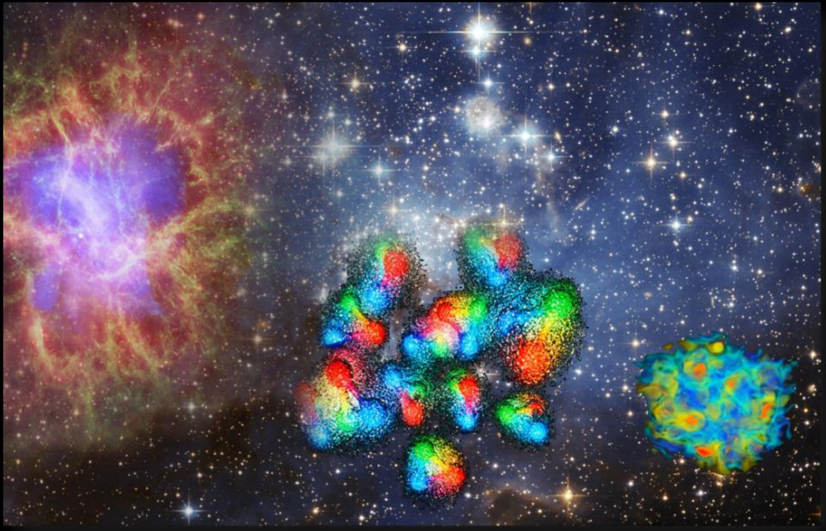
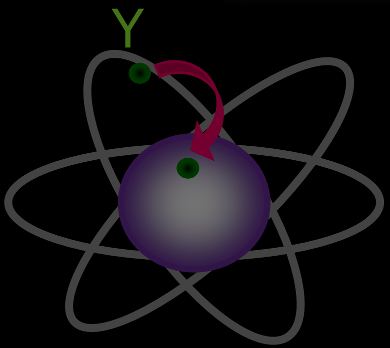
WASA @ GSI - 27th November 2017

Overview of/ Motivation for Hypernuclear Physics

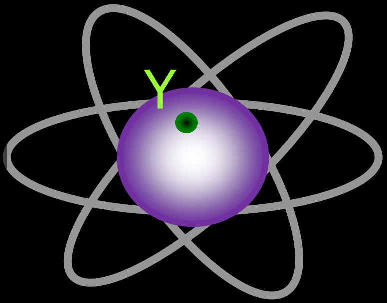
Bringing Heaven to Earth

Josef Pochodzalla

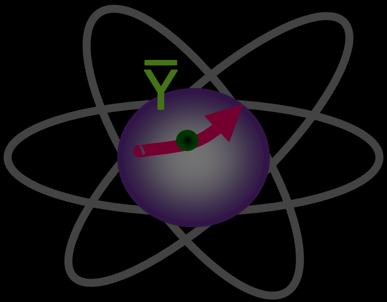




hyperatoms



hypernuclei

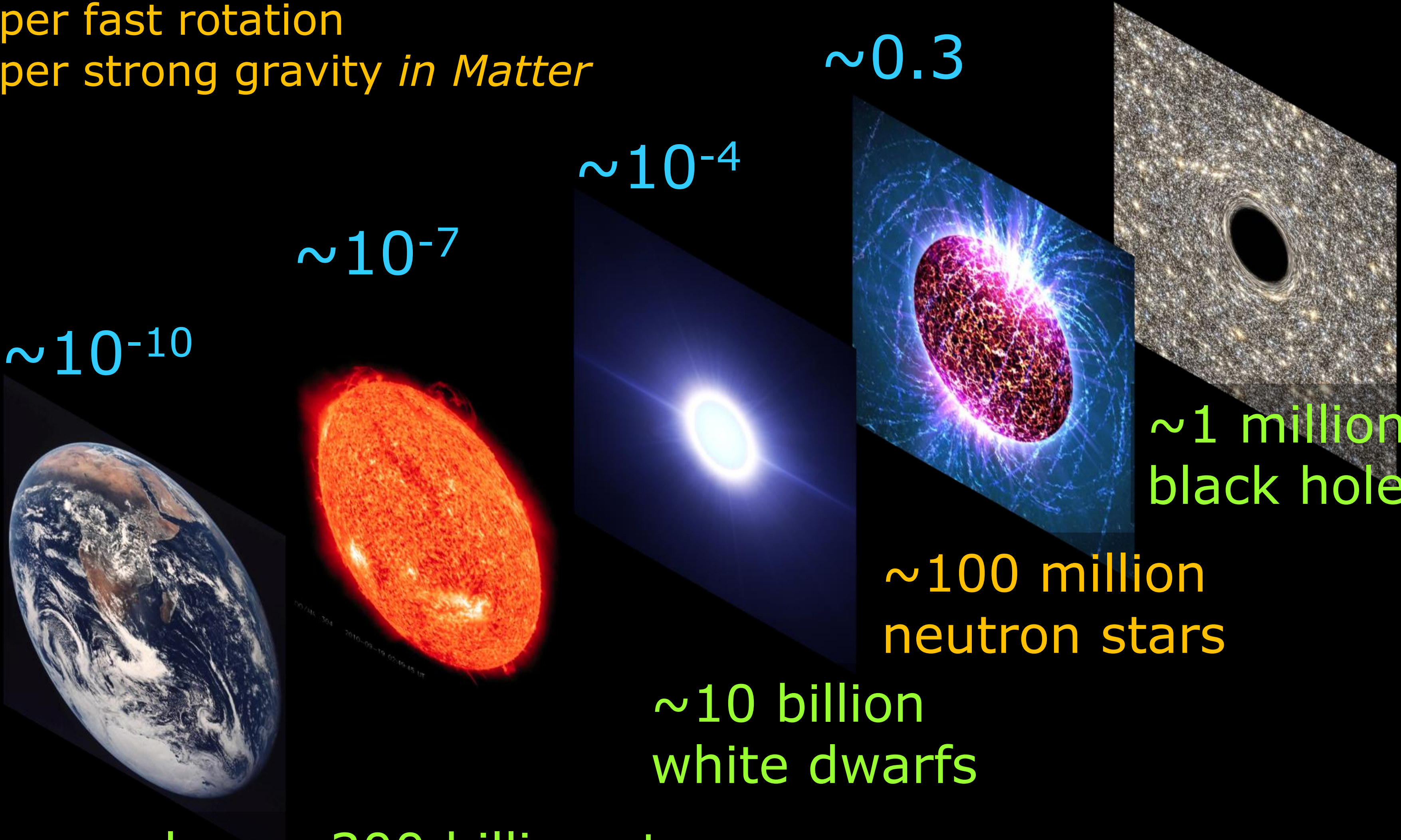


(anti)hyperon scattering

Neutron stars are Superstars

super high density
super strong magnetic fields
super fast rotation
super strong gravity *in Matter*

$$\frac{2GM}{c^2R}$$



$\sim 10^{-10}$

$\sim 10^{-7}$

$\sim 10^{-4}$

~ 0.3

1

in our galaxy ~300 billion stars

~10 billion
white dwarfs

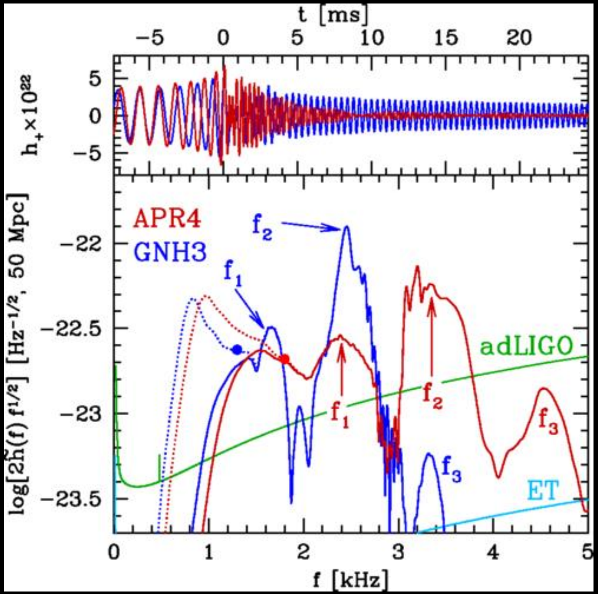
~100 million
neutron stars

~1 million
black holes

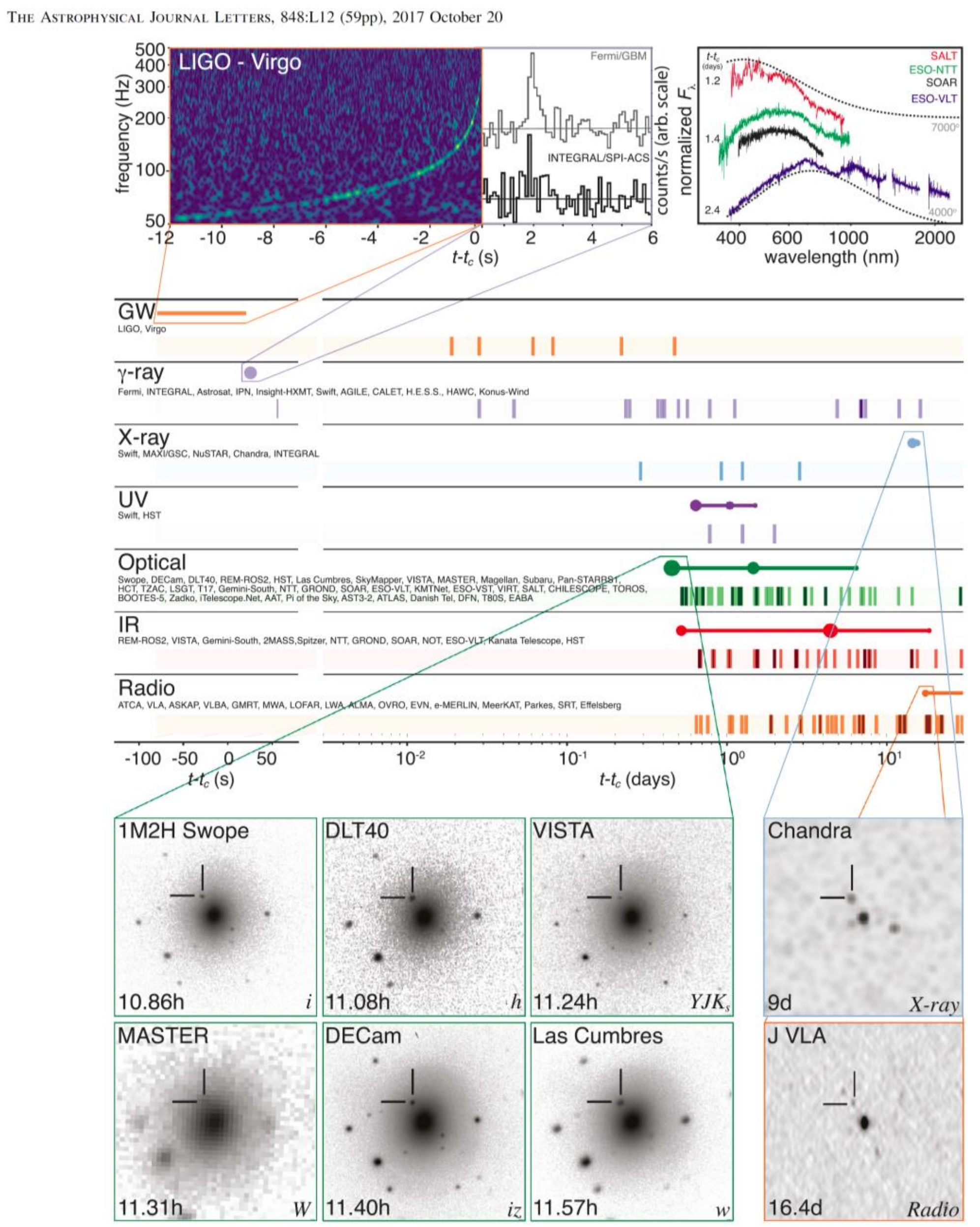
2017 August 17 12:41:04 UTC

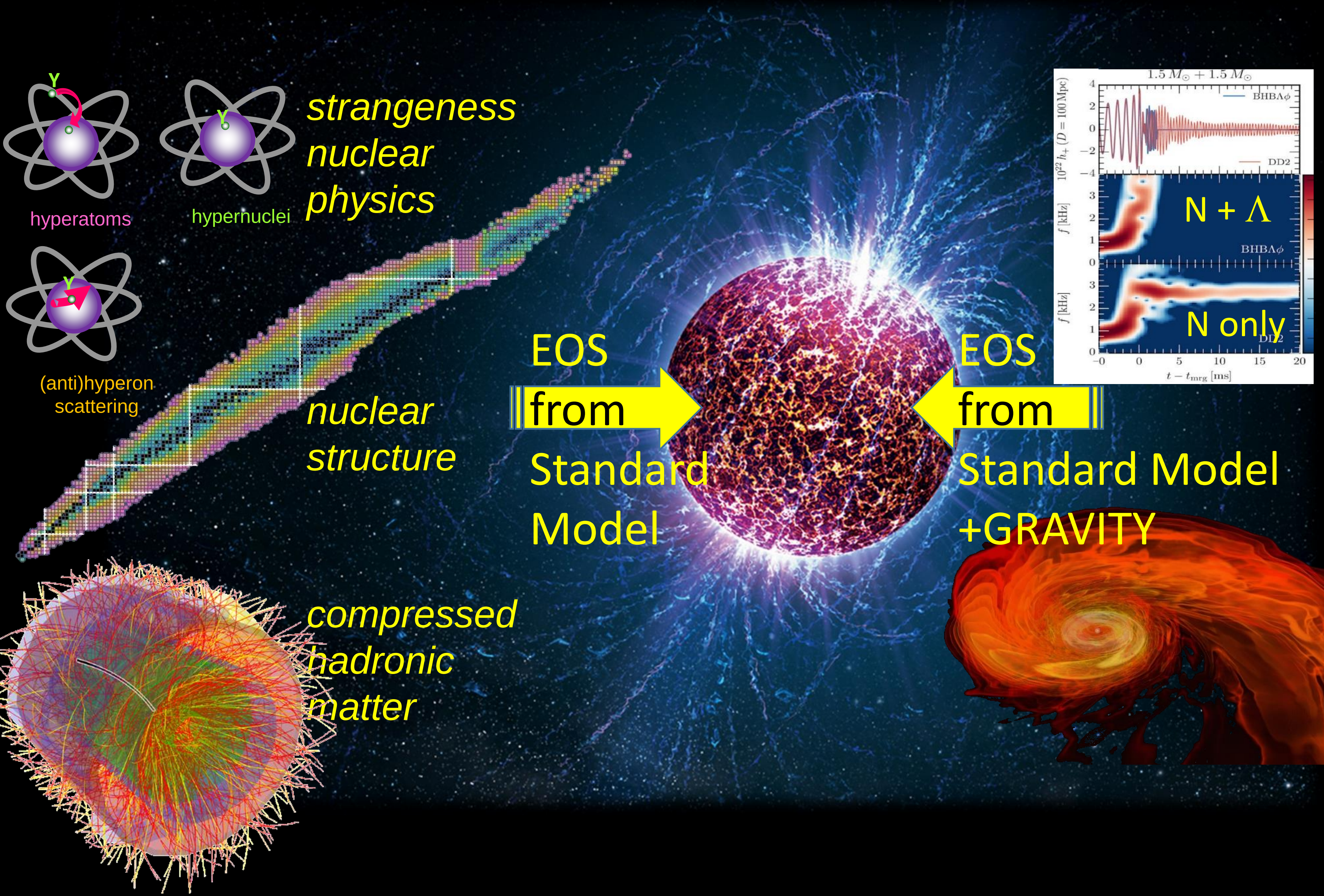
- GW170817 detected by LIGO and Virgo
- First multi-messenger observations of a binary neutron star merger
- Constraints in radius, …
- With improved sensitivity to post-merger spectrum $\Rightarrow$ EOS

A. Kentaro Takami, Luciano Rezzolla, and Luca Baiotti Phys. Rev. Lett. **113**, 091104



The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20





hyperatoms

hypernuclei

(anti)hyperon scattering

strangeness nuclear physics

nuclear structure

compressed hadronic matter

EOS from Standard Model

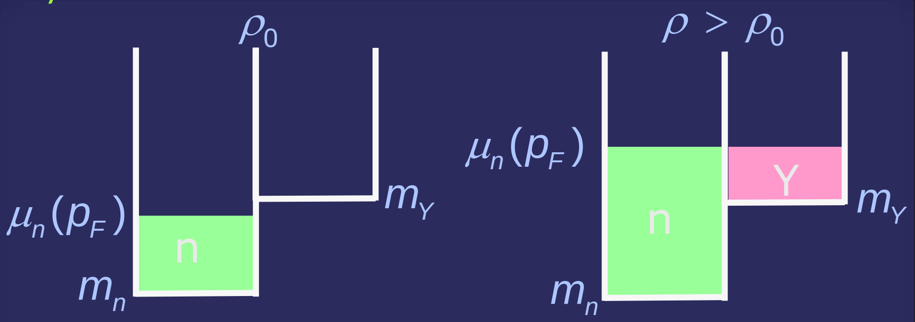
EOS from Standard Model +GRAVITY

N + Λ

N only

Hyperon Puzzle

Cameron 1959,
Ambartsumyan &
Saakyan 1960



$e^- + p \to \nu_e + \Lambda$ $\qquad$ $p_{F,n}^2 + m_n^2 \geq m_\Lambda^2$

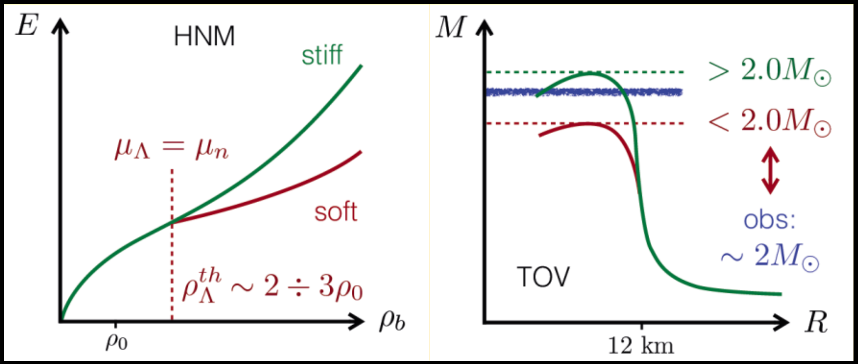
m_Λ=1116 MeV, m_n= 939MeV $\Rightarrow p_{F,n} \approx 600 MeV \simeq 3 fm^{-1}$

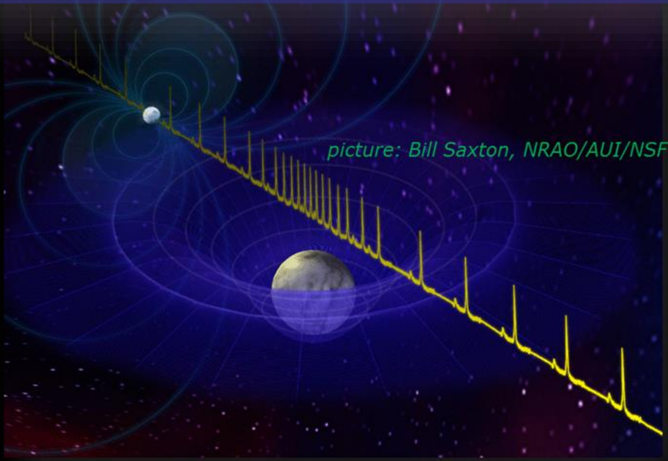
non-interacting Fermi-gas: $\rho = \frac{p_{F,n}^3}{3\pi^2} \Rightarrow p_{F,n}(\rho_0) = 1.7 fm^{-1}$

$\Rightarrow$ appearence of hyperons at $\rho_\Lambda \approx 5.5\rho_0$

with interactions $\rho_\Lambda \approx 2-3\rho_0$

But:
the appearance of hyperons
⇒ relieve of Fermi pressure
⇒ softer equation of state
⇒ reduction of maximal mass





picture: Bill Saxton, NRAO/AUI/NSF

M(PSR J1614-2230) =1.928 ± 0.017 $M_\odot$

M(PSR J0348+0432)=2.01 ± 0.04 $M_\odot$

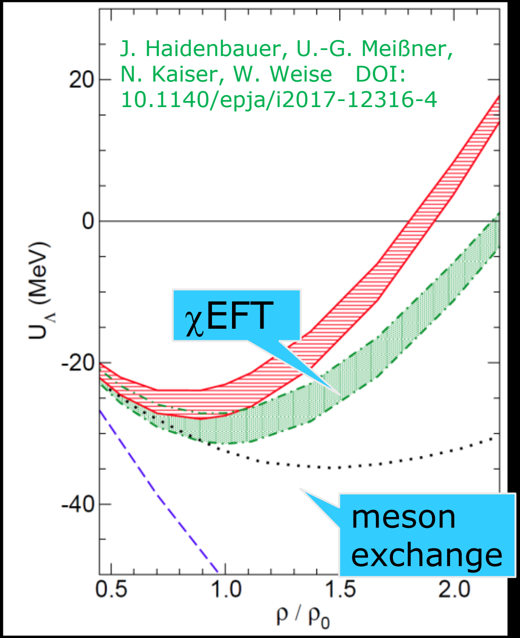
M(PSR J1946+3417)=1.828 ± 0.022 $M_\odot$

P. B. Demorest *et al.*, Nature 467 (2010)
update: E. Fonseca et al., ApJ 832, 167 (2016)
J. Antoniadis *et al.*, Science 340 (2013)
E.D. Barr *et al.*, MNRAS 465, 1711–1719 (2017)

Possible Solutions to the Puzzle

YN and YY Interaction

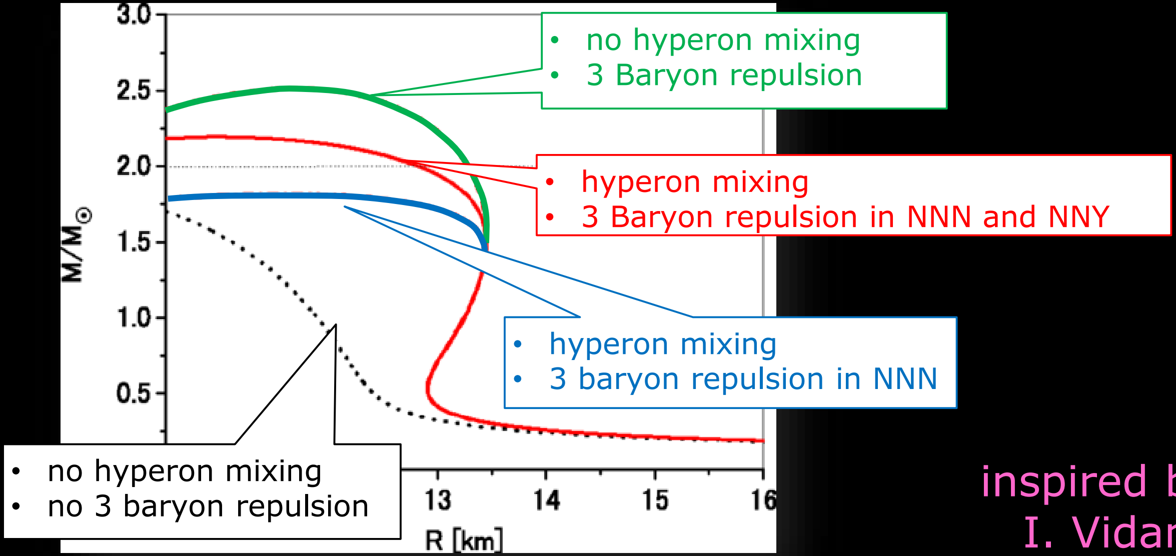
- YY vector meson repulsion: ϕ *meson coupled only to hyperons; yielding strong repulson at high* ρ
- Chiral forces: *YN from* χ*EFT predicts* Λ *s.p. potential more repulsive than from meson exchange*


J. Haidenbauer, U.-G. Meißner, N. Kaiser, W. Weise DOI: 10.1140/epja/i2017-12316-4

Hyperonic Three-body force

- Natural solution based on the known importance of 3NN forces in nuclear physics

Y. Yamamoto, T. Furumoto, N. Yasutake, Th. A Rijken, Phys. Rev. C 90, 045805 (2014)


- no hyperon mixing
- 3 Baryon repulsion

- hyperon mixing
- 3 Baryon repulsion in NNN and NNY

- hyperon mixing
- 3 baryon repulsion in NNN

- no hyperon mixing
- no 3 baryon repulsion

Quark Matter

- Phase transition to deconfined QM at densities lower than hyperon appearence
- That requires QM which
- (i) is significantly repulsive
- (ii) attractive enough to avoid reconfinement

inspired by
I. Vidana

Possible Solutions to the Puzzle

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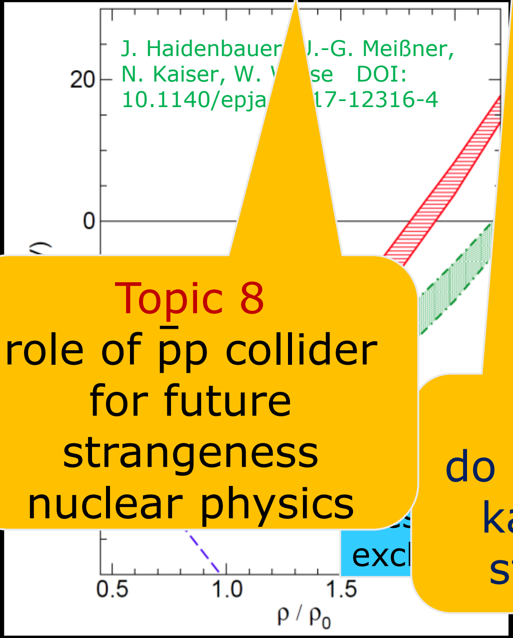

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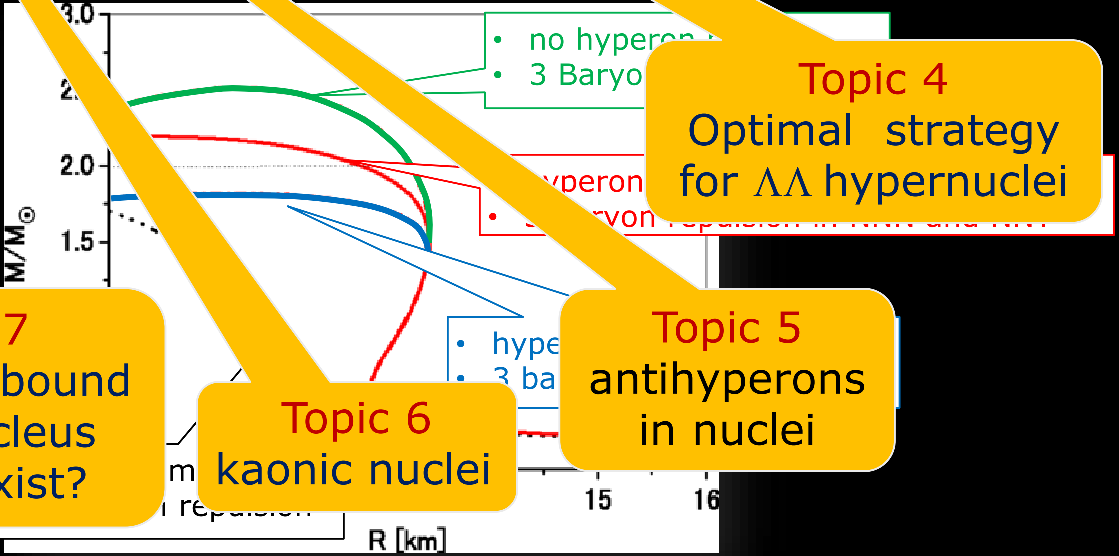

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densities lower than
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- That which
- (i) is significantly
- h
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Topic 1
Hypertriton puzzle

Topic 2
nnΛ puzzle

Topic 3
Charge Symmetry breaking Λn - Λp

Topic 4
Optimal strategy for $\Lambda\Lambda$ hypernuclei

Topic 5
antihyperons in nuclei

Topic 6
kaonic nuclei

Topic 7
do deeply bound kaon-nucleus states exist?

Topic 8
role of $\bar{p}$p collider for future strangeness nuclear physics

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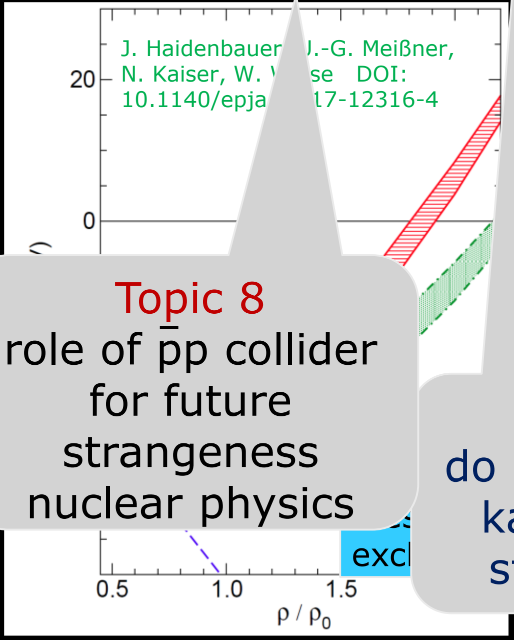
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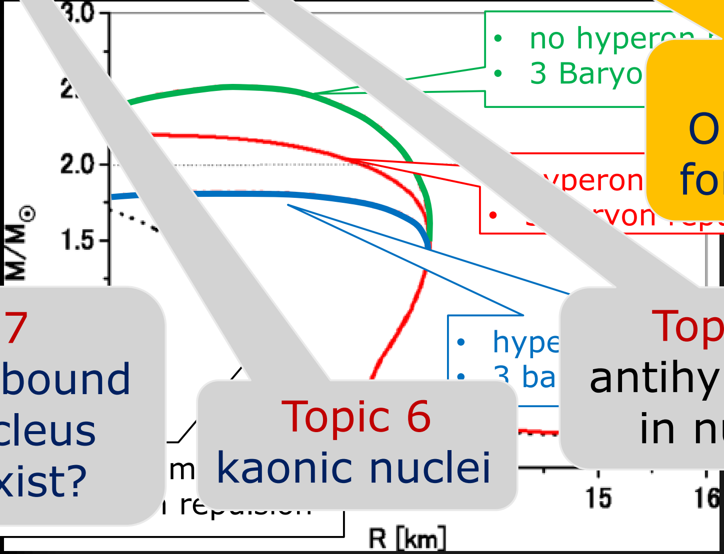

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- That which
- (i) is significantly
- h ent

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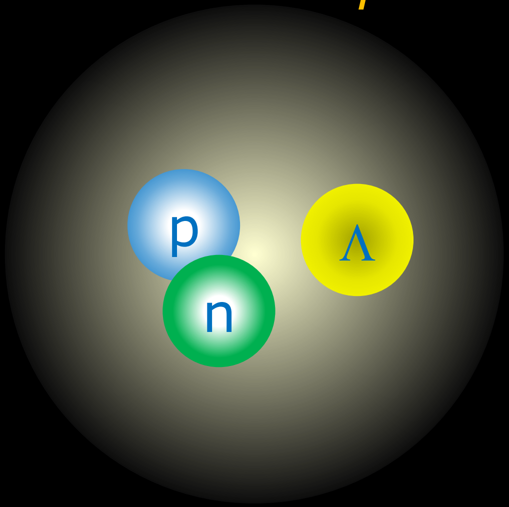
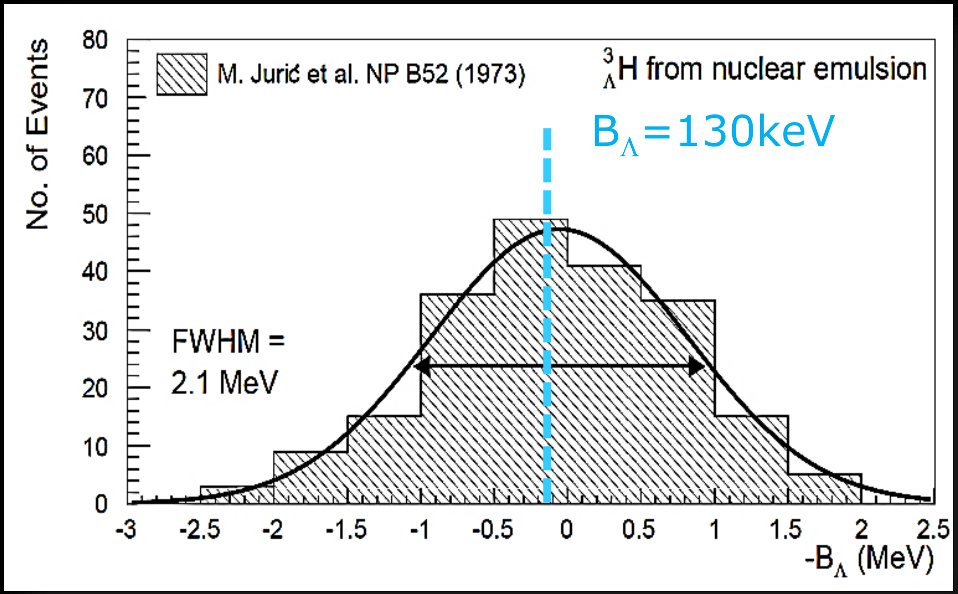
Topic 1: The Hypertriton Puzzle

Do we understand the simplest Hypernucleus?

$^{3}_{\Lambda}\mathrm{H}$



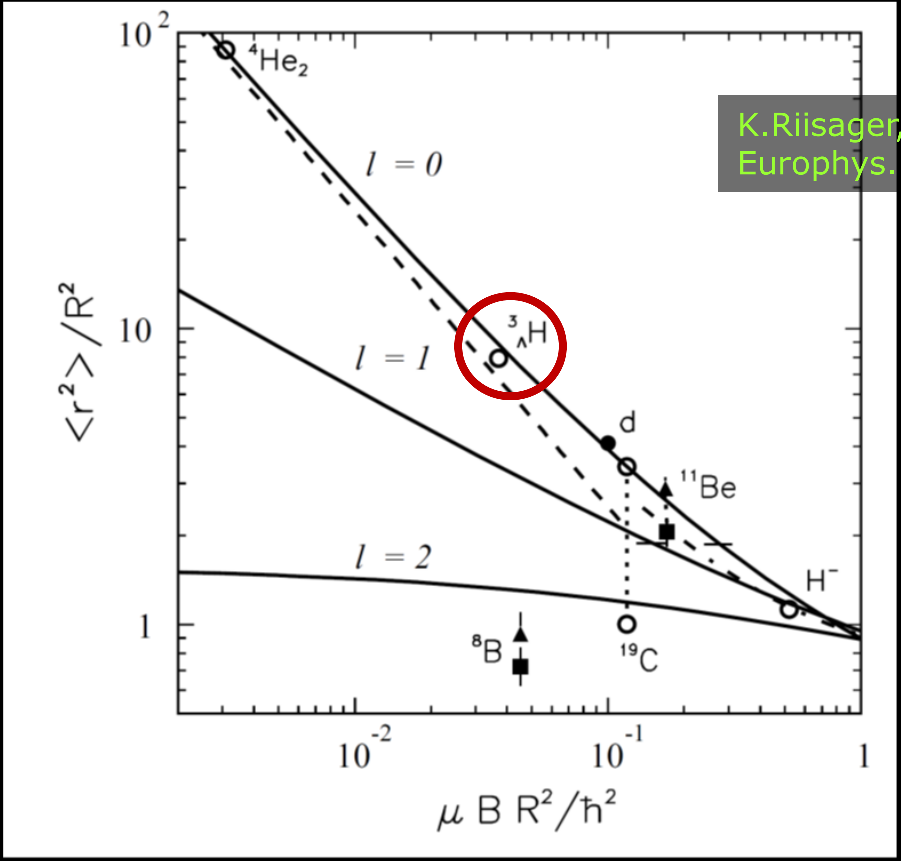


The ${}^{3}_{\Lambda}$H Puzzle: Part 1 - Λ Binding Energy

- ${}^{3}_{\Lambda}$H is most fascinating halo nucleus
  - Binding energy ≈130keV ⇒ Characteristic length of two-body s-wave halo system small

$$\langle \Delta r^2 \rangle = \hbar^2 / (4\mu B) \xrightarrow{{}^{3}_{\Lambda}\mathrm{H}} 10\,\mathrm{fm}$$

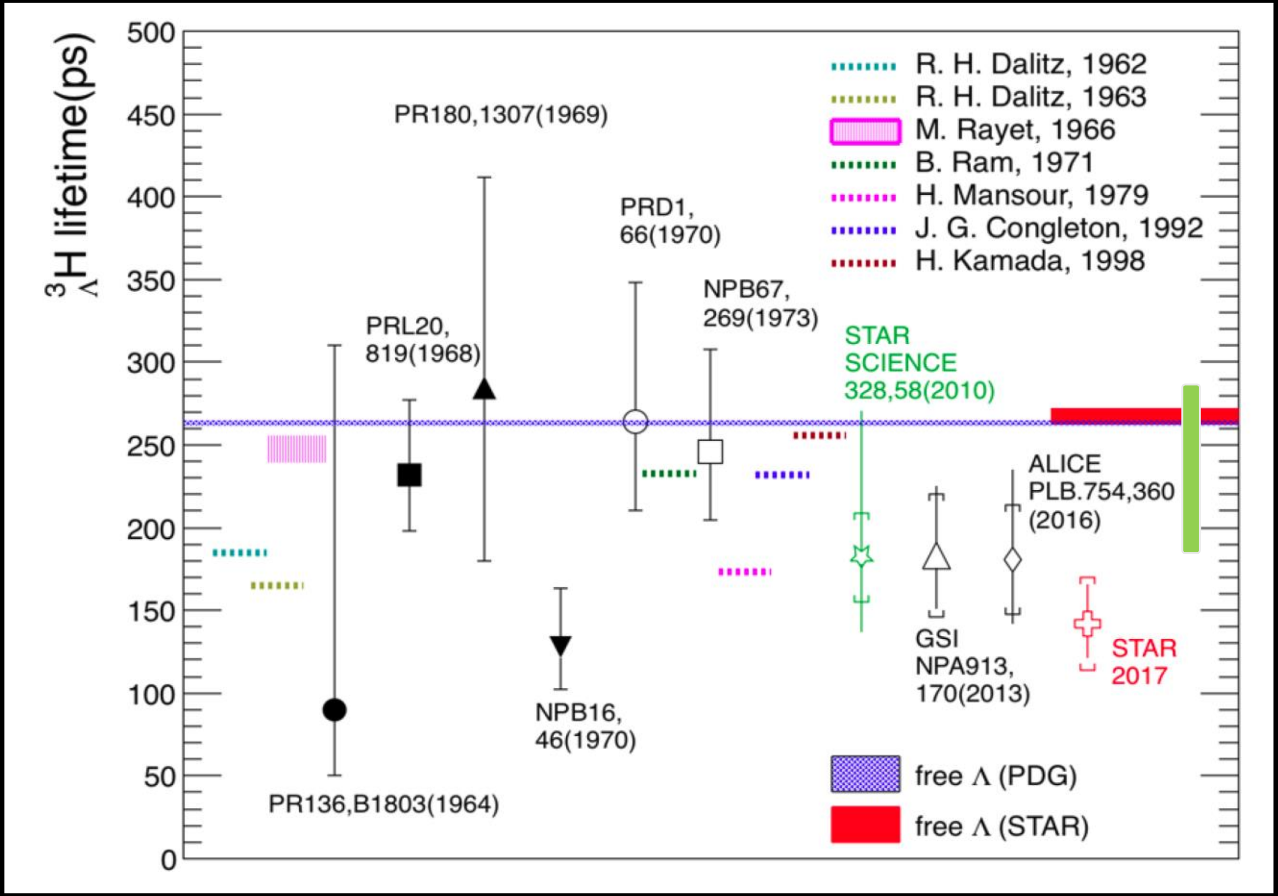
ratio of halo and core-potential square radii



K.Riisager,D.V.FedorovandA.S.Jensen, Europhys. Lett 49, 547 (2000)

scaled separation energy

The $^{3}_{\Lambda}$H Puzzle: Part 2 - Lifetime



ALICE, preliminary
237^{+33}_{-36}(stat.)±17(syst.)ps

STAR arXiv:1710.00436v1 [nucl-ex] 1st Oct 2017

small binding energy ? small lifetime

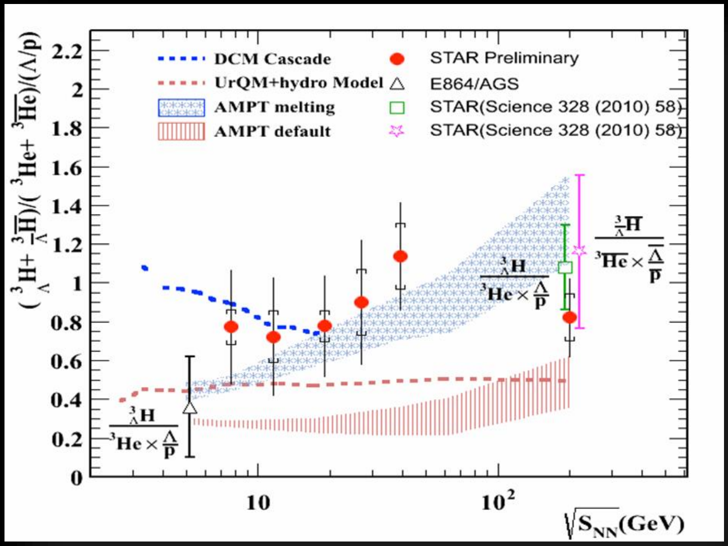
Approaching the $^3_\Lambda$H Puzzle

small binding energy ? small lifetime

- New precision mass measurement at MAMI in 2019
  - Make use of excellent beam quality at MAMI
  - Precision *absolute* energy calibration interference of undulator radiation

- new lifetime measurements
  - 2019: ELPH (γ,K^+)
  - 2019: WASA @ GSI/FAIR
  - 2018: ALICE - end Run2: 2x statistics
  - 2023: ALICE – end run 3: 200x stat.
  - 202x: J-PARC (π^-,K^0)

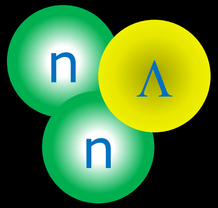
$$\frac{\overbrace{(np\Lambda)}^{^3_\Lambda H}\,/\,\Lambda}{\underbrace{(npp)}_{^3He}\,/\,p}$$



ALICE

Topic 2: The nnΛ Puzzle

Does this “Femto Neutron Star” really exist?



$^{3}_{\Lambda}n$

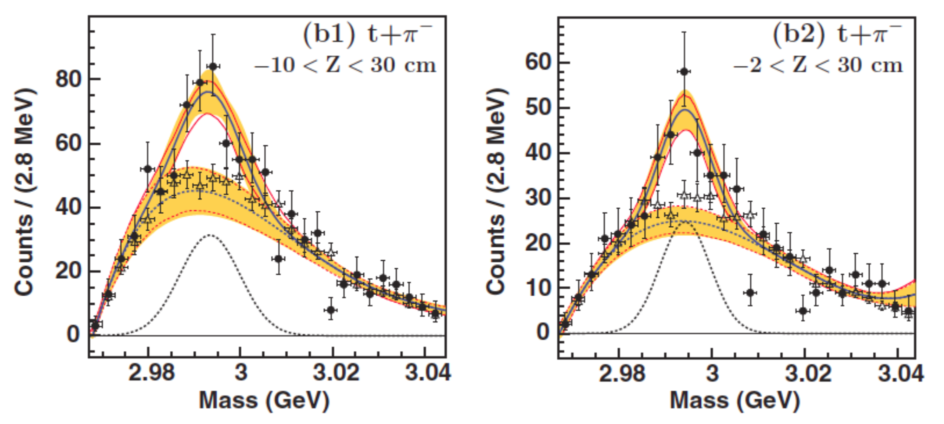
The nnΛ Puzzle

- Such a state has been suggested by the HypHI collaboration
- weak decay nnΛ→π-^{3}H
  ⇒ bound state
- Statistical Decay Model $^6{}_\Lambda$He* at E_x=40MeV

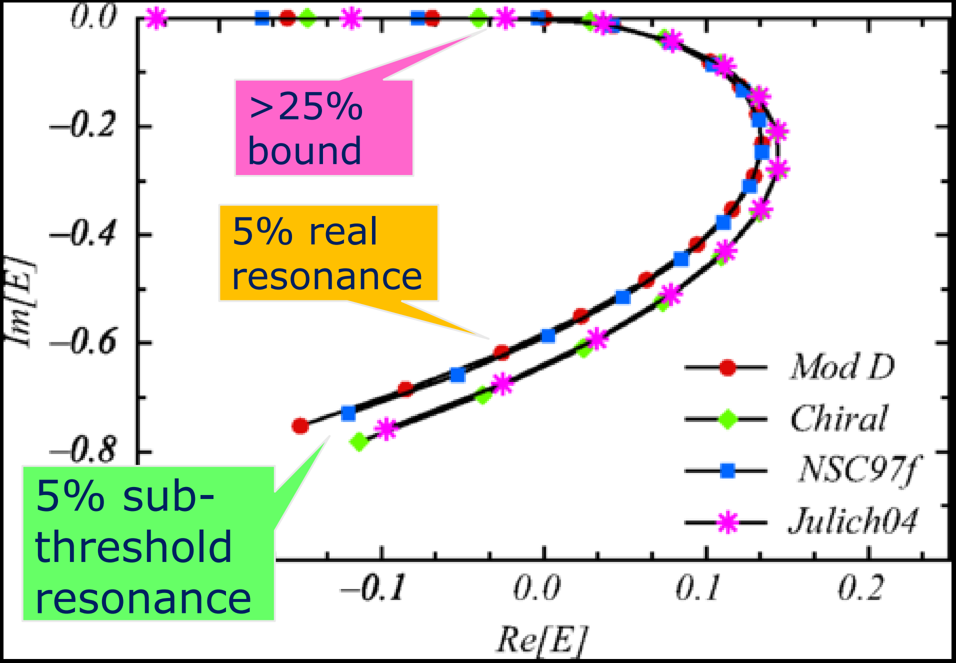
Λ	30.7%	nnΛ	17.3%
$^3{}_\Lambda$H	13.9%	$^4{}_\Lambda$H	29.2%
$^4{}_\Lambda$He	3.9%	$^5{}_\Lambda$He	4.8%

- but: all modern state of the art ab initio theories do not allow a bound nnΛ state

- Do we really understand the Λ–neutron interaction?
  - N-N scattering: 4000 data
  - Y-p scattering: 100 data
  - Y-n scattering: 0 data



C. Rappold et al., Phys. Rev. C 88 , 041001(R) (2013)



>25% bound

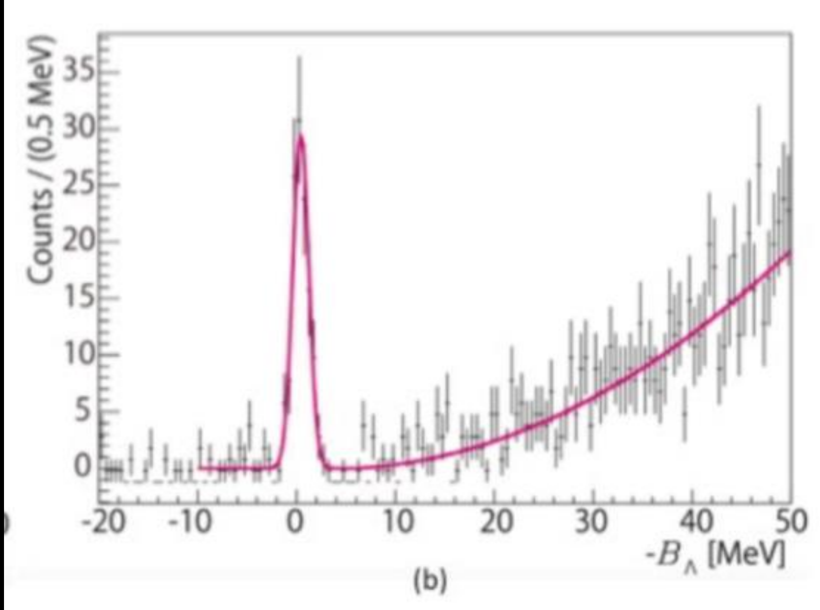
5% real resonance

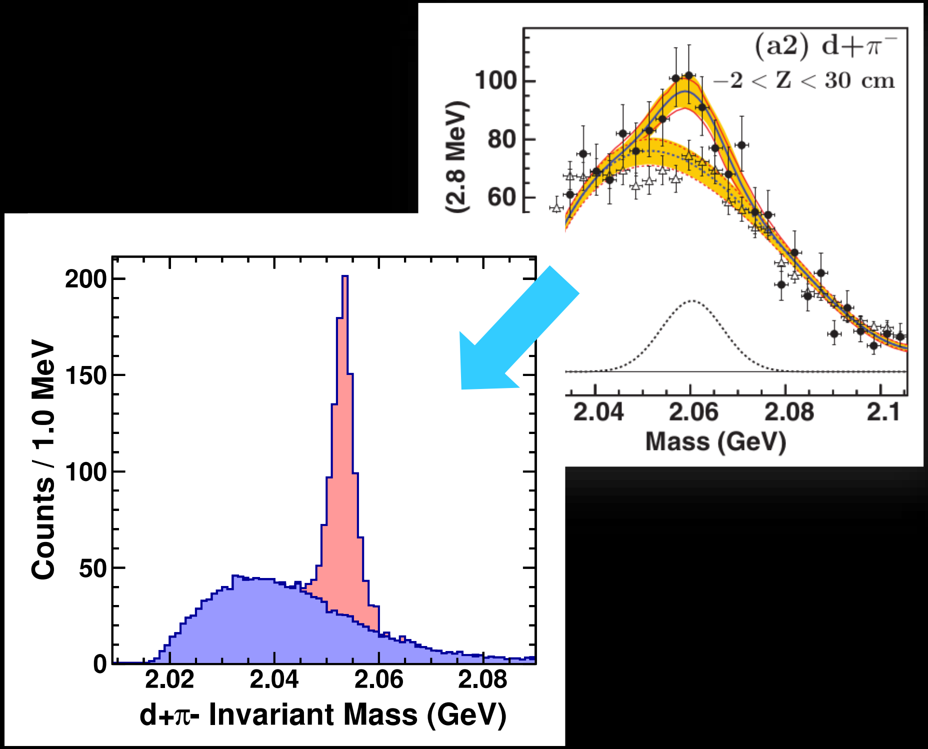
5% sub-threshold resonance

Iraj R. Afnan and Benjamin F. Gibson
Phys. Rev. C 92, 054608

Approaching the nnΛ

- 2018: J-Lab E12-17-003
  - ^{3}H(e,e‘K^{+})(nnΛ)
  - missing mass experiment
  - will measure mass and width
- 2019: FRS+WASA for S447
  - ^{6}Li+^{12}C
  - for d+π 2× better mass resolution
  - 8 times better S/BG ratio
  - lifetime

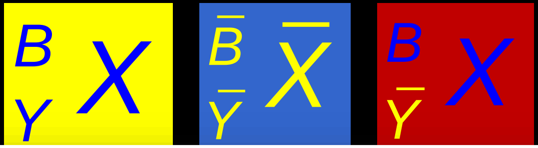


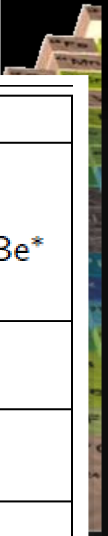


The existence of this „femto-neutron star“ would require to re-think our understanding of three-body interactions

Topic 4: Double Hypernuclei

H. Takahashi et al., PRL 87, 212502-1 (2001)





Nucleus	$\Delta B_{\Lambda\Lambda}(^{A}_{\Lambda\Lambda}Z)$ (MeV)	Experiment	Reference	Remark
$^{10}_{\Lambda\Lambda}$Be	4.3 ± 0.4	Danysz (1963)	[77, 78] [74]	K^- + nuclear emulsion; $\Delta B_{\Lambda\Lambda}$ consistent with NAGARA if decay to $^{9}_{\Lambda}$Be* at $E_x \approx 3$ MeV [81, 11]
$^{6}_{\Lambda\Lambda}$He	4.7 ± 0.6	Prowse (1966)	[198]	K^- + nuclear emulsion only schematic drawing
$^{10}_{\Lambda\Lambda}$Be or $^{13}_{\Lambda\Lambda}$B	-4.9 ± 0.7 0.6 ± 0.8	KEK-E176 (1991) Aoki event	[20, 245] [88, 24, 172]	hybrid-emulsion $(K^-,K^+)\Xi^-_{stopped}$
$^{6}_{\Lambda\Lambda}$He	0.67 ± 0.17	KEK-E373 (2001) NAGARA event	[226, 172] [11]	hybrid emulsion
$^{10}_{\Lambda\Lambda}$Be or $^{10}_{\Lambda\Lambda}$Be*	-1.65 ± 0.15	KEK-E373 (2001) DEMACHIYANAGI event	[10, 172] [11]	$B_{\Lambda\Lambda}$ consistent with Danysz if $E_x \approx 2.8$ MeV
$^{6}_{\Lambda\Lambda}$He or $^{11}_{\Lambda\Lambda}$Be*	3.77 ± 1.71 3.95 ± 3.00 or 4.85 ± 2.63	KEK-E373 (2003) MIKAGE event	[227, 11]	
$^{12}_{\Lambda\Lambda}$Be or $^{11}_{\Lambda\Lambda}$Be*	2.00 ± 1.21 2.61 ± 1.34	KEK-E373 (2010) HIDA event	[172, 11]	

$\Xi^- p \rightarrow \Lambda\Lambda + 28\,\mathrm{MeV}$

DIE WELT 4. September 2001

AGS-E906

FOTO: STEINMETZ/FOCUS

Mit riesigen Maschinen wandeln die modernen Alchimisten Materie ineinander um oder erzeugen gar Materieformen, die es auf der Erde überhaupt nicht gibt. Das Foto zeigt eine Kernfusionsanlage in Neu-Mexiko

Doppelt seltsame Atomkerne synthetisiert

Nach 40 Jahren gelingt Physikern in den USA die Herstellung von exotischer Neutronenstern-Materie

VON BRIGITTE RÖTHLEIN

Brookhaven – Drei Jahre nach Abschluss einer Serie von Experimenten konnten Forscher im Brookhaven National Lab auf Long Island bei der Auswertung der Ergebnisse eine bisher nicht bekannte Art von Materie nachweisen. Sie entstand 1998 bei Zusammenstößen von Wolframatomen mit superschnellen Protonen.

Die Physiker sprechen von „doppelt seltsamen Kernen“ und bringen damit zum Ausdruck, dass sich bei den Kollisionen im Beschleuniger ein Komplex aus mehreren Teilchen gebildet hat, der normalen Atomkernen nicht unähnlich ist. Das Besondere daran ist jedoch, dass diese Gebilde je zwei „seltsame“ Teilchen enthalten.

Die Experimente von Teilchenforschern laufen in Sekundenbruchteilen ab. Man lässt dabei beschleunigte Elementarteilchen auf Ziele prallen und untersucht mit Hilfe großer Detektoren, welche Bruchstücke dabei entstehen. Die Vielzahl der in den letzten Jahrzehnten auf diese Weise entdeckten Teilchen hat gezeigt, dass sich unsere „normale“ Materie auf zwei so genannte Quarks (mit den Namen „up“ und „down“) und Elektronen zurückführen lässt.

Daneben gib es aber auch noch exotische Arten von Materie, die aus schwereren Teilchen bestehen und auf der Erde üblicherweise nicht vorkommen. Zur Unterscheidung erhielten die Quarks dieser Materie die willkürlich gewählten Namen „strange“ (seltsam) und „charme“.

Aus den Millionen von Daten, die während einer Messkampagne entstehen, müssen die Physiker am Ende die wirklich relevanten „Ereignisse“ herausfinden, die sprichwörtliche Nadel im Heuhaufen. In Brookhaven hat sich die Mühe offenbar gelohnt; aus 100 Millionen infrage kommenden Ereignissen filterten Computer zunächst 100 000 heraus, unter denen man dann 30 bis 40 mit den gesuchten Eigenschaften fand. „Hier wurde zum ersten Mal eine größere Anzahl von seltsamen Atomkernen erzeugt“, erklärt Adam Rusek, der stellvertretende Sprecher der 50 beteiligten Physiker aus sechs Ländern.

40 Jahre lang hatte man in den USA, Europa und Japan nach den Gebilden gesucht, aber nur je eines davon gefunden, zum Teil mit zweifelhafter Sicherheit. Nun gelang es nachzuweisen, dass über einen mehrstufigen Zerfallsprozess Strukturen entstanden waren, die aus einem Neutron, einem Proton und zwei Lambda-Teilchen bestanden. Diese enthalten je ein up- und ein down-Quark und ein seltsames (strange) Quark. Die Lambda-Paare sind nun die bejubelten „doppelt seltsamen Kerne“. Es ist allerdings sehr schwierig, sie näher zu untersuchen, da sie bereits nach weniger als einer Milliardstel Sekunde wieder zerfallen.

Die Forscher erhoffen sich vom Studium der seltsamen Kerne Erkenntnisse über jene Kräfte, die zwischen den Teilchen wirken. Daraus wollen sie Rückschlüsse auf die Prozesse in so genannten Neutronensternen ziehen. Diese Himmelskörper entstehen, wenn heiße Sterne am Ende ihres Lebens ausgebrannt sind und in sich zusammenstürzen. Man vermutet, dass sie große Mengen seltsamer Teilchen enthalten und dass sie der einzige Ort im All sind, wo seltsame Materie stabil existiert.

Weitere Informationen im Web:
www.bnl.gov

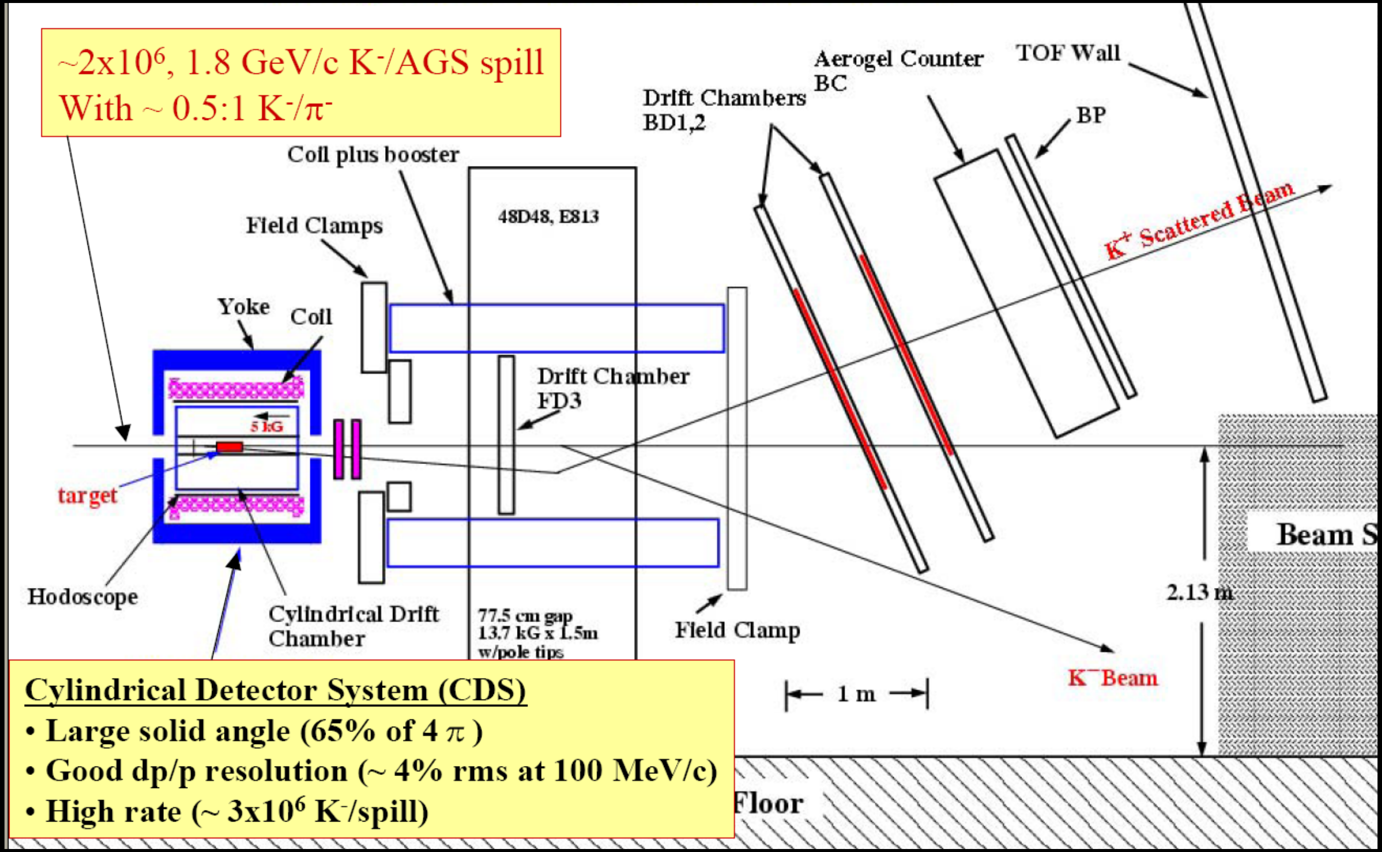
The E906: $^9Be(K^-,K^+\pi^-\pi^-)$

Doube Hypernulei $$ {}^{A0}_{\Lambda\Lambda}Z^* \rightarrow {}^{A}_{\Lambda\Lambda}Z + X $$

$$ \rightarrow \pi^- + {}^{A}_{\Lambda}(Z+1) $$

$$ \rightarrow \pi^- + {}^{A}(Z+2) $$

Twin Hypernuclei $$ {}^{A0}_{\Lambda\Lambda}Z^* \rightarrow {}^{A1}_{\Lambda}Z_1 + {}^{A2}_{\Lambda}Z_2 + X $$



~2x10⁶, 1.8 GeV/c K⁻/AGS spill
With ~ 0.5:1 K⁻/π⁻

Cylindrical Detector System (CDS)

- Large solid angle (65% of 4 π)
- Good dp/p resolution (~ 4% rms at 100 MeV/c)
- High rate (~ 3x10⁶ K⁻/spill)

K-

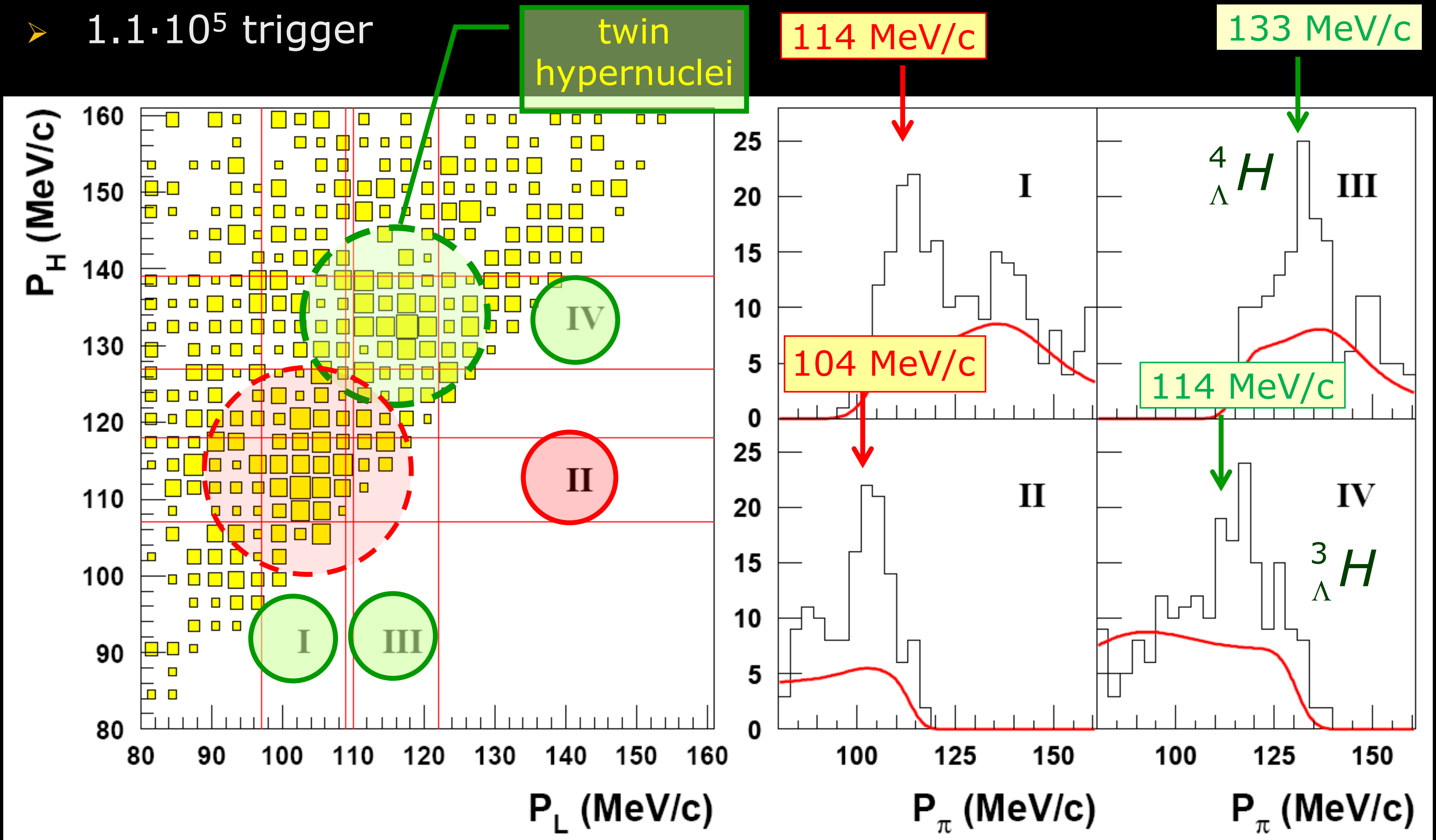
K+

beam dump

E906

- $9 \cdot 10^{11}$ K^- on Be target
- $1.1 \cdot 10^5$ trigger

consistent with single Λ-hypernuclei



twin hypernuclei

114 MeV/c

133 MeV/c

104 MeV/c

114 MeV/c

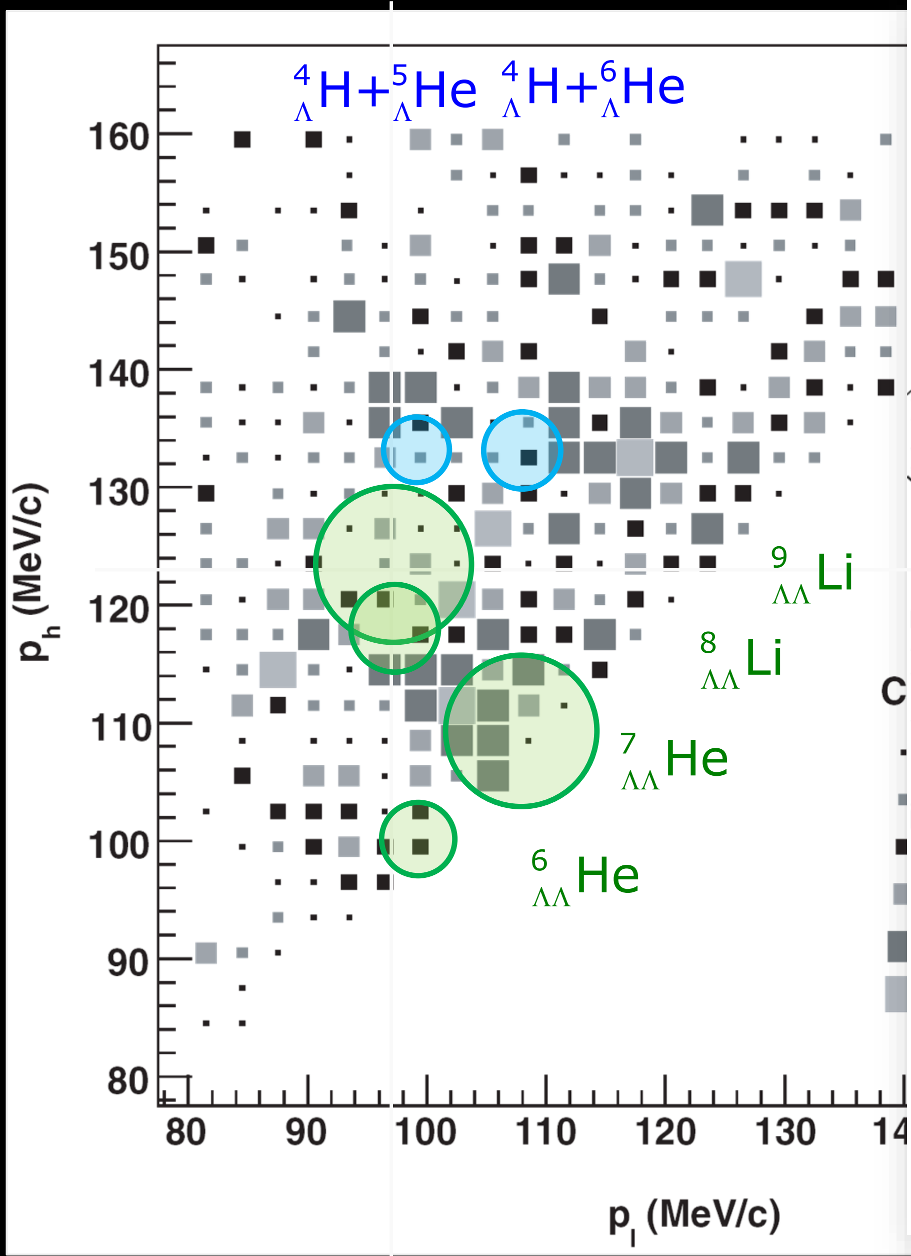
momentum of the pion with lower momentum

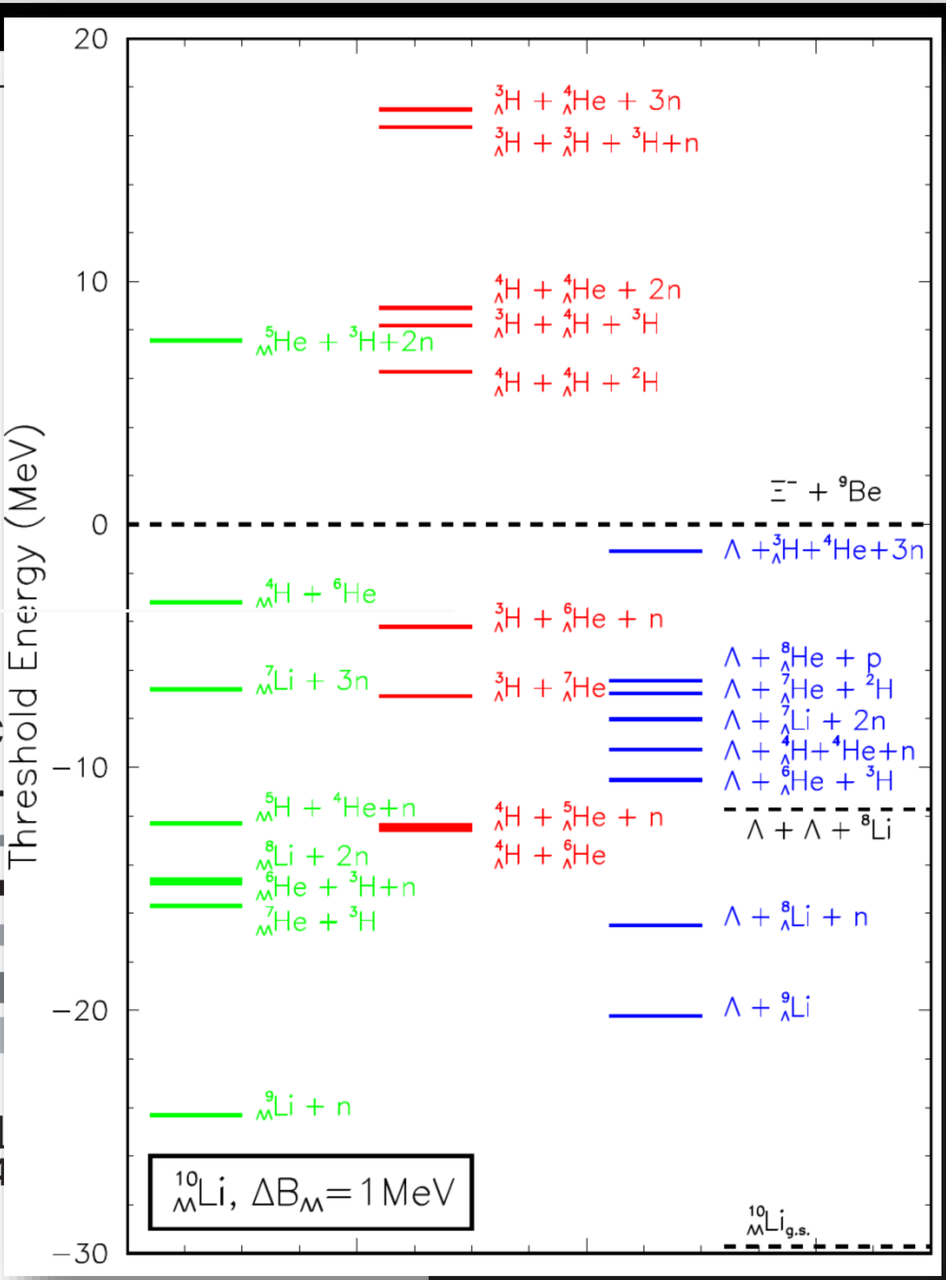
momentum of the pion with lower momentum

$^{4}_{\Lambda\Lambda}H$

$^{3}_{\Lambda}H + ^{4}_{\Lambda}H$

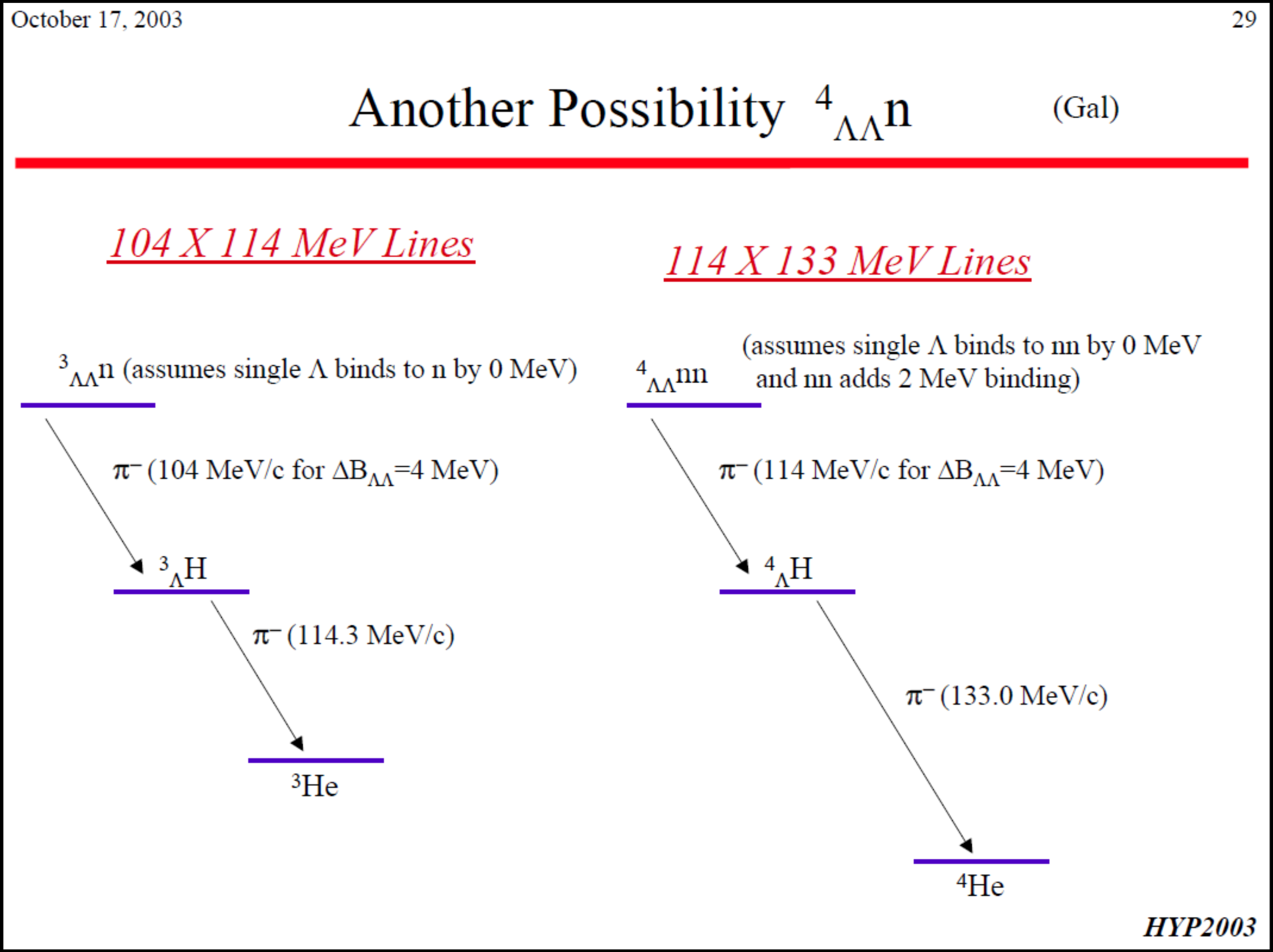
Ξ^- Stopping & Fusion: $\Xi^- + {}^{9}Be \rightarrow {}^{10}_{\Lambda\Lambda}Li^*$





Can nnΛΛ solve the puzzle?

A. Gal, HYP2003



October 17, 2003 29

Another Possibility ${}^{4}_{\Lambda\Lambda}n$ (Gal)

104 X 114 MeV Lines

${}^{3}_{\Lambda\Lambda}n$ (assumes single Λ binds to n by 0 MeV)

π^- (104 MeV/c for $\Delta B_{\Lambda\Lambda}$=4 MeV)

${}^{3}_{\Lambda}H$

π^- (114.3 MeV/c)

${}^{3}He$

114 X 133 MeV Lines

${}^{4}_{\Lambda\Lambda}nn$ (assumes single Λ binds to nn by 0 MeV and nn adds 2 MeV binding)

π^- (114 MeV/c for $\Delta B_{\Lambda\Lambda}$=4 MeV)

${}^{4}_{\Lambda}H$

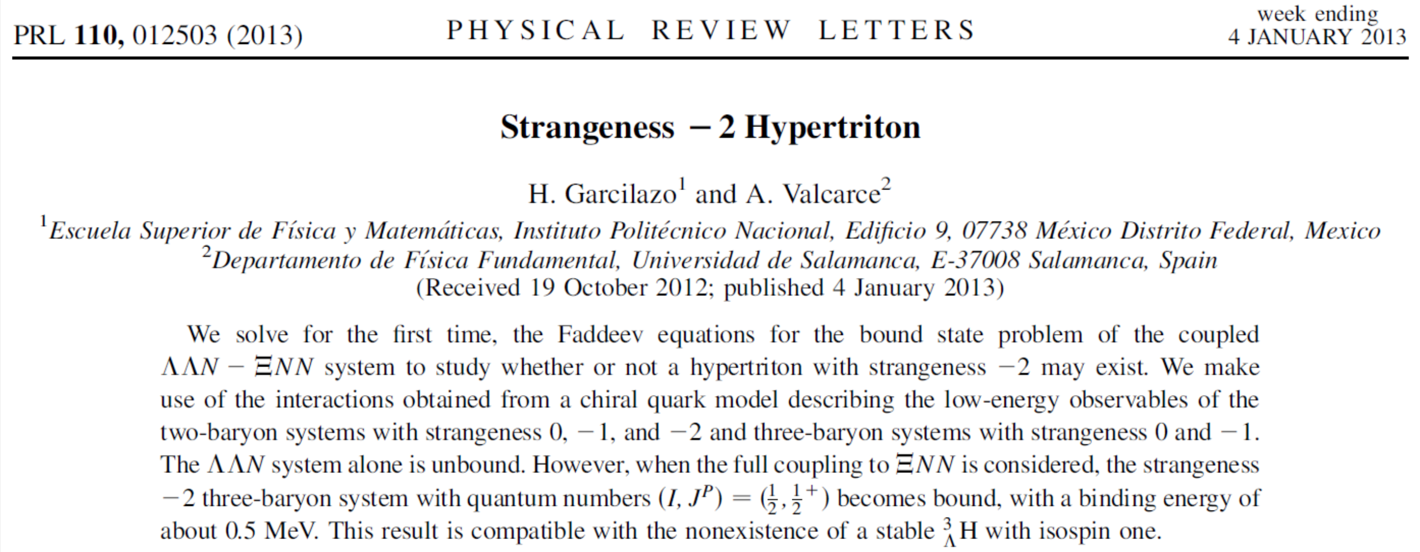
π^- (133.0 MeV/c)

${}^{4}He$

HYP2003

Are nΛΛ and nnΛΛ bound ?

- ΛΛn possibly bound



PRL **110,** 012503 (2013) PHYSICAL REVIEW LETTERS week ending 4 JANUARY 2013

Strangeness −2 Hypertriton

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(Received 19 October 2012; published 4 January 2013)

We solve for the first time, the Faddeev equations for the bound state problem of the coupled $\Lambda\Lambda N - \Xi NN$ system to study whether or not a hypertriton with strangeness −2 may exist. We make use of the interactions obtained from a chiral quark model describing the low-energy observables of the two-baryon systems with strangeness 0, −1, and −2 and three-baryon systems with strangeness 0 and −1. The $\Lambda\Lambda N$ system alone is unbound. However, when the full coupling to ΞNN is considered, the strangeness −2 three-baryon system with quantum numbers $(I, J^P) = (\frac{1}{2}, \frac{1}{2}^+)$ becomes bound, with a binding energy of about 0.5 MeV. This result is compatible with the nonexistence of a stable ${}^3_\Lambda$H with isospin one.

- nnΛΛ may be bound (particularly if nnΛ is bound)
  - S=0, I=1, L=0
  - No Pauli blocking
  - Groundstate: $J^P=0^+$
  - calculation still rather schematic

J.-M. Richard, Q. Wang, and Q. Zhao, Phys. Rev. C 91, 014003 (2015)

- If nΛΛ and nnΛΛ are bound, they might help to understand the E906 puzzle

Strangeness Nuclear Physics

strangeness in nuclei

- *Y^nN^m interaction are important*
- *precision studies are needed*
- *after 60 still many puzzles*

WASA@GSI/FAIR will address two important topics

- *existence of nnΛ*
- *lifetime of hypertriton*

many things could not be mentioned

- *charge symmetry breaking*
- *hyperon mixing*
- *hyper atoms*
- *...*
- *mini $\bar{p}\,p$ collider at FAIR^{++} ?*

Networking Activity @ HORIZON 2020

THEIA

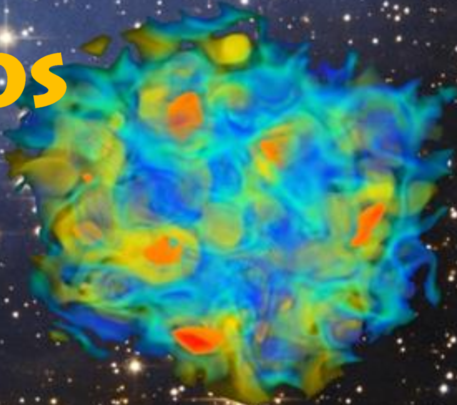
The role of strange Hadrons for the Equation-of-state In compact Astronomical bodies

Josef Pochodzalla

JGU Mainz & Helmholtz-Institut Mainz

HYPERION ∞

= EOS



Thank you for your attention