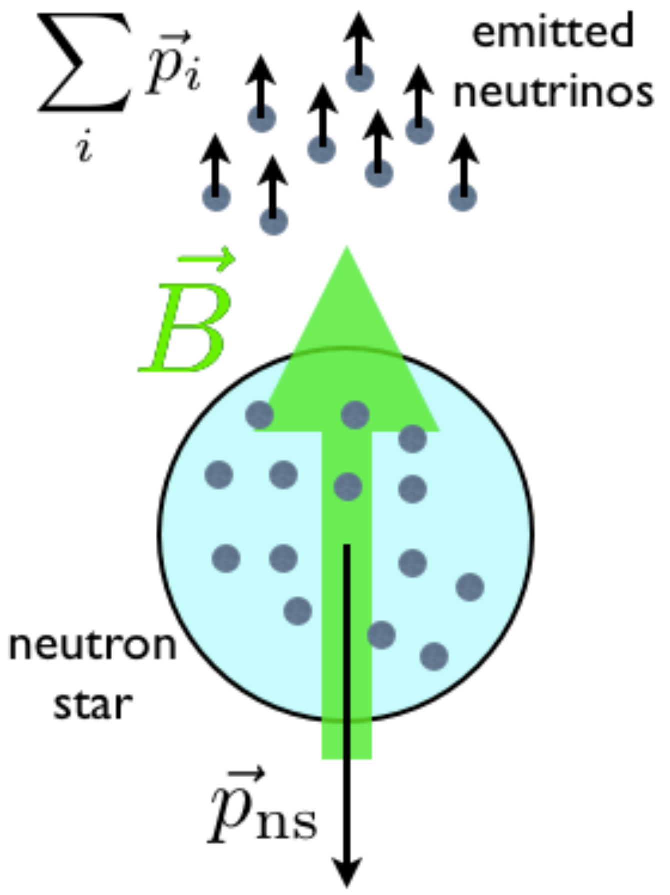

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Particle flux and momentum transfer:

$$\dot{N}_\nu = |\vec{J}|\, A_{\rm surface} \approx 10^{54}/\mathrm{s}$$

$$\Delta P_{\rm NS} = \Delta t \dot{N}_\nu \langle p_\nu \rangle$$

$$\Delta t \approx 10\,\mathrm{s}$$

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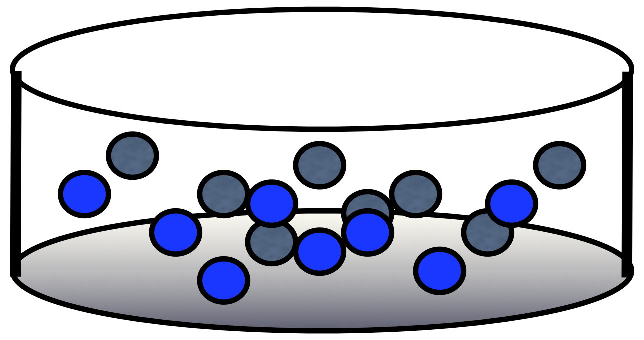

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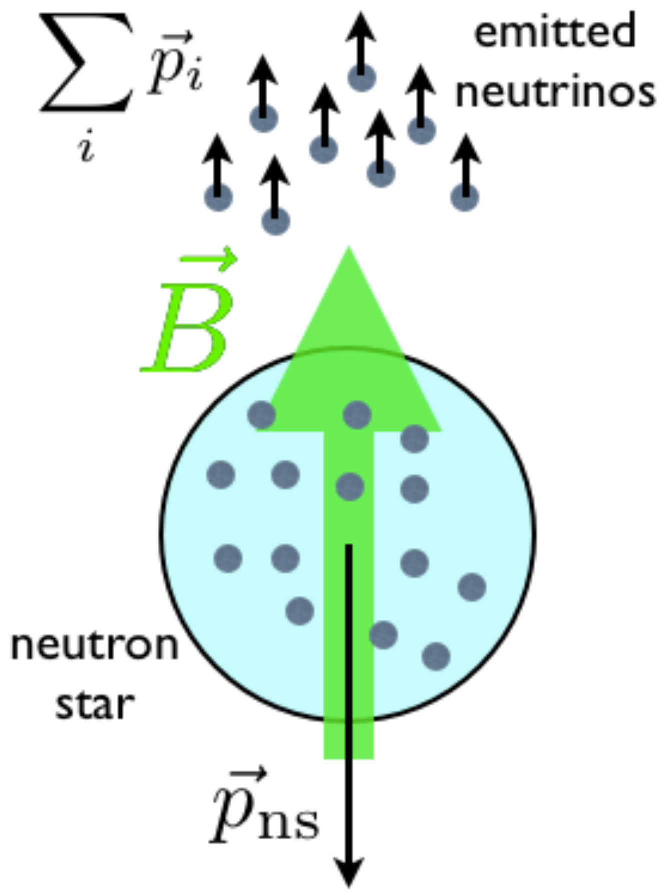

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Neutron star mass: $m_{\mathrm{NS}} = 3 \cdot 10^{30}\,\mathrm{kg}$

Estimate of the neutron star kick

[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; PLB (2016)]

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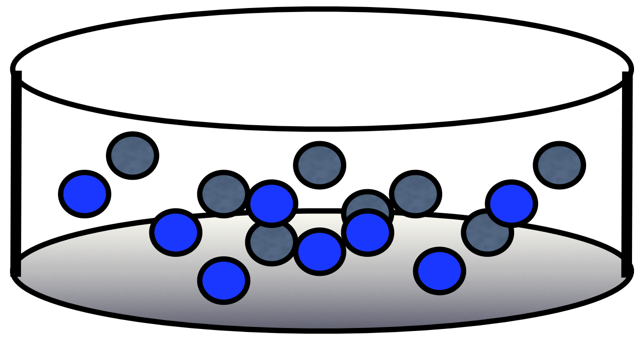

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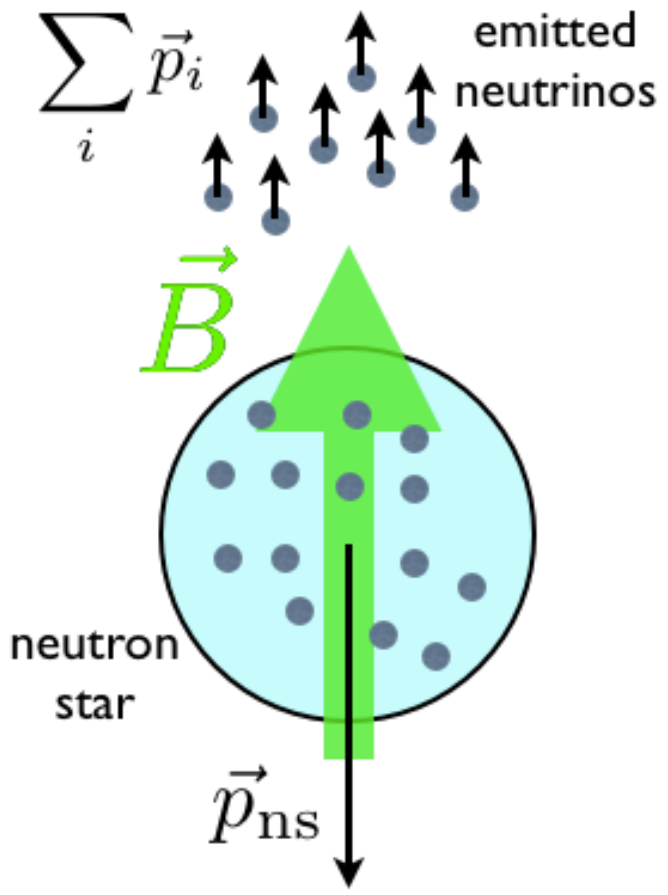

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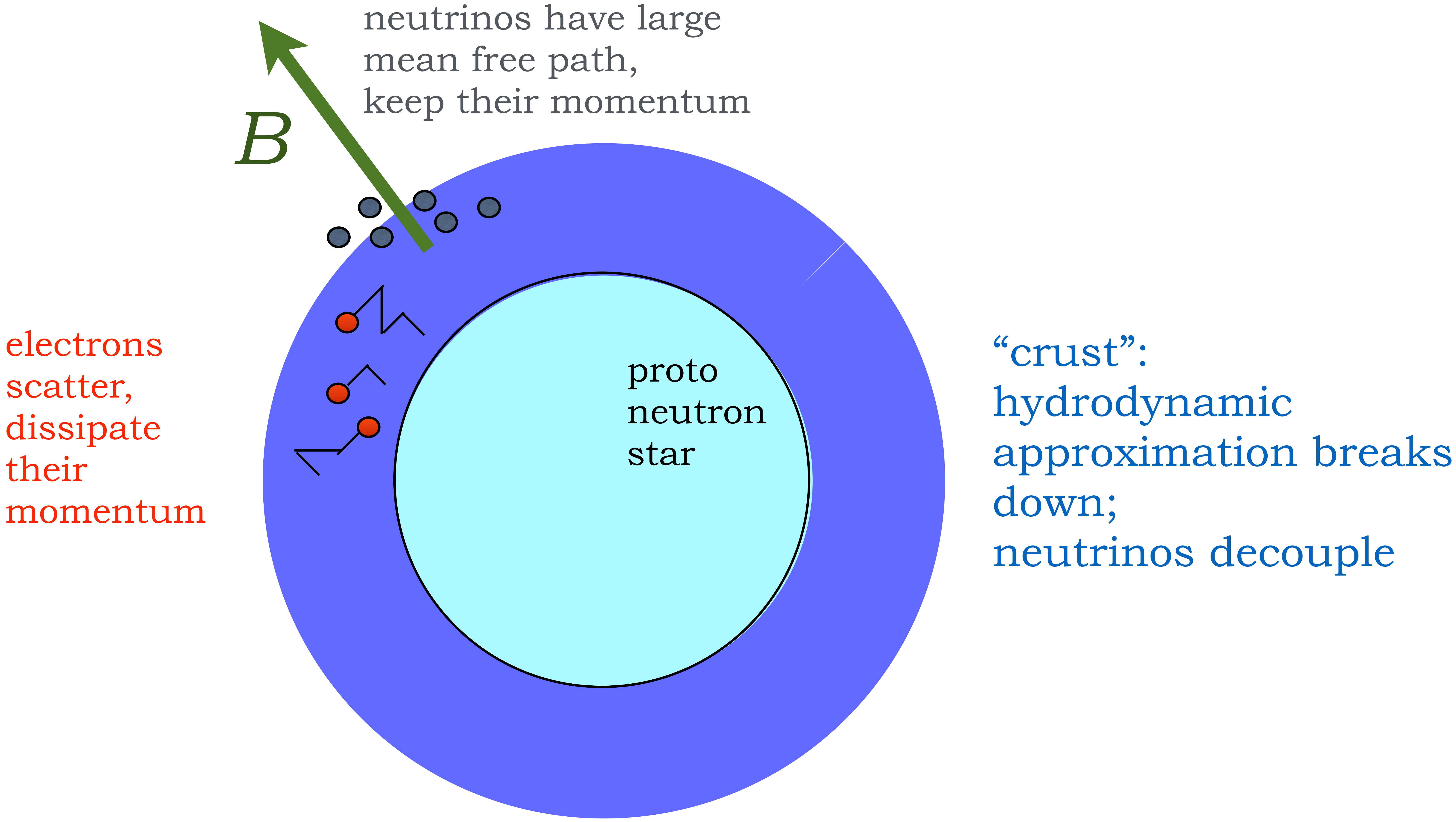
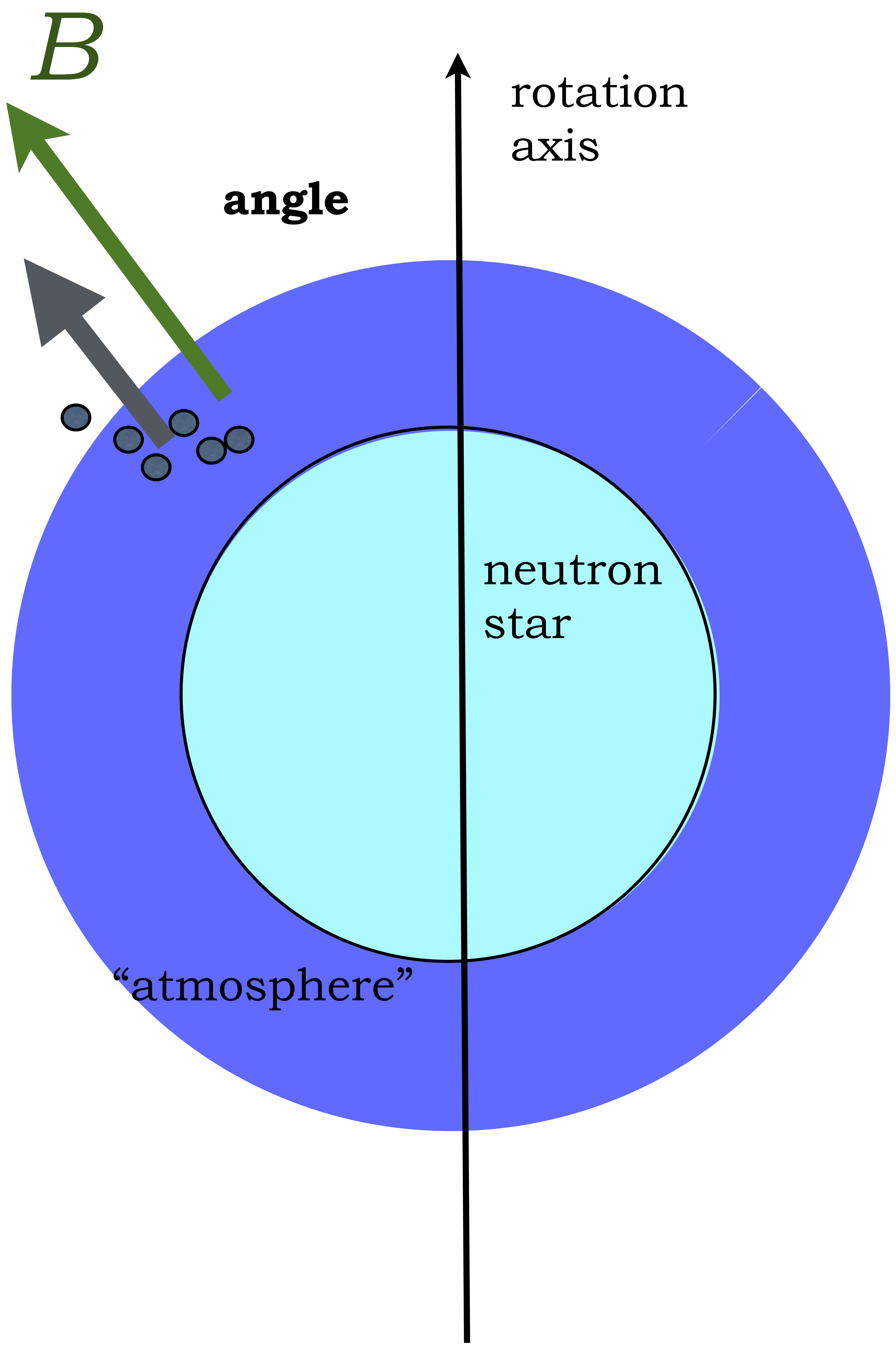
Neutron star mass: $m_{NS} = 3 \cdot 10^{30}\,\mathrm{kg}$

Kick velocity agrees with observations: $\Rightarrow \quad v_{\mathrm{kick}} \approx 1000\,\frac{\mathrm{km}}{\mathrm{s}}$

Filtering at the "crust"



Observable signal?



Prediction: Kick magnitude depends on angle between rotation axis and internal magnetic field axis.

For fast spinning neutron stars, kick directed along rotation axis.

Data on rotation/B/kick axes:

- http://adsabs.harvard.edu/abs/2012ApJ...755..141B
- http://adsabs.harvard.edu/abs/2007ApJ...670..635W
- http://adsabs.harvard.edu/abs/1988srim.conf...65W
- http://adsabs.harvard.edu/abs/2007ApJ...656..399W

CVE neutron star kicks

$$\sigma^V_a = \frac{1}{2} C_{abc}\mu^b\mu^c - \beta_a T^2 \,, \qquad \sigma^B_{ab} = C_{abc}\mu^c$$

$$j^\mu = n u^\mu + \sigma E^\mu + \sigma^B B^\mu + \sigma^V \omega^\mu + \ldots$$

"chiral vortical conductivity"

[Erdmenger, Haack, Kaminski, Yarom; JHEP (2008)]

[Banerjee et al.; JHEP (2011)]

CVE kick possible but suppressed by orders of magnitude

$\omega \approx 10^{-17}\,\mathrm{MeV}$

$B \sim 10^{12}\,\mathrm{G} \approx 0.1\,\mathrm{MeV}^2$

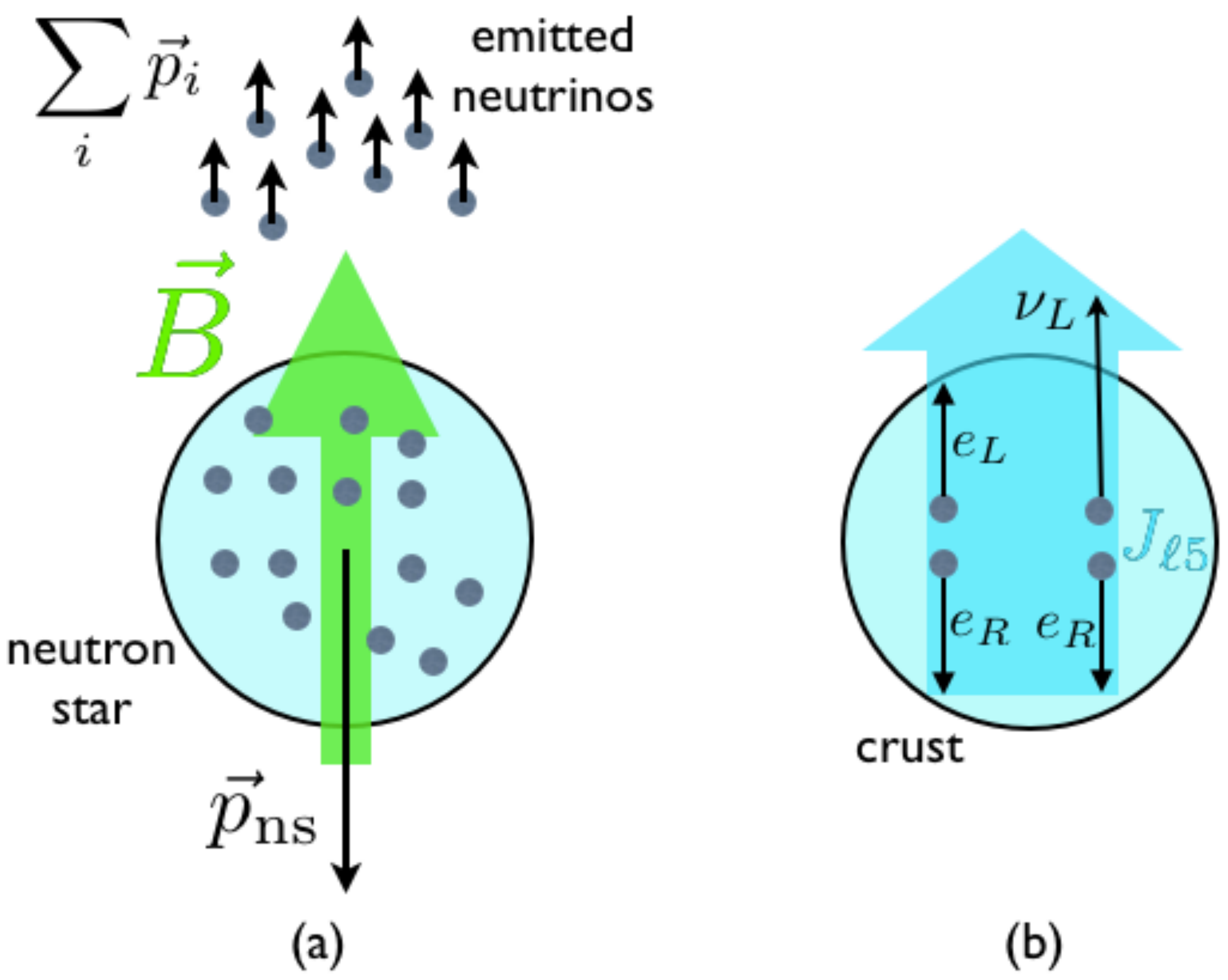
[Kaminski, Uhlemann, Schaffner-Bielich, Bleicher; PLB (2016)]

stronger CVE kick possible due to formation of ergo sphere

[Shaverin, Yarom; arXiv (2014)]

see also [Shaverin; arXiv (2018)]

Summary



- Yes, standard (first order) **CME (maybe CVE) can lead to neutron star kicks**

Two categories of kick mechanisms

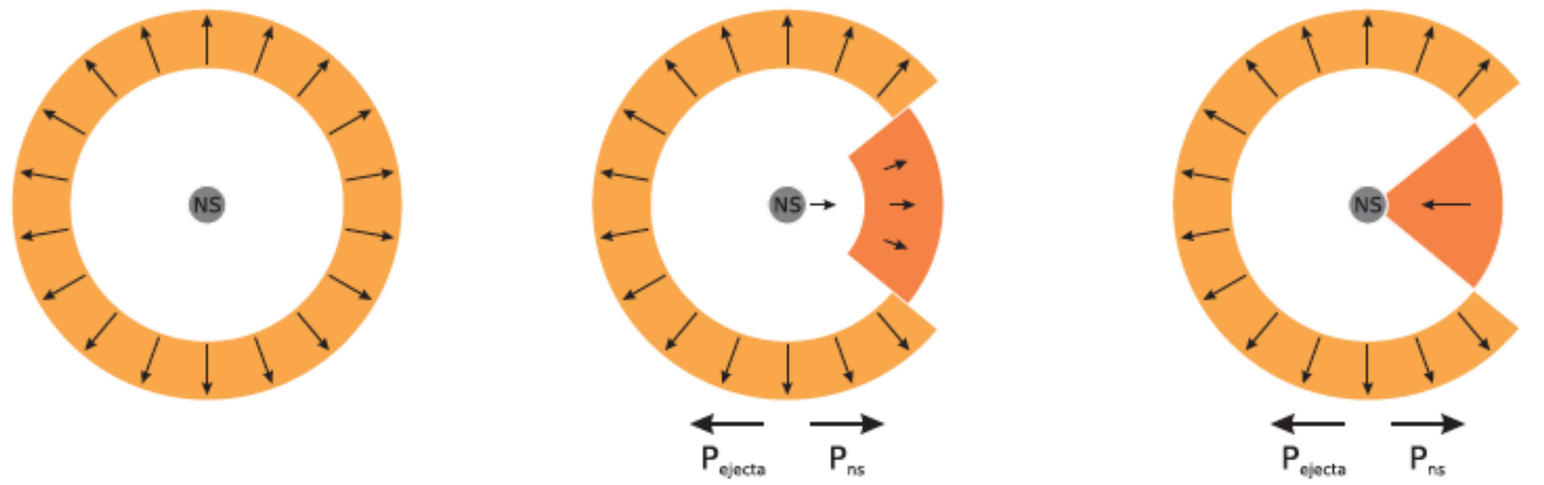
Something has to cause an asymmetry in the momentum distribution.

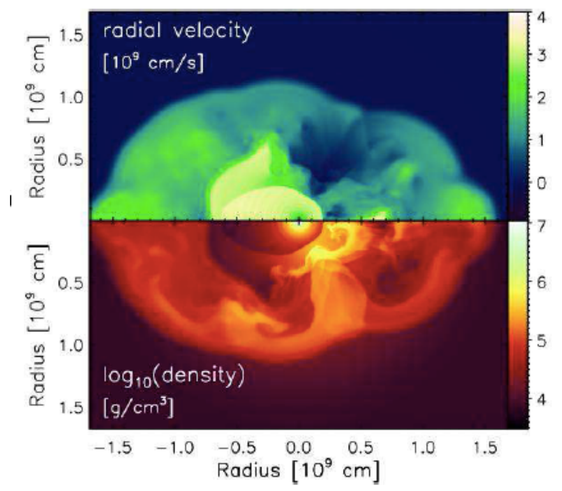
1.) asymmetric supernova explosion

[Scheck, Kifonidis, Janka, Muller; (2003)]
[Wongwathanarat, Janka, Muller; (2010)]
[Wongwathanarat, Janka, Muller; (2012)]

- kicks of about 1000 km/s
- random seed perturbations plus hydro instabilities (SASI)
- hydro model, neutrino transport, boundary cond's
- timescale: ~5 seconds

[Blondin et al; ('02)]





2.) asymmetric emission of matter

- neutrino emission *[Vilenkin (1978)]*
- beyond the standard model *[Fuller, Kusenko, Mocioiu, Pascoli (2003)]*
- neutrino kicks, nucl-th *[Sagert, Schaffner-Bielich (2007)]*

Problems with previous kick mechanisms

ad 1.) asymmetric supernova explosion

- numerical analysis, no analytic understanding
- no magnetic dipole fields, no chiral hydro
- instabilities disturbed by other hydro effects?

ad 2.) asymmetric emission of matter

- neutrino kick too small, neutrinos “too cold”
- microscopic asymmetry washed out *[Kusenko, Segre, Vilenkin (1998)]*
- need physics beyond the standard model

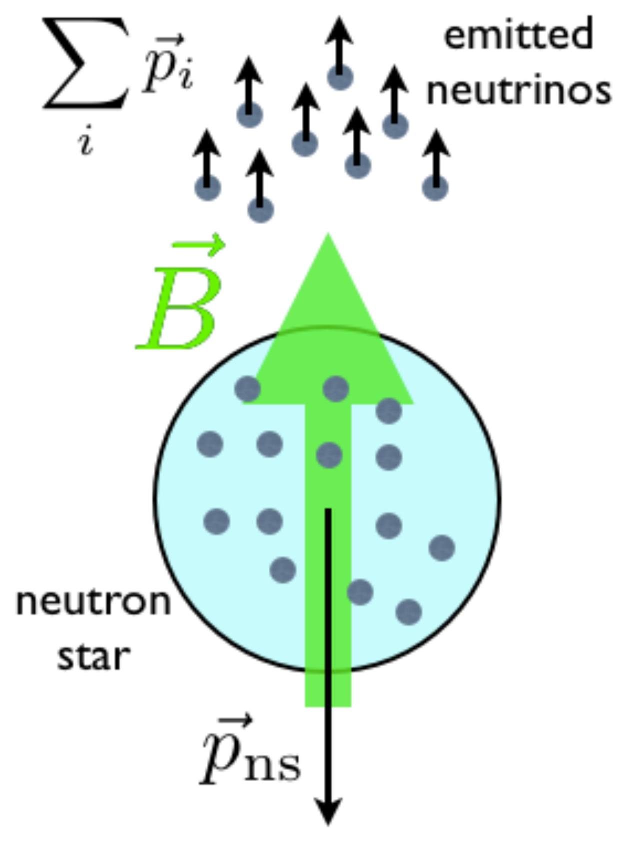
[Fuller, Kusenko, Mocioiu, Pascoli (2003)]

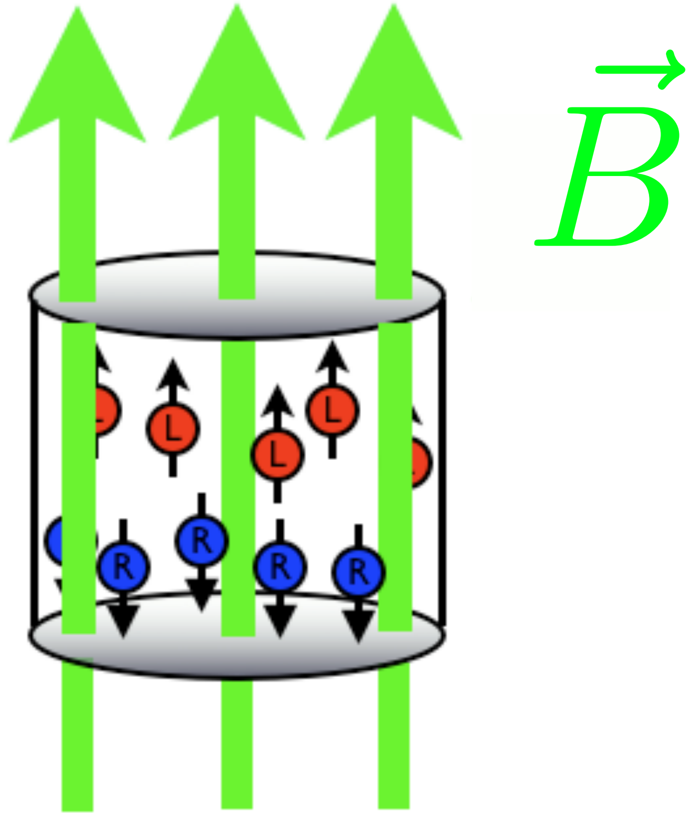
Our anomalous hydrodynamic formalism addresses and overcomes these problems.

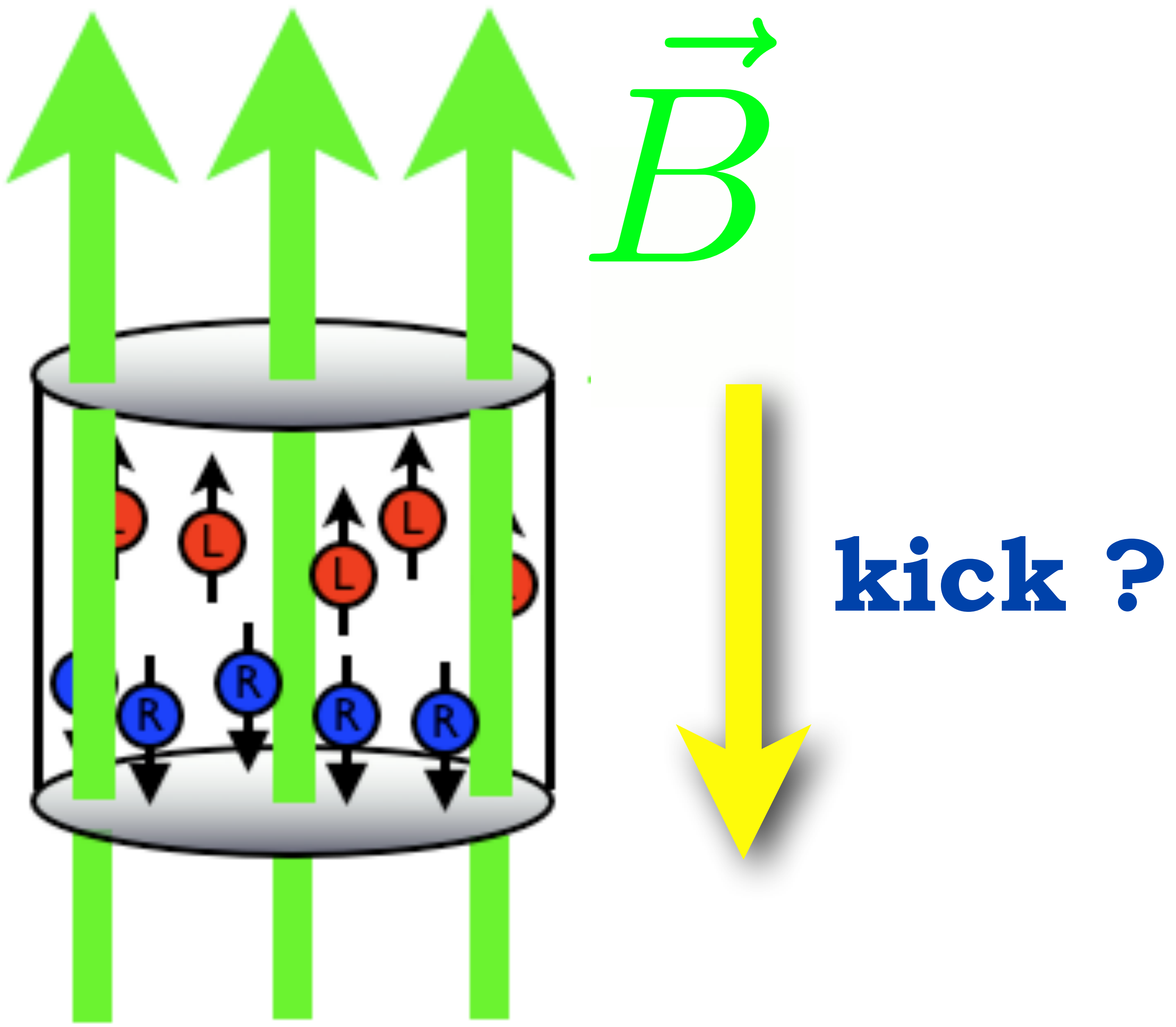
APPENDIX

Physics behind the kick

thermal energy of neutrinos is transformed
to kinetic energy of the neutron star
by chiral hydrodynamic process





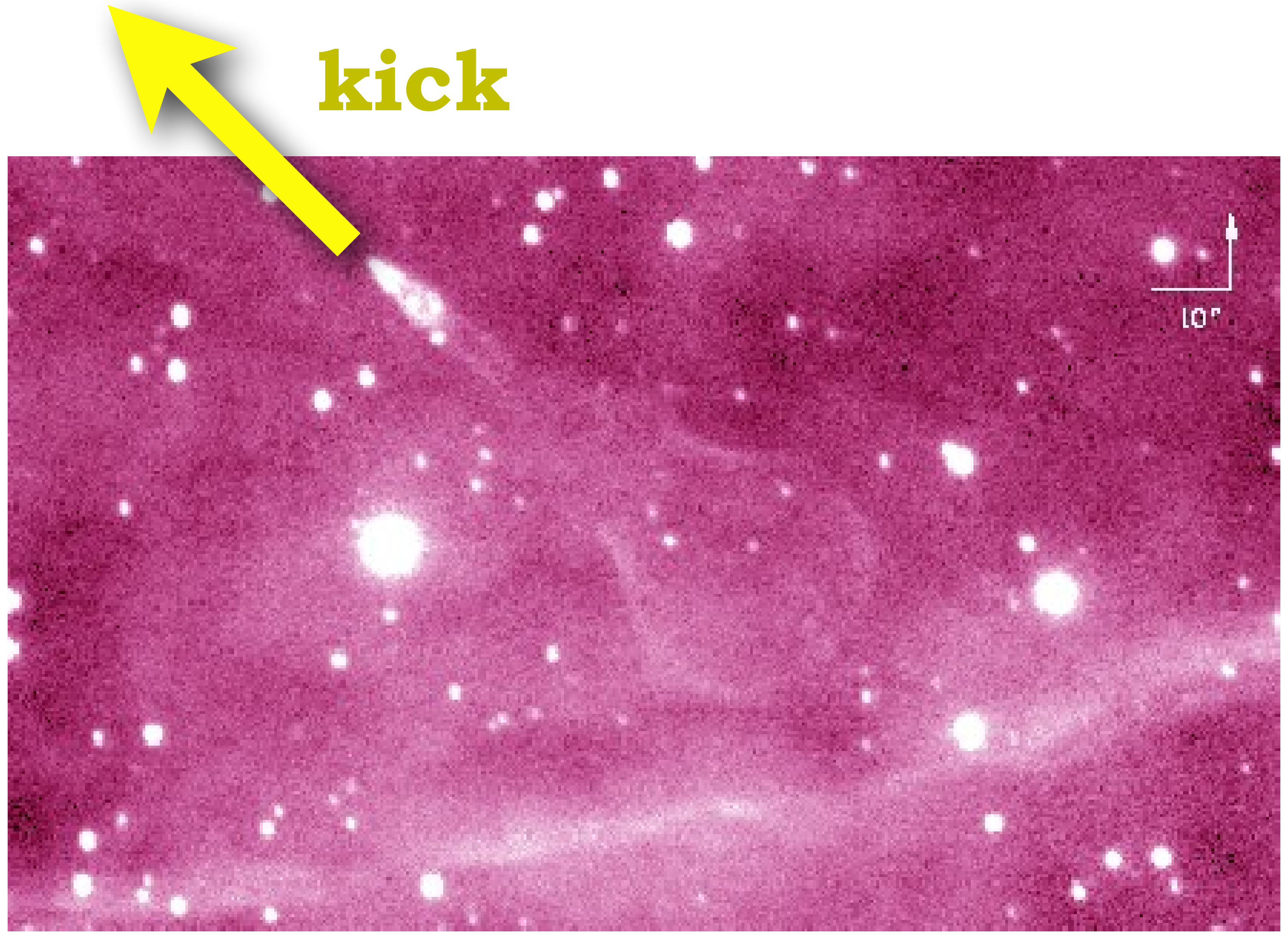


hydrodynamics: fluids with left-handed and right-handed particles produce a **current** along magnetic field

e.g. right/left-handed electrons, neutrinos, ...

theory: [Son,Surowka; PRL (2009)] [Landsteiner]

experiment: [Huang et al; PRX (2015)]



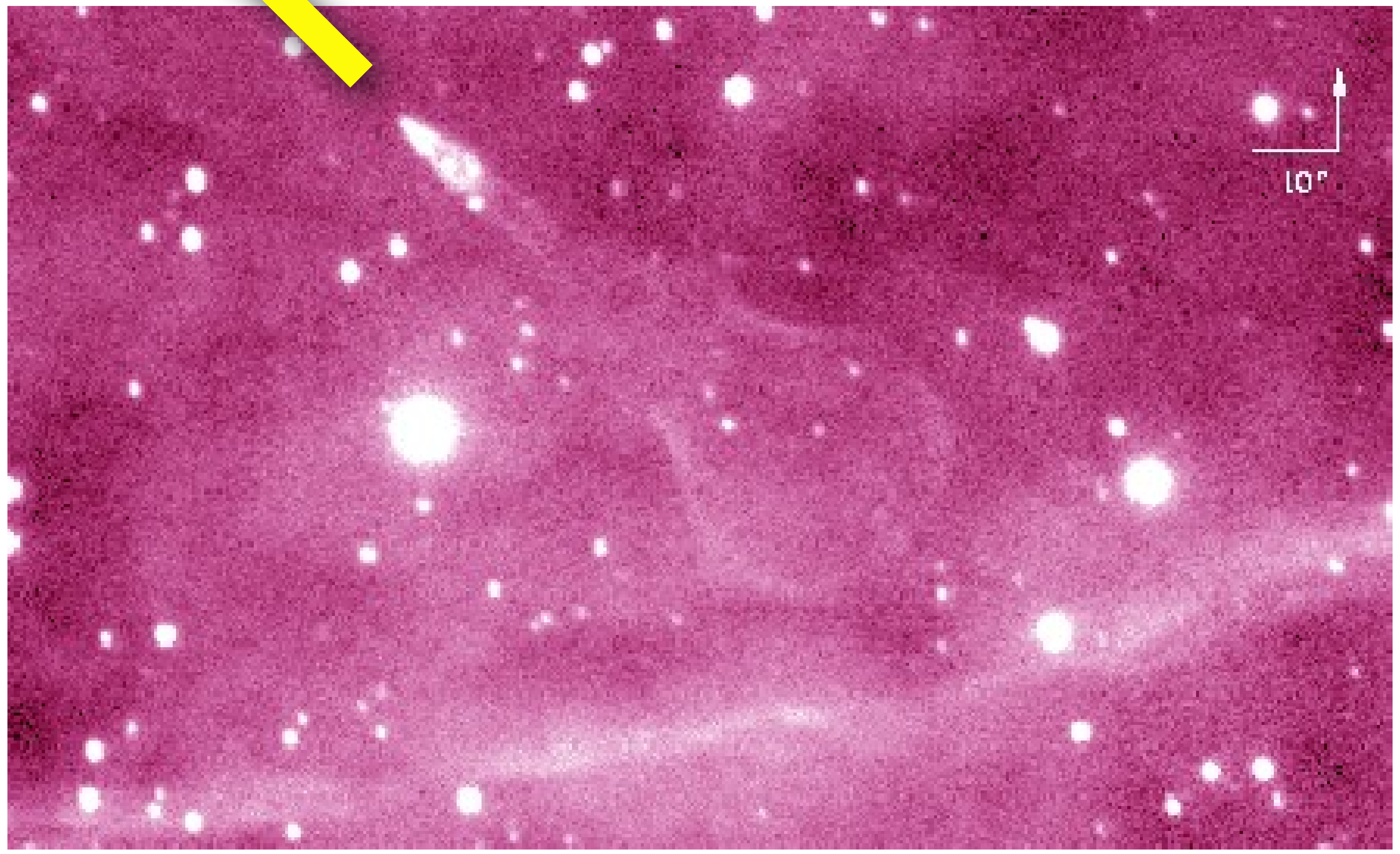
observation: neutron stars undergo a large momentum change (a kick)

[Chatterjee et al.; Astrophys. J (2005)]

Can chiral hydrodynamics be relevant for neutron star kicks?

Kick observations

kick



[Chatterjee et al.; Astrophys. J (2005)]

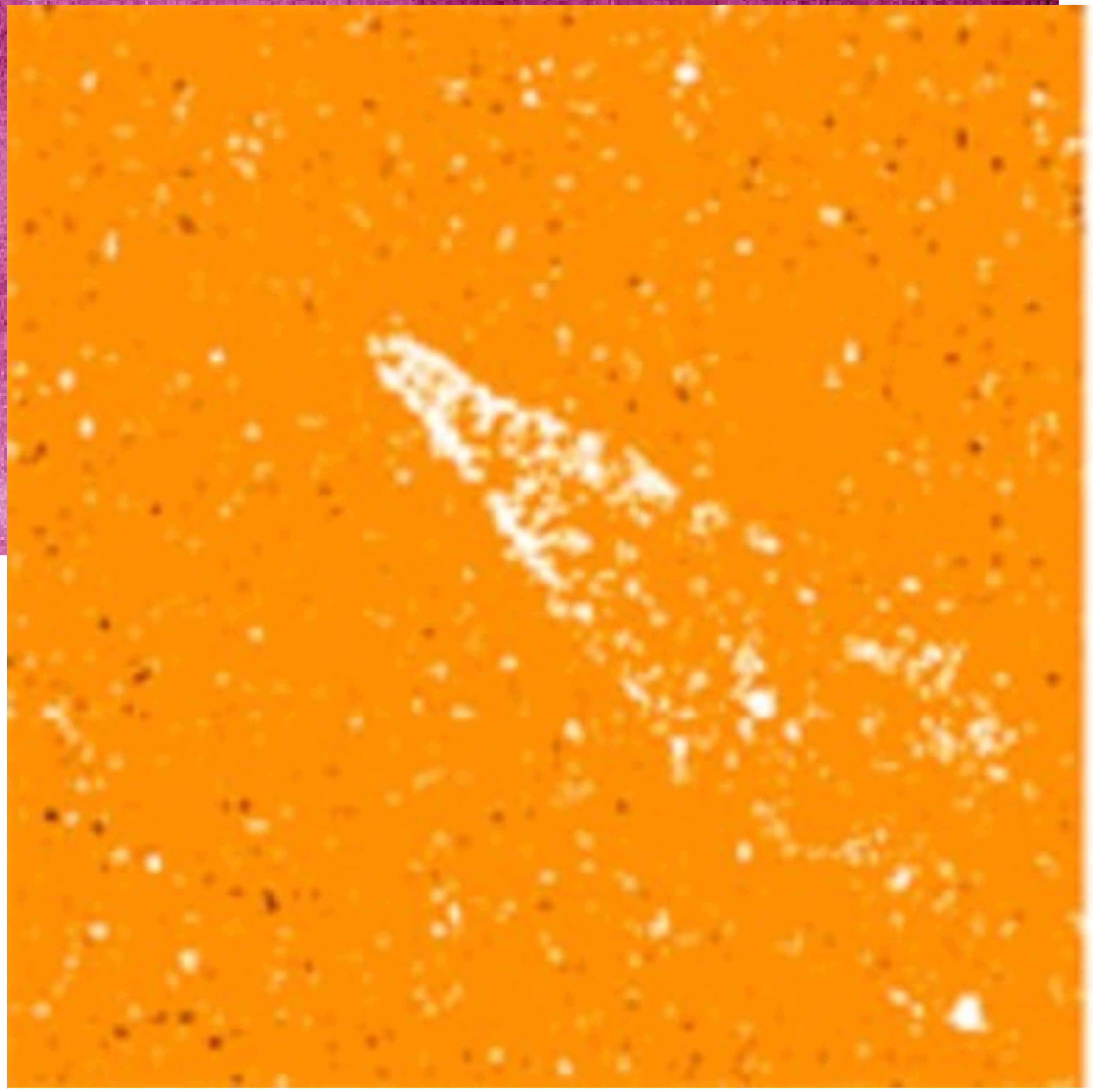
Nebula discovered: [Cordes et al; Nature (1993)]

Kick observations

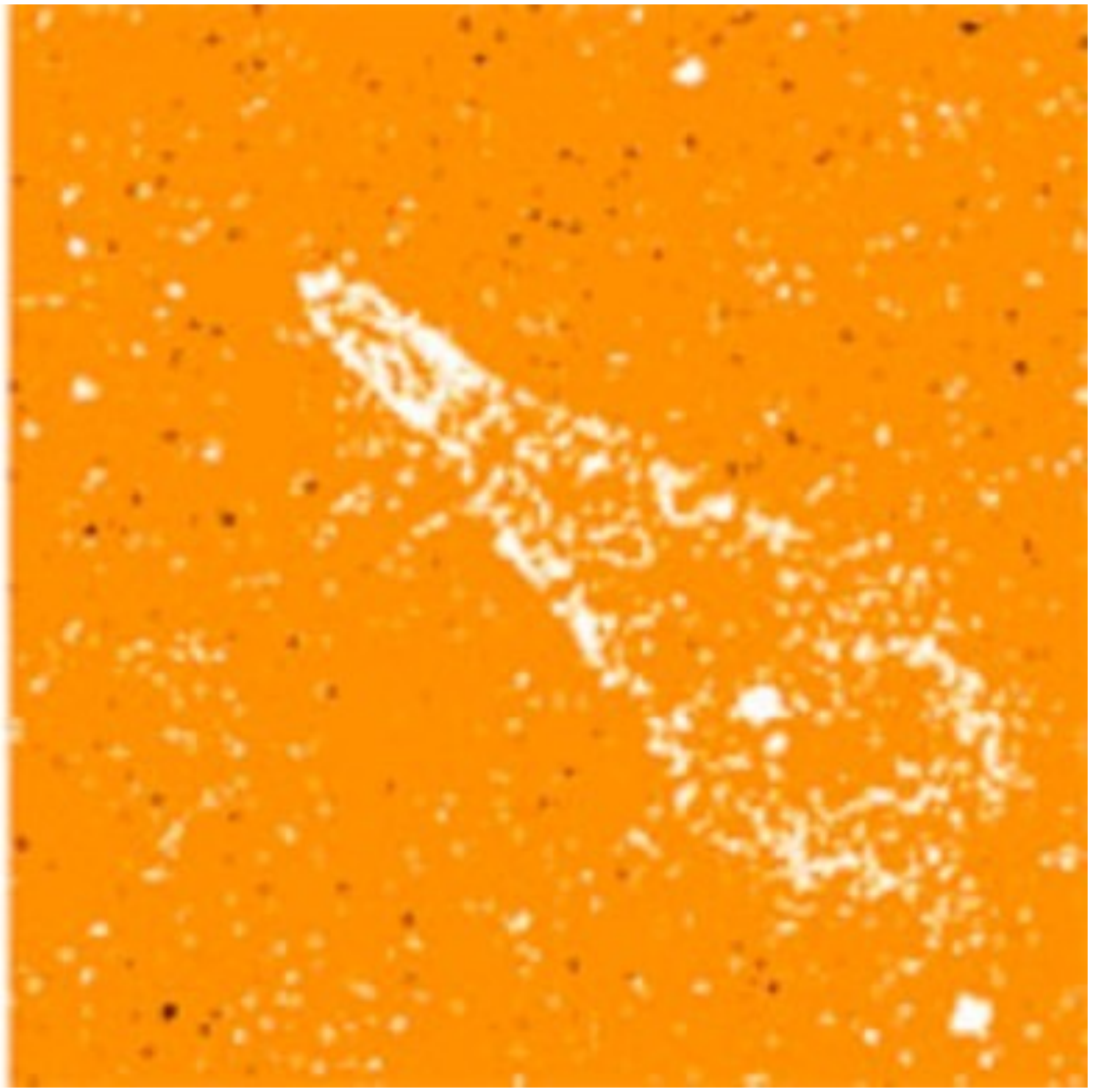
[Chatterjee et al.; Astrophys. J (2005)]

[Hubble Space Telescope (NASA/ESA), Shami Chatterjee, Cornell University]

Nebula

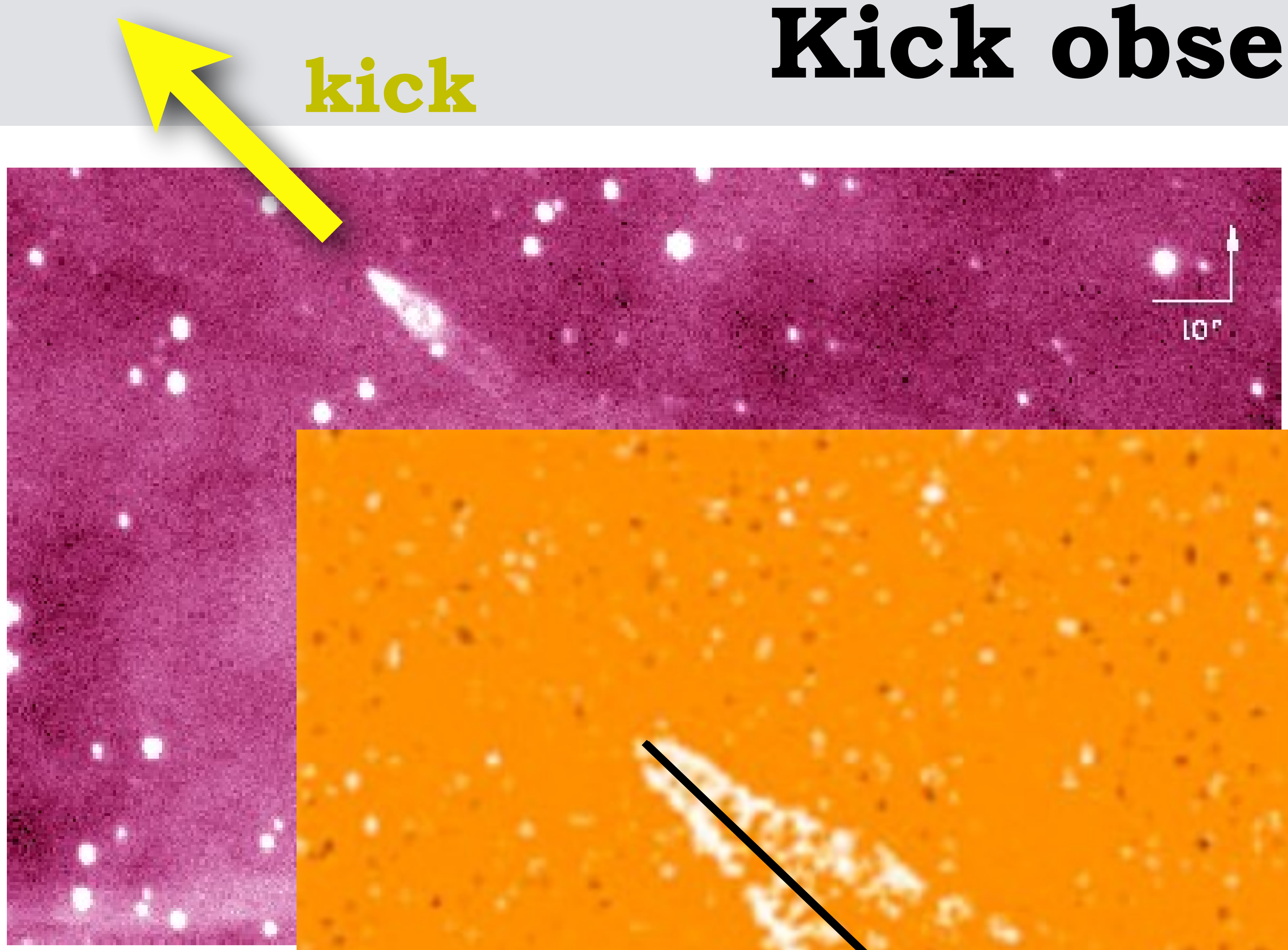


December 1994



December 2001

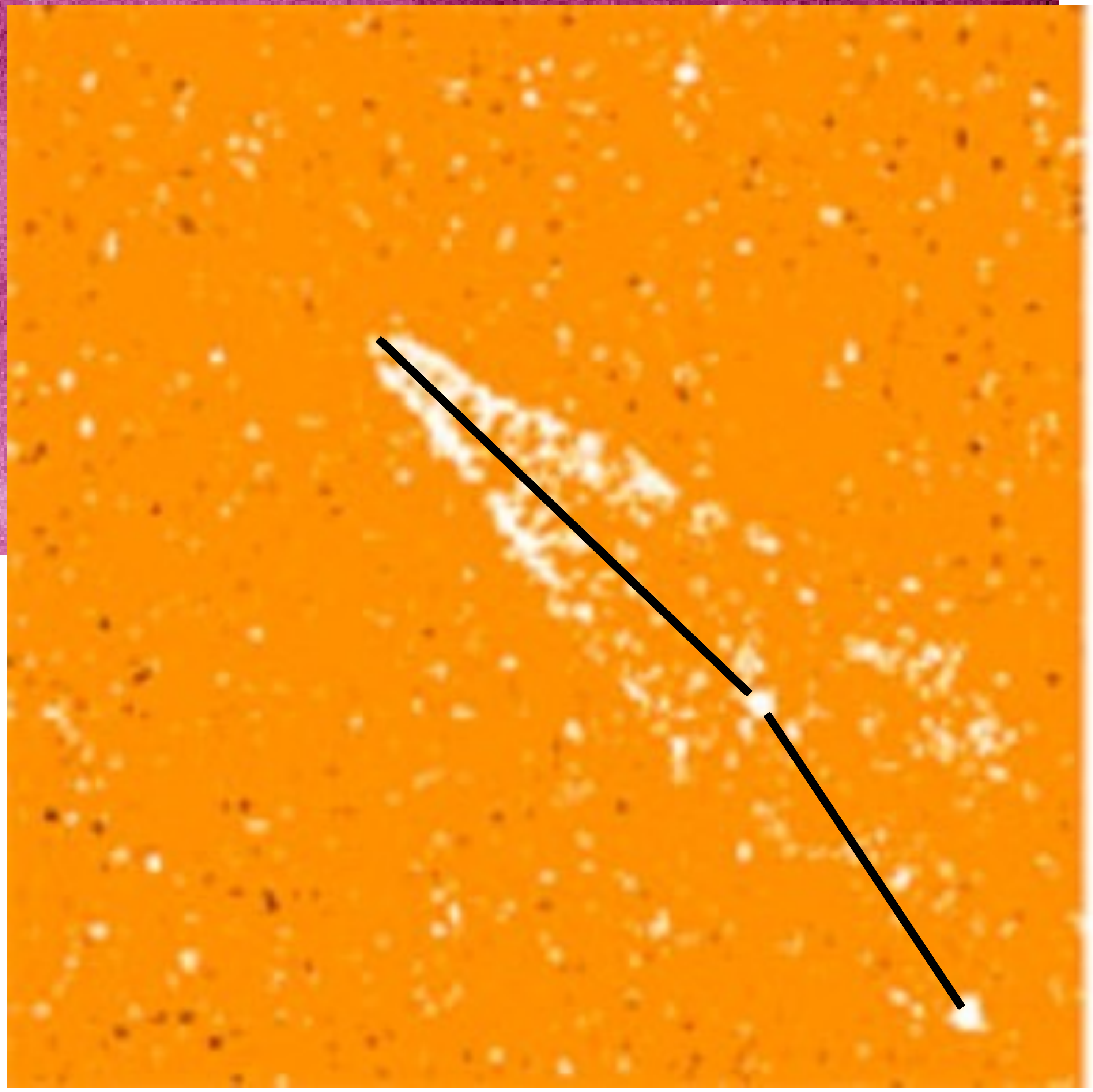
Kick observations



Nebula

[Chatterjee et al.; Astrophys. J (2005)]

[Hubble Space Telescope (NASA/ESA), Shami Chatterjee, Cornell University]



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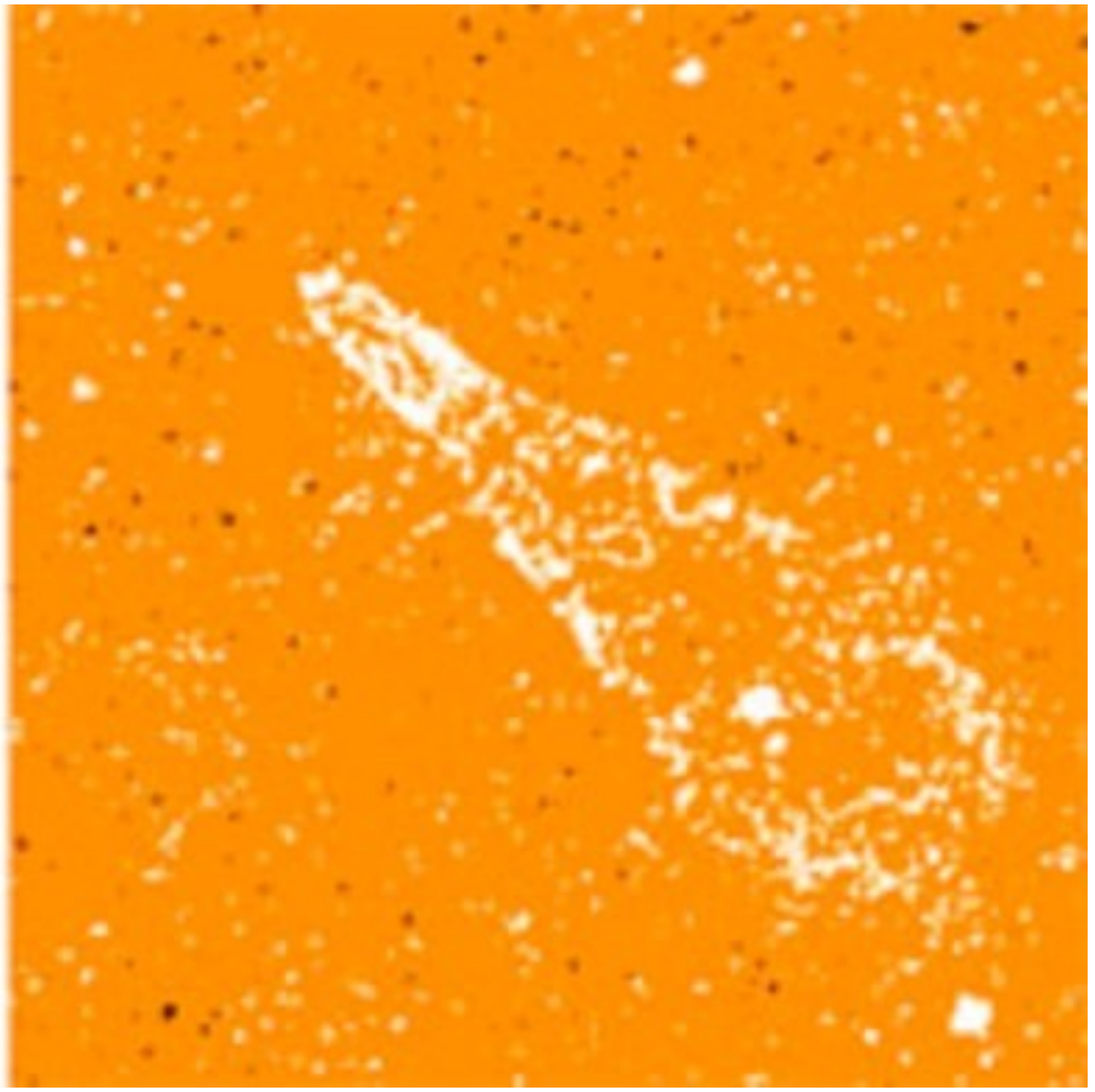

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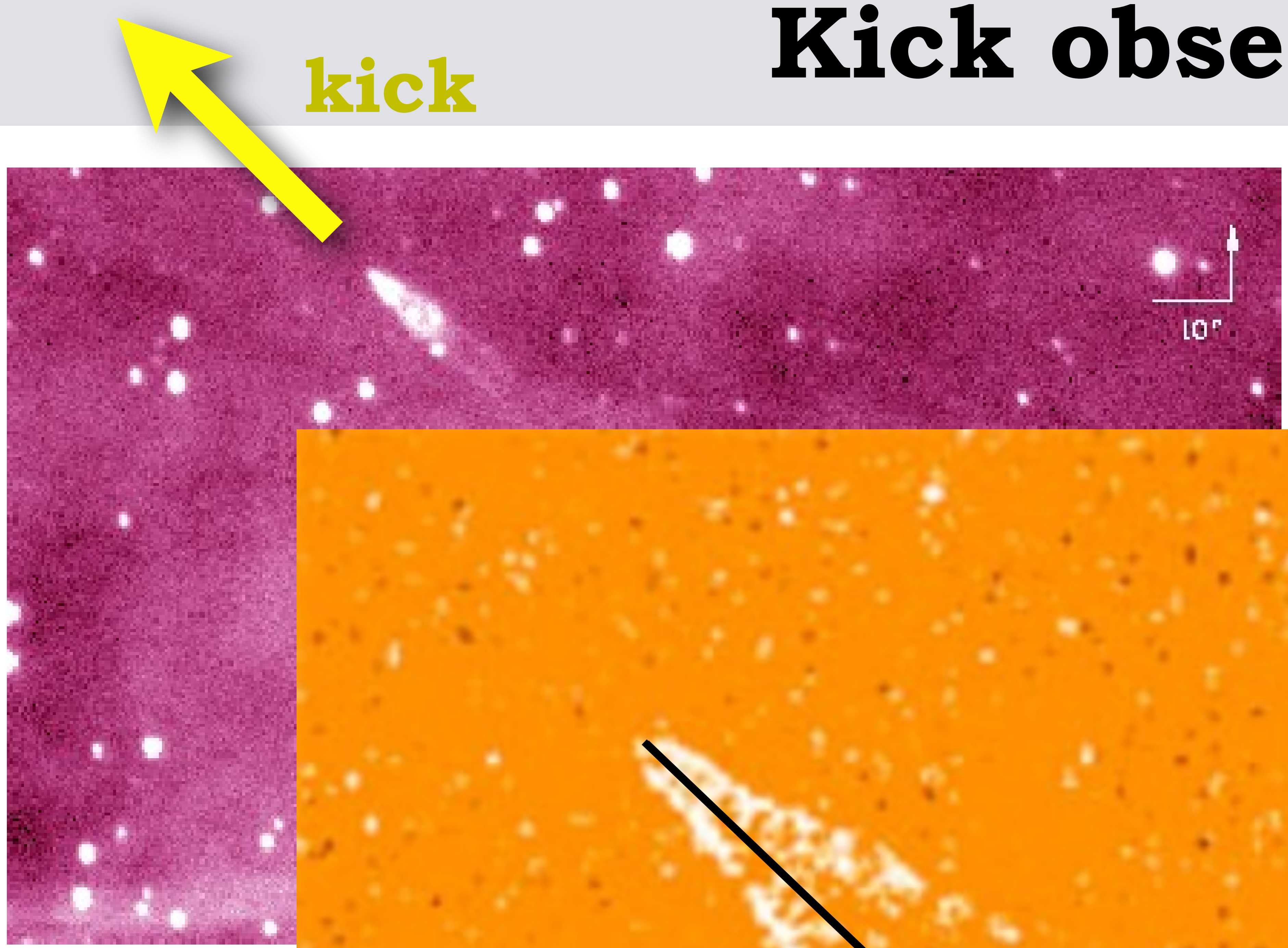

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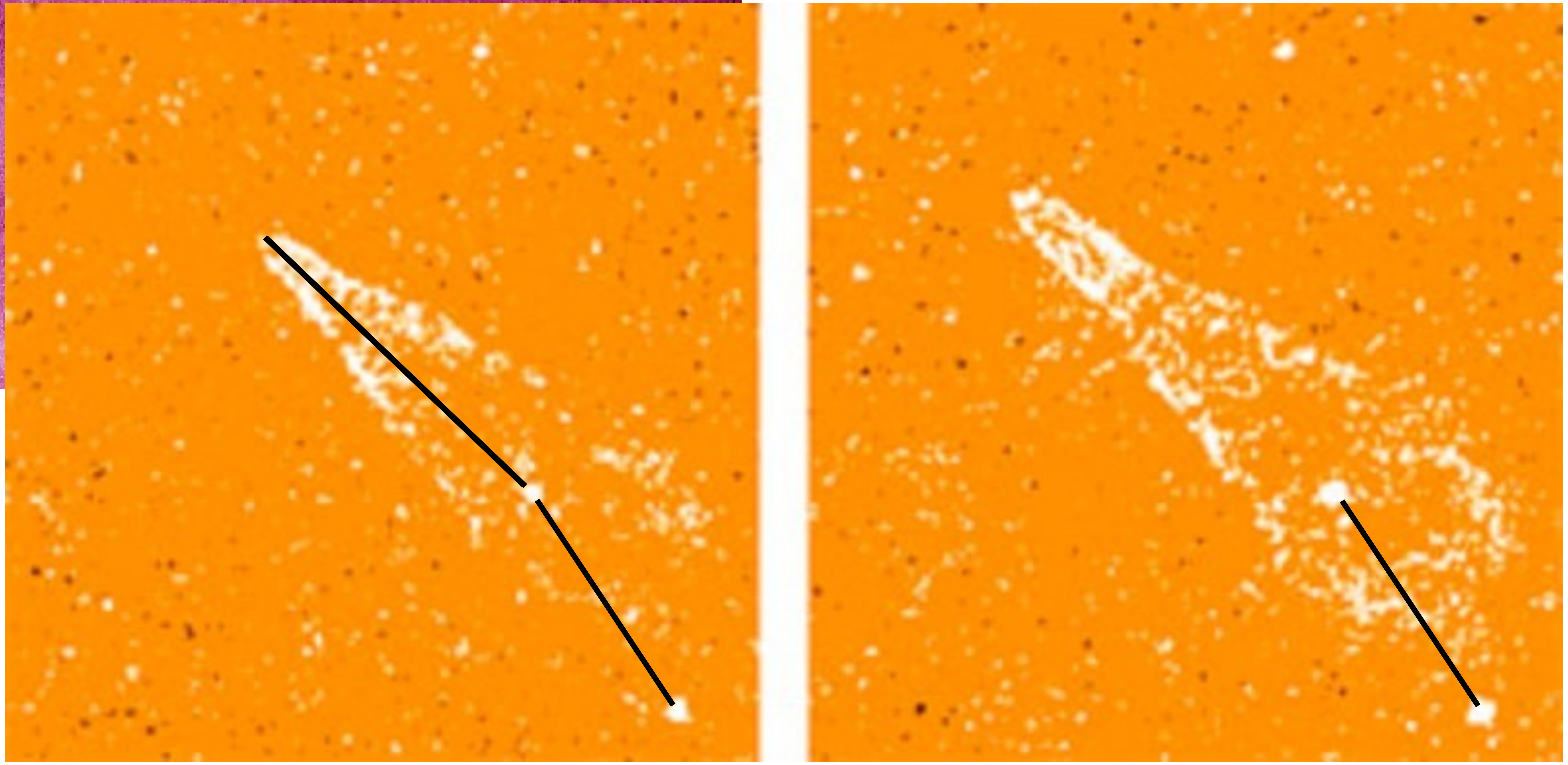

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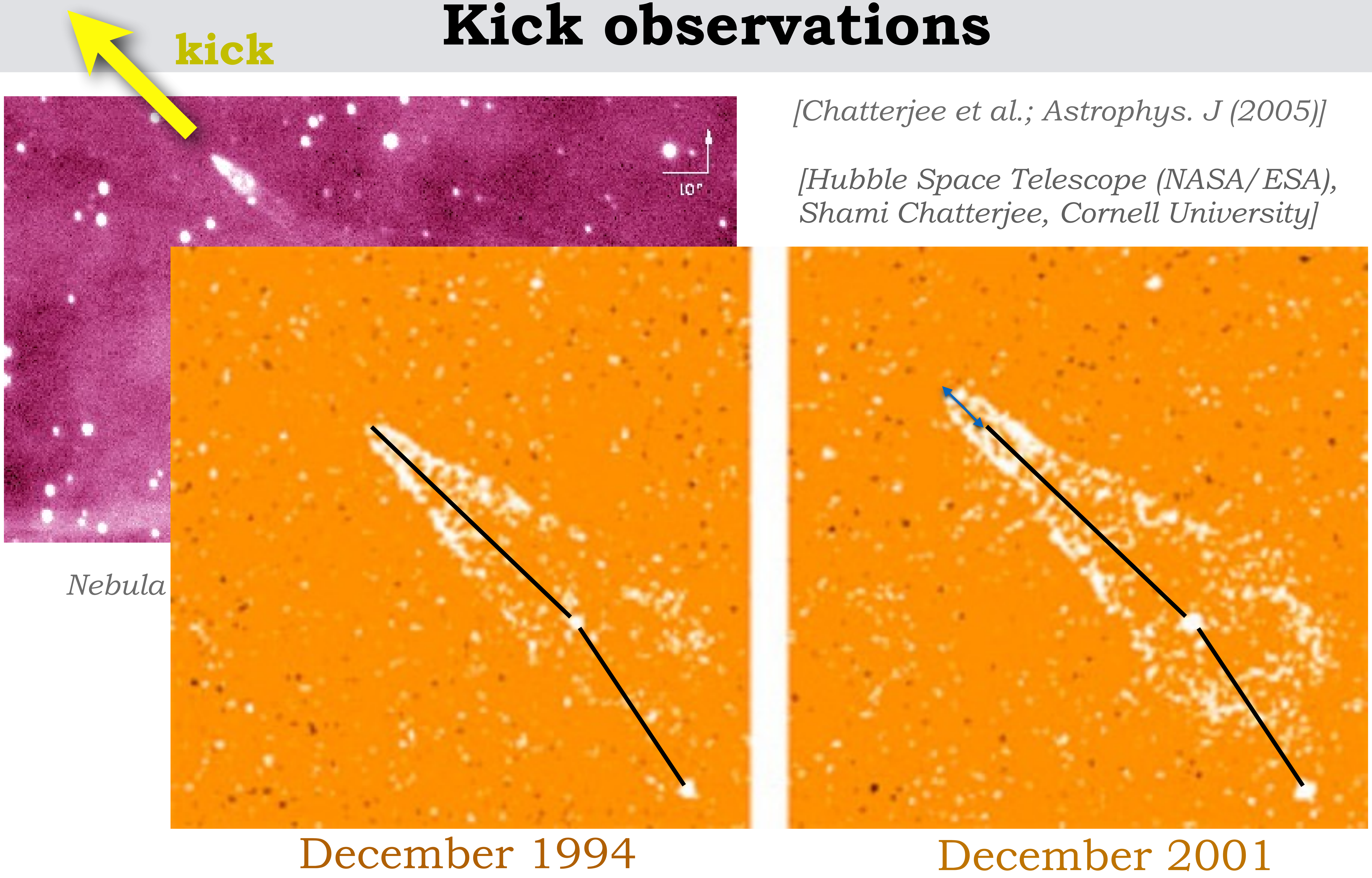

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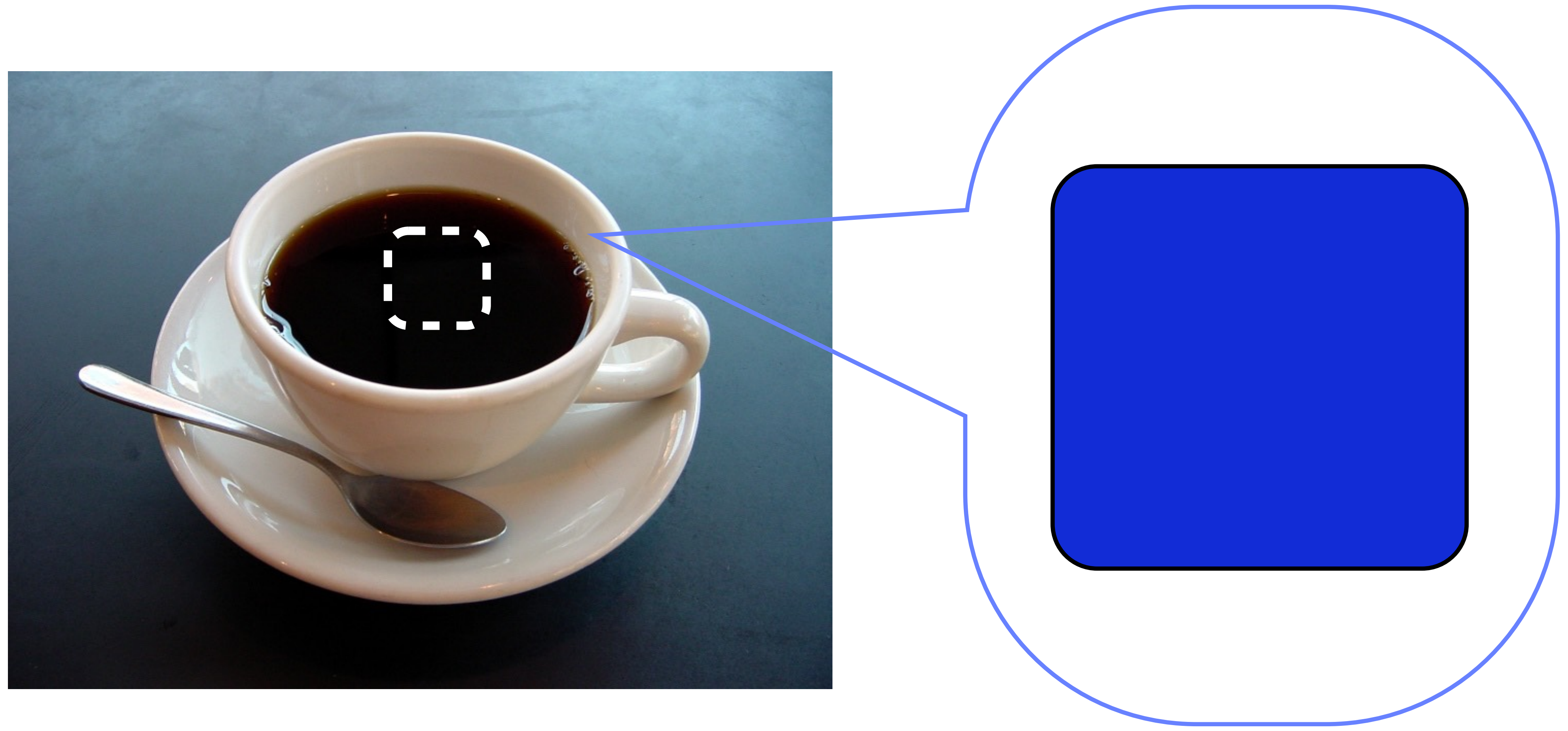
Neutron stars kicked out of their initial position with velocities ~ 1000 km/s

Hydrodynamic variables

Thermodynamics

$$T,\ \mu,\ u^\nu$$

thermodynamic variables:
temperature, chemical potential,
fluid velocity



Hydrodynamics

$$T(t,\vec{x}),\ \mu(t,\vec{x}),\ u^\nu(t,\vec{x})$$

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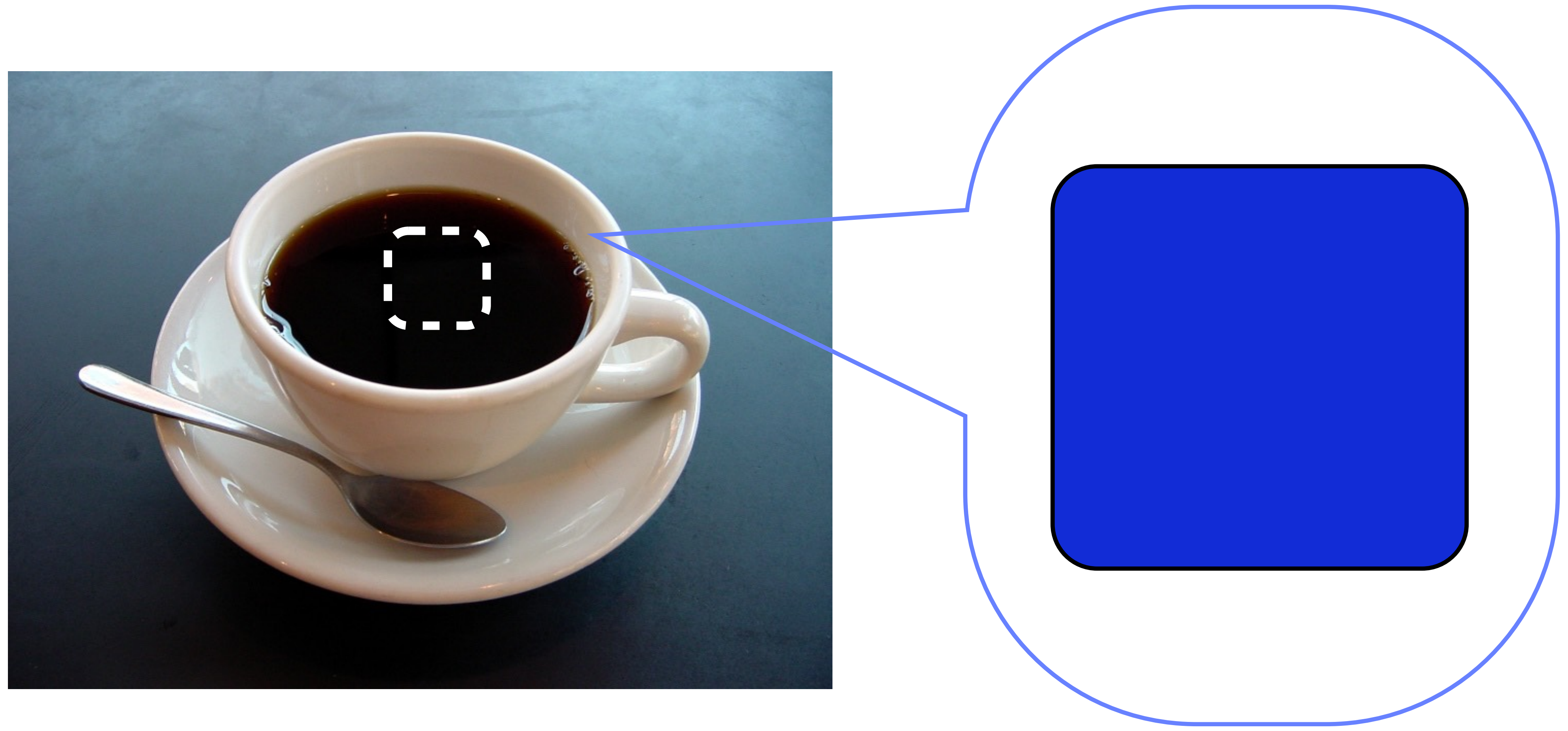
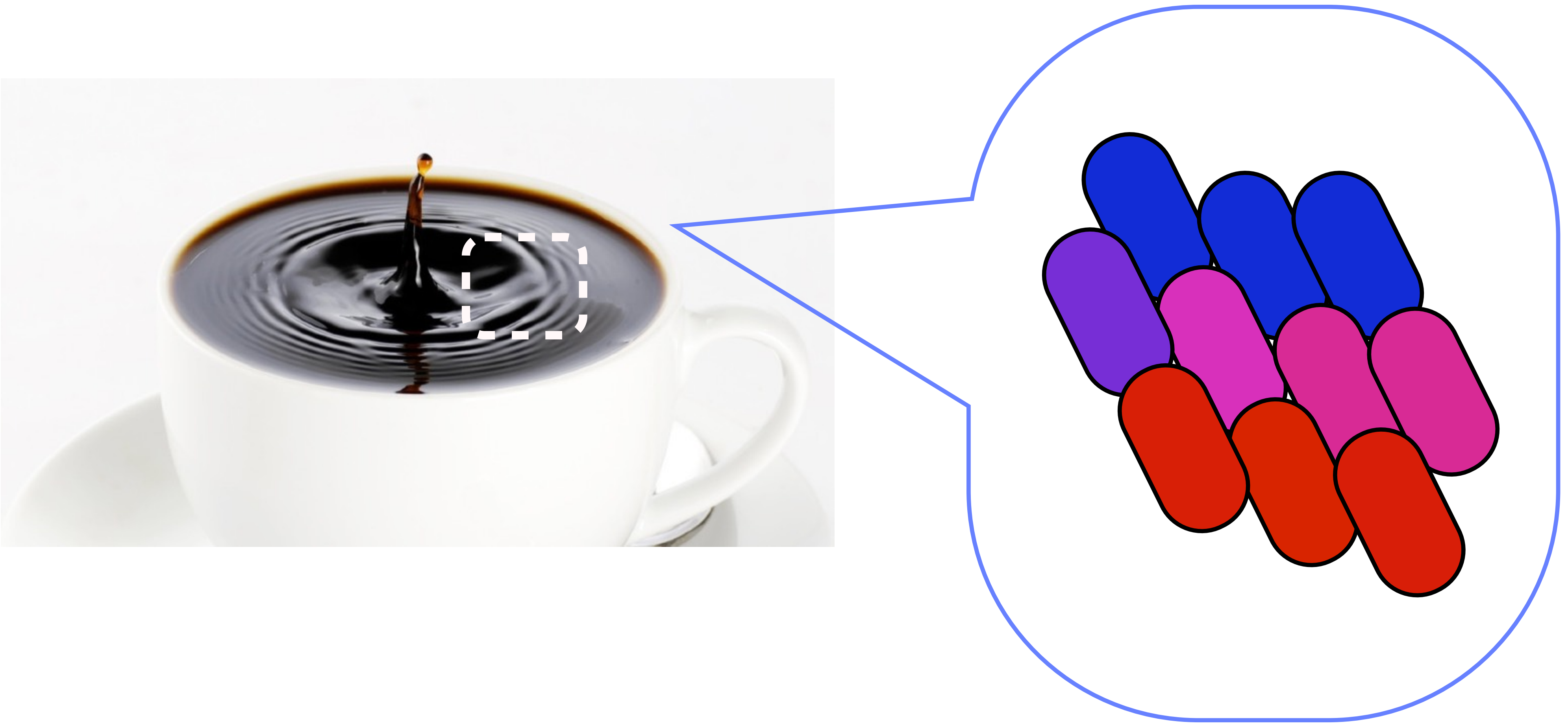


Hydrodynamics

$$T(t,\vec{x}),\ \mu(t,\vec{x}),\ u^\nu(\overbrace{t,\vec{x}}^{x})$$

hydrodynamic fields
-protected by symmetry



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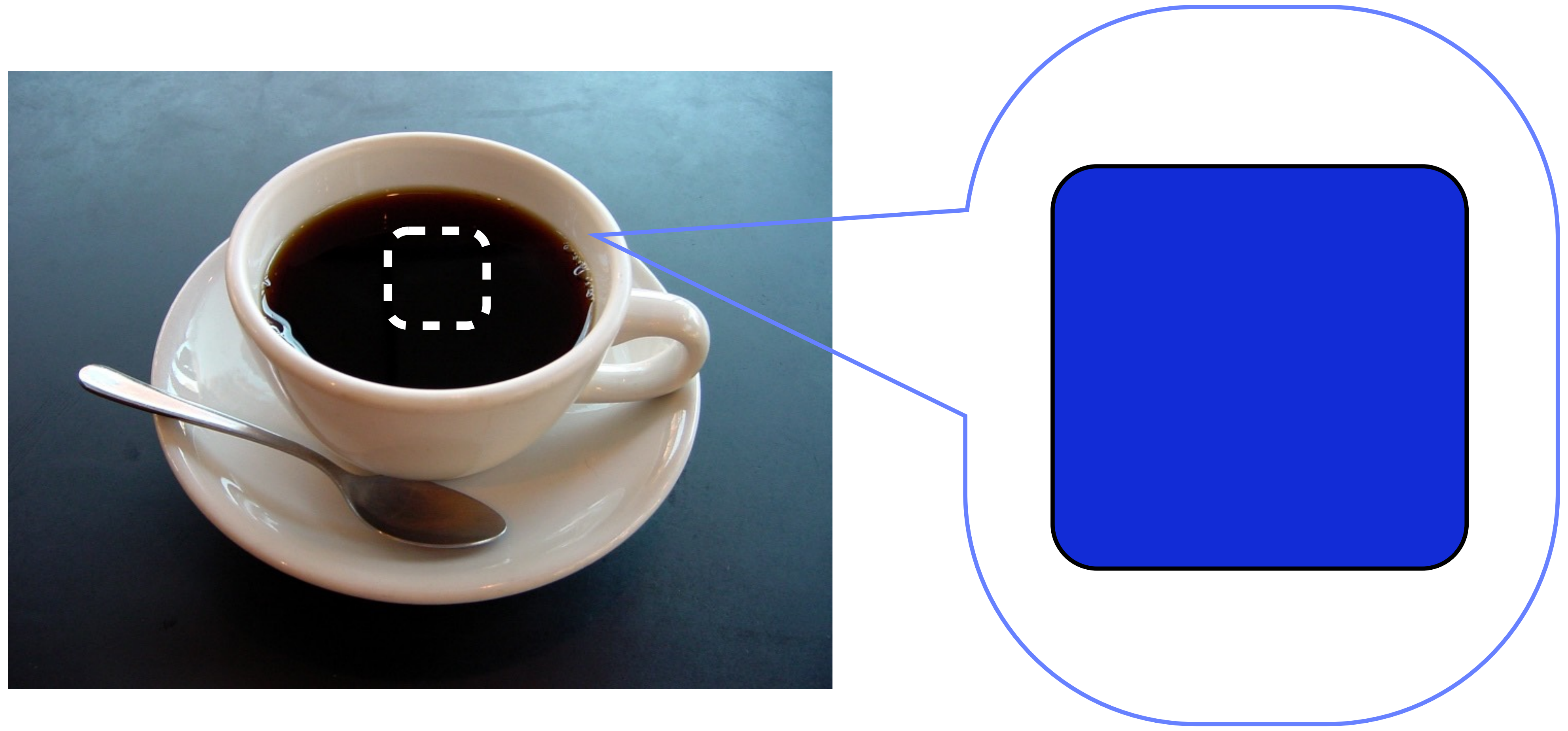

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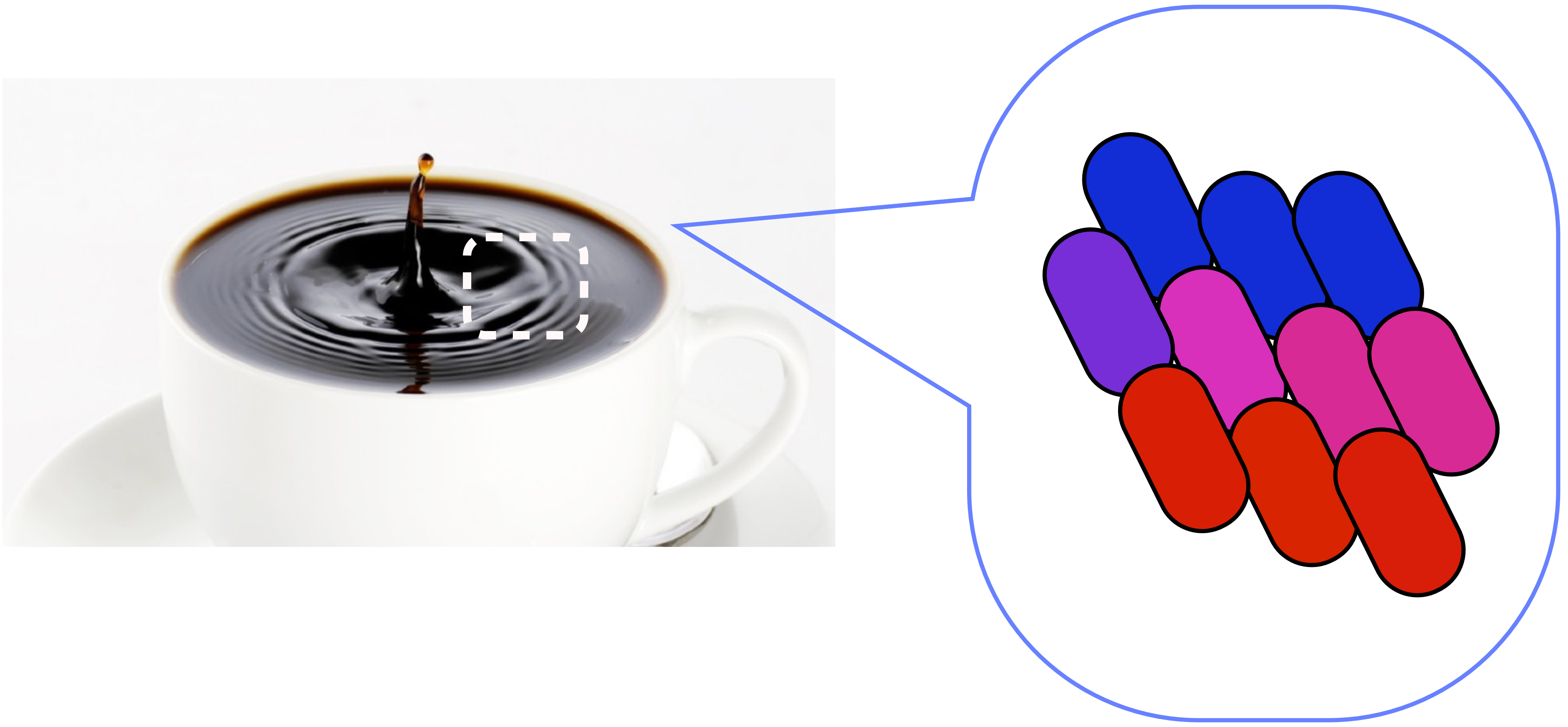

Hydrodynamics

effective field theory, expansion in gradients of fields

- fields $T(x),\ \mu(x),\ u^\nu(x)$
  temperature *chemical potential* *fluid velocity*
- sources $A_\mu(x),\ \ldots$
  gauge field
- conservation equation $\nabla_\nu j^\nu = 0$
- constitutive equation (Landau frame)

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Conserved current

$$j^\mu = n u^\mu + \nu^\mu$$

gradient terms

Form can be derived and restricted from first principles.

[Landau, Lifshitz]

[Jensen, Kaminski, Kovtun, Meyer, Ritz, Yarom; PRL (2012)]

Chiral hydrodynamics *[Son,Surowka; PRL (2009)]*

$\nabla_\nu j^\nu = 0$ classical theory

Chiral hydrodynamics *[Son,Surowka; PRL (2009)]*

Derived for any theory with chiral anomaly

(e.g. the standard model of particle physics)

$$\nabla_\mu j^\mu = C\,\epsilon^{\nu\rho\sigma\lambda} F_{\nu\rho} F_{\sigma\lambda}$$

quantum theory

Chiral hydrodynamics

[Son,Surowka; PRL (2009)]

Derived for any theory with chiral anomaly

(e.g. the standard model of particle physics)

$$\nabla_\mu j^\mu = C\,\epsilon^{\nu\rho\sigma\lambda}F_{\nu\rho}F_{\sigma\lambda}$$

quantum theory

Generalized constitutive equation with external fields:

$$j^\mu = n u^\mu + \sigma E^\mu + \sigma^B B^\mu + \sigma^V \omega^\mu + \ldots$$

(non) conserved current — *(ideal) charge flow* — *conductivity term* — *chiral magnetic conductivity*

Agrees with gauge/gravity prediction

[Erdmenger, Haack, Kaminski, Yarom; JHEP (2008)]

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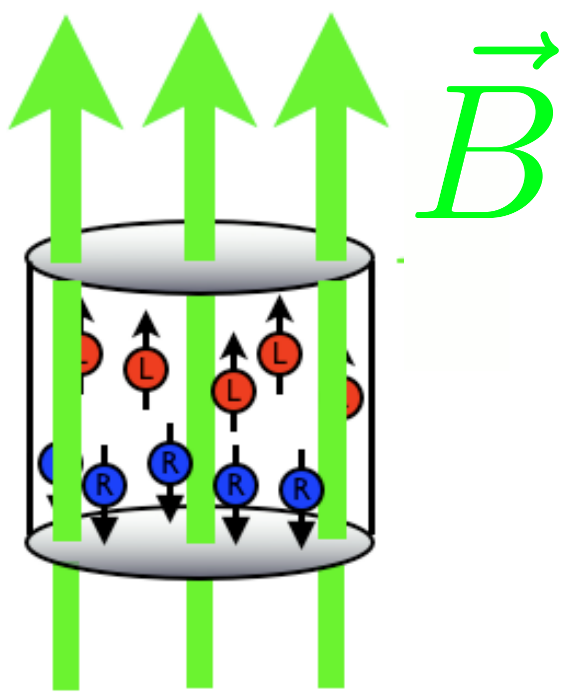
Chiral magnetic conductivity:

$$\sigma^B = C\,\mu$$

anomaly-coefficient C



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- j^μ: *(non) conserved current*
- $n u^\mu$: *(ideal) charge flow*
- σE^μ: *conductivity term*
- $\sigma^B B^\mu$: *chiral magnetic conductivity*
- $\sigma^V \omega^\mu$: *chiral vortical conductivity*

Agrees with gauge/ gravity prediction

[Erdmenger, Haack, Kaminski, Yarom; JHEP (2008)]

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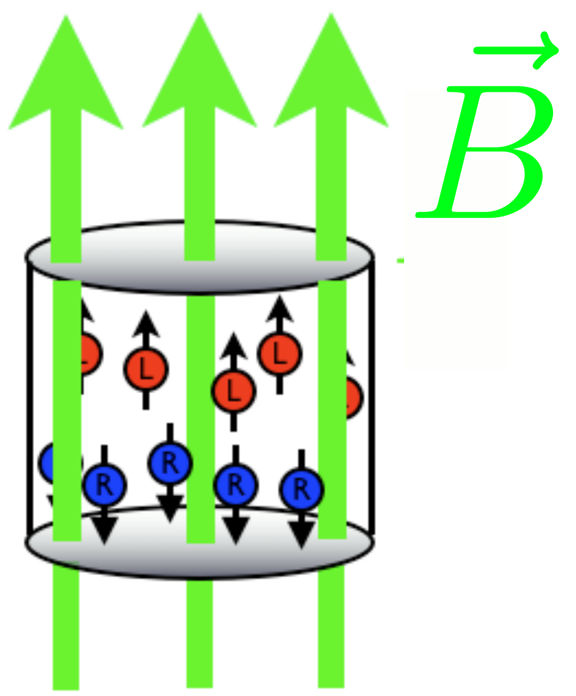

Measured in Weyl semi metals !

e.g. [Huang et al; PRX (2015)]
[Landsteiner] various others …

energy extraction ?

neutron stars ?