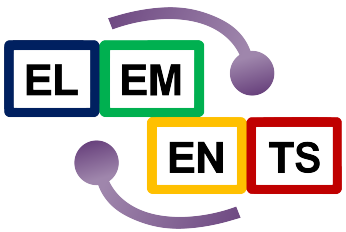
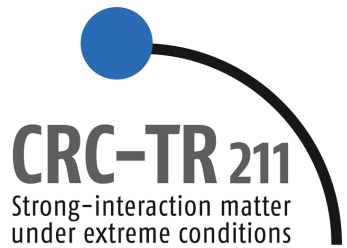
Neutronensterne als Labor für dichte Materie

Christian Ecker

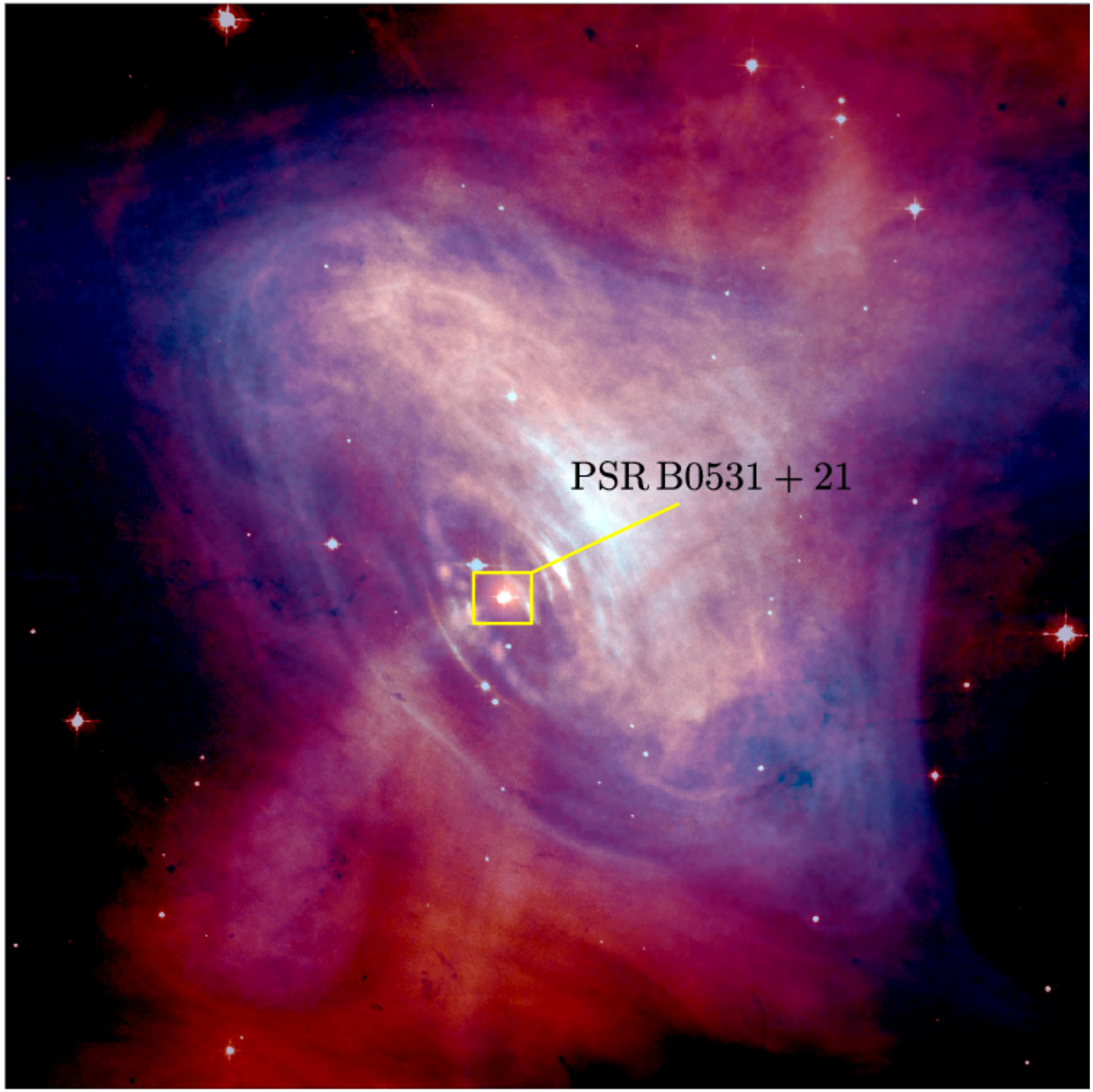


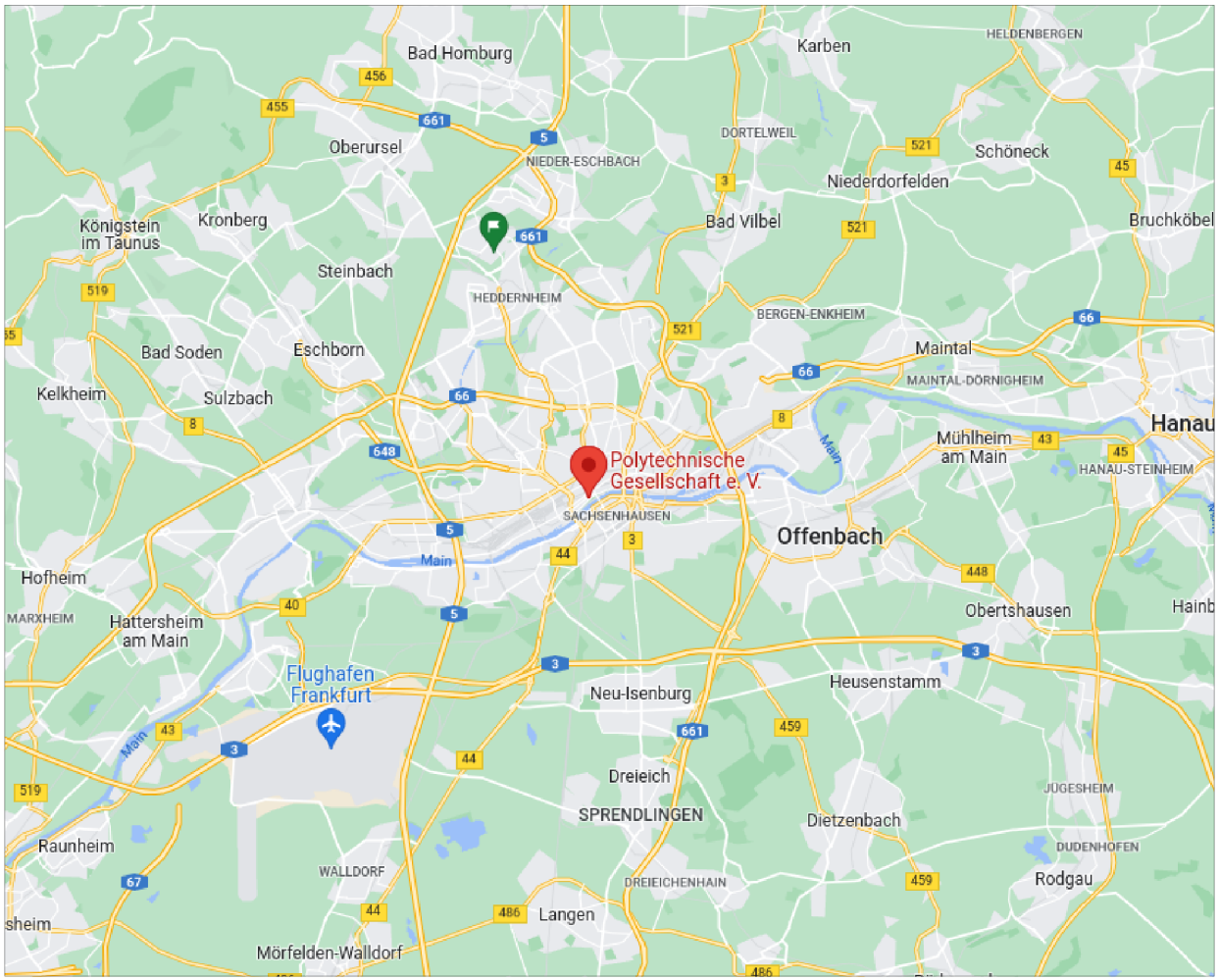


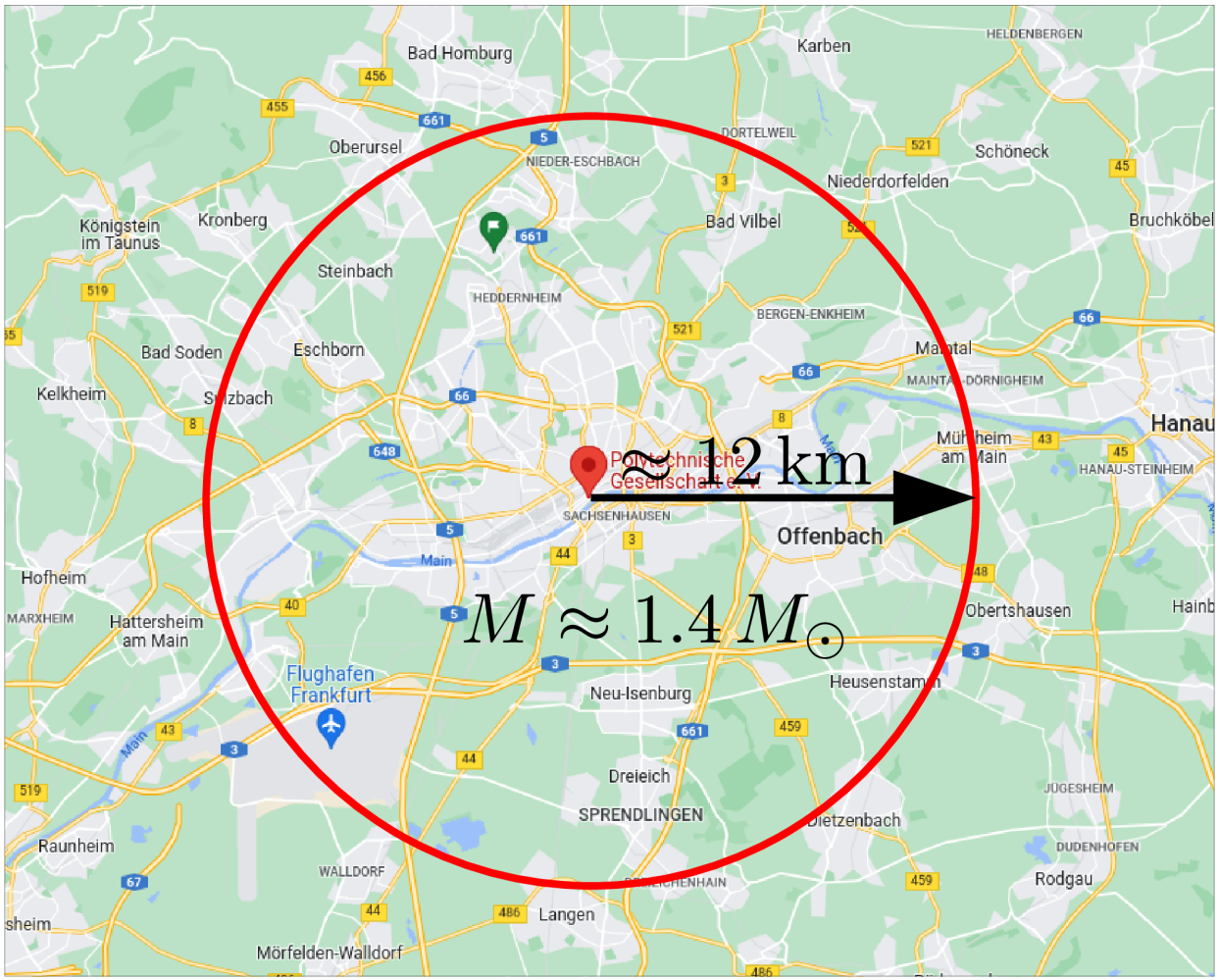
Interdisziplinäres Colloquium
Polytechnischen Gesellschaft, Frankfurt am Main
21 Juni 2022

Überblick

- Was ist ein Neutronenstern?
- Wie kann man Neutronensterne beobachten?
- Allgemeine Relativitätstheorie
- Theorie der Starken Wechselwirkung
- Zustandsgleichung für Neutronensternmaterie
- Quarkmaterie in Neutronensternkollisionen


PSR B0531 + 21


Bad Homburg
Karben
HELDENBERGEN
Oberursel
DORTELWEIL
Schöneck
NIEDER-ESCHBACH
Niederdorfelden
Bad Vilbel
Bruchköbel
Königstein im Taunus
Kronberg
Steinbach
HEDDERNHEIM
BERGEN-ENKHEIM
Maintal
Bad Soden
Eschborn
MAINTAL-DÖRNIGHEIM
Kelkheim
Sulzbach
Hanau
Mühlheim am Main
HANAU-STEINHEIM
Polytechnische Gesellschaft e. V.
SACHSENHAUSEN
Offenbach
Main
Hofheim
MARXHEIM
Hattersheim am Main
Obertshausen
Flughafen Frankfurt
Neu-Isenburg
Heusenstamm
Dreieich
SPRENDLINGEN
Dietzenbach
JÜGESHEIM
DUDENHOFEN
Raunheim
WALLDORF
DREIEICHENHAIN
Rodgau
Langen
Mörfelden-Walldorf


≈ 12 km
$M \approx 1.4\,M_\odot$
Bad Homburg
Karben
HELDENBERGEN
Oberursel
DORTELWEIL
NIEDER-ESCHBACH
Schöneck
Niederdorfelden
Bad Vilbel
Bruchköbel
Königstein im Taunus
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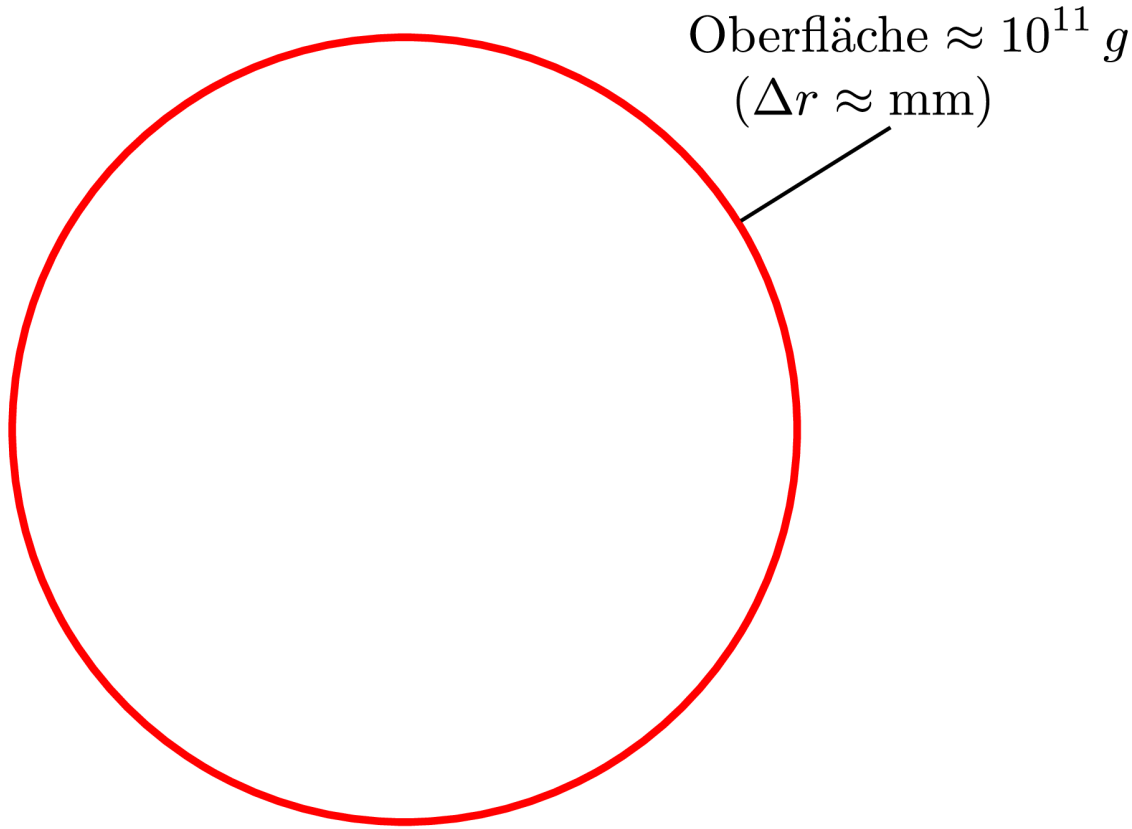
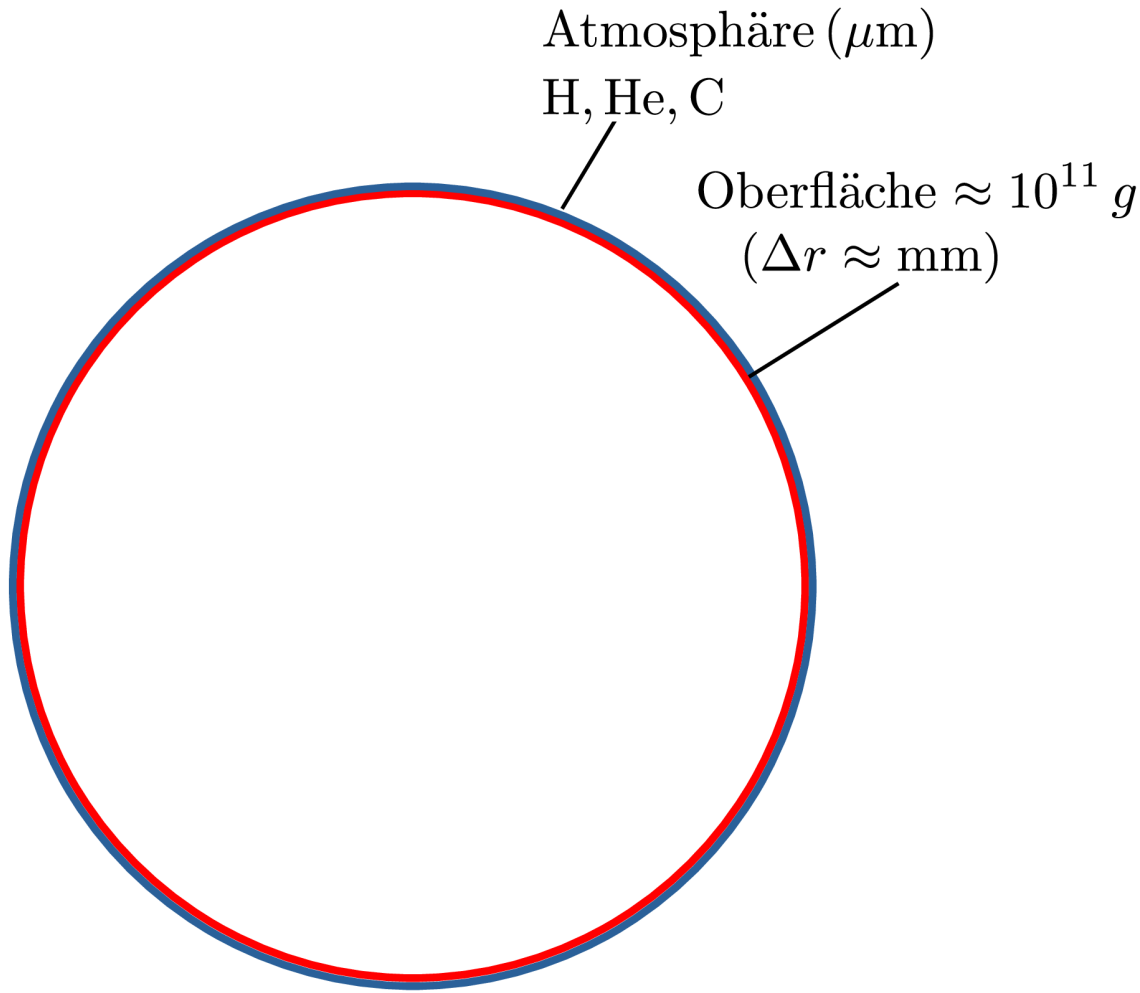
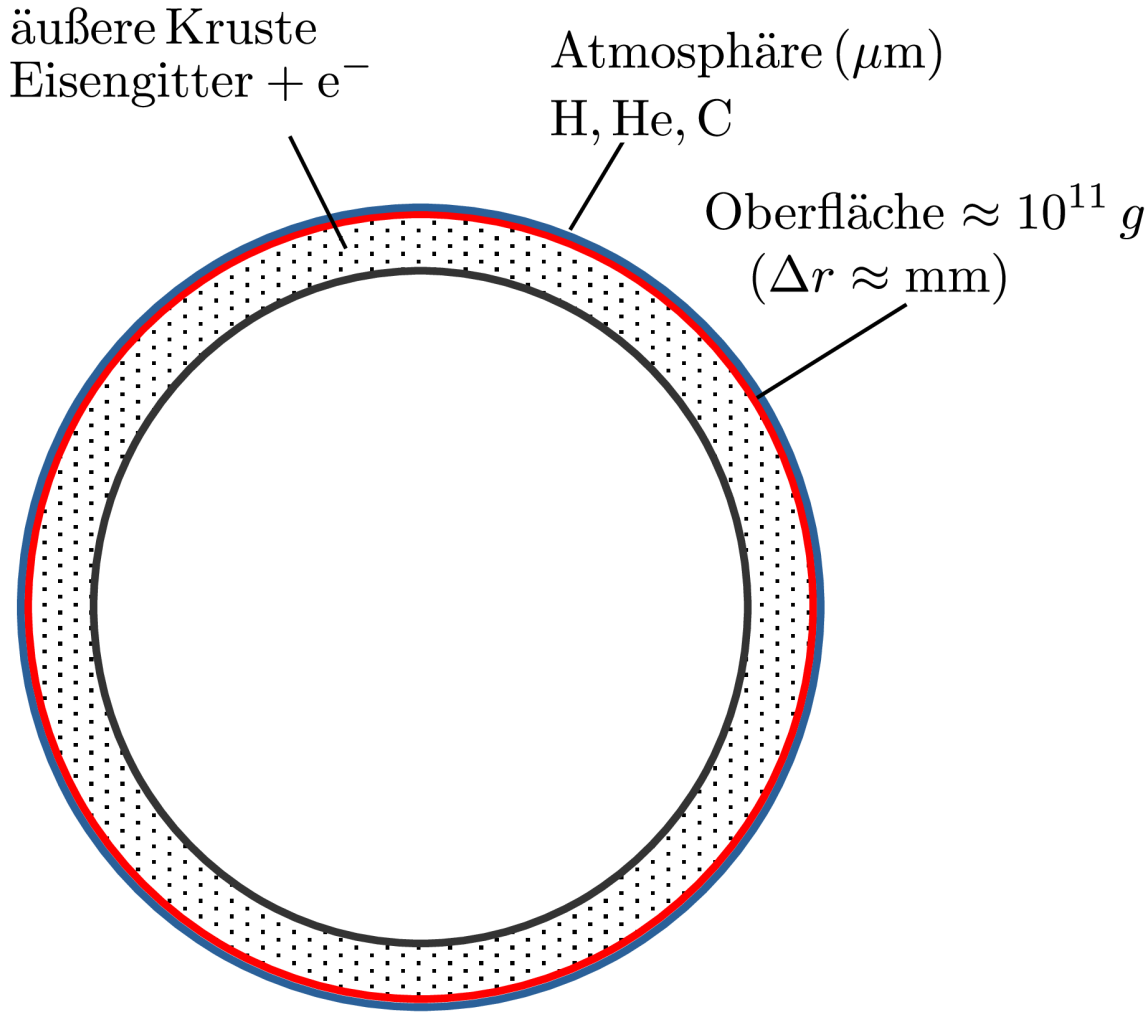
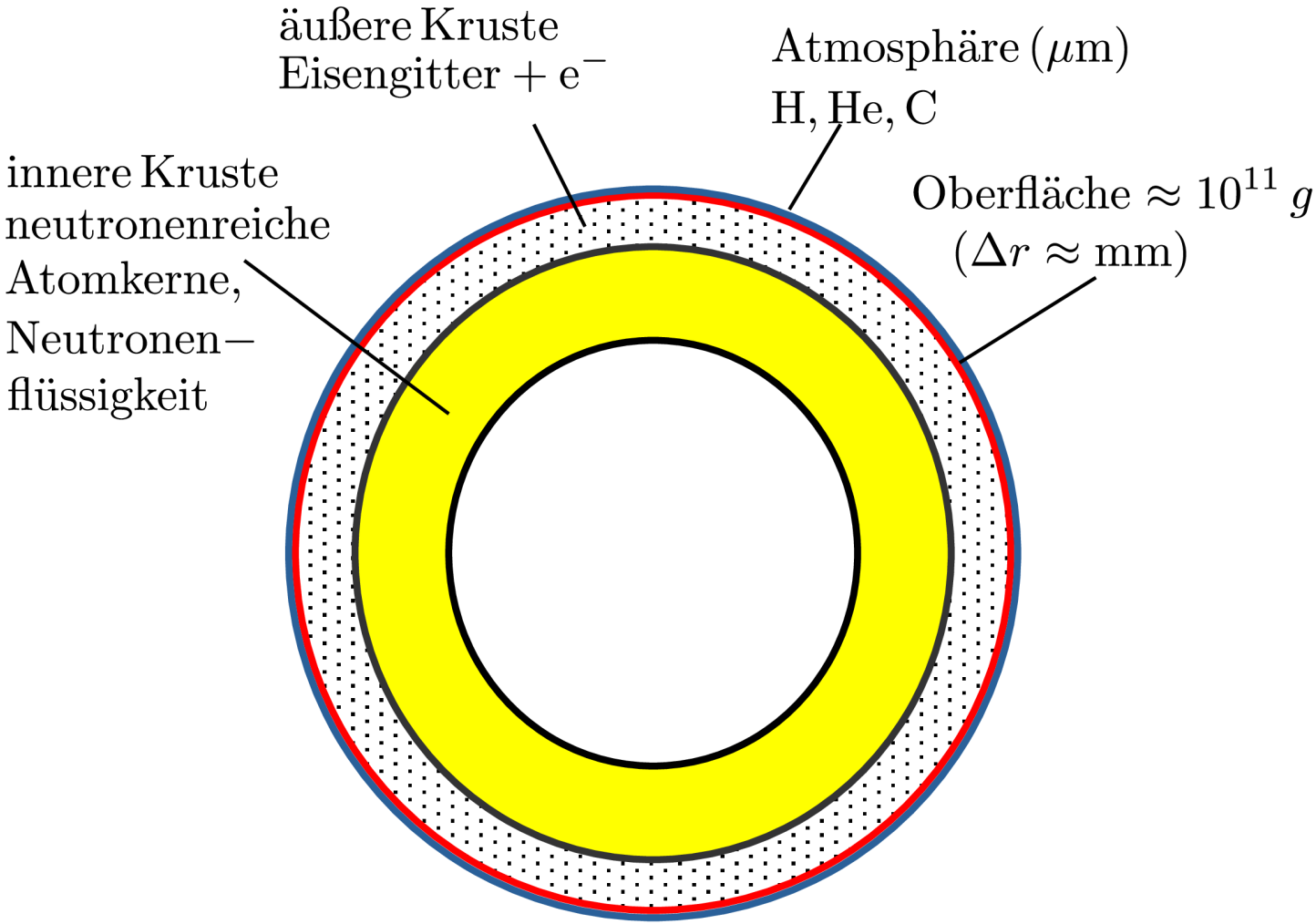
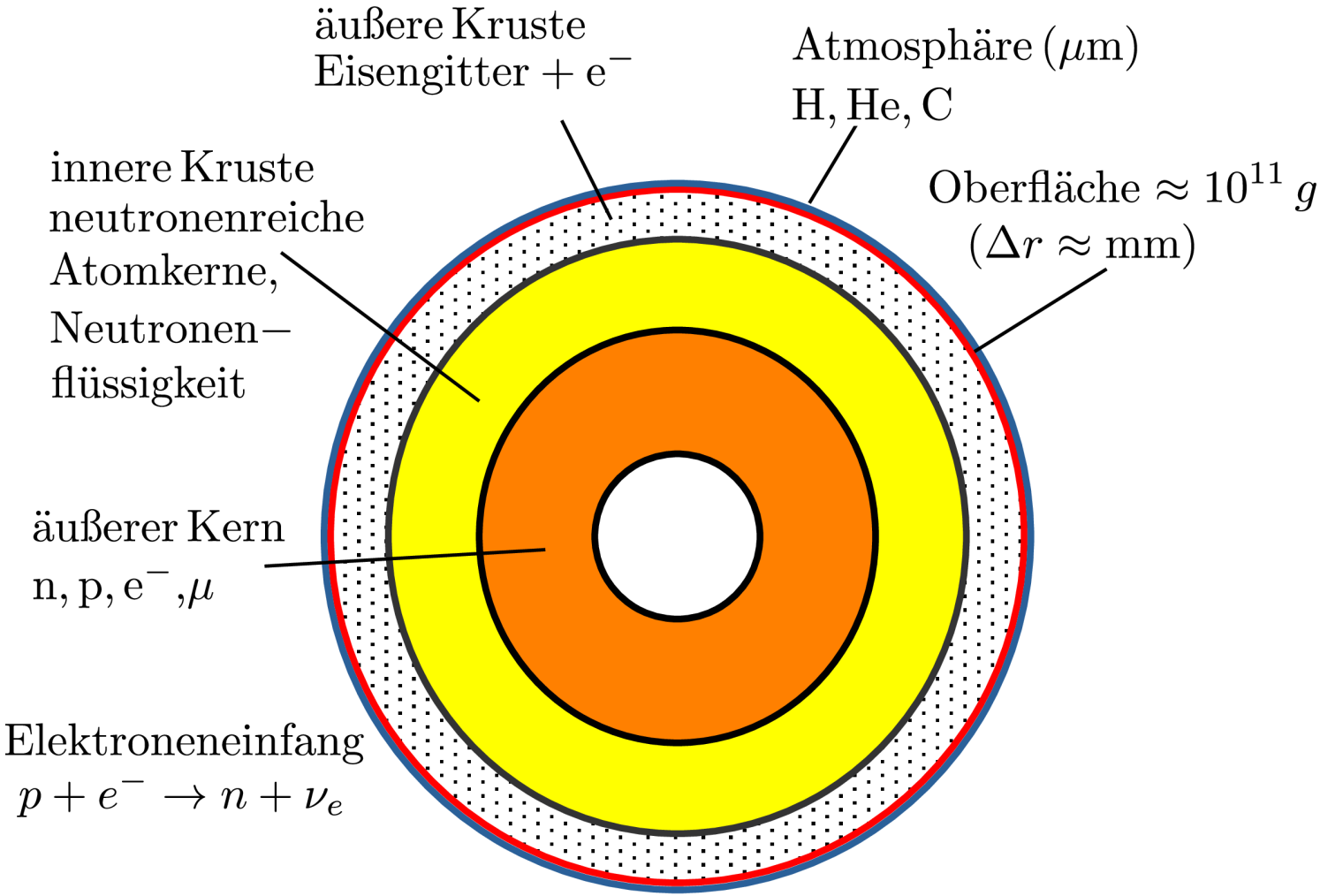
DUDENHOFEN
Raunheim
WALLDORF
Rodgau
Langen
Mörfelden-Walldorf

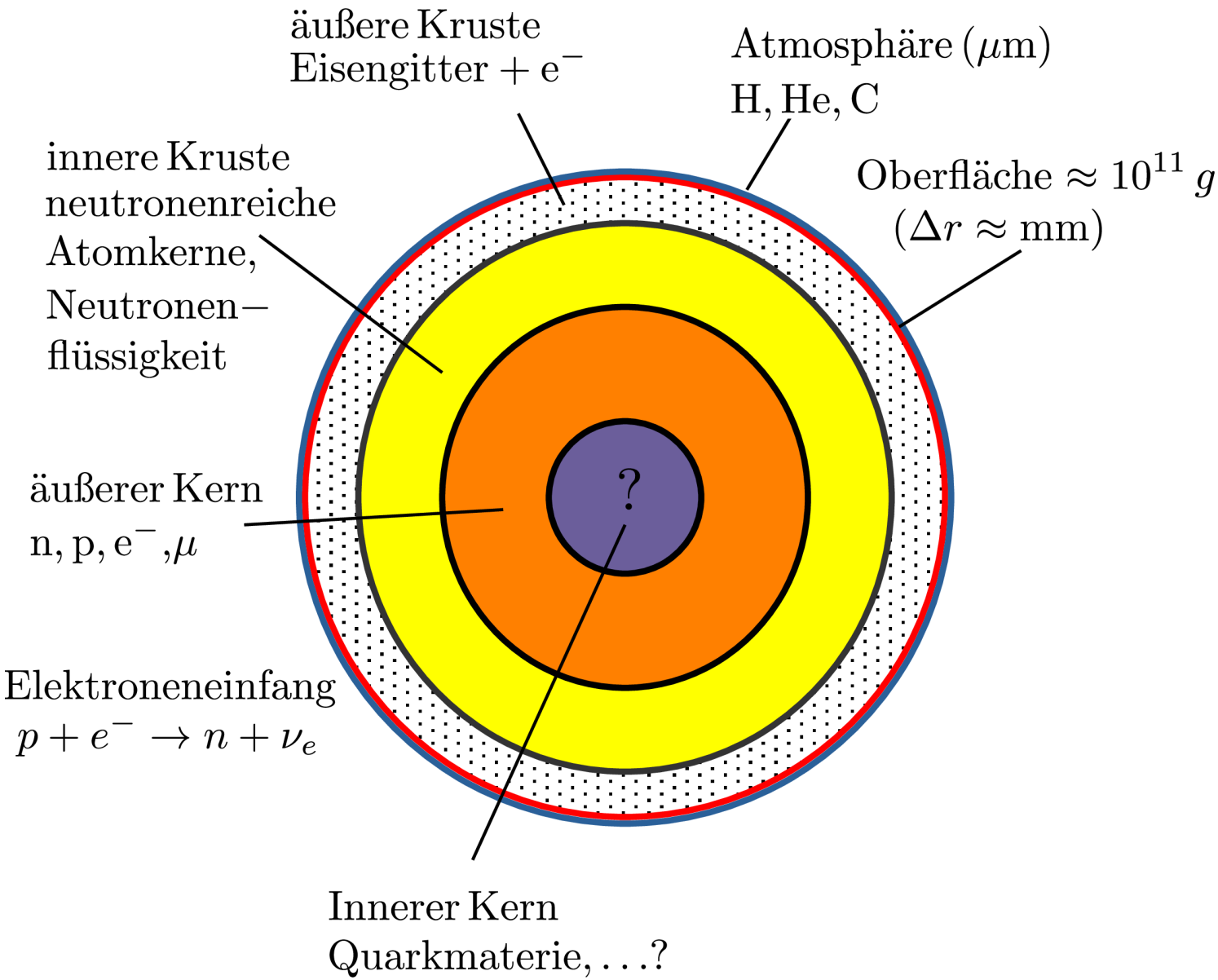

Oberfläche $\approx 10^{11}\,g$
$(\Delta r \approx \mathrm{mm})$


Atmosphäre (μm)
H, He, C
Oberfläche $\approx 10^{11}\,g$
($\Delta r \approx$ mm)


äußere Kruste
Eisengitter + e^-
Atmosphäre (μm)
H, He, C
Oberfläche $\approx 10^{11}\ g$
($\Delta r \approx$ mm)


äußere Kruste
Eisengitter + e^-
Atmosphäre (μm)
H, He, C
innere Kruste
neutronenreiche
Atomkerne,
Neutronen−
flüssigkeit
Oberfläche $\approx 10^{11}\ g$
($\Delta r \approx$ mm)


äußere Kruste
Eisengitter + e$^-$
Atmosphäre (μm)
H, He, C
innere Kruste
neutronenreiche
Atomkerne,
Neutronen−
flüssigkeit
Oberfläche $\approx 10^{11}\ g$
($\Delta r \approx$ mm)
äußerer Kern
n, p, e$^-$,μ
Elektroneneinfang
$p + e^- \rightarrow n + \nu_e$

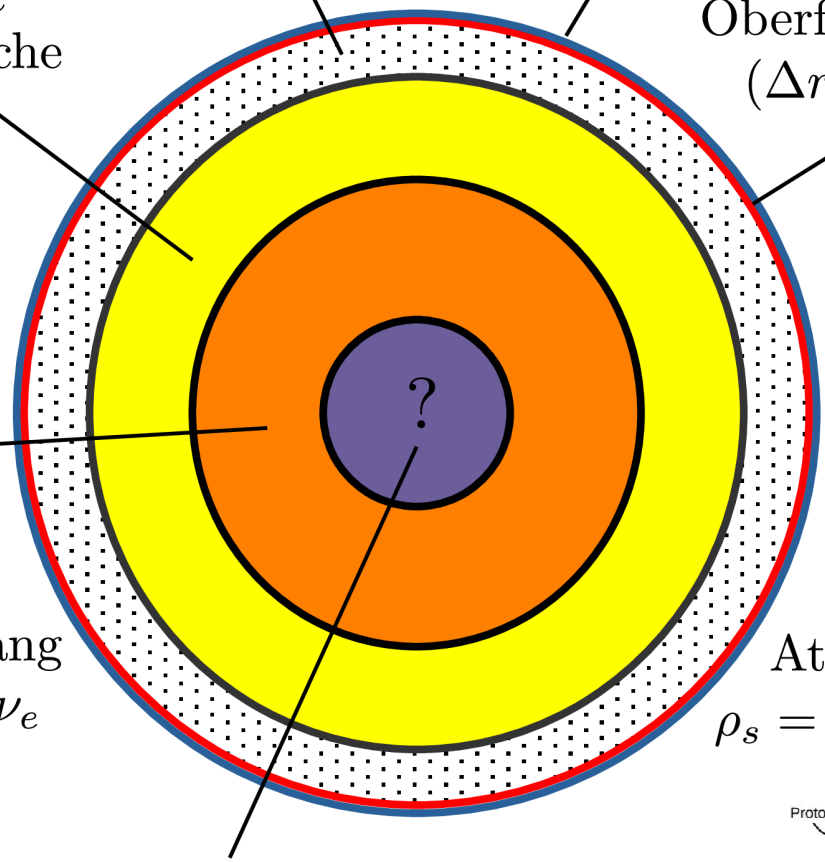

äußere Kruste
Eisengitter + e^-
Atmosphäre (μm)
H, He, C
innere Kruste
neutronenreiche
Atomkerne,
Neutronen−
flüssigkeit
Oberfläche $\approx 10^{11}\ g$
($\Delta r \approx$ mm)
äußerer Kern
n, p, e^-,μ
?
Elektroneneinfang
$p + e^- \rightarrow n + \nu_e$
Innerer Kern
Quarkmaterie, . . .?

äußere Kruste
Eisengitter + e^-

Atmosphäre (μm)
H, He, C

innere Kruste
neutronenreiche
Atomkerne,
Neutronen−
flüssigkeit

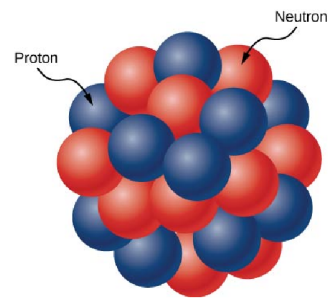
Oberfläche $\approx 10^{11}\ g$
($\Delta r \approx$ mm)



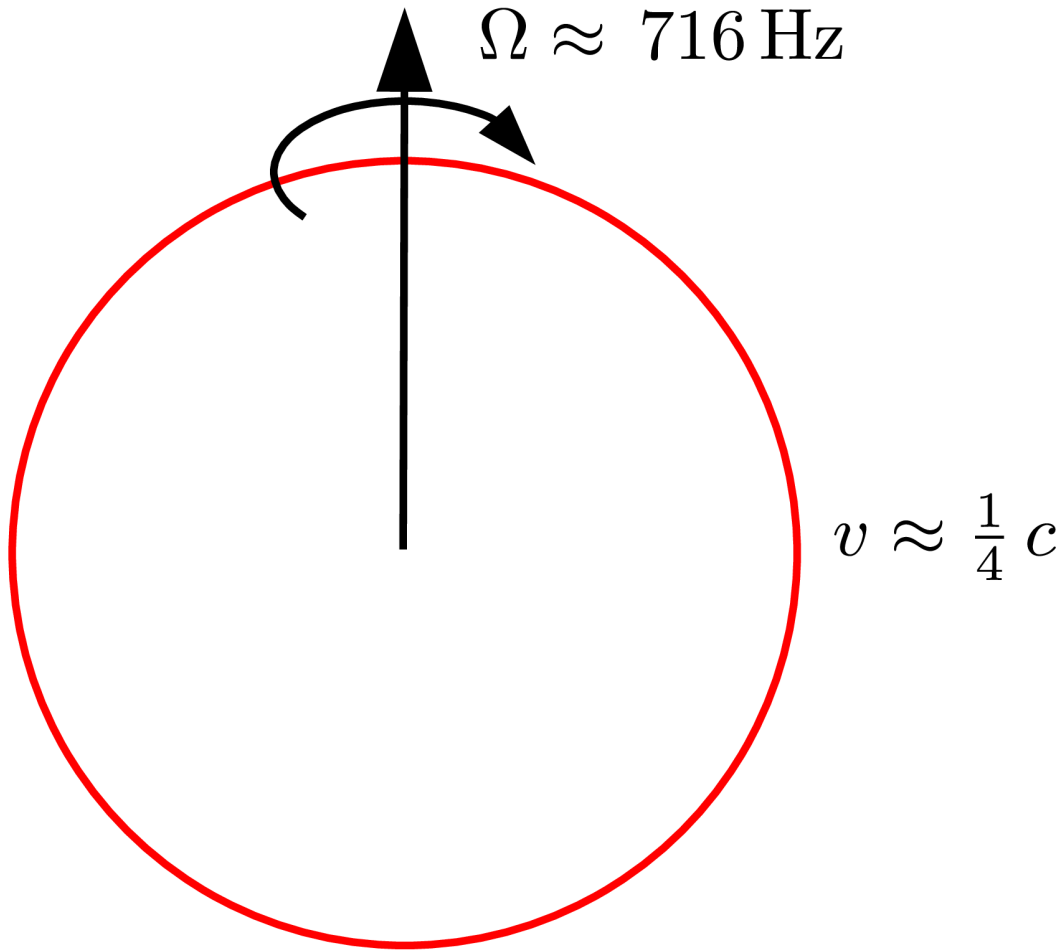
äußerer Kern
n, p, e^-,μ

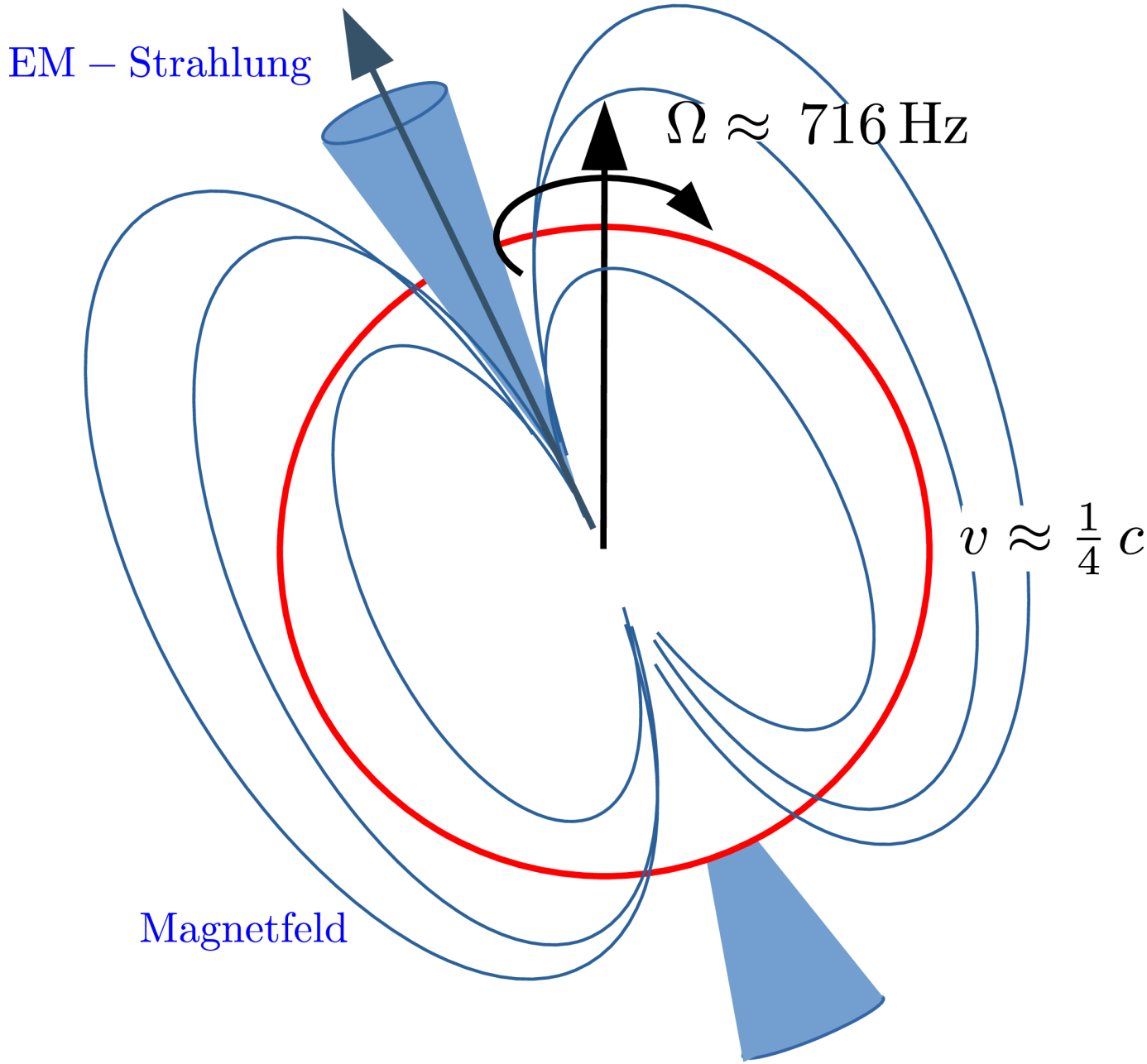
Elektroneneinfang
$p + e^- \rightarrow n + \nu_e$

Atomkerndichte
$\rho_s = 2.3 \cdot 10^{14}\ g/cm^3$

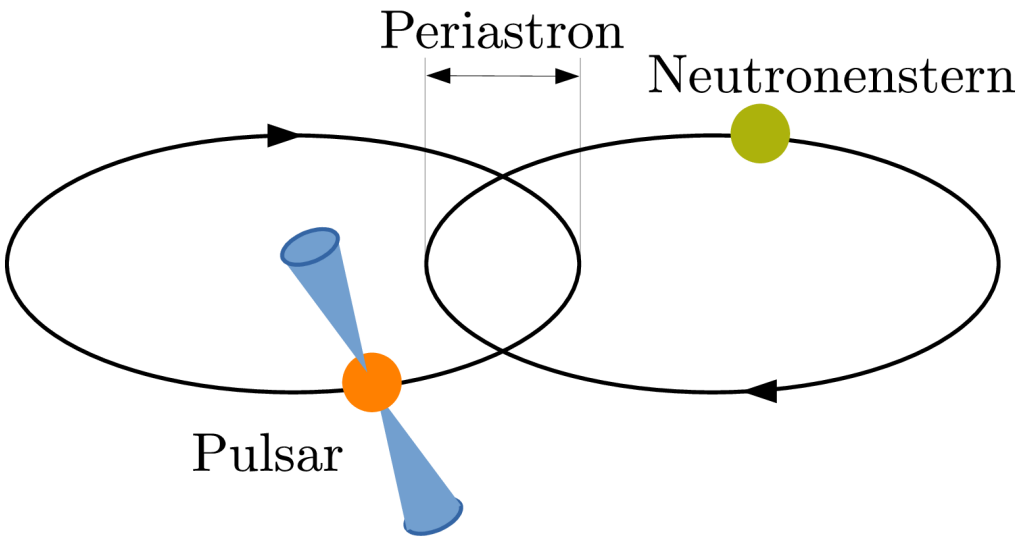


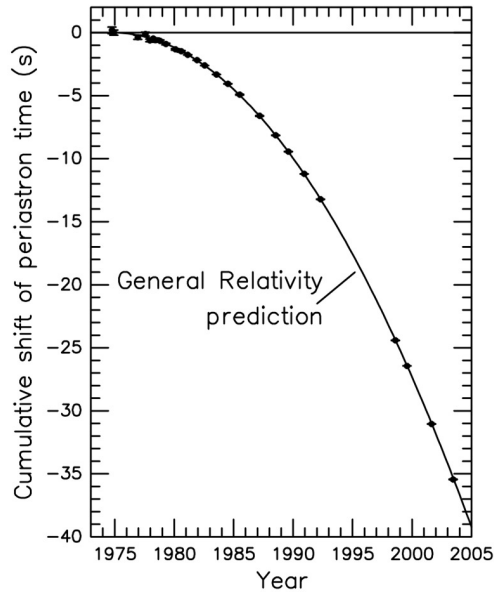
Innerer Kern
Quarkmaterie, . . .?
Dichte $\approx 2 - 5\rho_s$


$\Omega \approx 716\,\mathrm{Hz}$
$v \approx \frac{1}{4}\,c$


EM – Strahlung
$\Omega \approx 716\,\mathrm{Hz}$
$v \approx \frac{1}{4}\,c$
Magnetfeld

Hulse-Taylor Binärpulsar: PSR B1913+16





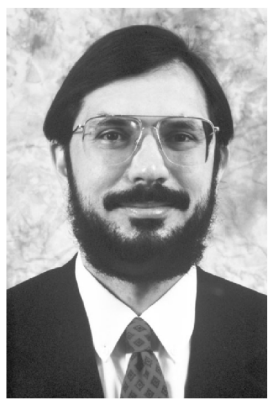


Photo from the Nobel Foundation archive.

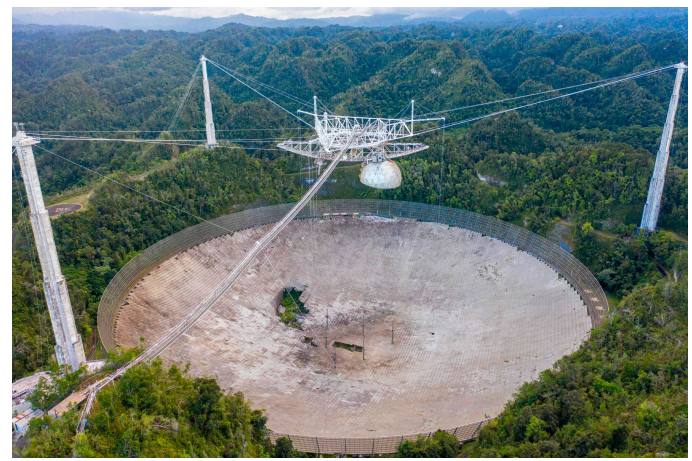
Russell A. Hulse

Prize share: 1/2

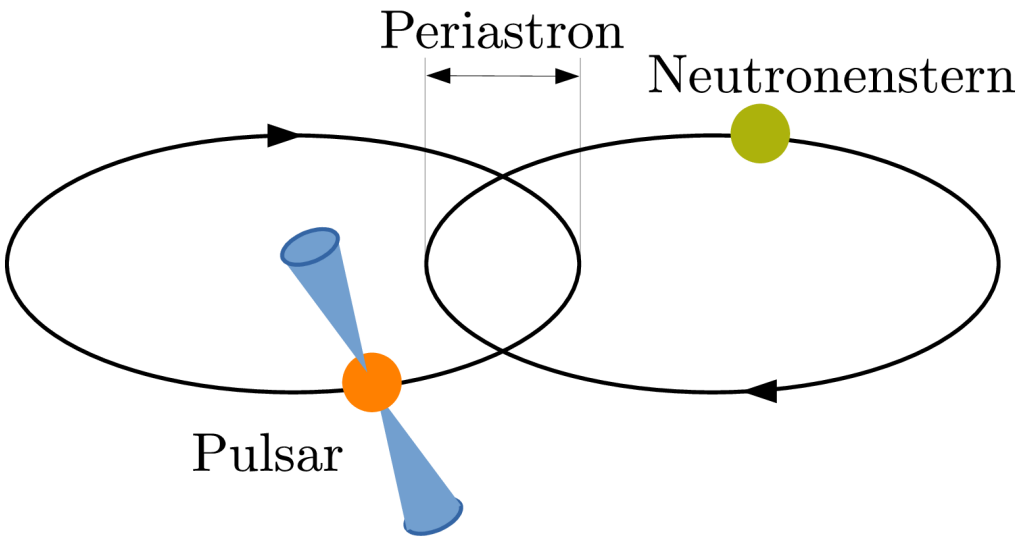
Photo from the Nobel Foundation archive.

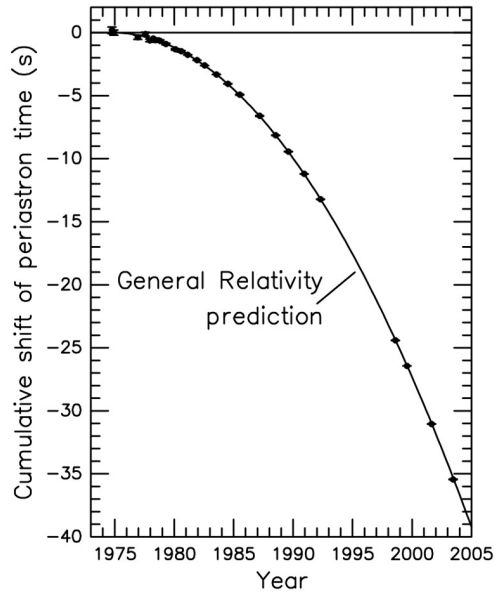
Joseph H. Taylor Jr.

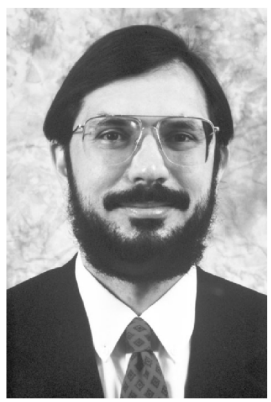
Prize share: 1/2



Hulse-Taylor Binärpulsar: PSR B1913+16







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Russell A. Hulse

Prize share: 1/2

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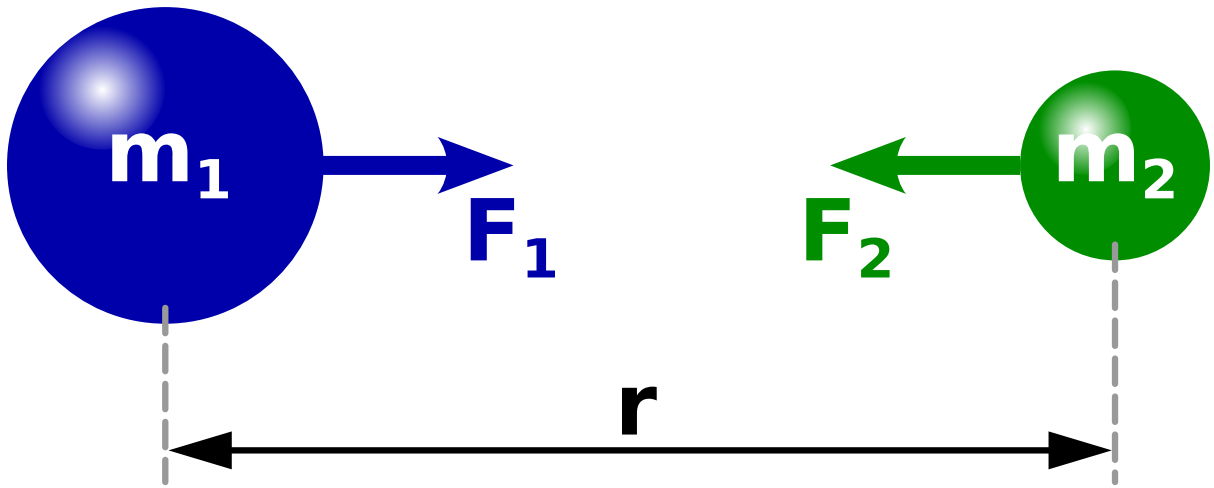
Joseph H. Taylor Jr.

Prize share: 1/2

Newton's Gravitation (1687)

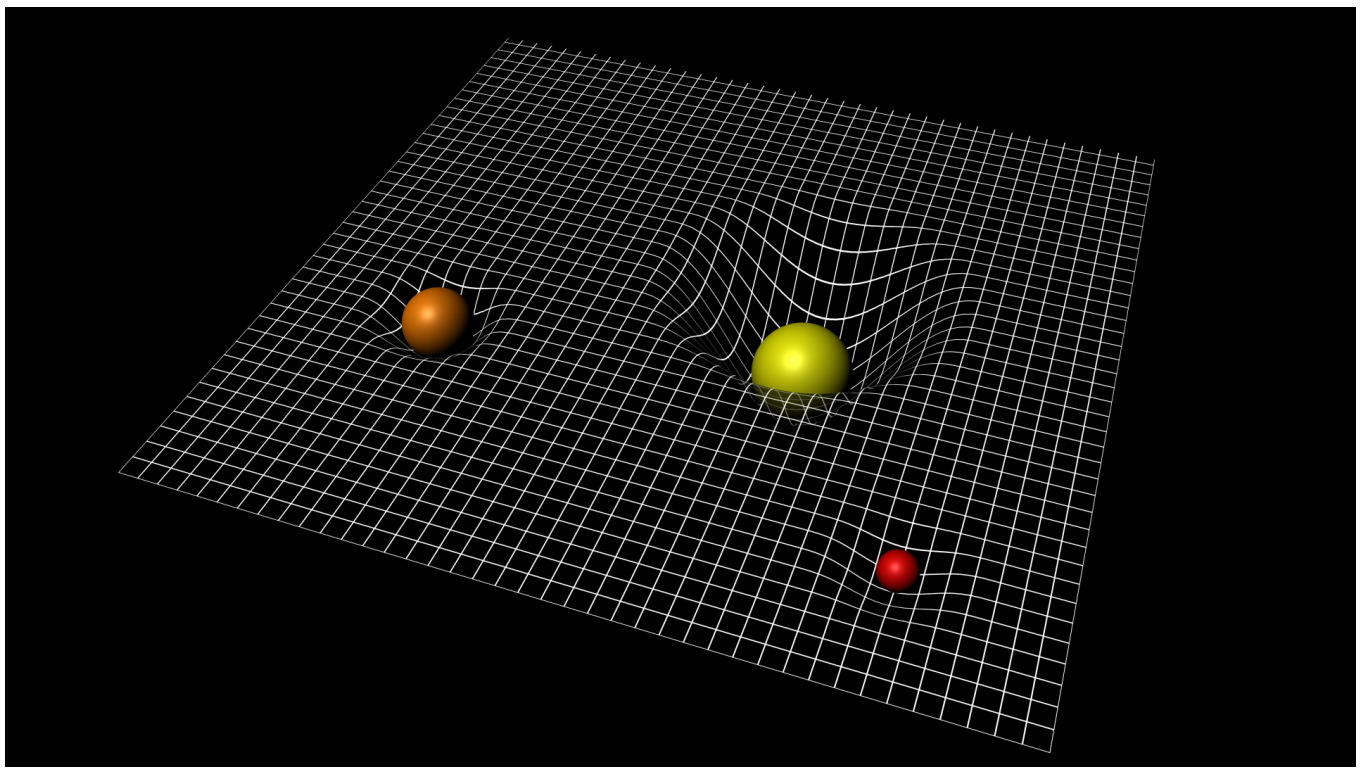


$$F_1 = F_2 = G \frac{m_1 \times m_2}{r^2}$$

Einsteins Allgemeine Relativitätstheorie (1915)

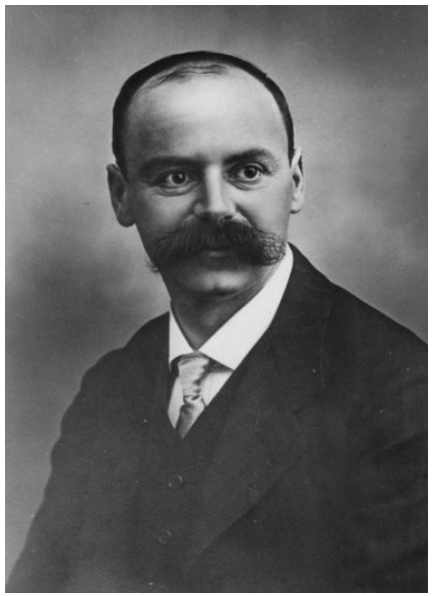
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi G_N T_{\mu\nu} \, .$$

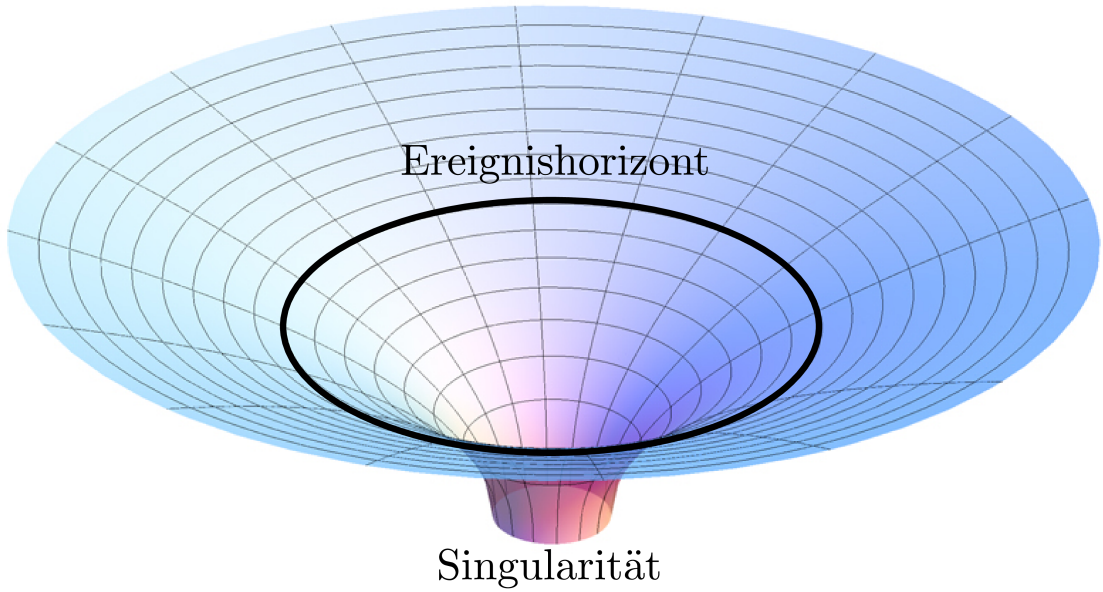
Verteilung von Materie bestimmt wie sich Raumzeit krümmt, Krümmung der Raumzeit bestimmt wie sich Materie verteilt.



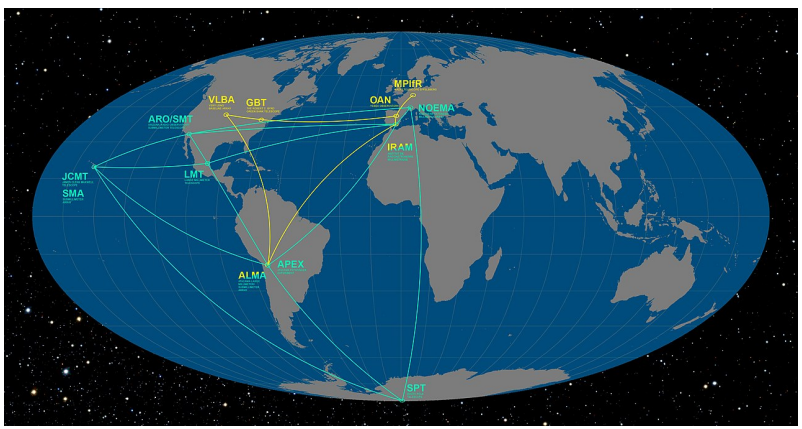
Schwarze Löcher

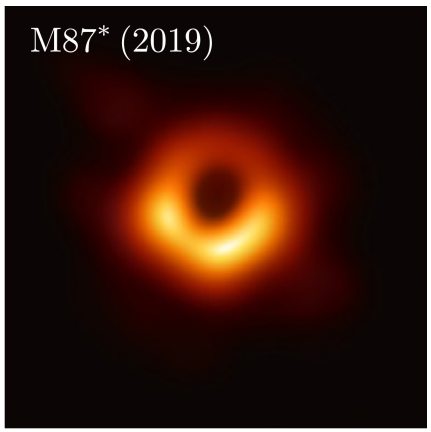
Karl Schwarzschild

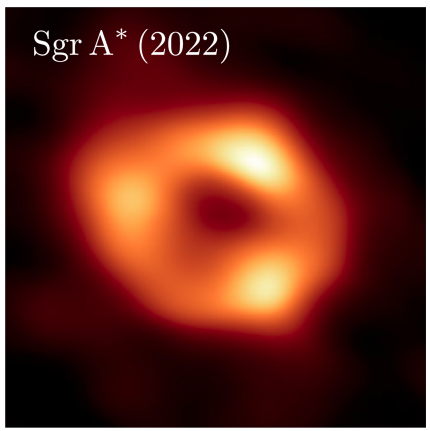




Event Horizon Telescope

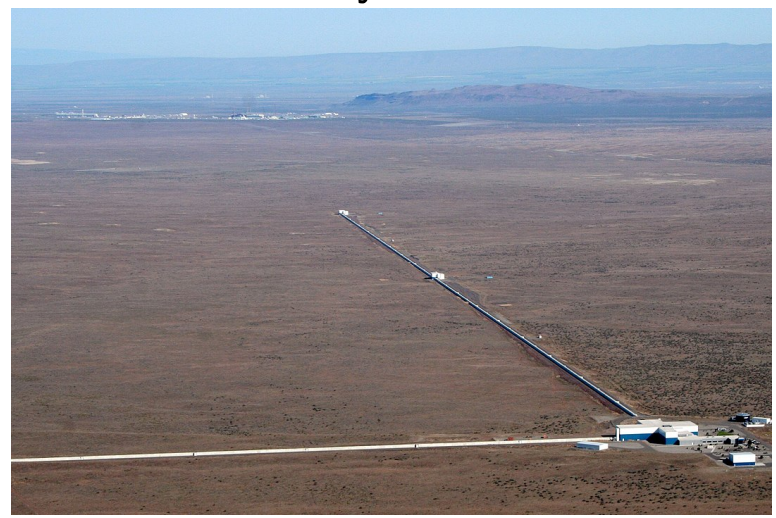


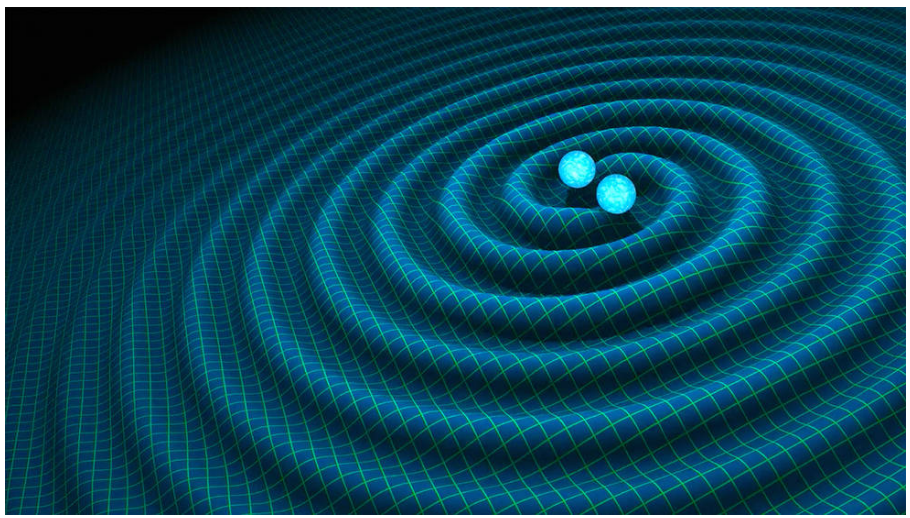


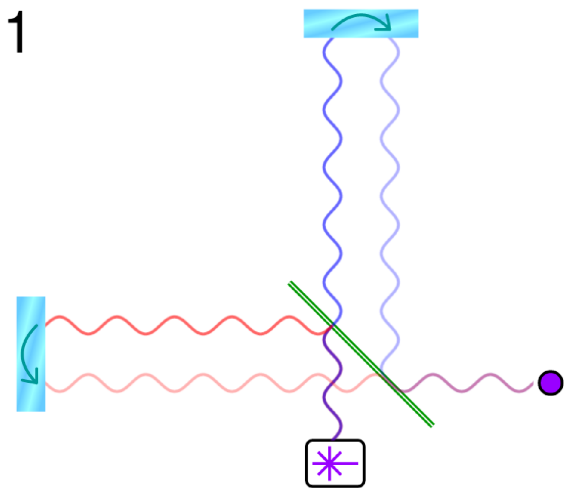


Gravitationswellen

LIGO: Laser Interferometer Gravitational-Wave Observatory

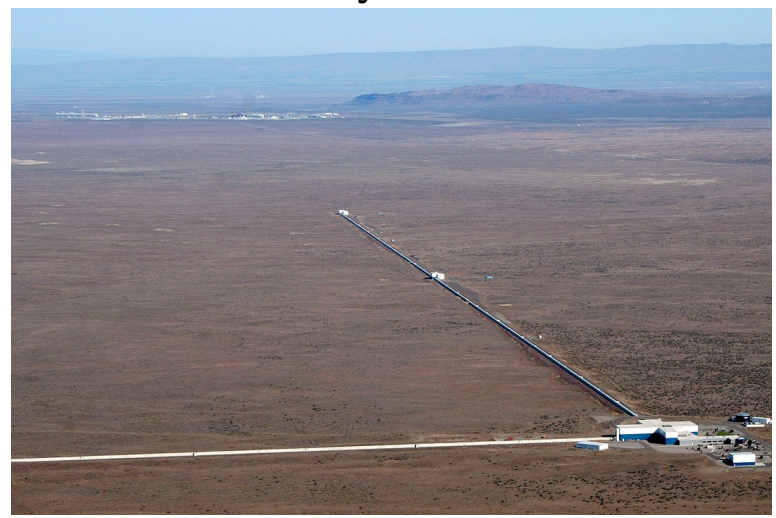


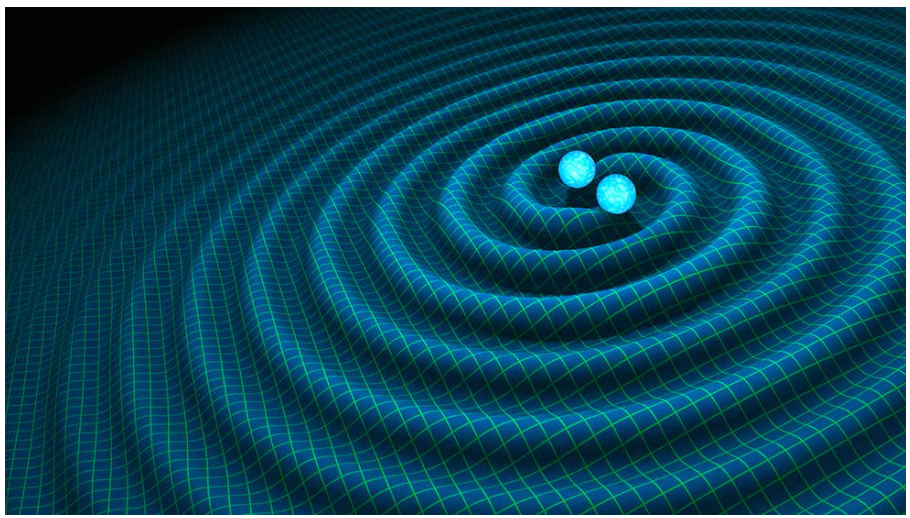


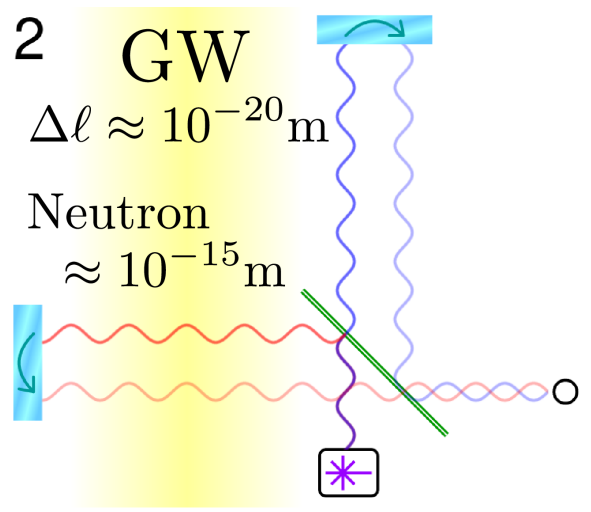


Gravitationswellen

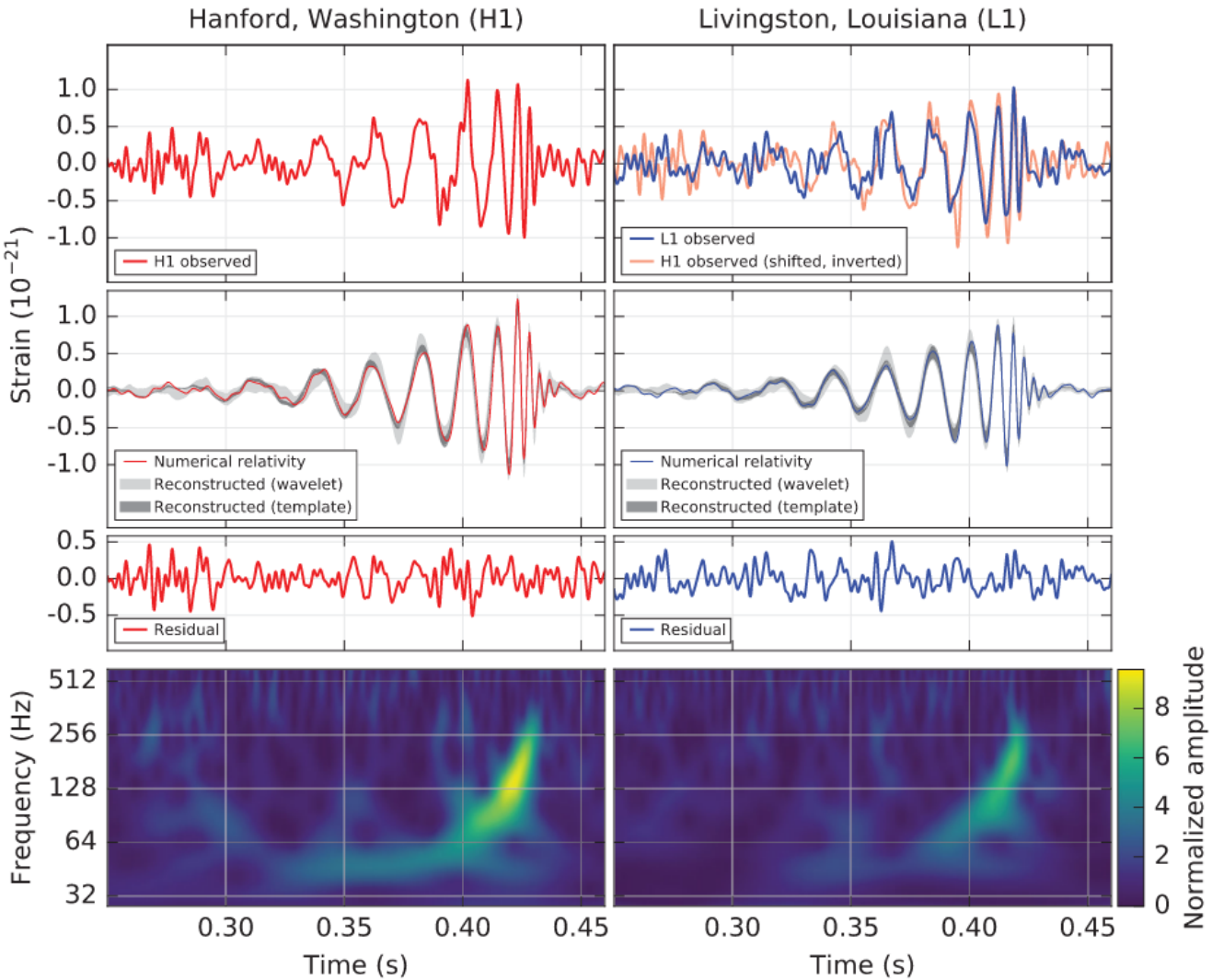
LIGO: Laser Interferometer Gravitational-Wave Observatory



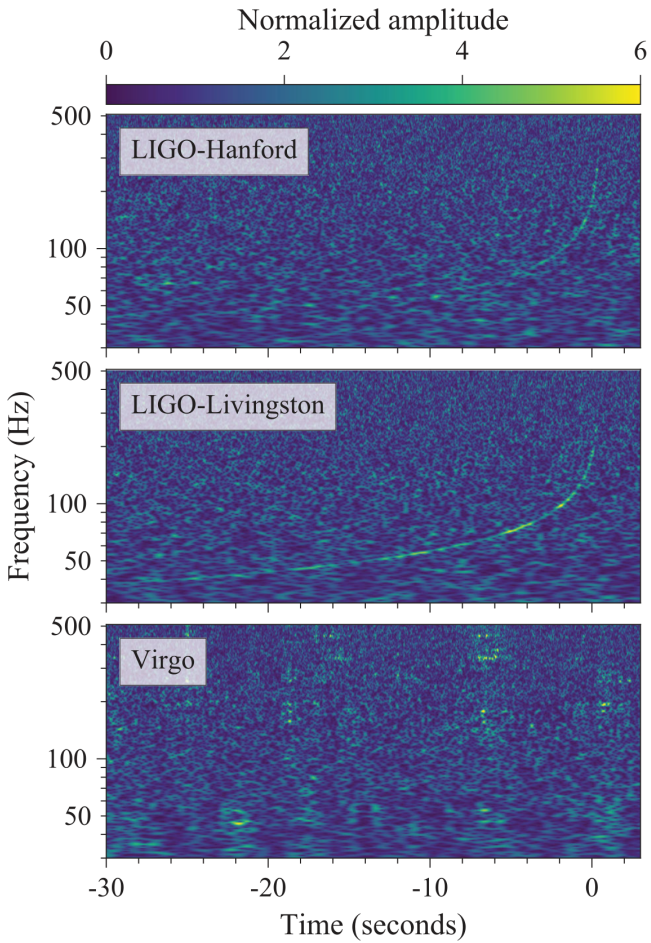


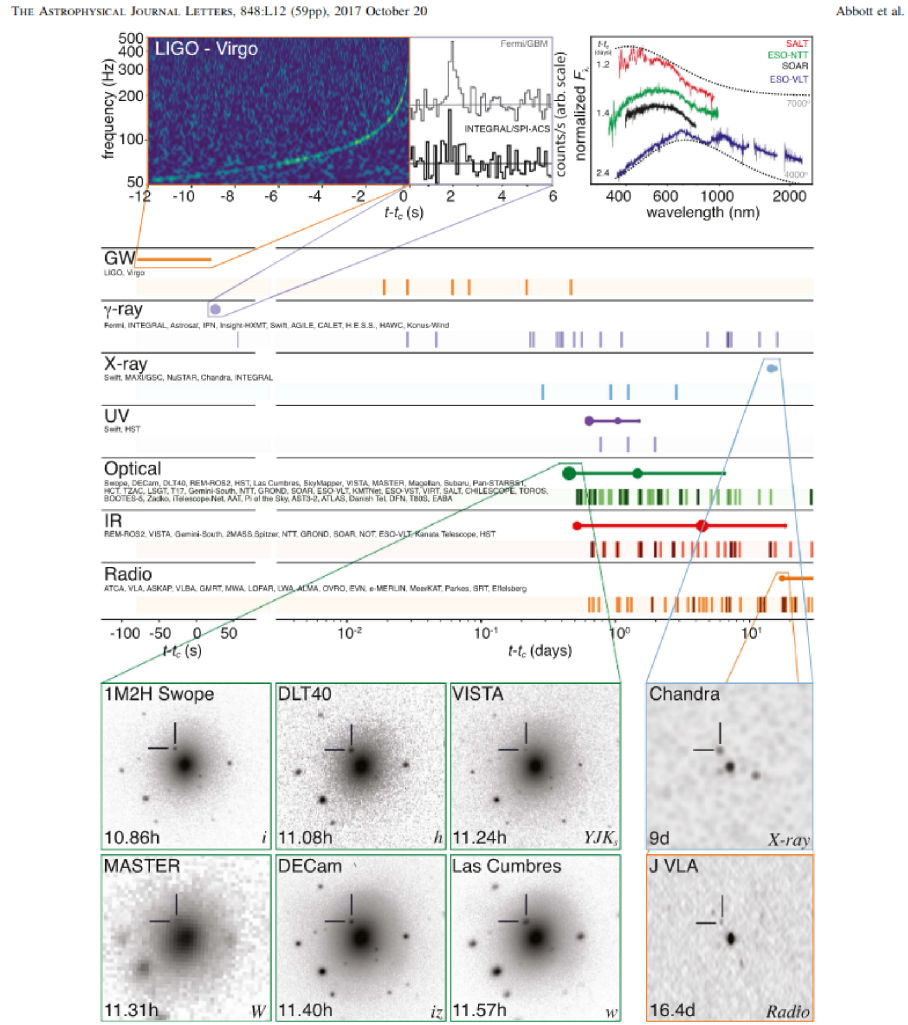


GW150914

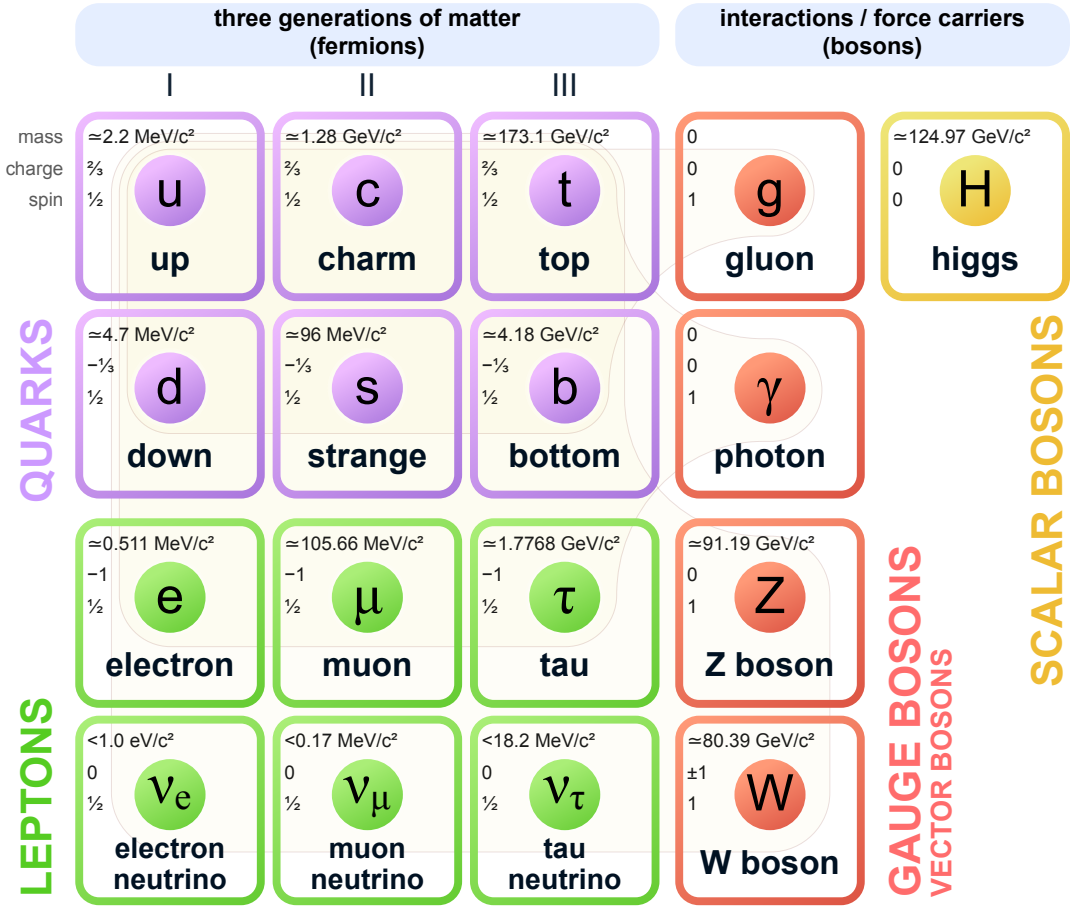

Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
512
256
128
64
32
Time (s)
0.30
0.35
0.40
0.45
Normalized amplitude

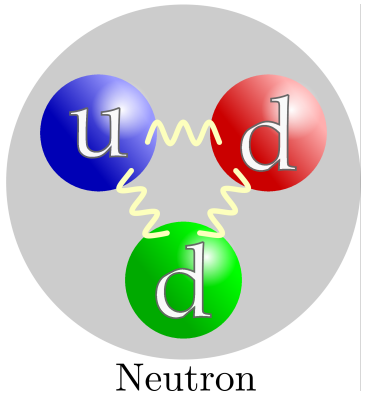
GW170817

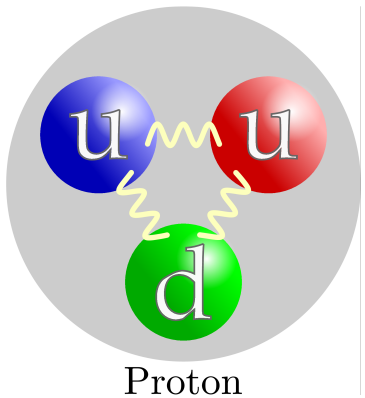

Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
500
100
50
Frequency (Hz)
-30
-20
-10
0
Time (seconds)


THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20
Abbott et al.
LIGO - Virgo
Fermi/GBM
INTEGRAL/SPI-ACS
frequency (Hz)
counts/s (arb. scale)
normalized F_ν
t-t_c (s)
SALT
ESO-NTT
SOAR
ESO-VLT
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LBGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, TBIS, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
t-t_c (days)
1M2H Swope
10.86h
DLT40
11.08h
VISTA
11.24h
Chandra
9d
X-ray
MASTER
11.31h
DECam
11.40h
Las Cumbres
11.57h
J VLA
16.4d
Radio

Standard Model of Elementary Particles



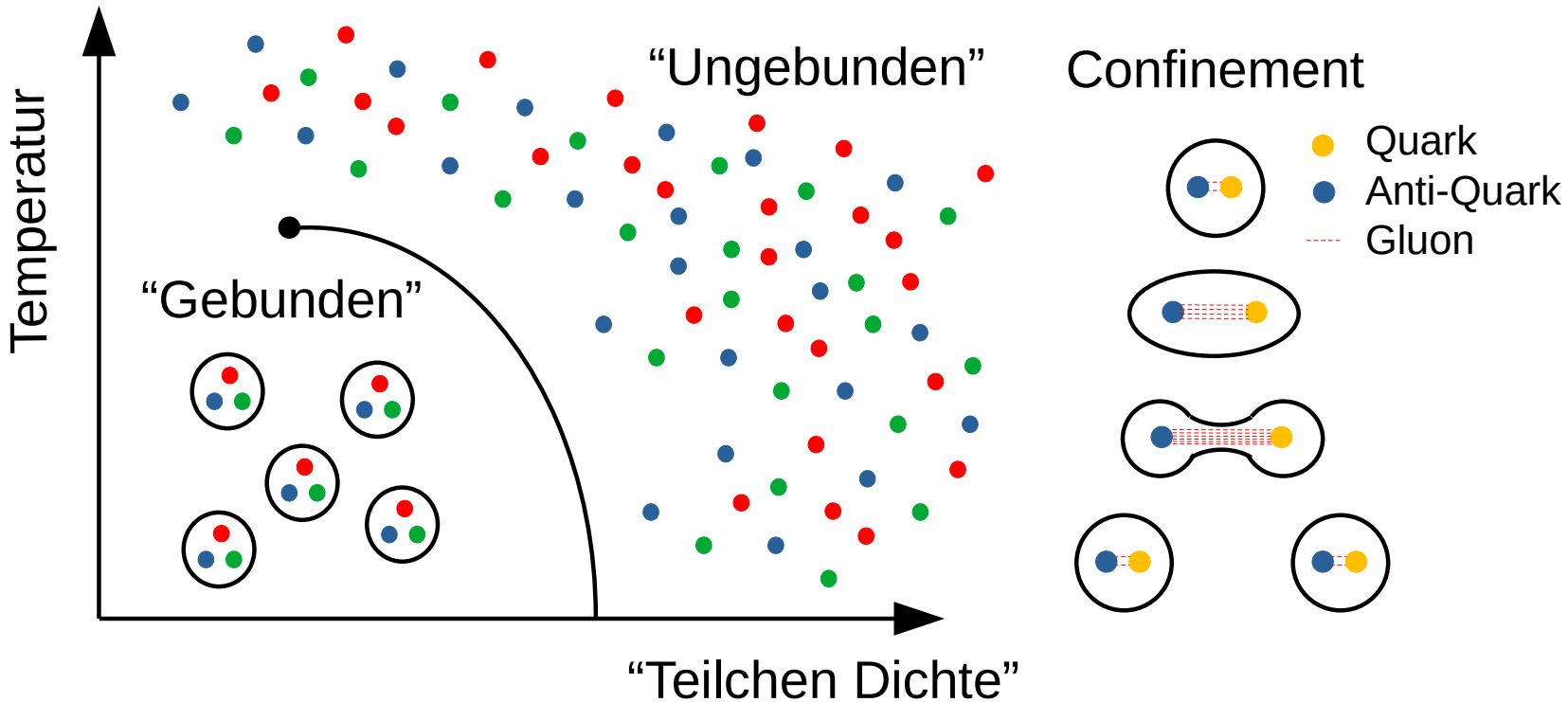




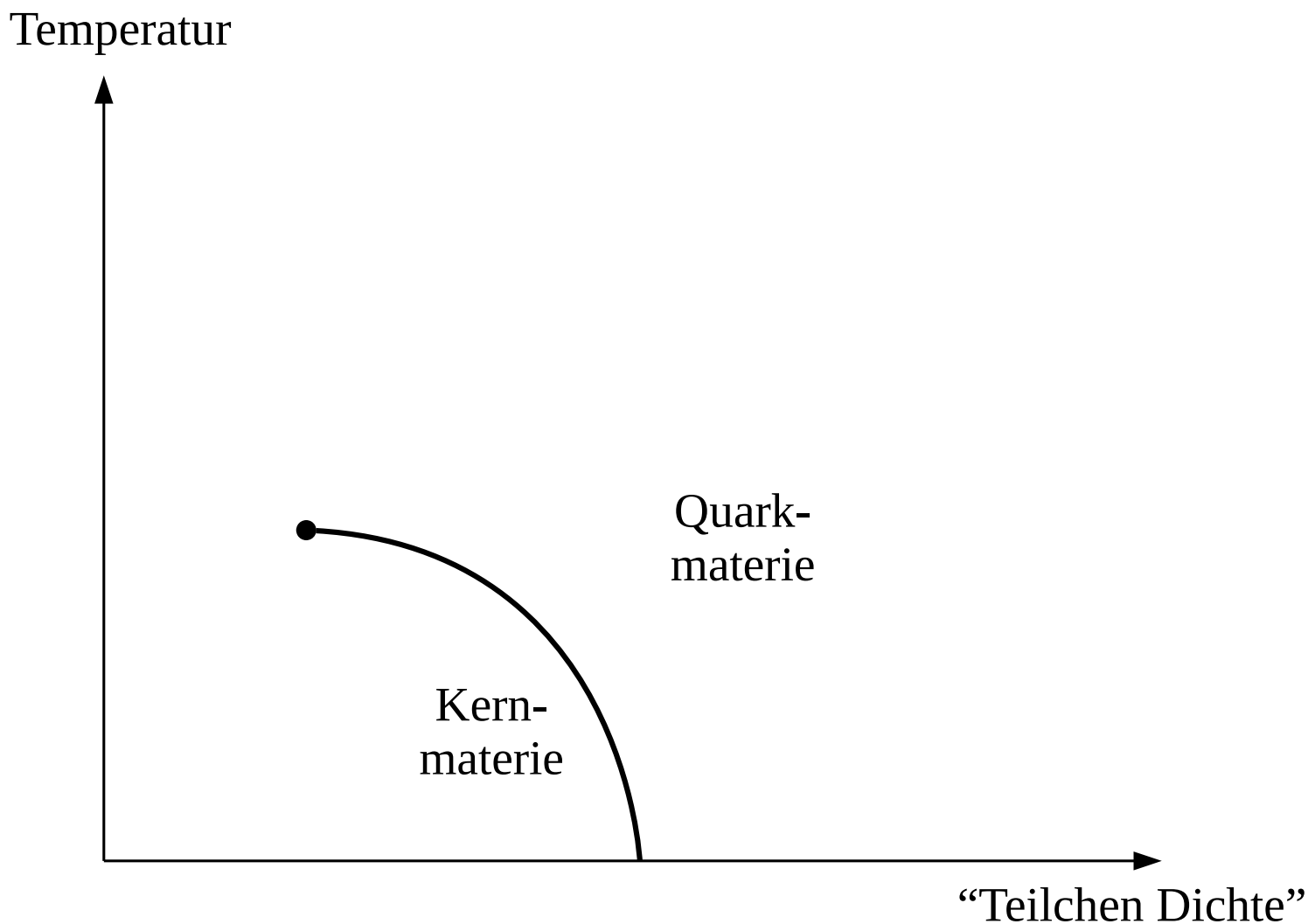
Kraft	relative Stärke	Reichweite [m]	Kraftteilchen
Starke Wechselwirkung	550	10^{-18}	gluon
Schwache Wechselwirkung	410	10^{-15}	W,Z boson
Elektromagnetismus	300	∞	photon
Gravitation	1	∞	graviton (?)

Das QCD Phasen Diagram

Theorie der Starken Wechselwirkung: Quantenchromodynamik (QCD)
Abstoßung/Anziehung durch Gluonenaustausch farbgeladener Quarks.



Was man (nicht) über QCD weiß



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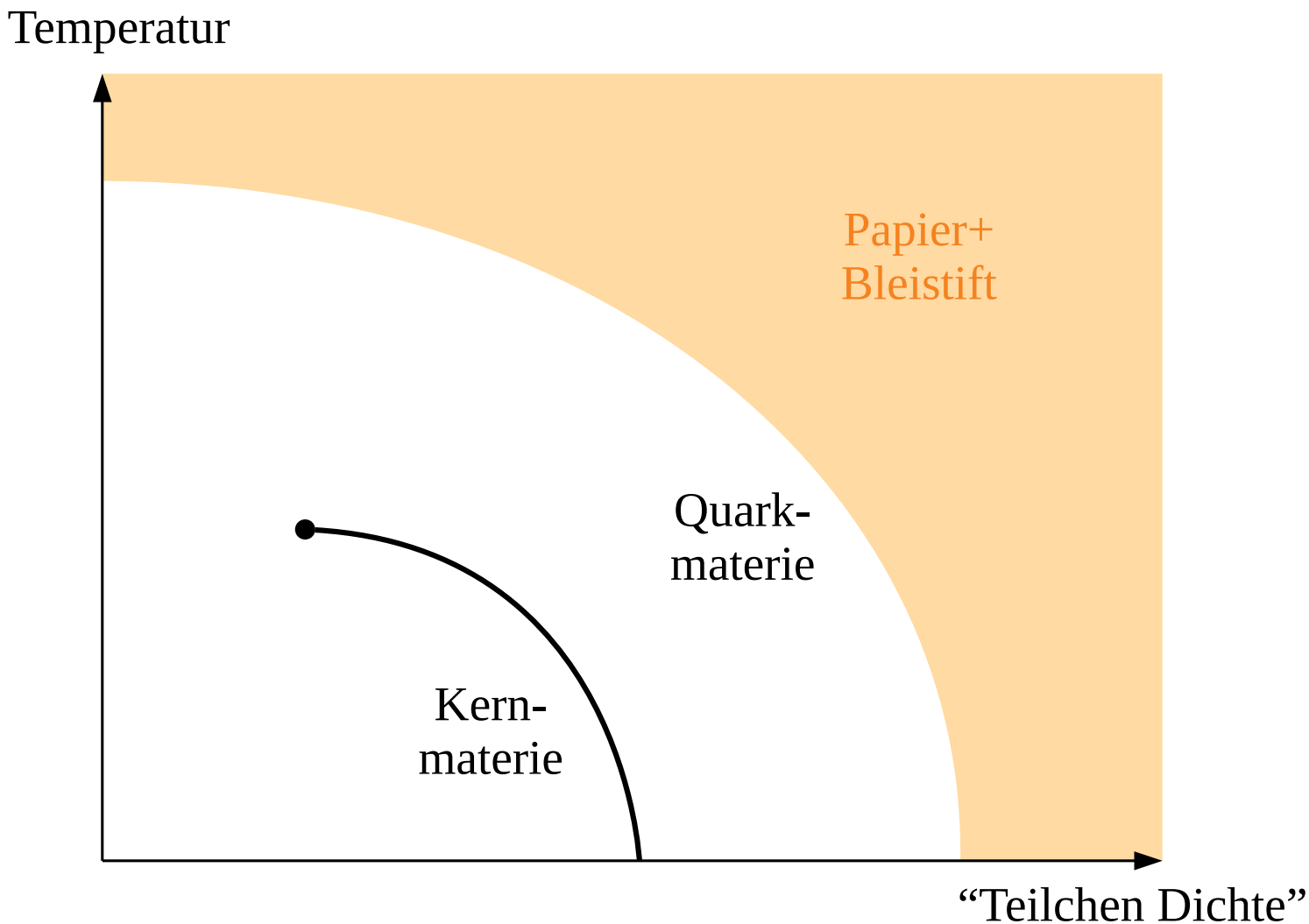

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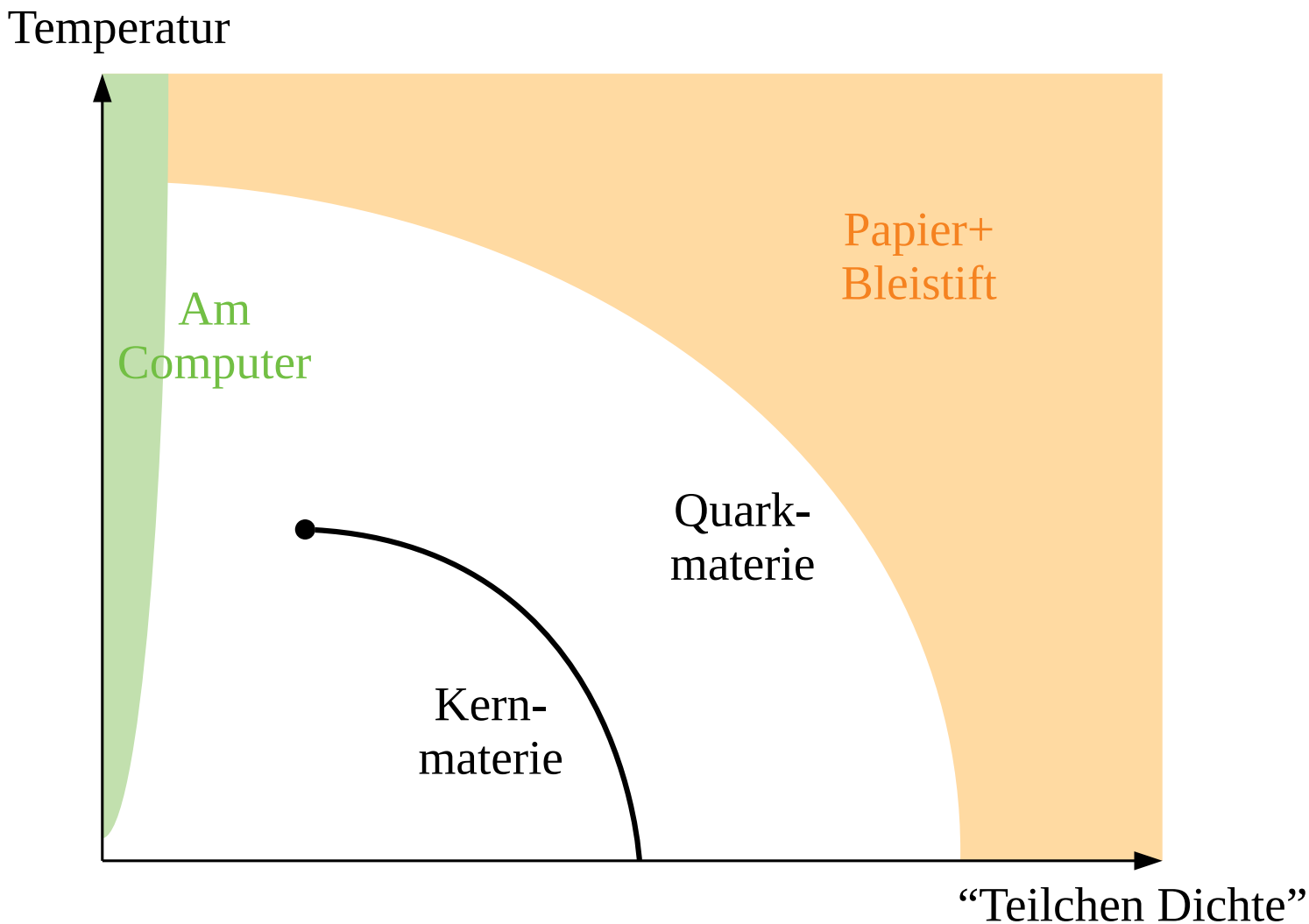

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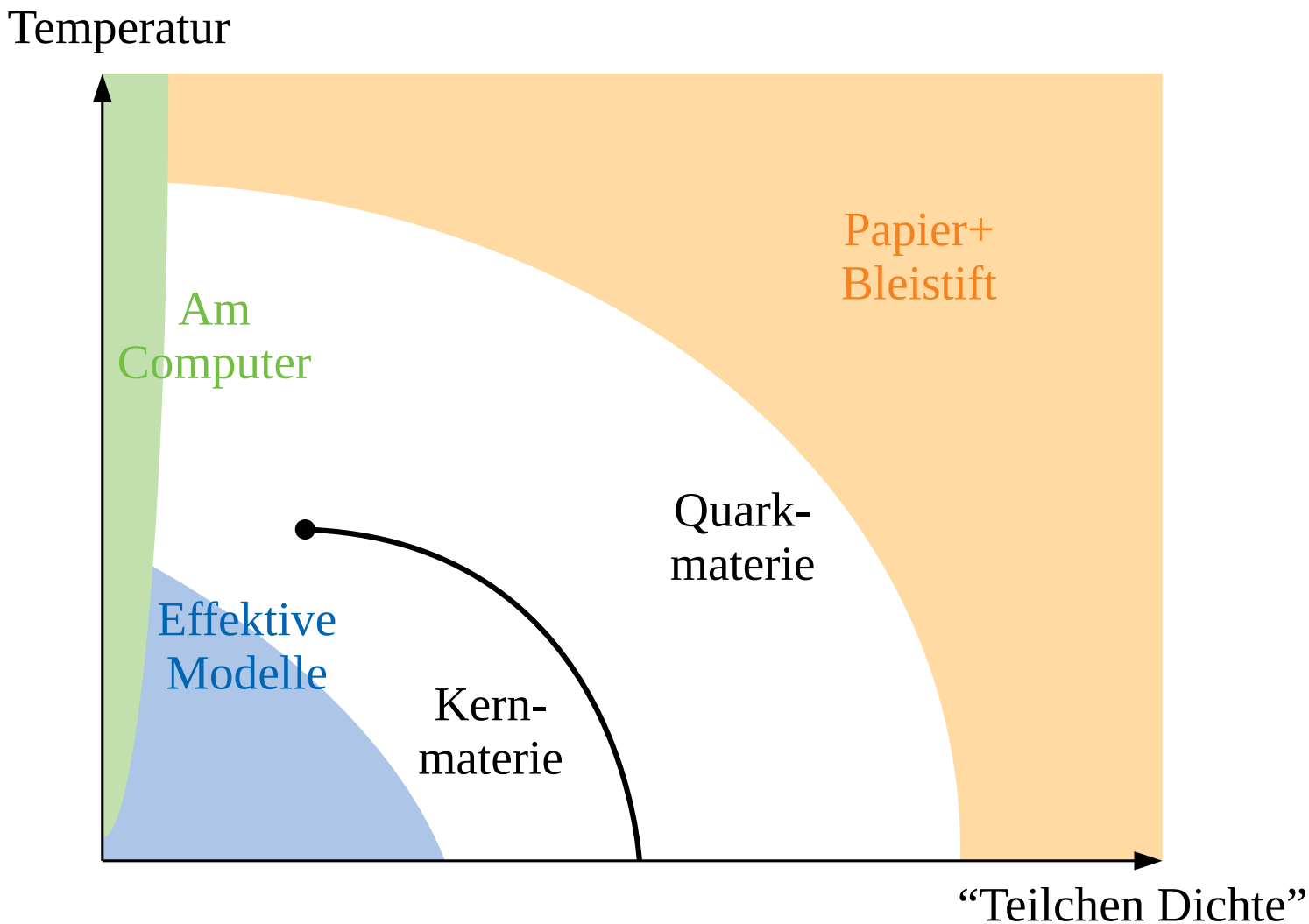

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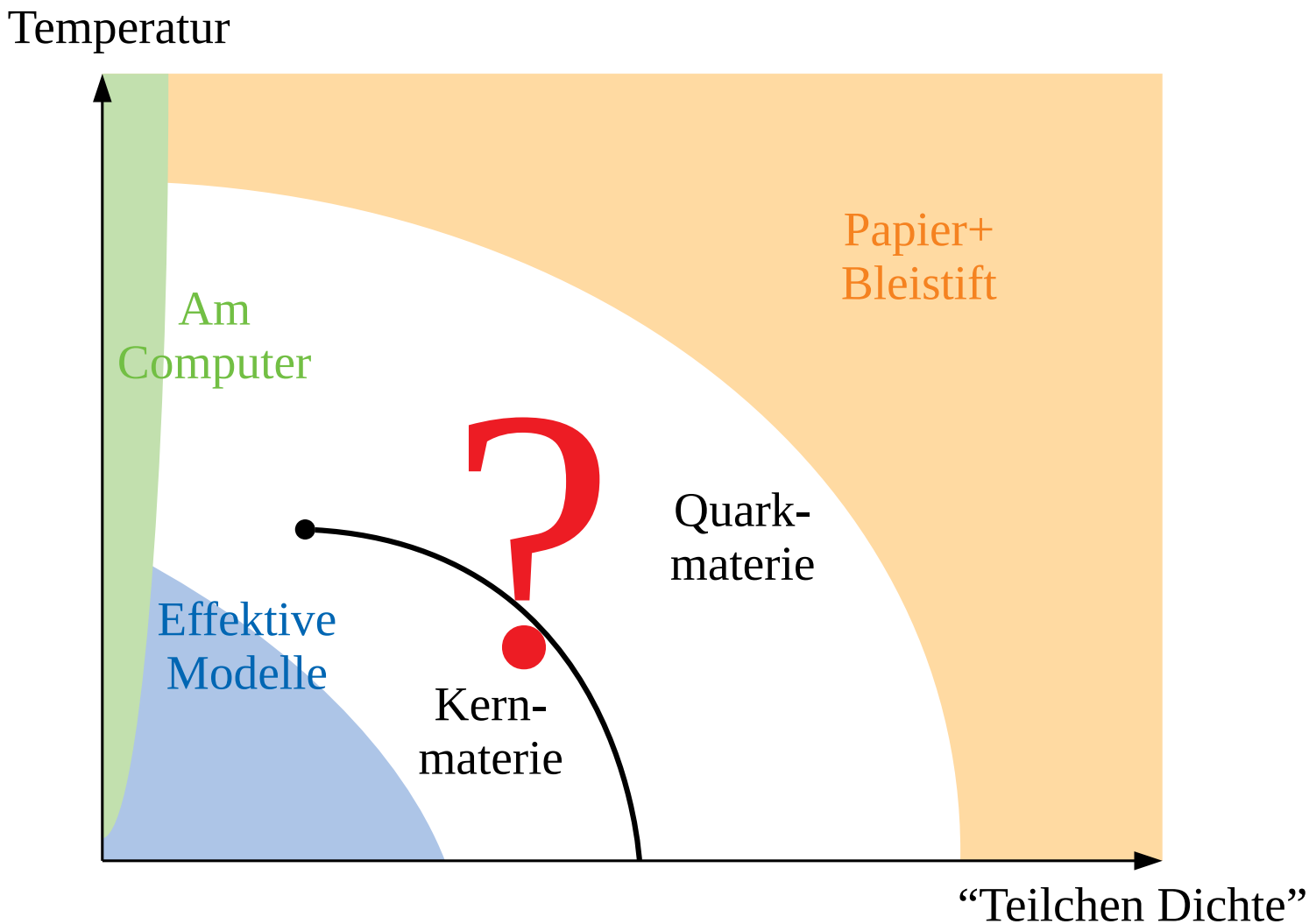

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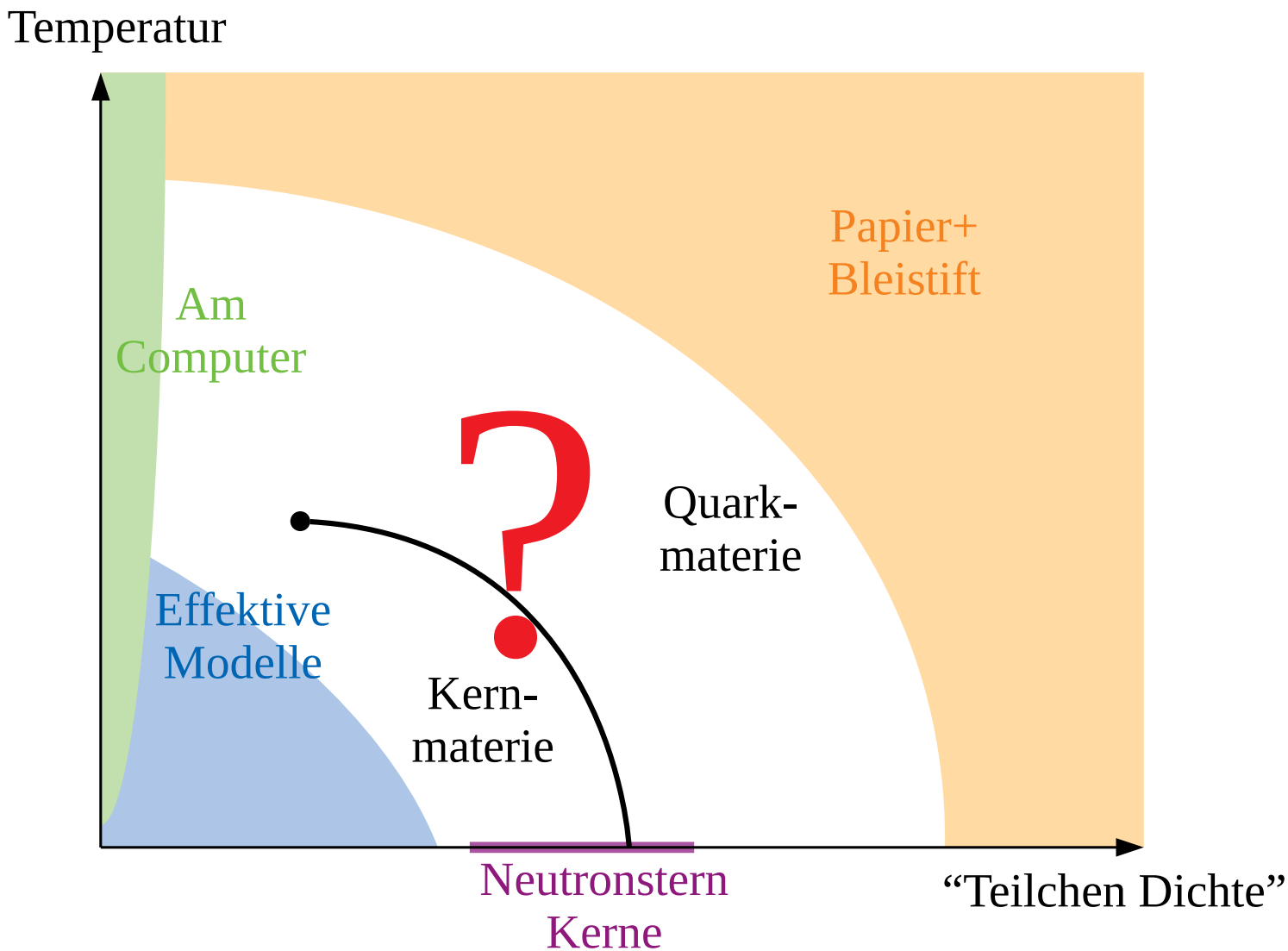
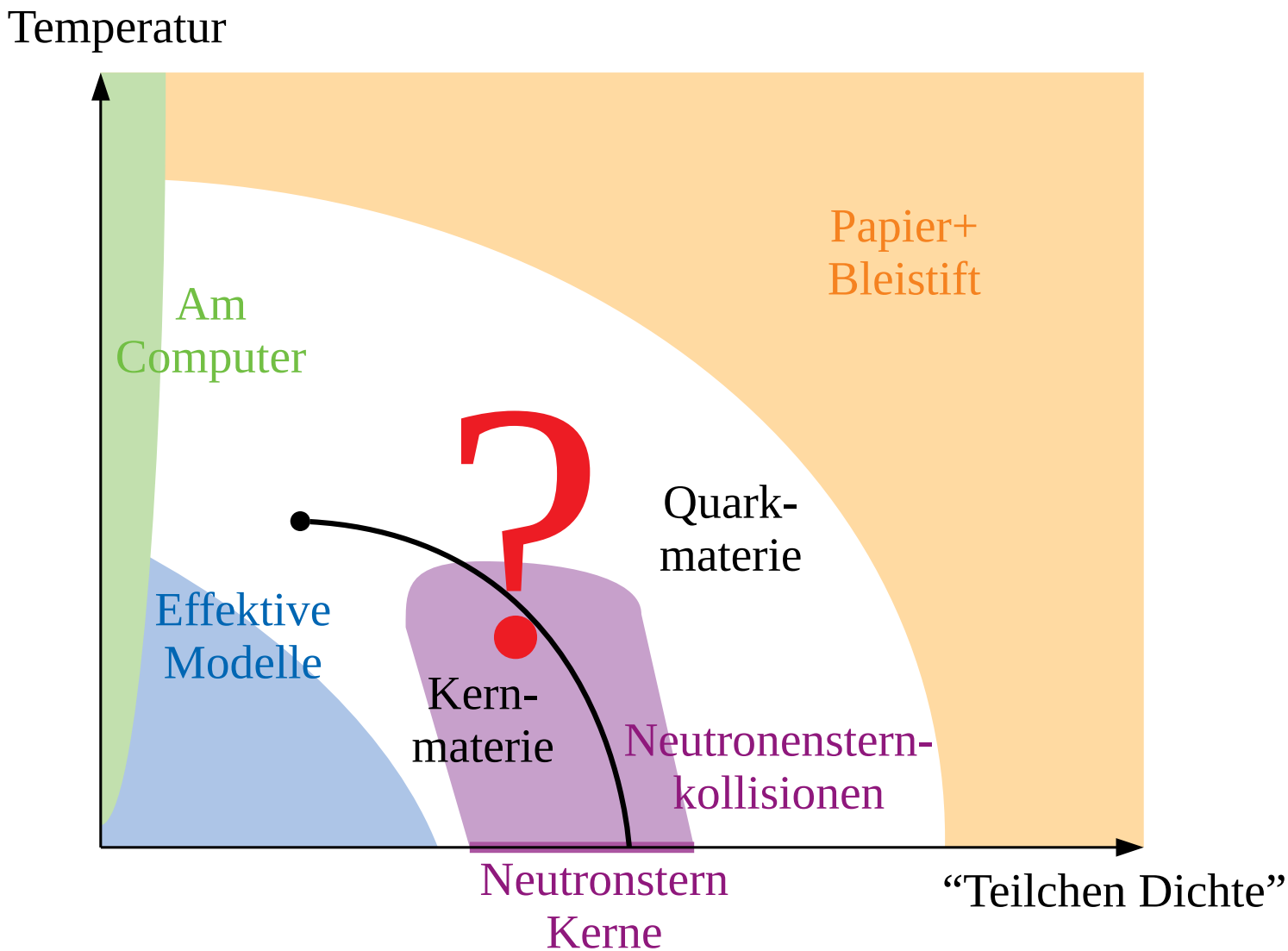


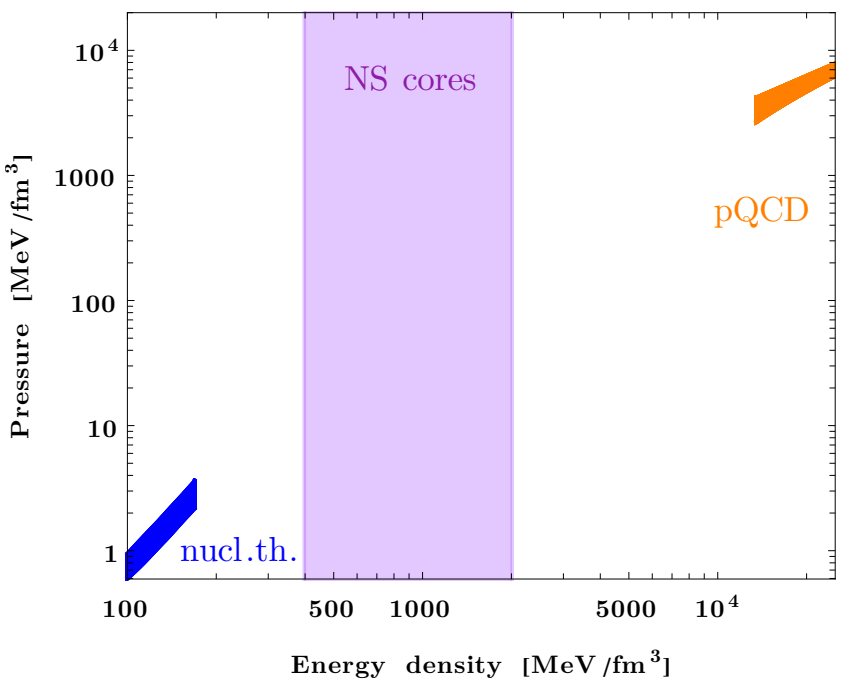
Was man (nicht) über QCD weiß

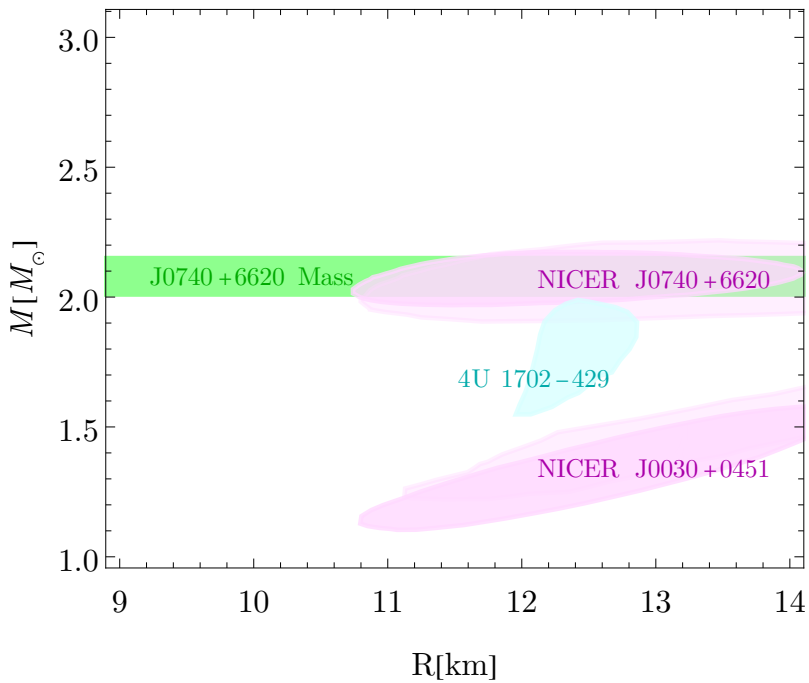


Zustandsgleichung

Beziehung zwischen Druck und Energiedichte (Eigenschaft von Materie) bestimmt
Beziehung zwischen Masse und Radius (Eigenschaft des Sterns)

$$p(e) \xrightarrow{\text{Einstein Eq.}} M(R)$$





Möglichkeiten

1. Aufgeben.

Möglichkeiten

1 ~~Aufgeben.~~

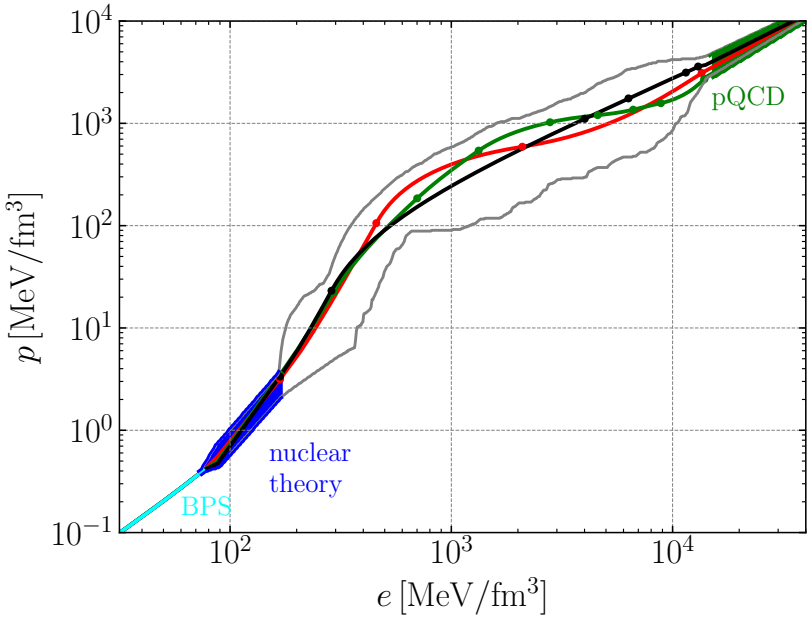
Möglichkeiten

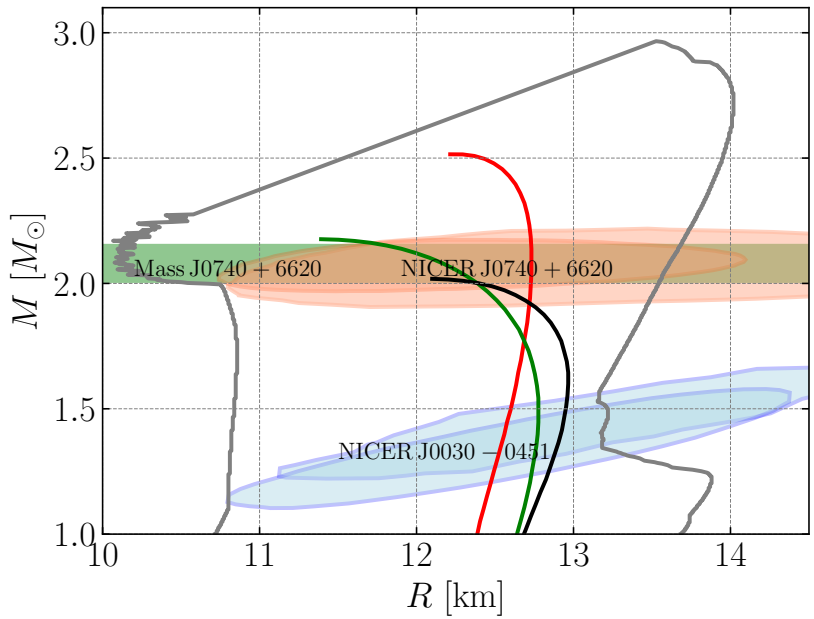
1. ~~Aufgeben.~~
2. Die Zustandsgleichung erraten.

Möglichkeiten

1. ~~Aufgeben.~~
2. Die Zustandsgleichung erraten.
3. Ein lösbares Ersatzmodell bauen.

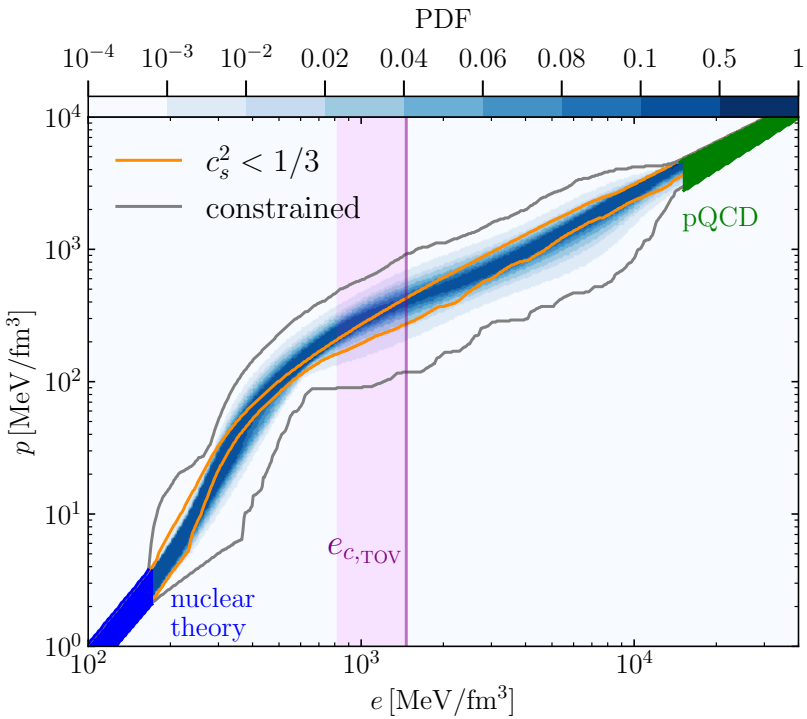
Die Zustandsgleichung erraten

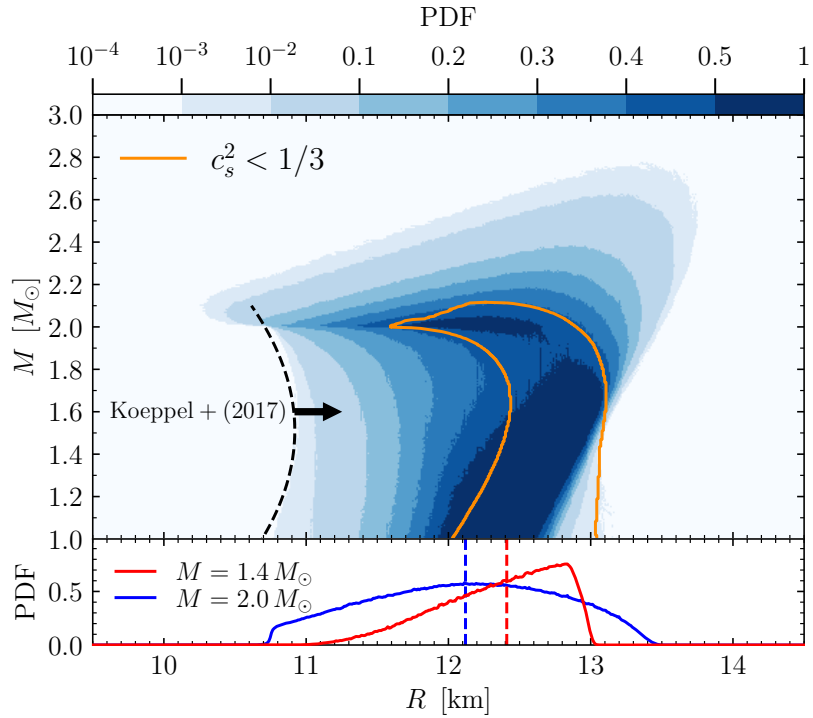




[S. Altiparmak, CE, L. Rezzolla arXiv:2203.14974]

Die Zustandsgleichung erraten

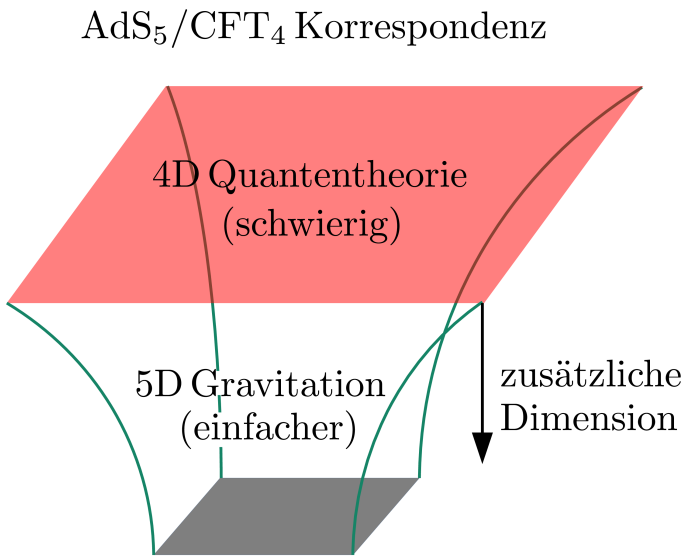


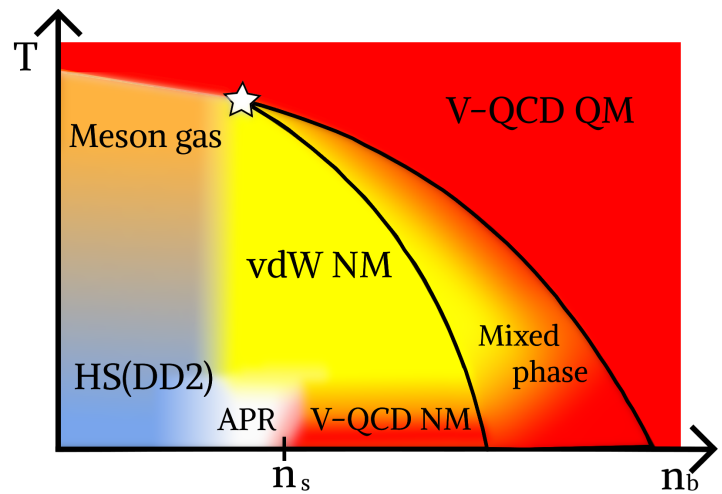


[S. Altiparmak, CE, L. Rezzolla arXiv:2203.14974]

Lösbares Ersatzmodell

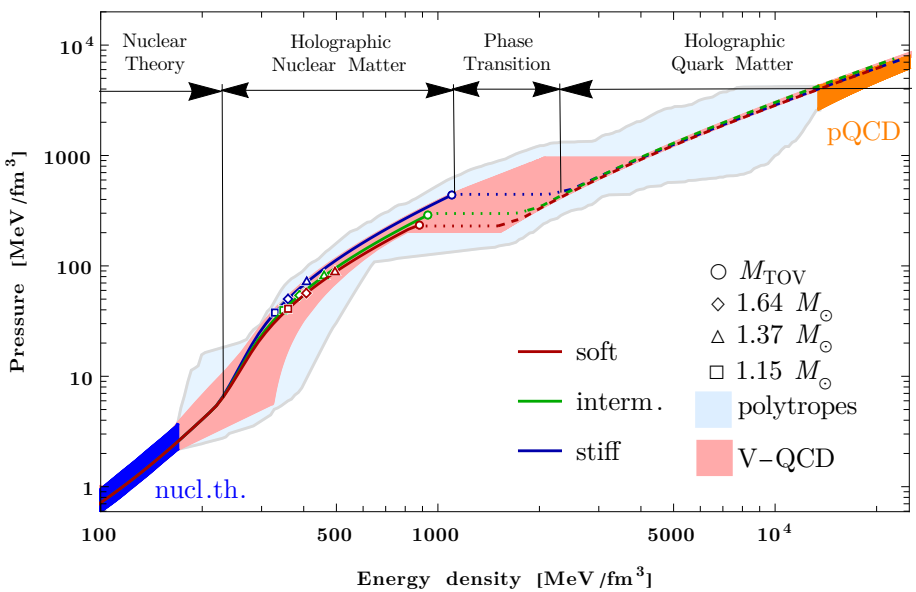
- Mathematischer Trick: holographisches Prinzip
- Übersetzt schwieriges Problem in Quantentheorie in einfacheres Problem in 5 dimensionaler Gravitationstheorie.
- Kombiniert mit traditionellen Modellen bei geringer Dichte.

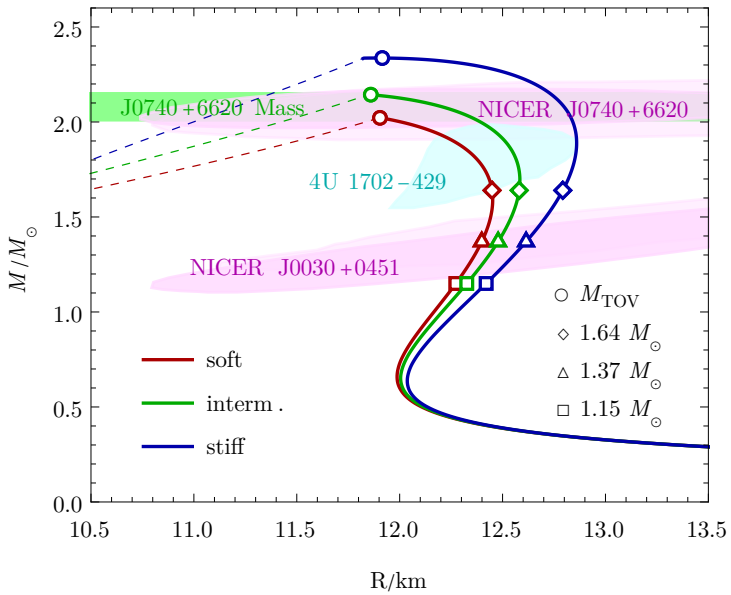




[T. Demircik, CE, M. Järvinen arXiv:2112.12157]

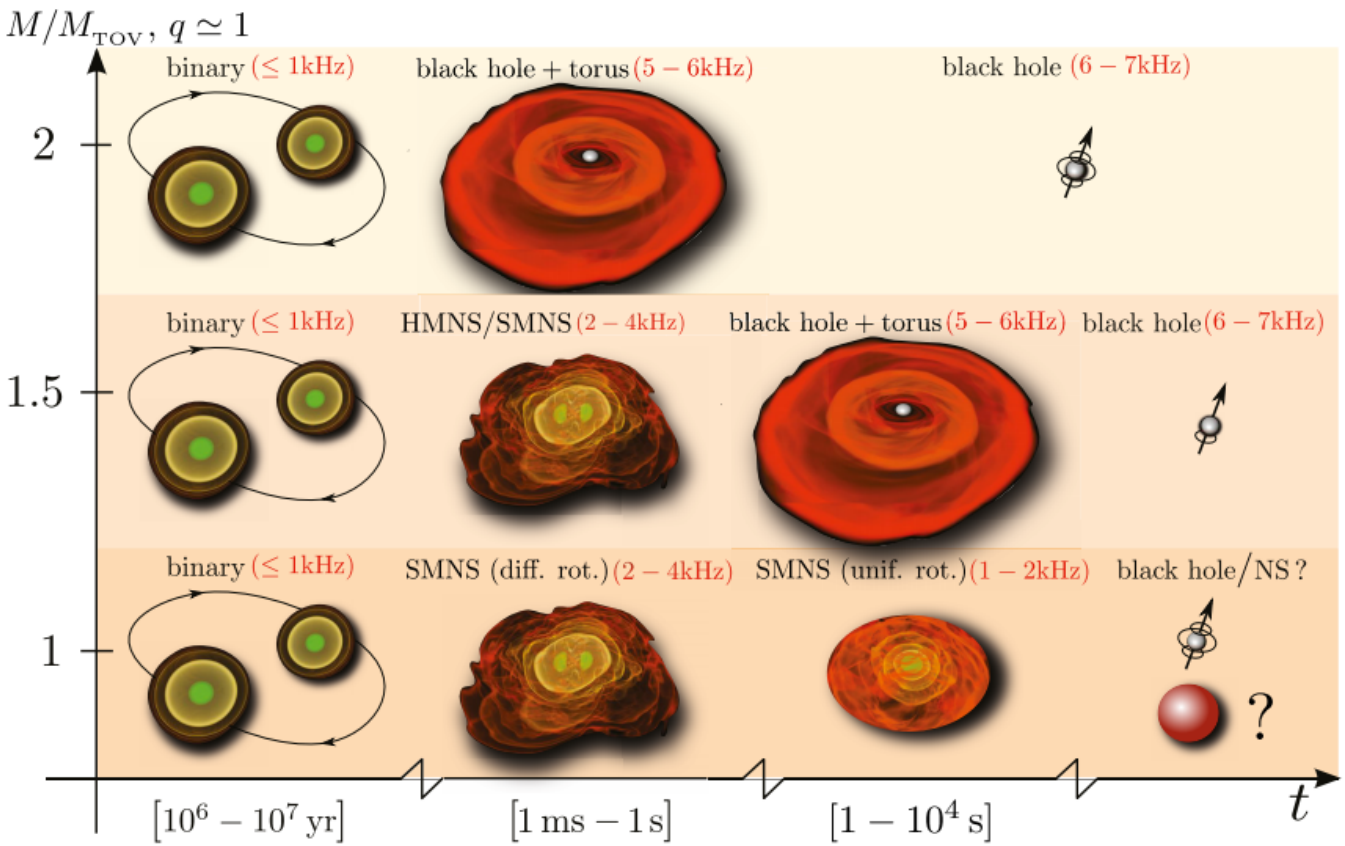
Lösbares Ersatzmodell





[S. Tootle, CE, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla arXiv:2205.05691]

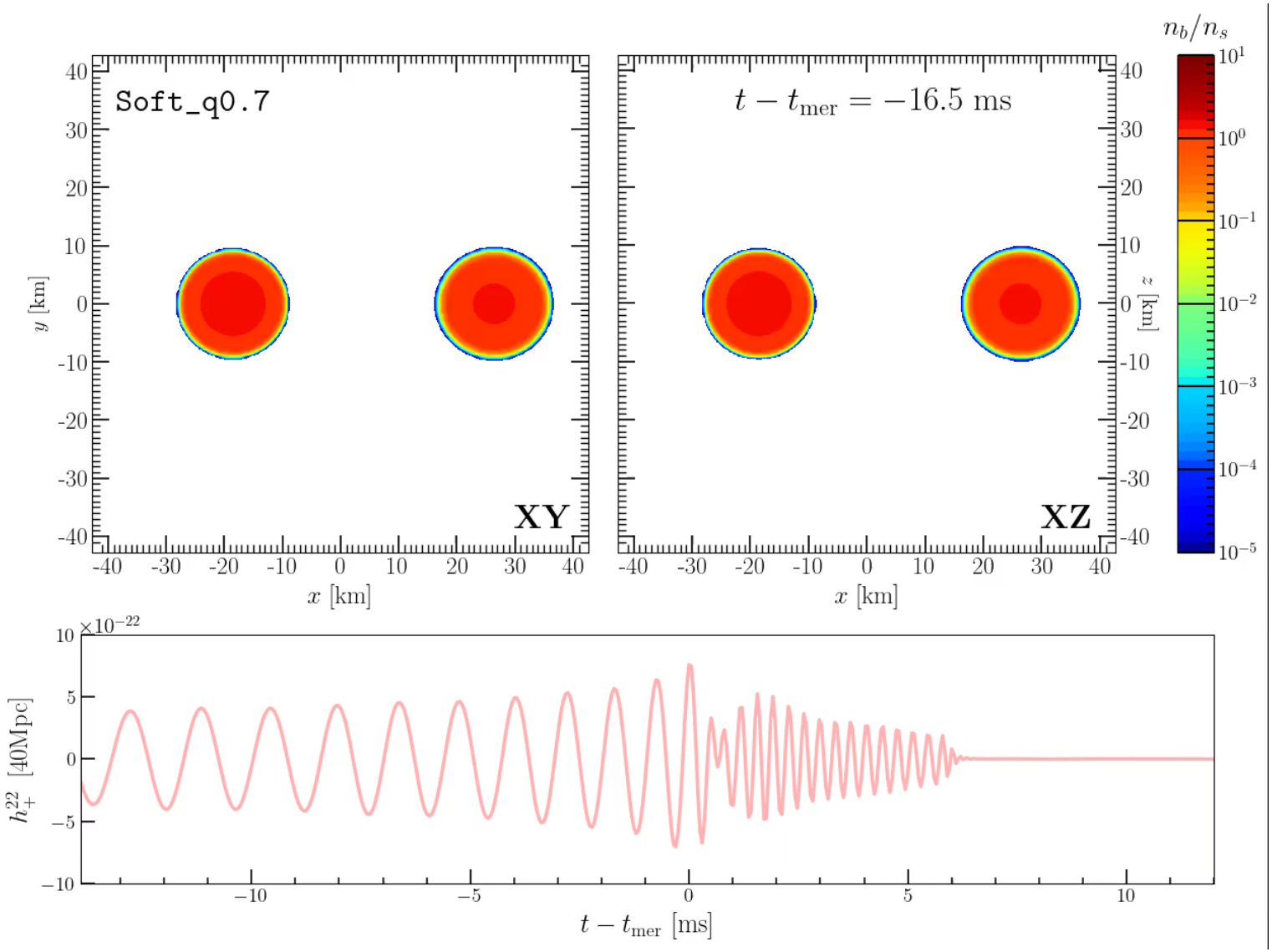
Neutronenstern Kollisionen



[picture: Baiotti, Rezzola arXiv:1607.03540]

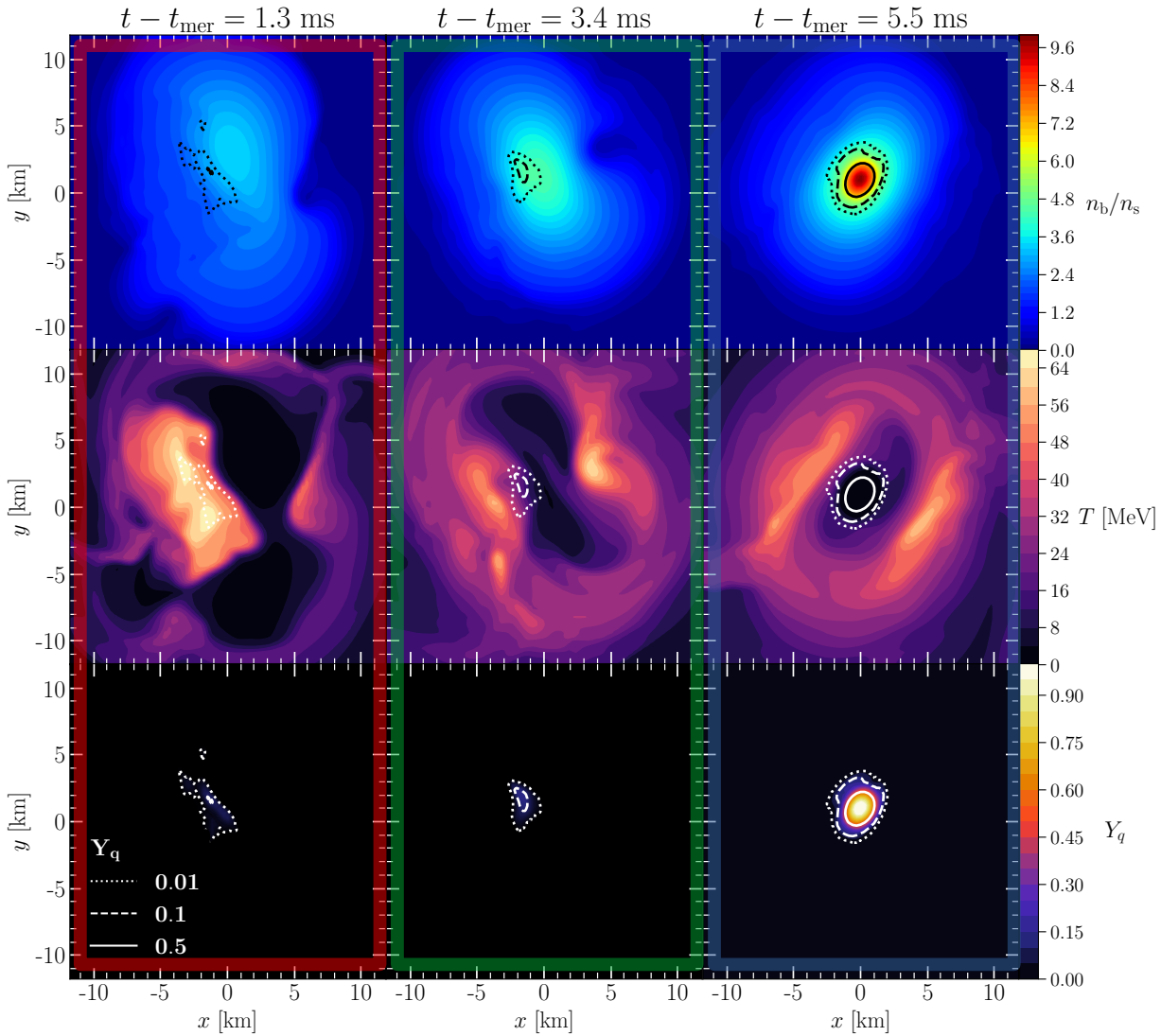
High-Performance Computing Center Stuttgart

[Picture Copyright: Ben Derzian for HLRS]



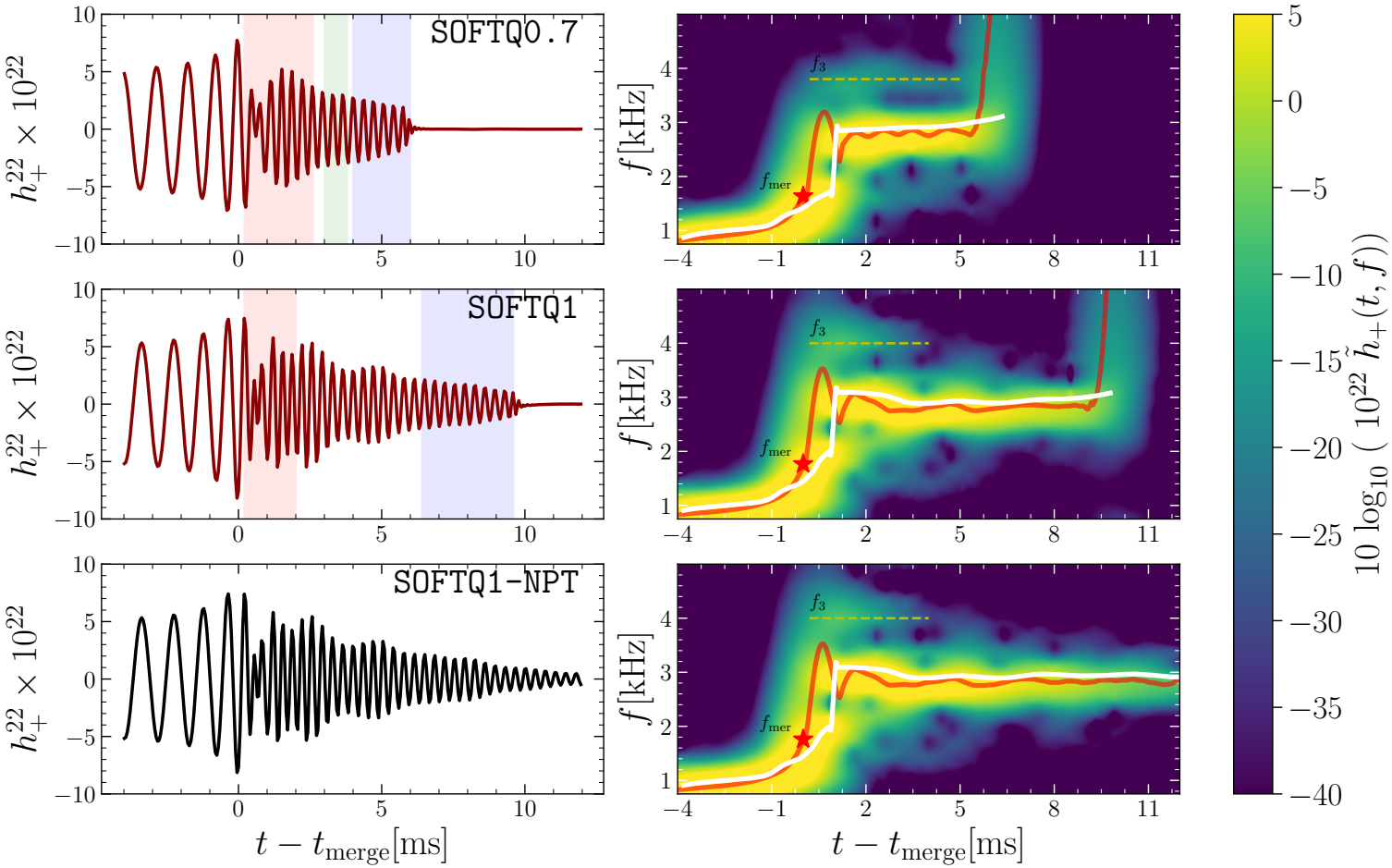
[S. Tootle, CE, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla arXiv:2205.05691]

Hot, Warm and Cold Quarks



[S. Tootle, CE, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla arXiv:2205.05691]

Vorhersagen für Gravitationswellen Signale



[S. Tootle, CE, K. Topolski, T. Demircik, M. Järvinen, L. Rezzolla arXiv:2205.05691]

Zusammenfassung

- Nach schwarzen Löchern sind Neutronensterne die dichtesten Objekte in unserem Universum.
- Beobachtent als Pulsare und Gravitationswellen (+ EM-Strahlung) von Neutronensternkollisionen.
- Beschreibung von dichter Materie in diesen Sternen extrem schwierig.
- Offene Frage: Quarkmaterie in Neutronensternen und deren Kollisionen?
- Ansatz: Ersatzmodelle für QCD aus holographischem Prinzip.
- Numerische Simulationen: 3 unterschiedliche Szenarien für Quarkformation, Vorhersagen für Gravitationswellen, etc.
- Zukunft: Lebenszeit hypermassiver Neutronensterne, Einfluss von Quarks auf Kollaps nach Kollision, weitere Einschränkung des holographischen Modells mit zukünftigen Observationen, etc.